SECRAL STATUS AND FIRST BEAM TEST AT 24GHZ

H. W. Zhao, W. Lu[1], L. T. Sun, X. H. Guo, X. Z. Zhang, Y. Cao, H. Y. Zhao,
Y.C.Feng, J. Y. Li, D. Z. Xie[2]
Institute of Modern Physics (IMP), Chinese Academy of Sciences, Lanzhou 730000
People's Republic of China

Abstract

SECRAL (Superconducting ECR ion source with Advanced design in Lanzhou) has been in routine operation at 18GHz for HIRFL (Heavy Ion Research Facility in Lanzhou) accelerator complex since May 2007. It has delivered a few highly charged heavy ion beams for the HIRFL accelerator and the total beam time so far has exceeded 3500 hours. To further enhance the SECRAL performance, a 24GHz/7kW gyrotron microwave amplifier has been installed and tested. Very exciting results were produced with quite a few new record highly-charged ion beam intensities. The latest results and reliable long-term operation for the accelerator have once again demonstrated that SECRAL is one of the best performance ECR ion source for the production of highly-charged heavy ion beams.

INTRODUCTION

SECRAL (Superconducting ECR ion source with Advanced design in Lanzhou) is a fully superconducting compact ECR ion source designed to operate at microwave frequency at 18-28GHz, which is dedicated for highly charged heavy ion beam production. SECRAL with an innovative superconducting magnet structure of solenoids-inside-sextupole [1-2], is different from all existing or under development high-magnetic-field superconducting ECR ion sources which utilize the conventional ECR magnetic structure of sextupole-inside-solenoids. The commissioning of the SECRAL at 18 GHz in 2006 and the experiments with double-frequency (18+14.5 GHz) heating in 2008 had yielded many world record ion beam intensities [2-3]. All these results and reliable operation have demonstrated that SECRAL performance at lower frequency is comparable or even better than those ECR ion sources operating at higher frequency of 28 GHz. To further enhance the performance of SECRAL and produce more intense highly charged heavy ion beams, a 24GHz/7kW gyrotron microwave generator was installed and SECRAL was tested at 24GHz. Some promising and exciting results at 24GHz with new record highly charged ion beam intensities were produced although the commissioning time was limited within a few weeks and RF power only 3-5kW. Bremstrahlung measurements at 24GHz have shown that X-ray is much stronger at higher RF frequency, higher RF power and higher minimum B field. An additional cryostat with five GM cryocoolers was installed at the SECRAL top to liquefy the boil-off helium gas to minimize the liquid helium consumption. The detailed results and the new development achieved at SECRAL in the past two years will be presented in this article.

SECRAL PRELIMINARY TEST RESULTS AT 24GHZ/3-5KW

To further enhance the SECRAL performance in production of highly charged heavy ion beams, finally a 24GHz gyrotron system with maximum output power 7 kW was chosen and installed. The SECRAL excellent results at 18+14.5 GHz double frequency heating for highly charged heavy ion beam production have convinced us that the best performance for SECRAL should be achieved at 24+18 GHz double frequency heating. The reason to choose 24GHz instead of 28GHz is that it is more difficult to compromise the magnetic field distribution for 28+18 GHz double frequency heating because the frequency difference is larger than that of 24+18 GHz. SECRAL does not need to couple very high RF power to reach the best performance because of its smaller plasma chamber, so 5-6 kW operational power is quite enough. The 24GHz transmission line and RF coupling system to SECRAL is similar to that developed at SERSE source [4-5]. The 24GHz transmission line from the gyrotron cabinet to the SECRAL source consists of arc detector, directional coupler, polarizer, mode convertor from T_{02} to T_{01}, mode filter, compensator, DC-breaker, 90-degree corrugated bend and bore-nitride microwave window, as shown in Fig.1. All components at the transmission line are water cooled and designed as compact as possible. The 24GHz microwave is coupled into the SECRAL source through the oversized waveguide WRC621D14. The 24GHz gyrotron system and all components at the transmission line were manufactured by Russia GYCOM.

The first beam tests at 24GHz were conducted in August 2009 with a stainless steel chamber in order to have quite stable beam. The beam commissioning has focused on Argon and Xenon beam production. The source extraction voltage was limited to 22kV due to the DC-breaker problem and the output power from the gyrotron system was limited to 5 kW due to problem of the high voltage power supply for the gyrotron cathode. The SECRAL magnet was set at 90%-95% of the maximum design field during 24 GHz beam tests in terms of the optimized beam and charge state, typically the axial injection field from 3.3 Tesla to 3.5 Tesla and the radial sextupole field at the chamber wall from 1.65 Tesla to 1.75 Tesla. The source conditioning at 24GHz was

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[1] Also of the Graduate School of CAS.

[2] IMP visiting scientist.

INTENSE BEAM PRODUCTION WITH SUSI

L. T. Sun*, J. Brandon, D. Cole, M. Doleans, D. Morris, G. Machicoane, E. Pozdeyev, T. Ropponen,
L. Tobos, National Superconducting Cyclotron Lab, MSU, East Lansing, MI 48824, USA

Abstract

SuSI ion source, a 3rd generation fully superconducting ECR ion source is now used for ion beam injection to the Coupled Cyclotron Facility since September 2009. Initial performances during the commissioning of SuSI (Superconducting Source for Ions) were mainly limited by the microwave power available from a single 18 GHz microwave amplifier, especially for the production of heavier ion beams. The Injection of SuSI was modified to add a second 18 GHz amplifier, to reach a maximum of 3.0 kW of RF power inside the plasma chamber. Production of heavy ion beams, such as Kr^{14+}, Bi^{30+} and U^{33+} is reported, to demonstrate the performance of SuSI. Additional studies were made with various ion source parameters to optimize the beam intensity within a normalized emittance of 0.9pi.mm.mrad as needed for the FRIB project and will be reported in this paper.

INTRODUCTION

As one of the latest developed fully superconducting electron cyclotron resonance ion sources (ECRIS) in the world, SuSI has been used for ion beam injection to the Couple Cyclotron Facility (CCF) since October 2009. Several ECRISs have been used for NSCL cyclotron operation, such as the 6.4 GHz SC-ECR [1] and the 14.5 GHz ARTEMIS [2]. The beam power available from CCF has steadily improved over the last few years due to an ongoing effort to improve both the performances of the ion source and the beam transport in the K500 injection line. But to further improve the performance of the coupled cyclotron facility (CCF), especially for heavy ion beams, a more powerful ion source that can produce more intense heavy ion beams with good beam quality is needed. In order to replace the aging 6.4 GHz ECR ion source, a new fully superconducting ECRIS SuSI was designed [3]. The source was completed and put into commissioning in early 2007 [4]. After some training of the superconducting coils, SuSI commissioning continued using an 18 GHz and a 14 GHz transmitter. Early results with gas and metallic beams showed that SuSI could produce high intensity of medium charge states of light to heavy ion beams [5]. In order to limit the beam transverse emittance propagating into the K500 injection line, a collimation scheme was developed and successfuly tested. In the summer 2009, SuSI was successfuly connected to the K500 cyclotron and put into operation since then. SuSI has now provided more than 1200 hours of operation to the CCF. Both gaseous and metallic ion beams have been produced, and good reliability and stability has been demonstrated. As a fully superconducting ECRIS with many flexibilities, SuSI has been used for basic ECRIS studies [6], beam developments and FRIB project R&D [7]. After a brief description of the new test setup of SuSI ion source, the latest results from SuSI will be presented.

SUSI ION SOURCE UPGRADES

Several components of SuSI have been upgraded. In particular a New18GHz klystron amplifier has replaced the 14.5GHz klystron amplifier. This configuration provides a maximum 18GHz microwave power of ~3.0 kW. Also, at the outer surface of the plasma chamber, a 2mm thickness tantalum tube has been added to shield the strong bremsstrahlung radiation to protect the high voltage insulator from degradation. The high voltage insulator is a PEEK material tube that has much higher radiation tolerance than the acrylic tube used previously.

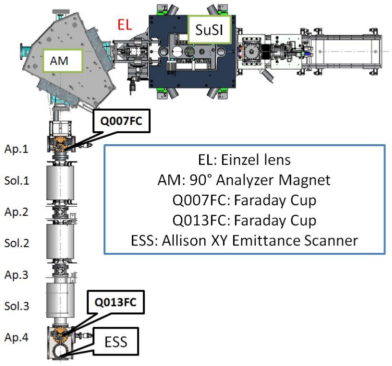

Figure 1: Layout plot of SuSI beam line.

Extracted beam is focused by an EINZEL lens with maximum operational voltage up to -30kV (negative voltage is proved with SuSI to give better ion beam transmission than that positive voltage can do, especially for intense beam transmission) and then analyzed by a 180mm gap 90° double focusing dipole magnet. Analyzed beam is detected by the faraday cup Q007FC with a 4-jaw slit in front of it. Past experience has showed that tuning the ion source for maximum intensity at this location may results in poor transmission through CCF. For example, large transverse emittance can lead to beam losses in the K500 cyclotron. Therefore, after the first analyzing faraday cup Q007FC, the SuSI beam line has been equipped with a setup to provide transverse collimation to the ion beam. The collimation is done by successive sets of apertures that cut the beam in transverse directions. A solenoid between every 2 apertures provides a possibility to do a rotation of the beam in phase space. Due to constraints in the space available, the collimation channel was designed to include four sets of slits and 3 solenoids. A drift space between each solenoid and each aperture is also included. The acceptance of the channel in the transverse direction is set by the size of the apertures. All the beam particles outside the acceptance of the collimation channel will be lost. 2 sets of steering

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*sunl@nscl.msu.edu

STATUS OF RIKEN SC-ECRIS

T. Nakagawa[#], Y. Higurashi, J. Ohnishi, RIKEN, Hirosawa 2-1, Wako, Saitama 351-0198, Japan
T. Aihara, M. Tamura, SAS, Ohsaki 1-17-6, Shinagawa, Tokyo 141-0032, Japan.

Abstract

To increase the beam intensity of highly charged heavy ions for RIKEN RIBF project, we constructed and tested the RIKEN new SC-ECRIS. After producing the first beam in the spring of 2009, we tried to optimize the ion source condition for maximizing the beam intensity with 18GHz microwave. We observed that the gentler field gradient and lager ECR zone size give higher beam intensity. Based on these studies, we produced 550µA of Ar^{11+} and 350µA of Ar^{12+} at the RF power of 1.8kW. In this summer, we will try use the 28GHz microwave to increase the beam intensity.

INTRODUCTION

Since middle of the 1990s, RIKEN has undertaken construction of new accelerator facility so-called Radio Isotope Beam Factory (RIBF) [1] and successfully produced 345MeV/u U beam (~0.4pnA on target) in 2008[2]. Using it, more than 40 new isotopes were produced with the in-flight fission reactions for only 4 days experiment.[3] It is clear that the intense U beam is strong tool to produce new isotopes in the region of medium mass nuclei and to study the mechanisms of the r-process in nuclear synthesis. For these reasons, the intense U beam is strongly demanded. To meet the requirement, we started to construct the new superconducting ECR ion source (SC-ECRIS) which has an optimum magnetic field strength for the operational microwave frequency of 28 GHz in the summer of 2007. In the end of 2008, we obtained the 102% of the designed value for the magnetic field strength. In the spring of 2009, SC-ECRIS produced first beam with 18GHz microwaves. Till now, we made various test experiments to increase the beam intensity of highly charged heavy ions with 18 GHz microwave [4].

In this article, we present the structure of the new ion source, new experimental results and the future plan to meet the requirements.

SC-ECRIS

The detailed structure of the ion source was described in refs [4, 5]. Schematic drawing of the Sc-coils is shown in Fig.1. For operation of 28GHz microwave, the B_{inj}, B_{ext} and B_{r} are 3.8, 2.2 and 2.2T, respectively. The main feature of the ion source is that it has six solenoid coils for producing magnetic mirror for the axial direction. Using this configuration, one can change the magnetic field gradient and ECR zone size independently. This magnetic system allows us to produce “conventional B_{min} “and so-called “flat B_{min}” [6] configurations. For keeping the superconductivity, the cryostat is equipped with three small GM refrigerators with 4 K, 20K and 70 K stages and operated without supplying liquid He after poured once. Amount of the liquid-He in the cryostat is ~500 L. The nine current leads made of high temperature superconducting material are used to minimize the heat load to 4 K stage. The heat load to 70 K stage is 123 W caused by copper current leads, supports of a cold mass and radiation through the multi-layer insulation. In the winter of 2009, we installed one GM-JT refrigerator, which have total cooling power of 5W at 4K, to increase the cooling power.

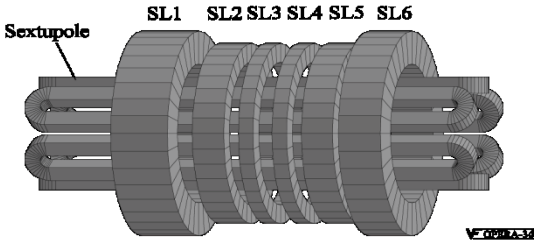

Figure 1: Schematic drawing of the Sc-coils.

EXPERIMENTAL RESULTS

The one of the strong interests for increasing the beam intensity of highly charged heavy ions are the effect of the resonance surface size and field gradient at ECR zone. As described in the previous section, the ion source has six solenoid coils for creating the mirror magnetic field. Using these coils, the ECR surface size can be changed without changing the average magnetic field gradient. Fig. 2 shows the beam intensity of Xe^{20+} as a function of the average magnetic field gradient for several ECR zone sizes at the RF power of 500W. For investigating these effects, B_{inj}, B_{ext} and B_{r} were fixed to 2.3, 1.2 and 1.3T, respectively. The extraction voltage was fixed to 17kV. It is clearly seen that the beam intensity increases with decreasing the field gradient. Furthermore, it seems that the beam intensity is higher for larger zone size at same field gradient. Fig. 3 a) and b) show the ratio of highly charged Xe beam intensity between two conditions. The ratio between two different field gradients increases with increasing the charge state (fig.2 a)) on the other hand, the ratio between different zone sizes are almost constant and independent on the charge state (Fig.3 b)). It is well-known that the energy transfer from microwave to electron increases with decreasing the gradient. It means that the electron temperature becomes higher at the gentler field gradient. The production rate of the higher charge state Xe ions increases with increasing the electron

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[#] nakagawa@riken.jp

STATUS OF THE VENUS ECR ION SOURCE

D. Leitner*, C.M. Lyneis, M. Leitner, A. Hodgkinson, T. Loew, P. Ferracin, G.L. Sabbi
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
G. Machicoane, E. Pozdeyev
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA.

Abstract

The status and future developments of the 28-GHz VENUS (Versatile ECR for NUclear Science) Electron Cyclotron Resonance (ECR) ion source after the two years repair are presented. The fully superconducting ECR ion source VENUS serves as prototype injector for the Facility for Rare Isotope Beams (FRIB) project at Michigan State University (MSU) [1] as well as injector ion source for the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory (LBNL). As such the source has produced many record beams of high charge state ions as well as high-intensity, medium charge state ions. As the FRIB project has now entered the preliminary design phase, LBNL is involved in the design of two new VENUS-like ECR injector ion sources for the FRIB facility. This paper will review the design changes for the FRIB injector, which will allow the installation of the FRIB injector source on a 100 kV platform. In support of the FRIB ion sources design systematic measurements of the heat load due to bremsstrahlung from the plasma for different magnetic fields have been performed and are presented. Finally, a possible future upgrade path for the FRIB injector using an advanced Nb_3Sn magnet structure is described.

A VENUS LIKE ECR ION SOURCE FOR THE FRIB INJECTOR

Fig. 1 shows the current installation of VENUS at the LBNL 88-Inch Cyclotron. The VENUS cryostat operates in a closed loop mode without additional helium transfers after the initial cool down as required for an installation on a high voltage platform as needed for the FRIB front end, but uses liquid nitrogen to cool the normal conducting leads. To adapt this design for the FRIB injector, the liquid nitrogen needs to be eliminated. In addition, the 4K cooling power will have to be increased. Finally, the extraction voltage needs to be enhanced.

HV insulation

The VENUS source high voltage insulation will need to be enhanced to allow reliable extraction at 40kV extraction voltage.

Pre-cooling of the normal conducting leads

The VENUS ECR ion source uses liquid nitrogen to dissipate the up to 70 watts of heat load from the normal conducting copper leads under full excitation. For FRIB the liquid nitrogen pre-cooling will be replaced by a single stage cryocooler.

4K cooling power

The VENUS cryostat is currently using four two stage Gifford-McMahon (GM) cryocoolers providing a total of 6W cooling power at 4K. But measurements of the x-ray heat load into the cryostat at the VENUS source, the SECRAL source, and the SC RIKEN indicate that more cooling power will be needed for the FRIB injector (see section3). For this purpose, three design options are currently being evaluated. In the first option a combination of two 2-stage and two 3-stage cryocoolers would provide a total cooling power of 13 W at 4K. Only minimal design changes are necessary for this option. Alternatively, we are evaluating the possibility of installing a compact external helium liquefier onto the HV platform, or the possibility of developing an insulated 100kV liquid helium fill line. While technically challenging, the last two options would have the advantage that ample cooling power would be available for potential future upgrades such as double frequency heating with 24 GHz or installing a higher frequency (>40GHz) Nb_3Sn based ECR ion source on the platform.

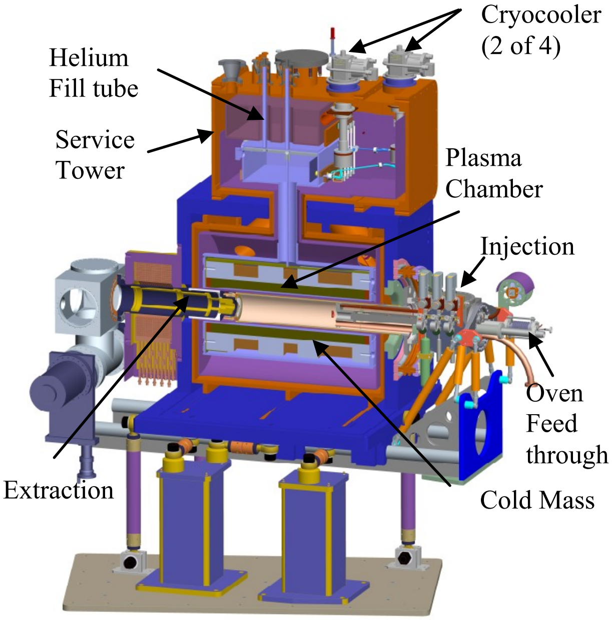

Figure 1: Mechanical layout of the VENUS ion source and cryogenic systems as installed on the vault roof of the 88-Inch Cyclotron

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* Corresponding Author: Leitnerd@nscl.msu.edu

ECR ION SOURCES FOR THE FACILITY FOR RARE ISOTOPE BEAMS (FRIB) PROJECT AT MICHIGAN STATE UNIVERSITY*

G. Machicoane, M. Doleans, O. Kester, E. Pozdeyev, T. Ropponen, L. Sun, E. Tanke, X. Wu
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA.
D. Leitner, 88 inch cyclotron Lawrence Berkeley National Laboratory, Berkeley CA 94720

Abstract

Once operational, the Facility for Rare Isotope Beams (FRIB) will open the possibility to gain key understanding in nuclear science and in particular regarding the properties of nuclei far from the valley of stability or the nuclear processes in the universe. In addition it will also allow experimenters to test fundamental symmetries. The production of rare isotopes with FRIB will be achieved, using a heavy ion driver linac that will accelerate a stable isotope beam to 200 Mev/u and deliver it on a fragmentation target. FRIB aims to reach a primary beam power of 400 kW for light to heavy elements up to uranium. To meet the intensity requirement, two high performance ECR ion sources operating at 28 GHz will be used to produce high intensity of medium to high charge states ion beams. Plans regarding initial beam production with the ECR ion sources and beam transport through the front end will be discussed.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) (formerly referred to as RIA - Rare Isotope Accelerator) will provide intense beams of rare isotopes for a wide variety of studies in nuclear science. In particular it will help to deepen the current understanding of nuclear structure and help develop a comprehensive model of nuclei. In nuclear astrophysics, it will allow astrophysicists to model and understand the origin and evolution of elements in the cosmos and will permit sensitive tests of the fundamental symmetries of nature. Finally it will provide the scientific community with a source of rare isotopes to develop new applications for medicine, stockpile stewardship and improve applications that benefit from the use of radioisotopes. The FRIB facility is based on a heavy-ion linac with a minimum energy of 200 MeV/u for all ions at a beam power of 400 kW. To minimize the cost of the conventional facility, the layout of the accelerator follows a double folded geometry. The linac has been designed to accelerate ions with a charge to mass ratio higher than 1/7. The first segment with superconducting λ/4 cavities will accelerates the ion beam to 17 MeV/u and will be followed by a folded section that includes a charge stripper and a 180º magnetic bend. A second section with superconducting λ/2 cavities will accelerate ions to 108 Mev/u and again will be followed by a 180º magnetic bend but without charge stripping. A final accelerating section will allow the ion beam to reach 200 Mev/u for all ions up to uranium. The facility will have a production target for in-flight production of rare isotopes. A three-stage fragment separator will be used to prepare fast rare isotope beams with high-purity that can be used at velocity for fast-beam experiments. A multiconcept beam stopping facility will provide thermalized ion beams for stopped beam experiments or for reacceleration at energies up to 3 MeV/u for uranium.

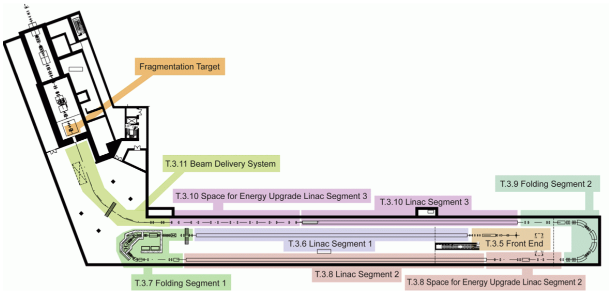

Figure1: Layout of the FRIB driver linac.

FRIB FRONT END

The main functions of the FRIB front end will be on one hand to produce the ion beam using an ECR ion source and on the other hand to prepare the beam for injection into the superconducting linac by providing an initial beam acceleration to 0.3 MeV/u through a Radio Frequency Quadrupole (RFQ) and to ensure proper beam matching in the longitudinal and transverse directions. The front end includes the following segments: First heavy ion beams for FRIB will be produced from high performance ECR ion sources operating at 28 GHz. Two ion sources are necessary to ensure maximum beam availability through redundancy. The initial ion beam energy after extraction from the ion source will be 12 keV/u. This corresponds to an accelerating voltage around 90 kV for U^{33+}. Such a potential difference can not be achieved directly in one acceleration gap at the ECR extraction and a high voltage platform will be used to reach the initial required energy. Then, following the high voltage platform, an achromatic charge to mass selection system will be used to minimize transverse emittance growth in particular for heavy ion beams. The low energy beam transport section (LEBT) will include a transverse collimation system to ensure that the full normalized transverse beam emittance does not exceed the acceptance of the Superconducting linac.

An ion beam chopper is also included in this section to reduce the average beam intensity without impacting the nominal beam bunch intensity for safe tuning and

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PRESENT STATUS OF FLNR (JINR) ECR ION SOURCES

S. Bogomolov, A. Efremov, V. Loginov, A. Lebedev, N. Yazvitsky, V. Bekhterev, Yu. Kostukhov,
G. Gulbekian, B. Gikal, V. Drobin, V. Seleznev, JINR, Dubna, Russia

Abstract

Six ECR ion sources have been operated in the Flerov Laboratory of Nuclear Reactions (JINR). Two 14 GHz ECR ion sources (ECR4M and DECRIS-2) supply various ion species for the U400 and U400M cyclotrons correspondingly for experiments on the synthesis of heavy and exotic nuclei using ion beams of stable and radioactive isotopes. The 18 GHz DECRIS-SC ion source with superconducting magnet system produces ions from Ar up to W for solid state physics experiments and polymer membrane fabrication at the IC-100 cyclotron. The third 14 GHz ion source DECRIS-4 with "flat" minimum of the axial magnetic field is used as a stand alone machine for test experiments and also for experiments on ion modification of materials. The other two compact ECR ion sources with all permanent magnet configuration have been developed for the production of single charged ions and are used at the DRIBs installation and at the MASHA mass-spectrometer. In this paper, present status of the ion sources, recent developments and plans for modernization are reported.

INTRODUCTION

Main theme of FLNR JINR is super heavy elements research. From 2000 up to 2010 more then 40 isotopes of elements 112, 113, 114, 115, 116, 117, 118 were synthesized in the laboratory.

At present four isochronous cyclotrons: U-400, U-400M, U-200 and IC-100 are under operation at the JINR FLNR. Three of them are equipped with ECR ion sources. In the DRIBs project for production of accelerated exotic nuclides as ^{6}He, ^{8}He etc. the U-400M is used as radioactive beam generator and U-400 is used as a post-accelerator. Layout of FLNR accelerators complex is presented at Figure 1 [1]. Red stars indicate the location of the ECR ion source.

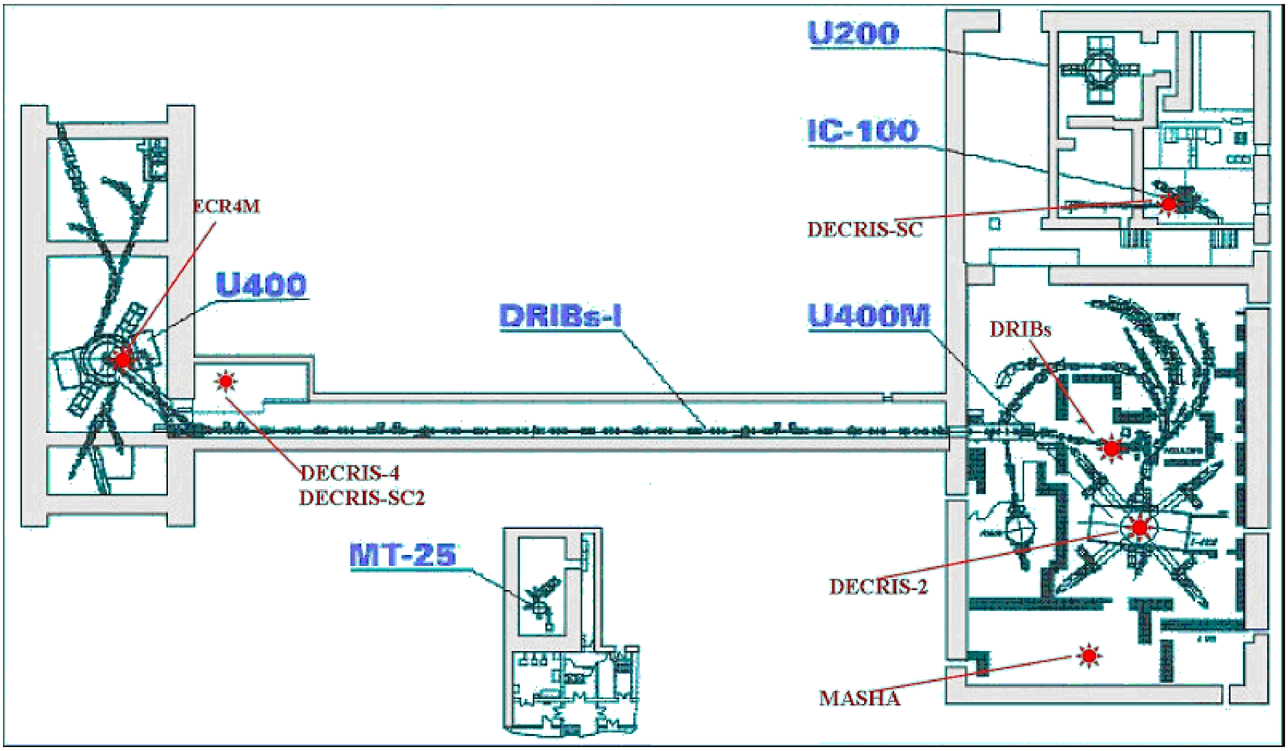

Figure 1: Layout of FLNR JINR accelerator complex. Red stars indicate the location of the ECR ion sources.

