ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-MOA3

FIRST ION BEAMS EXTRACTED FROM A NEW JYFL 18 GHz ECRIS: HIISI*

H. Koivisto†, T. Kalvas, R. Kronholm and O. Tarvainen, Department of Physics, University of Jyväskylä (JYFL), 40500 Jyväskylä, Finland

Abstract

A new 18 GHz ECR ion source HIISI is under commissioning at the Accelerator Laboratory at the University of Jyväskylä (JYFL). The main purpose of HIISI is to produce high-intensity ion beams for nuclear physics programme and high-energy beam cocktails for radiation effects testing of electronic components. The initial commissioning results in (18+14) GHz operation mode using 24 segment sextupole (1.3 T) were performed in autumn 2017. A stronger 36 segment sextupole (1.42 T) was constructed and tested during the spring 2018 demonstrating improved performance of HIISI. As an example, Ar^{12+} intensity of 0.57 mA was reached with 19.5 kV extraction voltage and total microwave power of 2.35 kW. In this article we will present the latest development work, ion beam intensities of oxygen, argon and xenon, and future prospects of HIISI.

INTRODUCTION

The K130-cyclotron [1] at JYFL is equipped with an AECR-U type, room temperature (RT) 14 GHz ECR ion source [2] for heavy ion production. The old 14 GHz ECR ion source has worked reliably for more than 60000 plasma-on hours since its construction in 1999. Most of the beams have been produced from natural or enriched gases or by using the MIVOC method [3]. Typical requested energy of the projectile is 5 MeV/u, which requires a q/A-ratio of 0.2. For example, in the case of argon and xenon ion beams charge states of 8+ and 27+ are often needed. Due to the demand for more intensive beams of highly charged ions and also for higher energy for irradiation tests of space electronics the project for a new ECR ion source was initiated in 2013. At the end of 2013 the Academy of Finland funded the JYFL Accelerator Laboratory to design and construct an 18 GHz ECR Heavy Ion Ion Source Injector (HIISI, ref. [4-6]). The objective of HIISI was two-fold: 1) the intensity of medium charge state ion beams, such as Ar^{8+} and Xe^{27+} ($E \approx 5$ MeV/u), has to be increased by a factor of 5 and 2) the energy of heavy ion beams ($A > 100$) has to exceed the value of 15 MeV/u. The first requirement is set by the nuclear physics program and the latter one by the irradiation testing program for the space electronic components. The testing program requires 10^6 particles/s/cm^2 on the irradiation target station. In the case of xenon, which is the heaviest element in 16 MeV/u cocktail, this corresponds to charge state of 44+, and the extracted ion beam intensity of about 10 nA when the total transport efficiency of accelerator facility is taken into account. In 2013, the presented requirement was beyond any existing RT-ECRIS, which forced us to design and construct a new room temperature 18 GHz ECRIS. In this article the present status of HIISI will be given.

*The project has received funding from the EU Horizon 2020 research and innovation programme under grant agreement No 654002 and the Academy of Finland under the Finnish Centre of Excellence Programme 2012-17 (Nuclear and Accelerator Based Physics Research at JYFL
† hannu.koivisto@phys.jyu.fi

HIISI SPECIFICATIONS

In 2013 only three ECRISs were able to produce the xenon ion beam intensity (Xe^{44+}/10 nA) required by the irradiation testing program at JYFL. Those ECR ion sources are VENUS [7], SECRAL [8] and SUSI [9]. The experimental data and operation parameters revealed that SUSI is able to produce the Xe^{44+} ion beam intensity of about 100 nA in 18 GHz operation mode (B_{inj} = 2.8 T/B_{ext} = 1.3 T and B_{rad} = 1.35 T) and at the microwave power of about 4 kW. In addition, it has produced 730 μA of Ar^{12+} with total microwave power of 3.8 kW. The aforementioned magnetic field configuration can be obtained by using normal conducting solenoids and permanent magnets. Consequently, it was decided that SUSI magnetic field configuration and plasma chamber dimensions will be used as the design goal of HIISI.

HIISI has two innovative features, which make it special compared to any other RT ECR ion source: 1) its permanent magnet array is vacuum insulated and 2) cylindrical symmetry of the plasma chamber has been broken. Both features have thoroughly been described in ref. [4 – 6]. The vacuum insulation allows the cooling of the permanent magnets, which improves the properties of the permanent magnets. The intrinsic coercivity H_{cJ} and residual magnetic induction B_r for the selected magnet grade (N45SH) increase 0.55 %/°C and 0.12 %/°C, respectively, when the temperature of the permanent magnet decreases. The HIISI design allows cooling of the permanent magnets to -20 C°. This will increase the H_{cJ} and B_r values from 1595 kA/m and 1.35 T (at 20 °C) to about 2100 kA/m and 1.42 T (at -20°C), respectively. According to demagnetization analysis HIISI is safely operated as long as the permanent magnet temperature does not exceed room temperature.

The cooling capacity of the HIISI plasma chamber allows the use of microwave power of up to 4 kW. The cooling geometry of the plasma chamber and the refrigerated PM array have been presented thoroughly in references [4-6]. Further development of the refrigerated permanent magnet array could make the construction of 1.5 T ECR ion source sextupole possible. This would

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-MOB2

IMPACT OF ION SOURCE STABILITY FOR A MEDICAL ACCELERATOR

N. Gambino†, S. Myalski, L. Adler, F. Ecker, A. De Franco, F. Farinon, G. Guidoboni, C. Kurfürst, M. Pivi, C. Schmitzer, I. Strasik, A. Wastl, EBG MedAustron, Wr. Neustadt, Austria
L. Penescu, Abstract Landscapes, Montpellier, France

Abstract

MedAustron is a synchrotron-based hadron therapy center located in Lower Austria. Accelerated proton beams with energies of 62-252 MeV/u are used to treat patients since 2016. The carbon ion beam is currently under commissioning and will provide treatment in 2019 with energies of 120-400MeV/u. Two of the four irradiation rooms are used for clinical treatment while the preparation of the Gantry beam line is ongoing. Proton beams of up to 800 MeV will be provided for non-clinical research. The Injector features three identical ECRIS from Pantechnik, two of which are used to generate the proton and the carbon beam respectively. The medical environment of the accelerator puts strict requirements on the ion source long-term stability operation. The extracted beam current from the source allow for maximum current fluctuations on the order of ±2.5% on continuous run. In this work we discuss the impact of the ion source performances on the characteristics and stability of the entire accelerator. Further, we discuss the latest progress on carbon commissioning and the future perspectives with particular emphasis on the source requirements.

INTRODUCTION

The MedAustron is a synchrotron-based therapy center for cancer treatment. The design of the accelerator is based on PIMMS and CNAO [1,2]. Currently 26 patients (fractions) per day are treated with proton ion beams since 2016. Medical treatment with carbon ions is planned to start in 2019 [3]. A proton beam up to 800 MeV/u will be provided for non-clinical research.

The Injector shown in Fig. 1 features three identical Supernanogan ECRIS from Pantechnik. One is reserved for proton beams production and one for carbon beams production. The third is foreseen as future use for clinical and non-clinical research. The extracted beam from the source at 8 keV/u is transported through the LEBT line to the linear accelerator. The LINAC contains a Radio Frequency Quadrupole (RFQ) module which accelerates the beam to 400 keV/u followed by a Buncher and an IH-Tank cavity where the energy reaches 7 MeV/u and finally by a Debuncher cavity. Through the Mid Energy Beam. Transport (MEBT) line the beam is then injected in the synchrotron where it reaches the clinical e non-clinical energies mentioned before. A slow extraction 3rd order resonance method via Betratron Core is used to extract the particles from the synchrotron. Through the High Energy Beam Line (HEBT) the beam is sent to four available irradiation rooms: IR1 with horizontal beamline for non-clinical research, IR2 with a horizontal and a vertical beamline, IR3 with a horizontal beamline and IR4 with a proton Gantry. The weekly machine uptime during clinical operation between 90% and 97% [4].

THE IONS SOURCE

The identical design and the availability of three independent source lines allows for parallel running of the sources and for source switching in case of emergency. The ion beam in the source is produced through the Electron Cyclotron Resonance (ECR) heating mechanism [5]. The neutral gas is brought into a state of plasma magnetically confined in the vacuum vessel and the ions are extracted from the chamber with a dedicated extraction system. The Supernanogan of Pantechnik has been described in detail in [6]. It operates at 14.5 GHz heating frequency and is it entirely equipped with permanent magnets both for the radial magnetic field than for the longitudinal magnetic field with a B_{ECR} of 0.5 T. An axial mirror ratio B_{max}/B_{min} about two times higher than the ECR resonance magnetic field is obtained [5].

The plasma has limited contact to the chamber walls and the high charge state ions concentrate in the center of the extracted beam with a triangular intensity distribution. The longitudinal beam profile depends mainly on extraction parameters with respect to the plasma potential. The source body is placed at 24 kV, while a puller electrode is placed at negative potentials of about 2 kV to accelerate the beam towards the focus. The focus electrode on the order of 1.5 kV is fine tuned to adapt the beam size to the focal point of the dipole magnet for a good transmission into the beam line and further matching into the RFQ. The DC Bias tip, introduced from the backside of the vacuum chamber into the plasma, reduces the ion losses towards the injection. The RF tuner position is used to reduce the reflected power. The typical source parameters used for the proton and the carbon source are indicated in table 1:

† nadia.gambino@medaustron.at

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-MOB3

COMMISSIONING OF THE AISHA ION SOURCE AT INFN-LNS

L. Celona †, G. Castro, F. Chines, S. Gammino, O. Leonardi, D. Mascali, S. Marletta, M. Mazzaglia, A. Miraglia, E. Naselli, L. Neri, S. Passarello, G. Torrisi, INFN-LNS, 95123 Catania, Italy

Abstract

The AISHa ion source has been designed to generate high brightness multiply charged ion beams for hadrontheraphy applications, with high reliability, easy operations and fast maintenance. In order to get a compact machine, the radial confinement is provided by a Hallbach-type permanent magnet hexapole structure, while axial confinement is allowed by four high field He-free superconducting magnets, allowing the optimization of the magnetic field gradient at ECR resonance. The present work shows the results of ion source commissioning along with next developments.

INTRODUCTION

The AISHa [1] ion source was funded within the framework of the program of Sicilian Government named PO FESR 2007-2013 and a pool of Sicilian small enterprises was associated with INFN for the realization of this new source. It was designed considering the typical requirements of hospital facilities, in order to provide highly charged ion beams with low ripple, high stability and high reproducibility. The minimization of the mean time between failures is also a key point together with the maintenance operations that should be fast and easy. The features included in the design exploit all the knowledge acquired from INFN-LNS in last decades in the ion source design and realization [2]. The assembly of the source and of the first part of the LEBT has been carried out in the fall of 2016 and it has been completed in the first months of 2017. The main features of the source are listed in Table 1.

THE EXPERIMENTAL SETUP

The analysis of the costs and risks, taking into account the main beams of interest for such kind of application, clearly indicated that the optimal solution is a hybrid magnetic system. It consists of a permanent magnet hexapole and of four superconducting coils to minimize the hot electron component (to keep the superconducting magnets safe) and to optimize the ECR heating by a fine control of the field gradients and of the resonance length. The compact cryostat is equipped with two double-stage cryocoolers that allow reaching the operating conditions in around 40 hours, the magnetic field generated on axis is shown in fig. 1.

Parameter	Value
Axial field	2.7 T–0.4 T–1.6T
Radial field	1.3 T
Operating frequency	17.3-18.5 GHz
Operating power	2 kW (max)
Extraction voltage	40 kV (max)
Chamber dimensions	Ø 92 mm/360 mm
Warm bore diameter	274 mm
Weight	1400 kg

Table 1: AISHa Main Parameters

The RF injection system was designed to operate in both single and double frequency mode in order to exploit at the same time the Frequency Tuning Effect (FTE) and the Two Frequencies Heating (TFH) mechanism.

The 2400 cm^3 plasma chamber is placed at high voltage (up to 40 kV). It was designed to operate at a maximum power rate of 2 kW. A 20 mm thick glass and carbon fiber tube, surrounding the hexapole, allows insulating the chamber in order to keep the superconducting magnets and the yoke at ground potential [3]. The microwave amplifier located at ground is insulated from the plasma chamber by a waveguide DC break, designed to permit reliable operation up to 40 kV [4].

The beamline consists of a focusing solenoid placed, downstream the source, a 90° bending dipole for ions selection and two diagnostic boxes. A Faraday Cup, a beam wire scanner and slit allow the beam characterization.

Figure 2 shows a view of the experimental area containing the source together with the low energy beam transfer line for its characterization.

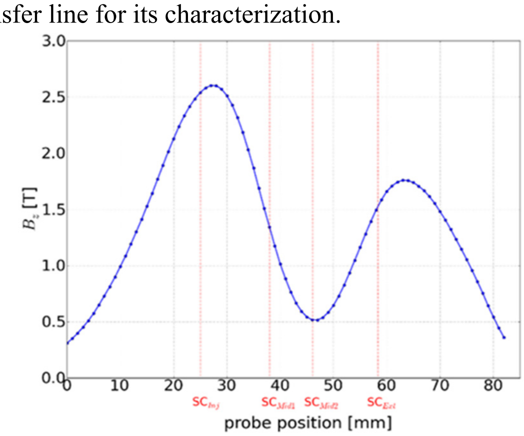


Figure 1: AISHa magnetic field profile

† celona@lns.infn.it

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-MOC1

CHALLENGES AND PROSPECTS OF ELECTRON CYCLOTRON RESONANCE CHARGE BREEDERS

T. Thuillier†, J. Angot, M. Baylac, B.S.B. Bhaskar, J.B. Cully, J. Jacob, T. Lamy, A. Leduc, P. Sole
LPSC, Grenoble, France

Abstract

Electron cyclotron resonance charge breeder (ECR CB) is one of the instruments used to boost the radioactive ion beam (RIB) charge state in isotope separator on-line (ISOL) facilities. While the ECR CB can manage intense 1+ RIB without difficulty, the present CB generation co extracts significant amounts of impurities which can be detrimental to the study of very low intensity N+ RIB in today facilities if no downstream high mass resolution separation is available. This work investigates the improvements achievable with a new generation 18 GHz ECR CB applicable to future facility like EURISOL. The study shows that with a modified ion source geometry, an optimized magnetic confinement, a careful wall metal choice like beryllium, a UHV vacuum technology, the charge breeder performance will improve as follows: 20 % higher capture efficiency, -40% charge breeding time, charge state ion production with mass over charge of 3 up to xenon and over 6 up to uranium, co-extracted contaminant density reduction by a factor 60 to 600. An 18 GHz ECR CB ion source layout is finally proposed for EURISOL.

STATUS OF ECR CHARGE BREEDING

Ion source charge breeders are used in Isotope Separation Online (ISOL) facilities to boost the 1+ radioactive ion beam (RIB) charge state produced by target ion source (TIS) to N+ high charge state. The RIB beam is next filtered by a mass separator and finally injected into a post accelerator. Figure 1 presents the layout of such ISOL installation. Among the numerous key parameters of ISOL facilities, one can cite the:

- reliability and selectivity of the TIS,
- quality of the 1+ RIB purification,
- charge breeding time,
- charge breeding efficiency and
- achievable ion charge state of the charge breeder,
- downstream mass separation of the N+ RIB after the ion source CB.

Two types of charge breeders applicable to ISOL have been developed: the electron beam ion source charge breeder [1] (EBIS CB) and the electron cyclotron resonance ion source charge breeders (ECR CB)[2]. Table 1 presents the majors characteristics of the two ions sources type. Experiments done at CERN and later on both technologies concluded that EBIS CB and ECR CB are complementary[3]. Recently, the ECR CB installed at the CARIBU facility (Argonne National Laboratory, ANL) was stopped and replaced by an EBIS CB[4]. The origin of this decision is as follows. The 1+ RIB signal intensity of CARIBU was in the range 10^2-10^4/s, lower than expected. The downstream mass resolution after the CB was M/ΔM~300, resulting in a large N+ RIB signal contamination > 97%. The downstream linear accelerator could not purify further the RIB and experiments were eventually not possible.

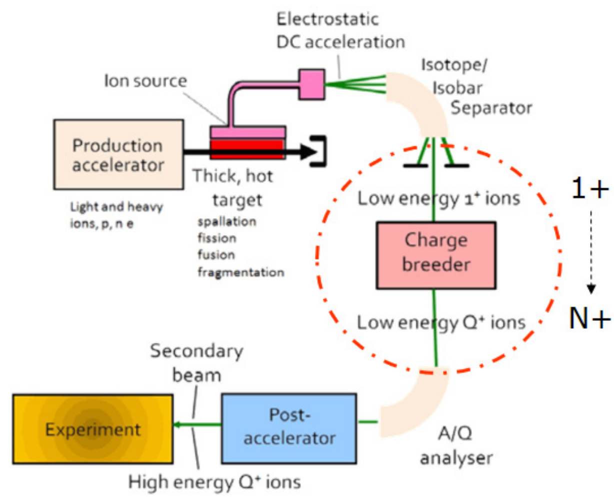


Figure 1: Layout of isotope online (ISOL) accelerator.

Table 1: Today EBIS and 14 GHz ECRIS CB Features.

	EBIS CB	today ECRIS CB
Max. 1+ RIB intensity	$<10^{10}$/s	$>10^{14}$/s
CB time to N+ (ms)	10-100	100-300
robustness	medium	High
1+N+ conversion efficiency	25%	5-20%
Operation mode	pulsed	CW or pulsed
RIB total contamination rate extracted	~10^5 /s	~10^9-10^{10}/s
Downstream mass resolution $M/\Delta M$	~300	≥ 1000
Upstream requirement	Ion cooling	None
Highest charge state	Bare ions	A/Q=3→A~60 A/Q=7→A~150

The same situation with low RIB intensity and low downstream mass separation condition also exists at the TRIAC facility (TRIUMF, Canada), but possibilities to purify the beam after the linac with thin strippers save some

† thuillier@lpc.in2p3.fr

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-MOC2

CHARGE-BREEDING OF RADIOACTIVE IONS AT THE TEXAS A&M CYCLOTRON INSTITUTE

G. Tabacaru, J. Ärje, F. P. Abegglen and D. P. May†, Texas A&M University, Cyclotron Institute, Texas A&M University, College Station, TX 77845, USA

Abstract

Singly charged, radioactive ions produced by high-energy protons in an ion-guide on-line target-cell have been charge-bred in an electron cyclotron resonance ion source (CB-ECRIS) and subsequently accelerated to high energy by the K500 cyclotron at Texas A&M University. The 1+ ions were accelerated to near the extraction voltage of the ECRIS and then decelerated through the injection-end magnetic mirror field of the ECRIS. The charge-breeding efficiency was only at most 1% into one high charge-state, and as a consequence another method of injection into the ECRIS is being attempted. Direct injection from a 1+ ion source via an rf-only sextupole ion-guide or SPIG has been accomplished with no high-voltage deceleration of ions through the mirror field into the ECRIS. Direct injection of 1+ radioactive ions via a longer (2.5 m) SPIG transporting products from the target-cell to CB-ECRIS is now being implemented.

INTRODUCTION

Reference [1] gives a complete description of the Texas A&M upgrade. As part of the upgrade the K150 cyclotron has been re-commissioned to use as a driver for the production of radioactive ions. The primary method is to first stop radioactive products from beam-target collisions and transport them as low-charge-state ions using the ion-guide on-line technique. This technique was pioneered and continues to be developed at the University of Jyväskylä Cyclotron Laboratory [2]. Using this technique both a light-ion guide (LIG) for reaction products resulting from energetic, light-ion beams (p. d, ^{3}He, or α) and a heavy-ion guide (HIG) for reaction products resulting from energetic, heavy-ion beams are being developed. These ions are then injected into CB-ECRIS for charge-breeding to higher charge states. A low-energy beam of ions of one selected charge-state is then transported to the K500 superconducting cyclotron for acceleration to high energy. Figure 1 illustrates the scheme. Now only the LIG will be considered.

LIGHT ION GUIDE

For LIG an energetic beam of light ions impinges on a thin target to produce radioactive products (via (p,n) for example) that then exit the target to encounter a rapid flow of helium gas, The products are mainly in the ionized state, and in the helium this ionization is reduced to the 1+ charge-state, taking advantage of the unfavorable energetics of neutralization of 1+ heavy ions colliding with neutral helium. The flow of helium through the target cell ushers the 1+ ions through an orifice into a highly pumped region where the helium can be pumped away. The ions are guided by a small electric field through an aperture in a skimmer electrode after which they can be accelerated to form a low energy (~10kV) beam.

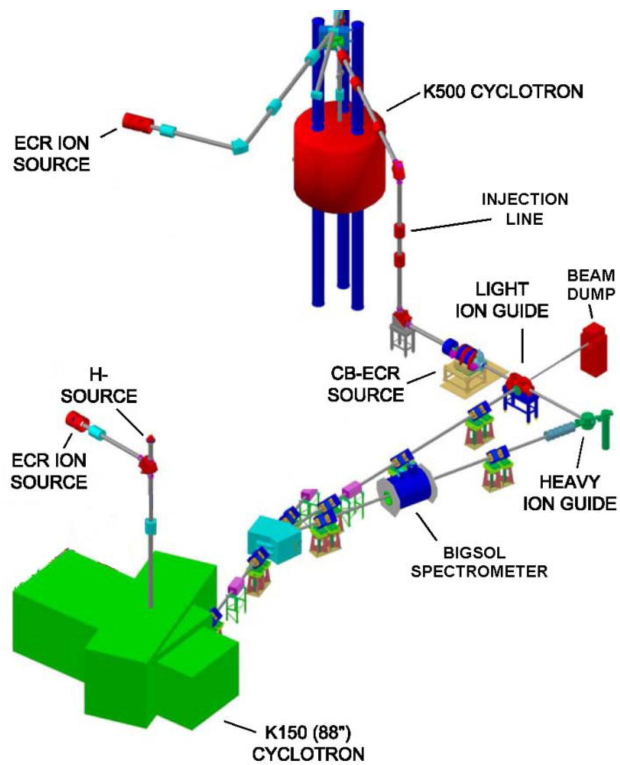


Figure 1: Simplified Layout of the Texas A&M Radioactive Beam Facility.

One disadvantage of this technique is that the ions encounter a significant pressure of helium in the acceleration region which introduces an energy spread in the beam. In order to counter this, a system was introduced where before acceleration the thermalized ions travel along an rf-only sextupole ion guide through a sequence of pumping baffles before being accelerated [3]. References [4] and [5] detail the development of the rf-only ion guide which consists of a parallel array, usually sextupolar, of conducting rods or vanes with low-power,

*Work supported by U. S. Dept. of Energy Grant DE-FG02-93ER40773
† may@comp.tamu.edu

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-MOC3

CHARGE BREEDING TIME STUDIES WITH SHORT PULSE BEAM INJECTION

J. Angot†, T. Thuillier, M. Baylac, T. Lamy, P. Sole, J. Jacob, Université Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, 38000 Grenoble, France
O. Tarvainen[1], University of Jyvaskÿlä, Departement of Physics, 40500 Jyväskylä, Finland

Abstract

Investigations on the Charge Breeding (CB) time have been done with the PHOENIX ECR Charge Breeder. The traditional measurement method consists of generating a 1+ ion beam rising front and measuring the time to reach 90% of the final N+ ion beam intensity. In order to study the possible self-consistent effects of the accumulation of injected ions in the plasma and to better understand the 1+N+ process, short Rb^+ pulses were injected and the time resolved N+ beam responses were measured. The new short pulse CB time method and the experimental results are presented. The effects of several parameters such as the amplitude and the width of the pulse are studied. Calculation methods are proposed for the efficiency and CB time in pulse mode. Compared with the traditional values, the efficiencies are found to be equivalent and CB time shorter by -10% in the case of short pulse injection; showing that the accumulation effect is low in the studied configuration.

The short pulse method was used to study the influence of B_{min} on the plasma behaviour. An increase of B_{min} leads to an increase of the Rb^{19+} efficiency that is found to be caused by a higher ion confinement time. The results are also used to estimate the 1+N+ efficiencies in the case of Radioactive Ion Beam (RIB) species, showing how the RIB efficiency is reduced as a function of the half-life and charge state.

INTRODUCTION

ECR charge breeders (ECR CB) are used in ISOL facilities to increase the charge state of a Radioactive Ion Beam (RIB) from 1+ to N+. They operate in continuous mode and can accept the injection of high particle flux, more than 10^{13} pps. They are mainly characterized by 3 parameters.

The first one is the Charge Breeding Time τ_{CB} of the charge state of interest N. It is traditionally measured by switching ON the injected beam and measuring the 90 % rise time of the N+ response [1-4]. In order to improve the signal over noise ratio, the time response is averaged over several measurements, the 1+ beam being pulsed ON / OFF at low frequency (about 0.5 Hz) with a duty cycle of 50%. This method is called here Long Pulse Injection (LPI). Figure 1 illustrates the principle of the τ_{CB} measurement with LPI.

The second is the ionization efficiency. It is the ratio between the extracted particle current of charge state N and the injected particle current. Using the LPI, the N+ particle current is determined taking into account the background level (1+ beam OFF).

The third parameter is the contaminant rate defined as the percentage of contaminants included into the N+ response measurement. It depends on the charge breeder cleanness, the RIB production yield and the resolution of the downstream spectrometer. In the case of low RIB production yield (10^2 to 10^6 pps) and low spectrometer resolution (ΔM/M of about 1/200), the beam of interest may represent a fraction that can be very small (some %), which has dramatic consequences for the physics experiments [5].

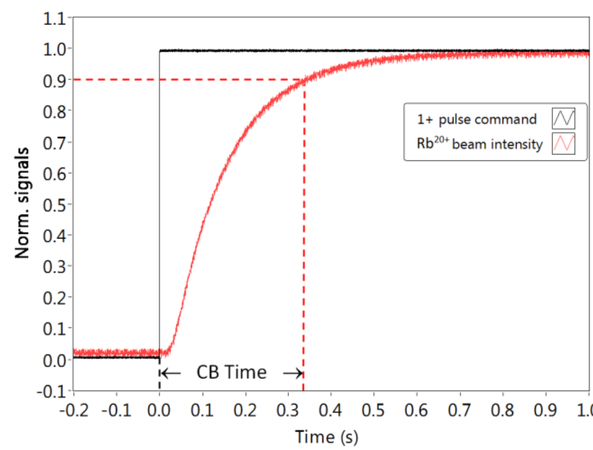


Figure 1: Principle of the traditional τ_{CB} measurement. The dashed lines are the references of the pulse start (black) and 90% level of the Rb^{20+} beam intensity (red).

Motivations for Short Pulse Injection

Previous experiments have shown that the 1+ beam injection can i) modify the CB plasma Charge State Distribution (CSD) [6] and ii) trigger instabilities in a time scale comparable to the CB Time [7].

In addition, the LPI method can appear to be ambigu-ous because the rise of the N+ response is simultaneously affected by the injection and capture of the 1+ ions and the extraction of the N+ ions.

Finally, large discrepancies were reported in the τ_{CB} measurements [8] with only small variations of CB parameters.

For these reasons it was proposed to measure τ_{CB} inject-ing the 1+ beam with very short pulses [9]. This method is called here the Short Pulse Injection (SPI).

† Julien.angot@lpsc.in2p3.fr.

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-MOC4

SPIRAL1: A VERSATILE USER FACILITY

L. Maunoury†, A. Annaluru, O. Bajeat, P. Delahaye, M. Dubois, R. Frigot, S. Hormigos, P. Jardin, O. Kamalou, N. Lechartier, P. Lecomte, B. Osmond, G. Peschard, P. Ujic, B. Retailleau, A. Savalle, J.C. Thomas, V. Toivanen, Grand Accélérateur National d'Ions Lourds, CEA-DRF/CNRS-IN2P3, bd Henri Becquerel, BP 55027, F-14076 Caen cedex 05, France
J. Angot, Laboratoire de Physique Subatomique et de Cosmologie - Université Grenoble Alpes - CNRS/IN2P3 - 53, rue des Martyrs, 38026 Grenoble Cedex, France
E. Traykov, Institut Pluridisciplinaire Hubert Curien, 23 rue du loess, BP 28, F-67037 Strasbourg cedex 02, France

Abstract

SPIRAL1 Upgrade hardware is now almost completed. The FEBIAD 1+ source has been tested for the production of new radioactive isotopes, the SPIRAL1 Charge Breeder (SP1 CB) is in place reproducing nearly the charge breeding efficiencies measured at LPSC laboratory and the infrastructure is operational. The commissioning phase started in the first semester of 2017. It has consisted of a stepwise process to test the upgrade of the SPIRAL1 facility from simple validation (operation of SP1 CB as a stand-alone source) up to the production of the first 1+/N+ Radioactive Ion Beam (RIB) with the $^{37}K^{9+}$ ion.

