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NUCLEAR PHYSICS RESEARCH AT HEAVY ION ACCELERATORS: PRECISION STUDIES WITH STORED AND COOLED EXOTIC NUCLEI

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Abstract

This contribution is based on the plenary presentation at the 14th International Conference on Heavy Ion Accelerator Technology (HIAT-2018) in Lanzhou, China.

Heavy-ion storage rings offer unparalleled opportunities for precision experiments in realm of nuclear structure, atomic- and astrophysics. A brief somewhat biased review of the presently ongoing research programs is given as well as the future projects are outlined. The limited space does not allow for detailed description of individual experiments, which shall – to some extent – be compensated by extended bibliography.

INTRODUCTION

Atomic nuclei are many-body systems which are composed of two types of quantum mechanical particles protons and neutrons. The strong, weak and electromagnetic fundamental interactions are in play in the nuclei, which makes them extremely complex systems to describe. However, the nuclei are "natural laboratories" themselves, by studying which one learns about underlaying fundamental interactions. The latter determine our world to be as it is and are thus the very reason for us to study them as good as we can.

Nuclear physics is more than 100 years old and is still one of the rapidly developing fields of research. This development is made possible by the progress in accelerator concepts and detector technologies, as were discussed *e.g.* at this conference. Today, scientists have created in laboratory about 3000 nuclides [1]. However, about 7000 nuclides are expected to exist with majority of yet unknown nuclei belonging to neutron-rich systems [2]. The path of the rapid-neutron capture process of element synthesis in cosmos is expected to be in this region [3–5]. There, the nuclear structure at large proton to neutron asymmetries is expected to change dramatically [6]. For instance, the nuclear shells in light neutron-rich nuclei are at different neutron numbers than the magic numbers established at stability [7, 8].

New-generation accelerator facilities aim at reaching further into the unknown nuclear territory. However, the yet unknown nuclei have extremely small production cross sections and short lifetimes [9]. Sophisticated experimental techniques are needed to be able to produce and handle them, especially if their precision studies are aimed for. Here, heavy-ion storage rings coupled to radioactive ion beam facilities offer unique capabilities [10].

EXISTING HEAVY-ION STORAGE RINGS

If focusing on the radioactive-ion beam facilities, there are presently three operational heavy-ion storage rings [11]. These are the Experimental Storage Ring (ESR) at GSI [12], the experimental Cooler-Storage Ring (CSRe) at IMP [13], and the Rare RI Ring (R3) Facility at RIKEN [14].

Historically the first, the ESR at GSI is in operation with radioactive beams since 1992 [15, 16]. There, the exotic nuclei are produced at the Fragment Separator FRS [17] through fragmentation or in-flight fission of primary beams accelerated by the heavy-ion synchrotron SIS. The exotic nuclei are produced at high energies such that they emerge the production target as highly charged ions (HCI) [18–21]. The FRS can either be used as a pure magnetic rigidity ($B\rho$) analyser efficiently transmitting all produced nuclides within its $B\rho$ acceptance or, if a specially shaped degrader is employed, a pure mono-isotopic beam can be prepared by means of $B\rho - \Delta E - B\rho$ separation method, where ΔE stands for the energy loss in the degrader material. Also a direct, bypassing the FRS, injection into the ESR of primary and intense secondary beams is possible [22].

The ESR is a versatile machine offering numerous and flexible beam manipulation options. The ESR can store ions in a broad range of energies from about 3 A MeV to about 420 A MeV, corresponding to the maximum $B\rho(\text{ESR})$ = 10 Tm. The average rest gas pressure of the ring is about 10^{-10} – 10^{-11} mbar. Such ultra-high vacuum environment sets strict constraints on experimental equipment that can be brought inside the vacuum.

Indispensable for experiments is the ability of cooling the secondary beams. The latter is especially important for radioactive beams which inevitably have a large momentum spread due to nuclear reaction process. Electron [23] and stochastic [24] cooling systems are routinely available.

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ADVANCES OF THE FRIB PROJECT*

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Abstract

The Facility for Rare Isotope Beams (FRIB) Project has entered the phase of beam commissioning starting from the room-temperature front end and the superconducting linac segment of first three cryomodules. With the newly commissioned helium refrigeration system supplying 4.5 K liquid helium to the quarter-wave resonators and solenoids, the FRIB accelerator team achieved the sectional key performance parameters as designed ahead of schedule. We also validated machine protection and personnel protection systems that will be crucial to the next phase of commissioning. FRIB is on track towards a national user facility at the power frontier with a beam power two orders of magnitude higher than operating heavy-ion facilities. This paper summarizes the status of accelerator design, technology development, construction, commissioning, as well as path to operations and upgrades.

INTRODUCTION

The FRIB project started technical construction at the Michigan State University in August 2014 [1]. Three years later, the project entered the stage of phased commissioning with the heavy ion beams (Ar and Kr) following the completion of the room temperature part of the front end, as shown in Fig. 1 and Table 1. In this paper, we present the main results of the first two stages of beam commissioning that have been completed covering nearly all major accelerator systems including the electron cyclotron resonance (ECR) ion source, the Radio-frequency quadrupole (RFQ), the cryomodules of β=0.041 quarter-wave resonators, the liquid helium refrigeration plant operating at 4 K temperature, and supporting systems including RF, power supply, diagnostics, vacuum, hardware and high level controls, machine protection, personnel protection, physics applications and integration.

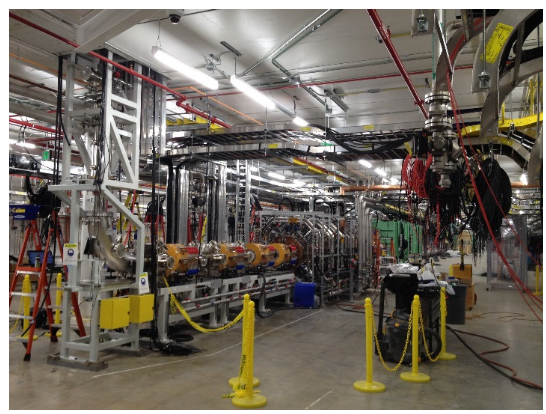

Figure 1: FRIB driver linac viewed from the lower LEBT towards the superconducting linac in the accelerator tunnel at the beginning of beam commissioning in 2017.

Table 1: Stages of Accelerator Readiness (ARR) for the Phased Beam Commissioning of the FRIB Accelerator

Phase	Area with beam	Date
ARR1	Front end	2017-7
ARR2	Plus β=0.041 cryomodules	2018-5
ARR3	Plus β=0.085 cryomodules	2019-2
	Plus lithium charge stripper	2020-7
ARR4/5	Plus β=0.29, 0.53 cryomodules	2020-12
ARR6	Plus target and beam dump	2021-9

Subsequently, we discuss resolutions to some leading technical issues including low-sensitivity loss detection and machine protection, charge stripping with liquid metal, and microphonics suppression. We continue with status reports on infrastructure build-up of the MSU cryogenics initiative and the superconducting RF (SRF) Highbay. We conclude with challenges in the beam power ramp up and the path forward of beam energy upgrade.

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STATUS OF THE SPES EXOTIC BEAM FACILITY

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Abstract

At Legnaro National Laboratories of INFN it is under construction a Rare Isotope Facility called "Selective Production of Exotic Species" (SPES) based on a 35-70 MeV proton cyclotron, able to deliver two beams with a total current up to 0.75 mA, an ISOL fission target station and an existing ALPI superconducting accelerator as a post accelerator (up to 10 MeV/u for A/q=7). The paper will cover notably: the high-resolution mass separator, the CW RFQ (80 MHz, 727 keV/u, with internal bunching), the 1+ low energy transfer line and the injection line from Charge Breeder to ALPI under installation.

INTRODUCTION

SPES, acronym of Selective Production of Exotic Species, is a CW radioactive ion beam facility under construction at LNL INFN in Italy. It will produce and accelerate neutron-rich radioactive ions, to perform nuclear physics experiments, which will require beams above Coulomb barrier [1].

The main functional steps of the facility are shown in Fig. 1: the primary beam delivered by the cyclotron, the beam from the fission target (as an example, up to 10^{13} particle/s of ^{132}Sn), the beam cooler, the separators, the charge breeder and the accelerator (the existing ALPI with a new RFQ injector). The use of the continuous beam from the +1 source, which can use different configuration types LIS, PIS, SIS, maximizes the RNB efficiency but need a CW post accelerator (RFQ and ALPI). The beam is prepared for the post-accelerator stage with a charge breeder device. The energy from 20 to 40 kV on the transfer lines are determined by the chosen RFQ input energy (5.7 keV/u); for this reason, all the devices where the beam is approximately stopped (production target, charge breeder and RFQ cooler) lay at a voltage proportional to the ratio A/q. The charge state range (3.5<A/q<7) is bounded by the RFQ field level for the upper limit and by the minimum voltage on q=1 transport line.

THE CYCLOTRON AS PRIMARY DRIVER FOR SPES AND TARGET

The proton beam is accelerated by a 35÷70 MeV, 700 μA commercial cyclotron C70 (Best Cyclotron Systems Inc.). It offers simultaneous double extraction from two 180° apart exit ports, to be used for both fundamental nuclear science and medical and material research [2].

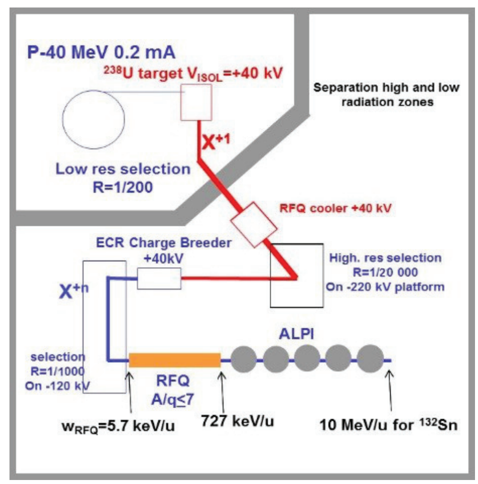

Figure 1: functional scheme of the SPES facility. There are two main areas: the 1+ line and the n+ line, where 1+ and n+ indicates the beam charge state.

C70 is an Azimuthally Varying Field (AVF) compact cyclotron with four sectors, with the main magnet energized by resistive coils.

Protons are extracted by H- stripping the electrons in a thin graphite foil. Installation and successful commissioning were accomplished in 2015-2017, driving the beam to a home designed and built beam dump.

Stability and reliability tests of C70 were conducted: e.g. in 5 days long run at 40 MeV, the average beam current was 201.18±0.97 μA. Tests were then extended to 70 MeV - 500 μA with good stability and repeatability. Dual extraction was proven as well.

The cyclotron will impinge the production target (7 properly spaced UCx discs, 40 mm diameter, 0,8 mm thick), generating about 10^13 fissions/s. RA isotopes produced by the 238U fissions are delivered to the 1+ ion source where they are ionized and accelerated to 20÷40 keV.

The target box must be kept a temperature of 2000÷2200 °C in vacuum to enhance RA isotope mobility, extraction and ionization. This temperature is achieved by combining

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PRESENT STATUS OF HIRFL COMPLEX IN LANZHOU*

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Abstract

Heavy Ion Research Facility in Lanzhou (HIRFL) is a cyclotron, synchrotron and storage ring accelerator complex, which accelerates ions of hydrogen to uranium from low to medium energy. Since the complete of HIRFL-CSR project in 2008, under the support from CAS, efforts have been put to improve the infrastructure for machine performance, including improvement of EMC environments, power distribution stations, PS stations, cooling water system, RF system of cyclotrons and adoption of EPICS control system, etc. New generation SC ECR source-SECRAL2 with high performance is put into operation. Experiments of electron cooling with pulsed electron beam are performed for the 1st time. Stochastic cooling and laser cooling are realized in CSRe. The performance of RIBLL2 and CSRe are gradually improved. The ISO mode of CSRe for precise atomic mass measurements is well studied and reaches state-of-art mass resolution of storage rings. The operation status and enhancement plan of HIRFL will be briefly reported in this paper.

INTRODUCTION

HIRFL[1,2] is one of the largest heavy ion research facility in China. It belongs to the National Laboratory of Heavy Ion Accelerator, which was established in 1991, at Institute of Modern Physics (IMP). HIRFL serves for the scientific researches in nuclear physics, atomic physics and nuclear science related interdisciplinary study.

HIRFL consists of two cyclotrons (SFC and SSC), one synchrotron (CSRm) and one storage ring spectrometer (CSRe), in chain, see Fig. 1. The SFC cyclotron was constructed in 1960s for light ions. It's upgraded in 1980s to accelerate heavy ions from hydrogen to uranium, as required to be an injector of cyclotron SSC. The CSR project, CSRm and CSRe are the major components, was constructed at the turn of this century, for higher energy pulsed beam and precise nuclear physics and atomic physics study at external target and in ring.

Within the half century construction period, the infrastructure of HIRFL has been improved gradually according to the development of technology. In recent years, under the strong support of the maintenance and renovation budget from CAS, we upgraded the power station of HIRFL, LLRF of cyclotrons, water-cooling systems [3] and intra-network; built up the environment control of power supply room of CSR and the monitoring systems of water-cooling, power station and water leakage detection; rearranged and rewired the cables of CSRe to improve the EMC condition of CSRe. Above all, new generation superconductive ECR source SECRAL-II as a back-up of SECRAL with better performance was constructed and put into operation this year [4,5]; EPICS was introduced to take over most of the control system [6].

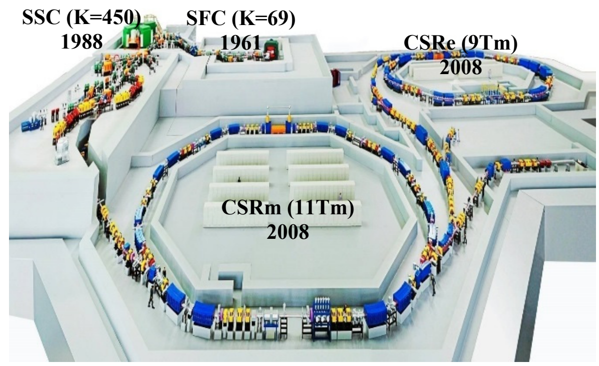

Figure 1: The layout of HIRFL complex.

To improve the performance of HIRFL, new technologies are researched and developed. Experiments of electron cooling with pulsed electron beam are performed for the 1st time for the development of e-coolers at future circular accelerator. The performance of RIBLL2 as on-line separator of secondary beams was gradually improved. The ISO mode of CSRe for precise atomic mass measurements is well studied and reaches state-of-art mass resolution of storage rings with unique two-TOF velocity measurement setups. The Stochastic cooling and laser cooling are realized in CSRe, which will help to extend the research ability of nuclear and atomic physics at CSRe.

Up to now, SFC is the only injector for both SSC and CSRm. This limited the total beam time of the HIRFL complex. To increase the beam time, new injectors are urgently needed. Under the support of CAS and IMP, a DC Linac injector of SSC is being developed since 2012, which will accelerator heavy ion beam to 1.024 MeV/u. New pulse Linac injector for direct injection to CSRm is designed and underdevelopment. With the new injectors the beam time for experiments will be increased dramatically.

OPERATION STATUS OF HIRFL

In last 5 years, the beam time requirement of HIRFL is increasing rapidly. New growth points mainly from anti-radiation testing and reinforcement study of circuits, pile radiation material study, production of super-heavy elements and experiments at storage rings. The machine time and beam time of HIRFL averaged to more than 7500 h/a and 5300 h/a separately. The failure time averaged to less than 250 h/a. With the only injector cyclotron SFC, beam time reached it's up-limit. Among the beam time provided, about 54 % is for nuclear physics and atomic physics, 16

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STATUS OF JINR FLNR CYCLOTRONS

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Abstract

Status of JINR FLNR cyclotrons and plans of their modernization together with plans on creation of new facilities will be reported. At present, three cyclotrons: U400, U400M and IC100 and MT-25 microtron are under operation at the JINR FLNR. U400 and U400M are the basic FLNR facilities that both are under operation is about 12000 hours per year. The U400 (pole diameter of D=4 m) was designed to accelerate ions from B to Bi up to 19 MeV/u. U400 reconstruction is planned. The U400M cyclotron (D=4 m) is used to accelerate ions from Li to Xe up to 60 MeV/u. U400M modernization is planned. The IC100 accelerator (D=1m) is used for applied researches with Ar, Kr and Xe ions at energy of 1.2 MeV/u. Creation of the dedicated DC-130 cyclotron (D=2m) with ion energies of 4.5 and 2 MeV/u is planned on the base of U200 cyclotron. The Super Heavy Element Factory (SHE factory) is the new FLNR JINR project. The DC-280 cyclotron (D=4 m) is the basic facility of the SHE factory, which will accelerate ions with energies 4 - 8 MeV/u cyclotron at intensities up to 10 pmkA for ion masses over A=50. The main systems of the DC-280 were assembled and tested, the cyclotron is preparing for commissioning.

INTRODUCTION

The scientific program of the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research (FLNR JINR) consists of experiments on synthesis of heavy and exotic nuclei using ion beams of stable and radioactive isotopes and studies of nuclear reactions, acceleration technology and applied research.

Presently, the FLNR JINR has four cyclotrons of heavy ions: U400, U400M, IC100 (IC-100), that provide performance of the basic and applied researches (Fig. 1). Total annual operating time of the U400 and U400M cyclotrons is more than 10000 for many years (Fig. 2).

The old U200 cyclotron will be reconstructed to the DC130 cyclotron for applied research.

At present time, the project of Super Heavy Element Factory is being performed at the FLNR JINR [1]. The project implies design and creation of the new experimental building with new DC280 cyclotron which has to provide intensities of ion beams with middle atomic masses (A~50) up to 10 pμA.

U400 CYCLOTRON

The isochronous U400 cyclotron has been in operation since 1978. [2] The cyclotron produces ion beams of atomic masses 4÷209 with energies of 3÷29 MeV/nucleon. Before 2017 about 66% of the total time has been used for acceleration of $^{48}Ca^{5+}$ ions with intensities up to 1.2 pμA for synthesis of super heavy elements. New prospects for the synthesis of super heavy elements may appear to be connected with the usage of the intense beam of neutron-rich ^{50}Ti. The beam of $^{50}Ti^{5+}$ ions has been accelerated into the U400 cyclotron with extracted beam intensity is about 0.5 pμA [3]. In 2017, about 40% of the total time was used for $^{50}Ti^{5+}$ acceleration.

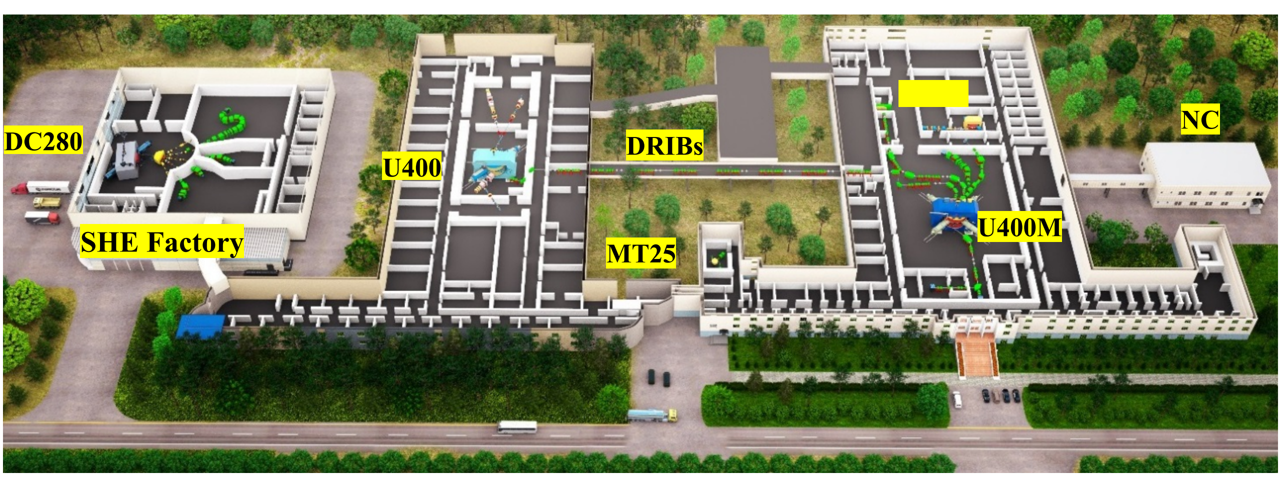

Figure 1: The layout of the Flerov Laboratory buildings, where: U400, U400M, IC100, DC280 are heavy ion cyclotrons, MT25 is microtron, SHE Factory is Super Heavy Element Factory, NC is Nanotechnology Centre.

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HIGH VOLTAGE PERFORMANCE DEGRADATION OF THE 14UD TANDEM ACCELERATOR*

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Abstract

The 14UD at the Australian National University's Heavy Ion Accelerator Facility (HIAF) operated at a maximum voltage of 15.5 MV after the installation of tubes with a compressed geometry in the 1990s. In recent years, the performance of the accelerator has shown a gradual decline to a maximum operation voltage of ~14.5 MV. There are some fundamental factors that limit the high voltage performance, such as SF_6 gas pressure, field enhancement due to triple junctions and total voltage effect. In addition, there are non-fundamental factors causing high voltage degradation. These are: operation with faulty ceramic gaps; operation at inappropriate voltage and SF_6 pressure combinations; SF_6 leaks into the vacuum space; use of SF_6 and O_2 as a stripper gases; poor electron suppression in the high energy stripper and frequent use of highly reactive ions such as sulphur and fluorine. In this paper we will discuss factors that limit the high voltage performance. The main outcomes of a preliminary investigation of titanium (Ti) electrodes removed from the accelerator after a few decades of operation will be reported. The investigation confirmed contamination of Ti electrodes with unstable films containing traces of oxides, sulphur and fluorine. The rehabilitation strategies for the accelerator will be discussed.

INTRODUCTION

The Heavy Ion Accelerator Facility (HIAF) at the Australian National University (ANU) operates a National Electrostatics Corporation (NEC) 14UD pelletron tandem electrostatic particle accelerator [1]. This accelerator has been in operation for over forty years after the first successful experiment in 1974. The original configuration used corona voltage distribution system, in which a maximum voltage of 14.8 MV was achieved for experiments in 1981. However, there was a consistent deterioration from this level that eventually lead to an examination of aging effects [2] and a major accelerator upgrade in around 1990 [3].

