SCALING LAWS IN ELECTRON CYCLOTRON RESONANCE ION SOURCES *

C. M. Lyneis, Lawrence Berkeley National Laboratory, CA 94720, USA

Abstract

In the last 36 years, the performance of high charge state ECRIS has improved dramatically as a result of improvements to the magnetic field confinement, increases in the microwave heating frequency and techniques to stabilize the plasma at high densities. For example, in 1980 15 eµA of O^{6+} was produced in an ECRIS[1] and now it is possible to produce as much as 4700 eµA. [2] In this paper the parameters and performance of ECRIS are reviewed and compared to empirical scaling laws to see what can be expected when fourth generation ECRIS begin to operate.

INTRODUCTION

Electron Cyclotron Resonance Ion Sources, ECRIS, are widely used to produce intense high charge state ions for accelerators used for nuclear physics and for hadron cancer therapy facilities. In nuclear physics, new heavy-ion driver accelerators are under construction and these machines require ion source production beyond the present day performance both in terms of ion charge states and ion intensities. In some ways, this parallels the efforts in the much larger field of magnetic fusion where the goal is to improve the performance beyond that of existing machines and demonstrate net power production. For many years the fusion community has used various scaling laws to both study the complex behavior of these plasma devices and to guide the design of future devices. For ECR ion sources, the search for and testing of scaling laws began with experiments in Grenoble in the 1970's, when the first high charge state ECRIS was built under Richard Geller's direction. During the last 40 years, the performance of ECRIS has progressed a great deal as illustrated with the 300 fold increase in O^{6+} currents going from 15 eµA to 4700 eµA. We now have a large number of ECRIS operating between 6.4 GHz and 28 GHz, built with a variety of shapes, sizes and operating parameters and these can be used to test existing scaling laws and perhaps uncover new ones.

Scaling laws for plasma devices can take several forms. In some cases they are used to describe the parameters of a single machine as a function of some external variable such as ECRH frequency, magnetic field confinement or RF power level. In other cases a scaling law could be used to summarize a general performance characteristic than can be applied across a wide variety of ECRIS sources. When this latter approach is applied to ECRIS, the result is often more qualitative than quantitative because there are a wide variety of source designs and only the very strong dependences will be clearly demonstrated.

Many aspects of the physics of ECR ion sources are well understood, such as the atomic physics of electron impact ionization and the magnetic confinement of plasmas and these processes can be simulated with computer codes. [3] However, the picture is not complete since these codes typically require that certain internal parameters be specified; such as the plasma density, electron energy distribution function, electron and ion confinement times and even the microwave electric field strength. Typically these parameters cannot be experimentally measured in an ECRIS plasma and so we have to rely on other methods to extrapolate ECRIS performance.

In this paper, we will review some of the scaling laws, which have been proposed over the years, and test them against to the data generated by the ECRIS now in operation. In addition we will look for new scaling laws or even rules of thumb that can help predict the performance of future ECRIS.
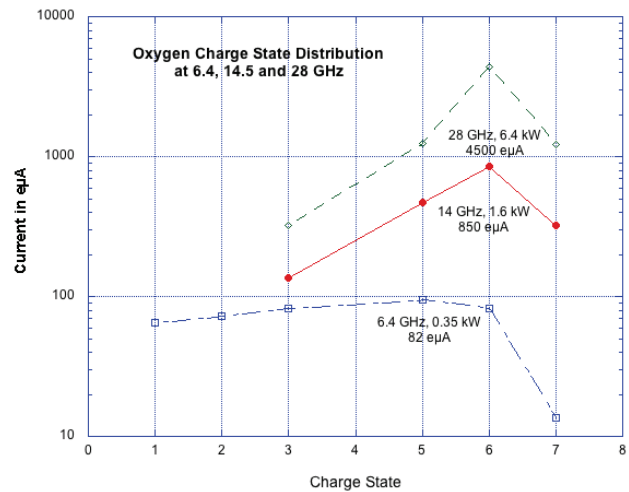

Figure 1: Oxygen charge state distributions produced on the 6.4 GHz LBL ECR, the 14 GHz AECR-U and VENUS at 28 GHz.

PHYSICS AND SCALING LAWS IN ECRIS

The physics and operation of ECRIS has been reviewed a number of times in depth. [4-6] This paper focuses on certain aspects of high charge state ECRIS, which could help in understanding the performance and scaling without an exhaustive review of the physics behind them. For the discussion that follows, it is still useful to briefly discuss the key plasma and physics mechanism in the production of high charge state ions in an ECRIS. For electrons in a magnetic field their cyclotron resonance frequency is given by

$$B_{ecr} = F_{rf}/28$$

where B_{ecr} is in Tesla and F_{rf} is in GHz.

POSSIBLE OPTIMIZATIONS OF EXISTING MAGNET STRUCTURES FOR THE NEXT GENERATION OF ECRIS

D. Z. Xie[†], W. Lu[1], G. Sabbi, D. S. Todd

Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

[1]also at Institute of Modern Physics, Lanzhou 730000, China

Abstract

The next generation of Electron Cyclotron Resonance Ion Sources (ECRISs) will operate with higher magnetic fields and higher heating frequencies than those currently in use. Constructing a min-B configuration with higher confining fields is the prerequisite for this next generation of sources. There are three leading candidates for superconducting magnet structures in future ECRISs: a Mixed Axial and Radial field System (MARS) that merges the sextupole racetrack coils and segmented end-solenoids into an exotic closed-loop-coil; a classical structure of Sextupole-In-Solenoids; and a non-classical structure of Solenoids-In-Sextupole. Focusing on efficient magnetic field generation, this article briefly reviews the advantages and disadvantages of each of these magnet structures. Though Sext-In-Sol and Sol-In-Sext magnetic structures using NbTi conductor have been proven in current ECRISs, there are still rooms for improvements of these magnet structures. Potential optimizations to these existing magnet structures, such as using a non-conventional sextupole magnet consisting of either V-bend or skew coils, are discussed. The development status of a MARS NbTi magnet for a new ECRIS at LBNL will be also presented.

INTRODUCTION

Geller's scaling laws [1] predict that ECRIS performance will improve with magnetic fields and heating frequencies. This is the most effective path as demonstrated by the successful ECRIS developments in the past decades, especially the great achievements of the 3rd generation NbTi-magnet-based ECRISs [2-7]. Future operations with even higher magnetic fields require superconducting magnet systems capable of generating higher strength min-B fields (B > 4 T) for operations at frequency f > 28 GHz. Presently there is a novel magnet system under development at LBNL, MARS (Mixed Axial and Radial field System), which merges a sextupole and two segmented end solenoids into a closed-loop-coil to efficiently generate a high strength min-B configuration. This structure is unique in that its closed-loop-coil generates not only the high radial field but also contributes substantially to the axial field. Once the MARS magnet structure has been successfully developed, it will play an important role in constructing future high-field ECRISs utilizing either NbTi or Nb₃Sn magnets [8, 9]. This new magnet structure, along with the existing classical Sextupole-In-Solenoids (Sext-In-Sol) and the non-classical structure of Solenoids-In-Sextupole (Sol-In-Sext), shown in Fig. 1, will provide three base magnet systems for constructing future ECRISs. Table 1 lists the advantages and disadvantages of each of these

[†]email address: zqxie@lbl.gov

structures. MARS' closed-loop-coil with its minimized forces on coils stands out as the magnet choice that harnesses the advantages but avoids the disadvantages of the two existing magnet structures. However, a price is paid in increased complexity in coil winding and the magnet cryostat, in which hexagonally-shaped warm bore and inner thermal shield are required to match the MARS cold mass [9].

Table 1: Comparison of the Three Potential Magnet Systems for Future ECRISs

System	Advantages	Disadvantages
a) Sext-In-Sol	Better utilization of the radial field **(~ 50%)***	Bulkier magnet and cryostat, higher and complex interaction forces
b) Sext-In-Sol	Lower and simpler interaction forces, smaller magnet and cryostat, simpler fabrication, lower cost.	Inefficient utilization of the radial field **(~ 34%)***
c) MARS	Least and simplest interaction forces, uses substantially less conductor, smallest magnet and cryostat, Best utilization of the radial field **(~ 67%)***	Complex fabrication of the closed-loop coil, slightly complex cryostat.
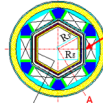
*: Defined as square of the ratio of the plasma chamber inner radius Rc over the smallest inner radius Rs of the sextupole coil: (Rc/Rs)².

The shortcoming of existing designs comes when looking toward the future with ECRIS operation at or above 45 GHz. For conventional operation of these sources at 45 GHz frequency, the required axial fields (6.5 and 3.3 T for injection and extraction) and radial fields (3.3 T at the wall) are shown in Figs. 2(a) and 2(b), respectively. The question arises as to whether there is any room to increase the magnetic field generation efficiency, where better efficiency would mean achieving the required fields with the lower total coil excitations CE = LI (wire length x current). A reduced coil excitation should lead to lower magnetic forces, system stored energy, conductor loading and smaller superconductor volume resulting in reduction of overall magnet size. Field calculations with TOSCA indicate that there are optimizations that can be made to the current structures, and they are presented below.

RECENT DEVELOPMENTS OF RIKEN 28 GHz SC-ECRIS

Y. Higurashi[†], J. Ohnishi ,H. Haba, M. Kidera, K. Ozeki and T. Nakagawa

RIKEN Nishina Center, Wako, Japan

Abstract

In the past two years, we have attempted to improve the performance of RIKEN 28GHz SC-ECRIS for the production of an intense U ion beam. Last year, we produced ~200 eµA of U^{35+} at an injected Radio frequency (RF) power of ~2.6 kW. For the RIKEN RIBF experiment, we produced ~110 eµA of U^{35+} ions with the sputtering method for longer than one month without a break. In this case, we surely require a very stable beam to increase the transmission efficiency in the accelerators and avoid any damage to the components of the accelerator due to the high-power beam. Very recently, we tested the production of a highly charged Zn ion beam to meet the requirements of the RIBF project and to produce an intense beam with a very low consumption rate.

INTRODUCTION

To increase the beam intensity of a highly charged U ion beam for the RIKEN RIBF project [1], we attempted to improve the performance of RIKEN 28 GHz SC-ECRIS for the past several years [2, 3]. Further, to increase the output beam from the accelerator, we need to increase the U beam intensity and stabilize it because we need to avoid any damage to the components of the accelerator due to the high-power beam. To produce U vapor, we chose the sputtering method, which has two advantages:

1. We can install a large amount of material in the chamber.
2. We only need to supply a negative voltage (several kilovolts) to obtain neutral U atoms, which is simpler than the use of a high-temperature oven.

On the other hand, in general, the beam intensity with the sputtering method is weaker than that with the oven method. Furthermore, the beam intensity is not very stable, which may be due to the sputtering process. To solve these problems, we experimentally searched for the optimum conditions of the ion source. In these experiments, we obtained an intense beam with a low material consumption rate and supplied an intense beam of U^{35+} ions to the accelerators over a long period of time without serious issues. To obtain a more stable beam, we are developing a high-temperature oven. This summer, we modified the crucible to increase the volume and carried out a test experiment to produce a U^{35+} ion beam for a long period of time.

Very recently, there has been strong demand for the production of an intense beam of medium-mass heavy ions such as ^{78}Kr and ^{70}Zn ions. To meet this requirement, we tested the Zn ion beam production with RIKEN 28 GHz SC-ECRIS and successfully obtained a highly charged Zn ion beam with a low consumption rate for the first time experimentally.

In this paper, we present the recent experimental results and the experiences of the long-term operation of the ion source for the production of a U ion beam. In the next section, the experimental results related to the increase in the beam intensity of the highly charged U ion beam are presented. Then, the performance of the ion source for long-term operation is described. Next, we describe the preliminary results of a test experiment for the production of a Zn ion beam. In last section, the conclusions and the plans for future work toward improving the performance are presented.

URANIUM ION PRODUCTION

The structure of the ion source and the method for producing neutral U atoms with the sputtering method are described in Refs. [2] and [3] in detail. The main feature of the ion source is that it has six solenoid coils for producing a mirror magnetic field. Using this configuration, one can produce the so-called "flat B_{min}" [4] and "classical B_{min}."

Figure 1a) shows the beam intensity of U^{35+} as a function of the injected RF power, which was calculated using the increase in the cooling water temperature of the plasma chamber. For the production of neutral U atoms, we used the sputtering method [3]. The extracted voltage was maintained at 22 kV in this experiment. Closed circles are the results with the magnetic field strength of RF injection side (B_{inj}) ~ 3.1 T, the minimum magnetic field of mirror magnetic field (B_{min}) ~ 0.66 T, magnetic field strength of the beam extraction side (B_{ext}) ~ 1.79 T, and the radial magnetic field strength on the inner wall of the plasma chamber (B_r) ~ 1.88 T, whereas open circles are the results with B_{inj} ~ 3.1 T, B_{min} ~ 0.56 T, B_{ext} ~ 1.76 T, and B_r ~ 1.88 T. In this case, we added 18 GHz microwaves (400–450 W, double frequency injection). The typical gas pressure with B_{min} ~ 0.66 T was ~7.6×10^{-5} Pa, and the optimum gas pressure for maximizing the beam intensity slightly increased as the injected RF power increased. Additionally, we observed that the beam stability improved with the use of double frequency injection, which is the same as the result in Ref. [5]. The beam intensity linearly increased as the injected RF power increased for both cases. The beam intensity with a lower B_{min} (~0.56 T) is slightly lower than that with a higher B_{min} (~0.66 T).

INNOVATIVE SCHEMES OF PLASMA HEATING FOR FUTURE MULTIPLY-CHARGED IONS SOURCES: MODELING AND EXPERIMENTAL INVESTIGATION

G. Castro[*][1], D. Mascali[1], G. Torrisi[1], L. Celona[1], O. Leonardi[1], M. Mazzaglia[1,2], D. Nicolosi[1], R. Reitano[1,2], G. Sorbello[1,3], C. Altana[1,2], F. P. Romano[1,4], and S. Gammino[1]

[1]LNS-INFN, Catania, Italy
[2]Università degli studi di Catania, dipartimento di Fisica, Catania, Italy
[3]Università degli studi di Catania, DIEEI, Catania, Italy
[4]CNR, Istituto per i Beni Archeologici e Monumentali, Via Biblioteca 4, 95124 Catania, Italy

Abstract

The application of plasma heating methods alternative to the direct Electron Cyclotron Resonance coupling, such as the Electron Bernstein Waves heating, is already a reality in large-size thermonuclear reactors. The heating driven by these plasma waves gives the unique opportunity to largely overcome the cut-off density. The downsizing of tools and methods needed to trigger EBW in compact traps such as ECRIS devices is still a challenge, requiring advanced modeling and innovative diagnostics. At Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali del Sud (INFN-LNS), the off-ECR heating (driven by Bernstein waves) has produced a highly overdense plasma. Interferometric measurements say the electron density has overcome by a factor ten the cut-off density at 3.76 GHz. More advanced schemes of wave launching have been then designed and implemented on the new test-bench called Flexible Plasma Trap, operating up to 7 GHz – 0.5 T, in flat/simple mirror/beach magnetic configuration. The paper will give an overview about modal-conversion investigation by a theoretical and experimental point of view, including the state of the art of the diagnostics developed to detect plasma emitted radiation in the RF, optical, soft-X and hard-X-ray domains.

INTRODUCTION

The Electron Cyclotron Resonance Ion Sources (ECRIS) and the Microwave Discharge Ion Sources (MDIS) are currently the best devices worldwide to feed effectively high-energy accelerators [1]. Plasma is produced by microwaves typically in the range 2.45-28 GHz by means of the so-called "Electron Cyclotron Resonance (ECR)". Most of the parameters of the extracted beam, such as the intensity, the emittance and the shape in the real space depend on the characteristics of the plasma from which the beam is extracted [2]. Any further development of ECR-type ion sources is thus intrinsically limited by physical properties of the plasmas. In microwaves-sustained plasmas, the density increases with RF power and stabilizes around a value below the critical density $n_{cut-off}$. An option to overcome this limitation consists in the use of ElectroStatic (ES) waves, showing no cut-offs within the plasma. An ES wave is a rarefaction-compression wave whose electric field is parallel to the wave propagation direction. Most of ES waves do not suffer any resonance within a plasma; however, Electron Bernstein Waves (EBW) [3] can be strongly absorbed by the plasma at cyclotron harmonics [4] . Due to their electrostatic nature, EBWs must be generated within the plasma from electromagnetic waves. EBWs are excited at UHR via the decay of a large-amplitude electromagnetic wave, propagating perpendicular to ambient magnetic field in the X-mode, into a short-wavelength electron Bernstein. Three main mechanisms of EM to EBW coupling have been studied and characterized in plasma fusion devices, as schematically depicted in Fig. 1:

- **High field side launch:** X waves are launched by regions where $B/B_{ECR} > 1$. X waves are here not screened by the R cut-off, reach the UHR crossing the ECR from the high field side, then being converted into EBWs.

- **Directed FX-B conversion:** The fast X-mode (FX) tunnels through the evanescent region between the R-wave cut-off and the UHR and couples to the slow X-mode (SX) that, in turn, mode converts to EBWs at Upper Hybrid Resonance (UHR).

If the UHR layer is enclosed by R and L cut-offs, the X wave can be reflected back and forth passing through the UHR, then leading to the establishment of the Budden-type conversion scenario. The module of the conversion efficiency of a FX wave into a B-mode in these conditions is [5]:

$$|C_{XB}| = 4e^{-\pi\eta}\left(1 - e^{-\pi\eta}\right) \qquad (1)$$

η is the Budden parameter, obtained by expanding the wave potential around the UHR. If the length scale of magnetic field variation $L_B = B/(\partial B/\partial x)$ is larger than electron density variation length-scale $L_n = n_e/(\partial n_e/\partial x)$, η can be written as:

$$\eta = 294 \left. |BL_n| \right.^{UHR} \qquad (2)$$

Direct FX-B conversion heating is used in experiments with relatively low magnetic field, where the normalized gradient length $k_0 L_n$ is ~ 0.3 (k_0 being the wave number of the incident wave in vacuum) and η ~ 0.22 [6, 7].

---

* Castrog@lns.infn.i

CAVITY TUNING EXPERIMENTS WITH THE JYFL 14 GHz ECRIS [*]

O. Tarvainen[†], T. Kalvas, H. Koivisto, R. Kronholm, J. Laulainen, J. Orpana

University of Jyväskylä, Jyväskylä, Finland

V. Toivanen

European Organization for Nuclear Research (CERN), 1211 Geneva 23, Switzerland

I. Izotov[1], V. Skalyga[1]

Institute of Applied Physics, RAS, 46 Ul'yanova St., 603950, Nizhny Novgorod, Russian Federation

[1]also at Lobachevsky State University of Nizhny Novgorod (UNN), 23 Gagarina St., 603950
Nizhny Novgorod, Russian Federation

Abstract

Experimental results showing the effect of cavity tuning on oxygen beam currents extracted from the AECR-type JYFL 14 GHz ECRIS are reported. The microwave-plasma coupling properties of the ion source were adjusted by inserting a conducting tuner stub through the injection plug, thus changing the dimensions of the plasma chamber and affecting the cavity properties of the system. The beam currents of high charge state ions were observed to vary up to some tens of percent depending on the tuner position and the microwave frequency. In this paper we focus on reporting results obtained in the frequency range of 10.75–12.75 GHz.

INTRODUCTION

Experiments with 2nd generation ECR ion sources have demonstrated that the beam currents of high charge state ions are sometimes sensitive to microwave frequency variations on the order of 10 MHz [1, 2]. The effect has been ascribed to frequency dependent electromagnetic field pattern over the resonance surface [3,4], i.e. excitation of cavity modes, and named frequency tuning effect (FTE). This explanation, however, has two significant shortcomings: (1) the electromagnetic properties of the cavity are strongly affected by the plasma [5], thus obscuring the mode structure, and (2) only Caprice-type ion sources [6] exhibit strong frequency dependence while the performances of A-ECR type sources [7] are less sensitive to FTE. The most significant difference between the two source types is the microwave coupling scheme. In Caprice-type sources the microwave power is launched into the plasma chamber through an external waveguide-to-coaxial transition component equipped with a stub tuner for impedance matching. In the AECR-type sources the microwave-plasma coupling is realized through a waveguide port inserted directly into the plasma chamber, hence making the A-ECR design less complex. These microwave coupling structures are presented in Fig. 1 [8].