DECRIS-2 ION SOURCE

The ion source DECRIS-2 is in regular operation at the U400M cyclotron since 1995 [2]. Nowadays the main physical setups at the cyclotron U400M are the fragment-separators ACCULINNA and COMBAS. Besides, the accelerator is used for the secondary beam production at the DRIBs facility. Intensive beams of ^{7}Li, ^{11}B, ^{13}C, ^{15}N, ^{18}O ions with energies of 35 -55 MeV/nucleon on the U400M cyclotron provide good possibilities for generation secondary beams of ^{6}He, ^{15}B, ^{9}Li, ^{11}Li, ^{12}Be,

STATUS OF ION SOURCES AT HIMAC

A. Kitagawa, T. Fujita, M. Muramatsu, Y. Sakamoto,
National Institute of Radiological Sciences (NIRS), 4-9-1 Anagawa, Inage, Chiba 263-8555, Japan
T. Sakuma, N. Sasaki, T. Sasano, W. Takasugi,
Accelerator Engineering Corporation (AEC), 2-10-14 Konakadai, Inage, Chiba 263-0043, Japan
S. Biri, Institute of Nuclear Research (ATOMKI), H-4026 Debrecen, Bem ter 18/C, Hungary
A.G. Drentje, Kernfysisch Versneller Instituut (KVI), 9747AA Groningen, The Netherlands

Abstract

The Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) was designed as a clinical dedicated facility. The carbon ions are utilized for the heavy-ion radiotherapy, so its production is the most important aim for ion sources at HIMAC. However HIMAC has a second essential task to operate as a facility for basic experiments. In that scope it accelerates many ions. In order to serve all HIMAC users at best, three ion sources have been installed. This report summarizes the status of the ion sources to produce carbon ions and to extend the range of ion species.

INTRODUCTION

The National Institute of Radiological Sciences (NIRS) was funded in 1957 and has been researching on the effects of radiation on the human body, protection from radiation, diagnosis and treatment of radiation injuries, and medical uses of radiation. The HIMAC (Heavy Ion Medical Accelerator in Chiba) project is one of the most important research subjects in NIRS [1], and it has successfully realized the heavy-ion radiotherapy with 140-400 MeV/u carbon beams since 1994 [2]. HIMAC was designed as a clinical dedicated facility, but it has as a second essential task to operate as a facility for basic experiments in e.g. biomedical and material science, physics and chemistry. In order to accelerate various ion species, two ECR ion sources and one PIG ion source are installed. The carbon ions for the daily treatment are mainly provided with a 10GHz ECR ion source called 'NIRS-ECR'[3]. The NIRS-ECR is sometimes utilized for lighter gaseous ions too. A PIG ion source, ('NIRS-PIG'), supplies relatively lighter ions, especially metallic ions by the sputtering method [4]. An 18GHz ECR ion source called 'NIRS-HEC', produces relatively heavier gaseous ions[5,6]. Since the three ion sources are almost occupied with daily operations, it's difficult to spend a time for the development to extend the range of ion species. The installation of a new local injector linac is scheduled to be completed in the spring of 2011. Another ECR ion source, called 'Kei2' had been developed as a prototype of a hospital specified facility[7], is now under commissioning for the new injector. It is expected that the other three ion sources will be free from the carbon production for the daily clinical operation. Several developments for these four ion sources are now in progress. The present status of carbon-ion production and the trial for the extension of the range of ion species with ECR ion sources are presented in this paper.

CARBON-ION PRODUCTION

Difficulty of carbon- ion production

The production of highly charged carbon ions with good stability and reproducibility is harder effort than other ions. NIRS-PIG realizes a very low-duty pulsed operation and a feedback of the arc power. In addition, its carbon vapour is supplied by sputtering from graphite resulting decreasing amount of carbon atoms in the chamber. So that, the lifetime can extend about one week [4]. However the change of conditions of consumptive parts like a cathode finally requires the tuning by manual operation. It's not satisfied for the medical requirement. Unfortunately, this difficulty is also true for the ECRIS, the source well known for its long lifetime and good performance for highly-charged ion production. Based on the experiences at NIRS-ECR and NIRS-Kei2, the performance of the ECR ion source is degraded due to carbon deposition on the parts, especially the chamber wall. In order to increase the intensity of highly charged carbon ions like C^{4+}, it's effective to feed hydro-carbonic C_xH_y gases[8]. However, the deposition is unavoidable under the use of such gases, and causes serious unfavourable effects.

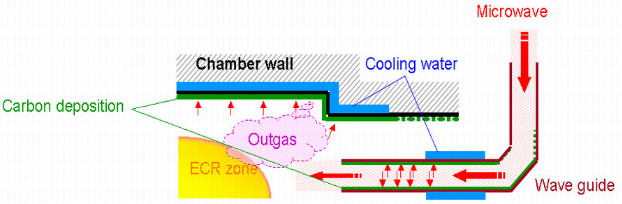

Figure 1: Microwave absorption on the dirty carbon deposited wall.

The microwave power absorbed on the walls of the waveguide and the plasma chamber increases with increasing the deposition on the walls. The less microwave power can reach into the ECR zone shown in Figure 1, thus the plasma density and the electron energy distribution must be low. When the microwave power is increased in order to compensate for this deficit, more loss of the microwave power causes heat-up of the walls and the heat-up induced the change of the vacuum pressure. As a result, reproducibility is much worse. In

RECENT ACTIVITIES AT THE ORNL MULTICHARGED ION RESEARCH FACILITY (MIRF)*

F.W. Meyer[#], M.E. Bannister, J.W. Hale, C.C. Havener, H.F. Krause[$], C.R. Vane, S. Deng,
I.N. Draganić, P.R. Harris, Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN
37831-6372 USA

Abstract

Recent activities at the ORNL Multicharged Ion Research Facility (MIRF) are summarized. A brief summary of the MIRF high voltage (HV) platform and floating beam line upgrade is provided. An expansion of our research program to the use of molecular ion beams in heavy-particle and electron collisions, as well as in ion-surface interactions is described, and a brief description is provided of the most recently added **I**on **C**ooling and **C**haracterization **E**nd-station (ICCE) trap. With the expansion to include molecular ion beams, the acronym MIRF for the facility, however, remains unchanged: "M" can now refer to either "Multicharged" or "Molecular."

THE MIRF UPGRADE PROJECT AND RECENT FACILITY ACTIVITIES

In order to enhance the capabilities of on-line experiments of the MIRF [1], a facility upgrade project was undertaken to add an all permanent magnet ECR source on a new 250 kV HV platform, and to modify the existing CAPRICE ECR source to inject a new floating beam line, from which beams could be decelerated into grounded end stations with final energies as low as a few eVxq, where q is the charge state of the analyzed beam [2][3][4]. An electrostatic trap end station was also added to the facility, for multi-second confinement of metastable-multicharged or hot-molecular ions to reduce their degree of internal excitation either for lifetime or subsequent cold collision studies [5].

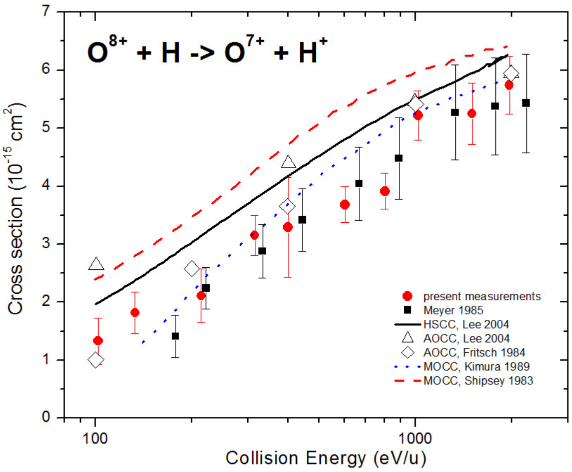

Figure 1: Results for O^{+8} – H electron capture [7].

Table 1: Performances of the MIRF ECR sources [6]

Ion		CAPRICE 10 GHz	Platform ECR source
Xe	+20	35 µA	52 µA
	+26	9	24
	+29	--	3
Ar	+8	500	510
	+11	70	90
O	+6	400	650
	+7	50	90

The new permanent magnet ECR source was designed and built at CEN-Grenoble, and has been previously described [6]. Table 1 summarizes typical multicharged ion performances for the CAPRICE and the new permanent magnet ECR sources injecting the low-energy and high-energy MIRF beam lines, respectively.

To illustrate the increased experimental capabilities made possible by the facility upgrade, Figure 1 shows recent results for electron capture by fully stripped oxygen ions from atomic hydrogen obtained with the upgraded ion-atom merged beams experiment. For these measurements, a well-collimated, small-cross section O^{8+} beam was merged with a fast ground-state atomic hydrogen beam produced by photodetachment, and the protons resulting from charge exchange collisions between the two fast beams monitored.

The present MIRF layout is shown in Figure 2. The facility is comprised of 5 on-line experiments fed by the new HV platform ECR source, and 3 on-line experiments injected from the new low-energy floating beam line.

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[#] meyerfw@ornl.gov

[$] retired

PK-ISIS: A NEW SUPERCONDUCTING ECR ION SOURCE AT PANTECHNIK

A. C. Villari[#], C. Bieth, W. Bougy, N. Brionne, X. Donzel, G. Gaubert, R. Leroy, A. Sineau,
O. Tasset, C. Vallerand, Pantechnik, Bayeux, France,
T. Thuillier, LPSC UJF CNRS/IN2P3 INPG, Grenoble, France

Abstract

The new ECR ion source PK-ISIS was recently commissioned at Pantechnik. Three superconducting coils generate the axial magnetic field configuration while the radial magnetic field is done with multi-layer permanent magnets. Special care was devoted in the design of the hexapolar structure, allowing a maximum magnetic field of 1.32 T at the wall of the 82 mm diameter plasma chamber. The three superconducting coils using Low Temperature Superconducting wires are cooled by a single double stage cryo-cooler (4.2 K). Cryogen-free technology is used, providing reliability, easy maintenance at low cost. The maximum installed RF power (18.0 GHz) is of 2 kW. Metallic beams can be produced with an oven (Tmax = 1400 °C) installed with an angle of 5° with respect to the source axis or a sputtering system, mounted in the axis of the source. The beam extraction system is constituted of three electrodes in accel-decel configuration.

Pantechnik has developed and improved its family of ECRIS in collaboration with research laboratories like GANIL and LPSC in France and IUAC in India. From this collaboration, the first ECRIS using He-free High Temperature Superconducting wire technology (HTS) was born in 2002: PK-DELIS.

The goals of that development were to reduce the power consumption of the coils from 200 kW to 15 kW, for avoiding liquid He in the superconducting coils and to demonstrate the feasibility of such hybrid HTS - permanent magnet (for the radial magnetic field) source. PK-DELIS works since then successfully at New Delhi.

The new source of Pantechnik is conceived for reaching optimum performances at 18 GHz RF frequencies. Moving to this direction, PK-ISIS, our new source, has much higher axial and radial magnetic fields (2.1 T axial B_{inj} and 1.32 T radial field in the wall), a larger plasma volume, variable B_{min} via an independent coil and a large and opened extraction region. Moreover, PK-ISIS integrates modern design concepts, like RF direct injection (2.5 kW availability), DC-bias moving disk, out-of-axis oven and axial sputtering facility for metal beams.

PK-ISIS delivers 5 to 10 times more beam intensity than the original PK-DELIS and/or shifting the charge state distribution to higher values.

PK-ISIS is built with Low Temperature Superconducting wire technology (LTS), but keeps the He-free concept, extremely important for a reliable and easy operation. The radial field circuit is permanent magnet made. Finally, PK-ISIS is also conceived for using in a High-Voltage platform with minor power consumption.

The intensities already obtained by PK-ISIS are listed in the Table 1 below. Please, note that these values were obtained during commissioning in the Pantechnik premises. *The intensities – mainly for metallic beams – should be taken as lower limits. Not all intensities were obtained after reaching the maximum magnetic field in the Superconducting coils.*

The problems we faced with the superconducting coils during the first commissioning were recently solved. PK-ISIS is running within the designed specifications.

Table 1: Beam intensities measured with PK-ISIS

Ion	**Intensity (µA – electrical)**
^{4}He (2+)	2,400
^{13}C (4+)	>500
^{13}C (6+)	50
^{14}N (5+)	>1,000
^{16}O (6+)	1,500
^{16}O (7+)	230
^{40}Ar (12+)	200
^{40}Ar (14+)	100
^{84}Kr (17+)	100
^{129}Xe (26+)	100
^{181}Ta (26+)	20
^{181}Ta (30+)	13
^{181}Ta (32+)	6
^{209}Bi (29+)	35
^{209}Bi (31+)	25
^{209}Bi (33+)	15

[#] antonio.villari@pantechnik.com

3D SIMULATION STUDIES AND OPTIMIZATION OF MAGNETIC HOLES OF HTS-ECRIS FOR IMPROVING THE EXTRACTION EFFICIENCY AND INTENSITIES OF HIGHLY CHARGED IONS

G. Rodrigues*, P.S. Lakshmy, Y. Mathur, R.N. Dutt, U.K. Rao, D. Kanjilal, A. Roy,
Inter University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi 110067, India
R. Baskaran, Indira Gandhi Centre for Atomic Research, Kalpakkam 603102, Tamilnadu, India

Abstract

3D simulation studies using RADIA code have been performed to optimise the magnetic holes in the high temperature superconducting electron cyclotron resonance (HTS-ECRIS) ion source for improving the extraction efficiency and intensities of highly charged ions. The magnetic field improvements using simple techniques like optimisation of iron regions is found to be economical. The extraction efficiency can be increased three-fold in the case of a hexapole magnet depending on the level of the uniformity of the fields in the high and low regions. This technique further minimises localized heating of the plasma chamber walls which can improve the vacuum conditions in an ECR ion source. For superconducting sources where the x-ray heat load poses severe problems during operation, such a reduction of heating load is of great significance. The typical triangular pattern of the plasma impact observed on the plasma electrode of HTS ECRIS at various tuning conditions are reproduced by the simulations. Details of the simulations and experimental results will be presented.

INTRODUCTION

Today, ECR ion sources are being utilized as high current injectors for various accelerator projects around the world due to its simplicity, robustness, wide mass range of ions with excellent beam intensities and long lifetime as compared to other ion sources [1]. The backbone of this kind of source is based on a minimum B magnetic configuration where the electrons are confined to increase the probability of stripping ions to higher charge states. The design of this kind of magnetic configuration is based on well known ECR scaling laws. This study was undertaken to improve the extraction efficiency and especially the intensities of the highly charged ions. Earlier, experiments have shown that the optimum plasma electrode position inside the plasma chamber is not the same for the extraction of low, medium and highly charged ions. It was observed for the RIKEN [2] and JYFL ECR ion sources [3] that the intensities of highly charged ions increased as the plasma electrode was moved further away from the ECR zone. On the other hand, the intensities of medium charged ions, increased as the plasma electrode was moved closer to the ECR zone. Normally the extraction field, B_{ext}, should be slightly lower than the last closed magnetic surface, B_{last}, for the efficient production of highly charged ions [4]. A closer look led us to investigate further the magnetic configuration of the source at the extraction side. The magnetic field region at extraction (towards the exit of the hexapole) where the highly charged ions are extracted shows that there exist three weaker field regions (due to the use of a hexapole) where the plasma can still escape rather than being extracted. This is due to the radial component of the solenoid field which only partially cancels the radial field produced by the hexapole especially at the ends of the hexapole. It is expected that by further optimizing these weaker field regions, much higher intensities of highly charged ions can be extracted. Since no detailed work is available in the literature, except for a brief mention [5], it was important to perform 3D calculations of the combined magnetic field using the computer code RADIA [6]. Localized heating of the plasma chamber walls could be reduced which in turn would improve the vacuum conditions in the ECR ion source. For superconducting sources, the x-ray heat load which poses severe problems during operation and localised heating in the superconducting coils (quenches) can be further minimized.

MAGNETIC STRUCTURE OF AN ECRIS

In ECR ion source, combined magnetic field consisting of an axial and radial components generated by solenoid and a multipole magnet respectively is used. This kind of open magnetic field configuration is found necessary for good plasma confinement, stability and also for ease of extraction of the ions [1]. For efficient operation, the combined magnetic field structure should follow the well known ECR scaling laws ; the last closed surface should be at least twice that of the resonance field, B_{ecr}, within the plasma chamber, where B_{ecr} is the field required for the electron cyclotron resonance condition. In addition, the periphery of the plasma should be far away from the walls of the chamber to reduce the probability of melting of the plasma chamber. For a typical magnetic field configuration in conventional ECR ion sources, a triangular shape at both extremes is evident on the plasma electrode at extraction side and on the bias electrode if the electrode is in the form of a disc at injection side. The radial losses have a pattern on the plasma chamber wall which is symmetric corresponding to the orientation of the multipole, where the plasma impacts are oriented on the pole directions of the multipole. For the case of a multipole where order of the multipole, n =3 (sextupole) ,

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*gerosro@gmail.com

DESIGN STUDY OF A HIGHER-MAGNETIC-FIELD SC ECRIS AT IMP

D. Z. Xie*, W. Lu#, X. Z. Zhang and H. W. Zhao
Institute of Modern Physics (IMP), Chinese Academy of Sciences (CAS), Lanzhou 730000
People's Republic of China

Abstract

Development of ECR ion source has demonstrated that, as the empirical scaling laws summarized, higher magnetic field with higher operation frequency will greatly improve the source performance. Based on the great success of SECRAL at IMP, a higher-magnetic-field SC ECRIS is planned to meet the new accelerator demands. However, there are many practical issues in the design and construction of a higher-field SC ECRIS which need addressed. In this paper we will present and discuss the design features of the higher-field SC ECR with a maximum axial field of 7.0 T and a radial field of 3.5 T at the plasma chamber wall of ID 110 mm, and operating frequency up to 50 GHz.

INTRODUCTION

Performance of high-charge-state Electron Cyclotron Resonance Ion Source (ECRIS) has been greatly improving since its advent and especially in the past decade, thanks to the continuous increase of magnetic-field-strength and operating frequency. Although a full understanding of the detailed physics process involved in ECR plasma is still in the horizon, higher-magnetic-field combined with higher-operating-frequency remains nowadays the relatively easy and straightforward way to further the development of ECRIS. Based on the empirical scaling laws [1], there were a few fully superconducting (SC) ECRISs all built with NbTi magnets in the past decade. At safe current loadings (up to about 90% of its critical current), the highest field strength reaches 4 T on axis and 2 T at the plasma chamber wall of ID 100 to 140 mm for operating frequency up to 28 GHz. These SC ECRISs have significantly improved the ECRIS performance by a great factor in both the ion beam intensity and charge state. To further enhance the ECRIS performance to meet new demands, higher-field ECRISs have been proposed and are under design. The maximum field strengths are to reach 8 T on axis and 4 T at the plasma chamber wall by using the higher-critical-current Nb_3Sn wires to construct the SC magnets [2].

At the Institute of Modern Physics (IMP), the great success of SECRAL has demonstrated that further ECRIS performance is not only possible but also needed. The institute is planning a future facility of higher-energy and higher-beam-intensity for nuclear physics research. This new facility requires very intense ion beams, for example, at least 15 pμA of Bi^{31+} and about the same intensity of U^{33+} are to be extracted from the proposed accelerator. Such intense beam intensities require at least a new higher-field SC ECRIS that leads to this design study.

A BRIEF REVIEW OF THE SC MAGNET STRUCTURES FOR ECRISs

Presently there are two different types of magnet structures used in the SC ECRISs. Figure 1 shows the "classical" structure, the sextupole coils sit inside the solenoid coils, that is used so far in all ECRISs but one. Because of the very strong Lorenz interaction forces, especially the repulsing force, the sextupole coils have to be ended at a good distance away from the solenoid coils so that the interaction forces can be reduced. The lengthy end extension results in a bulky magnet structure and cryostat. Sometimes a set of liquid-metal-filled bladders that increases the complexity of magnet fabrication is used to harness the very strong forces [3]. So far the best embodiment of the classical magnet structure remains to be the LBNL VENUS, the first ECRIS that has been designed and reached 4 T on axis and 2 T at the plasma chamber wall of ID 140 mm [4]. Its magnet assembly is wound with NbTi wires of high Cu/Sc Ratios of 3.0 and 4.0 for better thermal stability. Since 2002 it has been commissioning at 18, 28 GHz and double-frequency heating at 18+28 GHz with wave power up to ~10 kW and has produced very great performance. A few example beams produced with VENUS are listed in Table 1 below.

The "non-classical" magnet structure is shown in Figure 2. A striking feature of this structure is that the sextupole coils not only sit outside the solenoid coils but also ended right next to the solenoid coils. A set of simple cold irons, no bladders, is used to clamp down the magnet coils and reduce the stray field right inside the cryostat. This non-classical magnet structure results in a smaller magnet assembly and simplifies somewhat the fabrication process. The IMP's SECRAL is the first SC ECRIS built with this non-classical magnet structure. All the SECRAL magnet coils are wound with the NbTi wires of low Cu/Sc Ratio of 1.35. The field maxima are 3.6 T on axis and ~2.0 T at the plasma chamber wall of diameter of 126 mm. SECRAL had begun its commissioning at 18 GHz with maximum microwave power of about 3.5 kW in 2005. Though operated at lower magnetic fields, lower frequency and wave power, SECRAL has produced very compatible results in comparison to VENUS at higher fields, higher frequency and wave power. So far SECRAL has reliably provided more than three-thousand hours of ion beams to the IMP accelerators and sometimes the operation lasted months without system failures. SECRAL has recently begun its commissioning operation at 24 GHz and already shown better performance than at

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* Visiting Scientist

\# Also of the Graduate School of CAS, Beijing 100049, P. R. China

MEASUREMENT OF THE SIXTY GHZ ECR ION SOURCE USING MEGAWATT MAGNETS - SEISM MAGNETIC FIELD MAP*

M. Marie-Jeanne[#], J. Jacob, T. Lamy, L. Latrasse, LPSC UJF CNRS/IN2P3 INPG, Grenoble, France
F. Debray, J. Matera, R. Pfister, C. Trophime, LNCMI CNRS UJF INSA UPS, Grenoble, France.

Abstract

LPSC has developed a 60 GHz Electron Cyclotron Resonance (ECR) Ion Source prototype called SEISM. The magnetic structure uses resistive polyhelix coils designed in collaboration with the French National High Magnetic Fields Facility (LNCMI) to produce a CUSP magnetic configuration. A dedicated test bench and appropriate electrical and water cooling environments were built to study the validity of the mechanics, the thermal behaviour and magnetic field characteristics obtained at various current intensities. During the last months, measurements were performed for several magnetic configurations, with up to 7000 A applied on the injection and extraction coils sets. The magnetic field achieved at 13000 A is expected to allow 28 GHz ECR condition, so by extrapolation 60 GHz should be possible at about 28000 A. However, cavitation issues that appeared around 7000 A are to be solved before carrying on with the tests. This contribution will recall some of the crucial steps in the prototype fabrication, and show preliminary results from the measurements at 7000 A. Possible explanations for the differences observed between the results and the simulation will be given.

SCIENTIFIC CONTEXT

LPSC Grenoble has initiated an ambitious research and development program for high frequency ECRIS, i.e. with a resonance frequency above 28 GHz. Such a program benefits greatly from LNCMI research on split magnets described in reference [1]. The use of LNCMI radially cooled polyhelix technology allows investigating several magnetic configurations with low fabrication costs and short delays in comparison to classical and superconducting ECR ion sources.

As a first step, the SEISM prototype was designed to produce a CUSP magnetic structure with a closed 60 GHz resonance zone at 2.14 T for a 30000 A current in the helices. Reference [2] recalls the main steps for the design of the prototype, including the results from magnetic, mechanical, hydraulic and thermal calculations.

Due to many uncertainties concerning hydraulic and thermal behaviour of such an innovative helix design, a dedicated test stand was built at LNCMI to study the coils characteristics obtained for various current intensities. The goal of such tests is to validate the magnetic field map at half-current using 2 of the 4 available power supplies of LNCMI, thus creating a closed 28 GHz resonance zone at 1 T for 15000 A in the coils.

PROTOTYPE FABRICATION AND TESTS

Helices

Each helix was first machined with its final diameter, then rigidified by the insulators glued between its windings and finally adjusted to its final height. Helices fabrication process is shown on Fig. 1. According to thermal calculations, insulators had to be as narrow as possible (i.e. 2 mm wide) in order to limit local temperature rise in their centre. Thickness was calibrated to maintain a constant space between two windings (i.e. 0.32 mm thick) in order to avoid constraints on the helix. The difference of potential between two windings was expected not to exceed 10 V at 30000 A. Therefore, composite fibres already "pre-impregnated" (hence the name “pre-preg”) with the resin that would bond them to the windings surface have been chosen. Such pre-pregs can hold a maximum voltage of 35 kV/mm, and are easily cut to their final shape with an automatic cloth cutting machine. As calculated, 24 pre-pregs per winding were glued on internal helices H1 and H2, and 32 pre-pregs on external helices H3 and H4, in order to avoid windings distortion and contact under the magnetic field forces.

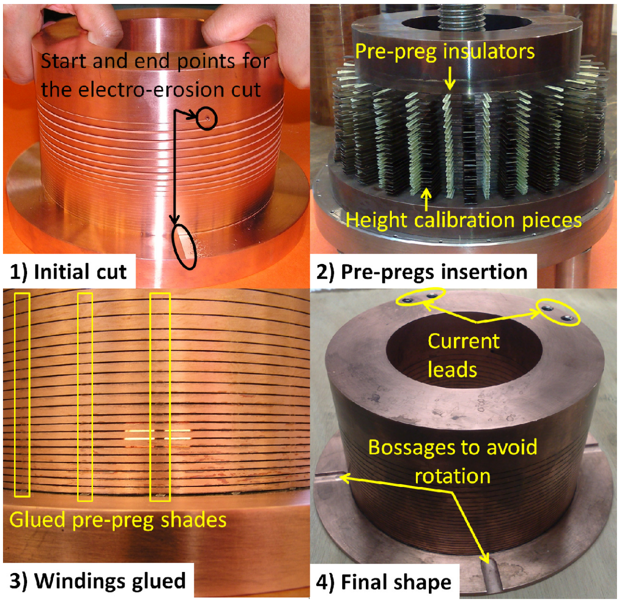

Figure 1: Inner injection helix H1 fabrication process from initial electro-erosion machining (1), through pre-preg insulators gluing (2, 3), to final adjustments in height and shape (4).

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[#] melanie.marie-jeanne@lpsc.in2p3.fr

MULTIGAN®: A NEW MULTICHARGED ION SOURCE BASED ON AXISYMETRIC MAGNETIC STRUCTURE

L. Maunoury[#], J.Y Pacquet. M. Dubois, P. Delahaye, P. Jardin, P. Lehérissier and M. Michel
GANIL, Caen, France
C. Pierret, CIMAP, Caen, France
X. Donzel, G. Gaubert, R. Leroy* and A.C.C. Villari, PANTECHNIK, Bayeux, France
S. Biri, ATOMKI, Debrecen, Hungary

Abstract

The regular ECR ion sources, allowing the production of multicharged ions, have openings only at their two ends. Based on the MONO1000 ECRIS [1] concept and experience, a new multicharged ECR ion source has been designed with a large opened space in the middle of the source enabling a direct contact with the ECR plasma. This source will combine the advantages of the axisymetric magnetic structures made only of permanent magnets with a high operating frequency.

The magnetic structure calculations as the mechanical design and stress will be described in details. An estimation of the electronic energy distribution has been calculated using the TrapCad code [2] and thus the performances of the source have been deduced. A rough calculation of the beam extraction and formation has also been calculated taking into account of the several fields (magnetic and electric) surrounding the extraction system.

