ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOAI01

STATUS OF THE HIAF ACCELERATOR FACILITY IN CHINA*

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Abstract

The High Intensity heavy-ion Accelerator Facility (HIAF) is under constructed at IMP in China. The HIAF main feature is to provide high intensity heavy ion beam pulse as well as high intensity CW beam. A rapid acceleration in the booster synchrotron ring (BRing) with the ramping rate of 12 T/s is used. The challenges related to the injector systems, RF cavities, power supplies, vacuum system are reported in this paper. The status of the HIAF project construction is presented.

INTRODUCTION

The High Intensity heavy-ion Accelerator Facility (HIAF) is a new accelerator under construction at the Institute of Modern Physics (IMP) in China [1]. It is designed to provide intense primary heavy ion beams for nuclear and atomic physics. The facility mainly consists of a superconducting electron-cyclotron-resonance (SECR) ion source, a continuous wave (CW) superconducting ion linac (iLinac), a booster synchrotron (BRing) and a high precision spectrometer ring (SRing). A fragment separator (HFRS) is also used as a beam line to connect BRing and SRing. Six experimental terminals will be built at HIAF. The layout of the HIAF accelerator is shown in Fig. 1. The main parameters are listed in Table 1.

The construction of the HIAF project was started in December 23rd, 2018. Up to now, roughly 50% of civil construction is finished, as shown in Fig. 2. The first component of SECR is planned to installed in the tunnel in 2023. The first accelerated beam at BRing is expected in the middle of 2025. Day-one experiment is scheduled by the end of 2025. A brief time schedule of HIAF construction is shown in Fig. 3.

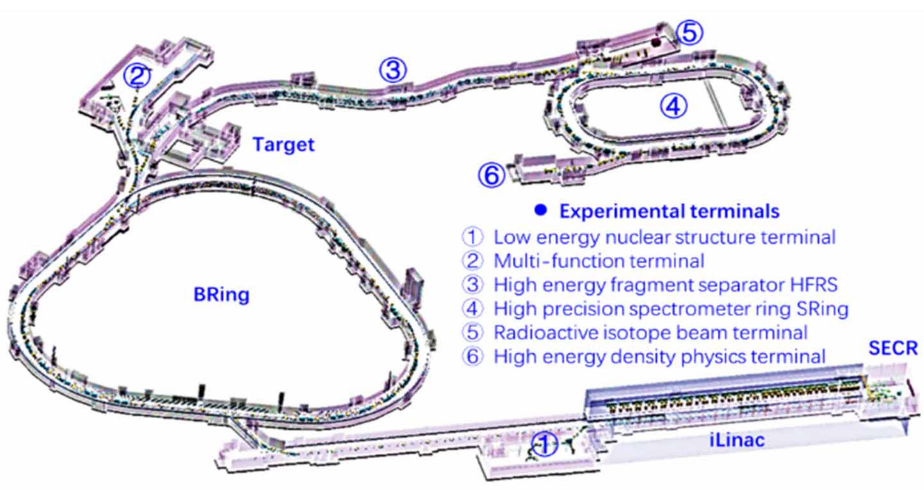

Figure 1: Layout of the HIAF project.

Figure 2: Civil construction of the HIAF project.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOAI02

UPGRADE AND CURRENT STATUS OF HIGH-FREQUENCY SYSTEMS FOR RIKEN RING CYCLOTRON

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Abstract

The high-frequency systems for the RIKEN Ring Cyclotron (RRC) were upgraded to increase the acceleration voltage at 18.25-MHz operation by remodeling its cavity resonators and rf controllers. After the upgrade, the maximum gap voltage at 18.25 MHz improved from about 80 kV to more than 150 kV. The beam intensity of ^{238}U for the RI Beam Factory was increased up to 117 pnA in 2020 by overcoming the beam intensity limitation of the RRC due to the space charge effect. This article presents the details of the upgrade as well as the current status of the high-frequency systems for the RRC.

INTRODUCTION

RI Beam Factory

The Radioactive Isotope Beam Factory (RIBF) [1, 2] at the RIKEN Nishina Center started operation in 2006 in order to pursue heavy-ion beam science through basic and applied research, such as determining the origin of the elements, establishing new nuclear models, synthesizing new elements and isotopes, researching nuclear transmutation, and supporting industrial applications including biological breeding and producing useful RIs. The RIBF has four separate-sector cyclotrons: the RIKEN ring cyclotron (RRC [3], K = 540 MeV), the fixed-frequency ring cyclotron (fRC [4–6], K = 700 MeV), the intermediate-stage ring cyclotron (IRC [7], K = 980 MeV), and the world's first superconducting ring cyclotron (SRC [8], K = 2600 MeV). The RIBF can provide the world's most intense RI beams for all masses by accelerating heavy-ion beams up to 70% of light speed in cw mode, using a cascade of the four ring cyclotrons combined with different types of injectors: a variable-frequency heavy-ion linac (RILAC [9, 10]), a fixed-frequency heavy-ion linac (RILAC2 [11, 12]), and a K70-MeV AVF cyclotron (AVF [13]).

Uranium is one of the most important beams in the RIBF because it can produce many rare isotopes via the in-flight fission of uranium ions by a superconducting in-flight fragment separator, BigRIPS [14]. As shown in Fig. 1, the uranium ions are produced with a powerful 28-GHz superconducting ECR ion source [15, 16] at the charge state of 35+ and accelerated through the RILAC2 and RRC up to 11 MeV/u. After changing their charge state to 64+ by a helium gas stripper [17], they are further accelerated in the fRC and converted to 86+ by a graphite sheet stripper [18]. Finally, they are boosted up to 345 MeV/u by the IRC and SRC, and directed to the BigRIPS.

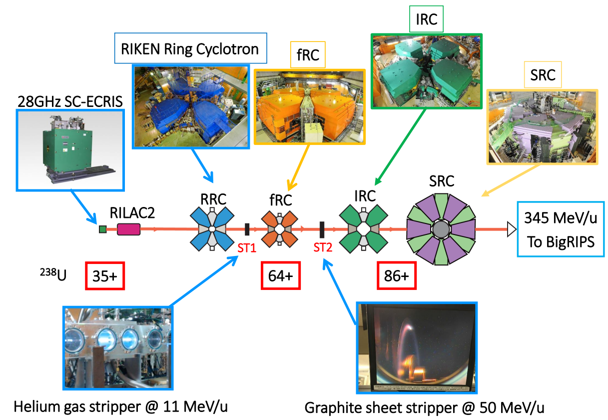

Figure 1: Schematic of uranium acceleration at the RIBF.

This article describes in detail the modification of the high-frequency systems for the RRC.

Overview of RRC

The RRC is a four-sector normal-conducting isochronous ring cyclotron that has been in operation for over 35 years. The RRC can accelerate light ions up to 135 MeV/u and is also frequently used to provide the intermediate-energy beams. Figure 2 indicates the equipment layout of the RRC. The RRC has an injection radius of 89.3 cm and an extraction radius of 356 cm, giving a large velocity gain of 4. Each radial sector has a sector angle of 50 degrees and is equipped with 26 trim coils. Beams are injected and extracted by one electrostatic deflector and two magnetic channels and bending magnets, respectively. The specifications of the RRC are summarized in Table. 1.

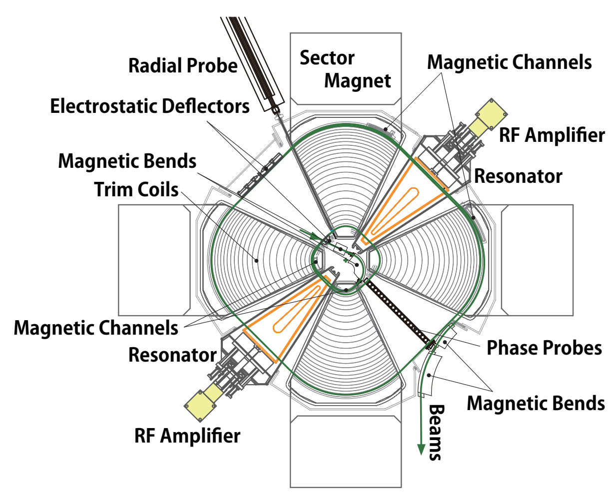

Figure 2: Equipment layout of the RRC.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOA001

STATUS OF THE IsoDAR HIGH-CURRENT H_2^+ CYCLOTRON (HCHC-XX) DEVELOPMENT

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Abstract

The potential existence of exotic neutrinos beyond the three standard model neutrinos is an important open question in particle physics. IsoDAR is a cyclotron-driven, pure electron-antineutrino source with a well-understood energy spectrum. High statistics of anti-electron neutrinos can be produced by IsoDAR, which, when coupled with an inverse beta decay detector such as the LSC at Yemilab, is capable of addressing observed anomalies attributed to sterile neutrinos at the 5 sigma level using electron-flavor disappearance. To achieve this high significance, the IsoDAR cyclotron must produce 10 mA of protons at 60 MeV. This is an order of magnitude more current than any commercially available cyclotron has produced. To achieve this, IsoDAR takes advantage of several innovations in accelerator physics, including the use of H_2^+ and RFQ direct injection, paving the way as a new high power accelerator technology. These high currents also allow for new experiments in dark matter, as well as high production rates of rare isotopes such as ^{225}Ac and ^{68}Ge.

INTRODUCTION

The design of the IsoDAR experiment is set to produce a high flux of anti-electron neutrinos using a compact system that will be in close proximity to a kiloton scale, underground neutrino detector, see Figure 1.

Leading exclusions of sterile neutrinos could be provided by this experiment over five years, in which the IsoDAR experiment could provide a five-sigma exclusion over several anomalies [1]. However, two conditions must be met:

1. The accelerator must be sufficiently compact to be constructed underground in close proximity to the detector, preventing the use of a separated sector cyclotron [2].
2. The accelerator must provide 10 mA of protons at 60 MeV.

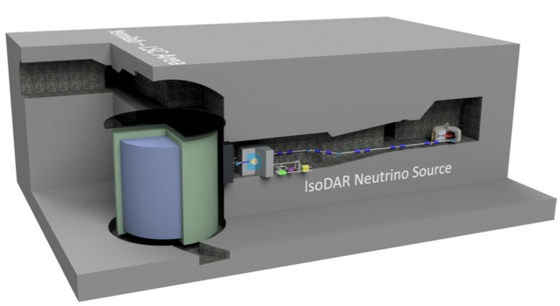

Figure 1: Diagram showing the layout of the IsoDAR experiment. The experiment uses an H_2^+ ion source, which is directly injected into a cyclotron, which accelerates the H_2^+ up to 60 MeV. The H_2^+ is stripped into protons before colliding with the a beryllium target, producing neutrons. The neutrons are absorbed by a highly pure ^{7}Li sleeve, which then undergoes beta decay, and produces anti-electron neutrinos. These neutrinos can then be detected by the nearby detector via inverse beta decay (IBD).

The use of H_2^+ can be used to alleviate space charge in the beam. This is critical for maintaining beam quality in low energy, high intensity regions. Another is the use of a Radio Frequency Quadrupole (RFQ) direct injection system that bunches the beam and leads to higher transmission through the system.

However, high power cyclotrons have applications beyond the particle physics scope. The most common use of cyclotrons is to produce medical isotopes. Rare isotopes are often prohibitively expensive to produce, limiting treatment options for those who require them. The IsoDAR cyclotron can address the bottlenecks of this industry, and help produce large yields of currently rare medical isotopes.

PATH TO HIGHER CURRENTS

Use of H_2^+

The Coulomb repulsion between ions within a beam can lead to emittance and beam size growth. This is particularly important in low energy regions. Most modern cyclotrons accelerate H^- ions, which allows convenient extraction using a stripping foil. However, there are significant advantages to accelerating and extracting H_2^+. This allows twice as many protons to be accelerated with limited space charge effects. The H_2^+ is later run through a stripping foil, which removes the molecular electrons and leaves protons, effectively doubling the beam current.

RFQ Direct Injection

Following the production of H_2^+ is extraction system with four electrodes which is designed to steer and shape the beam in order to properly match the desired input parameters of the RFQ and maximize end-to-end transmission.

The beam is injected as direct current (DC), however as it traverses the RFQ the beam is bunched by the shaped electrodes and RF acceleration. While the beam is only accelerated from 15 keV to 60 keV, the primary purpose of the RFQ is to act as a beam buncher. The RFQ converts the DC beam into a 32.8 MHz beam to match the frequency of the cyclotron. Transmission from ion source to the end of the RFQ has been calculated to be >90% [1].

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOA002

THE COMMISSIONING OF A 230 MeV SUPERCONDUCTING CYCLOTRON CYCIAE-230*

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Abstract

There are very strong demands for proton accelerators in medium energy range in recent years due to the fast growth of proton therapy and the space science in China. For the applications of proton therapy and proton irradiation, the energy range of proton beam is usually from 200 MeV to 250 MeV, or even higher for astronavigation. An R&D project for constructing a 230 MeV superconducting cyclotron (CYCIAE-230) has been initiated at China Institute of Atomic Energy (CIAE) since Jan 2015. In July of 2016, after the funding was approved by China National Nuclear Corporation (CNNC), the construction project was fully launched. In Dec 2019, the superconducting main magnet and the RF system were transferred to the newly built commissioning site. Then, the RF commissioning, ion source and central region test were performed even during the pandemic in early 2020. In September 2020, after finishing the commissioning tests of all subsystems, the beam was reached the extraction channel but with very low efficiency. Since then, with more efforts on beam diagnostics, the fine tuning of the beam phase and the adjusting of the superconducting coil have been proven to be useful to get higher beam extraction efficiency ~55%. In this paper, the commissioning of the key components, including the main magnet, SC coils, internal ion source and central region, extraction system, etc, as well as the commissioning progress of the machine CYCIAE-230 will be presented.

INTRODUCTION

To meet the requirements of proton beam in the energy range of 200 MeV to 250 MeV for the uses of proton therapy and space science research in China, a superconducting cyclotron CYCIAE-230 was designed in CIAE. The overall parameters are listed in Table 1. And the layout of the very compact CYCIAE-230 superconducting cyclotron is shown in Fig. 1 [1].

Table 1: The Overall Parameters of CYCIAE-230

Beam	
Beam current from ion source	>10 μA
Ion source type	Cold PIG
Extracted beam energy	≥230 MeV
Extracted beam current	a few hundreds of nA
Magnet	
Pole structure	Spiral
Pole radius	85 cm
Weight	~ 80 ton
Hill gap	5.0 cm
Central field	2.3 T
Coils	
Coil type	NbTi wire
Current density	≤50 A/mm^2
Ampere-Turn Number	~600000 A.T×2
RF Cavity	
Number of cavities	4
RF frequency	~71.1 MHz
Harmonic Mode	2
Cavity Voltage	80 kV～110 kV
RF Amp. output Power	200 kW (max)
Extraction	
Method	Resonance crossing & processional motion
Elements for extraction	2 electrostatic deflectors and 6 magnetic channels
Deflector voltage	< 100 kV/cm
Deflector gap	5–7 mm

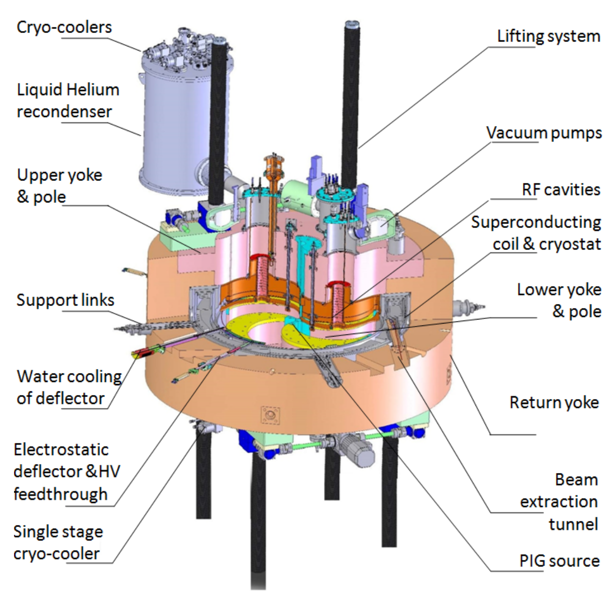

Figure 1: The layout of CYCIAE-230.

* Work supported by National Natural Science Foundation of China under Grants 11475269, 11375274; † cwang@ciae.ac.cn.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOBI01

SUMMARY OF THE SNOWMASS'21 WORKSHOP ON HIGH POWER CYCLOTRONS AND FFAS

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Abstract

In this talk, we summarize the presentations and findings of the "Workshop on High Power Cyclotrons and FFAs" that we held online in September 2021. The workshop was held as part of the 2021 Snowmass Community Exercise – in which the US particle physics community came together in a year-long effort to provide suggestions for a long-term strategy for the field – and the "Accelerators for Neutrinos" subpanel thereof. Topics that were discussed during our high-power cyclotron workshop were the application of cyclotrons in particle physics, specifically neutrino physics, and as drivers for muon production. Furthermore, as these same accelerators have important applications in the fields of isotope production and possibly in energy research, we have included those topics as well. Finally, we took a look at Fixed Field Alternating Gradient accelerators (FFAs) and their potential to become high-intensity machines.

INTRODUCTION

We report the state of the field of "High-Power Cyclotrons and FFAs" (Fixed Field alternating-gradient Accelerators) as discussed by international experts during a three-day workshop of the same name [1]. The workshop was held online Sep 7 to Sep 9, 2021 with 50 registered participants, as part of the US Snowmass'2021 community exercise; specifically, the Accelerator Frontier (AF) and the subpanel Accelerators for Neutrinos (AF02). This conference proceeding is a concise summary of the workshop reports available on the ArXiv [2] and in Ref. [3].

The workshop charge was to take stock of the world inventory of high-power cyclotrons and FFAs, to asses available beam currents and beam powers, and to investigate limitations. Furthermore, to evaluate the role of cyclotrons in particle physics, directly used or as injectors to other machines. Finally, to discuss novel concepts to push the power, and provide recommendations to the particle physics and accelerator physics communities.

The program of talks is listed on the Indico website [1], and slides are available by navigating to "Timetable" then "Detailed view." References to all individual presentations are also given in the bibliography of the workshop reports.

The workshop was coarsely organized in three topical areas (one per day): 1. State-of-the-Art and Limitations; 2. Applications of high-power cyclotrons and FFAs; 3. Novel Concepts and Computation. In this manuscript, we follow the same structure.

STATE-OF-THE-ART AND LIMITATIONS

State-of-the-Art

The classical cyclotron was invented and developed for research in nuclear physics. The first major evolution of this type of accelerator was the introduction of the azimuthally varying field (AVF) cyclotron, otherwise known as the isochronous cyclotron [4]. The development of computers and superconductivity produced a further broad band of cyclotrons of different types tuned for different researches in the field of nuclear physics but also for a wide range of applications. The golden age of the cyclotron was the period from 1960 to 1990 when many cyclotron projects were studied, financed and built. Some examples are LBNL [5–7], DUBNA [8–10], GANIL [11], MSU [12, 13], iThemba Labs [14], RCNP [15], and RIKEN [16], just to remember the largest and most famous laboratories. They were often equipped with more than one cyclotron, aimed mainly at research in the field of nuclear physics and in the projects of synthesis of Super Heavy Elements [17, 18]. A special mention goes to the two large cyclotrons of PSI (Switzerland) [19] and TRIUMF (Canada) [20], laboratories which delivered the first beam in 1974 and 1975 respectively. These two machines deliver proton beams with a maximum energy of 590 MeV and 520 MeV, respectively, and were built to feed the so-called Meson Factories. Despite the fact that the initial design beam currents were only 100 µA and 50 µA, respectively, today they have significantly exceeded their initial target. In particular, the PSI machine is able to supply proton beams with currents up to 2.4 mA and probably even more in the future. A survey of the RIKEN laboratory illustrates the flexibility of cyclotrons operated in cascade, up to 4 cyclotrons including the largest superconducting cyclotron [18]. Moreover, a talk presented by Jongwon Kim (IBS, South Korea) [21, 22] describes how a new generation

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOBI02

STATUS OF SPES CYCLOTRON AT LABORATORI NAZIONALI OF LEGNARO

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Abstract

The SPES cyclotron at Laboratori Nazionali of Legnaro (LNL) was installed and commissioned in 2017 and the accelerator was operational until March 2021. The shutdown was foreseen in order to permit the completion of the SPES facility, while the resume of activities is expected in 2023. The status of the SPES cyclotron and related high intensity beamlines will be presented as well as the last performance achieved in terms of accelerated current up to 1 MeV. Moreover, the program of upgrade of the ancillary systems shall be discussed.

STATUS OF SPES PROJECT

The SPES project [1] is developing in the international framework of the new facilities producing exotic beams for astrophysics research, fundamental interactions, and applications for society, including in medicine.

The project was divided into four phases aiming to provide a multipurpose facility whose accelerator complex is shown in Fig. 1:

- α-phase: construction of main building and installation and commissioning of the high intensity accelerator delivering the high-power proton beams.
- β-phase: installation and commissioning of Radioactive Ion Beams (RIB) facility. It consists of ISOL targets, low energy beam transport lines, beam cooling device and High-Resolution Mass Separator (HRMS), charge breeding system (ADIGE), new RFQ injector and re-acceleration by actual superconducting Linac ALPI.
- γ-phase: installation and commissioning of equipment and laboratories for production and R&D of radioisotopes for medical applications.
- δ-phase: realization of experimental hall to produce neutron beams by interaction of high intensity protons with heavy and light targets.

Once the alpha-phase was completed in 2017, the SPES project has entered in 2018 in the crucial beta-phase of installation of target and low energy beamlines. Moreover, at the same time, the completion of the related infrastructures is carrying on in order to provide a full power facility plant including the implementation of the HVAC upgrades.

Without a doubt. the emergency due to the Covid-19 pandemic had strongly impacted with the progress of the scheduled works. Moreover, the international situation worsening since beginning of 2022 has further delayed the planning, but nevertheless, very important progresses were done in the last three years.

The ISOL target station was installed in 2021, including the first section of the beam transport line downstream the source: i.e., the Wien filter beam selector and first electrostatic quadrupole. The High Voltage platform providing 40 kV voltage for the ion source is under commissioning. The main electrostatic lenses and the recombination magnets of the first leg of low energy beamline were also installed in 2022.

The beam cooler device which is necessary to improve the quality of beams produced by the plasma source, it was completed from the Laboratoire de Physique Curpusculaire (LPC) of Caen (France) and the beam commissioning is ongoing in the French laboratory. The installation in the SPES facility is foreseen in late 2023.

The final design of the High-Resolution Mass Spectrometer was accomplished out and the tender for the supply of the resistive magnets and the electrostatic lenses was awarded to the Elytt Energy company [2] in 2022. The delivery is expected by the end of 2024.

The charge breeder device is installed and the ion source for stable beams has been commissioned in 2022. The High Voltage platform has been finished while the installation of the Medium Resolution Mass Spectrometer is under completion.

The post acceleration section is progressing very well, as the new resistive RFQ injector is finalizing, and the first module was mounted at LNL. The upgrade of superconducting Linac ALPI has been carried out and the first accelerating beams started in December this year.

During the 2023, the resume of cyclotron operation is expected to allow the commissioning of new high intensity proton beamlines. In 2024, the first exotic beam produced by the small size ISOL target, hit by few hundred watts of primary beam, should be available for the low energy experiments in the dedicated area of SPES facility (see Fig.1).

SPES CYCLOTRON STATUS

The SPES Cyclotron is a four sectors compact cyclotron supplied by Best Theratronics [3], capable to accelerate H^- ions up to the maximum energy of 70 MeV. The protons are extracted by the stripping of the H- ions passing thru a thin graphite foil where the two electrons were stopped.

The proton beams are available in the energy range within 30-70 MeV and with an average current varying from few tens of nA up to the nominal value of 750 µA.

The vacuum system is equipped with four cryogenic pumps CTI-10 of Brooks Company installed into the two valleys, providing a vacuum level of 3×10^{-6} Pa. A scroll pump allows to get the primary vacuum level of 1.5 Pa.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOBO01

HIGH INTENSITY CYCLOTRONS FOR PRODUCTION OF MEDICAL RADIOISOTOPES

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Abstract

At the previous cyclotron conference an overview of the cyclotrons for radioisotopes production was shown. Here, we will focus on the development of IBA's accelerators in the recent three years. Notably the Cyclone® 70, the Cyclone® 30XP and the Cyclone® KIUBE have made progress. The expertise gained with the development of these machines has led IBA to develop a completely new cyclotron for 30 MeV protons, the Cyclone® IKON. As its first construction is ongoing, details on the design of this accelerator will be presented.

ONGOING COMMISSIONINGS

Two major projects are ongoing for the older generation cyclotrons: a Cyclone® 70 at IBS in Korea, and a Cyclone® 30XP at the INM in Germany [1].

Cyclone® 70

In 2019 a contract was signed between IBA and IBS for the installation of a 70 MeV cyclotron with beam lines leading to two separate target vaults [2]. After a design phase fitting the system in the already existing building, the installation was performed in 2021.

For this installation, IBA developed a beam profile monitor using a wire scanner. In Fig. 1, results from the tuning at 70 MeV are shown with the donut-shape requested by the customer. As of November 2022, only 12 months after the start of the rigging, the commissioning was finished with a beam of 715 µA on target.

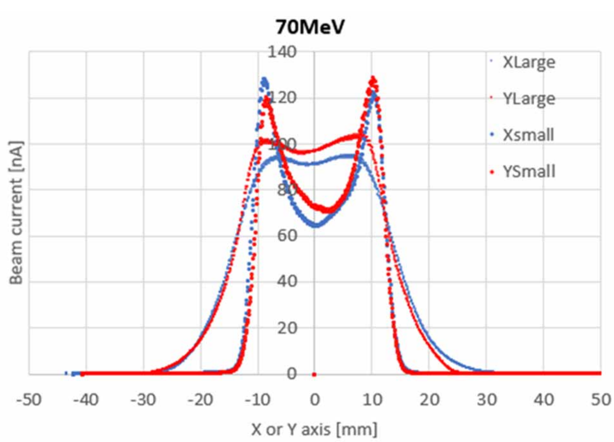

Figure 1: Beam current measured along the X and Y axis, using either a large or a small beam spot, with wobbler.

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Cyclone® 30XP

The Cyclone® 30XP is a multi-particle cyclotron that IBA is to install at the Forschungszentrum Jülich in Germany. The installation had been on hold for several years, but recently the commissioning could finally start.

Table 1: Properties of the Multi-particle Cyclone® 30XP

Particle	Energy	Beam Intensity	Extraction Method
Proton	15 ~ 30 MeV	300 eµA	Stripping
Deuteron	8 ~ 15 MeV	50 eµA	Stripping
Alpha	30 MeV	50 eµA	Electrostatic deflection

In Table 1, an overview is given of the different particle beams that can be extracted. For the proton and deuteron beams, stripping extraction is used. The latest results of the commissioning, only recently obtained, confirm that also the third particle type can be extracted: a stable alpha beam of 20 eµA has been measured on target, with an efficiency of the deflector of 75%. Higher beam intensities are expected soon.

CYCLONE® IKON

With the expertise gained on IBA's Cyclone® KIUBE [3, 4], the new Cyclone® IKON was designed, see Fig. 2. Compared to the previous 30 MeV cyclotron, it is more compact, more efficient and delivers better performance.

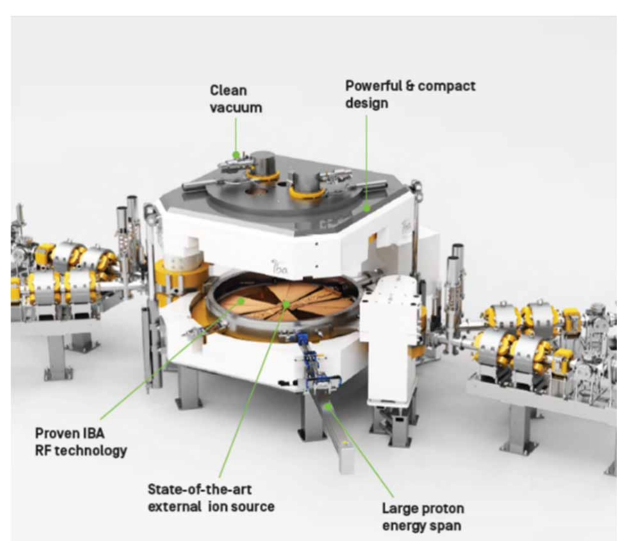

Figure 2: Image of the Cyclone® IKON with dual extraction, switching magnets and the start of four beam lines. A third target can be mounted on each switching magnet.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOB002

IMPACT: A SUBSTANTIAL UPGRADE TO THE HIPA INFRASTRUCTURE AT PSI

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Abstract

The High Intensity Proton Accelerator (HIPA) complex at the Paul Scherrer Institute (PSI), Switzerland, delivers a 590 MeV CW (50.6 MHz) proton beam with currents up to 2.4 mA (1.4 MW) to several user facilities and experimental stations. In addition to the two spallation targets for thermal/cold neutrons (SINQ) and ultracold neutrons (UCN), the beam feeds two meson production targets, Target M and Target E, serving particle physics experiments and materials research via seven secondary beam lines.

IMPACT (Isotope and Muon Production with Advanced Cyclotron and Target technologies) aims to expand the infrastructure at HIPA in two ways: by HIMB (High-Intensity Muon Beams), increasing the surface muon rate by a factor 100, and TATTOOS (Targeted Alpha Tumour Therapy and Other Oncological Solutions), producing promising radionuclides for diagnosis and therapy of cancer in doses sufficient for clinical studies. HIMB and TATTOOS are located close to each other. HIMB has to fit into the existing main proton beam line towards Target E and SINQ, while TATTOOS will occupy an area in a new, adjacent building using 100 µA, 590 MeV protons split from the main beam. TATTOOS will be a perfect complement to the existing radionuclide production using 72 MeV, adding a smorgasbord of nuclides at a large scale for potential medical purposes. At HIMB, the current Target M will be replaced by a four-fold thicker Target H consisting of a graphite wheel optimized for surface muon production. In addition, both muon beam lines feature optimized transmission from target to experiment. Due to the thicker Target H, the proton beam line has to be tuned to reduce the losses to an acceptable level and to maximize the transmission at the same time.

Installation towards the implementation of IMPACT is foreseen from 2027.

MOTIVATION

At the High Intensity Proton Accelerator (HIPA) [1], protons are accelerated using two cyclotrons, namely, Injector II to 72 MeV followed by the Ring cyclotron to 590 MeV. Up to 2.4 mA current is possible and has been demonstrated in routine operation. The 72 MeV beam also feeds the Isotope Production target station (IP2). The beam from the Ring cyclotron serves four target stations, two spallation targets (UCN for ultracold neutrons and SINQ for cold and thermal neutrons) and two meson production targets called Target M and Target E [2]. Before the beam reaches SINQ, it passes through Target M and Target E, whereas the full beam is kicked to UCN every five minutes for a few seconds.

IMPACT will add a new target station (TATTOOS) adjacent to UCN, providing innovative and otherwise not accessible radionuclides for research in nuclear medicine, and to replace the Target M station (built in 1985) with a new Target H(IMB) to increase the surface muon rate to 10^{10} µ/s. Figure 1 shows the close location of HIMB in the so-called experimental hall and TATTOOS in a new building.

The IMPACT collaboration at PSI consists of more than 100 people in 35 working groups. At the beginning of 2022, the Conceptual Design Report (CDR) [3] was submitted to support the project proposal for the Swiss Roadmap for Research Infrastructure, a joint application of PSI, University of Zurich (UZH) and University hospital Zurich (USZ). IMPACT was well received and reviewers gave the highest scientific evaluation in 2022.

In this paper, the purpose and concepts for HIMB and TATTOOS are described with focus on beam transport.

HIMB

The present Target M station consists of an effective 5 mm thick graphite target-wheel with two beam lines called PiM1 and PiM3 for secondary particles, both aligned in a forward direction. As a consequence, these beam lines are optimized for particles of higher momentum, originally pions of momenta larger than 100 MeV/c. The beam lines are used for different purposes: PiM1 for particle physics and PiM3 for material physics. While PiM3 already uses surface muons exclusively with the µSR technique, particle physics experiments aim for large rates of surface muons as well. A two orders of magnitude larger surface muon rate will boost the attractiveness for users as well as the competiveness of future experiments, both in the hunt for forbidden muon decay channels as stress test of the standard model and for the investigation of magnetic properties deeper below the surface.

To optimize the future target station H and its two beam lines for surface muons, the new concept comprises several improvements: Two large capture solenoids, one at each side of the target, with inner diameters of up to 500 mm are placed in a close distance of 250 mm to the interception of beam and target, perpendicular to the proton beam to guide a large fraction of the muons from the target to the second-

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOBO03

PROTON IRRADIATION SITE FOR HIGH-UNIFORMITY RADIATION HARDNESS TESTS OF SILICON DETECTORS AT THE BONN ISOCHRONOUS CYCLOTRON

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Abstract

The Bonn Isochronous Cyclotron provides proton, deuteron, alpha particle and other light ion beams, having a charge-to-mass ratio $Q/A \geq 1/2$, with kinetic energies in the range of 7 to 14 MeV per nucleon.

At the irradiation site, a 14 MeV proton beam with a diameter of a few mm is used to irradiate detectors, so-called devices under test (DUTs), housed in a thermally-insulated and gas-cooled box. To ensure homogeneous damage application, the DUT is moved through the beam in a row-wise scan pattern with constant velocity and a row separation, smaller than the beam diameter. During irradiation, beam parameters are continuously measured non-destructively using a calibrated, secondary electron emission-based beam monitor, installed at the exit to the site. This allows a beam-driven irradiation scheme, enabling the setup to autonomously react to changing beam conditions, resulting in highly-uniform proton fluence distributions with relative uncertainties of typically 2%.

In this work, the accelerator facility is introduced, the proton irradiation site with focus on its beam diagnostics is presented in detail and resulting fluence distributions are shown.

BONN ISOCHRONOUS CYCLOTRON

The accelerator facility of the Bonn Isochronous Cyclotron is shown in Fig. 1. Here, proton, deuteron, alpha and other light ion beams with kinetic energies of 7 to 14 MeV/A and currents of $\lesssim$ 1 µA, are provided to five experimental sites.

The ion beam is generated by two external electron cyclotron resonance sources: One source (two-stage, 5 GHz) located beside, the other (single-stage, 2.5 GHz, polarized beam) situated underneath the cyclotron. Here, the generated beam with a kinetic energy of 2 to 8 keV is guided through a low-energy beamline below the cyclotron and then is injected vertically into its magnetic center using an electrostatic hyperboloid inflector.

The Bonn Isochronous Cyclotron [1] is an isochronous, three-sector, azimuthally varying field cyclotron. Its main parameters are shown in Table 1. The cyclotron shows a 120°-symmetry in its azimuthal magnetic field pattern due to its magnet yoke being separated into three hill-and-valley sectors with 0° spiral angle. In each valley, a broadband

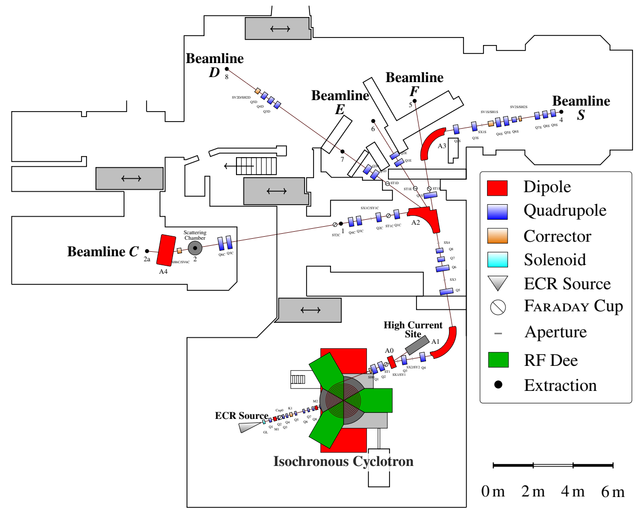

Figure 1: Overview of the accelerator facility.

Table 1: Parameters of the Bonn Isochronous Cyclotron

available ions	p, d, α, …, $^{16}O^{6+}$
energy (h = 3, $Q/A \geq \frac{1}{2}$)	7 to 14 MeV/A
beam current (ext.)	$\lesssim$ 1 µA
injection / extraction radius	38 mm / 910 mm
number of revolutions	approx. 120
hill sectors	3 × 40°, 0° spiral angle
hill / valley field strength	1.9 / 0.7 T (max.)
flutter factor	0.62
dees	3 × 40°, 40 kV (max.)
cyclotron harmonic h	3, 9
RF frequency ν_{RF}	20.1 to 28.5 MHz
hor. / vert. emittance	16 / 22 mm mrad
relative energy spread	4 × 10^{-3}

dual-gap dee is located, providing an acceleration voltage of up to 40 kV.

Due to its symmetry, the cyclotron typically operates at the third cyclotron harmonic $h = 3$, where the RF frequency ν_{RF} equals three times the ions' cyclotron frequency ν_0, but also an operation at $h = 9$ is possible for heavier ions with $Q/A \leq 1/3$. The RF frequency range of 20.1 to 28.5 MHz and the maximum average magnetic flux density $\langle B \rangle_{max}$ of approx. 1.4 T define the cyclotron's mass-to-charge acceptance, as shown in Fig. 2.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOBO04

EXPERIMENTAL STUDY ON PROTON IRRADIATION EFFECT OF GALLIUM NITRIDE HIGH ELECTRON MOBILITY TRANSISTOR

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Abstract

As a third-generation power semiconductor device, gallium nitride (GaN) high electron mobility transistor (HEMT) has a broad application prospects in the aerospace field. However, when a spacecraft is performing a flight mission, the GaN HEMT will inevitably be affected by the irradiation of high-energy charged particles from the space environment, most of which are protons. Therefore, it is of great significance to understand the effect of proton irradiation on GaN HEMT performance for its future development in the space field. In this paper, the proton radiation effect of GaN HEMT is studied by means of a medium energy proton irradiation platform. After proton irradiation, the threshold voltage of the GaN HEMT decreases, and the lower the incident proton energy, the more obvious the threshold decreases. The output characteristics curve, off-state leak current and gate forward leakage current of the GaN HEMT all increase after proton irradiation. After annealing at room temperature for 10 days, the electrical parameters of the GaN HEMT changed by proton irradiation are restored to the corresponding values before the proton irradiation. These changes indicate that medium energy proton irradiation with a fluence of 10^{12} p/cm^2 can improve the GaN HEMT performance, and the related reasons are discussed in detail.

INTRODUCTION

As an important third-generation semiconductor material, gallium nitride (GaN) has the advantages of high breakdown electric field, high electron saturation speed, high operating temperature and strong radiation resistance, and has broad application prospects in the aerospace field in the future [1, 2]. GaN HEMT is an important member of GaN-based electronic devices, and has super advantages in high frequency, high power, high temperature and high voltage applications. Therefore, GaN HEMT is widely considered to play an important role in spacecraft power supply and RF communication and other important fields in the future. However, GaN HEMT will inevitably be affected by the space radiation environment when the spacecraft performs relevant space flight missions [3–5]. Due to the wide band gap of GaN, GaN-based electronic devices should have an excellent radiation resistance in theory. Unfortunately, the radiation resistance of GaN HEMT is often affected by the preparation process and device structure, so the current radiation resistance of GaN HEMT still fails to reach the expected target.

Due to proton accounts for more than 85% and 90% of galactic cosmic rays and solar cosmic rays [6], respectively, the research work related to proton radiation effect of GaN HEMT has been widely concerned. White et al. found that GaN HEMT performance did not change significantly when proton fluence is lower than 10^{14} p/cm^2, the degradation of GaN HEMT is enhanced by the proton fluence when the proton fluence was greater than 10^{15} p/cm^2 [7]. Kim et al. found that when the proton fluence is 10^{15} p/cm^2, the degradation caused by low-energy proton is more serious than that caused by high-energy proton [8], the off-state stress creates more irradiated defects in GaN HEMT, while annealing can remove the stress-generated defects [9]. Greenlee et al. found that proton irradiation broadened the heterojunction interface in GaN HEMT, and then decreased the carrier density and mobility simultaneously [10]. Zheng et al. first observed changes in defects at the AlGaN/GaN heterojunction interface in GaN HEMTs after proton irradiation [11]. CareyIV et al. found that increasing the Al concentration can effectively weaken the effect of proton irradiation on GaN HEMT performance [12].

Previous researches on proton radiation effects of GaN HEMT are based on proton irradiation experiments with energy less than 10 MeV, and all the studies show that proton irradiation degrades the device performance. At present, the research work related to the radiation effect of medium-energy proton on GaN HEMT is rarely reported. Therefore, the proton radiation effect of GaN HEMT has been studied systematically through the medium energy proton irradiation platform in this paper. Different from previous research results, our research show that the electrical performance of the GaN HEMT is improved after medium-energy proton irradiation with fluence of 10^{12} p/cm^2. The deep physical mechanism of improving GaN HEMT performance by medium-energy proton irradiation is discussed in detail in this work.

EXPERIMENTAL DETAILS

In this experiment, eight qualified enhanced GaN HEMTs from the same batch produced by China Xinguan Semiconductor Co., LTD were randomly selected, and the official model of the GaN HEMTs is XG65T125PS1B. The proton irradiation experiment of the GaN HEMT was carried out in the medium-energy proton irradiation platform of China institute of atomic energy (CIAE), as shown in Fig. 1. The proton beam induced by the 100 MeV high-current proton cyclotron (CYCIAE-100) passes through different energy drop plates, and the proton energy decreases to 30 MeV, 40 MeV, 60 MeV and 90 MeV, respectively. During irradi-

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOP0001

A REAL-TIME CONTROLLER FOR RAPID ENERGY DEGRADING OF THE CYCIAE-230 CYCLOTRON BEAM PRODUCTION SYSTEM*

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Abstract

The energy selection system (ESS) plays an important role in a proton therapy system. Usually, it consists of an energy degrader, a set of achromatic bending magnets, an envelope collimator, and a momentum-selecting slit. In CIAE, a dedicated beam transportation line, including these essential elements, for the CYCIAE-230 superconducting cyclotron has been designed and manufactured for study purposes. To reduce the layer switching time, e.g. typically within 50 milliseconds, this ESS system takes advantage of VME-based real-time controller design. On one side, this controller uses S-curve to direct drive the step motors of various actuators, this is done by an off-the-shelf embedded controller. On the other hand, it uses Data Distribution Service (DDS) communication protocol to directly tap into the nozzle control system network. In such a manner, the energy requirement can be efficiently handled and the controller is also responsible for the current regulation for the 46 magnets. The design of this high-efficiency controller will be reported in this paper, both from hardware and software aspects. Preliminary test results will also be evaluated and analysed to direct further improvement of the system.

INTRODUCTION

The rate of human suffering from tumours has been increasing in recent years [1], and proton therapy is one of the effective means to treat tumours. "Bragg peaks" occur during the energy release of proton rays, and the excellent dose distribution of this Bragg peak drives the energy of the proton beam to be released concentrated at cancer cells, so the location of the proton beam energy release is directly related to the proton beam energy, and the proton beam energy is adjusted to achieve radiotherapy at different depths in the tissue to kill cancer cells [2, 3]. In cyclotron-based proton therapy facilities, the energy variation of the proton beam is carried out by controlling the thickness of the degrader [4]. Currently, well-established degrader materials use graphite, boron carbide [5], and beryllium [6]. The CYCIAE-230 is designed to achieve beam energy control mainly by controlling the graphite degrader of the double-wedge shape. The energy selection system (ESS) usually consists of an energy degrader, a set of achromatic bending magnets, an envelope collimator, and a momentum-selecting slit. In CIAE, a dedicated beam transportation line, including these essential elements, for the CYCIAE-230 superconducting cyclotron has been designed and manufactured for study purposes.

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OVERVIEW OF THE REAL-TIME CONTROL SYSTEM

The real-time control system (Fig. 1) is divided into a hardware part and a software part. The hardware part includes the VxWorks-based VME bus controller, while the software part is developed based on Qt and communicates between devices via the DDS middleware protocol. This real time controller is highly reliable and real time, and is able to quickly control the devices on the ESS section to adjust them to the appropriate values, it is capable of controlling the beam energy from 70 MeV to 240 MeV. The control effect of the controller is mainly reflected in: adjusting the degrader to the corresponding thickness to control the beam energy; adjusting the envelope collimator and the energy-selective slit to the corresponding position for suppressing the growth of beam emissivity; and indicating the achromatic bending magnets to the corresponding value to control the trajectory of the beam motion.

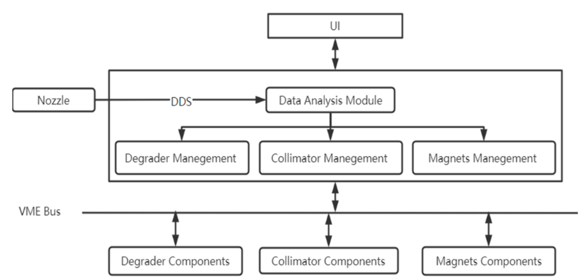

Figure 1: Architecture of the real-time control system.

Table 1: Performance Comparison of Existing Energy Degraders

Manu-facturer	Energy range	Material	Shape	Energy switch-ing time
IBA	70~230 MeV	C	Spiral type	≈ 500ms
Varian	70~250 MeV	C	Triangular wedge	≈ 150ms
Pronova	70~230 MeV	Be	Double-wedge wing type	≈ 500ms

Compared with the existing well-known degraders, as in Table 1, the real-time control system is able to receive energy information and issue commands to adjust the degrader to the corresponding energy position within 50 ms.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO003

SAWTOOTH WAVE BUNCHER UPGRADE FOR SFC CYCLOTRON *

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Abstract

To increase extracted beam intensity, the SFC cyclotron requires that the sawtooth wave buncher on its injection line provide the effective voltage up to 2.5kV and cover a wide frequency range of six times. We develope a multi-harmonic synthesis method by combining a broadband amplifier and impedance transformer, which provide a high-voltage single-gap buncher at limited space and cost. With this method, the maximum voltage of the new buncher exceeds 2.5kV and the beam intensity increases by a factor of 6.7.

INTRODUCTION

The Heavy Ion Research Facility in Lanzhou (HIRFL) is the largest heavy ion accelerator complex in China, which consists of two electron cyclotron resonant (ECR) ion sources, sector focused cyclotron (SFC), separated sector cyclotron (SSC), cooling storage ring ring (CSR), radioactive beam line and experimental terminal [1]. The injector SFC cyclotron is a 1.7 meters sector-focused cyclotron with the K value of 69. It is equipped with two exteranl ECR ion sources named LECR3 and SECRAL-II respectively [2]. The layout of SFC injection system is shown in Fig. 1. A linear buncher B02 was installed in the vertical beam line section underneath the cyclotron center area, about 2.3 meters upstream the inflector. As the only buncher used in the axial injection system, the B02 in principle improves the injection efficiency of the SFC and increases the extracted beam intensity compared with the case without it. However, from the operation in the past few years, there are still 3 aspects need to be improved: (1) intense beams with high and intermediate charge states from ECR ion sources requires high bunching voltage to compensate space charge effect; (2) there is no half-frequency mode which can increase longitudinal matching efficiency between SFC and SSC in cascade with SSC [3]; (3) equipment faults of B02 due to aging components have reduced the beam supply time of SFC [4].

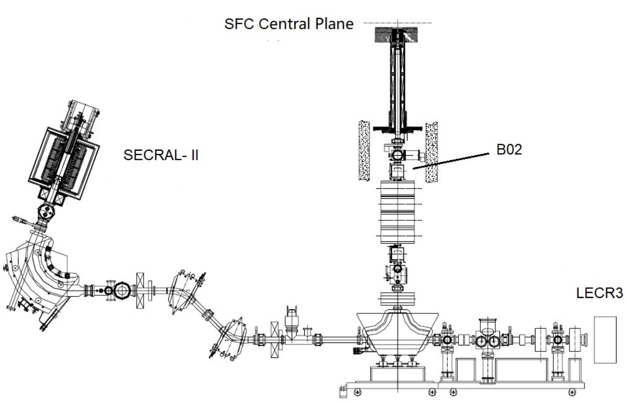

Figure 1: Layout of SFC axial injection system.

PHYSICAL REQUIREMENTS

In this chapter theoretical description of axial velocity modulation of continuous DC ion beam is given as well as the special physical requirements. The overall specification of buncer is shown in Table 1.

SFC is a multi-particle and variable energy accelerator, and the design specifications of the buncher should adapt to its transformation range. The voltage amplitude of the buncher can be expressed as [5]

$$V_b = (\beta\lambda/L)(\eta)V_{inj} , \qquad (1)$$

where L is the bunching distance, η is the effective duty cycle, and V_{inj} is the injection voltage. In our case the maximum ECR extraction voltage is 25 kV. The distance from the buncher to the inflector is 2.3 meters and $\beta\lambda$ is 16 mm when operating in the first harmonic mode with the maximum frequency of 16 MHz. These parameters give us an estimation of 1200 V for the saw-tooth voltage.

Due to mismatching of the SFC's extraction radius (R=0.75 meters) with the SSC's injection radius (R=1.0 meters), when SFC works at the mode h=1 and SSC at h=2, the longitudinal match efficiency between the two cyclotrons is only 50% in theory [3]. To regain the lost beam, a additional half-frequency bunching mode is required. In this mode, the buncher operates at half-frequency of SFC RF frequency with the double bunching voltage squeezing the original two packets into the one that can be accepted by the RF of SSC. Therefore, the buncher working frequency range is changed from 5.5-16.0 MHz to 2.75-8.0 MHz with the Maximum bunching voltage increasing from 1.27 kV to 2.54 kV.

Table 1: Design Parameters of Buncher

Parameter	Value
Input Frequency	5.5~16.0MHz
Input Level	7dBm
Work Frequency	5.5MHz~16.0MHz
Work Frequency*	2.75MHz~8.0MHz
Voltage	≤1.27kV
Voltage*	≤2.54kV
Amplitude Stability	≤1%
Phase Stability	≤1°

* Work supported by the HIRFL operation and maintenance project [grant number Y9HIRLL100]
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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO004

BEAM DUMP DEVELOPMENT FOR HIGH POWER PROTON AND ELECTRON BEAM

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Abstract

The high-intensity 100 MeV proton cyclotron CYCIAE-100 had provided 52 kW beam to the beam dump in 2018, is planning to be upgraded at China Institute of Atomic Energy (CIAE). It is designed to provide a 75-100 MeV, 1 mA proton beam. A new beam dump for higher beam power have been developed since 2020. At the same time, a 1:4 scale, RF cavity with Q value up to 42000, is constructed for the engineering feasibility verification of a 2 GeV/6 MW CW FFAG, which is also being considered as a main accelerating cavity of a 100 kW electron accelerator. The electron beam will be rotated and accelerated 7 times by the gradient dipoles and the high Q cavity. The beam dump is designed to also use for the 100 kW electron beam. With the same-level beam power of the two accelerators above the content, a beam dump for absorbing two kinds of particle beams according to the characteristics of the modification was designed. The energy deposition of 100 MeV proton beam and 5 MeV electron beam in the beam dump was investigated by the Monte-Carlo simulation program FLUKA. The beam dump cooling structure was optimizing by ICEM-CFD and fluent, so that the water temperature was controlled less than 100 °C, and the maximum temperature on the beam dump is less than 450 °C. The beam dump is designed as a cube (450 mm * 200 mm * 200 mm) with two 2.5° V-type copper pentagon and two flat parts. All the details about the simulation of energy deposition, thermal distribution and structure design will be presented in the paper.

INTRODUCTION

The high-intensity 100 MeV proton cyclotron CYCIAE-100 had provided 52 kW beam in 2018, is planning to be upgraded to provide the beam power reached 75-100 kW proton beam [1, 2]. A 1:4 scale, RF cavity is constructed for the engineering feasibility verification of a 2 GeV/6 MW CW FFAG, which is also being considered as a main accelerating cavity of a 100 kW electron accelerator [3]. The beam dump is the major part for absorbing high-energy particle beam at the end of accelerator. With high power density and small cross-section, if the heat flux is not reduced and the heat is not taken away in time, the vacuum will be destroyed, and even affect the normal operation of accelerator.