It can be argued that the observed differences between the source types could be explained solely by the sensitivity of the microwave-plasma coupling system on the frequency variations, not by the excitation of cavity modes. Thus, probing the source performance by varying the frequency of the microwave radiation is not the optimal technique to detect the existence of possible cavity modes and to study their effect on the high charge state ion beams. This is because both, the microwave launching system and the (possible) cavity modes are sensitive to frequency variations. The cavity modes and their Q-values are determined by the dimensions and surface properties of the plasma chamber. Thus, a preferred technique to probe the existence of the cavity modes and their influence on the source performance is to change the dimensions of the plasma chamber while keeping the microwave frequency constant. Such experiments probing the *cavity tuning effect* (CTE) of an A-ECR-type ion source operating in the frequency range of 14.00–14.15 GHz have been reported recently [9]. It was shown that the extracted currents of the high charge state ions can be increased only moderately (<10 % for O^{6+}) by tuning the cavity properties of the plasma chamber. Since the frquency range probed in Ref. [9] is rather narrow, the CTE was studied further in a wider range of frequencies as described in the following sections.

EXPERIMENTAL SETUP

The experimental data discussed hereafter were taken with the JYFL 14 GHz ECRIS [10] (see Fig. 2), which is a typical A-ECR-type room-temperature ion source. The plasma chamber of the JYFL 14 GHz ECRIS has an inner diameter of 76.2 mm and length of 278 mm and is made of aluminum. The cylindrical symmetry of the chamber is broken by two waveguide ports (WR62 and WR75) and radial pumping holes between each magnetic pole of the sextupole. Furthermore, the cavity properties are affected by ϕ =21 mm biased disc and ϕ =8 mm plasma electrode aperture. In the present study the cavity dimensions were modified by inserting a cylindrical (ϕ =15 mm) water-cooled copper rod shown in Fig. 2 into the plasma chamber through the opening in the injection plug, normally used as a port for a miniature oven. The rod was connected electrically to the plasma chamber and its position was adjusted online by using a linear feedthrough without compromising the vacuum or switching off the microwave power or the high voltage while monitoring the extracted beam currents. The rod position was varied from 0 mm, corresponding to the

RECENT BREMSSTRAHLUNG MEASUREMENTS FROM THE SUPERCONDUCTING ELECTRON CYCLOTRON RESONANCE ION SOURCE VENUS

J. Y. Benitez[#], C. M. Lyneis, L. W. Phair, D. S. Todd, D. Z. Xie
LBNL, Berkeley, CA 94720, USA

Abstract

Axial bremsstrahlung from the superconducting Electron Cyclotron Resonance ion source VENUS have been systematically measured as a function of RF heating frequency, and the axial and radial field strengths. The work focuses on bremsstrahlung with energies greater than 10 keV to extract the spectral temperature T_s. The three axial coils and the radial coils in the superconducting VENUS can all be set independently and have a large dynamic range, which makes it possible to decouple B_{min} and ∇B_{ECR} and study their effects on the bremsstrahlung independently. With typical pressure and RF power levels, the measurements show that T_s depends approximately linearly on B_{min} and is not correlated with the ∇B_{ECR}, the magnetic field mirror ratios, or the RF frequency. These results are important for the next generation of ECR ion sources, which are designed to operate at frequencies above 40 GHz and significantly higher magnetic fields where bremsstrahlung is expected to cause a significant cryogenic heat load and increase the radiation shielding requirements.

INTRODUCTION

Electron Cyclotron Resonance Heating (ECRH) is an efficient method to couple microwave energy into the plasma electrons. Use of ECRH to generate plasma began with the early mirror machines developed by the plasma fusion community and later as a spin-off in the high charge state ECR ion sources, ECRIS, initially developed by R. Geller in the 1970's [1]. VENUS is the first 3rd generation ECR ion source using both 18 and 28 GHz microwave power to produce a plasma with electrons of sufficient energy to produce high charge states such as Ar^{18+} [2], Xe^{43+}, and U^{50+} [3]. The ionization potential for these highly-charged ions is in the range of 2 to 5 keV and the maximum cross section for electron impact ionization occurs at three to five times those energies or approximately 6 to 25 keV. VENUS produces plasma with electrons of maximum energy up to several hundred keV as is evidenced in the hot tail of the emitted bremsstrahlung. The existence of the electron hot tail has been observed in both simple mirror machines for fusion research in the 60's [4] and in the minimum B magnetic field structures used in modern high charge state ECR ion sources [5].

The performance of high charge state ECR ion sources scales roughly with the square of RF heating frequency, as predicted by R. Geller [6]. The third generation ECRIS operating at either 24 or 28 GHz [2, 7-9] are presently the best performers. These sources operate at higher magnetic

fields than earlier generation sources operating at frequencies of 18 GHz or lower. The third generation ECRIS also produce significantly more intense and more energetic bremsstrahlung. The high energy bremsstrahlung adds a thermal load to the cryogenic system for superconducting ECRIS because the high energy x-rays ($\sim E > 300$ keV) easily pass through the plasma chamber and outer wall of the cryostat and then are absorbed in the cold mass [5]. The fourth generation sources currently being developed will operate at higher magnetic fields with heating frequencies above 40 GHz [10]. It is anticipated that the next generation source will produce even more intense and energetic hot electrons and therefore methods to understand, control, or reduce the bremsstrahlung production are needed. This research explores which ECRIS parameters including magnetic field geometry and microwave frequency affect the production of bremsstrahlung and the spectral temperature T_s obtained from it.

EXPERIMENTAL SETUP

VENUS uses three superconducting solenoids and one superconducting sextupole to generate the minimum-B magnetic field configuration to confine the plasma, as shown in Figure 1. Each coil is independently powered and the axial fields can produce up to 4 T at injection, 3T at extraction and a center coil that can produce a B_{min} value from 0 to 2 T. The sextupole coils can produce up to 2.2 T on the plasma wall at a radius of 72 mm and the radial field generated by the sextupole is typically set to values close to the peak axial field at extraction. This produces a closed resonance field at 2T or twice B_{ECR} at 28 GHz [11].

The central field can be lowered sufficiently so there are simultaneous resonance fields for 14, 18 and 28 GHz. The VENUS microwave system consists of a 2 kW 18 GHz klystron and a 10 kW 28 GHz gyrotron. A 2 kW 14 GHz klystron was also used briefly to test the frequency dependence of the spectral temperature.

The axially emitted bremsstrahlung spectra from VENUS were recorded using an Amptek XR-100-CdTe X-Ray and Gamma Ray diode detector [12]. It consist of a 1 mm thick, 25 mm^2 detector that sits behind a 4 mil Be window. Its resolution at 122 keV is < 1.5 keV FWHM, which is not as good as Si diode detectors. However, the CdTe detectors are much more sensitive at energies above 20 keV as they have a higher stopping power with shorter attenuation lengths [13]. In addition, the XR-100-CdTe detector has the advantage that it can be operated in vacuum, without attenuation caused by windows.

#jybenitez@lbl.gov

STRUCTURAL INFORMATION ON THE ECR PLASMA
BY X-RAY IMAGING

R. Rácz[†], S. Biri, J. Pálinkás, Institute for Nuclear Research, Hungarian Academy of Sciences
(Atomki), Debrecen, Hungary
D. Mascali, G. Castro, C. Caliri, L. Neri, F. P.Romano[1], S. Gammino
Instituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud, Catania, Italy
[1]also at CNR-Istituto per i Beni Archeologici e Monumentali

Abstract

Precise knowledge on the density distribution of the Electron Cyclotron Resonance Ion Source plasma is needed by several reasons: i) in order to possibly improve the quality parameters of the extracted ion beam (emittance, brightness) strongly linked to the plasma structure, ii) to correctly investigate the recently observed plasma instabilities and/or the implementation of alternative heating methods (e.g. modal conversion) iii) in order to improve the general microwave-to-plasma coupling efficiency, in view of a microwave-absorption oriented design of future ECRIS. The non-destructive spectroscopic diagnostic methods give information always corresponding to integration over the whole plasma volume. X-ray imaging by pin-hole camera can partly overcome this limitation. We performed volumetric and space resolved X-ray measurements at the ATOMKI ECRIS operated at lower frequencies than usual. The experimental setup in detail and the methods how the working parameters were selected will be shown. The integrated and photon-counting analyses of the collected plasma images show a strong effect of the frequency and magnetic field on the plasma structure and local energy content.

INTRODUCTION

Imaging of the electron cyclotron resonance (ECR) plasmas by using CCD camera in combination with a pinhole is a non-destructive diagnostics method to record the strongly inhomogeneous spatial density distribution of the X-ray emitted by the plasma and by the chamber walls. This method can provide information on the location of the collisions between warm electrons and multiple charged ions/atoms, opening the possibility to investigate plasma structure in more details. Precise knowledge on the density distribution of the Electron Cyclotron Resonance Ion Source (ECRIS) plasma is needed by several reasons: 1) ECRISs provide worldwide highly charged ion beams for high energy accelerators and also the low energy ion beam of the source can be used in various fields of science (e.g. in atomic physics research, material science). In both application cases the parameters of the extracted ion beam are essentially and strongly determined by the shape, structure and quality of the ECR plasma. 2) Development path of the ECRISs is mainly

traced by the trend to apply stronger magnetic confinement with higher RF frequency. However the coupling efficiency may also improves by a microwave-absorption oriented design. The next generation of ECRISs may take into account the optimisation of the spatial density distribution of the plasma. 3) The correct investigation of the recently observed plasma instabilities [1] and/or the implementation of alternative heating methods (e.g. modal conversion [2]) are inconceivable with the few existing experimental data on the precise plasma density profiles.

In 2002 the Atomki ECR group carried out and published for the first time space-resolved plasma diagnostics measurements by a pinhole X-ray camera [3]. In 2014 a new series of volumetric and space resolved X-ray measurements have been carried out at the Atomki ECR ion source. The measurement was done in close collaboration between the Atomki ECRIS team (Debrecen, Hungary) and the ion source group of INFN-LNS (Catania, Italy). The aim was to study mainly the effect of the microwave frequency but also the effect of some setting parameters like microwave power and strength of the axial magnetic field on the plasma structure. The result of the volumetric measurements and the comparison of the two (2002 and 2014) experimental setups were published already in recent articles [4, 5].

Two different type of exposing methods were applied. In case of the spectrally integrated mode the photos are taken with several ten seconds exposure time. The only limitation for the exposure time was to avoid the blooming of the CCD (when a pixel in a CCD image sensor is overloaded). Individual pixels can be loaded by many X-ray photons, therefore the energy information of a given photon are lost. Photos were also taken in photon counting mode. In that case thousands of images are exposed with experimentally adjusted short (milliseconds) exposure time. Each pixel registered either 0 or 1 X-ray events. Therefore any individual pixel can be used as a single photon detector to spectrally resolve the plasma image. Because of the strong inhomogenity of the plasma, region of interests (ROIs) were selected and the exposure time was settled by the intensity of the given region. The intensity of the other parts of the images was left out of consideration.

The huge amount of obtained experimental and then analysed data require the publication of the results in several papers. The present paper will show the methods how the working parameters for the pinhole camera measurements were selected. The presented preliminary

---

[†]rracz@atomki.hu

SPIRAL1 CHARGE BREEDER: PERFORMANCES AND STATUS

L. Maunoury[#], P. Delahaye, M. Dubois, O. Bajeat, C. Barthe-Dejean, R. Frigot, P. Jardin,
A. Jeanne, O. Kamalou, P. Lecomte, B. Osmond, G. Peschard, and A. Savalle
GANIL, bd Henri Becquerel, BP 55027, F-14076 Caen cedex 05, France
J. Angot, T. Lamy, and P. Sole
Laboratoire de Physique Subatomique et de Cosmologie - Université Grenoble Alpes -
CNRS/IN2P3 - 53, rue des Martyrs, 38026 Grenoble Cedex, France

Abstract

In the framework of the SPIRAL1 upgrade under progress at the GANIL lab, the charge breeder based on a LPSC Phoenix ECRIS, first tested at ISOLDE [1] has been modified as to benefit of the last enhancements of this device from the 1+ / n+ community [2].

Prior to its installation in the middle of the low energy beam line of the SPIRAL1 facility, it has been tested at the 1+/n+ LPSC test bench to validate its operation performances. Charge breeding efficiencies as well as charge breeding times have been measured for noble gases and alkali elements. The experimental results demonstrated that the modifications done were on the right track leading the SPIRAL1 charge breeder to the top worldwide in terms of performances. The experimental outcomes have shown a strong interrelationship between the charge breeding efficiency and the charge breeding times which is still under active discussion.

This paper will summarize the experimental results obtained and will discuss the specific phenomenons observed but still not fully explained as the charge breeding time evolution, the depletion of highly charged ions in the buffer gas etc.

INTRODUCTION

The SPIRAL 1 facility is under operation since 2001 and almost 35 Radioactive Ion Beams (RIBs) have been delivered to the Physicist. The first Target Ion Source System (TISS) developed at GANIL [3] was very chemically selective: only gaseous elements as noble gases, N, O and F could be ionized. These RIBs allowed numerous results in Nuclear Physics [4] but physicists need an enlarged palette to study the nuclear properties and to test the nuclear models including isotopes of condensable elements. The 1+/n+ [5] technique has been chosen as many different TISS providing 1+ beams can be developed for specific chemical family elements with high efficiency. The charge breeder is requested to boost the charge state from 1+ to n+ prior to the post-accelerator: the cyclotron CIME [6] is delivering a RIB with energy in the range 2 – 20 MeV/u suitable for the nuclear physicists. The charge breeder is based on one developed at LPSC and modifications have been already described in other papers [7, 8]. In the following, the experimental results of the charge breeder operation on the LPSC test bench will be presented as well as its status at the SPIRAL1 facility.

EXPERIMENTAL RESULTS

The installation of the SPIRAL1 charge breeder in the middle of the 1+/n+ test bench at LPSC needed a modification thereof. The Figure 1 is the layout of the experiment at LPSC. The Reference 8 describes the experimental conditions.
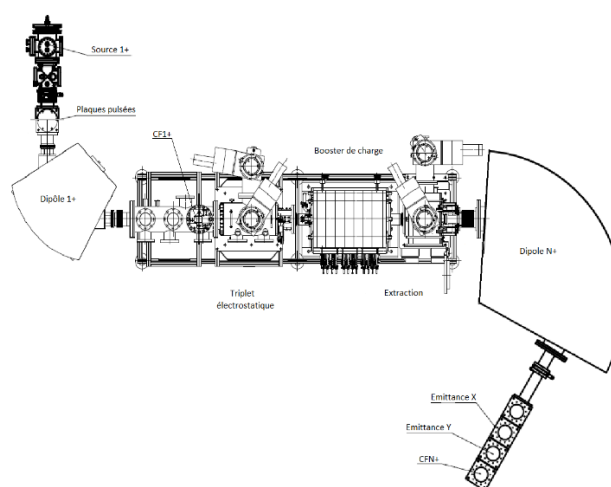

Figure 1: Layout of the Spiral1 charge breeder at LPSC laboratory.

Effect of the Residual Gas Pressure

The residual gas pressure value plays a major role on the charge breeding efficiencies as demonstrated at the CARIBU facility: charge breeding efficiencies get their higher values as soon as the pressure drops down to the level of few 10^{-8} mbar. The Figure 2 reports the evolution of the charge breeding efficiency of the Rb^{19+} versus the product of the pressure at injection times the pressure at extraction. The charge breeding efficiency drops continuously with the increase of the residual gas pressure. The CB has been modified such the conductances to the plasma chamber are optimized.

Effect of the 1+ Injected Current

The question is the following: is the charge breeding efficiency measured with a stable beam in the nA range still valid with RIBs in the pA even less range?

THE PROTON SOURCE FOR THE EUROPEAN SPALLATION SOURCE (PS-ESS): INSTALLATION AND COMMISSIONING AT INFN-LNS

L. Celona[†], L. Allegra, A. Amato, G. Calabrese, A. Caruso, G. Castro, F. Chines, G. Gallo, S. Gammino, O. Leonardi, A. Longhitano, G. Manno, S. Marletta, D. Mascali, A. Massara, M. Mazzaglia, A. Maugeri, L. Neri, S. Passarello, G. Pastore, A. Seminara, A. Spartà, G. Torrisi, S. Vinciguerra, Instituto Nazionale di Fisica Nucleare-Laboratori Nazionali del Sud, Catania, Italy
S. Di Martino, P. Nicotra, Si.a.tel., Catania, Italy

Abstract

A 2.45 GHz – 0.1 T microwave discharge Proton Source has been designed and assembled at INFN-LNS for the European Spallation Source (PS-ESS) in order to produce pulsed beams of protons up to 74 mA nominal current, at 75 keV of energy, with a transverse emittance containing 99 % of the nominal proton current below $2.25\,\pi$ mm mrad and a beam stability of ± 2 %. The challenging performances of the machine have triggered specific studies on the maximization of the proton fraction inside the plasma and of the overall plasma density, including dedicated modelling of the wave-to-plasma interaction and ionization processes. The plasma conditioning phase started in July and excellent RF to plasma coupling, more than 99.5% is evident since the beginning. Reflected power fluctuation less than 0.05 % was measured providing a great starting point to reach the beam stability requested by the ESS accelerator.

INTRODUCTION

The European Spallation Source will be one of the most advanced technological tools for scientific and industrial development in Europe in the next decades. A linear accelerator is going to be built for the production of 2 GeV protons to be used for neutron production via nuclear spallation. Peak beam power will be 125 MW. Neutrons will be finally used for fundamental science and applied research.

The source named Proton Source for ESS (PS-ESS) [1] was designed with a flexible magnetic system and a compact tetrode extraction system with the goal to minimize the emittance and the time needed for the maintenance operations. Figure 1 shows a picture of the High Voltage (HV) platform fully assembled with the source body and magnetic system, the microwave injection line, all power supplies, control system devices, cooling system, gas injection and measurement devices. The ESS injector design has taken advantage of recent theoretical updates together with the new plasma diagnostics tools developed at INFN-LNS. The improved know-how will permit to fulfil the requirements of the ESS normal conducting front-end; the proton beam should be 74 mA which can be obtained with a total beam current of about 90 mA. The beam stability during the normal operations (in terms of current and emittance) shall be within ± 3.5 % as for pulse to pulse variation and ± 2 % of the beam current if averaged over a period of 50 us. The pulse duration is 2.86 ms with 14 Hz repetition rate.

The requirements for the proton source and the LEBT are summarized in Table 1 and Table 2.

A detailed study of the beam transport in regime of space charge compensation was done and experimentally verified [2, 3, 4]. A reliability better than 95% is requested for the whole accelerator, thus meaning that the source reliability is expected to be greater than 99%. For that reason, the mechanical design was driven also to maximize the MTBF and minimize the MTTR.
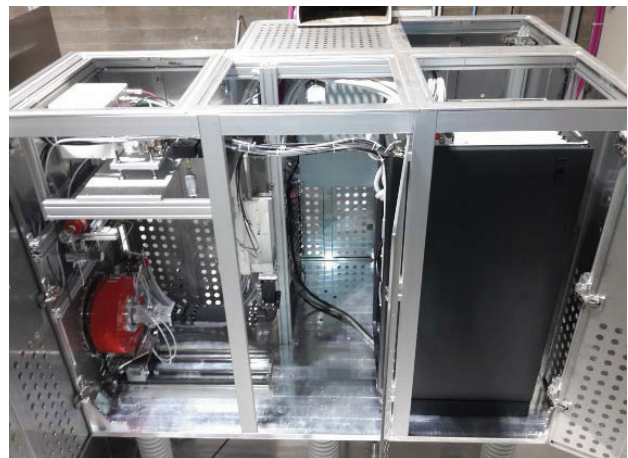

Figure 1: PS-ESS, high voltage platform detail.