The ion source presented in this paper is a prototype which shall validate the magnetic concept and which shall confirm the expected performances. The next step will be the design of an optimized ECRIS according to its future applications.

INTRODUCTION

In the framework of the SPIRAL1 facility upgrade, the design of a new ECR ion source ionizing radioactive metallic species in multicharged states is an alternate way in the actual NANOGANIII TIS system. It should contain open sides in order to have a close connection between the hot target and the plasma. Obviously the ECRIS should ionize the radioactive atoms with a high efficiency that requests to operate the ECRIS with a high value for the RF frequency. Based on an existing Mono1000 magnetic system, the prototype is under construction to demonstrate the ability of such an ECRIS to produce multicharged ions with an intermediate expected average charge state <Q> ≥ 2. This development is realized in collaboration with the Pantechnik company which has applications for this type of ECRIS.

MAGNETIC AND MECHANICAL DESIGN

The magnetic structure (principle has been used in two other ECRIS's [3,4]) takes back the two Mono1000 rings made of permanent magnets (NdFeB Vacodym 655HR) coupling with iron (ARMCO) which concentrates and transports the magnetic flux lines in the centre of the source. The magnetizations of the rings are similar and are aligned on the axis of the source. In our case, the trick is to shape the iron as to bring the maximum magnetic flux for creating a closed B iso-magnetic surface having a high value (here the last closed B iso-module reaches 4800 Gauss) far from the saturation of the iron (saturation value is 1.8T).

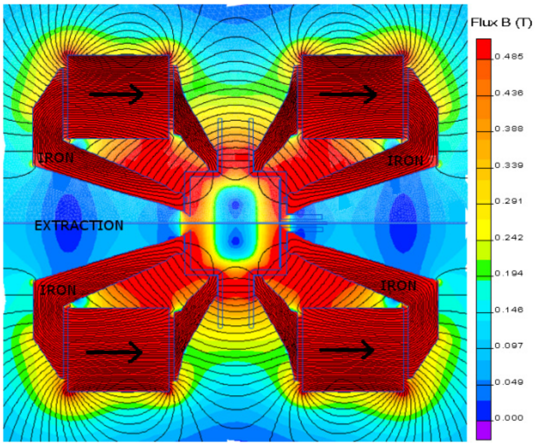

Figure 1: calculated magnetic structure with QuickField software

Figure 1 displays the output calculation made with the QuickField software: value of the total magnetic field at each point of the source. The magnetic field values decrease from the ECRIS wall down to almost 0 in the middle of the source. The magnetic field is lowered voluntarily in the extraction region in order to make a type of "ion funnel". Using a RF frequency of 7 GHz, corresponding to a resonant magnetic field of 2500 Gauss, the mirror ratio is 1.92.

After the iron design and the permanent magnet ring used, a mechanical design of the source has been realized. Figure 2 shows a sketch of the source. The ion source is relatively compact: length is 252 mm with a total diameter of 280 mm. The dimensions of the plasma chamber (grey) have been chosen such an RF wave with a frequency higher than 5.5 GHz can propagate inside the cavity. A movable disk is set on the back of the source, it has double objectives: RF tuning and plasma bias (negative voltage). Hence the RF is injected directly inside the cavity with a direct connection between the RF guide and the plasma chamber.

[#] maunoury@ganil.fr
* also at GANIL

OPERATION OF KEIGM FOR THE CARBON ION THERAPY FACILITY AT GUNMA UNIVERSITY

M. Muramatsu[#], A. Kitagawa, S. Hojo,
National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage-ku, Chiba 263-8555, Japan
H. Miyazaki, T. Ueno, K. Sawada,
Sumitomo Heavy Industries, Ltd., 5-2 Soubiraki, Niihama, Ehime 792-8588, Japan
M. Tsuchiyama, S. Ueda, Y. Kijima,
Mitsubishi electric corporation, 1-1-2, Wadasaki-cho, Hyogo-ku, Kobe 652-8555, Japan
K. Torikai, and S. Yamada
Gunma University, 3-39-22 Showa-machi, Maebashi, Gunma 371-8511, Japan

Abstract

Carbon-ion radiotherapy is being carried out at Gunma University Heavy Ion Medical Centre (GHMC) since March 2010. A compact electron cyclotron resonance ion source (ECRIS) for GHMC, so-called KeiGM, supplies carbon 4+ ions for treatment. The general structure of KeiGM was copied from a prototype compact source, so-called Kei2. Based on experimental studies for production of carbon 4+ ions with a 10 GHz ECR source at the Heavy Ion Medical Accelerator in Chiba (HIMAC), so-called NIRS-ECR, the field distribution of the mirror magnet for Kei2 and KeiGM was designed. A microwave source with the traveling-wave-tube (TWT) was adopted for KeiGM, with a frequency range and maximum power of 9.75 - 10.25 GHz and 750 W, respectively. The KeiGM was installed in the GHMC facility in December 2008.

INTRODUCTION

The Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) was the first heavy ion medical dedicated accelerator in the world [1]. Its aim has been to verify effectiveness and safety of heavy-ion radiotherapy. Carbon-ion radiotherapy (C-RT) started in 1994 and has mainly focused on the group of diseases in the whole body that are difficult to cure using conventional radiotherapy. The total number of patients enrolled by August 2009 was over 4,800 and various types of tumors have been treated. These results have clearly demonstrated the advantages of C-RT [2].

The Japanese government approved C-RT as a new treatment method in 2003, and promoted to development of new downsizing technologies under “the 3rd Comprehensive 10 year Strategy for Cancer Control (2004 – 2013)”. NIRS carried out R&D studies for various components and designed a hospital-specified C-RT facility [3]. The construction of the Gunma University Heavy Ion Medical Centre (GHMC [4]) was funded by the Japanese government and Gunma prefecture beginning in 2006, and construction started in 2007 at the Centre site in Maebashi, Gunma. The technologies concerned were transferred from NIRS to Gunma University. GHMC will be a demonstration of the new C-RT facility. Gunma University already started a clinical trial since March 2010. A compact electron cyclotron resonance ion source (ECRIS) for GHMC, the KeiGM, is also based on the development of the ECRIS at NIRS [5]. This article presents the operation of KeiGM and the status of their daily treatment.

CARBON ION THERAPY FACILITY AT GUNMA UNIVERSITY

In the design process, the following policies are considered to be important: (1) only high-energy carbon ions will be used in the facility to reduce the size and cost of the apparatus, and (2) beam characteristics should cover the same clinical beam characteristics as the HIMAC. Major specifications of the facility were determined on the basis of the statistics of clinical data from HIMAC. The reliable and well-established wobbler method with the respiratory-gated irradiation system was adopted for the beam delivery system [6]. It was decided to accelerate only carbon ions, with a maximum energy established at 400 MeV/n. This energy ensures a 25 cm residual range in water and, for example, carbon ions can penetrate the human body and reach the prostate through a patient’s pelvis. Another important requirement of the new facility is to have two orthogonal beam lines directed toward the same isocenter. This beam line configuration is required in order to realize sequential beam irradiation from different directions with single positioning of a patient. As a conclusion, GHMC consists of the following parts; an ECRIS, a Radio-Frequency-Quadrupole linac (RFQ), an Interdigital-H mode Drift Tube Linac (IH-DTL), a synchrotron and four treatment rooms. Of these the first room will have a horizontal beam line, the second will have a horizontal as well as a vertical beam line, and the third will have a vertical beam line. The fourth room will be used for developmental studies for advanced irradiation techniques. A fast beam course and energy switching are also required for the same purpose. The major specifications of the facility are summarized in Table 1. The main building of the facility is about 65 m × 45 m, and it was completed at the end of October 2008.

[#] m_mura@nirs.go.jp

TWO-CHAMBER CONFIGURATION OF THE BIO-NANO ECRIS

T. Uchida#, H. Minezaki, Y. Yoshida, Toyo University, Kawagoe, Japan
S. Biri, R. Racz, ATOMKI, Debrecen, Hungary
A. Kitagawa, M. Muramatsu, NIRS, Chiba, Japan
Y. Kato, Osaka University, Suita, Japan
T. Asaji, K. Tanaka, Tateyama Machine Co. Ltd., Toyama, Japan

Abstract

We are studying the application of the electron cyclotron resonance ion source (ECRIS) for the new materials production on nano-scale. Our main target is the endohedral fullerenes. There are several promising approaches to produce the endohedral fullerenes using an ECRIS. One of them is the ion-ion collision reaction of fullerenes and aliens ions to be encapsulated in the mixture plasma of them. Another way is the shooting of ion beam into a pre-prepared fullerene layer. In this study, the new device configuration of the Bio-Nano ECRIS is reported which allows the application of both methods. The basic concept and the preliminary results using Ar gas and fullerene plasmas are described.

INTRODUCTION

The Bio-Nano ECRIS was designed for new materials production on nano-scale [1,2]. Our main target is the endohedral fullerene, where endohedral means some alien atoms are encapsulated inside the fullerene cage. The endohedral fullerenes have much potential in medical care, biotechnology and nanotechnology. In particular, endohedral Fe-fullerene can be applied as a contrast material for magnetic resonance imaging or microwave heat therapy. There are several promising approaches to produce the endohedral fullerenes using an ECRIS. One of them is the ion-ion or molecule-ion collision reaction of fullerenes and aliens ions to be encapsulated in the mixture plasma of them. Here we call it the plasma method. Another way is the shooting of ion beam into a pre-prepared fullerene layer. Here we call it the ion implantation method.

One of our team has been successfully synthesized the endohedral N-fullerene using the plasma method [3]. Also the endohedral N-fullerene were synthesized using ion implantation method by S. Abe et al. [4]. In addition, several kinds of atomic species, such as Li, Na, K, Rb, and Xe were encapsulated into the fullerenes by ion implantation method [5,6,7]. However, the number of the atomic species, which are successfully encapsulated into fullerene cage, is limited. Also the yield of endohedral fullerenes is not enough to develop them for above-mentioned practical applications.

In this study, the new device configuration of the Bio-Nano ECRIS is reported which allows the application of both the plasma and the ion implantation methods. The ions of the synthesized materials can be checked by in-situ extraction and analysis. This device configuration will make it possible to produce the endohedral-Fe fullerene and improve the yield of the endohedral fullerenes.

DEVICE CONFIGURATION

Since 2006, we have developed and studied the Bio-Nano ECRIS with min-B configuration (see Fig. 1) [1,2,8]. Since 2008, the new device configuration, which we report in this paper, has been manufactured and tested.

Fig. 2 shows the schematic of the new device configuration. In contrast to the normal min-B ECRIS configuration, the plasma chamber is divided into two chambers by installing mesh electrodes and by installing an optional, second chamber (Fig. 3) which is also called processing chamber. Therefore we call this new device configuration the two-chamber configuration. The processing chamber is installed between the normal plasma chamber and the extraction box, and has 8 vacuum ports to host several connections like wave-guide, boat heater, substrate (plasma electrode) bias, substrate cooling, vacuum gauge, etc. In the gas injection side, a 2.45 GHz microwave can be introduced into the 1st chamber via coaxial waveguide. Also a 10 GHz microwave can be introduced in this chamber. There are several gas sources such as a resistance heating oven for fullerenes evaporation and an induction heating oven for iron evaporation, and a gas inlet for N_2, Ar, He, O_2, etc. Thus, we can make several plasmas in the 1st chamber. In the extraction-side 2nd chamber, a 10 GHz microwave can be introduced using a rectangular waveguide (WR75). We note that this frequency combination (2.45 GHz in the 1st chamber and 10 GHz in the 2nd chamber) was decided by some technical reasons and we do not consider them as the final solution. Later other frequencies are planned to be tested in both chambers.

An evaporation boat for fullerene is also installed in the processing chamber. The mesh electrode between the chambers and the plasma electrode can individually be biased to any DC voltage. The plasma electrode (frequently called also as collector or substrate holder) has a hole in its center to allow in-situ beam extraction.

Here let us explain the experimental procedure to produce the endohedral fullerenes using the two-chamber configuration. The gas ions to be encapsulated and the fullerene molecules or ions are generated in the 1st and the 2nd chambers, respectively. The injection of microwave into the second chamber and its power are

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uchida_t@toyo.jp

STUDY OF POTENTIAL APPLICATION OF COMPACT ECRIS TO ANALYTICAL SYSTEM *

M. Kidera[#], K. Takahashi, RIKEN, Wako, Saitama 351-0198, Japan
Y. Seto, S. Kishi, NRIPS, Kashiwa, Chiba 227-0882, Japan
S. Enomoto, Okayama University, Kita-ku, Okayama 700-8530, Japan
T. Nagamatsu, T. Tanaka, Tokyo University of Science, Shinjyuku-ku, Tokyo 162-8601, Japan

Abstract

The objective of this study is to develop a desktop-sized system of element mass analysis (element analysis system) with a compact electron cyclotron resonance (ECR) ion source in the ionization section. This system is different from other element analysis systems in terms of the effective use of ionization by ECR plasma. A compact ECR ion source is required to fit in the desktop-sized element analysis system. This paper reports the development of the compact ECR ion source.

INTRODUCTION

An ECR ion source has been developed to meet the demands of users for accelerated heavy-ion beams with high intensity, highly charged ions, high stability, a small consumption rate of rare sample, and new ionic species production. The development of large ECR ion sources is underway at large-scale heavy-ion accelerator facilities. The application of ECR ion sources or ECR plasma to various areas, for example, the use of multicharged ions in the field of atomic physics, the ionization of fullerene [1] and charge state breeding [2], has yielded positive results. The basic mass analysis and ion detection technologies for general mass analysis systems have already been established. The ionization section in mass analysis devices, however, continues to undergo intense development because of the development of new ionization techniques.

In 2007, we developed an ECR ion source for an element analysis system (ECRIS-MS) used for isotope ratio measurement [3]. This ECR ion source is, however, very large as compared to the ionization section of ICP-MS systems typically used for element analysis. In the case of an element analysis system, its size, the ease of handling, etc., are important factors determining its applicability. Thermal ionization mass spectrometers (TI-MSs) and surface ionization mass spectrometers (SIMSs) having both merits and demerits, the improvement is still given to ionize of a difficult sample now. We developed a small-sized ECR ion source for realizing a desktop-sized element mass analysis system.

FUNDAMENTAL CONSIDERATIONS IN FABRICATION OF COMPACT ECRIS

ECR plasma is nonequilibrium plasma; its ion temperature is low, although the electron temperature is high. It is advantageous to use ECR plasma sources in element analysis because the mass resolution is high when the ion temperature is low. No molecular ions are generated by the collision of radical ions, because ionization takes place in high vacuum, as compared to ionization by inductively coupled plasma. Further, numerous techniques have been developed to stably ionize gas and solid samples. In these techniques, it is necessary to maintain high vacuum in the plasma chamber. Therefore, the direct introduction of liquid samples is difficult. The directionality of development of the ECR ion source developed for the desktop-sized system differs significantly from the sources used in accelerators. A highly charged intense ion beam is not required, because the high-sensitivity channeltron detectors cannot receive intense ion beams. The charge number of the ions generated in the ECR plasma is optimized to 1+ and 2+. The stability of plasma is closely related to the accuracy of the measurement results. A confinement magnetic field has to be generated using permanent magnets if compact size and low-power consumption are the criteria for the source. A large magnetic field, however, cannot be generated with small permanent magnets. Therefore, the too high microwave frequency cannot be used significantly. In contrast, when an extremely low frequency is used, the miniaturization of the ECR ion source becomes difficult. Because the inside diameter of the magnet (i.e., plasma chamber diameter) cannot be small by the problem of the cutoff frequency. Fig. 1 shows plots of the diameter of circular waveguides (i.e., diameter of the plasma chamber) calculated from the lower cutoff frequency in the TE11 mode and the resonance magnetic field strength for microwave frequencies from 1 GHz to 32 GHz. It is necessary to miniaturize the mass analysis and detection sections.

For a compact and high-performance system, a small-sized quadrupole mass spectrometer or an ion-trap-type mass spectrometer is a promising candidate for the mass analysis and detection sections. In the case of time-of-flight spectrometers, miniaturization is difficult. Because the size of system is increased with the use of pulsed power supplies for time-of-flight method.

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[#] kidera@kindex.riken.jp

NEUTRALISATION OF ACCELERATED IONS AND DETECTION OF RESULTING NEUTRALS

T. Peleikis#, L. Panitzsch, M. Stalder, IEAP, Kiel, Germany

Abstract

At the University of Kiel, the Department of Experimental and Applied Physics is running an ECR ion source in order to, amongst others, calibrate space instruments designed to measure solar wind properties and suprathermal particles. The ion source is able to produce medium to highly charged ions which are then accelerated by an electrostatic field up to 400keV per charge. In order to extend the particle spectrum from ions to neutral atoms we are planning to install a device for the beam particle neutralisation. It will be used to calibrate instruments which measure neutral particles. This device will be located downstream from the sector magnet and the acceleration-stage. The sector magnet separates the ions by their m/q ratio. This way the type and the energy of the ions can be determined before the neutralisation. Neutralisation can be achieved either by passing the ions through a thin carbon foil (thickness ~88nm) or through a gastarget (thickness ~6mm, pressure ~0.1mbar) where charge-exchange occur. The remaining ions behind the neutraliser will be suppressed by an electrostatic separator. Both methods will alter the beam properties and lead to a divergence in energy and an angular spread of the beam. Simulations regarding these effects will be discussed. The overall progress on this project will be presented.

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peleikis@physik.uni-kiel.de

HIGH CURRENT PRODUCTION WITH 2.45 GHZ ECR ION SOURCE

A. Coly[#], T.Lamy, T. Thuillier, UJF CNRS-IN2P3 INPG, Grenoble, France
G. Gaubert, A. Villari, Pantechnik, Bayeux, France

Abstract

A new test bench has been installed at LPSC dedicated to 2.45 GHz ECR Ion Sources characterization. Several magnetic structures have been tested around the same plasma cavity. For example, a current density of 70 mA/cm2 has been measured with the MONO1000 source lent by GANIL. An original ECRIS, named SPEED (for 'Source d'ions à aimants PErmanents et Extraction Dipôlaire'), presenting a dipolar magnetic field at the extraction is also presented.

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[#] colyarona@yahoo.fr

IONIZATION EFFICIENCY OF A COMIC ION SOURCE EQUIPPED WITH A QUARTZ PLASMA CHAMBER

P. Suominen, T. Stora, CERN, Geneva, Switzerland
P. Sortais, J. Médard, LPSC, Grenoble, France

Abstract

Increased ionization efficiencies of light noble gases and molecules are required for new physics experiments in present and future radioactive ion beam facilities. In order to improve these beams, a new COMIC-type ion source with fully quartz made plasma chamber was tested. The beam current stability is typically better than 1 % and beams are easily reproducible. The highest efficiency for xenon is about 15 %. However, the main goal is produce molecular beam including radioactive carbon (in CO or CO_2), in which case the efficiency was measured to be only about 0.2 %. This paper describes the experimental prototype and its performance and provides ideas for future development.

INTRODUCTION

The ISOLDE facility at CERN produces a wide range of radioactive ion beams due to a long history on target and ion source development. Because the radioactive isotope production is very limited, the most important ion source parameters are high ionization efficiency, selectivity and reliable operation under intense radiation. Currently used ion sources (mainly laser (RILIS [1]) and arc discharge –type ion sources (VADIS [2])) do not efficiently ionize light noble gases, such as helium, and molecules, such as CO, CO_2, N_2 and NO. These beams were previously planned to be produced with 1+ ECR ion sources operating at 2.45 GHz (for example MINIMONO [3]). However, due to new and more efficient RF coupling of COMIC-type ion sources [4], we expect to advance in 2.45 GHz ECRIS utilization for radioactive beam production.

Q-COMIC

The new COMIC source (Fig. 1) designed by LPSC/Grenoble incorporates special features such as a plasma chamber fully made of quartz (Q-COMIC), which should provide chemically favourable conditions for molecular ion beam production, especially for CO_2. The beam is mainly formed between plasma (hole diameter 3.1 mm) and intermediate electrodes, which have 1.5 – 3 kV potential difference over 10 mm gap. The intermediate electrode is important in minimizing the effect of using different operation voltages to the beam formation and shape. Comprehensive emittance measurements will be performed in near future. Results are expected to be similar to those of standard COMIC [4].

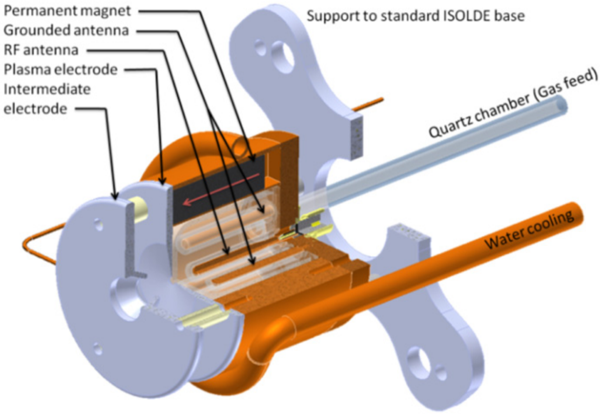

Figure 1: Schematic of Q-COMIC.

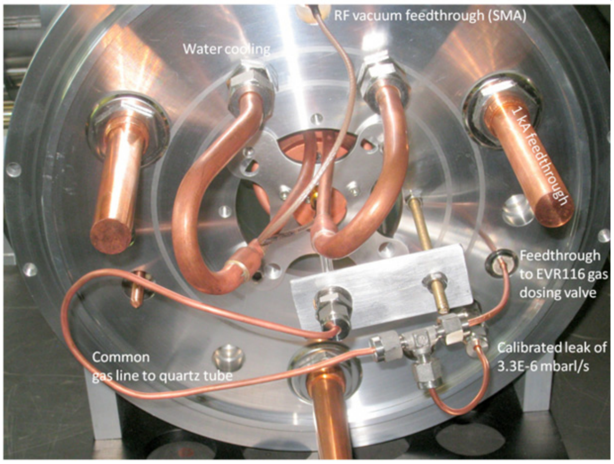

Figure 2: Q-COMIC setup and gas injection system

The source is placed inside a standard ISOLDE target base (Fig. 2), in vacuum. Consequently, a water cooling system is necessary to protect the NdFeB -permanent magnets from overheating. In this prototype unit there is no target container (between 1 kA current feedthroughs, Fig. 2) and the gas of interest (simulating a radioactive gas from target) is injected through a calibrated leak of 3.3E-6 mbarl/s (value corresponding air). The buffer gas is injected into the system by using a Pfeiffer EVR116 gas dosing valve operated by a RVC300 controller unit. Gas injection system calibration was verified with a calibrated helium leak detector.

The microwave power generator is Kuhne Electronic GmbH “KU SG 2.45-30A” operating at 2.45 GHz and capable of injecting up to 30 W microwave power. The plasma ignites typically at the pressure level of about 5E-5 mbar (at the extraction) when employing the full microwave power. However, at higher pressure of to 1E-2

HE2+ SOURCE BASED ON PENNING DISCHARGE WITH ADDITIONAL 75 GHZ ECR HEATING

I. Izotov[#], A. Vodopyanov, S. Golubev, D. Mansfeld,
IAP/RAS, Nizhny Novgorod, Russia
G. Yushkov, Institute of High Current Electronics, Tomsk, Russia

Abstract

It is well known that one can reach high average charge of ions in the ECR plasma by increasing plasma density and decreasing neutral gas pressure. ECR discharge could be realized at very low gas pressure, but discharge breakdown takes longer time when gas pressure is low. So, it is impossible to realize ECR discharge with limited microwave heating pulse duration at gas pressure lower certain threshold value. This problem could be solved with help of trigger plasma, which should be ignited at low gas pressure in the trap with high magnetic field. This fore plasma could help to decrease ECR plasma breakdown time significantly and make it possible to realize ECR plasma at very low pressure in pulse operation regime. We suggest penning type discharge as a trigger discharge for fast breakdown of pulsed ECR plasma. Penning type discharge glows at as low pressure as needed. Discharge was realized in the simple mirror magnetic trap at pressure about 1E-5 mbar. Helium was used as an operating gas. Significant plasma density (about 1e11 cm-3) was obtained at the moment just before microwave heating pulse started. Gyrotron radiation with frequency of 75 GHz, microwave power up to 200 kW and pulse duration up to 1 ms, was used for plasma heating. In the present work the fully striped helium ions were demonstrated, average charge of ions in the plasma was equal 2. Temporal evolution of charge state distribution was investigated. Charge state distribution over helium pressure was also studied.

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[#] izotov@appl.sci-nnov.ru

THE LIGHT ION GUIDE CB-ECRIS PROJECT AT THE TEXAS A&M UNIVERSITY CYCLOTRON INSTITUTE

G. Tabacaru, D. P. May, Cyclotron Institute, Texas A&M University, College Station, 77843 TX, U.S.A.
J. Ärje, JYFL, Jyväskylä, Finland

Abstract

Texas A&M University is currently configuring a scheme for the production of radioactive-ion beams that incorporates a light-ion guide (LIG) coupled with an ECRIS constructed for charge-boosting (CB-ECRIS). This scheme is part of an upgrade to the Cyclotron Institute and is intended to produce radioactive beams suitable for injection into the K500 superconducting cyclotron. The principle of operation is the following: the primary beam interacts with a production target placed in the gas cell. A continuous flow of helium gas maintains a constant pressure of 500 mbar maximum in the cell. Recoils are thermalized in the helium buffer gas and ejected from the cell within the gas flow through a small exit hole. The positively charged recoil ions (1^+) are guided into a 2.43 m long rf-only hexapole and will be transported in this manner on-axis into the CB-ECRIS (Charge Breeding – ECRIS). The CB-ECRIS will operate at 14.5 GHz and has been specially constructed by Scientific Solutions of San Diego, California for charge-boosting [1]. An overall image of the entire project will be presented with details on different construction phases. Specific measurements and results will be presented as well as future developments.

PROJECT OVERVIEW

In 2005 the Cyclotron Institute at Texas A&M University initiated a facility upgrade project [2]. This project will extend the research capabilities as a stable beam facility with moderate rare beam capabilities. This will be achieved by re-activating the 88” Cyclotron to deliver high intensity light-particle and heavy-ion beams, to be used for production of rare isotopes for acceleration in the existing K500 Cyclotron. The plan is to produce radioactive species for re-acceleration by the existing K500 Cyclotron. The main items of the scientific program that drive this project are summarized as: nuclear astrophysics (the extension of the Asymptotic Normalization Coefficients method and study of the (^{3}He,d) reactions), nuclear structure (study of the Giant Monopole Resonances and the cluster structure of the nuclei using the radioactive beams), fundamental interactions and nuclear thermodynamics (multifragmentation). We are expecting also to gain valuable experience in the development of radioactive ion sources and different methods of diagnosis for weak beams.

The project is divided in three tasks: a) recommission the existing 88” Cyclotron and install new beam lines; b) construct light-ion and heavy-ion guides and produce and transport 1^+ radioactive ions; c) charge boost radioactive ions, transport and accelerate in the K500 Cyclotron. Table 1 presents the new beams intended to be developed using the Light Ion Guide (LIG).

Table 1: Projected beam intensities from the LIG after K500 re-acceleration.