STRUCTURAL DESIGN

The beam dump, shown in Fig. 1, is located in a vacuum box at the end of the beam line designed, as a cube (450 mm * 200 mm * 200 mm). the beam dump consists of two 2.5° V-type pentagon and two flat parts fabricated from copper. Two fluid regions are distributed symmetrically as S-channels. The fluid regions are almost parallel to the 2.5° V-surface, and the distance from the V-surface is about 20~25 mm. The gap of channel is optimized to 3 mm and with 3 fins, the thickness is 1.5 mm, to enhance convective heat transfer. The purpose of the two side plates is to block the few edge beam particles that might be present.

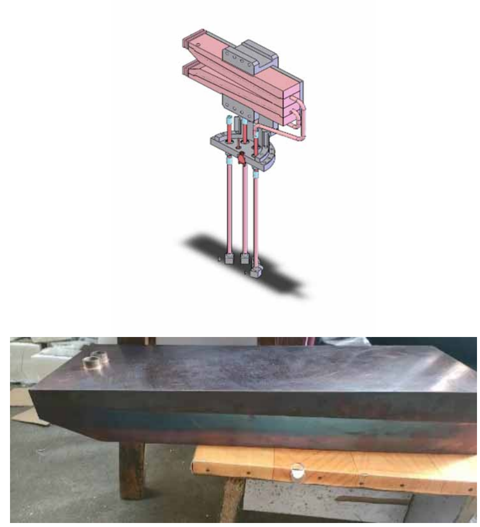

Figure 1: Three-dimensional drawing of the beam dump and the 2.5° V-type copper pentagon target in processing.

CALCULATION ABOUT THE BEAM ENERGY DISTRIBUTION

In order to obtain more accurate temperature distribution, the input condition of the V-type pentagon in the depth of direction is result of heat source probability density calculated by FLUKA, and the energy of the beam and copper has a Gaussian distribution. Figure 2 shows the energy probability of the proton/electron-copper interaction in the depth direction. The energy deposit increases with incidence depth, and the relation is not linear. For easy to calculation, the relationship between the energy deposit and incidence depth is assumed to be energy probability density.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO005

IMPEDANCE CHARACTERISTIC ANALYSIS AND MATCHING NETWORK DESIGN FOR A 100 mA H⁻ ION SOURCE

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Abstract

China Institute of Atomic Energy (CIAE) has developed a series of multi-cusp H^- ion sources (IS) with DC beam intensity ranging from 3 to 18 mA for high intensity proton cyclotron uses such as cyclotron PET application, neutron source and boron neutron capture therapy (BNCT) facilities. Based on the previous experiences, a new project of radio frequency (RF) antenna driving ion source has been launched for pulse accelerator research. This new ion source is expected to provide over 100 mA peak intensity H^- beams of 60 keV and a longer maintenance interval than conventional filament-driving ion sources above. Impedance matching is indispensable for efficient RF power coupling in the whole working process of the ion source for high-intensity H^- beam extraction. In this paper, impedance characteristic of the IS antenna with various plasma loading is analysed. Eight typical matching topologies are discussed on their electrical requirements. A type-L and a type-γ network are finally selected for the 2 MHz and 13.56 MHz chains respectively. This design may provide a better compromise between the matching performance and the cost of implementation for a wide dynamic loading range. Design of the network is evaluated on the power delivering efficiency in each of the two RF chains and isolation between one and the other. The IS structure and near-future work plan are also presented.

INTRODUCTION

A high-intensity H^- ion source driven by internal RF antenna is under development at CIAE. Design of this new ion source is based on a high-compatibility test-bench which shares similar plasma discharging chamber, magnet layout and extraction system with the conventional filament-driving ion sources [1]. An internal enamel-coated solenoid antenna of 2.5 turns would be applied for the new IS in replacement of the filament, expecting for a longer life-time (> 50 hours) immersed in large-volume plasma. This overall design is shown in Fig. 1.

To obtain a peak intensity over 100 mA, an 80 kW 2 MHz solid-state amplifier (SSA) is adopted in generating large-volume RF coupled hydrogen plasma. And in each pulse interval, from every falling-edge to the following rising-edge, the plasma would be kept *simmering* by a CW 500 W 13.56 MHz amplifier module, aiming to reduce the probability of large-volume plasma generation failure. This module would be set ON at the very beginning for plasma ignition and throughout the whole working process of the ion source. Shifting of the plasma discharging state follows the rule that shown in Fig. 2.

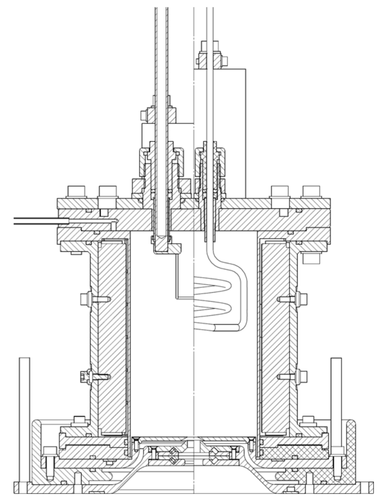

Figure 1: CIAE high-compatibility multi-cusp ion source test-bench. Left: filament driving design. Right: antenna driving design.

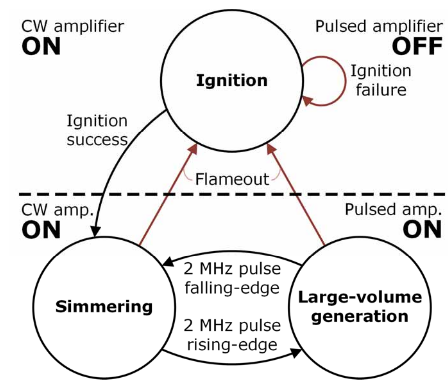

Figure 2: Plasma working states flow.

As the impedance of IS antenna varies dramatically from one discharging state to another, matching networks for the 2 MHz and the 13.56 MHz chains should be designed separately. Each of the networks demands a rather large adjustable matching range to cover most of possible antenna impedances with corresponding plasma loads. Efficient RF power delivery from the 50 Ω transmission-line system to the antenna could be attained only via careful designs of these matching networks, based on the reliable estimates of the IS antenna impedance characteristic. This paper is analysing the equivalent resistance and inductance of the antenna with different plasma loads, comparing basic matching network topologies, presenting and evaluating the design for the new 100 mA ion source.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO006

DEVELOPMENT OF HIGH TEMPERATURE SUPERCONDUCTING ECR ION SOURCE USING REBCO COILS

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Abstract

A High Temperature Superconducting ECR ion source (HTS-ECR) using REBCO coils is under development in Research Center for Nuclear Physics (RCNP), Osaka University. REBCO tapes are the second-generation high temperature superconductor, which maintains a high critical current even being placed in a strong external magnetic field. Using this REBCO coils as electromagnets, the HTS-ECR was designed to operate at microwave frequencies of 2.45 GHz and 10 GHz, for the purpose of propducing high intensity proton, deuteron and helium beams. In this work, the low-temperature perfromance test results of the REBCO coils will be presented. The coil system and plasma chamber designed for the HTS-ECR will also be discussed. Results yielded in this research will also be made the best use of the development of a skeleton cyclotron, a compact air-core cyclotron which is under development in RCNP, Osaka University.

REBCO COILS IN HTS-ECR

Electromagnet using REBCO Tape

REBCO ($REBa_2Cu_3O_{7-x}$, RE=rare earth) is a second generation high temperature superconducting material, which has critical temperature T_c higher than 90K. It also remain high critical current dendity even being placed in a strong external magnetic field. Under 20 T of external perpendicular magnetic field component, REBCO's critical current density remain larger than 400 A/mm^2 [1].

For its capability to carry high current under strong external magnetic field, REBCO tape is a promising material to construct iron-less electromagnet for cyclotron and ion source. An iron-less electromagnet, which has no hysteresis property, will permit quick adjustment on the magnetic field configuration according to the objective of the operation. An High Temperature Superconducting ECR ion source (HTS-ECR), which use only REBCO coils to induce magnetic field, is under development at Research Center for Nuclear Physics (RCNP), Osaka University. Results yielded in this research will also be made the best use of the development of a skeleton cyclotron [2]. a compact air-core cyclotron which is also under development in RCNP.

HTS-ECR

HTS-ECR has 4 circular REBCO solenoids and 6 racetrack sextupole coils to induce axial magnetic mirror field and sextupole field respectively. Figure 1 shows the coil assembel of HTS-ECR. Starting from the injection end, solenoid coils are called M1, PC and M2 solenoids, which has 106 turns two double pancakes, 103 turns double pancake and 68 turns double pancake configuration respectively.

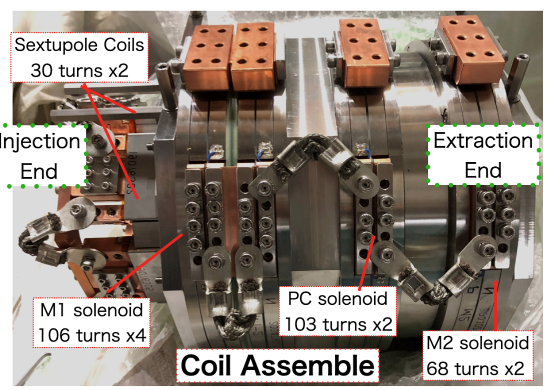

Figure 1: Coil assemble of HTS-ECR.

Specifications of HTS-ECR is shown in Table 1. HTS-ECR will provide high intensity proton, deuteron and He^{2+} to applications like RI production, BNCT and Targeted Alpha-particle Therapy. Although REBCO has critical temperature higher than 90K, HTS-ECR are designed to operate in 20~30 K, with large thermal margin to pursue stable operation. Also, in order to examine the adjustability of magnetic field configuration induced by REBCO coils, HTS-ECR are designed to operate at frequency of 2.45 GHz and 10 GHz.

LOW TEMPERATURE PERFORMANCE TEST ON REBCO COIL ASSEMBLE

The REBCO coils' capabilities of inducing magnetic field with high stability and reproducibilty in seperate operation

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO007

THE DESIGN AND COMMISSION OF VACUUM SYSTEM FOR CYCIAE-230 SUPERCONDUCTING CYCLOTRON

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Abstract

In this paper, the design, installation and commission of CYCIAE-230 superconducting cyclotron vacuum system are described. 8 sets of high compression ratio TMPs, which shielded by magnet material are used in combination with oil mechanical vacuum backing pumps and dry mechanical vacuum pumps. Another set of high compression ratio TMP is used to increase the central region degree. The pressure in the particle acceleration chamber is better than 2×10^{-6} mbar in 48 hours.

INTRODUCTION

CYCIAE-230, a superconducting cyclotron aims for proton therapy, is under design and construction at China Institute of Atomic Energy [1-3]. Vacuum system of CYCIAE-230 are studied for years. There are three technical difficulties of the CYCIAE-230 vacuum system, one is that 8 magnetic poles, 8 high frequency resonators, and 2 sets of striper targets and 2 sets of radial targets are installed in the accelerator vacuum chamber, which resulting in technical difficulties in many types of materials and large gases loads. Another is that CYCIAE-230 does not have a separate valley area for pumping, and can only be shared with RF vacuum vessel for exhaust. It means The more complex the high-frequency structure, the smaller conductance to pump. Third is that the residual magnetic field near the accelerator magnet is about 2000 Gs to 3000 Gs [4]. Many equipment, for example, molecular pumps, vacuum valves and other components will be damaged in such large residual magnetic fields. Therefore, these components need to be shielded from magnetic fields. To solve the above 3 technical problems of superconducting cyclotron CYCIAE-230 vacuum system, 8 sets of TMPs with magnet shields are installed on the valley of magnet poles, which also used as RF cavity [5], 1 set of TMP with magnet shields is installed on the central magnet pole to increase the vacuum degree of central region. The vacuum in the particle acceleration chamber is better than 5.6×10^{-7} mbar in 48 hours without ion source. The detail design and commission of CYCIAE-230 vacuum system will be presented.

CHALLENGES FOR VACUUM SYSTEM OF CYCIAE-230

Design of the vacuum system of CYCIAE-230 has gone through several listed and unlisted challenges:

- Shared with RF used the same cavity for exhaust.
- The strong residual magnetic for TMPs
- Inner Ion source.
- Thousands of internal welds in vacuum chamber

Meanwhile, technical requirements shall be met as the followings:

- Static pressure better than 2×10^{-6} mbar
- Dynamic pressure better than 5×10^{-5} mbar
- Clean, oil-free vacuum system
- Overall leakage rate less than 2×10^{-11} mbar·l/s

ACCELERATOR GAS LOAD IN ACCELERATION CHAMBER

The accelerator components in the superconducting cyclotron chamber include magnetic poles, high-frequency cavity, cryostat inner surface etc. The materials are accelerator iron, oxygen-free copper, stainless steel etc. The total volume is 10 m^3, and the outgassing area is about 200 m^2. CYCIAE-230 superconducting cyclotron is symmetric separated into two parts. The two halves and other seals on magnet yoke are sealed from the atmosphere using Viton O-rings with a hardness of 70 Shore, which cause more gas loading arising. The designing gas load of the ion source is less than 1 cm^3/min H_2. All sources of gas, such as the ion source gas inlet, leaks, permeation through gaskets and gas desorption is 210 mbar·l/s [6]. 2 sets of slim striper targets and 1 set of radial probes are also equipped with vacuum connector as shown in Figs. 1 and 2. The designation of vacuum devices and the cross-section of the inlet pipes have been dictated by their structure.

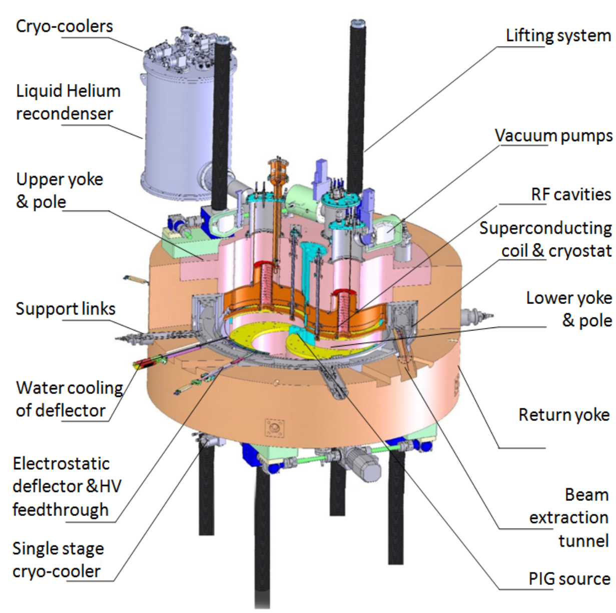

Figure 1: CYCIAE-230 cyclotron.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO008

PLC BASED VACUUM CONTROL AND INTERLOCK SYSTEM OF THE CYCIAE-230 SUPERCONDUCTING CYCLOTRON BEAM LINE

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Abstract

In the CYCIAE-230 superconducting cyclotron beam line, a vacuum system capable of providing a pressure of about 5E-4 Pa is required for particle beam transport. In order to provide adequate interlocking to safeguard the vacuum environment and ensure the regular transmission of particles within the beam line, a vacuum control system based on programmable logic controller (PLC) has been developed and integrated into the accelerator monitoring system. The PLC not only interfaces with the quick-acting relay based on interlocking signals but also interfaces with the equipment based on Profibus communication to monitor and control various parameters in the vacuum system, such as pump speed, vacuum pressure reading, valve status, water cooling status, etc. This work presents the structure and interface logic necessary for communication with a series of valves, vacuum gauges, and molecular pump controllers. Also presented is an interface approach between vacuum control and the rest of the accelerator control system.

INTRODUCTION

The CYCIAE-230 superconducting cyclotron leads out a proton beam with high energy and low current intensity, which is transmitted to the irradiation terminal through the beam line system. Figure 1 shows the complete layout [1].

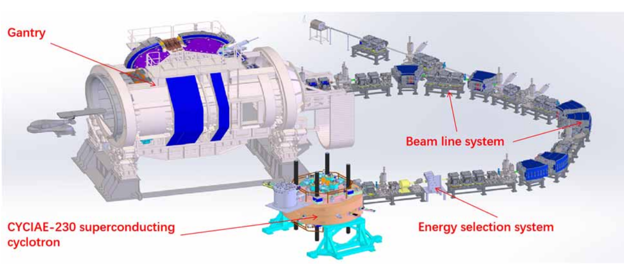

Figure 1: Layout of CYCIAE-230 and beam line.

Among them, the beam line control system is an essential part of proton therapy and is responsible for transmitting the proton beam with the energy needed for the therapy from the superconducting cyclotron to the therapeutic equipment. The general control equipment of the beam line includes: molecular pump power supply, mechanical pump, vacuum gauge, vacuum valve, water-cooled flowmeter, faraday cage, fluorescent target, etc. In this beam line control system, vacuum control and interlocking system is essential.

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SYSTEM REQUIREMENT

The pneumatic system can control the opening and closing of the valves and correspondingly assist in the realization of the vacuum environment of the beamline. The water cooling system mainly ensures that the equipment, including molecular pumps, magnets, etc., works regularly at the appropriate temperature. In order to ensure the normal transmission of particles in the beamline, the vacuum system needs to provide a vacuum environment with a pressure of about 5E-4 Pa.

According to the design principle of obtaining an oil-free vacuum as much as possible and the requirement of vacuum degree, a molecular pump with a pumping speed of more than 300 L/s is selected as the vacuum obtaining equipment on the beam line, and a mechanical pump is equipped as the backing pump. Before starting the molecular pump, it is necessary to start the mechanical pump for vacuum pre-extraction, and the molecular pump can only be started when the vacuum is better than 1E-2 Pa. Figure 2 shows the layout of the beamline vacuum system.

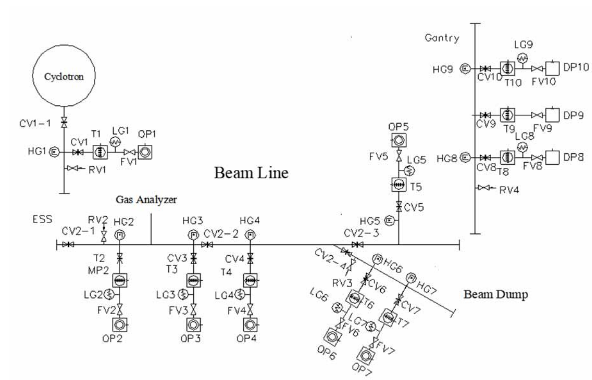

Figure 2: Layout of beam line vacuum system.

For machine protection and personal safety, it is necessary to design and add an interlocking system [2]. The vacuum interlock system will protect the vacuum gate valve to prevent it from accidentally closing during operation. At the same time, the interlocking system will also protect faraday cages, molecular pumps, magnets, and additional devices by monitoring temperature signals. If necessary, the beam line's vacuum interlocking system will notify the beam interlocking system to request that the beam be stopped to prevent additional operation [3].

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO009

STUDY ON THE EXTRACTION OF A COMPACT CYCLOTRON FOR BNCT

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Abstract

An 18 MeV, 1 mA H^- compact cyclotron is under design at China Institute of Atomic Energy (CIAE). The proton beam bombards a beryllium target, producing high-flux neutron beam for Boron Neutron Capture Therapy (BNCT). Stripping extraction is adopted in this cyclotron. The position of the stripping point affects the trajectory and beam quality of the extracted beam. In this paper, we use orbit-tracking method to simulate the beam trajectory and emittance with different positions and tilt angles of stripping foil, and adopt the extraction point whose radius is 53.6 cm, azimuth is 57° and the tilt angle of the stripping foil is 15°.

INTRODUCTION

BNCT is one of the most advanced cancer treatment technologies in the world because of its advantages of less toxic and relatively low cost [1]. Because the neutron beam of the accelerator has the characteristics of adjustable energy, and the accelerator also has the safety advantage that the reactor does not have, the accelerator-based BNCT (AB-BNCT) has been paid more and more attention by all countries [2].

CIAE has been developing clinical cyclotron since 2010. In 2012, PET cyclotron CYCIAE-14 was successfully developed, which can provide 14 MeV, 200 μA proton beam [3]. The 14 MeV, 1 mA BNCT high-intensity proton cyclotron developed by CIAE was installed in Sept. 2020, and in Jan. 2022, the extracted beam current reached 1 mA. At present, neutron target experiment and accelerator stability test are under way. In order to improve the neutron flux and product medical isotopes, we plan to develop a new cyclotron, increasing the extraction energy to 18 MeV.

THE POSITION OF THE STRIPPING FOIL

External H^- ion source and stripping extraction are adopted in this cyclotron. The 35 keV H^- beam is produced by a multi-cusp ion source [4] and vertically injected into the cyclotron by an electrostatic inflector. Accelerated over 100 turns, H^- beam is stripped by a carbon foil then extracted to the beam line. When accelerated to 18 MeV, the beam can be extracted at this energy by a stripping foil at any azimuth. However, considering the construction cost and compatibility with other systems, the following restrictions are proposed for the position of stripping foil:

(1) The stripping probe is installed on the magnet pole.
(2) The extracted beam passes through the valley of yoke.
(3) The extracted beam doesn't pass through the RF cavities.

The two RF cavities are installed in the valley at 0° and 180°, so the beam can be extracted in the valley at 90° and 270°. Due to the symmetry of the cyclotron, the extraction designs of the two valleys are the same. Here, the extraction design at 90° valley is taken as an example.

By orbit-tracking program, the reference particle is tracked from 1 MeV to the extraction region. The orbits after extraction are shown in Fig. 1. Compared with the radius of stripping foil, the azimuth has a greater impact on the trajectory. The azimuth should be within 52°-60° to make the beam pass through the valley of yoke.

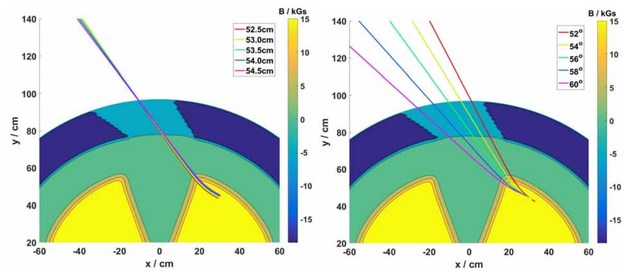

Figure 1: Extracted beam trajectory with different radii (left) and azimuths (right) of the stripping foil.

MULTI-PARTICLE SIMULATION FOR STRIPPING EXTRACTION

Distribution on the Stripping Foil

In the physical design of extraction, the emittance and beam envelope of the extracted beam are expected to be as small as possible, which is beneficial to reduce beam loss and provide higher quality beam. The multi-particle tracking method is used to simulate the emittance, beam envelope and other parameters of the extracted beam to optimize the position of stripping foil.

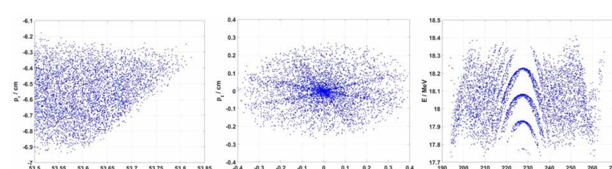

Figure 2: The particle distribution on the stripping foil in radial (left), axial (middle) and longitudinal (right) phase space.

Particles are tracked from 1 MeV. According to the acceptance of this cyclotron, initial horizontal acceptance is 4 π-mm-mrad and phase width is 60°. The result is shown in Fig. 2. τ is the RF time:

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO011

DESIGN AND OPERATION OF THE NEW FAST BEAM CHOPPER BETWEEN TANDETRON AND CYCLOTRON

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Abstract

In collaboration with Charite - Universitätsmedizin Berlin, patients with ocular melanomas are treated with protons at Helmholtz Zentrum Berlin. Accompanying research includes beam delivery for Flash irradiation, thus it became necessary to set up a fast and reliable beam Chopper. The new beam Chopper can deliver much shorter pulses than needed for Flash irradiation, minimum pulse widths down to 70 ns at 1 kV amplitude can be delivered. A short description of the design and installation process, which occurred in 2020, and the experiences of the first 2 years of operation with the new fast beam Chopper system is presented.

INTRODUCTION

At the cyclotron of the Helmholtz Zentrum Berlin two injectors can be used for tumor therapy and experiments. A 6 MV Van-de-Graaff injector and a 2 MV Tandetron (Fig. 1). Due to its stability and reliability, the Tandetron is mainly used for tumor therapy and Flash experiments [1]. For rapid beam on/off switching in Flash experiments, a mechanical scissor-like beam stop has been used in Tandetron operation to date. Due to the sluggish mechanics, the beam stop requires 40 ms to fully open and 47 ms to fully close. Since Flash experiments require beam pulses between 1-100 ms, the mechanical beam stop can only be used to a limited extent. Due to this limitation, it was necessary to build a fast beam Chopper that can realize minimum pulse widths of 1 ms. For this purpose, 1 m beamline is available directly behind the Tandetron. The deflection of the beam is to be done via two deflection plates. The setup of the new Chopper is to be done via an existing CAMAC power supply controller, whereas the Beam control runs via the FPGA and LabVIEW of the flash control.

DESIGN OF THE NEW FAST BEAM CHOPPER

An existing 94 cm long vacuum chamber with deflector plates was selected for the fast on/off switching of the beam. The available area directly behind the tandetron is 1m long and has so far only been used for steerer tests. For the complete setup of the Chopper, in addition to the vacuum chamber with the deflection plates, a fast semiconductor switch, processing and control electronics including power supply, a HV power supply for the deflection plates and a cooling system are required.

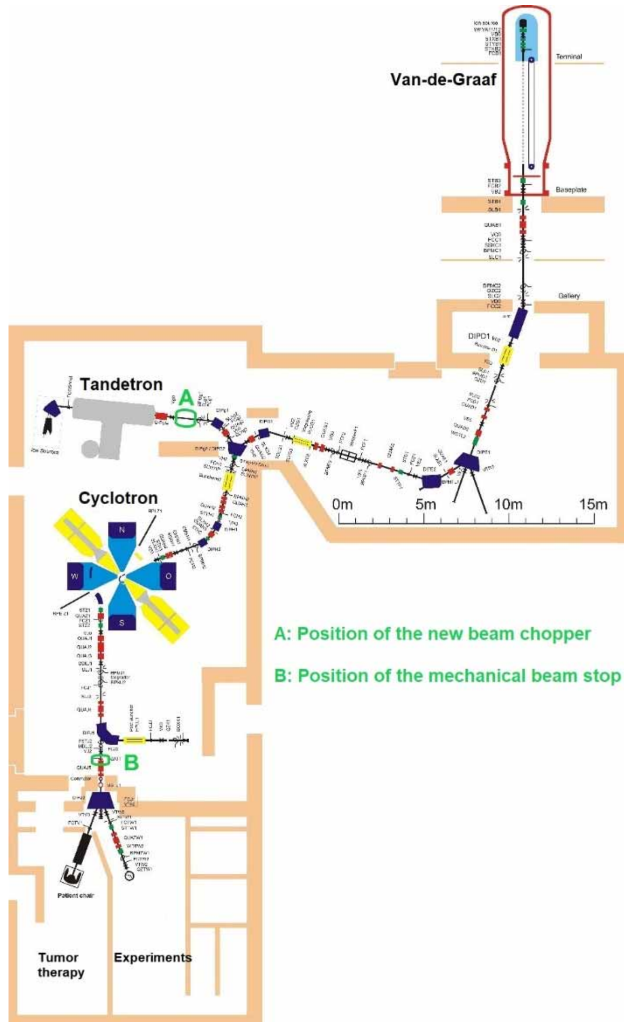

Figure 1: Layout of the accelerator complex including the location of the mechanical beam stop and the new Fast Beam Chopper.

VACUUM CHAMBER AND DEFLECTION PLATES

The existing vacuum chamber with deflection plates is 94 cm long and has 2 DN 160 CF flanges at the inlet and outlet. Another DN 200 CF flange is provided for an ion getter pump. Furthermore, there are two flanges for the HV voltage feed-through of the deflection plates as well as 4 adjusting screws for the adjustment of the plate distance. The already existing 4 cm wide deflection plates were reworked and shortened to 90 cm to avoid interference at the input and output of the Chopper. The two deflection plates made of V4A steel were then aligned with the beam axis and adjusted to 2 cm spacing (Fig. 2).

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO012

AN EMBEDDED BEAM DIAGNOSTIC ELECTRONICS FOR 230 MeV SUPERCONDUCTING CYCLOTRON RADIAL PROBE AND SCANNING WIRES

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Abstract

For the 230 MeV superconducting cyclotron, once again, the differential radial probe has been proven to be crucial for the beam commission procedure. It can provide various information about the particles inside the cyclotron, such as the vertical position, the relative intensity as well as the oscillation frequency and radius, etc. In practice, however, the electronics system suffered from the leaking alternating RF field as well as the static magnetic field. Besides the EM shielding, an absorptive high-frequency filter has been included as the first element of the readout electronics. A high dynamic range readout electronic unit has been included to adapt to the fluctuation of the beam in the hole commissioning phase. The electronics box is designed as a network-attached embedded device so that it can be powered by a POE switch and transmits measurement results via MODBUS protocol. A dedicated digital signal processor and calibration units are also included, together with the ADCs, to facilitate the daily calibration process. The same electronics are used for the beamline wire scan system to determine the position of the beam, with a small improvement at a lower range. The design of this multi-purpose beam diagnostics electronics will be reviewed in this paper, together with several measurement results.

INTRODUCTION

The China Institute of Atomic Energy (CIAE) is developing a 230 MeV superconducting cyclotron, a commercial prototype that can be used for proton therapy, which is designed to induce energy of 230 MeV and beam current over 300 nA [1, 2]. During the beam commission procedure, the radial probe can measure beam parameters from a radius of 300 mm to 850 mm inside the cyclotron. It can provide the intensity and the alignment information of the beam. The material of the head of the radial probe is tungsten, the beam will deposit on the head, so it's an interception measurement method. The drive unit of the radial probe is mounted on a stand and the rod drives the head, which is fixed to the drive unit. The drive unit drives the head in a reciprocating motion inside the cyclotron and a potentiometer determines the position of the head movement [3, 4]. Scanning wires is a non-intercepting beam diagnostic method used to measure beam position on the beamline [5]. The probe head used by CIAE is a double-wire structure with an angle of 90°. The material of the measuring strip is a copper alloy with a width of 5 mm and a thickness of 0.1 mm.

Since the beam current may work in the case of low intensity and high intensity, CIAE designed a beam diagnostic electronics system. The existing diagnostic electronics for 230 MeV superconducting cyclotron radial probe and scanning wires can measure currents from 1 pA to 10 mA range. However, its measurements are not continuous, and the readout electronic unit is based on a trans-impedance amplifier that requires manual switching of the different feedback resistors depending on the signal being measured. The data processing module of the existing wire scan system is based on PLC, and the sampling rate (2 Hz) of the system is also low.

DESIGN OVERVIEW

The new embedded electronics under development will eventually replace the existing boards used for the initial phase of the 230 MeV superconducting cyclotron project. The new electronics allow for continuous, high dynamic range measurements with higher sampling rates than previous designs.

The new electronics box is designed as a network-attached embedded device so that it can be powered by a POE switch and transmits measurement results via MODBUS protocol. To reduce electromagnetic interference, an absorptive high-frequency filter (RLC filter) has been included as the first block of the readout electronics. The core part of the electronics is the high dynamic range readout electronics unit. The board has 3 I/V conversion channels, each including a wide dynamic range I/V converter and a weak signal I/V converter. The 4 channels (3 I/V conversion channels and a position signal channel) are digitized using AD7665 16-bit ADCs, and then further processed on the DSP, Butterworth filter is applied to process the raw data. Embedded SRAM is used for the temporary storage of measurement data, while a calibration unit facilitates the daily calibration process. Triaxial connectors are used to transmit beam current signals to adapt to weak signal detection. A protection circuit (gas discharge tube and JFET) is set before the readout electronics unit to prevent accidental damage.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO013

EXPERIMENTAL STUDY OF BEAM ENERGY CONTROL AT THE TIARA AVF CYCLOTRON

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Abstract

The TIARA AVF cyclotron provides a helium (He) beam for producing ^{211}At, as one of its many beam applications. The generation rate of ^{211}At increases with the energy of the He beam. However, contamination of ^{210}Po produced by the radioactive decay of ^{210}At, which is generated by energy above 29 MeV, must be prevented for medical applications. Therefore, the energy of the He beam must be precisely measured and controlled. A time-of-flight beam energy monitor was installed in the direct beamline from the cyclotron to measure the beam energy in real-time. The cyclotron magnetic field and accelerating voltage, which are two potential causes of the beam energy change, were arbitrarily adjusted within a range of around 1%. With this control, the generation rate of ^{211}At and ^{210}At was investigated as the beam energy was varied. The results showed that the cyclotron parameters were easily controlled to the optimum beam energy that increased generation rate of ^{211}At and did not produce ^{210}At.

INTRODUCTION

The azimuthally varying field (AVF) cyclotron with a K number of 110 MeV in an ion beam irradiation facility, Takasaki Ion Accelerators for Advanced Radiation Application (TIARA) provides various ion beams from 10 MeV H^+ to 490 MeV Os^{30+} for experiments in the field of materials and biotechnology research, etc. [1]. To produce RI, light ion beams such as proton and helium (He) are mainly used. Recently, ^{211}At (half-life, 7.2 h) is produced for alpha nuclear medicine therapy research using the He beam accelerated by the TIARA AVF cyclotron. The production of ^{211}At uses the nuclear reaction of ^{209}Bi (α, 2n) ^{211}At. The ^{211}At yield in this nuclear reaction increases up to about 30 MeV in the injection energy of the He beam into the Bi target [2]. On the other hand, the nuclear reaction of ^{209}Bi (α, 3n) ^{210}At produces ^{210}At (half-life, 8.1 h) when the injection energy of the He beam into Bi surpasses 29 MeV. ^{210}At is chemically inseparable from ^{211}At, and radioactive decay produces ^{210}Po (half-life, 138 d), which is highly toxic [3]. Given that ^{210}Po has a longer half-life than that of ^{211}At, this poses the problem of being left as an impurity, such as in the case of drugs manufactured for clinical use. Therefore, for the mass production of ^{211}At, it is necessary to increase the intensity of the injection beam and precisely control the beam energy near the upper limit, wherein ^{210}At is not generated.

A precise bending magnet with beam slits installed in front of and behind it can be used to quantify the energy of the beam accelerated by the TIARA AVF cyclotron. However, this method cannot supply the beam to the RI production equipment installed in the beamline located straight from the cyclotron. Moreover, it was difficult to pass the beam through the slits before and after the magnets in a short time when parameters such as the magnetic field were changed in the cyclotron to fine-tune the beam energy. Therefore, a beam energy and position monitor (BEPM) system [4] was installed on this linear beamline to allow real-time measurements without blocking the beam. A BEPM can measure changes in beam energy due to changes in the cyclotron parameters in real-time. The generation rate of impurity-free ^{211}At can be maximized by controlling the He beam energy near the upper limit, where no ^{210}At is produced, based on the beam energy measurement using the BEPM. Therefore, the beam energy was measured using the BEPM to investigate the relationship between the cyclotron parameters and the beam energy and the variation of the beam energy from experiment to experiment.

In this study, we give an overview of the BEPM and the measurement results of the beam energy for each experiment and describe the beam-energy change measurement results using the Dee voltage and magnetic field used to tune the cyclotron. Additionally, the generation rate results from the measurement of ^{211}At obtained by irradiating the Bi target with the beam energy changed by the cyclotron tuning are described.

BEAM ENERGY MEASUREMENTS

Measurement Method

As shown in Fig. 1, RI production for the TIARA cyclotron is performed in the RI production equipment located at the end of the linear beamline from the cyclotron exit.

A precision-bending magnet (TAM) installed in this beamline deflects the beam to supply other experimental ports and measures the beam energy. However, when the beam energy to be supplied to the RI production system is measured using the TAM, irradiation for RI production cannot be performed for about 1 h because of the excitation and demagnetization of the TAM, beam energy measurement, and further beam transport adjustments. Therefore, a BEPM system was introduced to obtain the beam energy in real-time by measuring the time-of-flight of the beam bunch passing through the two pickup electrodes.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO014

DESIGN STUDIES OF THE CYLINDRICALLY SYMMETRIC MAGNETIC INFLECTOR

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Abstract

The magnetic inflector is a promising alternative to achieve axial beam injection in a cyclotron with high beam energy. To demonstrate the technology, we use the TR100, a conceptual H2+ cyclotron, as a testbench to study the inflection conditions and optics of the passive magnetic inflector with a cylindrically symmetric structure. A mirror-like field with optimized mirror length and ratio provides a well-focused beam arriving at the median plane. The required magnetic field is produced by shimming a center plug in the injection hole. The space charge effect is also discussed with the simulation of a high-intensity injection beam.

INTRODUCTION

The spiral inflector steers the beam from the bore in the main magnet into the median plane to achieve the axial injection with an external ion source. In a conventional electrostatic inflector, the injection beam energy is limited by the breakdown voltage on the electrodes. While the injection intensity is also limited by the small aperture in the electrostatic inflector. Magnetic inflector is promising to overcome these disadvantages.

Recently, There are two types of magnetic inflector. One is the passive type which uses the iron in the injection hole to produce the required magnetic field. [1] The other is the active one which uses a permanent magnet array. [2] The passive type is more robust because there is no concern about the degaussing of the permanent magnet under the high beam loss in the injection hole. But it is only a concept, that has no existing design. To demonstrate the technology, we designed a magnetic inflector model for the conceptual H2+ cyclotron, TR100 [3]. The inflection conditions and focal properties of the passive magnetic inflector are studied using the particle tracking method. The preliminary simulation considering space charge is also discussed.

REFERENCE ORBIT

Motion Equations

In a cylindrically symmetric magnet. The magnetic vector potential A only consists of the azimuthal component A_θ. A_θ is the function of r and z. Thus, the hamiltonian is independent from θ, which is written as:

$$H = \sqrt{P_r^2 c^2 + P_z^2 c^2 + c^4 m_0^2 + \frac{c^2\left(P_\theta - qr\,\mathrm{A}_\theta\,(r,z)\right)^2}{r^2}} \tag{1}$$

where the canonical momenta are:

$$\begin{aligned} P_r &= p_r \\ P_\theta &= \gamma m_0 \theta' r^2 + qrA_\theta\,. \\ P_z &= p_z \end{aligned} \tag{2}$$

We can easily find that the canonical momentum in the azimuthal direction is a constant. Defining a potential function U with the constant azimuthal momenta and the magnetic vector potential as:

$$U = \frac{\left(P_\theta - qr\,\mathrm{A}_\theta\,(r,z)\right)^2}{2\gamma m_0 r^2} \tag{3}$$

the motion equation, essentially as obtained by Glaser [4], could be written in the following form:

$$\begin{aligned} P'_r &= \frac{\partial U}{\partial r} \\ P'_\theta &= 0 \quad . \\ P'_z &= \frac{\partial U}{\partial z} \end{aligned} \tag{4}$$

Substituting Eq. (2) into Eq. (4), the motion equation is written as:

$$\begin{aligned} \theta' &= \theta'_0 r_0^2/r^2 + \frac{q}{\gamma m_0 r^2}(r_0\,\mathrm{A}_{\theta 0} - r\,\mathrm{A}_\theta) \\ \gamma m_0 r'' &- \frac{\partial U}{\partial r} = 0 \\ \gamma m_0 z'' &- \frac{\partial U}{\partial z} = 0 \end{aligned} \tag{5}$$

Because U is independent of θ and time t, the motion on the r-z plane is conservative. To find a proper reference orbit, we only need to solve the 2-D motion equation on the r-z plane.

Numerical Solution for a Mirror-like Magnetic Vector potential

The magnetic mirror is a component that is used to confine the charged particles. The particles inside a magnetic mirror are bounced back before the mirror point, in this paper we use a similar field to inflect the beam. The vector potential used to define the axial symmetric magnetic field in a mirror field is given as:

$$A_\theta = \frac{A_1 \beta r}{2} - A_2 I_1(\beta r)\cos\beta z \tag{6}$$

where π/β is the mirror length, $\beta(A_1 + A_2)/(A_1 - A_2)$ is the mirror ratio.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO015

TRIUMF LLRF CONTROL SYSTEM UPGRADE

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Abstract

The LLRF system for Transfer line from Drift Tube LINAC(DTL) to Superconducting Linac (SCB) (DSB) was an analog-digital hybrid system running at 35.36MHz. The system controls the amplitude/phase and tuning for a buncher cavity on the beamline. During the 2022 October shutdown, the system is upgraded to a new fully-digital LLRF system. The new digital LLRF system is based on TRIUMF's universal LLRF hardware with a new firmware. Instead of using a VXI mainframe, the new system adopts a NIM bin and uses USB communication with the local control PC. The amplitude/phase regulation is implemented in the FPGA firmware, and the tuning loop is implemented in the PC software, but driven by the FPGA. The Debian 11 linux OS is running on ARM CPU, and the new digital LLRF system works as a standard window HID device. The linux OS allows the firmware be updated in-situ using Ethernet communication. The detailed design is described in this paper.

INTRODUCTION

The previous LLRF system for DSB was an analog-digital hybrid system based on VXI mainframe that controls the amplitude/phase and tuning of the cavity. The LLRF system works at 35.36MHz, and this frequency is generated from the harmonics of the 5.89MHz main reference source. The tuning loop was implemented with phase comparison method, then upgraded with the sliding mode control. The RF part of the system works great for years. However, the motor control function of the tuning loop has minor problem related to the limit switch. Meanwhile, the VXI mainframe is obsolete and hard to buy for the future system. To fix the motor problem, a new digital LLRF system is designed to replace the existing system. The new system is based on ZYNQ FPGA and installed in the NIM bin crate instead of VXI mainframe. The daughter board is TRIUMF's universal LLRF hardware [1], and the mother board is equipped with RF signal conditioning circuit. The local control PC communicates with the LLRF system through USB and Ethernet. The new system adopts 35.36MHz reference signal and the output of the system is phase-locked to it. There are two outputs provided by the new system: one is for driving the amplifier chain and the other one is used as the reference for Isotope Separator and Accelerator(ISAC) II. The hardware of the new digital LLRF system is shown in Fig. 1.

SYSTEM DESIGN

The system requires amplitude/phase control, tuning(step motor) control, and the global phase control. The 35.36MHz signal is used as the reference input. There are one cavity pickup signal and two output signals in the system. The

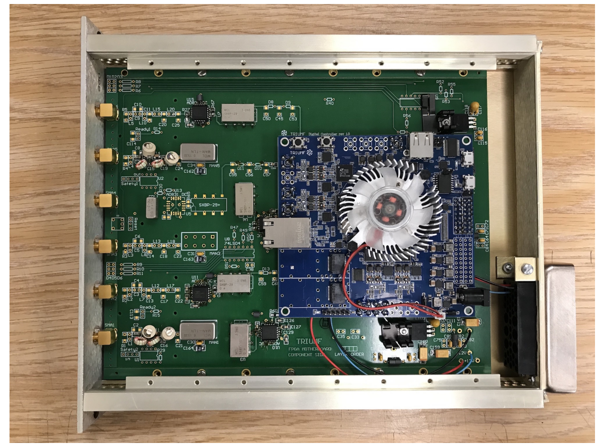

Figure 1: Picture of Digital LLRF system for DSB.

system works in generator driven mode. From the previous experience of TRIUMF's digital LLRF system [1, 2], the new system for DSB is designed as below in Fig. 2.

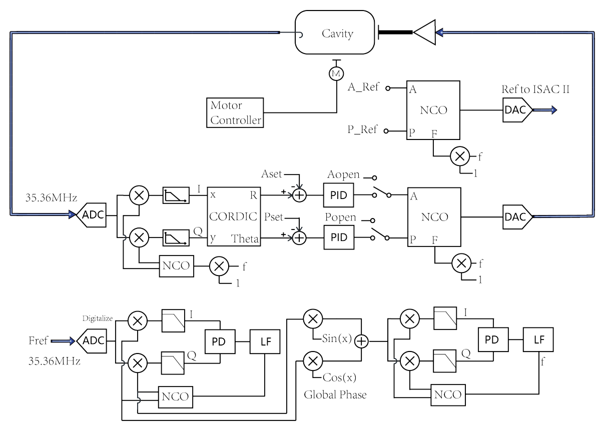

Figure 2: Digital LLRF system design for DSB.

Phase-locked Loop and Global Phase Shifter

The new digital LLRF system works in driven mode and the phase of the output signal is not phase-locked to the reference signal. To resolve this issue, a digital phase-locked loop is introduced to the system. The digital phase-locked loop is based on a Costas loop which is widely used in communication systems. The first Costas loop is used to lock the frequency of the NCO to the 35.36MHz reference signal. After the first digital phase-locked loop, a global phase shifter is used to shift the phase of the reference signal, then the phase-shifted signal is used as the reference of the second phase-locked loop. The output of the second phase-locked loop is used as the basic frequency correction value for the system. Then, the two outputs of the system can be locked to the phase-shifted reference signal by adjusting

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO016

CONTROL OF CYCLOTRON VERTICAL DEFLECTOR FOR PROTON THERAPY

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Abstract

China Institute of Atomic Energy (CIAE) has designed a superconducting cyclotron CYCIAE-230 to enhance the domestic development of proton therapy. A research program on the beamline and experimental stations for the proton therapy and the space science was launched by China National Nuclear Corporation (CNNC). The modern therapy methodology often requires rapid beam modulation on both the beam energy and the intensity. In this scenario, a vertical deflector is designed and installed in the cyclotron's central region. Applying a high-voltage electric field between the two plates can quickly adjust the intensity of the low-energy beam. Nevertheless, the voltage applied is nonlinear to the beam intensity. According to this requirement, a homemade controller for the vertical deflector is designed. Since the beam loss caused by the energy degrader is also nonlinear, this controller can compensate for the beam loss caused by energy modulation. To realize real-time control, the controller combines Field Programmable Gate Array (FPGA) and Digital Signal Process (DSP) as its control scheme design. Carried out by the DSP by interpolating the lookup table data, a feed-forward regulation is also designed to take care of the nonlinear compensation for the beam loss on the energy degrader. In the meantime, an ionized chamber provides feedback readings of the intensity just before the nozzle. A PID algorithm is also included by using FPGA, to archive the feedback control of the vertical deflector.

INTRODUCTION

Compact superconducting (SC) cyclotrons have the advantage of small size, cost effectiveness, high extraction efficiency and beam stability, which are very suitable for medical applications. A 230 MeV superconducting cyclotron is designed by China Institute of Atomic Energy (CIAE) to provide fix energy beam of 246 MeV with an intensity of about 300 nA for proton therapy [1, 2]. There are several items in the cyclotron that are related to the output beam current. For instance, the arc power of the internal ion source, the phase selecting system, the Dee voltage, and extracting high voltage (HV). Nonetheless, the arc power of the ion source and phase selecting system are not fast enough. The Dee voltage and extracting HV are too complicated to have fast modulation. Therefore, a fast beam modulation technique is urgently needed to speed up the beam intensity modulation in order to shorten the treatment time.

The upstream part of the beamline includes an energy degrader, which aims to adapt the beam energy to different treatment requirements, is adjusted by the Treatment Control System (TCS). The drawback of the energy degrader is that it modulates the current nonlinearly when changing beam energy. Due to the nonlinear nature of this energy change means, the beam transmission rate before and after the energy degrader will change drastically as the final energy changes.

Therefore, a vertical high voltage deflection system is installed in the central area of the cyclotron, which can modulate the beam in an independent manner and limit the loss of the beam at lower energy. Although this vertical high voltage deflection system is also nonlinear, the designed vertical deflector controller will solve this problem. It will compensate the beam lost on the degrader and the system. In the meantime, it will achieve fast switching of the beam within 100 µs and stable control of the beam to realize the new intensity modulated proton therapy (IMPT) and a new generation of time-driven intensity modulation continuous line scan technology to shorten patient treatment time. Last but not the least, it can provide redundant beam cut-offs for medical safety interlocks for proton therapy, safeguarding patient safety during the proton therapy.

OPERATING PRINCIPLES

This vertical high voltage deflection system comprises a pair of vertical deflector plates and a passive collimator. The plates are connected to a power supply outside of the cyclotron. It can actively provide initial power for low-energy beam. The vertical oscillation generated by the magnetic field will enhance the vertical off-axis motion, and the downstream collimator will eventually intercept these particles. The structure of the vertical deflector plate in the central area of the superconducting cyclotron and the principle of particles passing through the vertical deflector plate and collimator to regulate the beam intensity are shown in Figs. 1 and 2. The simulation assumes that the electric field in the vertical deflector plate is constant and acts in the 2nd to 4th turns of the particle trajectory to apply axial momentum to the particles. In contrast, the axial collimator acts in the 2nd to 5th turns, and the particles with

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO017

RF CAVITY RESONANT CONTROL USING MINIMAL SEEKING SLIDING MODE CONTROLLER

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Abstract

Accelerating RF normal conducting cavities having Quality Factors of over 10^3. These cavities must be constantly tuned to maintain resonance for maximum power efficiency. Traditional tuning method uses 'phase comparison method' by monitoring the phase shift across the input and output of the cavity. This method suffers from phase drift due to diurnal temperature variations. Since 2017, TRIUMF ISAC-1 cavities are tuned using minimal seeking sliding mode controllers, which eliminate effects drift due to temperature changes. As with all extremum seeking algorithm, chattering is present in the system, especially near the end-stage. This paper also includes a new chattering suppression method known as 'surface skipping', which is slated to be installed in ISAC-1 LLRF upgrade in 2023.

INTRODUCTION

In a RF cavity, with $\Delta\omega = \omega - \omega_c$, with ω as the operating frequency, τ the time constant of the cavity and ω_c its resonant frequency, the steady state complex cavity voltage V is given by [1]

$$V \cong \frac{\Gamma + 1}{1 + (\Delta\omega\tau)^2}(1 + j\Delta\omega\tau)v_F \qquad (1)$$

where Γ is the reflection coefficient, is the result of impedance matching. Using Kirchhoff's voltage law

$$v_F + v_R = V \qquad (2)$$

The reflected voltage v_R is [1]

$$v_r \cong v_f \frac{\Gamma + j\Delta\omega\tau}{1 - j\Delta\omega\tau} \qquad (3)$$

The reflected power P_R in relation to the forward power P_F is

$$P_R \cong P_F \frac{\Gamma^2 + (\Delta\omega\tau)^2}{1 + (\Delta\omega\tau)^2} \qquad (4)$$

and

$$\frac{dP_R}{d(\Delta\omega)} = P_F(1 - \Gamma^2)\tau^2\Delta\omega \qquad (5)$$

Minimum P_R occurs when

$$\frac{dP_R}{d(\Delta\omega)} = P_F(1 - \Gamma^2)\tau^2\Delta\omega = 0 \qquad (6)$$

or $\Delta\omega = 0$.

From Eq. (1), the phase angle between V and v_F is

$$\phi = \tan^{-1}\Delta\omega\tau \qquad (7)$$

At $\Delta\omega = 0$, the RF cavity in will be operating most efficiently. Most cavity do this by applying Eq. (6), monitoring the monotonic ϕ and move the tuner such that $\phi = 0$. However, ϕ cannot be measured in-situ, as there must be some lengths of cables from the input pickup and the output pickup. The lengths of these cables must be carefully matched to prevent phase drift due to diurnal temperature changes. In TRIUMF's ISAC-1, ϕ is measured from the output of the LLRF to the feedback input of the LLRF. This makes the phase measurement even more prone to error due to the rf amplifier chains inherent phase shift dependency on power and temperature. To avoid phase measurement, tuning algorithm in ISAC-1 cavities try to minimize the reflected power P_R instead. From Eq. (4), minimizing v_R or P_R will result in $\Delta\omega \to 0$ and therefore maximizing V. However, as can be seen from Eq. (4) and Fig. 1, P_R is neither linear nor monotonic. This leads us to minimum reflecting power seeking algorithm. There are several minimum seeking algorithms, all of them involve perturbing the system to detect the correct slope to minimization. In gradient estimation minimum seeking algorithm, $\frac{dP_R}{dt}$ is calculated to obtain the direction of travel for the tuner. However, numerical differentiation enhances high frequency noise. The sliding mode extremum seeking algorithm, P_R is used instead to suppress the noise generated by slope detection.