This upgrade was comprised of two components. The first was the installation of "compressed geometry" acceleration tubes that removed dead space and allowed the installation of additional acceleration tubes thereby reducing the field across each insulating gap. The second replaced the corona voltage distribution system that was causing corrosion of accelerator components [4] with a resistor grading system. With these upgrades, a peak conditioning voltage of 16.7 MV was achieved, with experiments performed at 15.5 MV. However, the maximum voltage available for experiments has now degraded to around 14.5 MV.

Since January 2016, the 14UD has had voltage on its terminal for 56% of the total time, with 16% of the time spent on major accelerator maintenance and repairs. Of the time with terminal volts, 27% has been with terminal volts above 13.5 MV.

Even with continued operation near or above the original design voltage of the 14UD, user demand for both operational time and even higher terminal voltages is increasing. Therefore, the degradation mechanisms of the 14UD should be understood in order to extend the useful life of the accelerator.

HIGH-VOLTAGE BREAKDOWN

Mechanical issues in an electrostatic accelerator can be readily dealt with, but it is the electrical breakdown mechanisms of the insulating gas and vacuum spaces that determine the limits on high-voltage performance. A thorough review of the mechanisms – and the damage created – is provided in [5] and discussed here with specific reference to the ANU 14UD.

SF_6 Breakdown

The insulating space between the accelerator column and the containing pressure vessel of the 14UD is filled with approximately 22 tonnes of sulphur hexafluoride (SF_6) gas at a pressure of 100 psia. Although considered to be inert, chemical reactions during and after electrical breakdown of SF_6 create long-lived toxic and corrosive by-products [6, 7].

The basic reaction scheme, even in high purity SF_6, is [8]:

$$SF_6 \rightarrow SF_4 + 2F \quad (1)$$

$$SF_4 + H_2O \rightarrow SOF_2 + 2HF \quad (2)$$

$$SOF_2 + H_2O \rightarrow SO_2 + 2HF \quad (3)$$

$$2F + M \rightarrow MF_n \quad (4)$$

where M is any exposed metal such as titanium electrodes or aluminium structural components. The breakdown product yield is influenced by the SF_6 pressure, H_2O content and spark discharge energy [6, 9].

In the era of corona voltage distribution in the 14UD, hydrofluoric acid (HF) products in particular may have caused repeated fracturing of the nylon links in the pelletron chains [4]. A move to resistor voltage distribution configurations ameliorated the problem, but the use of corona terminal voltage stabilisation and arc discharges of the terminal voltage between accelerator electrodes and to the

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MEASUREMENT FACILITY AND TEST RESULTS FOR FRIB SUPERCONDUCTING MAGNETS AT IMP

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Abstract

The superconducting magnets of the Facility of Rare Isotope Beams (FRIB) are used to focus and steer the heavy ion beams of the driver linac. All the magnets are designed as a solenoid with bucking coils to suppress the stray field. And all of the magnets have superconducting dipole correctors to steer both horizontal and vertical field. Two types of magnets are manufactured in China and most of them have been tested at Institute of Modern Physics (IMP). This paper describes the measurement facilities and magnetic axis measurement method. We also present a summary of the measurement process and test results of the magnetic performance for the magnets.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) will be a new national user facility for nuclear science. It is funded by the DOE-SC, Michigan State University (MSU) and the State of Michigan. The driver linac of the FRIB facility can accelerate all stable isotopes to energies beyond 200 MeV/u at beam powers up to 400 kW [1].

FRIB SC magnet packages are used to focus and steer the heavy ion beams of the driver linac. 80 magnets have purchased from XSMT Co. Ltd, China. It Include 9 short and 71 long magnets. IMP undertook the design tasks. And, then 30 of the magnets tested at IMP.

Each FRIB SC magnet package consists of a main focusing solenoid, a pair of stray field bucking coil, a pair of SC dipole correctors both in the vertical and horizontal directions, a helium vessel, a passive quench protection device and the reference points for showing the magnetic axis of the solenoid coil. The solenoid coil length is 25cm and 50cm respectively [2]. The simulation model for 25cm solenoid coil is shown in Fig.1.

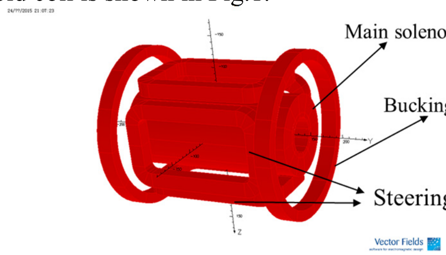

Figure 1: Simulation model of FRIB SC magnet package (25cm).

The FRIB SC magnet is designed as a bath-cooled magnet. The operating temperature of the liquid helium bath is up to 5.0K. The peak field on the beam axis is approximately 8 T. Table 1 summarizes the main parameters of the magnet.

Table 1: Parameters for the FRIB SC Magnet

Parameters	Unit	50cm	25cm
Main solenoid nominal current	A	90	90
Peak solenoid filed at I_{nom}	T	8	8
$\int B_Z^2\, dz$ at I_{nom}	T^2m	28.2	13.6
$\int B_Z^2\, dz$ uniformity within 80%×R	%	2	2
$\int B_x\, dz, \int B_y\, dz,$ integrated field strength	Tm	0.06	0.03
$\int B_x\, dz, \int B_y\, dz,$ Uniformity within 15mm	%	5	5
Maximum current of dipole	A	19	19

Due to the stringent space restriction inside the cryomodules, the solenoids was designed as compact as possible. The inner diameter of the cold bore is 40mm. The mechanical lengths of the SC magnets are 589.53mm and 349.76mm respectively. The solenoid and dipole correctors are mounted inside the helium vessel which has a diameter of 304.8mm. Figure 2 shows the two types of SC magnets after assembly.

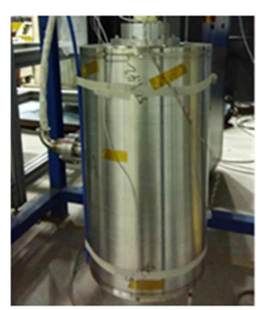

Figure 2: Two types of FRIB SC magnets after assembly and preparing for vertical test in the helium dewar. 50-cm solenoid package(left),25-cm solenoid package(right).

The design of the solenoids minimized the stray field in order to ensure the adjacent SC RF cavities exposed to a field less than specified. The stray field are suppressed by

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THE SUPERCONDUCTING CYCLOTRON RF SYSTEM R&D*

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Abstract

IMP is presently developing a 10MeV Superconducting Cyclotron (IMP-MK90) (see Fig. 1) for the nuclear pore membrane production and research purpose [1-5]. The cyclotron parameter see Table 1. The RF system comprises two separated resonators driven by independent amplifiers to allow for the phase and amplitude modulation technique to be applied for beam intensity modulation. The cyclotron works on 4th harmonic with Dee's voltage 70kV frequency 37MHz. According to the physical requirements of the superconducting cyclotron, the cavity is designed to be vertical 1/2 wavelength line structure. The RF system preliminary design has been completed (Fig. 2).

Figure1: The cyclotron structural model.

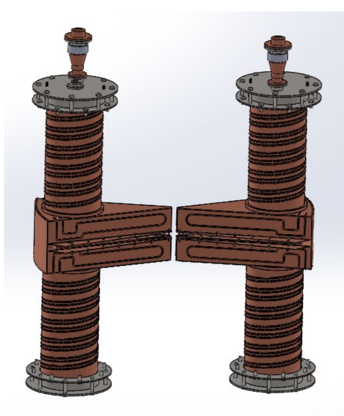

Figure 2: The RF cavity structural model.

THE CYCLOTRON AND RF SYSTEM DESIGN

On the basis of the physical design requirements, the relevant physical parameters shown in Table1.

Table 1: RF System Specifications

■ **Type of cyclotron**	
Heavy Ion	$^{40}Ar^{12+}$, $^{86}Kr^{26+}$
■ Axial injection with ECR ion source	
Split beam with either Septum Magnet or QWR cavity	
Beam current	>3euA
Beam energy	10MeV/u
■ **RF system parameter**	
Resonant Frequency	37MHz
Dee Voltage	60-80KV
Dee Angle	33°
Extraction Radius	750mm
Injection Radius	35mm
Phase Stability	≤±0.5°
Amplitude Stability	$\leq 1\times10^{-4}$
Frequency Stability	$\leq 1\times10^{-6}$
■ **Magnet**	
Magnet Coil	~300kAT
Maximum magnetic field	2.75T
Magnet Weight	~90 tons
■ **Production Lines**	
Multi-purpose Line	1 line
Industrial line	3 line with beam split

RF STRUCTURAL SIMULATION RESULTS WITH CST

According to the structure parameter, the three-dimensional model is founded, simulated and analyzed with CST. By changing and optimizing Dee's angel, stem dimension, stem height and position etc. parametrics of structure, The simulation results show that the resonant frequency is 37.05MHz, Q value is 7259 and power loss is 18kW. The voltage along the radial gap of Dee is from 82.25 kV in the center of Dee to 85.56 kV in the radius of Dee Extraction. The voltage distribution is uniformly rising along the radial gap of DEE. As shown in Fig. 3. The results shows that the voltage characteristics along the radius basically depend on the the position and diameter of the inner stem, and the Dee's angle. The electric field and magnetic field distribution map of the cavity are shown in Fig. 4 and 5. Surface current distribution result show in Fig. 6.

THE TUNING DESIGN OF THE RF CAVITY

The fine-tuning loop has been designed to meet the dynamically tuned requirements.the coarse-tuned with capacitor . The fine-tuning parameter shows in Table 2.

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DESIGN OF FAST PULSE GENERATOR FOR KICKER POWER SUPPLY IN HIAF

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Abstract

Kicker power Supply is one of the key components in the injection and extraction system of HIAF (High Intensity Heavy Ion Accelerator Facility, the 12th five-year national big science project). The PFN-Marx generator technology based on solid-state switch IGBT will be applied to HIAF-Kicker power supply. Hundreds of fast pulse signals are required for these IGBTs' control. The PFN-Marx generator has many requirements for their control signals, such as adjustable pulse-widths and time-delay. The maximum value of adjustment accuracy of the pulse-widths and delay among multiple control signals need to be 10ns. In this paper, a fast pulse generator circuit with adjustable pulse-widths and time-delay is designed for HIAF-Kicker power supply. This design is based on an emerging ARM-embedded FPGA. And the test results shown that the design can meet the required performance.

INTRODUCTION

The High Intensity Heavy Ion Accelerator Facility (HIAF) is a new accelerator facility under design at the Institute of Modern Physics (IMP), Chinese Academy of Sciences [1]. The Kicker power supply is a device that provides excitation current for the pulsed magnet in the injection and extraction system of HIAF. HIAF-Kicker power supply will use a solid-state PFN-Marx structure as an energy storage system. Since the limited withstand voltage and current capability of a single solid-state switch IGBT, the quantity of IGBTs in solid-state FPN-Marx generator is very large. The control accuracy of FPN-Marx generator directly affects the beam injection efficiency. Therefore, the synchronous driving of multi-channel IGBT has become a technical difficulty problem that must be solved for HIAF-Kicker power supplies.

To reduce the time-delay caused by the dispersion of circuit parameters on FPN-Marx generator, people used to adjust switches on and off manually. This method is time consuming and laborious. The switches cannot to be debugged online while the power supply is in operating. To solve these problems, we designed a fast pulse generator based on Cyclone V chip, which integrates FPGA and a dual-core ARM Cortex-A9 MP core processor. In this design, ARM is mainly used to upload and download the control data. The fast pulse generator circuit is designed to generate hundreds of fast pulse control signals. For such signals, the time-delay and pulse-widths are adjustable and the adjustment accuracy is 10 ns. The high-accuracy digital control design provide synchronous drive signals for multi-channel IGBT of FPN-Marx generator, which has a significant advantage over manual adjustment.

THE SOLID-STATE PFN-MARX GENERATOR ON HIAF-KICKER

Compared with FPN (Pulse-Forming Network) and PFL (Pulse-Forming Line), PFN-Marx generator is based on solid-state switch IGBT, which has advantages of smaller size, easy to repair and more flexible to adjust pulse-widths and delay. After the energy storage process has been completed in PFN-Marx circuit, the square wave excitation current can be generated by the solid-state switch IGBT for the magnet load [2].

The work principle of the solid-state PFN-Marx generator is: the charging power supply charges the PFN in parallel through the charging resistor. After the charging process has been completed, the solid-state switches are turned on at the same time. The charging resistor acts as an isolator, and the PFNs in each stage are discharged serially. Each level of PFN modulates the waveform and finally the approximate square wave pulse waveform is obtained on the load. The schematic of the solid-state PFN-Marx generator is shown in Fig. 1.

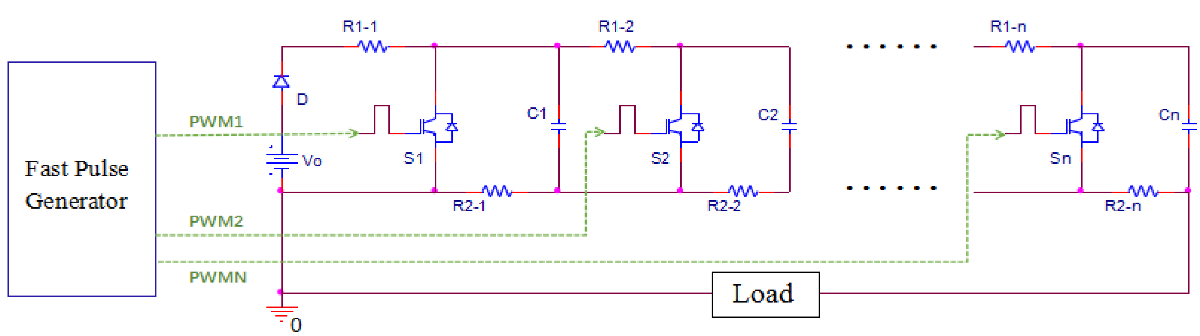

Figure 1: The schematic of the solid-state PFN-Marx generator.

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COMMISSIONING PROGRESS OF LEAF AT IMP

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Abstract

A Low Energy intense-highly-charged ion Accelerator Facility (LEAF), which is mainly consist of an 45 GHz superconducting ECR ion source, LEBT and an 81.25 MHz 4-vane RFQ, was designed to produce and accelerate heavy ions, from helium to uranium with A/Q between 2 and 7, to the energy of 0.5 MeV/u. The typical beam intensity is designed up to 2 emA CW for the uranium beam. The project was launched in 2015 and has been successfully commissioned with He^{+} (A/Q=4), N^{2+} (A/Q=7) beam and accelerated the beams in the CW regime to the designed energy of 0.5 MeV/u. Beam commissioning results of He^{+} beam have been reported previously. This paper presents the details of N^{2+} commissioning and beam studies.

INTRODUCTION

LEAF (Low Energy intense-highly-charged ion Accelerator Facility, see Fig. 1) [1] has been successfully commissioned with A/Q=4 ion He^{+} and A/Q=7 ion N^{2+}. Since the designed heaviest ion is Uranium with charge state of 34, N^{2+} could be a substitute of U^{34+} to evaluate the accelerator performance due to the same rigidities. Studies of the facility were carried out by beam commissioning with different intensities. Beam characteristics from ECR were measured and discussed. Beam phase space re-construction was developed to study the evolution process of the beam from source to RFQ, contributing to LEBT tuning and particle cutting with collimators.

SOURCE RESULTS

A 14.5 GHz room-temperature permanent magnetic ECR ion source was fabricated and employed for the commissioning of LEAF. The source performance meets intensity requirements for commissioning. The source demonstrated ~5 emA of He^{+} beam, 1.5 emA of He^{2+} beam, 1.7 emA of N^{2+} beam and 0.16 emA of N^{5+} beam. Beam emittances were measured for N^{2+} beam with several intensities. As shown in Fig.2, beam emittance increase with the intensity. The main reason should be attributed to the plasma meniscus change, related with source tuning. Aberrations from the magnets and space charge effects also contribute to the beam emittance degradation [2,3]. Figure 3 demonstrates the measured phase space distributions of N^{2+} beam with intensities of ~0.14 emA and ~1.52 emA, respectively. It is seen that by increasing the beam intensity the phase spaces are seriously distorted, resulting to emittance growth.

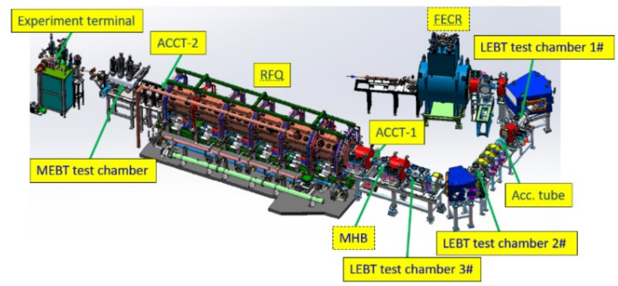

Figure 1: Layout of LEAF.

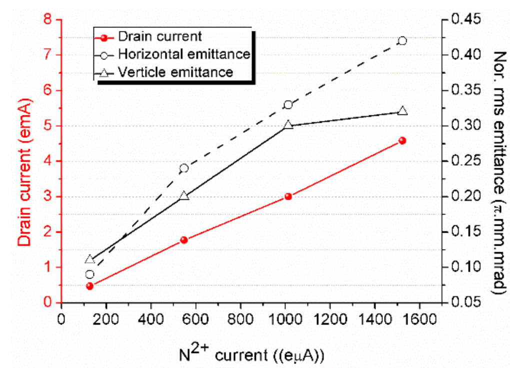

Figure 2: N^{2+} beam emittance versus beam current.

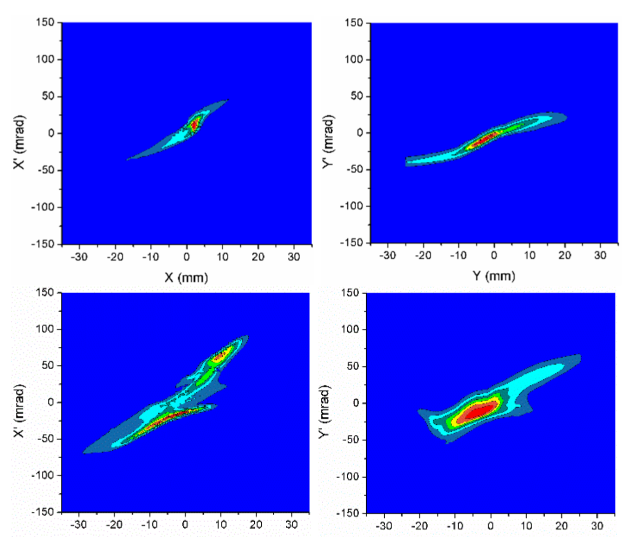

Figure 3: Measured beam phase space distributions for ~0.14 emA (up) and ~1.52 emA (down) N^{2+} beams.

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THE DIGITAL CONTROLLER FOR POWER SUPPLIES IN HIAF*

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Abstract

High Intensity Heavy Ion Accelerator Facility (HIAF) is a project proposed by Institute of Modern Physics, Chinese Academy of Sciences (IMP). This paper designs a digital controller for Bring in HIAF dipole power supplies system, which is several circuit boards consist of high precision ADC, optical fiber module, DDR3 SDRAM, Gigabit Ethernet module. It uses Cyclone V SX SoC FPGA, which integrated with dual-core ARM Cortex-A9 MP Core processor. This paper explains the hardware and software architecture of the controller and how can it improve power supplies performances. The FPGA finishes the PI regulating and PWM modulation. The ARM is responsible for data pre-setting, web service, database, and power supplies detection and protection management. At the end, this paper gives the output measurements when the controller is used in the prototype, which verifies the rationality and reliability of the design.

INTRODUCTION

HIAF [1] is a new facility for heavy ion researches [2], which consists of two ion sources, a high intensity Heavy Ion Superconducting Linac (HISCL), a 45 Tm Accumulation and Booster Ring (ABR-45) and a multifunction storage ring system. Because the Booster Ring has high quality requirement for beam, the power supplies for magnets should have high stability, reliability, and small tracking error, small current ripple. This paper describes a controller which is designed for Booster Ring dipole power supplies. The aim of the new controller is to improve the real-time performance, stability, and reliability.

HARDWARE ARCHITECTURE

This part describes the chip selecting of the controller and the main boards. Some papers have proposed the design of a new controller [3] uses Raspberry Pi and FPGA, which means that ARM and FPGA have both used in accelerator power supplies area. Further, this paper proposes SoC FPGA which integrates ARM and FPGA, which makes the design more reliable because of the simplicity.

Chip Selecting

The controller uses Cyclone V SX SoC FPGA, which has the main performance as: Hard memory controllers supporting 400 MHz DDR3 SDRAM with optional error correction code (ECC) support, PCI Express with multi-function support, variable-precision digital signal processing (DSP) blocks, and HPS Dual-core ARM Cortex-A9 MP Core processor. In controller, it has DDR3 SDRAM, FLASH, fiber optic 88e1111, and Ethernet module. What the old one used is Cyclone II FPGA EP2C70 [4]. The differences of two FPGA resources between two controllers are listed as Table 1. The change of the chip can improve the speed of the controller.

Table 1: The Differences Between FPGAs

Items	Cyclone V	Cyclone II
LEs	68,416	110,000
Pins	499	422
Memory bits	5,662,720	1,152,000
DSP blocks	112	/
Multipliers	224	150
Total PLLs	15	4

Main Boards

Figure 1 shows that the controller has 5 boards, which consists of main board, mother board, ADC board, extended board, and PLC board. All these boards use high speed protocol to communicate with each other. GXB is used between mother board and ADC board. Except for GXB, this controller also uses industrial general protocol such as RS232, RS485, and CAN. The old controller [4] has 7 boards, including the boards the same as the new one and MCU boards, power board. Giving up redundant boards makes the system be more reliable.

Figure 1: The photos of the controllers.

SOFTWARE ARCHITECTURE

The software architecture of the controller has two parts, which is FPGA and ARM. The FPGA part uses Verilog

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THE MULTI-PHYSICS ANALYSIS OF A DUAL-BEAM LINAC *

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Abstract

A prototype 81.25 MHz dual-beam drift tube linac (DB-DTL) is being designed to proof the feasibility of multi-beam type linac. The beam dynamics design and electromagnetic calculation have been completed [1]. The following step is the multi-physics analysis of the DB-DTL. The three-dimensional multi-physics analysis is very important for the design of the DB-DTL. The RF dissipated power will make the cavity temperature rise and cause cavity resonance frequency shifting due to the deformation of cavity structure. The distributions of cavity deformation and stress are calculated according to the cavity temperature distribution. All the simulation results, including cavity temperature rise, deformation and stress and the frequency shifting resulted in cavity deformation, should be within an acceptable range. The designing goal is to design the DB-DTL operated in pulse model with 1/1000 duty factor. The detailed multi-physics analysis of the prototype DB-TL will be presented in this paper.