(p,n) reaction Product $T_{1/2}$	Max Energy [MeV/A]	Intensity [particles/sec]
^{27}Si (4.16s)	57	5.4×10^3
^{50}Mn (0.28s)	45	2.1×10^4
^{54}Co (0.19s)	45	5.4×10^3
^{64}Ga (2.63m)	45	3.5×10^4
^{92}Tc (4.25m)	35	3.5×10^4
^{106}In (6.20m)	28	5.4×10^4
^{108}In (58.0m)	28	2.7×10^4
^{110}In (4.9h)	26	5.4×10^4

PRODUCTION OF RADIOACTIVE IONS

The Light-Ion Guide (LIG) will produce radioactive species mainly from (p,n) reactions. The beam (a proton beam around 30 MeV) interacts with a production target (e.g. ^{27}Al) placed in a gas cell. In the gas cell helium gas is flowing continuously at constant pressure of 500 mbar maximum. The recoil ions (e.g. ^{27}Si from ^{27}Al(p,n)^{27}Si)) are trapped in the buffer gas and ejected at a 90° direction (with respect to the beam direction) through a small exit hole [3]. All ions created in the gas cell are collected and transported by a rf-only hexapole: a resonant structure similar to the RFQ in a residual gas analyzer. The large flow of helium gas is evacuated by a differential pumping system. The ions are then injected into a Charge Breeding ECRIS (CB-ECRIS) source which will ionize them to higher charge states. The radioactive species are injected into the K500 Cyclotron and re-accelerated. The primary beam (proton beam) will exit the gas cell and will be stopped in the beam dump. Figure 1 shows an engineering drawing of the LIG coupled with the CB-ECRIS. The main new feature of the device is the rf-only hexapole with a length of 2.43 m. Extensive calculations performed with SIMION [4] software confirm early theoretical approaches [5] where it was shown that all the particles entering the central region of the hexapole should have almost 100 % transport efficiency. The rf-only hexapole is a non-selective device, meaning that all

DRAGON: A NEW 18 GHz RT ECRIS WITH A LARGE PLASMA CHAMBER*

W. Lu[1], D. Z. Xie[2], X. Z. Zhang and H. W. Zhao
Institute of Modern Physics (IMP), Chinese Academy of Sciences, Lanzhou 730000
L. Ruan, F. C. Song, B. Xiong, S. Yu and J. Yuan
Institute of Electrical Engineering (IEE), Chinese Academy of Sciences, Beijing 100190
People's Republic of China

Abstract

Building a strong radial magnetic field with a permanent sextupole magnet for an ECRIS is extremely challenging so that the conventional wisdom recommends a small but not optimal plasma chamber that is typically of ID less or equal to 80 mm. A new 18 GHz RT ECRIS, DRAGON, with a large bore permanent sextupole has been designed and is under construction at IMP. Its plasma chamber is of ID 126 mm, the same as that of the superconducting ion source SECRAL, with maximum radial field strength reaching 1.5 T at the plasma chamber wall. The overall magnetic strengths of DRAGON, with maximum axial fields of 2.7 T at the injection and 1.3 T at the extraction, are very similar to those of SECRAL operating at 18 GHz and hopefully its performance. The source solenoid magnets are cooled by medium evaporation at about 50 °C. In addition, the source is thickly insulated for beam extraction at 50 kV and higher voltage up to 100 kV can be explored. This article will present the design details and discussions of this new ion source.

INTRODUCTION

In recent years ECRIS has made tremendous progress with the continuing increase of magnetic field and higher operating frequency in which the fully superconducting (SC) ECRIS takes the leading roll, while the great contribution from the Hybrid ECRIS remains to be realized. A room temperature (RT) ECRIS has the advantages of easy operation and lower cost in comparison to a SC ECRIS but with lower performance. Because of the filed strength and ac power consumption restraints, there are essentially no new improvements on the RT ECRIS since the great success of the GTS [1]. However, there are still possible rooms to further enhance the RT ECRIS' performance for cost effective applications that do not require super performance.

An RT ECRIS consists of a set of water cooled resistive solenoids and a permanent sextupole magnet. The resistive solenoids are typically made of hollow-conductor cooled by de-ionized pressurized-water. As the field strengths keep increasing for better source performance, building a strong radial magnetic field with a permanent sextupole magnet is extremely challenging. So far all the permanent sextupoles are built with a small plasma chamber of ID less or equal to 80 mm to reach a strong radial field of ~1.2 to 2 T without/with iron tips [2]. These small plasma chambers are not optimal as evidenced by the larger chambers of the SC ECRISs at about the same field profiles. An embodiment is the IMP's SC ECRIS, SECRAL, which has demonstrated great performance [3] while operating at 18 GHz with axial field maxima of 2.5 T on the injection and 1.3 T at the extraction regions and a radial field of 1.4 T at the plasma chamber wall of ID 126 mm. If an RT ECRIS can duplicate these magnetic fields with the same large plasma chamber and can produce about the same performance, it would definitely be a good improvement on RT ECRIS that comes with much lower cost and easier source operation.

In this article, we will present and discuss the design features of DRAGON, the new 18 GHz RT ECRIS being constructed at IMP, Lanzhou, China.

THE NEW 18 GHZ RT ECRIS WITH A LARGE PLASMA CHAMBER

Figure 1 shows the overall features of DRAGON. Figure 2 shows the axial field profile that reaches 2.7 T at the injection with an iron plug field booster and 1.3 T at the extraction. Figure 3 shows the calculated radial field at the plasma chamber of ID of 126 mm reaches 1.4 T and 1.5 T if six small iron tips are embedded in the plasma chamber cooling channels. Shown in Figure 4 is a cross-section view of the sextupole magnet with a simple easy-axis rotation. DRAGON's plasma chamber volume is about 6 litters, about 15% larger than the SECRAL for a slightly larger ECR volume. The maximum source magnet power consumption is about 400 kW. This new RT ECRIS has a few new features in comparison to the existing RT ECRISs:

Large Bore Sextupole

Most of the high-field RT ECRISs use a Halbach-sextupole [4] of small bore that is typically made of M equal-size sections with the easy-axis rotating 8π/M from section to the next. Such an easy-axis rotation poses a risk of regional de-magnetization when the field approaching certain strength [5]. In addition the fabrication of such a Halbach-sextupole requires very complex and delicate magnet-block cutting and assembling.

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[1] Also of the Graduate School of Chinese Academy of Sciences, Beijing 100049, P. R. China

[2] Visiting Scientist

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TESTS OF THE VERSATILE ION SOURCE (VIS) FOR HIGH POWER PROTON BEAM PRODUCTION*

S. Gammino[#], L. Celona, R. Miracoli, D. Mascali, G. Castro, G. Ciavola, INFN-LNS, Catania, Italy
F. Maimone, GSI, 64291 Darmstadt, Germany and Univ. of Catania, D.M.F.C.I, Catania, Italy
R. Gobin, O. Delferrière, G. Adroit, F. Senèe, CEA-Saclay, DSM/IRFU, Gif sur Yvette, France

Abstract

The sources adapted to beam production for high power proton accelerators must obey to the request of high brightness, stability and reliability. The Versatile Ion Source (VIS) is based on permanent magnets to produce an off-resonance microwave discharge (the maximum field value on the chamber axis is around 0.1 T). It operates up to 75 kV without a bulky high voltage platform, producing several tens of mA of proton beams and monocharged ions. The microwave injection system and the extraction electrodes geometry have been designed in order to optimize the beam brightness. Moreover, the VIS source ensures long time operations without maintenance and high reliability. A description of the main components and of the source performances is given in the following. A brief summary of the possible next developments is also presented, particularly for pulsed mode operations, that are relevant for some future projects (e.g. the European Spallation Source of Lund).

INTRODUCTION

The layout of the VIS source is reported in figure 1. The source body consists of a water-cooled copper plasma chamber (100 mm long and 90 mm diameter) surrounded by permanent magnets [1]. The plasma chamber is coupled with a 2.45 GHz magnetron through a microwave line that has been deeply studied with tools for high frequency structures simulations in order to optimize the impedance match, to maximize the electric field in the plasma chamber and to reduce the microwave losses in the 80 kV DC-break. [2,3].The magnetic system is composed by three NdFeB rings permanent magnets; the stainless steel separation rings and inner and outer iron components has been adapted to the production of an almost flat magnetic field profile along the whole plasma chamber. Moreover, the magnetic field quickly falls in the extraction region along the axis and off axis as for other sources [4], thus minimizing the stray field effect on the extracted beam as well as the Penning discharges in the first gap. The ionic component of the plasma produced in the chamber is then extracted by means of a four electrodes extraction system. It consists of a plasma electrode made of molybdenum at 65 kV voltage, two water cooled grounded electrodes and a 3.5 kV negatively biased screening electrode inserted between them to stop the secondary electrons due to residual gas ionization, backstreaming to the extraction area. The VIS extraction has been optimized to work around 40 mA and a theoretical value of 0.07 π mm mrad normalized emittance has been calculated, i.e. fulfilling the requirement of high brightness. The low energy beam transport line (LEBT) allows the beam analysis and it consists of a focusing solenoid, a four-sector diaphragm to measure the beam misalignments, a Direct-Current Current Transformer (DCCT), a 30° bending magnet and an insulated beam stop to measure the beam current. author should submit the PostScript and all of the source files (text and figures), to enable the paper to be reconstructed if there are processing difficulties.

The emittance has been measured by means of an emittance measurement unit (EMU) provided by the CEA/Saclay SILHI group described in detail in ref[5]. The EMU was not originally considered in the design of the LEBT of VIS, but with minor beam line changes it has been easily installed.

Figure 1: The VIS Source with the Emittance Measurement unit.

EMITTANCE MEASUREMENTS

The emittance measurements have been carried out for different positions of the permanent magnets to check the role of the fine magnetic field tuning on the beam. For each position (see fig.2) we investigated the emittance variation by changing the puller voltage, the microwave power and the gas pressure.

For the different operational parameters, the beam current ranges from 30 to 50 mA for an extraction voltage of 60 kV and an extraction aperture of 8 mm.

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[#]Gammino@lns.infn.it

MONOBOB II : LATEST RESULTS OF MONOCHARGED IONS SOURCE FOR SPIRAL2 PROJECT

M. Dubois, P. Jardin, O. Bajeat, C. Barue, C. Canet, M. Dupuis, J.L. Flambard, R. Frigot, C. Leboucher,
N.Lecesne, P. Lecomte, P. Leherissier, F. Lemagnen, L. Maunoury, B. Osmond, J.Y. Pacquet, A. Pichard
GANIL, bd Henri Becquerel, BP 55027, F-14076 Caen cedex 05, France

Abstract

Among the sources which can be installed in the radioactive ion production module of SPIRAL II, a singly-charged ECRIS has been chosen to produce ions from gaseous elements. Its characterization is under way on a test bench at GANIL. Extraction, transport and response time results are presented.

INTRODUCTION

In the frame of the SPIRAL II project [1] (Système de Production d'Ions Radioactifs Accélérés en Ligne phase II), four techniques of ion source (IS) have been chosen to cover a large range of radioactive ions, *i.e.* FEBIAD and LASER [2] IS's for condensable elements, surface IS [3] for alkalis, and ECRIS [4] for gaseous elements. These sources can be installed in a vacuum chamber named "production module" which contains mainly the radioactive element production target and the IS. To limit the transient time of the atom from the target to the IS, the source is installed very close to the target. In this hostile environment, a standard ECRIS including permanent magnets and non mineral insulators cannot withstand the radiation dose more than few days, what must be compared to the three months of continuous operation expected. Then the techniques and materials available to design the sources are limited and only singly-charged IS can be built. To reach the charge states required by the post accelerator CIME [5] the delivered beams are then injected in a charge-booster [6].

The most interesting isotopes are the shortest lived ones; unfortunately, their production yields in the target decreases with their half-lives, and their losses tends to increase during the atom-to-ion transformation process as their half-lives decrease. The efficiency of each step of the process, diffusion of the isotopes out of the target, effusion up to the IS, ionization and transport must then be as high as possible to make the most of the isotopes produced in the target. By difference with stable elements, the process must also be as fast as possible to limit the losses by radioactive decay.

In this paper, we report the measurements of the beam transport from the exit of the ECRIS up to the Faraday cup situated after a magnetic mass spectrometer, the emittance measurement and the measurement of the atom-to-ion transformation time in the ECRIS.

DESCRIPTION OF THE SETUP

For gases, the production module includes a carbon converter, a uranium carbide target with its oven, a transfer tube and an ECRIS (Fig. 1). A primary beam of deuterons impinges the carbon of a wheel in front of the UC target, producing a flux of neutrons which induces the fission of the uranium. As the target is maintained at 2000°C, the fission fragments diffuse out of target material, effuse up to the ECRIS via the transfer tube and are ionized in a time and with an efficiency depending on the tuning of the source and of the element.

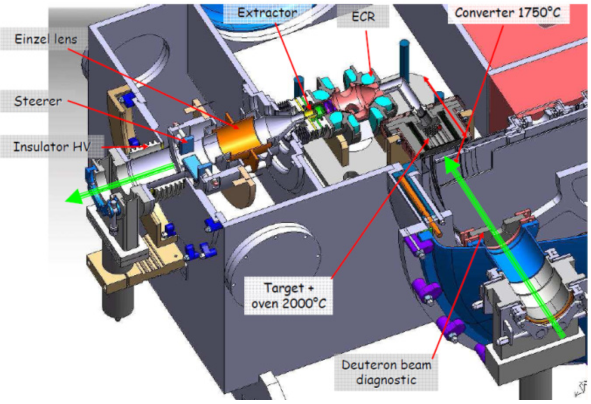

Figure 1 : Production module

The ions leave the IS trough the hole of the plasma electrode (7 mm in diameter) placed in front of the extraction electrode (14 mm in diameter, and with a tuneable position). The potential difference was maintained at 15 kV. After acceleration, the beam passes through an Einzel lens (with tuneable position), a magnetic mass analyser, an emittance meter (removable), before reaching a Faraday cup.

For safety reasons, in the frame of SPIRAL II operation, the TISS will be installed in a vacuum chamber where the pressure must be lower than 10^{-5} mbar after outgassing. During the present tests, the vacuum chamber reproduces these vacuum conditions, but the UC pills were replaced by carbon pills.

Two fast valves were installed on the TISS: one at the opposite of the plasma electrode hole to measure the response time of the source, and one on the target container, at the opposite of the aperture towards the IS to measure the contribution of the target to the response time of the TISS.

Fast valves were fed with a mixture of He, Ne, Ar, Kr, and Xe. Support gas was N_2, 0_2 being forbidden in case of carbon target at high temperature (max 1500°C).

TRANSPORT OPTIMISATION

The optimal distance between the extraction and plasma electrodes has been found equal to 31 mm. The transport of the beam from the exit of the ECRIS up to the Faraday cup has been estimated by comparing the total

THE DESIGN OF 28 GHZ ECR ION SOURCE FOR THE COMPACT LINEAR ACCELERATOR IN KOREA

B. S. Lee[#], M. Won, Korea Basic Science Institute, Busan, Republic of Korea

Abstract

The construction of a compact linear accelerator is in progress by Korea Basic Science Institute. The main capability of this facility is the production of multiply ionized metal clusters and the generation more intense beams of highly charged ions for material, medical and nuclear physical research. To produce the intense beam of highly charged ions, we will construct an Electron Cyclotron Resonance Ion Source (ECRIS) using 28 GHz micrewaves. For this ECRIS, The design of a superconducting magnet, microwave inlet, beam extraction and plasma chamber was completed. Also we are constructing a superconducing magnet system. In this presentation, we will report the current status of development of our 28GHz ECRIS.

Paper not received

[#] bslee@kbsi.re.kr

THE DESIGN STUDY OF SUPERCONDUCTING MAGNET SYSTEM FOR AN ADVANCED ECR ION SOURCE*

M. Won#, B. S. Lee, Korea Basic Science Institute, Busan, Republic of Korea

Abstract

The Korea Basic Science Institute is developing a superconducting magnet system for 28 GHz Electron Cyclotron Resonance Ion Source (ECRIS). We are investigating in order to realize compact size, economic operation and generation of high current beam. Although companies and researchers have valuable experience, skill and ability in designing of superconducting magnet for ECRIS, they did not exactly proposed a excellent superconducting magnet system for ECRIS because many superconducting magnets were not required. Of course they do if we required many magnets for the various applications of ECRIS. In this presentation, we have filed reports of former researcher and we have discussed the realization of ECRIS over 35 GHz.

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*Work was supported by KBSI grant D30300

mswon@kbsi.re.kr

A LOW POWER SURVEY OF RADIAL-OFFSET AXIAL SPUTTERING AND HIGH INTENSITY URANIUM PRODUCTION FROM AXIAL SPUTTERING IN SUSI[*]

D. Cole, G. Machicoane, T. Ropponen, L. Sun, and L. Tobos, National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA.

Abstract

Results of a low power survey of axial sputtering, to test sputtering efficiency at incremental radial offsets from on axis position, is reported. Also, prototype axial sputtering hardware has been tested in the SuSI ion source and the uranium ion production results is discussed.

INTRODUCTION

The National Superconducting Cyclotron Laboratory (NSCL) depends on each of its ECR ion sources for production of all required primary beams found on the Coupled Cyclotron Facility user beam list. A schedule of beam development for the SuSI ECRIS [1], supporting the NSCL experimental program since Fall 2009, is ongoing. Parallel efforts toward development of Uranium beams from SuSI are being pursued at this time. The process of producing uranium beams from axial sputtering has been investigated and is being developed.

The SuSI plasma chamber injection baffle is 100mm in diameter and therefore has limited area for installation of RF waveguides, gas port, biased disk, and RF inductive oven or resistive oven assemblies. The need to install a sputter target, for possible uranium beam development, on an already congested surface led to the question of where a sputter target must be located. Intuitively, the sputter surface would seem to be best on the plasma chamber axis, but the possibility of sputtering at positions radially offset from the axis and the relative sputter efficiency at such positions was unknown.

In December of 2009 a simple survey of relative sputter efficiency of radially off-axis sputter target positions and at increasing axial insertion toward the plasma was done. Based on the results, a prototype on axis sputter assembly was built, tested and is presented in this paper.

LOW POWER SURVEY OF SPUTTER TARGET POSITION

In December of 2009 a survey of radial offset sputtering was performed, The survey was done at very low RF power (500W) due to the sample not being cooled and the risk of X-ray damage to the plasma chamber insulation, which had not at that time been upgraded to tantalum shielding and PEEK insulation [2]. Considering the uranium target geometry, sputtering on the side of a cylindrical surface, was expected to be very inefficient. The sputter target was swept through an arc into the radial loss line and finally to the on axis position (see Fig. 1).

Measurements of uranium production intensities were made at radial positions of 0mm, 9mm, 18mm, 27.5mm and completely away from plasma interaction. The injection baffle was generally located on the injection field maximum. At each radial offset position the sample sputter surface was initially 10mm from the injection baffle surface and then moved longitudinally toward the plasma by increments of 5mm. The sputter target was biased over a limited range of 0 to -2kV.

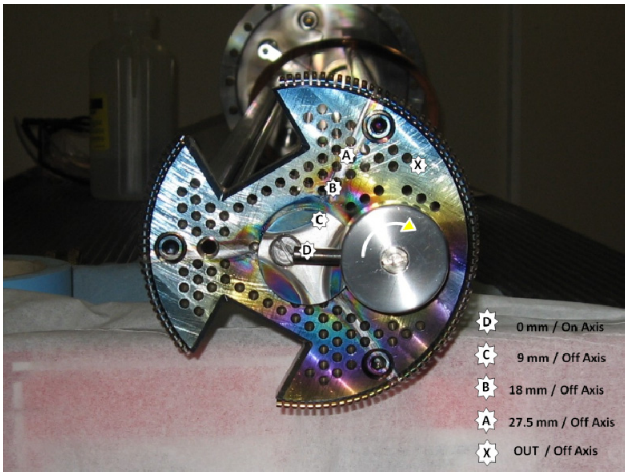

Figure 1: Low Power Radial-Offset Sputter Survey Hardware.

In addition to the survey, a small uranium sample with a diameter of 5 mm was mounted on axis and inline with the plasma chamber axis. It was positioned longitudinally 25mm above the injection baffle surface (toward the plasma). The baffle was located at the injection field maximum. A low power survey of sputter efficiency was done moving the sample into the plasma chamber in 5mm increments. Additionally, an assortment of support gases was tried.

Results of Survey

Results of the survey are shown in figure 2. It was clear that the Uranium sputter production yield is highest on the axis of the plasma loss cone, (0 mm radial offset). Sputter production does occur along the radial loss line with a sputter efficiency that is remarkably uniform from 9mm to 27.5 mm radius. In general the sputter yield increased with axial insertion of the sample from 0 – 15 mm and with target bias voltage from -1 kV to -2kV.

Sputter yield increased with heavier mass support gases, with oxygen and neon being reasonable choices for middle to high uranium charge states. Argon sputters very efficiently, but being a poor mixing gas drives the charge

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TESTS OF A NEW AXIAL SPUTTERING TECHNIQUE IN AN ECRIS*

R. Scott[#], R. Pardo, R. Vondrasek, Argonne National Laboratory, Argonne, IL 60439, U.S.A.

Abstract

Axial and radial sputtering techniques have been used over the years to create beams from an ECRIS at multiple accelerator facilities. Operational experience has shown greater beam production when using the radial sputtering method versus axial sputtering. At Argonne National Laboratory, previous work with radial sputtering has demonstrated that the position of the sputter sample relative to the plasma chamber wall influences sample drain current, beam production and charge state distribution. The possibility of the chamber wall acting as a ground plane which influences the sputtering of material has been considered, and an attempt has been made to mimic this possible ground plane effect with a coaxial sample introduced from the injection end. Results of these tests will be shown as well as comparisons of outputs using the two methods.

INTRODUCTION

There are two Electron Cyclotron Resonance Ion Sources (ECRIS) in operation at the ATLAS facility at Argonne National Laboratory. The ECR charge breeder (ECRCB) has been dedicated primarily for charge breeding development and production as the Californium Rare Ion Beam Upgrade CARIBU comes online. ECR2 has become the primary stable beam producer at ATLAS using a variety of techniques including gas injection, oven, and sputtering. Sputtering was developed at Argonne [1] and has been used often on both sources. ECR2 is an evolved version of an AECR-U [2] type ECRIS. While radial sputtering has been heavily used, axial sputtering has not been characterized on this specific source. A new co-axial sputtering technique has been tested and compared with radial and axial methods in hopes of better understanding this form of metal ion production. The characterizations obtained could also be useful for final development of the Actinide Accelerator Mass Spectroscopy project [3].

SPUTTERING TECHNIQUES

Three sputtering methods were used during the course of this evaluation. Efforts were made to provide consistency of measurements. The same negative bias power supply was used for all tests for repeatable voltage and current measurements. Single frequency (~14GHz) RF inputs at prescribed power levels as well as similar source bake out conditions were maintained. Oxygen was used for support with no additional gas mixing. The injection side bias disk was grounded to eliminate another variable. Standard radial, standard “bare” axial, and axial with grounded sleeve techniques are described next.

Standard Radial

This method is the preferred for sputtering at ATLAS. ECR2 has a generous radial port to allow up to a 5mm diameter sample to be inserted. The sample is inserted through an air-lock/insulator assembly toward the plasma into a pumping port that exists in a gap between the hexapole bars (see Fig. 1 below).

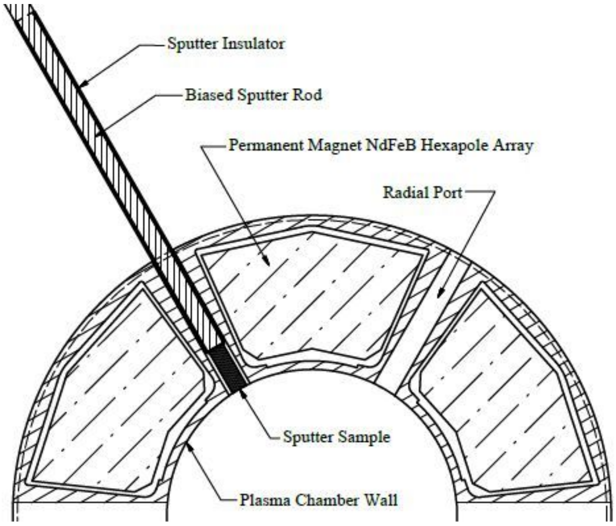

Figure 1: Section view of standard radial sputtering.

Typical gaps between the port wall and the sample are between 0.25 mm and 1.25 mm. Through previous experimentation with ECR2 the ideal location for sputtering has been found where the face of the sample is even with the plasma chamber wall. This location was chosen for our tests. Beam current and consumption rate measurements as well as radial sputtering parameters were used as a comparison to the 2 axial methods.

Standard Axial

Although radial sputtering is preferred, it cannot always be used. The use of radial ports spreads the magnet bars apart increasing the plasma chamber bore and weakening the hexapole magnetic confinement. Many groups omit this gap (and port) for this reason. Also, fundamental design constraints for all-permanent magnet ECRIS and 3rd and 4th generation superconducting ECRIS do not allow for radial ports. In these cases sputtering is only allowable axially.

Typically a sample is attached to a biased rod and inserted into the plasma chamber injection end (see Fig. 2). A location with an existing hole in the shaping plug was chosen. It is offset 2.2 cm from the centerline of the plasma chamber and in between the magnetic loss lines, evidenced by the plasma star on the biased disk, which

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[#] rscott@phy.anl.gov

FIRST A/Q=3 BEAMS OF PHOENIX V2 ON THE HEAVY IONS LOW ENERGY BEAM TRANSPORT LINE OF SPIRAL2

C. Peaucelle[#], CNRS-IN2P3, IPN Lyon, France
J. Angot, P. Grandemange, T. Lamy, T. Thuillier, CNRS-IN2P3, LPSC Grenoble, France
J-L Biarrotte, CNRS-IN2P3, IPN Orsay, France
D. Uriot, CEA Saclay, SACM France.

Abstract

The heavy ions low energy beam transport line (LEBT) of Spiral2 built at LPSC Grenoble is fully operational since the beginning of 2010. This LEBT has been calculated and designed to hold permanently 15 mA of multi charged ions extracted from the source at 60 kV extraction high voltage. The LEBT is shortly described. The PHOENIX V2 ECRIS is presently installed on the LEBT and first beam tests results are reported. A daily reliable beam of 1 mAe of O6+ beam at 45 kV has been obtained with a high LEBT transmission efficiency of 90. Preliminary Argon tuning shows a reproducible beam of 130 µA of Ar12+ beam. Improved currents are expected in the future. Associated emittance measurements, beam profiles are also presented. The future program, including A-PHOENIX restart, and planned improvements on the LEBT are discussed.

INTRODUCTION

The present configuration of Spiral 2 accelerator [1] features two electron Cyclotron resonance ion source (ECRIS) that produce either heavy or light ion beams. These beams are selected by a low energy beam transport line (LEBT) before being injected in an 88 MHz radio frequency quadrupole and a superconducting linear accelerator. LPSC is in charge of the assembly and commissioning of the heavy ion LEBT. This line is currently equipped with the PHOENIX V2 ECRIS, shortly described later.

THE HEAVY ION LOW ENERGY BEAM LINE

This new line, displayed on Fig. 1 was calculated and dimensioned by GANIL, CEA/IRFU and IPNO [2] to hold permanently 15 mA of total ionic beam current extracted from a heavy ion source at 60 kV voltage.

First, a solenoid is placed immediately after the ECR ion source. Then stand a quadripole triplet and a double-focusing 90° bending magnet designed with simple flat shimmed pole. An associated hexapole located before the dipole is used to reduce the non-linearities induced by such a dipole. Two faraday cups (FC) are available: one in front of the ECRIS extraction to measure the total ionic current and the second after the dipole to measure the selected beam. The overall transmission efficiency of the beam line can be deduced from these two measurements. The LEBT is also equipped with 3 profilers to centre the beams, a set of 3 motorized slits to clean the beam and perform the mass resolution through the dipole. Next, two Allison type emittancemeters are located after a second quadrupole triplet.

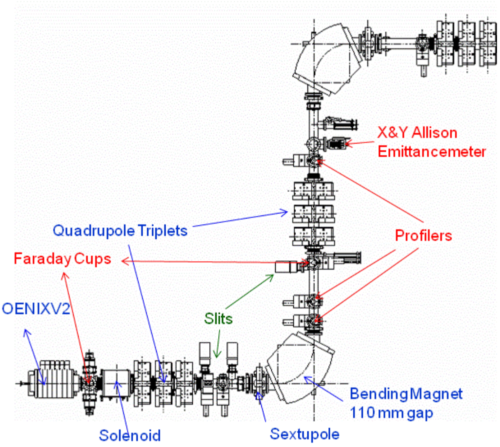

Figure 1: general sketch of the LEBT.