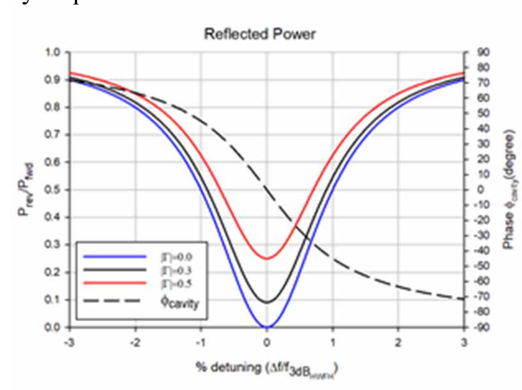

Figure 1. Reflected power vs tuning.

SLIDING MODE EXTREMUM SEEKING ALGORITHM

The original sliding mode equation is given as [2-4]

$$\frac{d\theta}{dt} = k_0 \operatorname{sgn}\left[\sin\left(\frac{\pi s}{\varepsilon}\right)\right]F(\theta) \qquad (8)$$

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO018

THE MAGNETIC FIELD DESIGN OF A 16 MeV VARIABLE ENERGY CYCLOTRON

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Abstract

The development of a 16 MeV H^- cyclotron is in progress at CIM company (Hefei, China). Such machine is designed for radio-isotope production which is used for nuclear medicine. Beam extraction is ensured by means of stripper foils located at different radii to achieve variable extraction energy between 10 and 16 MeV. In this paper, the main magnet design was demonstrated in detail. An AVF magnet with four radial sectors was adopt to get strong axial focusing. The hill angular widths and hill gaps with radius were designed to meet the isochronous magnetic field. The tunes were optimized to avoid dangerous resonance. The result of magnet design was verified by beam dynamics simulations. After the presentation of the magnet design, some results on stripping extraction were also discussed. TOSCA (OPERA-3D) was used to perform 3D magnetic field simulation. An efficient beam simulation code developed by MATLAB was used to do beam dynamics simulations.

INTRODUCTION

In recent years, the Institute of Plasma Physics of the Chinese Academy of Sciences (ASIPP) and Hefei CAS Ion Medical and Technical Devices Co., Ltd. (CIM) are jointly developing a 10~16 MeV variable energy proton cyclotron, which can be used to produce medical radioisotopes.

Medical radioisotopes, such as ^{18}F and ^{11}C, are in great demand in China. Chinese government issued the Medium and Long term Development Plan for Medical Isotopes (2021-2035) in 2021, vigorously encouraging the application and innovation of nuclear medicine technology. The low energy (10-20 MeV) proton cyclotron has become the main equipment for isotope preparation with its advantages of small size and low cost [1].

ASIPP and CIM have rich experience in the manufacture and commissioning of cyclotrons. The cyclotrons such as SC200 [2] and CIM14-A developed have successfully extracted the beam. In order to further enrich the company's accelerator product series and meet the growing demand for radioisotopes, ASIPP and CIM decided to develop a proton cyclotron with a maximum extraction energy of 16 MeV and a maximum extraction current of 100 µA. Because the extraction method is stripping extraction, the extraction energy can be adjusted from 10 to 16 MeV to produce as many kinds of radioisotopes as possible. The cyclotron accelerates H^- ions. H^- ions whirl in the magnetic field at a frequency of 23.45 MHz. After passing through the stripping foil at the extraction radius (29.9~37.1 cm), two electrons are stripped off and become protons. The magnetic field design and beam dynamics simulation are described below.

MAGNET DESIGN

The cyclotron magnet system is shown in Fig. 1. It is composed of a conventional conductor coil, an iron yoke and 4 pairs of radial sectors. The magnet system is square in shape, 185 cm in side length, 92 cm in height, and 19.7 tons in total weight. It conforms to the characteristics of compactness and flexibility of medical cyclotron, and can be installed in the built hospital. The radius of the magnetic pole is 44.8 cm, which is a flat magnetic pole, and the gap between the magnetic poles is 4.1 cm. The hill-valley modulated magnetic field formed by 4 pairs of magnetic poles can provide axial focusing force for the beam. By shimming the width of the magnetic pole, the isochronism of the magnetic field can be optimized, the phase slip of the beam can be reduced, and the acceleration efficiency can be improved. The central field is designed to be about 1.54 T, which can be realized by conventional conductor coil, and the current density of the main coil is 250 A/cm^2. The main parameters of the magnet system are shown in Table 1.

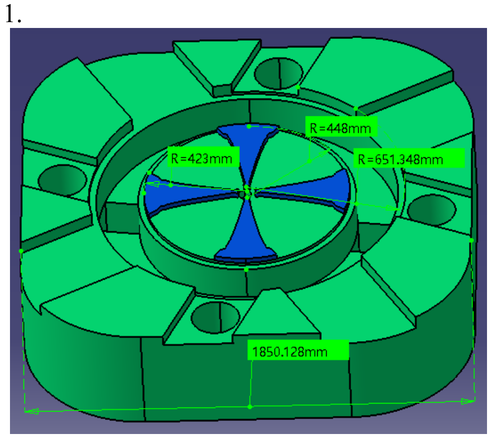

Figure 1: Magnet model of cyclotron.

Table 1: Preliminary Magnet System Parameters

Parameter [unit]	Value
Pole radius [cm]	44.8
Diameter of iron yoke [cm]	185
Hill gap [cm]	4.1
Valley gap [cm]	8.7
Main coil current density [A/cm2]	250
Magnet Height [cm]	92
Magnet weight [t]	19.7

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO019

OPTIMIZATION OF RAPID MAGNETIC FIELD CONTROL OF THE CYCIAE-230 CYCLOTRON BEAMLINE MAGNETS

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Abstract

The magnetic field precise and rapid control of the beamline magnets is essential to the Energy Selection System (ESS) for the proton therapy facility. During the scanning of proton beam for therapy, the field of each beamline magnet should be precisely controlled within the set time, layer upon layer. The position of beam spot to the nozzle should undoubtedly be stable and unchanged during the process. In practice, however, due to the wide energy range of proton therapy (70 ~ 230 MeV), the dynamic response of the beamline magnets usually shows nonlinear performances at a different energy, e.g., the magnetic field may cause a significant overshoot for some specific beam energy if one ignores the nonlinear effect. More challenge is that the magnetic field drops too slowly between the energy steps, which compromises the overall performance of rapid intensity modulated scanning therapy. A dynamic PID parameter optimization method is reported in this paper to address this issue. According to the transfer function of each magnet, the entire energy range is divided into several steps. Then, the experiments are carried out to find the most suitable PID parameters for each energy step. Finally, the "beam energy − excitation current − PID parameters" lookup table (LUT) is generated and stored in the beamline control system BCS for automation. During the treatment, using the LUT allows the energy setting for beamline magnets to be adjusted automatically with the most appropriate PID parameter, guaranteeing the overall performance of rapid scanning therapy. The experimental results show the overall response time of all the beamline magnets reduced from several hundred milliseconds to less than 65 ms, which meets the design requirement of less than 80 ms.

INTRODUCTION

CIAE is developing a proton therapy facility base on a superconducting cyclotron. The beamline is one of the important components of the therapy facility, which guarantees the proton track can be fixed from the cyclotron to the nozzle [1, 2]. When adjusting the treatment layer, the dynamic response of beamline magnets should be as fast as possible, reasons as follows: Firstly, it can reduce the treatment interval time between different layers and improve the efficiency of the therapy. Secondly, it minimizes the damage to the patient's healthy tissue. Thirdly, a long energy switching process will undoubtedly increase the cyclotron operation time when treating a patient. The total time loss added up by every treatment layer will be considerable. So, it will lead to a significant increase in total energy consumption. At present, the total energy selection time of proton therapy centers worldwide is mostly on the order of several hundred milliseconds scale. For example, the time for IBA in Belgium is 500 ms and the time for PSI in Swiss and Varian in America can be 150 ms. The energy selection time of the HUST-PTF proton therapy system at Huazhong University of Science and Technology is 144 ms, and its magnetic field dynamic response time is 105 ms [3].

The total energy selection time of CYCIAE-230 developed by CIAE is less than 80 ms. To guarantee the faster speed of magnetic field response, this paper presents a dynamic PID parameter optimization method.

MAGNET POWER SUPPLY CONTROL

The discrete PID algorithm is used for the magnet power supply. Figure 1 shows the control block diagram. The control loop adopts a double closed-loop control structure of output current outer loop and load voltage inner loop. The output current feedback value is obtained by DCCT. The load voltage control loop can solve the voltage disturbance in the main circuit of the power supply more quickly, and increase the stability of the system. In contrast, if there is only a single current control loop, the voltage disturbance needs to be reflected as output current fluctuation, then compensated. This process has hysteresis, and voltage disturbance cannot be eliminated essentially either.

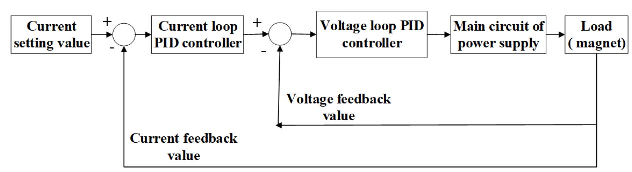

Figure 1: Control block diagram of magnet power supply.

OPTIMIZATION OF RAPID MAGNETIC FIELD CONTROL

Two Main Difficulty of Accelerating the Dynamic Response of Magnetic Field

The energy range of proton therapy is wide, which is 70 ~ 230 MeV. This leads to one set of PID parameters not being adapted to all the energy steps. The reasons are mainly divided into two aspects: the nonlinear variation of the magnetic field and the influence of hysteresis.

The Influence of Nonlinear Magnetic Field Variation The SRIM software was used to approximate the energy required for the beam to hit the body at various thicknesses. As the interval between each treatment layer is 2 mm in this project, the proton range interval is set as 2 mm in the calculation. Figure 2 shows the calculation results. It can be seen that the relationship between energy and range is not linear. To increase the same range, the energy variation

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-TUAI01

CYCLOTRON BEAM EXTRACTION BY ACCELERATION

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Abstract

One of the decisive issues in the design of a new cyclotron is the choice of the beam extraction method. Typical methods are extraction by electrostatic extractors and by stripping. The former method requires DC high voltage electrodes which are notorious for high-voltage breakdowns. The latter method requires beams of atomic or molecular ions which are notorious for rest-gas- and Lorentz-stripping. We discuss the conditions to be met such that a charged particle beam will leave the magnetic field of an isochronous cyclotron purely by fast acceleration.

INTRODUCTION

One of the first decisions to be made in the conceptual design phase of a new cyclotron regards the method of beam extraction. The most frequently used methods are extraction by electrostatic septum extractors or by stripper foils. The latter requires the use of projectiles which are not fully stripped yet, i.e., for instance H^- or H_2^+ instead of bare protons (H^+). But stripping of H^- or H_2^+ is also known due to scattering of the projectiles with rest gas or by strong fields (i.e., Lorentz stripping). In order to avoid internal loss of particles and the ambient activation due to these losses, the field must be limited to rather low values (especially in case of H^-), and/or an excellent vacuum pressure is obligatory, typically 10^{-7} bar and below.

The use of electrostatic extractors (EEs) has the disadvantage that such devices are notorious for high-voltage breakdowns. Experience at PSI has shown that EEs are also sensitive to contamination by dust and dirt and to rf-power leaking off the accelerating structures.

So-called "self-extracting" cyclotrons have been suggested and built before [1], but the conditions to be met by such cyclotrons have, to the author's knowledge, never been fully clarified.

Here we investigate the question whether cyclotrons can be designed such that the beam leaves the cyclotron purely by fast acceleration. In order to answer this question we will first review the reasons why the beam does (usually) not leave the field of isochronous cyclotrons simply by acceleration.

THE SMOOTH ACCELERATION APPROXIMATION

For this purpose we use a simplified cyclotron model, i.e., we will ignore the requirement to use azimuthally varying fields (AVF) to obtain vertical stability. In cases where one is interested exclusively in the radial motion, this approximation is adequate since the AVF has only a weak influence on the radial tune.

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Hence we assume rotational symmetry, that is, the field is a function of radius only $B = B(R)$. As well known, the field is isochronous for

$$B_{iso}(R) = B_0\,\gamma \tag{1}$$

where $\gamma = (1-\beta^2)^{-1}$ is the relativistic factor. Since the orbit length per revolution is $s = 2\pi\sqrt{R^2 + (\frac{dR}{d\theta})^2}$ and since $\frac{dR}{d\theta} \ll R$ usually holds, the velocity is in good approximation given by $v = \omega_{rev}\,R$ and hence we define the radial function

$$\gamma_R = \frac{1}{\sqrt{1 - R^2/a^2}} \tag{2}$$

with the so-called "cyclotron radius" $a = c/\omega_{rev}$. However any real world machine has a finite radius $R < a$ and is isochronous only up to the fringe field. A simple and reasonably realistic model of the fringe field is given by an Enge-type function [2, 3]

$$f(R) = (1 + \exp\left((R - R_h)/g\right))^{-1} \tag{3}$$

where R_h is the radius for $f = 1/2$ and g is a parameter which is approximately half of the pole gap. The magnetic field is then assumed to be

$$B(R) = B_{iso}\,f(R) = B_0\,\gamma_R\,f(R)\,. \tag{4}$$

When the beam enters the fringe field, the bunches will necessarily get out of sync with the accelerating rf voltage. The revolution frequency ω_{rev} is

$$\omega_{rev} = \frac{q}{m\,\gamma}\,B = \frac{q}{m\,\gamma}\,B_0\,\gamma_R\,f = \omega_0\,\frac{\gamma_R}{\gamma}\,f\,. \tag{5}$$

The velocity then is $v = \omega_{rev}\,R$ and the relativistic γ-factor

$$\gamma = 1/\sqrt{1 - \omega_{rev}^2\,R^2/c^2} = 1/\sqrt{1 - (\gamma_R^2 - 1)\,f^2/\gamma^2}\,. \tag{6}$$

Solving for γ gives

$$\gamma = \sqrt{1 + (\gamma_R^2 - 1)\,f^2}\,. \tag{7}$$

THE BENDING LIMIT

Any finite magnetic field has a bending limit, which can be obtained from

$$p = q\,R\,B(R)\,. \tag{8}$$

The momentum is maximal when $\frac{dp}{dR} = 0$ with

$$\frac{dp}{dR} = q\,B\,(1 + k) \tag{9}$$

where the field index k is defined by

$$k = \frac{R}{B}\,\frac{dB}{dR}\,. \tag{10}$$

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-TUA001

HISTORY AND PROSPECTIVES OF GANIL

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Abstract

The first beam of the GANIL facility (Grand Accélérateur National d'Ions Lourds) at Caen was ejected from the second separated sector cyclotron forty years ago (November 19th, 1982). Since then, several evolutions occurred. In 2001, the first exotic beam, produced by the Isotope Separation On-Line method at the SPIRAL1 facility, was delivered to physics. The GANIL team realized an upgrade of this facility in order to extend the range of post-accelerated radioactive ions in years 2013-2017, with first radioactive beams delivered in 2018. In 2019, GANIL became also a LINAC facility, with the first beam accelerated in the SPIRAL2 facility. The DESIR facility is aimed at using beams from SPIRAL2 and from SPIRAL1 facility, motivating a major renovation plan of the cyclotron facility. Parts of ancient and recent history of GANIL will be presented as well as its future.

FROM THE BEGINNING FORTY YEARS AGO TO UPGRADE OF SPIRAL1

November 19th, 1982, 12h30 am, the first beam was seen on the profiler located at the output of the second separated sector cyclotron at GANIL (Fig. 1) 5 nA were ejected from 150 nA injected ($^{40}Ar^{16+}$), starting from 200 nA $^{40}Ar^{4+}$ ejected of SSC1.

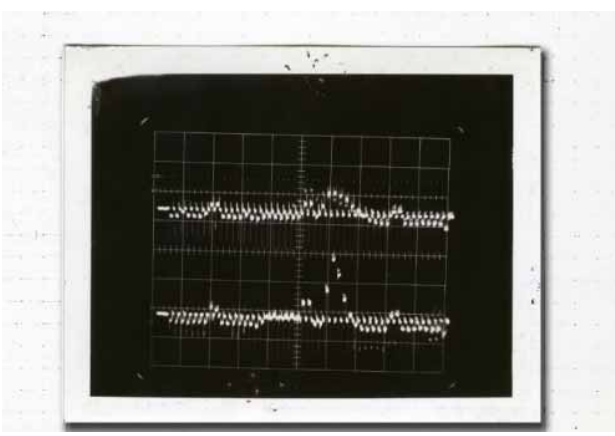

Figure 1: 1st beam profile, SSC2 ejection.

GANIL construction was decided in 1975. The design included two compact cyclotrons as injectors, one for SSC1 and for SSC2. In the final design, the two injectors may inject the beam into SSC1, and also SSC2 (the two SSCs were identical). There is one rebuncher between the injectors and SSC1, one stripper between SSC1 and SSC2, one low energy spectrometer and a high-energy one, called "Alpha" spectrometer due to its shape. The beam is distributed to experimental areas through a "fishbone" (Fig. 2).

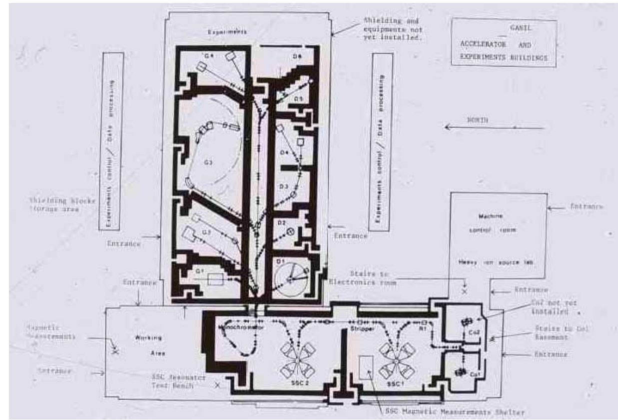

Figure 2: Design of GANIL.

The facility was built in the years 1978 – 1982. In 1983, the first experimental took place in January. That year, Ne, Ar, Kr, and O were accelerated. The O was accelerated at the maximal energy, 95 MeV/nucleon, but the energy was low for heavier beams (45 MeV/A for Kr beam).

Figure 3 shows an RF cavity ready for installation into the SSC.

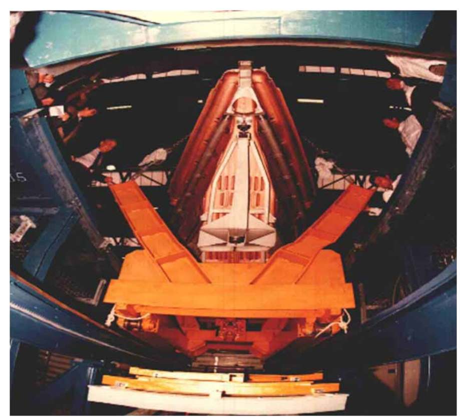

Figure 3: RF cavity installation.

In 1989, the OAE project was achieved [1], increasing the maximal energy for heavy beams. The key point was the stripping efficiency, increased with a higher SSC1 ejection energy (operation of SSC1 with harmonic 5 instead of 7, and new injection radius in SSC2 – 1,2 m instead of 0,825).

Increasing SSC1 energy was facilitated by the new sources, ECR technology replacing the PIG sources, inside the cyclotrons, in 1985. In 1992, the C01 ECR source was installed in a 100 kV platform and a new injection beam line was built, leading to better intensities and higher transmission (up to 65%). However, there were discharges in the accelerator tube and in 2004, we added a solenoid and a dipole inside the platform to have a pre-selection and limit the intensity in the tube.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-TUA004

DESIGN OF A MULTI-HARMONIC BUNCHER FOR TRIUMF 500 MeV CYCLOTRON

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Abstract

The TRIUMF 500 MeV cyclotron injection system consists of a 40 m long beamline to transport the 300 keV H^- ion beams into the cyclotron. Part of the original beamline, the vertical injection section, was replaced in 2011, while the remaining horizontal injection section is currently being redesigned for replacement. As part of the horizontal injection beamline upgrade, the present buncher system will be replaced with a new one. The current buncher configuration consists of two double gap bunchers: the first buncher operates at the cyclotron RF frequency (23.06 MHz) while the second operates at the second harmonic frequency (46.12 MHz). The proposed new buncher is based on a two-electrode multi-harmonic system, which will be operated by up to three harmonics. The beam dynamics studies have been performed, including the space-charge effects using the particle-in-cell code WARP. Simulation results of longitudinal beam dynamics are presented for transporting beam intensity up to 1 mA.

INTRODUCTION

The demand for the total extracted beam from the TRIUMF 500 MeV cyclotron is increasing with the addition of the new rare isotope beam facility ARIEL [1]. In order to meet the increased total output from the cyclotron, the injection intensity and beam brightness also needed to be improved. The injection beam upgrade program has started in order to meet the increased total output by improving the injection intensity of high-brightness beams. The vertical injection beamline was upgraded in 2011 as the initial phase [2]. The second phase of the upgrade program consists of upgrading the horizontal injection beamline [3] and adding a new ion source injection terminal (I2) [4]. The new buncher is part of the ongoing upgrade of the horizontal injection beamline. The basic parameters through the injection beamline is presented in Table 1.

Currently, two double gap bunchers are being used in the injection beamline [5]. The first buncher is located 21 m downstream from the injection point in the horizontal injection beamline, while the second buncher is located 4.54 m downstream from the first buncher. The first buncher operates at the cyclotron RF frequency of 23.06 MHz, while the second buncher operates at the second harmonic of 46.12 MHz. Using the current buncher system, the total extracted current from the cyclotron is approximately 0.28 mA, with an injection current of 0.4 mA. As part of the upgrade of the horizontal injection beamline, the current buncher system will be replaced with a new multi-harmonic buncher.

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Table 1: Basic Beam Specifications

Parameter	Value
Beam species	H^-
Beam energy	300 keV
Maximum beam intensity	1 mA
Maximum emittance ($4\epsilon_{RMS}$) at 300 keV	12.0 µm
Beam duty cycle	0.1% – 99%
Bunching frequency	23.06 MHz

MULTI-HARMONIC BUNCHER

The concept of a multi-harmonic buncher has been widely used elsewhere in an ion bunching system by combining the fundamental RF wave with its various higher harmonics to obtain a nearly sawtooth-like waveform [6–8]. In our case, a two-electrode three-gap multi-harmonic buncher system has been designed with a 1.27 cm cm aperture radius and a 0.5 cm gap between the electrodes. The layout of the buncher system is shown in Fig. 1. The center distance between the first and second RF gap is 16.765 cm and 8.383 cm for the second and third RF gap, respectively. The first (23.06 MHz) and third harmonics (69.18 MHz) are applied to the first electrode, while the second electrode is applied with the second harmonics (46.12 MHz). The electrostatic modeling of the buncher has been done with the code COMSOL [9]. Figure 2 shows the calculated electrostatic field along the

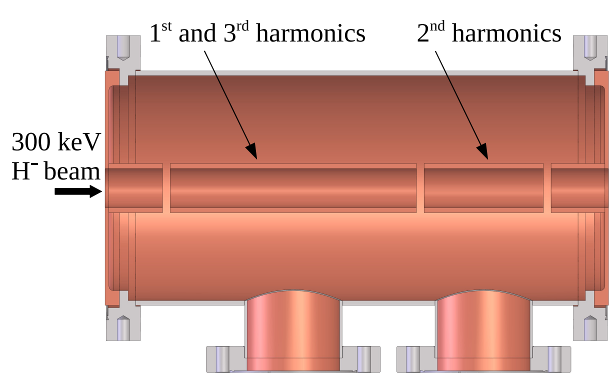

Figure 1: A cross section view of the new multi-harmonic buncher. Note that the RF resonators are not included in this figure.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-TUBO01

MEASUREMENT OF DETECTOR RESPONSE FUNCTIONS FOR FAST NEUTRON SPECTROSCOPY WITH ORGANIC SCINTILLATORS

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Abstract

Spectrum unfolding decouples spectroscopic measurements of neutron fields from accelerator facilities by making use of a well-characterised detector response matrix. Measurements of detector response matrices, derived from time-of-flight, were made at the fast neutron facility at iThemba LABS, South Africa, with neutrons with energies between 10 - 65 MeV for: a traditional BC-501A organic liquid scintillator detector with photomultiplier tube and analogue pulse processing and acquisition; and a modern system comprised of an EJ-276 plastic scintillator, silicon photomultiplier and digital pulse processing and acquisition. The detector response matrices were validated by unfolding neutron energy spectra from measured light output spectra, and compared to the associated energy spectra derived from time-of-flight. Both detector systems demonstrated good agreement between the energy spectra derived from time-of-flight, which is promising for fast neutron spectroscopy with organic scintillators in environments outside of the laboratory.

CONTEXT

Fast neutron fields with energies up to several GeV are a concern for aviation, manned space missions, workplace exposure and radiation therapy [1–3], and are often poorly understood due to a lack of appropriate measurement devices and reference facilities. In aviation environments the interaction of cosmic rays in the atmosphere and aircraft material produces a shower of secondary radiation with complex composition and energy distribution. At an altitude of 11 km fast neutrons contribute up to 40% of the equivalent dose [4], with peaks in the energy spectrum around 1 MeV and 100 MeV [5], and during unpredictable, short-lived space weather events, the flux of cosmic rays, and secondary neutrons, increases dramatically [6]. Fast neutron interactions with biological or electronic matter cause indirect damage through the production of ionising reaction products, which results in an increased risk to both people and electronic systems [7, 8] and requires continuous monitoring to properly assess, and regulate, the radiation exposure of aircrew. The recent developments of solid (plastic) scintillators capable of pulse shape discrimination (PSD), low-voltage silicon photomultipliers (SiPMs) and digital data acquisition, coupled with spectrum unfolding now offers a viable solution to the development of a compact fast neutron spectrometer, which is suitable for use in a range of applications, including dosimetry in aircraft. We present the measurement and validation of detector response functions for fast neutrons (10 – 65 MeV) with a traditional liquid scintillator and NIM-electronics based system, and a compact detector system utilising modern acquisition technologies.

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MEASUREMENTS

Measurements were made at the iThemba LABS (iTL) fast neutron facility [9, 10], where ns-pulsed fast neutron beams are produced in the energy range of 30 - 200 MeV using proton beams from the k = 200 cyclotron. The time spread of a proton bunch is approximately 1 ns, and a beam pulse selector is used to increase the time between bunches up to 360 ns. Neutrons were produced using a beam of 66 MeV protons incident on an 8.0 mm thick ^{nat}Li target. The neutron energy spectrum is comprised of a forward-biased mono-energetic peak from the ^{7}Li(p, n)^{7}Be reaction, which proceeds only by the transition to the ground state and the first excited state of ^{7}Be, with all higher levels being unstable [11], and a nearly isotropic, lower energy continuum that extends up to the primary peak [12]. Neutron beams are produced at 0° and 16° relative to the incident proton beam using a 2.0 m thick steel collimator (5.0 x 5.0 cm^2 apertures).

In time-of-flight spectroscopy [13], a ns-pulsed beam of ions are incident on a neutron producing target, and the time of arrival T of those neutrons reaching a detector is measured for a known distance d. The neutron energy E_n can then be determined from:

$$E_n = mc^2\left[\frac{1}{\sqrt{1-(d/cT)^2}} - 1\right] \quad (1)$$

where m is the rest-mass of a neutron, and c is the speed of light.

Measurements were made with a ⌀ 5.1 cm x 10.2 cm BC-501A organic liquid scintillation detector at 0° and at d = 8.0 m from the ^{nat}Li target, and data were acquired in coincidence in list-mode for time-of-flight (T), pulse shape (S) and pulse height (L) parameters using a NIM-based acquisition system (Fig. 1). The pulse shape parameter S is determined by the zero-crossover method and is implemented with a FAST ComTec 2160A module [14] on the fast anode output. Neutron only events are separated from gamma ray events as indicated by the dashed line in the L-S histogram in Fig. 2. The pulse height parameter L is calibrated with known gamma ray sources to produce a MeV electron-equivalent (MeV$_{ee}$) scale. The time-of-flight parameter T was calibrated by inserting several delays of known length

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-TUB002

REAL TIME DETERMINATIONS OF THE RANGE AND BRAGG PEAK OF PROTONS WITH A DEPTH PROFILE CAMERA AT HZB

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Abstract

The cyclotron at HZB provides a 68 MeV proton beam for therapy as well as for experiments. By using a novel camera setup, the range of the proton beam is measured optically. The setup consists of a phantom with a luminescent layer inside and a CMOS camera. By measuring the emission of the luminescent layer, the Bragg peak and the range of the proton beam can be visualized for different energies. In contrast to a water phantom, the camera system offers much shorter measurement times. A dedicated LabVIEW code provides various evaluation possibilities: the Bragg curve and the lateral beam profile are generated and displayed. The system is sensitive to energy differences of less than 400 keV. The results were obtained with a beam intensity of less than 10 pA/cm^2 homogenous proton beam in front of the degrader. The measurement is done in real time and provides live feedback on changes such as beam energy and beam size. The results of the camera are presented and compared to water phantom measurement.

MATERIALS AND METHODS

Cyclotron at HZB and Water Phantom

The HZB cyclotron provides protons for the eye tumor therapy since 1998. More than 4400 patients from all over the world have been treated here [1]. There are two injectors and a cyclotron as main accelerator which provides a 68 MeV proton beam for eye tumor therapy and for experiments. The facility is under continuous development for therapy.

A water phantom is normally used to determine the Bragg curve of the proton beam. To measure a complete Bragg curve with an energy of 68 MeV for the therapy, the measurement takes 5 minutes for a resolution of 0.1 mm [2]. A finer resolution with the water phantom is possible but means a much longer measuring time. For experiments where the Bragg curve is essential, the same water phantom has been used so far for calibration. This means for experiments with different energies a very long preparation time is needed. Even with smallest changes, the measurement of the Bragg curve must be repeated. Therefore, a measurement system had to be developed which reduces the preparation time and allows a real-time evaluation of the Bragg curve of the proton beam.

There are also other systems with different phantoms like liquid scintillators [3] or plate phantom systems [4]. Most of them need longer measuring time, have rather coarse resolutions and no real-time evaluation. Another system is a multi-leaf faraday cup [5]. This system can quickly evaluate a Bragg curve but is heavy and very expensive in commercial form.

Camera System

The camera system has a patent pending. It consists of a phantom, a luminescent layer (interaction layer), a housing and a camera shown in Fig. 1. The phantom is the main point of the system. It consists of two plastic blocks. The dimension of the phantom is matched to the maximum available energy of the proton beam. Between the blocks of the phantom is diagonal the luminescent layer (e.g., Gd_2O_2S) or interaction layer placed.

For the interaction layer, a material is used which exploits the effect of fluorescence. The proton beam is decelerated in the phantom. Depending on the position of the proton beam, it collides with the luminescent layer and the light intensity is equivalent to the energy loss.

Centered on the phantom is the camera. It is a FLIR camera with a CMOS sensor. The camera is equipped with a lens that focuses the detected signals of the luminescent layer. The captured image of the Bragg curve is readout by a LabVIEW (NI, Austin, USA) code. The entire setup is located in a housing sealed by light. A crosshair at the entrance of the beam in the system allows a fast optical alignment. The total size is as small as 35 cm x 20 cm x 20 cm and it's very light with only 1.5 kg. Due to the compactness of the system, it is easily transportable and can be used at different target stations. The system is easy and inexpensive to realize in contrast to conventional water phantoms.

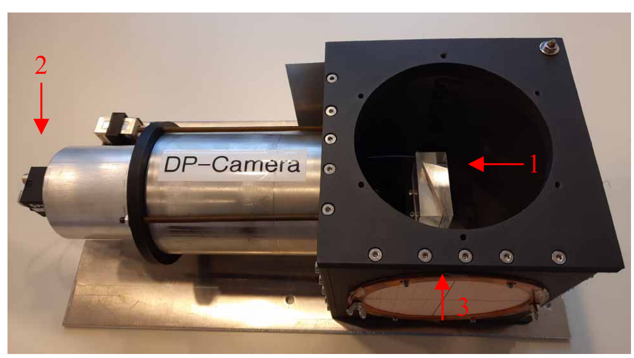

Figure 1: View inside the camera system. 1- shows the phantom block with the luminescent layer inside. 2 - position of the camera. 3 – beam direction.

LabVIEW Code

A LabVIEW code is used to evaluate and visualize the data from the camera system. Different aperture sizes can

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-TUB003

APPLICATION PROGRESS OF CYCIAE-100 HIGH CURRENT PROTON CYCLOTRON*

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China Institute of Atomic Energy, Beijing, China

Abstract

A new RIB facility, Beijing radioactive ion-beam facility (BRIF) had been constructed at CIAE. A 100 MeV H^- cyclotron (CYCIAE-100) is selected as the driving accelerator which can provide a 70–100 MeV, 10 pA–520 µA proton beam for basic and applied research in the field of nuclear science and technology. The application of this facility has promoted the development of frontier scientific research in China, such as radioactive nuclear beam physics, nuclear data, neutron physics and space radiation effects. Recently, quasi-monoenergetic neutron source above 20 MeV and the white light neutron source with the best time resolution were completed, which had filled the gap in the measurement of neutron data in the range of energy of 100 MeV in China. In this paper, the main milestones in the use and development of CYCIAE-100 high current proton cyclotron are reviewed, the scientific applications based on platform are described, and the important topics in proton applications based on intermediate energy are discussed, including space radiation hardening, neutron standard radiation field and biological radiation damage mechanism.

INTRODUCTION

BRIF was started at CIAE in 2004. The project outline is shown in Fig. 1. It consists of a 100 MeV cyclotron, an isotope separator online system (ISOL), modification of the existing tandem, a superconducting Linac booster (SCL), various experimental terminals, and an isotope production station [1].

Figure 1: Layout of BRIF.

On July 4th 2014, first 100 MeV/20 µA proton beam shot on the target from CYCIAE-100, and the achievement was awarded as Top10 scientific achievements of 2014 in China. Figure 2 illustrates the main parts of the cyclotron. It is connected with five beamlines as follows:

- Northward can supply beam to ISOL beamline and isotope target terminal.
- Southward can supply beams to three beam lines that are White light neutron target line (15 m neutron tube and 30 m neutron tube), single event effect test bench and quasi-monoenergetic neutron source terminal.

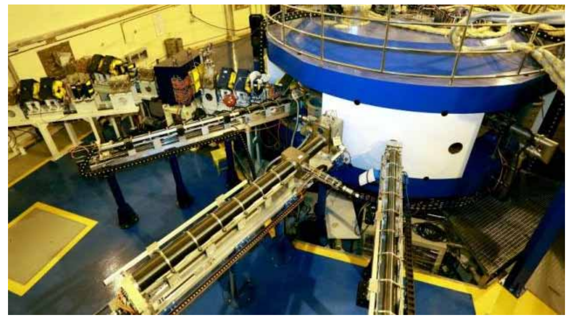

Figure 2: The CYCIAE-100 cyclotron.

APPLICATION ON CYCIAE-100

Up to Dec 2022, CYCIAE-100 has produced over 5000 hours beam time for users. Users are from different area institutes for nuclear physics, medical schools and institutes for electronic and space technology universities. The Usage of Cyclotron in our lab mainly focused on nuclear physics research, nuclear reaction, nuclear data, radiation effect Research proton-neutron SEE, radiation hardness, medical and other applications including medical isotope production and proton therapy.

Nuclear Reaction

Innovative achievements in radioactive nuclear beam physics had been carried out. The highest quality Na-20 radioactive beam is produced by using high resolution ISOL device in 2015, and the strange decay mode of β-γ-α of ^{20}Na is discovered for the first time in the world which brought China's nuclear astrophysics, radioactive nuclear beam physics and other scientific research into the international forefront. The ^{20}Na energy spectrum diagram is shown in Fig. 3.

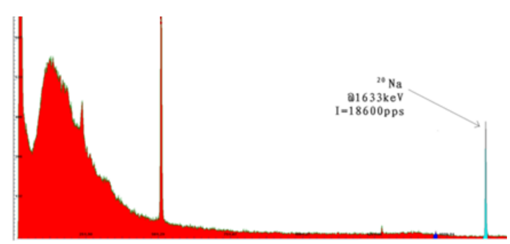

Figure 3: ^{20}Na energy spectrum diagram.

Nuclear Data

Quasi-monoenergetic neutron source above 20 MeV and the white light neutron source with the best time resolution were completed. In order to take the calibration of high energy neutron that is a bottleneck restricting space neutron

* Work supported by NNSF of China under Grant No.11375273.
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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-TUB004

EVALUATION OF PLC-BASED ETHERNET/IP COMMUNICATION FOR UPGRADE OF ELECTROMAGNET POWER SUPPLY CONTROL AT RIBF

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Abstract

In the Radioactive Isotope Beam Factory (RIBF), a front-end controller consisting of a computer automated measurement and control (CAMAC)-based system and I/O devices are utilized for the power supplies of many electromagnets upstream from the RIKEN RING Cyclotron. The CPU installed in the system is an x86-based CAMAC crate controller known as “CC/NET”. An experimental physics and industrial control system (EPICS) input/output controller (IOC) running embedded Linux is used to remotely control the electromagnet power supplies. However, these CAMAC-based systems are outdated and require replacement. The FA-M3 programmable logic controller (PLC) is an alternative candidate device that can be incorporated into the magnet power supply. However, a high-reliability network between the EPICS IOC and the device is required compared to a conventional socket connection via Ethernet. Therefore, we evaluated a system that uses EtherNet/IP to communicate between these devices and the EPICS IOC. The EtherNet/IP system is based on the TCP/IP protocol, which is widely used for field bus communications via Ethernet. An advantage of using EtherNet/IP is that it enables cost-effective reliable communication despite the use of TCP/IP. It is possible to improve the reliability of the interlock output even when using conventional TCP/IP-based network.

INTRODUCTION

RIKEN had the former accelerator facility, RARF (RIKEN Accelerator Research Facility), consisting of the RIKEN Ring Cyclotron (RRC), and RIKEN Linear Accelerator (RILAC) as an injector since 1986 [1]. Three new cyclotrons, the FRC, IRC, and SRC, were constructed downstream of the RRC in the new Radioactive Isotope Beam Factory (RIBF) project, and beam commissioning of the new cyclotrons was completed in the 2006 fiscal year [2]. RIBF is currently a heavy-ion accelerator facility with five cyclotrons and three injectors [3]. Furthermore, the original RARF power supplies are still in use while beam-tuning the electromagnets upstream of RRC because RIBF is an upgrade of project RARF. Thus, outdated I/O modules and communication boards used to control electromagnet power supplies are still in use.

Figure 1 shows a block diagram of the control system at the time of RARF. Furthermore, electromagnet power supply control in RARF is a computer-automated measurement and control (CAMAC) system. The system consists of a communication interface module (CIM), which is a communication module attached to the CAMAC crate, and a device interface module (DIM)[4], which is an I/O built into the electromagnet power supply and is connected via an optical fiber to enable serial communication. CAMAC was initially controlled by the MELCOM 350-60/500, a minicomputer manufactured by Mitsubishi Electric Corp [5]. The minicomputer was replaced in 2001 by a VME CPU board with a VxWorks OS to operate via the Experimental Physics and Industrial Control System (EPICS) [6]. To stabilize the control system, a CPU board running EPICS was replaced in 2004 with an x86 CAMAC crate controller, CC/NET manufactured by Toyo Tecnica [7]. This system is unique because it is an embedded system that runs EPICS on Debian 3.0, a Linux operating system for CC/NET. Figure 2 shows the CAMAC-based system for the electromagnet power supply that is currently in operation.

The VME CPU board has been replaced with CC/NET as the CAMAC-based controller of the electromagnet power supply systems, but CIM/DIM system have already been used for more than 30 years since the beginning of RARF operations and have become obsolete. For example, poor CIM/DIM communication causes a bottleneck in some cases during operation; hence, these CIM/DIM systems must be urgently replaced. The FA-M3 programmable logic controller (PLC) manufactured by Yokogawa Electric Corporation was chosen as a potential replacement for the DIM built inside the power supply chassis while considering replacing the outdated CIM/DIM system. Figure 3 shows the DIM functional part currently under development. The FA-M3 PLC is a candidate device for the function corresponding to the DIM, we designed the communication between the controllers corresponding to the CIM, and the EPICS implementation method.

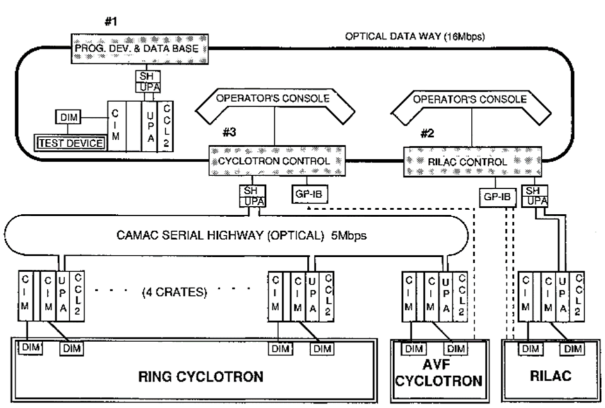

Figure 1: Block diagram of RARF control system (the original figure is Fig. 2 in reference 5).

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEAI01

SELF-CONSISTENT SIMULATION OF AN INTERNAL ION SOURCE PLASMA MENISCUS AND ITS EXTRACTED SPACE CHARGE DOMINATED BEAM IN THE CYCLOTRON CENTRAL REGION *

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Abstract

Central region design simulations for cyclotrons with internal ion source are often complicated by the fact that the initial particle phase space distribution is not well known. Especially for high-intensity cyclotrons, one would like to have a quantitative self-consistent approach for a more accurate simulation of the beam extracted from the ion source and its acceleration in the first accelerating gaps under space charge conditions. This paper proposes some new ideas and methods for this problem. The simulation approach has been developed at IBA for the high-intensity compact self-extracting cyclotron in the EU-H2020-MSCA InnovaTron project. Detailed results of simulations on plasma meniscus and space charge dominated beam extracted from it and accelerated in the cyclotron centre are shown in the paper.

INTRODUCTION

At IBA a high-intensity compact self-extracting cyclotron, called InnovaTron, is being studied. The machine is a promising tool for large-scale production of medical radioisotopes. Self-extraction allows spontaneous beam extraction. It is based on a very steep fall-off of the magnetic field near the outer pole radius [1]. First harmonic coils increase the turn-separation at extraction. A 14 MeV proton cyclotron build by IBA in 2000 provided the proof-of-principle for this extraction method (extracted beam currents up to 2 mA) [2]. However, rather poor beam quality was observed and the extraction efficiency was limited to about 80% at low intensities. Increase of the dee-voltage ripple resulting from the noisy PIG-source and beam-loading led to an extraction efficiency of about 70%-75% at higher intensities. Main goals set for the project are: i) improvement and optimization of the magnet, extraction elements and central region, ii) space charge simulations, iii) improvement of turn-separation at extraction. Proton currents up to 5 mA are aimed for.

Here, we discuss detailed results obtained for central region studies including space charge in beam dynamics simulations. Space charge plays an important role already during the process of bunch formation in the first gap. It also induces a vortex motion during beam acceleration and an increase of energy spread in the bunch [3]. Simulation results obtained for magnet optimization and a new IBA tool for automated optimization of cyclotron settings are also discussed.

* Work supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 886190.
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MAGNET OPTIMIZATION

Figure 1 shows the main features of the prototype. The pole gap has a quasi-elliptical shape, allowing for the steep fall-off of the magnetic field (Fig. 1 (a)) by the machining of a groove on the long pole (on which the beam is extracted) at a radius where the gap is small (Fig. 1 (b)). Figure 1 (c) shows one of the harmonic coils. A gradient corrector is used for radial and vertical focusing of the extracted beam. Parts of the beam that are not properly extracted are intercepted by a beam separator shown in Fig. 1 (d). The extraction path in the machine is shown in Fig. 1 (e). More details are in [2].

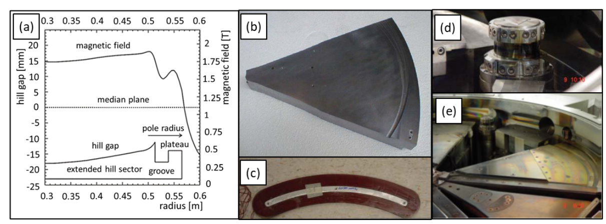

Figure 1: The prototype of the self-extracting cyclotron.

The following improvements have been implemented as compared to the prototype: i) the magnet (and also the accelerating structure) has perfect 2-fold symmetry. This allows irradiation of two targets stations at opposite exit ports and to place two internal ion sources. The latter will increase cyclotron reliability and uptime; ii) the groove in the extraction path is replaced by a "plateau" (Fig. 2 (a)). This reduces the strong sextupole component in the extraction path and improves the extracted beam quality. Figure 2 (b) shows the magnetic field along a line that bisects the long and short poles as shown in Fig. 2 (a); iii) the pole gaps still have a quasi-elliptical shape, decreasing towards larger radii, but the iso-gap contours follow equilibrium orbits. This enables a steeper transition from the internal stable orbit towards the non-stable extracted orbit; iv) an improved gradient corrector has been designed for radial focusing of the extracted beam (Fig. 2 (c,d)).

Figure 2 (e) is a view on the lower half of the magnet developed in Opera3D and shows the harmonic coils (in red), the gradient correctors (in green) and the beam separators (in yellow). The dees (in light blue) are also shown. A beam simulation of the last 5 turns superimposed on the FEM model is shown in Fig. 2 (f). Automatic and parametrized FEM models have been developed for the magnet but also for the central region. More details are given in [4].

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEAI02

UPGRADE OF THE RCNP AVF CYCLOTRON*

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Abstract

The upgrade program of the K140 AVF cyclotron at Research Center for Nuclear Physics (RCNP), Osaka University, was started in 2019 to provide not only intense light ion beams for production of short-lived radioisotopes (RIs), neutrons and muons but also high-quality intense beams for precision experiments in nuclear physics. Most of equipment besides the main coil, pole and yoke of the cyclotron magnet was replaced by new one. Especially the RF, injection and extraction systems were fully modified to increase a beam current. A new coaxial-type resonator was designed to cover a frequency range from 17 to 37 MHz for acceleration of staple particles using acceleration harmonic mode of 2 and 6. The acceleration voltage of ion sources was increased from 15 kV to 50 kV to enhance the beam intensity and to reduce the beam emittance for injecting a high-quality intense ion beam into the cyclotron. The central region of the cyclotron was fully redesigned to improve beam transmission from the LEBT system. Beam commissioning was started from May 2022, and a 28.5 MeV $^4He^{2+}$ beam was supplied to produce a short-lived RI of ^{211}At used for the targeted alpha-particle therapy. A 65 MeV proton beam was successfully injected into the K400 ring cyclotron to provide a 392 MeV proton beam for production of a white neutron flux and a muon beam. Several ion beams have been already used for academic research and industrial applications.

INTRODUCTION

RCNP was founded in 1971 as Domestic Joint Usage Center for nuclear physics research in Japan. Construction of the RCNP AVF cyclotron with K-number of 140 MeV was completed in 1973, and nuclear physics experiments started from 1976 [1]. The accelerator facility was fully opened to nuclear physics community globally. The cyclotron cascade project was started in 1987 and construction of the K400 ring cyclotron was completed in 1991 [2]. The AVF cyclotron was mainly used as an injector for the ring cyclotron. Partial upgrade of the two cyclotrons and beam lines was conducted in 2005 [3] and 2014. The bird-eye view of the cyclotron facility is shown in Fig. 1.

In recent years, the strong demand for increasing beam intensity was growing for production of short-lived RIs such as ^{211}At and secondarily produced particles such as neutrons and muons. In addition, intense halo-free high-quality light ion beams are required for very precise nuclear experiments with energy resolution less than 0.01 %. On the other hand, the number of troubles with the AVF cyclotron was increasing and the condition of the AVF cyclotron has deteriorated gradually. We decided the full-scale upgrading of the AVF cyclotron for improvement of beam performance and operation reliability.

Renovation and reinforcement of the RCNP accelerator facility was started in 2019. After completing the renewal of the building and facilities, the most of the AVF cyclotron components except for the main magnet were removed in 2020, and reinstallation of new components was completed in March 2021. Adjustment of the new components was conducted in 2021, and beam commissioning was started in March 2022. Trial beam utilization has been carried out occasionally in parallel with beam commissioning.

AIM OF THE UPGRADE

When the AVF cyclotron is operated in the standalone mode, lower energy proton and helium ion beams are mainly provided for RI production. We have two experiment rooms exclusively used for RI production in the AVF cyclotron building. In one of the experiment rooms, ^{211}At is frequently produced and provided for non-clinical research on targeted alpha-particle therapy. In November 2021, investigator-initiated clinical trial for practical treatment was started at Osaka University Hospital. We will need to supply ^{211}At of the order of more than several hundred MBq for the clinical trials in 2023. In addition, we have another beam line for production of short-lived RIs. In recent years, there is a growing need for supplying short-lived RIs for academic use, especially for the research on diagnosis and therapy in nuclear medicine. In Japan, the short-lived RI supply platform was organized in 2016 in cooperation among RCNP, Osaka University, RIKEN RIBF, CYRIC and ELPH, Tohoku University, QST NIRS and TIARA to support basic and applied research using RIs in a variety of academic fields. The ^{211}At with a half-life of 7.2 hours, is one of the major short-lived RIs which are provided from the short-lived RI supply platform. One of the main purposes of the AVF cyclotron upgrade was increase of the light ion beam intensity to more than 100 μA.

A 392 MeV proton beam is used to produce secondary particles such as neutrons and muons. Especially the neutrons, obtained at an emitted angle of 30 degrees from a tungsten target, have almost the same energy distribution as terrestrial neutrons. The so-called white neutrons are very useful for accelerated-simulation experiments of soft-errors occurred in semi-conductor devices resulting from

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEA001

OPAL SIMULATION ON THE BEAM TRANSMISSION IN THE CENTRAL REGION OF THE MEDICAL CYCLOTRON COMET AT PAUL SCHERRER INSTITUTE

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Abstract

The use of the medical cyclotron COMET for FLASH proton therapy requires a high beam transmission from the ion source through the central region apertures. This paper first presents a model of the COMET cyclotron featuring a rotatable ion source, a movable puller, and an adjustable first fixed slit (FFS), implemented with the OPAL framework. The electromagnetic field is individually created to match each specific configuration. The beam optics parameters, especially beam position and beam size upon approaching and after passing FFS, have been studied in detail. The OPAL simulations demonstrate that an optimal configuration of the ion source, the puller and the FFS is key to achieve a high beam transmission. An experimental test gave a 2.8 times higher intensity within COMET cyclotron with the modifications derived on the basis of the simulations: a 0.57 mm shift of puller and a 5.6° rotation of ion source. The simulations indicate that, with these modifications, the beam can still be centered and accelerated to the extraction energy of 250 MeV. Next step is to investigate the influence of such modifications upon the acceleration and the extraction, again with an iterative approach combining simulations and experiments.

INTRODUCTION

The compact superconducting cyclotron COMET delivers a 250 MeV beam for proton therapy at PSI [1-2]. The central region of the cyclotron, consisting of the ion source, the puller and the first fixed slit (FFS) as shown in Fig. 1, has been under investigation and development throughout the stages of design, commissioning, and routine operation [3-7]. It was recently reported that the beam transmission from the ion source passing through the FFS could be increased up to 60% after a puller shift of 0.56 mm towards the centre [8]. A high FFS transmission is an important step towards extracting beam of high intensity desirable for FLASH proton therapy as well as for patient treatment in a shorter treatment time in order to mitigate problems of organ motion during the treatment. Simulation may lead to a quantitative understanding on the factors correlated with FFS transmission, and to explore improvement potential. OPAL, a parallel open source tool developed at PSI for charged-particle optics in accelerators and beam lines [9], is suited not only for high intensity machines like PSI Ring Cyclotron operating up to 2.4 mA, but also for the medical cyclotron COMET extracting a beam well below 1 μA [6].