INTRODUCTION

The DB-DTL project has been proposed to proof the feasibility of multi-beam type linac in middle energy region acceleration [2] [3], which will apply to the design of new heavy ion inertial confinement fusion (HIF) facility [4]. The layout of the DB-DTL test bench is shown in Fig. 1, which include a 1mA permanent magnet type PIG ion source, faraday cups for measuring beam transmission, an existing CW 162.5 MHz RFQ accelerator [5], the prototype DB-DTL and an analyzer magnet for measuring beam energy. The DB-DTL is able to accelerate 1 mA proton from 0.56 MeV to 2.5 MeV. The normalized power dissipation of the DB-DTL is 35.83 kW according to the electromagnetic calculation results of the DB-DTL [1]. The main parameters of the DB-DTL are listed in Table 1. The DB-DTL will be operated in room temperature. The power dissipated on the internal surface on the DB-DTL will make cavity temperature rise, which also result in structure deformation and resonant frequency shifting. It is important to simulate the temperature rise, deformation and frequency shifting of the DB-DTL cavity. Actually, the DB-DTL will be operated in pulse mode with a duty of 1/1000, with cooling-water channels but without cooling-water because of the limitation of funds. The multi-physics analysis is performed to explore the maximum operating pulse duty factor, which will apply to the beam experiment. The detailed three-dimensional multi-physics analysis of the DB-TL will be presented in this paper, which is a coupled electromagnetic, thermal and structural analysis.

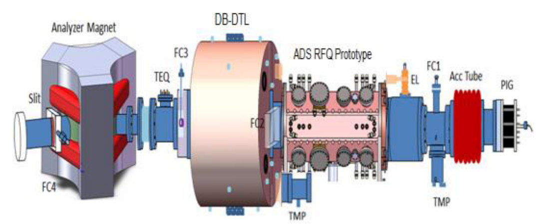

Figure 1: The layout of the DB-DTL beam test bench, which include a PIG ion source, faraday cups, the Prototype ADS RFQ, the DB-DTL and analyzer magnet.

Table 1: Main Parameters of the DB-DTL

Parameters	Value
Charge to mass ratio q/A	1
Frequency (MHz）	81.25
Beam current (mA)	1
Input/output energy (MeV)	0.56/2.5
Radius of beam-aperture (mm)	10
Maximum gap voltage (kV)	389.06
Transmission rate	34%
Operation mode	pulse
Cavity length	991.43
Shunt impedance (MΩ/m)	200.02
Normalized power dissipation (kW)	35.83

THE PROCEDURES AND GOAL OF MULTI-PHYSICS ANALYSIS

As shown in Fig. 2 [6], the procedures of multi-physics analysis include electromagnetic, thermal, structural and frequency shifting analysis. The ANSYS workbench [7] and CST Microwave Studio (MWS) [8] are utilized in the simulation. Firstly, the high frequency electromagnetic simulation is performed with the MWS and the distribution of RF thermal loss is simulated with ANSYS High Frequency Structure Simulator (HFSS) code. Based on the simulation results, the normalized cavity power dissipation is calculated, which is applied to the thermal analysis. The thermal analysis generate cavity temperature map according to the cavity internal surface heat flux. According to the distribution of cavity temperature, the distributions of structural stresses and deformations of the DB-DTL are calculated in structural analysis. Finally, the resonant frequency shifts, resulted in cavity the deformation, is simulated in HFSS code. The frequency sensitivity of cooling-water temperature and velocity are also

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DEVELOPMENT OF AN ALL PERMANENT MAGNET ECR ION SOURCE FOR LOW AND MEDIUM CHARGE STATE IONS PRODUCTION

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Abstract

An all permanent magnet Electron Cyclotron Resonance ion source-LAPECR1U (Lanzhou All Permanent magnet ECR ion source no.1 Upgraded), has been built at IMP in 2017 to satisfy the requirements of LEAF (Low Energy intense-highly-charged ion Accelerator Facility) for first two years commissioning. LAPECR1U was designed to be operated at 14.5 GHz to produce intense low and medium charge state ion beams. LAPECR1U features a compact structure, small size, and low cost. A cone-shape iron yoke in injection side and an iron plasma electrode in extraction side were used to enhance the axial magnetic field strength. The typical parameters and the preliminary beam results of the source are given in this paper.

INTRODUCTION

A Low Energy intense-highly-charged ion Accelerator Facility, LEAF, was launched at IMP in 2015 for researches of irradiation material, highly charged atomic physics, low energy nuclear astrophysics, *et. al.* The layout of LEAF is shown in Fig. 1. It mainly includes ECRIS, LEBT and a RFQ. The 4th generation ECR ion source FECR need to provide 2 emA U^{34+} beam with 45 GHz microwave hearting. The design of FECR has been completed and the ion source is under construction. To satisfy the requirement of LEAF platform for first two years commissioning, a substitute ECR ion source, which must be compact structure and low cost, is in demand.

With the development of Lanzhou All Permanent Magnet Electron Cyclotron Resonance ion source (LAPECR) in Institute of Modern Physics (IMP) in the last decades, it has become the cost-optimal machine to produce high intensity and multiple charge state ion beams. LAPECR series are widely used for heavy ion accelerators, atomic physics research [1], and Heavy Ion Medical Machine (HIMM) [2] because of such advantages as compact structure, low cost and small size. We have built an upgraded all permanent magnet ECR ion source No.1, named LAPECR1U to satisfy the requirements of LEAF facility as ion injector for preliminary experiment.

LAPECR1U was designed to be operated at 14.5 GHz with the extraction HV 10-40 kV, and expected to produce intensity low and medium charge state ion beams. Especially, high intensity N^{2+} ion beam with high beam quality was expected because of the same A/Q as U^{34+}.

LAPECR1U has successfully delivered He^{+} and N^{2+} ion beams for RFQ commissioning. This paper will give the details of the design of LAPECR1U. Then, the preliminary commissioning results of LAPECR1U on LEAF platform were presented.

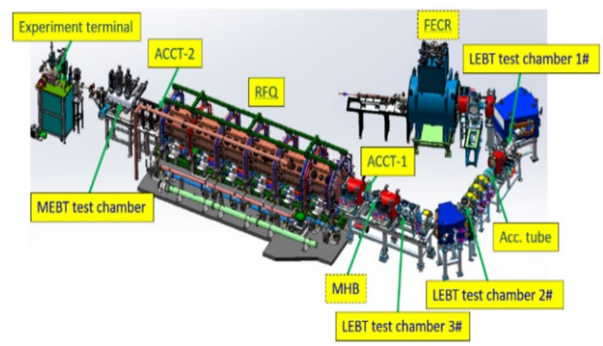

Figure 1: Layout of LEAF.

THE DESIGH OF LAPECR1U

LAPECR1U, which was designed based on older LAPECR1 [3], is a low and medium charge state ion source that can produce intense N^{2+} ion beam. In our design, the axial magnetic field is mainly produced by two permanent magnet rings and the radial magnetic field is provided by one hexapole. A 12-segmented axial magnetic ring at injection side provide the injection magnetic field with the peak up to about 0.63 T, and a 12-segmented cone shape magnetic ring at extraction side provide the extraction magnetic field up to 0.67 T. In order to improve the performance and control the size of LAPECR1U, a cone-shape iron yoke in injection side and an iron plasma electrode in extraction side were used to enhance the axial magnetic field strength, and the axial magnetic field can exceed 1.45 T at injection side and 0.72 T at extraction side. The B_{mini} field was optimized to 0.38 T by varying the space between injection ring and extraction ring. The radial magnet is a 12-segmented Halbach structure hexapole which provides a 0.94 T radial magnetic field at the inner wall of a 40 mm diameter plasma chamber, which is designed with double-wall structure allowing sufficient low conductivity water cooling. The typical parameters of LAPECR1U are given in Table 1. The schematic of LAPECR1U is shown in Fig. 2.

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DEVELOPMENT OF A PEPPER POT PROBE TO MEASURE THE FOUR-DIMENSIONAL EMITTANCE OF LOW ENERGY BEAM OF ELECTRON CYCLOTRON RESONANCE ION SOURCE AT IMP

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Abstract

The ion beams extracted from an Electron Cyclotron Resonance (ECR) ion source always exist strong transverse coupling effect that is caused by the field of the axis mirror magnets and the extraction solenoid. A Pepper Pot probe was developed and used to obtain the full four-dimensional (4D) phase space distribution of the low energy beam extracted from the ECR ion source at IMP. This paper describes the design of the Pepper Pot, the setup configuration, the detailed image processing procedure, especially the analysis results verification compared to another type emittance meter. The first 4D emittance is also determined through the Pepper Pot probe. The transverse phase space distribution measurement data of oxygen beams from the LECR4 experimental platform are presented and discussed.

INTRODUCTION

Electron cyclotron resonance (ECR) ion sources [1] were widely used in the particle accelerator because of their high performance on producing highly charged ions. During the last few years it became the evident that the ion beam extracted from the ECR ion sources excited complicated structure of phase space distributions [2]. The ion beam in the horizontal and vertical planes are strongly coupled due to the strength field of solenoid include extraction coil of the axial mirror magnets and the extraction solenoid [3]. In order to obtain the transverse distribution, some type of emittance device were previously used, like Slit to wire meter [4], Allison type meter [5], but these devices cannot provide full phase space distribution. Pepper Pot probe is another type emittance meter that can acquire 4D emittance. Another significant advantage of the Pepper Pot probe is the very short time of measurement progress. Pepper Pot probe were widely used to measure both electron [6] and heavy ion [7] emittance of the low energy beam transport line (LEBT). There were two types Pepper Pot probe, one is single-pass type [8] that the probe was rapidly insert to the beam center to measure whole beamlet [9] data, the laboratories like LBNL, ANL, RIKEN, BNL are all this type; the other is scanning type [10] that the beamlet data were obtained through probe moving step by step, KVI has designed this type probe and it was used to measure the beam transverse distribution. Most of exist Pepper Pot probes have acquired the beam transverse distribution of LEBT that without the verification, in most case the results of Pepper Pot probe whether reliable is uncertain. In this paper the Pepper Pot probe result was compared to Allison Scanner in order to certify the accuracy.

THE SETUP OF PEPPER POT

The prototype of the Pepper-Pot meter which was recently designed and commissioned is shown in Fig. 1. It contains a Pepper-Pot mask with two copper frames, a square scintillator and a 45 degree stainless steel mirror. The Pepper-Pot mask is a tantalum foil with a thickness of 100 micrometers with holes of 100 micrometers diameter and distance between adjacent holes is 3 mm in both x and y direction. A round potassium bromide (KBr) is used for the scintillator (5 mm thickness) with 50*50 mm available size. The mask is mounted in the copper frame which has one blocked hole in the center to provide an absolute spatial reference for the data processing. There was no additional cooling of the mask because the beam is low energy during the tests. A 45 degree mirror reflects the appearing light pattern to the CCD camera seem like perpendicular at the beam. The exposure time and gain of the camera can be adjusted online via the user interface and a real-time image can be acquired. A code based on the Matlab software is designed for the transverse emittance calculation.

The Pepper Pot probe is located on the LEBT line of the LECR4 platform [11, 12] at IMP. The layout of the LECR4 platform is shown in Fig. 2. It contains a room temperature ECR ion source and a LEBT line which includes two solenoids and a 90 degree analysis magnet to focus and select the expected ion beam to the RFQ. The Pepper Pot probe was mounted in the diagnostic box behind the RFQ, two Allison scanners [13] were recently added to the same cube in order to compare the measurement results between two types device.

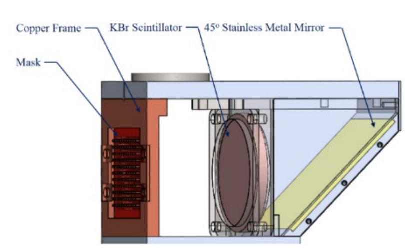

Figure 1: The draw of Pepper Pot probe with KBr scintillator at IMP.

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SINGLE HEAVY ION BUNCH GENERATION SCHEME IN BRING AT HIAF*

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Abstract

As the Booster Ring of the High Intensity Heavy-ion Accelerator Facility (HIAF), BRing is a synchrotron which can be able to accumulate and accelerate full ion species provided by iLinac to required energy with RF acceleration system. When accelerating uranium beam(e.g. $^{238}U^{35+}$), the variation range of the kinetic energy is 17MeV/u-830 MeV/u, and the corresponding revolution frequency f_{rev} range is 0.099MHz-0.447MHz. Because of the low frequency limit value of 0.099MHz, the RF frequency f_{RF} of RF cavity should be h(harmonic number) times of f_{rev} ,thus, there will have h(is equal to harmonic number) bunches after acceleration. To satisfy the extraction requirement, the accelerated multiple bunches should be recollected in one bunch by means of longitudinal manipulation.

The different single bunch generation method of debunching and bunch merging are investigated separately, and the beam parameters in different cases are obtained, meanwhile, the optimized RF program during the debunching and bunch merging are presented.

INTRODUCTION

In China, the Heavy Ion Research Facility at Lanzhou (HIRFL) [1] is one major national research facility focusing on nuclear physics, atomic physics, heavy ion applications and interdisciplinary researches. A series of remarkable results have been obtained at HIRFL. Based on the developments and experience with heavy ion beam accelerators, a new project HIAF [2] was proposed by IMP in 2009. The facility is being designed to provide intense primary and radioactive ion beams for nuclear physics, atomic physics, application research sciences and so on. The schematic layout of HIAF project is shown in Fig. 1.

The HIAF project consists of ion sources, linac accelerator, synchrotrons and several experimental terminals. The superconducting ion Linac accelerator (iLinac) is designed to accelerate ions with the charge-mass ratio Z/A=1/7 (e.g. $^{238}U^{35+}$) to the energy of 17 MeV/u. Ions provided by iLinac will be cooled, accumulated and accelerated to the required intensity and energy (up to 1×10^{11} and 830 MeV/u of $^{238}U^{35+}$) in the Booster Ring (BRing), then fast extracted and transferred either to the external targets or the Spectrometer Ring (SRing).

* Work supported by National Natural Science Foundation of China(11705253)

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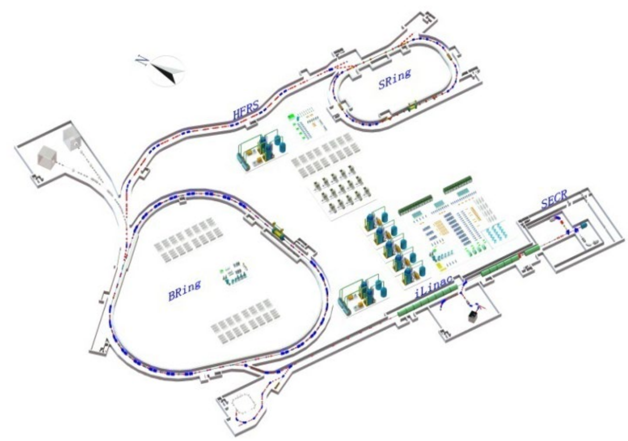

Figure 1: Layout of papers.

As a key part of the HIAF complex, BRing is a synchrotron which can be able to accumulate and accelerate full ion species with a circumference of 569 m and a maximum magnetic rigidity of 34 Tm, Table 1 shows the main configuration and parameters of the BRing.

Table 1: Main Parameters of BRing

Main parameters	Values
Circumference (m)	569
Maximum magnetic rigidity (Tm)	34
Accelerating rate (T/s)	12
Momentum acceptance (Δp/p)	$\pm5.0\times10^{-3}$
Injection	
Ion	$^{238}U^{35+}$
Energy (MeV/u)	17
Revolution frequency(MHz)	0.099
Momentum spread (Δp/p)	$\leq\pm2\times10^{-3}$
Extraction	
Maximum Energy (MeV/u)	830
Revolution frequency(MHz)	0.447
Particle number (ppp)	1.0×10^{11}

After two-plane painting injection and accumulation, the beam with the injection energy of 17 MeV/u is costing beam which will spread over 2π in rf phase and it has a momentum spread of $\Delta p/p = \pm2\times10^{-3}$ (see Fig. 2). Due to the evolution frequency of 0.099MHz at injection energy is beyond the working frequency range of the cavity, so the RF cavity will work at the harmonic number greater than 1, based on experience and dynamics results,

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ROSE - A ROTATING 4D EMITTANCE SCANNER

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Abstract

The detector system ROSE [1][2], allowing to perform 4D emittance measurements on heavy ion beams independent of their energy and time structure, has been built and successfully commissioned in 2016 at GSI in Darmstadt, Germany. This method to measure the four dimensional emittance has then been granted a patent in 2017. The inventors together with the technology transfer department of GSI have found an industrial partner to modify ROSE into a standalone, commercially available emittance scanner system. This is a three step process involving the hardware, the electronics and the software working packages. It is planned to have a configurable customer product ready by end of 2020. This contribution presents the actual status and introduces the multiple possibilities of this 4D emittance scanner.

INTRODUCTION

Usually just separated measurements of two-dimensional x-x′ and y-y′ sub phase-spaces (planes) are measured, as for simplicity correlations between the two planes, i.e. x-y, x-y′, x′-y, and x′-y′ are often assumed as zero. However, such inter-plane correlations may be produced by non-linear fields such as dipole fringes, tilted magnets or just simply by beam losses. Figure 1 shows the simulation of a coupled and an uncoupled beam with initially identical projected horizontal and vertical rms-emittances through a solenoid channel. This illustrates the fact that initial coupling influences the final horizontal and vertical beam size.

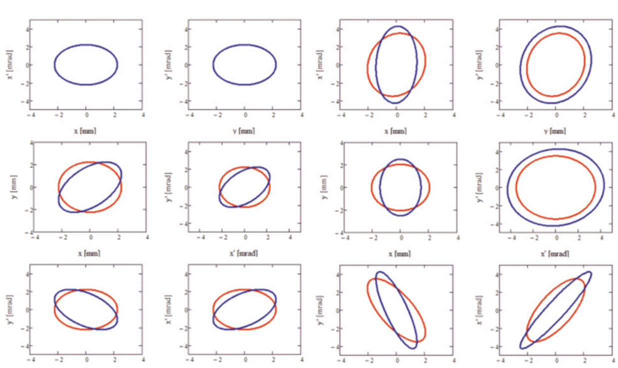

Figure 1: Simulation of an initially uncoupled (red) and coupled (blue) ion beam (left) at the exit of a solenoid channel (right).

For some applications, as for example matching the round transverse phase space of a linac beam Fig. 2 to the flat acceptance of a synchrotron [3], [4], inter-plane correlations are a prerequisite Fig. 3.

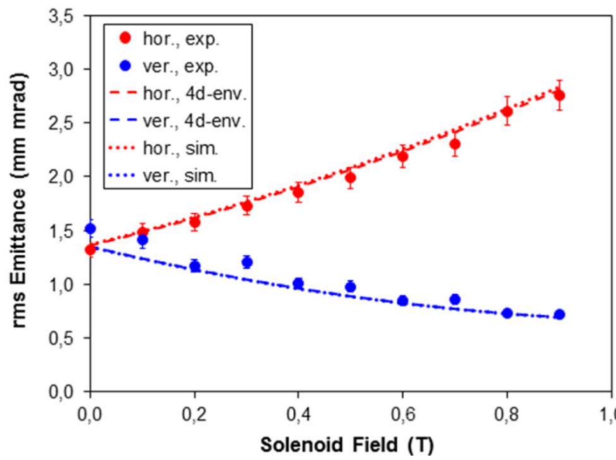

Figure 2: One knob emittance transfer using EMTEX [3].

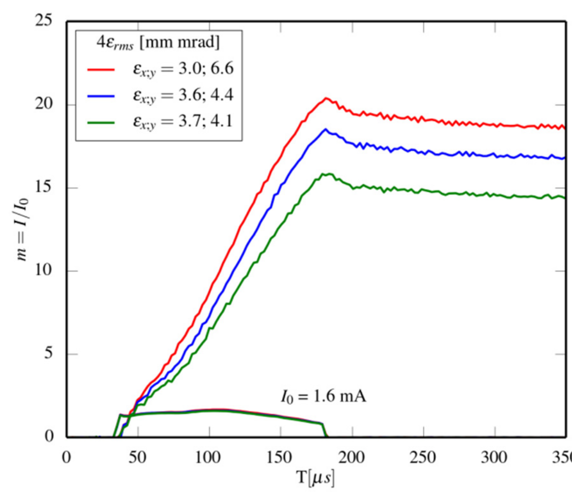

Figure 3: The emittance transfer using EMTEX directly translates in increased injection efficiency into SIS18 [4].

In order to remove correlations that do increase the projected rms-emittance, they must be quantified by measurements. This applies especially if space charge effects are involved as they cannot be calculated analytically. Using the skew triplet of the EMTEX setup we have measured the increase of the projected rms-emittance of a U^{28+} beam with 11.4 MeV/u to be in the order of 75%. Removing this inter-plane coupling could increase the beam brilliance and thus the injection efficiency into SIS18 by 75% [5].

There is considerable work on measuring four-dimensional distributions using pepper-pots [6] - [9] for electron beams or ion beams at energies below 150 keV/u, for which the beam is fully stopped by the pepper-pot mask. However, due to technical reasons this method is not

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PRESENT STATUS OF AND RECENT DEVELOPMENTS AT RIKEN RI BEAM FACTORY

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Abstract

The Radioactive Isotope Beam Factory (RIBF) is a cyclotron-based accelerator facility that is used for nuclear science studies and was completed at the end of 2006. RIBF can produce the most intense RI beams using fragmentation or fission of high speed heavy ion beams. Ever since the first beam was produced, effort has focused on increasing the intensity of uranium beams. Ions beams with high intensity and high availability have been used to produce many important scientific achievements. Upgrade programs have been proposed to further expand scientific opportunities. These programs have two goals. The first goal is to find heavier elements than element 118, which is already named. The upgrade program for the heavy ion linac (RILAC), including installation of a superconducting linac, has been funded and is under construction. The second goals is to increase the intensity of uranium ion beams up to 1 pμA, thus facilitating further investigations into the physics of unstable nuclei. This program for uranium beams is still been unfunded. We are pursuing a budget-friendly version without changing the project goals.

