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DEVELOPMENT TOWARDS INTENSE URANIUM ION BEAM PRODUCTION OF THE RIKEN 28 GHz SC-ECRIS

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Abstract

With the ongoing beam development for high intensity uranium beam production, we report the status and progress of the RIKEN 28-GHz Superconducting Electron Cyclotron Resonance Ion Source. The achieved beam currents for the uranium U^{35+} beam has reached up to 250 eμA as a result of optimizing the material consumption rates for high intensity beam production. The target beam intensity for U^{35+} is expected to yield 10 mA of extraction current and the analysis of beam emittance is estimated to be in the range of 0.25 π mm mrad. Furthermore, a semi-empirical method was used to examine a so-called initial emittance value and growth that correspond to space charge effects. Experiments to further investigate the initial beam emittance and the influence of space charge effects are still ongoing.

INTRODUCTION

High intensity Uranium U^{35+} ion beams are produced in the 28 GHz superconducting electron cyclotron resonance ion source (SC-ECRIS) and accelerated to high energies in the Radioactive Isotope Beam Factory (RIBF) at RIKEN [1]. With the increased demand for even higher intensity uranium beams for various nuclear physics research in RIBF, efforts have been made towards improving the performance of the SC-ECRIS. Currently, beam intensities for U^{35+} has reached up to 250 eμA beam current. This was possible through development techniques in optimizing the material consumption rates aimed at high intensity beam production [2]. Investigating the beam quality through beam emittance is the next step to confirm unforeseen issues of beam loss and aberrations along beamline components which is detrimental to the accelerator.

There have been many experimental and numerical studies on the beam emittance growth of the extracted beam from the ECRIS [3-5]. The analysis of beam emittances is complex since the ion source operational parameters, space charge effects and beamline components can easily affect the beam during transport.

The beam emittance from the ECRIS has been known to be mainly influenced by the ion temperature and the axial magnetic field at the extraction region [6]. In the case of highly charged ion production, electrons have much higher temperatures than ions and it has been a reasonable assumption that the dominant contributing factor to beam emittance is the magnetic field effect. Space charge effects on produced ion beams in the ECRIS have also been widely studied since this defocusing of the beam leads to growth in the emittance size and is found to be proportional to the beam intensity. In addition, interaction with downstream components along the beamline must also contribute to an emittance growth. In this paper, beam emittance measurement and analysis of the uranium U^{35+} beam is presented. A systematic study of different operational ECRIS parameters and its effect on the beam emittance size is examined.

URANIUM BEAM PRODUCTION

The RIKEN 28-GHz superconducting ECR ion source (SC-ECRIS) has been developed for providing high intensity heavy ion beams for the RI beam factory. Details regarding the design of the ion source has been previously reported [7]. Superconducting coil assembly with six solenoid coils and one hexapole coil allows the adjustment of the magnetic field at the B minimum to have control on the magnetic field gradient. This means it can produce a mirror magnetic field distribution from the so-called "classical B_{min}" to "Flat B_{min}" [8]. Basic specifications for the RIKEN 28-GHz ECRIS are listed in table 1.

Table 1: Specifications for the R28-GHz SC-ECRIS

Operational Frequency	28 GHz, 18GHz
Max. RF Power	10kW
Max. Magnetic Field	3.8 T
Max. Extraction	22 kV
Chamber Dimensions	Ø150 mm L525 mm
Extraction Aperture Radius	5 mm

With plans to improve the accelerator in the RIBF for studies on nuclear physics now requires output beam intensities of U^{35+} at 300 eμA from the ECRIS. Improvements on the design and performance of the high temperature oven was a crucial factor in increasing the achievable uranium beam intensities. Optimization of the material consumption rates which aimed at high intensity beam production has then allowed the beam current to reach 250 eμA.

With accumulated data sets for U^{35+} beam production, the beam intensity with respect to microwave power is shown in Fig. 1a. Assuming a linear relation between the two parameters, beam currents of 300 eμA will need ~4kW of microwave power and the corresponding extraction currents will be in the range of 10 mA as shown in Fig. 1b. From these expected beam conditions, ion source parameters should be checked thoroughly since high power operation may have some unforeseen issues in the ion source.

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GANIL ION SOURCES: OPTIMISATION FOR OPERATION

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Abstract

The GANIL (Grand Accélérateur National d'Ions Lourds) in Caen has been producing and accelerating stable and radioactive ion beams for nuclear physics, atomic physics, radiobiology and materials irradiation since 1982.

Long-term stability of the beam, which is a key parameter for accelerator operation and success of physics experiments is targeted. At the same time, improving stability will also reduce the need of on-call work for ion source experts.

Recently, studies and tests have been carried out to increase the intensity and/or stability of the metal ion beams by modifying the injection of the ion source on ECR4/4M. Depending on the configuration, the gain on intensity shall be up to a factor of 2 on the charge state required for acceleration, and stability has also been improved compared to previous one.

INTRODUCTION

GANIL laboratory is initially based on Cyclotron accelerators able to produce Carbone to Uranium ion beam with a maximum energy of 95MeV/u. To provide ion beams, two 14 GHz ECR4/4M ion sources [1, 2] are installed into the machine injectors. They provide around 4000 hours of total beam per year, of several type of ions (Fig. 1).

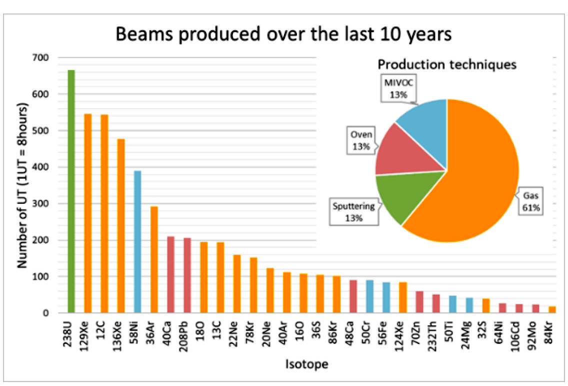

Figure 1: Beams produced by ECR4/4M over the last 10 years.

On the new SPIRAL2 accelerator (based superconducting LINAC), two injectors are installed: One dedicated to light element (2.45 GHz – H^+/D^+), and one dedicated to heavy ions (18 GHz – A/Q<3 - Phoenix V3). Main beams produced are currently proton and deuteron beams for Neutron for Science experimental hall, until the S^3 facility starts its experimental programme in 2026.

New experimental facilities will be set up in the coming years to offer more scientific possibilities for physicists. At the same time, new projects are being under construction or studied to deliver new attractive ion beams (Fig. 2).

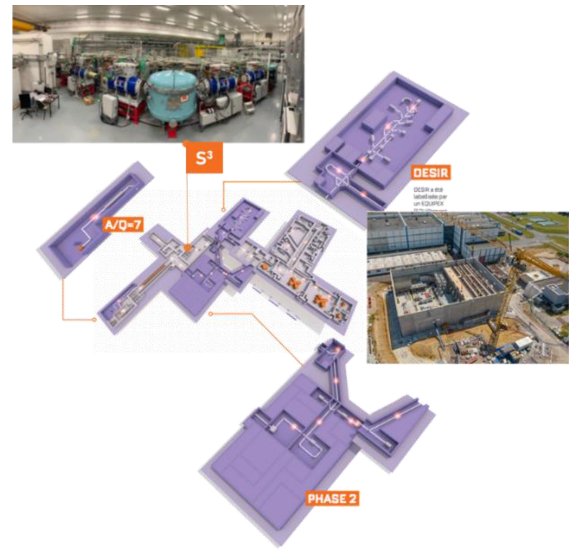

Figure 2: Layout of actual and future building at GANIL.

S^3

The Super Separator Spectrometer (S^3) [3] set up will start running in 2026 for the production and studies of super heavy elements. To create them, a high intense heavy ion beams (Q/A=1/3 => $^{14}Ca^{14+}$, $^{48}Ca^{16+}$, $^{58}Ni^{19+}$, 2 pμA) have to be provide by the heavy ion source injector on SPIRAL2 over a long period (3 weeks–1.5 month).

DESIR

DESIR [4] experimental hall, currently under construction, will use radioactive ion beams produced by S^3 and SPIRAL1 facility at 2027 horizon for experiments with low energy beams.

NEWGAIN (A/Q<7)

The NEWGAIN project [5] aims to install a new injector (Ion source + RFQ) for the SPIRAL2 accelerator with the goal of accelerating a beam characterized by A/Q<7.

A new 28 GHz superconducting ions source ASTERICS [6] is being studied to provide a 10 pμA of metallic beams up to ^{238}U. The new low-energy beamline and a RFQ are currently under construction and will start operating by 2028. The ion source will be assembled and commissioned at LPSC, Grenoble and hence moved to GANIL by 2030.

Future Upgrade for GANIL-SPIRAL2

Beyond 2030, future upgrade applied to GANIL-SPIRAL2 [7] is under evaluation: the design of a new radioactive ion beam (RIB) production facility that will be able to provide RIBs to DESIR for low-energy experiments or to adapt the beam to accelerate it to a range of 50–70 MeV/u before sending it to GANIL's existing experimental areas.

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ECRIS OPERATION AND DEVELOPMENTS AT TRIUMF

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Abstract

Rare isotope beams are used at the ISAC facility at TRIUMF for studies mainly in nuclear and astrophysics and applications ranging from material science to medicine. The isotopes are produced via the ISOL technique and ionized via a set of different ion sources depending on the application. In cases where highly charged ions are needed charge state breeding is done with a 14.5 GHz PHOENIX ECR ion source from PANTECHNIK. The source has been operational for over a decade, providing a wide range of ions from Na to U at A/Q < 7 for post-acceleration. A second ECR ion source, a SUPERNANOGAN, also from PANTECHNIK, is used to provide highly charged ions from stable isotopes either for set-up and calibration for the rare isotope beams or for nuclear reaction studies with stable ions. A summary of the results and the challenges and improvements to the original sources are presented. For the charge state breeding, this mainly optimizes the efficiency and purity of the delivered beams. In the case of the SUPERNANOGAN, special emphasis is put on operational aspects to cover a wide range of elements and ensure easy switchover. The latest in this series of improvements is the implementation of two-frequency plasma heating in both ion sources.

INTRODUCTION

At most rare isotope beams facilities, highly charged ions are not produced directly after the production target, but singly or low charged ions are injected into an ion source for charge state breeding like ECR ion sources or Electron Beam Ion Sources (EBIS) [1]. This allows the decoupling of the isotope production process in a highly radioactive environment and the production of the highly charged ions in a more accessible and controllable area. At TRIUMF, rare isotopes are produced by impinging up to 100 μA of 480 MeV protons on one of two solid targets. The targets are kept at high temperatures to allow the products to diffuse into an ion source for singly charged ions. Extracted ions are accelerated to up to 60 keV, mass separated and guided either directly to experiments or into a post accelerator, which consists of an RFQ, a room temperature drift tube linac (DTL) and a superconducting accelerator [2]. In the case of masses A > 30, higher charge states are needed for the post-acceleration, which is achieved by injecting the ions into the charge state breeder source and selecting the desired charge state with a Nier-type spectrometer before sending them to the accelerator [3]. The intensity of the rare isotopes can vary from up to several nA for isotopes close to stability to only a few per second for the most exotic ones. That means high efficiency for the charge state breeding is needed. In most cases the intensity of ions from the support gas of the ECRIS but also from residual gas and impurities of the source materials exceeds the intensity of the desired ions by many orders of magnitude. It is imperative to minimize the amount of residual gas and other impurities as much as possible by using high-purity gases and materials close to the ECR plasma and selecting a charge state of the radioactive ions with minimum overlap. Even with this, further purification by stripping at higher energy may be needed. Tools have been developed to guide this purification process and to choose the most optimal conditions for the experiments. Additionally, a SUPERNANOGAN ECR ion source from PANTECHNIK, part of the TRIUMF Off-line Ion Sources (OLIS) terminal, provides pilot beams for setting up the accelerators and stable ion beams for the experiments.

CHARGE STATE BREEDING

Several changes to the original design of the source have been implemented. Already shortly after taking it into operation in 2005 at a test set-up, it became clear that both the injection and extraction optics were not ideal for the requirement to operate at different voltages to match the energy acceptance of the RFQ (2.04 keV*A/Q). A two-step deceleration and acceleration scheme has been implemented on both sides, which gives the flexibility to operate at a source voltage between 10 and 15 kV. The next big change was the exchange of the stainless steel plasma chamber for aluminum and the application of an additional coating of pure aluminum to it in 2012. This reduced the background of ions from the stainless-steel components and slightly increased the efficiency. In 2014, the original Klystron RF amplifier was replaced by a TWT, which allowed some small-range frequency tuning. Most recently, two, two-frequency plasma heating has been implemented. It uses one waveguide to transport microwave power at two frequencies between 13 and 14.5 GHz into the source at up to 200 W each. Besides increasing the global charge breeding efficiency, it also shifts the charge state distribution to higher charges. More details and results are described in [4].

Charge State Distributions and Efficiencies

Figure 1 shows the charge state Q with the maximum intensity, or the one used for the experiment as a function of the atomic number Z, for all stable or radioactive isotopes used so far. The solid line indicates the minimum charge state, which is needed to satisfy the acceptance of the accelerator chain of A/Q < 7. It shows that up to about Z = 65, the charge state with the highest efficiency for the charge state breeding can be chosen. For neutron deficient isotopes the required charge state is lower, whereas for neutron rich isotopes a higher charge state is needed. For higher atomic

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RECENT ACHIEVEMENTS IN THE PRODUCTION OF METALLIC ION BEAMS WITH THE CAPRICE ECRIS AT GSI

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Abstract

The GSI CAPRICE Electron Cyclotron Resonance Ion Source (ECRIS) provides highly-charged ion beams for various experiments at GSI, enabling the delivery of continuous wave (CW) metallic ion beams with low material consumption, which is crucial for producing high charge state ion beams from rare or extremely rare isotopes such as ^{48}Ca. These metallic beams are produced utilizing the thermal evaporation technique by resistively heated ovens. Due to the research groups' demand for higher beam intensities and the introduction of new ion species, the CAPRICE ECRIS is now required to deliver increased ion currents of higher charge states, as well as to establish the production of the new beams.

INTRODUCTION

The CAPRICE Electron Cyclotron Resonance Ion Source (ECRIS) at the High Charge State Injector (HLI) of GSI is routinely used for the production of highly charged ion beams from both gaseous and metallic elements. The latter are produced utilizing the thermal evaporation technique by resistively heated ovens. This technique has been continuously optimized over the years to ensure high beam intensity and stable long-term operation. To ensure stable and reliable metal ion beam production, the ovens undergo a carefully controlled preparation process using a specialized oven preparation stand. Over the past years, significant developments have been made to optimize the production of metallic ion beams with CAPRICE ECRIS at GSI, improving both beam intensity and stability. A key focus has been on addressing the challenges associated with the long-term operation of the ECRIS due to material buildup within the plasma chamber, particularly during ^{48}Ca ion beam operation [1].

A diagnostic tool based on an optical emission spectrometer (OES) installed at the ECRIS at the HLI allows to monitor plasma condition in real time. The diagnostic capabilities of optical emission spectroscopy have been successfully utilized to detect plasma instabilities and to adjust ECRIS parameters accordingly, allowing for improved beam stability and performance. It has been demonstrated that the OES can be used to detect parasitic microwave heating of the oven and identify long-term instabilities during gaseous and metal ion beam operation [1, 2].

Metal ion beams are often requested for various research activities, including those conducted by the Super Heavy Element (SHE) groups. To meet their demand, a test campaign was conducted to establish and improve the production of high charge states of enriched ^{54}Cr and ^{55}Mn ion beams. During the tests, plasma and oven images were captured using a CCD camera to support the operation and enable real-time monitoring of the material consumption. Additionally, the use of a hot screen was investigated to protect the ceramic insulators in the extraction system from metal deposition, thereby improving the operational stability of the ECRIS. This paper describes the operational experience, the intensities and stability achieved for the aforementioned elements.

EXPERIMENTAL SETUP

Oven Preparation Stand

To produce metal ion beams, the CAPRICE ECRIS at GSI utilizes resistively heated ovens [3]. This method allows to produce metal ion beam with low material consumption and precise control over the evaporation rate, contributing to the stability and reproducibility of the beam. Before beam operation, the ovens are conditioned in a dedicated oven preparation stand, which allows to perform a controlled heating of the ovens in a vacuum environment. This conditioning process allows to remove residual gases and contaminants from the ovens, ensuring optimal conditions for material evaporation. It allows to improve the stability of the ion beam and extends the operational lifetime of the ovens and minimize downtime during the accelerator operation.

The oven preparation stand has recently undergone a redesign to further improve its functionality and efficiency. Figure 1 shows a photograph of the redesigned stand. It is

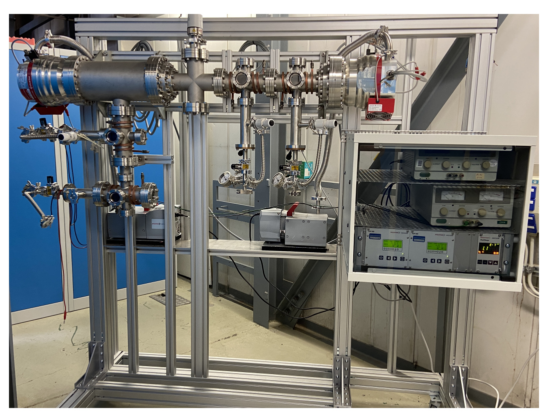

Figure 1: Photograph of the oven preparation stand.

equipped with airlocks that enable conditioning of several ovens simultaneously, increasing the operational efficiency. To further improve control over the oven preparation process, it is planned to equip the stand with a camera monitoring

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A NOVEL INDUCTIVE OVEN DESIGN FOR THE PRODUCTION OF HIGH CURRENT, METAL ION BEAMS*

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Abstract

Essential to the proposed search for element 120 at LBNL's 88-Inch Cyclotron is the continual delivery of over a particle microamp of ^{50}Ti for weeks-long campaigns spanning many months. The fully-superconducting ECR ion source VENUS will be the injector source for these runs, and we have developed a new inductive oven design that can survive VENUS' high magnetic fields while injecting metallic gas into the plasma with high efficiency. The new oven employs a vertical susceptor to permit use with metals that melt before outgassing sufficiently, while also allowing a rotation of the oven's material exit toward the plasma center for better conversion efficiency to the produced beam. The performance of VENUS with this oven has been outstanding. As reported here, ^{50}Ti^{12+} beams with stable currents between 1.0 and 1.5 pμA from this oven were used to produce two element 116 particles: the first time titanium beams have been used to have been used to create superheavy elements.

INTRODUCTION

Superheavy elements beyond copernicium (element 112) have been discovered by bombarding transuranic targets with high-current ^{48}Ca beams. For element 113, a plutonium target was used, and the target atomic number was increased for each successive element discovery. The short half-lives of target material with atomic number greater than californium (element 98, used to discover element 118) mean that there isn't enough material, nor would it last long enough, to serve as targets for the months-long experiments necessary for superheavy element production. A potential way to move forward is to use as projectile beams elements with higher atomic numbers for these searches .

Earlier this year (2024), researchers at LBNL announced they were able to use ^{50}Ti beams from the 88 Inch Cyclotron incident upon a plutonium target to produce two atoms of element 116 [1]. This was the first time that a titanium beam was used to produce superheavy elements, and this result opens the door to extending the periodic table by using ^{50}Ti beams on californium targets in the search for element 120.

The production and delivery of more than 1 pμA ^{50}Ti beams from the 88-Inch Cyclotron was no small feat: not because the cyclotron couldn't produce this high of currents (it has delivered over 2 pμA ^{48}Ca beams previously [2]), but because titanium beams are notoriously difficult to produce from an ion source. Titanium is highly reactive with other atoms, therefore any deposited on the walls of a plasma source producing these beams will affect plasma stability by pumping background gas in an unpredictable manner. Additionally, for sources relying on outgassing from pure titanium, sufficient partial pressures typically require heating the titanium to over 1600 °C.

Using a novel inductive oven within LBNL's superconducting electron cyclotron resonance (ECR) ion source VENUS, we were able to deliver 80–120 μA ^{50}Ti^{12+}; beams to the cyclotron with excellent stability and a relatively low material consumption rate. The inductive oven used for this work is described as are some of the difficulties overcome en route to its successful deployment.

ION SOURCE AND OVENS

Electron cyclotron resonance (ECR) ion sources produce ion beams from a magnetically confined plasma. This confinement is typically in the form of solenoids for axial confinement and a multipole (typically sextupole) for radial confinement. The superposition of these fields produces a net magnetic field magnitude whose minimum is at the source center and which grows in all directions about this center. Closed surfaces of constant magnetic field surround the source center, and by injecting microwaves with frequency that matches the electron cyclotron frequency on one or more of these surfaces, electron energies can be raised to the point that they can ionize atoms and confined ions. The ion beam species produced are determined by the material injected into the plasma, and these sources have the distinct advantage that beams can be formed from any material introduced to the plasma without destroying it. The easiest means of beam production is the injection of gas into the plasma, and a common means of producing beams from metals is to raise the temperature of the metals to the point its vapor pressure emits sufficient material quantity into the plasma.

Raising the temperature of metals is often performed through the use of ovens. The general oven has some sort of a crucible whose temperature is raised to outgassing temperatures for the material it holds, and often some sort of outlet directs that vaporized material toward the plasma. The low-temperature oven used at LBNL is an example of this, where a heater cartridge conductively heats a crucible containing the material of interest [3]. A series of channels then directs the evaporate toward the plasma. This oven has been extremely successful at efficiently delivering ^{48}Ca to the plasma, primarily as a result of the aiming channels. Consumption rates of this expensive material are typically 0.5 mg/hr. This oven is limited to low temperatures, however, reaching a practical maximum of approximately 700 °C.