This contribution will summarize the different steps completed successfully and especially the measurements performed to validate each of the commissioning stages. These include e.g. ionization efficiency measurements for CB; beam line optics for 1+/N+ and charge breeding tuning. The remaining effort required to ensure the reliability of the complete system for routine RIB operation is also presented. A section will be dedicated to the coupling of SP1 CB to the CIME cyclotron, leading to the delivery of stable beams at unprecedented energies at GANIL.

INTRODUCTION

SPIRAL 1 is in operation since 2001 [1]. Radioactive atoms are produced by fragmentation of heavy ions up to 95MeV/u on a graphite target, and ionized in a multi-charged ECR ion source before post-acceleration in the CIME (Cyclotron d'Ions de Moyenne Energie) cyclotron [2]. This original Target Ion Source System (TISS) [3] was designed to provide mainly gaseous radioactive beams thanks to a cold transfer tube between the target and the ion source, trapping the radioactive condensable elements. The natural extension is to expand the radioactive beam production capability to condensable elements with masses up to 90 a.m.u.; hence, an upgrade of SPIRAL1 has been undertaken. The new configuration is based on the use of the 1+/N+ method developed at LPSC [4]. The aim is to have a larger palette of 1+ TISS devoted to other chemical element families. In this framework, a development of a TISS containing a FEBIAD (Forced Electron Beam Induced Arc Discharge) type ion source [5] is realized and some optimizations are requested to increase the longevity of such a system as well as the global efficiency. Moreover, the charge breeder has been modified to increase its efficiency based on the conclusions of the Emilie collaboration studies [6]. More adjustments have been achieved during the commissioning phase at GANIL to enhance the production of highly charged ions. It started in June 2017 and ended in July 2018. During this period, numerous tests regarding beam optics, charge breeding efficiencies and coupling with the CIME cyclotron have been investigated to validate the whole system. This paper aims to present the outcomes and demonstrate that the SPIRAL1 facility is far beyond a unique 1+/N+ system.

SPIRAL1 CHARGE BREEDER

Figure 1 displays a scheme of the SP1 CB. It is mainly composed of an electrostatic quadrupole triplet aiming to focus the 1+ incoming beam into the SP1 CB injection part, the SP1 CB itself and an extraction system based on a movable grounded electrode connected to an Einzel lens. The SP1 CB is a version of the PHOENIX charge breeder developed at LPSC laboratory and built by the Pantechnik [http://www.pantechnik.com/] Company. During the commissioning, two main changes and one optimization have been done following the tests of this device done at LPSC in 2015. For the beam injection, an inner part of the injection iron plug, which acts as an RF blocker, was previously made of aluminium; it has been replaced by a soft iron piece having the same design to boost the maximum field at injection from 1.19T to 1.38T.

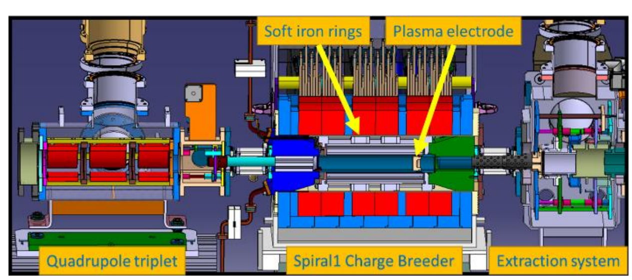


Figure 1: SPIRAL1 Charge Breeder.

At extraction, the plasma electrode has been moved closer to the maximum axial field by 10mm to reduce its interaction with the ECR plasma. The two soft iron rings, existing in the early design of the charge breeder, are placed on each side of the hexapole shaping the minimum

† maunoury@ganil.fr

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-MOC5

1+ / N+ METHOD: NUMERICAL SIMULATION STUDIES AND EXPERIMENTAL MEASUREMENTS ON THE SPIRAL1 CHARGE BREEDER

A. Annaluru†, P. Delahaye, M. Dubois, P. Jardin, O. Kamalou, L. Maunoury, A. Savalle, V. Toivanen and P. Ujic, GANIL, F-14076 Caen, France
E. Traykov, IPHC, F-67200 Strasbourg, France

Abstract

In the framework of the SPIRAL1 facility, the R & D of charge breeding technique is of primary interest for optimizing the yields of radioactive ion beams (RIBs). This technique involves the transformation of mono-charged ion beams into multi-charged ion beams by operating an Electron Cyclotron Resonance (ECR) charge breeder (CB). During the SPIRAL1 commissioning, experimental studies have been performed in order to understand the transport of the beam through the CB with and without ECR plasma. Numerical simulations including ion optics and some ECR plasma features have been developed to evaluate ion losses during the ion transport through the CB with and without a simplified model of the ECR plasma.

INTRODUCTION

The SPIRAL1 facility at GANIL is dedicated to produce and accelerate the stable and radioactive ion beams which are delivered to physicists for nuclear experimental studies. Extending their research on exotic nuclei properties far from stability, an upgrade has been undertaken at SPIRAL1 to extend the range of post-accelerated exotic beams as well as to provide low energy (keV) radioactive beams to the future DESIR (Désintégration, Excitation et Stockage d'Ions Radioactifs) experimental area. Different Target Ion Source System (TISS) based on a forced electron beam induced arc discharge (FEBIAD) type mono-charged ion source [1] has been chosen to provide 1+ beams of condensable elements with high efficiency. The 1+ beams from TISS are mass analyzed and transported to the 14.5 GHz SPIRAL1 ECR charge breeder (CB), which increases the charge state charge of the radioactive ions from 1+ to N+. The extracted high charge state ions are mass analyzed and post accelerated to CIME cyclotron (Cyclotron d'Ions de Moyenne Energie) [2]. Figure. 1 shows the 3D cross-section of the charge breeder placed in the Low Energy Beam Transport (LEBT) between the TISS and the CIME. In the injection side of the CB the beam is focused with an electrostatic quadrupole triplet and the extracted beam is focused with an einzel lens. The charge breeder has gone through several modifications which are reported in [3, 4], and experimental charge breeding results are presented in [5]. During its operation, a few technical changes have been done in the configuration of the charge breeder: the position of two soft iron rings has been modified to optimize the axial magnetic field and the optimization of the deceleration tube position to study its effect on beam stability and charge breeding efficiency. Experimental studies on LEBT transport and charge breeding efficiencies for $^{23}Na^{+}$ and $^{23}Na^{2+}$ have been carried out to understand the ion losses and 1+ capture processes by ECR plasma. A rough analysis on the experimental studies is described in the following sections by introducing a simplified ECR plasma model utilizing SIMION 3D. The results obtained from the simulations are presented and compared with the experimental ones.

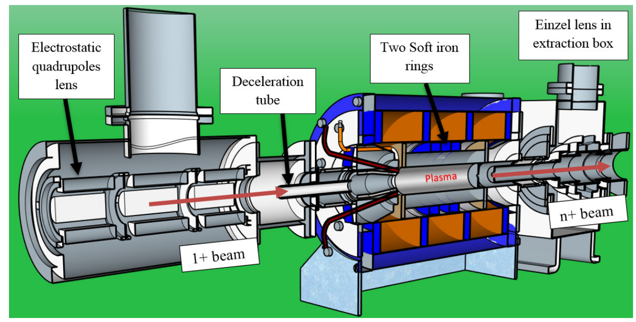


Figure 1: 3D view of ECR charge breeder connected with injection and extraction systems.

EXPERIMENTAL ACTIVITIES WITH SPIRAL1 ECR CHARGE BREEDER

Modification of Axial Magnetic Field

In ECR ion soruce based charge breeders, the "Minimum-B" magnetic field structure is created by 2 or 3 independent solenoids (axial field) and hexapole (radial field) magnets enclosed in an iron yoke. In this configuration, the magnetic field is minimum at the center of plasma chamber and increases in all directions. The Minimum-B configuration is essential to form a closed resonance surface in the plasma chamber where ECR condition is fulfilled.

In SPIRAL1 charge breeder, the axial magnetic field (B) can be adjusted with the center coil and two movable soft iron rings (R1 and R2) placed around the hexapole as shown in Fig. 2. Magnetic field calculations were performed with RADIA [6] to study the axial magnetic field profile by adjusting the rings to different positions. Before the modification, the two rings were placed at extraction end of CB. When the rings are pushed to different positions, significant variations were observed in the size of ECR zone in axial direction. Axial magnetic field profiles for different rings position are

† arun.annaluru@ganil.fr

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-MOC6

REDESIGN OF THE GANIL GTS ECRIS FOR 1+/N+ STUDIES

V. Toivanen†, P. Jardin, L. Maunoury, C. Michel
Grand Accélérateur National d'Ions Lourds (GANIL), F-14076 Caen Cedex 05, France

Abstract

More than half of the beams produced at GANIL are metallic elements, underlining the importance of their continuing development. Compared to the conventional techniques (oven, sputtering, MIVOC), the 1+/n+ method has demonstrated superior ionization efficiencies, suggesting the potential for improved metal beam production. Dedicated studies are required to assess the feasibility of this approach. The SPIRAL1 Charge Breeder is now in operation at the GANIL radioactive beam facility SPIRAL1. Operation in high radiation area poses challenges for its future development. A separate test stand supporting charge breeder and metal ion beam R&D is thus desirable.

The GTS 14.5 GHz ECRIS has been chosen as a platform for 1+/n+ studies. After the upgrade program of 2017-2018, the GTS provides good performance and versatility, making it well-suited for ion source R&D. A new injection module has been designed for 1+ injection into the GTS plasma to be used in the 1+/n+ studies. It can be easily replaced with the conventional system for normal ion source operation. The design of the new injection system will be presented in detail with ion optical simulations of the 1+ beam injection.

INTRODUCTION

The GTS 14.5 GHz Electron Cyclotron Resonance (ECR) ion source has undergone a substantial upgrade program in 2017 - 2018. As part of this upgrade, the ion source beam extraction system was refurbished, a new center coil was added to improve the magnetic field control and the injection side of the source was redesigned to reach higher injection magnetic fields and to allow double frequency operation in a wide frequency range. These changes are discussed in more detail in Ref. [1]. As presented there, the extraction system and center coil upgrades yielded an improvement of up to a factor of three for the delivered beam currents in 2017. In 2018 the new injection system has been commissioned for operation, which has provided further performance improvements, especially for the high charge state beams. For example, with double frequency operation (14.5 GHz + 11.215 GHz) the GTS has recently produced a 17.5 µA beam of $^{129}Xe^{30+}$, which is over eight times higher intensity than before the upgrade program.

The motivation for the GTS upgrades has been two-fold. First, the goal was to improve the beam capabilities available for the multidisciplinary low energy beam facility ARIBE (Accélérateurs pour les Recherches Interdisciplinaires avec les Ions de Basse Energie), which is the primary user of the GTS beams. The second goal was to establish a good baseline performance for continued ion source R&D with the GTS. As these goals have now been achieved, the next phase for the GTS is to utilize it for charge breeding (or 1+/n+ method) research. This will be a second role for the GTS, as it will also continue to serve the ARIBE facility in its conventional ion source configuration.

One potential future application of the 1+/n+ method is enhanced metal ion production. Metal ion beams are currently widely used in the accelerator facilities around the world, and as an example, more than 50 % of the beams delivered at GANIL are metallic elements. This highlights the importance to continue metal ion production development with ECR ion sources. With conventional techniques like sputtering, miniature ovens and MIVOC, the global ionization efficiencies of metal beams is low. Here, the global efficiency is defined as the ratio of the extracted ion flow (all ion species of the element) over the injected neutral flow. Based on the data collected from GANIL operation, published in Ref. [2], the typical measured global efficiencies for sputtering are around 1 %, oven beams around 10 % and MIVOC beams around 20 %. In total, all measured efficiency data is below 30 %. In contrast, experience with charge breeders has shown that with 1+ injection global efficiencies around and in excess of 50 % are achievable (see e.g. Ref. [3]). The higher efficiency would first of all reduce the material consumption, which is not an insignificant consideration for rare and expensive elements and isotopes. Secondly, decrease in injected material would reduce the plasma chamber contamination. Furthermore, decoupling the initial metal ion production and the stepwise multi-ionization allows both of these processes to be optimized independently.

However, dedicated studies are necessary to validate the feasibility of these ideas. One of the main challenges that needs to be assessed is the high intensity operation. Although several measurements performed so far suggest a weak relationship between the 1+ capture and ionization efficiencies and the injected 1+ current, this effect has been mainly studied with low currents up to only a few µA (see e.g. Refs. [4–7]). In order to make 1+/n+ method a realistic alternative for the conventional techniques, it must be demonstrated that the high efficiencies can be retained also with significantly higher current levels. The GTS can provide a suitable test bench for these studies.

The GTS will be used also for studying other aspects of charge breeding. The SPIRAL1 Charge Breeder has been recently installed and commissioned at the GANIL radioactive ion beam facility SPIRAL1 [8]. The role of the machine is to charge breed the singly charged radioactive elements produced by the Target Ion Source Systems (TISS) and deliver the multiply charged ions for post-acceleration and experiments. As an operational machine in a high radiation dose area, the access to the charge breeder will be limited

† ville.toivanen@ganil.fr

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUA1

DEVELOPMENT OF RIKEN 28 GHz SC-ECRIS FOR PRODUCTION OF INTENSE METAL ION BEAM

Y. Higurashi†, T. Nagatomo, J. Ohnishi, and T. Nakagawa,
Nishina center for accelerator based science, RIKEN, Wako, Saitama 351-0198, Japan

Abstract

To produce intense metal ion beams (e.g., Ti^{13+}, $V^{12+,13+}$, Cr^{13+}) for synthesizing new super heavy elements (Z=119,120) at RIKEN, we tried to optimize the performance of RIKEN 28 GHz SC-ECRIS. Based on the "scaling law" and the "high B mode" operation, we systematically measured the beam intensity of various heavy ions as a function of B_{inj}, B_r and B_{ext} with 28 and 18 GHz micro-waves. We observed that B_{ext} is dependent on the charge state of heavy ions as predicted by the "scaling law". Using these systematics, we obtained ~400 eμA of V^{13+} at the mi-crowave power of 2 kW (28 GHz) and B_{ext} of ~1.4 T with 28 GHz. For long term operation, we produced very stable beam of 100-200 eμA of V^{13+} ion. Following this, we con-structed new 28 GHz SC-ECRIS for new elements synthe-sis.

INTRODUCTION

At RIKEN, we planned to synthesize new elements, which have atomic number higher than 118, after the experiments for synthesizing the super-heavy element (atomic number of 113).[1] For this purpose, production of intense and stable highly charged metallic ion beams, such as $V^{12+,13+}$ ions, is required. Therefore, we conducted test experiments to produce these beams and studied the opti-mum structure of the ion source to increase the beam in-tensity and, especially, the effect of magnetic mirror ratio on plasma confinement, for several years. It is well-known that the "scaling law" [2,3] and the "high B mode" opera-tion [4-6] provide some of the important guidelines to op-timize the magnetic mirror ratio of ion sources for produc-tion of various charge states of heavy ions. Model calcula-tion based on the Fokker-Planck equation also shows the same tendency as the "scaling law". [7,8]

As a first step to improve the ion source performance for production of these metallic ion beams, we also conducted a systematic study to optimize the magnetic mirror ratio using the RIKEN 28 GHz SC-ECRIS and the liquid-He-free SC-ECRIS on the bases of these laws. Using the results of the systematic study, we attempted to produce intense metallic ion beams last year.

In addition, to further expand this project, new superconducting RF cavities are now under construction in the downstream of RIKEN heavy-ion linac (RILAC) to increase the beam energy. [9] In this project, we also planned to construct a new 28 GHz SC-ECRIS. Based on the experimental results, we completed the design and the construction last year. The ion source, the low energy beam transport line and first results for the ion source have been reported in ref. [10]. In this contribution, we present in de-tail the results of the systematic study and production of highly charged V ion beam.

†higurasi@riken.jp

SYSTEMATIC STUDY

In the test experiments, we used two different types of ion sources, Liquid-He-free SC-ECRIS [11] and RIKEN 28 GHz SC-ECRIS [12]. The main feature of the RIKEN 28 GHz SC-ECRIS is that it has six solenoid coils to pro-duce a flexible mirror magnetic field in the axial direction

and can produce both "classical" and "flat" B_{min}. [13,14]

In the middle of 1980s, the "scaling law" was proposed for describing the effect of the main ion source parameters (microwave power, magnetic field strength, microwave frequency, mass of heavy ions, etc.) on the output beam of highly charged heavy ions. In these papers [2,3], it was reported that the strength of the magnetic mirror affects the optimum charge state, i.e., a higher mirror ratio yields higher charge states of the output ion beam.

It is obvious that the maximum magnetic mirror field at the microwave injection side (B_{inj}), the maximum magnetic mirror field at the beam extraction side (B_{ext}), and the radial magnetic field (B_r) work as parts of the magnetic mirror to confine the plasma. In the middle of 1990s, the "high-B" mode that employs a high magnetic mirror ratio to confine the plasma was proposed to increase the beam intensities of highly charged heavy ions. This principle was adopted by many laboratories in the design of their ECR ion sources. Intense beam of highly charged heavy ions was successfully produced using this method.

In this section, the experimental results (effect of B_{inj}, B_r and B_{ext} on the beam intensity of highly charged heavy ions), which were obtained on the bases of these laws, are presented.

B_{inj} and B_r Effect

Figure 1 a) and b) show the two-dimensional contour plots (B_r vs. B_{ext} and B_{inj} vs. B_{ext}) for the beam intensity of Xe^{22+} produced with RIKEN 28 GHz SC-ECRIS. In these figures, red and blue colors indicate the highest and lowest beam intensity, respectively. In this study, we used the 18 GHz microwave instead of 28 GHz. The minimum strength of the mirror magnetic field (B_{min}) was set to ~0.5 T. The extraction voltage and the microwave power were 21 kV and ~500 W, respectively. The gas pressure and biased disc condition (negative voltage and position) were slightly changed to maximize the beam intensity at the measurement points.

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUA2

PRESENT STATUS AND FUTURE PROSPECT OF HEAVY ION RADIOTHERAPY

A. Kitagawa†, T. Fujita, and M. Muramatsu, National Institute of Radiological Sciences, National Institutes for Quantum and Radiological Science and Technology (QST-NIRS), 4-9-1 Anagawa, Inage, Chiba 263-8555, Japan

Abstract

Heavy Ion Radiotherapy (HI-RT) is one of important applications of an electron cyclotron resonance ion source (ECRIS). At present, ten facilities are under operation and eight are under commissioning or construction. All of them utilize ECRISs for the production of carbon ions, mainly. Heavy ion radiotherapy has been approved to cover by the National Health Insurance in Japan since 2016. In April 2018, fees for treatment in Japan were revised to 1,600,000 Yen for 'prostate tumor' and 2,375,000 Yen for 'bone and soft tissue tumor' and 'head and neck tumor', respectively. The expectation of wide-spread use has accelerated sharply. There is no failure that disturbs daily treatment due to ECRISs in facilities. The ECRISs have effectively contributed to the stable operation of the present facilities. On the other hand, the cost reduction for a facility has been urged too. Laser ion acceleration has a potential to take over the role of ECRIS in the future. However ECRIS still has a scope of research and development to improve clinical dose distribution for intractable radioresistance tumors at present.

INTRODUCTION

In order to treat a deep-seated tumor with the good localized dose distributions, carbon ion was predicted as one of good candidates for heavy-ion radiotherapy by Rovert R. Willson even in 1946[1]. Based on physics, lighter ion species cause larger multiple scattering in the deep side, and heavier ion species give unexpected dose over the end-point due to projectile fragmentation. In addition, the biological dose distribution depends on the depth and thickness of a tumor. In the case of ten and several cm depth and several cm thickness, the linear energy transfer of neon ions is too high than that of carbon ions shown by Lawrence Berkeley Laboratory, University of California in 1980's[2]. Although heavier ions shows other biological advantages like oxygen enhancement ratio, the National Institute of Radiological Sciences (NIRS) chose carbon ions for the clinical trial at the Heavy-Ion Medical Accelerator in Chiba (HIMAC) [3] in 1994. Figure 1 shows biological depth-dose distributions of the Spread-Out Bragg Peak in the case of a depth of 16 cm and a thickness of 6 cm with different ion species. By HIMAC's success, the existing and almost all the planned heavy-ion radiotherapy (HI-RT) facilities require a carbon beam at present.

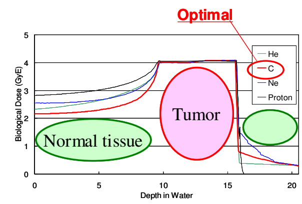


Figure 1: Biological depth-dose distributions of a 6cm Spread-Out Bragg Peak with a depth of 16cm.

The requirement of carbon-beam intensity strongly depends on the facility design, i.e. the volume and shape of the target, the efficiency of the irradiation method, the transmission of the accelerator complex and so on. In order to obtain the biological dose rate of 5 GyE/min. (it's roughly equals to a physical dose of 2 Gy/min.), a few 10^8 particles per second are required at a typical present facility. Long-term stability and reproducibility are important for daily treatment. On the other hand, the short-term stability of the ion sources is not so sensitive. Because the existing facilities consist of a synchrotron and any injector and the fine structure of the beam pulse will almost disappear during the acceleration in the synchrotron. Moreover easy operation and maintenance are also important to reduce the operation cost. An ion source should satisfy these requirements. An electron cyclotron resonance ion source (ECRIS) was expected to realize these requirements. The details and the history of the development of ECRISs have been described in Ref. [4]. As a result, ECRISs have been adopted at all existing carbon-ion radiotherapy (C-RT) facilities.

STATUS OF CARBON-ION RADIOTHERAPY

Clinical results

Clinical data of HIMAC have been accumulated under prescribed clinical protocols since 1994. All the clinical protocols and their results have been reported routinely through an authorities' committee. Since 2016, other Japanese C-RT facilities have gathered their data into a unified clinical database at the National Institute of Radiological Sciences, National Institutes for Quantum and Radiological Science and Technology (QST-NIRS, the former NIRS). At present, the total number of patients in Japan exceeded 20,000. The summaries for various diseases have clearly demonstrated the advantages of C-RT. There are three remarkable advantages of C-RT: lower toxicity, better local control and survival ratio, and shorter treatment period, the so-called Hypo-Fractionation.

† kitagawa.atsushi@qst.go.jp

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUA3

NEW 28-GHz SUPERCONDUCTING ELECTRON CYCLOTRON RESONANCE ION SOURCE FOR SYNTHESIZING SUPER-HEAVY ELEMENTS WITH Z >118

T. Nagatomo†, Y. Higurashi, J. Ohnishi, A. Uchiyama, K. Kumagai, M. Fujimaki, N. Fukunishi, N. Sakamoto, T. Nakagawa and O. Kamigaito

RIKEN Nishina Center for Accelerator Based Science, Wako, Saitama 351-0198, Japan

Abstract

The RIKEN linear accelerator is being upgraded to provide intense metal ion beams, from Ca and Zn for nuclear structure research to V and Cr for synthesizing new super-heavy elements with Z >118. In 2017, we started to construct a new superconducting electron cyclotron resonance ion source (SC-ECRIS) and a new low-energy beam transport (LEBT). Because of the short development period, we decided to give the new SC-ECRIS the same structure as the RIKEN 28-GHz SC-ECRIS. Although a solenoid and some steering magnets were not ready yet, during summer 2018, an ^{40}Ar beam was successfully extracted as the first beam with the 18-GHz microwave heat source. A pepper-pot emittance meter estimated the horizontal size of the $Ar^{8+, 9+, 11+}$ beam to be about 70 mm at 1,024 mm downstream from the edge of the analyzing magnet. Furthermore, we successfully obtained the four-dimensional phase-space distribution that is essential for evaluating the validity of the beam optics devices to improve the LEBT. We plan to finish the construction of a 28-GHz gyrotron and the LEBT by the end of 2018.

INTRODUCTION

A project to synthesize new super-heavy elements (SHEs) having an atomic number (Z) larger than 118 was started in FY2016. To synthesize SHEs with atomic numbers of Z = 119 and 120, highly intense and highly charged metallic ion beams of V and Cr, respectively, must be provided by the RIKEN linear accelerator (RILAC) [1]. Accordingly, the RILAC upgrade will increase the acceleration energy from 5 MeV/u to more than 6 MeV/u by installing superconducting quarter-wavelength resonators (SC-QWRs), as shown in Fig. 1. However, the RILAC is currently used as a variable-frequency injector for the RIKEN cascaded cyclotron for the Radioactive Isotope Beam Factory [2]. In this operation, the new SC-QWRs will be bypassed because they operate at a fixed frequency. In variable frequency operation, high-intensity Ca and Zn beams will still be required for nuclear structure research, as before. To meet this acceleration scheme without using the SC-QWR booster, the accelerated ions must be given an electric charge higher than that used before. For example, a Ca^{16+} beam is required at currents of ~100 eμA.

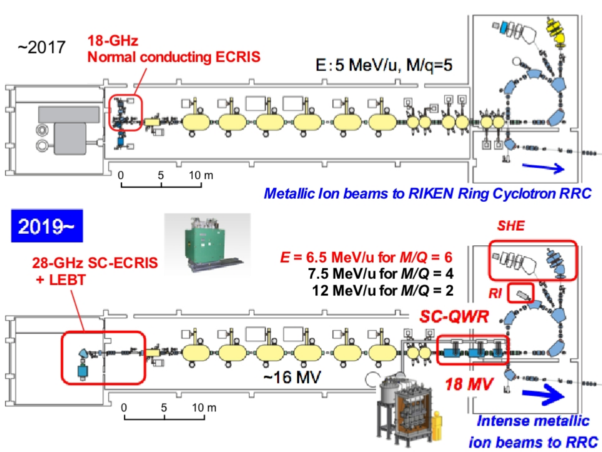


Figure 1: Ongoing upgrade of RILAC since 2017. The normal conducting 18-GHz ECRIS is being replaced with a 28-GHz ECRIS and LEBT. The new SC-QWRs will be installed at the end of drift tubes of the RILAC.

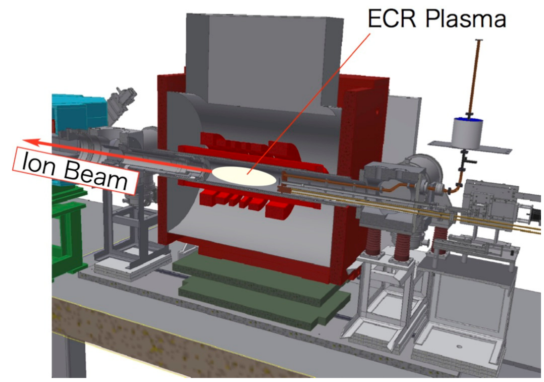


Figure 2: Schematic of the new 28-GHz SC-ECRIS.

Consequently, a wide $n_e\tau_i$ range of ~5 × 10^8 to ~5 × 10^9 cm^{-3} s must be covered, where n_e is the electron density and τ_i is the ion confinement time in the plasma [3] in the ion source. In addition, the development period is limited to about one year. Therefore, we decided to construct the new ion source with the same structure as the RIKEN 28-GHz SC-ECRIS [4,5] and match the new low-energy beam transport (LEBT) to the RILAC radio frequency quadrupole (RFQ).

In this paper, we report the current construction status and describe the first beam extraction, which was performed during the summer of 2018.

† nagatomo@riken.jp

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUA5

HIGH POWER OPERATION WITH SECRAL-II ION SOURCE*

L. Sun†, W. Lu, J. W. Guo, L. X. Li, Z. Shen, L. B. Li, W. Huang, X. Z. Zhang, H. Y. Ma, Y. Yang, J. B. Li, W. H. Zhang, X. Fang, H. W. Zhao
Institute of Modern Phsyics, CAS, Lanzhou, 730000, China

Abstract

SECRAL-II ion source has been successfully developed with the experiences from SECRAL that is another superconducting ECR ion source in operation at IMP. Other than that, SECRAL-II has been intentionally optimized in structure so as to make it optimum for 28 GHz microwave operation. This ion source was available on the test bench in early 2016, and has been used for 28 GHz high microwave power commissioning and tests. With a maximum power 10 kW@28 GHz and 2 kW@18 GHz, very high microwave power density and dense hot plasma could be built in the 5-liter volume plasma chamber. Consequently, very high current density ion beams of high charge states are achievable, which have already exceeded the performance the 24 GHz SECRAL had made couple of years ago. However, there is also the intractable issues stemmed from the hot dense electrons inside the plasma, such as plasma chamber cooling, dynamic heat load to the cryogenic system, and so on. This paper will present the recent results of SECRAL-II operated with high microwave power. The typical consequent issues during the high-power course other than high intensity high charge state ion beam production will be discussed.