INTRODUCTION TO RI BEAM FACTORY

The Radioactive Ion Beam Factory (RIBF) is a cyclotron-based accelerator facility that uses fragmentation or fission of heavy ion beams to produce intense radioactive ion (RI) beams over the entire atomic range [1]. RIBF is used to explore the inaccessible region of the periodic table, to discover the properties of unstable nuclei, and advance knowledge in nuclear physics, nuclear astrophysics, and applications of rare isotopes for society. The RIBF facility consists of four cyclotron rings (RRC [2], FRC [3], IRC [4], and SRC [5]) with three injectors, including two linacs (RILAC [6,7] and RILAC2 [8]) and one AVF cyclotron (AVF) [9]. Cyclotrons cascades can provide heavy ion beams from H_2^+ to uranium ions at more than 70% of the speed of light to efficiently produce RI beams. Three acceleration modes are available, as shown in Fig 1. The first mode is primarily used for mid-heavy ions, such as Ca, Ar, and Zn. The second mode is used for light ions, such as O and N. The third mode is used for very heavy ions such, as Xe and U. Of course many researchers use beams from the injectors. For example, synthesis of super heavy elements uses beams from RILAC, while beams from the AVF cyclotron are used for RI production. Table 1 lists the specifications of the four ring cyclotron in RIBF. RRC has been operating since 1986. FRC and IRC have structures similar to that of RRC. The weight per K-value is listed in the table, which clearly shows that FRC is very compact compared to the other cyclotrons. Obtaining an acceleration voltage of 640 MV for uranium acceleration up to energy of 345 MeV/u is the most challenging with SRC. Design and construction of RIBF accelerators began in 1997, and we obtained the first beam at the end of 2006.

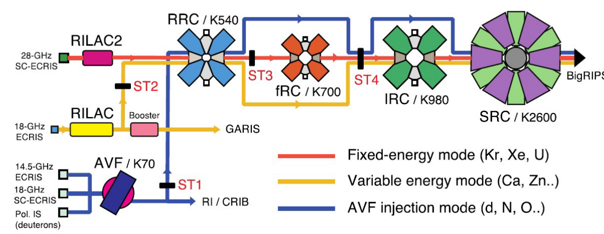

Figure 1: Acceleration modes for RIBF facility.

Table 1: RIBF cyclotron specifications. * in the table indicates that the values are shown for the case of uranium acceleration up to 345 MeV/u.

	RRC	fRC	IRC	SRC
K-value (MeV)	540	700	980	2600
$R_{inj}(cm)$	89	156	277	356
R_{ext} (cm)	356	330	415	536
Weight (ton)	2400	1300	2900	8300
K/W	0.23	0.54	0.34	0.31
N_{sec}	4	4	4	6
rf Resonator	2	2+FT	2+F	4+FT
Frequency range (MHz)	18–38	54.75	18–38	18–38
Total Acc. Volt. (MV)	2	2+FT	2+F	640
Acc. Volt. (MV/turn)*	0.28	0.8	1.1	2.0
Δr (cm)*	0.7	1.3	1.3	1.8
I_{sc}(pμA)*	1.8	11.2	3.7	2.6

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DEVELOPMENT OF RIKEN 28 GHz SC-ECRISs FOR SYNTHESIZING SUPER-HEAVY ELEMENTS

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Abstract

Production of intense metallic ion beams were required at RIKEN to synthesize new elements with atomic numbers higher than 118. To meet this requirement, we systematically studied the optimization of RIKEN 28 GHz SC-ECRIS performance. Using these results, we produced V^{13+} ion beam of 400 μA at ~2 kW microwave power (18+28 GHz) and a B_{ext} (maximum magnetic mirror field at the beam extraction side) of 1.4 T. For long-term operation, we successfully produced an intense and stable beam (100–200 μA). To progress this project, new super-conducting RF cavities are now under construction downstream of the RIKEN heavy-ion linac (RILAC) to increase beam energy. In this project, we also constructed a new 28 GHz SC-ECRIS based on these results to increase beam intensities. In addition, three sets of movable slits were installed in the low energy beam transport (LEBT) to inject the high-quality beam into the upgraded RIKEN heavy-ion LINAC (RILAC) to control the size of the transverse emittance of the beam.

INTRODUCTION

After synthesizing a super-heavy element (with an atomic number of 113), a new project was started at RIKEN for synthesizing a new element with an atomic number higher than 118 [1, 2]. For this project, intense, highly charged metallic ion beams, using ions such as Titanium (Ti^{13+}), Vanadium (V^{13+}), and Chromium (Cr^{13+}), were required. To progress the project, the RIKEN heavy-ion linac (RILAC) is up-graded by adding new super-conducting ratio frequency (RF) cavities. In this project, we also constructed a new SC-ECRIS for increasing beam intensity.

The up-graded RILAC is also used as an injector accelerator for the RIKEN radioactive isotope beam (RIBF) project [2, 3]. To accelerate the heavy ion beam for RIBF, the ion source has to provide it with a mass to charge state ratio smaller than three (e.g., $^{48}Ca^{16+}$ and $^{70}Zn^{24+}$). High electron density (n_e) and long confinement time (τ_i) in the ion source plasma are required to produce these highly charged, heavy ions. Using a crude calculation [4], the required $n_e\tau_i$ for $^{48}Ca^{16+}$ ion production was in the order of 10^9 (sec/cm^3), which is one order of magnitude larger than the required $n_e\tau_i$ for the $^{51}V^{13+}$ ion (in the order of 10^8(sec/cm^3)). Therefore, it was necessary to design an ion source that could provide the optimum condition to cover a wide range of $n_e\tau_i$ in the ion source plasma.

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In the last three decades, two guidelines (scaling laws [4, 5] and high B mode [6-8]) have been proposed and used to design and develop ion sources. Scaling laws were proposed to describe the effects of the main ion source parameters (microwave power, magnetic field strength, microwave frequency, mass of heavy ions, etc.) on the output beam of highly charged heavy ions. These studies reported that the strength of the magnetic mirror affects the optimum charge state (i.e., a higher mirror ratio yields higher output ion beam charge states). In the middle of the 1990s, the high-B mode, which employs a high magnetic mirror ratio to confine the plasma, was proposed to increase the beam intensities of highly charged heavy ions. To meet the requirement for the project, we systematically studied the effects of a magnetic mirror on beam intensity based on these guidelines.

It was clear that we need to produce enough metallic vapor to produce an intense beam. In addition, high transmission efficiency in the low-energy beam transport line (LEBT) was required for efficient operation of the ion source. Considering these points, we constructed and developed an ion source, a high temperature oven (HTO), and a LEBT for this project.

In the second and third sections of this contribution, the results of optimization of the ion source performance and the metallic ion beam production with HTO are described. In the fourth section, we present the structure of the LEBT and the first results from the new ion source.

OPTIMIZATION OF THE MAGNETIC MIRROR

In the test experiments for magnetic mirror effects, we used two different types of ion sources, Liquid-He-free SC-ECRIS [9] and RIKEN 28 GHz SC-ECRIS [10]. The RIKEN 28 GHz SC-ECRIS has six solenoid coils to produce a flexible mirror magnetic field in the axial direction, and it can produce both classical and flat B_{min} [11].

Generally, as an ECRIS has three magnetic mirrors (B_{inj}/B_{min}, B_r/B_{min}, and B_{ext}/B_{min}) (B_{inj}, maximum magnetic mirror field at the microwave injection side; B_{ext}, maximum magnetic mirror field at the beam extraction side; B_r, the radial magnetic field; and B_{min}, minimum strength of the mirror magnetic field), various combinations of the magnetic mirrors can exist to produce a beam of highly charged heavy ions. Therefore, we needed to carefully study the effects of the magnetic mirror to maximize beam intensity. Figure 1 a) and b) show the normalized beam intensities as a function of B_{inj}/B_{ext} and B_r/B_{ext} with the RIKEN 28 GHz SC-ECRIS (18 and 28 GHz microwaves) and the Liquid-He-free SC-ECRIS (18 GHz microwaves).

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HIGHLY CHARGED ECR ION SOURCE DEVELOPMENT AT IMP*

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Abstract

Highly charged ECR ion source development plays an important role in the heavy ion accelerators advancement at IMP, such as HIRFL upgrade, heavy ion treatment complex HIMM, future heavy ion facility HIAF, and so on. As requested by those projects, many high performance highly charged ECR ion sources with different technologies have been built, or under development. The representative ion sources are superconducting ECR ion sources SECRAL and recently built SECRAL-II, room temperature LECR4 ion source with an innovative evaporative cooling method, permanent magnet ECR ion sources of LAPECR series, and a 45 GHz 4th generation ECR ion source FECR. In this talk, a general review of highly charged ECR ion sources will be presented. The typical performances, operation status, as well as the future developments will be discussed.

INTRODUCTION

Requested by the development of cyclotrons at IMP, Electron Cyclotron Resonance (ECR) ion source had been incorporated to HIRFL dated to the late 1980s, when the first ECR ion source a Caprice type 10 GHz machine was bought from Grenoble, France in 1987 [1]. This ion source was lately modified and became the so called LECR0 source in the IMP highly charged ECR ion source series. Based on the experience of LECR0, a 10 GHz ECR ion source that was lately renamed as LECR1 had been developed and also put into routine operation during the years from 1995 to 2005. Since then, series of LECR type room temperature ECR ion source have been developed and put into operation for HIRFL successively, which has a fundamental impact to the performance of the facility and multiple discipline scientific goals (Fig. 1). The development of permanent magnet ECR ion sources was started after year 2000. The main goal of this type of compact machine is to prove intense multiple heavy ion beams for industrial applications and small-scale platforms that provide convenient beam time and ion species for users from diversity of fields. The development of superconducting ECR ion source is fundamentally boosted by the needs from the HIRFL upgrade, especially the heavy ion cooler storage ring synchrotron CSR program [2], and the nuclear sciences therein. The first superconducting ECR ion source SECRAL (Superconducting ECR ion source with Advanced design in Lanzhou) is also the 2nd so-called the 3rd generation ECR ion source after the VENUS ion source completed in 2002. Operated typically with the microwave power from a 24 GHz gyrotron generator and an 18 GHz klystron amplifier, SECRAL is one of the most powerful ECR ion sources with many world records of highly charged heavy ion beam intensities.

This paper will give a brief review of the highly charged ion sources developed by the Ion Source Group at IMP. The typical features and the performances will be given. In the last section of this paper, a general introduction of the new activities towards the 45 GHz ECR ion source FECR will also be given.

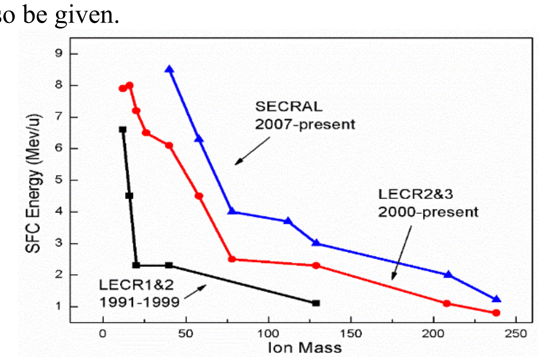

Figure 1: The impact of ion source development to SFC cyclotron performance at HIRFL.

PERMANENT MAGNET ECRIS

All permanent magnet ECR ion sources have many advantages over traditional ECR ion sources composed of several axial room temperature solenoids and one permanent magnet hexapole magnet, which make them the first choice for many heavy ion facilities and platforms. At IMP, three types of all permanent magnet ECR ion sources have been built for diverse applications, i.e. the very compact ECR ion source LAPECR1 for intense mono or multi charge state ion beams' production, the LAPECR2 ion source installed on the 320 kV high voltage multidisciplinary platform [3], and the LAPECR3 ion source dedicated to C^{5+} beam production for the cancer therapy facility HIMM [4].

LAPECR1

This ion source is designed with a very compact size of Ø200 mm×300 mm (including the extraction structure) which makes the source body weighs only 25 kg that can be easily moved around by an adult. Despite of the compactness, the source is equipped with a Ø40 mm ID plasma chamber that enables the direct microwave power feeding with a WR62 rectangular waveguide to simplify the injection plug structure. Iron plugs at both the injection and extraction sides have been incorporated to enhance the mirror peaks. The source is designed and operated at 14.5 GHz. Recently a LAPECR1 source has been used for LEAF platform beam commissioning at IMP. With 100~300 W microwave power, 5.0 emA He^{+}, 1.5 emA He^{2+}, 1.7 emA N^{2+},

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ALL-PERMANENT MAGNET ECR ION SOURCE DECRIS-PM

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Abstract

Super-heavy-element factory is under construction at the Flerov Laboratory for Nuclear Reactions, JINR, Dubna. The factory will include DC-280 cyclotron, which will be equipped with two 100 kV high voltage platforms. A high charge state all-permanent magnet 14 GHz ECRIS – DECRIS-PM has been designed and fabricated to provide intense multiple charge state ion beams. The request for the source is a production of medium mass ions with A/q=4÷7.5 such as 48Ca8+. The conceptual design of DECRIS-PM is presented. During the first tests at the ECR test bench, the source shows a good enough performance for the production of medium charge state ions (such as 900 eμA Ar8+, 550 eμA Ar9+, 200 eμA Ar11+, 160 eμA Kr15+, etc.).

INTRODUCTION

One of the basic scientific programs, which are carried out at the FLNR, is a synthesis of new elements requiring intense beams of heavy ions. To enhance the efficiency of experiments for next few years, it is necessary to obtain accelerated ion beams with the parameters listed in Table 1. These parameters have formed the base for the new cyclotron DC-280 [1]. Some required beam currents are collected in Table 2

Table 1: Required Beam Parameters

Ion energy	4÷8 MeV/n
Ion masses	10÷238
Beam intensity (A≤50)	up to10 pμA
Beam emittance	≤ 30 π mm×mrad
Total efficiency	> 50%.

Table 2: Required Beam Intensities

Ion	$^{48}Ar^{7+}$	$^{48}Ca^{8+}$	$^{58}Fe^{10}$
Intensity from ion source μA	300	150	125
Intensity on phys. target pps	3×10^{14}	5×10^{13}	4×10^{13}

The axial injection system of the DC-280 cyclotron will include two high voltage platforms, which will allow for efficient injection of ions from helium to uranium with M/Q ratio in the range of 4÷7. Each HV-platform will be equipped with the low power consuming ECR ion source.

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For production of ions with the low and medium masses (from He to Kr) the all-permanent-magnet (PM) ECR ion source will be used. Many good performance all-permanent magnet ECRISs have been built around the world. Most of them are compact versions of ECRIS. Parameters of some PM ECRIS are listed in Table 3.

Table 3: Parameters of PM ECRIS

Ion source	Nanogan 14 GHz	Super Nanogan	LAP ECR2
Frequency	14.5	14.5	14.5
Plasma Chamber Ø	28	45	67
Weight	90	200	~500
Ar^{8+}	60	200	460
Ar^{9+}	20	90	455

Nanogan and Supernanogan ion sources are available for purchase from Pantechnik [2]. However, it is obvious that the compact versions of the sources do not provide the required ion beam intensities for our project. The only previously created "full-size" ion source which practically reproduces the structure and ion yields of CAPRICE-type ECRIS is LAPECR2 [3]. For this reason, the following design parameters of DECRIS-PM were selected:

- Microwave frequency – 14 ÷ 14.5 GHz
- B_{inj} - ≥ 1.3 T
- B_{min} - 0.4 T
- B_{extr} - 1 ÷ 1.1 T
- Plasma chamber Ø - 70 mm

SOURCE DESIGN

The main advantages of the all permanent magnet ECRIS are low power consumption, low pressure in the cooling water system, simplified operation, etc. However, there are few significant drawbacks of all permanent magnet ECRIS. First, the magnetic field is fixed and comparatively low. Thus, the designed magnetic configuration should be optimized from the very beginning. Another drawback is strong mechanical force acting on the individual parts of the system. As a result the correction of the magnetic field after the assembly of the magnetic system is practically impossible without demagnetization.

Deviations from the required field distribution can occur for many reasons. The variation in properties of permanent magnets (about of 5%) and the variation of easy axis direc-

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NEW METHOD TO DESIGN MAGNETIC CHANNELS WITH 2D OPTIMIZATION TOOLS AND USING PERMENDUR VANADIUM

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Abstract

Magnetic channels are used in almost all cyclotrons to focus radially the beam along the extraction path through the coils and yoke region, where the rapid fall off of the magnetic field produces a strong vertical focusing and radial defocusing of the beam. These magnetic channels consist generally of three iron bars. The current sheet approximation has been generally used to evaluate quickly the performance of magnetic channels.

For the new magnetic channels to be used in the upgrade of the LNS-INFN k800 Superconducting Cyclotron, a new method was developed to investigate complex configurations and to achieve higher magnetic gradients in a larger area. The optimization procedure is based on a genetic algorithm implemented on MATLAB code and using the COMSOL code to perform the 2D magnetic field simulations.

Moreover, the use of permendur vanadium in alternative to iron allows to reduce the volume of the bars and mainly the magnetic force.

The results of our simulations are here presented.

INTRODUCTION

The LNS-INFN Superconducting Cyclotron (CS), Catania, has been working for 25 years delivering almost all ion beams in the mass range 2÷200 amu and energy range 10÷80 AMeV [1].

The CS was designed to perform nuclear physics experiments that generally use low intensity beams. Indeed, due to the compactness of the CS, the last accelerated orbit is not fully separated from the previous one, and the extraction efficiency is under 60%. The beam power dissipated on the septum of the first electrostatic deflector (E.D.) causes issues due to thermal deformation of the septum, extra outgassing, high dark current and E.D. discharges. For these problems the maximum beam power extracted from the cyclotron up to now stays below 100 W.

In 2016 the scientific community and the management of LNS-INFN approved a project to upgrade the CS to allow the extraction of beam power up to 10 kW for the ions with mass below 50 amu [2]. These high power beams are useful to perform the NUMEN experiment and also to drive the facility FRAISE (FRAgment In-flight SEparator) [3,4].

To achieve this goal, the beam will be extracted by stripping. This extraction method is based on the sudden change of charge state produced by the crossing of the beam through a thin carbon foil, so called stripper. The consequent decrease of the magnetic rigidity after the stripper produce a strong perturbation of the beam trajectory that naturally escapes from the cyclotron pole [5].

Although extraction by stripping is very convenient to achieve high extraction efficiency, its application is not trivial when extracting ions with a wide range of masses and/or energies. Indeed, the extraction trajectories are quite different for each different ion type, therefore a large Extraction Channel (Ex.Ch.) is mandatory, by far larger than the one used for electrostatic extraction. A new extraction system for a selected set of ions and energies has been designed [2].

In particular, two big Magnetic Channels (MC1, MC2) are mandatory to focus the beam along the extraction channel, see Fig.1. Moreover, these two channels have to provide large gradient, up to 2 kGauss/cm, over a large area (4 x 3 cm) to allow for an efficient transmission of the beams that have relatively large transversal sizes [6]. These MC were simulated using the so-called Current Sheet Approximation (CSA) [7]. The size of these channels are quite large and one of the problems, which appeared during the design of these magnetic channels was the magnetic force. As MC's have wide range of positions, according to the ion trajectory, it is very challenging from the mechanical point of view to offset these magnetic forces. In particular, the

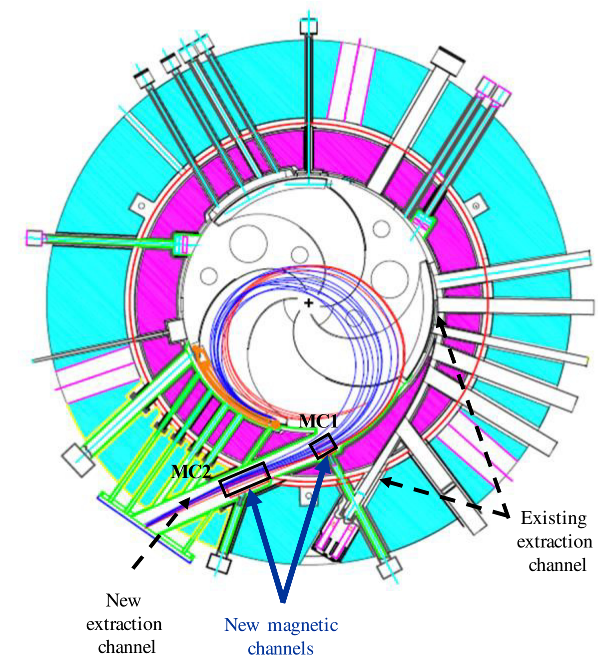

Figure 1: Layout of the two extractions channels from the CS. A set of new extraction trajectories achieved by stripping and the positions of the two new magnetic channels are also shown.

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DESIGN OF THE MULTI-ION INJECTOR LINAC FOR THE JLAB EIC (JLEIC)*

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Abstract

An Electron Ion Collider (EIC) is the highest priority for future U.S. accelerator-based nuclear physics facility following the completion of the Facility for Rare Isotope Beams (FRIB). Two laboratories are competing to host the future EIC: Brookhaven National Lab. (BNL) and Jefferson Lab. (JLab). The baseline design of JLab's Electron Ion Collider (JLEIC) ion complex comprises a pulsed superconducting (SC) linac injector capable of accelerating all ions from protons to lead, where proton and light ion beams can be polarized. After reviewing the design requirements for the injector linac, important design choices such as the room-temperature (RT) section design, the transition energy between the RT and SC sections and the stripping energy for heavy ions will be discussed. The design of the different linac sections will be presented as well as the results of end-to-end beam dynamics simulations for polarized deuterons and un-polarized lead ions.

INTRODUCTION

The electron-ion collider concept proposed by JLAB (JLEIC) requires a new ion accelerator complex which includes a multi-ion linac capable of delivering any ion beam from hydrogen to lead to the Booster. We have developed a design for a pulsed linac which consists of different ion sources, a room-temperature (RT) front-end, up to 5 MeV/u followed by a superconducting (SRF) section to the full linac energy. This work includes the beam dynamics and electrodynamics studies performed to design efficient and cost-effective accelerating structures for both the RT and SRF sections of the linac. The current design includes two separate RFQs one for heavy ions and one for polarized light-ion beams, and a common RT section with a special IH DTL design downstream of the RFQs. Quarter-wave and half-wave resonators are effectively used in the SRF section of the linac.