OPAL SIMULATION

Model of Central Region of COMET Cyclotron

As shown in Fig. 1, three key components in the central region, namely the chimney of the ion source, the puller, and the FFS, are approximated with multiple rectangular pieces, the only form to specify a collimator inside a cyclotron for OPAL simulation. In OPAL input, the chimney may be rotated around its axis, and the puller may be shifted towards the centre. We considered rotation angles θ in the order of a few degrees and displacements s in the sub-millimetre range. Furthermore, the position of the FFS may be shifted while its aperture may be varied. In practice, it is rather cumbersome to adjust the position of the real FFS. However, an FFS with an aperture of 0.16 mm, 0.18 mm, or 0.2 mm, has been applied for routine patient treatment. An FFS of 0.2 mm aperture is mostly used for both simulation and operation. In OPAL the model of COMET cyclotron is a mirror image of the real machine.

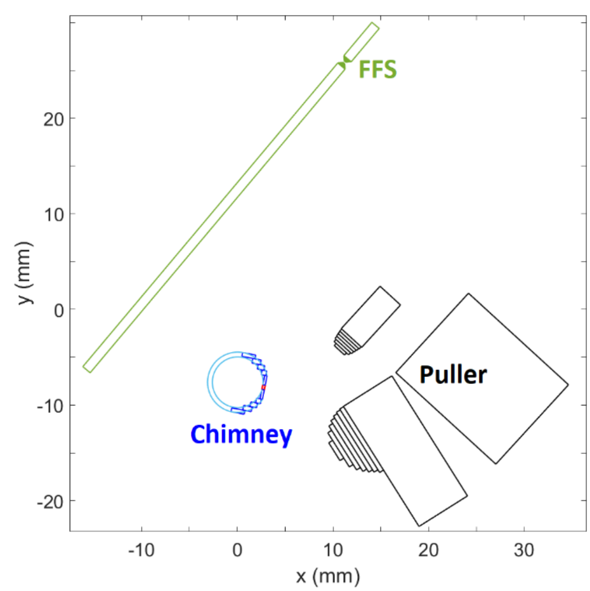

Figure 1: OPAL model for central region of COMET.

Field Maps for Particle Tracking

OPAL features particle tracking through multiple field maps, 2D and 3D, electric and magnetic, static and time varying, separated and overlapped, which is essential for the simulation of the central region of COMET cyclotron. Figure 2 shows the static magnetic field map in the median plane, while Fig. 3 shows the magnitude of the E component of the RF field in the median plane.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEA002

SIMULATION AND ANALYSIS OF HIMM-IC BEAM DYNAMICS WITH OPAL*

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Abstract

Since 2020, HIMM (Heavy ion medical machine) facilities in both Wuwei and Lanzhou cities have been installed and put into clinical application or commissioning experiments. As an injector cyclotron (IC), HIMM-IC can provide 6.8 MeV/10eμA $^{12}C^{5+}$ beam for the synchrotron. Nevertheless, in terms of better beam quality and operation efficiency, HIMM-IC design still has a lot of room for improvement. We used OPAL (Object oriented Parallel Accelerator Library) simulation program to complete the 3D multi-particle dynamics simulation of HIMM-IC including the space charge effect. And the results show that it is in good agreement with the actual experimental measurements.

INTRODUCTION

China's carbon ion therapy facility, also named HIMM, is a cancer treatment facility designed by the Institute of Modern Physics of the Chinese Academy of Sciences. It has two ECR ion sources and uses an axial injection to deliver $^{12}C^{5+}$ into HIMM-IC (see Fig. 1), which can accelerate the beam to about 7 MeV/u. The main accelerator HIMMSYN (HIMM Synchrotron) accelerates the beam further to 120-400 MeV/u. Its maximum particle number at the terminal is about 1.2×10^9 ppp. Through the HEBT line, the beam will be delivered to 5 fixed treatment terminals in 4 treatment rooms. As the injector cyclotron of the HIMM, HIMM-IC is a compact isochronous cyclotron. The overall diameter is only 2.92 m. The magnetic field is composed of a whole magnet without any trimming coils. It can provide 7 MeV/u, 10 eμA $^{12}C^{5+}$. The other basic parameters are shown in the Table 1 [1, 2].

Table 1: HIMM-IC Basic Parameter

Parameter	Value
Central magnetic fields	1.212 T
Injection radius	2.7 cm
Injection Energy	111.6 keV
RF frequency	31.02 MHz
Harmonic number	4
Extraction radius	75 cm

According to the operation of HIMM-IC (taking the Wuwei heavy ion therapy facility as an example) [3], the ECR ion source provides 82.5 eμA $^{12}C^{5+}$, and the extraction beam intensity of HIMM-IC is up to 11.06 eμA, with an overall transmission efficiency of about 13.75%. Considering the strict safety operation standard of the medical facility, we stop to overhaul (including check and clean inflector and RF cavities) every two years and clean the inflector once a year. In long-term stable operation, HIMM-IC can extract about 5.5 eμA $^{12}C^{5+}$ with the injection beam intensity of about 50 eμA provided by the ECR ion source and the total transmission efficiency is more than 10%. Although the operating status meets the need of clinical treatment, there is still a lot of room to upgrade it for better performance.

Figure 1: HIMM-IC.

During the design phase, we used the cyclotron dynamics simulation software – SNOP to model and simulate the HIMM–IC and obtained a better coincidence between the two by comparing with experimental measurements. Therefore, we use a new cyclotron dynamic simulation software, OPAL [3, 4], to re-model and simulate the HIMM-IC with 3D beam dynamics including space charge effects.

To overcome the operation problems of the low beam intensity and quality and to prepare for the further upgrade, the following approaches are considered in this work:

- Generation of the three-dimensional electric and two-dimensional magnetic field map.
- Analysis of the performance of the cyclotron units: CR (Central Region), Acceleration and Extraction. The other units (like LEBT) are not discussed in this work because they are not suitable for simulation using OPAL.
- Estimation of the overall cyclotron transmission (extraction to injection beam intensity ratio) and output beam parameters (emittance, energy spread, time pulse, and dispersion).

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEA003

DEVELOPMENT OF THE CYCLONE®KEY: HOW INTEROPERABILITY LEADS TO COMPACTNESS*

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Abstract

In 2020, IBA has started the design, construction, tests and industrialization of a new proton cyclotron for the low energy range, the Cyclone® KEY, for PET isotope production (^{18}F, ^{13}N, ^{11}C) for neurology, cardiology or oncology imaging. It is a compact and fully automated isochronous cyclotron accelerating H^{-} up to 9,2 MeV. Based on the successful design history and return of experience of the Cyclone® KIUBE, the Cyclone® KEY design has been focused on compactness (self-shielding enabled), cost effectiveness and ease of installation, operation, and maintenance. The innovative design consists in the interoperability of the different subsystems: the magnet, the RF system, the vacuum system, the ion source, the stripping extraction, and target changer (with up to three targets). First beam tests results will also be presented.

THE CYCLONE®KEY

The Cyclone® KEY (Fig. 1) is the little brother of the Cyclone® KIUBE [1, 2]. Aiming at the low energy radioisotope production market, it has been designed to be simple to install and operate. Its compact design enables self-shielding operation with the possibility of low activation concrete [3]. All the different subsystems of the cyclotron have been nested in each other to optimize the compactness of the machine. The main parameters of the cyclotron are summarized in Table 1.

Table 1: Cyclone® KEY Design Parameters

Parameter	Value
Accelerated ions	H^{-}
Ion source	Internal PIG
Number of sectors	4
RF frequency	41MHz
RF mode	2
Dee angle	40°
Dee voltage	32kV
Extraction	Stripper (1+5 spares)
Extracted energy	9.2MeV
Cyclotron footprint (L×W×H)	1.5m×1.4m×1.35m

* Work supported by Pole Mecatech/Biowin/SPW RW - convention 8150: CardiAmmonia.
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Figure 1: The Cyclone® KEY.

Magnet Design

The magnet inherited the vertical median plane of the Cyclone® 3d [4], which avoids the cost of a yoke lifting system. The magnetic structure, see Fig. 2, takes benefit from the successful design of the Cyclone® KIUBE [2]:

- Vertical gap between pole is 24mm to optimize the coil power consumption.
- The square shape to optimize the presence of iron only where it is needed, i.e. behind the poles.
- Symmetrical yoke penetrations for RF coupler (left), RF tuner and coil connections (right), ion source (bottom) and target (top).
- Pole inserts, in the centre of the pole, milled during magnetic mapping to obtain the isochronous magnetic field.
- The vacuum chamber sits on the sector behind the poles.

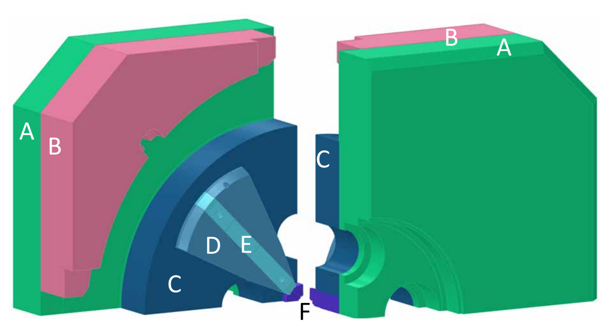

Figure 2: Magnetic circuit, including (A) the return yoke, (B) lateral return yoke, (C) sector, (D) the pole, (E) the pole insert and (F) the central plug.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEA004

STATUS OF THE HZB CYCLOTRON

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Abstract

For more than 20 years eye tumours are treated in collaboration between the Helmholtz-Zentrum Berlin (HZB) the Charité – Universitätsmedizin Berlin (Charité).

The close co-operation between Charité and HZB permits joint interdisciplinary research. Irradiations with either a sharp, well focused or a broad beam, either in vacuum or in air are possible. In the past few years, we concentrated on beam delivery for FLASH experiments and the related dosimetry. For example, intraocular lenses have been irradiated under normal and FLASH conditions to investigate possible changes in the translucence. Furthermore, radiation hardness tests on solar cells for space have been performed.

A modernization project has been started in order to secure a long term and sustainable operation of our accelerator complex for therapy and research.

The accelerator operation for therapy as well as ongoing experiments and results will be presented.

ACCELERATOR OPERATION

A layout of the facility can be found in Ref. [1]. Either the 2 MV Tandetron or the 6 MV Van-de-Graaff serves as injector into the k=130 cyclotron of HZB. Overall, accelerator operation went quite well in the past years (see Fig. 1). Only in 2015 and in 2021 the downtime was above 5%.

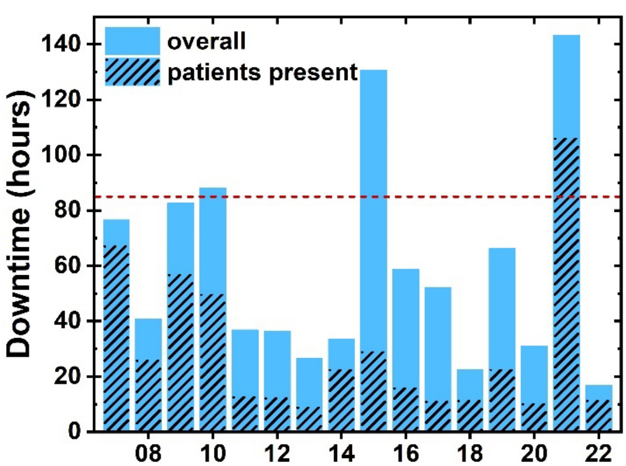

Figure 1: Downtime in hours for the past years. With exception of 2015 and 2021, the relative downtime was below 5%.

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In 2021, a water leak in the extraction magnet required an opening of the cyclotron. For this reason, the scheduled therapy week had to be suspended. This explains the large duration of downtime with patients present, as the postponement is counted as downtime.

Fortunately, a new coil for the extraction according to the original plans had already been acquired. Hence, a rapid 1:1 exchange was possible. In the extraction magnet resides also a correction coil (see Fig. 2), which has never been used in the past. After the exchange of the coil, we failed to extract the beam. Only after connecting and using the correction coil the beam could be extracted with the usual transmission. As the magnet has adjust pins and the extraction coil fits snugly in the magnet, it is most probably the vacuum chamber which is now on a slightly different position.

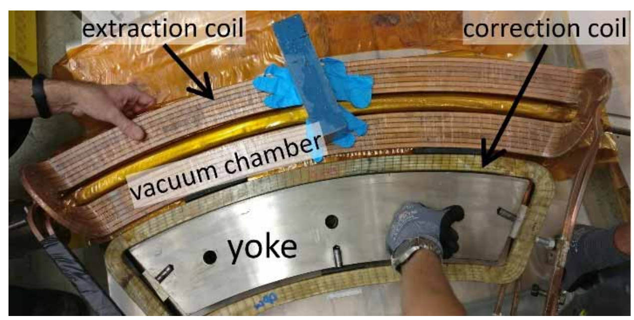

Figure 2: The extraction magnet with extraction and correction coil. On the yoke, the adjust pins are visible.

BEAM UTILIZATION

Roughly 83% of the beam time is used for therapy, the other 17% for experiments. Experiments comprise accelerator research and development (9%) [2, 3] as well as medical physics and dosimetry, (4%) e.g. [4, 5]. The distinction between the two topics is sometimes difficult. The final 4% of the beamtime is used for radiation hardness testing by external users, e.g. [6, 7].

Beam Delivery for FLASH Irradiations

The definition of FLASH irradiation is the delivery of the dose in a time of less than 1 s with a dose rate above 40 Gy/s [8]. The idea is to maintain tumour control and minimize side effects. The high dose rates pose challenges both for dosimetry in terms of linearity and saturation effects, and for reliable beam delivery in terms of beam stability and providing the same dose from shot to shot.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEA005

INVESTIGATION OF LONG RADIAL PROBE ACTIVATION IN THE PSI MAIN RING CYCLOTRON

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Abstract

During an inspection of a new Long Radial Probe, inserted into the Ring cyclotron only a month earlier, an activation hot spot has been identified. The nature of this hot spot has been investigated by performing measurements of the residual activation using shielded Al_2O_3:C dosimeters, 5 mm in diameter, and a portable gamma spectrometer. Monte Carlo simulations of the probe activation with various proton energies have been performed. Results show that most of the activation comes from relatively fast decaying radionuclides and therefore the residual dose drops sufficiently during the shutdown to allow for maintenance and upgrade works. Comparing the abundances of various radionuclides estimated from measured gamma spectra with simulations at various proton energies we conclude that the most probable loss mechanism is scattering of the protons on the upstream collimator.

INTRODUCTION

The Long Radial Probe (RRL) is a device installed in the PSI's Ring cyclotron. It measures transverse beam position and profile of all orbits by measuring the effects of interaction of the beam with a thin, moving target (carbon fibre). The measured radius extends between 2080 and 4500 mm [1].

A picture of the probe moved out of the cyclotron during the gamma spectroscopy measurement is shown in Fig. 1. The cyclotron chamber is behind the large vacuum valve on the right side of the plot. The RRL structure, here in a service box with side flanges open, is normally manually inserted into the cyclotron before the start of the beam operation.

After 19 days of being inserted into the cyclotron the RRL had to be serviced. A routine activation measurement revealed presence of a hot spot with 1 mSv/h. Red star marks the location of this hot spot. Additional measurements performed using small Al_2O_3:C chips exposed directly to activated structure and shielded from other directions revealed that the hot spot is on the upper structure of the RRL.

MONTE CARLO SIMULATIONS

The established method for the activation calculations at PSI is the coupling of Monte Carlo simulations with the general purpose radiation transport code MCNP [2] and the nuclide inventory code FISPACT [3].

The object under study is modeled in the MCNP 6.2 geometry and it is divided in smaller cells to estimate the activation as a function of the position. Particles are transported from the loss points to the regions of interest with MCNP. The flux of neutrons up to 20 MeV and the production rates of radionuclides are calculated in each cell of the geometry. The coupling script [4] is then used to prepare the input files for the FISPACT code, which include MCNP results and the irradiation history. The nuclide inventory of each cell at any time step is finally calculated.

The RRL device is modeled as two blocks of an aluminium-magnesium alloy called EN-AW-508, with dimensions of 1 m in the radial direction (x), 0.5 cm in the vertical direction (y) and 11.75 cm along the beam direction (z) (see Fig. 2). The distance between the two blocks in the vertical plane is 4 cm. The upper part, where higher activation has been measured, is divided in 12 cells. Cells 100-105 are between y=2 cm and y=2.2 cm, while cells 110-115 are between y=2.2 cm and y=2.5 cm. The lower part is not segmented and it is called cell 200.

Since the beam losses at the location of the RRL device are not known, some assumptions have been made for the simulations. The proton beam is moving along the z direction and it is impacting on the device front face. It is uniformly distributed over 1 m in x and between 2.0 cm and 2.2 cm in y. Twelve simulations have been performed considering the following beam energies (in MeV): 10, 20, 40, 60, 80, 100, 140, 200, 300, 400, 500, and 590.

The spectrum of the produced neutrons and the rates of residual nuclei have been calculated for each cell and used as input for the FISPACT calculations. The considered operation history is summarized in the Table 1. A constant lost current of 1 nA has been assumed for both irradiation periods. The end of the first cooling time corresponds to the moment when the hot spot was identified, while the end of the third cooling time corresponds to the time of the gamma spectra measurement.

Table 1: Part of the beam exposition history relevant for this activation study.

	Dates (2022)	Length
1^{st} irradiation	Apr., 27^{th} - May, 16^{th}	19 days
1^{st} cooling	May, 16^{th} ev. - May, 18^{th}	36 hours
2^{nd} cooling	May, 18^{th} - May, 19^{th}	29 hours
2^{nd} irradiation	May, 19^{th} - June, 13^{th}	25 days
3^{rd} cooling	June, 14^{th}	12 hours

For each cell, the nuclide inventory at each time step is calculated, as well as the residual dose that would be generated at 1 m by 1 g of material. The highest dose rates are always observed in cell 100.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEA006

DEVELOPMENT OF HEAVY ION RADIOTHERAPY FACILITIES IN CHINA*

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Abstract

In China, there are currently 2 carbon facilities in operation, Shanghai proton/heavy ion center and Wuwei heavy ion therapy center, 8 facilities are under construction. This paper will introduce the development of heavy ion radiotherapy facilities in China.

INTRODUCTION

Currently, there are about 19 million cancer cases arise every year and 10 million cases dead from cancer every year globally; these numbers will increase to 29.5 million and 16.4 million at 2040 according to the prediction of IARC (The International Agency for Research on Cancer), with an annual increase rate of 2.4% and 2.6% respectively. In China, whose population is about 20% of the world, there are 4.5 million new cases and 3 million cases dead from cancer every year, which will increase to about 6.7 million and 5.1 million at 2040, with an annual increase rate of 2.2% and 2.9%. Heavy (Carbon) ion radiotherapy offers superior dose conformity in the treatment of deep-seated tumors compared with conventional X-ray therapy due to its Bragg-peak feature of energy deposition, the higher RBE (Relative Biological Effectiveness) and lower OER (Oxygen Enhancement Ratio).

Shanghai Proton Heavy Ion Hospital purchased a heavy ion facility from Siemens in 2008 and began operation in 2015. At present, more than 1000 patients receive treatment every year. Wuwei Heavy Ion Center purchased HIMM (Heavy Ion Medical Machine) facility, which is designed and produced by IMP (Institute of Modern Physics). The construction of the facility was completed in 2019 and was put into operation in 2020. Affected by COVID-19, the number of patients treated in the first year was only 200, but the number of patients treated is increasing every year.

STATUS OF HEAVY ION RADIOTHERAPY FACILITIES IN CHINA

In China, there are 2 heavy ion facilities in operation. They are Shanghai proton and heavy ion center and Wuwei Heavy ion therapy center. There are also 8 facilities under construction, which are Lanzhou Heavy ion therapy hospital, Xuzhou heavy ion center (Hitachi), Mazu Health center, Hubei general hospital, Zhejiang cancer hospital, Jiangsu cancer hospital, The First Bethune hospital of Jilin University, Heyou international hospital (Hitachi). All the heavy ion facilities that are under construction list above are produced by IMP except Xuzhou and Heyou hospital.

HIMM FACILITY DEVELOPED BY IMP

Heavy ion medical machine (HIMM) was constructed on the basis and with the experience gained from the Heavy Ion Research Facility in Lanzhou-Cooler Storage Ring (HIRFL-CSR) project [1]. The facility consists of an electron cyclotron resonance (ECR) ion source, a cyclotron injector, a compact synchrotron ring, and 5 treating terminals [2]. The C^{5+} beam generated by the ECR ion source is accelerated by the cyclotron to 6.2 MeV/u and then injected into the synchrotron using the CEI (charge exchange injection) method [3]. The injected beam is accelerated from 6.2 MeV/u to an extraction energy ranging from 120 to 400 MeV/u.

Figure 1 shows an aerial view of the HIMM. The facility consists of four treatment rooms, A, B, C, and D. Five fixed irradiation ports are installed in the rooms: horizontal, horizontal plus vertical, vertical, and 45° irradiation ports. Active scanning is conducted in Room A, while passive scanning is adopted in the other rooms. The maximum irradiation field at the tumor is 200×200 mm^2 for all the irradiation ports.

Unlike other cancer therapy machines, the HIMM synchrotron uses a cyclotron as the injector. The beam intensity of the cyclotron injector is approximately 10 μA, and the emittance of the beam is approximately $25\,\pi \cdot$ mm $\cdot$ rad ($\pm 3\sigma$). Compared to the linear injector, the beam intensity is much weaker and the beam emittance is much larger. To store enough particles in the ring, the CEI method is adopted. This method overcomes the limitations set by Liouville's theorem so that beams can be injected at the point of phase space already occupied by previously injected beam. Therefore, an intense beam can be accumulated in the ring without increasing the beam emittance too much. In addition, the injected beam can be painted in the horizontal phase space by changing the local closed orbit during injection to reduce the probability the particles hit the stripping foil, thus increasing the injection efficiency. This scheme has been proved to be very efficient in the CSRm for light-heavy ions.

The beam orbit and envelopes during injection are shown in Fig. 2. Four bump magnets (Bpi1-Bpi4 in Fig. 1) are used to sweep the closed orbit of the circulating beam. Special vacuum chambers with large aperture are used at magnets located in the injection section. C^{5+} beam with an energy of 7 MeV/u from the cyclotron injector are injected into the synchrotron at a small angle (1.85°) and then reach the stripping foil, by which they are stripped to C^{6+}. The stripping

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEBI01

AN OVERVIEW OF THE SOUTH AFRICAN ISOTOPE FACILITY (SAIF) PROJECT

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Abstract

The South African Isotope Facility (SAIF) is a new radioisotope production facility currently under construction at iThemba LABS in Cape Town and scheduled for completion in 2023.

A commercial 70 MeV proton cyclotron from IBA with a number of beam lines equipped with isotope production stations, have been installed in retrofitted concrete vaults. The facility is supported by new infrastructure and services which are being commissioned. The completion of SAIF will greatly increase the radioisotope production capability of iThemba LABS, and enable the existing Separated Sector Cyclotron (SSC) to be dedicated to nuclear research activities.

An overview of the SAIF project from the inception phase through to the construction phase is provided here, discussing all related workstreams and progress made to date. A more detailed discussion of some specific systems is given, including the design of the isotope production stations, target handling system, and a new radioactive waste management facility.

INTRODUCTION

iThemba LABS is a national facility of the National Research Foundation (NRF) in South Africa, an entity of the Department of Science and Innovation. The mandate of iThemba LABS is to operate a number of cyclotrons for purposes of conducting research in subatomic physics, producing medical radioisotopes and performing patient treatment using proton and neutron beam therapeutic protocols.

The available beam time of the facility was historically divided more-or-less equally between the above-mentioned operational mandates since its commissioning in the early 1980's. However, in recent years the ageing facility for patient treatment was no longer compatible with modern neutron/proton treatment protocols and the patient treatment service was subsequently discontinued a few years ago. Since then, the allocation of available beam time gradually became more weighted towards medical radioisotope production due to growing demand for radioisotope products from the public and private health sectors. Today, iThemba LABS is a key producer and supplier of medical radioisotopes which are distributed throughout South Africa and globally into ~60 countries. As a result of this demand growth for radioisotopes, more than 50% of beam time is currently utilised for radioisotope production.

The demand for increased beam time for subatomic physics research at iThemba LABS as well as the necessity to continue to serve the health sector both locally and globally are the main driving factors for phase 1 of the South African Isotope Facility (SAIF) project which was conceived several years ago and which started officially in 2019 when the first budget for the SAIF project was approved. The SAIF project involves the installation of a new 70 MeV cyclotron into the decommissioned patient therapy vaults at iThemba LABS and which will be dedicated to radioisotope production. This will in turn release the existing Separated Sector Cyclotron (SSC) complex to be fully dedicated to the subatomic and nuclear physics research programmes of the international scientific user base of iThemba LABS (Fig. 1).

EXISTING ACCELERATOR FACILITIES AT iThemba LABS

A number of existing accelerator facilities are currently in operation at iThemba LABS. The main facility is located at Faure near Cape Town, South Africa where the following accelerators are installed:

General Layout

- 200 MeV Separated Sector Cyclotron
- 8 MeV Solid Pole injector Cyclotron (SPC1) with internal PIG ion source for proton beams
- 8 MeV Solid Pole injector Cyclotron (SPC2) with a number of external ion sources for both light and heavy ion production
- A number of experimental beam lines dedicated to neutron production, gamma ray arrays (ALBA and Aphrodite facilities) and radiation biophysics
- K600 magnetic spectrometer for light ions
- 11 MeV self-shielded cyclotron for F-18 production
- Hotlab and cleanroom complex for chemical extraction and production of radiochemical and radiopharmaceutical products under cGMP conditions
- 3MV Tandetron accelerator and beam lines for materials research using Ion Beam Analysis (IBA) and microprobe analysis.

Additionally, a 6 MV tandem accelerator is in operation in Johannesburg, South Africa. This facility is dedicated to materials research using IBA, microprobe analysis as well as Accelerator Mass Spectrometry (AMS).

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEBI02

COMPACT ACCELERATOR BASED EPITHERMAL NEUTRON SOURCE AND ITS APPLICATION FOR CANCER THERAPY

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Abstract

The world's first accelerator based epithermal neutron source for clinical boron neutron capture therapy (BNCT) was designed, developed, and commissioned between 2008 and 2010 by Sumitomo Heavy Industries in collaboration with Kyoto University at the Kyoto University Institute for Integrated Radiation and Nuclear Science. The Osaka Medical and Pharmaceutical University, Kansai BNCT Medical Center installed the same equipment in 2016. On March 11, 2020, the Japanese Ministry of Health, Labor, and Welfare approved the system as a novel medical device for the manufacture and sale of an accelerator BNCT system (NeuCure® System) and the dose calculation software (NeuCure® Dose Engine). On June 1st, 2020, the national health insurance system approved the reimbursement of these products for unresectable, locally advanced, and recurrent carcinoma of the head and neck. Commissioning tests were performed to evaluate the system before clinical use. Neutron and gamma ray distribution inside a water phantom was experimentally measured and compared with Monte Carlo simulation results. The peak thermal neutron flux inside a water phantom for a 12 cm diameter circular collimator was 1.4×10^{9} $n\cdot cm^{-2}\cdot s^{-1}$. The experimental values closely matched the Monte Carlo simulation results.

INTRODUCTION

BNCT is a form of particle therapy that selectively targets cancer cells by producing high-LET particles by the nuclear reaction between a thermal neutron and a ^{10}B atom. Up until 2012, all clinical BNCT were performed using neutrons generated from a nuclear reactor. Nowadays, neutrons generated from an accelerator is increasing and more hospital-based BNCT centers are opening, worldwide [1, 2]. The NeuCure® BNCT system was installed at the Kansai BNCT Medical Center in the Osaka Medical and Pharmaceutical University, shown in Fig. 1. This is the first facility in the world to provide BNCT at a university hospital that is covered by insurance. The system installed at the Kansai BNCT Medical Center is the same type as the one installed at the Kyoto University Institute for Integrated Radiation and Nuclear Science [3, 4].

The accelerator system is a cyclotron and accelerates a proton up to an energy of approximately 30 MeV. Fast neutrons are generated when the accelerated proton strikes the beryllium target traverse through a beam shaping assembly (BSA) to reduce the energy of the neutron down to the epithermal energy range, which has been shown to be an effective energy for deep-seated tumours [5]. This paper describes the beam characterisation tests performed at the Kansai BNCT Medical center as part of the clinical commissioning of the system.

Figure 1. Image of the NeuCure® BNCT system at the Kansai BNCT Medical Center.

MATERIAL AND METHODS

NeuCure® BNCT System: Beam Characteristics

Cyclotron-based Epithermal Neutron Source Beam Model The simulation of the neutron and gamma ray distribution was performed using a general-purpose Monte Carlo particle transport simulation code system (Particle and Heavy Ion Transport code System: PHITS version 3.24 [6]). The parameters were evaluated inside a water phantom for a 12 cm diameter circular collimator. The neutron energy range was defined as 0-5×10^{-2} eV (thermal), 5×10^{-2} eV-10 keV (epithermal), and 10 keV-30 MeV (fast). Detail on the beam modelling and source information can be found elsewhere [7].

Neutron Flux Determination A common method for measuring the neutron spectrum is metal activation, with gold and indium being frequently used for the measurement of thermal and fast neutrons, respectively. An acrylic phantom filled with distilled water was used. A 10 cm long gold wire (diameter of 0.25 mm with a 99.95% purity, The Nilaco Corporation) was placed along the central axis and off-axis at a depth of 2 cm inside the water phantom. As gold reacts to both thermal and epithermal neutrons, measurements were performed with and without a cadmium cover to shield the thermal neutrons. A total of 0.3 C for the gold wire and 0.6 C for the gold wire with cadmium cover was delivered. After irradiation, the gold wire was

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEB001

BENCH TO BEDSIDE: TRANSLATIONAL NUCLEAR MEDICINE RESEARCH AND CLINICAL THERANOSTICS IN PUMCH

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Abstract

Peking Union Medical College Hospital (PUMCH) was founded in 1921. In 1958, PUMCH established the first nuclear medicine (NM) department in the country which eventually became the most comprehensive unit of nuclear medicine in China. The department has topped the ranking in “China's Hospital Rankings” for consecutively 7 years and has done great efforts in translational research of nuclear medicine and molecular imaging. By now, over 10 isotopes and 100 radiopharmaceuticals are employed to support routine clinical work and more than 50 research projects as well, involving theranostic and preclinical exploration. These research achievements were highly glorified in the top international conferences and journals. The department not only keeps up with the advanced medical technologies in the world but also indulges in promoting novel technology applications in domestic hospitals. After a 60 years journey, the department of nuclear medicine in PUMCH with her superior capability will continuously lead NM exploration and development in China. The department will begin another new and prosperous journey in the new era.

INTRODUCTION OF PUMCH AND NUCLEAR MEDICINE DEPARTMENT

PUMCH is renowned both at home and abroad for its comprehensive disciplines, high technical capabilities, outstanding specialties, and integrated disciplinary strengths. Undergirded by a commitment to professional ethics and a rigorous academic attitude, each department indulges in providing the best possible medical service and being a hospital and department that is nothing less than the best in China and internationally renowned. Depending on the constant efforts of generations, PUMCH has been leading the advances of modern medical sciences in China, standing Top 1 every year from 2009 to 2022 in the Chinese best hospitals ranking.

PUMCH established the nuclear medicine department in 1958, which was also the first one in the mainland of China. Now, the department is the most comprehensive unit of nuclear medicine in China. It consists of 7 PET and 10 SPECT scanners for imaging diagnosis, 1 ward with 10 beds for nuclide therapy, radioimmunoassay lab, and radiochemistry labs. Each year, more than 30 thousand patients received NM service and 100 thousand samples were tested in our department. More than 10 isotopes and 90 radiopharmaceuticals are employed to support clinical work and nearly 50 research projects as well. As shown in Fig. 1, over 60 members now work and study every day in the department. Our department eventually made the history of nuclear medicine science in the country and takes the leading place in medical care, teaching, and scientific research in nuclear medicine. We have gained nuclear medicine top 1 for consecutively 7 years since NM was recruited in “China's Hospital Rankings” in 2014.

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Figure 1: Faculties and staffs of the PUMCH nuclear medicine department in 2021.

TRANSLATIONAL RESEARCH IN NUCLEAR MEDICINE DEPARTMENT

The UM department also attempts to do great efforts in translational research of nuclear medicine. For example, we attempted to use ^{188}Re, ^{89}Zr, ^{64}Cu, and ^{86}Y labeling novel precursors and endothelial progenitor cells for preclinical theranostic research [1-3], see Fig. 2 to 4. These

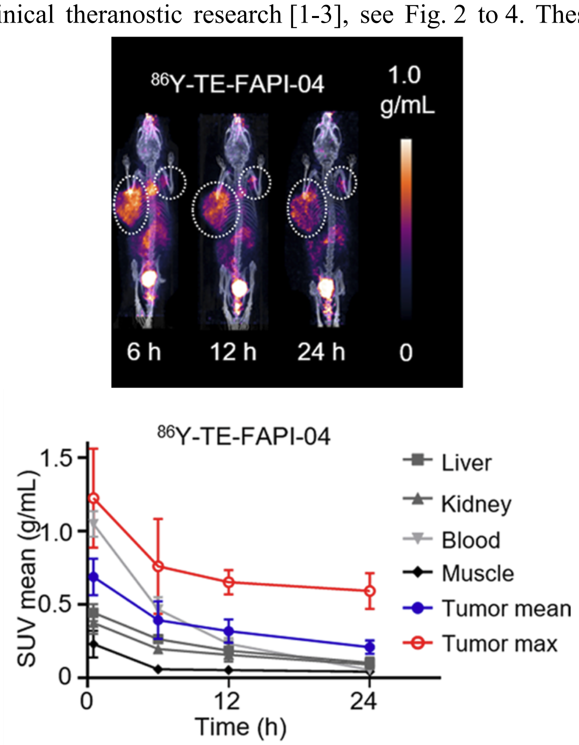

Figure 2: PET/CT MIP images and time activity curve of ^{86}Y-TE-FAPI-04 for late-time-point cancer diagnosis [1].

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEB003

POSITRON EMITTERS PRODUCED FROM NATURALLY OCCURRING TARGETS

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Abstract

Short lived positron emitters are used as flow following tracer particles in the study of dynamic processes within physics and engineering applications. For full representation of the materials of interest, tracer particles must be activated with proton rich radionuclides utilising reactions on their naturally abundant isotopic content. Cyclotron accelerated alpha particle beams incident upon (^{16}O) oxygen rich targets have been investigated in producing the positron emitter ^{18}F within naturally occurring materials.

Simulations and numeric calculations of the beam conditions are used to maximise the activation yield and minimise heat load by carefully placing the Bragg peak in relation to the water-cooled target. Corresponding to the target thickness, the 100 MeV extraction energy is degraded to match a broad resonance in ^{18}F production around 35 MeV, while maintaining energy above the 18 MeV threshold. Beam currents below 1 microamp resulted in typical ^{18}F yields of 1 - 2 mCi within spherical SiO_2 targets of diameters 1 - 10 mm, ideal for envisaged application studies.

INTRODUCTION

Positron emitting species are used in the non-invasive investigation and radiological imaging of dynamic physical and engineering systems, and those of industrial interest. Materials representation is critical in these applications, requiring the positron emitting species to be produced within naturally occurring materials as it is infeasible to use isotopically enriched targets for this purpose. Production of the medically significant positron emitting radioisotopes uses a range of different target systems and natural or isotopically enriched targets. The focus of this article is on ^{18}F production with naturally occurring solid targets. Production of ^{18}F and other isotopes within the context of this work are summarised in Table 1.

The predominant production of ^{18}F (110 minute half-life) results in free $^{18}F^-$ ions in aqueous solution (the use of gaseous targets is excluded in this discussion), with the majority of conventional global production prepared by irradiating ^{18}O-water targets. The resultant solution can be processed chemically, leading to the vector molecules of diagnostic imaging (including for example 18-fluorodeoxyglucose (^{18}FDG)), or other materials used as radiological tracers. Similarly, ^{68}Ge offers a convenient radiochemical synthesis route, being produced from a solid target loaded onto a SnO_2 based separation column. The long lived (271 day half-life) ^{68}Ge decays via electron capture to the short lived ^{68}Ga (68 minute half-life) which collects as free $^{68}Ga^{3+}$ ions in liquid form within the column. In the cases of both $^{18}F^-$ and $^{68}Ge^{3+}$, the ions can be extracted, concentrated, and processed radiochemically to produce tracer substances and radiopharmaceuticals as required by the imaging application in question. These techniques have been utilised in imaging physical and industrial systems with success, however they suffer from questionable species representation and often cannot survive the harsh conditions (e.g., temperatures, pressures, and chemical environment) they are subjected to in such devices.

Table 1: Reactions and Targets (adapted from Ref. [1])

Reaction	Target	State, % abundance	Energy range [MeV]
$^{18}O(p, n)^{18}F$	$H_2{}^{18}O$, $^{18}O_2$	Liquid, 0.2	18 – 4
$^{16}O(^3He, p)^{18}F$	$^{nat}H_2O$	Liquid, 99.7	15 – 1
$^{16}O(^3He, n)^{18}Ne \rightarrow {}^{18}F$			40 – 15
$^{16}O(\alpha, np)^{18}F$	$^{nat}H_2O$,	Liquid /	40 – 20
$^{16}O(\alpha, 2n)^{18}Ne \rightarrow {}^{18}F$	$^{nat}SiO_2$	Solid, 99.7	
$^{16}O(\alpha, d)^{18}F$			
$^{40}Ca(\alpha, p)^{43}Sc$	^{nat}Ca	Solid, 96.9	~ 50
$^{40}Ca(\alpha, n)43Ti \rightarrow 43Sc$			
$^{nat}Ga(p, xn)^{68}Ge$	^{nat}Ge	Solid, 60.1	< 66

Ideally, for applications in industrial systems, tracer materials produced from the bulk materials of interest are required, such that the imaging or other measurement is truly non-invasive. To this end, the production of ^{18}F in naturally occurring solid targets has been utilised. At the University of Birmingham, UK, the ^3He reactions are utilised, with ^3He beam of 35 MeV energy and ~ 5 µA beam current. Under these conditions the Birmingham MC40 cyclotron can produce up to 1.5 GBq / 40 mCi of ^{18}F activity in 3 ml of ($^{nat}H_2O$) water for radiochemical tracer production, and similar activity on solid targets containing sufficient oxides [1]. The $^{18}O(p, n)^{18}F$ reaction is used when preparing ^{18}F in solution to be processed chemically.

The University of Cape Town has established a positron imaging facility used for the study of physical, engineering, and industrial applications on the National Research Foundation (NRF) accelerator facility iThemba LABS (iThemba Laboratory for Accelerator Based Sciences) [2]. The primary tracer isotope used has been ^{68}Ga, produced from commercial $^{68}Ge/^{68}Ga$ radioisotope generators manufactured by iThemba LABS. The ^{68}Ge is extracted and radiochemically treated to produce a wide range of representative tracer materials, often starting from an ion-exchange resin polymer core and modifying the density and surface properties to match those characteristics required by the application and research questions [3]. Recently, ^{18}F has been extracted from commercial medical supplies of

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEB004

COMMISSIONING OF THE SUMITOMO SUPERCONDUCTING AVF CYCLOTRON SC230

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Abstract

A 230-MeV superconducting azimuthally varying field (AVF) cyclotron SC230 was developed by Sumitomo Heavy Industries, Ltd. This is the world's smallest isochronous cyclotron for proton therapy, and its weight is 65 tons, which is 0.3 times that of our previous cyclotron model. The size is reduced by generating high magnetic fields using NbTi superconducting coils cooled without cryogen. In addition, this cyclotron features the maximum beam current >1 μA and low power consumption <200 kW. The beam-commissioning test was started at the end of 2020. The first extracted beam was observed in July 2021. Subsequently, and the basic performance of the beam was measured. The processes and results of the beam commissioning are reported.

INTRODUCTION

Proton therapy was proposed in 1946 and first used to treat patients in 1954 [1, 2]. No incision is required, and the characteristic depth dose distribution with a Bragg peak minimizes damage to normal cells. Afterward, patients can receive outpatient treatment while continuing their daily lives, contributing to the maintenance of their quality of life (QOL). Therefore, proton therapy is becoming more prevalent in cancer treatment, and the number of proton therapy facilities is increasing. More than 100 facilities are in operation worldwide [3], and further growth is expected in the future. However, the large device size limits its use in hospitals. Therefore, miniaturization of the device size is one of the issues in proton therapy. Manufacturers have been promoting the development of miniaturization of equipment, and in recent years, the miniaturization of the accelerator, which is one of the primary mechanisms, has been conducted with superconducting coils. Commercial superconducting accelerators for proton therapy were developed by Varian, Mevion, and IBA [4-6].

Miniaturization of accelerators with superconducting coils has the following merits:

- Reduction of building cost
- Shorter delivery times
- Lower operating costs
- Reduced daily downtime

Downsizing is expected to lower the building cost by reducing the construction site area and lowering load-bearing requirements. Moreover, because the large assembly can be transported as it is, disassembly and reassembly times are reduced, and delivery times are shortened. Furthermore, with superconducting coils, the power consumption of coils and running costs can be reduced. In addition, as the power consumption of coils can be reduced, continuous energization at night is possible, which eliminates the daily coil excitation and demagnetization time in hospitals and contributes to the reduction of downtime. Hospitals benefit from a variety of services. Many superconducting accelerators for proton therapy are being designed and developed to provide such benefits.

Sumitomo Heavy Industries developed the superconducting cyclotron SC230. The weight of the yoke is 65 tons, equivalent to 3/10 times that of the conventional model [7]. Additionally, it is not only compact but also consumes low energy and offers a high beam current. Energy saving is not only a countermeasure against recent issues, such as unstable energy supply and global warming but it is also expected to reduce operating costs. The power consumption is ≤200 kW, equivalent to 3/5 times that of conventional models. Its high-current beam contributes to shortening the treatment time. The maximum beam current of the cyclotron is ≥1 μA, which is 3.3 times that of the conventional machine, which is the maximum for proton therapy accelerators. It reduces patient burden, increases patient throughput, and allows for more patients to be treated. In the future, it can be applied to treatment methods that require high-current beams, such as FLASH treatment and the breath-hold irradiation method.

The basic design of the cyclotron was reported in 2013 [8]. The design and fabrication of each component including the superconducting magnet have been completed thus far, and the mapping and formation of the magnetic field have been completed [9-13]. A new test site was established in 2020. The cyclotron was relocated to this site and conditioned. Commissioning tests started at the end of the same year and the beam was extracted in July 2021. Additionally, the extracted beams met the performance requirements, and the development of SC230 was completed. Here, we report on the commissioning.

SC AVF CYCLOTRON SC230

The developed superconducting AVF cyclotron SC230 for proton beams is a four-spiral sector-type AVF cyclotron. Figure 1 shows an image of the external appearance of the cyclotron. The main specifications for its components are presented in Table 1.

It produces a fixed-energy proton beam required for proton therapy. The cyclotron was miniaturized by using a superconducting magnet to generate a high magnetic field of 3–5 T. The average magnetic field was approximately 3.9 T at the extraction radius of 0.6 m.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEB005

UPGRADE OF A CLINICAL FACILITY TO ACHIEVE A HIGH TRANSMISSION AND GANTRY ANGLE-INDEPENDENT FLASH TUNE*

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Abstract

In proton therapy, FLASH-RT, irradiation at ultra-high dose rates (>40 Gy/s) that can minimize radiation-induced harm to healthy tissue without reducing its ability to treat tumors, is a topic of great interest. However, in cyclotron-based proton therapy facilities, losses caused by the energy degradation process reduce the transmission to less than 1% for low energies, making it difficult to achieve high dose rates over the clinical range (70-230 MeV).

We will demonstrate how an already existing clinical beamline can be converted into a FLASH beamline by mainly beam optic changes. To achieve maximum transmission, we have developed a new optics that transports the undegraded 250 MeV beam from the cyclotron to the isocenter. However, this has a slightly asymmetric emittance in the transverse planes, leading to gantry angle-dependent beam characteristics at the patient.

Particle transport has been simulated with MINT (in-house matrix multiplication transport program with Monte Carlo simulations for scattering effects) and benchmarked with beam profile measurements. We used the optimization criteria for sigma matrix matching to achieve gantry angle-independent optics.

Simulations and beam profile measurements showed a good agreement**,** and with FLASH optics, we experimentally achieved 90% transmission at the patient, translating to a maximum current of 720 nA (>9000 Gy/s on-axis). Further, we demonstrate that using the matrix matching optimization criteria together with fine tuning of the magnets, we could achieve gantry angle-independent beam profiles at the patient location.

In conclusion, we have shown how an already existing cyclotron-based proton gantry can be adapted to achieve ultra-high dose rates at 250 MeV, enabling investigations of FLASH radiotherapy with protons, with the drawback of downstream energy modulation, if required. Since most of the modifications are performed on the beam optics, it is completely transparent to clinical operations, making the method transferable to other facilities.

* Work supported by SNF (Grant No. 200822) and PSI's CROSS funding scheme
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INTRODUCTION

The delivery of ultra-high dose rates (>40 Gy/s), also known as FLASH radiotherapy, has proven in preclinical investigation to allow tumour control while minimizing damage to surrounding healthy tissues [1]. In 2014, the effect was demonstrated on mice with a 4.5 MeV electron beam [2] and in 2018, the first human patient was successfully treated with electron-FLASH radiotherapy at the Lausanne University Hospital (CHUV, Switzerland) [3]. After that, many biological cell experiments and even a few clinical trials started to investigate the parameters that triggers the FLASH effect. Nowadays, the effect has been confirmed by different institutes and for different beam modalities (electrons, photons, proton and heavy ions [4]) and organs [5].

Some proton centres around the world have begun to look at whether it's possible to use current treatment equipment to achieve FLASH dose rates. The FLASH dose rate requirements can theoretically be met by cyclotron-based facilities, at least for high energies [6]. However, there is no conclusive proof that dose rates greater than 40 Gy/s cause the FLASH effect since this limit was derived in a limited number of experiments and tissues. Therefore, flexibility is required.

In this study we report how the clinical Gantry 2 [7] at the Paul Scherrer Institute could be adapted to achieve ultra-high dose rates at 250 MeV, without affecting clinical operations. The aim of this update is to enable clinical investigation of conformal FLASH radiotherapy using protons in scanning mode, hence a symmetric and gantry-angle independent beam is required.

METHODS AND MATERIALS

PSI Beamline and Gantry 2

In the PSI proton therapy center the proton beam is generated by the COMET cyclotron (Fig. 1). The extracted beam has an energy of 250 MeV and up to 800 nA intensity. For treatment, energies in the range 70-230 MeV are required and the energy modulation is done by mean of a degrader placed right after the cyclotron. We lose more than 99% of the particle for low energies due to the collimators following the degrader and the energy selection slits, resulting in a transmission of less than 1% at the isocenter [8, 9]. Consequently, in order to obtain ultra-high

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEBO06

ACCELERATOR AND DETECTOR DEVELOPMENTS FOR THE PRODUCTION OF THERANOSTIC RADIOISOTOPES WITH SOLID TARGETS AT THE BERN MEDICAL CYCLOTRON

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Abstract

Theranostics in nuclear medicine is realized by using two different radionuclides to label the same radiopharmaceutical, one for diagnosis via PET or SPECT (positron or gamma emitter, respectively) and one for targeted radioligand therapy (alpha, beta minus, Auger emitter). To assure the same chemistry and metabolic behaviour in the human body, the best option is to employ two radioisotopes of the same element, the so called theranostic pair. In view of clinical trials and routine applications, the production and supply of novel radioisotopes for theranostics in adequate quality and quantity is essential and represents nowadays a scientific and technical challenge. The most promising methodology relies on hospital-based 15-25 MeV compact medical cyclotrons equipped with solid target stations. Being designed for the production of ^{18}F by means of liquid targets, innovative solutions are needed. Therefore, a research program is ongoing at the Bern medical cyclotron, a facility equipped with a Solid Target Station and a 6.5 m Beam Transfer Line ending in a separate bunker. To irradiate isotope-enriched materials in form of compressed powder pellets (6 mm diameter), a novel target coin was conceived and realized together with methods to assess the beam energy and the production cross sections. To optimize the irradiation procedure, a novel ultra-compact Active Focusing System based on a specific magnetic device and a two-dimensional beam monitoring detector was conceived, constructed and tested. Several solutions for the beam detector were developed and others are under study. The system allows to control on-line the size and position of the beam and to correct its characteristics by steering and focusing it in order to keep it on target. Results on accelerator and detector developments together with achievements in the production of radionuclides for theranostics (^{43}Sc, ^{44}Sc, ^{47}Sc, ^{61}Cu, ^{64}Cu, ^{67}Cu, ^{68}Ga, ^{165}Er, ^{165}Tm, ^{167}Tm and ^{155}Tb) are presented.

INTRODUCTION

To enhance the availability of novel medical radioisotopes that can be used as theranostic pairs is crucial for the advancement of nuclear medicine. Theranostic pairs consist of two complementary radionuclides; a β^+ or γ emitting radionuclide is used for diagnosis via PET or SPECT imaging respectively, while the other radionuclide undertakes the radioimmuno-therapeutic task of emitting β^-, Auger, or α particles. These radionuclides must have similar or identical chemical properties, as in the case of isotopes of the same element. They can be used to label the same biomolecules, which are then injected into the patient's body and undergo the same metabolic processes. This allows for the treatment of the disease while simultaneously assessing uptake and monitoring the progress of the therapy through medical imaging. Examples of promising theranostic pairs include ^{43,44}Sc/^{47}Sc and ^{61,64}Cu/^{67}Cu, which are bound to proteins and peptides.

The availability of these radionuclides is a limiting factor in the development of theranostics in nuclear medicine. One solution is to utilize compact medical cyclotrons for the radionuclides' production, as they are commonly installed at medical institutions. Medical cyclotrons produce proton beams of low energy (15-20 MeV) and relatively high intensity (>100 μA). They are primarily used to produce ^{18}F - the most common PET radioisotope - through irradiation of liquid targets. However, to produce radiometals, rare and expensive isotope-enriched materials must be bombarded, which are often only available in powder form. To obtain high yields, solid target stations represent the best solution. These solid target stations, however, are rare and are typically designed to irradiate target 'disks' on which the enriched material is electroplated, a method not suitable for the production of various radiometals. Therefore, new irradiation instruments and methods must be developed to bombard compressed materials in powder form and in small dimensions of 6 mm diameter and smaller.

At the Bern University Hospital's cyclotron laboratory, research programs are ongoing to address these challenges and develop new solutions. The facility is equipped with an IBA Cyclone 18/18 medical cyclotron (18 MeV proton beams, maximum extracted current of 150 μA, 8 output ports). Six outports are used for routine production of ^{18}F at night, while the other two are used for multidisciplinary research during the day. One of the research outports is equipped with a 6.5 m long Beam Transport Line leading to a second bunker with separate access, which facilitates daily research. This is uncommon for a hospital-based facility but has been essential to achieve the results reported in this paper. The second research outport is equipped with a commercial IBA Nirta Solid Target Station (STS). This STS was customized by our group and upgraded to optimize

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEPO001

FIELD MATCHING OF F-D-F, GAP SHAPING MAGNETS FOR A 2 GeV CW FFA*

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Abstract

Fixed Field Alternating Gradient Accelerators have been developed for decades. A continuous wave (CW) 2 GeV FFA which aims at high-power proton beam applications is under developing in China Institute of Atomic Energy (CIAE). To avoid dangerous resonance lines and manipulate the tune diagram flexibly, 3rd order magnetic field is applied along the radius and 10-fold symmetrical F-D-F scheme has been proved to be feasible. In this paper, Integral Equation Method (IEM) is introduced and shown more efficient than adjusting the variable gap manually, saving time for magnet design. First of all, the radial mean field is set as a main design goal and the ΔH at different radii is solved by linear equations based on IEM. The isochronism is done when the mean field is well matched with the design value, whereas some precise corrections are needed for the oscillating frequency ν_r and ν_z, such as fringe field effects and multipole components near the end of pole face. The tune shift caused by fringe field is also included in this paper. Fringe field is more crucial for HTS magnets especially, since the leaked field of superconducting coil is ~1 kGs. Considering that, we apply an angular matching method to compensate the tune shift by fringe field.