Higher temperatures have been reached at LBNL and at other laboratories using resistive ovens [4, 5]. Here, a high

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DEVELOPMENT OF DEUTERIUM-DEUTERIUM COMPACT NEUTRON SOURCE

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Abstract

In the present work, we will present the status of the deuterium-deuterium (D-D) neutron source that is being developed in collaboration between the University of Granada and the University of the Basque Country. Our neutron source consists of an Electron Cyclotron Resonance (ECR) ion source which accelerates a deuteron beam towards a deuterated target. The ionization to achieve the deuterium plasma is achieved by radiating the cylindrical ERC plasma chamber with a magnetron 2.45 GHz signal and an 875 G magnetic field generated by 6 NdFeB magnets located around the plasma chamber. Moreover, a cylindrical alumina Radio Frequency (RF) window is used to keep the vacuum status from the ambient pressure condition inside the WR340 and helping the plasma to ignite. Once the plasma is generated, the deuterons are extracted from the plasma chamber using a Pierce electrode geometry and three other electrostatic lenses, fixed to different negative potentials. The beam is accelerated towards the copper target disk with a deuterated titanium mesh fixed to –100 kV which generates the desired neutron radiation. There are several applications of D-D neutron sources across scientific and industrial domains. In case of the University of Granada and its deep relation with the IFMIF-DONES neutron source, it is worth to mention that we plan to carry out experiments for determining the cross-sections of relevant isotopes in the studies of IFMIF-DONES for a better simulation of the behaviour of such material under high neutron flux irradiation.

INTRODUCTION

A deuterium-deuterium (D-D) compact neutron source is being developed in collaboration of the University of the Basque Country and the University of Granada. The main goal of this project is to gain scientific and engineering know-how on this type of source. The source will be based on the D-D fusion reaction described as $^2H(d,n)^3He$ [1-2]]. By colliding with deuterium positive ions, known as deuterons, a 3.27 MeV reaction is generated, where 2.45 MeV corresponds to a neutron and the other 0.82 MeV corresponds to a nucleus of ^{3}He. The full 3D design of the neutron source can be seen in Figure 1. First, the radio frequency (RF) subsystem where a high-power RF signal is generated and transmitted toward the plasma chamber. This Rf signal combined to a proper magnetic field generates an electron cyclotron resonance (ECR) deuterium plasma formed of deuterons. As these deuterons have a positive charge, fixing the target to a negative potential will extract them from the plasma chamber and accelerate them towards it. The target is deuterated, so as the ion beam impacts the target the D-D reaction is going to be produced and 10^7 neutron flux will be generated [3-4].

This paper is organized in the following way. Each section will describe a different subsystem of the D-D source. Moreover, the actual state of the project will be described with the conclusions. Finally, the future works are given.

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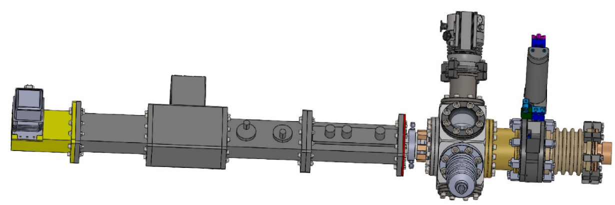

Figure 1: D-D source full 3D model design.

RF DESIGN

As stated in the previous section, an RF signal is needed to ionize the deuterium inside the plasma chamber. This RF signal is generated using a high-power magnetron able to achieve 1.3 kW of power with a frequency of 2.45 GHz. Once the RF wave is generated it needs to be transmitted towards the plasma chamber. A rectangular waveguide chain has been designed for this purpose, using the WR340 standard, which has an operating bandwidth from 2.2 GHz to 3.3 GHz. Following the magnetron an adaptor from magnetron to WR340 is used to optimize the power coupling from the RF source to the rest of the system. Then, a 3 kW water-cooled isolator has been implemented to avoid damaging the magnetron with the reflected power coming from the plasma chamber. Moreover, a directional coupler has been added to the design to monitor both forward and reflected power to the plasma chamber. Finally, a 3 manual probe tuner is used to modify the impedance of the WR340 system. When plasma is ignited, the impedance seen from the WR340 system towards the plasma chamber changes, and this will lead to worse RF coupling. Varying the position of the manual probes and monitoring the reflected power from the directional coupler, the impedance from the WR340 system can be modified to adapt it to the one in the plasma chamber. By doing so, the RF coupling will improve so with less RF power higher ion fractioned plasmas will be achieved.

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CHARACTERIZATION OF THE ECR ION SOURCE LEGIS EXTRACTION SYSTEM AND ITS LOW ENERGY BEAM TRANSPORT LINE AT LEGNARO NATIONAL LABORATORIES

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Abstract

At INFN-Legnaro National Laboratories the heavy ions accelerator complex is fed with beams produced by a permanent magnet Electron Cyclotron Resonance ion source called LEGIS (LEGnaro ecrIS). Although suitable intensities and charge states to fulfill the requests of the users are normally guaranteed, the first part of the Low Energy Beam Transport line (LEBT) downstream of the ion source suffers from non-negligible losses and a lack of scalability when switching between ions with different mass-over-charge ratios, thus leading to a machine preparation time longer than would be desirable. These criticalities called for a deep characterization of the beam coming out from the ion source, especially in the case of high charge states heavy ions production, normally showing the lowest intensities. This contribution describes the numerical studies performed on the extraction system of the LEGIS source and its LEBT. The physics case used is a $^{208}Pb^{31+}$ beam produced for a nuclear physics experiment in fall 2022. As will be shown, the results shed light on the reasons for the bad reproducibility and transmission, mostly due to aberrations induced on the extracted beam by the first optical elements.

INTRODUCTION

Electron Cyclotron Resonance Ion Source (ECRIS) [1] extraction systems for highly charged heavy ions beams necessitate of detailed studies, since they have to manage several ion species with different intensities, while ensuring the proper beam quality for the injection in the accelerators. Indeed, the beam quality directly affects the global acceleration line in terms of transmission, while the charge states are important in relation with the final beam energy.

At INFN–Legnaro National Laboratories (LNL) the PIAVE-ALPI [2–4] heavy ions accelerator complex is fed with highly charged heavy ions by a 2nd generation ECRIS called LEGIS (LEGnaro ecrIS) [5]. It is a full permanent magnet source of the Supernanogan type produced by the Pantechnik company [6], with an operating frequency range between 14 and 14.5 GHz. In order to match the optimum $\beta = v/c$ for the injection into PIAVE, LEGIS and the first part of the LEBT are installed on a high voltage platform (maximum voltage 400 kV).

Suitable intensities for the requests coming from the nuclear physics community are normally produced. Despite that, operational experience evidenced a not satisfactory transmission in the LEBT line installed on the platform, as well as a lack of scalability of the values of the steerers mounted in the downstream fixed-β magnetic beam line towards PIAVE.

To shed light on the above-mentioned criticalities, we carried out numerical simulations of beam extraction from LEGIS and its transport in the first part of the LEBT line, taking as case study the production of a lead beam for a nuclear physics experiments performed in fall 2022 at LNL.

This paper describes the results coming out from the simulations, drawing some conclusions on the possible explanations for the criticalities observed and the actions could be undertaken to solve them.

LEGIS AND THE LNL ACCELERATOR COMPLEX

The LEGIS source can produce heavy ions beam currents of the order of µA for the PIAVE-ALPI accelerator complex. Its extraction system consists of four electrodes (see Fig. 1): the plasma electrode, with a 7 mm extraction aperture and a voltage of 24 kV (voltage V_s always fixed), a puller (maximum operational voltage $V_p = -6$ kV), an electrostatic lens named focus (max voltage $V_f = 1$ kV) and a ground electrode. It is directly coupled to the analysis dipole, characterized by a maximum field of 0.5 T, a bending radius of 500 mm, a pole gap of 80 mm and edge angles of 28.3°, both at the entrance and at the exit. A selection slit (10 mm opening usually) and a Faraday cup are mounted more or less at its image point: this first part of the LEBT, installed on the high voltage platform (as shown in Fig. 1), is generally used to characterize the LEGIS' performances and is the part of the line object of the studies presented in this paper.

The line on the platform continues with a double Einzel lens (max operational voltage $V_{ein} = 10$ kV) that focuses the selected beam into the accelerating column, followed by an electrostatic triplet (max voltage $V_{trip} = 4$ kV) outside of the platform. From this point, the line continues with a fixed-β magnetic beam line for the injection in the PIAVE-ALPI accelerator complex.

PIAVE (Positive Ion Accelerator for Very-low Energy) is a positive ions linear accelerator preceded by a three harmonic buncher (40, 80, 160 MHz) and consisting of two 80 MHz superconducting RFQs, with β equal to 0.0089 and 0.0035 at the RFQs entrance and exit, respectively. The RFQs are

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CHARACTERIZATION OF THE 2.45 GHz DREEBIT ECRIS VIA OPTICAL SPECTROSCOPY

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Abstract

ECR ion sources are widely used at many research institutions to provide ions for various experimental setups. DREEBIT GmbH aims to industrialize this type of ion source technology. Our goal is to build table-top sized ion sources which can easily be handled and integrated into larger machine setups, thereby fulfilling high requirements on beam current, quality, stability and reproducibility in serial production. To achieve this, we had already optimized the microwave injection system and magnetic plasma confinement by introducing a simple method to allow for injection of circularly polarized microwaves and adjusted the magnetic field distribution which led to an 80 GHz increase of proton beam current [1]. In the present work, we show how optical emission spectroscopy was used to gain deeper information about the plasma of this specific type of ion source, independently from its ion extraction system. The plasma characterization includes studies of the electron density and temperature (n_e, T_e) and the density of atomic and molecular hydrogen (n_H, n_{H_2}) showing the performance of the 2.45 GHz DREEBIT ECRIS concerning plasma heating and proton production and indicating how the source performance can be enhanced in further steps.

INTRODUCTION

Electron Cyclotron Resonance Ion Sources (ECRIS) provide low, intermediate and highly charged ions for a broad range of applications, reaching from nuclear [2, 3] over materials [4] to medical physics research. In the future, they can be used in combination with particle accelerators or as part of irradiation facilities, e.g., for industrial semiconductor manufacturing or cancer therapy [5]. The goal of the present work is to characterize the plasma of the table-top sized 2.45 GHz DREEBIT ECRIS run with hydrogen in order to gain better understanding of the possibilities for source improvement. Using optical emission spectroscopy (OES) the intensities of the hydrogen Balmer and Fulcher lines depending on the power of the injected microwave and the phase shift of the two injected microwaves were studied. The electron density n_e, temperature T_e and ratio of atomic to molecular hydrogen n_H/n_{H_2} were deduced from the optical spectra using the Yacora solver [6].

EXPERIMENTAL METHOD

An Ocean Insight Flame UV-VIS Spectrometer was used for the optical spectroscopy setup. The spectrometer is sensitive in the wavelength range from 200 to 850 nm with a resolution of 1.37 nm. To couple the light into the spectrometer a reflective collimator with UV-enhanced aluminum coating with a diameter of $d = 8.5$ mm was employed. An optical cable with a fiber diameter of 200 µm couples the collimator to the spectrometer device. Intensity calibration was conducted on-site by using an Ulbricht sphere. The line of sight where the plasma was characterized is shown in Fig. 1.

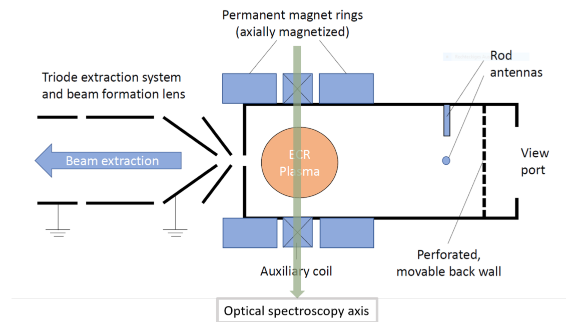

Figure 1: Experimental setup with optical spectroscopy axis marked in green.

The optical light emitted by the atomic and molecular hydrogen ions reveals information about the plasma. The Balmer line ratio H_β/H_γ relates to the electron density, the ratio between the Balmer line H_γ and the integrated Fulcher lines is a measure for the dissociation ratio, as the Fulcher lines are emitted during relaxation of excited vibrational and rotational states of the H_2 molecule [7]. While individual line ratios had been used to identify plasma parameters like the electron density directly in the past, this method was replaced by the Yacora solver, employing a collisional radiative model and identifying the best agreement between simulated and actual line ratios under variation of the desired plasma parameters.

RESULTS

In two separated measurement campaigns a scan of the microwave power and the phase shift of the two injected microwaves were performed. From this data set a range of the plasma parameters electron density n_e, electron temperature T_e and the neutral density ratio n_H/n_{H_2} were determined to characterize the plasma. The findings from the OES measurements are compared to measured spectra of extracted ions.

OES Measurements

Microwave Power Scan at 100° Phase Shift Figure 2 shows the results of the microwave power scan. Here, the intensity ratios of subsequent Balmer lines are shown as black (H_α/H_β), red (H_β/H_γ) and green (H_γ/H_δ) data points. Moreover, the previously discussed ratio of H_γ/H_{Ful}

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ALISES II SOURCE IS STILL ALIVE AT CEA SACLAY

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Abstract

Developments of ECR intense light ion sources is an important research axis of the Laboratory for Accelerator Study and Development at CEA-Saclay. Starting in the 90's from the SILHI proton source for the IPHI accelerator [1], several high intensity proton or deuteron SILHI-type sources were provided to international facilities like IFMIF, FAIR or SPIRAL2. From 2011, CEA started a new R&D program on high intensity ECR compact ion sources with the ALISES source family. The results obtained with the first ALISES source prototype [2,3] gave us the main goals for the design of the ALISES II source that ran several months on 50 kV BETSI [4] test bench and was dismounted at the end of 2016 to upgrade the test bench to 100kV. However, this source was never reinstalled and has been replaced by the ALISES III source [5] that runs on BETSI up to now. Recently, the ALISES II source and its equipment has been reassembled to be restarted on BETSI for beam characterization before sending it to the MIRROTRON company in Hungary as the proton source for a neutron beam facility. This paper describes the setup on BETSI and proton beam characteristics obtained by emittance measurements and spatial species proportion analysis. A Low Energy Beam Transport line is proposed to match the beam to the already constructed RFQ.

INTRODUCTION

ALISE II ion source was the first compact ECR light ion source at Saclay for proton beam extraction. The source installed on the BETSI test bench in February 2015 allowed a first extracted beam current of 35 mA hydrogen ion beam (H^+ and molecular ions) at 42kV, regularly extracted through a 6 mm diameter plasma electrode with a record of extracted intensity of 38.5mA at 42kV. The source operated up to 50 kV in pulsed or continuous mode. Several experiments were carried out with this source on BETSI up to 2016 like irradiation of scintillators for a 4D emittance meter or beam stop finger bombardment (Fig. 1) for S3 separator of SPIRAL2 project in Caen (France).

The beam emittance was measured with the Allison scanner designed and manufactured by IPHC in Strasbourg (France) for the FAIR project in Darmstadt (Germany). ALISES II ion source was then dismounted while upgrading BETSI test bench to 100kV.

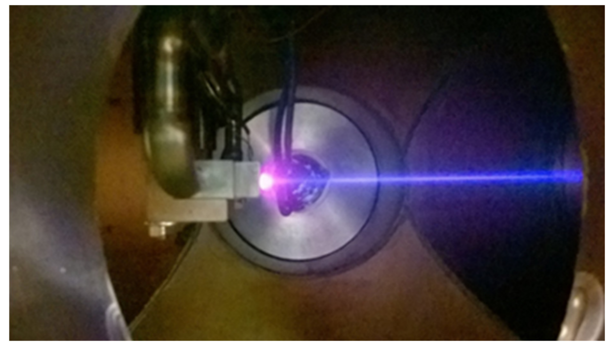

Figure 1: Finger bombardment for S3 separator of SPIRAL2 project.

ORIGINAL SOURCE SETUP AND EVOLUTION

ALISES II Ion source is a compact system originally designed to achieve the same performances as SILHI, around 100 mA of 95keV protons. A three steps ridges transition is implemented to concentrate the 2.45GHz High Frequency (*HF*) microwave onto the 90mm diameter plasma chamber axis. A copper cylinder has been machined to form the plasma chamber and the RF entrance ridged guide in one piece. A smooth ceramic cylinder built in two concentric parts realizes the insulating structure, and is in contact of the copper body. To connect the puller electrode to high voltage, a groove has been machined longitudinally on the external surface of the internal ceramic cylinder, and a hole has been drilled radially on the external ceramic cylinder up to the puller connector. Both the ceramic and the source body are screwed on a copper flange and connected to the RF guide. A tunable magnetic field creates the electron resonance at the cavity's entrance when the magnetic field reaches 87.5mT to give energy to the electrons to ionize the hydrogen gas inside the plasma chamber. To extract the proton beam and also the molecular ion H_2^+ and H_3^+ present in smaller proportion, a five electrodes extraction system is used which comprises the plasma electrode (95kV), the puller electrode (70kV), two ground electrode and the electron repeller (-3kV) placed in between the later. The electron repeller prevents the electrons from the LEBT produced by ionization of the residual gas to go upstream and being accelerated toward the plasma chamber with possible damage of the boron nitride disk at the bottom of the plasma chamber, but also to avoid high power deposition on the 90° RF bend wave-guide. The plasma electrode is fixed on the copper cylinder extremity to close the plasma chamber with an appropriate

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ALISES v3 ION SOURCE IN VARIOUS CONFIGURATION ALONG THE YEAR

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Abstract

ALISES v3 is a very compact light ion source that has been developed at CEA Saclay in 2018. The easy maintenance procedure of this source allowed us to test many different configurations. On the BETSI test bench equipped with a single Alisson Scanner and a pair a solenoid/deviator, we studied the extraction energy influence, we changed the number of electrodes in order to extract different kind of ions other than protons. This paper will describe briefly the ALISES v3 ion source and will present all the results that we gathered in a year with all those modifications

INTRODUCTION

The ALISE v3 ion source, developed at CEA Saclay in 2018, represents a significant advancement in light ion source technology using ECR heating process. It aims to achieve the same performance as the original SILHI source, known for its high intensity proton and deuteron beams, but with a smaller and more user-friendly design. This new iteration incorporates the best aspects of previous ALISE versions, resulting in a more compact and practical configuration. The manufacturing of ALISE v3 coincided with the upgrade of the BETSI (Banc d'Etudes et de Tests des Sources d'Ions) test bench, allowing for thorough testing and analysis of its beam characteristics. This innovative source holds promise for various applications requiring high-intensity light ion beams, offering improved efficiency and ease of maintenance. This article will summarize all the evolution and changes that were made to the original model of the ALISES v3 to increase the availability of the ion source at different energy.

ALISES v3 ION SOURCE ON BETSI TEST BENCH

The BETSI test bench, located at CEA Saclay [1], is a crucial facility dedicated to the optimization and characterization of high-intensity light ion sources. Operational since 2009, it has played a pivotal role in the development and testing of various ion sources, particularly those used in large-scale accelerator projects like Spiral2 and some component of various project (emittance measurement unit and Wien filter). Also this test bench is used for educational purposes with students for Paris-Saclay University. The core of the BETSI test bench is a versatile platform capable of accommodating and testing different ion source types, primarily those based on Electron Cyclotron Resonance (ECR) heating.

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The ALISE v3 ion source uses several key technical advantages. Its compact design, with a ceramic diameter of only 150 mm and a length of 300 mm, makes it significantly smaller than traditional high-intensity ion sources. This allows for easier integration into existing accelerator facilities and reduces the overall footprint of the system. Additionally, the simplified structure of the source facilitates maintenance and reduces the risk of operational issues.

A single coil at ground potential provides the magnetic field and is located around the source ceramic. This unique coil was used on both IPHI project (SILHI source [2]) and FAIR project ion source. On this latter project, a single coils was enough to heating up electrons to ignite the plasma source [3].

The gas injection system allow to control the mass flux of the injected gas (hydrogen or helium) that is needed to inject inside the plasma chamber, independently of the temperature in the experimental hall. The PR4000 MKS brand was chosen because of its good behaviour against sparks. The use of metallic capillaries with metallic gasket decrease the possibility of tiny leaks polluting the plasma with air and its components.

The energy id provided by a microwave generator at 2,45 GHz delivered by SAIREM company. Free electrons inside the magnetic field have at a moment the same gyration frequency than the magnetron generator and leads to an efficient energy transfer from the microwaves waves to the kinetic electrons velocity, causing them to get accelerated (heat up) and collide with neutral atoms of the injected gas. These collisions result in the ionization of the atoms of the gas, forming a plasma which contains the desired positive ions, electrons and also some ionized molecules in some cases.

The positive ions are extracted trough the plasma chamber extraction hole, focused and accelerated using a multi-electrode extraction system.

Extraction energy was designed to be 100 kV but unfortunately this value was never reached in normal source operation with the first design of the ceramics. With the second design [4], maximum extraction voltage reach the value of 80 kV but sparks occurs too frequently and did not allow to increase more because the risk of damaging any equipment.

INFLUENCE OF THE COIL POSITION

The single coil of the source can be moved easily. As the position changed, the current value of the Coil Power Supply (C-PS) must also be adjusted in order to keep the resonant zone at the same location to ignite the plasma. As the coil gets further away the RF ridge, the value of the C-PS must

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USE OF A 2.45 GHz ECR ION SOURCE FOR THE NEUTRON TARGET DEMONSTRATOR PROJECT*

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Abstract

D-Pace has licensed a 2.45 GHz ECR ion source from Neutron Therapeutics. The ion source will be used for the Neutron Target Demonstrator project at Los Alamos National Laboratory where 10 mA of singly charged krypton ions at 50 keV are required with a normalized 4-RMS emittance of less than 1 mm·mrad. The goal of the project is to show a reverse kinematics neutron capture reaction with krypton 84 ions. Due to the high radiation environment that the ion source will be subjected to, a solid state microwave power supply will be used instead of the traditional magnetron for the experiment. The main advantage of the solid state power supply is that the output is transmitted by a coax cable instead of a waveguide, so the power supply can be located a long distance away from the ion source without the need for complicated and expensive waveguide. The other advantage of the solid state device is that the frequency can be varied from 2.4 GHz to 2.5 GHz. This gives the operator an extra degree of freedom for tuning. We present how the frequency variation affects the beam parameters.