DESIGN REQUIREMENTS AND CHOICES FOR JLEIC INJECTOR LINAC

Design Requirements for JLEIC Injector Linac

The baseline design of the JLEIC ion complex [1] calls for the following requirements from the injector linac:

- Capable of accelerating all beams from protons to lead ions, including polarized light ion beams
- Deliver 280 MeV protons and 100 MeV/u lead ions Pb^{67+} for injection to the Booster, and equivalent energies for other ion beams
- Pulsed beam structure with 5-10 Hz repetition rate and 0.2 - 0.5 ms beam pulse length
- Pulsed beam current of ~ 2 mA for light ions and ~ 0.5 mA for heavy ions
- Compact and cost efficient

Important Design Choices for the Linac

In order to satisfy the design requirements listed above, the following design choices were made for the JLEIC injector linac:

- To accommodate the significantly different beam parameters from polarized light-ion and heavy-ion sources, the linac includes two separate RFQs, one for mass-to-charge ratio $A/q \leq 2$ and one for heavy ions with $A/q > 2$.
- As a consequence, two separate low-energy beam transport (LEBT) lines are required. However, this separate front-end choice allows a special LEBT design for polarized light ions to preserve polarization.
- Based on similar pulsed ion linacs [2, 3], a room-temperature (RT) section up to an energy of ~ 5 MeV/u is the most efficient and cost-effective option for the JLEIC linac, followed by a SRF section up to the full linac energy.
- A pulsed SRF linac can be more compact and cost-effective than the full RT option [4, 5]. It also offers wider acceptance and more tuning flexibility for light and heavy ion beams. In addition, taking advantage of state-of-the-art performance of quarter-wave (QWR) and half-wave (HWR) resonators [6, 7], which can deliver higher voltages in pulsed mode, the linac can be even more compact.
- In order to deliver Pb^{67+} at 100 MeV/u, the optimum stripping energy was found to be ~ 13 MeV/u, which is the energy following two QWRs modules made of 7 cavities each.

DESIGN OF THE DIFFERENT SECTIONS OF THE LINAC

Figure 1 shows the layout of the designed JLEIC injector linac with separate front-ends for light ion and heavy-ion beams, a DTL section made of three IH tanks followed by an SRF section made of three QWR cryomodules operating at 100 MHz and nine HWR cryomodules operating at 200 MHz. A stripper section for the heaviest ions is located between the second and third QWR modules.

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INVESTIGATIONS ON KONUS BEAM DYNAMICS USING THE PRE-STRIPPER DRIFT TUBE LINAC AT GSI

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Abstract

Interdigital H-mode (IH) drift tube linacs (DTLs) based on KONUS beam dynamics are very sensitive to the rf-phases and voltages at the gaps between tubes. In order to design these DTLs, a deep understanding of the underlying longitudinal beam dynamics is mandatory. The report presents tracking simulations along an IH-DTL using the PARTRAN and BEAMPATH codes together with MATHCAD and CST. Simulation results illustrate that the beam dynamics design of the pre-stripper IH-DTL at GSI is sensitive to slight deviations of rf-phase and gap voltages with impact to the mean beam energy at the DTL exit. Applying the existing geometrical design, rf-voltages, and rf-phases of the DTL were re-adjusted.

KONUS BEAM DYNAMICS DESIGN

A Hamiltonian can be constructed describing the longitudinal particle motion in phase space as

$$H = -\frac{\pi w^2}{\beta_s^3\gamma_s^3\lambda} - \frac{qE_{acc}T_n(\beta_r)}{mc^2}(\sin\psi_r - \psi_r\cos\psi_s), \quad (1)$$

since ψ and w are variables canonically dependant on s

$$\frac{d\psi}{ds} = -\frac{2\pi w}{\beta_s^3\gamma_s^3\lambda}, \quad \frac{dw}{ds} = \frac{qE_{acc}T_n(\beta_r)}{mc^2}(\cos\psi_r - \cos\psi_s), \quad (2)$$

where q is the electric charge, m is the mass of the particle, c is the velocity of light, λ is the rf-frequency, and γ_s is the relativistic gamma factor. ψ_r is the phase of the field when the particle is at gap center, ψ_s is the synchronous phase, E_{acc} is the accelerating gradient, and T is the transient time factor. The subscripts s and n refer to the synchronous particle and the cell number, respectively. The energy gain of a particle may be expressed through the difference of its individual phase to the synchronous phase. For simplicity this term is normalized to the rest energy of the particle under study, suggesting the substitution

$$w = \frac{W_n - W_{n,s}}{mc^2}. \quad (3)$$

In conventional longitudinal beam dynamics the reference particle and the synchronous particle are identical. Longitudinal focusing is obtained by operating at constant negative rf-phase, such that the reference particle passes the gap center before the crest of the cosine-like gap voltage is reached. In conventional linacs the reference particle with design rf-phase of 0° (on rf-crest) will have maximum energy gain, but the rf-phase range for stable longitudinal motion vanishes implying longitudinal acceptance of size zero.

In KONUS the reference particle and the synchronous particle are not the same. The gap-to-gap spacings are adjusted such that the synchronous particle arrives at 0° at each gap center. The beam is injected into a KONUS section such that the energy of the reference particle is higher than the synchronous particle energy. Additionally, the rf-phase of the reference particle at the first gap is close to the 0° synchronous phase. As the particle advances from gap to gap, the reference particle position will move counter clockwise in the longitudinal phase space diagram as illustrated in Fig. 1.

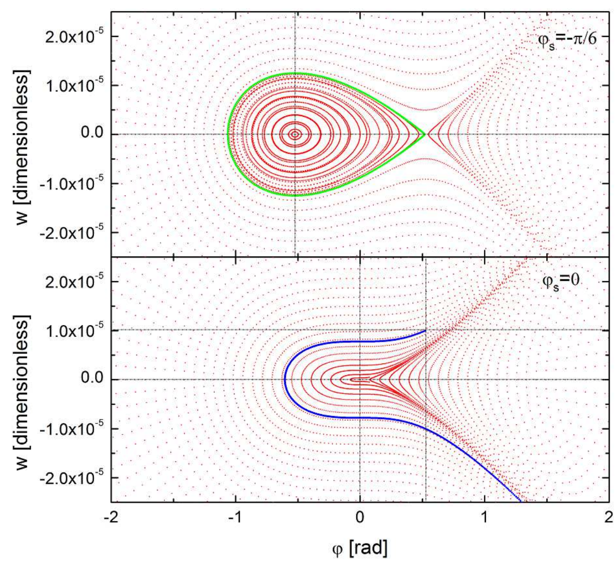

Figure 1: Conventional negative phase structure (upper) and KONUS structure (lower). In convectional designs, the rf-phase of the synchronous (reference) particle is always constant and negative (ψ_s≈-30°). Its energy is equal to the design energy (w=0). In KONUS the rf-phase and the energy difference of the reference particle w.r.t. the synchronous particle vary. The reference particle motion is not stable (blue line).

The parameters of the IH-DTL used as a reference in the following are listed in Table 1. This DTL provides transverse and longitudinal beam focusing for a long H-mode linac section, where the defocusing effects of transverse rf-fields and space-charge must be compensated avoiding quadrupole focusing lenses in each drift tube.

Almost all DTLs based on KONUS have been designed with LORASR [1]. One main feature of this code is provision of the gap field map. It builds the field map from

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STOCHASTIC COOLING SIMULATION OF RARE ISOTOPE BEAM AND ITS SECONDARY*

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Abstract

Stochastic cooling is a broadband feedback system, which is very effective for reducing the beam size without beam loss [1]. It has advantage over electron cooling in cooling low intensity beam with large emittance and momentum spread, and is required for precise study of the decay properties of RIB (Radioactive Ion Beam) by use of the SMS (Schottky Mass Spectrometry) method [2]. This paper mainly concerns on cooling of primary beam and its secondary beam, pointing out the range of mass-to-charge spread that could be cooled for secondary particles. Meanwhile, TOF cooling combined with filter cooling was also studied. The simulation results provide theoretical supports for analysing different ions circulating in the ring at the same time in the experiments.

INTRODUCTION TO HIAF STOCHASTIC COOLING SYSTEM

The High Intensity heavy ion Accelerator Facility (HIAF) was proposed by the Institute of Modern Physics in 2009. As one of 16 large-scale research facilities proposed in China, HIAF is the next-generation high intensity facility for advances in nuclear physics and related research fields.

Stochastic cooling will be built on the Spectrometer Ring (SRing) of the HIAF project. The space for pickups and kickers is reserved in advance for SRing stochastic cooling system. There are 4 m for pickups and 4 m for kickers. All of the electrodes will be installed in the straight section without dispersion, and it has the advantage of preventing the coupling between phase subspaces, especially the transverse heating due to longitudinal kicks. It is planned to have 2 pickup tanks and 2 kicker tanks which would perform both transverse and longitudinal cooling. The betatron phase advances from pickup to kicker are almost 90 deg for both horizontal and vertical cooling.

The kinetic energy was designed to be 400 MeV/u, for the consideration of nuclear physics and atomic physics. The radioactive ion beam injected into SRing has large momentum spread of ±1.5e-2. If stochastic cooling is used for such kind of beam, the cooling frequency would be small in order to have large cooling acceptance. Fortunately, bunch rotation was proposed to decrease the momentum spread to ±4.0e-3, which is suitable for stochastic cooling to be cooled to the appropriate values, and then combined with electron cooling for further momentum spread decrease.

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COOLING METHODS FOR SRING LONGITUDINAL STOCHASTIC COOLING

By comparisons of different cooling methods, TOF cooling has the maximum cooling acceptance for longitudinal cooling than the others. Therefore, TOF cooling [3,4] was proposed to be used for SRing longitudinal stochastic cooling for beam with large momentum spread. After the beam momentum spread was decreased to a small value stage, filter cooling [5] was used for continuous cooling in order to achieve a reasonable value for subsequent electron cooling.

For the beam energy 400 MeV/u, when the bandwidth was 1-2 GHz, the TOF cooling acceptance was smaller than the initial beam momentum spread ±4.0e-3. Therefore, the bandwidth was reduced to 0.6-1.2 GHz, and then the TOF cooling could be able to cool this kind of beam with its initial momentum spread within TOF cooling acceptance.

LONGITUDINAL STOCHASTIC COOLING SIMULATION ON SRING

Cooling of Primary Beam

Table 1: Longitudinal Stochastic Cooling parameters

Physical parameters	values
Ion	$^{132}Sn^{50+}$
Kinetic energy	740 MeV/u, 400 MeV/u
Total number of RI	1.0e5, 1.0e8
Initial Δp/p	±4.0e-3 (TOF Cooling) ±7.0e-4(Filter Cooling)
γt	3.317
Local γt	2.568
Bandwidth	0.6-1.2 GHz
Number of slot rings for Pickup/Kicker	64/128, 112/224
Number of faltin for Pickup/Kicker(0.75 m)	2/4
Temperature	300 K
Lpk	75.25 m

The SRing stochastic cooling parameters are listed in Table 1. $^{132}Sn^{50+}$ was chosen for the primary beam. We assumed the beam kinetic energy to be 740 MeV/u or 400 MeV/u for comparisons, and the particle number to be

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COMMISSIONING OF CHINA ADS DEMO LINAC AND BASELINE DESIGN OF CiADS PROJECT*

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Abstract

China Accelerator Driven Subcritical System (C-ADS) program was launched in China in 2011, which aims to design and build an ADS demonstration facility with the capability of more than 10 MW thermal power in multiple phases lasting about 20 years. In the first phase, a demo linac has been constructed and commissioned successfully to demonstrate the key technologies of the high-power CW mode superconducting linac. Followed the China ADS roadmap, a superconducting driver linac with 500MeV and 5mA proton beam is designed for the second phase of China Initiative Accelerator Driven Subcritical System (CiADS) program. The commissioning results of the China ADS 25 MeV demo linac and the RAMI oriented beam physics design of CiADS linac are presented in this paper.

INTRUDUCTION

China Initiative Accelerator Driven Subcritical System (CiADS) program is a strategy project to solve the nuclear waste problem and the resource problem for nuclear power plants in China [1]. It consists three parts, a high-power superconducting proton linac, heavy metal spallation target and the sub-critical nuclear reactor. The high-power superconducting proton linac is comprised of warm temperature front-end accelerator, superconducting section and high energy transportation line, and it will accelerate 10mA proton beam to 1.5GeV [1]. The main design specifications of proton beam at the ultimate stage are shown in Table 1.

Table 1: Specifications of the Required Proton Beams

Particle	Proton	
Energy	1.5	GeV
Current	10	mA
Beam power	15	MW
RF frequency	(162.5)/325/650	MHz
Duty factor	100	%
Beam Loss	<1	W/m
Beam trips/year	<25000 <2500 <25	1s<t<10s 10s<t<5m t>5m

It is extremely challenging to design and build tens of MWs beam power proton linac, and there is no existing machine in the world. To study the key technology and main factor affecting high reliability and availability of high power accelerator, the accelerator R&D based on a demo linac named China ADS demo linac has been carried out. The China ADS linac has been constructed by the collaborations between Institute of Modern Physics(IMP) and Institute of High Energy Physics(IHEP). This demo linac is composed of an ion source, a low energy beam transport line(LEBT), a 162.5MHz radio frequency quadrupole accelerator(RFQ), a medium energy beam transport line(MEBT), a superconducting accelerating section which contains Half Wave Resonators (HWR) and Spoke resonators and a high energy beam transport line(HEBT). In this paper, the commissioning results of the demo linac and the baseline physics design of CiADS will be presented.

COMMISSIONING OF CHINA ADS DEMO LINAC

China ADS demo linac is operated to accelerate CW proton to 25MeV with beam current of 10mA at 4.5K operation temperature. The total length is about 35m. The schematic view and the photo layout are shown in Fig.1.

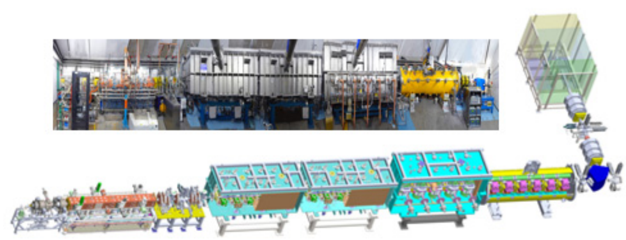

Figure 1: The schematic view and the photo layout of China ADS demo linac.

The installation of the demo linac at IMP has been started since August 2014. Up to now, the beam line includes a LEBT, a RFQ, a MEBT, three HWR Cryomodules, a Spoke Cryomodule, a HEBT and a beam dump which can sustain 100 kW beam power.

The 0.2mA CW proton beam with energy of 25MeV and the 12mA pulsed beam with energy of 26.2MeV were achieved in June 2017. The Fig.2 shows the 0.2mA CW beam current. The Time of Flight method is used for the energy measured, the measurement results and the simulation results are coincident as shown in Fig.3.

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HIGH-BRILLIANCE NEUTRON SOURCE PROJECT

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Abstract

The High-Brilliance Neutron Source (HBS) project aims to design a scalable compact accelerator driven neutron source (CANS) which is competitive and cost-efficient. The concept allows one to optimize the whole facility including accelerator, target, moderators and neutron optics to the demands of individual neutron instruments. Particle type, energy, timing, and pulse structure of the accelerator are fully defined by the requirements of a given neutron instrument. In the following, we present the current status of the HBS project.

INTRODUCTION

The neutron landscape in Europe is in a time of change. On the one hand, the European Spallation Source (ESS) is being constructed as world-leading neutron facility but on the other hand many research reactors used for neutron experiments, like the BER-II reactor in Germany or the ORPHEE-reactor in France, are fading out [1]. The European community for neutron research is therefore facing a mixed outlook towards the availability of neutrons in coming decades. As new reactor sources or spallation sources are costly and therefore difficult to realize, new possibilities for neutron production need to be investigated.

In the HBS project we are developing a scalable compact accelerator driven neutron source (CANS) optimized for scattering and neutron analytics. This type of source produces neutrons using nuclear reactions of protons or deuterons in a suitable target material. At these sources, the whole chain ranging from the accelerator to the target / moderator / shielding assembly and the neutron optics can be optimized according to the needs of the neutron experiments. This approach makes such sources very efficient enabling competitive neutron fluxes at the sample position compared to today's research reactors.

Being a scalable neutron source, the performance level can vary from a low power pulsed neutron source designed for universities and industry with an average power at the target of around 1 kW to a high performance neutron source with ~100 kW average power designed as a full-fledged national facility. We have named the low power CANS NOVA ERA ("Neutrons Obtained Via Accelerator for Education and Research Activities") [2] which is used for basic research, user training and method development, whereas the full-fledged facility compares favorably to nowadays medium flux neutron sources and is operated as a user facility.

In the subsequent text we will describe all basic components of such a source.

HBS LAYOUT

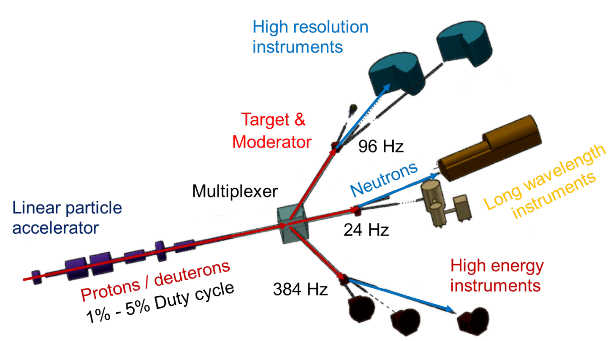

Figure 1: The layout for a high-performance accelerator driven neutron source.

The basic design of a CANS is shown in Figure 1. It consists of a pulsed proton or deuteron accelerator, a multiplexer distributing the protons or deuterons to different target stations each consisting of a target / moderator / shielding assembly and neutron experiments. The neutron experiments with similar requirements for the neutron beam properties are grouped together on the same target station and all upstream elements are optimized to meet these requirements.

This is a general layout which can differ in the specific realization. For example, a low power / low cost CANS like the NOVA ERA will not be equipped with a beam multiplexer and will only maintain one target station.

Accelerator

The protons or deuterons used for the nuclear reaction need to be accelerated to an energy between 10 MeV and 100 MeV. Various types of particle accelerators are available for this purpose, e.g a tandem accelerator, a cyclotron or a

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THE DC130 PROJECT: NEW MULTIPURPOSE APPLIED SCIENCE FACILITY FOR FLNR

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Abstract

The main activities of Flerov Laboratory of Nuclear Reactions, following its name - are related to fundamental science, but, in parallel, plenty of efforts are paid for practical applications. Certain amount of beam time every year is spent for applied science experiments on FLNR accelerator complex. For the moment, the main directions are: the production of the heterogeneous micro - and nano-structured materials; testing of electronic components (avionics and space electronics) for radiation hardness; ion-implantation nanotechnology and radiation materials science. Basing on FLNR long term experience in these fields and aiming to improve the instrumentation, the accelerator department start the Design Study for new cyclotron DC130 which will be dedicated machine for applied researches in FLNR. Following the user's requirements DC130 should accelerate the heavy ions with mass-to-charge ratio A/Z of the range from 5 to 8 up to fixed energies 2 and 4.5 MeV per unit mass. The first outlook of DC130 parameters, its features, layout of its casemate and general overview of the new FLNR facility for applied science is presented.

INTRODUCTION

The main point is that for applied science people use powerful machines which were created and developed to solve the wide range of fundamental research. The usage of 'science' accelerators for such activities is connected which high cost of beam time and difficulty to meet quick changes of user's requirements. There is a "time lack" problem when application begin to demand the beam time more than laboratory could provide to it in parallel with its scientific plan's realization. Usually, it means that all technical "bugs" and methodological questions were successfully fixed and answered, and users requesting the time as much as they could. That's why Flerov Laboratory of Nuclear Reaction of Joint Institute for Nuclear Research starts the Design Study of the dedicated applied science facility based on the new DC130 cyclotron. The irradiation facility will be used mainly for the following applications: creation and development of track membranes (nuclear filters) and the heavy ion induced modification of materials; activation analysis, applied radiochemistry and production of high purity isotopes; ion-implantation nanotechnology and radiation materials science; testing of electronic components (avionics and space electronics) for radiation hardness. From the common user's requirements, operation simplicity and cost reasons the main parameters of future machine were chosen. The facility will be based on new DC130 isochronous cyclotron: multiparticle, double - energy machine, capable with light and heavy ions up to bismuth (2 and 4.5 MeV/nucleon).

The research works on radiation physics, radiation resistance of materials and the production of track membranes will be carrying out by using the ion beams with energy of about 2 MeV per unit mass and A/Z ratio in the range from 7.58 to 8.0. Besides these, testing of avionics and space electronics by using of ion beams (^{20}Ne, ^{40}Ar, ^{84,86}Kr, ^{132}Xe, ^{197}Au or ^{209}Bi) with energy of 4.5 MeV per nucleon and with mass-to-charge ratio A/Z in the range from 5.0 to 5.5, will be proceeded. One of the significant requirements for this application is the "ion cocktail" means mixed of highly charged heavy ions with the same or very close mass/charge ratios produced and injected in the same time. Once the ions will be accelerated, the different species will be separated by the fine tuning of the cyclotron magnetic field. This issue allows to switch the type of ions quick and will reduce the time which user should spent for full scale testing of its samples.

The idea is to effectively use existing stuff to modernize and totally upgrade the old U200 machine which was decommissioned in 2013, because of being outdated physically and technologically. The design will be based on existing systems of IC100 (Fig.1) and U200 (Fig.2) cyclotrons [1].

The working diagram of DC130 cyclotron is shown in Fig.3. The acceleration of ion beam in the cyclotron will be performed at constant frequency f = 10.622 MHz of the RF-accelerating system for two different harmonic numbers h. The harmonic number h = 2 corresponds to the ion beam energy W = 4.5 MeV/u and value h = 3 corresponds to W = 1.993 Mev/nucleon. The intensity of the accelerated ions will be about 1 pμA for lighter ions ($A \leq 86$) and about 0.1 pμA for heavier ions ($A \geq 132$).

The axial injection system and its beam line for new accelerator will be adapted from the existing IC100 cyclotron systems.

In the frame of reconstruction of U200 to DC130 it is planned to upgrade the cyclotron magnetic structure, replace the magnet main coil and renovate RF system. Other systems: beam extraction, vacuum, cooling, control electronics and radiation safety will be new.

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MECHANICAL DESIGN OF SINGLE SPOKE RESONATOR TYPE-2 (SSR2) SUPERCONDUCTING CAVITY FOR RISP*

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Abstract

Superconducting linear accelerator and many beam experimental devices for the future of basic science research in Korea are being made and prepared for installation in Sindong linac tunnel north side of Daejeon, Korea. The key components of superconducting linac are the superconducting cavities and RISP linac has four types of superconducting cavities such as quarter-wave, half-wave, and single spoke resonator type-1 and 2. In this paper, we introduce about the initial RF/EM design of single spoke resonator type-2 (SSR2) superconducting (SC) cavity, and explain about mechanical design. Afterwards, we analyze mechanical design parameters of SSR2 SC cavity using ANSYS 18.0 structural solver and material properties of RRR 300 pure-niobium and stainless steel.