INTRODUCTION

Continuous wave (CW) FFA which combines the characteristics of both cyclotrons and synchrotrons is a potential solution to provide MW proton beams for many important applications, such as accelerator driven subcritical system (ADS), neutron sources and neutrino factory [1]. CIAE launched the researches on CW FFAs in 2013 and proposed an energy efficient FFA design in 2019 [2]. High temperature superconducting (HTS) magnets and high-Q value RF cavities are adopted in the overall design of 2 GeV CW FFA, for a higher energy efficiency and less operating cost. Different types of magnets are presented for both scaling and non-scaling FFA, such as room temperature magnets [3], superferric magnets [4] (superconducting coils with warm iron) and iron-free superconducting magnets [5]. Gap shaping iron with HTS coils is applied in consideration of engineering convenience and operating cost. The 10-fold symmetrical F-D-F lattice design for the main machine is completed, which leads to next stage of magnet design. HTS magnets for FFA application are researched for serval years and some experimental coils are wound to support engineering feasibility [6]. In practice, field matching is not crucial issue in FFA design. But for our non-scaling 2 GeV FFA, which introduces third order field in wide range along radius, it is important to match the second and third order field to ensure isochronism and tune.

Moreover, fringing fields of entrance and exit side can affect the working diagram and result in tune shift, which requires prudent evaluation and compensation [3, 7], even if we match the mean field almost perfectly. This problem is more prominent in superconducting magnets and need to be well considered. Above all, the basic design of F-D-F lattice is introduced. The F-D-F lattice and static equilibrium orbits are shown in Fig. 1, in which red blocks represent focusing magnets and yellow block for defocusing magnet.

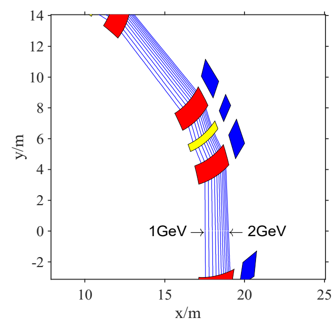

Figure 1: Layout of F-D-F magnets and static equilibrium orbits (1 GeV to 2 GeV).

Basic parameters of focusing and defocusing magnets are listed in Table 1.

Table 1: Parameters of Focusing and Defocusing Magnet

Item	Focusing magnet	Defocusing magnet
Pole length / m	2.1	2.1
Field range / T	1.57~2.66	-2.31~-1.15
Angular width / deg	4	1.6
Spiral angle / deg	0~36	0~36

ANALYTICAL MODEL

Approximation of Saturated Iron Blocks

In scaling FFAs, the magnetic field distribution is clear and defined using the Eq. (1) below:

$$B(r) = B_0\left(\frac{r}{r_0}\right)^k. \quad (1)$$

Therefore, the gap shape is expressed by:

$$g(r) = g_0\left(\frac{r}{r_0}\right)^k, \quad (2)$$

* Work supported by the National Natural Science Foundation of China under Grant 12135020 and the basic research fund from the Ministry of Finance of China under Grant BRF201901.
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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEPO002

A COMPARSION STUDY OF THE DESIGNING MODELS OF RANGE MODULATOR BY USING FLUKA SIMULATION CODES*

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Abstract

In this study, we investigated the optimization of the range modulator. Range modulator used in proton radiotherapy is expected to be accurate enough to achieve spread-out Bragg peak (SOBP). Based on the theory of Thomas Bortfeld, four different range modulator models were designed and compared using FLUKA simulation codes. The four models were: uneven ridge filter, smooth ridge filter, uneven range modulator wheel, and smooth range modulator wheel. Using 100 MeV and 230 MeV proton beams, the dose spatial distribution of the four models were calculated when the SOBP sections were 3, 5, 10, and 20 cm. The results showed that in ideal motion condition, the four models all showed the ideal range modulation effect. The best average value of the difference was less than 2%, while the worst one was still less than 5%. The evenness of the smooth models is improved compared with the uneven models. The smooth ridge filter model performed best. Based on this model, we tried to realize the movement of the SOBP region by adding a binary shielding layer. The results showed that the SOBP region can move in a small range at the expense of acceptable accuracy error. This study provides a design reference for the range modulator in proton therapy, and provides a new technical scheme to fill the target area for precise therapy.

INTRODUCTION

Radiation therapy is one of the three most effective treatments for cancer, the other two being chemotherapy and surgical resection. Radiation therapy refers to the use of radiation to irradiate the tumor area, and the relative biological effect of the radiation to damage the DNA of malignant tumor cells, so as to achieve the purpose of killing or reducing cancer cells.

Charged particle therapy (CPT), including proton and heavy ion therapy, is currently the advanced direction of radiotherapy. The advantage of CPT is that the concentrated dose distribution pattern of charged particles makes it possible to artificially and accurately control the dose distribution in the target area, thereby achieving higher tumor control probability and lower normal tissue complication probability. The unique Bragg peak dose distribution pattern of protons and heavy ions makes the advantages of CPT possible [1]. Taking protons as an example, single-energy protons have a low dose before the human body, slowly increase the dose after entering the human body, climb rapidly to the terminal peak, and finally decline rapidly, achieving a high concentration of doses, of which the highest point of the dose is called Bragg peak [2], see Fig. 1. In actual use, Bragg peak needs to include the lesion to ensure an even and flat dose distribution in the target area. The Bragg peak of a single-energy proton ray is extremely narrow, generally between a few millimeters and one centimeter. It is impossible to encompass the lesion completely, so the Bragg peak needs to be widened. The most basic broadening way is to use particle beams of different energies to irradiate together, and superimpose them according to different weights to form a relatively gentle flat area in the target area [3]. In actual use, only one single energy particle beam can be provided at one time, so the device that can convert a single energy particle beam into a multi-energy particle beam with a specified weight ratio is needed, which is called range modulator. The range modulator to achieve SOBP is an extremely important part of the treatment head system of CPT equipment.

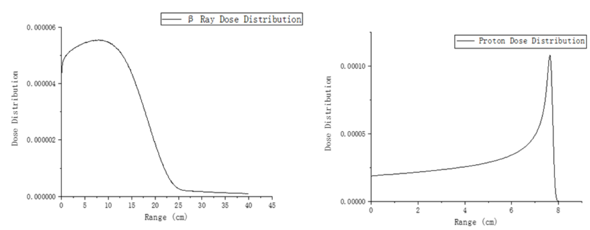

Figure 1: The dose distribution of β-ray and proton.

The Bragg peak of the single energy particle beam is broadened to a flat dose distribution region by the modulator's geometry and relative motion. Because the parameters of the range modulator vary with different width and depth of certain SOBP, it is necessary to customize the range modulator according to the patient's situation in actual use, so it is of great significance to study the design process and optimization of the range modulator.

SIMULATION METHOD

Since experimental opportunities are precious, it is necessary to conduct simulation studies of range modulators prior to experiments.

Monte Carlo Simulation Codes

In this study, FLUKA was selected as the Monte Carlo (MC) simulation software. FLUKA is a universal MC particle transport simulation software that runs on Linux. Through continuous updates, FLKUA now supports the transport process and measurement simulation of about 60 kinds of particles including photons, electrons, protons, and various heavy ions in magnetic field, electric field, and thermal field, and supports users to program the particle

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEPO003

BEAM DYNAMICS IN A NEW 230 MeV CYCLOTRON

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Abstract

A new cyclotron for proton therapy concept is a compact, but non-superconducting accelerator, that is simple, but cheap. Proposed concept uses 4 sectors with double spiral design and 4 RF cavities operating at harmonic 8, making the central region and extraction a challenging task that needs to be carefully simulated. High injection and extraction efficiency is presented.

INTRODUCTION

The cyclotron project for proton therapy using approach similar to [1] is presented. A detailed description of the proposed project is given in [2] this conference. Center region of the cyclotron is presented in [3] this conference.

Magnet sectors of the cyclotron consist of two parts:

- wide-aperture part with a vertical distance of 50 mm and low helicity,
- small-aperture part with a vertical distance of 25 mm and high helicity.

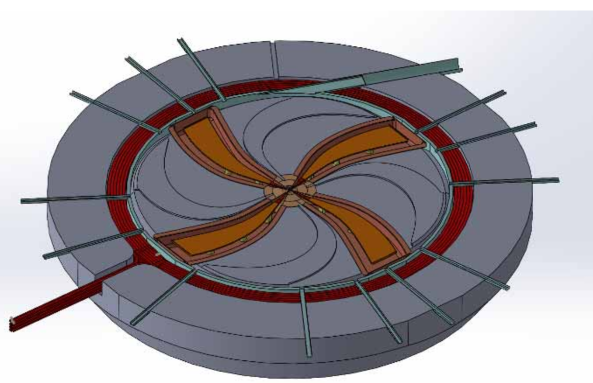

Figure 1: 3D computer model of the cyclotron.

Main parameters of the cyclotron are presented in Table 1.

Table 1: Cyclotron Parameters

Accelerated particles	protons
Final energy	232 MeV
Ion source	Internal, PIG
Extraction scheme	1 ESD, 2 correctors
Magnet Power Consumption	95 kW
RF power consumption	100 kW (wall losses)
Dimensions	(3850 x 3850 x 2000) mm^3
Beam current	Up to 100 µA

This structure makes it possible, firstly, to place the deflector between the sectors in the wide-aperture part, while retaining the valleys for placing the resonators, and, secondly, to ensure isochronous growth and vertical focusing due to the small-aperture part of the sector.

Computer model of the cyclotron (see Fig. 1) was built in CAD and simulated in CST studio.

CODE CORD

CORD code [4] was used for estimation of the field characteristics. CORD is providing particle dynamics analysis based on a combination of magnetic field map analysis with electric field map analysis. The first part of the code is searching for closed orbits (without acceleration) and calculating the focusing properties of the magnetic field. There are two types of closed orbits: orbits having the same N-fold symmetry as the cyclotron (no imperfections) and orbits obtained in a real field map with errors like low number harmonics.

In CORD we fix the radius r and match p_r and energy T. Initial values for each orbit are independent of other orbits, therefore parallel calculation is possible. A single iteration of the iterative scheme consists of the following 3 stages:

- Calculating the orbit's initial guess values $r(\theta_i)$, $pr(\theta_i)$, $T(r(\theta_i))$, θ_i is the initial angle and θ_f is the final angle.
- Finding $r(\theta_f)$, $pr(\theta_f)$, by solving ODE with MATLAB's ode45 solver, ODEs are simultaneously solved for a large set of radii (multiple orbits).
- New initial values for the next iteration:

$$p_r(\theta_i) \rightarrow p_r^{new}(\theta_i) = \frac{p_r(\theta_f)+p_r(\theta_i)}{2},$$

$$T \rightarrow T^{new} = T\frac{2r(\theta_i)}{r(\theta_i)+r(\theta_f)},$$

$$p^{new} = \sqrt{\frac{T^2}{c^2} + 2Tm}.$$

The number of iterations is constant and can be set to provide the necessary precision.

MAGNET FIELD ANALYSIS

Code CORD can present mean magnetic field and flutter (see Fig. 2), betatron frequencies in a tune operating diagram (see Fig. 3), calculates orbital frequency (see Fig. 4) and the difference between average magnetic field and isochronous one (see Fig. 5).

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEPO004

HIGH POWER CENTER REGION WITH INTERNAL ION SOURCE

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Abstract

Cyclotrons for medical isotope production require high beam current. Author proposes the design of central region with internal ion source at 6.6 kV potential placed in the center of cyclotron and delivering the beam to every RF cavity symmetrically, thus significantly increasing the beam current.

INTRODUCTION

The line of cyclotrons from 15 to 230 MeV, that uses same magnet field level and RF frequency 145 MHz and utilises many identical solutions within the line-up to make it cheaper to produce and run was described in IPAC 2022 [1]. The author has developed and presented here a variant of the similar line-up for the accelerating frequency 180 MHz [2].

Of course, high frequency of RF system can potentially lead to poor capture of particles in the first accelerating gap. In fact, if ion source would be placed in front of RF puller with such high frequency the capture would be equal to 0. But this problem can be solved if in the first accelerating gap particles will arrive with some energy, thus travel through first gap much quicker.

Particles start from the PIG source, which is placed under 6600 V and accelerate to the "ninja star" housing, see Fig. 5 (zero potential) and arrive to the first gap with 6.6 keV energy. Also, the advantage of such central region is that one ion source placed in the middle can deliver beam in each gap simultaneously, due to the symmetry of such central region. A similar center for three sectors cyclotron was described in [3], here the author presents a variant for four sectors structure and frequency 180 MHz at harmonic 8.

VIRTUAL PROTOTYPING

The idea of a new engineering methodology Virtual Prototyping is to replace physical mock-ups by an integrated software prototypes that include all functional simulations based on CAD/CAE/CAM techniques.

Usually when designing a cyclotron some systems are developing separately. An integrated platform which encapsulates these distributed components and provides an inter-communication mechanism is extremely useful, as it will contribute to the creation of a more optimal cyclotron.

We have combined the development of the individual cyclotron systems through a framework in MATLAB (Fig. 1).

The shapes of sectors and cavities of the magnet are selected directly in MATLAB, then sent to CAD (Solidworks) to create parametrized model of the cyclotron, and then individual systems are sent to CST studio to simulate in the corresponding modules. The calculation results of the electromagnetic fields from CST are imported into MATLAB, where they are analyzed using code CORD [4] and beam tracking codes. Careful calculations of the beam dynamics are performed for the central region and the exit zone. Based on the results of the analysis, changes are made to the structure of the cyclotron systems. The iterative procedure is repeated until an acceptable result is achieved, namely, successful injection, acceleration and beam extraction.

In a compact cyclotron, all systems compete with each other for space (Fig. 2). An integrated approach to design is necessary to ensure that the decision on the privileges of a particular system is made objectively, taking into account the interests of each system.

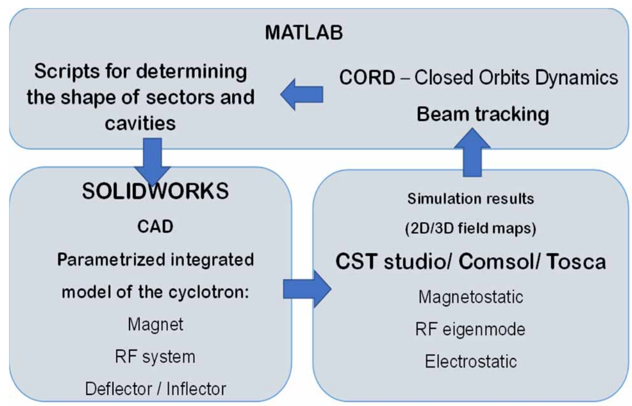

Figure 1: The framework of the cyclotron VP MATLAB integrated platform.

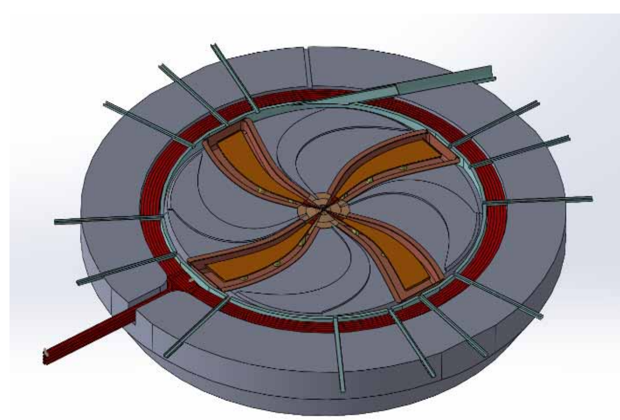

Figure 2: Parametrized model of the cyclotron.

BEAM DYNAMICS SIMULATION

When calculating particle, an electromagnetic field was specified in the form of a field maps obtained as a result of model calculations (3D field maps). We used 3D field maps received in CST RF eigenmode solver for accelerating field (Fig. 3) and magnetostatics solver for magnet simulation (Fig. 4).

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEPO007

THE DESIGN OF A SUPERCONDUCTING DIPOLE MAGNET BASED ON TILTED SOLENOIDS

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Abstract

As a core component of proton therapy equipment, the gantry can project the proton beam onto a tumor from different angles. The weight of the gantry with normal conducting magnets (mainly normal dipole magnets and quadrupole magnets) is usually more than 150 tons, which demands high requirements for the design, processing and fabrication. For the realization of light-weight gantry, this article puts forward a design of Canted-Cosine-Theta (CCT) superconducting magnet (to be used on superconducting gantry). Since the superconducting CCT magnet can produce higher magnetic field compared with normal magnets, for the proton beam with the same magnetic stiffness, the deflection radius of the magnet can be significantly reduced, thus reducing the radius and volume of the gantry.

In this article, the finite element analysis software and Biot-Savart principle were adopted to establish the method of magnetic field calculation for CCT superconducting magnet, and MATLAB was used to simulation and validation of particle path, which finally realize the design of CCT superconducting magnet applied on gantry.

INTRODUCTION

Table 1: Physical Requirements for the Deflecting CCT Magnet

Parameter	Value
Maximum proton energy	280 MeV
Deflecting Angle	58.5°
Deflecting Radius	0.9 m
Magnetic field intensity	2.8 T
Effective length	918.9 mm
Good field radius	30 mm
Magnetic field homogeneity	1×10^{-3}

CCT superconducting magnet has the following characteristics: high magnetic field strength, flexible multi-stage field combination, high uniformity of integral field and transverse field; and when it comes to structure, it has the characteristics of light weight, simple winding process, large range of good field (two-thirds of conductor coil radius), etc [1]. Both LBNL (USA) and CERN (Europe) have developed superconducting CCT dipole prototypes (linear CCT magnets) [2]. In order to optimize the rotating gantry, this paper specially studies the deflection CCT superconducting magnet used in the gantry, and determines its feasibility. According to beam optics requirements of the gantry, the physical requirements for the deflecting CCT superconducting magnet are shown in Table 1.

THEORETICAL MODEL OF DEFLECTING CCT SUPERCONDUCTING MAGNET

Deflecting CCT superconducting magnet trajectory equation can be established in two ways: one is in the cylindrical coordinates and another is in the toroidal coordinates [3-5].

The trajectory equation of the linear CCT superconducting magnet in the cartesian coordinates is as shown in Eq. (1), where the origin of coordinates is at the center of the cylindrical surface:

$$\begin{cases} x = r\cos\theta \\ y = r\sin\theta \\ z = \sum\left[\dfrac{r}{n\tan\alpha}\sin(n\theta) + \dfrac{\omega}{2\pi}\theta\right] \end{cases} \tag{1}$$

where: r is the radius of the cylindrical surface where the trajectory of the single-layer coil is located, unit mm; α is the tilt angle between single layered coil and horizontal plane, unit rad; θ is the azimutrical angle, the changing angle of trajectory in the cylindrical coordinate system, unit rad, with changing range of $[-N\pi, N\pi]$, N is the number of coil turns; ω is the distance between turns of single-layer coil, unit mm; n is the magnetic pole series (n = 1 for dipole, n = 2 for quadrupole, and so on).

It can be understood that the deflecting magnet, according to the definition, is like the linear magnet bends along the center trajectory with a radius of R, which is the deflecting radius of the deflecting magnet. Therefore, according to Eq. (1), the trajectory equation of deflecting CCT superconducting magnet can be shown as following in Eq. (2):

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEPO008

H^- INTRA-BEAM STRIPPING LOSS RATE IN ISOCHRONOUS CYCLOTRON*

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Abstract

Binary collisions inside a H^- bunch result in H^- stripping and subsequent particle loss. This phenomenon, called intra-beam stripping, was observed in LEAR and SNS superconducting linac. We mimic the derivation made for the linac to derive the intra-beam stripping loss rate for an isochronous cyclotron. And then, we apply this theory to the TRIUMF 500 MeV H^- cyclotron to estimate the loss.

INTRODUCTION

Beam loss is one of the major concerns for high power proton (and H^-) accelerators. With the growing of beam power, the fractional beam loss permitted by the machine radioactivation issue becomes smaller and thus more challenging. For H^- accelerators, the primary beam loss mechanisms include halo formation through beam dynamics problems (e.g. coupling resonance crossing) [1], residual gas stripping [2], electromagnetic (Lorentz) stripping [3], and intra-beam stripping [4]. In the TRIUMF 500 MeV H^- cyclotron, the total beam loss outside the central region is $<$ 10% at present: ~1% by gas stripping (under 2×10^{-8} Torr residual pressure), ~3% by electromagnetic stripping (from 400 to 480 MeV), and ≤2% by vertical halo growth due to resonance crossings. It was queried how much loss is caused by the intra-beam stripping. The intra-beam stripping arises from binary collisions inside a H^- bunch that cause loosely-bound electrons to be stripped off, leaving neutral H^0 particles, which are subsequently lost due to lack of focusing, steering, and acceleration. This phenomenon was first observed in LEAR [4] and afterwards at SNS superconducting linac [5]. To address this issue for the TRIUMF cyclotron [6], we mimic the derivation made for the linac to derive the intra-beam stripping loss rate for an isochronous cyclotron. And then, we apply the theory to the TRIUMF cyclotron to estimate the loss.

DERIVATION OF LOSS RATE

The particle loss rate due to the intra-beam stripping can be calculated by considering a differential volume $d\vec{r} = dxdydz$ in which the incident particles with velocities between $\vec{v}_1$ and $\vec{v}_1 + d\vec{v}_1$ impinge on the target particles in the same bunch at the same location with velocities between $\vec{v}_2$ and $\vec{v}_2 + d\vec{v}_2$. The number of particles scattered into a solid angle $d\Omega$ over unit time from this collision is the product of number of incident particles, the differential cross section, and the number of target particles. In the beam frame, the loss rate is represented as:

$$\begin{aligned}\frac{dN}{dt} &= -\frac{1}{2}\iint d\vec{r}d\vec{v}_1 Nf(\vec{r},\vec{v}_1)\int d\vec{v}_2 Nf(\vec{r},\vec{v}_2)|\vec{u}|\frac{d\sigma}{d\Omega}d\Omega \\ &= -\frac{N^2}{2}\iint d\vec{r}d\vec{v}_1 f(\vec{r},\vec{v}_1)\int d\vec{v}_2 f(\vec{r},\vec{v}_2)|\vec{u}|\sigma(|\vec{u}|), \quad (1)\end{aligned}$$

where the distribution function $f(\vec{r},\vec{v})$ is normalized to 1 and $f(\vec{r},\vec{v})d\vec{r}d\vec{v}$ gives the fraction of particles with coordinates and velocities in the range $\vec{r}$ to $\vec{r}+d\vec{r}$, and $\vec{v}$ to $\vec{v}+d\vec{v}$. N is the number of particles in the bunch, $\vec{u} = \vec{v}_1 - \vec{v}_2$ is the relative velocity between colliding particles, $\sigma(|\vec{u}|)$ is the total cross section for single electron stripping. The factor $1/2$ in the front of the integral removes the double counting of each collision in the integral.

Equation (1) is a general expression. In an isochronous cyclotron, particles in a bunch have no collision longitudinally. This is because any fast moving particle cannot surpass the slow moving ones. Unlike the synchrotron where there exists periodical phase oscillation longitudinally, isochronous cyclotron has no phase oscillation; instead, particles of different energies have the same revolution period. In this case, the particle's longitudinal velocity does not matter to the loss rate, only the transverse velocities involve. So, $f(\vec{r},\vec{v})$ can be written as a product of independent probability density as follows:

$$f(\vec{r},\vec{v}) = f(x,v_x)\,f(y,v_y)\,f(z). \quad (2)$$

The density distribution is assumed to be gaussian. For the x-x' plane (similar for the y-y' plane), it is:

$$f(x,x') = \frac{1}{2\pi\sigma_x\sqrt{\epsilon_x/\beta_x}}\exp\left[-\frac{x^2}{2\sigma_x^2} - \frac{(x'+\alpha_x x/\beta_x)^2}{2\epsilon_x/\beta_x}\right], \quad (3)$$

where $\sigma_x = \sqrt{\beta_x\epsilon_x}$. This means that the velocity distribution at certain location x has a mean value $\bar{x'} = -\alpha_x x/\beta_x$ and a standard deviation $\sqrt{\epsilon_x/\beta_x}$. What matters to the intra-beam stripping is the local velocity (angular) spread $\sqrt{\epsilon_x/\beta_x}$ rather than the entire velocity (angular) spread $\sqrt{\gamma_x\epsilon_x}$. So, in the beam frame, $f(x,v_x)$ can be written as:

$$f(x,v_x) = \frac{1}{2\pi\sigma_x\sigma_{v_x}}\exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{v_x^2}{2\sigma_{v_x}^2}\right), \quad (4)$$

similar for the $f(y,v_y)$, while $f(z)$ is expressed as:

$$f(z) = \frac{1}{\sqrt{2\pi}\sigma_z}\exp\left(-\frac{z^2}{2\sigma_z^2}\right). \quad (5)$$

Equation (1) is then represented as:

$$\frac{dN}{dt} = -\frac{N^2}{2}I_x I_y I_z|\vec{u}|\sigma(|\vec{u}|), \quad (6)$$

* TRIUMF receives funding via a contribution agreement through the National Research Council of Canada.
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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEPO009

STATUS REPORT AND FUTURE PLAN FOR MOLECULAR IMAGING CENTER (I-One) FACILITY

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Abstract

The radio-pharmaceuticals production and imaging facility is known as I-One at King Abdul-Aziz University in the western region of Saudi Arabia. Started the first production in 2018. We will discuss the facility features, considering the university's existence, where some basic research and training in different aspects of cyclotron operation and radio-pharmaceutical production.

INTRODUCTION

According to IAEA [1], the facility's layout should have planning to achieve the intended product quality and safety, and a manufacturing facility's design and layout must be adequate. Additionally, it is important to recognize that each facility will have its own unique characteristics depending on a variety of variables, such as any applicable national or international legislation and standards, the availability of resources, and the nature of the project. Aspects of facility architecture and layout also differ greatly between member states. For more details, the non-controlled area is the entrance to a facility with access restrictions, the offices, the cleaning facilities, the bathrooms, and the warehouses for materials while the controlled area that needs to be managed to guarantee GMP or radiation protection are included in the restricted area. Furthermore, cleanroom Production must take place in a controlled atmosphere to provide product quality control and conformity with GMP rules for pharmaceutical manufacturing, which may be accomplished in a suitably built cleanroom. Controlled access for both people and materials and the purity of the air inside the room are two aspects of the cleanroom's particular construction requirements. Layouts and air handling equipment that is appropriately constructed help to accomplish both qualities (HVAC). Other considerations, floors, walls and ceilings, doors and windows, benches, waste disposal sink, drainage pipes, ventilation and containment, and radioactive storage facilities these structural and auxiliary elements demand meticulous care.

Several studies used PETtrace™ 800 cyclotrons for medical applications [2–4]. The PETtrace™ 800 central component is a compact, well-proven negative ion cyclotron with a vertical mid-plane that includes both protons and deuterons for optimum versatility and reduced cost radioisotope synthesis [5]. Figure 1 shows a paper burn test with beam location and profile when it hits the target.

MOLECULAR IMAGING CENTER (I-One)

The I-One facility is the first cyclotron in the western region of Saudi Arabia. Building started in 2013 in King Abdul Aziz University. First Beam has been performed on Oct. 2017. In April 2019, I-One center started to distribution the radiotracer production under special consideration. Despite that the nearest cyclotron is more than 1000 km away in Riyadh city, I-One is the first and only center of its kind in the Kingdom of Saudi Arabia which specialized in both the production of radioactive isotopes and offers positron emission tomography scanning services. Moreover, I-One follows the highest standards of quality and good manufacturing for the building, quality management system, and productions that have been manufactured such as ^{18}F-FDG, ^{18}F-NaF, and ^{18}F-PSMA. The conducted of first bone examination in the western region using ^{18}F-NaF was performed in early 2022 besides the main and common radiotracer ^{18}F-FDG which is used for oncology, cardiology, and neurological examinations.

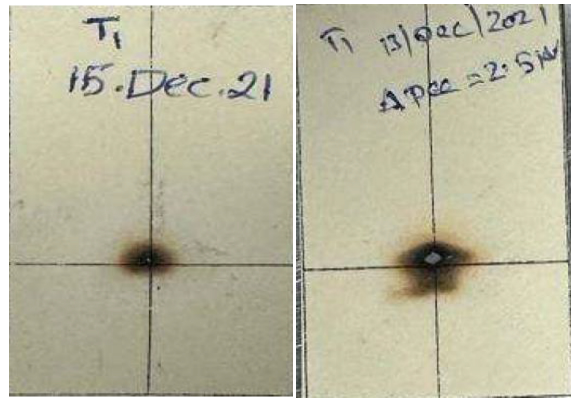

Figure 1: Here we see a paper burn test, which show the beam location and profile when it hits the target.

The I-One Facilities

The facility covers an area of 8000 m^2, where 1200 m^2 is for cyclotron and radio-pharmaceutical production (Fig. 2). The facility is near the university's gate 2 for easy access to radio-pharmaceutical distribution. The production department involves duplicated shielded rooms for any future investments. The radio-pharmaceuticals quality control room is substantial to accommodate more equipment in the future. The center facilities are following the highest standers and measurements. The controlled area includes:

Cyclotron Section The section contains four rooms which are the shielding vault housing of the cyclotron, the service room, the control room, and the power supply room. The cyclotron vault provides shields against ionizing radiation. Typically, strong steel is used to construct the vault. Also, an offer additional bunker to a self-shielded cyclotron is available.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEPO010

HIGH INTENSITY CYCLOTRON SYSTEM INTEGRATION AND COMMISSIONING FOR INDUSTRIALIZATION APPLICATION

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Abstract

Up to 430 μA beam intensity was obtained in 10 MeV CRM cyclotron (CYCIAE-CRM) at China Institute of Atomic Energy (CIAE) in 2010. Whereafter, CIAE built a series of 14 MeV high intensity external ion source cyclotrons for medical isotope application and its relevant research. Compared with research cyclotron facility, cyclotron for industrialization application requires higher level of safety, usability and stability. Therefore, mechanical and electrical system integration and optimum are applied in the cyclotron design and commissioning. Electrical devices of cyclotron, including power supply, RF amplifier and PLC controller, are integrated into four standard industrial shielding cabinets with electromagnetic compatibility (EMC) design to improve electromagnetic interference and operation stability. Besides, earthing system is rearranged in regular laboratory maintenance period to minimize electromagnetic coupling of different signal systems. Based on the previous compact system integration, communication system is integrated into each electrical device as well and could be operated in local and remote mode for the convenience of commissioning. Industrial Ethernet standard PROFINET is adopted as communication protocol to improve the efficiency of protocol interaction towards millisecond level. Regarding RF system, start-up sequence of LLRF is optimized to increase uptime and reliability. The commissioning is also presented in this paper.

INTRODUCTION

Cyclotron laboratory of China Institute of Atomic Energy is committed to the research and development of high intensity cyclotron. A 10 MeV CRM cyclotron (CYCIAE-CRM) was developed and 430 μA beam intensity was obtained in 2010 [1, 2]. This cyclotron is featured with external multi-cusp H- ion source, fundamental harmonic buncher [3], half-wave RF resonator [4] and vertically positioned extraction system. It's also the prototype and research platform of high intensity cyclotron CYCIAE-100. Then, CIAE develop a series of 14 MeV high intensity cyclotrons [5, 6] for medical isotope application (CYCIAE-14A) and its relevant research (CYCIAE-14B), based on the experience of CYCIAE-CRM.

In order to provide higher level of safety, usability and stability for industrialization application, system integration and other improvements have been carried out on the design and commissioning of research cyclotron, and thus CYCIAE-14A could achieve better performances.

SYSTEM INTEGRATION

CYCIAE-14A [6] could provide two kinds of injection line for various vaults: for type I, the injection line is installed on the top side of cyclotron, while for type II on the bottom. The latter one is optimized both in mechanical structure and electrical circuits, and then to be applicable for small vault with the advantage of compactness, economy and convenience.

Power Supply

Take the main magnet power supply for example, full bridge resonant soft switching inverter circuit is adopted to decrease switching noise (25 kHz) and its electromagnetic interference. One blocking capacitor is added into the primary circuit of the power transformer to improve the situation of core saturation, which is deduced by the unbalance of volt-second when the power IGBT is on and off. This topology also helps to reduce the volume of power supply.

Figure 1: Power supply integration comparison (Left: discrete power supply for CYCIAE - CRM , Right: integrated power supply for CYCIAE-14A).

Full digital control is used in main magnet power supply to realize the high precision regulation of PWM, and PID parameters could be adjusted locally and remotely. Current ramping rate adjustment is designed and applied for the convenience of field ramping commissioning. By the accurate control algorithm, the current instability of the main magnet power supply (180 A/110 V) is obtained as better than 0.01 % in long term operation (8 h) which meets the requirement of magnet system (Fig. 1).

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEPO011

UPGRADING THE BEAM DIAGNOSTIC OF THE HZB-CYCLOTRON FROM AN ANALOGUE TO A NEW DIGITAL PLATFORM

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Abstract

The HZB-Cyclotron delivers since a long time reliable beam for experiments and Proton Therapy. Now the old analogue beam diagnostic is outdated and hard to maintain. We developed a digital replacement for the multiplexers for 30 Faraday cups and 12 beam profile monitors. Both use as hardware platform a single-board-controller with FPGA-technology with integrated analogue and digital signals in a client-server architecture. Here we present the new features after more than one year of operation.

MOTIVATION FOR THE NEW MULTIPLEXER DESIGN

A layout of the accelerator complex can be found in [1]. Two injectors serve the k=130 isochronous sector cyclotron. One high energy beam leads to the treatment room and one to the experimental station. Overall, 27 Faraday cups and 10 beam profile monitors (BPM) are installed. The beam diagnosis system dates to the eighties, when the accelerator complex was erected. As more and more Faraday cup channels in the analogue cup current system failed due to contact problems in the wire-wrap cabling, a replacement system had to be designed and constructed.

In order to keep the financial effort for the new system in the accelerator within limits, it was decided to use also in the future the excellent working existing current transformers (I/U converter with 5 ranges from 1 nA to 10 µA full scale) and cabling between measuring points and multiplexer. The converters had been developed in-house and can still be easily repaired. Furthermore, they are working very reliable

One of the challenges for the conversion from the old system to the new design was that it had to be done without impacting on the scheduled beam time, especially not interfering with the scheduled proton therapy blocks. Thus, the installation and commissioning of the new system had to be carried out in just one service period of two weeks. Hence, the new design was developed in a separated setup.

LAYOUT OF THE NEW FARADAY CUP MULTIPLEXER

The following features were described as minimum demands:

- at least 24 channels for Faraday cups and radial probes available
- an auto range feature switching to the active Faraday cup channel in the optimum range of the I/U-converter automatically.
- an auto range feature switching to the active Faraday cup channel in the optimum range of the I/U-converter automatically.
- the choice to select a fixed range of a selected Faraday-cup channel to display
- two simultaneously measured channels with all information, as both injectors are sometimes operated in parallel
- readout of the I/U-converters with a sampling rate of 10 kHz and processing these data to provide information about the mean value, minimum, maximum, and the standard deviation
- display of the processed values to the operator (Min-Max-Mean-Standard Deviation)

Figure 1 shows the data of a Faraday cup as displayed in the control room. The operator sees which Faraday Cup or radial probe is selected, the range of the I/U converter, the beam intensity of 0.36 µA, the minimum value of 0.32 µA, maximum value of 0.4 µA and a standard deviation of 3.8%. Beam tuning is now easier, especially when aiming for high beam stability, i.e., low standard deviation. Two graphs in the lower part provide the history of the past 100 s. The upper graph shows mean, maximum, and minimum beam intensity. The lower part shows the standard deviation. All these data are updated every 100 ms. The dip in the minimum beam intensity and the rise in the standard deviation shows the influence of a beam profile monitor to the beam: The rotating wires cut a small section of the beam, such influencing the standard deviation quite a lot, while the mean beam intensity is scarcely affected.

For the off-line development of the Multiplexer, 15 I/U converters with current sources were set up. Some of the current sources were connected to function generators to simulate beam instabilities. Thus, the programming of the FPGAs and LabVIEW could be done without using beam time.

The layout of the new system is shown in Fig. 2. The backbone of the system are two sbRIO9637 FPGA boards from NI which are connected via a new backplane interface to the existing I/U converters. All the analogue input signals are sampled simultaneously with a sampling rate of 10 kHz. Every 100 ms the 1000 values of each channel are streamed via TCP-IP to the server, where they are processed to provide the desired values: mean, minimum and maximum beam intensity, and standard deviation

The communication between the server and the display PC is done via EPICS communication. Thus, we use in LabVIEW the CA Lab interface [2], which converts Lab-

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEPO012

UPGRADE OF BEAM DIAGNOSTIC SYSTEMS OF JULIC CYCLOTRON

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Abstract

The JULIC cyclotron is in operation since already more then 50 years. Many subsystems of the cyclotron have been upgraded since then, to meet a requirements of the users or simply to the state of the art. In this contribution status of upgrade of the cyclotron beam diagnostic and magnet field control system is presented. Besides that, an example of application of laser doppler vibrometer and proof-of-principle experiment for none-destructive low beam current and position measurement are described.

JULIC CYCLOTRON

The Institute für Kernphysik (IKP) of Forschungszentrum Jülich exploits JULIC cyclotron since already more than 50 years. The JULIC cyclotron is build as a classical isochronus cyclotron with axial injection from the external particle sources. It has a large normal conducting magnet, 100 kW power HF-system with three Dee's for the acceleration and electrostatic extraction system. Almost last 30 years JULIC is mainly used as injector for the accelerator and storage ring COoler-SYnchrotron Jülich (COSY-Jülich) [1]. This is why presently JULIC is only used for acceleration of light negative H - and D - ions for the stripping injection into the COSY ring, at the energies of 45 and 55 MeV, respectively.

Besides operation as COSY injector, JULIC is frequently used for the irradiation of the electronic components, new materials, and for the development of the new generation of the accelerator driven High Brilliance neutron Source (HBS) [2].

VIBRATION OF THE CYCLOTRON INTERNAL ELEMENTS

Since significant time JULIC users have been confronted with a 33 Hz noise ripple in the extraction pulse of the cyclotron. This strong intensity fluctuation disturb COSY operation and due to the injection scheme of the storage ring (20 ms injection pulse every two seconds) did not allow beam intensity optimisation in the machine. The ripple was sudden appearing and disappearing in the extraction pulse of the cyclotron in unpredictable manner, making search for the source of the noise extremely difficult.

To find a noise source, a special action to measure vibrations in the cyclotron bunker has been undertaken. Using commercial laser-doppler vibrometer [3] a presence of strong 33 Hz vibration at the internal parts of the cyclotron has been detected (see blue spectra in Fig. 1). With the help of the special microphone and frequency spectrum analysis software the source of the vibration in the cyclotron bunker has been identified and removed (red and green spectra in Fig. 1). The three scroll pumps in the cyclotron bunker, used only during regeneration of the main cyclotron cryo-pumps, have not been equipped with original vibration dampers and were producing strong vibrations at 33 Hz harmonic. After installation of standard and additional vibration dampers the level of the vibration at 33 Hz harmonic at the internal elements of the cyclotron even in case of simultaneous regeneration of all three cryo-pumps has been reduced to the insignificant level. As a result of this action, 33 Hz noise in the extraction pulse of the JULIC have completely disappeared and did not return.

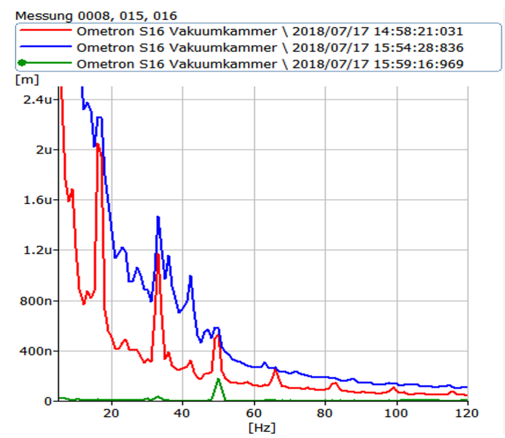

Figure 1: Vibration frequency spectra measured through the vacuum window at the HF-elements of the cyclotron using Omertron S16 vibrometer. The blue spectra is measured before any modification, red - after the first improvements, green - after all the dampers have been installed.

UPGRADE OF THE JULIC MAGNET FIELD CONTROL SYSTEM

The JULIC cyclotron magnet field control system is used to keep field in the cyclotron constant to the 0.1 ppm using a high precision magnet field measurement, special coil, and precision power supply. In this upgrade program an NMR magnet field measurement system has been upgraded

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEPO016

A NEW 18 GHz ECR ION SOURCE FOR CYCLOTRON AT CIAE

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Abstract

In order to meet the requirements of ion beam for the single event effect experiment, the ion source needs to supply ion beams of N, Ne, Si, Ar, Fe, Kr, Xe, and so on for the cyclotron. The most effective way to increase the energy of the cyclotron is to increase the charge state, and the Kr ion charge state reaches 22+ while the Xe ion charge state reaches 35+. A new room-temperature Electron Cyclotron Resonance (ECR) ion source operating at 18 GHz has been developed and assembled at China Institute of Atomic Energy (CIAE). This new ECR ion source is based on the Lanzhou Electron Cyclotron Resonance ion source No.5 (SESRI-LECR5) developed at Institute of Modern Physics (IMP). The magnetic confinement of the new ECR ion source is realized by the axial mirror field provided by two set of room temperature pancake coils while the radial hexapole field is supplied by a permanent magnet hexapole. A dual-sputter disk injection component was designed for the production of metallic cocktail ion beams. This paper will give the detailed design of this ion source, and some preliminary highly charge state ion beam production results will also be presented.

INTRODUCTION

A heavy ion cyclotron (K=120) [1] has been rebuilding at CIAE. The cyclotron is a versatile machine，
which is employed for the production of protons, deuterons, alpha-particles and heavy ions in the variable energy The energy of proton is variable at 10-72 MeV, the maximum current intensity is 200 eμA , the deuterium ion energy is variable at 10-65 MeV, the alpha ion energy is variable at 20-130 MeV, and the heavy ion energy is 120- MeV * Q^2/A (Q and A are the charge state and mass number of accelerated ions respectively). For heavy ions, the energy of the ion beam extracted by the accelerator is proportional to Q^2. It is very important to improve the charge state of the ion beam to improve the maximum beam energy accelerated by this accelerator. The original injector of the accelerator is a 10 GHz CAPRICE 1 Tesla ECR ion source was developed in 1992 [2]. The charge state that can be generated for heavy nuclide particles is low. For example, the charge state of Kr can only reach 18+, while the charge state of Xe can only reach 27+. Therefore, the development of a new ion source with the ability to produce higher charge state ion beam, is necessary to meet the requirements of the basic and application research of heavy ion, such as the research of low energy nuclear physics, single particle effect, ion radiation damage and so on.

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THE LAYOUT OF THE INJECTOR

The original 10 GHz ion source injector was equipped below the cyclotron. The horizontal ion beam is injected into the vertical section through a 90-degree electrostatic deflector and enters the central hole of the magnetic pole under the cyclotron. Two sets of triple quadrupole lens matching beam envelope are set in the vertical section, and finally injected into the cyclotron through an electrostatic deflector (mirror) for acceleration.

The new 18 GHz high charge state ECR ion source injector is set directly below the original 10 GHz ion source injector, as shown in Figs. 1 and 2. According to the requirements of cyclotron, the maximum high voltage of the ion source is 20 kV, and the total ion beam is about 5 emA. Magnetic elements are used on the beam line to reduce the influence of space charge effect on the ion beam. A solenoid lens is set behind the ion source to match the change of ion beam angle under different extraction voltage conditions to meet the requirements of the optical envelope of the dipole magnet. The dipole is a dual-focusing magnet with a deflection radius of 500 mm and the deflection angle is 90 degrees, and the mass resolution is better than 60.

A set of triple quadrupole lens is set behind the dipole magnet, and the analyzed ion beam is matched into the electrostatic deflector and injected into the vertical beam line of the original injector. The large radius electrode plate of the electrostatic deflector is movable. When the beam is supplied by the new injector, the large radius electrode plate of the electrostatic deflector will be move out, and then the ion beam can pass through the electrostatic deflector. Two XY magnetic guides are also set on the beam line to correct the ion beam transmission direction.

ION SOURCE

A high performance room temperature ECR ion source was proposed for various ion beams injection. According to the scaling laws of an ECR ion source [3, 4]. Its design is based on SESRI-LECR5 [5] parameters and optimized for the magnetic field of the SECRAL operating at 18 GHz [6]. Compared with a superconducting ECR ion source, a room temperature 18 GHz ECR ion source has the advantages of more accessible construction, lower cost, and more convenient maintenance.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEPO017

A NEW DESIGN OF CYCIAE230 SUPERCONDUCTING CYCLOTRON RF-DRIVEN SYSTEM*

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Abstract

A superconducting cyclotron with a beam energy of 246.2 MeV has been developed and commissioned by the China Institute of Atomic Energy. The RF system of the first CYCIAE-230 cyclotron adopts two tetrode amplifiers to drive the cavities simultaneously. The driven power is 180 degrees out of phase, and each amplifier was designed to deliver 75 kW RF power to the resonators. In practice, it was found that the driven power is beyond necessary, and only 80 kW RF power is required for the beam. Hence, an upgrade of the existing RF-driven system to the stare-of-art of solid-state technology is put forward by the CIAE cyclotron team. Furthermore, this alternative design also includes an optimization of the coupling between amplifiers and the cavities since the old coupler shows nonidealities under long-term high-power operations. A driven schema utilizing multiple low-power capacitive couplers is designed to address this issue, taking advantage of the cavity as a power combiner. In this paper, a review of the existing RF-driven system will be given first. It will be followed by an analysis of the limitation of such a system in practice. A new design of the solid amplifier, the new driven method, and a capacitive window will also be reported.

INTRODUCTION

Proton cancer therapy has been increasingly adopted in China's domestic medical activities. To address cancer, a growing threat to Chinese public health, a superconducting cyclotron, namely CYCIAE-230, has been developed and commissioned by the China Institute of Atomic Energy in the last serval years [1] under the support of the program of proton therapy and space science launched by China National Nuclear Corporation (CNNC).

This superconducting cyclotron uses Ni-Ti alloy in liquid hilum temperature to generate about 3 Tesla magnet fields [2] to constrain the proton and uses second harmonics RF field to accelerate it from several electron voltages to 242.6 MeV. In total, before extraction, the particle is accelerated about 5,300 times, eight times per turn. The diameter of the magnet pole is ~890 mm, while the weight is about 90 tons.

The RF system of CYCIAE230 consists of a set of resonators, two independent 75 kW amplifiers, and one set of LLRF control [3]. The resonators are two capacitive coupled similar coaxial cavities.

Each cavity shares the same resonance parameters, such as identical capacitance, inductance, and shunt impedance. Two identically designed cavities are electromagnetically joined together by the distributed capacitance in the central region. The system resonance frequency can be determined as formula below.

$$\begin{cases} Y_{AB} = \frac{1}{R_1} + j\left(\omega C_{11} - \frac{1}{\omega C L_1}\right) + \frac{\omega^2 C_{12}^2}{\frac{1}{R_2} + j\left(\omega C_{22} - \frac{1}{\omega C L_2}\right)} \\ C_{11} = C_{12} + C_1 \\ C_{22} = C_{12} + C_2 \end{cases}$$

R_1, L_1, C_1, R_2, L_2, and C_2 are parallel impedance, distributed inductance, and capacitance of the two Dees, respectively. C_{12} is the coupling capacitance between the two groups. In an ideal condition, let the two cavities be the same, e.g., $R_1 = R_2$, $C_1 = C_2$, and $L_1 = L_2$; the resonators have the same resonance frequency, ω_0. And, let the coupling coefficient be defined as $K = \frac{C_{12}}{\sqrt{C_{11}C_{22}}}$ The resonant frequency can be solved as,

$$\omega^2 = \frac{(1 \pm K)}{(1+K)(1-K)}\omega_0^2$$

this gives two resonance frequencies:

$$\begin{cases} \omega_l = \frac{1}{\sqrt{1+K}}\omega_0 \\ \omega_u = \frac{1}{\sqrt{1-K}}\omega_0 \end{cases}$$

The π resonance mode, ω_l , is selected as the operation mode for beam acceleration for cyclotron CYCIAE230, which is the 2nd harmonic particle cyclotron frequency. A push-pull driven method is chosen to roll out the resonance at ω_u.

CHARACTER OF EXISTING RF SYSTEM

Two groups of resonators are involved in the π mode beam acceleration, each of which has an independent power coupler. These two couplers are used simultaneously and are driven by two separated 75 kW tetrode amplifiers in a push-pull configuration. By applying RF power with 180 degrees out-of-phase, the simulated mode of the cavities group can be simplified, as shown in Fig. 1.

The measurement setup is shown in Fig. 1a. The drive RF is taken from network analyzer port-1 and is divided using a push-pull power divider to drive through the identical-length rigid transmission to the two couplers. A cavity

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEPO018

PROGRESS IN THE DESIGN OF A NEW 150-MHz FLAT TOP CAVITY FOR THE PSI RING CYCLOTRON

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Abstract

Increasing PSI's 590-MeV main cyclotron beam current to 3 mA requires the replacement of the existing power-limited 150-MHz flat top cavity with a new cavity. This new cavity has been designed to withstand a 700-kV peak voltage and a 140-kW dissipated average power. Although very similar in its geometry to the original flat top cavity currently in operation, in the new design, special attention has been paid to the shaping of the four electrodes for maximizing the shunt impedance. Furthermore, the topology of the cooling water channels has been optimized to increase the power handling capabilities of the cavity. Finally, in order to mitigate multipacting observed in the current design, variations on the new cavity baseline geometry have started to be explored.

INTRODUCTION

The PSI High Intensity Proton Accelerator (HIPA) facility consists primarily of the 72-MeV injector cyclotron (Injector II) and the 590-MeV Ring cyclotron. The Injector II cyclotron is currently being upgraded through the installation of new 50-MHz aluminum cavities designed to withstand a peak voltage of 400 kV and an average dissipated power of 50 kW [1]. The Ring cyclotron has been progressively upgraded with four new copper 50-MHz cavities capable of generating a 1-MV peak voltage and able to dissipate an average power of 500 kW [2]. However, the 150-MHz flat top cavity is currently the limiting feature of the Ring cyclotron [3].

For a 3-mA beam current, each 50-MHz main cavity of the Ring cyclotron requires a peak accelerating voltage of 910 kV. The required peak voltage of the 150-MHz flat top cavity would then be 640 kV [4]. Adding some reserve, the new cavity is being designed for a maximum peak voltage of 700 kV.

RF DESIGN STUDIES

Since the existing mechanical constraints severely limit deviations from the current geometry, the new cavity RF studies performed with the 3D electromagnetic code ANSYS HFSS [5] mainly focused on optimizing the electrodes that protrude into the cavity. Several cavities without RF coupler were designed with electrodes thickness of 45 mm, 55 mm and 65 mm and with a horizontal gap between electrodes ranging from 140 mm to 250 mm, this later distance being considered as maximum to reduce field leakage. The virtual tuning to reach the design frequency of 151.8984 MHz in each of these cavities was done by adjusting the cavity height (along the Z-axis in Fig. 1). The inner maximum length, the inner width and the length of the four electrodes, which are 2700 mm, 200 mm and 2585 mm, respectively, have been kept the same as in the actual cavity. The minimum vertical distance between the electrodes is also the same and is 30 mm. Figure 1 shows one-half of the vacuum volume of the new cavity.

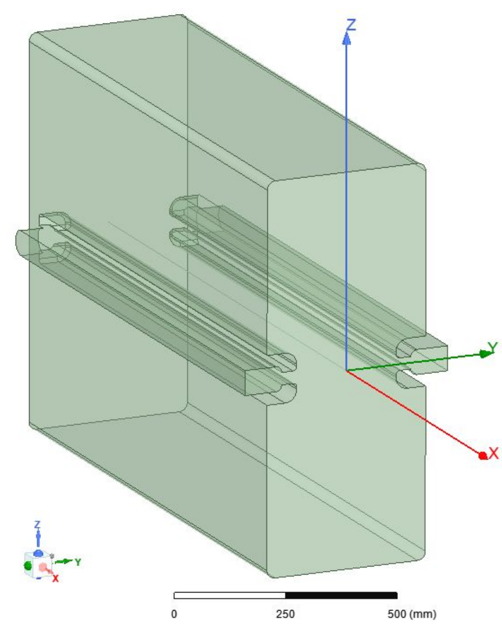

Figure 1: Vacuum volume of the new flat top cavity - One-half shown.