INTRODUCTION

The Neutron Target Demonstrator (NTD) project at the Los Alamos Neutron Science Center (LANSCE) will be the first demonstration of a reverse kinematics neutron capture reaction [1]. Neutrons will be created by spallation of the 800 MeV proton beam onto a target. A beam of Kr-84 ions will serve as the target ions for the neutron capture reaction $Kr^{84}(n,\gamma)Kr^{85}$. D-Pace is providing LANSCE an ECR ion source system capable of producing mA level beam of Kr-84 at an energy of up to 50 keV. Figure 1 shows a schematic of the NTD as well as a CAD model of the ion source system.

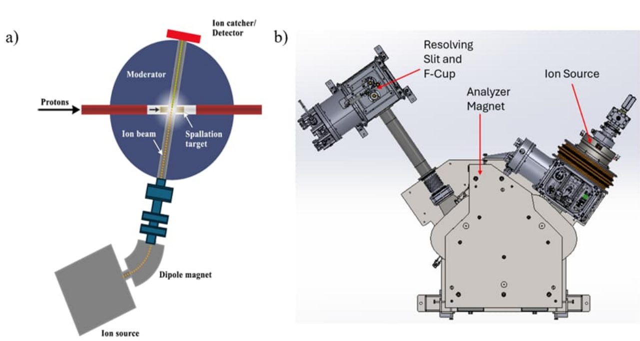

Figure 1:a) Schematic of the NTD project. Figure provided by A. Cooper at LANSCE under LA-UR-24-27491. b) Plan view of the CAD model for the ion source system.

* Work supported by Canada's SR&ED program, MITACS, NRC-IRAP, NSERC, Buckley Systems and BDC
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ION SOURCE

D-Pace has licensed a 2.45 GHz ion source from Neutron Therapeutics [2] which is based on the first 2.45 GHz ion source developed by Wills and Taylor [3]. The ion source is commonly used in their boron neutron capture therapy system producing 30 mA DC of protons at an energy of 50 keV.

The microwave injection system consists of a 3-stub tuner, forward and reverse power monitors. A high voltage waveguide break was designed with alternate layers of G10 and aluminium plates to allow for the microwave generator to be grounded while the ion source is at 50 kV. The microwave power is transmitted through an aluminium nitride window to the plasma chamber.

The magnetic field is produced by three solenoids, labelled back, centre and front, where the front solenoid is closest to the extraction and the back solenoid is closest to the microwave injection. The cylindrical plasma chamber is made of aluminium with a diameter of 76 mm and a length of 95 mm. Boron nitride plates are mounted on both the front and the back edges of the plasma chamber.

The extraction system is formed by four molybdenum electrodes. The plasma electrode aperture has a diameter of 6.5 mm. The first ground electrode, the suppression electrode and the second ground electrode apertures have diameters of 9 mm, 11 mm and 11.5 mm respectively. The suppression electrode is commonly biased at -3 kV relative to ground. The ground and suppression electrodes are installed on a moveable trolley allowing for active tuning of the distance between the plasma aperture and the first grounded electrode by 26 mm.

EXTRACTION OF KRYPTON

The test stand used for testing the extraction of Krypton ions for the NTD project is composed of the ion source, an emittance scanner and a Faraday cup. The Allison-type emittance scanner [4] was mounted at $z = 547$ mm where $z = 0$ mm is the ion source's plasma aperture. The emittance scanner can be mounted in both x and y directions. The Faraday cup was located at $z = 714$ mm. A CAD model of the test stand is presented in Fig. 2.

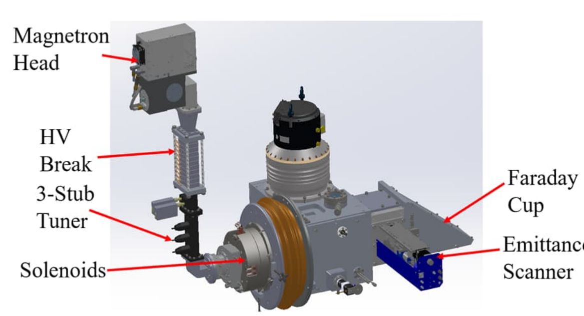

Figure 2: CAD model of the test stand.

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AUTOMATIC CLASSIFICATION OF PLASMA STATES IN AN ECR-TYPE ION SOURCE*

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Abstract

In this paper we present a methodology to infer the state of the plasma in an ECR source without using any sensor that modifies its behavior. For this purpose, machine learning techniques are explored. In a first stage a characterization experiment is carried out in which the different states of the plasma are detected, using clustering algorithms. Subsequently, a supervised learning paradigm is adopted to train a neural network that is capable of determining the state of the plasma at different working states. The control data: delivered RF power and gas flow, together with the data that can be measured without altering the plasma: incident power, reflected power and plasma luminosity, are provided to the system as an input, in order to achieve the state detection. Moreover, good results can also be achieved without measuring luminosity, which cannot be easily measured when the ECR source is the start of an injector. This methodology has been applied to a low-power ECR source in which low-density hydrogen plasmas are generated at the IZPILab laboratory of the University of the Basque Country.

INTRODUCTION

Electron cyclotron resonance ion sources (ECRIS) are now widely utilized for ion production in both basic research and industrial applications due to their dependability and ability to generate multiply charged ion beams from most stable elements. This widespread adoption is attributed to their consistent performance and versatility across various fields [1].

These sources generate plasma that undergoes state changes over time, necessitating precise measurements to enable effective operation. Furthermore, it is crucial to perform these measurements non-intrusively to avoid interference with the plasma dynamics. This necessity forms the primary motivation for developing the methodology presented in this paper, which aims to infer the state of the plasma in an ECRIS source without employing any sensors that could alter its behavior. This is achieved through the application of advanced Machine Learning (ML) techniques.

Ion Source Operational Details

The source designs and implementations used for the experiments are comprehensively described in Ref. [2]. These designs are tailored for low current industrial and bio-applications, leveraging Electron Cyclotron Resonance (ECR) principles. The main design parameters are summarized in Table 1. Although the table specifically references H_2, the ion source is versatile and can operate with other gases, such as Helium, Nitrogen, or any other elemental gas for ion production.

Table 1: Main Design Parameters of PIT30 Ion Source

ECRIS parameters	
Microwave frequency	3 GHz
Microwave power	<500 W
Gas mass flow	<5 sccm (H_2)
Magnetic field	110 mT
Extraction voltage	≤30 kV
Beam current	<50 µA (H^+)
Beam emittance	<0.2 mm mrad

Figure 1 depicts a CAD-rendered cross-sectional drawing of the proposed plasma chamber, assembled from standard components. This chamber is configured as a circular waveguide, and for the chosen operating frequency, the smallest commercial diameter suitable as a resonant cavity within the CF flange system was DN 63. To produce the required magnetic field within the chamber for electron resonance, permanent magnets were utilized. The magnetic field strength was determined using the equation for the resonant frequency of a free electron in a magnetic field ($B = 2\pi f \frac{m}{e}$), where B represents the magnetic flux density, f is the frequency of the microwaves, and m and e are the mass and charge of the electron, respectively. For the intended 3 GHz microwaves, this results in an approximate field of 110 mT. To achieve this, a Halbach array consisting of eight permanent magnet bars was designed to create an axial magnetic field aligned with the plasma chamber.

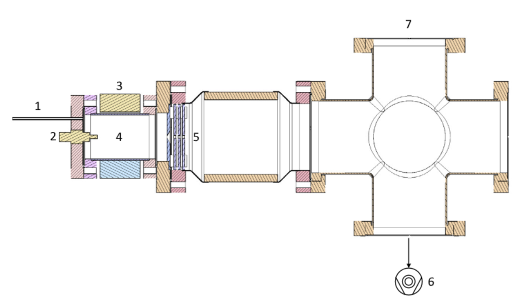

Figure 1: Cross section of a CAD drawing of the proposed plasma chamber made from standard CF components. (1) gas inlet, (2) RF port, (3) magnetic structure, (4) plasma chamber, (5) extraction electrodes, (6) turbo-molecular pump port, (7) pressure sensor, (8) Faraday cup/scintillator screen port. The entire assembly shown is 600 mm long.

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STATUS REPORT ON 60 GHz ECRIS ACTIVITY

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Abstract

After a record pulsed ion beam current density measured up to ~1 A cm^{-2} obtained with the 60 GHz SEISM (Sixty gigahErtz Ion Source using Megawatt magnets) ion source in 2014 at LNCMI, the experiment resumed in 2019, following a source repair and a beam line upgrade. New measurements shown a limitation in the beam pulsed current measured at ~0.3 A cm^{-2}. A careful investigation pointed out that the performance reduction is due to the upgrade of the beam line base vacuum from ~10^{-6} mbar to ~10^{-7} mbar. The characteristic time for the ion beam to reach the steady state's space charge compensation is calculated and is found to exceed the 500 µs pulse beam duration in the latter case. This analysis is confirmed using IBSIMU which can reproduce the beam intensities measured in the two pressure configurations, assuming a space charge compensation of 65 % in 2014 and 35 % in 2024. Finally, the development status of the superconducting cusp magnet planned to upgrade the source is presented.

INTRODUCTION

The development of new generation 45 GHz ECR ion sources is ongoing to increase the achievable beam intensities at IMP (Lanzhou, China) [1] and at LBNL (Berkeley, California) [2]. These new developments bring many stimulating technical challenges, among which are the high ion source microwave power and the high intensity ion beam transports. These challenges are being addressed with the LPSC 60 GHz program.

In the 2010s, LPSC developed a 60 GHz ECR ion source named SEISM (Sixty gigahertz Electron cyclotron resonance Ion Source using Megawatt magnets), using a gyrotron delivering high-intensity high-frequency (HF) pulses (up to 1 ms, 300 kW, 2 Hz) [3]. This development was historically intended to be applied to the CERN Beta-Beam factory project, as a radioactive ion source [4]. The source magnetic field is simplified to an axial cusp using a set of un-expensive polyhelix copper coils, resisting to radiations. The SEISM source is installed at the LNCMI high magnetic field facility in Grenoble on a dedicated test bench. The cusp generates a closed ECR magnetic surface at 2.14 T. The source produced its first ion beams in 2014 (extracted from a 1 mm diameter plasma electrode) with a record pulsed current density up to J ≈1 A cm^{-2} [5]. After a long shutdown, the experiment resumed in the allocated room at LNCMI in 2021 and the results obtained so far are presented in this paper.

STATUS OF THE SEISM EXPERIMENT

Experiment Upgrade

After the failure of a set of the ion source copper coils in 2014, new ones were designed and built, using advanced three dimensions printing techniques [6]. Numerical simulations performed with the Tracewin code [7] to reproduce the 2014 results campaign was used to design a new low energy beam line (LEBT), assuming a 80 % ion beam space charge compensation. It is composed of a quadrupole triplet and an available 90° bending magnet (with a 650 mm curvature radius and a 90 mm vertical gap). Figure 1 shows a top view of the experimental beam line. The LEBT is equipped with three faraday cups named: (1) FC-Source, to measure the ion beam intensity 397 mm away from the source extraction, (2) FC-Dipole, located between the quadrupole triplet and the bending magnet and (3) FC-Analysis to measure the beam selected after the dipole. A pepper pot emittancemeter

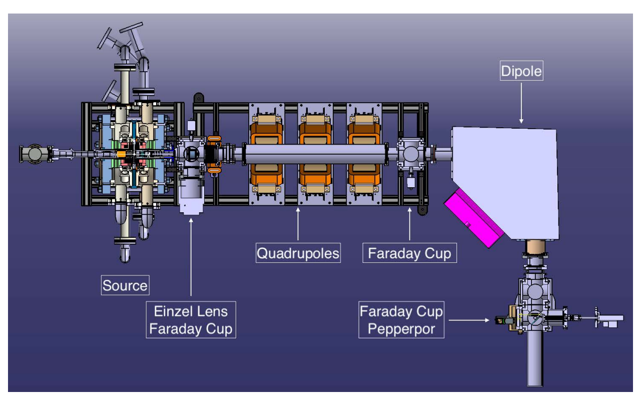

Figure 1: 2D top view of the experimental bench of the SEISM source. From left to right: Source, extraction box (Faraday cup source (FC-source)/Einzel lens), quadrupole triplet, Faraday cup dipole entrance (FC-dipole), dipole, end of line diagnostics (pepperpot/ Faraday cup (FC-analyze)).

is also installed close to FC-Analysis to measure the beam emittance. The IBSIMU simulations indicated a theoretical transmission of 90 % through the LEBT for a 1 mm plasma

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LIGHT IONS FROM THE GTS-LHC ION SOURCE FOR FUTURE PHYSICS AT CERN

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Abstract

Starting from 2028, physics programmes using ions at CERN have requested lighter ions than the lead usually produced. The Working Group on Future Ions in the CERN Accelerator Complex has been mandated to assess the feasibility of the production and operation of these new ion species. The ion beam production from two of the chosen elements, krypton and magnesium, was studied in the GTS-LHC ion source, and the preliminary results of beam intensity, stability and emittance will be presented, as well as proposed modifications to improve performance.

INTRODUCTION

The CERN accelerator complex was upgraded in 1994 to deliver heavy lead ions for the ion physics programme of the fixed target experimental area called North Area (NA) of the Superprotonsynchrotron (SPS) and since 2007 for the ion physics programme of the Large Hadron Collider (LHC). Some exceptions to the standard lead operation were indium (2003), oxygen (2005), argon (2015) and xenon (2017).

Recently a working group "Future Ions in the CERN Accelerator Complex" was created to define future ion operation needs based on the requests from the LHC and the fixed target experiments and their implications for the ion injector accelerator complex [1]. The aim is to find synergies between the different experiments to limit the number of different ion species, to study challenges and limitations in the ion accelerator complex and to make proposals to schedule tests of selected ion species.

Presently a limitation for the study of new ion species is the existence of only one ion source in the complex, the GTS-LHC ECR ion source [2], which has to be used for the operation of requested ion beams and the development of new ion beams.

The setup of the ion accelerator chain and the following physics period can be up to 6 months. This means, depending on the physics programme, only two ion species can be operated or studied per year. Only precise long-term schedule allows under this condition to serve all the needs of the ion community.

Due to these long operation periods it requires an excellent long-term stability over weeks or months of the source. This is more demanding than just reaching the target beam intensity, especially for metal ion beams based on oven operation.

For the LHC, the working group studied if by using different ions, the nucleon-nucleon luminosity could be increased. One candidate ion is krypton. With nobel gas ions the source conditioning time is usually shorter, and stable operation is reached within 2 weeks, so a short 3 week test with krypton before the start of the setup of the ion accelerator chain with lead was scheduled in the beginning of 2023.

For the fixed target physics the list of ions to be prepared for the next years could be limited to magnesium and boron. In the beginning of 2024 a 8 weeks test of magnesium was done. Boron has to be tested in one of the following years.

KRYPTON TEST

The aim of this test was to find the settings of the source for a reliable and stable operation, information about the charge state distribution, beam intensity and beam emittance. Due to the short time available the beam could be studied only in the Low Energy Beam Transport (LEBT) and in the following RFQ. The rest of the linear accelerator was not available at that moment. To transport the ion beam through the RFQ the extraction voltage has to be set to a value corresponding to a beam energy of 2.5 keV/u.

The linear accelerator Linac3 injects the ion beam into the Low Energy Ion Ring (LEIR) [3]. Depending on the ion species and the charge state available from the source the beam needs to be stripped at the end of the linear accelerator as only a limited range of charge-over-mass can be injected into LEIR. For the test isotopically pure ^{86}Kr was used (17.3 % abundance in natural krypton). A charge state around Kr^{22+} would have been a good option to avoid stripping.

The source was mechanically already set up for the following lead ion beam commissioning (to minimize the switch-over-time), i.e. the extraction gap was not adjusted for the low extraction voltages needed for the krypton ion beam. Oxygen was used as support gas.

In the first stage of testing a charge distribution peaking at Kr^{19+} could be achieved (see Fig. 1, FC2 is the Faraday cup directly after the separation spectrometer). But this charge state would have been too low for a direct injection into LEIR. After re-adjusting the source parameters a charge state distribution peaking at Kr^{22+} could be achieved (see Fig. 1).

After a couple of days of commissioning we achieved around 120 eμA of Kr^{22+} at an extraction voltage of 9.8 kV out of the source and around 80 eμA out of the RFQ (see Fig. 2). The stability of the ion beam was excellent compared to the standard lead ion beam.

The transverse emittance in front of the RFQ was measured using tomographic reconstruction [4] from beam profile measurements on a profile grid, as a function of current in a upstream quadrupole magnet. The results show that

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CONTINUOUS DATA-DRIVEN CONTROL OF THE GTS-LHC ION SOURCE AT CERN

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Abstract

Recent advances with the CERN infrastructure for machine learning allow to deploy state-of-the-art data-driven control algorithms for stabilising and optimising particle accelerator systems. This contribution summarises the results of the first tests with different algorithms to optimise the intensity out of the CERN LINAC3 source. The task is particularly challenging due to the different latencies for the various control parameters that range from instantaneous to full response after only ~30 minutes. Next steps and vision towards full deployment and autonomous source control will also be discussed.

INTRODUCTION

The GTS-LHC 14.5 GHz Electron Cyclotron Resonance (ECR) ion source [1] at the CERN LINAC3 provides different heavy ion beams for the LHC, as well as the PS and SPS fixed target experiments. In the case of the main species of lead ions, the beams are produced by vaporisation of solid samples that are heated with an oven in the plasma chamber. Tuning the various parameters of the source, such as oven power, to maximise its intensity output as well as ensuring reproducible intensity during the pulse and on a shot-by-shot level is non-trivial and is frequently slow due to conditioning effects. For example, during commissioning or after a stop, the oven's power needs to be slowly ramped up until lead evaporation is initiated. It is then increased over two to four weeks to maintain a sufficiently high evaporation rate until the next oven refill. Figure 1 shows an example of the reconditioning of the source in May 2018 with the discussed slow ramp-up of the oven power and non-linear response of intensity over the course of about 11 h. Various other parameters need to be adjusted as well as part of this process that are not indicated in Fig. 1. All of this is usually done manually.

This paper summarises the first tests of deploying CERN's Generic Optimisation Framework [2] to automatically optimise the intensity out of the LINAC3 source with the final goal of making recovery after oven refills and commissioning more efficient and less dependent on singular experts. Algorithms to stabilise the performance after commissioning were also part of the investigation.

To date, only preliminary tests of various sample-efficient optimisation and stabilisation algorithms could be carried out. However, they were already sufficient to start addressing the challenging aspects of time-varying dynamics and control knobs that act at significantly different time scales. Another test is planned towards the end of the 2024 run where the lessons learned will be incorporated.

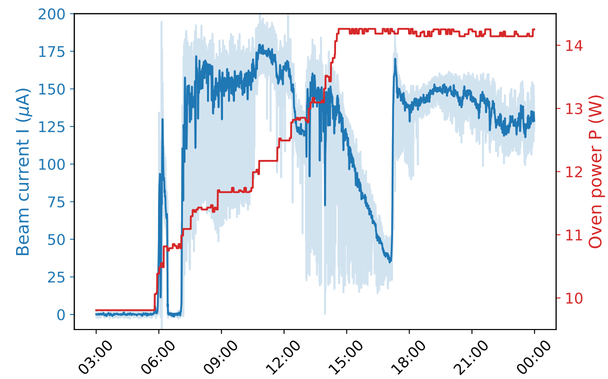

Figure 1: Evolution of the beam current measured by BCT.ITL05 at the end of the Low Energy Beam Transport in blue during lead ion beam setup in May 2018. The oven power (red) needs to be ramped up slowly. In this particular case this phase took roughly 11 h while tuning other parameters in addition.

GENERIC OPTIMISATION FRAMEWORK AND FRONTEND AT CERN

A significant step towards automating parameter optimisation and stabilisation was the implementation of the "Generic Optimisation Framework and Frontend" (GeOFF) in Python at CERN [2]. GeOFF standardises interfaces for optimisation tasks and provides adapters for various third-party packages such as SciPy, Stable Baselines 3, Scikit-Optimize, BoTorch. GeOFF tasks can scale to arbitrary complexity and depend on any Python package; they can use any controls system and even communicate with external simulation tools, as long as they have Python bindings. It comes with a GUI application, readily usable with the CERN control system in the various control rooms. It allows to add custom plotting in addition to a pre-defined set of plots that show the evolution of the objective function and the actors. It also allows to save the optimisation evolution in terms of objective function and actors, which was used to produce the plots in this paper.

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PRODUCTION OF "COCKTAIL BEAMS" WITH ECR BOOSTER, POST-ACCELERATED FOR INDUSTRIAL APPLICATIONS

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Abstract

The GANIL (**G**rand **A**ccélérateur **N**ational d'**I**ons **L**ourds) in Caen produces with cyclotrons up to 20 % of the beam times dedicated to industrial applications, such as the irradiation of electronic components. The SAGA project (**S**pace **A**pplication at **G**ANIL **A**ccelerators) aims to increase beam times for these applications in the future in order to meet demand from French and European industries.

INTRODUCTION

In this context, one of the challenges is to be able to switch rapidly from one beam to another in order to optimize the beam time available for irradiation. This project involves technical and organisational developments (on existing GANIL and SPIRAL2 facilities, see Fig. 1) to improve the supply of medium and high energy beams for experimental needs.