INTRODUCTION

Electron Cyclotron Resonance Ion Sources or ECRIS has play an indispensable role in the development of next generation heavy ion accelerators, such as FRIB at MSU, HIAF at IMP, and JLEIC at JLab, and so on [1, 2, 3]. ECRIS is the most efficient ion source in term of the production of dc and long pulse (~ms) highly charged heavy ion beams. After more than 40 years' continuous development by generations of ECRIS sourcerors, the state of the art ECRISs have evolved to 3rd generation, which is represented by superconducting machines, such as VENUS at LBNL, SCECRIS at RIKEN, SECRAL& SECRAL-II at IMP, and so on [4, 5, 6, 7]. High performance superconducting ECRIS provides by far the ultimate conditions for high charge state ion beams production, such as much higher operation microwave frequency, better magnetic field confinement, bigger plasma chamber volume and above all, more flexible conditions for ion source performance optimization. Intense highly charged ion beam production is mainly defined by three key factors, i.e. n_e-plasma density, T_e-electron energy, and τ- exposure time of the ions to a cloud of plasma electrons. State of the art ECRISs can provide flexible conditions for highly charged ion production with quasi-optimum T_e and τ, however, to get high intensity beams, sufficiently high microwave power, or to some extent the effective power density, is required to achieve high enough plasma density inside the plasma chamber. Therefore, high microwave power operation exploration is very necessary and might be mandatory for next generation heavy ion acceleration routine operation, for instance >0.7 emA U^{35+} for HIAF, >0.5 emA U^{35+} for RIBF, and so on.

SECRAL-II is a fully superconducting ECR ion source recently developed at IMP. Its superconducting magnet structure design inherits the features of SECRAL, except the cryogenic system. Table 1 summarizes the main parameters of SECRAL and SECRAL-II in comparison. The improved cryogenic system of SECRAL-II enables high microwave power operation (up to 10 kW) despite of the high bremsstrahlung radiation to the 4.2 K cold mass and the resultant high dynamic heat load, which allows the exploration of the ion source performance at high microwave power. This paper will report the high-power commissioning results and the typical issues of interests in terms of high power stability and beam quality. Challenges to a high power ECRIS are becoming apparent with increasing power density inside the plasma chamber, which are also discussed.

Table 1: Main Parameters of SECRAL-II

Parameters	SECRAL-II	SECRAL
ω rf (GHz)	18-28	18-24
Axial Field Peaks (T)	3.7 / 2.2	3.7/2.2
Mirror Length (mm)	420	420
No. of Axial SNs	3	3
Br (T)	2.0	1.7/ 1.83
Coldmass Length (mm)	~810	~810
SC-material	NbTi	NbTi
Magnet Cooling	LHe bathing	LHe bathing
Warm bore ID (mm)	142 .0	140.0
Chamber ID (mm)	125.0	116.0/120.5
Cooling power@4.2 K (W)	~6	0

HIGH POWER RF SYSTEM

In the high microwave power campaign with SECRAL-II source, several high power microwave generators have been used. 18 GHz CPI DBS-band klystron microwave generator with a maximum microwave power output of 2.4 kW, is used as secondary ECRH (ECR Heating) microwave power source. CPI 28 GHz VGA model CW

*Work supported by MOST (contract No. 2014CB845500), CAS (QYZDB-SSW-JSC025), and NSF (contract No. 11221064)
†sunlt@impcas.ac.cn

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUB2

PLASMA HEATING AND INNOVATIVE MICROWAVE LAUNCHING IN ECRIS: MODELS AND EXPERIMENTS

G. Torrisi*, D. Mascali, G. Castro, L. Celona, G. Mauro, M. Mazzaglia, E. Naselli[1], S. Gammino, INFN-LNS, Catania, Italy, [1]also at University of Catania, DFA, Catania, Italy
A. Galatà, INFN-LNL, Legnaro, Padua, Italy
G. Sorbello[2], University of Catania, DIIEI, Catania, Italy; [2]also at INFN-LNS, Catania, Italy

Abstract

Microwave-to-plasma coupling in ECRIS has been based on the classic scheme of waveguide-to-cylindrical plasma cavity matching. Optimization has been often obtained by empirical adjustments leading to an oversimplified model, obtaining however satisfying performances. In order to overcome the ECR-heating paradigm, on-purpose design of launchers' setup and adequate diagnostics have to be developed. This paper describes three-dimensional numerical simulations and Radio Frequency (RF) measurements of wave propagation in the microwave-heated magnetized plasmas of ion sources. Moreover, driven by an increasing demand of high frequency ECR ion sources, innovative ideas for the geometry for both the plasma chamber and the related RF launching system - in a plasma microwave absorption-oriented scenario – are presented. Finally, the design of optimized launchers enabling "single-pass" power deposition, not affected by cavity walls effects, are described.

INTRODUCTION AND MOTIVATION

In this paper, the electromagnetic wave propagation in microwave-heated plasma confined in a magnetic field, is addressed through numerical simulations and experiments, devoted to understand how the RF wave propagation depends on the electron density profile and external magnetic configuration [1–3]. In particular, we focus on the mechanism of RF propagation into the non-homogeneous magnetized anisotropic lossy plasma of Electron Cyclotron Resonance Ion Sources (ECRIs) [4], ECR-based charge breeder [5] and simple mirror linear plasma trap [6]. A better comprehension of electromagnetic wave propagation and RF power to plasma coupling mechanisms in ion-sources magnetoplasmas is crucial in order to provide a cost-effective upgrade of these machines alternative to the use of higher confinement magnetic fields, higher RF power level and higher pumping wave frequency [7]. Several full-wave numerical simulation codes have been developed [8–12] also exploiting ray-tracing technique [13].

The wave propagation at frequencies in the range 3-40 GHz in ECRIS compact plasma chamber (having magnetic field of the order of few Tesla, electron density in the order of 10^{18} m^{-3}) cannot be predicted by the plane wave model nor addressed by "ray-tracing"often adopted to describe waves in fusion toroidal devices [13–15]. These models, in fact, fail in minimum-B configuration scenarios where the scale length of plasma nonuniformity, $L_n = |n_e/\nabla n_e|$, and the magnetostatic field nonuniformity, $L_{B_0} = |B_0/\nabla B_0|$, are smaller than the free space, λ_0, and guided, λ_g, wavelengths.

We used COMSOL Multiphysics [16] software to model a "cold", anisotropic magnetized plasma, described by full-3D non uniform dielectric tensor, enclosed by the metallic cylindrical cavity where the plasma is generated. A proper mesh generation, exploiting FEM-based COMSOL versatility, allowed us to optimally modelize the cavity and microwave waveguide launching structure, with a good computational efficiency and high resolution especially around the resonance regions. The validity of the code was demonstrated by reproducing experimental results obtained with:

- X-ray imaging experiment on ATOMKI ECRIS ion source [4];
- PHOENIX Charge Breeder acceptance test at the Laboratoire de Physique et de Cosmologie [5];
- "Flexible Plasma Trap" (FPT) at INFN-LNS, where the numerical electric field profile has been compared with RF measurements of the wave amplitude inside the FPT plasma chamber [6]

The article is arranged as follows. In the first section wave field solution of the Maxwell's equations taking into account the magnetic field which makes plasma anisotropic, non-uniformity of plasma density, and the metallic plasma chamber is presented. Then, the above listed experimental benchmarks are described. Finally, some perspective is given as short term, mid-term and long term proposals for next generation ECRIS development based on: reshaping plasma chambers with non-conventional features, innovative RF launcher [17] and futuristic all-dielectric mm-waves launching structures.

RF WAVE-PLASMA INTERACTION MODELING

A magnetized plasma in the GHz range frequencies can be modeled as a cold magneto-fluid with collisions where the field-plasma interaction is described by the tensorial constitutive relation $\bar{\bar{\epsilon}} \cdot \vec{E}$. Tipically $\bar{\bar{\epsilon}}$ is derived assuming a magnetostatic field $\vec{B}_0$ directed along just one axis. This assumption is valid in most of cases but not in ECRIS where $\vec{B}_0$ is not strictly axis-symmetric. Considering the actual magneto-static structure of an ECRIS, that is not uniform nor axis-symmetric, $\bar{\bar{\epsilon}}$ depends in a complex way from the

* giuseppe.torrisi@lns.infn.it

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUB3

A POSSIBLE OPTIMIZATION OF ELECTRON CYCLOTRON RESONANCE ION SOURCES PLASMA CHAMBERS

C. S. Gallo *, A. Galatà, INFN-Laboratori Nazionali di Legnaro, (Padova), Italy
D. Mascali, G. Torrisi, INFN-Laboratori Nazionali del Sud, Catania, Italy

Abstract

In the cylindrical resonant cavities of Electron Cyclotron Resonance Ion Sources (ECRIS), microwave fields are used to generate and sustain the plasma. Normally, resonant modes of a higher order than the fundamental one are excited, due to the high frequency used compared to the dimensions of the plasma chambers: this can lead to small electric fields on the resonant surface, translating in low electrons energy and poor source performances. In this paper, we propose a possible modification of the conventional plasma chambers, resulting from an electromagnetic study carried out on a Caprice-type full permanent magnet ECRIS. Such modification implies the excitation of a "length-independent" resonant mode, having an intense and homogeneous electric field on the plasma chamber axis. This characteristic makes the modification suitable to be applied to numerous ECR sources. The positive effect on the plasma electrons density distribution will be also shown.

INTRODUCTION

Electron Cyclotron Resonance Ion Sources (ECRIS) [1] are nowadays the most effective devices to produce high intensity continuous or pulsed beams of medium-high charge states. In such sources, a plasma is created and sustained through a resonant interaction between microwaves (typically at 14 or 18 GHz) and the electrons motion, and is confined by a particular multi-Tesla magnetic configuration called B-minimum structure, generated by superimposing the field created by two or more coils to the one generated by a hexapole. Considering the particular topology of the magnetic field, the resonant interaction takes place on closed egg-shaped surfaces, called resonance surfaces. The performances of these devices have been evolving during the years following the well known scaling laws [1], the High-B mode concept [2] and the ECRIS standard model [3]: this has involved the necessity to employ higher and higher frequencies and magnetic fields, that often implies the development of expensive and technologically complex devices. At the same time, different "tricks" were discovered and have been applied to boost their performances: in particular, the injection of two close or well separated frequencies [4, 5], as well as the fine tuning of a single frequency, known as frequency tuning effect [6]. The main aim of those tricks is to increase the electrons density and energy by optimizing the power absorption by the microwave field. In fact, the beam extracted from an ECRIS consists of those ions that flow from a portion of the resonance surface around the plasma chamber axis toward the extraction aperture, following the magnetic field lines: consequently, for any given operating frequency and magnetic configuration, it is mandatory to maximize the energy transfer to plasma electrons in that specific part of the resonance surface. For plasma chambers with cylindrical shapes, possible modes that show an intense electric field around the axis and are length-independent are, for example, the $TM_{0,n,0}$ modes: this paper describes a simple but effective modification to the plasma chamber geometry in order to excite the plasma through one of the above mentioned modes, so as to maximize the energy transfer to plasma electrons. The modification has been studied with the electromagnetic solver COMSOL Multiphysics®and validated by simulating the electrons dynamics under the calculated electromagnetic fields, using an ad-hoc code developed in MatLab®.

* carmelo.gallo@lnl.infn.it

SIMULATION DOMAIN

The geometry used to validate numerically the modification proposed in this paper is the plasma chamber of the ECRIS called LEGIS (LEGnaro ecrIS) and installed at Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali di Legnaro (INFN-LNL). It is a full permanent magnet source of the Supernanogan type built by the Pantechnik company, whose typical operating frequency is 14.428 GHz. The plasma chamber, made in aluminum, consists in a cylinder with a radius of 22 mm, a length of 128 mm and two holes, one of 24 mm in diameter at the injection side and the other of 7 mm in diameter at the extraction side: Fig. 1 shows the model implemented in COMSOL®, together with the radial microwave input through a rectangular WR62 waveguide located at 10 mm from the injection hole.

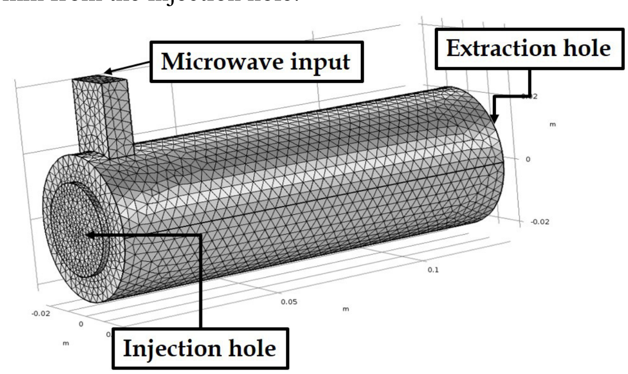


Figure 1: Model of the plasma chamber of the LEGIS source implemented in COMSOL®. Microwaves are injected through a radial rectangular WR62 waveguide. The extraction hole is not visible.

As a first step, the frequencies of the resonant modes $TM_{0,n,0}$ were calculated analytically for the present geom-

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP01

STATUS OF THE CARBON ION SOURCE COMMISSIONING AT MEDAUSTRON

S. Myalski [1], N. Gambino[1], L. Adler[1], F. Ecker[1], A. De Franco[1], F. Farinon[1], G. Guidoboni[1], C.Kurfürst[1], L. Penescu[2], M. Pivi[1], C. Schmitzer[1], I. Strasik[1], A. Wastl[1]

[1]EBG MedAustron, Wr. Neustadt, Austria, [2]Abstract Landscapes, Montpellier, France

Abstract

MedAustron is the synchrotron-based Ion therapy center of Austria. Accelerated proton beams with energies of 62-252 MeV are used to treat patients with cancer since 2016. Carbon ion beam is currently under commissioning and will provide treatment in 2019 with energies of 120-400MeV/u [1]. The Injector features three identical ECRIS from Pantechnik, two of which are used to generate the proton and the carbon beam with an energy of 8 keV/u. The generated beam is sent to a 400keV/u RFQ and a 7MeV/u H-mode Linac. Then follows the injection in a 77 m synchrotron via a middle energy transfer line, where the energies for patient treatment are reached. The beam is sent to four irradiation rooms via a high energy transfer line, two of which are currently used for medical treatment. The medical environment of the accelerator puts strict requirements on the source performances in terms of long term stability and uptime. The extracted carbon intensity needs to be on the order of 150 μA with maximum current fluctuations of ±2.5% on the continuous run. In this work we discuss the status of carbon commissioning with particular emphasis on the experimental results obtained during the ion source tuning [2].

INTRODUCTION

MedAustron Ion Therapy Center (Fig.1) is a medical facility. This creates an environment significantly different than in research facilities [3]. One source of limitation are law restrictions when using technical devices for patient treatment and procedures that the facility needs to fulfill to be certified for clinical operation. Furthermore sensitive data are processed, therefore certain standards are implemented, which affect not only the clinical part, but the company as a whole. This includes access control, available software, workflow and documentation. The other aspect is related to patients themselves. Each delay or failure directly affects people who wait for their therapy, relying on the help provided to them in a difficult situation created by a medical condition, cancer. Therefore, we continuously work to improve uptime, stability and limit even remote failure risks. This puts significant overhead on all our activities, but also motivates us to look for new ways to improve reliability of the system we use.

Although such work is not directly comparable to scientific investigations, it may provide another point of view on requirements and expectations to the systems used in non-scientific conditions. Out of three sources we use one exclusively in the medical environment and the second one (carbon source) is just being prepared to include into the medical accelerator by optimizing source performance to required level. The goal of this paper is to present constraints, challenges, the work invested to improve the system and unique opportunities which medical environment provide us.

Figure 1. MedAustron Ion Therapy Center

MEDICAL ENVIRONMENT REQUIREMENTS

Without external limitations the most effective approach to keep beam properties stable would be occasional re-tuning of the source parameters. In our case such approach is not effective because parameters are fixed and cannot be modified without and official release process approved by the QA department.

To allow the device to be used for patient treatment it needs to go through a certification process, which takes into account potential risks for patient, service personnel, other devices as well as natural environment. This process, implemented mostly on large-scale reproducible products, affects how we are able to work with device on the level of complication of Synchrotron. MedAustron Particle Therapy Accelerator (MAPTA) consists of hundreds of devices (ion sources, various magnets, linear accelerator and beam diagnostic devices). Starting from sub-components, through components and functional units it is needed to undergo through multi-step commissioning to make it possible to certify the whole device as a medical machine. This process is required also for parameters, set points and settings. Only when both the machine setup and parameters are 'fixed', the medical verification can commence. During this process various 'failure scenarios', tests and measurements are done. In the end the clinically released set of parameters is allowed to be used for treatment.

This changes the approach to beam stability in the ion source, as even the small change in parameters does include time consuming process of releasing new medical

† szymon.myalski@ifj.edu.pl

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP02

AN IRRADIATION TEST FACILITY AT INFN-LNS: STATUS AND PERSPECTIVES

G.G. Rapisarda†[1], V.P. Bonanno[1], R. Catalano[1], G.A.P. Cirrone[1], G. Cosentino[1], G. Cuttone[1], D. Mascali[1], M.S. Musumeci[1], G. Petringa[1], S.M.R. Puglia[1], S. Tudisco[1], D. Rifuggiato[1].

[1]INFN-Laboratori Nazionali del Sud, Catania, Italy

Abstract

In the framework of ASIF "ASI Supported Irradiation Facilities" project some beamlines available at Laboratori Nazionali del Sud - Istituto Nazionale di Fisica Nucleare (LNS-INFN) have been dedicated to irradiation tests. These beamlines have been recently upgraded in order to meet the European Space Agency specifications about radiation hardness testing of devices suitable for space applications. The Superconducting Cyclotron K800 installed at LNS can provide protons up to 80 MeV for integrated dose tests and a number of heavy ion beams for Single Event Effect studies. The beamlines are equipped with detectors that allow beam diagnostic in term of spatial uniformity, purity and energy measurements, including on-line monitoring of flux and fluence received by the device under test. Upgrades activities are now ongoing, especially to broaden up the number of available beams, both in terms of ion species and energy, to optimize the switching times from one beam to another. The paper will present an overview of the developed facility, which will take benefit of the ongoing SERSE (the superconducting ECR ion source) revamping: the new gas-box system, plasma chamber and controls system are ready to be installed within autumn 2018.

INTRODUCTION

Among the research activity carried out at at Laboratori Nazionali del Sud of the Istituto Nazionale di Fisica Nucleare (LNS - INFN) based in Catania, a part of the beam time is dedicated to irradiation tests of electronic devices and detectors as well as of cells and biological samples [1].

Irradiation activity takes advantage of a large number of ions that can be accelerated by the 15 MV Tandem Van de Graaff and by the K800 Superconducting Cyclotron (CS). In particular, this last accelerator coupled with the two high performance ECR sources operating at LNS-INFN, that is SERSE and CAESAR, can provide ion beams in a very wide range of mass, from hydrogen to lead, and energy up to 80 MeV/amu.

Two beamlines, Zero-Degree (ZD) and CATANA (Centro di AdroTerapia e Applicazioni Nucleari Avanzate) are equipped for irradiation tests. CATANA beamline is mainly used for hadron therapy purpose with proton beams [2,3], while the ZD beamline can be adapted to perform different kind of irradiation tests using various ion beams provided by the CS, as well as by the Tandem accelerator. Moreover, the ZD beamline is equipped for both in-air and in-vacuum radiation hardness testing.

† grapisarda@lns.infn.it

Recently, in the framework of ASIF "ASI Supported Irradiation Facilities" project, these beamlines and in particular the ZD one have been upgraded in order to meet the European Space Agency (ESA) ESCC No. 25100 specifications about radiation hardness testing of devices suitable for space applications.

THE IRRADIATION FACILITY

Available beams for irradiation at LNS

According to the ASIF project requirements, a list of beams and a number of diagnostic devices have been defined and developed in order to perform irradiation with protons for integrated dose tests and with heavy ion beams for Single Event Effect (SEE) studies.

In particular, for integrated dose tests proton beams are available according to the energies and the flux shown in Table 1. If necessary, energy can be reduced by means of a stack of plastic degraders.

Table 1: Proton Beams: Energies and Flux

Energy *MeV/amu*		**Flux** ions $cm^{-2}s^{-1}$
10 - 26	from Tandem	up to 10^7
60, 80	from CS*	

SEE tests are performed by using mainly ^{20}Ne, ^{40}Ar, ^{84}Kr, ^{129}Xe beams at 20 MeV/amu, corresponding Linear Energy Transfer (LET) and range in silicon, calculated with SRIM2008, are reported in Table 2. The selected ions provide, at the moment, the best compromise in reducing the time required for beam change (4-8 hours) and in providing a large range of LET values. In in-air irradiation, air is used to reduce beam energy, this provides several LET points up to 60 MeV/(mg/cm^2) allowing to measure the cross-section (number of events per unit of fluence) from the threshold to the saturation value.

Table 2: Ions Available For SEE Test.

Ion	**Energy** *MeV/amu*	**LET^{SRIM}** *MeV/(mg/cm^2)*	**Range^{SRIM}** *μm*
^{20}Ne	20	1.996	504.54
^{40}Ar	20	6.266	356.49
^{84}Kr	20	21.59	245.12
^{129}Xe	20	44.05	204.46

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP03

PRODUCTION OF VARIOUS ION SPECIES BY GAS PULSING TECHNIQUE FOR MULTI-ION IRRADIATION AT NIRS-HEC ION SOURCE

M. Muramatsu†, Y. Iwata, K. Mizushima, T. Inaniwa, A. Kitagawa, QST-NIRS, Chiba, Japan
K. Takahashi, T. Shiraishi, T. Suzuki, F. Ouchi, T. Sasano, AEC, Chiba, Japan

Abstract

High-energy carbon-ion radiotherapy is being carried out at Heavy Ion Medical Accelerator in Chiba (HIMAC). Over 11000 cancer patients have been treated with carbon beams having energies of between 56-430 MeV/u since 1994. At present, multi-ion irradiation method by various ion species is being studied for optimization of LET and dose distribution. An ion source has to produce the helium, carbon, oxygen and neon at pulse by pulse for this method. Requirement currents for He^{2+}, C^{2+}, O^{3+} and Ne^{4+} are 500, 150, 230 and 300 eμA, respectively. We obtained beam current of 482, 151, and 270 eμA for He^{2+}, C^{2+} and O^{3+} with mixed helium and CO_2 gases under the extraction voltage of 27 kV. Beam current of 27 and 15 eμA for C^{5+} and O^{7+} ions were also obtained in this time. He^{2+} beam include full striped ion such as C^{6+}, N^{7+} and O^{8+}. We have to increase the purity of He^{2+} beam. The gas feed system was modified for making pulsed gas by using a solenoid valve for switching different gas.

INTRODUCTION

Four ion sources produce various ions for medical use, biological and physical experiment in HIMAC at the National Institute of Radiological Sciences (NIRS). The multi-ion irradiation with dose distribution and Liner Energy Transfer (LET) optimization is being studied at NIRS [1, 2]. Helium, carbon, oxygen and neon ions are considered as ion species for multi-ion irradiation. When we use more than one ion sources, it is possible to switch different ion species easily. However, we considered the switching method with only one ion source. Ionization gases were helium, CO_2 and neon to produce He^{2+}, C^{2+}, O^{3+} and Ne^{4+} ions. These set points of intensity were 500 eμA correspond to He^{2+}, 150 eμA to C^{2+}, 230 eμA to O^{3+}, and 300 eμA to Ne^{4+}. At first, we tested production of the He^{2+}, C^{2+} and O^{3+} with mixing the gases of helium and CO_2 at 18 GHz NIRS-HEC [3]. Next, we measured the switching time of different ion species with gas pulsing technique.

GAS MIXING EXPERIMENT

The CO_2 and helium gases were introduced at the same time to the plasma chamber for production of He^{2+}, C^{2+}, O^{3+} at this experiment. Dependences of the microwave power and the mirror field were measured under the same parameters. The microwave frequency was 18.0 GHz. The gas flow of helium was 0.075 cc/min. The extraction voltage was 27.0 kV. The downstream coil current was 500 A. Figure 1 shows microwave power dependence of He^{2+}, C^{2+}, O^{3+}. The gas flow of CO_2 and upstream coil current were 0.016 cc/min and 840 A, respectively. When microwave power was increases, He^{2+} was increased, but O^{3+}, C^{2+} was decreases. The microwave power of 800 W was good for production of He^{2+}. Figure 2 shows dependence of the upstream coil current. The ion source parameters were same as the microwave power dependence. The respective ions became highest when coil current was 790 A. We obtained the beam current of 482, 151, and 270 eμA for He^{2+}, C^{2+} and O^{3+} with microwave power of 800 W and upstream coil current of 790 A. However, the beam current of He^{2+} is not yet reach the requirement value due to the gas mixing effect. If more neon gas is added, it is difficult to reach the requirement value of helium ion.

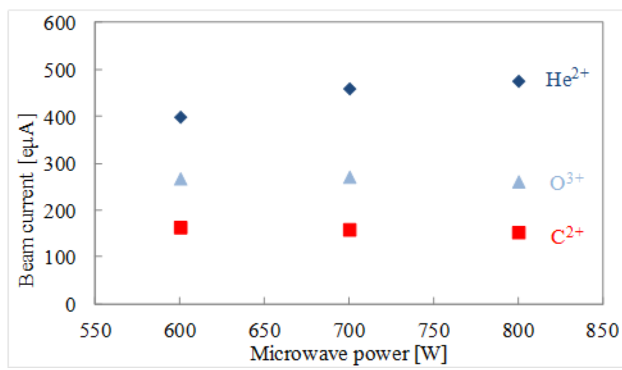


Figure 1: Dependence of microwave power.

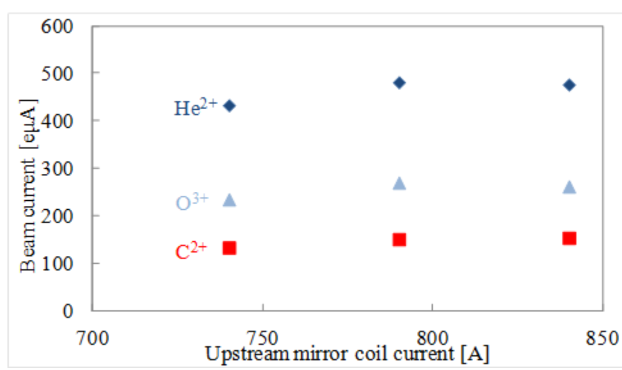


Figure 2: Dependence of upstream mirror magnetic field.

GAS SWITCHING EXPERIMENT

We try to produce He^{2+}, C^{2+}, O^{3+} and Ne^{4+} ions by using helium, CO_2 and neon gases. The high speed solenoid valve (Parker, Series 9) and controller (Parker, Iota One)

† muramatsu.masayuki@qst.go.jp

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP04

COMMISSIONING OF THE PROTON-LINAC ECR SOURCE FOR FAIR

J. Fils†, R. Berezov, R. Hollinger, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
B. Bolzon, N. Chauvin, O. Delferrière, O. Tuske, Y. Gauthier, Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA), IRFU, 91191 Gif-sur-Yvette, France

Abstract

The Facility for Antiproton and Ion Research (FAIR) presently built in Darmstadt, Germany, will be dedicated to physics of unstable nuclei and antiprotons. The antiproton program at FAIR needs for various experiments the delivery of $7x10^{10}$ pbar/h beams. Consequently, the acceleration chain composed of a proton-Linac and two synchrotrons, SIS 18 and SIS 100 has to deliver $2x10^{16}$ protons [1]. To this purpose, a 75 mA/ 68 MeV proton-Linac (p-Linac) is under construction. Its injector is composed of an Electron Cyclotron Resonance (ECR) ion source, a Low Energy Beam Transport (LEBT) line, a 3 MeV Radio-Frequency Quadrupole (RFQ) and a Drift Transport Line (DTL) using Cross-bar H-mode cavities (CH). The CEA/Saclay is in charge, in the framework of a French-German collaboration, of designing, constructing and commissioning the proton-Linac injector composed of both the ECR proton source and the LEBT with dedicated diagnostics [2]. The on-axis species repartition of the proton beam is measured with a Wien Filter (WF), and the 2D-emittance with an Allison Scanner (AS) [3]. The targeted specifications are a proton beam current of 100 mA for an energy of 95 keV at the entrance of the RFQ within an emittance of 0.3π mm.mrad (rms norm). We present in this paper the latest results obtained with the injector in view of commissioning.

PROTON LINAC

At FAIR, the primary proton beam for the antiproton production is delivered by the p-Linac at an energy of 68 MeV and a repetition rate of 4 Hz (Fig. 1). Its main parameters are listed in Table 1.