Table 1: PS-ESS Requirements

Parameters	Value
Proton current range	67 – 74 mA
Proton fraction	> 75 %
Current stability (50us avr.)	± 2 %
Pulse to pulse stability	± 3.5 %
Beam energy	70 – 80 ± 0.01 keV
Repetition rate	1 – 14 Hz
Pulse length	5 – 2860 ± 1 us
Current reduced (with iris)	2 – 74 ± 1 mA
Restart after vacuum break	< 32 h
Restart after cold start	< 16 h

† celona@lns.infn.it

SECRAL II ION SOURCE DEVELOPMENT AND THE FIRST COMMISSIONING AT 28 GHz*

L. Sun[#], W. H. Zhang, X. Fang, J. W. Guo, W. Wu, Y. C. Feng, X. Z. Zhang, Y. M. Ma,
H. Y. Ma, Z. Shen, T. J. Yang, Y. Yang, B. Zhao, H. W. Zhao, L. Z. Ma
IMP/CAS, Lanzhou, 730000, China

Abstract

SECRAL II ion source has been successfully designed and developed at IMP. This ion source is a 3rd generation ECR machine optimized for the operation at 28 GHz. As a second superconducting ECR ion source developed at IMP with the identical cold mass design as SECRAL ion source, which has the sextupole coils external to the axial solenoids, the magnet performance is more robust according the training test. After a short time beam test at 18 GHz, SECRAL II has been commissioned at 28 GHz, and some preliminary results have been achieved with high charge state ion beam production. This paper will present the magnet design and test results. The first beam at 28 GHz will also be given.

INTRODUCTION

ECR ion sources have been used in IMP as the heavy ion injectors for over 20 years. Absolutely, the incorporation of ECR ion source to the heavy ion accelerator complex has already improved the machines' performance. The existing facility HIRFL (Heavy Ion Research Facility in Lanzhou) as shown in Fig. 1, which is mainly composed of one K69 cyclotron SFC, one K450 cyclotron SSC, RIBLL1 for radioactive beam production, cooler storage rings CSRm and CSRe, and the radioactive beam line RIBLL2 to connect the two rings [1, 2], has 3 injector ion sources, i.e. all permanent magnet ion source LA-PECR1 for intense light ion beam beams, room temperature ion source LECR3 for intense medium charge state heavy ion beams (A≤40), and SECRAL the superconducting ion source for intense highly charged heavy ion beams (A≥40). SECRAL is now the main working horse of heavy ion beam for HIRFL, therefore in case of any big failure with the ion source, especially the superconducting magnet that has been in operation for over 11 years, the facility would be impossible to run heavy ion beams heavier than Ar, and the performance of the facility will be greatly affected. It has been highly recommend having a second high performance superconducting ECR ion source as the spare one. Additionally, as an upgrade program to boost the performance of the SSC cyclotron and also the storage ring, a project proposal has been issued to build a dedicated injection linac injector for SSC. The most interested ion beam for the design is several puA of U^{34+}, and the more preferred one is U^{37+}. Fun-

damentally, only with a 3rd generation ECR ion source, the goal could be achieved. Therefore, for a dual-purpose strategy, SECRAL II project was initiated.
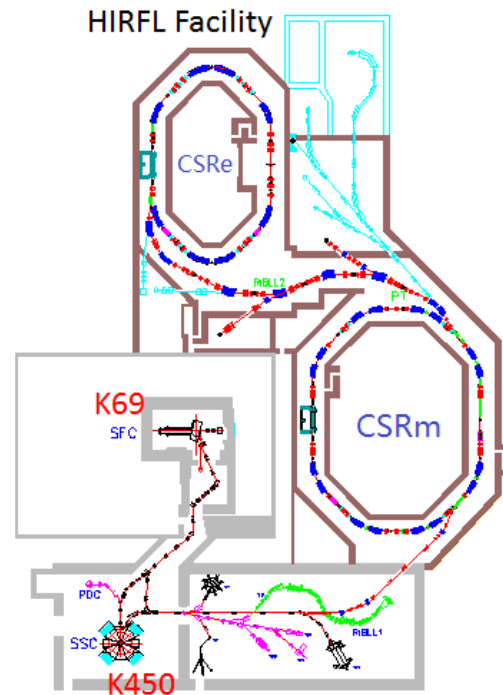

Figure 1: Layout of HIRFL facility.

SECRAL was connected to the injection line of HIRFL complex in 2007 and as of early 2016, more than 24,000 hours' beam time has been accomplished. It has been demonstrated as a very reliable and high performance ECR ion source. Especially, the recent progress with high intensity Ar and Xe beams, such as 1.42 emA Ar^{12+}, 1.1 emA Xe^{26+}, 0.67 emA Ca^{12+}, 0.68 emA Bi^{31+} and etc., has demonstrated its performance and capacity [3]. Logically, SECRAL II will be a duplicated one of SECRAL.

MAGNET DESIGN

The SECRAL II cold mass is almost a duplicated one of SECRAL. In that case, the axial fields inside the plasma chamber wouldn't be different from SECRAL. The radial field gradient would be the same as SECRAL. Therefore, the sextupole field at the same chamber wall would be the same. SECRAL was initially designed with 63 mm inner radius of plasma chamber, but after 1.5 mm thickness Ta shielding cylinder was integrated to do bremsstrahlung X-ray shielding to protect the main insu-

FIRST PLASMA OF THE PHOENIX V3 ECR ION SOURCE *

T. Thuillier[†], J. Angot, L. Bonny, J. Jacob, A. Leduc, T. Lamy, P. Sole, LPSC, Grenoble, France

L. Maunoury, J.-L. Flambard, GANIL, France

C. Peaucelle, IPNL, France

T. Kalvas, JYFL, Finland

Abstract

PHOENIX V3 is an upgrade of the PHOENIX V2 ECR ion source granted by the European CRISP project. This new ECRIS features a larger plasma chamber and a reduced vacuum pressure under operation. The V3 source will replace the V2 one on the SPIRAL2 accelerator in 2018. The first plasma of PHOENIX V3 was achieved on May 9th 2016. The early commissioning of the V3 source at low 18 GHz power demonstrates as expected an enhancement of the high charge state production and Ar^{14+} intensity already exceeds the V2 one. Further enhancements are expected the outgassing will be achieved and the full RF power will be injected in the source.

MOTIVATION FOR THE SOURCE UPGRADE

The new SPIRAL2 accelerator at GANIL (Caen, France) includes a nuclear physics program dedicated to heavy ions with the S3 collaboration [1]. The present acceleration scheme of the LINAC imposes the production of ion beams with M/Q=3. High intensity beams are possible with such a M/Q up to M~40. Above this mass, the charge state is so high for a given mass that the achievable intensity collapses rapidly when the mass increases. S3 collaboration is thus interested in the procurement of ion beams with an intensity of several pµA up to the mass M~60. The availability of a European fund (CRISP Project) made an upgrade of the existing PHOENIX V2 source possible. The goal is to enhance the high charge state production to fulfil the need expressed by the S3 collaboration. The strategy of the upgrade is:

- to enhance the plasma chamber volume radially to increase the ion confinement time,
- to reduce the vacuum pressure in the source to decrease the charge exchange process, by adding a pumping system on the injection side of the source.

These two effects are expected to increase by 50 to 100% the M/Q=3 ions up to the mass 60 with respect to the existing V2 source.

V3 DESIGN

The magnetic simulation of V3 and some information on the mechanical design can be found here [2, 3]. For completion, a summary of the information is proposed below. The available funding allowed designing a new hexapole, a new plasma chamber and a vacuum box located on the injection side of the source. An overview of the V3 design

is displayed in Fig. 1 (see next page). In order to minimize the impact of the modifications, the axial magnetic structure of the existing V2 source was kept unchanged. The main design difference came from a new hexapole providing a much larger radius at the plasma chamber wall of 45 mm (31 mm for V2). The new chamber volume is 1.4 liter, being ~2.2 time larger than the V2. The radial intensity at wall with the bare hexapole is 1.18T. Later, a special plasma chamber including soft iron slits on its outer part will be installed to reach ~1.25T along the magnetic poles at the aluminium wall. The source can accept new generation ovens up to Ø20 mm. The oven axis is slightly pointing toward the sky to prevent any liquid metal spill toward the plasma chamber. Two WR 62 waveguide ports are available (see Fig. 2). One is currently fed with an 18 GHz 2 kW RF Klystron. The second will be used to inject a 14 GHz power when it will be available for the project. A bias disk with some water cooling is also installed on the injection flange. Two new ovens will be tested in the source. The first, developed at LPSC, is a low temperature oven working up to ~600°C with a design similar to the one used in LBNL and MSU. The new oven will be commissioned in the early 2017 with calcium. The second oven is a new high temperature large capacity oven developed by GANIL. This oven is also expected to be commissioned in 2017 to feed the source.
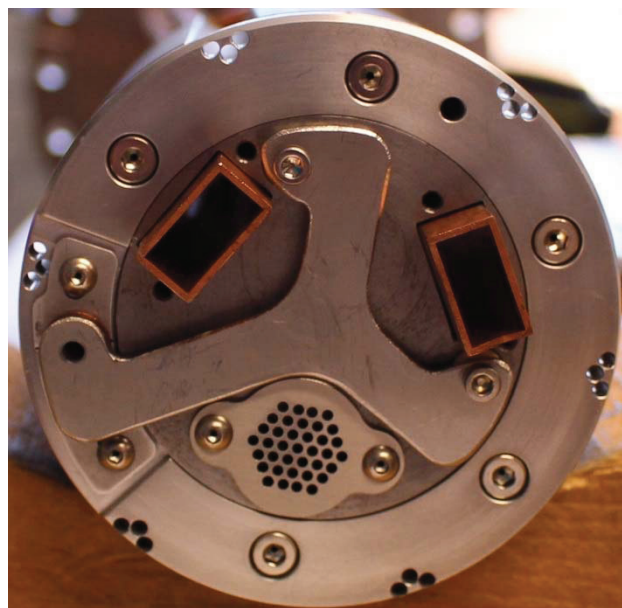

Figure 2: Photograph of the source injection flange.

RECENT DEVELOPMENTS WITH THE
GTS-LHC ECR ION SOURCE AT CERN

V. Toivanen*, G. Bellodi, C. Fichera, D. Küchler, A. M. Lombardi,
M. Maintrot, A. Michet, M. O'Neil, S. Sadovich, F. Wenander
European Organization for Nuclear Research (CERN), Geneva, Switzerland
O. Tarvainen, University of Jyväskylä, Department of Physics (JYFL), Jyväskylä, Finland

Abstract

Linac3 is the first link in the chain of accelerators providing highly charged heavy ion beams for the CERN experimental program. The beams, predominantly lead, are produced with the GTS-LHC 14.5 GHz Electron Cyclotron Resonance (ECR) ion source, operated in afterglow mode. In the framework of the LHC Injector Upgrade program (LIU), several activities have been carried out to improve the GTS-LHC and Linac3 performance, in terms of delivered beam current.

The extraction region of the GTS-LHC has been upgraded with redesigned apertures and the addition of an einzel lens, yielding improved Linac3 output. Also, a series of measurements has been performed to study the effects of double frequency heating on the afterglow performance of the GTS-LHC. A Travelling Wave Tube Amplifier (TWTA) with variable frequency and pulse pattern was utilized as a secondary microwave source. The double frequency effect commonly reported with CW operation of ECR ion sources boosting high charge state ion production was also observed in afterglow mode. Lastly, for studies of metal ion beam production, a dedicated test stand has been assembled to characterize the GTS-LHC resistively heated miniature oven performance.

INTRODUCTION

In order to prepare for the future high luminosity operation of the Large Hadron Collider (LHC), all the accelerators providing beam for the LHC experiments are undergoing an extensive upgrade program; the LHC Injector Upgrade (LIU). For the heavy ion accelerator chain this includes, from the lowest beam energy to the highest, the Linac3 linear accelerator, the Low Energy Ion Ring (LEIR), the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS). As part of the Linac3 upgrades, several activities have been carried out with the GTS-LHC Electron Cyclotron Resonance (ECR) ion source [1], which produces the primary heavy ion beams for the CERN experiments.

GTS-LHC is a 14.5 GHz second generation ECR ion source which is based on the Grenoble Test Source (GTS) by CEA, Grenoble [2]. The main differences to the GTS include a modified magnetic field structure with an added center coil and a stronger Halbach-style 36-piece permanent magnet hexapole. GTS-LHC is exclusively operated in afterglow mode to produce mainly lead ion beams, although also argon beam was delivered for experiments in 2015 and xenon is

planned for 2017. The afterglow operation is performed with a 10 Hz RF heating cycle at 50 % duty factor. A ~200 µs ion beam pulse is selected and accelerated through the linac from the afterglow burst which is exhibited by the extracted ion beam after the microwave switch-off. The lead beam is produced as $^{208}Pb^{29+}$ with 2.5 keV/u initial energy, as it provides the highest particle current during afterglow, and is stripped to $^{208}Pb^{54+}$ at the end of the linac for injection into LEIR with 4.2 MeV/u energy.

This paper presents three activities that have been recently carried out with the GTS-LHC; the GTS-LHC extraction region upgrade, double frequency plasma heating combined with afterglow operation and oven studies for metal ion beam production. These topics are discussed in the following chapters.

EXTRACTION REGION UPGRADE

Following a dedicated simulation study [3–5] the beam extraction region of the GTS-LHC was modified in the beginning of 2016. The goal of this upgrade was to increase the beam currents out of Linac3 by mitigating the beam losses immediately after the ion source and by improving the flexibility of the ion source tuning and matching to the following low energy beam transport (LEBT) section.

One of the main issues of the original extraction system that was observed with the simulations and verified with inspection of the extraction chamber was the strong divergence of the extracted ion beams. Due to the limited tuning capabilities of the extraction system this resulted in the collimation of a significant part of the extracted ion beam at the entrance of the beam pipe at the end of the ion source extraction chamber [4]. In order to improve the beam transmission in this region, the section immediately downstream from the extraction electrodes was redesigned with two main modifications. Firstly, in order to improve the transport flexibility and to mitigate beam collimation, the aperture restrictions were relaxed by increasing the beam pipe bore through the first beam line solenoid from 65 to 100 mm. Secondly, a new bipolar einzel lens was installed inside the extraction chamber to provide additional beam focusing and matching to the following beam transport section. A comparison of the original and the upgraded extraction regions are presented in Fig. 1. Further details of the designs are given in Ref. [5].

The performance of Linac3 has improved steadily after the implementation of the extraction region upgrade, as experience has been gained on how to optimize the ion source matching to the new beam transport conditions. The present

___
* ville.aleksi.toivanen@cern.ch

PRACTICAL COMPARISON OF TWO-FREQUENCY HEATING PHENOMENA IN DIFFERENT ECR ION SOURCES

A. Kitagawa[#], M. Muramatsu, NIRS, QST, Chiba, Japan
R. Rácz, S. Biri, ATOMKI, Debrecen, Hungary
Y. Kato, Osaka Univ., Osaka, Japan
W. Takasugi, AEC, Chiba, Japan

Abstract

Plasma heating in electron cyclotron resonance ion sources (ECRIS) with the injection of two microwaves having different frequencies has been studied. An 18 GHz ECRIS installed in the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) and a 14 GHz ECRIS at the Institute for Nuclear Research (ATOMKI) were utilized for this study. One was operated with the frequencies close together each; the other was tested with the two frequencies being even far from each other. The tendencies of the phenomena at both ECRISs were similar, and the output currents of highly charged ions increased with increasing the sum of two microwave powers.

INTRODUCTION

In order to improve highly charged ion production, the two-frequency heating technique was initiated by ECR pioneers Jongen and Lyneis in Berkeley, and some years later more successfully by Xie and Lyneis, again at Berkeley [1]. Since then, many ECR laboratories have tested this technique. The two-frequency heating technique has several advantages: it is effective for any kind of ion species, it is coexistent with almost all other techniques, and no modification of the existing structure is necessary, except for an additional microwave feeding.

Between 1998 and 2014 numerous experiments were carried out at NIRS; in each experiment a positive effect of the second microwave was demonstrated [2, 3]. Our basic observation concerning the productions of C, Ar, Fe, Ni, Kr, and Xe ions is that when the primary microwave power increases, the plasma shows instability, and it is difficult to keep. When an additional microwave with a different frequency is added in the above situation, the plasma stability is improved at greater microwave power. Our conclusion is that the output current of the highly charged ion beam is proportional to the total power of both microwaves. The dependence on the additional frequency showed fine structure. Since this structure depended on the magnetic field, vacuum pressure, and so on, precise frequency adjustment for the maximum output was required under each condition.

It is considered that the plasma instability of the ECR heating plasma is a 'microscopic instability'; like the velocity space instability. In an ECR ion source for the production of highly charged ions, a great deviation of the electron energy distribution from the Maxwell-Boltzmann distribution and the anisotropy of its velocity distribution may adversely affect the plasma stability [2].

Our group has focused on studying the mixture of two microwaves of which the two frequencies are each close together (close 2f) since 2008 at NIRS-HEC. An interest has arisen as to whether the above-mentioned phenomenon can be demonstrated using a different ion source where the two frequencies are even far apart from each other (far 2f). That is why we installed a 17.75-18.25 GHz microwave system in addition to the 14.3 GHz klystron amplifier of the ATOMKI ECRIS. The argon output currents at various values of the microwave power and frequency were recently studied.

TECHNICAL METHOD

18GHz NIRS-HEC ECRIS

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 synchrotron in 1994. HIMAC has treated more than 10,000 patients as of 2016 [4]. It has also been utilized as a second essential task to operate as a user facility for basic experiments in e.g. physics, chemistry, material science, and other life-science studies. In order to extend the range of available ion species for HIMAC, an 18 GHz ECRIS, named NIRS-HEC, was constructed in 1996. The detailed specifications of NIRS-HEC are described in reference [5].

The primary microwave source is an 18 GHz fixed-frequency Klystron (KLY) amplifier system with a maximum power of 1500 W. The additional source is a travelling-wave tube (TWT) amplifier system with a frequency range from 17.10 to 18.55 GHz and with the maximum power of 1200 W. Since the power stability is important for the reproducibility, both microwave systems have been equipped with power feedback. Pulse operation is available with both microwave sources.

14GHz ATOMKI ECRIS

A multi-purpose ECR ion source has been operating since 1996 at the Institute for Nuclear Research (ATOMKI). The ATOMKI-ECRIS does not serve as an injector for an accelerator; instead, it was designed and has been used for low-energy atomic physics research, for plasma studies and for medical and industrial applications [6,7]. The mechanical and electrical structures of the ATOMKI-ECRIS are not fixed; depending on the actual application goal, it has several configurations. During the present experiment, two external microwave sources are

#kitagawa.atsushi@qst.go.jp

AN ECRIS FACILITY FOR INVESTIGATING NUCLEAR REACTIONS IN ASTROPHYSICAL PLASMAS

M. Kreller*, G. Zschornack[1], C. Baumgart, Dreebit GmbH, Großröhrsdorf, Germany

[1] also at Dresden University of Technology, Dresden, Germany

K. Czerski, M. Kaczmarski, N. Targosz-Ślęczka

University of Szczecin Institute of Physics, Szczecin, Poland

A. Huke, G. Ruprecht, D. Weißbach, Institute for Solid State Nuclear Physics, Berlin, Germany

Abstract

Nuclear reactions at low energies can be strongly enhanced due to screening of the Coulomb barrier by the surrounding electrons. This effect was studied for the deuteron fusion reactions taking place in metallic environments as a model for dense astrophysical plasmas. Experimentally determined screening energies corresponding to the reduction of the Coulomb barrier height are much larger than the theoretical predictions. One possible explanation is the excitation of a hypothetical threshold resonance in the ^{4}He nucleus. As the energy dependence of the resonant reaction cross section differs to that of the electron screening effect, one can distinguish between both processes expanding measurements down to the deuteron energies of 1 keV. A novel ion accelerator was implemented at the University of Szczecin. Ions are produced by a Dresden ECRIS-2.45M as a high-current, low-Z ion source. The associated beamline designed to work on HV potential is combined with an ultra-high vacuum target chamber on ground potential. This setup enables decelerating ions below a kinetic energy of 1 keV and reduces target impurities. The ion irradiation facility as well as first experimental results are described and discussed.