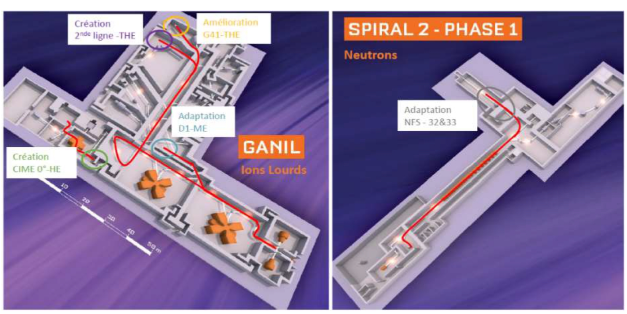
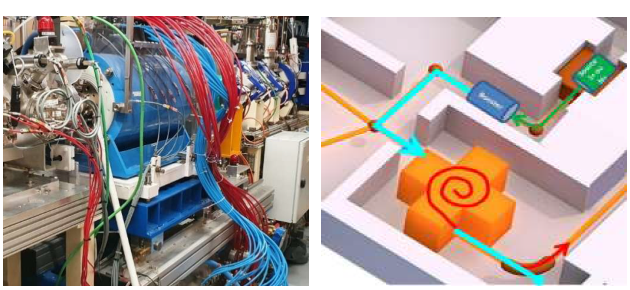


Figure 1: Layout of GANIL/SPIRAL2 accelerators.

The work package *CIME 0°-HE* plans to install a new irradiation station for medium energy beams (up to 20 MeV/u), using the Charge Booster as stable ion source (from SPIRAL1 facility) to provide cocktail beams (Fig. 2).



(a) Phoenix Charge Booster (b) ECR SPIRAL1 Facility

Figure 2: Charge breeder (a) and SPIRAL1 layout (b).

To meet the requirements, this ECR Ion Source has to produce several elements, with very close A/Q, which were separated and post-accelerated by CIME cyclotron.

The Phoenix Booster, usually dedicated to increase the charge state of a monocharged radioactive beams produced by target ion source (FEBIAD, surface ionisation ion source), can also produce gaseous stable beams in ECR source mode. However, the needs for industrial application require a cocktail beam including metallic one. That implies few modifications on Booster to be able to provide this cocktail with acceptable intensities.

Finally, the chosen cocktail beam must be optimised to deliver the highest energy reachable with the CIME cyclotron, and to ensure a reasonable switch time between each beam.

EXISTING SPIRAL1 FACILITY

The SPIRAL1 facility at GANIL (Caen, France) is a RIB factory using the ISOL method [1]. It has been providing post-accelerated RIBs to experimental areas since 2001. Over the last decade, SPIRAL1 has been upgraded to provide beams of condensable elements, by coupling one or several types of TISS emitting 1^+ ions [2] to a charge breeder, to boost the charge state of radioactive ions from 1^+ to n^+ for subsequent post-acceleration.

The charge breeder is a PHOENIX type ECR ion source developed at LPSC and tested at ISOLDE, that was then improved before being installed at SPIRAL1 [3, 4].

Standalone, the Booster device can also produce stable beams of gaseous elements.

A post acceleration of these beams, up to 20 MeV/u, is feasible using the CIME cyclotron [5].

SAGA PROJECT – CIME 0°

Irradiation Station Project

The cyclotron extraction line has to be redesigned to accommodate the SAGA's irradiation station (see Fig. 3).

To allow the use of the beam, from 2026 ideally, some arrangements are necessary for tunings and measurements:

- stripper and collimator to vary the flux and/or the energy,
- diagnostics to measure intensities, alignment, shape and homogeneity of the beam,
- wobbler or high gradient quadrupole to adjust irradiation surface.

The chamber, ending the line, would be equipped with a vacuum-atmospheric pressure window to allow irradiation in both modes: in a vacuum or controlled atmosphere. In consequence, a fast protection valve system has to be developed to ensure the protection of devices and cyclotron in the event of a breakage.

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STUDY OF NOBLE GAS MEMORY EFFECT OF ECR3 AT ATLAS*

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Abstract

Over the past three decades a portion of the accelerated beam time at the Argonne Tandem Linac Accelerator System (ATLAS) has been reserved for ultra-sensitive detection of argon radioisotopes. A unique noble-gas accelerator mass spectrometry (NOGAMS) technique at ATLAS combines electron cyclotron resonance ion source (ECRIS) positive ion production, acceleration up to ~6 MeV/u and detection methods for separating isobars and other m/q contaminants. The ECR3 ion source was recently chosen for such experiments due to the limited scope of material introduced into the plasma chamber, inferring a lower background production compared to ECR2. A recent ^{39,42}Ar NOGAMS experiment has highlighted a need to understand the beam production of material that is no longer being actively introduced into the ECRIS, known as memory effect. A quantitative study of source memory was performed to determine the decay characteristics of argon in the ECR3 ion source. Results of this study as well as details of setup and operation of ECR3 for NOGAMS experiments are presented.

INTRODUCTION

The ATLAS facility at Argonne National Laboratory has provided heavy ion beams for nuclear physics experiments for over 40 years. ATLAS runs experiments 24 hours a day, 7 days a week with a typical ion beam species change once per week and maintenance time dispersed throughout. The ultra-sensitive noble-gas accelerator mass spectrometry NOGAMS [1,2] technique has been developed and improved at ATLAS over the past 30 years. The technique differs from conventional accelerator mass spectrometry (AMS) which, based on negative ion injection, cannot analyze noble-gas ions. Positive ions are produced from an electron cyclotron resonance ion source (ECRIS) followed by mass/charge (m/q) selection with a dipole magnet, acceleration to ~6 MeV/u using linear accelerator sections and delivery to the gas-filled Enge split-pole spectrograph [3] for ion detection, as well as isobaric and background separation (see Fig. 1).

The first detection of low concentrations of ^{81}Kr and ^{39}Ar at ATLAS occurred in 1992 [4] using the now retired ECR1 [5]. In 2002, ECR2 [6] was used to provide ion beams for ^{39}Ar detection in ocean samples for the study of ocean circulation, allowing smaller sample sizes than those required for low level counting (LLC) [7]. ECR2 was used again in 2015-16 to provide ion beams of low concentration ^{37,39}Ar for a measurement of ^{36}Ar(n,γ)^{37}Ar and ^{38}Ar(n,γ)^{39}Ar neutron-capture cross sections [8]. ECR3 [9] was used for the most recent NOGAMS detection of ^{39,42}Ar in a study of neutron induced reactions at the National Ignition Facility (NIF) [1,10,11]. Parameters of ECR3 operation are discussed later. Table 1 provides a summary of a few of the ion source operating parameters of the mentioned NOGAMS experiments.

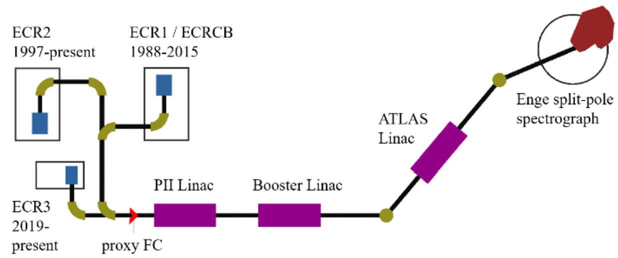

Figure 1: ATLAS accelerator NOGAMS layout.

Part of the recent ECR3 NOGAMS experiment was devoted to detection of ^{42}Ar in a NIF shot gas sample. Prior to running the NIF sample, a sample with a high concentration of ^{42}Ar [12] was used in ECR3 for identification and calibration with the detection system. Unexpected, but verified ^{42}Ar counts were observed with the NIF sample following the calibration run. Ion source memory of the calibration gas was suspected to produce those counts. A study of the ion source memory was performed, replicating the same ion source operating conditions. These results are provided within.

NOGAMS BEAM CONTAMINATION

Early NOGAMS experiments were predicated on a high sensitivity ^{39}Ar/Ar measurement, below naturally occurring Ar (8.1×10^{-16}), of multiple samples in ~ one week. A 100 eμA ^{40}Ar^{8+} beam, with a ^{39}Ar/^{40}Ar concentration of 1×10^{-17} at the ion source would yield 1 count/hr, assuming a typical 35% transmission from ECRIS Faraday cup (FC) to experimental station. At these low rates, m/q beam contaminants, such as the isobar ^{39}K, can limit the measurement due to pile up at the detector. The work done to reduce ^{39}Ar m/q contamination in ECR2, including quartz liners and cleaning methods, has been presented here [13]. In 2015, higher ^{39}Ar concentration samples ≥ 1×10^{-13} were to be measured. Therefore, a lower beam intensity at the ion source could achieve sufficient detection. ECR2 was run at low RF power (22 W) without support gas. With a weaker plasma and less electron interaction with the plasma chamber surfaces, this operation resulted in significantly lower contamination rates of ^{39}K^{8+}, without using any of the previous experiments mitigation methods (see Tables 1, 2).

Based on these results, ECR3 was chosen for the 2021 ^{39}Ar and ^{42}Ar series of experiments. ECR3, which was commissioned at ATLAS in 2019, has no history of solid

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DESIGN OF A NEW IRON PLUG FOR THE TRIUMF ECRIS CHARGE STATE BOOSTER CONFERENCES*

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Abstract

This paper presents a solution to address the issue of asymmetric dipole fields in the injection region of the TRIUMF electron cyclotron resonance ion source PHOENIX booster. The asymmetric fields arise from a wide gap in the injection soft iron plug of the booster, which allows the connection of the RF waveguide to the plasma chamber. Simulations and experimental measurements have revealed that singly charged ions, injected for charge breeding, experience deflection and get lost due to the asymmetric magnetic fields instead of being effectively captured by the plasma, thereby diminishing the efficiency of the charge state booster. To address this problem, an iron plug with an enlarged inner diameter, which allows the RF waveguide to connect to the plasma chamber, was designed. This redesign necessitated modifications to the injection electrodes and plasma chamber, including repositioning the waveguide and gas-inlet windows. By implementing these changes, the TRIUMF charge state booster is anticipated to achieve efficiency levels comparable to other PHOENIX boosters.

INTRODUCTION

The Electron Cyclotron Resonance Ion Source (ECRIS) has been used at TRIUMF's Isotope Separator and Accelerator (ISAC) facility since 2010 [1] to charge-breed exotic isotopes, particularly those with an atomic mass greater than 30. This is essential to match the mass-to-charge (A/Q) ratio of the linear accelerator (LINAC) before post-acceleration, enabling the use of these isotopes in nuclear physics and astrophysics research. The ECRIS is a highly efficient ion source that operates continuously and can produce highly charged ions at high intensities. It offers several advantages over the electron beam ion source (EBIS), including low-maintenance requirements and a prolonged operational lifespan. Systematic investigations conducted at TRIUMF [2, 3] have shown that the ECRIS charge state booster (CSB) performance can be significantly enhanced by optimizing and improving various components, such as the injection optics, injection system, RF power and frequency, magnetic field, plasma parameters, extraction system and optics. Research activities have commenced at TRIUMF to improve the performance of the CSB based on the results of these investigations. The superior two-frequency heating technique using a single waveguide was recently implemented, and the associated transport optics and the extraction system were optimized. The global efficiency of the booster for cesium charge states between 20^+ and 32^+, increased from 34 % under single-frequency heating operation to 41 % under two-frequency heating [2]. While this improvement is substantial compared to previous performance results, it's important to note that the efficiency still needs to improve compared to other PHOENIX boosters. For instance, the LPSC booster has reported a remarkable global efficiency of up to 92 % [4]. This comparison highlights the potential for further enhancements of the TRIUMF booster. Furthermore, during the systematic investigations, it was discovered that the wide gap created in the injection soft iron plug to connect the waveguide to the plasma chamber creates an asymmetry in the magnetic field in the plasma chamber that steers ions to the electrodes and chamber wall during injection, thus reducing the charge breeding efficiency. To address this problem, a new soft iron plug was designed. The redesign led to modifying the injection electrodes and plasma chamber and repositioning the waveguide and gas-inlet windows. The paper presents the results of designing a new soft iron plug, magnetic field simulation of the CSB, and RF modelling of the plasma chamber without plasma.

THE TRIUMF PHOENIX BOOSTER AND EFFECT OF A GAP IN THE INJECTION SOFT IRON PLUG

The TRIUMF ECRIS PHOENIX booster, initially developed by Pantechnik for single-frequency heating operation at 14.5 GHz, has recently been upgraded to support two-frequency heating using the existing single waveguide. Refer to [2, 3] for detailed information about the two-frequency heating setup. The single charge state efficiency of the CSB under the single-frequency heating operation has been measured up to 8.8 % for $^{133}Cs^{23+}$ and up to 9.1 % for $^{133}Cs^{26+}$ under the two-frequency heating operation [3]. The source utilizes three room-temperature solenoid coils and hexapole permanent magnets to generate axial and radial magnetic field distributions for plasma confinement. ARMCO™ soft iron plugs are installed in the injection and extraction regions to enhance the injection and extraction magnetic fields. However, a wide gap was created in the injection iron plug to allow the waveguide and water cooling lines to be connected to the plasma chamber. Figure 1 shows the injection iron plug as designed by Pantechnik. To investigate the effect of the wide gap, the geometry of the CSB was modelled in OPERA 3D [5], and the trajectories of an ion beam were calculated and visualized using the ray tracing package of the software. The simulations, which considered only the magnetic fields created by the three solenoids and hexapole of the ion source (excluding plasma space charge and electric fields from the injection system), revealed significant beam deflection. Figure 2 shows the trajectories of $^{133}Cs^{+}$ ion beam, initially travelling parallel to the beam axis. The

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ECR2 PERFORMANCE UPGRADES AT ATLAS

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Abstract

The user requests for higher beam energies and intensities have driven the decision to upgrade the ECR2 ion source at the Argonne Tandem Linac Accelerator System. Multiple upgrades are in progress with the expected outcome of dramatically increased ECR2 beam intensities and charge state capabilities. The magnetic upgrades include integrating an improved hexapole permanent magnet array that provides the ion source radial fields, reworking the magnetic materials surrounding the plasma chamber, and installing a new cooling system for the electromagnetic solenoids that govern the ion source axial fields. The new hexapole and higher solenoid magnet operating currents will increase the ion source magnetic fields and support the use of 18GHz RF heating, further increasing the ECR2 beam capabilities. Following these improvements and subsequent source performance, simulations of beam transport devices on the ion source platform will need to be revisited for transmission of high intensity beams. Details of these upgrade projects and simulations of the ion optics are presented.

INTRODUCTION

ECR2 at The Argonne Tandem Linac Accelerator System (ATLAS) was commissioned in 1997 [1] and has since delivered the majority of the delivered ion beams for the internationally supported user facility. The electron cyclotron resonance ion source (ECRIS) has a normal running condition that includes multiple frequency heating of nominally 12 GHz and 14 GHz at powers up to 1100W using frequency generators that feed into traveling tube wave amplifiers (TWTA). The ECR2 configuration includes two water cooled solenoids to produce the axial magnetic fields, an open hexapole permanent magnet assembly to provide the radial magnetic fields in the plasma chamber, and turbomolecular pumps to pump on the plasma chamber, both axially and radially through the open ports in the plasma chamber, made possible with an open hexapole design. Lastly, gaseous material can be easily introduced to the plasma chamber through the vacuum system or solid materials can be introduced radially through the hexapole ports with either an oven or sputter rod that is biased to release material from the probe.

Since 2015, ECR2 was the exclusive ECRIS at ATLAS until the commissioning of ECR3 [2], an entirely permanent magnet ECRIS. This ion source does not have the same level of flexibility that ECR2 leverages for a few reasons. The solenoid magnets are not adjustable, the hexapole is not upgradeable, the plasma chamber has a smaller volume, and there is not radial access to the plasma chamber for material introduction. However, the performance of the ion source is sufficient for many of the requested ion beams at ATLAS, especially the requests for species that can be introduced in gaseous form. For this reason, a two-source dynamic is utilized to allow for both ion sources to be properly maintained and consistently upgraded without jeopardizing the beam hours that the facility delivers annually.

The ATLAS facility continues to make improvements, including the capabilities of the superconducting linac and target stations. The beam requests for higher energies and intensities have followed suit. Although the ion sources have been able to keep up with the requests, there are an increasing number of requests that exceed the capabilities of even ECR2 in its current configuration. It is decided to upgrade ECR2 to produce these increasingly difficult beams. The plan is to support 18 GHz operation of ECR2 while keeping a room temperature design [3]. Other facilities' results from similar upgrades [4,5,6,7] would all achieve the intensities that are needed, further justifying that this path forward will meet our operational goals of doubling the intensities that we currently produce. The upgrade projects that are needed to support this goal were a redesign of the hexapole permanent magnet array and corresponding plasma chamber, an improvement of the magnetic materials surrounding the plasma chamber, a solenoid magnet cooling upgrade, and an improvement of the transport capabilities of the ion beam directly downstream of ECR2.

MAGNETIC UPGRADES

The first and most complicated technical upgrade needed is the hexapole magnet array. The same hexapole has been used in ECR2 since 2005 and produces a simulated B_{rad} of 0.98 T. For this reason, ECR2 typically runs at 14 GHz for peak performance but would not be able to run at 18 GHz. A hexapole upgrade that could produce a B_{rad} of 1.18 T would optimize performance at 14.5 GHz and support operation of an 18 GHz driving frequency. To satisfy the ECRIS scaling laws, the axial magnetic fields must also increase. The extraction iron was modified slightly, and the injection iron was upgraded to incorporate a vanadium permendur cap and a thinner boron nitride insulation disk behind the biased disk, bringing the iron closer to the plasma chamber. Figure 1 shows the upgraded axial magnetic field from these modifications with the solenoid magnets set at 500A each.

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PROGRESS IN 3D SELF-CONSISTENT FULL WAVE-PIC MODELLING OF SPACE RESOLVED ECR PLASMA PROPERTIES

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Abstract

We present updates of a simulation suite to model in-plasma ion-electron dynamics, including self-consistent electromagnetic (EM) wave propagation and population kinetics to study atomic processes in ECR plasmas. The EM absorption is modelled by a heuristic collisional term in the cold dielectric tensor. The tool calculates steady-state particle distributions via a full-wave Particle-In-Cell code and solves for collisional-radiative process giving atomic and charge state distributions (CSD). The scheme is general and applicable to many physics' cases of interest for the ECRIS community, including the build-up of the CSD and the plasma emitted X-ray and optical radiation. We present the code's last updates and future perspectives, using as a case-study the PANDORA scenario. We report about studying in-plasma dynamics of injected metallic species and radioisotopes ionisation efficiencies for different injection conditions and plasma parameters. The code is capable of reconstructing space-resolved plasma emissivity comparable to measurements and modelling plasma-induced modification of radioactivity.

INTRODUCTION

Electron cyclotron resonance ion sources (ECRIS) are widely used in accelerator facilities around the world to provide high current ion beams with charge states tuned according to experimental requirements. They operate on the dual concept of resonance heating with microwaves and magnetic confinement using a min-B profile that generates a compact and dense plasma composed of energetic electrons and multicharged ions. In a complementary way, ECR ion trap can be also serve as a facility resembling stellar plasma conditions, useful for performing interdisciplinary experiments interesting for nuclear physics, atomic physics and astrophysics [1]. While operational ECRIS are often designed using empirical scaling laws [2], the physics of plasma leading the ion generation process as well as the charged particles' dynamics in it is really intricate due to the multi-physics interactions between static and dynamic electromagnetic fields and particles. Simulations are a powerful tool to investigate the microscopic structure of ECR plasma and improve our fundamental understanding of these devices thereof. In the following, various aspects of space-resolved 3D full-wave Particle-In-Cell (PIC) model developed to study the ECR plasma properties and therein particle interactions are presented in detail. The description of the code will follow a schematic simulation pipeline: a first-level high-precision input given in terms of steady-state electrons distributions in the simulation domain; in cascade, a second-level input will be given by computing steady-state ion charge distribution in plasma imposed by the pre-simulated electron dynamics; finally, external neutral/charged particles interaction with the electron/ion distributions is studied aiming at reconstructing their in-plasma reactions.

PLASMA ELECTRONS DYNAMIC SIMULATIONS

The ground level of the 3D full-wave electron PIC code is a set of routines employing MATLAB© as a particle pusher and COMSOL Multiphysics© as a FEM solver to generate 3D profiles of electron density (n_e) and average energy (E_e) self-consistent with EM field distribution [3, 4]. The electrons simulation implies a looped scheme where initial macro-particles are first moved and energised by the EM field distribution of the microwaves injected into the vacuum chamber, generating a first density profile based on the dielectric tensor treatment in *cold* plasma approximation. Then, fields are recalculated based on the updated electron density, including long-range Coulomb collisions for catching both particles' deterministic frictions and random diffusion, till convergence between the particle and field profiles is reached. A flowchart representing the simulation scheme is shown in Fig. 1(a). The algorithm has been applied to various types of ECRIS configurations [5–8], and is an excellent tool to produce space- and energy-resolved distributions of n_e and E_e. Figure 1(b-c) shows a comparison of E_e obtained from the simulations of a 14.28 GHz, 200 W ECRIS operational at ATOMKI, Debrecen and of a 14.428 GHz, 100 W ECRIS operations at INFN-LNL, Legnaro, hereafter LEGIS. In both ECRIS distributions are strongly space-dependent, owing to differences in shape and size of the plasma chamber, microwave frequency and power. The data in these plots represent the source maps which form the basis of ion dynamics calculations. We have recently attempted to overcome the *cold* plasma approximation in the EM wave damping in plasma. Preliminary results of the developed 1D semi-analytical model of EM wave propagation including a *hot* tensor plasma response have been presented. The study allowed to investigate on the coupling of antenna-generated 60 MHz fast X-waves to realistic plasma fusion scenario within the Divertor Tokamak Test (DTT) project. Considering linearised Vlasov-Maxwell equations, stationary and

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SIMULATION OF SURFACE X-RAY EMISSION FROM THE ASTERICS ECR ION SOURCE

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Abstract

The bremsstrahlung x-ray emission induced by the impact of plasma electrons deconfined on the chamber wall of the ASTERICS ion source is investigated by a suite of two simulations. First, the electron velocity and density distribution of lost electrons is calculated by a dedicated Monte-Carlo code. The specificity of the electron velocity, energy and spatial distribution function on the walls is presented and discussed. Second, the electron information is used as an input for the Fluka Monte-Carlo code, used to investigate the surface induced bremsstrahlung x-ray emission. The electron distribution temperature at the wall is found to be anisotropic and increases with B_{min}. The electrons impinge the walls with large angles values with respect to the local normal surface, which has consequences on the emission direction of the x-ray. The x-ray dose is mapped inside and around the ion source for two cases: (i) for a low B_{min} magnetic confinement and an electron temperature set to 50 keV; and (ii) for a large B_{min} and an electron temperature artificially increased to 120 keV. The latter configuration gives a dose in the cave at 5 m from the source of ~100 µSv/h per kW of impacting electrons. A set of internal tungsten shielding placed inside the source have been modelled to investigate the dose attenuation inside the cave. This shielding is very effective and significantly reduces the need for external x-ray shielding to spatially limited solid angles located on the injection side of the ion source, facilitating the source maintenance and associated safety processes.