Table 1: Proton Linac Parameters

Parameter	Value
Beam Energy	68 MeV
Maximum design current	70 mA
Current at SIS18-injection	35 mA
Proton per pulse	$7.9\ 10^{12}$
Beam pulse length	36 µs
RF-frequency	325.224 MHz
Repetition rate	≤ 4 Hz
Emittance (norm)	≤ 2.1 mm.mrad
Momentum spread (tot., norm)	$\leq \pm 10^{-3}$
Overall length	43 m

† j.fils@gsi.de

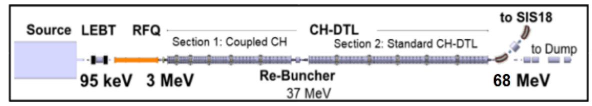


Figure 1: Schematic of the future p-Linac.

The proton injector being commissioned at CEA/Saclay is composed of the proton source and the LEBT until the entrance of the RFQ (Fig. 2).

PROTON INJECTOR

The proton source, acceleration column and LEBT presently under construction and test at CEA/Saclay has been designed according to the SILHI model and the IPHI deuteron injector.

General Layout

The injector has to deliver a proton-beam at 95 keV with a proton beam intensity of 100 mA at the entrance of the RFQ. All general requirements are listed in Table 2. Its general layout is represented in Fig. 1. Different parts are described more precisely in following sections.

Table 2: Proton Injector Parameters

Parameter	Value
Beam Energy	95 keV
Beam Intensity	100 mA (H^+)
Repetition rate	4 Hz
Energy spread	< 60 eV
Final emittance	≤ 0.33 π mm.mrad
Pulse length	≥ 36 µs
α Twiss parameter	0.27 ≤ α ≤ 0.59 mm/π.mrad
β Twiss parameter	0.037 ≤ β ≤ 0.046 mm/π.mrad

Ion Source and Extraction System

Its design was taken from the SILHI high intensity light ion source [4] developed at CEA. The cylindrical plasma chamber, 90 mm wide and 100 mm long, is put on a 100 kV-platform in a Faraday cage. H_2 gas is injected through a capillary. Its flow is tuned by a mass flow controller. To occur, the ECR condition needs the presence of an axial magnetic field produced by two coils, independently power-supplied and tuned in order to reach a constant on-axis magnetic field value of 0.875 T, possibly as close as possible to the ridge output concentrating the 2.45 GHz RF-wave from the magnetron. Electron density is increased thanks to two boron nitride disks inside the plasma chamber.

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP06

PROGRESSES IN THE INSTALLATION OF THE SPES-CHARGE BREEDER BEAM LINE

A. Galatà*, C. Roncolato, G. Bisoffi, P. Francescon, L. Bellan, J. Bermudez, D. Bortolato, M. Comunian, A. Conte, M. De Lazzari, F. Gelain, D. Marcato, M. Miglioranza, M.F. Moisio, E. Munaron, S. Pavinato, D. Pedretti, A. Pisent, M. Rossignoli, M. Roetta, G. Savarese, INFN-Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy,
M. Bellato, INFN-Sez. di Padova, Padova, Italy,
V. Andreev, ITEP, Moscow, Russian Federation

Abstract

Since fall 2017, the ADIGE (Acceleratore Di Ioni a Grande carica Esotici) injector of the SPES (Selective Production of Exotic Species) project entered the installation phase. The injector includes an Electron Cyclotron Resonance (ECR)-based Charge Breeder (SPES-CB) and its complete beam line, as well as a newly designed RFQ, to allow the post-acceleration of the radioactive ions produced in the so-called target-ion source-system. The injector has different peculiarities, deriving from particular needs of SPES: a complete electrostatic beam line equipped with a 1+ source for test purposes, and a unique Medium Resolution Mass Spectrometer (MRMS, R∼1/1000), mounted downstream the SPES-CB, to clean the radioactive beam from the contaminants induced by the breeding stage. This contribution reports about the status of the installation of the injector, describing the various technical solution adopted, and giving a realistic planning for the commission and following operation of its main parts.

INTRODUCTION

SPES [1] (Selective Production of Exotic Species) is an INFN project with the aim at developing an Isotop Separation On Line (ISOL) Radioactive Ion Beam (RIB) facility as an intermediate step toward EURISOL. The SPES project is under construction at the INFN-Laboratori Nazionali di Legnaro (LNL): the main goal is the production and post-acceleration of exotic beams to perform forefront research in nuclear physics by studying nuclei far from stability. The project is concentrating on the production of neutron-rich radioactive nuclei with a mass range A=80–160: they are fission fragments that will be produced by delivering a proton beam on a UC_x target developed at LNL. The proton driver will be a commercial cyclotron [2] with a variable energy (30–70 MeV) and a maximum current of 0.75 mA (upgradeable to 1.5 mA), with the possibility to split the beam on two exit ports. The accelerator was installed in a new dedicated building in 2016 and the factory acceptance tests were succesfully carried out in 2017. The radioactive species produced will be extracted as a 1+ beam from dedicated sources [3], cooled in a RFQ-cooler [4] and purified from the isobars contaminants through a High Resolution Mass Spectrometer (HRMS) presently in the design phase. In order to allow post-acceleration with the LNL booster ALPI (up to 10 MeV/A for A/q = 7), the project will employ an Electron Cyclotron Resonance (ECR)-based charge breeding technique [5]: the Charge Breeder will be equipped with a complete test bench totally integrated with the SPES beam line. This part of the post-accelerator, together with the newly designed RFQ [6], composes the so-called ADIGE (Acceleratore Di Ioni a Grande carica Esotici) injector [7], whose layout is shown in Fig. 1. Since fall 2017, the injector entered the installation phase: this paper will describe its main components, the various technical solutions adopted, and will report on the status of the installation, giving a realistic planning for the commissioning and following operation of its main parts.

* alessio.galata@lnl.infn.it

BEAM LINE DESCRIPTION

The ADIGE injector consists of a 1+ beam line producing stable beams for test purposes, and a N+ beam line to deliver the beams extracted from the Charge Breeder to the post-acceleration. Those parts will be described in separated sub-sections.

The 1+ Beam Line

Depending on the particular element to be charge bred, two kind of sources will be employed (alternatively), sharing the same vacuum chamber: a surface ionizaion source (SIS) or a plasma ionization source (PIS). Those sources are semplified copies of the ones which will be installed in the target-ion source-system of SPES and are described elsewhere [3]: the ionization machanisms employed will allow the production of beams from most of the elements of the periodic table, except for the refractory metals. The stable 1+ ions produced will be extracted by applying a positive high voltage between 20 keV and 40 keV to the common vessel through a 3 mm hole, and placing a movable electrode at ground potential, in order to optimize the electric field depending on the extracted intenisty. The beam will pass through two couples of X-Y electrostatic steerers (±2 kV max) that will correct possible beam misalignments, and will then be focused by an electrostatic quadrupoles triplet (5 kV max, total length 848 mm) to the first beam instrumentation box, equipped with a faraday cup, two beam profile monitors (one for each transversal plane) and selection slits. Such box is mounted at the object point of the 1+ selection dipole: it is a 90°, 750 mm radius magnet, with entrance

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP07

ADDRESSING CONTAMINATION IN ECR CHARGE BREEDERS

R.C. Vondrasek†, Physics Division, Argonne National Laboratory, Lemont, IL, USA 60439

Abstract

The Electron Cyclotron Resonance (ECR) ion source was first utilized for charge breeding in 1995 [1]. Since that time the charge breeding technique has been refined. Single charge state efficiency has improved by a factor of ten, the efficiency discrepancy between solid and gaseous species has narrowed, and low-mass species efficiency has improved. But the limiting characteristic of the ECR charge breeder continues to be a high level of contamination which often obscures the beam of interest [2]. Multiple techniques have been employed to reduce this contamination with varying levels of success, and attempts are currently underway to improve upon the successes achieved to date. This paper will review those past techniques, current attempts, and possible future paths for reducing the contamination level in ECR charge breeders.

INTRODUCTION

Caribu Facility

The CAlifornium Rare Isotope Breeder Upgrade (CARIBU) [3] provides radioactive beams to the Argonne Tandem Linac Accelerator System (ATLAS). Fission fragments are produced by a 200 mCi 252Cf fission source located inside a large-volume helium gas catcher. The fragments are thermalized and rapidly extracted at up to 50 kV forming a low-energy beam of 1+ or 2+ ions. The isotope of interest is selected via a high-resolution (1:20,000) magnetic separator. The beam is then transported to either an in-room experimental area, a remote stopped beam experimental area, or an ion source where the beam is charge bred for subsequent acceleration in the ATLAS linac. Originally, an ECR source charge bred the CARIBU beams, but due to the inability to adequately reduce the stable beam contamination that source was replaced by an EBIS in 2016.

ANL ECR CHARGE BREEDER

The ANL ECR breeder [4] (Fig. 1) is a room temperature source with the plasma excited by two RF frequencies – a 10.44 GHz klystron and an 11-13 GHz traveling wave tube amplifier (TWTA). It has an open hexapole structure providing good pumping to the plasma chamber region and allowing the RF and support gas to be introduced radially. This scheme eliminates the need for cut-outs in the field shaping iron to accept the RF waveguides. The 1+ ions were introduced into the plasma through a grounded high-purity aluminum tube mounted on a linear motion stage with a 30 mm range of travel. The source is designed to operate at a 50 kV potential although it typically operated at 36 kV.

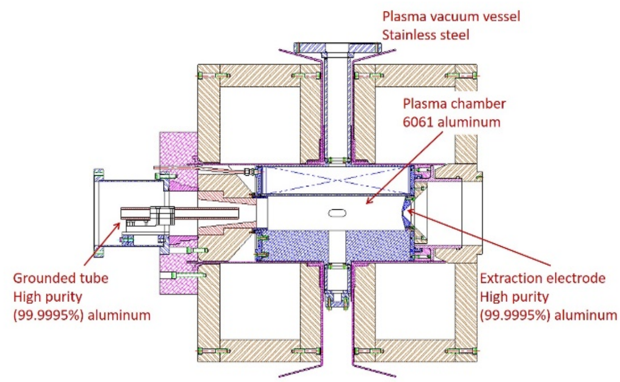


Figure 1: The Argonne National Laboratory ECRCB.

BACKGROUND CONTAMINATION

The background contamination which plagues ECR charge breeders has been well documented [5, 6, 7]. A mass scan of an oxygen plasma in the A/q region in which the ANL ECR breeder operated showed numerous peaks for nitrogen, argon, aluminum, fluorine, and chlorine on the >1 epA scale. Even in A/q regions within the spectrum that showed no background as measured with a picoammeter, a more sensitive examination with a silicon barrier energy detector revealed significant levels of background which dominated the radioactive ion beam of interest, as shown in Fig. 2. In the case of 146Ba28+, the radioactive beam accounted for only 3% of the total rate into the detector. The stable contaminants (Ti, Zn, Zr, Mo, Sn, Xe, Ir, Hg) were all within the LEBT resolution window and could only be eliminated by addressing the contamination at the source. In fact, even with a 1:1000 spectrometer after the charge breeder such as the one employed at SPES [8], only the Zn and Xe would be eliminated from the 146Ba spectrum.

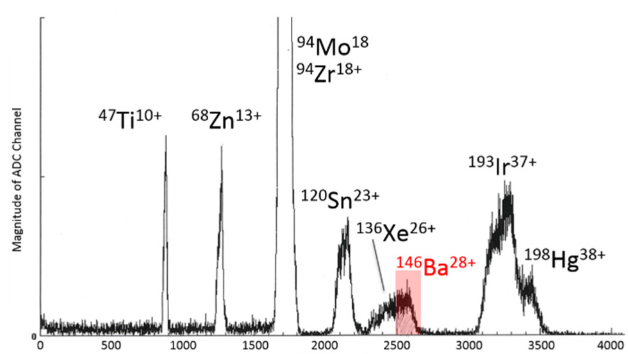


Figure 2: Spectrum is the radioactive beam 146Ba (highlighted in red) and its contaminants from the ECRCB.

† vondrasek@anl.gov

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP09

OPERATION OF THE PHOENIX V3 ECRIS APPLYING DOUBLE FREQUENCY HEATING

F. Maimone[1,†], T. Thuillier[2], K. Tinschert [1], J. Jacob[2], J. Angot[2], L. Bonny[2], A. Leduc[2], P. Sole[2], R. Lang[1], J. Mäder[1], P.T. Patchakui[1], D. van Rooyen[1]

[1] GSI Helmholtzzentrum für Schwerionenforschung, Planckstr. 1, 64291, Darmstadt
[2] Université Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, 38000 Grenoble, France

Abstract

PHOENIX V3 is an upgraded version of the V2 ECRIS to be installed at the heavy ion injector at SPIRAL2. The source is under commissioning at LPSC since 2016. One of the main upgrades of the V3 concerns the new microwave injection system including two WR62 waveguide apertures. This new plug having two waveguide ports allows running the ECRIS with the double frequency heating mode by connecting two different high power microwave sources. For the investigation of this plasma feeding method a klystron generator at 18 GHz proving up to 2 kW microwave power was used together with a traveling wave tube amplifier with a 12.75-14.5 GHz bandwidth and 650 W maximum output power. Several experiments were carried out in order to verify the performance with respect to the single frequency operation. Different ion source configurations were investigated and different frequencies and power combinations were analyzed with the aim to maximize the high charge state ion production and to reduce the ion beam instability. The results are reported here.

INTRODUCTION

At LPSC the room temperature PHOENIX V3 ECRIS is under commissioning since 2016. This upgraded version of the PHOENIX V2 ECRIS features a larger plasma chamber, a new hexapole and a reduced vacuum pressure under operation [1]. So far high current of highly charged ions of gaseous and metallic elements has been extracted from this ion source. [2-4].

In order to enhance the high charge state production to fulfil the requirements of SPIRAL2 (i.e. ion beams with intensities of several pμA up to ion mass M~60) high microwave power and other techniques must be applied.

An operation mode successfully used to enhance the beam current of highly charged ions is the "double frequency heating" which consists of the injection of two electromagnetic waves at different frequencies into the ion source. [5]

For this purpose the PHOENIX V3 is equipped with a new microwave injection system including two separate WR62 waveguide apertures where two different high power microwave sources can be connected. The ion source performance has been tested with double frequency heating and has been compared with the single frequency operation. Different ion source parameters were investigated and different frequencies and power combinations were analysed with the aim to maximize the high charge state ion production and to reduce the ion beam instabilities. The results are reported here.

† f.maimone@gsi.de

EXPERIMENTAL SET-UP

The PHOENIX V3 ECRIS is designed to operate at 18 GHz and a klystron generator proving up to 2 kW microwave power is used for the ion source commissioning.

The double frequency heating has been performed by connecting a Traveling Wave Tube Amplifier (TWTA) with a 12.75-14.5 GHz bandwidth and 650 W maximum output power to the second waveguide port of the injection plug. In order to properly perform the measurements, following components have been used:

- A WR62 high power wideband 20 dB isolator in order to prevent the reflected and cross coupled power to the TWTA;
- Waveguide vacuum windows covering the TWTA´s bandwidth and the klystron frequency;
- A specially designed 60 kV DC-Break for the TWTA connection with low insertion loss.

Concerning the DC-Break, full wave simulations were performed at LPSC in order to find the best geometrical configuration and the proper dielectric material to achieve a flat insertion within the bandwidth of the amplifier.

The prototype measurements done with a Network Analyser confirmed that the requirement of a flat insertion loss higher than 0.4 dB in the 12.75-14.5 GHz frequency range is fulfilled.

Two WR62 directional couplers are inserted between the isolator and the ion source. Microwave power probes are connected to each directional coupler to measure the forward and the cross-coupled power from the ECRIS. Once the microwave sources have been connected, safety tests were performed to check the power levels crossing between the two waveguides in order to prevent any damage of the microwave sources.

The measurement campaign was carried out with Argon as main gas and Oxygen as support gas and the main focus was the optimization of the intensity of the extracted Ar^{14+} charge state. A 20 kV extraction voltage and a -2 kV voltage were applied to the ECRIS and to the electron repeller electrode, respectively.

One should note that the second waveguide was used for the first time in the source for this experiment and that the second RF vacuum window was installed 2 days

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP10

HTS MAGNET TECHNOLOGY AS PATH TO FOURTH AND FIFTH GENERATION ECR ION SOURCES

T. Shen*, D. Leitner, L. Garcia Fajardo, S. Prestemon, G. Sabbi
LBNL, Berkeley, California, USA

Abstract

Novel superconducting magnet systems for ECR ion sources (ECRIS) operating at frequencies above 28 GHz is a core technology to be developed. Current state-of-the-art magnet systems are based on the Nb-Ti technology at 4.2 K and are the new standard injectors for next generation heavy ion beam facilities. However, increasing the frequency beyond 28 GHz will further advance the performance of high charge state ECR ion sources. Nb_3Sn provides an immediate option for reaching higher frequencies, but Nb_3Sn designs would ultimately be limited to about 56 GHz. A versatile longer-term option is the high-temperature superconducting magnet technologies, which can enable operations of high field ECRIS magnets at $T \geq 20$ K. The ultimate operating frequency of HTS magnet systems is not limited to 56 GHz but in principle could even attain 84 GHz, due to the critical field and current density limits that can be achieved at high fields. The paper will first discuss the ECR ion source parameters driving the design of the Next Generation Superconducting ECR magnets, and will then focus on HTS magnet technology and its potential to further increase the performance of ECR ion sources.

ECR ION SOURCE PHYSICS PARAMETERS

ECR Ion Source Confinement

ECR ion sources use magnetic confinement and electron cyclotron resonance heating to produce a plasma consisting of energetic electrons (up to hundreds of keV) and relatively cold ions (a few eV). High charge state ions are primarily produced by sequential impact ionization. Therefore, the ions must remain in the plasma long enough (tens of ms) to reach high charge states and the main parameter determining the performance of an ECR ion source is the product of the plasma density and ion confinement time: $(n_e \cdot \tau_i)$. Together with the neutral gas density in the plasma this product determines both the peak of the charge state distribution and the highest charge state that can be produced in the plasma. Following the semi-empirical scaling laws first proposed by Geller [1], the plasma density scales with the square of the frequency $n_e \propto \omega_{rf}^2$. As the frequency increases, the magnetic fields have to be scaled accordingly to fulfill the resonant heating condition for the plasma electrons. As a consequence the plasma confinement time (τ_i) in the trap improves since it is proportional to the average field strength and the axial and radial magnetic mirror ratios B_{inj}/B_{min}, B_{ext}/B_{min}, B_{rad}/B_{min} of the magnetic trap [1].

* tshen@lbl.gov

Following these fundamental principles, the trend for new ECR ion source constructions has been to design for both the highest confinement fields and highest heating frequency resulting in a number of high performance ECR ion sources developed over the last few decades. Compiling results from these high performing devices, guidelines for the design of an optimized magnetic confinement field configurations were established applicable to any heating frequency of an ion source [2]. These established field ratios are listed below with F_{rf} being the chosen operating microwave frequency for the new ECR ion source, with B_{inj}, B_{ext}, B_{min}, the maxima and minimum fields of the magnetic mirror, and B_{rad} the radial field strength on the plasma chamber wall.

- $B_{ECR} = F_{rf}(GHz)/28(GHz) \cdot T$
- $B_{inj}/B_{ECR} = 4$
- $B_{rad}/B_{ECR} = 2$
- $B_{ext} \approx 0.9 B_{rad}$

For the minimum B-field of the trap one can find [2, 3]

- $B_{min} \approx 0.4 B_{rad}$ and
- $0.4 < B_{min}/B_{ECR} < 0.8$

Another important parameter for establishing the overall plasma confinement is the electron energy distribution in the ECR plasma, which can be characterized by three components: a cold population (20 eV) - important for the overall plasma density and confinement time; a warm population (up to 100 kev) - responsible for the ionization process, and a hot population with a high energy tail reaching up to several hundreds of keV, which is highly confined in the core of the plasma and quasi collissionless. While the hot electron population does not contribute to the ionization process, these hot electrons are nevertheless crucial to establish the electrostatic confinement for the ions in the trap. Therefore, their presence is a necessary condition for the creation of high charge state ions [3]. However, one undesired consequence of this hot electron population is the creation of high energy x-rays that penetrate the plasma chamber and, in the case of a superconducting ECR ion source, add a substantial heat load to the cryostat. It would be desirable to optimize this temperature while minimizing the x-ray production and maintaining a strong electrostatic confinement. Results from recent x-ray studies suggest that this could be possible [4, 5].

Key results from experimental studies to understand the role of the hot energy tail ECR plasma are summarized below:

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP11

THE FIRST MEASUREMENT OF PLASMA DENSITY BY MEANS OF AN INTERFERO-POLARIMETRIC SETUP IN A COMPACT ECR-PLASMA TRAP*

E. Naselli†[1], D. Mascali, G. Torrisi, G. Castro, L. Celona, S. Gammino, M. Mazzaglia, G. Sorbello[2], Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud (INFN-LNS), 95123 Catania, Italy
[1]also at Department of Physics and Astronomy, University of Catania, Via Santa Sofia, 64, 95123 Catania, Italy
[2]also at Department of Electrical, Electronics and Computer Engineering (DIEEI), University of Catania, viale A. Doria, 6, 95125 Catania, Italy

Abstract

This paper presents the first measurement of plasma density by a K-band microwave polarimetric setup able to measure the magnetoplasma-induced Faraday rotation in a compact size plasma trap. The polarimeter, based on rotating waveguide OMTs (OrthoModeTransducers), has been proven to provide reliable measurements of the plasma density even in the unfavorable conditions $\lambda_p \sim L_p \sim L_c$ (being λ_p, L_p and L_c the probing signal wavelength, the plasma dimension and the plasma chamber length respectively) that complicates the measurements due to multi-patterns caused by reflections of the probing wave on the metallic walls of the plasma chamber. An analysis method has been developed on purpose in order to discriminate the polarization plane rotation due to magnetoplasma Faraday rotation only, excluding the effects of the cavity resonator. The measured density is consistent with the previous plasma density interferometric estimations. The developed method is a powerful tool for probing plasmas in very compact magnetic traps such as Electron Cyclotron Resonance Ion Sources and for in-plasma β-radionuclides' decay studies.

INTRODUCTION

For the development of future ECRIS dedicated and advanced plasma diagnostic tools will be crucial. It is particularly necessary to implement non-intrusive diagnostics for probing electron density and temperatures. Among the others, a special mention is worth by Optical Emission Spectroscopy (OES) [1,2] and X-rays spectroscopy (XRS) [3] which however are both able to measure "partial" densities only, i.e. the ones related to specific energy domains.

Interferometry and microwave polarimetry (i.e., taking profit by magnetoplasma induced Faraday Rotation) are able to probe to whole plasma electron population, regardless of energy contents. These techniques have been fruitfully applied already in large-scale fusion reactors [4] and – regarding the Faraday rotation especially – are a standard in astrophysical plasmas, where used for either magnetic field and/or stellar density measurements [5].

However, the implementation of both the techniques in compact plasma traps, such as ECRIS, is still a challenge: the main constrain consists in the small-size of the plasma chamber and of the plasma itself if compared with the probing wavelength. The following condition holds: $\lambda_p \sim L_p \sim L_c$, being λ_p, L_p and L_c the probing signal wavelength, the plasma dimension and the plasma chamber length respectively. That means, interference effects due to the metallic walls of the plasma chamber cannot be neglected, and in some conditions even prevail. A specific approach has been therefore proposed and implemented, and a new double-purpose tool named VESPRI has been constructed: it is a microwave interfero-polarimeter suitable for total electron density measurements in ECRIS plasmas. At least for the interferometry in compact devices, data are already published elsewhere [6].

Hereby we show the data coming from polarimetric measurements (preliminary dataset are already commented in the paper [7]) that have allowed the first line-integrated measurement of plasma density via Faraday-rotation in ECRISs.

EXPERIMENTAL SETUP

The measurement of the magnetoplasma induced rotation of the polarization plane in the VESPRI setup has been based on broadband waveguide OrthoModeTransducers (OMTs) system (see Fig. 1).

The turnstile junction OMTs enable the TE11 mode from the circular input port of the conical horn antennas to be split equally into the two single-mode rectangular waveguide outputs TE10 modes, thus obtaining a return loss better than 13 dB in the 18÷26.5 GHz band. One of the twos OMTs can rotate at ± 95°, with an angular precision of 0.05°, handling up to 100 W of microwave power (but the probing signal was below 100 mW due to the high sensitivity of the power probe). The OMTs were inserted along the plasma leg, upstream and downstream to the emitting/receiving antennas.

*Work has received funding from 5th Nat. Committee of INFN, under the grants VESPRI and PANDORA
† naselli@lns.infn.it

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP12

RESULTS OF THE OPTICAL EMISSION SPECTROSCOPY DIAGNOSTICS OF THE ESS PROTON SOURCE*

G. Castro†, M. Mazzaglia, D. Mascali, R. Reitano[1], L. Celona, E. Naselli[1], L. Neri, G. Torrisi and S. Gammino,
INFN – Laboratori Nazionali del Sud, Catania, Italy
[1]also at Università degli studi di Catania, Catania, Italy

Abstract

The evaluation of the electron density and proton fraction of hydrogen plasmas has a relevant importance for plasma traps used as sources of intense proton, H2+ or H3+ beams. Optical Emission Spectroscopy (OES) enables to evaluate simultaneously and on-line the H/H2 relative abundances together with plasma and electron temperature. In this work, the experimental results of the OES measurements on the Proton Source of the European Spallation Source plasma has been related to the properties of the ion beam extracted by the source (proton fraction and beam intensity, in particular). Benefit of the diagnostics and the further improvements foreseen in next future will be highlighted.

INTRODUCTION

The Proton Source for the European Spallation Source (PS-ESS) is a Microwave Discharge Ion Source (MDIS) operating at 2.45 GHz microwave frequency for high intensity proton beam generation. PS-ESS has been designed and assembled at INFN-LNS as injector for the European Spallation Source (PS-ESS); it produces pulsed proton beams (14 Hz, 2.84 ms puls) from 40 mA to 90 mA nominal current, at 75 keV energy and 2.25 π mm mrad maximum normalized emittance [1]. The source has been characterized by means of a Faraday Cup, an Emittance Measurement Unit and a Doppler shift measurement unit. The standard beam diagnostics allows the measurement of the beam characteristics (as the extracted current, the species fraction and the RMS emittance). However, the beam properties depend on the characteristics of the plasma which generates it. Good performances of a proton source are obtained only if a homogenous, stable, dense and cold plasma is generated within the proton source. Therefore, the knowledge of the plasma parameters represents a fundamental information for the full comprehension of the source performances, but also an essential information for any further improvement of proton sources and ECRIS.

Among the different plasma diagnostics tools, Optical Emission Spectroscopy (OES) is the only diagnostics which is not affected by the plasma generation and does not affects the plasma itself during measurements. Since OES requires just the light emitted by the plasma, a small quartz window is sufficient for the evaluation of the plasma parameters and of the relative abundances of the neutral species. In this work, the results of the OES characterization of PS-ESS, performed in the best machine operative conditions, will be described.

* Work supported by ESS-Miur and Pandora
† Castrog@lns.infn.it

EXPERIMENTAL SET-UP

Figure 1 shows a schematic diagram of the PS-ESS OES experimental set-up. It includes the RF power injection system, the three magnetic coils and the OES diagnostics system. PS-ESS is fed by microwaves at 2.45 GHz generated by a Magnetron, while the magnetic field is obtained by means of three solenoids which permit different magnetic configurations, from off-resonance configurations to simple mirror or magnetic beach (see Fig. 2). In this work, OES measurements has been carried out in best PS-ESS experimental performances, obtained in flat magnetic field configuration. The OES diagnostics system consists of a spectrometer ImSpector V8E, coupled to an ACA2040 CMOS camera. The spectrometer resolution is 2 nm and it is sensitive in the spectral range of 380 - 1000 nm. The whole system is connected to the PS-ESS by means of a 1500 μm diameter fiberglass that is, in turn, properly connected to a quartz window, which "looks" towards the centre of the PS-SS plasma chamber.

The whole OES experimental set-up has been properly calibrated and commissioned by using another plasma device, the Flexible Plasma Trap [2]. Preliminary measurements has been already published in reference [3]. The experimental measurements have been carried out at $2.7 \cdot 10^{-5}$ mbar pressure, measured in low energy beam transport. simulations performed by Comsol permitted to evaluate the pressure as ~ $3 \cdot 10^{-3}$ mbar within the plasma chamber. Microwave power has been increased from 120 to 1200 W.