A substantial modification of the cavity consisted in shaping the electrodes to increase the peak shunt impedance R_{sh} ($R_{sh} = V_g^2/P_d$ where $V_g = \int \mid E_y(0, y, 0) \mid dy$ is the peak gap voltage and P_d is the power dissipated on the total inner surface). Whereas the tip of the electrodes in the actual cavity is characterized by the single radius 22.5 mm, leading to a maximum electrodes thickness of 45 mm, in the new cavity, the curvature radius closest to the beam plane (XY plane in Fig. 1) was decreased to 10 mm. Such a radius reduction leads to an increase of the shunt impedance. The maximum surface electric field also increases but still stays well below the Kilpatrick limit.

The results of the parametric studies done by varying the horizontal gap between electrodes and the electrode thickness Δz_{elec} are illustrated by Fig. 2. For an aluminum conductivity of 34 MS/m, a peak gap voltage maintained to 700 kV and a gap between electrodes increasing from

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THAI01

RECENT PROGRESS OF RESEARCH AND DEVELOPMENT FOR THE COST-EFFECTIVE, ENERGY-EFFICIENT PROTON ACCELERATOR CYCIAE-2000*

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Abstract

The MW class proton accelerators are expected to play important roles in many fields, attracting institutions to continue research and tackle key problems. The continuous wave (CW) isochronous accelerator obtains a high-power beam with higher energy efficiency, which is very attractive to many applications. Scholars generally believe that the energy limitation of the isochronous cyclotron is ~1 GeV. Enhancing the beam focusing becomes the most crucial issue for the isochronous machine to get higher beam power.

Adjusting the radial gradient of the average magnetic field makes the field distribution match the isochronism. When we adjust the radial gradient of the peak field, the first-order gradient is equivalent to the quadrupole field, the second-order, the hexapole field, and so on. Just like the synchrotron, there are quadrupoles, hexapole magnets, and so on, along the orbits to get higher energy, as all we know.

If we adjust the radial gradient for the peak field of an FFA's FDF lattice and cooperate with the angular width (azimuth flutter) and spiral angle (edge focusing) of the traditional cyclotron pole, we can manipulate the working path in the tune diagram very flexibly. During enhancing the axial focusing, both the beam intensity and the energy of the isochronous accelerator are significantly increased. And a 2 GeV CW FFA with 3 mA of average beam intensity is designed. It is essentially an isochronous cyclotron, although we use 10 folders of FDF lattices. The key difficulty is that the magnetic field and each order of gradient should be accurately adjusted in a large radius range.

As a high-power proton accelerator with high energy efficiency, we adopt high-temperature superconducting (HTS) technology for the magnets. 15 RF cavities with a Q value of 90000 provide energy gain per turn of ~15 MeV to ensure the CW beam intensity reaches 3 mA. A 1:4 scale, 15-ton HTS magnet, and a 1:4 scale, 177 MHz cavity, have been completed. The results of such R&D will also be presented in this paper.

INTRODUCTION

High energy and high current proton accelerators are widely and importantly applied in frontier research fields such as nuclear physics and particle physics, national economic fields such as public health and advanced energy, and even national security [1, 2]. A Proton accelerator with an average beam power of 5-10 MW has been the world's dream machine for more than 30 years [3, 4]. LINAC is considered to be the most promising, and high-energy CW superconducting LINAC is still under development so far [5]. On the other hand, a serious limitation of CW cyclotrons is the maximum energy achievable, which for protons is about 1 GeV for isochronous operation, due to relativistic effects [6, 7]. A 2 GeV CW FFA (or it can be called an alternating gradient cyclotron) has been investigated since 2013 at CIAE, and more detailed R&D activities have been conducted in recent years. The design goal is to provide a 6 MW proton beam with higher energy efficiency than LINAC. It is expected to be up to 30% with overall energy efficiency and keep the cyclotron's advantages of being cost effective for construction and operation.

GENERAL CONSIDERATIONS IN THE OVERALL DESIGN OF 2 GEV CW FFA

Basic Description and Progress of Overall Design since 2019

The 2 GeV FFA facility, CYCIAE-2000, consists of three stages: a 100 MeV isochronous cyclotron as a pre-injector, an 800 MeV isochronous cyclotron as an injector, and the main machine of 2 GeV CW FFA, which are shown in Fig. 1. Compared with the design scheme published in 2019, the main progress is summarized as follows.

FDF field distribution In the previous study [8], the working path in the tune diagram which crosses the resonance of νr=3 asks to control the third harmonics B3 at about 1 Gs level. This is particularly challenging for magnet construction. Two more possible solutions to the working path were studied and will be described in the following sections of this paper. Instead of the tremendous amount of tentative numerical calculations by adjusting the magnetic field intensity, angular width, and spiral angle of the 10-fold F and D magnets, along the radius, the third-order peak field distribution of F and D magnets, was analysed into zero-order (dipole, traditional cyclotron sector field), first-order (quadrupole), second-order (hexapole), and third-order (octupole) radial gradients of the peak magnetic field. This method of accurately adjusting the radial gradients of the peak magnetic field, assisted by traditional

* This work was supported in part by the National Natural Science Foundation of China under Grant 12135020 and the basic research fund from the Ministry of Finance of China under Grant BRF201901.
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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THAI02

STRIPPING EXTRACTION AND LORENTZ DISSOCIATION

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Abstract

Stripping extraction of hydrogen molecular ions has gained immense interest in the cyclotron industry due to its high extraction efficiency. However, the magnetic field could result in undesired Lorentz dissociation of the hydrogen anion/molecular ions during acceleration. This work summarizes and compares the Lorentz dissociation of several types of hydrogen ions, as well as other important aspects that are crucial when deciding the best candidate for stripping extraction in a cyclotron.

INTRODUCTION

This paper is a brief summary of a more extensive and in-depth discussion of Lorentz dissociation of hydrogen ions in [1]. Generally, stripping extraction involves the stripping of one or more electrons from the accelerated ions. Owing to the nature of the change in the charge-to-mass ratio, the stripped particles have different trajectories after stripping. This leads to the possibility of having a close to 100% extraction efficiency. This feature is appealing, as final turn separation is no longer mandatory for a clean extraction. However, there are other issues associated with this. Among all, one of the very critical one is the Lorentz dissociation of the accelerated ions under the effect of external magnetic field. The following will discuss briefly the effect of Lorentz dissociation on the potential candidates to produce a proton beam: H^-, H_2^+ and H_3^+.

LORENTZ DISSOCIATION OF HYDROGEN IONS

In general, Lorentz dissociation is a quantum mechanical effect where the bound electron or proton can tunnel out of its potential well because in its own reference frame, the magnetic field is an electric field that tilts the well. Dissociation occurs anywhere along ions' orbits and so they are lost, not extracted and eventually cause activation.

In the particle's rest frame, the electric field component perpendicular to the motion can be simplified as:

$$\mathcal{E} = \gamma\beta c B_z \cong (3\,\mathrm{MV/cm})\gamma\beta(B_z/1\,\mathrm{T})\,, \qquad (1)$$

where $\mathcal{E}$ and B_z are the equivalent electric field and the perpendicular magnetic field respectively; β is the ratio of the particle's speed, v, to the speed of light, c and $\gamma = \frac{1}{\sqrt{1-\beta^2}}$.

H^-

The time constant, i.e. the probability of the ion to survive a time t is $e^{-t/\tau}$. It can be expressed by [2]:

$$\tau = \frac{A_1}{\mathcal{E}} \exp\frac{A_2}{\mathcal{E}}\,. \qquad (2)$$

The constants A_1 and A_2 are fitted constants from experimental results [3]. They are: $A_1 = 3.07 \times 10^{-6}$ V-s/m and $A_2 = 4.414 \times 10^9$ V/m respectively. Due to the popularity of stripping extraction of H^-, this effect is well studied and documented by many past researchers [3, 4]. Using Eq. (2) and assuming B is a constant, the integrated fractional loss F is shown in Fig. 1 (the energy gain per turn is taken as 0.48 MeV).

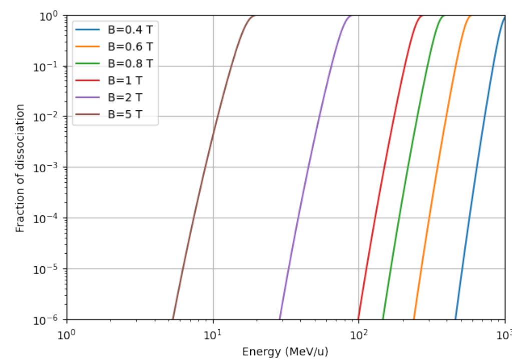

Figure 1: Integrated fractional dissociation of H^- as a function of energy for various B. Note that this calculation assumed a constant B and the energy gain per turn is 0.48 MeV. However since the loss as such a steep function of B, this can be taken as the peak B for cyclotrons with flutter.

From Fig. 1, F of H^- particles accelerated up to 1 GeV is 100% for any $B > 0.4$ T. Taking a maximum loss of 0.01%, the maximum permissible beam energy at a low B of 0.4 T is about 600 MeV; at a very large radius of $r = 10$ m. Hence, any acceleration at high energy is uneconomic, as the average magnetic field will be too low to achieve the desired beam loss, and the machine has to be extremely large to accommodate such a low magnetic field.

H_2^+

H_2^+ is a diatomic ion with an equilibrium bond distance of about 1.06 Å. The binding energy of H_2^+ is about 2.7 eV, which is 3.6 times larger than the binding energy of H^-. Unlike the H^- ion that has a well-studied time constant, there is a lack of experimental work to study Lorentz dissociation of H_2^+. To fill in the missing piece of information, some theoretical models are used here as the preliminary tools to estimate the Lorentz dissociation of H_2^+.

The ionic lifetime of each vibrational v state (rotational state $J = 0$) at different electric fields can be obtained from Hiskes' calculation [5]. The lifetimes of high v states are generally comparable to the revolution period of H_2^+ in a cyclotron (~10^{-8} s), i.e. the ions at high v states will dissociate completely within a turn of revolution. Therefore, instead of the lifetime, it is the state population that limits the fraction of dissociation. Unlike H^- that has only one bound state,

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THAO01

ON THE ENERGY LIMIT OF COMPACT ISOCHRONOUS CYCLOTRONS

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Abstract

Existing analytical models for transverse beam dynamics in isochronous cyclotrons are often not valid or not precise for relativistic energies. The main difficulty in developing such models lies in the fact that cross-terms between derivatives of the average magnetic field and the azimuthally varying components cannot be neglected at higher energies. Taking such cross-terms rigorously into account results in an even larger number of terms that need to be included in the equations. In this paper, a method is developed which is relativistically correct and which provides results that are practical and easy to use. We derive new formulas, graphs, and tables for the radial and vertical tunes in terms of the flutter, its radial derivatives, the spiral angle and the relativistic gamma γ. Using this method, we study the $2\nu_r = N$ structural resonance (N is number of sectors) and provide formulas and graphs for its stopband. Combining those equations with the new equation for the vertical tune, we find the stability zone and the energy limit of compact isochronous cyclotrons for any value of N. We confront the new analytical method with closed orbit simulations of the IBA C400 cyclotron for hadron therapy.

INTRODUCTION

In this paper we derive the maximum energy that can be realized in compact isochronous cyclotrons. This limit is determined by two competing requirements namely the need for sufficient vertical focusing on the one hand and the need to avoid the stopband of the half-integer resonance $2\nu_r = N$ on the other hand (ν_r is the radial tune). With increasing energy, the isochronous field index increases rapidly and more and more azimuthal field variation f is needed to remain vertically stable; but with higher f, the stopband of the resonance broadens, and the energy limit associated with it rapidly reduces. The energy limit depends on N and on the spiral angle ξ of the sectors. We assume that the magnetic field is perfectly N-fold rotational and median plane symmetric and therefore do not consider other, than the half-integer linear resonance. We derive practical formulas which are useful especially in the cyclotron design phase. Our main assumption/approximation is that f is not too large. Results are derived up to $O(f^2)$ (equivalent to $O(F)$, where F is the flutter). For compact cyclotrons F is generally well below 1 and for these machines we expect our results to be precise. For separate sector cyclotrons, care should be taken, however. The special case of such cyclotrons with radial sectors (no spiraling) has been studied by Gordon [1], by assuming a hard-edge model where in the magnet sections the orbits are perfectly circular and in the empty straight sections the magnetic field is zero. In Gordon's model, there is no need to assume a small flutter, but on the other hand, his assumptions will probably not be valid for compact cyclotrons and maybe also less accurate for coil-dominated superconducting ring cyclotrons where the magnetic field has the tendency to spread out more smoothly and non-uniformly. For separate sector cyclotrons with a larger magnetic filling factor, the flutter drops quickly ($F \approx 0.25$ for a filling factor of 80%) and we expect our results to become more accurate. Another interesting derivation of the isochronous cyclotron energy limit has been made by Danilov *et al.* from the JINR [2]. In their analysis however, they consider only the first dominant Fourier component of the field and they further assume that its amplitude is independent on radius and its phase increases linearly with radius. Also, contributions due to higher order radial derivatives of the average magnetic field are ignored. A similar approach was used by King and Walkinshaw [3]. We closely follow the Hamiltonian approach that has been firstly introduced by Hagedoorn and Verster [4]; in this paper we wish to pay tribute to them. The derivation is too elaborate and complex to show in detail and therefore in this paper, we present a strongly compressed version. The full derivation and results can be found in reference [5].

METHOD OF DERIVATION

We study the static (non-accelerated) motion near a given constant radius r_0 defined by $P_0 = qr_0\bar{B}(r_0)$, where P_0 is the particle kinetic momentum. The reduced magnetic field $\mu(r,\theta) = B(r,\theta)/\bar{B}(r_0)$ is represented by a Fourier series with respect to the azimuth θ. The radial dependence of the average field $\bar{\mu}(r)$ and of the Fourier components $A_n(r), B_n(r)$ of the azimuthally varying field profile $f(r,\theta)$, are Taylor expanded relative to the same radius r_0. The magnitude of f is approximately equal to the magnitude of the dominant Fourier component $C_N = (A_N^2 + B_N^2)^{1/2}$ and the flutter F is approximately equal to $C_N^2/2$. In all our derivations we use a perturbation analysis where $|f|$ serves as the measure for precision. In general any quantity of interest $g(\theta)$ can be split in its average part $\bar{g} = \frac{1}{2\pi}\oint g(\theta)d\theta$ and its oscillating part $\mathrm{osc}(g) = g(\theta) - \bar{g}$. Oscillating parts of $O(f)$ can be moved to the next higher order by a properly constructed canonical transformation. In doing so, new average contributions of $O(f^2)$ are generated. Our goal is to derive results up to $O(f^2)$. The reason for this is that the first significant terms in the expressions for the isochronous magnetic field and the radial and vertical tunes are of $O(f^2)$. In line with the HV-paper [4], we keep the average part of any azimuthally varying term up to $O(f^2)$, but neglect oscillating terms $O(f^2)$ as they would generate new terms of $O(f^3)$ when transforming them to higher order. However, we make one important generalization/improvement as compared to the HV-paper. Hagedoorn and Verster assumed that radial derivatives of the average magnetic field $(\bar{\mu}', \bar{\mu}'', \bar{\mu}''', \ldots)$ are small quantities of $O(f^2)$ and therefore neglected cross-terms between those derivatives and

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THAO02

BEAM EXTRACTION SIMULATION AND MAGNETIC CHANNELS' DESIGN FOR MSC230 CYCLOTRON

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Abstract

MSC230 is a novate cyclotron for proton (FLASH included) therapy research, designed and developed by JINR. The extraction system of this machine includes only one electrostatic deflector followed by two magnetic correctors. These correctors were designed and included in global model to simulate beam extraction. The peculiarities of the design procedure and the outcome of the simulation is discussed in this paper.

INTRODUCTION

Joint Institute for Nuclear Research (JINR) is working on the design for the new cyclotron for proton therapy: MSC230 – Medical Super Conducting cyclotron of 230 MeV energy [1].

The main idea is to build very reliable and easy in production machine. This allows to maximize extracted beam current to be enough to FLASH therapy.

In order to do that, MSC230 combines advantages of two most successful accelerators in proton therapy – PROSCAN's Varian and IBA's C235. From C235 we took a low magnetic field and the fourth harmonic of acceleration, from Varian we took a superconducting coil, to reduce its weight to ~100 tones, and a constant gap between the sectors along the radius, wide enough to accommodate an electrostatic deflector, and as a result we have four free valleys for placing accelerating cavities connected in center.

JINR International Biomedical Research Center

The final goal of the project is to design and create an international biomedical innovation center at JINR, based on MSC230, for the next purposes:

1. Carrying out fundamental and applied research in the field of radiation biology and medicine, first of all, the FLASH method based on the methods of conformal irradiation from the medical beam of the Medical Technical Complex (MTC DLNP).
2. Training and improving qualifications of specialists in the field of radiation biology and medicine.
3. Creating necessary conditions for the introduction of the latest technologies in the field of proton therapy of oncological diseases into clinical practice.

ABOUT THE EXTRACTION SYSTEM

The extraction system of MSC230 is planned to be done by placing one electrostatic deflector (ESD) followed by two magnetic channels (MC1 and MC2), see Fig. 1. Every element is located under the sectors and surely must take into the account the dimension restriction caused the length of the sector's gap, normal to median plane, is being 50 mm. The azimuthal extent of every element is 40°.

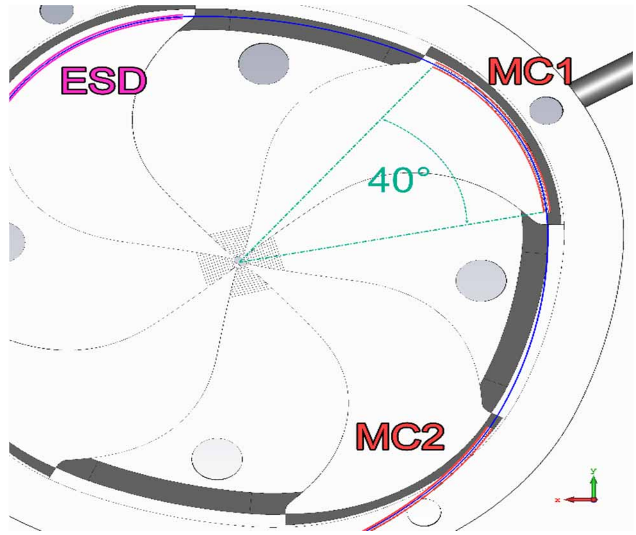

Figure 1: The location of the extraction system elements along beam extraction trajectory (blue curve).

ESD is placed with the idea to catch the beam right after it exits the second accelerating gap. The reliable design of the cyclotron allows to accelerate the beam only in 500 turns which provides the distance between equilibrium orbits of 1.5 mm at the deflector entry. Such design also decreases the requirements for voltage to be quite safe: the eclectic filed strength is only 100 kV/cm at maximum, i.e. the electrode voltage – 50 kV. Due to main beam losses mostly happen on the encounter face of the deflector's septum, septum thickness was chosen 0.1 mm. The aperture of the deflector is 5 mm

The beam, deflected by ESD, enters the first magnetic channel MC1 which continues extraction and decrease horizontal defocusing.

The sole purpose of MC2 is to suppress horizontal defocusing, for the beam to fit the required aperture.

MAGNETIC CHANNELS' REQUIREMENTS

The basic requirements for the channels are the following (see Table 1), which should be delivered along the intervals of the beam trajectory into the magnetic field shown in the Fig. 2.

Table 1: The Requirements for the Magnetic Channels

Channel	Aperture [mm]	Gradient [Gs/mm]	B_z shift [Gs]
MC1	10	100	-600
MC2	10	170	0

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THBI01

STATUS ON NHa C400 CYCLOTRON FOR HADRONTHERAPY

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Abstract

The NHa C400 is an isochronous cyclotron for cancer therapy delivering high dose rates of alphas to carbons at 400 MeV/amu and protons at 260 MeV. NHa company, of which IBA is a major shareholder, designs, produces and markets the new multi-ions C400 based therapy system while IBA experts are deeply involved in all aspects of its conception. IBA and NHa have restarted studies in 2019 based on the conceptual report from the JINR and IBA collaboration, reviewed in 2009 by cyclotron community experts. Final designs of major subsystems are presented highlighting some specific aspects related to the complexity of this large cyclotron.

THE C400

Parameters in Table 1 have barely changed from the conceptual study [1], published in [2, 3]. IBA and NHa have launched an extra pass on the design of subsystems before releasing drawings for manufacturing.

Table 1: C400 Design Parameters

Parameter	Value
Accelerated ions	H_2^+;$^4He^{2+}$;($^6Li^{3+}$); ($^{10}B^{5+}$);$^{12}C^{6+}$
Injection energy	26 keV/Z
Final energy of ions,	400 MeV/amu
protons	265 MeV
Number of turns (ions)	~2100
Magnet system	
Iron weight	738 Tons
Outer diameter	7 m
Pole radius	1.87 m
Max field (Hill; Valley)	~4.5 T; 2.45 T
Stored energy	55 MJ
Superconducting material	NbTi
Conductor peak field	3.9 T
Current density	~31 A/mm²
RF system	
Frequencies ($^{12}C^{6+}$; H_2^+)	75 MHz; 75.6 MHz
Operation	4th harmonic
Number of dees	2
Voltage (centre; extraction)	60 kV;150 kV

The C400 has three independent ion sources (H_2^+;$^4He^{2+}$;$^{12}C^{6+}$) mounted on a platform on top of the cyclotron vault (Fig. 1). Protons are obtained via stripping of H_2^+ at 265 MeV/amu while ions are extracted via an electrostatic deflector followed by a magnetostatic channel. Magnet poles are 4-fold symmetry, hills and valleys are strongly spiralized, hills have an elliptical shaped vertical aperture for the beam (Figs. 2 and 3).

The cryostat houses two subsoils per coil (Fig.4) balancing currents between them allows magnetic field profile corrections, which is necessary to switch between isochronous fields of each particle.

The large size of the cyclotron is inherently challenging for many aspects of the project. Indeed, transport/handling/assembly on site, accessibility for maintenance, etc. all become critical requirements for any subsystem design. The multi-particle feature also provides its share of complexity, especially concerning the management of the specific beam tuning required for each extraction modes.

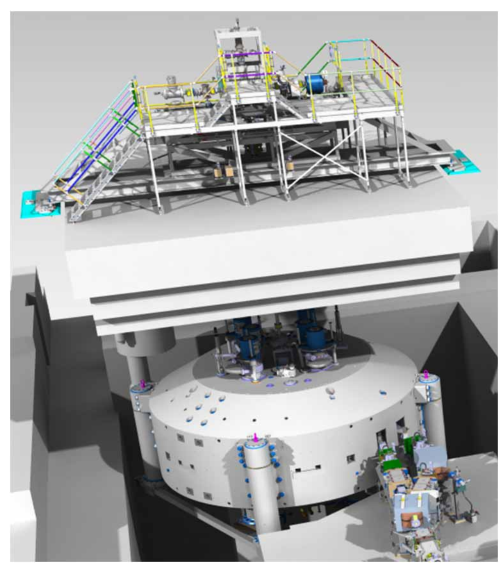

Figure 1: Layout of the C400 cyclotron and its injection system. A vertical transport line passing through the concrete floor connects the two systems.

Magnet Design

Few recent modifications had a large impact on the magnet detailed design. To reduce pumping time and to keep high transmission for molecular hydrogen acceleration, as described in [4], the holes in the valleys of the pole have been significantly enlarged since [1], this imposing a slight reduction of the azimuthal width of the hills.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THBI02

STATUS REPORT ON THE CYCLOTRON INJECTOR FOR HIMM*

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Abstract

HIMM (Heavy Ion Medical Machine) is an accelerator complex designed by Institute of Modern Physics, CAS, which accelerates carbon ions to the energy 400 MeV/A for tumour therapy. The main accelerator of HIMM is a synchronous accelerator. As a special design, we use a cyclotron as the injector of the synchrotron. The cyclotron is a compact cyclotron to accelerate $^{12}C^{5+}$ ions to the energy 6.8 MeV/A, and the extracted beam intensity of the cyclotron is 10 eμA. For stability and simplicity operation, we use two identical permanent magnet ECR ion sources in the axial injection line, that the ion sources can interchange with each other rapidly with the same performance, and only one main exciting coil with no trim coils in the cyclotron magnet. Up to now, three cyclotrons have been accomplished, one of them was operated in Gansu Wuwei Tumour Hospital to treat more than six hundred cancer patients in the last two and a half years, the other one had been fully commissioned in Lanzhou Heavy Ion Hospital about two years ago. After a short introduction to the heavy ion cancer treatment facility development in China, this paper will present operation status of the cyclotrons for HIMM. Typical performance and on-line operation reliability will be discussed.

INTRODUCTION

HIMM (see Fig. 1) is an accelerator complex designed by Institute of Modern Physics, CAS, which can accelerate carbon ions to the energy 400 MeV/A for tumour therapy. The beam is generated from the ECR ion source and passes through the LEBT, the injector HIMM-IC (Injector cyclotron), the MEBT, the main accelerator HIMM-SYN (Synchrotron) and the HEBT to the treatment terminals.

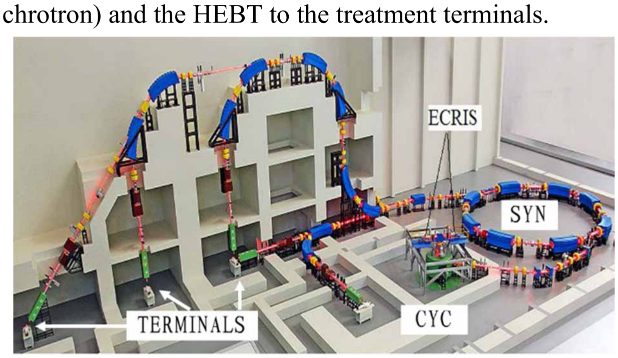

Figure 1: Layout of HIMM. ECRIS: ECR ion sources. CYC: Injector cyclotron. SYN: Synchrotron. TERMINALS: Treatment terminals.

*Work supported by Technology development programme 22ZY2QA003.
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As a unique design, HIMM is the only medical cancer treatment facility in the world that uses a cyclotron as an injector. HIMM-IC (see Fig. 2) is a compact isochronous cyclotron [1, 2], which has a whole magnet without any trimming coils. It can accelerate $^{12}C^{5+}$ ions to the energy of 6.8 MeV/A at extraction, beam intensity no less than 10 eμA.

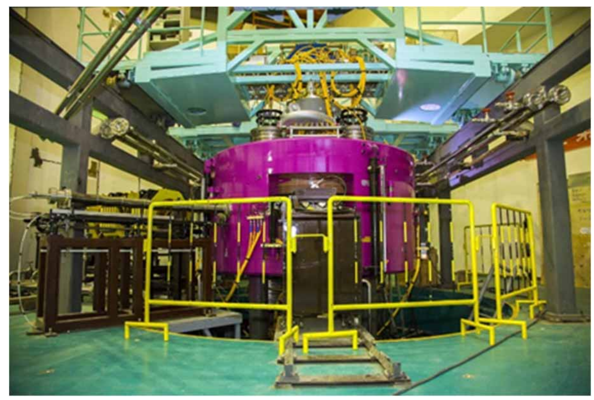

Figure 2: HIMM-IC installed on site.

Up to now, there are three HIMM facilities built and installed in China [3]. The HIMM in Gansu Wuwei Tumour Hospital (see Fig. 3) has treated more than six hundred cancer patients in the last two and a half years. The other two HIMMs in Lanzhou and Putian have also completed installation and are now being prepared and commissioned before clinical treatment.

Taking Wuwei's HIMM facility as an example, for routine operation of the HIMM-IC, an extraction of 5.5 μA (CW) ion beam has been made, which enables the acceleration of 2000 μA (pulsed) C^{5+} beam intensity (see Fig.3) with the main accelerator HIMMSYN, and the beam intensity delivered to the treatment terminals is typically 4×10^8 ppp. These indexes have well met the requirements of medical cancer treatment facilities.

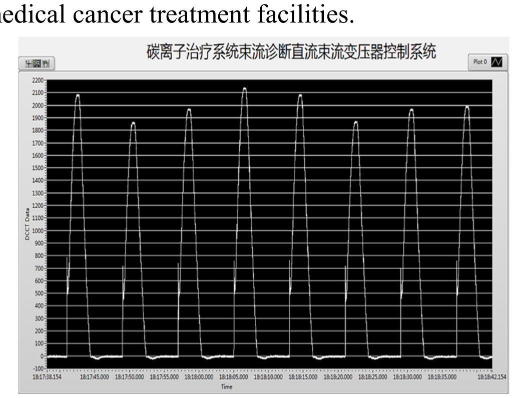

Figure 3: Beam intensity in the synchrotron.

23rd Int. Conf. Cyclotrons Appl. CYCLOTRONS2022, Beijing, China JACoW Publishing
ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THBO01

A NEW CONCEPT OF CYCLOTRONS FOR MEDICAL APPLICATIONS

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Abstract

Demand for cyclotrons for medical applications is growing rapidly. Cyclotrons delivering proton beams from 15 MeV up to 230 MeV are being used for isotopes production and proton therapy. Author proposes a concept that allows to significantly reduce cost of cyclotrons by making them more compact and power efficient without using superconducting coil. In the proposed design ratio between azimuthal length of sectors and valleys is over 3 to 1, with RF system operating at high frequency and acceleration at harmonic mode of 2 times the number of sectors. Compact size is achieved not by increasing the magnet field level, but by reducing the coil and RF system dimension. Cyclotrons will have 4 sectors and 4 rf cavities operating at harmonic 8 with 1.55 T mean field and accelerating frequency 180 MHz.

MOTIVATION

The production of new cyclotrons for physics research has slowed down since the 1990s (see Fig. 1, the green triangles). At the same time, demand for cyclotrons intended for isotope production and proton therapy is growing. Cyclotrons have a limited lifetime due to irradiation, etc., which means there is a need to replace old cyclotrons with new ones. Cyclotrons are becoming better: more compact, cheaper, more reliable, power efficient.

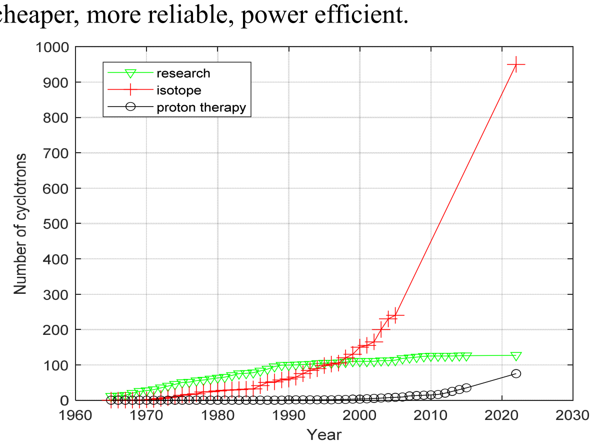

Figure 1: Number of cyclotrons versus years. The green triangles are cyclotrons in operation at research centers, the red crosses the cyclotron for medical radioisotopes production, and the black circles cyclotron for proton therapy [1]. Graphs are updated for year 2020 by data from [2, 3].

THE NEW CONCEPT

The main goal in creating a cyclotron is to make a light and compact design. In past years, the trend has been to increase the magnetic field, thereby decreasing the pole radius (see Fig. 2).

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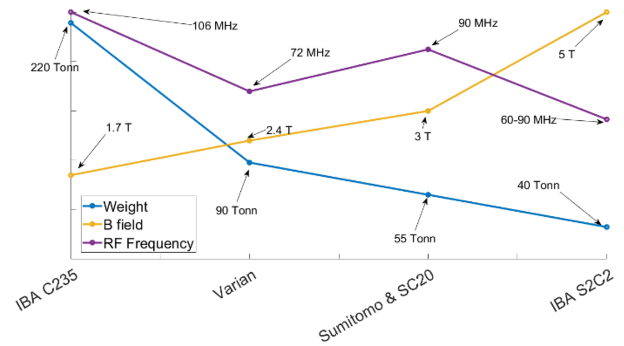

Figure 2: Weight, mean magnetic field and accelerating frequency of the proton therapy cyclotrons.

Superconducting coils is the only way to achieve high B field in cyclotron. Do cyclotrons with superconducting coils are more compact? Yes, the pole diameter is smaller, but cryogenics equipment around cyclotron is huge! Dry magnets with cryocoolers are more compact, but are there power efficient? Cryocoolers consume power 24x7 during operation and more during cooling down. So cyclotrons with superconducting coils have smaller pole diameter but they have the following disadvantages:

- Long time to turn on/off the magnet.
- Long time to cool down.
- Expensive.
- Requires servicing.

Moreover, superconducting cyclotrons do not exist! We only have cyclotrons with superconducting coils. Cyclotron is an accelerator and number one system of any accelerator is an accelerating system, magnet just keeps the beam focused and arrive in time! Superconducting RF systems do not yet work in cyclotrons.

I propose another way to reduce the size of the cyclotron, to make the accelerating RF system and coils more compact by increasing the frequency of the RF system, thereby reducing the valley depth. Reducing the valley depth will result in fewer A coils in the magnet, which will make the coil smaller, which in turn will result in a smaller yoke size. (Fig. 3).

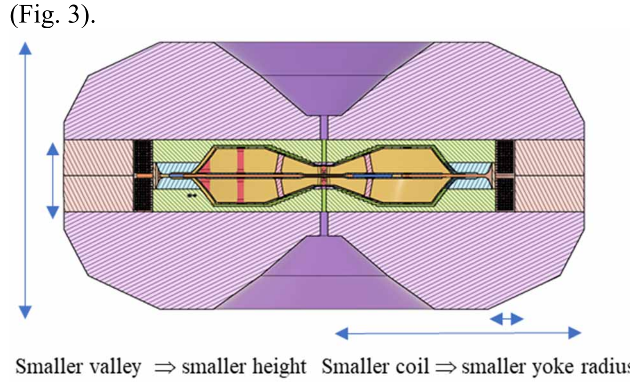

Figure 3: Dimensions of the cyclotron.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THBO02

SAPT- A SYNCHROTRON BASED PROTON THERAPY

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Abstract

SAPT is a synchrotron-based proton therapy which built in Shanghai, China. There are 4 treatment rooms and a main ring, a linac injector and the transport lines that between them. The main ring is a 24.6 m long and 8 dipoles synchrotron. The synchrotron employees multi-turn injection and 3rd order extraction. The treatment rooms are ocular beam line, fixed beam line, 180-degree gantry beam line and 360 gantry beam line. Now, the first unit (fixed beam line, 180-degree gantry beam line) has finished the 3rd party testing and clinical trial, will open to patient treatment soon. the accelerator and beam lines will be described in this paper.

INTRODUCTION

As the first proposal by Wilson at 1946 [1], proton deposits most energy at the end of its trace [2], well known as 'Bragg Peak'. In comparison with photons, the normal tissue that proton passed receive very low dose. The most important thing is proton can stop. And the vital organs are refrained from irradiation, because there is no energy deposited after the 'Bragg Peak'. These features, proton therapy is known as one of the best ways for cancer treatment. Since the and the first dedicated proton therapy in hospital in 1990s [3], the requirement and application of proton therapy grew rapidly, especially in the 2010s. The number of proton centers in operation increases to 98 and 31 centers under construction at 2022 [4].

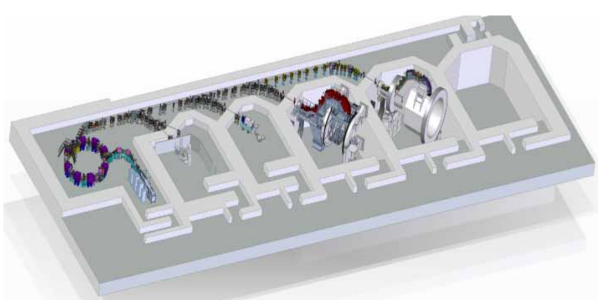

Figure 1: Layout of gantry beam lines.

Shanghai APACTRON proton therapy (SAPT) [5] is a synchrotron-based proton therapy that funded by Shanghai local government and science and technology department of China. There are 4 treatment rooms and 5 beam lines, including an ocular beam line, an experiment beam line, a fixed beam line, a half gantry beam line and a full gantry beam line, as shown in Fig. 1. The installation started at the end of 2016 and the commissioning of the accelerator started at the end of April 2017. The first unit (accelerator, fixed treatment room and half gantry room) has passed the 3rd party testing and clinical trial at 2021 and 2022, and will open to patient soon. The general specifications of this facility are shown in Table 1. The details of accelerator and treatment systems are described in the next sections.

Table 1: General Specifications

Parameters	Value
Energy Range	70~235 MeV
Energy Levels	94
Range in Water：	0~34.0 g/cm^2
Dose rate：	1 Gy/min/Liter
Extraction intensity per spill：	4~8×10^{10}
Accelerator：	FODO, 8 bends
Circumference：	24.6 m
Injection：	Multi turn painting
Extraction:	3rd resonance
Ramping time：	0.7 s
Repetition rate：	0.5~0.1 Hz(variable)
Field size：	30 cm ×40 cm
Beam Delivery Method:	Spot Scanning

ACCELERATOR

The accelerator includes a 7 MeV LINAC, a synchrotron, two different gantries, and transport lines between them. Synchrotron is the main part of the accelerator.

Synchrotron

The synchrotron of SAPT is a FODO-like structure of 4 cells and 2 super periods, totally 24.6 meters long ring. It consists of 8 dipoles and 12 quadrupoles to suppress the beta function to less than 5 meters at the vertical plane in dipole, as shown in Fig. 2. More smaller beta function will make more larger acceptance. The space charge effect [7], which leads to tune shift and limits the maximum beam current, will benefit from the large acceptance. There are 4 long straight section for injection and extraction, RF cavity. 8 short straight sections are used for the beam diagnostic and vacuum elements.

In order to reduce the beam loss at the electronic extraction septum, the Hardt condition that aligns the separatrices of different momentum [8] is satisfied on the lattice. The protons keep below transition energy, and in order to avoid head-tail instability, the chromaticity should be negative. That means the sign of dispersion and its derivative should

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THBO05

COMMISSIONING OF A 70 MeV PROTON CYCLOTRON SYSTEM OF IBS, KOREA*

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Abstract

A 70 MeV H- cyclotron system was installed at the Shindong campus of Institute for Basic Science from Nov. 2021. Installation was guided by precision survey so as to locate main components to their final positions. Electrical cables and utility lines were then connected and validation was followed for the control and safety systems. Internal beams were accelerated in May and utilized to isochronize the magnetic field by Smith-Garren method involving a series of magnetic shimming. A beam of 70 MeV was firstly extracted in July and two beam lines were commissioned for the beam energies of 40-70 MeV. Site acceptance tests were carried out with a temporary beam line installed to measure beam profiles at the location of ISOL target, Finally, a maximum beam power of 50 kW was successfully tested for six hours.

INTRODUCTION

Institute for Basics Science (IBS), Korea made a contract with IBA, Belgium for a 70 MeV cyclotron and two beam line systems in July, 2019 as part of Rare Isotope Science Project (RISP) [1, 2]. Table 1 lists main parameters of the cyclotron [3] to be used as a driver of ISOL system. The building was in fact already built prior to this contract, so that pre-survey could be carried out in the end of 2019.

Table 1: Main Cyclotron Parameters

Parameter	Value
Energy	30-70 MeV
I_{max}	750 μA
Number of sectors	2
Hill field B_{max}	1.6 T
Harmonic number	4
Rf frequency	61 MHz
Ion source I_{max}	10 mA
Weight	140 tons

When cyclotron yokes were transported to the Shindong site in Nov. 2021 we started to install entire system. A crane of 1200 tons was used to rig a half of cyclotron yoke weighing around 70 tons because of the need of a long arm. Components were located to their final positions guided by precision survey, which took about two weeks to complete for the cyclotron and main beam line components.

By the end of March 2022, most of utilities were connected to the cyclotron and beam line components. Then connections were verified by involving the control system. Furthermore, since IBS PLC system dedicated to personal safety overlooking building interlocks was already available, secure cables were simply connected to IBA PLC, which handles beam safety enabling beam on and off.

A temporary beam line was installed in a cave to measure beam properties using beam profile monitor at the position of ISOL target. At the end of the beam line, a beam dump was attached along with a collimator defining the beam size. A beam wobbler placed a few meters upstream was used to manipulate beam shapes at the profile monitor. High-power beam tests were then performed in the other cave. Beam tests for site acceptance were completed at the end of Oct.

*Work supported through the National Research Foundation of Korea (NRF) funded by Ministry of Science, ICT and Future Planning (MSIP) under Contract 2013M7A1A1075764.
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INSTALLATION AND TESTS

The facility layout is shown in Fig. 1. Two caves are prepared for ISOL uses, but only one is equipped with modules in Cave A that can be remotely handled. Two beam lines were first installed up to the entrance of ISOL tunnels, ending with beam dumps capable of handling up to 50 kW of beam power. Beam line commissioning was performed using 40 and 70 MeV protons to check beam alignments while measuring beam properties.

Spare area shown in Fig. 1 is ready to be used for future expansion when a new beam line is constructed to 2nd extraction port, where switching magnet already exists to adjust beam trajectories of different energies.

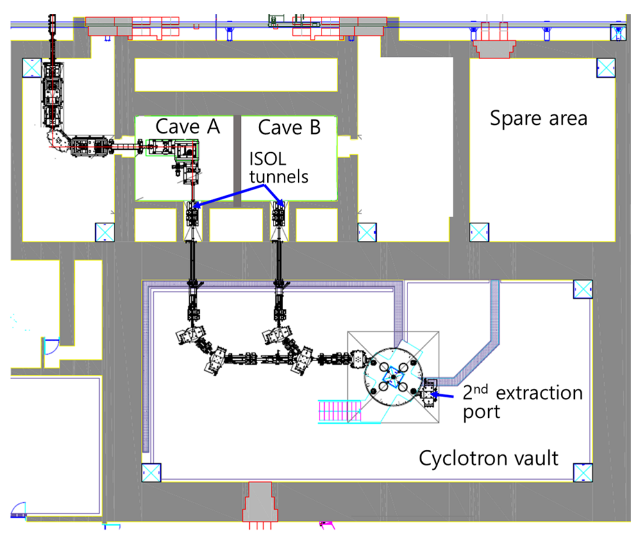

Figure 1: Layout of the cyclotron facility showing two caves and spare area.

Most of utilities such as electricity, compressed air and cooling water were connected by April, 2022. Since power supply room shared by control room is located in first floor

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THBO06

THE DESIGN OF THE CENTER REGION OF MSC230 CYCLOTRON

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Abstract

MSC230 is an innovative efficient medical superconducting cyclotron for the study and investigation of the conventional proton and FLASH therapy, developed by JINR for its new biomedical research center. The machine has an internal injection system provided by a PIG ion source and, for better efficiency, 4 RF dees connected in the center. Despite these restrictions, it is possible to create a center region design which allows initial acceleration with minimal losses sufficient for the FLASH therapy. The design and its features presented in this talk.

INTRODUCTION

MSC230 cyclotron's project is expected to be implemented in the next few years by the joint efforts of Joint Institute for Nuclear Research (JINR, Dubna, Russia) and Efremov Institute of Electrophysical Apparatus (NIIEFA, St. Petersburg, Russia) [1].

JINR has been developing such medical cyclotrons as C400 and C235 together with IBA. And the CS200 cyclotron, together with the Institute of Plasma Physics in China, which was successfully launched recently. The MSC230 accelerator should become a source of an intense proton beam. It is a part of a planned modernization of the equipment of the Medical-Technical Complex at JINR. It is required to increase the current for the possibility of FLASH therapy. An important advantage of using a cyclotron is a sufficiently high beam intensity for FLASH therapy. This is a promising method of therapy that can significantly reduce damage to healthy tissues. In addition, this allows to reduce the number of necessary procedures and work with types of cancer that are not treatable by conventional therapy. Compared to radiation therapy at a conventional dose rate (1–7 Gy/min), FLASH irradiation is performed at a dose rate ~ 100 Gy/s. In order to deliver 100 Gy/s, extracted beam current should be at least 10 μA [2].

When developing the MSC230, we focused on the closest analogues - C235 and Varian. The goal was to take the best from both projects. Such as low magnetic field in the center, constant gap between sectors, sufficient for ESD, superconducting winding, 4 resonators operating at the 4th harmonic. Therefore, the MSC230 design aims for the following features: low power consumption, high beam quality, reduced engineering effort and complexity, rather small size and weight of the accelerator.

Central Region of SC200

The successful launch of the SC200 cyclotron was mentioned in the introduction. The project of the SC200 center was proposed by JINR. In the recent experiments an internal beam of 350 nA was achieved. The internal beam current is in good accordance with calculations (400 nA internal current was predicted).

However, this design had problems, caused by the high magnetic field in the center (3 T): the bump design makes the field in the very center below isochronous, causing the lagging particles at the beginning to lag even more (the phase reached 60°), if the lag is too large, there is not enough acceleration. This was solved by varying the size of the gaps in the center to increase the efficiency of proton extraction from the source while at the same time trying to avoid breakdowns. The experience of designing SC200 was useful in designing the new MSC230 cyclotron.

CENTRAL REGION OF MSC230

The project was developed in such a way that the following tasks were solved:

- Ensuring the possibility of forming a well-centered beam (less than 1 mm offset at a radius of 100 mm), consistent with the acceptance of the accelerator. Phase acceptance ± 20° RF.
- By varying the position of the accelerating gaps, we have to ensure sufficient vertical focusing by the electric field in the first or second turn.
- Minimization of the possibilities of breakdowns.

Two different center region designs are offered (operating with the same RF system). The first is an axially symmetrical design of the central region (see Fig. 1), the second is an optimized central region design developed for reducing the variation in the kinetic energies of the particles (shown in Fig. 2).

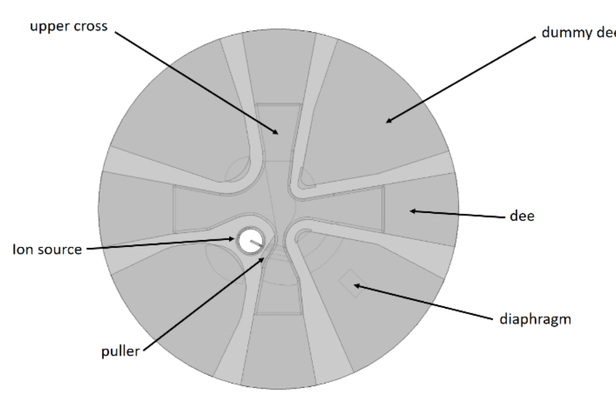

Figure 1: Structure of the central region: axially-symmetric version.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO001

COLUMBUS - A SMALL CYCLOTRON FOR SCHOOL AND TEACHING PURPOSES

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Abstract

In the early 2012 the project "COLUMBUS - a Small Cyclotron for School- and Teaching Purposes" started. Supported by the FZ Jülich and some German companies a small cyclotron was built at the University of Applied Sciences of Coburg, Germany. After the first beam was detected in 2014, the cyclotron was continuously improved and expanded. At the same time, an educational concept based on the studies and curricula in Germany was developed. Since then, workshops and internships, which are the two columns of the concept, have enjoyed increasing popularity among students and, fortunately, among female students as well. Furthermore, future improvements of the accelerator and the educational concept are presented.

INTRODUCTION

A cyclotron is, in theory at least, an easy-to-understand accelerator. It is therefore part of the standard repertoire in all physics books in secondary schools. In practice, however, it looks very different. This shows that a cyclotron is a complex structure made up of a wide variety of systems that must be precisely coordinated with one another. For this reason, hardly any student has had any practical experience with this accelerator. This is where the COLUMBUS project comes in, providing students with a functioning small cyclotron with which they can learn accelerator physics and carry out their own experiments.

TECHNICAL DEVELOPMENT

After the FZ Jülich provided a magnet, VACOM, a company for vacuum components, sponsored a suitable vacuum chamber and a pumping station was bought by the University of Applied Sciences of Coburg, the assembly of the cyclotron COLUMBUS began in 2012. The first results were presented at Cyclotrons'13 in Vancouver [1]. Figure 1 shows the setup of the cyclotron COLUMBUS at the end of 2013.

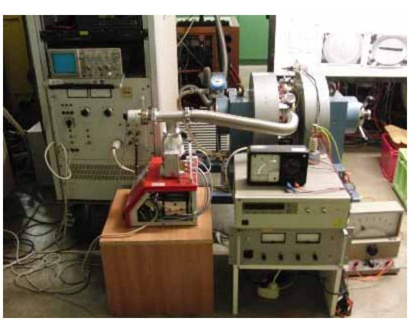

Figure 1: Cyclotron COLUMBUS 2013.

The first beam was registered in April 2014 (see Fig. 2), which was followed by the first workshop with students in autumn of the same year.

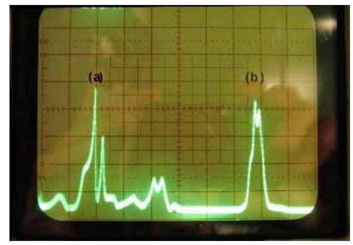

Figure 2: First Beam (a) H^+ (b) H_2^+.

The cyclotron was continuously improved and expanded with the involvement of pupils and students. A cooling system for the magnet, a linear translator for the detector and many other improvements complemented the accelerator.

A mechanical cyclotron, as shown in Fig. 3, and a simulation of the ion paths which was presented at Cyclotrons'16 in Zurich [2], improved the educational concept.

Figure 3: Mechanical Cyclotron.

Pupils and students are currently dealing with topics related to the accelerator in workshops and internships. For example, the first 3D-printed vacuum chamber was shown at Cyclotrons'19 in Cape Town [3].

The cyclotron available today (see Fig. 4) has a vacuum chamber with a diameter of 200 mm and a height of 75 mm. With an improved matchbox, two cyclotron frequencies of 2.82 MHz and 5.64 MHz are available. The technical data of the cyclotron are shown in Table 1.

Figure 4: Cyclotron COLUMBUS 2022.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO002

STUDY ON PROTON RADIATION EFFECT AND SELF-REPAIR OF SiC-JBS DIODES

C. C. Liu†, G. Guo, Z. Zhang, F. Q. Zhang, Q. M. Chen, H. L. Shi
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Abstract

In this study, the influence of proton irradiation experiments at 40 MeV and 2.2×10^{12} p/cm^2 on Silicon Carbide Junction Barrier Schottky (SiC-JBS) diodes with stripe cell and hexagonal cell was investigated, respectively. The experiment was implemented based on 100 MeV high intensity proton cyclotron of China Institute of Atomic Energy. The results show that the current voltage (IV) and capacitive voltage (CV) characteristics of the SiC-JBS diodes are obviously degraded by proton irradiation. After 168 h and 336 h room temperature annealing, the forward IV characteristics of the diodes are basically restored but the reverse leakage current is increased. And the CV characteristics are degraded of the two kinds of diodes permanently, which indicating that room temperature annealing cannot restore the proton radiation displacement damage defects. The analysis of structure of the diodes shows that the diodes with hexagonal cells are more resistant to proton irradiation and have stronger room temperature annealing self-repair ability than the diodes with stripe cells, even though its chip area is smaller. This means that the SiC-JBS diodes with hexagonal cells can be used preferentially in the radiation environment where there is a large amount of proton.

INTRODUCTION

The physical and electronic properties such as band gap width, thermal conductivity, electric field strength of SiC is attractive [1]. Also, the energy required to kick an atom out of the lattice position, i.e., the mean displacement energy, is higher than silicon (Si) [2]. Compared with other semiconductor materials, the performance advantages of SiC are shown in Fig. 1.