INTRODUCTION

From 2011 to now, RISP proceeded enormous research and development of superconducting linac and experimental devices. In our group - Accelerator System Team (AST) – four types of SC cavity, RF coupler, tuner, and cryomodule are designed, fabricated, and tested in the Munji SRF test facility. At the low energy linac region, quarter-wave (QWR) and half-wave (HWR) resonator will be installed, and single spoke resonator type-1 (SSR1) and type-2 (SSR2) also will be installed into the high energy linac region [1]. Between 2012 and 2014, we proceeded first prototyping of every SC cavity types and tested using different SRF facility like TRIUMF, Canada, or Cornell Univ., USA. Unfortunately, we didn't reach our target performance of both SSR1 and SSR2 SC cavity. Therefore, we tried to find out proper design of SSR1 SC cavity with the collaboration of TRIUMF, Canada. Based on the MOU and general contracts, TRIUMF invented a new concept of SSR1 SC cavity called 'Balloon Variant' [2,3]. TRIUMF also proceeded fabrication with PAVAC and 4K/2K cold test using their test facilities [4]. The essential advantage of balloon variant SC cavity shape is the suppression of multi-pacting effects. We decided to apply same balloon variant concept to the SSR2 SC cavity after SSR1 2K cold test was satisfied our expected performances.

SSR1/2 SPECIFICATIONS AND RF DESIGN

Table 1 shows the design specifications of SSR1/2 SC cavity for RISP. For satisfying our high energy SC linac beam lattice, we should evaluate our design specifications.

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Figure 1 shows the SSR2 RF volume design for EM simulations. Balloon variant concept was applied same as SSR1 due to its high suppression effect for multi-pacting.

Table 1: Design Specifications of SSR1/2

	Unit	SSR1	SSR2
Operating Frequency	MHz	325	
Beta		0.3	0.51
Operating Temperature	K	2.05	
Q Factor		>5E9	
Epeak	MV/m	35	
Vacc	MV	>2.4	>4.1
df/dp	Hz/mbar	<10	
Beam bore	mm	50	
Pressure Envelope @ 300K	bar	2	
Pressure Envelope @ 5K	bar	5	

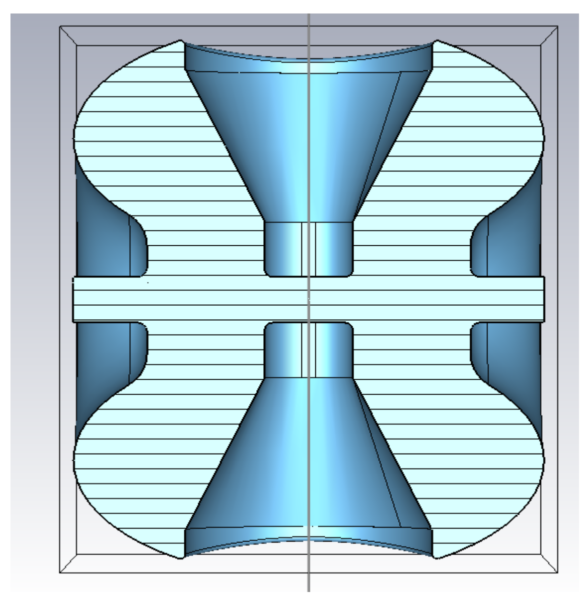

Figure 1: RF volume design done by RF engineer.

With this shape, RF engineer proceeded multi-pacting simulation with CST PIC-solver code, and Fig. 2 shows that the multi-pacting is reduced comparing with RISP SSR2 first prototype and modified RISP SSR2 with double radius corners from the ideation of FNAL [5].

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FIRST ACCELERATION OF HEAVY ION BEAMS WITH A SUPERCONDUCTING CONTINOUS WAVE HIM/GSI CW-LINAC*

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Abstract

In the future a new superconducting (sc) continuous wave (cw) high intensity heavy ion Linac should provide ion beams with a max. beam energy above the coulomb barrier for the Super Heavy Element (SHE) program at GSI Helmholtzzentrum für Schwerionenforschung. As a first step a newly developed superconducting 15-gap Crossbar H-cavity (CH-cavity) operated at 217 MHz has been successfully tested with heavy ion beam up to the design beam energy of 1.85 MeV/u for the first time. The design energy gain of 3.5 MV within a length of less than 70 cm has been validated with heavy ion beams of up to 1.5 pμA. The measured beam parameters showed excellent beam quality, while a dedicated beam dynamics layout provides beam energy variation between 1.2 and 2.2 MeV/u. The beam commissioning is a milestone of the R&D work of Helmholtz Institute Mainz (HIM) and GSI in collaboration with Goethe University Frankfurt (GUF) and the first step towards a sc heavy ion cw-Linac with variable beam energy. The first tests under cryogenic conditions of the next two CH-cavities have already been started at GUF in a vertical cryostat. The results of the first successful heavy ion beam acceleration with a superconducting CH-cavity will be presented.

INTRODUCTION

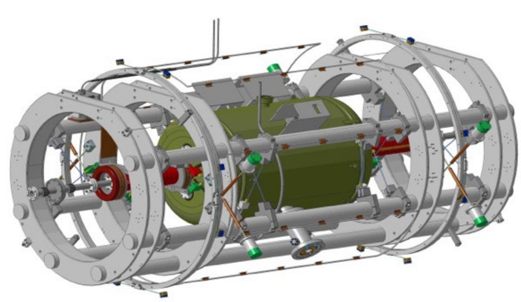

Figure 1: Demonstrator CH-cavity (CH0) with two sc-solenoids inside the support frame.

The design and construction of cw high intensity Linacs is a crucial goal of worldwide accelerator technology development [1]. Above all, compactness of a particle accelerator is a beneficial demand for the development of high intensity cw proton and ion Linacs [2]. The study and investigation of the design, operation and optimization of a cw-Linac, as well as progress in elaboration of the superconducting technology [3] is of high relevance.

For the HIM/GSI cw-Linac HELIAC (HElmholtz LInear ACcelerator) several superconducting CH cavities operated at 217 MHz are used to provide acceleration of ions with a mass to charge ratio of up to 6 to beam energies between 3.5 MeV/u and 7.3 MeV/u, while the energy spread should be kept smaller than ±3 keV/u. For proper beam focusing superconducting solenoids have to be mounted between the CH cavities. The general parameters are listed in Table 1 [4]. R&D and prototyping (demonstrator project) [5] in preparation of the proposed HELIAC is assigned to a collaboration of GSI, HIM and GUF. The demonstrator setup is located in straightforward direction of the GSI–High Charge State Injector (HLI).

Table 1: Design Parameters of the cw-Linac

Mass/charge		6
Frequency	MHz	216.816
Max. beam current	mA	1
Injection energy	MeV/u	1.4
Output energy	MeV/u	3.5 – 7.3
Output energy spread	keV/u	±3
Length of acceleration	m	12.7
Sc CH-cavities	#	9
Sc solenoids	#	7

The demonstrator comprises a 15 gap sc CH-cavity (CH0) embedded by two superconducting solenoids; all three components are mounted on a common support frame (see Fig. 1) [6]. The beam focusing solenoids consist of one main Nb_3Sn-coil and two compensation coils made from NbTi that shield the maximum magnetic field of 9.3 T within a longitudinal distance of 10 cm down to 30 mT. The solenoids are connected to LHe ports inside the cryostat by copper tapes allowing dry cooling. The sc CH structure CH0 is the key component and offers a variety of research and development [7].

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DESIGN AND BEAM COMMISSIONING OF THE LEAF-RFQ*

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Abstract

An 81.25 MHz continuous wave (CW) radio frequency quadrupole (RFQ) accelerator has been designed and fabricated for the Low Energy Accelerator Facility (LEAF) by the Institute of Modern Physics (IMP) of the Chinese Academy of Science (CAS). The operation frequency is 81.25 MHz and the inter-vane voltage is a constant of 70 kV. It took about 44 hours continuous conditioning to reach RF power of 75 kW which is 1.1 time of the maximum designed operational power, and the successful CW acceleration of 150 eμA He^{+} beam to the designed energy of 0.5 MeV/u. Both the results of the high power test and the beam test will be reported in this paper.

INTRODUCTION

The LEAF project was launched as a pre-research facility for the high intensity Heavy Ion Accelerator Facility (HIAF) project and a heavy ion irradiation facility for material research at IMP [1] [2]. The LEAF will consist of a 2 mA U^{34+} electron cyclotron resonance ion source, a low energy beam transport line, a CW 81.25MHz RFQ accelerator [3], a medium energy beam transport line and an experimental platform for nuclear physics. The layout of the LEAF project is shown in Fig. 1. The LEAF-RFQ shown in Fig. 2 will operate as a CW injector with the capability of accelerating all ion species from proton to uranium from 14 keV/u up to 500 keV/u. The design goal is to design a compact type cavity with lower power loss and high operation stability. Considering the LEAF-RFQ will operate in CW mode, a four-vane structure is a better choice than four-rod type, because the four-vane structure is a more stable structure for water cooling. The PISL (Pi-mode stabilizing loop) structure is adopted to suppress the dipole effect. In addition, tuners and undercuts are used for frequency tuning and field flatness. The main parameters of the LEAF-RFQ are listed in the table 1. In this paper, we report the designs and results of the low power test and the high power test.

Table 1: Main Parameters of the LEAF-RFQ

Parameters	Value
A/q	7
Operation	CW/pulsed
Vane type	Four vane
Frequency (MHz)	81.25
Input energy (keV/u)	14
Output energy (MeV/u)	0.5
Inter-vane voltage (kV)	70
Kilpatrick factor	1.55
Peak current (emA)	2
Transmission efficiency (%)	97.2
Acceleration efficiency (%)	81.7
Length of vane (mm)	5946.92
Average radius of aperture (mm)	5.805

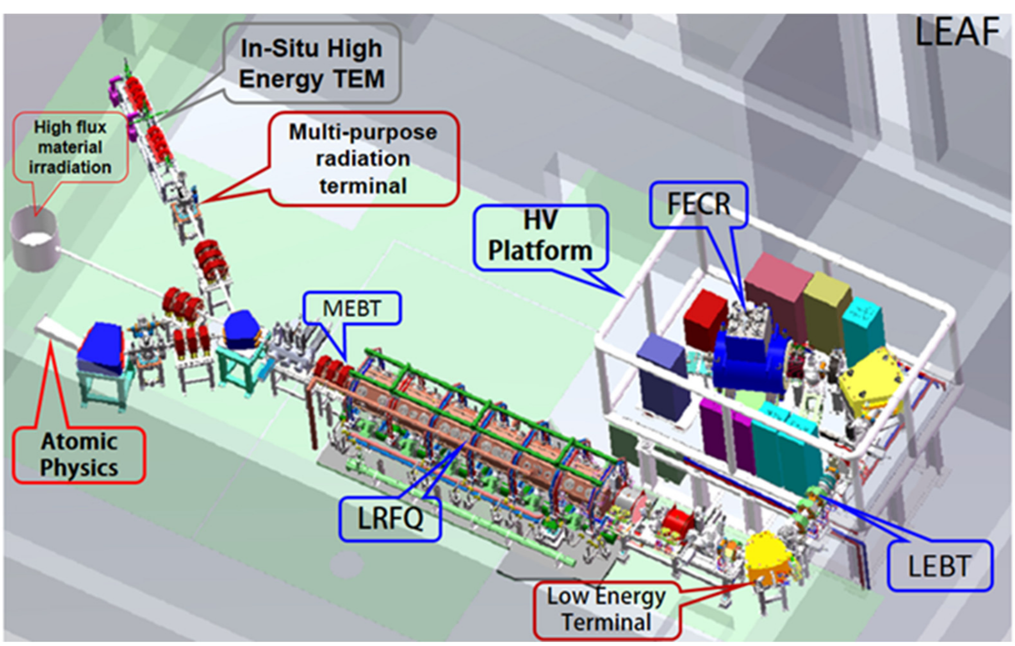

Figure 1: Layout of LEAF facility.

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MULTI-PHYSICS ANALYSIS OF A CW FOUR-ROD RFQ *

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Abstract

The new injector SSC-LINAC is under design and construction to improve the efficiency and intensity of beams for the Separated-Sector Cyclotron (SSC). This will be accomplished with a normal conducting radio-frequency quadrupole (RFQ) accelerator. To match with the SSC, the RFQ must be operated on Continuous Wave (CW) mode with a frequency of 53.667 MHz. A four-rod structure was adopted for small dimensions of the cavity. While, it was a huge challenge on CW mode. A multi-physics theoretical analysis, including RF, thermal, structural and frequency shift coupling analysis, have been completed in response to the security and stable operation of the RFQ. The experimental measurement of frequency shift was also completed, which is consistent with the simulation. In this paper, the results of theoretical analysis and experiment are reported in detail.

INTRODUCTION

To achieve excellent performance in nuclear and atomic physics, the Heavy Ion Research Facility in Lanzhou (HIRFL) was upgraded successfully with a multifunctional Cooler Storage Ring (CSR) [1]. As the only injector of the HIRFL, the Sector Focusing Cyclotron (SFC) has to provide ion beams for both SSC and CSR. The SSC has to be shut down when the SFC provides the beams to the CSR, which causes the low utilization of the HIRFL. Furthermore, a higher beam intensity, which cannot be satisfied by the SFC, is required by several new experiments such as the super heavy element and precise mass measurement experiments. In order to solve the two problems, a linear accelerator called SSC-LINAC was proposed as a new injector of the SSC to replace the SFC [2]. The SSC-LINAC consists of a superconducting high-charge-state electron cyclotron resonance (ECR) ion source, a low energy beam transport (LEBT) line, a four-rod RFQ, a medium energy beam transport (MEBT) line, three DTLs and a high energy beam transport (HEBT) line [3], as shown in Fig. 1.

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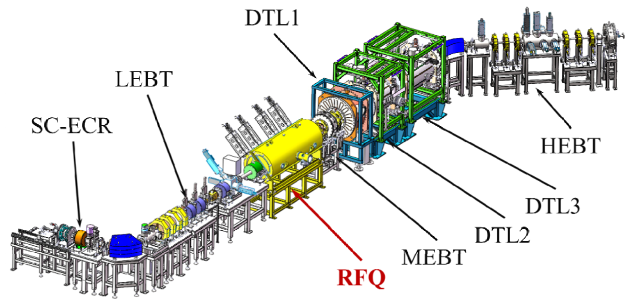

Figure 1: Layout of the SSC-LINAC.

The RFQ accelerator is a critical component of the SSC-LINAC. It accelerates intense beams and operate in CW mode, which was the greatest challenge for a four-rod structure. To control the emittance growth and beam losses caused by intense beams, a quasi-equipartitioning design strategy was applied in beam dynamics [4]. The main parameters of the RFQ are listed in Table 1. Furthermore, cooling channels design have been finished carefully. The bottom plate, stems and mini-vanes are all cooled by deionized water to ensure the CW mode operation [5].

Table 1: Main Parameters of the SSC-LINAC RFQ [4]

Parameters	Values
Frequency	53.667 MHz
Ratio of Mass to Charge	3~7
Design Beam Current	0.5 pmA
Input Energy	3.728 keV/u
Output Energy	143 keV/u
Inter-Vane Voltage	70 kV
Cavity Length	2.527
Transmission efficiency	94.1%

MULTI-PHYSICS THEORETICAL ANALYSIS

To demonstrate the security and stable operation of the RFQ, a multi-physics theoretical analysis was finished by using the Computer Simulation Technology (CST) [6] code. The analysis consists of RF, thermal, structural and frequency shift coupling analysis. The RF analysis determine the power losses of the RFQ cavity. In the thermal analysis, the power losses are used as heat loads to determine temperatures. Displacements and stresses are deter-

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NEW TYPE OF INJECTOR FOR CANCER THERAPY

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Abstract

We performed a compact design for 100 MHz Hybrid Single Cavity (HSC) for injector of cancer therapy. The proposed designs are conventional four-rod structure and DTL in a single IH cavity. This compact linac injector, running in frequency of 100 MHz, accelerates C^{6+} beams with 20 mA from 0.02 MeV/u up to 4 MeV/u. The total length of HSC is designed less than 4 meters.

INTRODUCTION

Compared with traditional structure, firstly, the HSC model consists of RFQ structure and DT structure without MEBT. Secondly, the IH structure provides the higher shunt impedance and acceleration gradient. In the structure, E-field is focused in the connection parts of 4-rod and first DT.

For DTL section, the section adopts the Alternative Phase Focus (APF). The DTL section with APF can achieve three-dimensional focusing without the installation of quadrupole lenses into the drift tubes.

Further, traditional injector has a complex control system and huge injector. Compared with traditional types, HSC adopts Direct Plasma Injection Scheme (DPIS). The DPIS could easily create enough C^{6+}ions to the linac by adjusting the distance from target to laser.

BEAM AYNAMICS

In this part, the beam dynamics ware divided into 3 sections, RFQ section, DTL section, and HSC section [1][2]. For RFQ section, it accelerates the C^{6+} with 20 mA from 0.02 MeV/u up to 0.6 MeV/u. The DTL section accelerates C^{6+} from 0.6 MeV/u up to 4 MeV/u. For RFQ section was designed by RFQGen code. DTL section and HSC ware designed by PIMLOC code. More details will be given in the next.

RFQ Section and DTL Section

The RFQ section is divided into 4 section: radial matching section (RMS), shaper section (SH), gentle buncher section (GB), and accelerator section (ACC) [3]. The length of IH-RFQ is short 1 m. The original main parameters ware given in the Fig. 1.

We want the length of RFQ to be as short as possible, meanwhile, ensure the acceptable transmission and beam quality. To achieve the aims and realize an efficient bunching for RFQ section, we adopt some basic ides, as follows: Firstly, we must vary the transverse focusing strength B along the beam direction because of the corresponding space-charge conditions at different positions.

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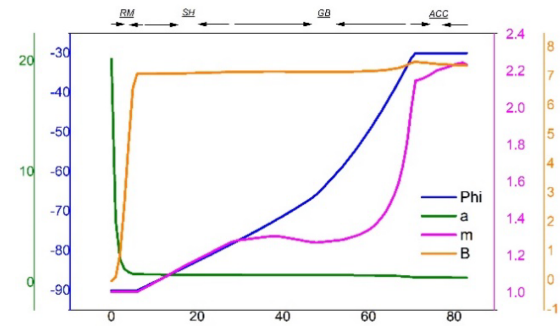

Figure 1: The original parameters in RFQ section.

Traditionally, the transverse B should be increasing with the space-charge force until the transverse defocusing force is weakened. After that it should go down. Secondly, the evolution speeds of the synchronous phase and the modulation parameters can also improve the bunching process.

When we followed the important conditions. We can get the optimized parameters, shown in Fig. 2.

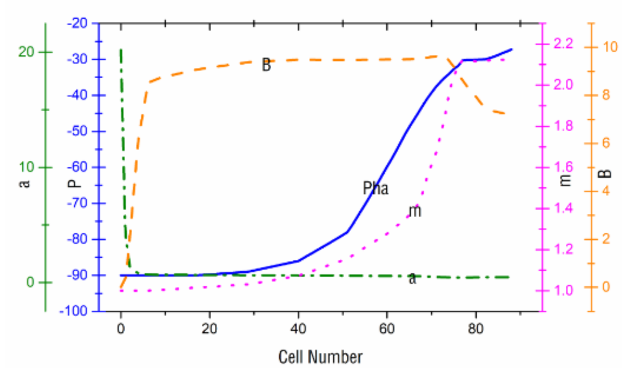

Figure 2: The optimized parameters in RFQ section.

Figure 3 gives the transmission efficiency, which almost over 95%, at last cell.

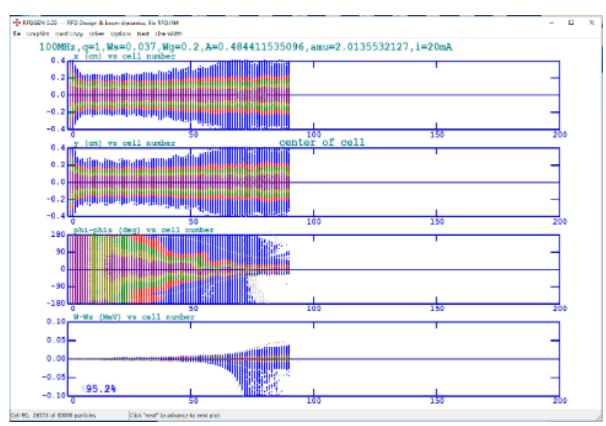

Figure 3: Transmission efficiency at last cell.

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Nb SPUTTERED 325 MHz QWR CAVITIES FOR CiADS*

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Abstract

The possibility for adopting niobium thin film coated copper (Nb/Cu) quarter wave resonators (QWRs) in the low energy section of CiADS project [1] is being evaluated. Comparing with bulk niobium cavities, the Nb/Cu cavities feature a much better thermal and mechanical stability at 4.5 K. Two 325 MHz Nb/Cu QWR cavities have been fabricated at IMP, to demonstrate whether the niobium coated copper cavity technique can meet the requirements of CiADS. The cavity is coated with biased DC diode sputtering technique. This paper covers resulting film characters, vertical tests with the evolution of the sputtering process, and improvements to mitigate issues we met.

INTRODUCTION

The operational stability of SRF cavities is one of the foremost challenges that hinder CiADS linear accelerator from continuous running [2]. Let Nb/Cu cavities replace the bulk niobium cavities could be an effective solution, because Nb/Cu cavities come up with advantages in terms of both thermal stability and mechanical stability [3]. At 4.2 K, the heat conductance of high purity bulk Nb is about 75 W/(m·K), while the number is as high as 300-2000 W/(m·K) for high purity oxygen free copper [3]. The poor thermal conductivity of Nb put an upper limit for SRF cavity wall thickness, in order for the inner surface to be effectively cooled, which impairs the robustness of the cavity's mechanical structure. The use of a copper cavity as a substrate can effectively solve the major problems of poor thermal conductivity and sensitivity to external pressure and vibration at the same time, because the thicker copper wall can provide rigid stiffening in the SRF cavity. Furthermore, Nb/Cu cavity is economical than bulk Nb cavity in terms of fabrication and processing cost. The material cost of OFHC copper is only about 4% of the price for SRF grade bulk Nb. In addition, copper is easier to anneal, polish, and machine than niobium, the cavity processing cost for Nb/Cu cavities would be much lower than that for bulk Nb cavities [3].

IMP launched its Nb/Cu cavity project in 2016. Up to now, the film characters, including thickness profile along the cavity, structure and morphology tests have been performed at IMP. Two dummy QWR cavities had been produced and coated to understand and optimize the sputtering setup and process.