INTRODUCTION

Hydrogen and Deuterium ions are used in various scientific and technical applications. An area of interest is for example the cold fusion research. Recent cold fusion experiments are based on chemonuclear Deuterium-Deuterium (D-D) and Hydrogen-Deuterium (H-D) fusion reactions in metals [1] or transition metals like palladium [2]. An important aspect for solid-state fusion is a sufficient Deuterium density [3] in the target made of palladium or other materials. Often ion implantation of Deuterium or Hydrogen is used to reach the required density [3–5].

The enhanced electron screening effect was observed for the first time in the ^{2}H(d,n)^{3}He and ^{2}H(d,p)^{3}H reactions preceding in metallic environments [6]. An exponential-like increase of experimental reaction cross sections for decreasing projectile energies could be explained as a result of shielding nuclear charges by surrounding electrons leading to a reduction of the Coulomb barrier in terms of a so-called screening energy U_e. The screening energies experimentally determined for the (D-D) fusion reactions in metals are about a factor of ten larger than that obtained for gas targets [7] and up to a factor of two larger than the theoretical predictions [8]. The results are particularly interesting for nuclear astrophysics since deuterized metals represent a good model for strongly coupled plasmas where the kinetic energy of plasma particles is smaller than the mean Coulomb repulsion energy. In such a case, nuclear reaction rates can be increased by many orders of magnitude as probably realized in White and Brown Dwarfs or Giant Planets [9].

Our first experimental results have been confirmed by other groups [10, 11]. Especially, the data obtained by the LUNA collaboration for almost 60 different target materials [12] allow to compare the experimental results of different groups and to look for a theoretical description of the observed target material dependence as well as for the absolute screening energy values. However, there are significant discrepancies between the data of different groups.

As discussed in previous papers [13], the strong variation of the experimental screening energy arises from the contamination of the target surfaces by Carbon and Oxygen. Even small amounts of the Oxygen contamination correlated with high deuteron densities lead to vanishing screening energies and thick contamination layers connected with low and unstable deuteron densities result in artificially high values of U_e. Thus, new experiments performed under ultra-high vacuum (UHV) conditions at the lowest possible energies with atomically clean targets are required.

In this work we present a newly developed electron cyclotron resonance ion source (ECRIS) and demonstrate the production of Hydrogen and Deuterium ions which are used to investigate (D-D) reactions in a Zirconium environment. Zirconium as a target has been chosen because of its high affinity to form oxides so that it is of advantage to perform measurements under UHV conditions. The screening energy for Zirconium determined in our previous high-vacuum experiment amounted to about 300 eV. This is in contradiction to the experimental result obtained by the LUNA collaboration with $U_e < 40$ eV [14]. The new experiment was intended to clear up this discrepancy.

EXPERIMENTAL SETUP

Ion Source

For the production of Hydrogen and Deuterium ions an electron cyclotron resonance ion source has been developed.

---

* martin.kreller@dreebit.com

DESIGN OF COMPACT ECR ION SOURCE FOR C^{5+} PRODUCTION

M. Muramatsu[†], A. Kitagawa, E. Noda, Y. Iwata, M. Sekiguchi, NIRS, QST, Chiba, Japan
K. Fukushima, K. Takahashi, T. Suzuki, T. Sasano, AEC, Chiba, Japan
N. Takahashi, H. Murata, SHI, Yokosuka, Kanagawa, Japan

Abstract

The Heavy Ion Medical Accelerator in Chiba (HIMAC) was constructed as the first medical dedicated heavy ion accelerator facility at National Institute of Radiological Sciences (NIRS). Over 10000 cancer patients have been treated with 140-430 MeV/u carbon beams since 1994. Compact ECR ion source with all permanent magnets, named Kei2, was developed for production of C^{4+} ions for medical treatment at NIRS. A compact ECR ion source for Gunma University (Gunma University Heavy Ion Medical Center: GHMC), Saga carbon-ion radiotherapy (Saga Heavy Ion Medical Accelerator in Tosu: SAGA HIMAT) and Kanagawa carbon-ion radiotherapy (Ion-beam Radiation Oncology Center in Kanagawa: i-ROCK) facility has been operated for medical use. It is a copy of the Kei2 which was developed by NIRS.

In order to reduce operation cost of the injector for next designed carbon ion facility, we start design of new compact ECR ion source for C^{5+} production. Some dependence (mirror field, microwave power and frequency) were checked for optimal parameter of C^{5+} production at 18 GHz NIRS-HEC.

INTRODUCTION

Four ion sources have been operated in HIMAC for medical treatment, physics and biological experiments at NIRS. Two ECR ion sources with normal conducting mirror coils, named 10 GHz NIRS-ECR [1] and 18 GHz NIRS-HEC [2], produce carbon ion for treatment and heavier ions (i.e. Ar, Fe, Xe) for experiment. Compact ECR ion source with all permanent magnet, named Kei2 [3], was installed to HIMAC with prototype injector [4] for backup of existing injector. Cold cathode type of PIG source, named, NIRS-PIG, produces ions of hydrogen, helium and neon from gases. Boron and aluminium ions are also produce by spattering method at NIRS-PIG.

There are five carbon ion radiotherapy facilities in Japan and two are under construction. If we can reduce the size and the operating cost of a facility, the spread of carbon ion radiotherapy is expected. Compact ECR ion sources (Kei series) at Gunma University, Saga carbon-ion radiotherapy and Kanagawa carbon-ion radiotherapy facility have been operated for medical use. Those are copies of the Kei2 which was developed by NIRS. Mirror magnetic field of the Kei series is optimized for production of C^{4+} under the experiment of 10 GHz NIRS-ECR. It is possible to reduce of the size of injector Linac when an ion source produces carbon 5+ or 6+ for a next facility.

However, it is difficult to separate C^{6+} from other ions such as nitrogen and oxygen. Therefore, we design a new compact ECR ion source with all permanent magnets to produce C^{5+} ions with an output current of 300 eμA. The other requirements are similar as the Kei series.

TRIAL EXPERIMENTS

NIRS-HEC has produced C^{5+} with 500 eμA. So the size of the magnets and their arrangement of the new ion source were determined in such a way that both the maximum peak and B minimum values of the mirror field would become close to those of the NIRS-HEC. For design of the magnetic field, beam test was done for production of the C^{5+} at NIRS-HEC. NIRS-HEC are usually operated with two microwave amplifiers, 18 GHz klystron power amplifier and 17.10 – 18.55 GHz Traveling-Wave-Tube (TWT) amplifier. Output power of these amplifier are 1400 W and 1200 W, respectively. However, we plan that the frequency of the new ion source is around 14 GHz because high magnetic field is difficult to produce by using permanent magnets. Therefore we used other TWT amplifier for this trial experiment. Microwave frequency and output power are 10 – 18 GHz and 300 W, respectively.

In this experiment, some dependences (mirror field, microwave power and frequency) were checked for optimal parameter of C^{5+} production.

Production of Carbon Ion with CH$_4$ and CO$_2$

Usually, CH$_4$ gas is used at Kei series in carbon-ion medical facility. At first, we compared between CH$_4$ and CO$_2$ gas for production of C^{5+}. Figure 1 and 2 show charge state distribution (CSD) of carbon with CH$_4$ and CO$_2$ gases, respectively. Operation parameters were optimized for C^{5+}. Extraction voltage was 30 kV. In the case of CH$_4$, there was little oxygen peak from residual water. Beam intensity of C^{5+} was 160 eμA. in the case of CO$_2$, beam intensity of C^{5+} was only 36 eμA. CSD of CH$_4$ was better than CO$_2$.
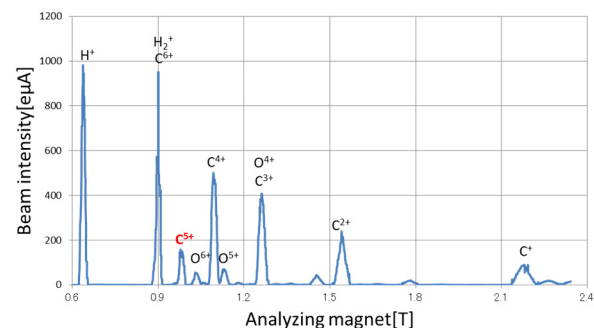

Figure 1: Charge state distribution under the CH$_4$ gas.

---

† muramatsu.masayuki@qst.go.jp

INTERMEDIATE COMMISSIONING RESULTS OF THE REQUIRED 140 mA/100 keV CW D+ ECR INJECTOR OF LIPAC, IFMIF'S PROTOTYPE

B. Bolzon[†], N. Chauvin, R. Gobin, F. Harrault, F. Senée, CEA, Gif-sur-Yvette, France

J. Knaster, A. Marqueta, K. Nishiyama, Y. Okumura, G. Pruneri, F. Scantamburlo, IFMIF/EVEDA Project Team, Rokkasho, Japan

L. Bellan[1], M. Comunian, E. Fagotti, A. Pisent, INFN, Legnaro, Italy

P-Y. Beauvais, P. Cara, H. Dzitko, R. Heidinger, F4E, Garching, Germany

R. Ichimiya, A. Ihara, A. Kasugai, T. Kitano, M. Komata, K. Kondo, K. Sakamoto, T. Shinya, M. Sugimoto, QST, Rokkasho Fusion Institute, Rokkasho, Japan

[1]also at Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Padova, Italy

Abstract

The LIPAc accelerator aims to operate in Rokkasho Fusion Institute a 125 mA/CW deuteron beam at 9 MeV to validate the concept of IFMIF's accelerators that will operate in CW 125 mA at 40 MeV. The 2.45 GHz ECR injector developed by CEA-Saclay is designed to deliver 140 mA/100 keV CW D+ beam with 99% D+ fraction ratio. Its LEBT relies on a dual solenoid focusing system to transport and match the beam into the RFQ. The normalized RMS emittance at the RFQ injection cone is required to be within 0.25π mm·mrad to allow 96% transmission through the 9.81 m long RFQ. An equal perveance H+ beam of half current and half energy as nominal with D+ is expected to be used to avoid activation during commissioning. The injector commissioning at Rokkasho is divided into three phases to characterize the emittance between the two solenoids of the LEBT (A1) and just downstream the RFQ injection cone (A2) and the extraction system of the source (A3). Phase A1 has been achieved and phase A2 continues in 2016 in order to reach the required beam parameters and to match the beam into the RFQ. This paper reports the commissioning results of phase A1 and the intermediate ones of phase A2 for H+ and D+ beams.

INTRODUCTION

IFMIF (International Fusion Materials Irradiation Facility) is a projected accelerator-driven-type neutron source for qualifying fusion reactor materials. It is characterised by its beam current frontier accelerator producing two sets of 125 mA/CW deuterium ion beams up to 40 MeV [1]. The current EVEDA (Engineering Validation and Engineering Design Activities) phase is developed to validate the IFMIF accelerator with a challenging 125 mA/9 MeV CW deuteron accelerator called LIPAc (Linear IFMIF Prototype Accelerator). LIPAc was designed and constructed mainly by European laboratories with the participation of QST in the RFQ couplers and the control system. It is being assembled, commissioned and will be operated at Rokkasho [2, 3]. It is composed of an injector delivered by CEA-Saclay [4], a RFQ [5] delivered by INFN on April 2016, a superconducting SRF Linac designed by CEA-Saclay [6], RF power, Me-

dium and High Energy Beam Transfer lines and a beam dump designed by CIEMAT.

The injector is composed of a 2.45 GHz ECR ion source based on the CEA-Saclay SILHI source design [7] and a LEBT line to transport and match the beam into the RFQ using a dual solenoid focusing system with integrated H/V steerers. Its commissioning started in November 2014 at Rokkasho and continues in 2016 interleaved with the RFQ installation to optimize the project schedule. It has to deliver to the RFQ 140 mA/100 keV CW D+ beam to meet LIPAc requirements. Moreover, simulations showed that the normalized RMS emittance at the RFQ injection cone has to be no higher than 0.30π mm·mrad [8] with well-matched Twiss parameters in order to minimize losses to less than 10% in the RFQ (target of 0.25π mm·mrad for 4% of losses).

Commissioning program plans to use an equal perveance H+ beam of half current and half energy as deuterons at nominal conditions to avoid activation and ease maintenance activities. However, it has to be stressed that the injector design has been optimized to produce high intensity 100 keV D+ beam. In terms of beam extraction and transport at low energy, the performance of the injector can thus be lower by operating this one with 70 mA/50 keV H+ beam due to lower plasma density.

The injector commissioning is divided in different phases. During phase A1, the emittance was measured in the first diagnostic chamber located between the two solenoids of the LEBT while it is measured in the second diagnostic chamber located downstream the RFQ injection cone at phase A2 (for both phases, the RFQ cannot be placed at its final position). The realization of a third phase A3, where the emittance is measured just downstream the 5-electrode beam extraction system to characterize the source itself, is still under discussion.

This paper presents the results of phase A1 with D+ beam (completed at the beginning of September 2015) and the intermediate ones of phase A2 with D+ and H+ beams. In view of machine protection system during the RFQ commissioning, the injector was operated at low duty cycle with sharp beam pulses down to 100 μs length (use and test of an electrostatic chopper) up to CW operation. The different diagnostics of the injector used to characterize the beam are described in [9].

---

† benoit.bolzon@cea.fr

DEVELOPMENT OF A COMPACT HIGH INTENSITY ION SOURCE FOR LIGHT IONS AT CEA-SACLAY

O. Delferrière[†], R. Gobin, Y. Gauthier, F. Harrault, O. Tuske

Commissariat à l'Energie Atomique et aux Energies Alternatives, CEA/Saclay, DSM/IRFU,

91191-Gif/Yvette, France

Abstract

During the past 5 years, a R&D program has been launched to improve the beam quality of ECR 2.45 GHz high intensity light ion sources for high power accelerators. The main goal was to minimize the divergence and emittance growth of intense beams due to the space charge as early as possible on the low energy transfer line for a better injection in the second stage of acceleration (RFQ). This has been achieved by reducing the length of the extraction system, to be able to put the first solenoid as close as possible to the extraction aperture. This was performed with the ALISES [1] concept (Advanced Light Ion Source Extraction System). Encouraging results have been obtained in 2012 but with limitations due to Penning discharges in the accelerating column. Taking advantages of ALISES geometry, intensive studies and simulations have been undertaken to eliminate the discharge phenomena. An Innovative and compact source geometry has been found and the source has been fabricated. This new prototype and its performances will be described, as well as magnetic field configuration studies and its influence on the extracted beam.

INTRODUCTION

The ALISES concept developed at CEA/Saclay is based on the use of the stray field of a solenoid located downstream the extraction system to produce the ECR resonance in the plasma chamber. The other characteristic of ALISES source is that the insulating structure between the source potential and the LEBT potential is located upstream of the plasma electrode. The design of the accelerator column (Fig. 1), reversed compared to standard high current light ions sources like SILHI [2] or IFMIF [3] source, allows a gain of several tens of cm on LEBT length. This also gives available space at the beginning of the LEBT, to put focalizing and/or guiding elements as early as possible to adjust the beam dimensions and angle, in order to minimize the emittance growth due to the beam space charge effects. The ALISES source has produced about 18 mA extracted from a 6mm diameter plasma extraction hole at 23 keV during the commissioning in 2011-2012 [4], but strong limitations were observed [5] due to Penning discharge in the accelerator column.

After two years of intensive work on electromagnetic simulations and design improvement to eliminate the penning discharge process, an innovative and compact source geometry has been developed, fabricated and successfully tested on BETSI [6] test bench in 2015.
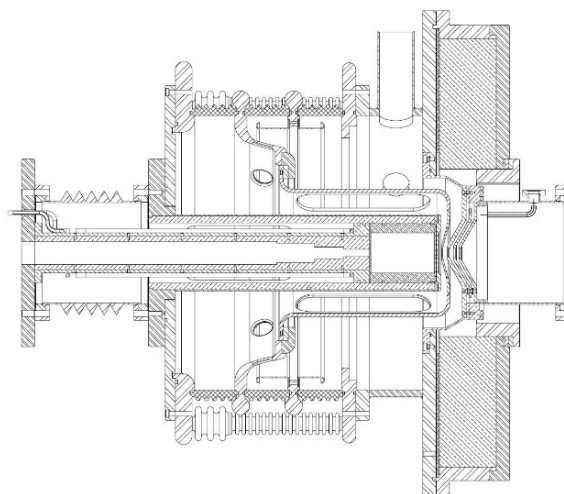

Figure 1: ALISES source geometry characteristic.

ALISES II[*] INOVATIVE ION SOURCE

The undesirable Penning discharge occurred at different locations in the ALISES accelerator column due to favorable combination of electromagnetic and electrostatic field lines. This was due first, to electrode shape with alternative parts along axial direction and radial direction, and second to higher magnetic field value in the system compare to standard source configuration, because of increasing field from the RF injection up to the extraction end. At the location of changes in direction of electrode shape, Penning trap electromagnetic configuration can occur. Then, at several locations, electrons are accelerated up to several kilovolts and trapped with enough energy to ionize the residual gas, leading to the Penning discharge.

The Insulating structure used for ALISES source was a spare part of SILHI source with a large 410mm internal diameter. In this big volume of vacuum, the electrodes geometry have been designed with smooth shape and sufficient space in between, to prevent from electrostatic sparks, especially the shape of the puller electrode between the plasma chamber at 100 kV, and the first grounded electrode, but not for Penning discharge reason. To eliminate all the sources of Penning discharge, the idea was to reduce the vacuum part as much as possible where they could appear. The main characteristic of this source

---

† Olivier.delferriere@cea.fr

TRANSVERSE COUPLING OF ION BEAMS FROM AN RCR ION SOURCE

Y. Yang[#], Y. Liu, L.T. Sun, Y. J. Yuan, H.W. Zhao, IMP/CAS, Lanzhou 730000, China

Abstract

Transverse coupling of ion beams out of an ECR ion source has been studied from two aspects. One is the coupling induced during beam extraction and the other is the coupling effect of a solenoid. Ion beams extracted from an electron cyclotron resonance (ECR) ion source will experience a descending axial magnetic field at the extraction region, resulting in a strong transverse coupling to the extracted beam, with projection root-mean-square (RMS) emittance growth both in horizontal and vertical directions and two eigen-emittances separation. Simulations of particle beam extraction from an ECR ion source in the present of the magnetic field have been carried out to investigate the coupling property. The results indicate the magnetic field in the extraction region can determine the beam emittances and the transverse coupling by affecting the beam formation. In addition, coupling effect of a solenoid on an initially non-round beam has been illustrated by introducing the matrix algorithm, which can qualitatively and indirectly explain the experimental phenomenon of SECRAL (Superconducting Electron Cyclotron Resonance ion source with Advance design in Lanzhou) at institute of modern physics (IMP).