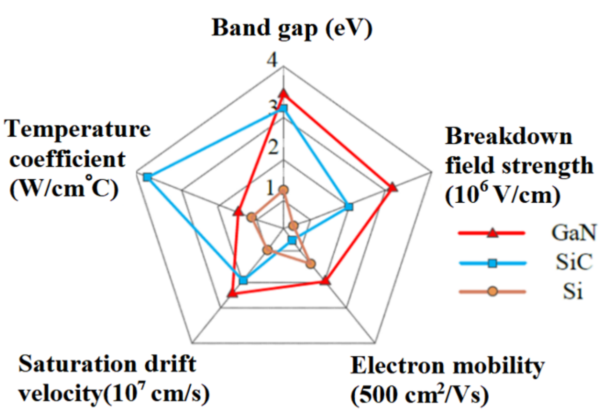

Figure 1: Performance advantages of SiC compared with other semiconductor materials.

As can be seen from Fig. 1, SiC is a promising semiconductor material for power device applications with additional advantages for harsh environments with high temperature and radiation [3]. At present, power systems for examples electric propulsion systems and photovoltaic inverter systems based SiC diodes, have further developed towards miniaturization, lightweight, high efficiency and low loss [4, 5]. And one of the most important points is radiation hardness, which makes SiC power devices the better choice than Si to complete space exploration tasks.

SiC junction barrier Schottky (JBS) diodes is a kind of SiC power device with simple structure and excellent performances. The previous researches show that after proton irradiation with a certain fluence, the breakdown voltage of SiC-JBS diodes will degrade, which is mainly related to the change of ionized charge at the SiO_2/4H-SiC interface in the device and the reduction of carrier concentration in the drift region [6]. And, the decrease of carrier concentration is attributed to the carrier removal phenomenon caused by radiation defects [7]. However, numerous degradation performances after proton or other high energy particles irradiation on SiC-JBS diodes without power supply are attributed to the displacement damage effect of irradiation defects, and there is little analysis on the impact of ionized charges [8, 9]. In order to study the influence of proton irradiation defects on the macro electrical performance of SiC-JBS diodes, and explore whether the diodes are also affected by ionization defects in the process of displacement damage, a proton irradiation experiment of SiC-JBS diodes under unbiased voltage was carried out, and the influence of ionized charges was investigated through room temperature annealing method.

PROTON IRRADIATION EXPERIMENT

Two kinds of 1200 V/40A SiC-JBS diodes with different cell designs were selected and named #a and #b respectively. The top surface and section structure of the diodes obtained by scanning electron microscope (SEM) analysis technology are shown in Fig. 2. Combined with the microstructure of these SiC-JBS diodes, the key performance parameters such as barrier height and carrier concentration can be calculated theoretically. It can be seen from Fig. 2 that the #a is with hexagonal cell designs, and its typical breakdown voltage (BV) is about 1230 V, the average Schottky barrier height (SBH) is about 1.15 eV, the average ideality factor (n) is about 1.02. The #b is with stripe cell design, and its typical BV is about 1450 V, the average SBH is about 1.13 eV, and the average n is about 1.06, respectively. Both diodes have extremely stable switching on voltages of about 0.4 V.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO003

APPLICATIONS OF THE CYCIAE-100 CYCLOTRON IN NEUTRON-INDUCED SINGLE EVENT EFFECT

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Abstract

Neutron-induced single event effect is one of the significant factors affecting the reliability of semiconductor devices in avionics and ground facilities. The 100 MeV proton cyclotron in China Institute of Atomic Energy (CYCIAE-100) provides white neutron and quasi-monoenergetic neutron induced by proton and W/Li bombardment. Based on the white neutron beam of CYCIAE-100, the white neutron energy spectrum was measured by neutron time-of-flight method with double scintillator spectrometer, as well as the theoretical energy spectrum was calculated by the Monte Carlo method. The neutron irradiation test for ESA SEU monitor with different technology nodes were carried out, and the neutron single event upset sections are obtained simultaneously. In addition, based on the quasi-monoenergetic neutron beam line, the simulation of neutron energy spectrum was carried out. As a conclusion, the white neutron and quasi-monoenergetic neutron provided by CYCIAE-100 are well suitable applied to the study of neutron single event effects.

INTRODUCTION

Galactic cosmic rays and solar rays interact with nitrogen and oxygen in the earth's atmosphere to produce a large number of neutrons. Neutron incident semiconductor devices cause single event effects (SEEs), leading to logic inversion and functional failure, which seriously threaten the safety and reliability of aircraft electronic systems [1-3]. In addition, in the nuclear power stations and spent fuel reprocessing plants, neutron radiation produced by the nuclear reaction also reduce the reliability of electronic control systems and visual monitoring systems.

In order to measure the neutron-induced single event effects and to evaluate the risks of neutron radiation, accelerated tests based on the ground neutron sources were performed and progressively became the predominant approach, since the environmental atmospheric neutron test is time-consuming. Many neutron irradiation test equipment from white neutron source, quasi-monoenergetic neutron source and 14 MeV monoenergetic neutron source has been established, such as CHIPIR of ISIS [4], QMN of TSL [5], and so on. The white neutron source, which has an energy spectrum very close to the atmosphere neutron environment, are used to directly evaluate the atmospheric neutron effect. As a contrast, the monoenergetic and quasi-monoenergetic neutron sources are used to measure the cross-section curve of SEEs as a function of neutron energy, which is helpful in exploring the mechanism of the neutron SEEs.

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In 2016, the first SEE experiment for electronic devices was carried out on the 100 MeV proton cyclotron (CYCIAE-100) in China Institute of Atomic energy (CIAE). This cyclotron provides a 70–100 MeV, 0.01-200 μA proton beam [6]. Meanwhile, with W and Li targets, both white neutron and quasi-monoenergetic neutron can be produced by proton and W/Li bombardment, which provides good neutron sources for experimental research of neutron SEEs.

In this paper, we first measured the white neutron energy spectrum by time-of-flight method with double scintillator, and then tested neutron SEE for ESA SEU monitor. The possibility and ability of irradiation test by quasi-monoenergetic neutron were also analysed.

WHITE NEUTRON EXPERIMENT

Prior to SEE testing, the neutron energy spectrum shall be accurately measured. Since the CYCIAE-100 induces a continuous proton beam, the withe neutron beam produced by proton bombards W targets is also a continuous beam. The conventional neutron measurement methods for pulsed neutron are not adequate. Therefore, the neutron time-of-flight (TOF) experiment with two scintillator detectors were performed. By measuring the neutron flight time at a certain distance, we obtain the flight speed of neutrons, and hence the energy of neutrons.

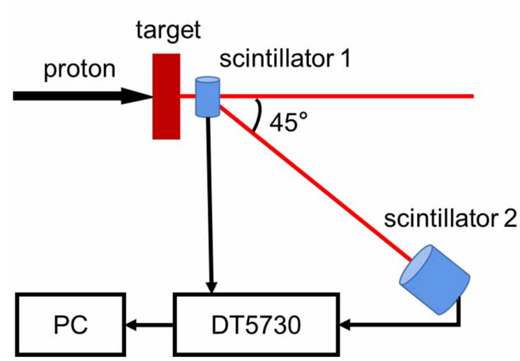

Figure 1: The measurement of white neutron spectrum.

The white neutron target is tungsten copper alloy WCu7, 93% of which is tungsten, 12 mm thickness and 75 mm diameter. After passing through 2 mm copper and 5 mm water, 100 MeV protons bombard the 12 mm thick WCu7 target and white neutron are produced.

As shown in Fig. 1, one liquid scintillator detector (scattering detector) is placed on the neutron beam behind the target, which is detect the start signal of flight neutron, and the other (main detector with high efficiency) is placed at a distance L (L=3 m) and 45° direction of the proton beam, which is detected the stop signal of flight neutron. The

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO004

CSPT: A GPU-ACCELERATED LATTICE DESIGN TOOLKIT ESPECIALLY FOR CCT*

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Abstract

Canted-Cosine-Thera (CCT) superconducting magnet is a promising alternative for normal-conducting magnets in compact accelerator systems such as large hadron colliders or particle therapy facilities. For the convenience of lattice design with CCT, we develop the CCT Simulation and Particle Tracking (CSPT) toolkit. It's a program that can perform both simulations of the beam dynamic process within particle accelerators and basic electromagnetic harmonic analysis. The charged-particle tracking and electromagnetic calculation process can be accelerated by either CPU multicore or GPU parallel, with a maximum speed-up ratio of 457. The simulation result of the program is well consistent with Opera and COSY Infinity.

INTRODUCTION

In pursuit of high-field magnets, advanced superconducting technology is introduced into the accelerator area. Among the existing superconducting magnets, Canted-Cosine-Theta(CCT) has become quite popular with magnet designers due to it's superior field quality, outstanding mechanical properties and simple winding process [1]. The concept of CCT magnet is based on pairs of conductor wound and powered such that their transverse field components sum up and their axial (solenoidal) field components cancel [2]. As it possesses promising potential in collider, storage ring and particle therapy facility, many laboratories have carried out research on CCT magnets in recent years [3–6].

Thanks to the winding flexibility of CCT magnet, complex multipole field components can be generated. However, few optics and particle tracking software have embedded this type of magnet. Great efforts would be put forward for researchers to accurately simulate and control the beam dynamics in a lattice with CCT magnets. For the convenience of the CCT-related research, we present the CCT Simulation and Particle Tracking (CSPT) toolkit. In this report, the structure of the CSPT toolkit is discussed, and the calculation results are testified with finite element analysis software Opera and optics code COSY Infinity [7].

* Work supported by the National Natural Science Foundation of China under Grant No. 11975107, 12205111.
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SOFTWARE STRUCTURE

The CSPT toolkit, written in C++17 standard, is compatible with beam dynamic simulation and electromagnetic field analysis within CCT magnet. The structure of the toolkit is shown in Fig. 1.

Fundamental Classes

The gray block at the top of the structure contains the fundamental (low-level) classes of the toolkit that users are not supposed to call directly. The *P2/P3* class characterizes points or vectors in two or three dimensions. The *Coordinate System* class, composed of *P3* vectors, denotes the position of each element and particle.

In CSPT, lines in two dimensions are needed for every magnetic element, so that the position of a particle can be defined in the curvilinear coordinate system. The *Line2* class, which can generate lines in arbitrary curvature, is the base class of 2D lines. It's made up of *P2* points. The *Straight Line* and *Arc line* classes are the derived class of *Line2*. The ideal orbit of a lattice in the toolkit consists of several 2D lines with the vertical axis $y \equiv 0$. Each 2D line belongs to a magnetic element.

Magnetic Elements

At present, only magnetic elements are supported in CSPT toolkit. The *Uniform Magnet* and the *Multipole Magnet* generate ideal fields within the element regions (hard-edge). The *Multipole Magnet* can combine fields from dipole to octupole. To describe a complex field shape, the *Input Magnet Table* class shall be applied. And the class supports the Opera field format. The field calculation process of *CCT* is based on Biot-Savart Law. The field shape of the CCT magnet can be adjusted by modifying the path function of the windings. The CCT model in the CSPT can also be loaded to Opera as conductors. Besides, common harmonic analysis programs are provided for the magnetic classes so that users can check the field quality in the lattice space.

High-level Classes

Above all, the Particle classes and *Beamline* are the highest-level classes in the toolkit. They can be directly called by users. A type of particle with specific values of mass and charge can be defined in *Particle type* class. Then, the toolkit provides two methods to produce running particles. Users can generate a particle with position (x, y, z) and velocity (V_x, V_y, V_z) of a chosen type in *Particle Source*, or

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO005

JULIC – DRIVER ACCELERATOR FOR HBS

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Abstract

At the Forschungszentrum Jülich (FZJ) the energy variable cyclotron JULIC is used as injector of the Cooler Synchrotron (COSY) and for low to medium current irradiations of different types. Recently a new target-moderator-reflector-station (TMR) was set up and is mainly used for tests of new target materials, neutron target development and neutron yield investigations with high power proton or deuteron beam in perspective of a high brilliance accelerator based neutron source (HBS) with the Jülich Centre for Neutron Science (JCNS). Beside this, ToF-experiments are performed to investigate and optimize the pulsing structure for HBS. The TMR-station is installed inside an Experimental area close to the cyclotron bunker, offering space for complex detector and component setups for nuclear and neutron related experiments. It is used for other purposes like electronic or detector tests and irradiation as well. This report briefly summarizes the history of JULIC and the activities for its future perspectives.

INTRODUCTION

The Institute for Nuclear Physics (IKP) [1] is focusing on the tasks given by the Helmholtz Association (HGF). This comprises the design and preparations for the High Energy Storage Ring (HESR) of FAIR [2] with the PANDA experiment. The hadron physics program at the Cooler Synchrotron COSY exploits the internal experimental setups PAX, KOALA and the PANDA Cluster-Jet Target Development. The Jülich Electric Dipole Moment Investigation project (JEDI) [3] profits from the availability of polarized beams from the injector cyclotron and the unique capabilities and experiences at the COSY facility. The extracted beam is used for the PANDA experiment, detector tests and for high-energy irradiation in the area of the finished TOF experiment. The JESSICA and Big Karl-Experiment areas are also used with extracted beam for other FAIR related detector tests and developments like CBM e.g., Fig. 1 presents the layout of the COSY facility with the JULIC cyclotron and the experimental areas.

The COSY accelerator facility [4], operated by the Institute for Nuclear Physics at the Forschungszentrum Jülich, consists of the injector cyclotron JULIC and the Cooler Synchrotron COSY. Both accelerators are originally dedicated to fundamental research in the field of hadron, particle, and nuclear physics, to study the properties and behaviour of hadrons in an energy range that resides between the nuclear and the high energy regime. Operation of the cyclotron JULIC started 1968 and it provides mainly 45 MeV H^- respectively 76 MeV D^- with beam currents up to ~10 μA.

Within the framework of the High Brilliance neutron Source project [5], Jülich is developing a scalable pulsed accelerator-based neutron source capable of supporting thelarge scale facilities and providing an efficient network of small and medium neutron sources throughout Europa.

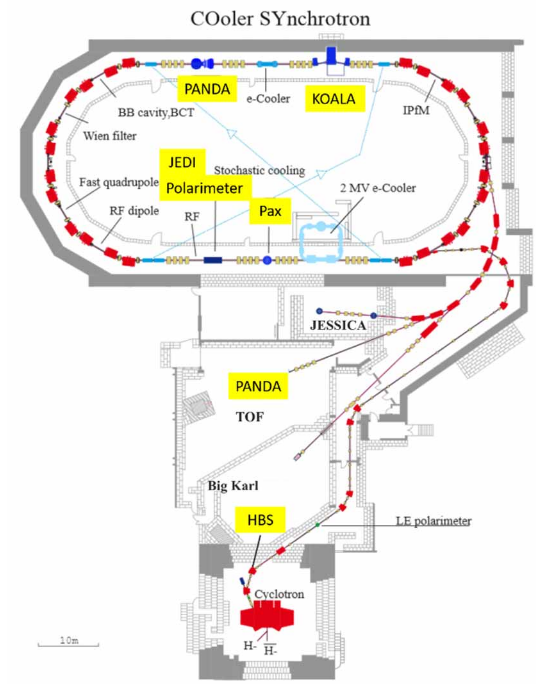

Figure 1: Layout of the COSY facility with the new beamline from the cyclotron into the Big Karl Experiment area.

The HBS JULIC Neutron Platform is installed at the Big Karl experimental area aside the JULIC cyclotron providing experimental space for the development, testing and operation of components of pulsed accelerator-based neutron sources within the HBS project together with the Jülich Centre for Neutron Science.

Figure 2 shows the experimental setup in Big Karl-area with the Target-Moderator-Reflector-Setup (TMR) and possible experimental setups at different neutron beamlines like ToF-PGNAA or reflectometer, e.g., it further allows the design, construction and operation of basic scientific neutron scattering and neutron analytic instruments for development, training, education, and research in collaboration with university groups and industry.

CURRENT STATUS OF HBS ACTIVITIES

For experiments related to the HBS project, a dedicated beam line at the JULIC cyclotron at the COSY facility into the Big Karl area (Fig. 3) has been built in beginning of 2019.

At this beamline, experimental validations of cross section measurements and component tests for the HBS target development had been performed. With installation of the TMR the beamline was extended with additional kicker

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO006

DESIGN AND IMPLEMENTATION OF ROBOT ADAPTER IN THERAPY CONTROL SYSTEM

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Abstract

The China Institute of Atomic Energy (CIAE) in Beijing has designed and established a proton therapy facility based on a superconducting cyclotron CYCIAE-230, which can provide proton beams with energy from 70 MeV to 230 MeV for cancer treatment. As the most critical and core part of the proton therapy system, therapy control system (TCS) consists of various components, each of which has corresponding processing services. Motion control of external hardware systems is one of the essential parts of TCS development, and adapters figure prominently in the interaction between services and these external hardware systems. One of the adapters, called robot adapter, is specially developed for the external robotic couch system, which is a vital equipment that directly contacts patients in the whole process of proton therapy. This adapter serves as the connection between TCS and robotic couch for communication and corresponding movement. In this paper, we introduced the communication protocols, design, and characteristics of robot adapter as well as the actual test contents and results with the robotic couch. The test results indicated that the robot adapter can satisfy the needs of couch motion control and status monitoring.

INTRODUCTION

Protons have been successfully utilized in the treatment of cancer in recent years, and proton therapy is superior to the conventional photon radiation therapy due to its physical properties, making it one of the world's preferred choice for cancer particle radiotherapy methods [1]. From 1954 to 2021, more than 324,000 patients worldwide underwent particle therapy, 86% of whom received proton therapy. According to Made in China 2025, high-performance medical equipment including proton heavy ion therapy system is explicitly listed as one of the top ten key industries [2]. CIAE has established a superconducting cyclotron that generates 230 MeV proton beam to promote the development of proton therapy in China [3].

Accelerator control system (ACS) is a complete automatic system for medical accelerator equipment, which realizes the automatic start-up, real-time monitoring, control, and protection of 230 MeV superconducting cyclotron related equipment. The system has complete status monitoring and fault diagnosis functions, including automation, operation status monitoring, equipment safety interlocking, automatic recording of operation data, etc. in each accelerator subsystem equipment.

Beam control system (BCS) is a distributed control system with a standard control model structure. It uses an energy selection system that adjusts the energy of the extracted proton beam according to the different depths and thicknesses of the tumor. Energy degrader, the core component of the proton energy selection system, is mainly used to adjust the energy between 230 MeV and 70 MeV.

As the central system of proton radiotherapy, therapy control system (TCS) not only integrates all the execution systems involved in the treatment, but also is responsible for the management of the whole proton radiotherapy process. The treatment process includes patient setup, setup verification, equipment movement, dose delivery, treatment report, etc. It commands and controls the proton beam hardware in each link of the treatment process.

Scan dose diagnostic (SDD) is a software program of the Scan Dose system that enables a complete dose delivery nozzle by running maps and generating records, even though it is not designed for clinical dose administration. SDD can compute the threshold used and monitor the beam characteristics to ensure that the treatment is performed according to preset limits. In addition, SDD can record all parameters relevant to the treatment and provide room-centric and facility-centric interlock chains, so as to achieve fast beam shutdown.

In the whole proton therapy system, ACS can ensure the normal operation of the accelerator and the proton beam at 230 MeV. BCS can adjust the proton energy between 230 MeV and 70 MeV to meet the requirements of the clinical treatment regimen. It receives and processes the beam request of TCS, and arranges the beam supply to the designated treatment room. TCS uses the adapter to provide treatment prescription data to SDD. SDD distributes a predetermined dose of beam by controlling the extraction and monitoring the ionization chamber. If SDD is not directly connected to ACS, TCS can provide a channel between them.

ROBOT ADAPTER

Adapters support each specific subsystem independently. Each adapter is responsible for monitoring the status of its corresponding subsystem, and receiving and processing the operation information issued by services in TCS.

The robot adapter is designed for the external robotic couch system amid various adapters. Figure 1 shows the overview of the interaction between the robot adapter and the robotic couch and internal components in TCS.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO007

DIRECT SAMPLING DIGITAL LOW-LEVEL RF CONTROL FOR CIAE BNCT CYCLOTRON

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Abstract

Boron neutron capture therapy (BNCT) can be delivered using a high current cyclotron, resulting more compact and environmentally friendly design, yet the difficulties remain in the cyclotron part, particularly in RF systems. The high beam loading challenges the stability of the amplifiers, as well as the control loops. Especially in our case, the wall loss of each cavity is more than the beam-loading power of the CIAE BNCT cyclotron. To address the heavy beam loading coefficient, a higher-performance ADRC control algorithm is evaluated, together with the regular PID control. In the meantime, a direct sampling/synthesizing digital low-level RF control hardware design is put forward to have more flexibility in control implementation. Since this new design adopts Xilinx SOC as the main controller, it is convenient to combine real-time control algorithm with high-level control through Advanced Extensible Interface. In this LLRF design, the amplitude and phase control using PID control is implemented in the PS end, and the tuning control is taking advantage of the ADRC algorithm in the PL end. Using a symmetrical design, together with the buncher control, in total, regulation of three loops are achieved using two control boards. The software/hardware design as well as the commission result will be reported in this paper.

INTRODUCTION

The boron neutron capture therapy (BNCT) method can protect normal cells as much as possible while killing cancer cells. BNCT technology based on high current proton accelerators is gaining increasing attention in various countries due to the adjustable energy of the neutron beam of the accelerator and the fact that the accelerator also has safety advantages that reactors do not possess [1, 2].

The CYCIAE-14B cyclotron [3] for BNCT developed by the CIAE provides a 14 MeV, 1 mA proton beam for the production of neutrons for BNCT. The CYCIAE-14B cyclotron uses two 20 kW transmitters to drive two independent cavities respectively, and a 300 W amplifier to drive the buncher to increase the beam intensity. The low-level RF (LLRF) system requires amplitude and phase control of the three signals and tuning control of the two cavities [4]. Based on the characteristics of CYCIAE-14B high-frequency system, this paper proposes a design method of direct sampling/synthesis all digital low level control system, and completes the debugging task of this digital low level control system in CYCIAE-14B.

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DESIGN OF BNCT LLRF SYSTEM

The design requirement of the digital LLRF system designed by the CIAE is to realize a set of broadband RF system to control the amplitude and phase of three channels of signals and the tuning of two cavities. The digital LLRF system is universal and can be applied to the RF control system of cyclotron in the CIAE. This paper mainly introduces the application of this system in CYCIAE-14B LLRF system. The LLRF system block diagram of CYCIAE-14B cyclotron is shown in Fig. 1.

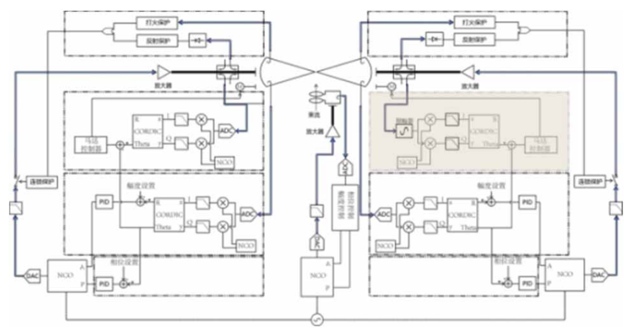

Figure 1: The LLRF system block diagram of CYCIAE-14B.

Hardware Design

The hardware architecture of the system is based on the ZYNQ series FPGA + dual ARM architecture. The FPGA is mainly used to modulate and demodulate the digital signal: After ADC sampling, the radio-frequency sampling signal and the sampling signal of the buncher form the IQ sequence. FPGA reads the IQ sequence, calculates the amplitude and phase information, and completes the demodulation operation. The function of the modulator is realized by DAC and NCO. The output amplitude of NCO is modulated by multiplying the output of NCO by hardware multiplier, and the modulation result is output by DAC to drive the amplifier. The dual ARM structure completes the control of the two RF auto-start processes [5], abnormal protection and online parameter modification, allowing the two RF systems to operate independently. The hardware system is designed with a 14-layer PCB and the physical diagram of the hardware system is shown in Fig. 2.

The LLRF system board will be installed in a LLRF chassis which will display the LLRF operation on the front panel. In order to visually display the running state of the LLRF system and provide driving for the stepping motor, a motherboard has been designed for the system and the core board can be plugged into the motherboard for use. A physical diagram of the motherboard is shown in Fig. 3. In the design of the motherboard, all input and output ports of

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO008

CONSIDERATION OF USING NON-DESTRUCTIVE DETECTORS IN THE BEAMLINE OF A PROTON THERAPY FACILITY*

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Abstract

Ionization profile monitors (IPM) are a kind of nondestructive monitors mostly used in accelerators of high intensity pulsed beams. As for particle therapy accelerators, either based on cyclotrons or synchrotrons, the extracted beams are very weak, usually on the level of nano-Amperes. Up to date, the commonly used detectors in such low current machines are all destructive, such as fluorescent screens and gas ionization chambers. In this paper, we proposed for the first time to use a residual gas ionization monitor to measure the beam profiles in a proton therapy facility based on a superconducting cyclotron. The feasibility of such a scheme and some basic issues are discussed in this paper.

INTRODUCTION

There is a proton therapy facility based on a superconducting cyclotron under construction in the Huazhong University of Science and Technology (HUST-PTF) [1,2]. The HUST-PTF uses an energy degrader to modulate the beam energy from the cyclotron to match the clinical requirements [3]. The beam parameters from the superconducting cyclotron are summarized in Table 1. The layout of HUST-PTF is shown in Fig. 1.

Table 1: Beam parameters from the SC cyclotron.

Parameter	Value
Frequency	73 MHz (CW mode)
Energy	250 MeV
Energy spread	<0.5%
Intensity	60 ~ 500 nA

The proton beam extracted from the cyclotron has a fixed energy of 250 MeV and then is modulated to 70 ~ 230 MeV with an energy degrader, followed by three collimators to constrain the emittance and a momentum slit in the middle of the DBA section to restrict the energy spread [4]. Taking all the beam loss into consideration, the transmission rates of different beam energies vary dramatically, which is not acceptable in clinical treatment. So it is demanded that the cyclotron has the ability to output different intensity beams in accordance with the working energy points. According to our optimization result, the beam intensity from the cyclotron is divided into three levels (Fig. 2) and the final intensity for clinical treatment is shown in Fig. 3.

ANALYSIS OF THE IONIZATION PROFILE MONITOR

Nondestructive detection is always preferred in an accelerator. However, as the first attempt to build such a proton machine, the traditional fluorescent screen and strip ionization chamber are the two primary detectors used in the beamline [5]. Even so, the residual gas monitor, or ionization profile monitor (IPM), is considered as a potential candidate in the future upgrade. IPM is a kind of nondestructive detector, which collects the secondary particles produced from the interaction between the incoming high energy particles and the residual gas molecules [6–8]. The biggest challenging of using an IPM in our machine is the extremely low signal due to the nA-level beam current. In the following, some basic issues are discussed to investigate its performance.

Gain Analysis

Gain is the first issue that needs to be considered. The process of producing an ion-electron pair is evaluated with the Bethe-Bloch formula:

$$-\frac{dE}{dx} = (4\pi N_a r_e^2 m_e c^2)\rho \frac{Z}{A}\frac{z^2}{\beta^2}\left(\ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \beta^2\right) \quad (1)$$

The gain is calculated from the energy of proton beams deposited in the residual gas and the ionization energy of the gas. The parameters used in our simulation is displayed in Table 2. As it is hard to tell the ingredient of the residual gas at the 10^{-4} Pa level, both the hydrogen and the nitrogen cases are calculated and the results are shown in Fig. 4.

Table 2: Simulation parameters for the gain of Hydrogen and Nitrogen.

Parameter	Value
Pressure	10^{-4}Pa
Temperature	298.15K
Detector length	10cm
Ionization energy	36eV of H_2, 36.4 of N_2

It is easy to conclude from the Bethe-Bloch formula and the simulation results that the hydrogen curve gives a lower gain, so it is reasonable to use the hydrogen curve to estimate the gain of the detector.

* Work supported by the National Natural Science Foundation of China (No. 12175077)
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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO009

VACUUM MODEL OF THE C400 CYCLOTRON FOR HADRONTHERAPY

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Abstract

Since 2020, NHa and IBA collaborate on the development of the C400 cyclotron dedicated to hadron therapy. This machine accelerates C^{6+} and He^{2+} up to 400 MeV/n and H_2^+ up to 260 MeV/n. The H_2^+ are extracted by stripping and the other particles by an electrostatic deflexion.

Vacuum management in the injection line and in the cyclotron are of prime importance to avoid large beam losses. Indeed, C^{6+} ions are subjected to charge exchange during collision with the residual gas. On the opposite, H_2^+ will suffer from molecular binding break up. According to cross section data, the constraints on the residual gas pressure is driven by C^{6+} in the injection line and by H_2^+ in the cyclotron. An electrical equivalent model of the vacuum system of the cyclotron, its injection and extraction lines has been developed in LTSpice® software to determine the pressure along the particle path. Contributions from outgassing surfaces, O-ring outgassing, and permeation are included, and vacuum pump requirement could be obtained. The expected beam transmission is then evaluated based on cross sections available from the literature.

INTRODUCTION

Detailed theoretical studies has been conducted to estimate the beam transmission expected in each sub-part of the C400 hadron therapy system. Electrical equivalent circuits are built using inputs as detailed as possible and coming from the IBA design office, including the complex geometries of the numerous components located inside the cyclotron accelerator chamber (RF parts, elements of the extraction systems, etc.). This enables to compute the pressure level expected in any point of the circuit which in turn drives the dimensioning and location of the vacuum pumps to achieve the required pressure level. Combining these outputs with the relevant cross-sections of the interaction of the ion beam with the residual gas, the transmission can be estimated with a reasonable level of confidence.

VACUUM MODEL IN LTSPICE®

Electrical Equivalent Circuit

Thanks to the similarity between the electrical equations and the molecular flow equations, it is possible to make use of modelling tools such as LTSpice® [1] to build simulated vacuum circuits providing the equivalencies shown in Table 1. Providing the vacuum system can be approximated by an ensemble of elements connected either in series or parallel and defined by their conductance and/or gas throughput, such a model can provide a relatively precise estimation of the pressure at any point in the circuit.

Table 1: Electricity/Vacuum Equivalencies

Electricity	Vacuum
Voltage / [V]	Pressure / [mbar]
Current / [A]	Gas throughput / [mbar.L/s]
Resistance / [Ω]	Conductance / $[L/s]^{-1}$

Conductance

The general conductance equation for a vacuum element is:

$$C = \frac{aAv}{4} \tag{1}$$

where a is the transmission probability ϵ [0,1];
A is the vacuum element transverse cross section in [m²];
$v = \sqrt{\frac{8RT}{\pi m}}$ is the average speed of the gas molecule of molar mass m in kg/mol at temperature T in K; $R = 8.3144621$ J/mol/K is the gas constant.

In the electrical equivalent circuit, the generic conductance is a simple resistor with resistance value equal to the inverse of the conductance.

The coefficient a is component dependent, in particular function of its geometry, see [2] for more detailed information of how the transmission probability is modelled using tabulated data for specific geometry taken from [3]. Moreover, parametric formula is directly implemented in LTSpice® to enable modelling of various geometries: tubes of different inner diameter, conduct having rectangular slit-like shapes, etc. The impact of the gas nature is modelled entirely into the gas speed through its molar mass. Therefore, to consider multiple gas effect, specific runs must be performed for each gas.

Gas Throughput

All gas throughput present in a vacuum system (outgassing surfaces, permeation, leaks) are modelled in the software by means of a source current. For example, an outgassing pipe will be represented by two resistors in series whose conductance value is computed as explained previously and with a source current connected between them. The total gas throughput is parameterized with the product of the inner pipe surface times the outgassing rate of the considered material.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO010

AN AUTOMATED DOSE VERIFICATION TOOL FOR PROTON THERAPY PLANS USING GEANT4/TOPAS*

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Abstract

Proton therapy has become a significant treatment option for many tumors. In commercial treatment planning systems (TPS), the computationally efficient pencil-beam (PB) analytical algorithm is frequently utilized for dose calculation. Due to the PB algorithm's limited accuracy, a higher accuracy dose verification tool is a legal requirement for proton therapy. Therefore, we developed an automated treatment plan dose verification framework based on the Monte-Carlo (MC) algorithm.The MC beam model, including the phase space, energy spectrum, and the number of protons per MU, was derived from commissioning data and fed into our automated software. CT and treatment plan from TPS were input for the automated software. The developed tool was validated and compared with the PB algorithm of Pinnacle3 TPS for 85 prostate patients.The difference between the PB dose and the MC dose of our automated tool was evaluated using gamma analysis (3 mm/3%, and 2 mm/2% criteria) and mean absolute errors. Although the result shows good agreement and the passing rate was about 95%, the difference of all the indices was found to increase as the degree of tissue heterogeneity increased. The MC dose has a higher MAE in CTV, and femoral head compared to the PB dose.An automated framework can quickly calculate the MC dose with high accuracy among different cases. The automated software can facilitate patient plan verification in institutions and be useful for other clinical applications.

INTRODUCTION

Due to its Bragg peak characteristic, proton radiotherapy has increased clinical use in the last decade [1]. It has more homogeneous, conformal, and normal sparing than conventional photon radiotherapy. The actual dose distribution may differ from the planned dose because of the existence of uncertainties such as dose calculation uncertainties, anatomy changes, and so on [2]. Therefore, providing accurate dose calculation tools is essential for treatment planning and plan quality assurance.

Due to its high computation speed, the pencil beam (PB) analytic algorithm is widely used in commercial treatment planning systems (TPS). It uses the water-equivalent thickness longitudinally and assumes that the material on the central axis is laterally homogeneous [3]. Particularly in inhomogeneous tissues, the approximation of multiple Coulomb and nuclear reactions in the PB algorithm leads to dose discrepancy and range uncertainties [4]. The Monte-Carlo methods, regarded as the gold standard for dose calculation in radiotherapy, simulate physics interactions by many random sampling cross-sectional interactions [5]. Thus, developing the MC dose recalculation tool for post-planning dose verification is necessary for hospitals.

This study aims to build an automated MC dose recalculation framework for proton therapy treatment plans. Additionally, we compared it with the PB algorithm in prostate cancers. The dose discrepancy was evaluated using the gamma analysis method (3 mm/3% and 2 mm/2%). The mean absolute error between the MC dose and PB dose also was calculated to evaluate the dose discrepancy.

METHOD AND MATERIAL

An automated MC re-calculation framework was developed for dose checking of treatment plans. Figure 1. shows the workflow of the proposed tool. The Geant4-based TOPAS toolkit was used in our study [6]. The default physics list contains G4EMStandardPhysics_option4, HadronPhysics-QGSP_BIC_HIP, G4DecayPhysics, G4IonBinaryCascade Physics, G4HadronElasticPhyscisHP, and G4Stopping Physics. The IMPT plans were optimized in the Pinnacle3 TPS, v15.0 (Philips Healthcare, Fitchburg, WI, USA) and calculated by the PB algorithm. The DICOM data (CT, RS, and RN) were exported from TPS and then fed into our tool. After the simulation, the dose calculated by the MC tool was compared with that of the PB algorithm.

Beam Modeling

The beam data library (BDL), which contains beam parameters for various energies, is implemented in TOPAS as a look-up table. These parameters must be tuned to align the Monte-Carlo simulation with experimental measurement. The BDL includes three sections: energy spread, phase space, and the number of protons per MU.

- Energy spread: the energy distribution of proton beams is a Gaussian distribution with a mean and standard deviation.

* This work was supported by the National Key Research and Development Program of China (2016YFC0105305), the National Natural Science Foundation of China (12205111), and the Fundamental Research Funds for the Central Universities (HUST: 2022JYCXJJ010).
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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO011

EFFECT OF 90 MeV PROTON IRRADIATION ON SPLEEN INJURY IN C57BL/6J MICE

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Abstract

Proton therapy has become one of the most important physiotherapies for tumors in the world, which can greatly improve the cure rate of tumors that are ineffective by conventional treatments. In addition, proton is also the main source of radiation in space environment. Therefore, it is of great scientific significance to use accelerators to carry out basic research on proton radiotherapy and space radiobiology, which can provide technical support and basic data for the optimal design of proton therapy and risk assessment of personnel in space environment.

In this study, C57 mice were irradiated with 0, 0.2, 0.5 and 2Gy by 90 MeV protons from 100MeV cyclotron of China Institute of Atomic Energy. The mice were killed one day after irradiation. Body weight change and spleen organ coefficient were calculated. The expression of DNA damage-related protein γH2AX was detected by western blotting.

The results showed that compared with the control group, the body weight of mice in each irradiation group had no significant change, and the spleen organ coefficient decreased, indicating that the spleen atrophied after proton radiation, especially in 2Gy. The results of Western blotting showed that the expression of γ H2AX in spleen increased significantly on the 1 day after irradiation, especially in 0.5 and 2 Gy, indicating that the spleen DNA damage was the serious on the 1 day after proton radiation.

INTRODUCTION

With the development of China's aerospace industry, especially the advent of the space station era, the time spent by astronauts in space in the future will increase, and the impact of the space environment on the health of astronauts has also received more and more attention. Existing aerospace data show that medium and long-term space flight will affect multiple physiological systems of astronauts, such as genomic instability, cardiovascular function changes, bone loss, metabolic disorders, immune function changes and even the risk of carcinogenesis [1-3]. Space radiation is one of the important factors restricting manned spaceflight, protons are one of the main sources of space radiation, and its health effects on astronauts' health are particularly important [4].

The immune system is an important system for the body to perform immune responses and immune functions. It is composed of immune organs, immune cells and immune molecules. The immune system has the function of recognizing and eliminating antigenic foreign bodies, coordinating with other systems of the body, and jointly maintaining the stability of the environment and physiological balance in the body.

The spleen is the largest immune organ in the human body and the center of cellular and humoral immunity. Therefore, it is important to study the effect of proton radiation on the damage effect of the spleen.

In this study, 90 MeV medium energy protons generated by the 100 MeV proton cyclotron of the Chinese Institute of Atomic Energy were irradiated at different doses to mice, and the effect of 90 MeV proton irradiation on the spleen of C57 mice was studied. Spleen injury in C57 mice at different doses was obtained. In order to provide basic data and scientific basis for proton radiation protection.

MATERIALS AND METHODS

Animals and Experimental Design

Male C57BL/6J mice aged 6-8 weeks were obtained from SIPEIFU company, Beijing, China. The mice were acclimatized for a week under standard vivarium conditions. Next, we randomly divided the 24 animals into the experimental and control groups, including the control group of C57BL/6J(n=6), 0.2、0.5 and 2 Gy experimental group of C57BL/6J(n=6). At the end of the experiment, samples were collected on the first, third and seventh day.

Radiation Exposure

Proton irradiation was performed at the single-particle effect experimental terminal of CYCIAE-100 (Figs.1 and 2). Mice were exposed to 0.2、0.5 and 2 Gy of 90 MeV proton with 0.8 Gy/min. Control groups were subjected to a sham radiation procedure.

Figure1: The 100 MeV proton cyclotron.

Work supported by the Continuous Basic Scientific Research Project (No.WDJC-2019-11)
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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO012

PROGRESS IN DESIGN OF MSC230 SUPERCONDUCTING CYCLOTRON FOR PROTON THERAPY

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Abstract

The current status of the MSC230 superconducting cyclotron designed for biomedical research is presented. MSC230 is an isochronous four-sector compact cyclotron with a magnetic field in the center of 1.7 T. Acceleration is performed at the fourth harmonic mode of the accelerating radio-frequency (RF) system consisting of four cavities located in the cyclotron valleys. The accelerator will use an internal Penning type source with a hot cathode. Particular attention is paid to extraction, as it must have a high extraction efficiency.

INTRODUCTION

Recent studies of a promising new method, called FLASH [1, 2], have shown that it has great potential for expanding the use of proton therapy on tumors that previously could not be treated with protons, at the same time significantly improving the quality of treatment. Compared to radiation therapy at a conventional dose rate (1–7 Gy/min), FLASH irradiation is performed at a dose rate over 50 Gy/s in less than 0.5 seconds. Healthy tissue is better able to withstand FLASH radiation, while the level of damage to the tumor is the same as with conventional treatment.

However, before proton FLASH therapy can be fully implemented in practice, it is necessary to solve several engineering and technical challenges. More particularly, there is a need in an accelerator that provides a high average beam current, which, according to various estimates, is 0.5-100 μA for the entire range of energies used in treatment.

The task of the FLASH research makes relevant the creation of a research and innovation center at JINR equipped with a modern proton accelerator, a beam delivery system and laboratory equipment for biomedical research.

An isochronous cyclotron cannot compete with synchrocyclotrons in dimensions and weight, but a cyclotron accelerates a quasi-continuous beam, therefore, it is the most promising accelerator for the application of a new method of radiation therapy - flash.

The MSC230 cyclotron [3] can produce a 230 MeV proton beam for therapy and biomedical research. Table 1 shows the main parameters of the MSC230 cyclotron. We plan to get about 10 μA of beam current in our cyclotron to study the efficiency of the flash method.

Figure 1 shows the interior of the magnetic and accelerating systems of the cyclotron.

Table 1: MSC230 Cyclotron Main Parameters

General properties	
Accelerated particles	Protons
Magnet type	SC coils, ‹‹warm›› yoke
Injection	Internal source
Number of turns	500
Beam Parameters	
Energy, MeV	230
The relative error of the proton beam energy, %	0.15
Extracted beam intensity (continuous mode), nA	2-1000
Extracted beam intensity (flash mode), nA	5000-10 000
Emittances of the extracted beam, π*mm*mrad, (2σ)	
Radial	8
Vertical	2
Magnetic system	
Average magnetic field (R_o/$R_{extr.}$), T	1,7/2,15
Dimensions (height × width), m	1,7 × 3,9
Magnet weight, tonne	~130
Hill/valley gap, mm	50(25)/700
Excitation current (1 coil), A*turns	270 000
Accelerating system	
Frequency, MHz	106.5
Harmonic number	4
Number of cavities	4
Power losses, kW (total)	60
Voltage center/extraction, kV	40/100
Extraction	
Extraction radius, m	1.08
Extraction system	ESD+2MC

Figure 1: View of the MSC230 cyclotron model.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO013

MAGNET DESIGN OF A COMPACT 16 MeV VARIABLE ENERGY CYCLOTRON FOR ISOTOPE PRODUCTION

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Abstract

A compact isochronous cyclotron, CIMV16, is under research and development at Hefei CAS Ion Medical and Technical Devices Co., Ltd, China (HFCIM). This cyclotron can accelerate negative hydrogen ion to variable energy in the range of 10~16 MeV for the stable production of widely-used medical isotopes in this energy range. It has a maximal diameter of only 1.8 m and adopts three radial-sector poles with the third harmonic acceleration. The design of magnet system and the analysis of final simulated static magnetic field were described in detail in this paper. Meanwhile, two suitable shimming methods were also proposed for later engineering optimization.

INTRODUCTION

To meet the explosive growth of domestic health needs, China is actively producing medical radioisotopes. Important among them are ^{11}C, ^{13}N, ^{15}O, ^{18}F, etc. for PET (Positron Emission Tomography) and ^{64}Cu, ^{67}Ga, ^{86}Y, ^{124}I, ^{225}Ac, etc. for other medical applications, all of which require proton energy in the range of 10~16 MeV to yield them through nuclear reactions [1]. Due to the advantages of producing isotopes with high specific activity and less radioactive waste, the cyclotron has gradually become a critical option for the production of short-lived radioisotopes [2].

A cyclotron with a single extraction energy could not be suitable for producing various isotopes efficiently, so a variable-energy cyclotron that can simultaneously produce several isotopes is more adopted to the market demand. Internationally, the existing variable-energy cyclotrons below 20 MeV are TR-19, BEST 35p, CYCLONE 30, CC-18/9M, and so on [2]. However, in China, only a few cyclotrons with single-energy are available, such as CYCIAE-14 from China institute of atomic energy (CIAE) [3]. For these reasons, HFCIM is developing a variable-energy cyclotron, CIMV16. To improve the extraction efficiency, it accelerates negative hydrogen (H^-) ion and extracts them by stripping foil, which can produce more than 100 μA protons with energies of 10~16 MeV, satisfying the production of the important isotopes described above.

The design of magnet system is the primacy of CIMV16. After the initial determine of magnet system parameters, the poles are further optimized according to the isochronous requirements. Then, the beam dynamics analysis is performed for a single particle, and the position of stripping foil is adjusted so that this particle can be extracted to a same focus point at different energies, which finally confirms that the magnet system meets our design requirements.

STRUCTURE DESIGN

The preliminary design of CIMV16 is based on the following assumptions:

- Primarily accelerates H^- ion.
- Isochronous cyclotron.
- Maximal extraction energy is 16 MeV.
- Isochronous field at $R = 0$ (B_0) is about 1.55 T.
- Axial betatron frequency (ν_z) is in the range of $0.10 < \nu_z < 0.25$ (beyond the central region).
- Radial-sector poles (spiral angle $\mu = 0$).
- Make enough space for RF system, and decrease RF voltage as much as possible.

Based on the above assumptions, The relativistic mass factor of H^- ion at maximal energy is expressed as $\gamma = (E_0 + E_k) / E_0 \approx 1.017$ (where E_0 is the rest energy 939.278 MeV and E_k is the maximal kinetic energy 16 MeV). Isochronism requires the maximal averaged field is calculated as $\langle B_e \rangle = \gamma B_0 \approx 1.58$ T. Therefore, the final orbit radius of particle (R_e) is estimated as 36.8 cm. Considering the magnetic field weakens so quickly in the pole-edge region and its distribution does not meet the requirements of radial focusing and isochronism, so the radius of pole is a little larger than R_e.

The next step is to evaluate the axial and radial focusing characteristics. Referring to the calculation by H. L. Hagedoorn and N. F. Verster [4], the 2nd order approximate expansion of radial and axial betatron frequency (ν_r and ν_z) can be written as Eq. (1) and (2):

$$\nu_r^2 \approx 1 + k + \frac{3N^2}{(N^2-1)(N^2-4)} F(1+\tan^2\mu), \quad (1)$$

$$\nu_z^2 \approx -k + \frac{N^2}{N^2-1} F(1+2\tan^2\mu), \quad (2)$$

where N is the number of poles, μ is the spiral angle of pole, F is the field flutter ($F = \langle B^2 \rangle / \langle B \rangle^2 - 1$) and k is the positive field index ($k = R / \langle B \rangle \times \mathrm{d}\langle B \rangle / \mathrm{d}R$) for each radius R. k approaches to 0 at the radius of maximal averaged field. In order to make the ν_z here close to 0.20 without spiral angle ($\mu = 0$), the minimal field flutter 3.6% for 3 poles or 3.8% for 4 poles is required at this radius. For providing sufficient space for the RF system and other systems and ensuring the enough axial focusing, the three radial-sector poles with third harmonic acceleration is finally adopted in CIMV16.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO014

THE BEAM DYNAMICS SIMULATION OF A VARIABLE ENERGY CYCLOTRON FOR ISOTOPE PRODUCTION

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Abstract

The isochronous cyclotron, CIMV16, has been designed by Hefei CAS Ion Medical and Technical Devices Co., Ltd, China (HFCIM) for widely used isotope production, which can extract proton with variable energy in range of 10~16 MeV. In this cyclotron, negative hydrogen ion will be accelerated to 10~16 MeV, and then stripped out two electrons to become proton to be extracted. We have performed beam tracking starting from the ion source to the extraction reference point, and optimized the position of the stripping target to make the beam of different energies converge at radius of 110 cm. The orbit centralization is optimized by the design of first harmonic, and the axial size of extraction beam is also optimized. All the results of beam dynamics simulations will be presented.

INTRODUCTION

Small cyclotrons for isotope production have developed greatly in past few years. According to the International Atomic Energy Agency (IEAE) official statistics, the energy distribution of low-level cyclotrons in China, the United States and Japan is mainly 10~18 MeV, and 75% of them are between 10~16 MeV. For cyclotrons with single energy extraction, it is difficult to meet the production of multiple isotopes at the same time. Therefore, if variable energy extraction can be realized in this energy range, it will certainly meet the demand of isotope production better. Based on this precondition, CIMV16 has been designed by HFCIM.

Referring to other medical isotope products of the same type, the CIMV16 adopts three Sector-shaped poles and use 3rd harmonic to accelerate. The parameters are shown in Table 1.

Table 1: Parameters of CIMV16

Parameter	Value
Accelerated particle	H^-
Central field	1.36 T
Max. averaged field	1.57 T
Outer radius of yoke	900 mm
RF frequency	70.8 MHz
Harmonic number	3
Energy	10~16 MeV
Beam Current	150 uA
Extraction mode	Stripping

SINGLE PARTICLE BEAM DYNAMICS SIMULATION

Based on the analysis of the equilibrium orbits, we finished the Single particle beam dynamics simulation. From the simulation results of single particles, we can see that particle can be accelerated to more than 16 MeV, and by adjusting the position of the stripping target, Proton with different energies in range of 10~16 MeV can be extracted, and we also make the beam converges at 110 cm after extracted by optimizing the position of the stripping target. The trajectories of different energy particle are shown in Fig. 1 and the positions of the stripping target corresponding to different energies are shown in Table 2.

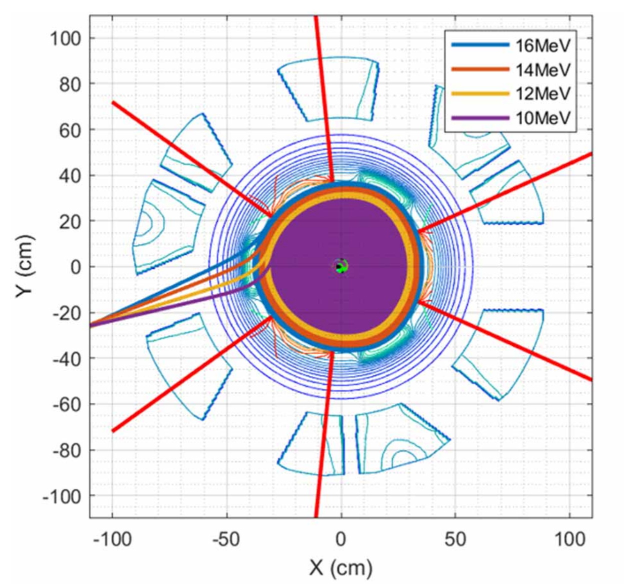

Figure 1: Trajectories of single particle with different energies.

Table 2: Position of Stripping Target

Energy (MeV)	Radius (cm)	Azimuth (deg)
16	30.0	170
14	34.5	164
12	32.5	158
10	37.0	153

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO015

R&D STUDIES ON A 177.6 MHz 1:4 SCALE BOAT SHAPE PROTOTYPE RF CAVITY FOR THE 2 GeV CW FFA*

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Abstract

A proton circular accelerator complex composed of a 100 MeV separated radial sector cyclotron, an 800 MeV separated spiral sector cyclotron and a 2 GeV FFA was proposed and is being studied at CIAE. To satisfy the beam dynamics requirements of the FFA, NC RF cavity with high Q and R will be adopted. It is found that the boat shape cavity is the most promising candidate. Therefore, R&D on a 177.6 MHz 1:4 scale boat shape prototype cavity is being carried out to study all aspects of developing such a high-power cavity. In this scenario, self-consistent multi-physics coupled simulation study with ANSYS HFSS and Workbench was carried out. This paper describes the method to deal with a mechanical model including hundreds of bodies in the FEM analysis and shows the simulation results. In addition, the manufacturing technology and some testing results are also presented.

INTRODUCTION

CIAE has committed to the development of cyclotrons and constructed series of cyclotrons toward higher beam energy and intensity with a compact size. In recent years, the proton beam accelerator with ~GeV energy and ~MW power is being pursued, the purpose is to expand the application scopes of the proton accelerator in the fields of the fundamental physics, the nuclear industry, the home security, etc. In this situation, a proton circular accelerator complex was proposed and is being studied at CIAE [1]. The design goal is to extract a 2 GeV, 6 MW CW proton beam.

For the 2 GeV FFA, NC RF cavities will be applied to boost the proton beam energy from 800 MeV to 2 GeV. Due to the heavy beam loading, development of the NC high power waveguide type RF cavity with high Q and R is extremely important, which is unquestionably beneficial for the energy efficiency enhancement. Four geometries (i.e., rectangular, omega, racetrack, and boat) of the waveguide-type RF cavities were investigated extensively [2], it was found that the boat shape RF cavity has the highest Q and R, and is the most promising candidate.