The LEBT uses ultra high vacuum standards for vacuum in order to minimize charge exchange in the accelerator. The pumping system is designed to reach 1.10^{-8} mbar in the whole beam line during high current production operation. Concerning the control command system, EPICS (Experimental Physics and Industrial Control System) [3] was chosen by Spiral 2 project.

THE PHOENIX V2 AND A-PHOENIX HEAVY ION SOURCES

In a first step the 18 GHz ECR ion source PHOENIX V2 [4] (see Fig. 2) is installed on the LEBT to commission it. This source has already been tested with Ar, Xe, O and He beam. Several upgrades have been made to improve the performance of this ECRIS: a water-cooled bias disk was added and new design of iron yoke allows increasing the magnetic field at the injection side from 1.7 T to 2.1 T now. The new injection flange designed accepts an oven reaching 1600°C performed by GANIL to produce ion metallic beam.

A-PHOENIX is a compact hybrid ECR ion source [5, 6] with two High Temperature Superconducting (HTS) coils and an innovative large permanent magnet hexapole. The magnetic structure allows reaching 2T radial magnetic field and 3T axial magnetic confinement. A-PHOENIX is designed to operate with frequencies from 18 to 28 GHz.

Because of the weld break of one the HTS cryostat, experiments on A-PHOENIX stopped in December 2009.

[#] peaucelle@ipnl.in2p3.fr

TRACE SPACE RECONSTRUCTION FROM PEPPERPOT DATA

H.R. Kremers*, J.P.M. Beijers, V. Mironov, J.Mulder, S. Saminathan, S. Brandenburg,
Kernfysisch Versneller Instituut, Groningen, The Netherlands

Abstract

In this paper we present a simple model that we developed to reconstruct the 4D trace space distribution from the convoluted spatial images of a pepperpot emittance meter. Straightforward analysis of the images is hampered because of multiple and/or overlapping beamlets emerging from a single hole in the pepper plate. The model allows us to unambiguously assign each transmitted beamlet to its corresponding hole in the pepper plate from which it emerged. We will illustrate our analysis model with the reconstruction of the 4D trace space distribution behind the analyzing magnet of a He^{1+} beam extracted from an electron cyclotron resonance ion source.

INTRODUCTION

It is well known that electron cyclotron resonance ion sources (ECRIS) produce ion beams with relatively large emittances, i.e. several tens of π mm-mrad or even larger. Such low-quality ion beams are difficult to transport to and inject into an accelerator with high efficiency. Much work is therefore being devoted to better understand and improve low-energy ion beam transport. At KVI we made some progress by a combined effort of detailed beam transport simulations and measurements of beam profiles and emittances. This is reported in an accompanying paper to these proceedings [1]. To measure the 4D beam emittance of low-energy multiply-charged ion beams we built a pepperpot emittance meter and installed it in the image plane of the analyzing magnet [2]. However, overlapping and multiple beamlets emerging from a single hole in the pepper plate complicate a straightforward reconstruction of the 4D trace-space of the ion beam. This paper presents a simple method that we developed to overcome this problem. After a brief description of the emittance meter the above-mentioned problem will be illustrated with an emittance measurement of a 21 keV He^{1+} beam. Then the analysis method will be outlined that we developed to unambiguously reconstruct the 4D trace-space distribution of the ion beam.

PEPPERPOT EMITTANCE METER

The KVI4D emittance meter combines the pepperpot and scanning techniques to measure the 4D trace-space distribution of ion beams which have a large divergence and narrow width in the horizontal plane and a small divergence and large width in the vertical plane [2]. This is done by stepping a pepper plate with a linear array of holes aligned in the vertical direction horizontally through the beam and measuring the images of the transmitted beamlets at each step with a position-sensitive detector positioned 59 mm downstream of the pepper plate. The pepper plate is a 25 μm tantalum foil, mounted on a water-cooled copper block, with a vertical row of 20 holes each with a diameter of 20 μm and a pitch of 2 mm. The step width in the horizontal direction depends on the desired resolution, and is typically around 0.5 mm. We installed the pepperpot emittance meter near the focal plane of the 110° analyzing magnet.

An emittance measurement consists of measuring a series of spatial images of the transmitted beamlets, one at each horizontal step. As an example we measured the emittance of a 21 keV He^{1+} beam. The horizontal step size was set at 0.56 mm and we measured 39 spatial images of the transmitted beamlets from which the 4D trace-space distribution has to be reconstructed. A single spatial image taken at the horizontal position of x=-4 mm is shown in Fig. 1a. Also the location of the holes in the pepper plate is indicated. Fig. 1a clearly shows that there are i) more beamlets than there are holes and ii) some of the beamlets are overlapping. This complicates the analysis.

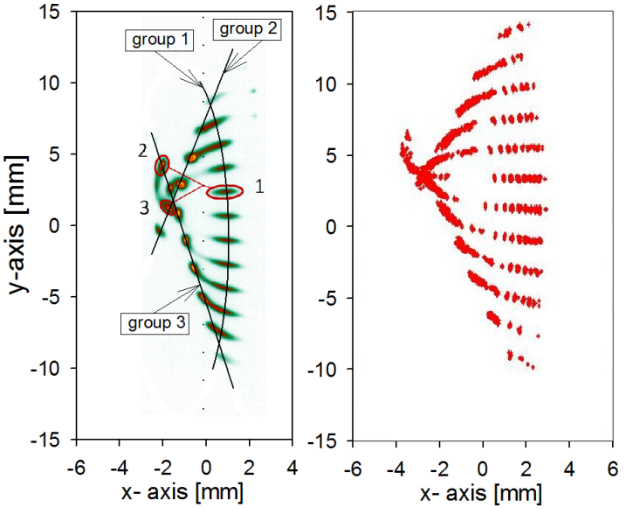

Figure 1: Measured a) and simulated b) spatial image obtained with the KVI4D emittance meter of transmitted beamlets with the pepper plate positioned at x=-4 mm for a 21 keV He^{1+} beam.

THE ANALYSIS

As already mentioned above the measured spatial images sometimes show both overlapping beamlets and, particularly around the median plane, multiple beamlets emerging from a single hole. From the systematic trend in the series of 39 images we could connect each beamlet with the hole in the pepper plate from which it emerged. An example is shown in Fig. 1a where three beamlets are connected that emerge from one hole. In addition, it

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* kremers@kvi.nl

PLASMA-TO-TARGET WARP SIMULATIONS OF URANIUM BEAMS EXTRACTED FROM VENUS COMPARED TO EMITTANCE MEASUREMENTS AND BEAM IMAGES *

D. Winklehner[#], D. Todd, LBNL, Berkeley, CA 94704, USA
D. Grote, LLNL, Livermore, CA 94551, USA
D. Leitner, J. Benitez, M. Strohmeier, LBNL, Berkeley, CA 94704, USA

Abstract

This work presents the latest results of an ongoing effort to simulate the extraction from ECR ion sources and the Low Energy Beam Transport (LEBT). Its aim is to help understand the influence of parameters like initial ion distributions at the extraction aperture, ion temperatures and beam neutralization on the quality of the beam and to provide a design-tool for extraction- and transport-systems. Simulations of multispecies beams (Uranium of charge state 15+ to 42+ and Oxygen) extracted from the VENUS ECR ion source are presented and compared to experimentally obtained emittance values.

INTRODUCTION

The superconducting Versatile ECR ion source for NUclear Science (VENUS) [1, 2], was developed as the prototype injector for the Facility for Rare Isotope Beams (FRIB) and as injector ion source for the 88" – Cyclotron at Lawrence Berkeley National Laboratory [3, 4]. Like most ECR ion sources VENUS operates in a minimum B field configuration which means that a magnetic sextupolar field for radial confinement is superimposed with a magnetic mirror field for axial confinement. Consequently:

- Ions are extracted out of a region with high axial magnetic field (in VENUS typically 2 T) which then continuously decreases as the ions move along in axial direction, adding a rotational component to the beam.
- Due to the sextupolar field, the total magnetic field inside the source is not rotationally symmetric and thus the spatial distribution of ions at extraction resembles a triangle rather than a circle [5].

Furthermore, the extracted beam often consists of more than 30 different ion species with different mass-to-charge ratios which makes modeling even more complicated. The work described here represents the current status of a long-term effort to create a highly adaptable, advanced simulation script utilizing the well-established particle-in-cell (PIC) code WARP [6].

SIMULATIONS

Many of the issues regarding the extraction simulation and the beam transport through the beam line have been addressed in earlier work by D. Todd et al. (e.g. [5, 7]) and will only be reviewed briefly here.

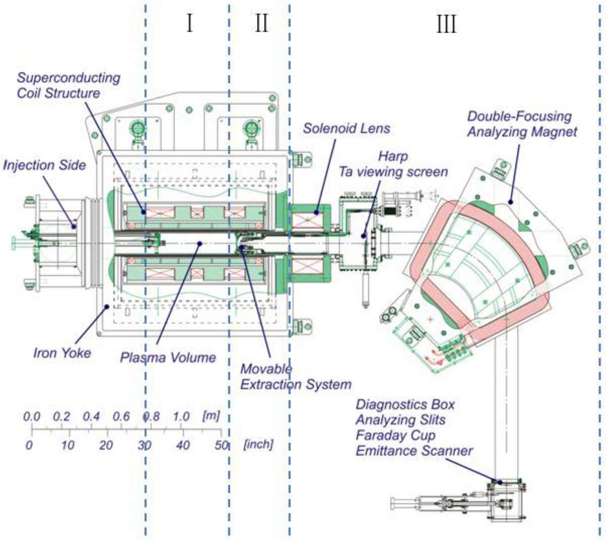

Figure 1: VENUS source and LEBT layout.

Initial Conditions

(See Figure 1, region I: Inside the plasma) For this work, a semi-empirical approach to obtain initial conditions on the plasma side of the extraction simulation was taken: VENUS's biased disk on the far side of the source is kept at a voltage of -50 V to -100V, thus providing the ions with enough kinetic energy to sputter the surface. A triangle with sharp edges was found to be etched into the disk, showing the spatial distribution of the ion beam on the injection side of the source. Because the ions are cold (a few eV) resulting in small Larmor radii it is reasonable to assume that they mainly follow the magnetic field lines. In addition, there is no reason why the direction towards the biased disk should be preferred, thus it can be argued that a similar ion beam distribution can be found on the extraction side of the source. To obtain the initial conditions the following recipe was used for each species: 10000 ions are randomly distributed on a triangle corresponding to the sputtered triangle and are given a random velocity corresponding to a Boltzmann distribution with a peak temperature of 2 eV. Then, each particle's respective gyro-motion guiding-centre is calculated and the field-line originating at that point is tracked through the source. At the respective end-point, an appropriately scaled Larmor radius is applied and the particle is put on a random point on a circle with this scaled radius around the guiding-centre. Because travelling through the

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dwinklehner@lbl.gov

PRODUCTION OF HIGHLY CHARGED U ION BEAM FROM RIKEN SC-ECRIS

Y. Higurashi#,1, T. Nakagawa1, J. Ohnishi1 ,H. Haba1, E. ikezawa1, M. Fujimaki1, Y. Watanabe1,
M. Komiyama1, M. Kase1, A. Goto1, O. Kamigaito1, T. Aihara2, M. Tamura2, A. Uchiyama2,
1 RIKEN Nishina Center 2-1 hirosawa Wako, Saitama JAPAN, 351-0198
2 SHI Accelerator Service, Ltd. 1-17-6 ohsaki, Shinagawa-ku Tokyo JAPAN, 141-0032.

Abstract

In 2008, we produced 345 MeV/u beam (~0.4pnA on target) for RIKEN RIBF. To increase the U beam intensity, we produced U^{35+} from RIKEN SC-ECRIS with sputtering method. To maximize the beam intensity, we made various test experiments. We obtained 2~0.7 pμA of highly charged U ion (27~35+) at the RF power of ~1.2kW.

INTRODUCTION

In 2008, we produced 345 MeV/u U beam (0.4 pnA on target) and observed more than 40 new isotopes with in-flight fission reaction for only 4 days experiments [1]. This experiment shows that the intense U beam is strong tool to produce very neutron rich nuclei and to study the r-process in nuclear synthesis. Using 18 GHz RIKEN ECRIS, we only produced 2~4 eμA of U^{35+} beam, which was much lower than the required beam intensity for RIKEN RIBF. For this reason, to meet the requirement, we constructed new SC-ECRIS which has the optimum magnetic field strength for 28GHz.[2] In the autumn of 2009, we obtained first beam of U^{35+} from RIKEN-SC-ECRIS with 18 GHz microwave. Since then, we tried to increase the beam intensity of highly charged U ion beam.

In this article, we report the results of the test experiment for production of highly charged U ion beam.

SC-ECRIS

The detailed structure of the SC-ECRIS and the test experiment was described in refs. 2, 3. For operation of 28 GHz microwaves, the B_{inj}, B_{ext} and B_{r} are 3.8, 2.2 and 2.2 T, respectively. The main feature of this ion source is that it has six solenoid coils to produce mirror magnetic field at the axial direction. Using this configuration, one can change the magnetic field gradient at ECR zone and ECR zone size independently. To keep the superconductivity, the cryostat is equipped with three small GM refrigerators. The amount of liquid He is about 500 L. The cooling power at 4 K is about 1 W. It was reported that the higher microwave frequency gives stronger heat load. [4] To keep the superconductivity against the heat load, we need stronger cooling power for cryostat. For this reason, we installed GM-JT refrigerator (cooling power of 5 W at 4 K) to increase the cooling power in the end of 2009.

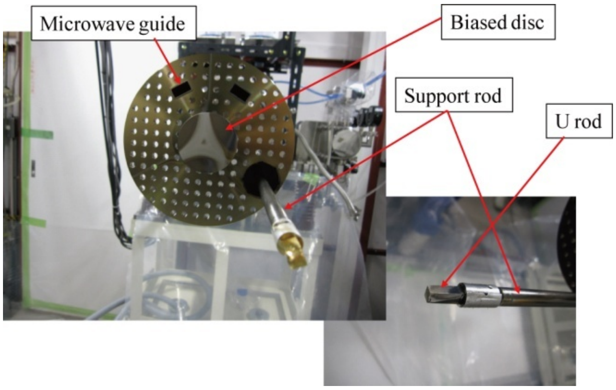

Figure 1: Photograph of the RF injection side and U rod.

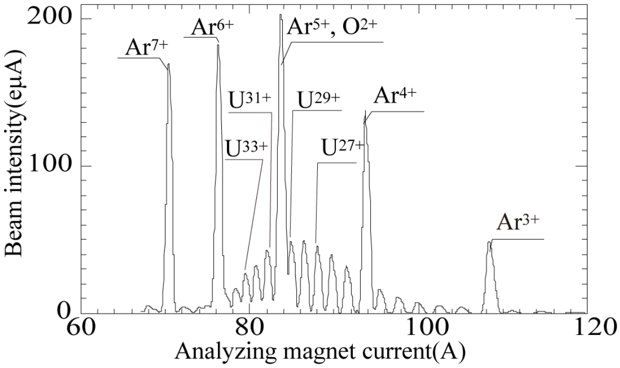

Figure 2: Charge state distribution of the U ion, when using the O2+Ar gas as an ionized gas.

U BEAM PRODUCTION

Fig. 1 shows the photograph of the RF injection side. To produce U ion beam, we used the sputtering method. As shown in Fig. 1, the metal uranium was installed at off-center axis. The metal U was supported by supporting rod. The position of rod was remotely controlled within the error of ~0.2mm. The support rod was water cooled for minimizing the chemical reaction between metal uranium and material of uranium holder at high temperature. The rod position and high voltage for sputtering were optimized for maximizing the beam intensity of highly charged U ions.

For investigating the support gas effect, we used the O_2 , Ar and Ar+O_2 gas as an ionized gas. Fig. 2 shows the charge distribution of the highly charged U ion with using O_2+Ar gas. The RF power was 980 W. The extraction voltage was 17 kV.

[#] higurasi@riken.jp

PREGLOW PHENOMENON ORIGIN AND ITS SCALING FOR ECRIS

I. Izotov[#], A. Sidorov, V. Skalyga, V. Zorin, IAP RAS, Nizhny Novgorod, Russia

Abstract

Preglow effect investigation is one of topical directions of ECR ion sources development at present. Preglow is of interest for efficient short-pulsed multicharged ion source creation. Particularly, such source of intense beams of shortliving radioactive isotopes multi-charged ions is one of key elements in “Beta-Beam” European project [1]. Use of Preglow-generating regime of an ECRIS operation is a promising way of pulsed high-intense multi-charged ion beams production with much shorter edges in comparison with usual operation regime. The first theoretical investigations of Preglow phenomenon were performed in references [2, 3]. Numerical simulations made with the updated theoretical model allow authors to propose more physical and intuitive explanation of Preglow phenomenon origins. Obtained dependences of Preglow characteristics on experimental conditions offer a scaling for a wide range of ECRISes.

INTRODUCTION

The preglow effect was first observed in experiments in LPSC (Grenoble, France) and later modeled theoretically in the works [2,3]. Theoretical model of ECR discharge development in a magnetic trap of an ECR MCI source, modified as compared to [2], allowed us to simulate the process of preglow peak more accurately and to assess dependence of its parameters on experimental conditions. The performed theoretical research and results of the numerical modeling give a new, more physical and clear insight into the nature of the preglow effect. We investigated preglow peak duration and intensity as a function of parameters controlled in experiments. Besides, we found a dimensionless parameter characterizing the regime of plasma confinement in the source trap that universally defines the preglow properties and may be used as scaling for a wide class of available and future experimental facilities. These results are also presented in the paper.

PHYSICAL INTERPRETATION OF PREGLOW

Theoretical research demonstrated that the condition necessary for the existence of multicharged ion current burst at the beginning of the pulse, i.e., preglow, is intense heating of electrons by microwave radiation at the initial stage of gas breakdown that must be sufficient for formation and maintaining for some time of superadiabatic energy electron distribution function (EEDF, see [3]). The EEDF form ensures efficient neutral gas ionization due to the presence of electrons in the energy region corresponding to maximum ionization cross-sections, on the one hand, and allows “storing” higher energy (compared to the maxwellian EEDF with the same mean energy) of “hot” electrons whose lifetime in the trap is large in comparison with the characteristic time of discharge evolution, on the other hand. Hereinafter, under plasma energy content we understand the quantity $w=<E>*Ne$, where $<E>$ is average electron energy over EEDF, and Ne is electron concentration.

With a definite combination of parameters of seed plasma, the concentration of neutral particles at the beginning of the discharge and characteristics of heating microwave radiation, there may occurs a situation when the energy stored at the initial stage of plasma breakdown is much higher than its energy content at the steady-state stage of discharge combustion. Fast withdrawal of this excess energy in the form of an intense flux of charged particles from the trap gives rise to a preglow peak. In other words, at the stage of avalanche-like growth of plasma concentration, when its magnitude reaches a high enough level, the energy stored in hot electrons as well as the energy of microwave radiation is expended on intense gas ionization. This energy reserve makes it possible in a short time to create plasma with concentration and temperature higher than those attainable by means of microwave radiation. A particle flux from the magnetic trap, too, may be much higher than the steady-state one. Note that, if the power of microwave radiation is so small that sufficient energy cannot be stored, there will be no preglow effect. Nor will it occur in the case of too large power, when all the electrons, even with total-lot gas ionization, are heated up to maximum energies.

The said above may be readily illustrated by means of numerical modeling of the evolution of ECR discharge within the framework of the considered theoretical model. Results of computation of the dynamics of plasma energy content, its concentration and density of particles flux from the trap at the initial stage of discharge are presented in fig. 1 for the following parameters: 28 GHz, 200 W/cm^2.

It is clearly seen from the time plots in fig. 1 that, by the time the particle flux from the trap starts to grow, the plasma energy content is almost an order of magnitude higher than the steady-state level and termination of the stored energy release exactly coincides with termination of the burst of particle flux, after which the discharge parameters take on steady-state values. The preglow current peak intensity (the ratio of the amplitude of peak current to a steady-state value) in this case is the larger, the higher the maximum plasma energy content was in comparison with the steady-state one.

[#] izotov@appl.sci-nnov.ru

“PREGLOW” INVESTIGATION IN ECR DISCHARGE AT 37 GHZ, 100 KW

V.G. Zorin, V.A. Skalyga, I.V. Izotov, S.V. Razin, A.V. Sidorov, Institute of Applied Physics of
Russian Academy of Sciences, 46 Ul’yanova st., Nizhny Novgorod, Russia, 603950*
T.Lamy, T. Thuillier, The Laboratoire de Physique Subatomique et de Cosmologie UJF-IN2P3-
CNRS, 53 Av. Des Martyrs, 38026 Grenoble Cedex, France.

Abstract

Multicharged ion beams generation in "Preglow" regime is now considered as the main way of short pulsed ion source creation for “Beta Beam” project [1]. The "Preglow" effect has been investigated at a several laboratories (LPSC, JYFL, IAP RAS). The effect was discovered at LPSC on PHOENIX ion source using 18 GHz radiation for plasma heating. Investigations at 14 GHz frequency were made at JYFL. Theoretical analysis demonstrated the advantage of MW frequency increase. Theoretical calculations predict possibility of "Preglow" peaks generation with duration about tens microseconds and rather high average ion charge. At present time at LPSC a joint construction of a new generation ECR ion source with 60 GHz gyrotron plasma heating is running.

As a continuation of previous research at 14, 18 and 28 GHz at present work results of experimental and theoretical "Preglow" effect investigations at SMIS 37 setup with 37,5 GHz MW plasma heating are reported. Received data are important as fundamental result in physics of ECRISs and at the same time it is the next step on the way of 60 GHz SEISM facility creation.

“Preglow” effect was observed and investigated in experiments with ECR discharge stimulated with gyrotron radiation @ 37.5 GHz, 100 kW. Received dependencies of the “Preglow” parameters are in good correspondence with results of numerical simulations. It was shown in experiments that generation of “Preglow” peak with duration about 30 μs is possible.

INTRODUCTION

Investigation of the preglow effect is one of the topical trends in the field of ECR sources of multicharged particles. This effect is, basically, generation of a sharp burst of multicharged ion (MCI) current at the beginning of a microwave pulse, which ensures gas breakdown and plasma confinement in an ion-source magnetic trap. The interest in the preglow effect is associated with prospects of creating an efficient short-pulse MCI source. Such sources are currently in great demand for research in nuclear physics and physics of elementary particles to be carried out on accelerators of new generation.

The preglow effect was first observed in experiments in LPSC and later modeled theoretically in the works [2, 3]. Present work is devoted to experimental demonstration of preglow effect in ECR ion source with gyrotron plasma heating @ 37 GHz, 100 kW.

FORMULATION OF THE PROBLEM

In frame of short pulse creation problem first of all it is necessary to perform the analysis of gas breakdown dynamics dependences on different parameters.

A microwave breakdown of a rarefied gas in a magnetic trap under the ECR conditions may be separated conventionally into two stages [4], for which the rate of plasma density growth are determined by basically different processes. At the first stage the main process is ionization of the neutral gas by collisions with hot electrons; plasma density grows exponentially, the degree of gas ionization is less than unity, low-charge ions dominate in the distribution of ions over their charge states, and the power absorbed in the plasma is much less than the power of the microwave pumping. At the second stage the rate of density growth slows down significantly, the process of ion peeling goes further, their charge becomes higher, and the power absorbed by the plasma is equal to the power of the microwave pumping, approximately.

Electron energy distribution function (EEDF) which determines plasma life time and efficiency of gas ionization is rather different on those two stages. As it was shown in [2] that transition from breakdown to quasi-stationary stage could be attended with a unexpected transient peak of multicharged ions current. This effect was called preglow [2] and it looks very promising as a way of short pulses creation. Its amplitude and duration are depends on initial breakdown conditions which also determine discharge steady state parameters. It was shown that Preglow peak with duration about of a few tens of microseconds and high average ion charge could be created only with using of microwave with high frequency (more than 30 GHz) and power.

In present work experimental results obtained on SMIS 37 [5] stand demonstrating creation of short pulses under conditions of powerful plasma heating with gyrotron radiation @ 37 GHz are observed.

EXPERIMENTAL SETUP

The experimental research presented in this work was carried out on the SMIS 37 shown schematically in fig. 1.

A gyrotron generating linearly polarized 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 as a source of pulsed microwave radiation.

In the greatest majority of the experiments the field in the magnetic plugs of the system was 2 Tesla.

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* sva1@appl.sci-nnov.ru.

TIME EVOLUTION OF PLASMA POTENTIAL IN PULSED OPERATION OF ECRIS*

O. Tarvainen[#], H. Koivisto, T. Ropponen and V. Toivanen, University of Jyvaskyla, Finland
Y. Higurashi and T. Nakagawa, Institute of Physical and Chemical Research (RIKEN), Japan

Abstract

The time evolution of plasma potential has been measured with a retarding field analyzer in pulsed operation mode with electron cyclotron resonance ion sources at JYFL and RIKEN. Three different ion sources with microwave frequencies ranging from 6.4 to 18 GHz were employed for the experiments. The plasma potential was observed to increase 10-75 % during the preglow and 10-30 % during the afterglow compared to steady state.

INTRODUCTION

Electron Cyclotron Resonance Ion Sources (ECRIS) exhibit fast transient peaks of extracted ion beam currents at the leading and trailing edges of the applied microwave pulse [1,2]. The fundamental difference between these transients, called preglow and afterglow, is the charge state distribution (CSD) of extracted ion beams - low charge ions (LCI) exhibit preglow while the afterglow boosts the beam currents of highly charged ions (HCI). Studies [1,3,4] of the preglow are driven by the aim of creating a short-pulsed multi-charged ion source with high ionization efficiency. The afterglow mode is utilized e.g. for injection into circular accelerators [5] as it offers intensive beams of HCI.

In order to gain understanding on the plasma processes associated with these transients we measured the time evolution of plasma potential during the microwave pulse. Furthermore, the results allow us to estimate beam transport properties during the transients as the variations of the plasma potential are reflected to the beam energy spread.

EXPERIMENTAL PROCEDURE

The plasma potential of an ECRIS can be deduced by measuring the exact energy of extracted ion beams. The study presented in this article was performed with retarding field analyzers described in detail in references 6 (JYFL) and 7 (RIKEN). Three different ion sources, the JYFL 6.4 GHz ECRIS, the JYFL 14 GHz ECRIS, and a room temperature 18 GHz ECRIS at RIKEN, were employed for the experiments. The retarding field analyzer was located in the beam line downstream from the analyzing magnet to allow charge state dependent studies of the plasma potential. The output of the klystron was controlled by pulsing the input signal from a solid state oscillator with an rf-switch controlled by a pulse generator. The pulsing signal was also used as a trigger for the data acquisition. The klystron gain i.e. attenuator setting was kept constant. The voltage regulated power supply for the retarding electrode was floating on the high voltage of the ion source. This eliminates the error due to small fluctuations of the source bias, typically associated with the plasma breakdown. Signals from the retarding field analyzer and Faraday cup were measured across a resistor and stored with an oscilloscope. Schematic of the measurement setup is shown in Figure 1.

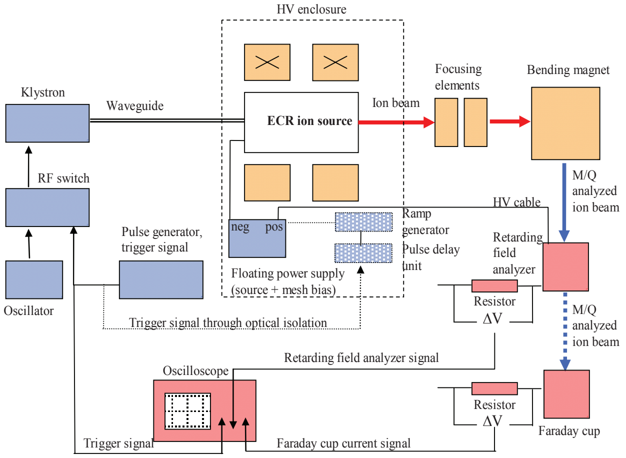

Figure 1: Schematic of the measurement setup.