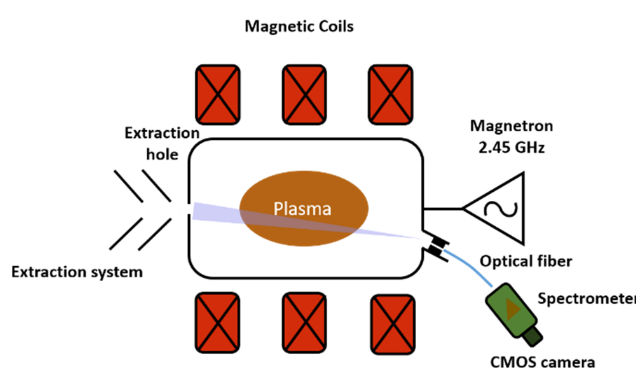


Figure 1: Schematic of the PS-ESS experimental setup at the INFN-LNS.

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP13

CHARACTERIZATION OF ECR PLASMA BY MEANS OF RADIAL AND AXIAL X-RAY DIAGNOSTICS

R. Miracoli†, ESS Bilbao, Poligono Ugaldeguren III,Pol. A, 7B. 48170 Zamudio, Spain
G. Castro, L. Celona, S. Gammino, D. Mascali, M. Mazzaglia, E. Naselli[1], G. Torrisi
INFN-LNS,Via S. Sofia 62, 95123, Catania, Italy
[1] Universitá degli studi di Catania, Dipartimento di Fisica e Astronomia,
Via S. Sofia 64, 95123, Catania, Italy

Abstract

This work presents the X -ray characterization of the plasma generated in a simple mirror axis symmetric trap as a function of the magnetic field profile. A Si-Pin detec-tor has been used to characterize warm electron populati-on in axial and radial directions at two different operating frequencies: 4.1 GHz and 6.8 GHz. Moreover, the hot electrons emitted in axial direction has been measured by means of a HyperPure Germanium (HpGe) detector. Results show that X-ray emission is not homogenous and its homogeneity and temperature depends strongly on the magnetic field profile.

INTRODUCTION

The electron cyclotron resonance ion sources (ECRIS) are mainly used to produce highly charged ions currents for accelerators, nuclear physics research and industrial applications. In recent years many studies have been made in order to understand better the wave-to-plasma interactions that produce plasma instability [1], in particu-lar about the non-linear response of electron heating to pumping wave frequency and anisotropy in plasma densi-ty and electron energy distribution function [2,3]. It is observed that B_{min} value (the minimum value in the mid-plane of the plasma chamber), changes the gradient (de-scribed here in terms of B_{min}/B_{ECR} ratio) of the magnetic field close to ECR surface. The moderate gradient, ob-tained for higher B_{min}, increases the ECR heating effi-ciency and the electron temperature in the plasma. More-over, it is noted that in a moderate gradient regime the plasmas become unstable and can generate intense emis-sions of fluxes of bremsstrahlung and microwaves. In this paper we wanted to show the characterization of the Flexible Plasma Trap (FPT) through measurements of x-rays spectra, acquired by HyperPure Germanium (HpGe) and Si-Pin detectors. X-rays were recorded in both the radial and axial directions for different magnetic field profiles and frequency heating.

EXPERIMENTAL SET-UP

FPT is a test bench for plasma diagnostics and develop-ment of new sources, operating at INFN-LNS [4]. Three solenoids generate different magnetic profiles (off-resonance, simple mirror and magnetic beach configuration) and allow to tune the magnetic field value as a function of the frequency. FPT has three different microwave sys-tems, one parallel and two perpendicular respect to the plasma chamber. The axial injection operates from 4 to 7 GHz. The signal is generated by a Rohde & Schwarz generator, amplified by a TWT and sent to the FPT by WRD350 waveguides. The axial microwave line is com-posed by a directional coupler and an isolator to protect the TWT from the reflected power. The perpendicular microwave launcher can work at 14 GHz and allow oper-ating in double frequency (first and second frequency) mode [5]. The water-cooled copper plasma chamber is 260.1 mm length and its inner diameter is about 82 mm. A stainless-steel vacuum chamber is connected to the plas-ma chamber to host the vacuum system and the diagnostic tools. Figure 1 shows the schematic drawing of the FPT and the diagnostics.

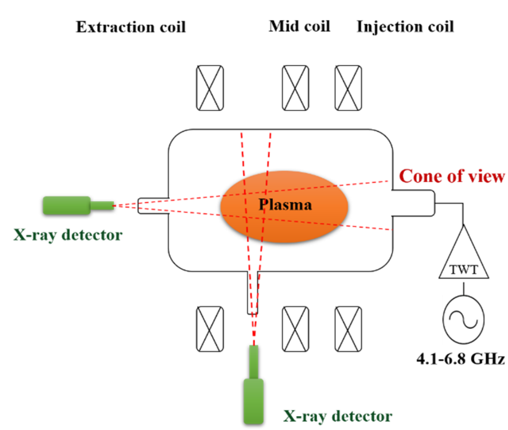


Figure 1: Schematic drawing of the FPT and of x-rays detectors used during the experimental campaign.

High energy X radiation was detected by a HpGe, lo-cated on the axial port of the vacuum chamber, the detec-tor was used for monitoring the x-rays generated by the high energy electrons, from inside the plasma or when they hit the vacuum vessel walls. The HpGe consists of a 15 mm thick, 20 cm^2 crystal protected by a 0.3 mm thick Be window. Its resolution at 122 keV is 0.61 keV. The detector is shielded with lead blocks of 2 cm thickness and ϕ= 1 mm to avoid detecting x-rays scattered from the environmental material. The HpGe detects the radiation

† rmiracoli@essbilbao.org

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP14

MULTI-DIAGNOSTIC SETUP TO INVESTIGATE THE TWO-CLOSE-FREQUENCY PHENOMENA*

S. Biri†, J. Pálinkás, Z. Perduk, R. Rácz, Hungarian Academy of Sciences (Atomki), H-4026 Debrecen, Hungary
C. Caliri, G. Castro, L. Celona, S. Gammino, D. Mascali, M. Mazzaglia, E. Naselli, P. Romano, G. Torrisi, Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud (INFN-LNS), 95123 Catania, Italy
A. Galatà, Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro (INFN-LNL) 35020 Legnaro, Italy

Abstract

While the mechanism is still not fully clear, the beneficial effect (higher intensity of highly charged ions, stable plasma conditions) of the second micro-wave injected to the ECR plasma was observed in many laboratories, both with close and far frequencies. Due to the complexity of the phenomena (e.g. interaction of resonant zones, damped instabilities) complex diagnostic methods are demanded to under-stand its mechanism better and to fully exploit the potential hidden in it. It is a challenging task since complex diagnostics methods require the arsenal of diagnostic tools to be installed to a relatively small size plasma chamber. Effect of the injected second 13.6-14.6 GHz microwave to the 14.25 GHz basic plasma has been investigated by means of soft and (time-resolved) hard X-ray spectroscopy, by X-ray imaging and space-resolved spectroscopy and by probing the rf signals emitted by the plasma. Concerning the characterization of the X radiation, in order to separate the source and position of different X-ray photons special metallic materials for the main parts of the plasma chamber were chosen. A detailed description and explanation of the full experimental setup and the applied non-invasive diagnostics tools and its roles are presented in this paper.

INTRODUCTION

Electron Cyclotron Resonance (ECR) Ion Sources (ECRIS) are able to produce highly charged plasma in their plasma chamber from which positive ions with very different charge states can be extracted and transported to a target or into an accelerator. In order to deliver more and more intense, higher and higher charged ion beams, first a time-stabile, highly ionized plasma has to be generated. By a simplified approach two tasks have to be solved: (1) to inject more and more electromagnetic energy from outside into the plasma on an efficient way and (2) to suppress or decrease those processes (instability, recombination, etc.) which work against the ionization process. The studying the ECR plasma itself for both purposes is thus essential and such investigations have been carried out in many laboratories since the discovery of ion sources of this type.

The ECR groups of two laboratories (Atomki-Debrecen and INFN-LNS Catania) from time to time unify their forces to carry out diagnostics measurements of the ECR plasma for the purposes described above. In an earlier joint experiment [1, 2] a campaign for correlating the plasma density and temperature with the output charge states and the beam intensity for different pumping wave frequencies, different magnetic field profiles was carried out. The results revealed surprisingly very good agreement between warm-electrons density fluctuations, output beam currents and the calculated electromagnetic modal density of the plasma chamber. That experiment was based on the pioneering measurement of this type carried out and published for the first time space-resolved plasma diagnostics measurements by a pinhole X-ray camera [3].

In 2018 a new series of experiment was designed and realized by the collaborating groups. The experiments were carried out in Debrecen, at the Atomki ECRIS Laboratory basing to the Atomki-ECRIS to deliver the necessary plasmas and ion beams.

The main aims were to study these phenomena:

- Exact mechanism of the two-close-frequency heating;
- Role of the 2nd frequency in the suppression of plasma instabilities;
- To obtain volumetric and spatially resolved X-ray emissions from two-frequency plasmas;
- Hard X-ray spectra in unstable regimes;
- Structural changes triggered by instabilities;
- Structural changes when the turbulences are suppressed;

In some of the above goals significant results were obtained, in some others the first promising steps were done. The post-processing of the data is still not finished completely. For the high amount of the material and for the complexity of the results we decided to publish them in three different accompanying papers. The present paper here describes the technical setups of the measurements and shows those technical modifications on the Atomki-ECRIS which were necessary for the investigations. The first part of the results are shown in [4], where an outlook to the history of the two-frequency effect is also presented with references to others' works. The second part of the results, mostly related to the investigation of stable and unstable plasma regimes in single or double frequency operations, is discussed in our third paper [5].

*Work has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 654002 (ENSAR2-MIDAS).
† biri@atomki.mta.hu

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP15

X-RAY INVESTIGATION ON THE SUPERCONDUCTING SOURCE FOR IONS (SUSI)*

Derek Neben†, Jesse Fogleman, Bryan Isherwood, Daniela Leitner[1], Guillaume Machicoane
Shane Renteria, Jeffry Stetson, Larry Tobos
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI, USA
[1] Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

Heavy ion facilities such as the National Superconducting Cyclotron Laboratory (NSCL) often use ECR Ion Sources (ECRIS) for the production of highly charged ions to increase the efficiency of accelerating structures. Axial bremsstrahlung emission was studied on the Superconducting Source for Ions (SuSI) at the NSCL for 18 GHz and 13 GHz operation with oxygen. The hot electron temperatures were estimated from the bremsstrahlung high energy tail and seem to depend only on magnetic minimum in the same way as was found on VENUS [1], even in the case where 18 GHz and 13 GHz frequencies were compared for similarly sized ECR zones. Additionally, the time independent x-ray power increased at a significantly larger rate when operating the source in known regions of instability such as where the magnetic minimum approaches the ECR zone [2]. The results are discussed in the context of electron losses due to magnetic confinement.

INTRODUCTION

We present the bremsstrahlung measurements from a fast sputtering campaign conducted on the Superconducting Source for Ions (SuSI) at the National Superconducting Cyclotron Laboratory (NSCL). The SuSI source is a fully superconducting ECR ion source nominally operating at 18 GHz [3] and 24 GHz [4] microwave frequencies. Following the path set by Geller's scaling laws for ECRIS [5] the plasma density and beam current of ECR ion sources increase with the square of the operating frequency and as proposed more recently [6] with the square of the magnetic field. However, increasing the magnetic field increases the bremsstrahlung emission from the source and stresses the cryostats of 3^{rd} generation fully superconducting ion sources. Dynamic heat loads on the order of several watts [7] have been observed as a result of x-rays produced by bremsstrahlung as electrons escape the ECR plasma, in particular when operating with higher magnetic fields. The x-ray investigation presented herein focused on how x-ray temperature changed with magnetic minimum following measurements previously done by the LBNL group using the VENUS source [1].

Bremsstrahlung results are presented for 18 GHz operation up to 400 W applied microwave power and 13 GHz for a microwave power level of 100 W. Continuous Wave (CW)

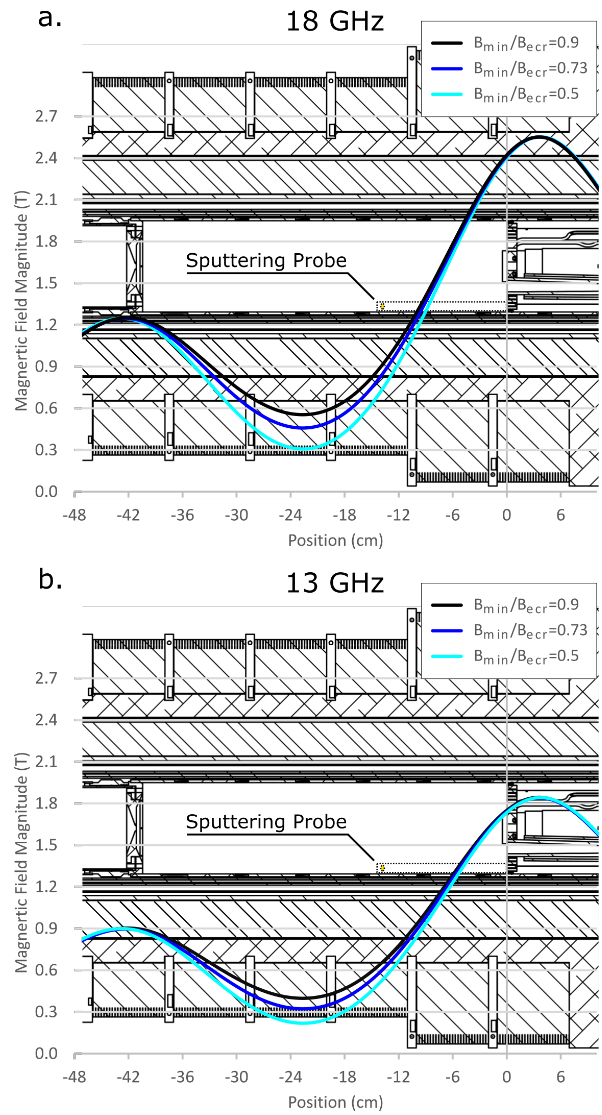


Figure 1: SuSI Magnetic field as simulated using Poisson with the radial sputtering probe developed for SuSI (dotted line). Three field configurations: B_{min}/B_{ecr}=0.5, 0.73. and 0.9 were selected for both 18 GHz and 13 GHz operation. The magnetic fields were scaled with frequency resulting in the same ECR zone size for constant B_{min}/B_{ecr} ratio. The radial sputtering probe was inserted in between the electron flutes on the injection baffle along the plasma chamber wall.

* Work supported by Michigan State University and the National Science Foundation: NSF Award Number PHY-1415462
† neben@nscl.msu.edu

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP19

STATUS REPORT ON THE AECR-U ION SOURCE AT KVI-CART

H. R. Kremers†, J. P. M. Beijers, S. Brandenburg, B. N. Jones, KVI-CART University of Groningen, The Netherlands.

Abstract

A new hexapole, equipped with a pole tip field of 0.87 T has been installed in the AECR ion source. The new hexapole improves the performance of the source, which includes an observed enhancement in all charge state distributions. For the xenon charge state distribution this resulted in a significant increase of the higher charge states that now allows for the production of an $^{129}Xe^{33+}$ beam with intensities of 0.5 μA (collimated beam) that can be used for regular operations.

INTRODUCTION

The interest in intense highly-charged heavy-ion beams used by experimentalists and radiation hardness researchers motivates us to further develop our AECR-U ion source [1]. As the production of intense highly-charge heavy-ions ions requires high-magnetic longitudinal and radial confinement fields, a degraded hexapole with pole tip fields of 0.72 T limits us to achieve the high beam-currents for the highest charge-states of heavy ions. The most optimal design strength of the longitudinal and radial magnetic fields with respect to the heating frequency has experimentally been found and described by scaling laws [2]. According to the law $B_{rad} = 2 \times B_{ecr}$ our radial field should be close to 1 T ($B_{ecr} = 0.5$T). The new hexapole has pole tip fields of 0.87 T; a little lower than the optimal B_{rad} of 1 T. Furthermore, with the installation of the new hexapole, the homogeneity of the magnetic field along the bars improved from 14% to 5% and the maximum value of each bar does now vary within a range of 0.15 Tesla instead of 0.4T. In this paper we describe the exchange of the hexapole including the modification on the plasma chamber. Furthermore, we present beam intensity measurements before and after the replacement of the hexapole and discuss these measurements. Finally, the paper will be close off with the conclusions and a future outlook.

THE HEXAPOLE REPLACEMENT

The conceptual idea behind the design of the hexapole structure is that the design aims for a low background vacuum in the plasma chamber. This is done by incorporating six radial pumping ports in between the magnet bars (Fig.1a.). Unfortunately, it comes with the cost of having no magnetic material at the location of these pumping ports. Therefore, the maximum achievable pole tip fields are lower than for example a Halbach structure [3]. Background pressures are achieved in the order of 2×10^{-8} mbar measured on top of the vacuum chamber. The original design [4] has six pumping slots. But due to a rupture of the aluminium wall between the cooling system and the vacuum chamber of the original chamber, we have changed the six pumping ports of the original design into 6 x 3 smaller pumping slots which, close to the plasma chamber, end in an array of 8 holes with a diameter of 4.8 mm (Fig.1b, 2) which increases the integrity of the support structure.

The Support Structure of the Magnet Bars

The hexapole support structure is made from an 7075 T6 aluminium cylinder in which spaces have been machined by wire cutting in which the six magnetic bars are mounted (Fig.1). The six magnet-bars, made of Nd-Fe-B material, are each build up by two rows of 10 blocks (Fig.1,2), and mounted in a stainless steel AISI 304 can to prevent the magnetic material to oxidize. All blocks are made of MCE N5064 material and have an identical shape with an easy axis of 43 +/- 2% deg (Fig.1f). During operation, the left over spaces around the bars are also used for cooling. The cooling water is directed specifically to the area of the loss-lines (Fig.1c), where the electrons hit the aluminium plasma chamber on the inside. This is done by filling up all the space around the bars with SS sheets and rods (not shown).

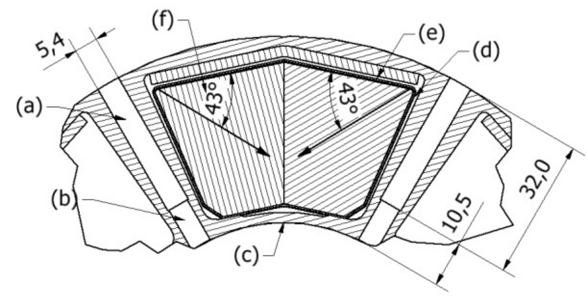


Figure 1: A through cut of a section of the aluminium hexapole container including the canned magnet bar, (a) pumping ports, (b) pumping holes, (c) loss-lines, (d) space filled with SS sheets, (e) can, (f) easy axis.

Pole Tip Field Measurement.

After assembly of the bars in the aluminium container, the hexapole is mounted in a magnetic-field measurement setup. In this setup the hexapole, supported by a v-shaped base, is positioned such that a hall-probe (LPT-141-10s), located at the center line of a hexapole bar, can be moved along the plasma wall. As the actual hall-probe "loop" is located asymmetrically in the head of the hall-probe, a holder is made such that the actual loop inside the probe is symmetrically in front of a pole on a radius of 32.92 mm. The distance between the source axis and the plasma chamber wall is 38.2 mm. To obtain the magnetic field values (Fig.3) at the wall the measured values have been multiplied by $(38.1/32.9)^2$ as the magnetic field quadratically increases as function of the radius. The magnetic field is measured over 300 mm with steps of 1 mm. At every step the longitudinal position and the radial magnet-

† h.r.kremers@rug.nl

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP20

HOMOGENOUS DENSE PLASMA FLUXES FORMATION FROM HIGH FREQUENCY ECR DISCHARGE

S.V. Golubev, R.A. Shaposhnikov†, I.V. Izotov, R.L. Lapin, S.V. Razin,
A.V. Sidorov, V.A. Skalyga, Institute of Applied Physics Russian Academy of Science, 603950
Nizhny Novgorod, Russian Federation

Abstract

Formation of ion beams with wide apertures and current at level of tens and hundreds Amperes is required in a wide range of studies. Usually plasmas of arc or high-frequency discharges are used for such applications. In this paper the possibility of using of an ECR discharge sustained by powerful millimetre wave gyrotron radiation for these purposes is considered. A high plasma density is required to solve the problem of obtaining high values of ion beam current density. The use of gyrotron as a source of millimetre wave radiation in the ECR discharge makes it possible to obtain plasma with high density and high ionization rate, close to 100%. Earlier at the IAP RAS the possibility of dense plasma fluxes production on the basis of ECR discharge in a magnetic field of one solenoid was demonstrated. In this paper, the characteristics of the outgoing plasma flux (density and homogeneity) were investigated. Estimations of the prospects for using such systems for high-current ion beams formation are presented.

INTRODUCTION

Electron-cyclotron resonance (ECR) ion sources are one of the most widespread types of systems for producing ion beams. Previous experiments in IAP RAS were aimed at creating sources of multiply charged ions with a high plasma density in such magnetic field configurations as open magnetic trap and cusp. It was demonstrated that in such systems the electron concentration can reach values 10^{13} cm^{-3}, electron temperature at the level of 100 eV, and the ion beam current has record values up to 500 mA [1-3]. System which is based on the ECR discharge in one solenoid magnetic fields has prospects for producing sources of singly charged ions and formation of plasma fluxes with large apertures as an alternative to existing magnetic plasma confinement systems. This paper is con-cerned with an experimental investigation the transversal plasma fluxes distribution and measurements of plasma pa-rameters obtained in the ECR discharge in a single mag-netic coil sustained by a powerful millimeter-wave gyro-tron radiation.

EXPERIMENTAL RESULTS

The experiments were carried out at the IAP RAS on fa-cility SMIS 37 (see Fig. 1), partly modified the single coil studies. Gyrotron radiation at the frequency of 37.5 GHz with the power up to 100 kW and pulse duration up to 1.5 ms was used for electron heating and discharge ignition. The microwave radiation is launched through a quasiopti-cal system into the discharge chamber with diameter of 68 mm and 250 mm long placed inside pulsed magnetic coil. Magnetic field in the center of the coil varies from 1 to 4 T. ECR value of magnetic field for the frequency of exter-nal electromagnetic radiation 37.5 GHz is 1.34 T.

The operating gas (hydrogen) was inlet into the dis-charge chamber in pulsed mode along the axis of the mag netic system through a gas-entry system integrated into the electrodynamic system for microwave radiation injection. To control neutral gas inlet the pressure in the gas buffer chamber above the gas valve was varied from 0.25 atm. up

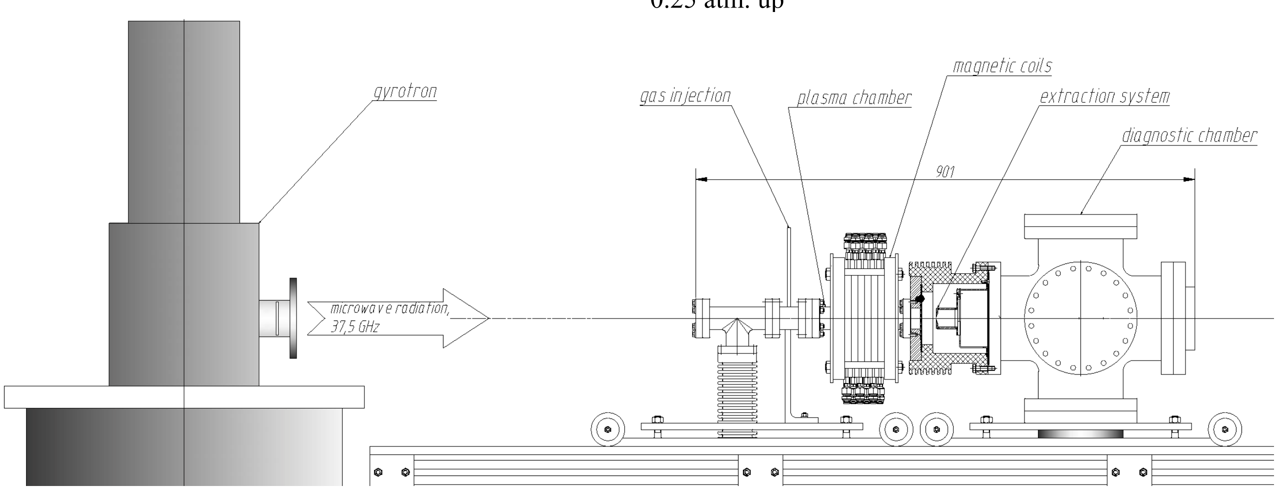


Figure 1: The experimental facility SMIS 37.

† shaposhnikov-roma@mail.ru

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP21

STUDY OF THE LEAD EVAPORATION FROM THE OVEN OF THE GTS-LHC ION SOURCE

T. Kövener[1 2 *], D. Küchler[1], V. Toivanen[3]

[1]European Organization for Nuclear Research (CERN), CH-1211 Geneva 23, Switzerland
[2]University of Hamburg, 20146 Hamburg, Germany
[3]Grand Accélérateur National d'Ions Lourds (GANIL), F-14076 Caen Cedex 5, France

Abstract

The GTS-LHC ECR ion source at CERN provides heavy ion beams for the chain of accelerators from Linac3 up to the LHC and the SPS fixed target experiments. During the standard operation the oven technique is used to insert lead into the source plasma to produce multiply charged lead ion beams. Many years of experience show that some of the source instabilities can be linked to the oven performance. The evaporation seems not to be constant and when the oven reaches its maximum power, an indication that a refill is required, often half of the original lead sample is still present inside the oven crucible.

A dedicated study of the oven using an offline test stand as well as thermal and gas dynamics simulations intends to help to identify the reasons for these experimental observations. The goal is to find design modifications to stabilize the evaporation rate and to prolong the oven runtime. This contribution presents the latest results of the study.

INTRODUCTION

At CERN a number of experiments, in particular the heavy ion runs at the Large Hadron Collider (LHC) rely on a consistent supply of lead ions delivered by the GTS-LHC ion source [1]. This source uses ovens (schematically depicted and described in Fig. 1 (a)) to produce the lead vapour which is then ionized. The produced ions are then injected into the LHC injector chain starting with Linac3. The oven technique is a widely used method to evaporate substances that are solid at room temperature into the plasma chamber of an ion source. The necessary temperature for such an oven depends on the vapour pressure of the evaporated material. Especially lead has a high gas pressure at relatively low temperatures, which makes the evaporation inside a heated oven a natural choice. During a normal run the oven's power is initially ramped up to a suitable value to initiate the lead evaporation and then it is increased slowly throughout the operation to maintain a sufficient evaporation rate. The adjustment is done manually by the source expert as the evaporation rate differs between individual oven fills. Reaching 20 W, which usually happens after two weeks of operation, indicates the end of the runtime as the oven does not maintain a stable evaporation rate any longer and the oven can not be heated up more without damaging the filament or other oven elements. The general experience though is, that after each run the oven crucible still contains approximately half of the original lead sample. This is an indication that there might be room to improve the oven runtime when it is understood what causes the drop of the evaporation rate.

To understand the limitation of the oven runtime and the link between input parameters and the evaporation rate, a dedicated offline oven test stand (OTS) is used, that provides several diagnostic tools to study the oven in a source like environment. Figure 1 (b) shows the main parts of the test stand. To monitor the evaporation rate of the oven, an INFICON quartz crystal deposition detector is used [2]. A shutter in front of the sensor that is only opened at predefined times protects the sensor and extends the crystal life time. Visual observations can be made through a vacuum window and K-type thermocouples allow temperature measurements on the outer cover of the oven.