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THIN FILM COATING SETUP

The coating system employed in this project is modify from an existed equipment at NIN with biased DC diode sputtering [4] ability. Figure 1(a) showed the side view of this very system. For the purpose of R&D tests, a 325 MHz QWR dummy cavity without a beam line has been designed at IMP. The dimension of the dummy cavity is shown in Fig. 1(b). For simplicity, two dummy cavities were machined directly from OFHC ingot to avoid any difficulties brought by welding seams inside the cavity [5]. S.S. flanges were brazed onto the cavities. Before coating process, surfaces were treated with mechanical and electrical polishing. From electromagnetic simulation, the unloaded quality factor (Q_0) for an uncoated copper cavity is 1×10^5, and is 8×10^8 for a superconducting Nb/Cu cavity.

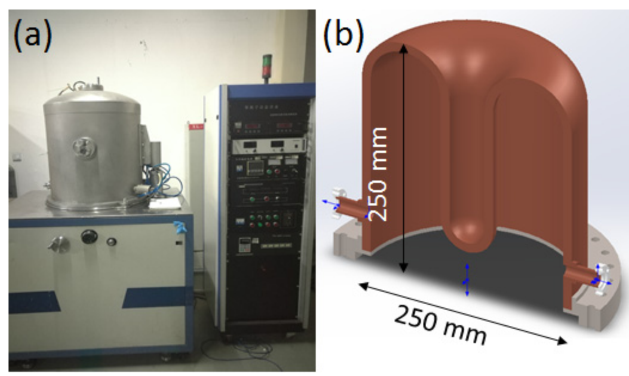

Figure 1: (a) the deposition system and (b) the dimension of the 325 QWR cavity.

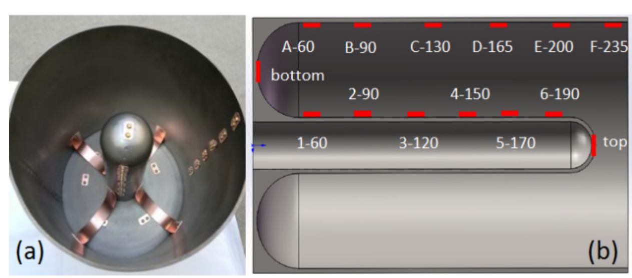

Figure 2: The sample holder's (a) appearance and (b) the exact location of the samples' locations.

A QWR-like sample holder with 16 samples positions along the outer and inner conductors had been used before the actual cavity coating. This setup allows access to the film properties in different positions by small sample characterizations. Thus the thickness and T_c distribution of the coating film could be investigated from clipped samples. The surface treatment of small sized samples is similar to the dummy cavity. The samples' locations and their distance to the bottom plate are marked on Fig. 2(b).

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DYNAMICS STUDY OF A DRIFT TUBE LINAC FOR BOTH HEAVY IONS AND PROTON*

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Abstract

An accelerator complex for Space Environment Simulation and Research Infrastructure (SESRI) has been designed by Institute of Modern Physics (IMP) and will be constructed in Harbin Institute of Technology (HIT). This accelerator consists of an ECR ion source, a linac injector, a synchrotron and 3 research terminals. As an important part of the complex, the linac injector should provide both proton and different kinds of heavy ions, from helium to bismuth, with energy of 5 MeV and 1 MeV/u respectively for the synchrotron. In order to provide beams with the mass to charge ratio (A/Q) range from 1 – 6.5(for proton to $^{209}Bi^{32+}$) by only one linac injector, a special solution of the main acceleration section DTL is carried out. The relevant dynamics calculations, such as beam matching, stripping process of the hydrogen molecule ion and beam energy spread reducing, are performed by Particle in Cell (PIC) method.

INTRODUCTION

In order to simulation and research the damage to the electronic equipment and organism on the spacecraft by high-energy particles in the universe, Harbin Institute of Technology (HIT) proposed building an accelerator based nuclear irradiation source named Space Environment Simulation and Research Infrastructure (SESRI). The accelerator complex of SESRI is designed and constructed by Institute of Modern Physics (IMP) which contains an ECR ion source, a linac injector, a synchrotron and 3 research terminals [1] as shown in Fig. 1. The ECR ion source can provide mostly all stable ions from proton to bismuth. These ions are accelerated by the linac injector to the injection energy of the synchrotron. The synchrotron accelerates different kinds of ions to specific energy and then slowing extracts them to the experiment terminals. The design of the linac injector must meet the preliminary requirements of the synchrotron, which can be seen in Table 1. For this linac injector, the main problem is how to accelerate very heavy ions like $^{209}Bi^{32}$ and lightest ion proton and make it more compact. Between the linac injector and the synchrotron, there is a long beam transport line used for vacuum degree transition.

According to the project requirement, preliminary dynamics design of the DTL is finished. And then, Beam dynamics tracking with a PIC simulation code for different operation mode alone the main acceleration section is accomplished. The simulation takes beam matching into account and verifies the preliminary design. On the other hand, effects of stripping foil on the hydrogen molecule ion are studied. A short beam transport line used for reducing the beam energy spread of proton and heavy ion is also designed in the PIC simulation.

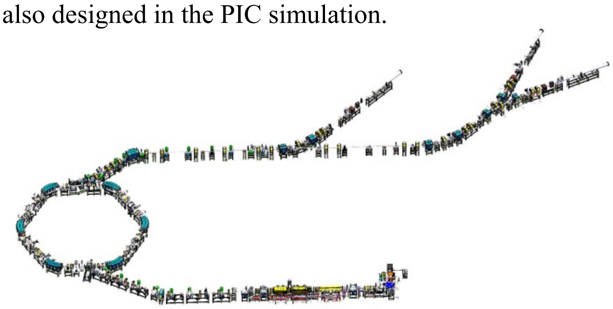

Figure 1: Integrated layout of SESRI accelerator complex.

Table 1: Inject Beam Parameters of the Synchrotron

Parameter	Value
Beam energy	1 MeV/u($^{209}Bi^{32+}$), 5 MeV (proton)
Energy spread	±0.3%
Transverse emittance	≤13πmm·mrad
Beam current	30 eμA($^{209}Bi^{32+}$), 300 eμA(proton)

PRELIMINARY DYNAMICS DESIGN OF THE DTL

The R/Q of the injection ion for the synchrotron ranges from 1 to 6.5 and it is too large for a normal conducting muticell linac which is because the cavity power range is squared of the R/Q. The whole RF system cannot operate stably in such a large power range. So in order to provide proton beam to the synchrotron, H_2^+ is accelerated to 1MeV/u by RFQ and DTL1 firstly and then be stripped to proton to continue accelerate by DTL2. In this way, the R/Q range of the RFQ and the first section of the DTL will be only from 2 to 6.5. Beam extract energy of the RFQ is set to 300 keV/u for H_2^+ and other heavy ions. The RF frequency is 108 MHz for the whole linac injector.

KONUS dynamics [2] concept and LORASR code [3] are adopted to make the preliminary dynamics design of the DTL for the linac injector. On the basis of the injection energy requirements of the synchrotron for proton and heavy ions, this linac injector contains two DTL cavities. All heavy ions including H_2^+ can be accelerated to 1 MeV/u by the DTL1 which contains an inner focusing quadrupole triplet. And DTL2 is only used to accelerate the proton from 1 MeV to 5 MeV. For heavy ions, the DTL2 is just regard as a drift section. Between the two

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STUDY ON A HOM TYPE BUNCHER*

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Abstract

Normally, drift tube linacs (DTL) are used following RFQ linacs for beam acceleration in middle and high beam energy region. The acceleration efficiency of DTLs is decreasing with beam energy increasing. Using resonated higher order mode (HOM) of cavity, DTL can achieve higher effective shunt impedance. We proposed a 325MHz DTL with TE_{115} mode. In this paper, the dynamics calculation and electromagnetic design of the HOM-DTL will be reported.

INTRODUCTION

Shown in Fig. 1, in the low energy region, the Interdigital-H (IH) type drift tube linacs (DTLs) have a higher shunt impedance and suitable accelerating structure for heavy ion acceleration, thus the DTLs operated in TE_{111} mode are normal used following the RFQ type linac [1–3]. However, in the medium and high energy region, the Alvarez type DTLs operated in TM_{010} mode are normally used although its shunt impedance reduces rapidly [4,5], shown in Fig. 2, because its shunt impedance is higher than the IH-DTLs in those energy regions.

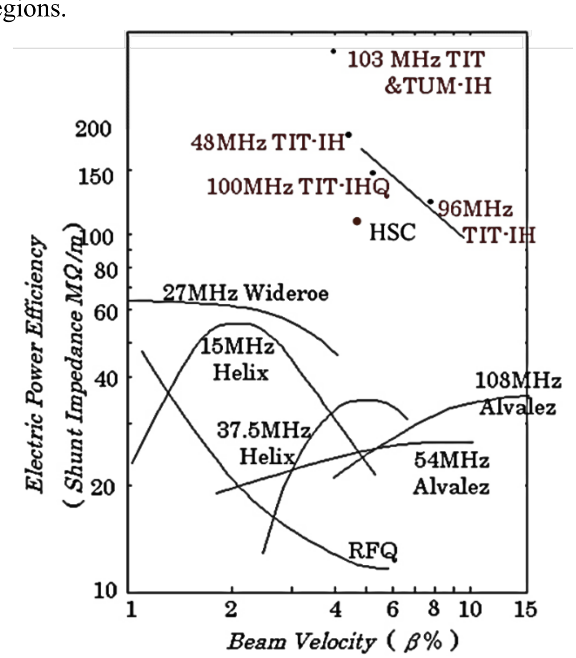

Figure 1: The shunt impedance of the low beta linacs.

Since the DTLs operated in TE_{11n} mode of the higher order mode have a property which is suitable to accelerate ions in medium and high energy region [6]. We proposed a 325MHz DTL operated in TE_{115} mode. Our proposed HOM-DTL is designed as a prototype buncher and its structure is shown in Fig. 3.

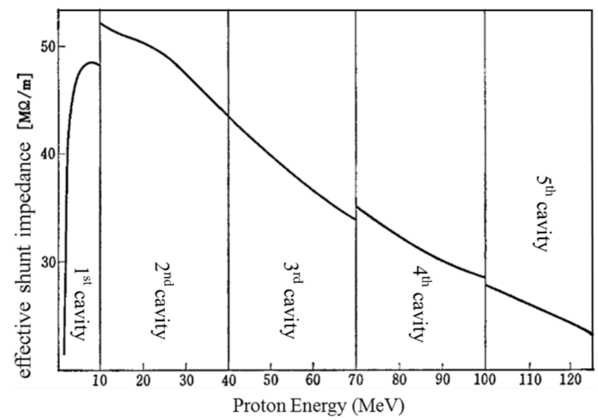

Figure 2: The shunt impedance changing of the Alvarez type DTLs in medium and high energy region.

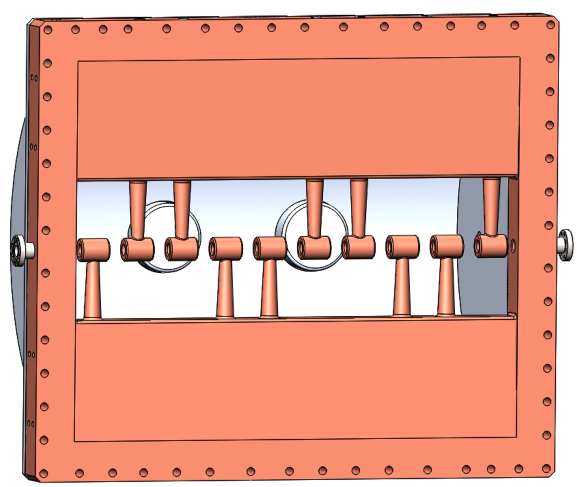

Figure 3: The inner structure of proposed HOM-DTL.

ELECTROMAGNETIC DESIGN

The frequency of proposed HOM-DTL is 325MHz which is 4th harmonic of the frequency of 81.25MHz. This HOM-DTL is a prototype research for future heavy ion buncher. The estimated peak voltage is rather high as several mega-voltages (MV). The Microwave Studio (MWS) code and ANSYS code are used to calculate the cavity electromagnetic simulation and mechanical simulation [7,8].

As shown in Fig. 3, the HOM-DTL has normal DTs and ridges that is same to the normal type IH-DTLs with TE_{111} mode and Alvarez type DTLs with TM_{010} mode,

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ERROR ANALYSIS AND RF OPTIMIZATION OF A COMPACT RFQ*

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Abstract

A 162.5 MHz, 7.2 MeV 4-rod radio frequency quadruples (RFQ) dynamics design has been finished for injector of a carbon ion cancer therapy facility which is promoted by the Institution of Modern Physics (IMP) of the Chinese Academy of Science (CAS). A detailed error analysis was performed after the optimization process. Field flatness error is analysed for determining a RF optimization target. The RF structure is designed based on a new type dynamics design. Electric field of the RF structure is optimized in order to supporting the dynamics design. The error analysis and detailed field flatness optimization of this compact RFQ have been presented and discussed in this paper.

INTRODUCTION

Hadron therapy offers superior dose conformity in the treatment of deep-seated tumours compared with conventional X-ray therapy due to its Bragg-peak feature of energy deposition in organs [1]. So many accelerator facility dedicated to cancer therapies have been constructed in these years. One of them is Heavy Ion Medical Machine in Lanzhou (HIMM), which has been designed and constructed by IMP (Institute of Modern Physics). A linac is designed to replace cyclotron as the accelerator injector in the next generation HIMM, which consists of an ECR ion source, a 162.5 MHz RFQ, a compact Interdigital H-mode Drift-Tube-Linac (IH-DTL), and beam transport lines. The layout is shown in Fig. 1.

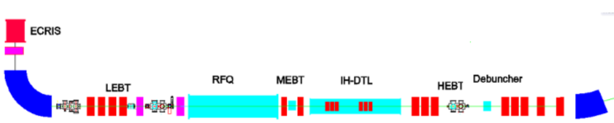

Figure 1: Layout of the linac injector of cancer therapy facility.

A RFQ operated under 162.5MHz as important part of this linac has been designed. It accelerate $^{12}C^{4+}$ beam from 8keV/u to 600keV/u with 0.1% duty factor. Unlike most research facilities, this RFQ need not running with high current and high duty factor. The optimization of designing this type RFQ is focus on compact structure, high stability and low cost. Based on a traditional setup, a new compact fast-bunching design is introduced to optimize. The whole dynamics design process is supported by PARMTEQM [2]. This method is used to create a more compact structure by ignoring the space-charge effect [3]. Finally, RFQ structure length is shorten from the standard design value 272cm to 230 cm, while effectively regulating the particle loss and emittance growth. The final parameters is shown in the Table 1. And main parameters as a function of position z. is shown in Fig. 2.

Table 1: Main Dynamics Parameters for RFQ

Parameter	Value
Frequency (MHz)	162.5
Beam current (euA)	200
Input energy (keV/u)	8
Output energy (keV/u)	601.45
Duty factor	0.1%
Kilpatrick factor	1.83
Minimum aperture (a)(cm)	0.3
Input trans. emit. (π·mm·mrad)	0.200
Output trans. emit. (π·mm·mrad)	0.199
Output longitudinal emit. (π·MeV·deg)	0.242
Length of the vane (cm)	230.14
Transmission efficiency	99.3%

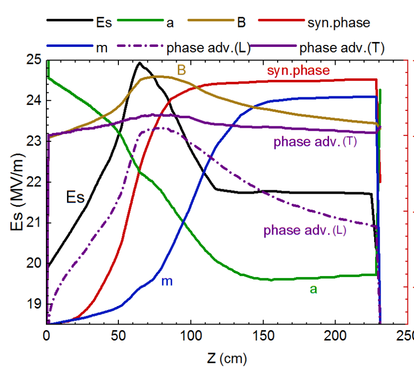

Figure 2: The RFQ beam dynamics parameters as a function of position z.

It can be seen from Fig. 2 that the bunch process is completed in a short time in this design, which shorten overall structure length. Based on the dynamics design, the error is analysed from two aspects: 1. Input beam errors; 2. Errors of field flatness distribution along inter-vane. The dynamic design of RFQ is tested by the tolerance of mismatched beam. And optimization objective of RF design is carried out by the error analysis of field flatness. The RF design has been optimized to meet the requirement of field flatness.

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A NEW RF STRUCTURE: BENT-VANE TYPE RFQ*

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Abstract

A new cavity structure of RFQ accelerator with bent vanes is proposed to meet the miniaturization requirement of low frequency accelerators. The new structure has a downsized cross section by bending vanes while keeping a certain vane lengths. It also possesses the advantages of simple cooling structure in low frequency field. The new structure has obvious advantages in reducing manufacturing difficulty of cavity, cutting down project cost, enhancing facility reliability and stability.

INTRODUCTION

Radio frequency quadrupole (RFQ) can accelerate, focus and bunch particle beam in the low energy field, which is generally used as an injector for high energy accelerator. Four-rod type and four-vane type are main RFQ accelerator structures. Four-rod RFQ is used in the low frequency field and four-vane RFQ is applied in the high frequency field [1]. However, the cooling structure of four-rod RFQ is quite complex so that it is difficult to design and machine cavity and the lateral dimension of four-vane RFQ is large in the low frequency band which increases machining difficulty and cost [2]. In addition, four vane with windows RFQ can decrease the cross-section length in the low frequency band, but its cooling structure is extremely complicated and the windows can directly influence mechanical strength of the cavity and electric field flatness.

In order to overcome the disadvantages of above three kinds of RFQ accelerators, a new RFQ structure is proposed called bent-vane type RFQ at Institute of Modern Physics (IMP), Chinese Academy of Sciences. It significantly reduces the lateral dimension of the cavity in the low frequency field and has a water-cooled system with a simple structure and sufficient cooling efficiency. The RF structure of bent-vane RFQ is presented in this paper.

THEORETICAL FOUNDATION

Considering an ideal four-vane RFQ with a cloverleaf geometry (Fig. 1), its equivalent circuit is shown in Fig. 2 [1]. According to the equivalent circuit, the cavity quadrant radius is

$$r^2 = \frac{16}{\mu_0(4+3\pi)\omega_0{}^2C'}$$

where ω_0 is the resonant frequency, C' is the total capacitance per unit length and μ_0 is the permeability constant. This equation indicates that the lateral dimension can be decreased by increasing the capacitance at a fixed frequency.

Based on the discussion above, the vanes of four-vane RFQ are bent to increase the capacitance for reducing the lateral dimension of cavity. Hence, a new RFQ structure is proposed called bent-vane type RFQ, shown in Fig. 3.

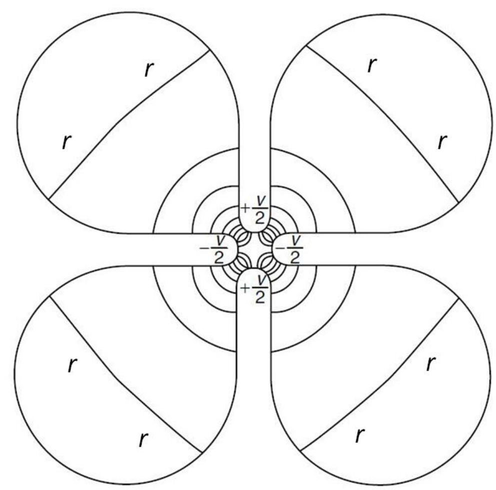

Figure 1: The ideal four-vane RFQ with a cloverleaf geometry.

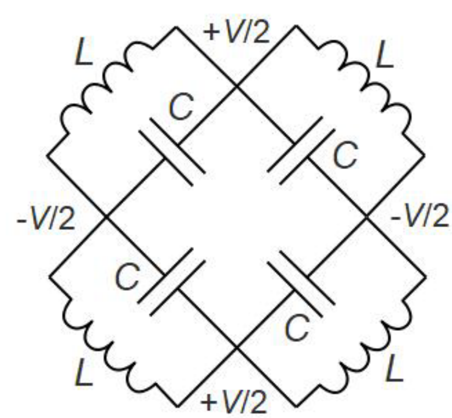

Figure 2: The equivalent circuit of the ideal four-vane RFQ with a cloverleaf geometry.

RF STRUCTURE

In order to obtain suitable lateral dimension and quality factor of bent-vane RFQ, the cross-section profile of bent-vane RFQ is put forward with 13 independent variables, shown in Fig. 4.

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BEAM COMMISSIONING IN THE FIRST CHINESE DEMO CANCER THERAPY SYNCHROTRON *

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Abstract

Heavy Ion Medical Machine in Wuwei (HIMM-ww) is the first Chinese heavy ion accelerator facility developed for cancer therapy. After commissioning, the particle number after acceleration reached 1.5e9 ppp (particles per pulse), while injection exceeded 3e9 ppp. The slow extraction efficiency reached nearly 90% for all energies from 120 to 400 MeV/u. The spill duty factor exceeded 90% at a sample rate of 10 kHz. This paper reports the results of the synchrotron commissioning.

INTRODUCTION OF THE SYNCHROTRON

Heavy ion medical machine (HIMM) was constructed on the basis of the experience gained from the Heavy Ion Research Facility in Lanzhou-Cooler Storage Ring (HIRFL-CSR) project [1]. HIMM facility consists of an electron cyclotron resonance (ECR) ion source, a cyclotron injector, a compact synchrotron ring, and 5 nozzles [2]. The C5+ beam generated by the ECR ion source is pre-accelerated by the cyclotron to 6.2 MeV/u and then injected into the synchrotron using the 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.

The layout of the synchrotron, which has a two-fold symmetry structure composed by 8 dipoles and 12 quadrupoles, is shown in Fig. 1. Two long straight sections are used for injection and extraction respectively and four medium-long straight sections are occupied by RF cavity, DCCT (DC Current Transformers), ES (Electrostatic Septum), transverse RF, respectively. The parameters of the ring are listed in Table 1.

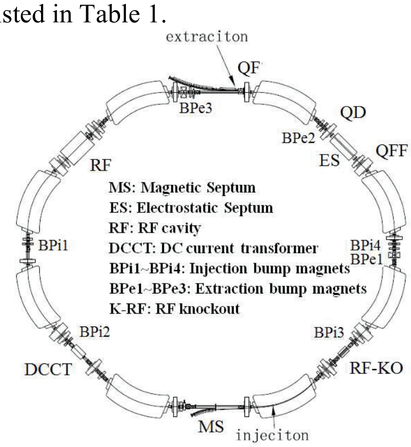

Figure 1: Schematic layout of the HIMM synchrotron ring.

BEAM COMMISSIONING RESULTS OF THE SYNCHROTRON

Figure 2 shows the current ramping shape of the synchrotron's main quadrupole power supply (the power supply of the dipoles has the same shape as the quadrupoles) and the extraction bump at the extraction flattop [3]. The synchrotron cycle is 7 seconds. The extraction beam energy is 260 MeV/u. The horizontal and vertical axes represent the time and amplitude of the power supply, respectively. The extraction duration is 2 seconds. The ramping time of the extraction bump is less than 10 ms, and the flattop duration is the same as that of the dipole magnet.