Two slightly different methods were used for controlling the bias voltage of the retarding field analyzer. The more elegant method utilizes floating, optically isolated, pulse delay unit and voltage ramp generator. The trigger signal was fed into a pulse delay unit gating a fast (1 ms) linear voltage ramp from a signal generator. Adjustment of the pulse delay (measured from the leading edge of rf pulse) was used for selecting the time window for ramping the retarding voltage and acquiring the IV-curve for deducing the plasma potential as described in reference 6. This method was used always when possible i.e. when the variations of the plasma potential were found to be slower than the voltage ramp time of 1 ms, limited by the four-quadrant bias power supply.

Unfortunately, it was observed that this condition does not hold during the preglow and afterglow. For studying fast variations of the plasma potential (preglow and afterglow) the retarding voltage was fixed to a constant value for the duration of the microwave pulse. Increasing the retarding voltage in discrete steps between consecutive pulses makes it possible to deduce the plasma potential at arbitrary time within the microwave pulse after reconstructing IV-curves from the data.

The goal of the experiments was to compare the plasma potential during preglow and afterglow transient with the steady-state value with frequencies from 6.4 to 18 GHz.

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[#] olli.tarvainen@jyu.fi

MICROPULSES GENERATION IN ECR BREAKDOWN STIMULATED BY GYROTRON RADIATION AT 37,5 GHZ

V.Skalyga*, V. Zorin, I. Izotov, S. Golubev, S. Razin, A. Sidorov, A. Vodopyanov
Russian Academy of Sciences, 46 Ulyanova st., Nizhny Novgorod, Russia, 603950

Abstract

Present work is devoted to experimental and theoretical investigation of possibility of short pulsed (< 100 μs) multicharged ion beams creation.

The possibility of quasi-stationary generation of short pulsed beams under conditions of quasi-gasdynamic plasma confinement was shown in recent experiments. Later another way of such beams creation based on “Preglow” effect was proposed. In present work it was demonstrated that in the case when duration of MW pulse is less then formation time of “Preglow” peak, realization of a regime when ion current is negligible during MW pulse and intense multicharged ions flux appears only when MW ends could be possible. Such pulses after the end of MW were called "micropulses". In present work generation of micropulses was observed in experiments with ECR discharge stimulated by gyrotron radiation @ 37,5GHz, 100 kW. In this case pulses with duration less than 30 μs were obtained. Probably the same effect was observed in GANIL where 14 GHz radiation was used and pulses with duration about 2 ms were registered [1].

In present work it was shown that intensity of such micropulse could be higher than intensity of “Preglow” peak at the same conditions but with longer MW pulse. The generation of micropulses of nitrogen and argon multicharged ions with current of a few mA and length about 30 μs after MW pulse with duration of 30-100 μs was demonstrated. The low level of impurities, high current density and rather high average charge make possible to consider such micropulse regime as perspective way for creation of a short pulsed ion source.

INTRODUCTION

Realization of the European programme for neutrino oscillations research, "Beta Beam Project" [2], requires that short-pulse (10 to 100 μs) beams of multicharged ions of radioactive gases (^{6}He or ^{18}Ne) with high gas efficiency be created. A possible way to achieve formation of such beams is associated with the use of a pulsed ECR source of multi-charged ions (MCI). Application of modern classical ECR ion sources for this is not feasible, since the time of gas breakdown and the plasma density's reaching the stationary level is long (over 1 ms) as compared with the required pulse duration. In [3] possibility of gas breakdown process shortening by using of microwave radiation with higher frequency for plasma heating was demonstrated theoretically. Plasma life time decreases with increase of its density (plasma density could be increased by using of higher frequency microwaves) in the case of classical plasma confinement [4] and reaches its minimum value determined by quasi-gasdynamic plasma outflow from the trap though magnetic plugs [5]. That is why present work is devoted to experimental demonstration of short pulsed multicharged ion beams creation possibility in ECR ion source with gyrotron plasma heating with frequency 37 GHz and power 100 kW. Such parameters of microwave heating are much higher than in traditional ECR ion sources [6]. In the article two regimes of short pulsed beams generation are discussed: quasi-stationary and non-stationary.

FORMULATION OF THE PROBLEM

To solve a problem of short pulse creation, first of all it is necessary to perform the analysis of gas breakdown dynamics dependences on different parameters.

In the very beginning of microwave breakdown of a gas in a magnetic trap under the ECR conditions the main process is ionization of the neutral gas by collisions with hot electrons; plasma density grows exponentially, the degree of gas ionization is less than unity, low-charge ions dominate in the distribution of ions over their charge states, and the power absorbed in the plasma is much less than the power of the microwave pumping. Electron energy distribution function (EEDF), which determines plasma life time and efficiency of gas ionization, has a form corresponding to superadiabatic regime of electron heating in a mirror trap under ECR condition. Average energy of electrons in this case is as high as hundreds kilo electron-volts [7]. Energy content of plasma grows with plasma density. Plasma confinement time is rather high. If one stop microwave pulse on this stage, ionization would continue as long as electron temperature is high. In this case appearing of ion beam after end of microwaves pulse is possible like it happen in afterglow mode.

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*Corresponding author :
sva1@appl.sci-nnov.ru

BEAM, MULTI-BEAM AND BROAD BEAM PRODUCTION WITH COMIC DEVICES*

P. Sortais#, T. Lamy, J. Médard, J. Angot, UJF CNRS-IN2P3 INPG, LPSC, Grenoble, France
C. Peaucelle, IPNL, Grenoble, France

Abstract

The COMIC discharge cavity is a very versatile technology. We will present new results and devices that match new applications like: molecular beams, ultra compact beam line for detectors calibrations, quartz source for on-line application, high voltage platform source, sputtering /assistance broad beams and finally, a quite new use, high energy multi-beam production for surface material modifications.

In more details, we will show that the tiny discharge of COMIC can mainly produce molecular ions (H_3^+). We will present the preliminary operation of the fully quartz ISOLDE COMIC version, in collaboration with IPN-Lyon, we will present a first approach for a slit extraction version of a three cavity device, and after discussing about various extraction systems on the multi discharge device (41 cavities) we will show the low energy broad beam (2 KV) and high energy multi-beams (10 beams up to 30 KV) productions.

We will specially present the different extraction systems adapted to each application and the beams characteristics which are strongly dependent on the voltage distribution of an accel-accel two electrodes extraction system.

THE COMIC PRINCIPLE

The basic principle of the COMIC (COmpact MIcroonde & Coaxial) discharge have been previously presented [1]. This principle is a very basic and low power way of plasma generation and we will present here the different discharge customization ways for beam, broad beam of multi-beam generation. The plasma is ignited between a quarter wave antenna and grounded couplers where the over voltage can reach the Paschen's conditions (Fig.1). This discharge is magnetized by a small gradient of a magnetic field that reach ECR conditions at the level of this over voltage. The weak generated plasma (roughly 5eV and 5 10^{10} cm^{-3}, measured after 5 mm of diffusion outside the cavity) is very suitable for molecular and monocharged ion production .The very small confinement time allows the creation of non negligible current densities in the range of 0.1 to 10 mA/cm^2. The consequence of these compromises is the use of relatively high gas flux by respect to a high confinement ECR source.

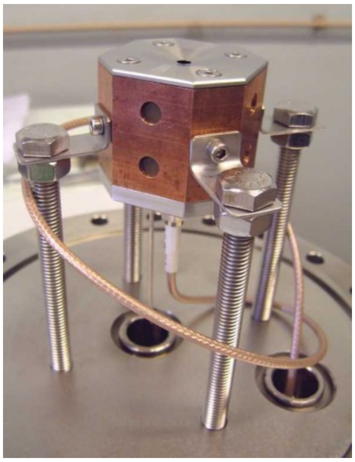

Figure 1: The elementary COMIC discharge.

We can see (Fig.2) an optimization for the production of H_3^+ molecular ions (15 µAe with 1 mm extraction hole). Due the poor pumping of hydrogen we have observe the breaking of the 20 KV H_3^+ in two peaces : H_2^+ at 13.6 and H^+ at 6.8 KV and also H^+ at 10 KV coming from 20 KV H_2^+. The production of high currents of hydrogen could be done only with a strong pumping dedicated to hydrogen.

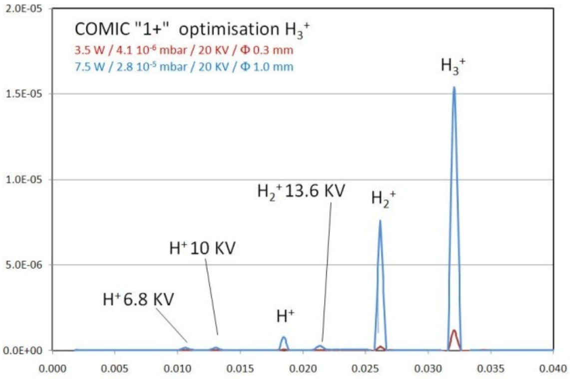

Figure 2: H_3^+ optimisation with partial energy beams generated by gas interaction of H_3^+ and H_2^+.

MONOBEAM / MONOCAVITY DEVICES

Due to the small size and low power operation, it is easy to match a COMIC source to compact devices.

A first one, now under assembly, is a moveable beam line for detectors calibrations. The purpose here is to deliver very low ion and electron currents (down to some

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#sortais@lpsc.in2p3.fr

STATUS OF THE HIGH CURRENT PERMANENT MAGNET 2.45GHZ ECR ION SOURCE AT PEKING UNIVERSITY*

S. X. Peng#, Z. Z. Song, J. X. Yu, H. T. Ren, M. Zhang, Z. X. Yuan, P. N. Lu, J. Zhao, J. E. Chen, Z. Y. Guo, Y. R. Lu, SKLNPT, Peking University, Beijing 100871, China

Abstract

Several compact 2.45 GHz Electron Cyclotron Resonance Ion Sources (ECRISs) have been developed at Peking University for ion implantation [1], Separated Function Radio Frequency Quadrupole project (SFRFQ)[2] and for the Peking University Neutron Imaging FaciliTY project (PKUNIFTY) [3]. Studies on 2.45 GHz ECR ion sources are concentrated on methods of microwave coupling and microwave window design, magnetic field generation and configuration, as well as the extraction electrodes structure. Investigation also covers the influence of the size of plasma chamber on the discharge efficiency and species factor. Up to now, our sources have produced 25 mA of O^+ ion, 40 mA of He^+ ion, 10 mA of N^+ ion, 100 mA of H^+ ions and 83 mA of D^+ ions, respectively.

INTRODUCTION

In recent years the production of high current beams is a key point for many research projects [4]. The 2.45 GHz electron cyclotron resonance (ECR) ion sources, invented 30 years ago by Sakudo [5] and Ishikawa *et al.* [6] for industrial applications, are the suitable candidates of producing high current and high brightness proton, deuteron, oxygen and other mono-charged light ion beams. The special characteristics of 2.45 GHz ECR sources, such as high ion current density, compact structure, high reliability, ability to operate in both CW and pulsed mode, good reproducibility and low maintenance, make it popular as a High Current Ion Source in the world [7-10].

Research on the 2.45 GHz high current ECR ion source at Peking University (PKU) can trace back to 1980's [10]. Since then, several 2.45 GHz ECR sources were developed for different purposes [1-3]. Fig.1 is a schematic configuration diagram of the PKU ECR ion source developed for Peking University Neutron Imaging FaciliTy (PKUNIFTY) project (PMECR IV, see below). As shown in fig.1, special designed alumina dielectric microwave window is used for the microwave coupling between the rectangle microwave guide and plasma chamber. The axial magnetic field needed by the ECR in the plasma chamber with 2.45 GHz rf wave is provided by three permanent magnet rings, so the source is named PMECR ion source. Its out diameter and its length are 10 cm, and its weight is less than 5 kg. The discharge chamber is a cylinder with diameter about 40 mm and length of 50 mm. For beam extraction, a 45° angle cone-expansion type electrode is used to suppressing the beam divergence. Heretofore, we have got several tens of milliampere of various gas ions, such as H^+, D^+, He^+, N^+ and O^+ [1][11][12][13][14]. Now the PMECR I ion source is routinely delivering ion beams for Separated Function Radio Frequency Quadrupole (SFRFQ) project [2] and the PMECR IV, for PKUNIFTY project [3].

The technical achievements and progresses on methods of magnetic field generation and configuration, source body structure, microwave coupling, and beam extraction electrodes design of PKU 2.45GHz ECR ion source in the past decades will be described in this paper.

MICROWAVE COUPLING METHODS

The microwave system of an ECR ion source is used to generate 2.45 GHz microwave and transport the microwave to the ion source. At PKU, the system is a very simple one with a microwave generator, a magnetron cavity, a circulator or isolator, a tuner, some rectangular waveguide, a high voltage break wave guide (HV break) and a coupling part with source body. The tuner (manual three-stub or automatic stub) is adapted for matching the waveguide to plasma impedance, which enhances the plasma density and finally increases the current density of the extracted beam. The WR340 and WR284 rectangular waveguides were compared during the source running. Results show that using the WR340 rectangular waveguide can save more than 30% microwave power comparing with the WR284 to obtain the same beam current extracted at the same conditions [12].

The microwave coupling part refers to the matching unit to adapt the standard rectangular waveguide to the source body. Ridged waveguide, dielectric microwave window and antennas are the three ways to fulfil the coupling. Most Labs, such as Chalk River National Laboratory, Saclay/CEA [15][8], are using a ridged waveguide to match the microwave line with source body. At PKU, ridged waveguide, dielectric microwave window as well as T-shape antenna were tested at the early stage of ECRIS development [11][1][12]. The presence of antennas is not convenient to the routine operation because of periodical maintenance. Experimental results show that the function of dielectric microwave windows with special design is equivalent to a ridged waveguide for microwave coupling between the microwave line and the discharge plasma. As shown in fig.1, the dielectric microwave window for 2.45GHz ECR ion source at PKU which consists of an alumina block with dielectric constant 9 is special design for microwave coupling. It works as vacuum sealing as well. In the meantime, a piece of thin BN or SiN disk toward the plasma is used to protect the microwave window from the bombarding of electrons. The lifetime of SiN is longer than BN for

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#Sxpeng@pku.edu.cn

DEVELOPMENT OF 14.5 GHZ ELECTRON CYCLOTRON RESONANCE ION SOURCE AT KAERI*

Byung-Hoon Oh, Sang-Ryul In, Kwang-Won Lee, Chang Seog Seo, Jung-Tae Jin, Dae-Sik Chang, Seong Ho Jeong, and Chul-Kew Hwang, KAERI, Daejeon, Korea.

Abstract

A 14.5 GHz ECRIS has been designed and fabricated at KAERI (Korea Atomic Energy Research Institute) to produce multi-charged ion beam (especially for C^{6+} ion beam) for medical application. The magnet system has cupper conductor solenoid coils and a permanent magnet hexapole. A welded tube with aluminium and stainless steel is used for an ECR plasma chamber to improve the production of secondary electron. A Krystron supplies microwave energy to the plasma. A movable beam extractor with 8 mm aperture covers different species and different charge numbers of the beam. Fabrication and initial experimental results on ECR plasma are discussed in this paper.

INTRODUCTION

A heavy ion accelerator for cancer treatment [1] by a cyclotron or a synchrotron is planned in Korea. As an important activity of this project a 14.5 GHz ECRIS has been designed and fabricated. The main design goal of the ion source is to produce C^{6+} ions with a current level of several tens of electro-microampere, and to meet this goal key parameters were designed as summarized in Table 1.

In this paper the design and fabrication results of the ion source, and the initial experimental results on the ECR plasma are described. An image camera and an optical sensor with a photo multiplier (PM) tube near the beam extraction aperture, and a NaI(Tl) detector at the outside of a beam extraction chamber with multi-channel analyzer (MCA) system to measure the X-ray spectrum were used to understand the characteristics of the ECR plasma.

SOURCE DESIGN AND FABRICATION

To get high current for the fully striped carbon ions with 14.5 GHz frequency strong-field ECR ion source, as shown in Fig. 1, was designed. The solenoid coils are composed of two axial coils to make mirror fields in both sides of the chamber and one trim coil at the center to control the layer of the resonance region (B_{min}). There are also three different yokes to make effective and strong axial field at the both ends of the ECR plasma region such as main yokes, hexapole fixing yokes and chamber yokes as shown in Fig. 2. The volume of the chamber yoke at the input side is maximized except the needed openings for microwave injection, vacuum pumping, and gas injection. Their positions and shapes are designed to minimize magnetic reluctance in the magnetic circuit. The hexapole [2] is composed of NdFeB permanent magnet. The sector number and outer diameter are optimized to make a strong hexapole field with a fixed inner diameter.

Table 1: Design Parameters of KAERI ECRIS

Parameters	Values
Microwave Max. Power	2.0 kW
B_{inj}	1.65 T
B_{ext}	1.1 T
B_r max	1.1 T
Max. Mirror Ratio	3.3
Chamber Inner Diameter	68 mm
Chamber Length	320 mm
Beam Extraction Diameter	8 mm
Beam Extraction Voltage (Max.)	30 kV
I_{C6+}	> 20 μA

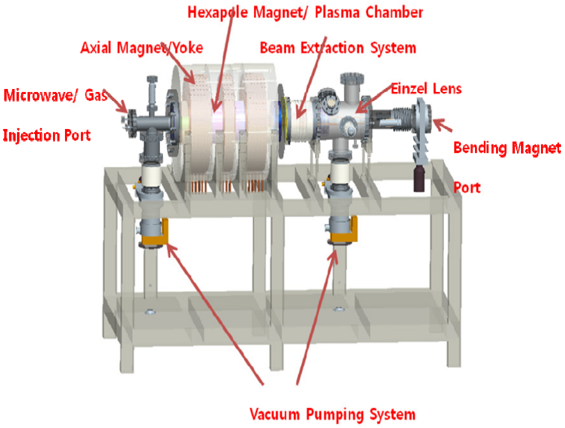

Figure 1. Main structure of KAERI ECR ion source.

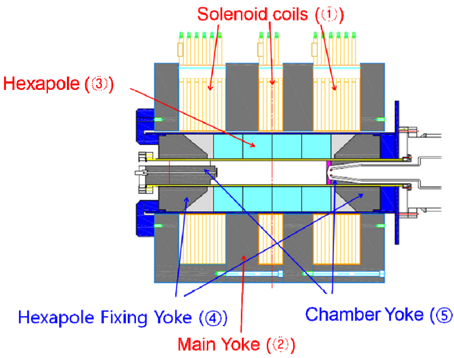

Figure 2. Inner structure of magnets and insulators.

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*This study was performed as a part of Nuclear R&D Program funded by the Ministry of Education, Science and Technology of Korea.

MASS SPECTROMETRY WITH AN ECR ION SOURCE

M. Hotchkis[#], D. Button, ANSTO, Menai, Australia

Abstract

Several groups [1-3] have demonstrated the usefulness of ECR ion sources in forms of mass spectrometry, for the detection of rare long-lived radioisotopes, trace elements and stable isotope ratios. Mass spectrometry imposes strict constraints on the ion source. First, the ion source must be free of backgrounds at the same m/q ratio as isotope of interest. Backgrounds take several forms, including beams generated from residual gas or other materials in the source, either of the element of interest, or other elements which cause isobaric or other m/q ambiguities. Second, the ion source must exhibit a minimum 'memory' effect from sample to sample. We are interested in isotopic ratios of carbon, nitrogen and oxygen. These elements are ubiquitous in vacuum systems and so this work has its own particular challenges, especially in relation to the design and operational characteristics of the ion source. Initial work has revealed retention effects which reduce the sample clear out rates, and cause persistent backgrounds [4]. We will present results of our most recent efforts to control these problems.

[1] P. Collon et al., Nucl. Instrum. Methods B 2004; 223/224: 428.
[2] M. Kidera et al., Eur. J. Mass Spectrom. 2007; 13: 239.
[3] M. Hotchkis et al., Rapid Comm. Mass Spec. 2008; 22: 1408-1414.
[4] D. Button and M.A.C. Hotchkis, Proc. 18th ECRIS Workshop, Sept 15-18, 2008, Chicago, USA, http://www.JACoW.org/.

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[#] mah@ansto.gov.au

PLANS FOR LASER ABLATION OF ACTINIDES INTO AN ECRIS FOR ACCELERATOR MASS SPECTROSCOPY*

R.C. Pardo#, F.G. Kondev, S. Kondrashev, C. Nair, T. Palchan, E. Rehm, R. Scott, R. Vondrasek,
Argonne National Laboratory, Argonne, IL , USA,
M. Paul, Racah Institute of Physics, Hebrew University, Jerusalem, Israel
P. Collon, Nuclear Structure Laboratory, University of Notre Dame, Notre Dame, IN, USA
G. Youinou, M. Salvatores, G. Palmotti, C. McGrath, Idaho National Laboratory, Idaho Falls, ID, USA
G. Imel, Idaho State University, Pocatello, ID, USA

Abstract

A project using Accelerator Mass Spectrometry (AMS) at the ATLAS facility to measure neutron capture rates on a wide range of actinides in a reactor environment is underway. This project will require the measurement of many samples with high precision and accuracy. The AMS technique at ATLAS is based on production of highly-charged positive ions in an electron cyclotron resonance ion source (ECRIS) followed by linear acceleration. We have chosen to use laser ablation as the best means of feeding the actinide material into the ion source because we believe this technique will have more efficiency and lower chamber contamination thus reducing ‘cross talk’ between samples. In addition construction of a new multi-sample holder/changer to allow quick change between multiple samples is part of the project. The status of the project, design, and goals for initial off-line ablation tests will be discussed as well as the overall project schedule.

INTRODUCTION

Advanced nuclear fuel cycles are currently under evaluation in order to assess their potential to cope with new requirements of radioactive waste minimization, optimization of resource utilization, and reduced risk of proliferation. This assessment should account for several key features of the fuel cycle, including irradiated fuel processing, innovative fuel development and fabrication, waste characterization, and disposal. In some cases, the impact of nuclear data and their associated uncertainties can be crucial in order to further explore an option, or to reject it. The need for accurate data has been pointed out in recent studies devoted to Generation-IV systems, see e.g. [1]. The very high mass actinides can play a significant role in the feasibility assessment of innovative fuel cycles. As an example, the potential build-up of ^{252}Cf when recycling all transuranics in a light water reactor, leads to increased neutron emissions that could impact the fuel fabrication process. As a consequence, the poorly known nuclear data of higher mass transuranics need to be significantly improved.

At present, there is data to provide some information on the performance of these isotopes in reactor environments, but up to now, there has been little emphasis on the quality of these data and few reliable uncertainty estimates have been provided. This situation is due to the difficulty to make both integral and differential cross section measurements for these isotopes.

The objective of this project is to obtain valuable integral information about neutron cross sections for actinides that are of importance for advanced nuclear fuel cycles in a relatively short time compared to the more standard, and time consuming, route which consists of irradiating samples in a reactor and then performing chemical analysis to characterize the different isotopes produced during irradiation.

The proposed work intends to develop an original approach that takes advantage of two experimental facilities: the neutron irradiation capabilities of the Advanced Test Reactor (ATR) at the Idaho National Laboratory and the Accelerator Mass Spectrometry (AMS) capabilities of the Argonne Tandem Linac Accelerator System (ATLAS)[2] at Argonne National Laboratory.

The novelty of this approach relies on the use of AMS which is expected to provide very sensitive measurements of the production of different actinides that are built up during the irradiation, up to the highest mass isotopes. AMS at ATLAS can detect down to about 10^6 atoms in samples consumed in the ion source, which is out of the range of more classical chemical analysis traditionally used to analyze irradiated fuel samples.

In order to succeed in this project, the work can be decomposed into three major steps:

1. Preparation and irradiation of some pure actinide samples in ATR. The samples that are available at INL and which are of interest for advanced reactor fuel cycles are the following: ^{232}Th, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am and ^{248}Cm.

2. Measurements of the amount of the different isotopes produced in the irradiated samples at ATLAS.

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#pardo@phy.anl.gov

ENHANCEMENT OF ECR PERFORMANCES BY MEANS OF CARBON NANOTUBES BASED ELECTRON GUNS*

F. Odorici, M. Cuffiani and L. Malferrari, ,INFN-Bologna, 40127 Bologna, Italy
R. Rizzoli and G. P. Veronese, CNR-IMM and INFN-Bologna, Bologna, Italy
L. Celona, S. Gammino#, D. Mascali, R. Miracoli, F. P. Romano, N. Gambino,
G. Castro and G. Ciavola, INFN-LNS, 95123 Catania, Italy and CSFNSM, 95125 Catania
T. Serafino, Univ. Messina, 98100 Messina, Italy

Abstract

The CANTES experiment at INFN-LNS tested the use of carbon nanotubes (CNTs) to emit electrons by field emission effect, in order to provide additional electrons to the plasma core of an ECR ion source. This technique was used with the Caesar source, demonstrating that the total extracted ion current is increased and that a relevant reduction of the number of "high energy" electrons (above 100 keV) may be observed. The injection of additional electrons inside the plasma increases the amount of cold and warm electrons, and then the number of ionizing collisions. Details of the construction of CNTs based electron gun and of the improvement of performances of the Caesar ECR ion source will be presented.

EXPERIMENTAL SET-UP

The ECR ion source CAESAR, operating at INFN-LNS laboratories as injector of the K-800 Superconducting Cyclotron since 2000, has been used as testbench for the CANTES technique,.

In the past, several passive techniques for the injection of secondary electrons were tested [1], with the purpose to increase the electron density and to prolong the ion lifetime in the plasma, enhancing the ionization probability. For example alumina was tested as source of secondary electrons [2].

Active materials, like ferroelectric cathodes, such as PBZT doped with 2 % of Bi_2O_3, have been employed because of their capability of producing high emission yields of energetic electrons [3]. However, their robustness is not sufficient for stable applications into ECRIS. In fact, they showed not only a lack of reliability, but also a limited resistance in plasma environment, and they failed after short time.

During this experiment, we tested a new active technique which makes use of CNTs-based electron guns. In our set-up, two electron guns are placed on a copper plate connected to the RF waveguide, that is usually employed as bias disk in the CAESAR source. A potential in the range 0-2.5 kV, is then applied between the chamber and the waveguide, and the same potential is used to produce the emission field (i.e. the extraction field) between CNTs and the anodic grid.

At an earlier stage, CNTs samples of the same type as used for CAESAR have been tested in microwave discharge plasma (MDIS), in order to preliminary verify if electron and ion collisions can damage them. The adopted MDIS apparatus operates at 2.45 GHz and generates, in presence of an off-resonance magnetic field, a weakly ionized and strongly collisional plasma because of the low electron temperature (T_e<10 eV) and high pressure (0.4 mbar). Tests were made both for air plasma and nitrogen plasma. Results were collected in fall of 2008 and they have shown that CNTs exposed to intense plasma milling (up to 4 mA/cm^2 current density and 300 C/cm^2 of integral dose) have been damaged in presence of oxygen (air plasma) but were perfectly resistant to nitrogen plasma. After the response of this preliminary test-bench, CNTs cathodes have been used for tests in ECR ion sources.

The CNTs electron gun used for the test is made of three elements: a CNTs cathode obtained on a 300 µm thick silicon substrate, a 150 µm thick mica spacer and an anodic copper grid with quad cells of 350 µm side. CNTs eject electrons because of the field emission effect, i.e. quantum tunneling, which is obtained by applying an electric field higher than 3-4 V/µm.