INTRODUCTION

As one of the most powerful devices to produce intense highly-charged heavy ion beams, ECR ion sources are widely adopted by many large accelerator facilities. However, because of its special magnetic confinement fields ECR ion source beam quality has always been concerned and achieved much attention. Since the extraction of the ions takes place in the vicinity of a local magnetic field maximum, the following descending axial magnetic field adds an azimuthal momentum to the beam, leading to the transverse emittances blow up and coupling. It is generally believed that the beam emittance is primarily determined by the axial field strength at the extraction region if the ion temperature in the ECR plasma is low [1, 2]. The magnetic contribution to the (Normalized RMS) emittance can be given by

$$\varepsilon_{mag} = 0.032 \cdot (R_{extr})^2 \cdot (\frac{B_{extr}}{M/Q}), \qquad (1)$$

where R_{extr} [mm] is the radius of the effective extraction aperture and M/Q the ion mass-to-charge ratio and B_{extr} [T] the maximum magnetic field at the extraction region. This equation indicates the beam projection emittance is proportional to the extraction field strength. However, beam emittance measurements for the ECR ion source at

RIKEN with a pepper-pot scanner do not have a good agreement with the accepted theorem as described above [3, 4]. In their experiment both the projection RMS emittances and the 4-D emittance are lower under a relatively larger B_{extr}, which indicates a more complicated extraction process. Besides the coupling induced by the semi-solenoid field in the ion source extraction region, a complete solenoid, which is usually employed as the initial focusing element, can also lead to beam coupling since the ion density distribution across the extraction aperture is inhomogeneous due to the asymmetric plasma distribution at extraction, resulting in a non-round beam [5].

This paper starts with an introduction of the relationship between the projection RMS emittances and eigen-emittances based on modeling a beam passing through a semi-solenoid field. Afterwards beam extraction simulations are carried out toward SECRAL [6] to investigate the transverse coupling property of the extracted beam. Then coupling effect of a solenoid field on a non-round beam is demonstrated by analytical theory in combination with the experimental results with SECRAL. The last section makes some conclusions and an outlook.

BASIC THEOREM

Beam RMS emittances are defined through the beam second moment matrix [7, 8]

$$C = \begin{bmatrix} <xx> & <xx'> & <xy> & <xy'> \\ <x'x> & <x'x'> & <x'y> & <x'y'> \\ <yx> & <yx'> & <yy> & <yy'> \\ <y'x> & <y'x'> & <y'y> & <y'y'> \end{bmatrix}, \qquad (2)$$

where the full 4-D emittance is defined by

$$\varepsilon_{4d} = \sqrt{\det(C)} . \qquad (3)$$

The projection RMS emittances ε_x and ε_y are defined by the corresponding sub phase space determinants, which can completely characterize the transverse quality when the beam is transversely uncoupled. Diagonalization of the beam matrix yields the eigen-emittances ε_1 and ε_2, whose values can be expressed as:

$$\varepsilon_{1,2} = \frac{1}{2}\sqrt{-tr[(CJ)^2] \pm \sqrt{tr^2[(CJ)^2] - 16\det(C)}} . \qquad (4)$$

The 4-D matrix J is the skew-symmetric matrix with non-zero entries on the block diagonal off form. A symplectic transformation M obeys

HIGH INTENSITY BEAM PRODUCTION AT CEA/SACLAY FOR THE IPHI PROJECT

R. Gobin*, D. Bogard, O. Delferrière, M. Desmons, Y. Gauthier, F. Harrault, F. Peauger, G. Perreu,
B. Pottin, Y. Sauce, J. Schwindling, F. Senée, O. Tuske, D. Uriot, T. Vacher,
Commissariat à l'Energie Atomique et aux Energies Alternatives,
CEA/Saclay, DRF/IRFU,91191 - Gif/Yvette, France

Abstract

CEA/Saclay is involved in high power proton accelerators for many years. This activity started in the 90's, with the development of the SILHI source which routinely produces tens mA of proton beam. Several industrial difficulties led to a very long IPHI RFQ construction process. The 352 MHz RFQ conditioning is presently in progress. Before the completion of the conditioning in CW mode, tests with pulsed proton beam have been performed.

As a consequence, the SILHI source recently produced very short H+ beam pulses in order to allow the first IPHI beam acceleration. Such very short pulses, in the range of few hundred microseconds, allowed analyzing the beam loading of the RFQ cavity as well as conditioning the middle energy diagnostic. This article reports the source parameters and beam characteristics in the low energy beam line leading to the best RFQ transmission as well as several results concerning the accelerated beam at 3 MeV.

INTRODUCTION

In the middle of 90's, CEA and CNRS which are 2 important national research organizations, decided to start a collaboration in the development of high power proton accelerator. It was then decided to concentrate the activities on 3 items: (i) the injector of proton for high intensity (IPHI) which is a prototype of linac front end able to accelerate up to 100 mA cw H+ beam, (ii) construction and test of β<1 superconducting cavities and (iii) development and improvement of the codes for accurate beam dynamics calculations.

The development and construction of the High Intensity Light Ion Source (SILHI) with its associated low energy beam line were the first steps of the IPHI program. To fulfil the IPHI requests (high intensity cw beam), a 2.45 GHz ECR source has been chosen for the SILHI source producing the H$^+$ particles.

Then the design and construction of the RFQ and a dedicated diagnostic beam line was decided. In a 1st step, the goal of IPHI was to accelerate the proton beam from 100 keV to 5 MeV with an RFQ and up to 11 MeV with a DTL. For different reasons (mainly economical and strategic ones), the final energy has been reduced from 11 to 3 MeV [1]; as a consequence, the DTL was not needed any more.

In parallel to the long IPHI RFQ construction, the SILHI source was producing high intensity beam. The obtained

performance allowed us developing and constructing new injectors for Spiral 2, FAIR and IFMIF. The production of such high intensity beams also permitted the development and improvement of innovative diagnostics.

In the past years, the IPHI project faced industrial (company closure), administrative (end of collaboration) and technical difficulties (RFQ brazing troubles for example); and the completion of the RFQ assembly ended few months ago. Then the 352 MHz RFQ conditioning has been undertaken at very low duty cycle; it is still in progress by increasing the duty cycle. Once the conditioning reached a high enough RF field into the cavity, it has been decided to inject the SILHI beam into the RFQ. And the acceleration of the first proton beam up to 3 MeV has been recently achieved in pulsed mode.

This article briefly recalls the IPHI general design as well as the SILHI and LEBT components. The following section presents the SILHI parameters with very low duty cycle and before to conclude, the last section reports the preliminary 3 MeV H$^+$ beam results.

IPHI AND SILHI DESIGN

The 4 vane type RFQ of the IPHI project [1, 2] is made of 6 modules (Fig. 1). Each module is 1 meter long and is built in 4 parts brazed together. Large copper pieces with very tight tolerances after machining (10 µm over 1 meter long) and precise brazing pushed to use unconventional technics. The whole RFQ is assembled in 3 segments (made of 2 coupled modules) linked with 2 coupling plates. The 352 MHz RF power, generated by 2 klystrons, is injected in the 4th module via 4 ridges and 4 windows. During the operation, to avoid RFQ detuning due to geometry modifications, the cavity is water cooled by means of 268 different circuits and its temperature is precisely adjusted (0.1° C) by regulating the temperature of several circuits.

The RFQ is followed by a dedicated diagnostic beam line designed to fully characterize the 3 MeV beam. At the end of the beam line, a 300 kW water cooled beam dump has been installed. The beam dump conical shape allows minimizing the beam power density and the inner cone made of nickel allows minimizing the activation.

*rjgobin@cea.fr

COMMISSIONING OF THE HIGH INTENSITY PROTON INJECTOR OF THE FACILITY FOR ANTI PROTONAND ION RESEARCH AT CEA-SACLAY

O. Tuske, O. Delferrière, N. Chauvin, Y. Gauthier, P. Girardot, N. Misiara,
Y. Sauce, F. Senée, C. Simon, T. Vacher
CEA Saclay, France
F. Ameil, R. Berezov, J. Fils, R. Hollinger
GSI, Darmstadt, Germany

Abstract

The Facility for Antiproton and Ion Research (FAIR) located at GSI (Darmstadt) in Germany addresses several fields of physics research within a single installation. These include the physics of exotic nuclei, hadron physics using proton-antiproton collisions, relativistic heavy ion reactions at a few tens of GeV per nucleon, plasma physics, and atomic physics. The FAIR accelerator complex will deliver stable and rare isotope beams covering a huge range of intensities and beam energies. A significant part of the experimental program at FAIR is dedicated to antiproton physics that requires an ultimate number 7.10^{10} cooled pbar/h. The high-intensity proton beam that is necessary for antiproton production will be delivered by a dedicated 75 mA/ 70 MeV proton linac. One of the contributions of Irfu/SACM at CEA-Saclay to the FAIR linear proton accelerator concerns the development and construction of the ion source and the low energy line.

The 2.45 GHz microwave ion source will deliver a 100 mA H^+ beam pulsed at 4 Hz with an energy of 95 keV. A low energy beam transport (LEBT) line based on a dual solenoids focusing scheme allows the injection of the proton beam into the radio frequency quadrupole (RFQ) within an acceptance of 0.3π mm.mrad (norm. rms). An electrostatic chopper system located between the second solenoid and the RFQ is used to cut the beam macro pulse from the source to inject 36 µs long beam pulses into the RFQ.

At the end of 2015, a first plasma of 80 Watt at 4 Hz has been produced by the FAIR proton linac ion source.

Then the commissioning of the injector has started beginning by the characterization of the ion beam just after the accelerating column.

This article reports the finalization of the installation of the injector with the details of dedicated diagnostics, the first beam measurements, and gives a planning of the different commissioning phases

INTRODUCTION

The beam commissioning at CEA/Saclay will be divided in three main phases.

- During the phase one, already started, the beam intensity, emittance and species proportion extracted from the source are measured at the source exit, just behind the accelerating column, using a dedicated diagnostic chamber (DIAG2).

- For the phase 2, the LEBT is assembled without the chopper. The same diagnostics are installed first in the FAIR injector diagnostic chamber (DIAG1) between the 2 solenoids, and in a second time the beam is analyzed in the chamber DIAG2 connected at the exit of the second solenoid.

- During the phase 3, the nominal source and LEBT apparatus is assembled. All the diagnostics of the diagnostic chamber DIAG1 are available. The chopper is tested. The beam intensity and emittance are measured after the injection cone. The FAIR p-linac source and LEBT are validated.

INJECTOR LAYOUT

The injector section of the FAIR p-linac [1-2] is composed by an ECR source, delivering a pulsed 100 mA H^+ beam (4 Hz) at 95 keV and a low energy beam transport line required to match the beam for the RFQ injection (Fig. 1). The LEBT is based on a dual solenoids focusing scheme. A dedicated chamber DIAG1 containing several diagnostics (Alisson scanner, Wien filter, SEM grid, Iris, Faraday Cup) will be located between the two solenoids. At the end of the LEBT, an electrostatic chopper system is foreseen to inject 36 µs beam pulses into the RFQ.
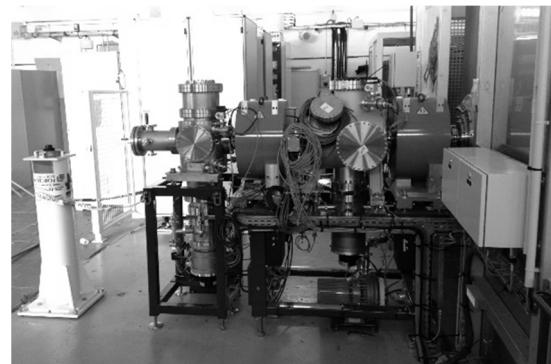

Figure 1: FAIR p-linac injector at Saclay.

ION SOURCE & LEBT REQUIREMENTS

The FAIR p-linac source & LEBT is aimed to produce a 100 mA/95 keV proton beam and to transport and match it for its injection into the RFQ. The main beam parameters that are required are summarized in Table 1.

NEVER RUN YOUR ECR ION SOURCE WITH ARGON IN AFTERGLOW FOR 6 MONTHS!

D. Küchler, J. Ferreira Somoza, A. Michet, V. Toivanen

European Organization for Nuclear Research (CERN), 1211 Geneva 23, Switzerland

Abstract

The fixed target experiment NA61/SHINE in the North Area of the SPS at CERN studies phase transitions in strongly interacting matter using the primary beams available from the CERN accelerator complex (protons and lead ions). In order to explore a wider range of energies and densities a primary argon beam was requested for the physics run in 2015. The GTS-LHC ECR ion source was running for many months during 2013 and 2014 to study the source behaviour and to set-up the accelerator chain with argon ions.

This paper reports the long term effects of the argon operation on the GTS-LHC ion source and the Low Energy Beam Transport (LEBT). Heavy sputtering inside the source caused a degradation of the plasma chamber and metal coating of insulators inside the beam extraction system. Iron ions could be found in the extracted beam. Also the pumping performance of ion getter pumps in the LEBT degraded significantly. Additional preventive maintenance was necessary to be able to run for long periods without risking serious damage to the ion source.

INTRODUCTION

NA61/SHINE [1] is a fixed target experiment in the North area of the Super Proton Synchrotron (SPS). NA61/SHINE studies the hadron production in hadron-nucleus and nucleus-nucleus collisions. The aim of this experiment is to study phase transitions in strongly interacting matter (quark gluon plasma), the onset of deconfinement and to take reference measurements for the hadron production.

In the last years proton and lead as primary beams and light ions from fragmented beams were used. In 2015 a primary argon beam was delivered to be able to explore a wider range of energies and densities in the experiment. In preparation the accelerator chain was set up with the argon beam in the second half of 2014.

In 2013 a test run was done at the linear accelerator Linac3 to find and optimize the settings for the source and the linac, to measure the beam parameters (intensity, stability, emittance) and to study the long term behaviour of the source and the linac [2].

The GTS-LHC ion source [3,4], running at 14.5 GHz, was set-up to provide an $^{40}Ar^{11+}$ beam. The source is running in the afterglow mode with a heating pulse of 50 ms and a repetition rate of 10 Hz. No mixing gas was used. The beam was extracted with an extraction voltage of 9.6 kV to match the injection energy of 2.5 keV/u into the RFQ. In the linac a pulse of 200 μs cut out of the afterglow discharge was accelerated. At the end of the linac the beam reaches the final energy of 4.2 MeV/u.

The source delivered around 100 eμA of Ar^{11+}. At the exit of the linac the current was around 70 eμA (this is more than 10 times the particle current compared to the lead operation). The intensity varied up to 20 % during operation [2].

The total time operated with argon was nearly 12 months, 24 h per day, 7 days a week. But as the first tests in 2013 showed already after 10 weeks of operation some degradation of the source hardware, it was decided to do a preventive maintenance after roughly 6 months of operation where plasma chamber and extraction system were replaced with spare parts.

INVESTIGATIONS

Operating with argon the source can be tuned to a stable operation point (more stable over long periods than during Pb ion production) and also returns to the same conditions quickly after a source stop. The fixed target physics programme was limited by event pile up, and therefore high intensities were not requested from the accelerator chain. Therefore the tuning of the source could also be made with low power parameters (for example the ECR source microwave power was kept below 500W). This allowed to reduce the hardware degradation (known from the 2013 experiment) and to maximize the source lifetime.

The different parts of the source and the linac were affected by the argon operation in different ways. The three main issues will be described in the following.

The Plasma Chamber

As already reported in Ref. [2], after 10 weeks of operation first sputter marks could be seen in the plasma chamber and in the ion beam co-extracted iron ions could be found (several eμA).

After a period of 6 months the plasma chamber was taken out and measured (Fig. 1). The spots where the plasma is lost dominantly are clearly visible and along these loss lines grooves up to 100 μm deep were measured (the chamber has a wall thickness of 2mm). During the lead operation only some marks were visible at the same spots.

The Extraction System

The GTS-LHC source operates with a 3 electrode extraction system. After the replacement of the extraction system during the maintenance two observations could be made.

The aperture of the intermediate electrode showed clear sputter marks and some metal flakes after removal from the source (Fig. 2).

STATUS REPORT ON METALLIC BEAM PRODUCTION AT GANIL/SPIRAL 2

C. Barué [†], O. Bajeat, J.L. Flambard, R. Frigot, P. Jardin, N. Lechartier, F. Lemagnen, L. Maunoury, V. Métayer, B. Osmond, GANIL, CEA/CNRS, Caen, France
P. Sole, T. Thuillier, LPSC, CNRS, Grenoble, France
C. Peaucelle, IPNL, CNRS, Lyon, France

Abstract

Primary ion beams from metallic elements are routinely produced at GANIL using ECR4 [1] and ECR4M [2] room temperature (RT) ECR ion sources. Ionization efficiency measurements, partially presented in the past, are summarized in this paper together with updated and new results obtained with Cd, Mo and Ta. Preliminary results obtained at Grenoble with the PhoenixV2 [3] ion source for Ni and Ca beam production [4] are also included. These ionization efficiencies are compared according to the ordinary production methods: oven, sputtering, MIVOC, gaseous compounds. The present SPIRAL 2 heavy ion injector designed for ions Q/A=1/3 is of interest to accelerate metallic ions up to the mass ~60. Above this value, the achievable intensities are dramatically limited by the atomic physics processes in the ECR plasma (intensities $\ll$ 1 pµA). This limitation will be overcome with the future Q/A=1/6,1/7 injector. In order to choose the best ion source for such an injector, best world results have been compiled for different existing RT (Room temperature) and superconducting (SC) ECR ion sources.

ECR4/4M AND PHOENIX V2 ION SOURCES

In this section, the main differences between ECR4/4M (ECR4 or ECR4M) and Phoenix V2 ion sources are presented. Although the global magnetic structure of these ion sources is comparable, i.e. superposition of an axial magnetic field created by resistive coils and of a radial field created by permanent magnets, some differences have to be pointed out:

RF Injection

Phoenix V2 is working at 18 GHz (instead of 14 GHz for ECR4/4M) with a direct rectangular RF injection (coaxial RF injection for ECR4/4M) allowing more RF power to be injected into the source.

Magnetic Confinement

Due to its direct RF injection, a massive iron plug can be placed behind the injection flange of Phoenix V2, leading to a much stronger injection magnetic field: 2 T for Phoenix-V2 compared to the 1 T for ECR4/4M. Moreover, Phoenix-V2 is equipped with a third coil located at the middle, helping to get a better shaped axial magnetic field.

† barue@ganil.fr

Access to the Plasma

The internal diameter of the plasma chamber is about the same for ECR4/4M and Phoenix V2 (~63 mm). Using ECR4/4M, the oven used to evaporate metals can be placed only on axis (in front of the hot plasma) without any bias voltage, unlike Phoenix V2 where the oven is located off axis (beside the hot plasma) while keeping the biased disk functionality.

Beam Extraction

The beam is extracted at 60 kV from Phoenix V2 (2 accelerating gaps) instead of 25 kV for ECR4/4M (1 accelerating gap). The beam line inner diameter is higher for Phoenix V2 than the one of ECR4/4M, resp. 150 mm and ~65 mm. These differences lead to a better beam transmission for Phoenix V2 (~80-90%) than for ECR4/4M (~50%).

For Phoenix V2, the use of high speed turbo molecular pumps (2x1000 L/s) at the extraction leads to a vacuum level one order of magnitude lower than ECR4/4M (10^{-8} mbar for Phoenix V2 and 10^{-7} mbar for ECR4/4M). This is a crucial requirement to reduce the charge exchange process in the source and in the beam line, and therefore to keep alive the high charge states escaping the source.
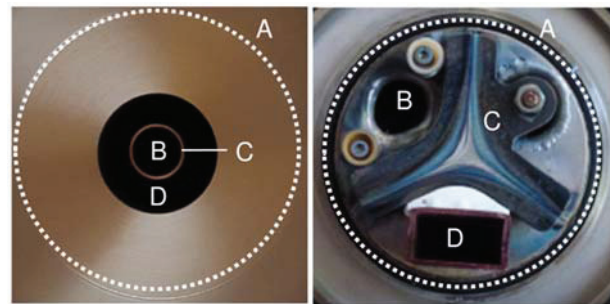

Figure 1: Injection view of ECR4/4M (left side), injection view of Phoenix V2 (right side). (A): inner diameter of the plasma chamber; (B): oven port and gas injection, (C) left side: biased tube, (C) right side: biased disk, (D) left side: 14 GHz coaxial RF injection, (D) right side: 18 GHz rectangular RF injection.