ASTERICS ION SOURCE

The ASTERICS ion source is currently under development as part of the new GANIL injector (NEWGAIN) project [1], aiming at designing and building a second injector for the SPIRAL2 linear accelerator, able to manage heavy ion beams up to a mass over charge ratio equal to 7. ASTERICS is a 28 GHz ECR ion source using a superconducting magnet system, composed of a cos 3θ hexapole coil and 3 axial solenoids to generate the minimum-B confinement magnetic field [2, 3]. A cutaway view of the (work in progress) ion source design is proposed in Fig. 1. The superconducting magnet system is very close to the VENUS-FRIB design, except for the plasma chamber dimension which is enlarged to 600 mm length and 91 mm radius, in order to enhance the achievable ion beam intensities during operation. The goal is to produce steadily 10 pµA beams of U^{34+} for nuclear physics experiments lasting several weeks.

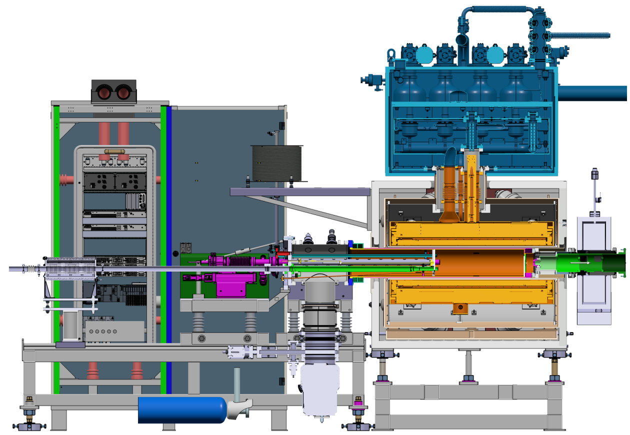

Figure 1: Cutaway view of the ASTERICS ion source design.

ELECTRON LOSSES TO THE WALL

An existing Monte-Carlo code was adapted to study the electron dynamics inside the ASTERICS ion source plasma chamber [4]. The 28 GHz radio-frequency (RF) electric field considered in the simulation is modelled with a transverse travelling plane wave with a circular polarization and a constant electric field intensity $E = 10$ kV/m (corresponding to 7 kW of injected RF power). Electrons are randomly generated inside the ECR volume with a random velocity direction in space. The initial electron energies are randomly sampled using a set of Gaussian distributions centered on each argon ionization potential energies IP with a standard deviation of 10 % × IP, with a relative abundance following a typical argon ion spectrum having a mean charge state number of 8. The electrons are tracked until they touch the 3 possible walls: injection at $z_{\text{inj}} \approx -0.3$ m, extraction at $z_{\text{ext}} \approx 0.3$ m and radial wall at $r_W = 0.091$ m. Two static electric fields are modelled in the Monte-Carlo simulation. One for the injection biased disk with a voltage of 100 V and a diameter of 20 mm. The second for the accelerating electric field of the ion source on the extraction, being 10 kV/cm, extending for 4 cm right after the extraction electrode hole of 10 mm diameter. The electrons are propagated up to 1 ms and are stopped above this time limit. Coulomb collision and electron impact are considered in the simulation to model at best the electron deconfinement. The plasma density considered is 15 % of the cut-off density at 28 GHz. A set of 1.25×10^6 electrons was simulated for each magnetic configuration.

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TIME-RESOLVED MEASUREMENT OF ION BEAM ENERGY SPREAD VARIATION DUE TO KINETIC PLASMA INSTABILITIES IN CW AND PULSED OPERATION OF AN ECRIS

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Abstract

The energy spread of ion beams extracted from Electron Cyclotron Resonance (ECR) ion sources is influenced by plasma conditions such as the plasma potential, and effects taking place in the beam formation region. Kinetic plasma instabilities have a significant impact on the plasma properties, and consequently on the ion beam energy spread. We present experimental results of time-resolved energy spread behaviour when kinetic plasma instabilities are present in CW and pulsed operation of the JYFL 14 GHz ECR ion source. It is shown that the instability-induced energy spread variation corresponds to a momentary plasma potential increase up to several kV from the steady-state value of 5–30 V. The method for measuring the time-resolved energy spread variation is presented, and the consequences of the energy spread and the underlying plasma potential variation for ECRIS operation are discussed.

INTRODUCTION

Energy spread is a relevant parameter when assessing the quality of ion beams produced with ECR ion sources, both for the beam transmission considerations and the eventual application the beam is used for. Recently, a comprehensive simulation and experimental study has been performed to determine the influence of different factors on the energy spread of ion beams extracted from ECR ion sources [1]. The study concludes that with stable plasma conditions the electrostatic focusing effects taking place during beam formation, i.e. extraction geometry and plasma beam boundary, are the dominant factors determining the beam energy spread, and exceed the contributions from magnetic field induced beam rotation, ion temperature and plasma potential.

ECR-plasmas are prone to kinetic instabilities driven by the anisotropy of the electron velocity distribution (see e.g. [2, 3]). The onset of the instability is characterised by a sudden expulsion of electrons from the plasma, resulting in a strong increase in net positive charge in the plasma volume as the heavier and less mobile ions are left behind. As a consequence, the plasma potential experiences a significant momentary (a few μs) increase, until the situation is balanced by the losses of positive ions, which restores the plasma quasi-neutrality. Because the potential has a spatial profile, this leads to a significant increase in the longitudinal energy spread of the extracted beam during the instability event.

The growth rate and broadly speaking the trigger point for the onset of the instabilities is determined by the ratio of the hot and cold electron densities in the plasma [4, 5]. As such, the instabilities can occur both in CW and pulsed operation of ECRIS. In CW operation the plasma heating and confinement leads to build-up of the hot electron population, until a threshold is reached resulting to the instability onset. In pulsed operation, following the switch-off of the plasma heating microwaves, the loss rates of the hot and cold electron populations are different as the plasma decays. The hot electrons are better confined by the magnetic trap compared to the more collisional cold electrons, hence the ratio of hot to cold electrons increases as the plasma decay progresses, eventually leading to the trigger point for the instability [6]. Several instability events can be observed during the plasma decay.

Previous studies [3, 7] have shown that the plasma potential can reach values in excess of 1 kV during a kinetic instability event, i.e. two orders of magnitude higher than the 5–30 V values typically measured in stable plasma conditions [1, 8, 9]. Consequently, in the presence of kinetic instabilities the plasma potential becomes the dominating contributor to the longitudinal energy spread of the extracted beam. As such, temporally resolved measurement of the energy spread allows determining the plasma potential during the instability. A proof-of-principle of this approach has been demonstrated for CW operation in Refs. [3, 7], where the magnetic spectrometer of an ECRIS was utilized as an ion energy analyzer. Here, this work is expanded to pulsed ECRIS operation, studying the properties of the kinetic instabilities during the plasma decay following the microwave switch-off where the instabilities are stronger than in the CW mode.

The following section describes the experimental setup to measure the variations in ion beam energy spread (and plasma potential) during the plasma instabilities. The experimental results section collates the main observations in CW operation from earlier measurement campaigns [3, 7],

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OPERATION WITH THE LAPECR3 ION SOURCE FOR CANCER THERAPY ACCELERATORS*

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Abstract

An all-permanent magnet electron cyclotron resonance ion source-LAPECR3 (Lanzhou All Permanent magnet Electron Cyclotron Resonance ion source No.3) had been developed as the C^{5+} ion beam injector of Heavy Ion Medical Machine (HIMM) accelerator facility since 2009 in China. The first HIMM demo facility was built in Wuwei city in 2015, which had been officially licensed to treat patients in early 2020. The facility has been proven to be very effective, and more than 1400 patients have been treated so far. In order to prevent ion source failure, each facility employs two identical LAPECR3 ion sources. At present, there are eight HIMM facilities are under construction or in operation, and more than 16 LAPECR3 ion sources were built. In order to improve the performance of the ion source for long term operation, some techniques were employed to optimize source performance and to avoid the damage of key equipment. This paper will introduce the operation status of LAPECR ion sources at these HIMM facilities and present the latest results of carbon beam production.

INTRODUCTION

Carbon ion radiotherapy, with its unique Bragg peak, good Relative Biological Effect (RBE) and higher Liner Energy Transfer (LET), is considered to be one of the best tumour treatment methods and has developed rapidly in recent 30 years. Since the heavy ion medical accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) was constructed as the first medical dedicated heavy ion accelerator in 1994[1], many countries began to developed their own medical accelerator as a high-tech medical instrument. Researchers at Institute of Modern Physics (IMP) in China started carbon irradiation research since 1996. The first medical carbon ion irradiation accelerator in China, which was named Heavy Ion Medical Machine (HIMM), was constructed in Wuwei city in 2015[2]. The schematic layout ot HIMM facility as showed in Fig. 1. Since the first HIMM facility was officially permitted to clinical treatment in March 2020, more than 1400 patients have received carbon ion radiotherapy.

So far, there are 8 HIMM facilities either in operation or under construction in China, and more than 16 LAPECR3 ion sources were built. These facilities are distributed in Wuwei, Lanzhou, Putian, Wuhan, Hangzhou, Nanjing, Changchun and Jinan separately.

Although the first demonstration facility in Wuwei city has achieved remarkable results in the past 7 years, there were some problems which affected the routine operation of the accelerator. For example, the carbon contamination leads the instability of the beam, short the lifetime of the ion source. In the early operation of HIMM facility, the performance of the ion source has degraded significantly after one mouth operation. The beam intensity and the beam stability were decreased. Besides, the insulator ceramics of the ion source could damage sometimes and the ion sources could not sustain any more. In order to solve the problems, continuous work had been carried out. This paper will illustrate the operation status of LAPECR ion sources in the HIMM facilities and present the latest results of carbon beam production.

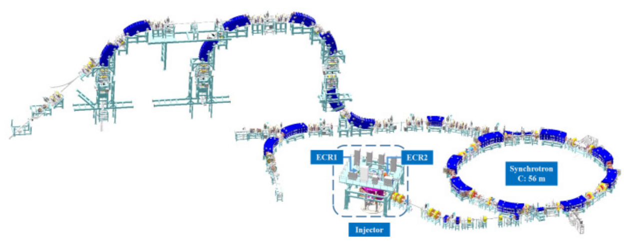

Figure 1: Schematic layout of HIMM facility.

LAPECR3

According to the requirements of ion source applications, the LAPECR series ion sources were developed successfully at IMP [3], including the LAPECR1 ion source for light ion application, the LAPECR2 for atomic physics research and the LAPECR3 ion source which was dedicate designed for carbon irradiation. Table 1 presents the key parameters of these ion sources. The LAPECR series ion sources were designed to operate at 14.5 GHz, and the magnetic field was generated from permanent magnet to lower the power consumption and easy to maintain. The LAPECR3 ion source features as compact size and high performance, the requirements of the ion source are to produce intense carbon beams with better beam emittance, such like more than 100 eμA of C^{5+} and more than 300 eμA of C^{4+}. So, an iron plug was adopted in injection side of the LAPECR3 ion source to enhance the injection field. To optimize the microwave coupling, a movable bias disc was designed with adjusting distance of ±5 mm. Moreover, a movable extraction puller electrode, which consists of a Mo head and a stainless-steel base, was employed to optimize the beam extraction. It is necessary to use a bigger ceramic to improve the gas flow conductance at the extraction region. Besides, the plasma chamber was made from stainless-steel with good water cooling，which allowed

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TESTS OF A LOW-ENERGY PEPPERPOT BASED ON A MICRO-CHANNEL PLATE FOR HIGH CURRENT PROTONS SOURCES 4D-EMITTANCE CHARACTERIZATION*

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Abstract

In the scope of high current protons sources characterization, the CEA is working on a 4D-emittancemeter based on the pepperpot technology. After some unsuccessful developments with phosphorous scintillators, we decided to test micro-channel plates (MCP) for measurements of proton beams at very low energy (typically between 50 and 100 keV). MCP are supposed to resist to proton beams at very low energy better than scintillators. This work presents some results for MCPs with an Advanced Light Ions Sources Extraction System (ALISES) on the Banc d'Etude et de Test de Sources d'Ions (BETSI).

INTRODUCTION

In recent years, there has been a growing interest in accelerator instrumentation, particularly emittancemeter. Beam characterization through emittance measurement is a key factor in improving the efficiency of beam transport systems.

Nowadays, most emittancemeters are 2D emittancemeters, measuring the [x-x′] or [y-y′] phase space. Although studies on 4D-emittancemeter (given in a single shot the six projections: x-x′, y-y′, x-y, x′-y′, x-y′, y-x′) have become increasingly numerous in recent years, one problem re-mains: projection resolution. The fundamental principle of the 4D-emittancemeter (pepperpot) is described as the re-construction of position and angular distribution of the beam as like the slit-scan method but in a single shot by applying a metallic mask which has equidistant pinholes with the same diameter [1].

In this way, the angular and position resolutions of the projections depends on the diameter of the holes, the distance between them, and the resolution of the imaging device. Thus, the resolution will in most cases be lower compared to e. g. a slit-grid-assembly [2].

To achieve better resolution, the Accelerator Research and Development Laboratory (LEDA) at CEA Saclay has rethought the principle of the 4D-emittancemeter by proposing a pepperpot that scans the beam as an Allison scanner emittancemeter. Measurement is no longer performed in a single shot, enabling more data to be acquired. The first 4D-emittancemeter was designed in 2016 for low-energy (some keV) and intermediate-energy (some MeV) beams [3].

Due to unsuccessful developments with phosphorous scintillators for characterization of ion sources, the specifications were reduced.

Today, the laboratory focuses its studies on a 4D-emittancemeter with a MCP. The diagnostic is designed to be tested on an ALISES source producing a 50 keV beam of 28 mA, on BETSI [4] since this source is easily available for the experiments. Results are presented in this paper.

PREVIOUS WORK

The first version of the emittancemeter built in 2016 was made of a pepperpot with an integrated cooling system, a scintillator and a synchronized CCD camera. The entire diagnostic is linked to a displacement system consisting of two stepper motors (along the x and y axes).

When the pepperpot was manufactured, the assembly welds failed to withstand hot isostatic pressing, resulting in deformation, loss of thermal conductivity and loss of flatness, making it difficult to drill the sampling holes. In addition, several scintillators were studied and tested [5] but no one satisfied the need for ion sources characterization because of the first atomic layers of the scintillators quick degradation. Even with MeV beams, the scintillators degradation was too quick for precise measurements.

Combining the pepperpot defects and the scintillator heterogeneous light signal degradation (due to certain areas more exposed to the beam), the results obtained for a beam on the Injecteur de Protons à Haute Intensité (IPHI) (3 MeV, 9 mA, 1 Hz, 1 ms pulse time) were not those ex-pected (see Fig, 1).

The data obtained could not be processed, and none of the six projections gave an accurate and precise emittance value [3]. At lower energy (around 60 keV), scintillators were destroyed after a single pulse.

UPDATED EMITTANCEMETER

The pepperpot was redesigned without the cooling system making the manufacturing easier. Thermal simulations were carried out using COMSOL software. An aluminium plate with the dimensions of the pepperpot was tested in front of the ALISES 3 source beam (1 Hz, 29 mA and 65 kV) [6]. Various operating cycles were tested in order to measure the maximal local temperature and to avoid dam-aging the pepperpot before measuring the emittance. For a 10 % duty

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RF AND MULTIPACTOR SIMULATIONS IN THE PLASMA CHAMBER OF THE SILHI PROTON SOURCE

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Abstract

In the scope of high current protons sources simulations, we tried to simulate the plasma chamber of the SILHI proton source with HFSS. This work focuses on the RF and multipactor simulation close to the boron nitride window.

INTRODUCTION

The CEA Saclay develops and produces ECR sources for various projects. In particular, several sources have been developed for high-intensity proton and/or deuteron beams, as the SILHI and ALISES sources. Currents typically vary between 5 mA (Spiral 2) to 125 mA (IPHI, IFMIF), and several test benches have been assembled, BETSI and PACIFICS, to analyse these sources [1].

ECR sources, in general, require the production of electrons, which, by interacting with the molecules and ions of the gas, produce the ions beam. Part of these electrons are produced by a dielectric window, (here made of boron nitride), possessing very high primary and secondary electron emission coefficients [2].

Electron production is certainly mainly due to secondary emission. Among the different processes that generate secondary emission, the multipactor, under certain conditions, can be one of them. It has been widely described for example on the ceramic windows of high-power RF couplers [3]. The objective for RF couplers is in principle to minimize this phenomenon. Here, we try to show that the multipactor can affect the production of electrons at the ceramic level of an ECR source.

For this, we have simulated the RF field on the boron nitride, in order to describe the field at the dielectric level. Then, we tried, based on some analytical calculations, to estimate the best conditions to get (or to do not get) multipactor.

ABOUT MULTIPACTOR

The multipactor is a potential source of secondary electrons in ECR sources, and Boron Nitride (BN) has a high secondary emission coefficient [2]. So, the primary electrons produced by the BN ceramic can themselves produce new electrons, if their trajectory brings them back on the ceramic.

The primary and secondary electrons follow a trajectory defined by the RF electromagnetic field at 2.45 GHz, at the time of their appearance (or their initial phase), as well as by the external magnetic field. If the kinetic energy of the primary electron acquired thanks to the RF field is sufficient, secondary electrons can be produced.

The ionization energy (or gap energy) of 5.8 eV for H-BN (Hexagonal) [4] gives an estimate of the minimum energy to produce secondary electrons.

Moreover, if an electron comes back after an whole number of RF periods, the secondary electron starts with the same phase, and thus, follows the same trajectory, and the phenomenon continues indefinitely. The number of electrons increases exponentially until reaching saturation, which depends on the available electrons, the available RF power, and the space charge generated. This phenomenon was known as multipactor.

To test our hypothesis, we modeled the distribution of electromagnetic fields in the cavity with HFSS software and identified potential areas producing multipactor. An analysis of the electron trajectory near the window is proposed.

HFSS SIMULATION

These simulations were realised with the HFSS software. We reproduced the cavity of the plasma chamber of the SILHI source, measuring 45 mm in radius and 100 mm in length, and the boron nitride plate with a thickness of 2 mm. The coupler of SILHI was simulated with its three ridges.

The waveguide was modelled by a 550 mm long line. The ATU (Automatic Tunning Unit) was modelled by a single piston that modifies the coupling of the ECR cavity.

We have calculated the electric field on the BN for several position of piston. For each position of the piston, we have modified its penetration to adapt the cavity by minimizing the reflected power. The frequency remained close to 2.45 GHz ± 100 MHz.

To realize the simulation, we defined a port in TE10 mode at the extremity of the waveguide. In a perfect cylinder in the TE mode theory, the electric field is only axial. Here, due to the coupler, the electric field on the longitudinal axis is not zero on the boron nitride window.

The simulation was made for different distances between the piston and the RF cavity, to observe how the piston position affects the RF field on the window. All field patterns are presented at the resonance frequency of the ensemble, which always remains close to 2.45 GHz.

Figures 1 and 2 show that the electric field at the center of the window is very intense (281 kV/m) at 335 mm, but becomes less intense (11.4 kV/m) when the piston position was at 410 mm, for an injected power of 50 W at the extremity of the waveguide. It seems reasonable to imagine that the multipactor acts differently in both cases.

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WIEN FILTER UPGRADE AND MEASUREMENT FOR BETSI TEST BENCH*

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Abstract

During first operation of SILHI in 1995 at CEA Saclay, a velocity filter diagnostic (Wien Filter) was installed on the LEBT (Low Energy Beam Transport), analysing the 100 mA of protons at 95 keV. The device was used many years providing beam proportion measurements on the beam axis. Unfortunately, it was damaged while handling and was no longer working as intended. This paper describes the maintenance and upgrade of the diagnostic as well as the first beam proportion figures with ALISES v2 ion source.

INTRODUCTION

A velocity filter or also called a Wien Filter combines a constant dipole with a varying electric field, perpendicular to the magnetic forces. When a sample of the beam enters the dipole, the particles are naturally deviated thanks to the magnetic field. By applying an electrostatic force, these particles are brought back on the beam axis and can be collected on an isolated wire. Depending on the mass of the species, there is a specific value of bias to counter act the dipole effect. For the same energy, the lighter the particle, the stronger the electric field is required. So with the Wien Filter it is possible to estimate the proton fraction of the beam of an ion source. This value is an important value for ion source characterization. The second question that was never discussed before: does this proton fraction uniform all over the transverse plane?

This Wien Filter was developed in the 90s for SILHI ion source [1, 2], to analyse the proportion of H^+, $H_2{}^+$ and $H_3{}^+$ as well as measuring the total beam intensity. It was later installed on BETSI test bench [3] to characterize the new sources developed at Saclay, especially the ALISES ion source family [4, 5]. However, the clearance between the diagnostic and the vacuum chamber is very tight and it got stuck during the removal of the Wien Filter from BETSI test bench, damaging the actuator and the measurement system.

DESCRIPTION

This Wien Filter (see Fig.1) is composed of a water cooled beam-stopper (A) that can handle 10 kW beam power. It is equipped with a removable tantalum diaphragm (B) drilled with a ø 250 µm diameter hole and 0.2 mm in length to let a very small part of the beam through.