BEHAVIOUR IN OXYGEN ATMOSPHERE

One candidate for a mechanism that limits the runtime of the oven is clogging. It is regularly observed after a two weeks run of the Linac3 ion source that the oven tip is clogged with a formation of material that appears to be lead oxide. As the GTS-LHC ion source uses oxygen as a buffer gas within the plasma chamber it can be assumed that the formation might be due to a chemical reaction between the lead and the oxygen. The oven test stand was used to reproduce and study this behaviour. The clogging was not observed during previous experiments in the OTS, when the oven was operated in vacuum ($< 1.0 \times 10^{-7}$ mbar), or in nitrogen. When oxygen is injected into the vacuum system, the formation of lead oxide is observed at the tip of the oven. A thermovalve controlled by a feedback loop from the vacuum gauge stabilized the total pressure inside the OTS at 1.0×10^{-5} mbar over the duration of the run. The oven was ramped to a sufficient evaporation rate, based on prior experiences on the test stand. During the measurement the oven power was then only adjusted when the signal on the deposition sensor dropped notably. Throughout the experiment the oven tip was photographed to document the formation of the blockage. Figure 2 shows the evaporation rate during the run together with four pictures of the oven tip taken at different times indicated in the plot. Mainly three characteristics could be observed:

- The evaporation rate at a constant power level is decreasing over time. To maintain a relatively constant

* toke.koevener@cern.ch

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP22

PRODUCTION OF INTENSE METAL ION BEAMS AT THE DC-60 CYCLOTRON

V.N. Loginov†, S.L. Bogomolov, A.E. Bondarchenko, V.E. Mironov,
Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia
V.V. Alexandrenko, I.A. Ivanov, M.V. Koloberdin, S.G. Kozin, A.E. Kurakhmedov,
D.A. Mustafin, E.K. Sambayev, M.V. Zdorovets,
Astana Branch of Institute of Nuclear Physics, 010000 Astana, Kazakhstan

Abstract

In 2017-2018, research program of the DC-60 cyclotron (Astana Branch of the Institute of Nuclear Physics, Kazakhstan) requests acceleration of intense ion beams of solid elements. Beams of B and Fe ions are produced in ECR ion source by using the volatile compounds, while ions of Li, Mg, P and Ca are produced by evaporation from an oven. Beams of $^{56}Fe^{10+}$, $^{7}Li^{1+}$, $^{24}Mg^{4+}$, $^{31}P^{5+}$, $^{40}Ca^{7+}$, and $^{11}B^{2+}$ ions were accelerated up to energies of 1.32-1.75 MeV/u.

INTRODUCTION

The DC-60 cyclotron [1] is designed for acceleration of ions from Li to Xe with A/Z in the range from 6 to 12. The accelerator is equipped with the normally-conducting 14-GHz DECRIS-3 ion source [2]. The main parameters of the source are: magnetic fields at the injection and extraction sides of the source are 1.3 and 1.1 T respectively, the hexapole field at the wall is 1.0 T, the source chamber length is 20 cm, and the chamber diameter is 6.4 cm. Microwaves are injected into the source through the coaxial waveguide along the source axis. The extraction voltage of the source is up to 25 kV.

We use three different methods for metal ion production: evaporation of material from container heated by microwaves in the source chamber, evaporation from a filament-heated oven, and injection into the source of volatile compounds that contain the desired atoms.

When producing ions of the solid elements, thin cylindrical tantalum sheet is inserted into the source chamber to facilitate atom recycling from the walls [3]. As a support gas, we always use helium, which was found to be the best choice for production of moderately charged ions requested by the DC-60 cyclotron.

EVAPORATION FROM OVEN

The upper temperature limit for our oven is 900 °C, which defines the range of working materials. The heating power is 25 W, the 0.1-mm diameter nichrome wire is used to heat the tantalum (standard) crucible (SC), with length of 28 mm, inner diameter 2 mm, outer diameter 2.8 mm. The oven is mounted on a movable holder inside the waveguide such that the orifice position can be regulated in the range (-15÷15) mm in respect to the edge of biased electrode.

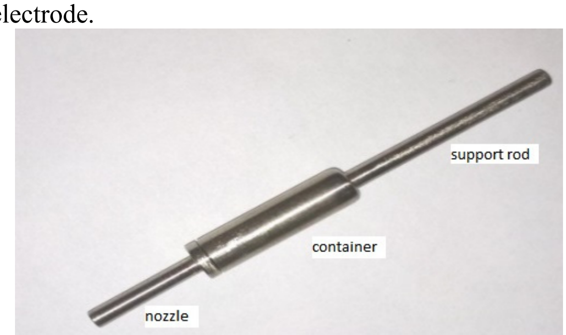


Figure 1: The large volume crucible.

To increase the oven's operational time, we use enlarged crucible (EC) for some materials. This crucible is presented in Fig. 1. The central cylinder contains the working material; inner diameter of the container is 6 mm, outer diameter is 7 mm, the container length is 20 mm. On one side, the container is connected to the solid rod heated by the filament; the rod has the same sizes as the standard crucible. Vapors leave the container through the 10-mm-long nozzle with the inner diameter of 1 mm. Twisted tantalum wire is pressurized inside the nozzle to shield the working material from the plasma and to prevent spilling of the melted material into the source chamber.

The nozzle and container are mainly heated by microwaves with some extra-heating by plasma. The crucible temperature is controlled by moving the holder in and out of the source chamber and by changing the filament current. Heating of the container from backside by filament is optional feature that gives additional control for adjusting the material evaporation rate.

Charge state distributions of the extracted Li ions are shown in Figs. 2 and 3 for enlarged crucible (Fig. 2) and for the standard crucible. Operational temperatures of the crucibles are 200 °C, and metal consumptions are 0.7 and 1.1 mg/h for EC and SC respectively, with the extracted Li^{1+} currents of 200 and 500 μA.

† loginov@jinr.ru

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP23

OPERATION OF THE GTS-LHC ECR ION SOURCE IN AFTERGLOW WITH VARYING KLYSTRON FREQUENCY

D. Küchler†, M. O'Neil
CERN, BE Department, CH-1211 Geneva, Switzerland
V. Toivanen
Grand Accélérateur National d'Ions Lourds (GANIL), F-14076 Caen Cedex 05, France

Abstract

The GTS-LHC ECR ion source delivers lead ions for the CERN heavy ion programme at the LHC and the SPS fixed target physics. The source is normally operated with a main microwave frequency of 14.5 GHz in the afterglow mode. As part of the consolidation the microwave generator was replaced with a klystron based generator that allows free variation of the operating frequency in a range of 14.0 – 14.5 GHz.

The aim of this study was to see how the lead charge state Pb^{29+}, which is the main ion species produced for experiments, is influenced by the different frequencies. Variations in performance were observed (beam intensity and beam stability), but no frequencies were found that would provide significant performance improvements compared to normal operation at 14.5 GHz. The results in general suggest that for the GTS-LHC ion source the optimal operating frequency depends on the overall source tuning and the influence of varying the main frequency is comparable to adjusting the other tuning parameters.

INTRODUCTION

The GTS-LHC ECR ion source is based on the original Grenoble Test Source (GTS) and provides since 2005 the CERN heavy ion injector complex with ions [1]. Over the last years the source has delivered lead, argon and xenon ions for the two main clients — the fixed target experiments in the North Area of the Super Proton Synchotron (SPS) and the experiments at the LHC.

The main 14.5 GHz microwave generator of the source was taken over from the predecessor source (ECR4) and was meanwhile more than 20 years old. As the old generator suffered from increasing failure rate and obsolete components it was decided to replace it within the CERN consolidation project.

Recent experiments with a travelling wave tube amplifier (TWTA) showed that for the lead ion of interest (Pb^{29+}) some increase of the beam intensity can be reached [2]. And as the frequency where this happens is covered by the new microwave generator it became of interest to study the ion beam production varying the frequency from the microwave generator and to see if a similar behaviour as with the TWTA can be reproduced. This would help to get a better understanding of the TWTA experimental results and in the positive case provide more beam for the users.

† detlef.kuchler@cern.ch

THE MICROWAVE GENERATOR

The spare generator of the source, which was used in the past for experiments with 18 GHz [3], was delivered by Sairem. To have only one provider for the source microwave generators it was decided to have also the new main generator from Sairem.

The new microwave generator has the following characteristics:

- Klystron based
- frequency range: 14.0 – 14.5 GHz
- number of Klystron channels: 20
- bandwidth of each Klystron channel: 25 MHz
- step size of the synthesizer: 1 kHz
- nominal peak power: 2.2 kW (for a matched load)
- operation mode: cw or pulsed (via external timing)

Table 1: Central Frequencies of the 20 Klystron Channels.

channel number	central frequency/GHz
1	14.0125
2	14.0375
3	14.0625
4	14.0875
5	14.1125
6	14.1375
7	14.1625
8	14.1875
9	14.2125
10	14.2375
11	14.2625
12	14.2875
13	14.3125
14	14.3375
15	14.3625
16	14.3875
17	14.4125
18	14.4375
19	14.4625
20	14.4875

The change of the Klystron channels is motorized and the synthesizer can be programmed via a USB interface from a Windows based computer.

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP25

STUDY OF THE INFLUENCE OF MAGNETIC FIELD PROFILE ON PLASMA PARAMETERS IN A SIMPLE MIRROR TRAP

M. Mazzaglia[1,†], G. Castro[1], D. Mascali[1], R. Miracoli[3], S. Briefi[2], U. Fantz[2], L. Celona[1], E. Naselli[1,4], R. Reitano[1,4], G. Torrisi[1] and S. Gammino[1]

[1] *INFN – Laboratori Nazionali del Sud, Catania, Italy*
[2] *Max-Planck-Institut fur Plasmaphysik, Garching, Germany*
[3] *ESS Bilbao, Zamudio, Spain*
[4] *Università degli studi di Catania, Catania, Italy*

Abstract

This work presents the multiple diagnostics characterization of the plasma in an axis-symmetric simple mirror trap as a function of magnetic field profile (mirror ratios and magnetic field gradient), especially in the quasi-flat B field configuration that is typical of Microwave Discharge Ion Sources, and also of neutral gas pressure and microwave power. The simultaneous use of Optical Emission Spectroscopy, Langmuir Probe and X-ray diagnostics allows the characterization of the whole electron energy distribution function (EEDF), from a few eV to hundreds of keV. Results show non-linear behaviour under small variations of even one source parameter and strong influence on EEDF of the B_{min}/B_{ECR} ratio. Benefit and next developments will be highlighted.

INTRODUCTION

Plasma diagnostics plays a crucial role for the development of high-performance ion sources for accelerators. A detailed knowledge of the electron energy distribution function (EEDF) is mandatory for any improvement of existing or future devices. For sake of compactness (mechanical constraints limit ECRIS ion source accessibility), historically only a limited number of diagnostics have been applied to ECRIS plasmas. Therefore, in most of the cases, plasma properties were only estimated from semi-empirical considerations. Over the last years, few groups have directly probed ECRIS plasma via diagnostics [1, 2, 3, 4]. Never performed in the past, multi-diagnostics allow to measure simultaneously plasma parameters in different energy domains. At LNS we plan to implement a multi-diagnostics system able to probe the plasma from RF to gamma-ray emission, performing space and time-resolved measurements. In this paper we present data already acquired in multi-diagnostics, at the Flexible Plasma Trap (FPT) test-bench [5], using at the same time Langmuir Probe (LP), optical Emission Spectroscopy (OES) and X-Ray spectroscopy. Despite the results have been obtained on a test-bench, the plasma trap emulates several features of existing ECRIS, and especially we hereby will focus the simple-mirror and Flat-B field configurations which is common in the field of Microwave Discharge Ion Sources for high current proton beams. The simultaneous use of these different diagnostics allowed to characterize the plasma parameters as a function of the applied external magnetic field, of microwave power and gas pressure.

† maria.mazzaglia@lns.infn.it

EXPERIMENTAL SETUP AND DIAGNOSTIC METHODS

Multi-diagnostics measurements have been carried out on the FPT, installed at INFN-LNS and described in [5]. Figure 1 shows a schematic diagram of the FPT, including the RF power injection system, the three magnetic coils, LP, OES and X-rays diagnostics.

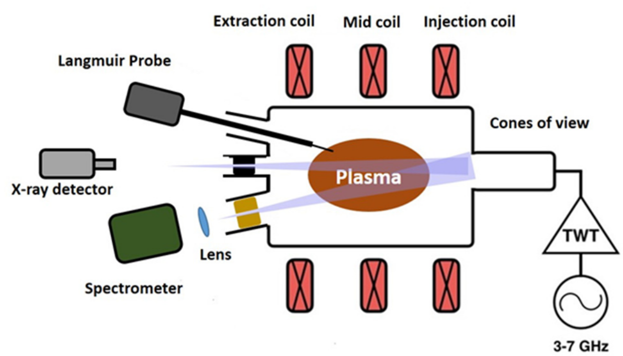


Figure 1: Schematic of the FPT experimental setup at the INFN-LNS.

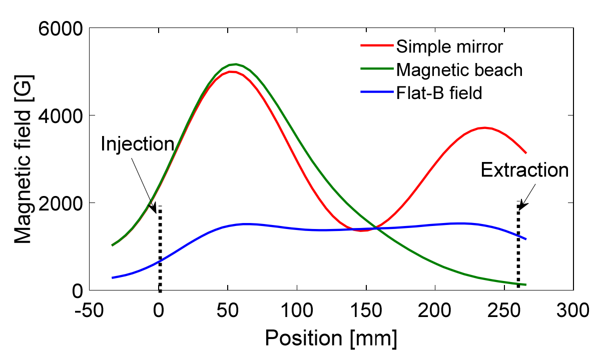


Figure 2: Magnetic field profiles that can be generated by the FPT.

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP26

A PARTICLE-IN-CELL/MONTE-CARLO-COLLISION CODE FOR THE SIMULATION OF A 2.45 GHz LITHIUM ECR ION SOURCE*

J. F. Zhang†, S. X. Peng, W. B. Wu, T. H. Ma, T. Zhang, J. M. Wen, Y. X. Jiang, Y. Xu, A. L. Zhang, J. Sun, H. T. Ren, Z. Y. Guo, J. E. Chen
State Key Laboratory of Nuclear Physics and Technology & Institue of Heavy Ion Physics, Peking University, 100871 Beijing, China

Abstract

A 2.45 GHz hybrid $^7Li^{3+}$ ion source has been designed at Peking University (PKU). In order to better understand the physical processes inside the hybrid lithium ion source, a Particle-in-Cell/Monte-Carlo-Collision (PIC/MCC) code is developed recently. In this model, the propagation of the 2.45 GHz microwave is processed using Finite-Difference Time-Domain (FDTD) method, and PIC and MCC method are used to handle the interaction of charged particles with electromagnetic field and collision process between particles, respectively. It can be used to simulate the motion of particles in single spatial dimension and three velocity dimensions, abbreviated as 1D3V. The validity of the PIC method has been confirmed by the simulation of two stream instability in this work. The preliminary simulation results show that the 2.45 GHz microwave energy can be absorbed effectively by electrons in the presence of an external magnetic field of 875 G. And the mirror magnetic field can increase the transverse velocities of electrons.

INTRODUCTION

To fulfil the requirement of the Compact Intense Fast NEutron Facility (CIFNEF) which is proposed by Peking University (PKU) and China Institute of Atomic Energy (CIAE), a 2.45 GHz hybrid ion source for the production of $^7Li^{3+}$ is designed [1]. Its schematic view is plotted in Fig. 1.

This hybrid $^7Li^{3+}$ ion source is composed of a hot surface ionizer and a 2.45 GHz microwave ion source. To get lithium vapour, an oven and a heater are used. In order to avoid the condensation of the lithium vapour, the transport pipeline and the liner are all adiabatic. The red boundary in Fig. 1 will be hot surface. Like other ECR ion source developed at PKU, a three-layer Al_2O_3 window plus a BN disc will be used to introduce the 2.45 GHz microwave into the plasma chamber. A minimum-B magnetic configuration generated by permanent magnets will be used to confine the plasma.

Electron Cyclotron Resonance (ECR) ion sources based on the minimum-B trap are efficient for the production of high charge state ions [2]. One of numerical models which paid more attention on the microwave in the ECR plasma was presented by Muta et al [3].

In Muta's model, a three-dimensional simulation of microwave propagation in an ECR plasma using finite-difference time-domain (FDTD) method has been presented. And the propagation characteristics of the microwave in an inhomogeneous plasma filled in a cylindrical chamber was investigated. In this work, ECR plasma was treated as an anisotropic, dispersive medium. Edgell et al developed a 1D spatially computer model for both electrons and multiple ion species in an ECR plasma [4].

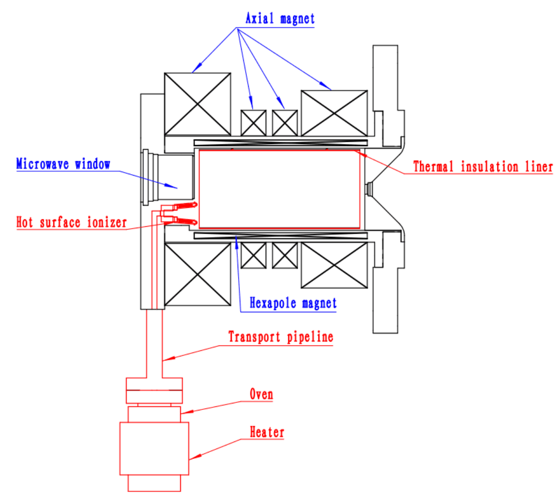


Figure 1: The schematic view of the structure of the $^7Li^{3+}$ ion source.

In that model, ECR heating was treated as a quasi-linear RF-diffusion term including relativistic detuning and RF pitch-angle scattering. Electrostatic models are also used in the simulation of ECR plasma. Dougar et al presented an electrostatic model with the use of an eight-point CIC schemes to simulate the plasma confinement in a minimum-B and a zero-B traps for ion source based on the ECR phenomenon [5]. In 2004, the group of Dougar developed a Particle-in-Cell (PIC) code to simulate the heating and escaping of plasma confined to the 14 GHz minimum-B magnetic trap [6]. The microwaves injected into the chamber were treated as a multimode standing waves regime. Although electromagnetic models are complex, they are close to the real conditions of ECR plasma. Koh et al studied the ECR microwave discharge using a 1D3V electromagnetic Particle-in-Cell Monte Carlo Collision (PIC/MCC) method [7]. In the model, the electric and magnetic fields were calculated

* Work supported by the National Natural Science Foundation of China (Grant No. 11775007 and No. 11575013).
† zhangjingfeng@pku.edu.cn

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-TUP27

NUMERICAL SIMULATIONS OF MAGNETICALLY CONFINED PLASMAS

A. Galatà*, C. S. Gallo, INFN-Laboratori Nazionali di Legnaro, (Padova), Italy
D. Mascali, G. Torrisi, INFN-Laboratori Nazionali del Sud, Catania, Italy

Abstract

Since 2012, the INFN ion source group has been undertaking an intense activity on numerical modelling of magnetically confined plasmas, presently carried out in the framework of the PANDORA project. The aim is the development of a predictive tool for the design of Electron Cyclotron Resonance (ECR) Ion Sources or Traps and ECR-based Charge Breeders, able to determine spatial density and energy distributions for both electrons and ions. The work mainly concerns the study of two aspects: on one hand, the interaction of an ion beam with a magnetized plasma; on the other hand, the microwave-to-plasma coupling, including the 3D plasma electrons dynamics in the confinement magnetic field and intra-particles collisions. This contribution describes the state-of-the-art of the work on both fronts: an overview of the beam-plasma interaction, the latest results about the ECR-plasma density fine structure, as well as electrons spatial temperature distribution will be shown.

INTRODUCTION

For the last years, the INFN ion source group has been focusing its research activity on the PANDORA (Plasmas for Astrophysics, Nuclear Decays Observation and Radiation for Archaeometry) project [1]. Its aim is a feasibility study of a new facility based on a state-of-the-art plasma trap confining extremely energetic plasma, to perform interdisciplinary research in the fields of nuclear astrophysics, astrophysics, plasma physics and applications in material science and archeometry. The plasma will become the environment for measuring, for the first time, nuclear decays rates in stellar-like conditions, in particular for ^{7}Be, as a function of the in-plasma ionization state. These studies are of paramount importance for addressing several astrophysical issues in both stellar and primordial nucleosynthesis environment (e.g. determination of solar neutrino flux and ^{7}Li Cosmological Problem). The design of the trap, and in particular its magnetic field, will be based on the "B-minimum" geometry typical of Electron Cyclotron Resonance (ECR) ion sources [2]: in such machines, a dense and hot plasma, made of multicharged ions immersed in a dense cloud of energetic electrons, is confined by multi-Tesla magnetic fields and resonantly heated by some kWs of microwave power in the 2.45–28 GHz frequency range. ^{7}Be will be injected inside the trap as a 1+ beam, using the well known ECR-based charge breeding technique [3], while its decay to ^{7}Li through electron capture will be tagged by detecting the 478 keV γ-ray emitted by the transition of ^{7}Li from the excited to the ground state (10% of branching ratio). In this framework, the efforts are mainly dedicated to two fundamental aspects: on one hand, the developement of a complete plasma diagnostic set-up able to detect plasma emission from the visible range to X-ray, in order to obtain spatially resolved ions and electrons density, as well as electrons temperature. Part of this work is presently carried out in collaboration with the Hungarian laboratory ATOMKI [4]. On the other hand, the development of an innovative numerical tool able to describe the interaction of the injected beam with the confined plasma, and also predict the plasma density and temperature fine structure, so as to maximize the injection and subsequent capture of the radioactive ions inside the trap. The paper will describe the state-of-the-art of the work on this last aspect: the results of the simulations of the beam-plasma interaction will be shown first, followed by the progresses made towards a plasma self-consistent description in terms of electrons density and temperature.

* alessio.galata@lnl.infn.it

THE BEAM-PLASMA INTERACTION

A mentioned before, radioactive species will be injected in the PANDORA trap by employing the charge breeding technique, widely used in Isotope Separation On Line (ISOL) facilities whose aim is the post-acceleration of radioactive ions for nuclear physics experiments. As in the case of the SPES project, under construction at INFN-LNL [5], the charge breeding within PANDORA will be ECR-based: with this technique, the radioactive species produced in the so-called target-ion source-system are extracted as a 1+ beam from dedicated sources, transported along electrostatic beam lines, decelerated to very low energies (in the eV range), and then injected into the Charge Breeder. Once inside the plasma, radioactive 1+ ions suffer a huge number of small angle elastic ion-ion collisions (the so-called Spitzer collisions [6]) that eventually lead to thermalization with plasma ions, and are then extracted as a highly charged ion beam after charge multiplication through step-by-step ionizations by energetic electrons. The INFN ion source group developed an innovative fully 3D numerical approach in a MatLab environment, able to reproduce the beam-plasma interaction and its subsequent ionization [7]. The code implements a formalism based on the Langevin equation [8] to describe the Spitzer collisions, while ionizations are calculated by using the Lotz formula [9] and included with a MonteCarlo approach. The validity of the code was demonstrated by reproducing two experimental results obtained with the PHOENIX Charge Breeder at the Laboratoire de Physique et de Cosmologie, by injecting sodium [10] and rubidium ions [7]. It also revealed to be very useful in understanding the influce of the injected beam parameters on the capture process, in particular the

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-WEA3

PLASMA INSTABILITY STUDIES OF THE SUSI 18 GHz SOURCE

Bryan Isherwood[†], Eduard Pozdeyev, Guillaume Machicoane, Jeffry Stetson, and Derek Neben
National Superconduction Cyclotron Laboratory, East Lansing, MI, USA
Facility for Rare Isotope Beams, East Lansing, MI, USA

Abstract

Instabilities in magnetized plasmas, such as the cyclotron instabilities identified at JYFL [1], can cause fast variations of the extracted Electron Cyclotron Resonance Ion Source (ECRIS) beam current. In order to understand the effect of the radial component and longitudinal gradient of the magnetic field on plasma stability a series of measurements has taken place using the Superconducting Source for Ions (SuSI) at the National Superconducting Cyclotron Laboratory (NSCL). We present here the results from investigations into the instability characteristics of the beam current from SuSI at 18 GHz by varying longitudinal and radial magnetic field profiles, injected microwave power, and bias disk voltage. Our investigation shows multiple regions of beam current variation within the magnetic field vs. power parameter space with multiple distinct modes of variance.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) and the National Superconducting Cyclotron Laboratory (NSCL) require intense, high charge state beams for normal facility operations. As a result, any limitation of the transmitted beam current can diminish the total operational capacity of the facilities. The limitation of the extracted beam current from ion sources operated at high magnetic field strengths is one such diminishing factor. Investigations into the limitations of Electron Cyclotron Resonance Ion Source (ECRIS) performance at the high-performance limit for high charge state extraction have made great strides in the last several years. In particular the studies out of Jyväskylä [1,2] and Nizhny Novgorod [3,4] have revealed that kinetic plasma microinstabilites, in the form of cyclotron instabilities, are a driving factor of these limitations.

These instabilities occur in local regions of the ECR plasma where the magnetic field induced temperature anisotropy heavily favors the transverse component of the hot (T > 10 keV) electron population, $T_{\perp} >> T_{\parallel}$ [1]. Those electrons can escape into the magnetic loss cone by depositing the energy stored in their gyro-motion into the background plasma in the form of microwave radiation [3,5]. The plasma, in response to suddenly losing part of its electron population, ejects part of its ion population until quasi-neutrality can be regained. At this point the heating process returns to its desired role of creating more ions until the degree of anisotropy requires the instability to be triggered. These events create the beam current oscillations that are observed in the extracted beam.

As reported in [2], a threshold has been measured for these instabilities to occur relative to the magnetic minimum and injected microwave power within the plasma chamber. This threshold measurement does not include two key features of the magnetic field structure: the radial field and the field's gradient at the resonance surface. An electromagnet hexapole coil is required in order to probe the former and the latter must be probed by an ECR with more than two longitudinal coils. Insight to the latter issue has been given by Benitez with her measurement of the spectral temperature in VENUS [6]. It was found that the spectral temperature of the plasma is independent of the axial gradient at resonance, while having a strong dependence on the minimum of the field structure. However, this measurement is incapable of distinguishing the degree of anisotropy of the electron population in the system. This limitation is due to its reliance upon a bremsstrahlung spectrum that carries no information on the anisotropy; leaving open an avenue for exploration into the field structures influence upon the ECR plasma characteristics.

We report here measurements into the effect of the hexapole and magnetic field structure upon the state of stability of the ECR plasma. Sweeping the injected microwave power across multiple magnetic field distributions revealed stability characteristics dependent on the field distribution rather than only the minimum value. Two potentially new instabilities were found and are named here as "fast" and "slow", for their repetition frequencies with respect to the previously mentioned cyclotron instabilities. An increasing hexapole was found to decrease the probability of finding a stable operating point in three of four experimental cases. X-ray measurements were also made in order to confirm that the hot electron population is the population predominately affected by the instabilities.

APPARATUS AND PROCEDURE

All measurements were taken using SuSI at the NSCL. The four superconducting solenoid coils and superconducting hexapole create its longitudinal and radial magnetic fields respectively [7]. The four solenoids coils allow us to create different magnetic field distributions with the same B_{min} but with different magnetic mirror ratios at injection and extraction; isolating the effect of the magnetic field distribution from its local minimum. Four sets of fields were used to explore the stability characteristics of the ECR plasma. Each set was designed to have a magnetic mirror ratio that was either larger or smaller than the standard operating field scaling laws [8], for both the injection and extraction sides of the

* Work supported by the National Science Foundation under NSF Grant 1632761
† Isherwoo@nscl.msu.edu

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-WEA4

TIME RESOLVED X-RAY MEASUREMENTS IN A SIMPLE MIRROR TRAP

S. Tudisco†, C. Altana, G. Castro, G. Lanzalone, G. Litrico, A. Muoio, L. Celona, S. Gammino, D. Mascali, M. Mazzaglia, G. Torrisi INFN-LNS, 95123 Catania, Italy
E. Naselli, INFN-LNS, 95123 Catania, Italy
Università degli Studi di Catania, 95123 Catania, Italy
R. Miracoli, ESS Bilbao, 48170 Zamudio, Spain

Abstract

The time-resolved characterization of the X-ray emission represents an innovative technique to investigate the heating mechanism of the worm/hot electron component in ECRIS devices. In this paper, the technique will be described and the results of an experimental campaign of measurements in order to characterize the X-rays emission of an axis-symmetric simple mirror trap will be showed.

INTRODUCTION

The Electron Cyclotron Resonance Ion Sources (ECRIS) are used to produce charged ion beams at high intensity characterized by high stability and high reliability for accelerators and others applications both in nuclear physics and industrial area. Over the years, many studies have been conducted to understand the scaling of plasma parameters as function of tuning parameters, such as pumping wave power and frequency and magnetic field profiles. In particular, it was observed that the B_{min}/B_{ECR} ratio, namely the gradient of the magnetic field, is one of the parameters that mainly generate instability and anisotropy in plasmas: a non-linear increase of X-ray fluxes has been observed.

In this work, we want to investigate the X-ray emission from the Flexible Plasma Trap (FTP) by means of a Hyper-Pure Germanium (HpGe) in time-resolved configuration.

EXPERIMENTAL SETUP

The FTP, designed, developed and installed at INFN-LNS, allows the plasma characterization. The chamber is a cylindrical water-cooled copper vessel with an inner diameter of about 82 mm and a length of 260 mm. The plasma chamber is connected with a stainless-steel made "pre-chamber" in order to host the vacuum system and the diagnostics tools.