METALLIC BEAM PRODUCTION METHODS

In view of the very high charge states required for SPIRAL 2 (Q/A=1/3 => $^{14}Ca^{14+}$, $^{48}Ca^{16+}$, $^{58}Ni^{19+}$), the choice of the oven method and the use of pure metallic samples seems to be the most relevant alternative: the buffer gas

DEVELOPMENT OF COMPACT H⁺ ECR ION SOURCE WITH PULSE GAS VALVE

Y. Fuwa*†, Y. Iwashita, H. Tongu, E. Miyawaki, Kyoto University, Uji, Kyoto, Japan
M. Ichikawa, QST, Tokai, Ibaraki, Japan

Abstract

A compact H^+ ECR ion source is under development. For reduction of the gas load to vacuum evacuation systems, the gas flow into the plasma chamber is chopped by a piezo-electric gas valve. To achieve the enough short time constant of gas flow, a small plasma chamber with 50 cm^2 is adopted and the chamber is operated in 6 GHz TE111 mode. The magnetic field is generated by permanent magnet for reduction of the required volume. For the evaluation of the ion source performance, a Wien filter is fabricated and the ion species distribution is measured. As the result of experiments, the population of protons in the extracted beam was about 15 %.

INTRODUCTION

Ion sources using gas discharge eject not only ion beam but also neutral gas. Most of the neutral gas is evacuated by the vacuum system in Low Energy Beam Transport (LEBT) region and some of the gas diffuse into the accelerator tanks. For pulsed ion sources, the ion beams are extracted from the ion source in just pulse duration, while the neutral gas get out of the plasma chamber constantly. Considering the ion accelerator with high intensity, the length of the LEBT should be as short as possible to reduce the space charge effect. However, with the short LEBT, the quantity of the neutral gas flow into the accelerator tank would become large. The gas flow in the tank may lead discharge and disturb stable operation. For the reduction of the gas flow, the supply of the gas into the plasma chamber should be chopped.

COMPACT ECR ION SOURCE WITH PULSE GAS VALVE

For evaluation of the performance of the ion source with pulsed gas system, a prototype ion source is developed. Proton was chosen as the ions produced in the prototype, supposing that the ion source would applied to compact neutron sources. The ECR plasma production scheme was adopted intending to achieve high H^+ fraction in the extracted beam. A piezo-electric gas valve was developed to chop the gas supply into the plasma chamber. The volume of the chamber is about 50 cm^2 to set the time constant of gas filling and gas evacuation enough small. The chamber was designed to have resonance at the 6 GHz. The magnetic field for the ECR condition at 6GHz is about 2.2 kG and the magnetic

---

* Research Fellow of Japan Society for the Promotion of Science
† fuwa@kyticr.kuicr.kyoto-u.ac.jp

field is generated by permanent magnets. The detailed description about the prototype ECR ion source can be found in Reference [1].

RECENT UPDATE ON THE ECR ION SOURCE AND THE TEST BENCH

RF System

The RF power is fed into the cavity through a coaxial line. To couple the coaxial line with the plasma chamber, the tip of the inner conductor inserted into the chamber as a antenna. The radius of the inserted antenna is 0.3 mm and the length of that is about 12.5 cm, which corresponds to the quarter wavelength of light at 6 GHz. The cross-sectional view of the plasma chamber is shown in Figure 1. For evaluation of the coupling condition, a frequency domain analysis with CST microwave studio was performed. The calculated S_{11} parameter is shown in Figure 2. From the result, it was found that the chamber had resonance at 6.038 GHz and the mode of the resonance was TE111 mode.
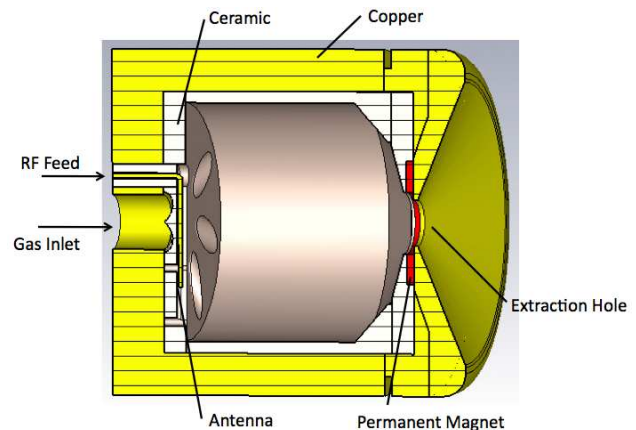
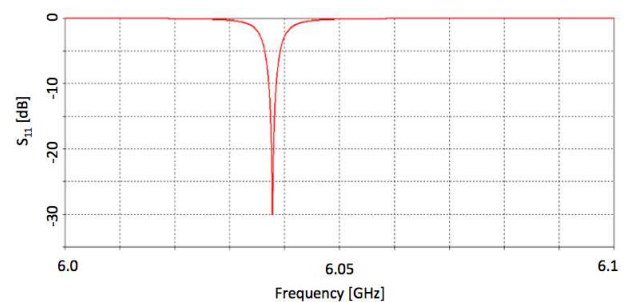

Figure 1: Cross-sectional view of the plasma chamber.

Figure 2: Calculated S_{11} parameter. The plasma chamber has resonance at 6.039 GHz with TE111 mode.

DEVELOPMENT OF A NEW COMPACT 5.8 GHZ ECR ION SOURCE*

J. Angot[†], L. Bonny, J. Jacob, T. Lamy, P. Sole, T. Thuillier, F. Villa, LPSC – Université Grenoble Alpes – CNRS/IN2P3, 53, Avenue des Martyrs, 38026 Grenoble cedex, France
P. Sortais, Polygon Physics, 53, Avenue des Martyrs, 38026 Grenoble cedex, France

Abstract

LPSC is developing a new 5.8 GHz compact ion source to produce low charge state ion beams and study their capture into the PHOENIX charge breeder plasma. The source was designed to meet criteria like stability, compactness, and low cost. It is mounted on a NW200 flange and is fully under vacuum during operation. The technology brings modularity to ease the development. It operates up to 60 kV. The plasma is heated by a 100 W solid state amplifier. The ECRIS produces 1 mA of H^+ beam with 20 W of HF power and can produce too, low charge state argon ions. It was tested under several microwave and magnetic configurations on a test bench equipped with a mass spectrometer and diagnostics. Given its good performances, this source is being installed to drive the accelerator-based neutron source, GENEPI 2, at LPSC. The developments of the source together with the results of the experiments are presented. Future plans for this ion source are also discussed.

INTRODUCTION

To characterise a charge breeder, a test bench has to be equipped with reliable and easy to install sources producing singly charged ions [1]. Such sources, regarding their performances, must ensure beam stability and quality (emittance) as well as produce the desired species with the required beam intensity. In order to study the capture of low charge state ions into the PHOENIX charge breeder plasma, one LPSC task of the EMILIE project aims to develop a new ion source targeting the specifications listed above.

Since 2013, many developments and experiments have been carried out to improve the 1^+ source. As good performances were obtained, the source was duplicated and installed in order to produce D^+ beams for the accelerator-based neutrons source operating at LPSC, GENEPI2. In parallel, developments will continue to improve the performances and to test innovative configurations.

5.8 GHZ ION SOURCE DEVELOPMENT

To develop this new source, the first idea was to use a socket type connexion to obtain a compact and easy to dismount assembly. We also opted for a modular design to easily change the magnetic structure and the microwave coupling. Thus, the first configurations were based on the compact microwave ion sources technology

(COMIC 2.45 GHz) [2] using a 5.8 GHz microwave (µw) frequency and with a larger plasma chamber to optimize the coaxial µw coupling. Recently, a minimum-B configuration with a waveguide coupling has been tested.

Design

The source is fixed on a NW200 flange and its length is about 400 mm (Fig. 1). The plasma chamber is water-cooled and surrounded by a container enclosing the permanent magnets. The microwave circuit passes through the flange and is axially connected to the plasma chamber. The extraction system is composed of a plasma electrode and a polarized puller allowing extraction electric field (E) tuning, a set of three electrodes (one with a negative potential inserted between two grounded electrodes) allowing space charge compensation during beam transport.
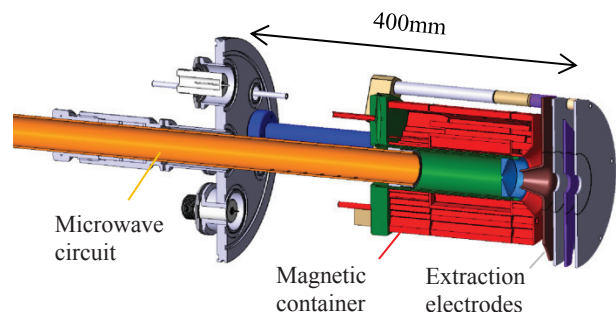

Figure 1: Cut view of the 5.8 GHz ion source modular structure.

Compact Microwave Configuration

In the compact microwave design, the goal is to produce high microwave electric field in the plasma chamber, at the ECR surface. This is done using a resonant µw structure composed of antennas and couplers with a coaxial input. The gas pressure is tuned to reach the Paschen's condition to ignite and sustain the plasma. These sources produce stable beams with a low beam emittance at low power [2].

The 5.8 GHz µw coupling assuring a high electric field at the plasma electrode hole was simulated with HFSS [3]. It is done with a 14 mm long antenna in a 41 mm inner diameter cavity. The maximum E field on the axis is 15 kV/m (Fig. 2a). Another microwave coupling using a longer antenna with 4 radial couplers has also been designed and tested. In this configuration, the µw E electric field reaches 100 kV/m on the axis, close to the plasma chamber hole, for 1 W of injected power (Fig. 2b).

A NEW ECRIS INSTALLATION AT THE ARGONNE TANDEM LINAC ACCELERATOR SYSTEM*

R. H. Scott[†], C. A. Dickerson, R. C. Pardo, R. C. Vondrasek

Argonne National Laboratory, Lemont IL, 60439, USA

Abstract

An existing all permanent magnet ECRIS, the BIE100 [1], will be installed at ATLAS to recover operational flexibility by providing ATLAS with a second ECR ion source for stable beams. For years ATLAS has operated with two ECR ion sources, ECR2 and the ECR charge breeder as well as a tandem electrostatic injector. The tandem was retired in 2013 and in mid-2015 the ECR charge breeder was decommissioned to make room for a new Electron Beam Ion Source exclusively for charge breeding radioactive ion beams. This left the facility with a single ECR source for virtually all stable ion beam production. Design, installation plans and anticipated operational parameters are discussed.

ATLAS MULTI-SOURCE HISTORY

The Argonne Tandem-Linac Accelerator System (AT-LAS) has mostly relied on the use of multiple ion sources since inception in 1985. This has allowed for enhanced operational flexibility and time to develop new beams and improve ion source performance. One source can be prepared, maintained and conditioned while another is in use for the experimental program. If there is a major failure of an ion source system another one can be called into duty to continue accelerator operations and reduce overall downtime.

Early on two negative ion source injector platforms (east and north) were used to feed the Tandem Vandegraff Accelerator, stripping to positive ion beams and subsequently feeding the Booster and Atlas superconducting linac sections (see Fig. 1). In 1992 the Electron Cyclotron Resonance Ion Source (ECRIS) ECR1 and Positive Ion Injector (PII) linac were commissioned to also feed into Booster, while the east injector was retired. Through the years, and a variety of upgrades, ATLAS has maintained multiple ion sources for the production of stable beams as can be seen in Fig. 2. Recently the ECRCB (charge breeding upgrade of ECR1) was only used for stable beams that did not affect the low background essential for effective charge-bred radioactive beam delivery. In the summer of 2013, the tandem injector was retired and in June of 2015 the ECRCB was retired from part time stable beam operation to be dismantled a few months later and replaced with an Electron Beam Ion Source (EBIS) dedicated solely to radioactive beam charge breeding.
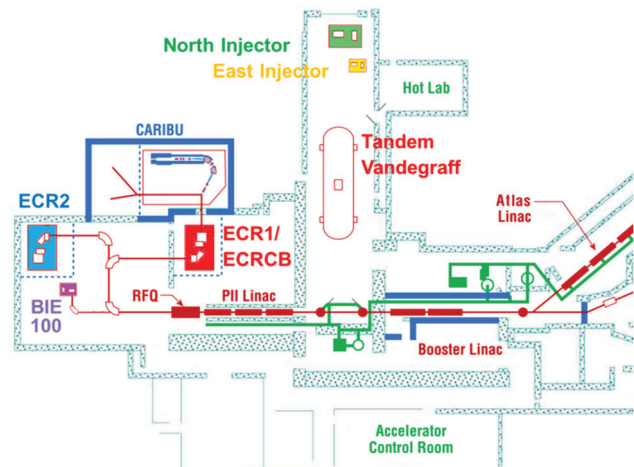

Figure 1: Layout of ATLAS accelerator section.

PRESENT SOURCE OPERATIONS

Since ECRCB removal, ATLAS has been left with a single source, ECR2, for all stable beam production. This source limitation has been very taxing for ATLAS operations. ATLAS essentially follows a 24 hour 7 day/week operational schedule. Typical experiments last 3-7 days with a very quick turnaround time expected of less than 24hrs for a new ion species to be tuned on target. Scheduling of beam time has become more complicated with more consideration needed for outside user schedules in relation to ion source preparation demands. Some of the scheduling burden will be lifted from ECR2 when the EBIS is brought online in late 2016 for breeding CARIBU radioactive ions, but there will still be no alternate ion source for stable beam production.

Carbon-14 Beams

Carbon-14 ion beam production ended at ATLAS with the retirement of the tandem in 2013. The demand for this beam has not diminished, and experiments delivering ^{14}C have been approved by the ATLAS program advisory committee. Until now, resumption of ^{14}C beam production in ECR2 has been avoided, mostly due to time prohibitive radioactive contamination procedures that would make maintenance and operation very difficult. Based on experience with the tandem ion sources, ^{14}C contamination also continues into the beamline past the ion source for quite some distance.

DESIGN, CONSTRUCTION AND COMMISSIONING OF THE NEW SUPERCONDUCTING ION SOURCE AISHA

L. Celona*, S. Gammino, G. Ciavola, F. Chines, F. Noto, G. Costa, G. Torrisi, O. Leonardi,
D. Mascali, G. Castro, S. Marletta, G. Pastore, S. Vinciguerra
Instituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud, Catania, Italy

Abstract

At INFN-LNS a new superconducting ECRIS named AISHa has been designed with the aim to provide highly charged ion beams with low ripple, high stability and high reproducibility, also fulfilling the needs of hospital installations (e.g. L-He free, easy to use, etc.). It is a hybrid ion source based on a permanent magnet hexapole providing 1.3 T on plasma chamber walls and four superconducting coils for the axial confinement. The axial magnetic system is very flexible in order to minimize the hot electron component and to optimize the ECR heating by controlling the field gradients and the resonance length. The design of the hexapole aimed to minimize the demagnetization due to SC coils. The magnetic system measurement confirmed the effectiveness of the adopted solutions. Innovative solutions have been also implemented as it concerns the RF system design. It will permit to operate in single/double frequency mode, supported by variable frequency high power klystron generators, thus exploiting at the same time the FTE – Frequency Tuning Effect and the Two Frequency Heating. The source has been assembled at the INFN-LNS site and the commissioning phase already started.

INTRODUCTION

The **A**dvanced **I**ons **S**ource for **Ha**drontherapy (AISHa) was designed in 2012 by taking into account the typical requirements of hospital-based facilities, including the minimization of the mean time between failures (MTBF) and the maintenance operations.

In 2013 the proposal of AISHA construction was approved by the Regional Government of Sicily and it was funded within the framework of the program of Sicilian Government named PO FESR 2007-2013 and a pool of Sicilian SME was associated with INFN for its construction. Today the AISHa source is entirely assembled and its complete commissioning is scheduled by the end of 2016.

Figure 1 shows an overall view of the source together with the components of the beamline.

The compact AISHa source has been designed to be an intermediate step between the 2nd generation ECRIS, unable to provide the requested current and/or brightness and the 3rd generation, too complex and expensive.
It is a multipurpose device with the aim to provide highly charged ion beams with low ripple, high stability and high reproducibility.
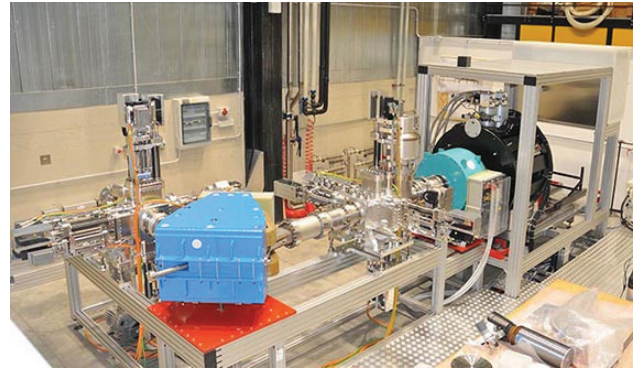

Figure 1: An overall view of the Ions Source and LEBT of the AISHa project.

Furthermore, the introduction of an oven for metallic ion beams will permit the production of new beam for hadrontherapy and for other applications in radiobiology. The main source characteristics are described in Table 1.

Table 1: Major Source Parameters

Radial field (max)	1.3 T
Axial field (INJ/MID/EXTR)	2.6 T / 0.4 T / 1.7 T
Plasma Chamber diameter	92 mm
Operating frequencies	18 GHz
Operating power (max)	1.5 kW
Extraction voltage (max)	40 kV
Cryostat length	620 mm
Cryostat diameter	550 mm
L-He	Free

MECHANICAL DESIGN

The majors mechanical improvements of the AISHa with respect to the usual layout of similar sources concern the use of the carbon fibers and composite materials to realize the hexapole containment chamber and the HV insulation.

---

* celona@lns.infn.it

INNOVATIVE MECHANICAL SOLUTIONS FOR THE DESIGN OF THE HIGH INTENSITY PROTON INJECTOR FOR THE EUROPEAN SPALLATION SOURCE

G. Gallo, L. Allegra, L. Celona, L. Neri, D. Mascali, G. Torrisi, S. Gammino
INFN/LNS, Catania, Italy

Abstract

The design of the 2.45 GHz, 0.1 T microwave discharge Proton Source for the European Spallation Source (PS-ESS) has required on-purpose solutions in order to maximize the beam brightness, keeping a very high reliability figure. The mitigation of maintenance issues has been the main guideline through the design phase to maximize the MTBF and minimize the MTTR. The mechanical design has been based on advanced solutions in order to reduce as much as possible the venting time for the plasma chamber, to facilitate the replacement of extraction electrodes and/or plasma chamber, and to simplify any after-maintenance alignment procedure. The paper will describe the strategy which has driven the design phase, the solutions adopted to fulfil the project goals and the results of the assembly phase recently concluded at INFN-LNS with successful first plasma.

INTRODUCTION

The Proton Source for ESS (PS-ESS) (see Fig. 1) was designed with a flexible magnetic system and a compact tetrode extraction system with the goal to minimize the emittance and the time needed for the maintenance operations [1].

The PS-ESS source body has been designed with the aim to fulfil the needs of an industrial installation. In particular, in order to maximize the MTBF and minimize the MTTR, the entire assembly has been designed by taking into account the allotted times for maintenance operations. In particular, efforts have been done to optimize the following operations:

- Source opening and closing procedures;
- Easy replacing of the extraction electrodes and plasma chamber;
- Automatic realignment of the plasma chamber on the extraction electrodes, after the maintenance operations;
- Easy replacement of the internal inserts of the matching water-cooled transformer which is used as impedance matching system, maintaining the same outer structure.

MECHANICAL DEVELOPMENT

Hereinafter a description of the mechanical solution adopted is presented for the subsystems constituting the body source. In particular, the extraction electrodes assembly, the suspension based on a pin junction and the water-cooled radiofrequency injection system will be described.