Right behind this diaphragm, the measurement unit is composed of a Permanent Magnet structure (C), two electrodes (D), a charge collecting wire (E) and a negative polarized electron repeller (F). All these elements are enclosed in a box constructed of 4 mm thick ARMCO plates (G) bolted together to create a magnetic shield. The side panels of this box are hollowed with an array of holes to allow the pumping of the inside.

The (C) dipole is formed by six permanent magnets, distributed equally over and under the beam, originally designed to create a 0.19 T magnetic field on the beam axis. During the reassembly of the measurement unit, it was measured at 0.183 T with a Hall probe, which remains acceptable to separate Proton from molecular $H_2{}^+$ and $H_3{}^+$ at 95 keV energy.

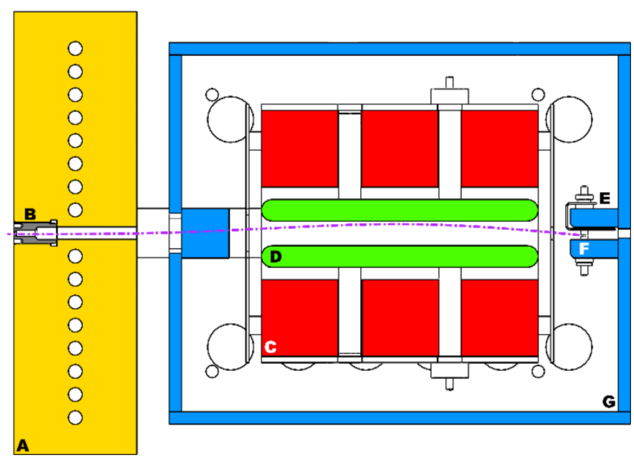

Figure 1: SILHI Wien Filter cross section.

The two stainless steel electrodes (D) are placed inside the magnetic system with the following dimensions, 90 mm along the beam axis, 36 mm in width, 7 mm thick and spaced 8 mm apart. Both of them are connected to SHV 10 kV feedthrough with Kapton insulated wire.

Coming after the deviation structure, an isolated ø 0.25 mm Tungsten wire (E) collects the particles, measuring their intensity. A thin stainless steel (F) sheet connected to another SHV feedthrough sits over the Tungsten wire to act as an electron repeller electrode.

In order to measure the beam intensity on the beam stopper (A), it must be isolated from the measurement unit and the actuator. Moreover, the measuring unit has to be mechanically mounted on the beam-stopper to ensure a good alignment of the sampling pinhole (B) and the collecting wire (E). The size of the measuring unit (see Fig. 2) left very little space to design a stiff assembly. Therefore, the mechanical attachment of the iron box to the shield was not sturdy

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MODIFICATION OF THE FLEXIBLE PLASMA TRAP FOR HIGH-INTENSITY METAL ION BEAMS PRODUCTION

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Abstract

NQSTI (National Quantum Science and Technology Institute) is the enlarged partnership on QST established under the National Recovery and Resilience Plan (NRRP) funded by the European Union – NextGenerationEU. In this framework, there is a growing interest in the availability of mA beams of singly charged (1+) metallic ions to realise quantum devices. To satisfy this request, the joint INFN Laboratories LNS and LNL proposed to modify the Flexible Plasma Trap (FPT), installed at LNS, thus transforming it into a simple mirror Electron Cyclotron Resonance Ion Source (ECRIS). This contribution describes the various technical solutions that will be adopted, foreseeing novel radial RF and gas/metal injection systems, focusing particularly on the design and simulations of a flexible extraction system capable of handling different beam intensities and ion species. Specifically, the project targets the production of high-intensity beams of singly charged ions such as Fe^{+}' and Ba^{+}, highlighting the versatility and innovation of the proposed modifications.

INTRODUCTION

Within the NextGeneration EU project NQSTI (National Quantum Science and Technology Institute), the scope of the Task 3.1 of Spoke 3 is to develop novel atomic/molecular systems to extend coherence time in quantum system. In fact, there is an active field of research in the quantum technologies concerning the measure of the permanent electric dipole moment of specific molecules' electrons in a solid matrix, looking for evidence of CP violation [1]. This atomic-embedding in low-temperature solid matrix conventionally resorts to glow discharge chamber and electrostatic elements to select and transport ions to be embedded [2]. The two INFN Laboratories LNL and LNS have studied novel techniques to produce isotopically enriched metallic ion beams (iron, barium), with intensities in the mA range end energies of tens of keV. This will be accomplished by proper modifications of the Flexible Plasma Trap (FPT) [3], installed at LNS and used to date for fundamental studies of magnetically confined plasmas, thus turning it into a simple mirror Electron Cyclotron Resonance Ion Source (ECRIS) [4]. This contribution describes the innovative technical solutions adopted, with greater emphasis to the design of the extraction system through numerical simulations. Finally, preliminary results of the beam optics studies will be also reported.

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UPGRADES OF THE FLEXIBLE PLASMA TRAP

The Flexible Plasma Trap (FPT) is an ECR plasma-based facility present at the INFN-LNS to trap ionised particles in plasma and perform in-plasma interdisciplinary measurements. The FPT magnetic field is provided by means of three solenoids, which allow the tuning of the field profile. The plasma can be generated in both simple mirror and quasi-B-flat configuration, adequately tuning the coils currents. The RF power up to 500 W is injected through a WRD 350 waveguide entering radially the trap [5], at frequencies from 3 to 7 GHz, leaving the longitudinal axis to the access of plasma diagnostics. As being a trap, ions' extractions have never been attempted and thus no extraction system has been developed so far. The modifications to the Flexible Plasma Trap (FPT) have been focused on implementing innovative metal/radiofrequency injection and beam extraction systems, which are crucial for upgrading FPT to an ion source and optimizing the production of singly charged metallic ion beams. With reference to Fig. 1, the key upgrades include the following listed below.

Radial RF and Gas/Metal Injection

The FPT will be equipped with a radial injection of radiofrequency (RF) through a WRD 475, working at 5-7 GHz, and a radial gas/metal injection system. This will improve the power coupling to the plasma, as well as the efficiency of metals ionisation, thus increasing the intensity of the extracted beam.

Advanced Diagnostic Systems

Plasma and extraction conditions will be monitored through a Langmuir probe and an optical emission spectroscopy (OES) quartz window. These diagnostic tools will allow for precise assessment of plasma parameters, thus facilitating the optimization of the source.

Flexible Extraction System

A three-electrode (accel-decel) extraction system has been designed to produce beams with suitable quality for isotopic selection. We conceived a flexible design that enables the extraction gap to be adjusted without breaking the vacuum, adapting the system to the specific requirements of the produced beam (a more detailed description will be given in the next section).

DESIGN OF THE EXTRACTION SYSTEM

The requirements to fulfil the goal of task 3.1, Spoke 3 of the NQSTI project concern the production of a currents

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PLANNED OPTIMIZATION OF THE ION SOURCES ON THE HIT TEST BENCH

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Abstract

The Heidelberg Ion Beam Therapy Center (HIT) is a hospital-based treatment facility in Germany. Since the first treatments in 2009, more than 8,500 patients have been irradiated with protons or carbon ions and since July 2021 with helium ions. At HIT, three supernanogan ion sources from Pantechnik are in operation 24/7 for therapy up to 335 days a year. A fourth supernanogan ECR ion source is installed at the HIT test bench. The test bench is currently being prepared for a measurement campaign that will start in October. The aim of the investigations is to obtain more beam current for the carbon ions used in the therapy by feeding two microwave frequencies in parallel. We expect this experiment to lead to a better understanding of the ionization process in the ion source. In the first step, we will feed 14.5 GHz and an additional frequency close to the resonance frequency of 14.5 GHz ± 0.5 GHz and in the second step 14.5 GHz and 18 GHz are injected.

To characterize and evaluate the beam quality in this setup, we use the Pepperpot as a 4D emittance meter. In addition, it is possible to measure the beam current and the beam profile on the test bench.

INTRODUCTION

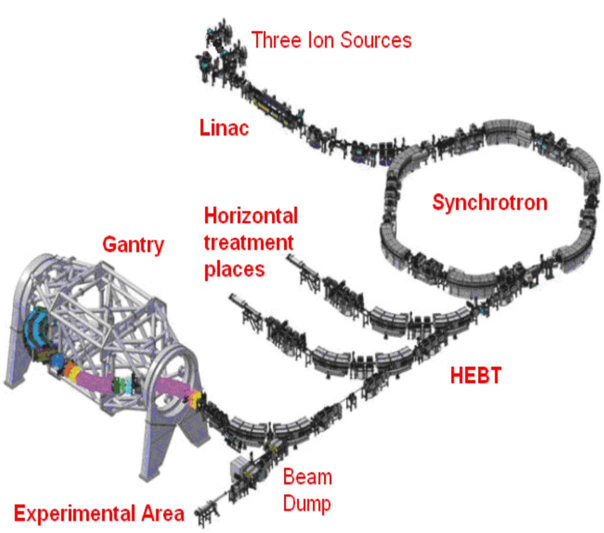

Figure 1: Overview of the HIT facility.

The beam production at HIT (see Figure 1) consists of three ECR Supernanogan ion sources [1] for the routine operation of proton, carbon and helium beams at 8 keV/u.

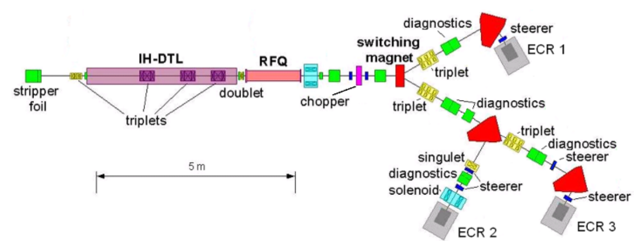

Figure 2: Low energy beam line (LEBT) and the linear accelerator (LINAC).

The compact 217 MHz linear accelerator (LINAC) consists of a radio frequency quadrupole accelerator (RFQ) and an IH-type drift tube linac (IH-DTL) with the end energy of 7 MeV/u for all ions; a foil stripper directly located behind these cavities produces fully stripped ions (see Figure 2). A synchrotron of 65 m circumference accelerates protons, helium, carbon and oxygen to predefined end energies e.g. for carbon ions from 89 to 430 MeV/u in 255 steps.

In order to minimize the already very short downtimes at the ion source (Figure 3), we started testing the 14.5 GHz solid-state amplifier (R&S PKU100) some years ago [2]. Until then, only tube amplifiers were used in clinical operations at HIT. After testing and checking the beam quality, the tube amplifiers were gradually replaced by solid-state amplifiers.

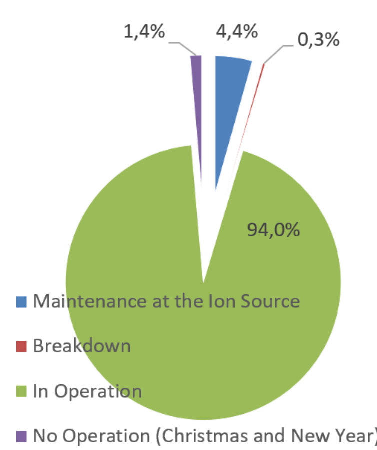

Figure 3: Statistics of the three ion sources in 2023.

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CHARACTERIZATION OF AN PROTON ECR ION SOURCE FOR LOW BEAM CURRENT*

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Abstract

In this paper we analyze the behavior of a low beam current proton ECR ion source for linac. During the operation of the source, as a function of the operating parameters we have observed a complex behavior. The state of the plasma is highly dependent on the input parameters, and in some cases even bi-stable conditions can be achieved showing abrupt changes in the state. To try to understand this behavior we carried out a series of experiments varying the input parameters both sequentially and randomly to avoid following the same path every time. Thanks to these experiments we have been able to observe the change in the luminosity of the plasma, which is an indirect measure of the degree of ionization in the plasma, along with the changes in reflected and transmitted RF power delivered to the source. We also characterized the relation between the outer temperature of the ion source chamber walls and the plasma. In addition to this we have analyzed the resulting extracted ion beam using a pepperpot and a faraday cup. We have observed that our beam does not have one dominant species and has three species that are found in comparable quantities.

INTRODUCTION

The LINAC 7 project is a research project that aims to create a compact low intensity proton accelerator with an energy of 7 MeV. As detailed in Ref. [1], while some accelerator stages are still in design, this work focuses on characterizing the Ion Source where positively charged particles are generated, the beam extraction to create the particle beam, and the Low Energy Beam Transport (LEBT) stage, which focuses the beam to go onto the next accelerating stage. A good understanding and control of the first stages of a LINAC is essential, because this is where many of the most important properties of the beam are determined. Among them, the most important are the current of the beam, which mostly depends on the performance of the Ion Source and the beam extraction [2], and the emittance of the beam, which once the beam is generated keeps constant through all the path of the accelerator [3].

To better understand the Ion Source and the extracted beam, various experiments have been conducted, exciting different behaviors in the plasma and beam and measuring relevant parameters. By analyzing the results of the experiments, it is possible to better understand the behavior of the first stages of the LINAC 7 accelerator.

Between the instruments used to manage and measure the parameters of the accelerator, many are of common use, like gas flow control, pressure measurement, a pepperpot and a Faraday cup to measure the characteristics of the beam, and luminosity measurements to determine the ignition degree of the plasma on the Ion Source. In addition to those, there is a specialized instrument developed for the LINAC 7 project that allows to measure the amplitude and phase of the incident and reflected RF signals used to excite the Ion Source, allowing calculation of the reflection coefficient, which varies with plasma state [4].

Some of those experiments deal with the effects of the temperature on the inner walls of the Ion Source, which increases during its operation, affecting the plasma [5]. The rest of the experiments are about better understanding different states on the plasma, which are believed to be linked with the chemical reactions on the ionized plasma, where different states belong to different predominant chemical species generated inside [6]. By better understanding this phenomena, it is intended to prioritize a state on the plasma where H^+ is the main generated element, and to maximize the amount of generated H^+.

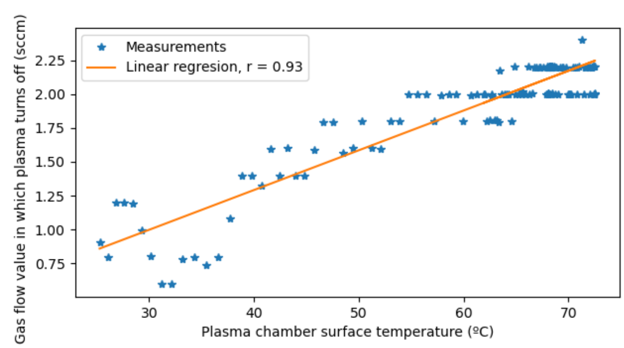

Figure 1: The relation between the temperature on the surface of the Ion Source, and the value of gas flow in which the plasma turns off.

PLASMA EXTINCTION AND TEMPERATURE RELATION

Since during the operation of the ion source a considerable amount of energy is used to generate the plasma, the temperature of the resonant cavity increases over time. This

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OPTICAL DIAGNOSTIC STUDIES TO ANALYSE ELECTRON CYCLOTRON RESONANCE PLASMA PRODUCED IN THE GTS-LHC ION SOURCE

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T. Kövener

Abstract

The GTS-LHC electron cyclotron resonance (ECR) ion source is an integral part of the chain of accelerators at CERN. It produces the heavy ion beams which are accelerated using a series of accelerators from LINAC up to the LHC. The ion beams are extracted from an ECR plasma generated at the GTS-LHC ion source, however, there has not yet been a non-invasive diagnostic device to study the plasma. This research focuses on the implementation of an optical diagnostics and studies the optical emission spectra (OES) as a monitor of the performance of the ion source. Furthermore, we explore the correlation between spectral properties and changing source parameters, offering insights into the behaviour of the ion source, which in turn helps in fine-tuning of the source. Specifically, the study concentrates on long-term OES analysis spanning several weeks, focusing on the production of magnesium and lead ions using the GTS-LHC ion source.

INTRODUCTION

The production of ion beams at CERN is crucial for a wide range of research activities, particularly in the field of heavy-ion physics, where specific ion species are required for diverse experimental needs. The GTS-LHC 14.5 GHz Electron Cyclotron Resonance (ECR) ion source [1], located at the start of the Linac3 accelerator, is essential to this process. It has been predominantly used for producing lead ions, which are vital for many of CERN's high-energy physics experiments.

A new working group was formed recently "Future Ions in the CERN Accelerator Complex" to define future ion operations based on requests from LHC and other fixed target experiments at North Area (NA) of CERN. One light ion selected is magnesium. Mg Highly Charged Ions (HCIs) can be produced by the GTS-LHC ion source, the magnesium atoms are introduced into the source by a micro-oven, which evaporates the metal samples by controlling the oven power based on the required vapour pressure. Helium is injected as a buffer gas to enhance magnesium ion production.

The study of new ions at CERN is limited because there is only one ECR ion source, which is used for both current experiments and developing new ion beams. Due to the complex accelerator setup and long experimental periods (up to six months), only two types of ions can typically be studied each year. These long periods require the ion source to remain stable for extended times, which is an additional challenge for metal ion beams made with oven-based evaporation. Maintaining stability over time is often harder than achieving high beam intensity.

To address these challenges, recent research has focused on optimising the ion source's performance using Optical Emission Spectroscopy (OES). OES is a non-invasive diagnostic tool that allows for the analysis of plasma by examining the emitted light, providing insights into parameters like electron density, electron temperature (T_e), ion temperature (T_i), and the densities of both neutral atoms and ions [2, 3]. These parameters are crucial for fine-tuning the ion source to ensure efficient and stable ion beam production.

The installation of a new OES setup has further enhanced the diagnostic capabilities of the ECR ion source, enabling continuous monitoring of the plasma. This study is focused on finding a correlation between the optical emissions with ion source parameters and thereby helping to optimise the production of HCIs.

EXPERIMENTAL SETUP AND PROCEDURE

The experiment is performed on the 14.5 GHz GTS-LHC ECR ion source at CERN. The HCIs are generated based on stepwise ionisation of neutral atoms. The neutral atoms are primarily introduced to the source by means of evaporation using a micro oven [4]. The resultant ions are extracted via a suitable extraction system [5] and is directed through a dipole magnet, which is employed to isolate and select the specific charge state of interest, a Faraday cup for direct measurement of beam current by blocking the ion beam, and a beam current transformer (BCT), which enables non-invasive beam current measurements. Subsequently, the ions are accelerated through a series of accelerators.

The experimental setup includes an optical spectrometer system designed to observe the optical emissions from the plasma through the port on the first dipole magnet as shown in Fig. 1. A concave mirror is placed at this point which collects and focuses the light onto the entrance of an optical fiber. The other end of the optical fiber is connected to the optical spectrometer (Ocean Optics USB4000 Spectrometer). A vacuum valve is positioned between the concave mirror and the dipole magnet, providing the flexibility to change or adjust the optical components without needing to vent the entire low-energy beamline thereby maintaining the vacuum. This valve also serves as an external shutter for measuring the background spectrum.

The experiments were performed by simultaneously collecting optical spectra and monitoring the total beam current using the BCT. An OES measured during magnesium pro-

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EFFICIENT INJECTION OF HIGH-INTENSITY LIGHT IONS FROM AN ECR ION SOURCE INTO AN RFQ ACCELERATOR

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Abstract

This study investigates an efficient injection of high-intensity light ions from an Electron Cyclotron Resonance (ECR) ion source into a Radio Frequency Quadrupole (RFQ) accelerator. An often-adopted solution for the beam matching between an ion source and an RFQ is to apply two solenoids as a Low Energy Beam Transport (LEBT) section. There are also other solutions which skip the LEBT section and inject the ion-source output beam directly into an RFQ e.g. the so-called Direct Plasma Injection Scheme (DPIS). For this study, a compact electrostatic LEBT using an einzel lens as well as an efficient RFQ based on a special design method have been developed to achieve high transmission of a 60 mA proton beam. Additionally, the RFQ design has been also checked with the LEBT removed. The design and simulation results will be presented.

INTRODUCTION

Usually a particle beam extracted from an Ion Source (IS) is defocused in both transverse (x and y) planes. At the entrance to an RFQ accelerator, however, an input beam focused in both x and y planes are desired. To transport a particle beam from an IS to an RFQ accelerator, there are different approaches:

- Using a magnetic LEBT (M-LEBT) typically consisting of two solenoids, e.g. [1].
- Using an electrostatic LEBT (E-LEBT) with one or two einzel lenses, e.g. [2].
- Using a zero-length LEBT (Z-LEBT) i.e. direct injection, e.g. [3].

An M-LEBT often needs more space than an E-LEBT and a Z-LEBT solution usually causes high beam losses at the injection due to lake of beam matching, this study focuses on the R&D of a compact einzel lens for an efficient injection of a 50 keV, 60 mA proton beam into an RFQ.

EINZEL-LENS DESIGN

For the design of the aimed einzel lens, a particle distribution with 10000 macro particles (see the left graphs of Fig. 1) generated at the extractor exit of an ECR-IS was taken as the input beam. This generated 50 keV, DC input beam has a transverse size of ~5 mm in diameter and it is defocused in both transverse planes. The task of the aimed einzel lens is to convert the particle beam to be focused in both transverse planes, whereby the beam energy should be kept almost unchanged and the transverse beam size should not increase too much.