The gun elements are kept together by a MACOR holder, on which the electrical connection is obtained by an evaporated gold track. The MACOR holder is then fixed on a copper plate, i.e. the bias disk of the source, connected to the waveguide of the plasma chamber. The anodic grids are linked to the ground potential of the plasma chamber wall by means of copper creeping contacts. Two of such electron guns were mounted on the same bias disk during the experimental tests. A picture of a CNTs sample and the assembled guns is shown in Figure 1. The CNT e-gun scheme inside the plasma chamber is shown in figure 2 and the CAESAR source during the experiment is shown in figure 3. Prior to the plasma test, each CNTs sample was tested in terms of field emission, by means of a custom-designed apparatus [4]. The field emission properties of similar samples (i.e. CNTs arrays in free-standing porous alumina foils) were already tested [5] and found to be able to produce current densities up to 10-40 mA/cm^2. Emission measurements for the samples tested in CAESAR (i.e. CNTs arrays in porous alumina on silicon), gave even better results, with

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#gammino@lns.infn.it

A NEW BETSI TEST BENCH AT CEA/SACLAY

S. Nyckees, G. Adroit, O. Delferrière, R. Duperrier, Y. Gauthier, R. Gobin, F. Harrault,
C. M. Mateo, O. Napoly, B. Pottin, Y. Sauce, F. Senée, O. Tuske, T. Vacher,
CEA/Saclay, DSM/IRFU/SACM, F- 91191-Gif/Yvette, France.

Abstract

By the 90s, CEA has undertaken to develop the production of high intensity light ion beams from plasma generated by electron cyclotron resonance (ECR). Important results were obtained with the SILHI source in pulsed or continuous mode. Presently, CEA/Saclay is now involved in the construction of different injectors dedicated to large infrastructures like IFMIF or SPIRAL2. Other installations are also interested by high intensity ion sources like ESS or FAIR.

To improve and test new sources, a new test bench named BETSI (Banc d'Etudes et de Tests des Sources d'Ions) is now operating for several years. Low energy beam line diagnostics consist of a Faraday cup, cameras and a species analyzer. The SILHI emittance scanner can also be installed on the beam line. On this test bench, different permanent magnet source configurations are tested.

INTRODUCTION

In the middle of the 90s, CEA/Saclay developed the SILHI source, operating at 2.45 GHz and based on the Chalk River (Canada) principle. More than 100 mA proton or deuteron beams are routinely produced in pulsed or continuous mode. To answer new machine requests, specific source designs have already been performed. For example, a permanent magnet source has been developed to fit in with the 5 mA deuteron expected beam for Spiral 2. Then, to answer the IFMIF (International Fusion Material Irradiation Facility) high intensity deuteron beam request (125 mA), a copy of the SILHI source with a 4 electrode extraction system has been proposed.

Since the IPHI project will enter in a new phase of development, the availability of the SILHI platform will be reduced for source developments. Therefore, the construction of the new test bench named BETSI (described in the following section) has been decided [1]. Up to now, a new accelerator column designed for the Spiral2 ion source has been installed and tested on this test bench. Several simulations have been realized to find an optimization of magnetic configuration.

THE BETSI TEST BENCH

The Low Energy Beam Transport

The BETSI test bench is dedicated to study the influence of the source parameters on the beam characteristics. It operates up to 50 kV and ignites continuous or pulsed hydrogen plasma with a 2.45 GHz magnetron. The LEBT is composed of a pair of solenoids that has to reduce beam divergence and focus it into a classical mass analyzer magnet (Fig. 1).

Between the pair of solenoids and the analyzer magnet, a pumping and diagnostic box is installed. The analyzing part is composed of a vertical and horizontal viewport for CCD camera diagnostics and a vertical movable Faraday cup. Pumping of LEBT is realized by a turbo molecular pump of 1000 l/s, it allows easily obtaining vacuum of 10^{-4} Pascal. A beam stop with magnetic electron reppeler is installed after the mass analyzer for ion beam intensity measurement.

Currently, the two old solenoids have been installed close to each other to obtain a magnetic field as high as possible to focalize the extracted beam. But the field strength is not high enough to focalize H_2^+ or H_3^+. New solenoid, including vertical and horizontal steerers has been designed and built to replace them. It length is 310 mm (including the magnetic shielding) with a maximum magnetic field of .85 T. It will be installed during the next months.

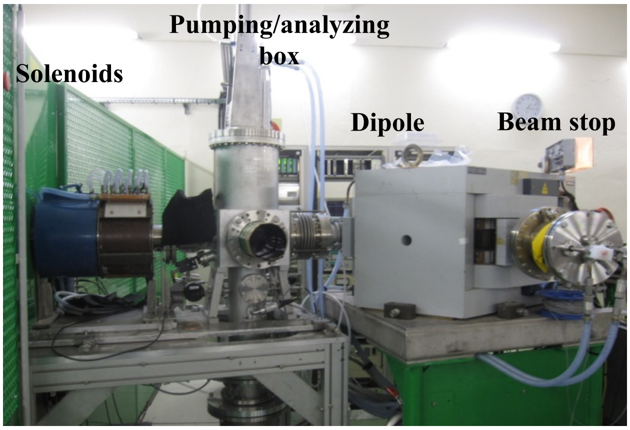

Figure 1: The LEBT of BETSI test bench

The analyzer magnet is a 104° dipole with a radius of 400 mm and double focusing corners. The magnetic field homogeneity within 110 mm from the axis is better than 10^{-3}, for a maximum transverse field of 230 mT. The dipole chamber height is 80 mm. The analyzer dipole is monitored by a Labview program and allows to realize spectra in order to dissociate the three H^+, H_2^+ and H_3^+ species in the beam. A species analysis with transport optimization of both H^+ and H_2^+ is presented in Fig. 2. This optimization is obtained by varying pair of solenoids focalization field. These measurements have been done by successively optimizing H^+ and H_2^+ transport in order to really determine the effective species fractions.

MICROGAN ECR ION SOURCE IN A VAN DE GRAAFF ACCELERATOR TERMINAL

G. Gaubert, O. Tasset-Mayé, A.C.C. Villari, C. Bieth, W. Bougy, N. Brionne, X. Donzel, A. Sineau, C. Vallerand, PANTECHNIK, Bayeux, France.
C. Chaves, T. Gamboni, W. Geerts, G. Giorginis, R. Jaime Tornin, G. Lövestam, W. Mondelaers, EC-JRC-IRMM, Institute for Reference Materials and Measurements, Geel, Belgium

Abstract

The Van de Graaff accelerator at IRMM works since many years providing proton, deuteron and helium beams for nuclear data measurements. The original ion source was of RF type with quartz bottle. This kind of source, as well known, needs regular maintenance for which the accelerator tank must be completely opened. The heavy usage at high currents of the IRMM accelerator necessitated an opening about once every month. Recently, the full permanent magnet Microgan ECR ion source from PANTECHNIK was installed into a new terminal platform together with a solid state amplifier of 50 W, a dedicated dosing system for 4 gases (with respective gas bottles H2, D2, He and Ar), and a set of dedicated power supplies and electronic devices for the remote tuning of the source. The new system shows a very stable behaviour of the produced beam allowing running the Van de Graaf without maintenance for several months.

INTRODUCTION

The high intensity quasi mono-energetic neutron source at IRMM is driven by a vertical 7 MV Van de Graaff accelerator (VDG) producing either continuous or pulsed ion beams [1]. The accelerator is operated 24 hours a day and seven days a week. The maintenance cycle with the original RF source was about once a month. In order to improve availability of the machine as well as the operation of the ion source, it was decided to replace the RF source with an ECR ion source and also update the high voltage platform.

The Microgan ECR ion source [2] working at 10 GHz is now providing single-charged or multi-charged ions like proton, deuteron, helium and argon.

We will recall the principle of this ion source adapted to the existing beam line before describing the Van de Graaff accelerator high voltage platform constraints and technical solution adopted. The command and control hardware/software will be discussed. Finally, beam results in term of tuning, intensity and stability will be presented.

Microgan Ion source

The Microgan is an ECR ion source, for which the magnetic circuit is entirely made with permanent magnets both for the radial and longitudinal fields, so the total electrical power is extremely low. The minimum B structure (Fig. 1) is made to work with a 10 GHz RF wave. This source can work with RF power up to 200 W (if water cooled) depending on the element and charge state needed.

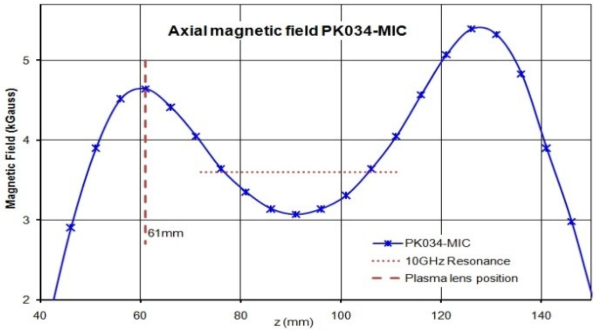

Figure 1: Microgan axial magnetic field

In this application, the requirement of 60 µA intensity for all beams (see table 1), led us to work with 50 W of maximum RF power if the plasma chamber is not cooled.

Table 1: Microgan intensities & VDG requirements

Usual guaranteed intensities (in µAe)							**VDG**
Ions/Q	1	2	3	4	5	8	1
H	7000						60
D							60
He	5000						60
O	4000	400	170				
P	2000	1200	700	200	20		
Ar	2000	1290	600	220		20	

Nevertheless, the ion source produces too high intensity with respect to the Van de Graaff limitations and the emittance of such an ECR ion source. Simulations with QuickfieldTM software and beam transport calculations combined with measurements done on a dedicated test bench at the Pantechnik's factory, that reproduced the first part of the accelerator, rendered the final set-up as shown in Fig. 2.

The plasma electrode aperture has been reduced to 3 mm in diameter. A simple gap extracting puller is followed by an Einzel lens to adapt the beam at the entrance of the present 30° analysing magnet. The plasma electrode aperture has been reduced to 3 mm in diameter. A simple gap extracting puller is followed by an Einzel lens to adapt the beam at the entrance of the present 30° analysing magnet.

AN ECR TABLE PLASMA GENERATOR

R. Rácz[1, 2, #], S. Biri[1], J. Pálinkás[1, 2]
[1]Institute of Nuclear Research (ATOMKI), Hungary, H-4026 Debrecen, Bem tér 18/c
[2]University of Debrecen, Hungary, H- 4010 Debrecen, Egyetem tér 1.

Abstract

A compact ECR plasma device was built in our lab using the "spare parts" of the ATOMKI ECR ion source. We call it "ECR Table Plasma Generator". It consists of a relatively big plasma chamber (ID=10 cm, L=40 cm) in a thin NdFeB hexapole magnet with independent vacuum and gas dosing systems. For microwave coupling two low power TWTAs can be applied individually or simultaneously, operating in the 6-18 GHz range. There is no axial magnetic trap and there is no extraction. The technical details of the plasma generator and preliminary plasma photo study results are shown.

THE ATOMKI-ECRIS

In the ATOMKI a room-temperature, variable frequency ECR ion source operates as a stand-alone device to produce plasmas and ion beams from a variety of materials. So far H, He, N, O, Ar, Kr, Xe (from gases) and F, Ni, Fe, Zn, C, C_{60}, Zn, Pb (from solids) plasmas and beams were produced. The technical details and the recent applications of the ECRIS are shown elsewhere [1, 2]. The homepage of the ECR Laboratory [3] stores lots of information and photos.

The ATOMKI-ECRIS is a modular ion source which means that some of its main sub-systems are variable or changeable. It has two plasma chambers. The first one (internal diameter ID=5.8 cm, length L=20 cm) serves for highly charged ions (HCI) and a bigger one (ID=10 cm, L=20…40 cm, variable) was designed to host large-size, low charged plasmas (LCP). Both plasma chambers can be fit into their own NdFeB hexapole magnet which have logically appropriate IDs for the plasma chambers [4]. In Fig. 1 the plasma chambers and hexapoles are shown. Two room-temperature solenoid coils with optional iron plugs build the axial mirror trap of the ECRIS. The main microwave source is a klystron amplifier operating at 14.3 GHz frequency, with transmitted power between 5 and 1000 W. Occasionally we use a second microwave source which is one of our three travelling wave tube (TWT) amplifiers. The TWTAs can deliver microwave power up to 20 W in a wide frequency range (6-18 GHz).

The original goal was the usage of these two configurations (HCI and LCP) alternatively. But the frequent ECRIS disassembling and re-building sometimes caused inconvenience and the starting-up times (pumping down, plasma aging, etc.) was too long, occasionally 2-5 days. Furthermore, after more than 10 years of operation time our ECR laboratory owns many spare parts and devices (as pumping systems, vacuum measurement units, gas dosing tools, ovens, electrical and motion feedthroughs etc).

Therefore we decided to build a second ECR facility from the spare parts of the "big" ECRIS. It became a compact device which can be placed even on a table so we call it "ECR Table Plasma Generator". Its main elements are:

- plasma chamber (ID=10.2 cm, L=20-40 cm, variable), SS, double walled, water-cooled,
- NdFeB hexapole radial trap (L=24 cm, Br=0.65 T at chamber wall), Halbach-type,
- WR62 and WR90 connections
- microwave oscillator (HP 8350B + plug-ins)
- TWT amplifiers (max 20 W) with frequency 6-18 GHz (variable). One or two microwaves can be coupled.
- three vacuum ports for electrical or motion feedthroughs, for ovens, probes, etc.
- observing window or sample holder (alternative)
- gas dosing system, turbopump vacuum system.

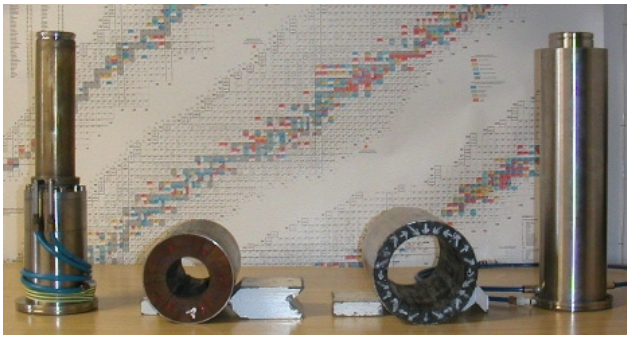

Figure 1. The HCI plasma chamber with its strong hexapole (left) and the LCP chamber with the large, weak hexapole (right).

The device is not equipped however, with axial magnetic trap (there are no coils or axial magnets) and there is no extraction system at all. In Fig. 2 the Table Generator is shown with explanation texts.

The first tests of the table device passed off without any major problems. A relatively high pressure (10^{-4} mbar) is necessary to ignite the plasma without a closed ECR-zone. In Fig. 3 residual gas plasma is shown. The strong asymmetry is caused by the side position of the gas tube.

[#]rracz@atomki.hu

USING MASS-FLOW CONTROLLERS FOR OBTAINING EXTREMELY STABLE ECR ION SOURCE BEAMS

X. Donzel#, W. Bougy, N. Brionne, G. Gaubert, A. Sineau, O. Tasset-Mayé, C. Vallerand,
A.C.C. Villari, PANTECHNIK, Bayeux, France
R. Leroy, GANIL, Caen, France

Abstract

Beam stability and reproducibility is of paramount importance in applications requiring precise control of implanted radiation dose, like in the case of hadrontherapy. The beam intensity over several weeks or months should be kept constant. Moreover, the timing for changing the nature of the beam and, as a consequence, the tuning of the source should be minimized. Standard valves usually used in conjunction of ECR ion sources have the disadvantage of controlling the conductance, which can vary significantly with external conditions, like ambient temperature and inlet pressure of the gas. The use of flow controllers is the natural way for avoiding these external constraints. In this contribution we present the results obtained using a new model of Mass-flow controller in the Supernanogan [1] source, for production of C^{4+} and $H^{3\ +}$ beams. Extremely stable beams (+/- 2.5%) without retuning of the source over several weeks can be obtained. The reproducibility of the source tuning parameters can also be demonstrated.

GAZ SYSTEM

The previous Pantechnik's gas system using UDV 140 thermo-valve has been replaced by Mass flow-controller but keeping in state the rest of the system (see Fig. 1).

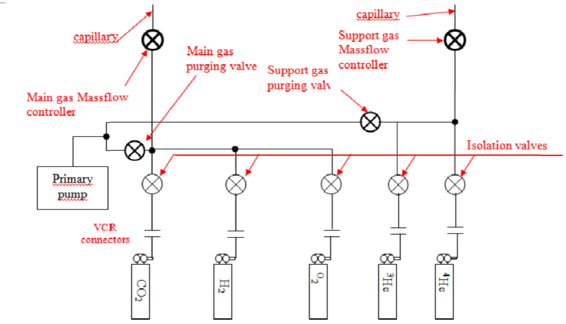

Figure 1: Schematic Gas System

The sensor's principle [2] inside the Mass flow-controller is made of a stainless steel capillary tube with resistance thermometer elements (see Fig. 2). A part of the gas flows through this bypass sensor, and is warmed up by heating elements. Consequently the measured temperatures T1 and T2 drift apart. The temperature difference is directly proportional to mass flow through the sensor. In the main channel Bronkhorst Company applies a patented laminar flow element consisting of a stack of stainless steel discs with precision-etched flow channels. Thanks to the flow-split the sensor output is proportional to the total mass flow rate. The minimum flow with this system is 0.014 mln/min until 0.06ml$_n$/min at max aperture.

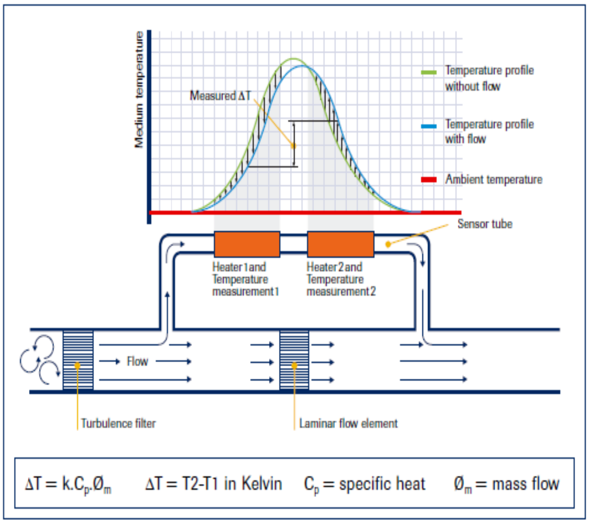

Figure 2: Mass-Flow sensor's principle

SYSTEM REACTIVITY AND STABILITY WITH TEMPERATURE

The behaviour of the Mass flow controller has been studied for different temperature variations.

Reactivity with sudden temperature changes

We recorded the current beam during 6400s and forced the temperature of the test room from 22°C to 14°C in 25 minutes (Fig. 3 & Table 1). The Mass-flow is only sensitive to very high variation of temperature.

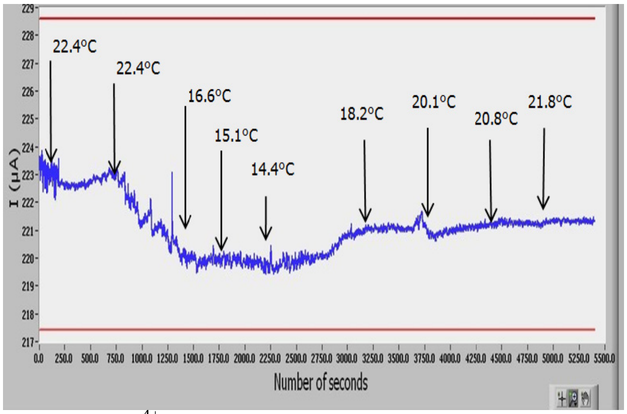

Figure 3: C^{4+} current with huge temperature's room variations.

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xdonzel@pantechnik.com

PRELIMINARY DESIGN OF BLISI, AN OFF RESONANCE MICROWAVE PROTON SOURCE

Slobodan Djekic, Ibon Bustinduy, David de Cos, David Fernandez-Cañoto, Jorge Feuchtwanger,
Hooman Hassanzadegan, Igor Rueda, Juan Luis Munoz, ESS Bilbao, Bilbao, Spain
Daniel Cortazar, ESS Bilbao, Bilbao and Universidad de Castilla-La Mancha, Ciudad Real, Spain
F. Javier Bermejo Bilbao, Bilbao, Spain
Victor Etxebarria, Josu Jugo, Joaquin Portilla, University of the Basque Country, Bilbao, Spain
Miguel Angel Carrera, Julio Huguet Galipienzo, AVS, Eibar, Spain
Julio Lucas Elytt Energy, Madrid, Spain

Abstract

A new high current off resonance microwave H^+ source is currently in the last stages of design at ESS-Bilbao, in collaboration with two external companies Elytt and AVS. The design is intended to be a high-stability, high-current ion source capable of delivering a 70 mA proton beam with a 70 keV energy.

INTRODUCTION

The Bilbao Center for Accelerator Science and Technology is a large scale accelerator facility under construction in Spain. Its main headquarters have been inaugurated at the University of the Basque Country (UPV/EHU) campus at Leioa, Biscay. The first machine of the future facility will be a high intensity Proton Linear Accelerator. The first part of such a proton LINAC will be BLISI – Basque Light Ion Source Injector, that is to be completed within two years.

The main parts of the future BLISI Ion Source are magnetic structure, microwave system, gas inlet system and extraction system. The first two parts are designed in collaboration with Elytt. They are consists of a water-cooled plasma chamber that sits between two independently powered magnetic coils that generate the ECR magnetic field, a CPI 2.7 GHz klystron which provides the microwave energy and a fully controlled microwave system to minimize reflected power and improve the source overall performance.

The gas inlet system is designed for simultaneous introducing of two gases and it will have an automatic control loop for the gas flow stabilization.

The extraction system has been designed in collaboration with AVS. It will consist of a movable tetrode system designed for a maximum acceleration potential of 70 kV, the shape of the electrodes is at an earlier design stage at ESS-Bilbao.

The list of the desired parameters of the BLISI proton beam is given in Table 1.

We will present the current layout of the source, simulations and schematics of the source.

MAGNETIC STRUCTURE

The magnetic structure of the BLISI Ion Source consists of two solenoid coils divided into two pancakes and shielded by an iron yoke. The coils will be powered via four power supplies for higher flexibility in shaping of the magnetic field configuration. The coils are remotely movable via use of two stepping motors with a linear accuracy of 20 µm.

General Consideration

For optimal microwave power absorption in plasma chamber that will enhance production of high current of single charged ions one has to provide the special magnetic field configuration. Experimentally has been proven that such configuration has to have electron cyclotron resonance (ECR) conditions at both ends of the chamber and across the chamber to have a flat field around 10% higher then ECR field [1]. For our working frequency of 2.7 GHz corresponding resonance field will be B_{ECR} = 96.4 mT, so we have to provide flat magnetic field of around 106 mT through the whole length of the plasma chamber. We have considered two different solutions for the BLISI magnetic structure configurations.

Magnetic Field Proposals

In the first proposed magnetic structure, a plasma electrode and its support are made of magnetic material so they have a strong influence on the overall magnetic field shape. It is shown on the left part of the Fig.1.

Table 1: Expected proton beam characteristics

Proton Beam Parameters	Values
Beam energy	70 keV
Total current	80 mA
Proton fraction	>85 %
Emittance	<0.2 π mm mrad
Availability	98 %
Reliability	170 hours
Duty Factor	3 % to 10 % (pulsed beam)
Pulse	1.5 to 2 ms
Repetition Rate	Up to 50 Hz
Klystron	2 kW @ 2.7 GHz

PERFORMANCE OF THE LBNL AECR-U WITH A TWTA

J. Benitez#, D. Leitner, M. Kireeff-Covo, C.Lyneis,
Lawrence Berkeley National Laboratory, Berkeley, USA

Abstract

The Advanced Electron Cyclotron Resonance - Upgrade ion source (AECR-U) at the Lawrence Berkeley National Laboratory has successfully utilized double frequency microwave heating (14.3 GHz and 10.4 GHz) for several years [1]. Recently a traveling wave tube amplifier (TWTA), providing frequencies in the range of 10.75GHz-12.75GHz, was added as a secondary heating frequency, replacing the previous 10.4 GHz Klystron. The TWTA opens the possibility to explore a wide range of secondary frequencies and a study has been conducted to understand and optimize its coupling into the AECR-U. In particular, the reflected power dependence on heating frequency has been mapped out with and without the presence of plasma. A comparison is made to determine how the presence of plasma, confinement fields, and other source parameters affect the reflected power and if and how the amount of reflected power can be correlated to the source ion beam performance.

[1] Z. Q. Xie and C. M. Lyneis, RSI 66 (1995).

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jybenitez@lbl.gov

MEASUREMENTS OF BREMSSTRAHLUNG RADIATION AND X-RAY HEAT LOAD TO CRYOSTAT ON SECRAL *

H. Y. Zhao [#,‡], W. H. Zhang [#], Y. Cao [#,†], H. W. Zhao [#], W. Lu [#,†], X. Z. Zhang [#], Y. H. Zhu [#],
X. X. Li [#], and D. Z Xie [#]
[#]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[†]Graduate School of Chinese Academy of Sciences, Beijing 100049, China

Abstract

Measurement of Bremsstrahlung radiation from ECR (Electron Cyclotron Resonance) plasma can yield certain information about the ECR heating process and the plasma confinement, and more important a plausible estimate of the X-ray heat load to the cryostat of a superconducting ECR source which needs seriously addressed. To better understand the additional heat load to the cryostat due to Bremsstrahlung radiation, the axial Bremsstrahlung measurements have been conducted on SECRAL (Superconducting Electron Cyclotron Resonance ion source with Advanced design in Lanzhou) with different source parameters. In addition, the heat load induced by intense X-ray or even ϒ-ray was estimated in terms of liquid helium consumption. The relationship between these two parameters is presented here. Thick-target Bremsstrahlung, induced by the collision of the hot electrons with the wall or electrode of the source, is much more intensive compared with the radiation produced in the plasma and, consequently, much more difficult to shield off. In this paper the presence of the thick-target Bremsstrahlung is correlated with the magnetic confinement configuration, specifically, the ratio of B_{last} to B_{ext}. And possible solutions to reduce the X-ray heat load induced by Bremsstrahlung radiation are proposed and discussed.

INTRODUCTION

Driven by the increasing demand of heavy ion accelerators devoted to nuclear physics and high energy physics for more intense and higher charge state heavy ion beam, the technology of highly charged ECR (Electron Cyclotron Resonance) ion sources have been developed dramatically in the past decades. The production of more intense and higher charged state heavy ions can be realized by the increase of the plasma density and confinement time and, according to the scaling laws [1], finally realized by the enhancement of the frequency and power of the microwave and the magnetic confinement field. In the past twenty years, beam intensities of highly charged heavy ions produced by ECR ion sources have increase by a factor of 10-100 for different ions. However, nowadays the trend of ECR ion sources towards to higher microwave frequency and power and higher magnetic field is limited not only by the technological limits of microwave and superconducting magnets but also by the presence of intense high-energy X-ray flux produced by electron-ion collisions in the plasma or electron-wall collisions, which is severe especially for superconducting ECR ion sources because the X-ray can lead to substantial heat load to the cryostat. The presence of high energy electrons, with energy up to 1 MeV, in third generation ECR ion sources has been proved experimentally [2], [3]. The collisions of these high energy electrons with plasma ions lead to Bremsstrahlung radiation. In addition, some lost electrons strike on the chamber wall or the electrode and, consequently, thick-target Bremsstrahlung is produced. The produced X-ray deposits energy in the structure of ion sources, and turns out to be substantial heat load to the cryostat in the case of superconducting ECR ion sources.

To better understand the heat load of SECRAL, the axial Bremsstrahlung spectra have been measured at 24 GHz with different source parameters, and the heat load to the cryostat was estimated in terms of LHe (Liquid Helium) consumption simultaneously.

In some cases, the plasma electrons lose confinement and strike on the structure of the source, which leads to thick-target Bremsstrahlung that is much more intense and with much higher energy compared with the radiation produced in plasma. Obviously, this kind of radiation should be avoided in the point view of the reliable operation of the source. The axial Bremsstrahlung measurements have been carried out in different magnetic confinement configuration to provide insights about the thick-target Bremsstrahlung in ECR ion sources.