ESS Body Source

The body source is mechanically divided into two distinct parts as it is shown in Fig. 1:

- A movable part consisting of: injection system, plasma chamber, magnetic system and extraction column, called hereinafter "part A";
- A fixed part consisting of the extraction electrodes together with the first element of LEBT which also houses the vacuum instrumentations, called hereinafter "part B".
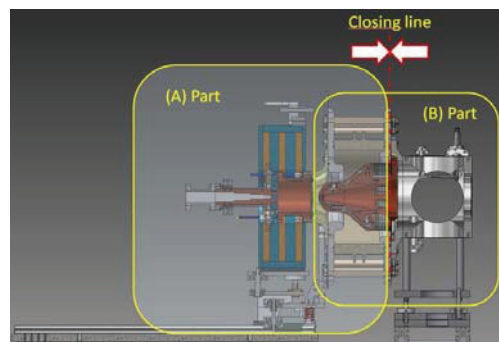

Figure 1: A view of the ESS source body totally assembled on its supports in the high voltage platform.

Part A

The part A consists of:

1) Insulating Al_2O_3 column
2) Oxygen Free High Conductivity Cu plasma chamber (OFHC)
3) RF waveguide and matching transformer
4) Magnetic system

Parts 1, 2 and 3 are rigidly joined together, and mounted on a single block supported on a "pin joint", as discussed in a next paragraph, which naturally allows several degrees of freedom.

On the other hand, the magnetic system is independent and it has an adjustable position.

The pin joint and the magnetic system can mutually translate along the beam line until the desired position.

Part B

The part B is composed by a stainless steel chamber, which is the first component of the LEBT, rigidly joined to the extraction electrode assembly. The first component is mechanically decoupled from the rest of the LEBT through

VERSATILE HIGH POWER MICROWAVE SYSTEM FOR FREQUENCY TUNING OF THE CAPRICE ECRIS

F. Maimone, M. Endermann, R. Lang, J. Mäder, P. T. Patchakui, P. Spädtke, K. Tinschert
GSI, Planckstraße 1, 64291 Darmstadt, Germany

Abstract

In the last years it was demonstrated that the variation of the microwave frequency generating the plasma inside ECR Ion Sources (ECRISs) allows to enhance the extracted current of highly charged ions both for gaseous and for metallic elements. In order to use this technique for the performance improvement of the CAPRICE-type ECRIS installed at the High Charge State Injector (HLI) of GSI, the microwave system has been modified. The new arrangement includes - besides the existing Klystron high power amplifier (HPA; max. 2 kW at 14.5 GHz) - two combined Traveling Wave Tube Amplifiers (TWTA) covering a bandwidth of 12.75-14.5 GHz, providing 750 W output power each, which are driven by one or two synthesizer tuners. The new system has been used during the routine operation of the ECRIS for production of different ion beams to be injected into the RFQ of the HLI. A detailed description of the main components of the new microwave system is presented, and the achieved characteristics of ion beam production using different microwave frequencies are described.

INTRODUCTION

In the last years several experiments using the technique of frequency tuning were carried out at the ECR injector test setup (EIS) of GSI in order to investigate the influence on the performance of the CAPRICE-type ECR Ion Source (ECRIS) in terms of enhanced ion currents of high charge states [1, 2]. It was demonstrated that this technique allows increasing the ion current extracted from an ECRIS both for gaseous and for metallic elements [3]. In order to use this technique for the routine operation of the ECRIS installed at the high charge state injector (HLI) of GSI, the microwave injection system has been modified.

At the HLI a CAPRICE-type ECRIS is installed for the production of high charge state ion beams at mass/charge ratios of up to 8.5 for the UNILAC at GSI. The ECRIS is designed to operate at 14.5 GHz and so far Klystron amplifiers were used to send the high power microwaves to the ECRIS to generate the plasma. In order to use the frequency tuning technique at the HLI an upgraded system using wideband high power Traveling Wave Tube Amplifiers (TWTA) has been conceived and assembled. The new arrangement includes two combined TWTAs covering a bandwidth of 12.75-14.5 GHz, providing up to 1500 W CW power, which are driven by one or two synthesizer tuners. In the following the upgraded system and the achieved results of ion beam production using different microwave frequencies are described.

HLI UPGRADED MICROWAVE SYSTEM DESCRIPTION

The schematic view of the upgraded microwave system installed at HLI is shown in Fig. 1. A sweeping signal generator provides the microwave signal to be amplified by two TWTAs. Each of them provides up to 750 W in the frequency range 12.75-14.5 GHz. When the required power is higher than 750 W, the power of the two amplifiers is summed up through a WR62 waveguide power combiner. Otherwise the power combiner is replaced by a high power wideband isolator. Both, the isolator and the power combiner have an insertion loss lower than 0.5 dB and an isolation higher than 20 dB. This last feature allows running the frequency sweeping without interruption of forward power due to the high reflected power amplifier protection in case of power mismatch. For the maximum summed power at the high power combiner, a phase shifter is used and the phase shift is adjusted whenever the frequency is tuned to an optimized condition. The system is integrated into the existing waveguide system with a WR62 mechanical switch. With this versatile setup the microwave input can be switched from the waveguide line connected to the klystron HPA to the one where the upgraded system including the TWTAs is installed. A high power load able to handle up to a CW power of 3000 W is connected to the switch and is used to test and perform measurements of the amplifiers.
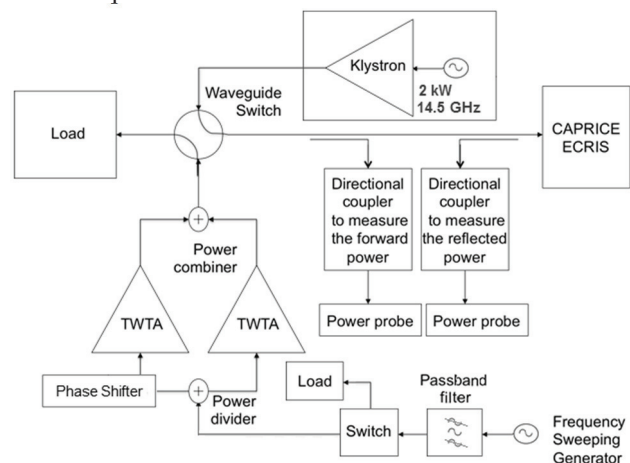

Figure 1: Block diagram describing the main components of the microwave injection system at HLI.

Two directional couplers are inserted between the switch and the ion source. Microwave power probes are connected to each directional coupler to measure the forward power to and the reflected power from the

MAGNETIC FIELD DESIGN FOR 2.45 GHz NEGATIVE HYDROGEN PMECRIS CHAMBER USING FEM SIMULATION

Chinmoy Mallick[†], Somesh V Tewari, Rajesh Kumar, Mainak Bandyopadhyay

Institute for Plasma Research, HBNI, Gandhinagar-382428, Gujarat, India

Abstract

Negative hydrogen ECRIS plasma is confined by NdFeB permanent magnet antenna around cylindrical cavity wall. A combination of four axially magnetized ring magnets of remanence flux density of 1.17T is simulated using bounded current ampere's law technique. Gradient of radial and axial magnetic flux density is calculated to estimate the leaking out fraction of lighter ions from the plasma wall sheath region. Measured axial and radial magnetic fields are benchmarked with the simulated data. The peak values of radial magnetic field gradient between plasma sheath region and cavity outer wall surface increases from $0.1×10^7$ A/m^2 to $-0.2×10^7$ A/m^2 respectively. Axial magnetic field gradient along inner ECR chamber wall increases from $-2.1×10^7$ A/m^2 to $2.5×10^7$ A/m^2. ECR contour dimensions of 0.0875 T which corresponds to microwave plasma, having resonating frequency of 2.45 GHz. The thickness of resonating surface is ~1 mm and having major and minor radius of 30 mm and 28 mm respectively.

INTRODUCTION

Gaseous plasma has a significant role in the fabrication of semiconductor chips and sputtering purposes. Since last few decades, rigorous research work has been carried out in generation of capacitive and inductively coupled plasma for these industrial applications. Negative ion beam is being extensively used in accelerator and fusion related applications. Microwave ECR plasma is also important for these applications but one limitation is when large substrate are used but for smaller substrate it is an excellent technique. Low pressure (in the range of 10^{-3} mbar) microwave ECR plasma is very useful in the removal of impure material from semiconductor materials. Negative ion plasma demand is increasing in the reduction of air pollution [1]. Low pressure microwave plasma under ECR conditions can produce beams having high etching rates which are crucial for semiconductor fabrication technology [2, 3, and 4].

Permanent magnet ECR ion source (PMECRIS) will use microwave power of 500W at frequency 2.45 GHz to produce primary hydrogen plasma inside the source, which will further be optimized to generate negative hydrogen ions through surface conversion technique using cesium catalyst. Design optimization of ion source taking into account of minimum-B magnetic field configuration, microwave E-field launching and effects of Doppler

Broadening on resonance is demonstrated. This compact four ring magnet based ECR ion source is easy to

handle because it eliminates all the high voltage active components as is required in solenoid based electromagnets. The only system component that crosses the high voltage boundary is the microwave waveguide section and gas feed section, all other components are at high voltage situations. PMECRIS system can produce high charge state ion beams which has wide applications ranges from nuclear physics research to the material processing [3 and 4]. Four permanent magnet based ECR ion source is designed to construct a compact linear RFQ accelerator for research purposes. Magnetic field design is important for the expected performance of the ECR ion source system.
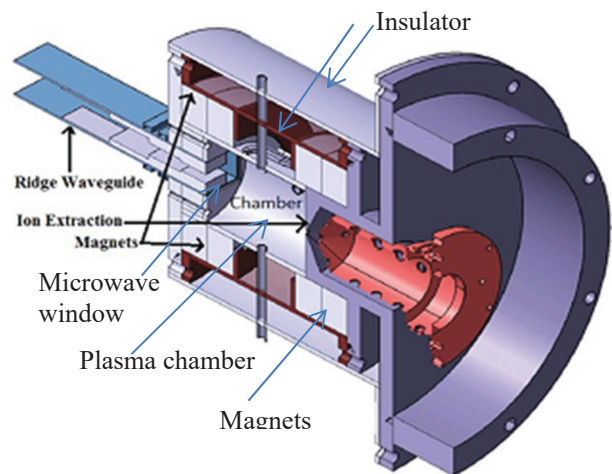

Figure 1:Section cut-view of negative PMECRIS.

MAGNETOSTATICS THEORY

This 2D axis symmetric model describes the magnetic field distribution inside the plasma chamber in cylindrical coordinates (Using azimuthal symmetry). The magnetic field of the NdFeB ring magnets is obtained from Ampere's law (bounded current) technique by the use of magnetic vector potential A which has only azimuthal non zero component [5]. The rare earth ring magnets are defined as two surface currents at inner and outer radial surfaces directed azimuthally in the opposite direction to each other. In this 2D axis-symmetric model, because of no variation of magnetic flux density at each point in the azimuthal direction, there exist only azimuthal component of the magnetic vector potential [5 and 6]. This is justified analytically as well as with simulation results. Axial component of magnetic field is given as $B_z = \frac{1}{r}\frac{\partial(rA_\theta)}{\partial r}$ and radial component of magnetic field calculated as $B_r = -\frac{\partial A_\theta}{\partial z}$

————————————

†chinmoy.mallick@ipr.res.in

RECENT BEAM DYNAMICS STUDIES FOR THE SCL DEMO OF RISP

Hyunchang Jin*, Ji-Ho Jang, In-Seok Hong

Institute for Basic Science, Yuseong-daero 1689-gil, Yuseong-gu, Daejeon, Korea

Abstract

The rare isotope science project (RISP) has been developed the RAON accelerator to accelerate heavy ion and rare isotope beams for the various kinds of science programs. In the RAON accelerator, the beams created by a superconducting electron cyclotron resonance ion source (ECR-IS) will be accelerated by the radio-frequency quadrupole (RFQ) after passing through the low energy beam transport (LEBT) section. These accelerated beams will pass the medium energy beam transport (MEBT) section for the beam matching and be re-accelerated by the superconducting linac (SCL) for the higher beam energy. Prior to the construction of the RAON accelerator, the performance of each component of LEBT, RFQ, MEBT and SCL should be examined for the efficient mass production. Accordingly, we have been constructing the test facility, which is named SCL demo, since 2015. First beam test with an oxygen beam will be carried out at the end of 2016 and the next test with a bismuth beam will be performed in 2017. In this paper, we will present the beam dynamics studies with the recent lattice design of the SCL demo and describe the simulations results with the bismuth and oxygen beams.

INTRODUCTION

The RAON (Rare Isotope Accelerator of Newness) accelerator [1] being developed by the rare isotope science project (RISP) is designed to accelerate the stable ion beams from proton to uranium and transport these beams to the targets of experimental halls for a wide range of science programs with various rare isotopes created from the targets. An 28 GHz electron cyclotron resonance ion source (ECR-IS) creates various kinds of stable ion beams, and these beams are transported and accelerated through the low energy beam transport (LEBT) section [2], the radio-frequency quadrupole (RFQ), the medium energy beam transport (MEBT) section, and the superconducting linac (SCL) section. Here, the SCL section is divided into low and high energy sections: the low energy SCL (SCL1 and SCL3) section consists of two kinds of cavities, quarter-wave resonator (QWR) and half-wave resonator (HWR), depending on the beam velocity, and the high energy SCL (SCL2) section does two kinds of single-spoke cavities (SSR). The beam accelerated by the SCL1 or SCL3 are transported to the low energy experimental hall or can be accelerated again by the SCL2 after passing through the charge stripping section [3] for the high energy experiments. The schematic view of the RAON accelerator is shown in Fig. 1.

The lattice design of the RISP test facility started since 2014 as an injector test facility which did not include the SCL
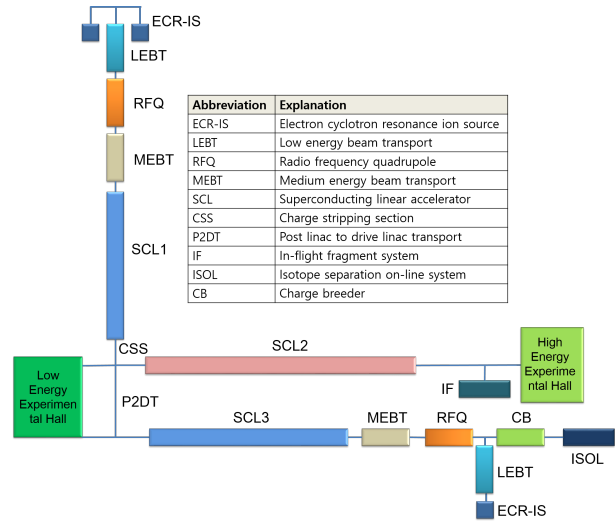
---

* hcjin@ibs.re.kr

Figure 1: Schematic view of the RAON accelerator.

section [4], and then the lattice of this test facility was newly re-designed with the superconducting cavity and named SCL demo in 2015 [5]. Now the lattice of the SCL demo becomes more simplified and optimized within the limited space to test the front-end section of the RAON accelerator, and each equipment is being installed and tested individually for the beam commissioning at the end of 2016. Figure 2 shows the recent layout of the SCL demo, and one QWR cavity is located at the end of the SCL demo.
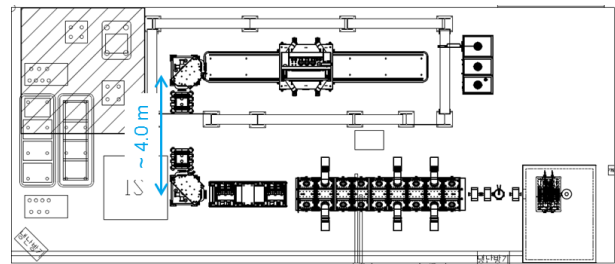

Figure 2: Layout of the SCLdemo.

In this paper, we will present the recent lattice design of the SCL demo and describe the results of the beam optics calculation and the particle tracking simulations with the bismuth beam and the oxygen beam. In the following beam dynamics simulations, the ELEGANT [6] and TRACK [7] codes were used.

DESIGN POINTS

For designing of the SCL demo lattice, several design points are considered as listed in Table 1. The bismuth and oxygen beams are selected as reference beams at the SCL

FOUR-DIMENSIONAL TRANSVERSE PHASE-SPACE DISTRIBUTION MEASURED BY A PEPPER-POT EMITTANCE METER

T. Nagatomo*, V. Tzoganis[1], M. Kase, O. Kamigaito, and T. Nakagawa,
RIKEN Nishina Center, Wako, Japan
[1]Kockkroft Institute, Warrington, United Kingdom

Abstract

In this study, we observed variations in the four-dimensional transverse emittance, ϵ_{4D}, of argon beams having several charge states with respect to the amount of residual gas in the low-energy beam transport (LEBT) of a 18-GHz superconducting electron cyclotron resonance ion source (18-GHz SC-ECRIS) at RIKEN, as measured by a pepper-pot emittance meter. Natural krypton gas was injected into the LEBT to control the amount of residual gases. Collisions between the beams and the residual gaseous atoms generated electrons that were expected to cancel out the positive electric potential inside the beam, or, in other words, achieve space-charge compensation. Reductions in the emittance of $^{40}Ar^{8+}$, $^{9+}$ and $^{11+}$ beams were observed by the injection of krypton gas into the LEBT. The reductions in projected emittances such as ϵ_x and ϵ_y were different for each charge state; however, the reduction in ϵ_{4D} of these charge states were similar to each other. The degree of reduction in ϵ_{4D} was about 50% when the residual gas pressure of the LEBT was changed from 1.9×10^{-7} mbar to 1.3×10^{-5} mbar. The mechanism of the reduction in emittance is not clarified in this paper because there is a possibility that the reduction was caused by the change in electron cyclotron resonance plasma, which is induced by the penetration of the injected krypton gas into the plasma chamber.

INTRODUCTION

Recently, the importance of the emittance of four-dimensional (4-D) phase space, ϵ_{4D}, has received much attention, and it has been discussed with the aim of improving beam quality [1–3]. ϵ_{4D} is an invariant under linear 4-D symplectic transformation, such as beam transport using linear optical components including solenoid and skew-quadrupole lenses. On the other hand, the two-dimensional (2-D) emittances, ϵ_x and ϵ_y, are not invariant when a solenoid lens or a skew-quadruple lens are used because both types of lenses can couple these quantities. If there is no acceleration/deceleration, no beam loss, and no non-linear effects, ϵ_{4D} should remain constant during beam transport. Thus, measurement of ϵ_{4D} provides quantitative and essential information that can be used to improve beam quality in the real sense of the term.

As is well known, attention must be paid to any aberrations in the beam optics components and the space-charge effect when the ion-beam current is high, as these degrade the beam quality through the enhancement of the beam emit-

---

* email nagatomo@riken.jp

tance. The possibility of space-charge compensation by a deliberate injection of a neutral gas into the LEBT was discussed by Toivanen et al. [4]. Based on that report, we have developed an on-line pepper-pot emittance meter that is suitable for obtaining ϵ_{4D} [5], and studied how the ϵ_{4D} of multiply charged argon beams evolves with respect to the amount of neutral krypton gas injected in the LEBT. We report some preliminary, but interesting, trends in these emittances.

EXPERIMENTAL SETUP

Pepper-pot Emittance Meter

The pepper-pot emittance meter consists of a thin metallic plate (50 μm thick) with a 25 × 25-pinhole array and an imaging screen to detect transverse deviation of the beamlets. The diameter of each pinhole is 0.1 mm, and the pitch of the pinholes is 2.0 mm in both the horizontal and vertical directions. An imaging screen (P46) was placed behind a microchannel plate (MCP) that was employed to convert the heavy ions into electrons in order to prolong the lifetime of the screen. The pinhole plate was translated along the beam axis using a stepper motor to find the optimum distance between the pinhole plate and the MCP. The distance could be varied from 23 mm to 56 mm, and was calibrated with respect to the number of electric pulses driving the stepper motor. The beamlet image reflected by a mirror angled at 45 degrees was detected through a viewport by a CMOS camera. An electrical beam chopper placed in front of the emittance meter was synchronized with the CMOS camera to stop the beam when images were not being acquired. For more details of the mechanical design, please refer to [5].