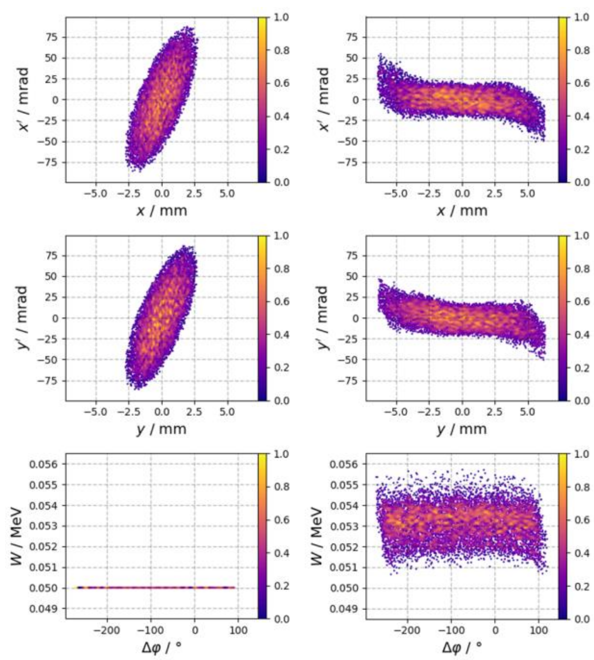

Figure 1: Particle distributions at the extractor exit of the ECR-IS (left) and at the RFQ entrance (right, obtained from the beam dynamic simulation using TraceWin [4]).

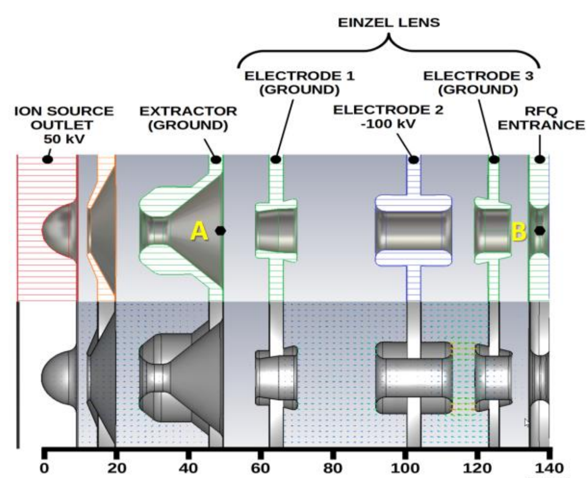

Figure 2: Schematic layout of the designed einzel lens, where Points A and B represent the start and end positions of the beam transport simulation through the einzel lens, respectively (the electrostatic field calculated using the CST Studio Suite [5] is shown in the bottom graph).

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TRANSPORT OF INTENSE BISMUTH AND URANIUM BEAMS INTO A RADIO FREQUENCY QUADRUPOLE ACCELERATOR

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Abstract

A 48.5 MHz RFQ has been designed to transport and accelerate $^{238}U^{40+}$ (0.52 emA) and $^{209}Bi^{30+}$ (1.047 emA) beams extracted from a high performance ECR ion source. The RFQ design comprises of a pre-buncher built into the vanes to narrow the transmitted charge state distribution as much as possible. The design parameters as a function of cell length is optimised on $^{209}Bi^{30+}$. It is shown that the losses of various ions without using an inlet aperture are inevitable, but by proper coating of the vanes of the RFQ, sputtering can be minimised to a great extent. Titanium shows better results when compared with gold or copper and this has been verified using the modelling results from SRIM. The design details of matching the ECR and the RFQ and the predicted performance will be presented.

INTRODUCTION

Recent emphasis at many heavy ion accelerator facilities has been to develop, extract and transport intense beams of highly-charged, heavy ions from ECR ion sources. Assuming that these highly charged ion beams can be extracted with high intensities, the next technical challenge is to determine how to transport them without large losses of the desired ion species. All recent high performance, third generation, superconducting Electron Cyclotron Resonance (ECR) ion sources, such as the VENUS (LBNL) [1], SECRAL (IMP) [2], SUSI (MSU) [3], and the SCECRIS (RIKEN) [4], operate at higher frequencies than older sources and hence have higher plasma densities and magnetic fields. A design study of a 56 GHz source by the ECR ion source group at Berkeley shows that the source can have even higher plasma densities, since the density scales as the square root of the operating frequency [5]. A new type of ECR source has been proposed by D.Z. Xie [6] for operation at 50 GHz. Further, an upcoming new ion source, FECRAL [7], being built by the ECR group at Lanzhou, is designed to be operated at 45 GHz. The enhancement in the beam intensity for $^{209}Bi^{30+}$ at 45 GHz is expected to be greater than 1 emA at an extraction voltage of 50 kV. Considering the frequency scaling for the VENUS ion source from 28 GHz to 56 GHz with an increased volume of the plasma chamber of a factor of 10, the heavy ion beam of $^{238}U^{40+}$ produced earlier by the VENUS source [1] at an intensity of 13 eμA can be extracted with an intensity of possibly as much as 0.52 emA at the higher 56 GHz operating frequency. The extraction of these intense highly charged heavy ion beams, however, poses several problems. Generally, conventional accelerating–decelerating systems coupled to these ECR ion sources have shown inherent problems extracting intense beams of highly-charged ions due to sparking at the high voltages required and the poor vacuum conditions, which in turn limit the extraction currents. Therefore, this type of extraction system generally fails due to problems with the high voltage power supplies. This eventually keeps the ion source from functioning smoothly and increases the downtime of the accelerator.

In the applications of laser ion sources, with their much higher plasma densities, severe problems of handling intense beams due to sparking and/or beam loading are avoided by using an ingenious technique, the so-called Direct Plasma Injection Scheme (DPIS) [8]. This technique was utilized for injecting intense beams directly into an RFQ using the combined focusing of the gap between the ion source and RFQ vanes (or rods) and the focusing of the RF fields from the RFQ penetrating into this gap. In this scheme, the plasma expands to the entrance of the RFQ where the electrons are deflected by the RFQ's fringe field and only the ions get trapped by the RFQ focusing field. Hence, space charge effects are efficiently controlled, with the great advantage being the ability to transport very intense highly-charged beams. This technique was experimentally demonstrated for the acceleration of carbon (C^{3+}, C^{4+}, C^{5+}) and aluminum (Al^{9+}) ions with beam intensities greater than 60 mA [9].

In the case of the next generation ECR ion sources, the development of higher operating frequencies in superconducting ECR ion sources will result in higher plasma densities. Therefore, much higher beam intensities will not only be possible by using extraction voltages higher than the 30 kV in use today in most ECR sources, but also by changing the extraction electrode aspect ratio. Operating at these higher extraction voltages would result in operating the conventional accelerating–decelerating extraction systems at relatively higher voltages, thus increasing the probability of sparking. In order to circumvent this problem in conventional ECR ion source extraction systems, a proposed solution is to couple an RFQ directly to a high performance ECR ion source using the DPI scheme. For high performance ECR sources that use superconducting solenoids, the stray magnetic field of the source can also be used in the DPI scheme to provide more focusing in order to overcome the space charge blow-up of the beam [10].

After the correct matching is accomplished between the ion source and the RFQ, the next task is to design the RFQ to select the ion of interest for further beam transport and to

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3D SIMULATIONS OF THE CAPRICE ECRIS EXTRACTION SYSTEM

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Abstract

The simulation of the ion extraction from the Electron Cyclotron Resonance Ion Sources (ECRISs) is necessary for the optimization and development of the performance of ion sources. Due to the magnetic field configuration of the ECRISs the calculations need to be performed in 3D. For this reason simulations based on the C++ library “Ion Beam Simulator” (IBSimu) were developed. In this work, a physical model was implemented in IBSimu for performing detailed 3D simulations of ion extraction from a CAPRICE-type ECRIS. Simulations of multi-species Argon ion beam including Helium contribution as support gas extracted from CAPRICE are carried out. Simulation results are presented and compared to experimental findings, in particular for ion beam intensities and beam profiles measured with viewing screens.

INTRODUCTION

Understanding and optimizing the performance of the ECR ion sources, particularly in terms of beam formation and transport, is crucial for their application in scientific research and industrial processes. In this work, a study of the CAPRICE ECRIS focusing on the comparison between experimental beam profile measurements and a novel three-dimensional simulation is presented. The use of a 3D simulation model provides a more comprehensive analysis of the ion source behavior compared to a two-dimensional approach and allows for a more accurate prediction of the ion extraction from an ECRIS source. The simulation results obtained using IBSimu [1], a versatile ion beam simulation tool, have been compared with experimental measurements. For the experiment, a viewing screen was employed to capture and analyze the beam profile, providing valuable data to benchmark the simulation.

MATERIALS AND METHODS

Simulations

For the simulations, the C++ library IBSimu was utilized. This software was designed for ion beam simulations calculating the ion trajectories. However, since the library was not originally intended for simulating ion beam extraction from deep within a plasma volume, several modifications were necessary to adapt the program for this purpose. Additionally, some fundamental assumptions regarding the ion extraction process had to be made. These assumptions align with the prevailing consensus in the field of ion sources, however, their applicability to this specific type of simulation requires further validation.

In the simulation, the ions are generated from a surface located at the center of the plasma chamber (see simulation results). This position was chosen based on the assumption that the plasma occupies the majority of the chamber and by results of previous simulations, which indicate that the ions for each ion beam extracted from an ECR ion source originate from various positions within the plasma volume [2]. By placing the ion origin at this location, the simulation aims to more accurately predict the real ion production and transport dynamics. Additionally, an initial plasma had to be defined to ensure accurate results for the simulation. For this simulation the plasma potential was set to 20 V and the plasma was positioned in the area inside the plasma chamber (from $x = 0$ m to $x = 0.17$ m). A 98% space charge compensation was also applied from $x = 0.204$ m to $x = 0.5$ m.

The simulations were conducted for various charge states of argon (Ar^{3+} to Ar^{10+}) together with helium (He^{+} and He^{2+}) and hydrogen (H^{+}) ions. The initial distribution of the different charge states and different ion species used in the simulation was based on a previously conducted experiment. The magnetic field parameters and electrode geometry (STL files) utilized in the simulation were based on the results of simulations previously performed [3]. The following Table 1 presents the parameters setting used for the simulation.

Table 1: Parameters Used in the Simulation

Parameter		Value	Unit
parallel ion temperature	T_p	0.1	eV
transversal ion temperature	T_t	0.15	eV
electron temperature	T_e	5	eV
start energy of the ions	E_i	0.8	eV
screening electrode voltage		−2	kV
plasma electrode voltage		15	kV
number of ions	N	100000	
plane of ion creation		$x = 0.1$	m

The current density j at the starting plane of the ions is not included as different values for this parameter were tested, and this parameter appears to have the biggest influence of the outcome of the simulations.

Experimental Setup

The experimental setup employs a CAPRICE ECRIS (see Fig. 1), whose plasma chamber and ion extraction system are modeled in IBSmu by implementing its geometry, electric potential and internal magnetic field. This computer model is the base for all the simulations that will be presented in this proceeding.

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CHARACTERIZATION OF D^+ SPECIES IN THE 2.45 GHz ECRIS FOR 14-MeV NEUTRON PRODUCTION

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Abstract

The Institute for Plasma Research has set up a 14-MeV neutron generator facility. The stability, quality, and repeatability of the D^+ ion beam are critical parameters for ensuring the reliable operation of the neutron generator. Hence, a 2.45 GHz ECR ion source has been installed to produce the deuterium beam. The primary D beam characteristics are assessed by varying extraction voltage, microwave power, gas flow, and solenoid current of the ECRIS. By optimizing these parameters, the maximum design beam current is achieved. The D ion beam contains various species, including D^+, D_2^+, D_3^+, and impurities. Accurate measurement of the D^+ content within the D ion beam is the key parameter for a neutron generator. Multiple experiments were conducted to determine the D^+ species and optimise the ECRIS parameters for maximum production of D^+ species. Two beam current measurement devices, the DCCT and the Faraday Cup, were installed in the beamline to measure the total deuterium beam current and D^+ beam current, respectively. Especially, the variation in the D^+ fraction primarily depends on the operating parameters of the ECRIS, such as extraction voltage, microwave power and gas flow. This paper presents the results of the D^+ ion current as a function of extraction voltage, microwave power, and gas flow rate. Understanding and characterizing the D^+ species are essential steps toward achieving stable and efficient neutron production in fusion applications.

INTRODUCTION

The Institute for Plasma Research (IPR), India, has recently commissioned a 2.45 GHz Electron Cyclotron Resonance Ion Source (ECRIS)-based high-yield 14 MeV neutron generator. This sophisticated system is designed to produce a remarkable 10^{12} neutrons per second, both in continuous mode and pulse mode [1-3]. Deuterons, extracted from the SILHI ECRIS [4-6], are directed onto a solid titanium tritide (TiT) target. The collision of deuterons with the TiT target results in the production of fast neutrons. These fast neutrons are essential for various applications, such as benchmark experiments for the Fusion Evaluated Nuclear Data Library (FENDL), neutron spectroscopy measurements, double differential cross-section measurements, and neutron diagnostics, all aimed at the development of future fusion reactors. Additional applications of the neutron generator include neutron radiography, medical isotope production, explosive detection, and the characterization of electronic components used in space applications. The Institute for Plasma Research (IPR) has developed an accelerator-based D-T neutron generator capable of producing 10^{12} neutrons per second as shown in Fig. 1 [7].

The 2.45 GHz Electron Cyclotron Resonance (ECR) ion source is a critical component of the 14 MeV neutron source, significantly contributing to its stability, reliability, and performance. This paper details the experimental setup of the accelerator-based 14 MeV neutron generator and presents experimental results on ion beam characterization and neutron yield measurement using various diagnostic techniques.

Figure 1: Photograph of Accelerator based 14 MeV Neutron Generator.

EXPERIMENTAL SETUP

The beam characterization process begins at the ion source and is carried out in a step-by-step manner. To ensure smooth and successful beam characterization, extensive preparatory work on accelerator physics and hardware has been conducted. The beamline is evacuated to a base pressure of 10^{-7} mbar before the production of the deuterium beam. Deuterium plasma is generated in the Electron Cyclotron Resonance Ion Source (ECRIS), from which the deuterium ion beam is extracted.

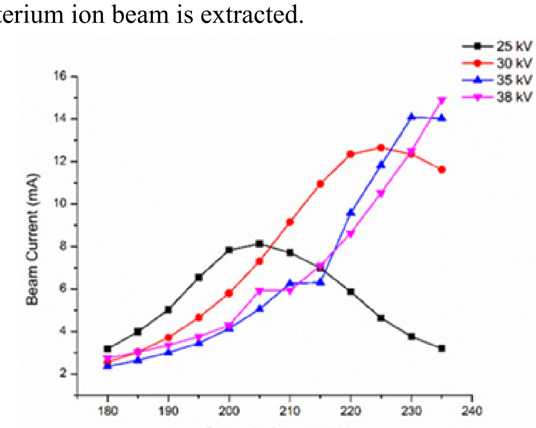

Figure 2: Beam current as function of solenoid current at different extraction voltage.

The extracted deuterium ion beam is then focused into the acceleration column via the Low Energy Beam Transport (LEBT) system and further accelerated using

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COMPACT 2.45 GHz PMECR ION SOURCES AND LEBTS DEVELOPED FOR ACCELERATOR BASED RADIATION THERAPY FACILITIES AT PEKING UNIVERSITY

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Abstract

Recently, Accelerator Based Radiation Therapy (ABRT) facilities for cancer treatment, that includes ion therapy and BNCT, have been bloomed up rapidly and are being established as a future modality to start a new era of in-hospital facilities around the world. A high current, small emittance, easy maintenance, long lifetime, high stability and reliability ion source is crucially important for those ABRT facilities. Research on this kind of ion source has been launched at Peking University (PKU) ion source group for more than 30 years and some exciting progresses, such as hundred mA beam current of $H^+/N^+/O^+$ etc., less than 0.2 π·mm·mrad emittance, a continue 300 hours operation record of CW proton beam without spark have been achieved. In recent years, our involvement in the ABRT campaign has extended to include responsibilities for ion sources and LEBT section. In this paper, we will provide a summary of two compact PKU standard 2.45 GHz permanent magnet ECR sources (PM SMIS) that were developed for a proton therapy (PT) machine and an accelerator based BNCT facility (AB-BNCT). The individual structure of the sources as well as the LEBT along with the commissioning results will be presented then.

INTRODUCTION

Cancer is a general term for a large category of diseases that can affect any part of the body. It is a leading cause of death worldwide, accounting for nearly 10 million deaths in 2020, or nearly one sixth of deaths are due to cancer [1]. Many cancers can be cured if detected early and treated effectively. Radiation therapy (also called radiotherapy) is a cancer treatment that uses high doses of radiation to kill cancer cells and shrink tumors. There are two main types of radiation therapy, external beam and internal. External beam radiation therapy comes from a machine that aims radiation at the cancer. The machine does not touch but can move around the patient, sending radiation to a part of patient's body from many directions. External beam radiation therapy is a local treatment, it treats a specific diseased part of the body. Proton therapy (PT), heavier ions therapy (HIRT) and boron neutron capture therapy (BNCT), are new highly targeted external beam radiation therapy for cancer treatment. Accelerator Based Radiation Therapy (ABRT) facilities are compact and useful tools to generate desired particles, such as energized protons, carbon ions or neutrons, to kill the cancer cells. Therefor ABRT has been bloomed up rapidly and is being established as a future modality to start a new era of in-hospital facilities around the world [2,3].

For any ABRT type PT or BNCT facilities, a proton beam with a current of several tens of mA in pulsed or continuous wave (CW) mode is required from the ion sources by the accelerator. The 2.45 GHz Electron Cyclotron Resonance (ECR) ion source is considered to be the optimal choice for ABRT facilities due to its advantages in high beam intensity, stable performance, low emittance, good reproducibility, high stability, simple structure, convenient maintenance, low cost, long lifespan and ability to operate in both CW and pulsed modes. Ion source group of Peking University (PKU) initiated an ABRT campaign by developing compact 2.45 GHz ECR ion sources and LEBT for these facilities.

The study on permanent magnet 2.45 GHz ECR ion sources (PMECR) started at 1980's at PKU [4]. Since then, several series of 2.45 GHz PMECR ion sources have been developed, including the PKU Standard permanent magnet Microwave Ion Source (SMIS) [5], Miniaturized Microwave ion source (MMIS) [6], Surface plasma electron source (SPS) [7], H_2^+/H_3^+ ion source [8], 2.45 GHz microwave driven H- source [9], O^{3+}, Ar^{3+} multicharged ion source [10] and C^{2+} ion source for PIMS [11]. The SMIS has achieved a proton beam of more than 130 mA at 50 keV with a Φ6 mm emittance aperture [5]. In June 2016, a long-term operation of 300 hours with a continuous wave proton beam of 50 mA@50 keV was conducted using the SMIS. Throughout this period, no sparks appeared and no plasma generator failure caused any interruptions to the beam. More than ten copies of SMISs have been developed for different facilities such as SFRFQ [12], PKYNIFTY [13], C-RFQ [14], DWA [15] and Proton therapy facility [16]. To better understand the discharge ignition and plasma sustain process within a miniaturized 2.45 GHz microwave driven ion source, a hybrid discharge heating (HDH) mode has been proposed at PKU [6]. Additionally, a global model based on electronic equilibrium equations has been proposed to explain H^+, H_2^+ and H_3^+ generation [17].

This paper primarily focuses on the compact permanent magnet 2.45 GHz ECR ion sources (PMECR) along with LEBT developed for a PT machine and a BNCT facility. The ion sources belong to SMIS type. In both cases, we have followed the same structure as PKUNIFTY by designing the ion source and the LEBT as a whole. In section II, we will present the commissioning results of the Proton Injector for PT Machine. Section III will depict details of the pulsed/CW proton PMECR and two-solenoid LEBT

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A PLASMA BASED, CHARGE STATE STRIPPER FOR HEAVY ION ACCELERATORS

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Abstract

The ionization of ions to a higher charge state is of central importance for the development of new accelerator facilities like FAIR (Facility for Antiproton and Ion Research) at GSI, Darmstadt,and the resulting cost savings. That is why the comparative analysis of the charge state stripping alternatives is a relevant topic. Currently, mainly gas and foil strippers are used for increasing the charge state even after using a high performance ECR ion source in a typical Accelerator chain. Even when the foil or/and gas efficiency or lifetime has proved to be less than optimal, as these alternatives either require great effort or are practically not suitable for smooth operation in the long term.

INTRODUCTION

Free electrons in highly ionized plasmas can be effectively used for improving the charge state of heavy ions as the rates of radiative recombination of free electrons are much smaller than those of electron capture on bound electrons, which leads to a substantial increase of the effective charge in a plasma compared to a cold-gas target of the same element. Therefore, the use of highly ionized plasmas for charge state enhancement are more effective than in the case of using gas and foil stripper mediums and are advantageous when compared to the limited lifetime of foils and lower mean charge state distributions in gaseous media. In order to realize such a plasma device, various types of pinch plasmas have been explored to look into the possibility of heavy ion stripping with an enhanced mean charge state distribution. Theta and Z pinch plasmas are possible options which have been explored and experimentally studied at IAP, Frankfurt, Germany [1]. Typical electron line densities required to be achieved are in the range of 10^{16} to 10^{19} cm^{-3} and electron temperatures of the order of few tens of eV are found to be favourable as per modelling with the FLYCHK code [2], but also challenging. Such a plasma device, the challenges to be overcome, together with their design details will be presented.

A collaboration [3] between BARC, Vishakhapatnam and IUAC, New Delhi has been initiated to further modify plasma pinch devices and optimise them for the accelerator conditions, in particular for the High Current Injector [4] programme at IUAC, New Delhi, and to plan for the beam tests as "proof of principle".

With regard to the development of new accelerator technologies for high-intensity ion beams and efficient acceleration, the transfer of beam ions into higher-charged states is a necessary prerequisite for numerous experiments. The acceleration of heavy ions is being pursued with increasing efforts and especially during the last, few ten years, acceleration techniques have been studied in detail. In reaching the goal to produce intense beams of ions as heavy as uranium and energetic enough to overcome the Coulomb barrier even for the heaviest targets, many new problems must be solved which were not important for the design of conventional light particle accelerators. One of these problems concerns the ionic charge of heavy ions which is an influential new parameter. In this paper, the variation of ionic charge due to collisions with matter ("stripping") will be discussed, as well as some associated phenomena of practical interest.