The external magnetic field used for ECR heating and plasma confinement is generated by means of three solenoids which allow tuning the magnetic field in function of the frequency. In particular, a simple magnetic mirror, a constant B field along the axis of the cylindrical discharge vessel and a magnetic beach configuration can be generated by tuning the current flowing in the coils. In this work we focused on the investigation of the simple mirror, with varying B_{min}/B_{ECR} ratio. Moreover, FTP has three different microwaves system, one parallel and two perpendicular respect to the plasma chamber. Microwaves of axial injection are generated by a Travelling Wave Tube (TWT) operating in a range from 4 to 7 GHz. The perpendicular microwave launcher can work at 14 GHz and allow operating in double frequency (first and second frequency) mode [1]. Further information about the FPT can be found in reference [2].

The HpGe detector, located on the axial port of the vacuum chamber, as shown in Fig. 1, was used in order to investigate the X-ray emission from high energy electrons of the plasma or of those that hit the chamber walls.

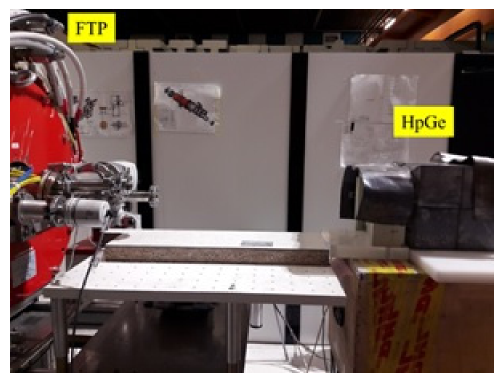


Figure 1: Experimental setup.

The HpGe consists of a 15 mm thick, 20 cm^2 detector that sits behind a 0.3 mm thick Be window. Its resolution at 122 keV is 0.61 keV. The detector is shielded with lead blocks of 2 cm thickness and ϕ= 1 mm to avoid detecting x-rays scattered from the environmental material. The HpGe detects the radiation that pass mostly through the collimator of the vacuum vessel.

The detector was connected, at the same time, at the acquisition system MultiChannel Analyzer (MCA) and at the oscilloscope. In order to allow the time resolved X-ray spectroscopy, by means of an external trigger, the plasma was "switched on" for a duration of 40 ms and then it was "switched off". In Fig. 2 is shown a typical signal obtained from oscilloscope.

† tudisco@lns.infn.it

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-WEA5

EFFECT OF THE TWO-CLOSE-FREQUENCY HEATING TO THE EXTRACTED ION BEAM AND TO THE X-RAY FLUX EMITTED BY THE ECR PLASMA

R. Rácz†, S. Biri, Z. Perduk, J. Pálinkás, Institute for Nuclear Research, Hungarian Academy of Sciences (Atomki), [H-4026] Debrecen, Hungary
D. Mascali, M. Mazzaglia, E. Naselli, G. Torrisi, G. Castro, L. Celona, S. Gammino, Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud (INFN-LNS), [95123] Catania, Italy
A. Galatà, Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro (INFN-LNL) [35020] Legnaro, Italy

Abstract

Multiple frequency heating has been used since the '90 in ECR ion sources as heating schemes able to improve current intensities especially for highly charged ions. More recently "Two Close Frequency Heating", where the frequency gap is comparable with the scale-length of the resonance, has been proposed, expected also to be sensitive to the relative waves' phase relationship. At ATOMKI – Debrecen a dedicated experiment has been carried out for exploring the effects of the combined frequencies and their relative phase-difference in an argon plasma. The second frequency was finely tuned between 13.6-14.6 GHz with respect to the first one (fixed 14.25 GHz). An optimal frequency gap (in terms of Ar^{11+}/Ar^{6+} beam currents ratios) has been experimentally found, in agreement with the theory; the optimal power balance (total RF power was 200 W) between the two frequencies has been determined empirically. A weak but clear effect of the relative phase shift has been observed. Each configuration has been characterized by a multi-diagnostics set-up: HPGe and SDD detectors were used for the X-rays, a RF probe was introduced inside the plasma chamber to detect the radio-emission from the plasma.

INTRODUCTION

Demand from the users of ion beams are continuously motivating the development of ion sources to produce as high current of highly charged ions as possible. Electron Cyclotron Resonance (ECR) Ion Sources (ECRIS) seem to be the best candidates to fulfil the strict requirements in terms of beam intensity, emittance, ion choice, stability, etc [1]. To obtain intense highly charged ion current the ions should be extracted from dense and energetic ECR plasma, having anisotropic distribution of the electrons in the velocity space.

General approach of the way for the improvement is pointed by the scaling laws [2]. Accordingly, higher plasma density is needed to produce higher charge state ions, which requires higher microwave heating power. However in order to still remain below the critical density (to avoid the cut-off of the microwaves), which is scaling with the frequency square the heating frequency and the corresponding magnetic field should be increased, as well.

Milestones in this way are symbolized by different generations of ECRISs. However, the steps between two generations are money- and time-consuming, requiring many investments from cryogenic and radiofrequency engineering sides. Therefore, at a given generation level (where the magnetic field and frequency configuration is determined) tricks were worked out to significantly improve the beam parameters without drastically changing the ECRIS configuration. They are widely applied in the ECRIS committee e.g. gas mixing [3], biased disc [4], fine frequency tuning [5], and two frequency heating [6].

Since the first half of the '90 multiple frequency heating has been tested and used as a technic which provides remarkable improvement of the ion source performance by improving the stability of the plasma and by shifting the ion charge state distribution toward the higher charge ones [7]. The first experiments providing promising results were performed applying two far frequencies (e.g. 10 GHz + 14 GHz, 14 GHz + 18 GHz) obtaining two well separated ECR heating zones (Two Far Frequency Heating (TFFH)). The effects were explained by the increase of the ECR heating volumes [8]. However, in 2008 Gammino at al. [9] pointed out a possible "extra" interplay between the two resonant zones having the two frequencies close to each other (Two Close Frequency Heating (TCFH)). Particularly, some kind of "electron surfing" is expected; the electrons that leave the first resonant zone may further accelerated by the second one (two close frequency is needed because the phase randomization of the electrons should not be occurred). The idea was confirmed by numerical simulations showing remarkable variation in electron energy as function of the relative phase difference between the two close frequencies.

Independently of the magnitude of the relative frequency difference (TCFH or TFFH) the importance of the fine tuning at least one of the two microwave frequencies was stated, since strong fluctuation of highly charged ions were obtained by slight tuning of the relative frequency difference [10, 11]. In case of TCFH mode the optimal effect was obtained when the distance between the two resonant layers were close to the Larmor radius of the warm electrons [10].

It was highlighted that the plasma stability and therefore the ion beam stability can be improved by adding an extra

† rracz@atomki.mta.hu

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-WEB1

SIMULATIONS OF ECRIS PERFORMANCE FOR DIFFERENT WORKING MATERIALS

V. Mironov*, S. Bogomolov, A. Bondarchenko, A. Efremov, K. Kuzmenkov, V. Loginov, Joint Institute for Nuclear Research, Flerov Laboratory of Nuclear Reactions, Dubna, Moscow Reg. 141980, Russia

Abstract

Free parameters of Numerical Advanced Model of ECRIS (NAM-ECRIS) are selected such as to reproduce the experimental charge-state-distribution of the extracted argon ions for the DECRIS-PM source tuned to produce the maximized Ar^{8+} currents. Using these fixed parameters, we calculate the extracted currents for Kr, Xe and Bi ions in mix with oxygen, for Ca in mix with helium, and for pure O and He plasmas. Comparison is made with the experimental data, good correspondence is observed.

INTRODUCTION

We had already applied our numerical model of ECRIS for studying several important aspects of the source operation [1, 2, 3]. Better understanding is obtained of the source reactions to changes in injected microwave power, gas flow and magnetic field profiles, of the gas-mixing, isotope anomaly, afterglow and others effects. As the next step, we calculate the extracted ion currents for variety of working elements injected into the DECRIS-PM source [4] (all-permanent magnet structure, 14.5 GHz microwave frequency).

The model is still not self-consistent in the sense that some of its parameters should be tuned in order to reproduce the experimentally measured ion currents. These parameters are connected to the unknown value of the microwave electric field at the ECR surface that defines the rate of electron heating and consequently the electron confinement time. As the experimental input we use the charge-state-distribution of argon ions for the source optimized to produce the moderately charged Ar^{8+} ions; at that, injected microwave power is close to maximum value available for the DECRIS-PM source, and the gas flow is relatively high. Selected set of the input parameters is then used for other injected gases and we check whether it is possible to reach a good correspondence with experiments.

BASIC FEATURES OF THE MODEL

The NAM-ECRIS model includes two separate modules that calculate electron (e) and ion (i) dynamics in the source. Ions are supposed to behave differently inside the relativistically broadened ECR zone and outside it: there is no electric field in the zone, ions are retarded by potential dip Δφ when crossing the resonance surface, and the presheath electric field accelerates ions if they are leaving the potential trap. To characterize the plasma, we calculate two parameters in NAM-ECRIS(i). The ion life time (τ_i) is defined as the ratio between the sum of ion electric charges inside the ECR zone and total electric current of ions toward the source chamber walls and into the extraction aperture. The total ion current is equal to the electron current because of charge neutrality of the plasma. After multiplying the current by mean energy of the lost electrons, we obtain the total power of microwaves coupled to the electron component of the plasma (P_c), neglecting small contributions from other power loss channels.

The averaged electron-ion scattering factor is defined as $\langle n_s \rangle = \sum_i \langle n_i \rangle Q_i^2$, where averaging of ion densities n_i with charge state Q_i is performed over the ECR volume. Spatially resolved array of the electron-ion scattering factors $n_s(x,y,z)$ is prepared by the ion module to be imported into the electron module NAM-ECRIS(e). Also, there are fixed the spatial coordinates of ionization events and ionization potential of the related parent particle (atom, molecule or ion).

The electron module traces movement of a large number of computational electrons in magnetic field of the source. Electrons are injected into the computational domain with initial energies that correspond to the ionization potential of the parent particle and with randomly oriented velocity vector. While bouncing along the source magnetic field lines, electrons experience kicks in the perpendicular direction whenever they cross the ECR surface; the kick's magnitude depends on the local magnetic field gradient, on the electron velocity and on the microwave electric field at the resonance, which is the free parameter in our model [2]. Among other factors, the microwave fields depend on the injected microwave power and on the wave absorption and reflection by the plasma. Our basic assumption is that for the fixed magnetic field profile, the microwave electric fields are the same in the plasmas with the same levels of the injected and of the coupled microwave powers.

Electrons are elastically scattered in electron-ion collisions as defined by the imported map of scattering factors. The scattering rate depends on the electron velocity as v_e^{-3}, and the probability for electrons to be scattered into the loss-cone is decreasing fast while electrons are heated. We define the electron life time τ_e in the similar manner as for ions. The global life time is inversely proportional to the averaged scattering factor and increases with increasing the velocity kick's magnitude. From the

* vemironov@jinr.ru

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-WEB2

PLASMA MODELIZATION AND STUDY FOR THE PHOENIX V3 ECR ION SOURCE

A. Leduc*, L. Maunoury, GANIL, 14000 Caen, France
T. Thuillier, Grenoble INP, LPSC-IN2P3, 38000 Grenoble, France

Abstract

In the framework of the Spiral2 project, the PHOENIX V3 Electron Cyclotron Resonance Ion Source (ECRIS) (upgraded version from the previous PHOENIX V2) has been developed to optimize the production of ion beams with charge over mass Q/A=1/3. The ion source aims to produce mainly metallic ions. For such beams, the atoms are, for a majority of them, trapped into the plasma wall of the plasma chamber leading to a poor global ionization efficiency. A hybrid particle in cells (PIC) code is under development to study and reproduce the experimental spectrum from ion source PHOENIX V3. The simulation is 3D and focuses on the propagation of the ion. The simulation have several free parameters to adjust the distribution of the ion charge stat at the exit of the ion source. The simulation has already given some encouraging preliminary results.

INTRODUCTION

For plasma modelization, like for the ion thruster, the simulation are done using Particle-In-Cell (PIC) code method. Traditional PIC codes propagate neutral atoms, ions, and electrons in electromagnetic fields. It also includes computation of collisions between particles (neutrals and charged) as well as the resolution of the Poisson equation to, dynamically, take into account the electric field generated by the charged particles. To be confident into the results coming up from the simulation, PIC code must meet specific conditions. The time step of the particles propagation must be less than half of the lowest chara-cteristic time. It is the same for the space discretization, which must be thin enough for the Poisson equation resolution.

In the case of a PIC code applied to an ECR ion source plasma, the characteristic time is the electron rotation period around a magnetic flux line while the Debye length defines the spatial mesh. The ECR ion source plasma contains high-energy electrons; the minimum time step is of the order of picosecond, and the Debye length about micrometer. The aims of the simulation is to reproduce the ionization evolution of charged particles in the ECR ion source for different species and magnetic configuration in order to understand their dynamics of with the final goal to improve the global ionization efficiency. It is necessary to simulate the ion source operation for a duration greater than one milli-second at least in order to reach the equilibrium of the plasma. Propagation of charged particles during a millisecond within these conditions would require too much computing time. It has been decided to approximate some.

HYPOTHESIS

To shrink the computing time, it is necessary to reduce the number of mathematical operations done by the simulation does, while meeting the Physics hypothesis.

Electron Simplification

The first assumption is to consider that the electrons, more energetic than the ions, adapt their movements to those of the ions. Hence, it is possible to increase the time step imposed to the simulation by a factor of one thousand but also to reduce the number of particles moving into the simulation.

As the electrons follow the ions, the major electric charged are screened, and the plasma in the ion source is globally neutral. The Poisson equation resolution is no longer needed and neither the ion source mesh with one micrometer side cell. The plasma neutrality and the screening effect of the charged particles involve the nonexistence of plasma sheath and extraction meniscus.

Macroparticles Method

The PHOENIX V3 ion source has a volume of 1.45 liters, and operates with a pressure of 10^{-7} millibar. A rough estimation gives 10^{10} particles. The simulation cannot handle as many particles. The neutral atoms and the ions are injected and propagated, as macroparticle for the simulation. The particle number, and at the same time the macroparticle number, is not constant during the simulation.

It's extremely tough to estimate what value of particles belonging to a macroparticles the system evolves. However, it is important that the macroparticle numberpresent in the simulation doesn't increase too much. For this, it is necessary to establish a maximum for the macroparticle value and modify the particle number per macroparticle during the simulation. The charge exchange involves two macroparticles, whose charges and species may differ. To maintain the global charge and keep an equal charge for the particles in the same macroparticle, all macroparticles must have the same weight. The macroparticles weight variation must hold the charge and the number of particles.

SIMULATION

Propagation in Magnetic Field

The ion source is immersed in a intense magnetic field. The use of the "Leap Frog" method with a magnetic field produces a particles energy divergence. Propagation of charged particles is done with the Boris method [1], and the neutral particles are propagated in a straight line to reduce the computation time. In addition to the magnetic field, some

* alexandre.leduc@ganil.fr

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-WEB4

PRACTICAL USE OF HIGH-TEMPERATURE OVEN FOR 28 GHz SUPERCONDUCTING ECR ION SOURCE AT RIKEN

J. Ohnishi†, Y. Higurashi, T. Nakagawa, RIKEN Nishina Center, 351-0198 Wako, Japan

Abstract

To accelerate uranium beams at the RI-beam Factory (RIBF) at RIKEN, U^{35+} ions are extracted from a 28 GHz superconducting ECR ion source by using a high-temperature oven. Our high-temperature oven uses a tungsten crucible, joule-heated with a large DC current. The crucible is heated to approximately 2000°C to achieve a UO_2 vapor pressure of 0.1–1 Pa. The high-temperature oven, which is being developed since 2013, was first used to operate the ion source for the RIBF experiments in the autumn of 2016 and was successfully operated for 34 consecutive days. The use of the high-temperature oven enables the extraction of higher intensity and more stable U^{35+} beams compared to the previous sputtering method. However, due to the vapor ejection hole of the crucible getting blocked, the beam time was interrupted in the autumn of 2017. The high-temperature oven was also used to produce high intensity vanadium beams in the 28 GHz ECR ion source. V^{13+} beams with a current of 100 μA or more were supplied to the beam time for experiments on super heavy element synthesis in 2018. This paper describes the crucible design and operation status of the high-temperature oven.

INTRODUCTION

Uranium beams are most frequently used for experiments on unstable nuclei at the RI-beam Factory. U^{35+} ions extracted from a 28 GHz superconducting ECR ion source (SC-ECRIS) [1, 2] are used for the acceleration of uranium beams. The current beam intensity supplied to the accelerators is 100–130 μA at the ion source. Previously, a sputtering method with a metal uranium rod was used in the ion source, but since 2013, we have begun to develop the high-temperature oven (HTO) method [3–5] and have practically used it for the beam time (BT) of RIBF since 2016. The HTO method makes it easier to increase the amount of vapor supplied to the plasma in an ion source and is more stable than the sputtering method. Therefore, the HTO method enables the increase of the extracted beam current. The HTO is also used to produce vanadium beams in the 28 GHz SC-ECRIS. Several production tests of V^{13+} have been made since Dec. 2016. Vanadium beams were first supplied to the BT in Jan. 2018 and experiments to synthesize the super-heavy element, whose atomic number is higher than 118, were conducted.

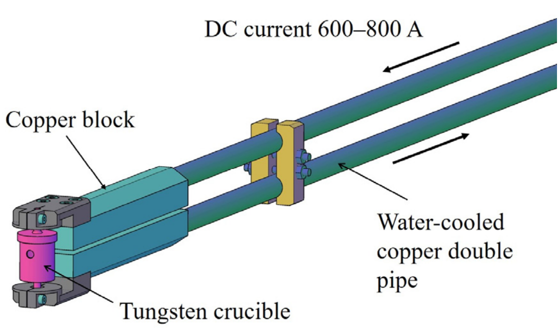
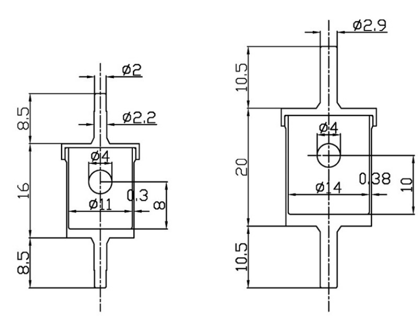


Figure 1: Schematic of the high-temperature oven.

HIGH-TEMPERATURE OVEN AND CRUCIBLE DESIGN

Figure 1 shows a schematic of the HTO. Our HTO uses a crucible of pure tungsten in which a high-melting-point material is loaded. The crucible is directly joule-heated with a DC current of 600–700 A to around 2000°C to achieve a vapor pressure of 0.1–1 Pa for uranium oxide. Figure 2 shows two shapes of a crucible (described later). The crucibles are made by machining a tungsten rod, with body and cap fitted but not fixed.

The crucible's shape is designed with ANSYS Multiphysics [6], which can perform electric, thermal, and structural analyses simultaneously. The analyses carried out were reported in Ref. [5]. The ANSYS calculations do not converge when the voltages of the upper and lower cupper blocks, given as a boundary conditions, are increased. This is because the electric current density in the upper and lower rods is too high and beyond a cooling limit. Therefore, we needed to optimize the radius of the upper and lower rods and the crucible's body thickness. Figures 2 (a) and 2 (b) show crucible shapes of the previous R345-type and the current R692-type, respectively. Since the R692-type had to be used for a long period of BT, the capacity was designed to be approximately twice as large as that of



(a) type R435 (previous) (b) type R692 (present)

Figure 2: Schematic of the tungsten crucibles.

† ohnishi@riken.jp

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-THA2

POINT-LIKE NEUTRON EMISSION OBSERVATION USING A NEUTRON GENERATOR BASED ON A GASDYNAMIC ECR ION SOURCE

R.A. Shaposhnikov, S.V. Golubev†, I.V. Izotov, R.L. Lapin, S.V. Razin, A.V. Sidorov, V.A. Skalyga, 603950 Nizhny Novgorod, Russian Federation

Abstract

One of the interesting applications of ECR ion sources is their use as a part of neutron generators. The use of high-current gasdynamic sources with plasma heating by high-frequency gyrotron radiation allows to increase neutron yield, and obtain a point-like neutron emission by sharp focusing of a high-quality deuterium ion beam on a target. Such point-like neutron source could perspective for neutron tomography. In the first experiments at tha SMIS 37 facility the high-current deuterium ion beam was focused by a simple magnetic coil (magnetic field strength up to 3 T) placed behind two-electrode extraction system on a titanium target saturated with deuterium. It was demonstrated that in such system a weakly descending 60 mA ion beam with the convergence of 50 could be focused in 1 mm spot resulting in $8\ \mathrm{A/cm^2}$ of current density at the focal plane. Measured neutron yield from the target placed in the focal region under conditions of the beam energy of 80 keV reached a value of 10^{10} neutrons per second in 1 ms pulse.

INTRODUCTION

Electron-cyclotron resonance (ECR) ion source is one of the most width spread types of systems that are designed to produce ion beams of multicharged ions or protons. One of directions of ion sources development is an increase of extracted ion beam current. The problem of the beam current increase is related to the problem of maximum attainable values of plasma density in a discharge. The solution of this problem can be based on the implementation of the gas-dynamic plasma confinement regime, which is characterized by a high plasma density and its low lifetime. Previous experiments conducted at the IAP RAS were aimed at investigating the possibility of proton beams formation from the ECR discharge in a simple mirror magnetic trap [1].

The experimentally obtained dependence of the ion beam current extracted through the 10 mm aperture on the extraction voltage demonstrated the possibility of obtaining current values up to 500 mA, which corresponds to a current density about $600\ \mathrm{mA/cm^2}$.

A pepper-pot method was used in a purpose to measure the ion beam emittance. This method has been described in detail in [2]. The results of measurements showed the possibility of obtaining beams with normalized emittance at the level of 0.05 pi · mm · mrad. Such a low value of emittance opens the possibility for effective focusing of the ion beam.

IBSimu code [3] was used for ion trajectories simulation in the field of magnetic focusing lens [4]. As a result of numerical simulation, the theoretical possibility of high-current ion beam focusing into a region of the order of 100 μm was demonstrated. The results of numerical calculations demonstrating the possibility of obtaining ion beams with small widths, as well as experimental data on obtaining high-current ion beams, open the possibility of creating a point-like neutron source based on the deuterium-deuterium synthesis reaction, which occurs when a focused beam of deuterium ions hits the deuterium containing target. There is an isotropic neutron emission from the target during the reaction. In this case, the characteristic size of the neutron source is determined by the quality of the ion beam and by the effectiveness of the focusing system.

The main application of the point-like neutron source could be neutron tomography [5].

EXPERIMENTS

Experiments aimed at producing the point-like neutron source were carried out at the SMIS 37 facility (Fig. 1). Gyrotron microwave radiation with a frequency of 37.5 GHz, power up to 100 kW and a pulse duration of 1.5 ms was used for plasma heating and discharge ignition. The plasma was created in a simple mirror magnetic trap operating in a pulsed mode with 0.1 Hz repetition rate. The use of powerful gyrotron radiation allowed to realize a gas-dynamic plasma confinement regime with the lifetime $\tau = \frac{R \cdot L}{2 \cdot V_S}$, where R is the mirror ratio, L is the length of the trap and V_S is the ion-sound speed. The operating gas (hydrogen) was inlet into the discharge chamber in pulsed mode along the axis of the magnetic system through a gas-entry system integrated into the electrodynamic system for microwave radiation injection. A two-electrode system consisting of a plasma electrode with a diameter of 10 mm and a puller electrode with a diameter of 22 mm was used in a purpose of ion beam extraction. The distance between electrodes was 15 mm. A magnetic coil which was used as the magnetic lens was placed behind the extraction system. It's magnetic field was regulated independently of the magnetic field of the trap (the magnetic field strength reached 3 T).

† gol@appl.sci-nnov.ru

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-THA4

DEVELOPMENT OF LECR4 ION SOURCE FOR INTENSE BEAM PRODUCTION AND LECR5 FOR SESRI PROJECT*

C. Qian†, L. T. Sun, W. Lu, Z. H. Jia, W. Huang, X. Fang, J. W. Guo, H. Wang, Y. Yang, Y. C. Feng, X. X. Li, X. Z. Zhang, Y. J. Yuan, H. W. Zhao, Institute of Modern Physics, CAS, 730000 Lanzhou, China

Abstract

Several intense highly charged heavy ion beams have been produced from Lanzhou ECR ion source No.4 (LECR4) since 2014. Recently an attempt to generate intense light ion beam was tested by High-B mode of LECR4 ion source. We firstly produced 8.72 emA of $^{4}He^{2+}$ beam with 1.7 kW of 18 GHz microwave power at 30 kV extraction voltage. According to the experience of LECR4. A new room temperature ECR ion source (named LECR5) has been designed to deliver multiple charge ion beams for the Space Environment Simulation Research Infrastructure (SESRI) at Harbin Institute of Technology. It aims to produce almost all ion beams from H_2^+ to $^{209}Bi^{32+}$. This article reviews the latest result of LECR4 and preliminary design of LECR5 in detail.

INTRODUCION

ECR Ion Sources are used to produce highly charge state ion beams of intermediate and heavy mass elements. They are widely used to produce ion beams for accelerators, atomic physics research and industrial applications. Some room temperature Electron Cyclotron Resonance ion sources (LECR1, LECR2 and LECR3) have been successively built at IMP [1, 2]. One unique feature of LECR4 is that the solenoid coils are fully immersed in a special me-dium and cooled by evaporative cooling technology when excited [3]. To satisfy the requirement of intense multi-charged ion beam, a research program named Space Envi-ronment Simulation and Research Infrastructure (SESRI). LECR5 was proposed in 2016. The traditional cooling technology that solid quadrate copper wire was used to wind the solenoid pancakes instead of hollow copper wire, which means it is high pressure de-ionized water free.

DEVLOPMENT OF LECR4

LECR4 is used for SSC-Linac injector at Institute of Modern Physics (IMP). The SSC-Linac consists of an ECR ion source, low energy beam transport (LEBT), a 4-rod RFQ, medium energy beam transport (MEBT) and IH-DTL, as shown in Fig. 1. LECR4 was redesigned from DRAGON concept in 2012. Its radial field at plasma cham-ber wall of 76 mm inner diameter is about ~1.0 T. LECR4 was built and started commissioning at 18 GHz in 2014. The source has successfully delivered H_2^+, O^{5+}, C^{4+}, O^{4+}+C^{3+}, Ar^{8+} and Bi^{30+} ion beams for RFQ and DTL com-missioning.

Heavy Ion Beam Production

Based on the original research of LECR4 M/Q selector, an updating selection system for LECR4 has been designed to handle the higher beam intensities. Figure 1 shows the schematic design of the new M/Q selection system. As the actual beam envelope and beam waist cannot be controlled with a single solenoid lens, an additional solenoid is introduced before the dipole magnet. To further study the production of very high charge state heavy ion beams, LECR4 was tested with bismuth by oven, the attempt to produce uranium ion beam by sputtering. Table1 shows some of the latest results from LECR4 and compares beam intensity with other high performance sources for reference [4]. The microwave power is less than 2.3 kW with operation frequency 18 GHz (beam intensity: eμA).

Table1. Latest Results of LECR4 at 18 GHz in Comparison With Other High Performance ECRIS

	Charge State	GTS	LECR4
^{16}O	6+	1950	2110
	7+		560
^{40}Ar	8+	1100	1717
	9+	920	1230
	11+	510	620
	12+	380	430
	14+	174	185
^{129}Xe	20+	310	430
	21+	274	320
	23+		275
	25+	244	215
	27+	168	135
^{209}Bi	28+		170
	29+		145
	31+		92
	32+		63
^{238}U	31+		35
	32+		30

* This work was supported by the NSFC (National Nature Science Foun-dation of China) research program with Contract No. 11427904
† qianc@impcas.ac.cn

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-THA5

GASDYNAMIC ECR ION SOURCE FOR NEGATIVE ION PRODUCTION

R. L. Lapin†, I. V. Izotov, V. A. Skalyga, S. V. Razin, R. A. Shaposhnikov, Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia
O. Tarvainen, University of Jyväskylä, Department of Physics, Jyväskylä, Finland

Abstract

H^- ion sources are needed in various areas of accelerator technology, such as beam injection into cyclotrons and storage rings and as a part of neutral beam injectors for plasma heating in experimental facilities studying thermonuclear fusion. It was recently demonstrated that gasdynamic ion source based on ECR discharge in a simple mirror trap is very efficient for proton beam production [1]. Here we use the gasdynamic plasma source as the first stage driver of volumetric negative ion production through dissociative electron attachment (DEA) [2]. Experiments were performed with a pulsed 37 GHz / up to 100 kW gyrotron radiation in a dual-trap magnetic system, which consists of two identical simple mirror traps. The first trap was used for the plasma production under ECR condition. Dense hydrogen plasma flux from the first trap flows into the second trap through a perforated plate, which prevented the propagation of microwaves into the second one. The configuration helps to separate plasma volumes with "hot" and "cold" electrons. We present recent experimental results on this topic. A negative ion current density of 80 mA/cm^2 through 1 mm plasma electrode was demonstrated.