We also developed image-capture and emittance-analysis programs using LabVIEW (National Instruments Co.). We programmed a process that automatically identifies the correspondence between each of the beam spots and the pinhole through which the beamlet passed. It is possible to obtain the particle distribution in 4-D transverse phase-space from this analysis. Therefore, from the distribution in the 4-D phase space, (x, x', y, y'), six types of two-dimensional projections can be generated, i.e. x-x', y-y', x-y, x'-y', x-y' and y-x' projections. The developed program displays all the projected distributions simultaneously, as shown in Fig. 1, immediately after the beamlet image is captured. In addition, the ϵ_{4D}, the transverse beam matrix C and the two-dimensional emittances, which are described in the following section, are also calculated and displayed. All of these processes, including the image-capture process, can be com-

FAST SPUTTERING MEASUREMENT STUDIES USING URANIUM WITH THE NSCL ECR ION SOURCES*

Derek Neben[†], Jesse Fogleman, Daniela Leitner[1], Guillaume Machicoane, Guy Parsey,
Alfonse Pham, Shane Renteria, Jeffry Stetson, Larry Tobos, and John Verboncoeur
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI, USA
[1] Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

Existing heavy ion facilities such as the National Super-conducting Cyclotron Laboratory (NSCL) at Michigan State University rely on Electron Cyclotron Resonance (ECR) ion sources as injectors of highly charged ion beams. Long ion confinement times are necessary to produce dense populations of highly charged ions because of steadily decreasing ionization cross sections with increasing charge state. To further understand ion extraction and confinement we are using a fast sputtering technique first developed at Argonne National Laboratory [1] to introduce a small amount of uranium metal into the plasma at a well-defined time. In addition we utilize an axial x-ray apparatus [2] to characterize the hot electron plasma population via its bremsstrahlung emission.

INTRODUCTION

The Coupled Cyclotron Facility (CCF) at the NSCL [5] can accelerate ion beams up to 160 MeV/u with a corresponding beam power on target ranging from a few hundred watts to up to a kilowatt. Heavy ions from oxygen to uranium are injected from two ECR ion sources: a 14.5 GHz normal conducting Advanced Room TEMperature Ion Source (ARTEMIS) and the Superconducting Source for Ions (SuSI) operating at 18 and 24 GHz [8,9]. Typically a Mass to Charge (M/Q) range between 8 and 5 is injected for CCF operations, and some typical beams are: $^{48}Ca^{8+}$, $^{76}Ge^{12+}$, $^{238}U^{30+}$, and $^{16}O^{3+}$. The medium charge state is necessary because the final magnetic rigidity needs to be reduced approximately by half to inject properly into the K1200 after charge stripping inside the cyclotron.

We aim to probe ion confinement time by introducing a plasma contaminant and measuring its breeding and decay time. The fast sputtering technique, pioneered by ANL [1], was employed on ARTEMIS and SuSI with an uranium sample. Sputtering is a process where plasma ions are pulled onto a cathode, typically negatively charged to a few hundred to a few thousand volts, and cathode material is ejected [10]. Because ionization is an endothermic process cathode material cools the plasma and supplies cold electrons that perturb the plasma energy balance, therefore the smallest measurable contaminant currents are used. The high negative voltage applied to the sputter probe might perturb the electron losses and therefore plasma confinement [3]. Fast sputtering using
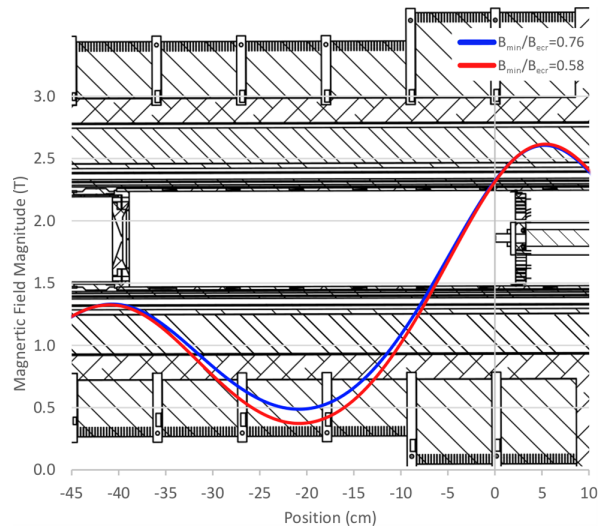
Figure 1: SuSI Magnetic field as simulated with Poisson Superfish overlaid with axial sputtering injection. The sputter probe was 55 mm forward of the peak at injection, and 10 mm forward of the bias ring.

an axial and radial geometry was investigated on ARTEMIS. On SuSI only the axial method was available.

EXPERIMENTAL SET-UP

The extracted beam current was measured on a Faraday cup after the analyzing magnet the current was sampled using an oscilloscope as a voltage across a 100 kΩ resistor. A low-pass circuit with cutoff frequency at 109 kHz was attached in series to suppress noise in the MHz range, and oscilloscope waveforms were converted to real currents in post-processing. The sputter probe voltage was pulsed using a PVX-4140 high voltage switch and a DC high voltage supply. We could operate in DC mode by driving the switch to a constant on or off state. The timing and width of the high voltage pulse was controlled by a TTL signal sent to the high voltage switch from a signal generator located at ground through a TTL-to-fiber converter. The output voltage was monitored at the high voltage switch through a port allowing us to measure the rise and fall times of voltage applied to the probe. The microwave power was measured at the forward coupler on the klystron for both ARTEMIS and SuSI.

On SuSI an axial High Purity Germanium (HPGe) x-ray detector and collimation system was used similar to [2] for observation of the high energy electron tail. The HPGe detection efficiency was measured offline using a ^{152}Eu source

MEASUREMENT OF MICROWAVE FREQUENCIES EMITTED BY INSTABILITIES OF ECRIS PLASMA WITH WAVEGUIDE FILTERS AND MICROWAVE SENSITIVE DIODES[*]

J. Orpana[†], O. Tarvainen, T. Kalvas, H. Koivisto, R. Kronholm, J. Laulainen

University of Jyväskylä, Jyväskylä, Finland

I. Izotov[1], D. Mansfeld, V. Skalyga[1]

Institute of Applied Physics, RAS, 46 Ul'yanova St., 603950, Nizhny Novgorod, Russian Federation

[1]also at Lobachevsky State University of Nizhny Novgorod (UNN), 23 Gagarina St., 603950 Nizhny Novgorod, Russian Federation

Abstract

Periodic emission of strong microwave bursts at certain frequencies is a characteristic feature of kinetic instabilities in ECRIS plasmas. Precise measurement of the temporally evolving microwave frequency spectra requires a high bandwidth oscilloscope, which can make the experiments prohibitively expensive to conduct. An alternative low-cost method to study the microwave emission in narrow frequency bands is to apply band-pass waveguide filters and microwave sensitive diodes. The microwave emission from the plasma of the JYFL 14 GHz ECRIS has been studied with both methods. The results of the experiments are compared and their interpretation is discussed. It is demonstrated that the method based on filters and diodes can provide useful information about the microwave emission spectra induced by electron cyclotron instabilities.

INTRODUCTION

The electron velocity distribution in electron cyclotron resonance ion source (ECRIS) plasmas is non-Maxwellian and strongly anisotropic i.e. $v_{e,\perp} \gg v_{e,\parallel}$ [1, 2]. Magnetized non-equilibrium plasmas are prone to cyclotron instabilities emitting microwaves due to resonant amplification of plasma waves by hot electrons [3]. The Doppler shifted emission frequency (see e.g. Ref. [4]) can be expressed as

$$\omega = \frac{\omega_{ce}}{\gamma} \pm |k_\parallel v_{e,\parallel}|, \qquad (1)$$

where $\omega_{ce} = eB/m_e$ is the cold electron gyrofrequency, $\gamma = 1 + E_k/E_0$ the relativistic Lorentz factor expressed here with the electron kinetic (E_k) and rest ($E_0 = 511$ keV) energies, $k_\parallel$ the longitudinal wave number of the plasma wave and $v_{e,\parallel}$ the longitudinal (hot) electron velocity. The measurement of the emission frequency serves as an indirect plasma diagnostics method, which can be used e.g. to determine the excited wave mode [5]. Since ω is a function of magnetic field strength B and electron kinetic energy E_k, measuring the emitted microwave frequencies together with

the energies of the electrons escaping the magnetic confinement as a result of the interaction with the plasma wave, would also allow determining the range of magnetic field values where the instability is triggered.

The purpose of this paper is to demonstrate the feasibility of low-cost bandpass filters and Schottky diodes for the measurement of the microwave emission frequencies related to kinetic instabilites of ECRIS plasmas.

EXPERIMENTAL SETUP

In earlier experiments two techniques have been used for the detection and diagnostics of the instability-related microwave emission of the A-ECR-U type JYFL 14 GHz ECRIS [6]:

- a Schottky diode, sensitive to frequencies of 0.01–50 GHz [7] and

- a high-bandwidth (25 GHz / 100 Gs/s) oscilloscope [5].

In both experiments the microwave emission was detected by connecting the diagnostics system to the ECRIS through an off-axis WR-75 waveguide port (cut-off frequency of 7.9 GHz) normally used for injection of microwave power at secondary frequency. Appropriate adapters and attenuators were used to transport the signal and protect the equipment. The Schottky diode alone is sufficient for measuring the duration of the microwave bursts while the oscilloscope can be used for measuring the dynamic spectrum of the microwave emission i.e. the frequencies emitted by the instabilities as illustrated in Fig. 1.

The dynamic spectrum yields all the necessary information on the microwave emission, i.e. temporal evolution of the emission frequencies and their intensities. However, the measurement technique requires purchasing or renting a high-bandwidth oscilloscope, preferably having a sampling rate ≥ 100 Gs/s to allow collecting sufficient number of data points per microwave cycle for a Fourier transform. Unfortunately, such devices are prohibitively expensive in most cases. Thus, development of an alternative method for detecting the emission frequencies on daily basis is desirable. This work benefits from the fact that the microwave emission has been shown [5] to exhibit certain characteristic features that are also visible in Fig. 1. The emission

INVESTIGATION OF 2.45 GHz MICROWAVE RADIATED ARGON PLASMA UNDER MAGNETIZED CONDITION

Chinmoy Mallick†, Somesh V. Tewari, Rajesh Kumar, Mainak Bandyopadhyay

Institute for Plasma Research, HBNI, Gandhinagar-382428, Gujarat, India

Abstract

Permanent magnet based ECR ion source (PMECRIS) is a compact microwave discharged ECR ion source. This work models microwave plasma coupling in 2D axis symmetric configuration to investigates plasma parameters and corresponding influence of electric field in plasma environment. A microwave field of the order of 1.3×10^5 V/m is obtained at the Centre of the plasma chamber cavity for an input microwave power of 500 W. Present microwave coupled plasma has a maximum density of 9.04×10^{16} / m^3. The steady state peak electron temperature is around 3 eV under various pressure (1mbar-10^{-3} mbar) conditions of argon gas. Most of power deposition takes place on the ECR surface zone which corresponds to 0.0875 T contour. Steady state argon plasma results show that beyond a critical plasma density of 7.4×10^{16} /m^3 most of the microwave power is deposited at the plasma edge.

INTRODUCTION

Since last few decades, dipolar and multipolar based microwave plasma based ECR ion source have been studied[1 and 2]. Hagelaar et.al [3and 4] and J Pelletier group [5] obtained a uniform high density plasma up to gas pressures 10^{-2} mbar.
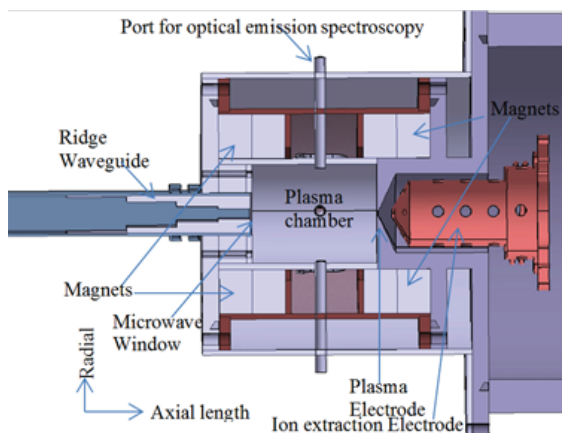

Figure 1: Cut section of negative hydrogen PMECRIS.

A detailed insight on microwave fed ion source physics is discussed for different absorbed power conditions by Hagelaar. Microwave heated ECR plasma is growing its interest in numerous number of applications under low pressure conditions, in plasma electron heating and power deposition by microwave electric field infusion plasma. A

†chinmoy.mallick@ipr.res.in

recent trend in the ion source technology aims at decreasing the gas pressure in the 10^{-3}mbar range using the same resonance heating by creating MW plasma.
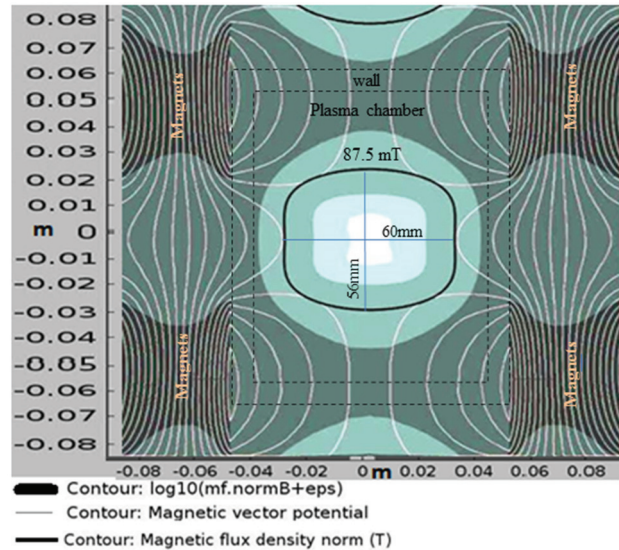

Figure 2: ECR contour for 2.45 GHz frequency.

At high pressures, ohmic heating (collision based) occurs in which gyrating electron motion is randomized by collisions with background gas molecules[6, 7 and 8]. With spatially varying electric fields in resonance zone, phase randomization can also happen due to thermal electrons motions even in the absence of collisions. This collision less heating dominates under low pressures. Under low pressure conditions plasma can be maintained uniformly and parameters can be well controlled [4-9]. However, in low pressure (10^{-3} mbar range), sufficient database is not available for negative ion source in R&D sectors.

This paper investigates a microwave coupled PMECRIS plasma under low gas pressure ($\leq 10^{-2}$mbar), which finally will be used as a negative hydrogen ion source for an RFQ accelerator. Effect of time scale dependent microwave propagation into the plasma is also discussed. A further study on how the power deposition is taking place with time into the plasma volume has been done. A detailed picture of time varying electric field distribution in plasma environment has been demonstrated clearly.

MICROWAVE PLASMA MODEL

This model is based on the finite element method (FEM) considering fluid approach with drift diffusion approximation. Ion motion is negligible w.r.t the electron motion in microwave timescale (ns). Electron density is

RECENT PRODUCTION OF INTENSE HIGH CHARGE ION BEAMS WITH VENUS

D. Z. Xie[†], W. Lu[1], J. Y. Benitez, C. M. Lyneis, D. S. Todd

Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

[1]also at Institute of Modern Physics, Lanzhou 730000, China

Abstract

Several modifications have been made to VENUS to enhance its performance at high microwave power and bring its beam production closer to the levels predicted by scaling laws for 28 GHz operation. Two of these modifications allowed for an increase of injected microwave power: the cooling scheme on the plasma chamber wall was improved to eliminate damage caused by localized electron heating, and the extraction electrode was redesigned to remove the thermal energy from incident hot electrons more effectively. A further modification was the reduction in the diameter of the waveguide which launches 28 GHz power into the plasma chamber. With these remedies, the source now operates stably up to 10 kW of injected power and allows for more favorable magnetic field configurations. The extraction of high charge state ion beams from VENUS has been substantially enhanced as demonstrated by the recent production of a number of intense CW beams: 4.75 emA of O^{6+}, 1.90 emA of O^{7+}, 1.06 emA of Ar^{12+}, 0.523 emA of Ar^{16+}, 0.115 emA of Ar^{17+}, 0.77 emA of Kr^{18+}, 0.355 emA of Kr^{26+} and 0.007 emA of Kr^{31+}. For the first time VENUS has been able to produce more than 1 emA of O^{7+} and Ar^{12+}, and enhance the intensity of the higher charge state ion beams by a factor of 2 and higher.

INTRODUCTION

VENUS is the first 3rd generation superconducting ECR ion source (ECRIS) operating at 28 GHz with magnetic field maxima of 4 T on axis and 2 T radial at the inner surfaces of the plasma chamber [1]. Beginning with its initial operation in 2002, VENUS produced a number of record CW beams from an ECR source and delivered a wide variety of highly-charged, heavy ion beams to enhance the capability of the 88-Inch Cyclotron [2]. However, VENUS was limited in its potential magnetic field configurations at higher input microwave power due to a thin-edged plasma electrode, shown in Fig. 1, which insufficiently transported away the heat load generated by hot electron bombardment. In order to avoid melting this electrode, higher extraction peak fields were required to reduce the flux of hot electrons to the plasma electrode by guiding them to the chamber radial walls. Consequently these higher extraction fields resulted in the lowest total magnetic fields on the chamber surface occurring in localized areas on the chamber radial walls, as shown in Fig. 2, leading to an intense heat transfer to these spots by the hot electrons. This localized heating severely

_____
[†] zqxie@lbl.gov

deteriorated the plasma chamber walls over time and resulted in two burned out plasma chambers; even while operating with microwave power limited to 7 kW or lower [3, 4]. This very restrictive constraint on input heating power resulted in VENUS not reaching its full potential even after 15 years of operations.

This article presents and discusses the two recent modifications addressing insufficient chamber cooling, which now allow for more input microwave power. These improvements, coupled with the studies into the effects of reducing the exit diameter of the 28 GHz waveguide from 31.8 mm to 20.0 mm which are also discussed, have allowed for operating VENUS with more preferable magnetic field configurations, with more power, and have led to a stable plasma resulted in significant enhancements on the extracted beam current.

NEW PLASMA ELECTRODE

Figure 1 shows the previous plasma electrode having a slant taper of a minimum thickness of ~ 0.6 mm at the aperture edge of Ø10 mm and ~1.4 mm at Ø16 mm slant-step transition region. This electrode design is poor in transporting away the thermal load on the thin edge and thus not suitable for the hot ECR plasma operating at high microwave power. The high thermal heat load on the electrode thin edge could lead to microscopic and macroscopic surface melting in certain locations, and the presence of molten aluminium decreases plasma stability. Heat transport simulations indicate that for a circular region of radius of ~ 8 mm it takes ~ 950 W power, equivalent of 775 W/cm^2 in an area of $S = \pi(0.8^2\text{-}0.5^2)$ cm^2, for the thin edge temperature rising up to ~ 350 ^{0}C in which the aluminium recrystallization will occur.
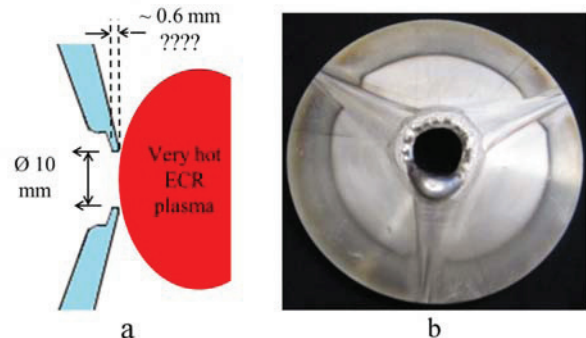

Figure 1: a). The previous plasma electrode with the aperture supported by a very thin slant backing resulted in poor power transportation; b). This thin aperture edge was melted for a few hours of operation at ~ 7.5 kW microwave power with extraction peak field lower than the minimum total field at the chamber walls.