In order to master the key technology of developing such a high-power RF cavity, R&D on a 177.6 MHz 1:4 scale boat shape prototype cavity is being carried out. For this cavity, ~100 kW RF power dissipated on the copper cavity walls needs to be brought away by the cooling water, ±170 kHz tuning range needs to be reached by deforming the RF cavity walls with the electrical cylinders. To make sure the mechanical design can meet the design demands, self-consistent multi-physics coupled simulation study (i.e., RF-thermal-structural-RF analysis) with ANSYS [3] was carried out, the optimized design results were obtained. Afterwards, the prototype cavity was fabricated by using technologies of the stamping forming, the vacuum EBW, etc. Cold test is being performed; hot test is being prepared and will be done in the very near future.

* Work supported in part by the National Natural Science Foundation of China under Grant 12135020 and the basic research fund from the Ministry of Finance of China under Grant BRF201901.
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CAVITY AND COUPLER'S RF DESIGN

Figure 1 shows the RF design of the cavity and coupler. The calculated unloaded Q of the cavity is ~43500; the maximum and minimum shunt impedances along the midplane of the rectangular beam aperture (1 m × 0.03 m) are 7.61 MΩ and 3.79 MΩ, respectively. The accelerating gap length is 0.2 m. The scale of the cavity itself is 2 m×0.5 m×0.8 m. In the realistic cavity, two identical couplers are arranged; one is for RF power coupling, another is connected with a high-power RF load to simulate the beam loading. The calculated maximum β of the coupler is ~2.6.

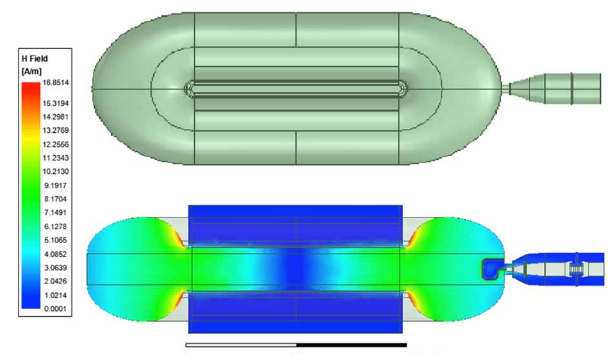

Figure 1: RF design of the cavity and coupler.

MULTI-PHYSICS ANALYSIS

Figure 2 shows the workflow and ANSYS Project Schematic giving the data linkage between the Geometry, the HFSS Design, the Static-State Thermal and the Static Structural. The bodies of the SolidWorks mechanical model imported into the Geometry can be divided into two types, namely the metal and the nonmetal ones. Each body should be named or numbered correctly in the Geometry to avoid unpredictable errors. In the HFSS Design, since only the nonmetal bodies and the metal bodies related to the RF fields are useful for the RF field calculation, all the other metal bodies can be set as Non Model to make the

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO016

DESIGN AND ANALYSIS OF THE 230 MeV CYCLOTRON MAGNET FOR THE PROTON THERAPY SYSTEM

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Abstract

This paper demonstrates the design and analysis of 230 MeV cyclotron magnet of the proton therapy system. The magnet is the core of the 230 MeV cyclotron, which can keep the beam orbit and limit beam divergence. The magnetic field calculation and modification are analyzed in detail, with the isochronous error of the magnetic field less than 0.2%. Meanwhile, the thermal analysis of the coil has been calculated by the empirical formula.

INTRODUCTION

The overall model of the C230 cyclotron and the structure of the accelerator is shown in Fig. 1.

The proton cyclotron magnet is mainly composed of magnetic pole, magnetic yoke and pad. In order to achieve the design goal of 230 MeV proton energy, a helical sector focusing structure, four blade poles and four harmonic accelerations are adopted (Fig. 1). To compensate for the increasing energy with radius and the increasing defocusing by the main field, the angle by which the hill-valley boundary is crossed increasing by making the hill-valley structure spirally shaped [1]. This kind of magnet structure is relatively simple and more compact. A replaceable tuning block is installed in the edge of the magnetic pole, and the isochronicity of the magnetic field can be adjusted by changing the tuning block size. In order to ensure isochronous acceleration conditions, the design goal is to limit isochronous error less than 0.2%.

The main magnet model of the accelerator was established in Opera3D, whose yoke material is low carbon steel. The magnetization curve was shown as the Fig. 2 below. The acceleration frequency and energy curves of the initial model are present respectively. Final particle energy can meet the design requirements, indicating that the profile is basically correct. However, the acceleration frequency fluctuation is large in the initial model, which does not full-fill the condition of iso-chronicity.

The change of the phase, stipulated by the change of the frequency of the accelerating voltage the electric intensity [2]. When the RF frequency is large, it indicates that the ideal reference particle is ahead of the acceleration voltage.

The cyclotron frequency of the particle will be reduced, through changing the magnetic field by adjusting the angle of the magnetic pole at the radius. Instead, it is necessary to increase the magnetic field, through increase the angle of the magnetic pole also. Finally, the particle energy can reach 232 MeV at the radius of 1060 mm, which meets the design requirements. The final optimized magnetic field has been shown in Fig. 3.

The custom oxygen-free copper wire with inner circle and outer square is selected, whose specification is 9.5 × 20.9 × 20.5 mm, further more total resistance of the coil is 298 mΩ. There are 352 turns of single coil totally, inner diameter of 2,360 mm, outer diameter of 3,340 mm, height of 350 mm.

Through the simulated resulting, the coil current density is 1.525 A/mm², and the ampere-turns 261,537.5 A. The coil current is about 743 A, and the power consumption is about 165 kW.

It is generally believed that the inlet temperature of coil cooling water is about 20 °C, and the outlet temperature is below 45 °C.

The total water flow $q = \frac{P}{c_p \cdot \rho \cdot \Delta T}$ is 94 L/min. The calculated pressure loss of cooling water in the coil is 1.149 MPa. The cooling system is set to cooling water pressure of 1.5 MPa, coil cooling flow of 99.2 L/min.

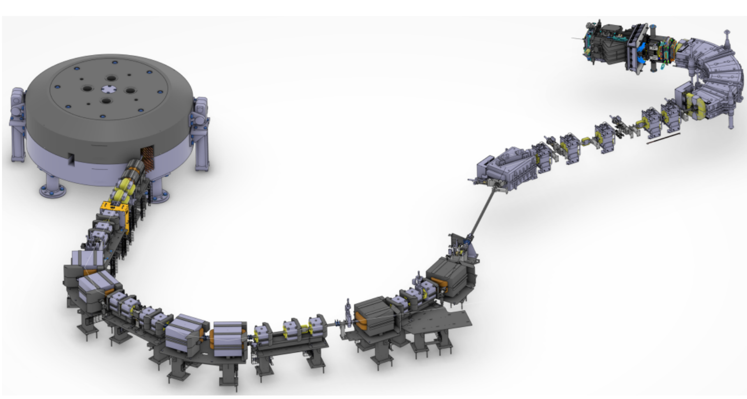
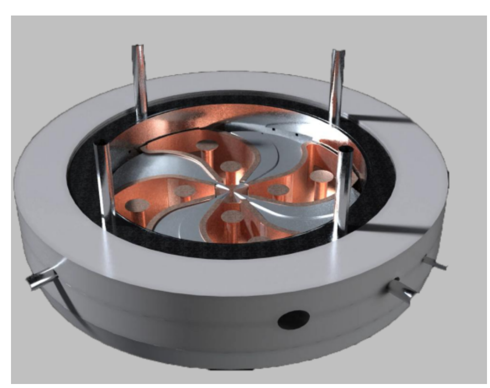

Figure 1: Overall model of C230 cyclotron and internal structure of the accelerator.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO018

FFA ACTIVITY IN JAPAN AND FUTURE PROJECTS

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Abstract

An FFA facility at KURNS(Institute for Integrated Radiation and Nuclear Science, Kyoto University) has been operating for the experiment of various fields such as ADS(accelerator driven system), material science, medical physics and radiation damage of the memory chips since 2009. As ADS experiment which is original aim of this facility has been completed, we are planning several upgrade modifications of the ring aiming secondary particle production using the ERIT which stands for energy recovery internal target. In this presentation, two options of ERIT for the muon production facility and nuclear experiment of super heavy elements.

INTRODUCTION

At the Kyoto University Research Reactor Institute (KURRI), basic experimental studies on the ADS, which stands for accelerator driven system, have been started since 2009 using a one of research reactors Kyoto University Critical Assembly (KUCA) [1]. In these studies, the KUCA has been operated in the sub-critical mode and FFA accelerators has been used as a proton driver. In this report, an overview of the FFA accelerator complex, a current status of the usage of beams generated by the complex and discussion of possible upgrades of it will be presented.

It has been 12 years since the main ring started operation. In early 2009, we demonstrated the feasibility of ADS in the Uranium loaded sub-critical core under thermal system, hitting the tungsten target with proton beams of which energy is 100 MeV to generate the spallation neutron) [2]. In the next year, ADS experiments with Thorium loaded core were performed. For the next decade, experiments were conducted at this facility with a variety of core configurations. Finally, in 2019, phenomena of transmutations of MAs such as 237Np and 241Am in the ADS was confirmed using this facility [3]. As almost all the originally planned ADS experiments have been completed, reuse plans of the main ring of FFA facility at KURNS is now under consideration. In this report, we present two major options. One is modifying the main ring to a pion production ring aiming for producing decay muons for various purposes such as muon transmutations and muon-catalyzed fusion. The other modification is for producing super heavy elements of which mass is 119 or more. Both options are aimed at producing secondary particles using an ERIT mechanism [4].

CURRENT CONFIGURATION OF THE COMPLEX AT KURNS

The FFA accelerator complex at KURNS is shown in Fig. 1. It consists of an H^- ion source, a linac, an FFA synchrotron as a main ring and beam transport lines. The basic parameters of the KURNS FFA facility is shown in the Table 1. The output energy of the ion source is 30 keV

Table 1: Basic Parameters of KURNS FFA Accelerator Complex

LINAC	
Energy	11 MeV
Peak current	< 5 µA
Pulse length	< 100 µs (uniform)
Repetition rate	30 Hz 200 Hz(max.)
MAIN RING	
Energy	11 - 100 (150) MeV
Field index k	7.5
Magnetic field	1.6 T (max.)
Revolution frequency	1.6 - 4.3 (5.0) MHz
Rf voltage	4 kV
Repetition rate	< 30 Hz

and the peak current is 2 mA with a duration of 100 µs. The linac is composed of 3 MeV RFQ, 7 MeV DTL and 11 MeV DTL. A charge stripping injection scheme is used in the main ring. The thickness of the stripping foil is 20 µg/cm^2 which is 2-fold of 10 µg/cm^2 thin carbon foil. It is located around the center of one of 12 main DFD triplet magnets to merge the injected beam to the circulating beam. Only one rf station is inserted in the straight section to accelerate the beam from 11 to 150 MeV with the peak rf voltage of 4 kV sweeping the frequency from 1.6 MHz to 6 MHz. As the turn separation in the FFA ring is much smaller than the beam size because of the high k value, the beam extraction needs kicker and septum magnets. The repetition rate is 30 Hz and the pulse length of the extracted beam is variable such as 10-100 ns using the bunch rotation scheme in the longitudinal phase space.

As the time structure of the beam from KURNS FFA synchrotron has very unique properties, it is very suitable for experiments such as nuclear data taking, flash radiotherapy, radiation damage on the memory chips and high energy physics detector development.

The H^- linac was built as an injector of the ERIT [1] ring which was a proof-of-principle ring of a neutron production ring with energy recovery internal target.The ERIT ring was

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[1] stands for Energy Recovery Internal Target

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO019

CONTROL OF A CYCLOTRON AND AN ECR ION SOURCE USING BAYESIAN OPTIMIZATION METHOD*

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Abstract

An enormous number of parameters are tuned during accelerator operation. The tuning is ultimately dependent on the operator's knowledge and experience. Therefore, there is a risk that tuning time and accuracy may vary depending on the operator. This tuning difficulty is an extremely important issue when implementing accelerometers in society, such as in medical applications. In this study, we developed an automatic tuning method using Bayesian optimization, one of the machine learning technique. The aim is to realize a tuning method that can supply beams in a short time with good reproducibility and comparable to manual tuning.

BAYESIAN OPTIMIZATION

Bayesian optimization [1] is a method that can efficiently utilize Gaussian process regression. The most important feature of Gaussian process regression is that it can calculate the expected value of the forecast (μ) and its variance (σ) from the obtained data. In general methods, the model is trained with a huge amount of data, and the next action is decided based only on the calculated predictions. Therefore, when the number of data is insufficient, the prediction may be inaccurate, and there is the problem of being trapped in local maxima. Bayesian optimization has the advantage that it can be used even with a small number of data because the model is less complex. Also, since the next action is determined from the mu and sigma calculated by Gaussian process regression, it actively adopts regions with a small number of data and is less likely to be trapped in local maxima. For example, in Lower Confidence Bound (LCB), the next action is determined from the acquisition function as shown in Eq. (1).

$$L_{LCB} = \mu + \alpha\sigma \tag{1}$$

where α is a constant. When this α is large, the error is more important and is less likely to be trapped in the local maxima. On the other hand, if the error is considered important, the number of searches increases, and the number of times required to find the optimal solution is likely to increase. Therefore, it is necessary to select a value that is somewhat appropriate for the problem. In this study, experiments were conducted with α = 4 fixed.

TUNING TEST FOR ECR ION SOURCE

Set Up

First, we developed an automatic tuning system using Bayesian optimization for tuning ion sources. In this experiment, a 10 GHz ECR ion source 'NANOGAN [2]' manufactured by Pantechnik was used as the ion source, and He ions were extracted at 50 kV acceleration. A schematic diagram of the test bench is shown in Fig. 1.

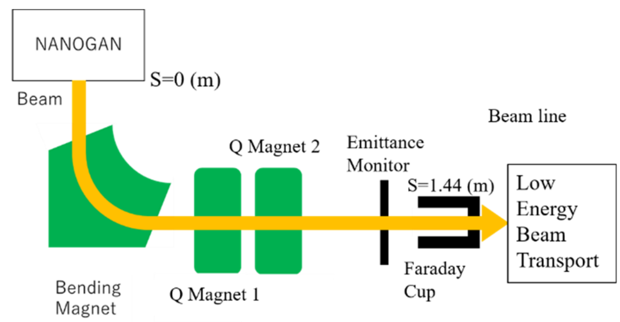

Figure 1: Schematic diagram of the test bench.

After extraction, the beam was bent 90° by a bending magnet to analyze the ion species, and then the beam emittance (ε) and beam intensity (I) were measured with a Pepper-pot emittance monitor (PPEM) [3] and Faraday cup (FC), respectively, using two quadrupole magnets. Beam brightness $(I/\varepsilon_{x-x'}\varepsilon_{y-y'})$ was calculated from the PPEM and FC measurements and adjusted to maximize brightness.

Tuning Experiments

In this experiment, four of the tuning parameters of the ion source were tuned: RF frequency, RF power, gas valve, and intermediate electrode voltage. The RF power was tuned by fixing the amplification factor of the Traveling Wave Tube Amplifier (TWTA) and varying the signal source power. The gas valve had a motor attached to the knob of the needle valve, and the amount of opening and closing was controlled by the amount of rotation [4]. The tuning range and minimum change for each tuning parameter are shown in Table 1. In this experiment, the number of parameter tuning was set to 108 times: 8 times for initial conditions and 100 times for tuning by Bayesian optimization. This is the number of tuning cycles that would take approximately 1.5 hours to complete.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-FRAI01

DEVELOPMENTS AND PROSPECTS OF FFAS AT RAL

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on behalf of the FFA task team,

Abstract

A Fixed Field Alternating Gradient Accelerator (FFA) can offer several advantages for use as a proton driver for high power beam applications. In particular, control of the pulse structure can be easily done by RF gymnastics. A FFA is a sustainable (energy efficient) and reliable accelerator with the main magnets with DC operation. We will discuss the development of a FFA physics design for ISIS (spallation neutron and muon source) upgrade and its proto-type status.

INTRODUCTION

Studies are in progress to upgrade ISIS, the UK's spallation neutron and muon source, in a plan referred to as ISIS-II. The beam power of the proton driver is in the range 1.25 to 2.5 MW with a beam energy of 1.2 GeV. That level of beam power has already been achieved at PSI in Switzerland, SNS in the US and J-PARC in Japan and is therefore not seen as a major challenge. However, beam power is not the only figure of merit for future proton drivers. There are some other essential factors we must take into account.

The most important consideration is sustainability, a feature that becomes increasingly relevant of late. Without assuring a good measure of sustainability, we cannot operate the facility. At the present time a cyclotron is the most energy efficient accelerator. Another key factor is reliability of operation. Even if an accelerator has a state-of-the-arc design, users will hesitate to use it if it frequently breaks down. An accelerator like a cyclotron using DC magnets is robust and its robustness can be an important contributor to the reliability.

More specifically, in the spallation neutron community, accelerator-based facilities should have two features: capacity and capability. Capacity means that a facility can comfortably deal with the large number of experiments that is essential to meet or expand demand from the scientific community. Capability means that a facility can provide bespoke experiments. For example, it can provide flexible operation such as high peak current with low repetition or low peak current with high repetition depending on users' requests.

As a candidate for a future high power proton driver a cyclotron has many attractive features The only caveat is that it is not a pulsed machine, whereas neutron users need pulsed protons. A synchro-cyclotron is an option, or a Fixed Field Alternating Gradient Accelerator, FFA [1-3]. However, people are not easily convinced about the idea because no high power FFA exists. To show viability and convince the community that an FFA can provide the high power beams required, a project RAL has in mind to design and construct a small-scale demonstrator of an FFA-based high power machine [4]. Referred to as FETS-FFA, the ring will use the existing Front End Test Stand (FETS) as its injector. Since an FFA is a pulsed accelerator like a synchro-cyclotron, there are many challenges that are similar to those in a high intensity synchrotron. Table 1 shows the main parameters of FETS-FFA. The average current is about three orders of magnitude higher than any existing fixed-field accelerating ring.

Table 1: FETS-FFA Main Parameters

Parameter	Value
Beam energy	3 – 12 MeV
Average radius	4 – 4.2 m
Repetition rate	100 – 120 Hz
Number of protons per pulse	3×10^{11}
Average current	about 5 mA
Space charge tune shift	about -0.25

BEAM DYNAMICS ISSUES OF THE HIGH POWER BEAMS

This paper considers four topics that are of importance in the realisation of a high power FFA.

FD Doublet Spiral Lattice

We know that the operating tune should be close to the diagonal line in tune space. In other words, both horizontal and vertical tunes should be similar in a high power synchrotron. Radial sector FFAs use the field index k and the strength ratio of normal bend Bf and reverse bend Bd, which changes the flutter factor. However, the reverse bend makes the circumference larger. Spiral sector FFAs eliminate the reverse bend so that the circumference is smaller.

However, they do not provide full tune control because of the loss of flutter factor control. The idea of an FD spiral lattice was introduced a few years ago [5]. We keep the reverse bend for full control of tune, but make the strength of the reverse bend a minimum by having vertical focusing from the spiral angle as well.

In FETS-FFA, we choose the nominal tunes to be similar in both horizontal and vertical planes with values (3.41, 3.39). We have full control of tune at least as large as an integer to optimise high power operation by changing the field index k and Bd/Bf ratio. The directions of tune change under variations in each parameter are shown in Fig. 1.

We found that an FD doublet spiral lattice behaves like a triplet focusing with one focusing and one defocusing magnet. It is interesting to see that there is smooth transition from FD doublet radial sector optics (FD doublet) to spiral sector optics (DF doublet) through FD spiral optics (DFD triplet) as shown in Fig. 2.

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-FRAI02

DESIGN OF A 2 GeV CYCLOTRON WITH CONSTANT RADIAL AND VERTICAL TUNES

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Abstract

We demonstrate that a cyclotron can be made to have precisely constant betatron tunes over wide energy ranges. In particular, we show that the horizontal tune can be made constant and does not have to follow the Lorentz factor γ, while still perfectly satisfying the isochronous condition. To make this demonstration we developed a technique based on the calculation of the betatron tunes entirely from the geometry of realistic non-hard-edge closed orbits. The technique is applied to the particular case of a 800 MeV to 2 GeV proton cyclotron to produce a design that is presented here.

INTRODUCTION

This paper is a brief summary of a more detailed article [1]. There we demonstrate that, in a cyclotron with mid-plane symmetry, the transverse tunes are entirely determined by the geometry of its closed orbits. Capitalizing on this property, we have established a method to calculate tunes and produce isochronous field maps by starting from the geometry of realistic non-hard-edge orbits. The main advantage of this method is that it produces realistic and perfectly isochronous field distributions, and the corresponding transverse tunes, in a split second. We take advantage of this speed to explore the range of possible isochronous fields, which leads us to find solutions with simultaneously constant vertical and horizontal tunes over wide energy ranges.

We have applied this technique and proposed designs for several sets of cyclotron parameters [1, 2]. In this paper, we focus our effort on the case of a high-energy cyclotron, choosing a set of parameters that resembles that of the recently proposed 2 GeV CIAE machine [3, 4].

THEORY: TUNES OF ISOCHRONOUS ORBITS

Let's consider a fixed-(magnetic-)field accelerator with mid-plane symmetry. In this circular accelerator, let's consider one closed orbit at one particular energy, to which is attached the Frenet-Serret coordinate system (x, y, s). It is interesting to note that, as a result of the application of Maxwell's equations, the infinitesimal transverse motion of particles is fully determined by the curvature $\rho(s)$ and the local field index $n(s) = -\frac{\rho}{B_0}\frac{\partial B}{\partial x}\Big|_{x=y=0}$ of the corresponding closed orbit [5, 6]. This implies that it is sufficient to know the functions $\rho(s)$ and $n(s)$ over one period of the accelerator to know the value of the transverse betatron tunes.

Now, instead of starting from a magnetic field distribution to compute the properties of the orbits, which is the common practice for designing a cyclotron, let's start from the geometry of the orbits represented by some arbitrary function:

$$\begin{aligned} r:\ & \mathbb{R}^+ \times \mathbb{R} \to \mathbb{R}^+ \\ & (a, \theta) \mapsto r(a, \theta)\ , \end{aligned} \tag{1}$$

where r is the radius of the closed orbit, a is the orbit's average radius, and θ is the azimuth. The periodicity of the closed orbits imposes that:

$$r(a, \theta) = r(a, \theta + 2\pi/N) \text{ with } N \in \mathbb{N}^*\ , \tag{2}$$

where N is the lattice periodicity, i.e. number of sectors. The question now becomes: can we calculate both $\rho(s)$ and $n(s)$ directly from $r(a, \theta)$?

Firstly, the relation between s and θ is, first of all, given by:

$$\frac{\mathrm{d}s}{\mathrm{d}\theta} = \sqrt{r^2 + \left(\frac{\partial r}{\partial \theta}\right)^2}\ , \tag{3}$$

secondly, ρ is immediately obtained from the standard formula for polar coordinates:

$$\frac{1}{\rho} = \frac{r^2 + 2\left(\frac{\partial r}{\partial \theta}\right)^2 - r\frac{\partial^2 r}{\partial \theta^2}}{\left(r^2 + \left(\frac{\partial r}{\partial \theta}\right)^2\right)^{3/2}}\ . \tag{4}$$

Finally, obtaining $n(s)$ requires a little more work. We start by remarking that, in a cyclotron, orbits are isochronous which imposes a relation between the particle velocity and the orbit circumference:

$$\beta(a) = \frac{\mathcal{R}(a)}{\mathcal{R}_\infty}\ , \tag{5}$$

where $\mathcal{R}_\infty$ is a constant, corresponding to the value of $\mathcal{R}$ in the limit that the particles' speed is light speed; and $\mathcal{R}$ is the orbit circumference divided by 2π:

$$\mathcal{R}(a) = \frac{1}{2\pi}\int_0^{2\pi} \frac{\mathrm{d}s}{\mathrm{d}\theta}\,\mathrm{d}\theta\ , \tag{6}$$

after imposing the isochronous condition, and applying the chain rule, we find an expression for n that depends only in $r(a, \theta)$ and its partial derivatives [1].

In conclusion, for any arbitrary continuum of closed orbits defined by the function $r(a, \theta)$, provided that r is smooth enough for the required partial derivatives to be defined, the transverse tunes of cyclotron depends on $r(a, \theta)$ and nothing else.

Corresponding Isochronous Field Map

So far we have needed only the knowledge of the shape $r(a, \theta)$ of the closed orbits to calculate tunes. The question

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-FRA002

FEASIBILITY STUDY ON 10 MW-CLASS ULTRA-HIGH POWER CYCLOTRON

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Abstract

10 MW-class ultra-high power cyclotron (UHPC) has great application prospects in cutting-edge sciences, neutron source, advanced energy and advanced material, etc. So far, Cyclotron with average beam power of 10 MW still have some bottleneck problems. Beam energy and current of a high-power cyclotron are typically less than 800 MeV and 3 mA. In this paper, bottleneck problems of UHPC are analysed, and then a preliminary design of UHPC-10 MW is presented.

INTRODUCTION

GeV-class proton beam with an average power of several megawatts has many important applications in particle physics towards the intensity frontier, as well as in the advanced energy and material science. There are three different types of constructed accelerators for high power proton beam production: The cyclotron, linear accelerator and rapid-cycling synchrotron. The highest beam power of these accelerators currently is 1.4 MW. Reference [1] reported the energy efficiency of the three operational accelerators with the highest beam power in the world, which showed that the energy efficiency of the PSI cyclotron is about 2 times of the other types, as shown in Table 1. W. Weng made a judgement that the beam/grid efficiency should be better than 30%, otherwise the Accelerator Driven subcritical-reactor System (ADS) becomes nonsense [2]. Studies have shown that the energy efficiency cyclotron is the highest which is expected to be 60%~65% in superconducting ring cyclotron [3]. As cyclotron is a good technical route to develop proton machines with high beam power and high-power efficiency, it shows good prospect in advanced energy.

The beam power of UHPC-10 MW aims at 10 MW, it composes of two stages. The first stage is a 150 MeV/amu injector and the second stage is a 1 GeV/amu ring cyclotron. If UHPC-10 MW is used to drive a spallation neutron source, the injector and the ring cyclotron can produce thermal neutron flux in the order of 10^{14} n/cm^2/s and 10^{15}n/cm^2/s, respectively. UHPC-10 MW based spallation neutron source will have higher thermal neutron flux than high-flux reactor based neutron source. Even the 150MeV/amu injector can produce high thermal neutron flux which comparable to middle flux reactor neutron source. Figure 1 shows the history of thermal neutron flux [4], and UHPC-10 MW based spallation neutron sources are marked with stars.

* This work was supported by the National Natural Science Foundation of China (Grant No. 12105370) and the Scientific Research Program for Young Talent Elite Project of China National Nuclear Corporation (Grant No. FY212406000404).
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Table 1: Efficiency of different types of high-power accelerators.

Accel-eator	Type	Energy (MeV)	Power (MW)	Effi-ciency
SNS	Linac	1000	1.3	8.6%
JPARC	synchro-tron	3000	1.0	3%
SINQ	cyclotron	590	1.4	18%

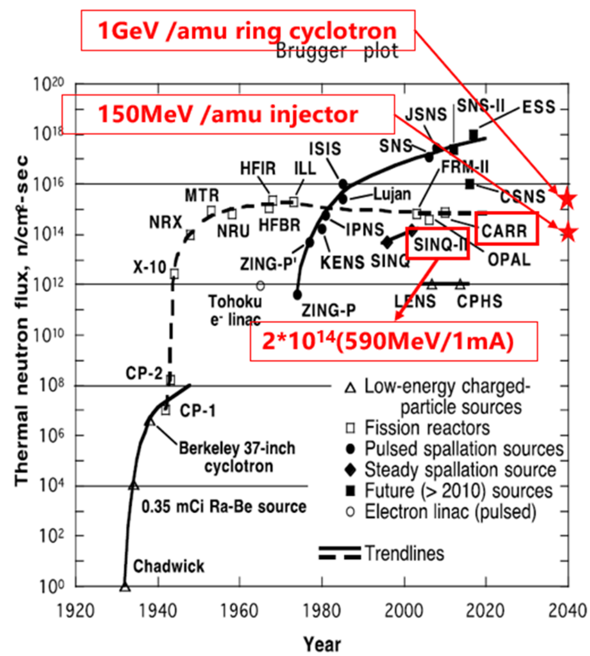

Figure 1: Thermal neutron flux history.

OVERALL DESIGN AND CONSIDERATION

Figure 2 shows the layout of UHPC-10MW. We choose a 1 MeV/amu RFQ as the pre-injector, and a separate sector cyclotron accelerate the beam from RFQ to 150 MeV/amu, finally the beam is injected to a 1 GeV/amu ring cyclotron.

Superconducting linac is the mainstream of high-power accelerator, due to relative higher technical maturity. So far, no well-approved design of 10 MW-class cyclotron is made due to some bottleneck problems. Radial tune is increasing linearly with beam energy in isochronous cyclotron, and thus the integer resonance crossing problem becomes an inevitable problem. Isochronous cyclotron is considered impossible to accelerate particles to a kinetic energy above its rest mass [5] typically 800 MeV/amu. Although cyclotron has continuous beam structure, the beam intensity is considered lower than 3 mA. The reason is enough clear region is need for beam extraction, otherwise the halo or tail particles will activate the deflector.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-FRA003

ENGINEERING DESIGN AND FABRICATION TECHNOLOGY FOR SUPERCONDUCTING MAGNETS IN CYCLOTRON

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Abstract

Magnets play an import role in cyclotrons. Application of superconducting magnets can make the cyclotron more compact, magnet field higher, and operation cost lower. In recent years superconducting cyclotrons is increasing number in heavy iron therapy application, and they are an easy and cheap way to get ion beams. As a superconducting magnet besides the electromagnetic design to meet the beam transport requirement, there are many special engineering design points, including mechanical, cooling, stability, safety, measurement and so on. To fabricate the superconducting magnets, especially those with specially winding shape and configuration, need to study the process including winding, resin vacuum pressure impregnation, superconductor welding, assembling and so on. This report describes the trends of superconducting magnet in cyclotron. Some projects and products developed in Bama Superconductive Tech Co. Ltd are also presented in this report,

INTRODUCTION

The applications of cyclotron accelerators have covered a number of research areas, such as for medical or industrial applications. One typical application of cyclotron as particle therapy system is shown in Fig 1. The basic modular of a particle therapy system include beam production system, beam transport system and beam delivery system. Magnets play import roles in each modular. In beam production system magnets are used in the cyclotron to accelerate the beam to designed energy level. In beam transport system magnet are used to guide the beam. In delivery system magnets are used to deliver the beam to the exact location of focal lesions.

Application of superconducting magnets can make the cyclotron more compact, magnet field higher, and operation cost lower. From 1982 the first external beam was extracted from the K500 cyclotron at MSU, cyclotrons based on superconducting magnets became a popular research field in science, research, medicine and so on. Especially in recent years superconducting cyclotrons is increasing number in heavy iron therapy application, and they are an easy and cheap way to get ion beams.

With the development of superconductive materials and superconducting magnet technology, many new design and fabricating technology are proposed. As a superconducting magnet besides the electromagnetic design to meet the beam transport requirement, there are many special engineering design points, including mechanical, cooling, stability, safety, measurement and so on. To fabricate the superconducting magnet, especially those with specially winding shape and configuration, need to study the process including winding, resin vacuum pressure impregnation, super-conductor welding, assembling and so on. This report describes the trends of superconducting magnet in cyclotron. Some projects and products developed in Bama Superconductive Tech Co. Ltd are also presented in this report.

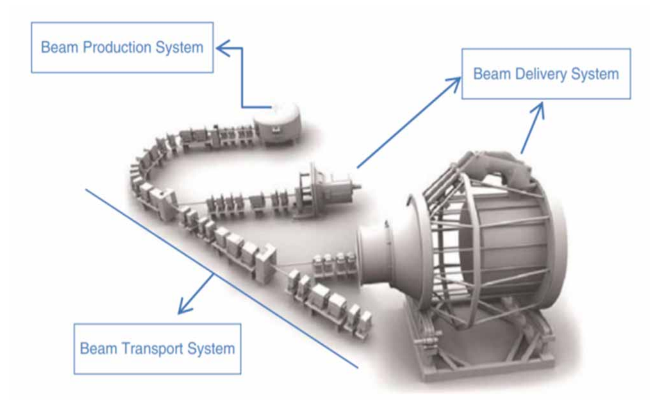

Figure 1: Basic modular design of particle therapy systems [1].

TRENDS OF SUPERCONDUCITNG MAGNETS IN CYCLOTRON

With the development of superconducting magnets technology and the requirement of particle therapy systems. Some new trends appeared in recent years.

Cryogen-free Superconducting Magnet

A superconducting azimuthally varying field (AVF) cyclotron, SC230, was developed for proton therapy by Sumitomo Heavy Industries, Ltd. in 2021. This isochronous cyclotron is compact owing to the high magnetic field generated by NbTi superconducting coils. The average magnetic field is 3.9 T at the outer region, and the extraction radius is 0.6 m. Because iron magnetization brings a limitation to iron-yoke isochronous cyclotrons, this SC230 SHI designed is probably at the lower limit in terms of weight and size. The coils are cryogen-free and cooled by conduction cooling using four 4 K-GM cryocoolers. The system is highly safe and easy to maintain, which reduces the effects of unstable helium supply. The heat inputs to the coils during beam operation are larger owing to the leakage radio frequency (RF) and beam loss are considered in detailed. The magnet is designed to have a sufficient temperature margin for stable operation. The coil temperature during the RF excitation is about 4.5 K. It was confirmed that the coil cools sufficiently at the critical temperature [2-3]. The schematic of the AVF cyclotron SC230 are shown in Fig. 2.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-FRBI01

DIFFERENT METHODS TO INCREASE THE TRANSMISSION IN CYCLOTRON-BASED PROTON THERAPY FACILITIES*

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Abstract

In proton therapy (PT), high dose rates could allow efficient utilization of motion mitigation techniques for moving targets, and potentially enhance normal tissue sparing due to the FLASH effect. Cyclotrons are currently the most common accelerator for PT, accounting for two-thirds of the total installations. However, for cyclotron-based facilities, high dose rates are difficult to reach for low-energy beams, which are generated by passing a high-energy beam through an energy degrader and an energy selection system (ESS); due to scattering and range straggling in the degrader, the emittance and energy/momentum spread increase significantly, incurring large losses from the cyclotron to the patient position. To solve these problems, we propose different options to transport the maximum acceptable emittance in both transverse planes (using new gantry beam optics, asymmetric collimators and/or scattering foil). We demonstrate in simulation that low-energy beam transmission can be increased up to a factor of 6 using these approaches compared to the currently used beamline and ESS. This concept is key to enhance the potential of PT by increasing the possibilities to treat new indications in current and future PT facilities while reducing the cost.

INTRODUCTION

The most advanced, and nowadays the most used method to deliver the dose is spot scanning or pencil beam scanning (PBS) [1]. Treatment delivery time with PBS PT depends both on the beam-on time and the dead time (the time required to change energy layers and/or lateral position) between pencil beams [2,3]. As such, PBS irradiation with high-intensity beams will reduce beam-on time and thus shorten total delivery times, making motion mitigation techniques such as breath-hold or gating more efficient and patient-friendly [4].

Most of the PT facilities use a cyclotron, which extracts proton beams at fixed energy (at PSI, we extract 250 MeV beam). However, to spread the dose over the depth of the tumor, different beam energies are needed for the treatment (70-230 MeV). In a cyclotron-based facility, the energy is lowered by passing the beam through energy-degrading material(s) (so-called energy degraders). However, due to scattering in the degrader, for low energy beams, the emittance after the degrader is in the range of a few hundred of π*mm*mrad. Additionally, due to range straggling in the degrader, the momentum spread of the beam will also increase. Therefore, to minimize beam losses in the beamline, it is necessary to use beam emittance selection collimators after the degrader and momentum selection slits in the energy selection system (ESS) to restrict the emittance and momentum spread to the requirement of the following beamline or gantry. Currently, all cyclotron-based PT facilities transport a maximum emittance of 30 π*mm*mrad through the beamline, which limits the transmission of low-energy beams. For example, for the lower energies transported by the Gantry 2 at our institute (70-100 MeV), transmission from the cyclotron to the isocenter is of the order of only 0.1% [5,6,7,8].

Therefore, to limit the losses in the beamline, in this paper, we are providing a summary of different ways to efficiently transport higher emittance through the beamline.

First, we propose the use of a large beam size and low divergence beam at the coupling point (CP) along with an imaging factor of 0.5 (2:1) in a new design of gantry beam optics to transport higher emittance through gantry while achieving higher transmission and thus increase beam intensity at the isocenter. Secondly, we propose the use of scattering foil to achieve the same emittance in both planes at the entrance of the gantry while transporting maximum acceptable emittance in both planes from the degrader, thus ensuring gantry angle-independent beam shape at the isocenter. In the end, to maximize the emittance transport through both transverse planes, we propose to use a collimation system, asymmetric in both beam size and divergence, resulting in symmetric emittance in both beam transverse planes as required for a gantry system.

This study was performed as a collaborative doctoral project between the center for proton therapy and a large accelerator facility group at PSI and published in [5,6,7,9,10,11]. In the following, all beam sizes, divergences, and emittances are expressed as 2-sigma values.

TRANSMISSION OPTIMIZATION THROUGH GANTRY

Conventional beam optics of cyclotron-based proton gantries were designed to provide point-to-point focusing in both planes, with an imaging factor of between 1 to 2 from

* THIS WORK IS SUPPORTED BY A PSI INTER-DEPARTMENTAL FUNDING INITIATIVE (CROSS)
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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-FRBI02

DESIGN OF A SPIRAL INFLECTOR AT iTHEMBA LABS FOR INJECTING THE BEAM INTO A CYCLOTRON

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Abstract

Using a Belmont-Pabot spiral inflector for axial beam injection presents difficulties when matching the beam emittance to the cyclotron acceptance. For an electrostatic inflector one of the potential solutions to this problem is to use transverse electric field gradients to influence and optimise the optics. Here we extend this approach to magnetic spiral inflectors. It is demonstrated that the gradient of the magnetic field along the central trajectory can be controlled by an appropriate permanent magnet inflector design, and that these gradients have a large influence on the optics. The transverse gradients are numerically optimised and the performance compared to an optimised electrostatic spiral inflector. A faster numerical method for accurately determining the electric field of an electrostatic inflector is also presented.

INTRODUCTION

Traditional Belmont-Pabot spiral inflectors suffer from a large vertical divergence, and in addition to this the transverse-longitudinal coupling results in a de-bunching longitudinal spread [1]. Both of these issues decrease the transmission of the cyclotron. Recent attempts at addressing these problems at several cyclotron facilities have made use of transverse electric field gradients along the central path to attempt to influence the optics and focus the beam [2-5]. In previous work [1] we have shown that in the most general case the electric potential can be described, to second order in the transverse displacements, by:

$$\phi = -u_r E_0 - Q_1 E_0 \frac{u_r^2 - h_r^2}{2} - Q_2 E_0 h_r u_r - \frac{u_r^2}{2} \hat{s}' \cdot \boldsymbol{E}_0$$

Where $Q_1(s)$ and $Q_2(s)$ are quadrupole parameters, and may be freely selected by an inflector designer. The coordinates $(u_r, h_r s)$ are the standard rotated coordinates used in spiral inflector design, where the electric field points in the $\hat{u}_r$ direction. The corresponding electric fields are then:

$$E_{u_r} = E_0 + u_r(Q_1 E_0 + \hat{s}' \cdot \boldsymbol{E}_0) + h_r Q_2 E_0 \quad \text{(1a)}$$

$$E_{h_r} = u_r Q_2 E_0 - h_r Q_1 E_0 \quad \text{(1b)}$$

$$E_s = u_r E_0' - h_r \kappa_s E_0 \quad \text{(1c)}$$

By numerically optimising the two free quadrupole parameters $Q_1(s), Q_2(s)$ an inflector design was obtained that showed good vertical and longitudinal performance. This device was constructed and experimentally shown to improve the transmission through the Solid Pole Cyclotron 2 (SPC2) at iThemba LABS by 60%.

In this article the application of a similar optimisation process to a permanent magnet spiral inflector is presented.

FASTER NUMERICAL METHOD

Optimisation of an electrostatic inflector design involves repeated numerical computations of the electric field, for a great number of proposed inflectors. This was previously done using TOSCA, which required about an hour per inflector. To speed this up in the past a method was used to estimate the electric field, by combining the results from a number of pre-calculated TOSCA simulations and linearly extrapolating [5]. This method could compute the transfer matrix of a new inflector within about 5 seconds, but lacked accuracy.

A new numerical method was therefore developed that is able to accurately compute the inflector transfer matrix in a short time (about 4 seconds). It is based on calculating the surface charge density on the inflector electrodes, by minimising the potential energy.

Suppose that the inflector surface has been divided into approximate squares, of side length L_i and containing a charge q_i per square. Such a meshing of the electrodes is shown in Fig. 1.

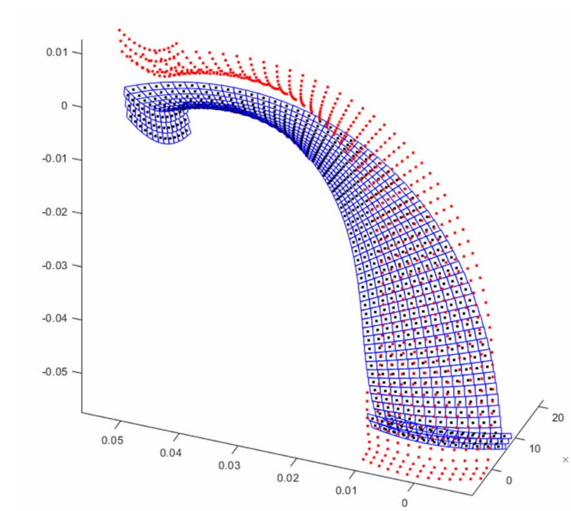

Figure 1: Square meshing of the negative electrode, also showing the centroids of the squares on both electrodes.

The total potential energy can be expressed as:

$$U = \frac{1}{2} \boldsymbol{q} \cdot \boldsymbol{V}_q + \boldsymbol{q} \cdot \boldsymbol{V}_E$$

Where $\boldsymbol{V}_q$ is the voltage due to the surface charges and $\boldsymbol{V}_E$ is an externally applied voltage. We write the voltage as $\boldsymbol{V}_q = D\boldsymbol{q}$ where:

$$D_{ij} = \frac{f_{ij}}{4\pi\epsilon_0 |\boldsymbol{r}_i - \boldsymbol{r}_j|}$$

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ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-FRB003

THE STUDY OF THE ISOCHRONOUS MAGNETIC FIELD AND THE EQUILIBRIUM ORBIT OF CS-30 CYCLOTRON

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Abstract

The CS-30 accelerator of the Institute of Nuclear Science and Technology of Sichuan University is a three-fan accelerator with constant angular width (45 degrees) at small radius and blade thickness increasing with radius at larger radius. In this paper, the magnetic field is analyzed, and the static equilibrium orbit, revolution frequency, oscillation frequencies and other data are calculated. These functions can be integrated to guide the accurate magnet numerical model setup of the existing CS-30 accelerator, which can be used in de education demonstration and experimental phenomena analysis. The optimization algorithm is innovatively introduced in the static equilibrium orbit calculation, which reduces the dependence of the results on the initial value and significantly improves the calculation speed. The calculation method presented in this paper is suitable for all cyclotron.

INTRODUCTION

CS-30 is produced by TCC Company in the United States and introduced by the State Science and Technology Commission in February 1984. It is the first cyclotron with compact structure introduced from abroad in China. In 2003, the cyclotron was moved from Beijing to the Institute of Nuclear Science and Technology of Sichuan University. After one year of installation and tuning, proton beams and α ions were accelerated to the internal target. After then it was routinely in operation and provide beams for experimental more than 100 hours per year. Now, it's mainly be used to produce isotopes, study irradiation effect of materials, and teaching demonstration device. Its application was limited by the absence of the external target system. The extraction elements are works well, what we need to extract the beam out of the cyclotron are just the beam line and the target station. Recently a beam line will be built and an external He^{2+} radiation target station will be built, which can significantly expend the application of the cyclotron. Since we never extract beam out before and lack of the data of the extraction elements settings, we need to study the beam dynamics properties to guide us in finding them. In order to do this, we need setup the numerical model of the cyclotron, so that we can get the detailed magnetic field distribution, which can be used in beam dynamics analysis. At the same time, the numerical model can also be used in the education.

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METHODS AND MODEL

The 3D model of CS-30 magnet is shown in Fig. 1. The only thing we are not sure is the height of the steps on the fan, which are used to get the final isochronous magnetic field. In order to find the right number of the steps height, we need to analysis the magnetic field calculated from the model. If it is the isochronous, then the model is right; if it is not, we need to change the steps height until the isochronous field is obtained.

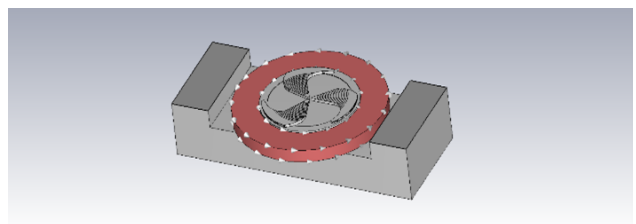

Figure 1: 3D model of the cyclotron magnet.

The magnetic induction intensity of CS-30 is shown in Fig. 2. To analyze the magnetic field. The most important thing is to calculate the equilibrium orbits. There are two main methods to calculate the equilibrium orbit. The first is the analytical method, which makes Fourier expansion of the magnetic field along the azimuth angle, and obtains the analytical solution under the first order approximation; the second is the numerical method, which is solved by the integral formula.

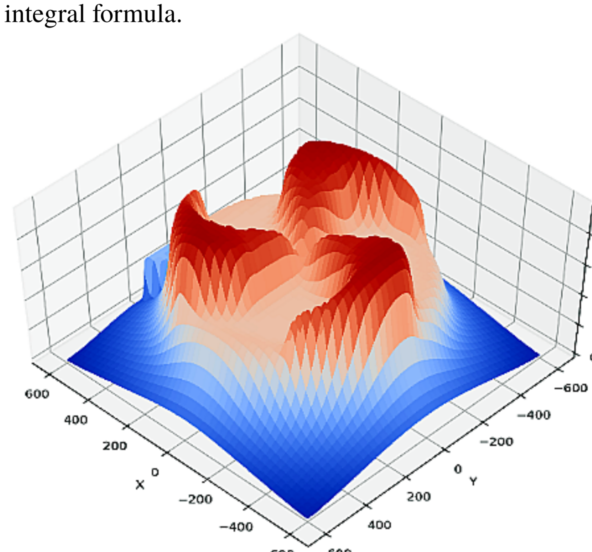

Figure 2: Magnetic induction intensity.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-FRB004

ERROR MAGNETIC FIELD DUE TO THE MEDIAN PLANE ASYMMETRY AND ITS APPLICATIONS IN THE CYCLOTRON

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Abstract

Cyclotrons have a median plane symmetric structure. But the pole's geometric error and the unevenly magnetized soft iron give rise to non-zero asymmetrical fields in the geometric median plane. The asymmetric field can shift the vertical position of the beam. Moreover, The error of the tilted median plane can be the driving force when the tunes pass through coupling resonances. In this paper, we take the TRIUMF 500 MeV cyclotron as an example to study the asymmetric field resulting from imperfect median plane symmetry. An approach due to M. Gordon, and a highly accurate compact finite differentiation method are used to investigate the historical field survey data, which reveals redundancy in the survey data. The redundancy was used in this study to correct the error in the measurement data. Further, the median plane asymmetry field could be manipulated using trim coils or harmonic coils with top and bottom coil currents in opposite directions ('Br-mode'). Using the created asymmetric field, we improved the vertical tune measurement method to investigate the linear coupling resonance in TRIUMF 500 MeV cyclotron. Eventually, the coupling resonance is corrected and avoided using the available harmonic coils and trim coils.

INTRODUCTION

The median plane asymmetric field in a small gap cyclotron or cyclotron with a high magnetic field is usually negligible, and in that case, the surveyed or calculated axial field B_z in the median plane is usually sufficient for the beam dynamics study. But for a large gap magnet with low magnetic field, such as the TRIUMF 500 MeV cyclotron, the asymmetric field can significantly shift the vertical position of the beam. Moreover, the error of the tilted median plane can be the driving force when the tunes pass through coupling resonances [1]. To study the effect of the asymmetric field on the beam dynamics, only the field survey data can be used while the finite element analysis calculation can not reveal the pole machining errors and the variations of material properties of the steel. Using Gordon's field expansion technique [2], we have discovered self-consistency errors in these field data. However, these are easily and convincingly corrected, as will be shown. After correcting the errors in the measurement data, we recalculated the properties of static equilibrium orbits. Further, we have optimized the trim coils' settings to achieve a better beam vertical centering.

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FIELD EXPANSION OUT OF MEDIAN PLANE: GORDON'S APPROACH

The magnetic field map must satisfy Maxwell's equations to sufficient order. In a cyclotron, a typical way is to expand the field relative to the median plane. Gordon's approach is one of these; it is derived from the scalar potential Ψ that satisfies Laplace's equation. By solving the 3D Laplace equation using an operator trick, we get the potential Ψ expanded in powers of axial position z as follows [2]

$$\begin{aligned}\Psi &= \Psi_o + \Psi_e,\\ \Psi_o &= zB - \frac{z^3}{3!}\nabla_2^2 B + \frac{z^5}{5!}\nabla_2^4 B - \ldots,\\ \Psi_e &= C - \frac{z^2}{2!}\nabla_2^2 C + \frac{z^4}{4!}\nabla_2^4 C - \ldots,\end{aligned} \tag{1}$$

where $B = B(r,\theta)$ and $C = C(r,\theta)$, and where ∇_2^2 is the 2-dimensional Laplace operator

$$\nabla_2^2\Psi = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\Psi}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2\Psi}{\partial\theta^2}. \tag{2}$$

Thus, for example, $\nabla^2\Psi = \frac{\partial^2\Psi}{\partial z^2} + \nabla_2^2\Psi = 0$.

The odd term Ψ_o produces a field with median plane symmetry, while the even term Ψ_e spoils this symmetry. The magnetic field is given by $\vec{B} = -\nabla\Psi$, that is

$$\begin{aligned}B_z &= -B + z\nabla_2^2 C + \frac{z^2}{2!}\nabla_2^2 B - \frac{z^3}{3!}\nabla_2^4 C - \frac{z^4}{4!}\nabla_2^4 B + \ldots,\\ B_r &= -\frac{\partial C}{\partial r} - z\frac{\partial B}{\partial r} + \frac{z^2}{2!}\frac{\partial\nabla_2^2 C}{\partial r} + \frac{z^3}{3!}\frac{\partial\nabla_2^2 B}{\partial r} - \ldots,\\ rB_\theta &= -\frac{\partial C}{\partial\theta} - z\frac{\partial B}{\partial\theta} + \frac{z^2}{2!}\frac{\partial\nabla_2^2 C}{\partial\theta} + \frac{z^3}{3!}\frac{\partial\nabla_2^2 B}{\partial\theta} - \ldots.\end{aligned} \tag{3}$$

In most orbit programs, C is ignored and only the zero-order B_z value and the first-order B_r and B_θ values are used. This is acceptable only for z very small compared with the magnet gap since it violates $\nabla\cdot\vec{B} = 0$ and can therefore lead to non-physical results for finite z values. This can be remedied by including the z^2 term in B_z. In general, when B_r and B_θ are given to order z^n, then B_z should be given to order z^{n+1}.

Ignoring C is appropriate in the initial design stage of a cyclotron, but not for finding tolerances for manufacturing errors, nor for detailed investigations of orbit excursions and resonance crossings in an as-built cyclotron. In the TRIUMF cyclotron, the vertical closed orbit excursion is as large as ±1.3 cm even after correction, as shown below. In a synchrotron, the closed orbit distortion is corrected with