INTRODUCTION

The first attempt to use a gasdynamic ECR discharge for a volumetric negative ion production was performed in 2017 [3]. It was shown that it is possible to achieve total negative ion current of 0.2 mA through 5 mm extraction aperture by optimizing the gas injection scheme, but with high level of impurities caused by residual water. In the present work we demonstrate results of the next stage experiments, in which measures have been taken to reduce the level of impurities.

EXPERIMENTAL SCHEME

We used 37 GHz / up to 100 kW gyrotron radiation for plasma production in a dual-trap simple mirror magnetic system (plug magnetic field ranging from 1 to 2.5 T). In the first trap the plasma was created under ECR condition. Dense hydrogen plasma flux from the first trap was allowed to flow into the second trap through a perforated conducting plate, acting as a microwave reflector preventing electron heating in the second trap. Presumably, that allowed to produce two electron fractions: "hot" electrons in the first chamber with the energy of about 50 – 100 eV and "cold" electrons in the second chamber, with the energy below 15 eV. The "hot" electrons effectively ionized the gas and excited high vibrational states of hydrogen molecules through excitation to B and C singlet states. These molecules then propagated into the second trap and produced H^- ions there as the result of dissociative electron attachment (DEA) with "cold" electrons. Such approach is similar to the one suggested in [4] where 2.45 GHz ECR discharge was used as a plasma cathode producing "hot" electrons. The scheme of the experimental facility is presented in Fig. 1. We used an extraction system consisting of plasma and puller electrodes to form a beam of negative particles and a magnetic filter made of two pairs of rectangular permanent magnets placed after the puller for electron dumping. Both magnet pairs produced a magnetic field transverse to the extracted beam and had the opposite magnetization directions to compensate each other's influence on the ion trajectories. In the first experiment we investigated the influence of the neutral gas injection scheme on the negative ion current. Various gas injection schemes were used: continuous, pulsed and their combination. The pulsed injection was realized with an electromagnetic valve connected to a buffer vessel with pressure of 0.05 - 1 bar.

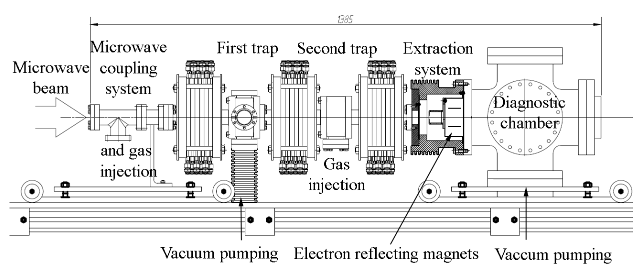


Figure 1: The scheme of the experimental facility.

Various diagnostic tools were used: a magnetostatic analyzer, a Faraday cup and a quadrupole mass spectrometer. The analyzer was used for the measurement of the ion beam spectrum, determination of the impurity level and investigation of the dependence of the H^- current on various parameters. The analyzer was used to measure the relative quantity of negative ions, as the significant beam line losses make absolute measurements obscure. Meanwhile, the Faraday cup placed right after the extraction system and electron deflection magnets was used for the measurement of the total current of negative ions. The quadrupole mass spectrometer was used in a diagnostic chamber to determine the composition of the injected gas.

* Work supported by Russian Science Foundation grant #-16-12-10343
† lapin@ipfran.ru

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-THC1

DEVELOPMENT OF 2.45 GHz ECR ION SOURCES AT IMP

Q. Wu[1,2,†], Y.G. Liu[1], J.L. Liu[1], H.Y. Ma[1], L.T. Sun[1], and H.W. Zhao[1], [1]Institute of Modern Physics (IMP), Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China,
[2]also at University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China

Abstract

The Ion Source Group at IMP has undertaken series of high intensity ion beam R&D projects. The first project is the development of the intense proton source and low energy beam (LEBT) for China Initiative Accelerator Driven Sub-Critical reactor (*CiADS*). The specific characteristics of the proton source are long term operation reliability and beam manipulation for the commissioning needs of the SRF accelerator. A low energy beam transport system is used to deliver 35 keV H^+ beam to the entrance of a 2.1 MeV RFQ. And then the 2.1 MeV proton beam is further accelerated by the superconducting cavities to 25 MeV and eventually goes into a high power beam dumper. The 2nd project is the development of the intense ion source for Jinping underground Nuclear Astrophysics experiments (JUNA). The ion source was requested to provide 10 emA H^+, 10 emA He^+ and 2.5 emA He^{2+} beams for the study of (p, γ), (p, α), (α, p) and(α, γ) reactions in the first phase of the JUNA project. The main challenges of ion source for JUNA project are production of intense He^{2+} beam, control of the beam contaminations and wide beam energy range（70~800keV）beam commissioning. Other projects mainly include the development of pulsed intense proton source and LEBT for Compact Pulsed Hadron Source (CPHS) at Tsing Hua university and the commissioning of an intense H_2^+ ion source. In this paper, the studies of this intense beam injector system, for instance, beam intensities, species and ratio, beam transmission efficiency in LEBT and also the beam matching to the downstream accelerator system will be presented.

INTRODUCTION

The Ion Source Group at IMP has undertaken series of high intensity ion beam R&D projects including development and operation of intense proton source for intense beam accelerators and special experimental platform. A project named China Initiative Accelerator Driven Sub-Critical (CiADS) was launched and begun construction in 2011 by Chinese Academy of Sciences[1-3] . The CiADS project mainly included superconducting Linac, a spallation target and beam line. The major target of superconducting linac is to demonstrate the key technologies of 10 mA CW beam of superducting front-end linac. As a key component of linac, the performance of ion source is very important. a 2.45GHz ECR ion source with the energy of 35 keV was developed to meet the requirements of superconducting linac. Next project named Jinping underground nuclear astrophysics (JUNA) project. Experimental investigations of such tiny reaction rates in laboratories at the earth's surface are hampered by the cosmic-ray back ground into detectors. Jinping Underground Laboratory for Nuclear Astrophysics is being constructed. The project need design of a 10mA, 400kV accelerator. Electron Cyclotron Resonance (ECR) ion source is selected to produce required ion beams such as H^+, He^+, He^{2+}. The 2.45 GHz ECR ion source has been proved to be able to produce very high beam currents and was successfully used in ADS at the Lanzhou Institute of Modern Physics [1]. Detailed reports on ion source and the elements of beam transport on the platform will be introduced in addition. In this paper, the status of ion source of CiADS project and development of JUNA project were present.

I. RUNNING STATUS OF THE INTENSE PROTON SOURCE FOR ADS LINAC

To produce the requested 10 mA proton beam for China Accelerator Driven Sub-Critical system(C-ADS) [2,3], electron cyclotron resonance (ECR) ion source operating at 2.45 GHz have been developed. As shown in Fig. 1, the cutaway view is the configuration of the proton source and extraction system. The proton source includes a waveguide, all-permanent magnet source body and discharge chamber. A dual-ridge waveguide is connected with the plasma chamber through the microwave window in order to couple microwave power efficiency. The plasma chamber was made of copper, which is 70 mm long and 54 mm in diameter. In order to obtain the small initial emittance, a diameter of 4 mm hole was designed to extraction proton beam. A 3-electrode extraction geometry was designed to extract the 20 mA, 35 keV ion beam. Meanwhile, in order to enhance the operation life of plasma electrode, the Molybdenum electrode with high temperature resistance was fabrication.

† wuq@impcas.ac.cn

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-THC2

DEVELOPMENT OF A TEST BENCH OF 2.45 GHz ECR ION SOURCE FOR RFQ ACCELERATOR

Sudhirsinh Vala†, Ratnesh Kumar, Mitul Abhangi, Rajesh Kumar and Mainak Bandyopadhyay,
Ins-titute for Plasma Research, 382428 Gandhinagar, India
also Homibhabha National Institute, 400094 Mumbai, India

Abstract

The optimization of beam quality at the entrance of a RFQ system requires a test bench for the optimization of the ion source and beam parameters. The aim of this test bench is to produce a 5 mA proton/deuterium beam with rms normalized emittances lower than *0.2 pi.mm.mrad* for the 5 MeV RFQ. This bench consists of an indigenously developed permanent magnet based 2.45GHz ECR ion source with three electrode ion extraction system and a LEBT to match the beam for the injection into the RFQ. The LEBT system has been designed using TRACEWIN© code. The LEBT parameters have been optimized in order to maximize the beam transmission through the RFQ.The ECR ion source test bench has been setup and operated up to 50 kV. The plasma parameters of the ECR ion source have been measured using optical emission spectroscopy system. The electron temperature and electron density are typically 3.6 eV to 1.3 eV and 1- 6 × 10^{19} m^{-3} at chamber pressure in the rang of 10^{-4} torr to 10^{-5} torr respectively. Deuterium ion beam of 9.8 mA is extracted from the test bench.This paper presents the design of the test bench, results of latest extracted ion beam and plasma parameters

INTRODUCTION

Institute for Plasma Research is developing a Radio Frequency Quadruple (RFQ) based 5-MeV accelerator facility for fusion material studies. The 5-MeV RFQ accelerator is mainly consist of an ECR ion source, a Low Energy Beam Transport (LEBT) system and a RFQ [1]. The low-energy transport between the ion source and the RFQ, is probably the utmost complex portion of any linear accelerator. LEBT plays an important role to transport the beam from ion source to RFQ as well as in matching the beam properties at the injection plane of the RFQ i.e., twiss parameters α_{Twiss}, β_{Twiss}, γ_{Twiss} and the emittance ε. The main objective of the development of this ECR Ion Source (ECRIS) test bench is to produce a 5 mA H+/D+ pulse/CW ion beam up to 50 keV energy with rms normalized emittance lower than 0.2 π•mm•mrad, as per the requirements of the RFQ accelerator. This paper presents development of the test bench setup, results of ion beam extraction and plasma parameters and the design of the LEBT system.

† sudhir@ipr.res.in

SETUP OF ECR ION SOURCE TEST BENCH

ECR ion source test bench consists indigenously developed 2.45 GHz ECR ion source followed by three electrode ion extraction system, Einzel lens, vacuum chamber, beam profile monitor, faraday cup and the control system. The photograph of the ECR ion source test bench is shown in Fig.1.

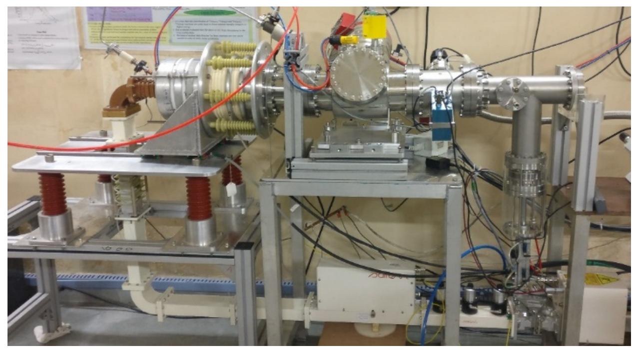


Figure 1: Experimental setup of ECR ion source test bench.

The ECR ion source is floated on a 50 kV high voltage platform. 50 kV HVDC isolation break is present between the ECR ion source and the 2.45 GHz microwave source system. 2.45 GHz microwave is transferred from the microwave source to the plasma chamber of the ECRIS through 3-stub tuner, 50 kV HVDC break, vacuum window, 90 degree bend and a 3-step ridge wave guide. Two 3mm Boron nitride disks are placed at the both end of the circular water cooled plasma chamber. One boron nitride disk at inlet side protects the microwave system from the back streaming electrons from the plasma and also provide the vacuum barrier between the plasma chamber and microwave system. The other disk, near the extraction side, covers the plasma electrode to avoid the high outgassing during plasma discharge [2]. To achieve the resonance magnetic field of 0.0875 T for 2.45 GHz frequency, three axially magnetized permanent NdFeB ring magnets are used. Each ring consists of 24 elementary NdFeB magnet of pre-defined shape and sizes [3-4].

To extract the high quality bright beam from the ECR ion source, a three electrode accel-decel system have been installed. In accel- decel extraction system, first plasma electrode placed at positive 50kV followed by accel electrode at the -2 kV and then decel electrode at ground potential.

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-THC4

DEVELOPMENT OF COMPACT 2.45 GHz ECR ION SOURCE FOR GENERATION OF SINGLY CHARGED IONS

S. L. Bogomolov†, A. E. Bondarchenko, A. A. Efremov, Yu. E. Kostyukhov, K. I. Kuzmenkov, V. N. Loginov, D. K. Pugachev, JINR, 141980, Dubna, Russia, R. D. Fatkullin, ITEP, 117218, Moscow, Russia

Abstract

2.45 GHz ECR ion sources are widely used for production of single charged heavy ions and secondary radioactive ion beams. This paper describes the development of a compact ECR ion source based on coaxial quarter wave resonator. The first results of extracted current measurements at different resonator configuration as a function of UHF frequency, power and gas flow are presented. At the extraction voltage about of 10 kV and UHF power about of 100 W more than 500 μA of He^+ ions were produced with the extraction hole of 3 mm in diameter that corresponds to the current density 7.5 mA/cm^2.

INTRODUCTION

Several ECR ion sources for production of radioactive ion beams operating at 2.45 GHz were developed at the FLNR JINR [1]. Such ion sources are used for production of $^6He^+$ ions in the DRIBs project [2] and at the MASHA mass-spectrometer [3]. The magnetic system of such sources is composed of NdFeB permanent magnet rings, and it provides the creation of pseudo-closed resonant surfaces (875 Gs). The plasma chamber of such sources is based on a single-mode cylindrical resonator with an internal diameter of 90 mm and a length of 100 mm. The measured gas efficiency of those sources is about 90% for noble gases (Ar, Kr). The transformation time of atoms into ions of this ion source has not been investigated yet, however, according to the results of paper [4], this time decreases with the decrease of the plasma chamber volume.

The volume of plasma chamber can be reduced if the chamber will be based on a coaxial resonator loaded with a capacitor. Pseudo-closed surfaces should be located in the gap of the capacitor to achieve optimum conditions for plasma confinement. In this paper we present the further investigations of the developed ion source [5].

DESIGN OF THE SOURCE

The magnetic system of the source is composed of a radially magnetized ring with an external diameter of 52 mm, an inner diameter of 22 mm and a thickness of 10 mm. The distribution of the magnetic field on the axis of the ring is shown in Fig. 1, the lines of an equal field are shown in Fig. 2. It can be seen that this magnetic system provides creation of pseudo-closed surfaces with a field level from 875 Gs up to 1750 Gs.

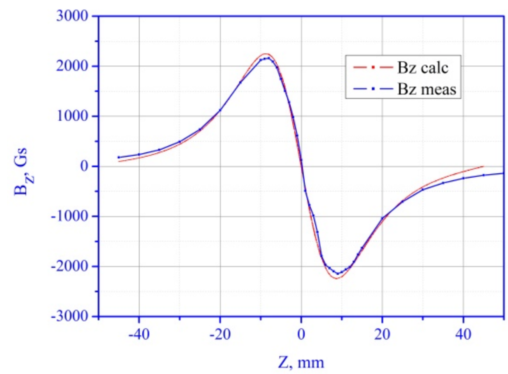


Figure 1: Axial magnetic field distribution of a ring magnet.

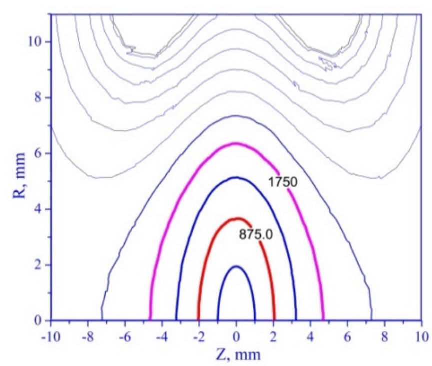


Figure 2: Magnetic field contour plot.

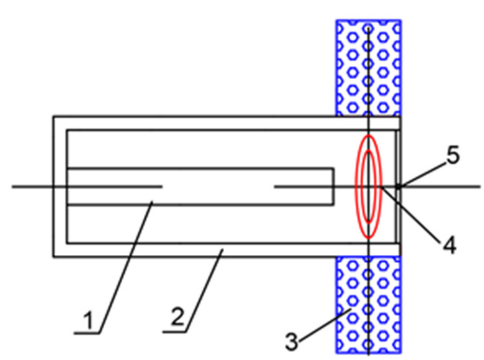


Figure 3: Schematic structure of the ECR ion source based on a coaxial resonator. 1 - central conductor of a coaxial resonator; 2 - resonator casing; 3 - magnetic

† sbogomolov@jinr.ru

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-FRA1

HIGH RESOLUTION SPECTROMETER DEVELOPMENT FOR USE IN ECR ION SOURCE*

R. Kronholm†, T. Kalvas, H. Koivisto and O. Tarvainen
University of Jyvaskylä, Jyvaskylä, Finland

Abstract

A high resolution spectrometer setup have been developed for optical emission spectroscopy of ECRIS plasmas. The spectrometer has been used in multiple studies with the JYFL 14 GHz ECRIS yielding new information on the low energy electron population and ion temperatures. This is a overview of the development process and recent studies.

INTRODUCTION

Electron cyclotron resonance ion sources (ECRIS) are under constant development, which motivates understanding the plasma properties. Therefore the ECRIS plasma is continuously studied, theoretically, numerically and experimentally. Experimental studies are usually complicated as the measurement setup easily affects the plasma and skew the results.

Spontaneous de-excitation of electronic states of atoms and molecules, present in Electron Cyclotron Resonance Ion Source (ECRIS) plasmas, enables studying them non-invasively through optical emission spectroscopy (OES). A high resolution spectrometer (10 pm FWHM at 632 nm) with phase-sensitive lock-in data acquisition setup has been developed at JYFL specifically for the diagnostics of weak emission lines characteristic to ECRIS plasmas.

PHYSICS BACKGROUND

In ECRIS plasma heating is based on energy transfer from microwaves to electrons via electron cyclotron resonance. This leads to wide electron energy distribution function, starting from cold electrons with a few eV energies up to hot electrons with energies on the order of 100 keV. Collisions between electrons and ions and neutral atoms results to energy transfer from free electrons to electrons bound to potential of the atomic nucleus. If the bound electron receives enough energy, ions are generated or the charge state of the ions is increased. This reaction is called electron impact ionization. In addition to ionization bound electron can be also excited to higher energy state. This reaction is called electron impact excitation. Excited electronic states can decay via radiative transition from higher energy state to lower energy states by emitting electromagnetic radiation. The wavelength of the emitted photon can be expressed as

$$\lambda = hc/(E_J - E_K), \quad (1)$$

where h is Planck constant, c is speed of light, E_J and E_K are energies of the higher and lower energy states, respectively. The intensity of emission is given by

$$I_\lambda = n_J A_{JK}, \quad (2)$$

where n_J is the electron density in energy state J and A_{JK} is the Einstein coefficient for the JK transition.

The wavelength spectrum of emitted light is a fingerprint of an element and therefore optical emission plasma spectroscopy can be used to identify particle species present in the plasma e.g. the impurity content. As the intensity of the emission depends on the ion density and electron energy distribution, the diagnostic can be used to study cold electron energies and relative ion densities [1]. Optical emission lines never have delta function profile ($\Delta\lambda > 0$). In addition to intensity and wavelength of the emission also the broadening of the emission line gives insight on fundamental plasma physics such as ion temperature, pressure, electric and magnetic fields.

MEASUREMENT SETUP

The optical emission spectroscopy setup has been developed mainly for use with the JYFL 14 GHz ECRIS [2]. Nevertheless, the system can easily be adapted to other ECR ion source. The JYFL 14 GHz ECRIS uses a minimum-B magnetic field configuration generated by two solenoid coils and a sextupole permanent magnet array. This magnetic field configuration and microwave plasma heating enables high charge state ion production. The primary heating frequency of the source is 14.1 GHz. The source allows monitoring optical emission both radially (between the magnetic poles) and axially (through an oven port). More information about the source can be found from Ref. [2].

In the case of heavy ion plasma, the number of emission lines in the visible light range is high, which requires a high resolution monochromator to separate individual radiative transitions. High resolution is also beneficial, if the interest is in emission line broadening. The intensity of the optical transition of interest can be very low and, therefore, a high optical throughput and good high signal-to-noise (SNR) is required. The developed OES setup of three main parts: The optical interface between the ion source and the spectrometer, the spectrometer and the data acquisition and control. The spectroscopy setup is described in Ref. [1] in detail.

CONDUCTED EXPERIMENTS

The development process of the high resolution spectrometer setup has been successful. The spectrometer setup is now free of "infant problems" and can be operated on regular

* Work supported by European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 654002.
† risto.j.kronholm@jyu.fi

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-FRA3

HIGH RESOLUTION SPECTROPOLARIMETRY: FROM ASTROPHYSICS TO ECR PLASMAS

M. Giarrusso†, S. Gammino, D. Mascali, M. Mazzaglia, E. Naselli[1], G. Castro, L. Celona,
INFN-Laboratori Nazionali del Sud, I95123 Catania, Italy
[1]also at Dip. di Fisica e Astronomia, Università degli Studi di Catania, I95123 Catania, Italy
G. Avila, European Southern Observatory, Munchen, Germany
G. Del Zanna, University of Cambridge, Cambridge, UK
E. Landi, University of Michigan, Ann Arbor, USA
M. Munari, INAF-Osservatorio Astrofisico di Catania, I95123 Catania, Italy
F. Leone[2], Dip. di Fisica e Astronomia, Università degli Studi di Catania, I95123 Catania, Italy
[2]also at INAF-Osservatorio Astrofisico di Catania, I95123 Catania, Italy

Abstract

Electron Cyclotron Resonance (ECR) plasmas with high density and high temperature are required by the injectors for the Accelerators and by interdisciplinary studies in Astrophysics and Nuclear Astrophysics. The magnetic traps need a very fine analysis of plasma conditions in terms of density, temperature and ionization state, not allowed by the present diagnostic methods (imaging, low resolution spectroscopy not spatially resolved).

We here describe the results routinely obtained in Astrophysics with high resolution spectroscopy, largely used to analyze astrophysical plasma in the visible range, which allows to determine physical parameters of stars as effective temperature, surface gravity, chemical abundances. In addition, we show that polarimetry is the only technique to derive the morphology of stellar magnetic fields, whose knowledge is necessary for a correct interpretation of spectra from magnetized plasmas. An application of these non-invasive methods to B-min ECR plasma concerning optical emission is discussed in view of a better comprehension of the plasma structure, magnetic confinement properties and heating processes.

INTRODUCTION

Intense beams of multiply charged ions are going to be a critical requirement for experiments in Nuclear Physics, Plasma Physics and Nuclear-Astrophysics. Most of ion sources are plasma-based, where the average charge state ($<q>$) and the current intensity (I_q) of the extracted beam depend on the electron density (n_e) and the ion confinement time (τ_q) as $<q> \propto n_e \tau_q$ and $I_q \propto \frac{n_e}{\tau_q}$. Among the sources that ensure a good compromise between charge state and current intensity there are the Electron Cyclotron Resonance Ion Sources (ECRIS, [1]) where the gas injected in a chamber is ionised by microwaves and confined by a Magneto-Hydro-Dynamic (MHD) stable B-min configuration. The ionization efficiency of these systems, producing high density ($n_e \sim 10^{10}$-10^{13} cm^{-3}) and high temperature ($T_e \sim$ 0.1-100 keV) plasma, depends on a not yet fully understood large number of parameters, and semi-empirical relations are adopted to optimize the extracted beam. According to the Geller's scaling laws [2] and the so-called "High-B mode" condition for the MHD stability [3], in order to improve the ECRIS performances we have to increase the magnetic field intensity and the microwave frequency. This trend is now limited by the rising costs and feasibility of magnets and RF generators, and a better comprehension of plasma formation and heating is therefore needed, to be performed by means of new diagnostic tools.

Present non-invasive techniques developed for plasma diagnostic range from X-ray to near infrared and are routinely based on imaging and spectroscopy. Anyway these methods are able to characterize plasma electrons, as for the X spectral range (see, e.g., [4,5]).

Not so much information is instead available concerning the ions. In addition, the ion confinement optimization, affected by the still not fully explained gas-mixing effect [6], requires a complete control of cold electrons displacement which is inaccessible by X-ray diagnostics. As to the visible spectral range, low resolution (an arbitrary boundary could be placed at $R = \lambda/\Delta\lambda < 40000$) Optical Emission Spectroscopy (OES) is commonly carried out with the aim to determine electron temperatures and densities as well as to obtain information about atomic and molecular populations by means of the line-ratio method (see e.g. [7]).

* Work supported by 5th Nat. Comm. of INFN under the grants MAPS_3D and PANDORA
† marina.giarrusso@lns.infn.it

ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-FRB2

IMPACT OF THE TWO CLOSE FREQUENCY HEATING ON ECRIS PLASMAS STABILITY

E. Naselli †[1], D. Mascali, M. Mazzaglia, G. Torrisi, G. Castro, L. Celona, S. Gammino, F.P. Romano[2], C. Caliri, Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud (INFN-LNS), 95123 Catania, Italy

[1]also at Department of Physics and Astronomy, University of Catania, Via Santa Sofia, 64, 95123 Catania, Italy

[2]also at CNR-Istituto per i Beni Archeologici e Monumentali, Catania, Italy

R. Rácz, S. Biri, Z. Perduk, J. Pálinkás, Institute for Nuclear Research, Hungarian Academy of Sciences (Atomki), H-4026 Debrecen, Hungary

A. Galatà, Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro (INFN-LNL) 35020 Legnaro, Italy

Abstract

Several experiments have recently demonstrated that plasma instabilities are powerful limiting factors to the flux of highly charged ion beam extracted from ECRIS. One of the methods for damping the instabilities is to feed the plasma in two frequency heating mode. Since the fundamental physical mechanism is still unclear (diffusion in velocity space? additional confinement?), a deeper experimental investigation is necessary, using multi-diagnostics setups. At ATOMKI-Debrecen the effect on the plasma instabilities of an argon plasma in a “Two Close Frequencies” scheme has been explored. Spectra of radio-emission from the plasma have been collected for different frequency gaps and relative power balances. The measurements show the plasma self-emitted radiation comes out from the internal plasma (i.e. around the lower frequency) but the instability damping can be effective for some specific combinations of frequency-gap and power balance. Radiofrequency spectra have been collected simultaneously produced by the instabilities and detected via a microwave diode connected to a plasma-chamber-immersed multi-pin RF probe.

INTRODUCTION

Electron Cyclotron Resonance Ion Sources (ECRIS) are able to produce beams of highly charged ions with high intensity and stability, which are necessary for accelerators, in applied and nuclear physics research.

In order to produce these beams, continuous improvements of the performances of ECR ion sources are needed. For many years these improvements consisted principally in the use of higher power of RF wave heating, and more intense magnetic field, on the basis of the “scaling laws” [1]. More recently, this approach has become more difficult because of the technological limits.

A deeper knowledge of plasma parameters (electron density, temperature and charge state distribution CSD) is thus fundamental: characteristics of the extracted beam (in terms of current intensity and production of high charge states) are directly connected with plasma parameters and structure.

Several experiments have in fact demonstrated that plasma instabilities limit the flux of highly charged ions extracted from ECR ion sources, causing beam ripple, as well [2]. The instability threshold depends principally from the strength of the magnetic field in terms of B_{min}/B_{ECR} and from other parameters as RF pumping power and pressure [3]. Even if many studies have been done, the exact mechanism of turbulent regimes of plasmas is still unknown and a deeper investigation is so necessary.

Plasma kinetic instabilities are characterized by fast RF and X-ray bursts causing performance deterioration of the ECRIS; to overcome this limitation more studies aiming at characterizing in detail this still unknown process and at finding a way for damping the turbulence are required. Some indications say that a key role for damping turbulences may be played by the Two Close Frequency Heating (TCFH).

In this work the experiment that has been done at ATOMKI, Debrecen (Hungary), is presented, where stable and unstable ECR plasmas in a B-min magnetic configuration have been characterized through a multi-diagnostic setup. The characterization has been carried out for the first time in Two Close Frequency Heating (TCFH) mode, through the use of two frequencies with a gap difference of the order of some hundreds of MHz.

It is well known that when the plasma is excited in double (far or close) frequencies, it is possible to observe improvements in the characteristics of the extracted beam. This process is still unknown in detail and here some experimental evidences regarding how the TCFH is able to damp instabilities are presented. Evidences of an increase of the electron confinement inside the “plasmoid region” can be argued from the experimental results.

† eugenia.naselli@lns.infn.it