The effects of charge stripping on heavy ion acceleration are twofold, On the one hand, the passage of heavy ions through specially designed strippers can be exploited to produce a substantial increase of the ion charge which reduces the effective potential required for further acceleration, In order to find the most suitable stripper and to utilize the highest possible charge states, it is necessary to investigate the effects of strippers on heavy ion beams in great detail. On the other hand, random stripping in the residual gas of an accelerator may lead to beam losses. In order to calculate the vacuum which guarantees a satisfactory particle transmission, it is necessary to know charge changing cross sections. These cross sections are very complex quantities and they can hardly be estimated without extensive knowledge about fundamentals of charge changing processes.

BACKGROUND INFORMATION

Plasma has been discussed as a possible medium for ion strippers since the 1960s. In his paper from 1991, T. Peter calculated the achievable equilibrium charge states in cold gas and plasma for iodine ions [5,6]. The equilibrium charge states for uranium ions were calculated by V. Shevlko in 2012

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MIXED CARBON AND HELIUM ION BEAMS FOR SIMULTANEOUS HEAVY ION RADIOTHERAPY AND RADIOGRAPHY: AN ION SOURCE PERSPECTIVE

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Abstract

Within the framework of research on simultaneous heavy ion radiotherapy and radiography, a mixed carbon/helium ion beam with a variable He percentage has been successfully established and investigated at GSI for the first time in order to study this new mode of image guidance for carbon ion beam therapy. The mixed C / He ion beam was provided by the 14.5 GHz CAPRICE ECR ion source for the subsequent linac-synchrotron accelerator systems at GSI. Prior to that experiment, different ion combinations ($^{12}C^{3+}$/ $^{4}He^{+}$ or $^{12}C^{4+}$/ $^{3}He^{+}$) out of CH_4 or CO_2 have been investigated at the ECR test bench in terms of ion beam currents, stability, and C-to-He-fraction quantified by optical spectral lines and mass spectra. From an ion source perspective, it turned out that each of the different combinations comply with all the requirements of the experiments which successfully took place utilizing a $^{12}C^{3+}$/ $^{4}He^{+}$- ion beam with an energy of 225 MeV/u. Finally, both ions were simultaneously accelerated, extracted and characterised in the biophysics cave. This paper briefly outlines some of the measurements obtained at the test bench and during the beam time from an ion source perspective.

INTRODUCTION

Particle therapy, as a Bragg peak method of irradiation, is subject to even small range uncertainties in especially for anatomical changes like moving tumours. Mixed carbon and helium on beams have been proposed for simultaneous therapy and online monitoring [1–6].

Due to the similar mass-to-charge-ratio C^{3+} and $^{4}He^{+}$ (or C^{4+} and $^{3}He^{+}$) ions can be accelerated to the same energy per nucleon. At this same velocity the penetration depth of He in water is three times the one of carbon ions. Therefore, carbon ions stop in the tumour volume applying the dose there while helium ions exit the patient and can be detected and used for range verification and imaging. Previous works revealed that the additional dose from a small, 10 % helium percentage in the plateau of the depth-dose-profile of helium is sufficiently low [1–4].

Most recent simulation works analysed the injection and extraction process at a medical facility while the experimental exploration is still ongoing [7, 8]. Recently, such a mixed beam has been produced at GSI with an energy of 225 MeV/u, slowly extracted with a particle rate of about 10^8 particles/second [9, 10]. This paper briefly reviews the major steps of the dual isotope beam production and some of the important results achieved with an emphasis on ion source development.

MATERIALS AND METHODS

Ion Source Set Ups

In order to meet the requirement of 10^8 particles/second at the experiment an ion beam of circa 150 µA ($^{12}C^{3+}$ or $^{12}C^{4+}$) with a helium fraction of approx. 10 %, i.e. circa 5 µA ($^{4}He^{+}$ or $^{3}He^{+}$) has to be provided upstream the subsequent linac-sychrotron system UNILAC-SIS18 at GSI. The 14.5 GHz CAPRICE type ECR ion source was utilised for this purpose meeting all the requirements given.

The preliminary measurements were conducted at the ECR ion source test bench which includes a low energy beam transport line (Fig. 1). Different reasonable combinations of methane/carbon dioxide and $^{4}He^{+}$/ $^{3}He^{+}$ were checked in terms of feasibility.

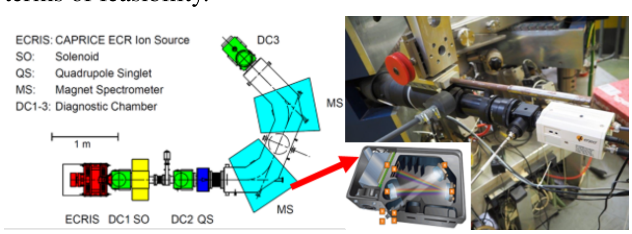

Figure 1: Sketch of the test bench: ion source and LEBT (left), camera and optical spectrometer system (right).

The helium percentage was controlled by stepwise altering the helium inflow to the plasma and by measuring a) the optical emission spectrum (OES) with an optical spectrometer (Oceaninsight QE Pro [11]) covering approx. the visible light spectrum, b) the analysed ion beam current in a Faraday cup, and c) the corresponding mass spectra. In the two latter cases, it is impossible to distinguish between the $^{12}C^{3+}$/ $^{4}He^{+}$ or $^{12}C^{4+}$/ $^{3}He^{+}$ ions, but the C-to-He ratio and its long term stability also during operation can be estimated by the optical emission lines of carbon (wavelength 465 nm) and helium I (728 nm).

Finally, a mixed ion beam of $^{12}C^{3+}$ and $^{4}He^{+}$ was provided from the high charge state injector (HLI) to the experiment (smaller deviation of the mass-to-charge ratios compared to $^{12}C^{4+}$ and $^{3}He^{+}$). After setting up the ion source, the C-to-He ratio was adjusted and constantly monitored by measuring the analysed ion beam current in a current transformer and by measuring the optical emission lines that is by non-destructive beam instrumentation.

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APPLYING MACHINE LEARNING TECHNIQUES TO THE OPERATION OF THE SUPERCONDUCTING ECR ION SOURCE VENUS*

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Abstract

An operator of the superconducting ECR ion source VENUS tasked with optimizing the current of a specific ion species or finding a stable operating mode is faced with an operation space composed of ten-to-twenty knobs in which to determine the next move. Machine learning techniques are well-suited to multidimensional optimization spaces. Over the last three years we have been working to employ such techniques with the VENUS ion source. We will present how the introduction of computer control has allowed us to automate tasks such as source baking or to utilize optimization tools to maximize beam currents with no human intervention. Finally, we will discuss control and diagnostic changes that we have employed to exploit the faster data collection and decision making abilities when VENUS is under computer control.

INTRODUCTION

Electron cyclotron resonance (ECR) ion sources are employed as injector sources for many accelerator facilities around the world. The reason for this is simple: these sources are capable of producing high current, highly-charged ion beams from any material that can be introduced to the ECR ion source plasma without destroying the plasma.

The typical ion source has an operation space defined by ten-to-twenty control parameters, depending on the ion beam being produced. Though this results in an enormous operation space, the operator is typically tasked with maximizing or minimizing some beam quantity. For example, it may be required that the species current be maximized, its emittance be minimized, its stability kept below some threshold, or some combination of these. Therefore, though the operation space is broad, the problem is made somewhat more tractable by the fact that much of that space may be eliminated from contention.

Bayesian optimization [1] operates in this spirit: an operation space is populated (typically) randomly with some number of exploratory measurements . The code models a distribution over the operation space using these measurements and, using a user-determined balance between exploring far from measured points and searching near currently known extrema, searches a new point where it has determined the probability of being an extrema is largest. The newly-measured point is used to update the modeled distribution and the process repeats. In this work, we use Bayesian optimization to maximize the beam current of a species of interest from LBNL's superconducting ECR ion source, VENUS, discuss the results, and use these results to motivate and implement improvements to data collection times that will aid our continued machine learning efforts with this ion source.

VENUS ION SOURCE AND COMPUTER INTERFACE

LBNL's VENUS ion source is a fully-superconducting ECR ion source optimized for 28 GHz operation [2]. The plasma-confining magnetic field is produced through a superposition of solenoidal and sextupolar NbTi coils. A sextupole at each end provides radial confinement while one in the center opposes these fields and helps set the center minimum field. The source is able to produce over 2 tesla fields on the radial walls and on axis at extraction, and up to 4 tesla axially opposite the plasma from extraction. Two frequency heating, 28 and 18 GHz, is used with up to 10 kW and 4.4 kW available, respectively.

In recent years we have established the ability to both completely control and read all of VENUS' diagnostics by computer. This was achieved by employing the Python library pylogix [3] to interface with VENUS' programmable logic controller (PLC). We created a Python class so the computer could set and read all parameters that a human operator can when running VENUS.

Controlling VENUS through the PLC has the distinct advantage that the computer is operating the source just as human operators do, and the more-than-two-decades of safety logic written into the PLC to preserve safe operation immediately applies to computer operation. However, this comes at the cost of speed as the PLC has been designed for human interaction rates, so data can only be written or read at about 3 Hz.

Using this interface, we have been able to automate a number of tasks that previously were time-consuming. Experimental data taking (e.g. sweeping a parameter between two values and recording all source data) is now trivial. Baking, the process where materials on plasma chamber surfaces from previous runs, contaminants, or exposure to atmosphere are removed by plasma-chamber interaction, has been performed many times now with absolutely no human interaction with the source. The heating microwave power is brought up by the computer in a controlled manner until full power is reached. At that point the confining magnetic fields are adjusted by computer to alter the wall-plasma interaction and accerate the removal of material from the wall. The methods of doing this are no different than those that might be undertaken by a human, but the computer is continually

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BEAM INTENSITY PREDICTION USING ECR PLASMA IMAGES AND MACHINE LEARNING

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Abstract

Long-term beam stability is crucial for supplying multivalent heavy-ion beams using an electron cyclotron resonance (ECR) ion source . When the beam intensity drops during long-term operation, the ECR ion source parameters must be adjusted to restore the original beam intensity. Continuous measurement of beam intensity using a Faraday cup (FC) while using the beam is impractical. Currently, we estimate the beam intensity during beamtime by monitoring the total drain current, which is an unreliable method. Therefore, we propose a new method for predicting the beam intensity at FC using machine learning. In the proposed method, plasma images captured through a hole in the beam extraction electrode and the operating parameters are considered as input data for training a machine learning model. The proposed method successfully produced rough predictions of beam intensity in short-term validation datasets. This paper presents the prediction model and its prediction results using validation data. The developed model can immediately respond to fluctuations in beam intensity and enable efficient operation of the ECR ion source over extended periods.

INTRODUCTION

In the long-term operation of electron cyclotron resonance (ECR) ion sources, the beam intensity frequently fluctuates during delivery. However, methods such as Faraday cups (FC) cannot be used to diagnose beam intensity during delivery because FC interferes with the beam. Consequently, we have been operating ECR ion sources by inferring changes in beam intensity using the drain current as the leading indicator. Nevertheless, a non-destructive beam intensity measurement method must be developed to automate its long-term operation. Based on the empirical knowledge that operators consider plasma light in the visible light region crucial when tuning ECR ion sources, we devised a method to predict beam intensity from plasma light. In this study, we created and evaluated a model to predict the beam intensity by processing images of visible plasma light obtained through a CCD camera using machine learning. Previous studies have suggested a relationship between plasma light intensity and beam intensity [1]; consequently, this study further aims to predict the absolute value of beam intensity based on this relationship.

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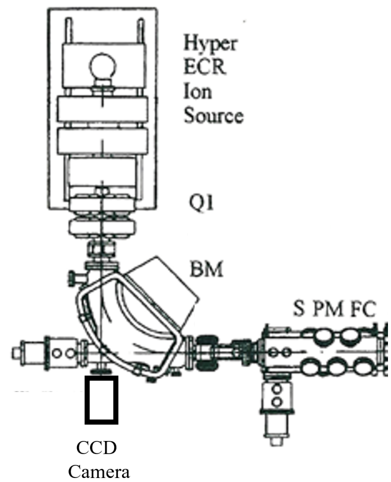

Figure 1: Schematic representation of the LEBT, where beams extracted from the HyperECRIS are focused by quadrupole magnets and then selected for the required charge by bending magnets and slits. The plasma light was captured using a CCD camera through a window in the bending magnet and through an extraction electrode.

EXPERIMENTAL CONDITIONS

HyperECR Ion Source

The 14-GHz ECR ion source “HyperECR Ion Source” (HyperECRIS) [2] at the Center for Nuclear Study, The University of Tokyo, was used to acquire training and validation data for developing the machine learning model. The HyperECRIS can supply gas ion species such as proton, helium, and argon and metal ions such as lithium and iron. In the HyperECRIS, a crucible containing metallic material was attached to a rod tip, and the heat of the plasma was used to vaporize the metallic material to provide metal ions. Therefore, compared to gas ion species, the intensity of the beam tends to fluctuate when metal ion species are supplied. In this experiment, we used a $^{56}Fe^{15+}$ beam, considering that a more stable gas ion species would not be suitable for evaluating the prediction accuracy, mainly because the fluctuation of the beam intensity is slight.

Parameters

The low energy beam transport (LEBT) from HyperECRIS to FC is shown in Fig. 1. The beam extracted from HyperECRIS was selected through the bending magnets and slits, and the beam intensity was measured at FC. The param-

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NUMERICAL DESIGN OF AN INNOVATIVE SUPERCONDUCTING MAGNETIC TRAP FOR PROBING β-DECAY IN ECR PLASMAS

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Abstract

The main aim of Plasmas for Astrophysics Nuclear Decays Observation and Radiation for Archaeometry (PANDORA) project is to build a flexible magnetic plasma trap where plasma reaches a density $n_e \sim 10^{11} - 10^{13}\,\mathrm{cm}^{-3}$, and a temperature, in units of kT, $kT_e \sim 0.1 - 30\,\mathrm{kV}$ in order to measure, for the first time, nuclear β-decay rates in stellar-like conditions. Here we present the numerical design of the PANDORA magnetic system, carried out by using the commercial simulators OPERA® and CST Studio Suite®. In particular, we discuss the design choices taken to: 1) obtain the required magnetic field levels at relevant axial and radial positions; 2) avoid the magnetic branches along the plasma chamber wall; 3) find the optimal position for the set of plasma diagnostics that will be employed. The magnetic trap has been conceived to be as large as possible, both in radial and axial directions, in order to exploit the plasma confinement mechanism on a bigger plasmoid volume. The plasma chamber will have a length of 700 mm and a diameter of 280 mm. The magnetic trap tender procedure has been completed in June 2024 and the structure realization is expected to start in late 2024.

INTRODUCTION AND MOTIVATION

In the last decades, much experimental and theoretical efforts have been dedicated to investigate various possible scenarios which can influence nuclear decays rates. It has been predicted that sizeable variations in the decay properties can be observed in highly ionized nuclides. This would have a strong impact in the stellar nucleosynthesis where a hot plasma is formed and atoms can be found in different ionization states. In particular, β decay properties of radioactive nuclei can be strongly affected by the high-temperature plasma of stellar environment. Few experimental evidences showing variations in the beta decay rates as a function of the atomic ionization state have been collected, up to now, using storage rings. However, the storage ring approach is based on the investigations of a single charge state at a time: while clearly showing the role played by the high ionization state of an atom in the β-decay process, is not able to reproduce stellar-like conditions where, due to the high temperature of the plasma, a Charge State Distribution (CSD) of the ions is established. A totally new and challenging approach, based on the study of decays rates in a plasma whose conditions can mimic the hot stellar environment, has been conceived in the PANDORA project [1]. The main idea is to build a flexible magnetic plasma trap and use it to measure, for the first time, nuclear β-decay rates in stellar-like conditions. The decay rates of the radioactive ions will be measured through the detection of the γ-rays emitted by the β-decaying daughter nuclei, as a function of the charge state distribution of the in-plasma ions by varying plasma conditions. This task will be accomplished by an array of several Hyper-Pure Germanium (HPGe) detectors placed around the trap, in specific positions where holes were made in the cryostat structure to directly look into the plasma through thin aluminium windows. This new approach is expected to have a major impact in the study of nuclear-astrophysics processes and cosmology. The magnetic field, necessary for plasma confinement, will be produced by employing a superconducting magnetic system (as typical for ECR ion sources), consisting of six hexapole coils (for radial confinement) nested inside three solenoid coils (for axial confinement), i. e. a SEXT-IN-SOL configuration. This magnetic system configuration is called *minimum-B* and allows the confinement of a plasma located around the plasma chamber axis (here z axis), providing magnetohydrodynamical (MHD) equilibrium and stability.

MAGNETIC TRAP NUMERICAL DESIGN

Some considerations can be made for the design of a magnetic system for ECRIS plasma confinement [2]. The optimum charge state is proportional to the average magnetic field as $q_{\mathrm{opt}} \propto B^{3/2}$, so it is of our interest to increase the average confining field. The highest value of the magnetic field will be in correspondence of the injection and/or extraction axial coils inner surface, so during the numerical design of the magnetic system one has to be careful at not exceeding the threshold field values relative to the magnet material. In superconducting traps, special attention must be paid to the minimum field, B_{min}, that should be tuneable within a wide range of values: it has been experimental observed that, in order to obtain the highest electron density and to reach the optimal charge state, one has to have $0.65 < B_{\mathrm{min}}/B_{\mathrm{ECR}} < 0.75$ [3–5]. If this ratio exceeds the upper value, sudden non linear effects arise, increasing the plasma x-ray emission and thus the heat load on the cryostat. The requirements and considerations previously discussed, together with the necessity to have enough space for non-invasive diagnostic tools and for the array of γ-ray detectors [6], allowed us to fix the plasma chamber dimensions (internal radius $R_{\mathrm{CH\_IN}} = 140\,\mathrm{mm}$ and axial length $L = 700\,\mathrm{mm}$) and RF pumping frequencies ($f_{\mathrm{RF1}} = 18\,\mathrm{GHz}$, $f_{\mathrm{RF2}} = 21\,\mathrm{GHz}$). Taking into account these values, the PANDORA magnetic system field specifications have been ob-

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WAVEGUIDE DC BREAKS WITH OPTIMIZED IMPEDANCE MATCHING NETWORKS*

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Abstract

A custom 18 GHz waveguide DC break with a built-in impedance matching network, consisting of two inductive irises adjacent to a capacitive gap assembled around a quartz disk, was built for Versatile ECR for Nuclear Science (VENUS) ion source and simulated using the ANSYS High Frequency Structure Simulator, a finite element analysis tool. The DC break effectively doubled the RF power available for plasma production at the secondary frequency of 18 GHz while maintaining a DC isolation of 32 kV. Measurements of the forward and reflected power coefficients, performed with a network analyzer, showed excellent agreement with the simulations [1]. Additionally, an extended study was conducted to tailor the frequencies of 28, 35, and 45 GHz using WR-34, WR-28, and WR-22 waveguides with built-in impedance matching networks, aiming to predict performance for our upcoming 4th generation low-power, multi-frequency operation of the MARS-D ion source.

INTRODUCTION

The Versatile Electron Cyclotron Resonance (VENUS) ion source, developed at Lawrence Berkeley National Laboratory's 88-Inch Cyclotron [2], operates at frequencies of 28 GHz and 18 GHz. It utilizes a superconducting magnet system to generate a strong, well-defined magnetic field for confinement, creating two enclosed regions for plasma heating and enabling the production of ion beams with high charge states and intensities.

Since the VENUS ion source operates on a high-voltage platform meanwhile the RF system is at ground potential, a waveguide HV DC break is required to maintain isolation while allowing RF signals to pass with minimal microwave leakage and insertion losses [3].

DC breaks can be mainly categorized into two types. One common type is the choke flange [4–6], which creates a gap in the waveguide using dielectric materials to achieve isolation. Another type is the multi-layer DC break [7, 8], which uses multiple layers of insulating materials between sections of metal, enhancing the overall dielectric strength and reducing RF leakage. Some advanced designs use innovative techniques, such as a lattice structure made of dielectric materials [9] or tapered waveguide transitions combined with low-loss dielectrics [10]. To further enhance RF power delivery and compensate for waveguide mismatches, tuners equipped with screws, posts, or stubs are often used just before the DC break, improving impedance matching and maximizing power transfer to the plasma [11–13].

WAVEGUIDE DC BREAK

The DC break is constructed using two open-ended copper sections that conform to the WR-62 waveguide's dimensions, with a width of 15.8 mm and a height of 7.9 mm. This break includes a gap within the waveguide filled by a fused quartz disk, measuring 100 mm in diameter and 1 mm in thickness [14]. The quartz, known for its excellent thermal properties and high dielectric strength, allows the system to withstand up to 32 kV DC, furthermore, its low dielectric constant of 3.9 and very low dielectric loss tangent of less than 1×10^{-3} ensure minimal RF energy loss, calculated to be about 0.003 dB. This results in the primary losses being due to RF leakage, calculated by subtracting the total transmitted and reflected power from 100 %.

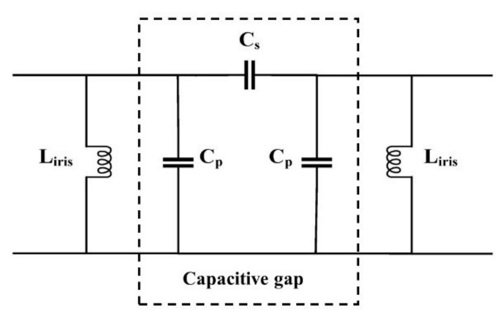

Figure 1: Waveguide DC break equivalent circuit.

To address impedance mismatches caused by the gap, the design incorporates two symmetrical inductive matching irises [15], each 1.85 mm thick, positioned adjacent to the gap. As illustrated in Fig. 1, the gap introduces lumped capacitance C_p due to fringing fields at the open-ended waveguides and series capacitive coupling C_s across the gap, leading to impedance mismatch. The irises generate lumped shunt inductances L_{iris}, which compensates for the lumped shunt capacitances C_p, effectively creating a band-pass filter centered around the desired frequency. Additionally, the waveguide apertures near the gap are expanded to form a

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