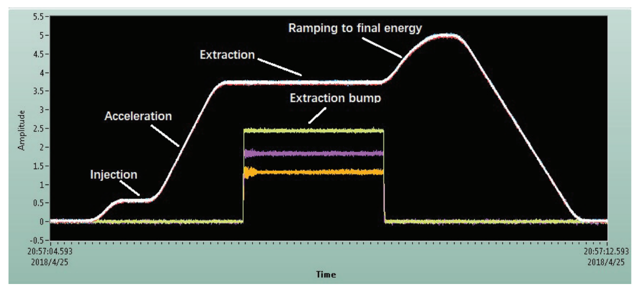

Figure 2: Ramping shape of the quadrupole and extraction bump.

Beam Injection and Acceleration

Different with other cancer therapy facility in the world, the cyclotron is adopted as the injector. The beam intensity of the cyclotron is less than 10 uA. To store enough particles in the ring, the CEI (charge exchange injection) method, which regardless of Liouville's theorem allows beams to be injected at the point of phase space already occupied by previously injected beam [3], is adopted. Therefore, an intense beam can be accumulated in the ring without largely increasing the beam emittance. In addition, the injected beam can be painted in the horizontal phase space by changing the local closed orbit during injection to reduce the hitting probability at the stripping foil, thus increasing the injection efficiency.

Figure 3 is the DCCT signal which shows the beam intensity during the whole cycle. The extraction beam energy is 260 MeV/u in Fig. 3. The beam intensity after injection is 1800uA which corresponding to the particles number of 3e9. The beam capture efficiency is 50%, and the accelerate efficiency is approximately 95%.

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HIGH RESOLUTION MASS SEPARATOR DIPOLE DESIGN STUDIES FOR SPES PROJECT

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Abstract

The purposes of the SPES (Selective Production of Exotic Species) project at INFN laboratory in Legnaro (Italy) is to study nuclei close to the drip lines. Therefore, a High-Resolution Mass Separator (HRMS) must provide full separation of the ions with a resolution 1/20000, to be sensible to the proton-neutron mass difference in the fission products. SPES HRMS consists of: two 90° magnet dipoles, one electrostatic multipole in between them, six electrostatic quadrupoles, two electrostatic hexapoles and two electrostatic triplets before and after the slits on the object and image point. All these components will be installed on a high voltage platform with a maximum operating voltage of -240 kV. Before entering the HRMS, a 40 keV energy beam go through an RFQ Cooler, designed to have an output energy spread of 1 eV. Mass separation within target resolution is the most critical part: dipoles must provide a magnetic field homogeneity of 4 10^{-5} throughout beam occupancy (half magnet pole surface), at a field intensity of 0.562 T for the reference ion 132 Sn. Therefore, a very accurate dipole design is mandatory. This contribute will show the studies which lead to a possible dipole design.

INTRODUCTION

The Selective Production of Exotic Species (SPES) project at INFN-LNL Legnaro, Italy is a radioactive ion beam (RIB) facility [1,2]. Many field of interests will characterize its experimental life, ranging from basic research in nuclear physics and astrophysics to interdisciplinary applications, like production of radionuclides of medical interest and the generation of neutrons for material studies, nuclear technologies and medicine. SPES RIB production is based on the ISOL method with an UCx Direct Target able to sustain a power of 10 kW. The primary proton beam is delivered by a high current Cyclotron accelerator, with energy 35-70 MeV and a beam current of 0.2-0.5 mA. Neutron-rich radioactive ions will be produced by proton induced Uranium fission in the UCx target at an expected fission rate in the order of 10^{13} fissions per second. The exotic isotopes will be re-accelerated by the ALPI superconducting LINAC at energies of 10A MeV and higher, for masses in the region A=130 amu at expected rate on the secondary target of $10^7 – 10^9$ pps.

In the framework of the SPES project, the High-Resolution Mass Spectrometer (HRMS) must provide high purification of the ^{132}Sn ion beam and > 95% transmission. The design goal is to achieve a mass resolving power $\Delta m/m = 1/20000$.

HRMS LAYOUT

The design choices made for the HRMS are common from the medium mass separator (MRMS) of SPES [3], which is now under installation and will be used as a test stand for the HRMS. Similar optics layout is used in recent projects [4,5,6], with different choice of parameters.

The HRMS general layout, which is perfectly symmetric with respect to the central axis, is presented in Fig. 1.

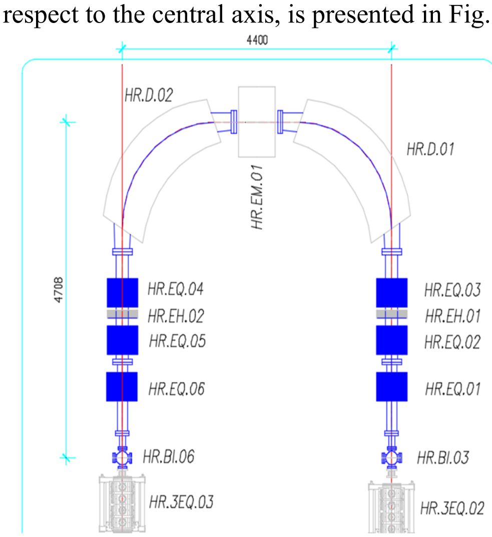

Figure 1: HRMS layout on high voltage platform.

HRMS will be installed on a High Voltage platform (represented by the light blue line) with a maximum operating voltage of -240 kV. The beam, which is extracted from the source with 40 keV energy, enters HRMS from the right-hand side branch of the device. The object and image slits (HR.BI.03-6) delimit separator entrance and exit.

More in details, following the beam path, an accelerating column (HR.AT.01) gradually accelerates the beam to accommodate its energy for the HV platform and then it will pass through the following components:

- an electrostatic triplet (HR.3EQ.02);
- two electrostatic quadrupoles (HR.EQ.01-2);
- one electrostatic hexapole (HR.EH.01-2);
- a single electrostatic quadrupoles (HR.EQ.03);
- a magnetic dipole (HR.D.01-2), H-shaped with bending angle $\varphi = 90°$;
- one electrostatic multipole (HR.EM.01);

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MULTIPOLE MAGNETS FOR THE HIAF FRAGMENT SEPARATOR USING THE CANTED-COSINE-THETA (CCT) GEOMETRY*

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Abstract

The fragment separator of the HIAF (High Intensity Heavy Ion Accelerator Facility) project called HFRS requires quadrupoles with high gradients (11.4 T/m) and large bores (gap width of 420 mm). The iron dominated magnets with superconducting coils have been widely used in the similar facilities such as A1900, BigRIPS, Super-FRS and RISP with the advantages of low request for coils installation precision, simple fabrication and low cost, but they have large cold mass and helium containment, which result in long time cooling down and high pressure rise during a quench. In addition, due to iron saturation, it is hard to guarantee on the field quality in the operated field range. A new coil dominated design based on the Canted-Cosine-Theta geometry is presented for HFRS, which is expected to overcome these problems. The design superimposes several layers of oppositely wound helical windings to generate high quality quadrupole. Sextupole, octupole and steering dipole can also be easily integrated to reduce the length of cryostat. This paper reports the detailed design of HFRS multiplets based on the CCT concept and the construction of a sub-scale prototype.

INTRODUCTION

The **H**igh **I**ntensity **A**ccelerator **F**acility is a new project to pursue nuclear physics research and is under construction at the Institute of Modern Physics in China [1]. As shown in Fig. 1, it consists of a 45 GHz superconducting ECR ion source, a superconducting Linac, a fast cycling booster ring, a fragmentation separator and a spectrometer ring. The fragmentation separator of HIAF called HFRS is an important connection between BRing and SRing. It is used to produce, separate, purify, and identify the desired exotic nuclei. The field rigidity is 25 T • m. It has a big beam acceptance of ±160 mm. For similar facilities, such as A1900 [2], BigRIPS [3],[4], SuperFRS [5] and RISP [6], to meet the magnetic field requirement within a large aperture, the superferric design with cold iron have been widely used. They are easy to fabricate and wind, while their coils require lower positioning precision. But because of the iron saturation, it is hard to achieve good field quality at both low and high field with the superferric design. And large cold mass also brings about new challenges, such as long-time cooling-down, high pressure during a quench and difficulties of supports and alignments. Air-core type magnets have the advantages of light weight and good field linearity and are used in BigRIPS as the first element near the target to lower the radiation heat load [7]. Walstrom type coil with better field quality are used in the S^3 device of SPIRAL2 project [8]. But their magnetic field are more sensitives to coil positioning error and they are difficult to fabricate and wind, especially Walstrom type coil [9].

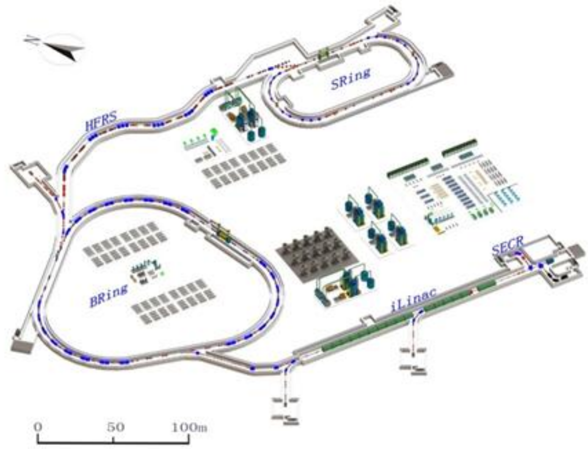

Figure 1: Layout of HIAF project.

CANTED–COSINE–THETA MAGNET

The basic idea of **C**anted-**C**osine-**T**heta was firstly published by D. I. Meyer and R.Flasck in 1970 [10]. As shown in Fig. 2, by the superposition of two oppositely tilted solenoids with respect to the bore axis, the azimuthal component of the magnetic field is cancelled and the high-quality dipole field can be generated.

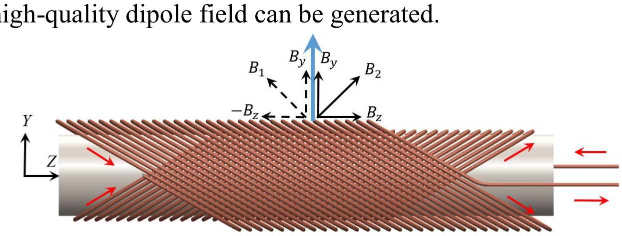

Figure 2: Conceptual view of CCT dipole windings.

Higher order multipole fields can also be obtained by superimposed current with an z direction oscillation as shown in following equations. For example, n=2 produces a quadrupole field as shown in Fig. 3, and so forth.

$$x(\theta) = R \cdot \cos(\theta) \tag{1}$$

$$y(\theta) = R \cdot \cos(\theta) \tag{2}$$

$$z(\theta) = \frac{h}{2\pi}\theta + \sum_n A_n \sin(n\theta + \varphi_n) \tag{3}$$

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NOVEL METHODS FOR THE PRODUCTION OF RADIONUCLIDES OF MEDICAL INTEREST WITH ACCELERATORS

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Abstract

Radionuclides for radiopharmaceuticals preparation are currently produced in cyclotrons, generators or nuclear reactors. However, none of these modes is free from serious issues, like: high costs of targets, production of undesired radionuclide contaminants, long and expensive separation methods and formation of long-lived radioactive wastes. For this purpose, novel methods are being developed for the production of highly pure radionuclides. The ISOL (Isotope Separation On-Line) method can be applied to produce high purity radionuclides of medium and heavy masses. ISOL is nowadays established as a major method for the production of high intensity and high quality radioactive ion beams for nuclear physics studies. The SPES-ISOLPHARM project at INFN-LNL (Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Legnaro) aims to provide a feasibility study for an innovative technology for the production of high specific activity radionuclides based on the ISOL method. The ongoing experimental activities on primary and secondary (ion collectors) targets production, construction and testing of the selection and transport apparatus is here presented.

INTRODUCTION

Radiopharmaceuticals are medicines that deliver a predefined amount of radiation to a target tissue for diagnostic or therapeutic purposes depending on the mechanism of decay. Radiopharmaceuticals are usually made of two parts: a "radioactive core" and a "carrier system"; the latter allows the irradiation of malignant cell populations, avoiding damage to healthy tissues [1].

Beta-emitting radionuclides are usually produced mainly by direct reaction in dedicated targets using neutrons from nuclear reactors. By means of those reactions it is possible to produce a large number of isotopes and different nuclei in the target. The chemical methods to extract the desired radionuclide leads to the presence of a considerable amount of carrier. In this case, the specific activity, which is the ratio between the activity of the radioisotope and the mass of the element taken into account, is very low.

The global network of accelerators used for the production of medical radioisotopes, in particular cyclotrons, has seen a rapid expansion over the last decade, with a huge increase on the number of installed machines [2].

The accelerators based on the ISOL (Isotope Separation On-Line) technique [3] might be an efficient way to produce radioisotopes for radiopharmaceuticals application, thanks to the mass separation, which guarantees the possibility to produce radioisotopes with high specific activity, close to theoretical value.

THE ISOLPHARM PROJECT

At INFN-LNL (Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Legnaro), the SPES (Selective Production of Exotic Species) facility will allow the production of radioactive ion beams of neutron-rich nuclei with high purity, in the range of mass between 80 and 160 amu [4].

At SPES the production of the radioactive isotopes is obtained by nuclear reactions induced by 40 MeV protons, accelerated by a cyclotron, recently installed at LNL, that will collide a multi-foil target with discs of different materials, mostly uranium carbide [5], properly spaced to dissipate the heat (8 kW) generated by the reaction. Most of the produced nuclides will be neutron-rich (uranium fission) but using different target materials it could be possible to produce proton-rich isotopes. The reaction products will be extracted from the target by evaporation at high temperature (about 2000 °C), and then forced to pass through a transfer tube towards an ionization cavity, where they will be ionized to the 1+ state. Once ionized, these isotopes will be accelerated through an electrode at high potential (up to 40 kV).

The ground-breaking idea of the ISOLPHARM method was granted an International patent (INFN). The driving idea is the obtainment of carrier-free radioisotopes, to be used as radiopharmaceutical precursors, thanks to the extreme purity of ISOL radioactive beams.

The formed beam will be focused using different electromagnetic systems and purified in order to have a pure isotope beam without any contaminants. It will therefore be possible to collect the radionuclides of interest using a proper substrate placed at the end of the experimental line. In Fig. 1 a general scheme of the process is shown.

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PRELIMINARY DESIGN AND SIMULATION RESULTS OF Ne^+ BEAM SOURCE*

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Abstract

An ion source of Ne beam was designed for basic physical research in the Institute of Plasma Physics, Chinese Academy of Science (ASIPP). The ion source was designed with hot cathode plasma source with three electrodes accelerator. The designed beam energy is 10-20 keV, the beam power is 50 kW, beam size is 250 mm × 250 mm and beam duration is 2 seconds. The three electrodes accelerator with slit type was designed. The extracted beam current and beam divergence angle was simulated. The maximum beam power of 40 kW can be extracted when the divergence angle less than 5 degree with beam energy of 10 keV and the beam power of 28 kW can be extracted with minimum divergence angle of 2.2 degree. When the beam energy is 20 keV, the maximum beam power of 180 kW can be extracted when divergence angle less than 5 degree. And the beam power is 130 kW with minimum beam divergence angle is 2.2 degree too. The results shown that, the maximum beam power can't got 50 kW with beam energy of 10 kW, but the beam power can achieve 130 kW with beam energy of 20 keV.

INTRODUCTION

In order to support the basic physical research in Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP), a fast ion source was needed. The desired fast ions with beam energy of 10-20 keV, beam power of 50 kW with beam duration of 2 seconds. A Ne^+ beam system was designed based on the R&D experiences of high power neutral beam injector on Experimental Advanced Superconducting Tokamak (EAST) [1-7].

The ion beam system contains a Ne^+ beam source, vacuum vessel, calorimeter, power supply system, water cooling system, control system and gas pumping system. The Ne^+ beam source was designed and the beam performance was simulated. The preliminary simulation results were presented in this manuscript.

THE Ne^+ BEAM SOURCE

The Ne^+ beam source contains a hot cathode plasma generator and an accelerator with three electrodes. The schematic map of beam source is shown in Fig. 1. The designed parameters of the beam source are shown in Table 1. The plasma generator has a rectangle cross section arc chamber with dimension of 400 mm × 400 mm × 300 mm (W×L×H). There are three lines of permanent magnets installed on the back electron dump plate and 36 lines on the arc chamber body to form axial line-cusp configuration. Each Sm-Co permanent magnet has the magnet intensity of 3500G, and can form a large magnetic-free-area region to generate plasma. In the opposite direction of accelerate grids, 16 pure tungsten filaments are installed near the back electron plate, which to provide sufficient primary electrons. The filaments are made of pure tungsten with hairpin shape and each of them is 160 mm long with the diameter of 1.5 mm. The multiple slit type apertures are used in the accelerator system, which have the transparence of 60%. Each layer of the two accelerator grids have 28 rails, which has cavity structure and made of molybdenum.

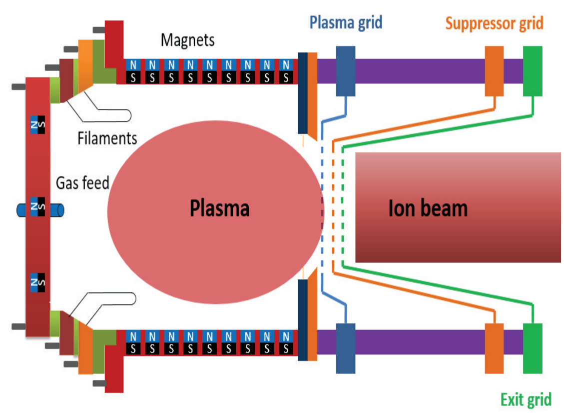

Figure 1: Schematic of high current ion source.

Table 1: The Designed Parameters of Beam Source

Source Species	Ne^+
Source type	Hot cathode
Beam energy	10-20keV
Beam power	50 kW
Beam duration	2s
Beam cross section	250 mm × 250 mm
Number of accelerator	3
Extraction sort	Multi-slot
Transparence	0.6
Divergence angle	Less than 5°

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JINR HEAVY ION ACCELERATORS APPLICATION FOR SEE TESTING IN ISDE

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Abstract

Thousands satellites and spacecrafts are lunched worldwide every year. All of them, without exception, are exposed to space ionizing radiation. The radiation consists of galactic cosmic rays, solar energetic particles, as well as electrons and protons from Earth's radiation belts. Radiation environment results in upsets and even failures of spacecraft system electronics. To ensure mission success, electronic engineers must perform a series of operations to validate the radiation hardness level of electronic components used. For modern electronic parts the most hazardous upsets and failures are due to the impact of single high-energy particles. Such radiation effects are called as SEEs – Single Event Effects – since undesirable event is induced by a single particle strike. The spectrum of space radiation environment is extremely wide, but as the measure for the single particle environment with particular energy Liner Energy Transfer (LET) can be used. Ground tests are unable to reproduce the space environment, yet heavy-ion accelerators allow us to create experimental environment simulating LETs similar to space radiation. LET spectrum is from a few MeV cm/mg up to one hundred MeV cm/mg. The goal of SEE tests is to obtain the dependence of SEE cross-section from LET for each type of effects (upsets and failures). To ensure energy deposition in a sensitive region and register SEEs, particles with at least 30-40 um range in Device Under Test (DUT) die are required. To meet the test requirements, the wide range of ions – from O to Bi and energies from 3 MeV/nucleon – shall be used, while a lid should be removed from a DUT. A number of devices, due to their design, require the longer-range, and hence the higher-energy ions, while maintaining the requirements for LET. To meet the needs of Russian space equipment designers and manufacturers of integrated circuits and other semiconductor devices, ISDE in collaboration with JINR have created the unique in Russia SEE Test Facilities. In this paper, we introduce readers the test facilities specifications, ion beam formation and monitoring techniques, certified methods for ion energy and fluence measurement and technical means for their implementation. The paper presents statistics on the use of test facilities, directions for their further development and upgrade.

GENERAL INFORMATION ABOUT TEST FACILITIES

Since 2010, we have been acting in the field of SEE testing. Up to now, 3 test facilities on the basis of U-400 and U-400M accelerators that provide all types of SEE radiation tests of electronic components of any functional class are in operation. The test facilities allow to irradiate DUTs in the following test environments: range of ions from C to Bi; initial energy from 3 to 60 (for light ions) MeV/A; LETs (Si) from 1 to 100 MeV×cm^2/mg; ranges (Si) from 0.03 to 2 mm (depending on the energy); adjustable fluxes from 10 to 10^5 particles/(cm^2 × s); irradiation area up to 200×200 mm; beam nonuniformity less than 10 % [1]. The general structure of SEE Test Facilities is shown in Fig. 1. Equipment in green belongs to the heavy ion accelerator, and all others have been designed especially for SEE testing.

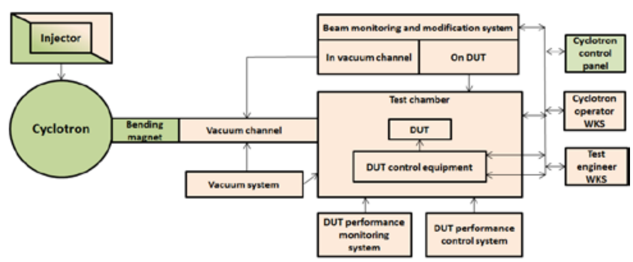

Figure 1: General structure of SEE Test Facilities based on ion sources.

In Fig. 2 we can see a layout of a beam transfer channel with a large number of tools which are used for beam formation, monitoring and measurement. To provide the high accuracy of the beam in a test chamber (on DUT) we use multistage control of the beam parameters [2].

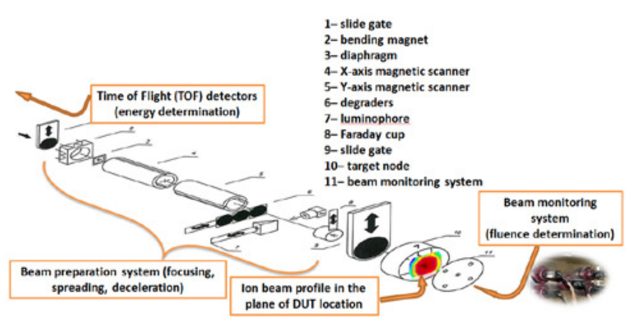

Figure 2: Beam transfer channel layout.

SEE tests are considered to be one of the most expensive parts of ground testing of spacecraft electronic equipment. And the largest expenses are related to the ion accelerators operation. Thus, it is essential to optimize the test procedure. A key advantage of our test facility is a

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