EXPERIMENTAL SETUP

The bremsstrahlung spectra were measured with an HPGe (High Purity Germanium) detector. To measure the axial radiation, the HPGe detector was located behind the straight-through port of the 110° analyzing magnet. The signals produced by the detector were amplified and shaped by a main amplifier, then sent to a MCA (Multi-Channel Analyzer) and finally displayed and stored on a PC (personal computer).

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[‡] zhaohy@impcas.ac.cn

EFFECTS OF MICROWAVE FREQUENCY FINE TUNING ON THE PERFORMANCE OF JYFL 14 GHz ECRIS*

V. Toivanen[†], V. Aho, P. Jones, J. Kauppinen, H. Koivisto, P. Peura, T. Ropponen[‡],
O. Tarvainen, J. Ärje, JYFL, Jyväskylä, Finland
L. Celona, G. Ciavola, S. Gammino, INFN-LNS, Catania, Italy
D. Mascali, INFN-LNS and CSFNSM, Catania, Italy
A. Galatà, INFN-LNL, Legnaro, Italy

Abstract

Measurements have been carried out at the Department of Physics, University of Jyväskylä (JYFL) to study the effects of microwave frequency fine tuning on the performance of JYFL 14 GHz electron cyclotron resonance ion source. The frequency was varied within an 85 MHz band around the normal operation frequency of 14.085 GHz. The radial bremsstrahlung emission was measured for plasma diagnostics purposes and mass separated ion beam currents extracted from the ion source were recorded at the same time. Also, beam quality studies were conducted by measuring the ion beam emittance and shape with and without enhanced space charge compensation achieved by increased neutral gas pressure in the beam line. The obtained results are presented and possible origins of observed phenomena in measured quantities are discussed.

INTRODUCTION

The microwave frequency fine tuning has become an interesting subject concerning the enhancement of ECR ion source capabilities. In this method the ECRIS microwave frequency is altered in a narrow frequency band around the normal operation point to achieve improved source performance. Studies done by L. Celona et al. have given promising results showing strong frequency dependent variations in ion beam currents and beam shape [1]. Encouraged by these results, similar experiments were conducted with JYFL 14 GHz ECRIS including studies of mass separated ion beam currents and emittance. The results were promising but the origin of many phenomena were still left unanswered [2]. It was clear that additional measurements were needed. This paper presents the results of the latest frequency tuning measurements conducted at JYFL.

ELECTROMAGNETIC MODE STRUCTURE

When microwaves are fed into an ECRIS plasma chamber in vacuum, certain kinds of electromagnetic field structures can be excited inside. With frequencies around 14 GHz and typical plasma chamber dimensions these electromagnetic modes are closely packed and have separation of the order of some MHz [3]. Thus only a slight change in the feeding microwave frequency can induce a notable difference in the electric field structure on the ECR surface.

It is not clear how the situation changes when the chamber is filled with anisotropic inhomogeneous plasma. If the mode structure behavior remains, it should affect the electron heating efficiency, charge state distribution, ion dynamics and confinement time in the plasma, having an obvious influence on the characteristics of the ion beam [4].

EXPERIMENTAL PROCEDURE AND RESULTS

All measurements were conducted with JYFL 14 GHz ECR ion source [5]. The local 14.085 GHz oscillator was replaced with Rohde & Schwartz signal generator set to sweep a frequency range of 14.050 - 14.135 GHz in 100 seconds. The klystron was set to maintain constant power output during the sweeps. A signal given by the signal generator at the beginning of each sweep was used for triggering and time stamping of all time resolved data acquisition. Bremsstrahlung was measured radially from the plasma chamber with a germanium detector. The ECRIS and beam parameters were collectively measured with a computerized data acquisition system. The quality studies of m/q separated beams were conducted by measuring the beam emittance with an Allison type emittance scanner and the beam shape with a KBr scintillation screen at discrete frequencies. In these measurements the enhancement of space charge compensation (ESCC) was achieved by feeding argon into the beam line section between the ECRIS and the analyzing magnet resulting to beam line pressure of $4 \cdot 10^{-6}$ mbar. More details of similar gas feeding method can be found from reference [6]. All measurements were performed using argon beams with charge states between 5+ and 16+, except the transmission studies, where oxygen and krypton beams were also used. The ion source tuning was performed with 14.085 GHz frequency.

Beam current, bremsstrahlung and reflected power studies

The ion beam currents exhibited a clear oscillating behavior with varying microwave frequency. The fluctuations

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[†] E-mail: ville.toivanen@jyu.fi

[‡] Currently at NSCL/MSU, East Lansing, Michigan, USA.

MEASUREMENT OF THE DIAMAGNETIC CURRENT ON THE LBNL 6.4 GHz ECR ION SOURCE

J. Noland[#], J. Benitez, M. Kireeff Covo, D. Leitner, C. Lyneis, LBNL, Berkeley, CA 94720, USA.
J. Verboncoeur, Department of Nuclear Engineering, UC Berkeley, Berkeley, CA 94720, USA.
O. Tarvainen, Department of Physics, University of Jyvaskyla, Jyvaskyla 40500, Finland.

Abstract

A method of measuring the diamagnetic current on the LBNL 6.4 GHz ECR ion source is described. The diamagnetic signal is proportional to the rate of plasma formation and decay. Furthermore, the integrated signal can be used to estimate the total plasma pressure, or energy density, and can thus be used to study the warm and hot electron populations in an ECR plasma.

INTRODUCTION

ECR ion source (ECRIS) plasmas are capable of creating large amounts of high energy x-rays[1]. These x-rays present hazards to personnel and can add a substantial heat load to the cryostat of superconducting ECRIS's. As the heating frequency is increased, the problem will only worsen. In order to understand the production of x-rays in ECRIS plasmas, it is important to understand the electron heating mechanism, as it is the high energy electrons that are responsible for the creation of penetrating x-rays.

One common, non-invasive, high temperature plasma diagnostics that can be used to study high energy electrons is measurement of the plasma diamagnetic current. This diagnostic has been successfully applied to ECRIS plasmas previously[2]. Plasma diamagnetism is related to the energy density of all charged particles in the plasma. In a typical ECRIS plasma, though, the diamagnetic currrent is dominated by warm and hot electrons[3].

This paper describes the methods used to record diamagnetic signals on the LBNL 6.4 GHz ECRIS[4]. First,the theory of plasma diamagnetism is briefly discussed. In the second section of the article we discuss the diamagnetic loop experimental setup. Finally, examples of typical diamagnetic current measurements made over the course of our study are shown.

PLASMA DIAMAGNETISM

Charged particles orbit around magnetic field lines in such a way that the magnetic field created by their motion opposes the externally applied magnetic field. If a plasma is uniform, i.e., no density or temperature gradients, then the currents created by neighboring charged particles will cancel, and no net current will exist. If, on the other hand, gradients are present in a plasma a net current can arise. This macroscopic current creates a magnetic field that acts to decrease any external magnetic field, and is thus called a “diamagnetic” current. A common method of measuring the diamagnetic current is to use a loop of wire that is wrapped around the plasma chamber.

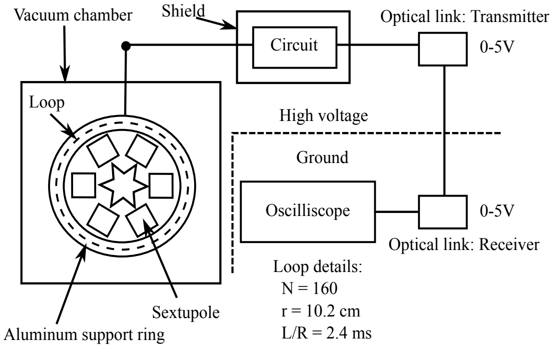

Figure 1: Experiment setup of diamagnetic loop used for plasma energy density measurements.

As the plasma in an ECR ion source forms or decays, the changing diamagnetic current creates a time varying magnetic field that opposes the steady, external magnetic field. By Faraday's law, an electric field is created. The electric field is responsible for creating a voltage across the leads of the diamagnetic loop, which is what is ultimately measured.

The electromotive force (emf) in the diamagnetic loop can be written:

$$\epsilon = -N \frac{d\phi}{dt}, \quad (1)$$

where N is the number of turns in the diamagnetic loop, and Φ is the total magnetic flux passing through the loop. Starting with Eq. 1, the following equation relating the integrated diamagnetic signal to the plasma pressure can be derived [5]:

$$\int^{t} \epsilon_P \, dt = \frac{\pi \mu_0 r_0^2}{B_0} nkT, \quad (2)$$

where r_0 is the plasma radius, and nkT is the plasma pressure due to all particles in the plasma. To arrive at this equation it is assumed that the velocity distribution is isotropic so that the pressure tensor reduces to a scalar, that the plasma can be represented by the ideal MHD equilibrium equation, and that the density profile is given by:

$$n = n_0 \exp\left(-(r/r_0)^2\right). \quad (3)$$

[#] jdnoland@lbl.gov

MICROWAVE FREQUENCY DEPENDENCE OF THE PROPERTIES OF THE ION BEAM EXTRACTED FROM A CAPRICE TYPE ECRIS

F. Maimone[1,2], K. Tinschert[1], P. Spädtke[1], J.Mäder[1], J. Roßbach[1], R. Lang[1],
[1]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, 64291 Darmstadt,Germany
[2]Universita' degli Studi di Catania, D.M.F.C.I, Viale A. Doria 6, 95125 Catania, Italy
L. Celona[3], [3]INFN-LNS, Via S. Sofia 62, 95123 Catania, Italy

Abstract

In order to improve the quality of ion beams extracted from ECR ion sources it is mandatory to better understand the relations between the plasma conditions and the beam properties. The present investigations concentrate on the analysis of different beam properties under the influence of various applications of frequency tuning and of multiple frequency heating. The changes in the microwave frequency feeding the plasma affect the electromagnetic field distribution and the dimension and position of the ECR surface inside the plasma chamber. This in turn has an influence on the generation of the extracted ion beam in terms of intensity, shape and emittance. In order to analyze the corresponding effects, measurements have been performed with the CAPRICE-Type ECRIS installed at the ECR Injector Setup (EIS) of GSI. The experimental setup uses a microwave sweep generator which feed a TWTA (Traveling Wave Tube Amplifier) covering a wide frequency range from 12.5 to 16.5 GHz. This arrangement provides a precise determination of the frequencies and of the reflection coefficient along with the beam properties. A sequence of viewing targets positioned inside the beam line monitors the beam shape evolution.

INTRODUCTION

The increasing request of higher energies for higher charge states pushes towards the development of more performing ECR ion sources or to the research of methods to enhance the performances of the existing ones. The tuning of the microwave frequency feeding the plasma can be a promising technique even if a better understanding of this effect is mandatory. In 1998 the ORNL CAPRICE-Type ECRIS was used to demonstrate how the frequency domain technique was useful to enhance the ECRIS performances [1]. In 2008 several measurements were carried out with the CAPRICE ion source at GSI in order to investigate the frequency tuning effect on the extracted Helium beam intensity and shape [2]. In 2009 an experiment was carried out at JYFL in order to measure the effect of the frequency tuning on the intensity, quality and emittance of a mass separated Argon beam [3]. In both of these last tests the frequency was swept over a narrow range of ±40 MHz around the Klystron center frequency of 14.5 GHz and in the 14.04-14.13 GHz range, respectively. In the present experiment the frequency tuning effect has been analyzed in the 12.5-16.5 GHz frequency range. The availability of a TWTA driven by a signal generator gave the possibility to change the source operating frequency with steps of a few hundred kHz. This experiment allows to analyze the beam properties when the ECRIS operative frequency sweeps over a wide range of 4 GHz, and hence for increasing ECR surfaces. The influence on lower and higher charge states has been analyzed for different source conditions concerning the magnetic field configuration, the gas pressure and the power setting.

EXPERIMENTAL SET-UP DESCRIPTION

The CAPRICE-Type [4] ECR ion source used for this experiment is equipped with a 1.2 T maximum radial magnetic field. The plasma chamber dimension was 179 mm of length and 64 mm of diameter. The RF power was provided by a TWTA working in the 8÷18 GHz frequency range and able to provide an output power higher than 650 W in the frequency range of 12÷18 GHz. The input of the amplifier was driven by a signal generator able to sweep from 1 to 20 GHz. According to the maximum manageable power reflected to the amplifier, it has been restricted to work at a power of 100 W and in the frequency range of 12.5÷16.5 GHz. The use of a waveguide microwave isolator covering this frequency range and handling up to 650 W could allow to work with higher powers. The frequency steps were set to 200 kHz with a dwell time of 20 ms for each step. Then the duration of one measurement was around 400 seconds. Two directional couplers of high directivity were inserted in the waveguide line in order to measure the forward power and the reflected power with two microwave power probes. The experiment has been carried out with Argon and Helium as a support gas at gas pressures of 3.9÷5 $*10^{-6}$ mbar. The ion currents of the charge states Ar^{7+}, Ar^{8+} and Ar^{9+} have been measured with a faraday cup; the drain current of the high voltage power supply of the extraction has been recorded as well. The extraction voltage was set to 15 kV; a -2 kV voltage was applied to the screening electrode. Viewing targets could be remotely inserted at three positions along the beam line in order to monitor the beam shape evolution right after the extraction, the focused beam and analyzed beam [5]. KBr was used as target coating material for this experiment.

INFLUENCE OF INITIAL PLASMA DENSITY AND MEAN ELECTRON ENERGY ON THE PREGLOW EFFECT

I. Izotov#, A. Sidorov, V. Skalyga, V. Zorin, IAP/RAS, Nizhny Novgorod, Russia
H. Koivisto, O. Tarvainen, V. A. Toivanen, University of Jyvaskyla, Finland

Abstract

The investigation of the Preglow effect is driven with the aim of creating a short-pulsed multicharged ion source. Recent experimental investigations have revealed strong influence of seed electrons, i.e. initial plasma density, on the amplitude and duration of the Preglow peak [1]. Present work, consisting of experiments and simulations, is dedicated to further investigation of the Preglow dependence on initial plasma density and electrons energy. Experimental investigation was performed at University of Jyvaskyla (JYFL) with the A-ECR type ECRIS operated with 14 GHz frequency. Helium was used for the study. An initial ionization degree of the gas was varied by changing the pulse duration and duty factor. Time-resolved ion currents of He+ and He2+ were recorded. Calculations were made by using 0-dimensional model described in references [2], [3] and based on the balance equations for the particles confined in the magnetic trap. Results of simulation are compared with experimental Preglow peaks and discussed. Good agreement between experimental data and simulation encourages us to conduct a further study, aimed at optimizing the Preglow by tuning source parameters and initial plasma conditions.

[1] O. Tarvainen et all. R.S.I., 81, 02A303, 2010
[2] T. Thuillier et all. R.S.I., 79, 02A314, 2008
[3] I. Izotov et all. IEEE Trans. Plasma Sci. 36, 1494, 2008.

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izotov@appl.sci-nnov.ru

OPTIMIZED EXTRACTION CONDITIONS FROM HIGH POWER-ECRIS BY DEDICATED DIELECTRIC STRUCTURES

L. Schachter[1], K. E. Stiebing[2], S. Dobrescu[1]

[1] National Institute for Physics and Nuclear Engineering (IFIN-HH), P.O. Box MG-6, Bucharest, Romania; [2] Institut für Kernphysik der Johann Wolfgang Goethe- Universität(IKF), Max- von-Laue- Straße 1, D-60438 Frankfurt/Main, Germany

Abstract

The MD-method of enhancing the ion output from ECR ion sources is well established and basically works via two mechanisms, the regenerative injection of cold electrons from an emissive dielectric layer on the plasma chamber walls and via the cutting of compensating wall currents, which results in an improved ion extraction from the plasma. As this extraction from the plasma becomes a more and more challenging issue for modern ECRIS installations with high microwave power input, a series of experiments was carried out at the 14 GHz ECRIS of the Institut für Kernphysik in Frankfurt/Main, Germany (IKF). In contrast to our earlier work, in these experiments emphasis was put on the second of the above mechanisms namely to influence the sheath potential at the extraction by structures with special dielectric properties. Two different types of dielectric structures, Tantalum-oxide and Aluminium oxide (the latter also being used for the MD-method) with contrastingly different electrical properties were mounted on the extraction electrode of the IKF-ECRIS, facing the plasma. For both structures an increase of the extracted ion beam currents for middle and high charge states by 60-80 % was observed. The method is able to be applied also to other ECR ion sources for increasing the extracted ion beam performances.

INTRODUCTION

The MD-method, using special insolating structures with high secondary electron emission coefficients, to enhance the ion output from ECR ion sources is well established and has been extremely successful. In second generation ECRIS sources (e.g. typically sources with 14GHz microwave systems at maximum powers of 2kW), enhancement factors for the highest charge states (e.g. Ar 16+) of up to 100 have been measured and were clearly attributed to the enrichment of the plasma by cold electrons form the secondary emission effect [1,2]. In a dedicated experiment an increase of the plasma density and electron temperature was observed for the Frankfurt 14GHz source equipped with a MD-liner as compared to the standard stainless steel source.

In a series of experiments it also could be shown that the secondary emission is only part of the mechanism that leads to the particularly good results for the highest charge states. A second effect clearly is the isolating properties of such a layer, which blocks all fast recombination currents and hence restores the ambipolarity at those parts of the surface of the plasma chamber where the structure is installed. This enhanced ambipolarity leads to considerably longer ion dwell times and hence serves to augment especially the high charge states by a better ion breeding.

It also has been demonstrated that, also with a MD-structure best results are obtained when the extraction from the source is optimized by carefully shaping the extraction conditions by a biased disk and that this can still be improved by using a MD-structure at the extraction electrode. This additional improvement was ascribed rather to the isolating properties of the MD-structure at the extraction electrode than to its secondary electron emission [3].

This allows for "tailoring" a MD structure to the needs of a respective installation. While a deficit in electron density may best be compensated by the secondary electron effect, for new generation sources with much better plasma densities and temperatures the improvement of the ion extraction by a MD extraction electrode my more appropriate.

In order to support this argumentation we have carried out a new series of experiments, where we have investigated the role of the dielectric character of the MD-structure by inserting two types of structure into the Frankfurt 14 GHz ECRIS, the very successful Al-MD structure with high secondary electron emission coefficient but only moderate dielectric constant and a Ta-MD structure which has a poor secondary electron emission but a distinctly higher dielectric constant as compared to the Al-MD.

EXPERIMENTAL SET-UP

The experiments reported in this article have been carried out at the 14GHz ECRIS installation at the Institute für Kernphysik, Frankfurt, Germany (IKF-ECRIS). Dielectric structures of Tantalum oxide and Aluminium oxide (denoted here as Ta/Al-MD electrode) were successively installed on the plasma electrode facing the plasma. The structures were made of 1 mm of pure Tantalum or Aluminium plates. The MD liner in this experiment was similar to those used in our previous experiments. It covers the radial walls of the plasma chamber on a length of 150 mm centred at the hexapole magnet.

PERMANENT MAGNET ECRIS FOR THE KEK DIGITAL ACCELERATOR*

Leo Kwee Wah[1#], K.Okazaki[2], T.Arai[3], T.Adachi[1,3], K.Takayama[1,3,4], K. Koyama[3], and M.Wake[1,3]
[1]The Graduate University for Advanced Studies, KEK, Tsukuba, Ibaraki, Japan
[2]Nippon Advanced Technology Co. Ltd. (NAT), Tokaimura, Ibaraki, Japan
[3]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan
[4]Tokyo Institute of Technology, Nagatsuda, Kanagawa, Japan

Abstract

The KEK-Digital Accelerator (DA) is an induction synchrotron renovated from the KEK 500 MeV booster synchrotron [1]. Its concept was demonstrated in 2006 using the 12 GeV proton synchrotron [2,3], where a proton bunch was accelerated with pulse voltages generated by a transformer instead of RF cavity. In the KEK-DA, O, Ne, and Ar ions from the ECRIS embedded in the 200 kV high-voltage terminal (HVT) are directly injected into the ring though the low energy beam transport line. The permanent magnet ECRIS, in which a plasma is fired by x-band microwave pulses of 3 msec at 10 Hz, has been assembled at KEK. Its operational performance such as charge-state spectrum, emittance and current have been tested since the last year. Beam dynamics through the test bench is discussed as well as operational characteristics of the ECRIS.

INTRODUCTION

The KEK-DA is a recycling of the KEK 500 MeV PS-Booster, which was shut down in March, 2006, and is being renovated as the first DA.

The operational schematic of the ion source and LEBT to the KEK-DA is shown in Fig.1 [1,2]. An ion beam is directly injected into the KEK-DA from the ion source without a gigantic injector. In order to mitigate space-charge effects during injection, the ion beam is accelerated through a high voltage acceleration column of 185 kV.

A permanent magnet ECRIS is a unique solution when an ion source is mounted in a high voltage terminal, because it does not require a large amount of electric power and its size is small and its weight is less than 50 kg. Since 2008 a pulse-mode x-band ECRIS has been developed.

An Ar beam including Ar^{1+}~Ar^{8+} is extracted through the extraction electrode of 14-15 kV and focused in the downstream Einzel lens system and guided into the acceleration column with inner focusing electrodes and enters into the separation magnet to be selected a desired charge state (Z) ion beam. Through the quadrupole focusing channel, an A^{8+} beam pulse of 3-5 msec long is guided and chopped by an Einzel lens or electrostatic chopper placed at the downstream.

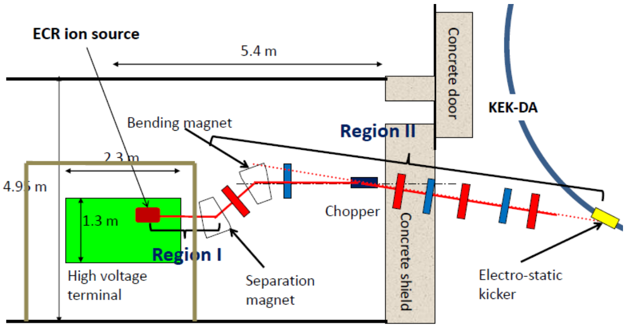

Figure 1: High voltage ion source and LEBT

ECRIS

The all-permanent magnet ECRIS has been built and tested over the last two years. Presently obtained results are discussed here. In addition remained issues are addressed.

Mechanical Design

The mechanical design of this ECRIS is shown in Fig. 2. It shows the complete assembly including two permanent ring magnets, hexapole magnet, return york, the microwave horn antenna and the extraction system with a screen to protect metal ions from spattering on the surface of the insulating ceramic pipe. The position of the antenna horn aperture can be optimized for matching. A plasma chamber with water cooling channels has been originally designed assuming a CW operation. As a result, the aperture size of 4cm in diameter is rather big compared with a similar x-band permanent ECRIS such as Nanogan [4].

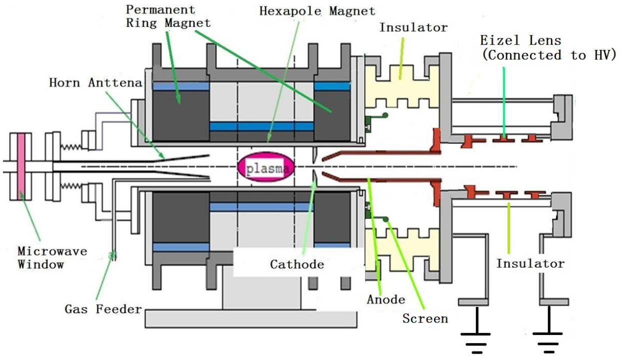

Figure 2: Schematic overview of the X-band ECR for The KEK-DA

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#leokw@post.kek.jp

LONG-TERM OPERATION EXPERIENCE WITH TWO ECR ION SOURCES AND PLANNED EXTENSIONS AT HIT

Tim Winkelmann, Rainer Cee, Thomas Haberer, Bernd Naas, Andreas Peters (HIT, Heidelberg)

Abstract

The HIT (Heidelberg Ion Beam Therapy Center) is the first treatment facility at a hospital in Europe where patients can be treated with protons and carbon ions. Since the commissioning starting in 2006 two 14.5 GHz electron cyclotron resonance ion sources are routinely used to produce a variety of ion beams from protons up to oxygen. The operating time is 330 days per year, our experience after three years of continuous operation will be presented. In the future a helium beam for patient treatment is requested, therefore a third ion source will be integrated. This third ECR source with a newly designed extraction system and a spectrometer line will be installed at a testbench to commission and validate this section. Different test settings are foreseen to study helium operation as well as enhanced parameter sets for proton and carbon beams in combination with a modified beam transport line for higher transmission efficiency. An outlook to the possible integration scheme of the new ion source into the production facility will be discussed.

INTRODUCTION

The facility of the Heidelberg Ion Beam Therapy Center (HIT) [1] is the first dedicated proton and carbon therapy facility in Europe. HIT is located at the university hospital in Heidelberg (Universitätsklinik Heidelberg, Germany).

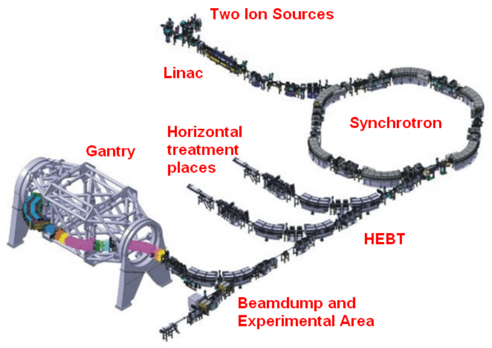

Figure 1: Overview of the HIT accelerator facility.

The beam production at HIT consists of two 14.5 GHz permanent magnet ECR ion sources from PANTECHNIK [2]. The 7 MeV/u injector linac [3] comprises the LEBT (Low Energie Beam Transport), a 400 keV/u radio frequency quadrupole accelerator (RFQ) [4,5], and a 7 MeV/u IH-type drift tube linac (IH-DTL) [3,4,5]. The linac beam is injected in a compact 6.5 Tm synchrotron [6] with a circumference of about 65m to accelerate the ions to final energies of 50 – 430 MeV/u, which is the key to the enormous variety of beam parameters provided by the HIT accelerator.

The maximum available beam intensity at the patient treatment place are 4·108 ions/spill for carbon and 1.6·1010 ions/spill for protons. With respect to the patient treatment, these intensities are sufficient, but for an effective quality assurance it will be important to reach the design parameters (C: 1·109 ions/spill, p: 4·1010 ions/spill). Taking into account the variable spill-length, the intensity shout be increased by a factor of 2.5 for carbon and protons.

The main contribution of particle losses is caused by the suboptimal transmission of the beam through the RFQ. Therefore the upgrade programme concentrates on a redesign of the RFQ [7]. In parallel we start to optimize the ion source performance for an improved brilliance to achieve a better adaption. Therefore we integrate a frequency variable microwave in a narrow range of 250 MHz around the 14.5 GHz center frequency. The frequency tuning is a method to optimize the electron cyclotron resonance ion source performances to maximize the extracted beam current and lower the beam emittance [8, 9, 10]. Furthermore for higher beam brilliance we designed a new extraction system.

LONG-TERM OPERATION EXPERIENCE

During the first three years of operation mainly carbon ions were used by 60 %, followed by hydrogen (38 %), helium (1 %) and oxygen (1 %). The continuous operation runtime of the two sources are 330 days per year 24h-operation!

Our challenge in the first three years of operation was the enhancement of the source components durability to stretch the time between maintenance intervals [10].

The operation-statistics (see Fig. 2) since summer 2007 of the two ion sources are: 97% of the time in operation, 2.9% of the time for planed maintenance shifts and 0.1% of the time are the “off time” caused by multiple RF-amplifier breakdowns. The time to exchange the defect amplifier by a spare part took mostly just one hour. By installing 3mm μ-metal shielding this instability is resolved in the meantime.

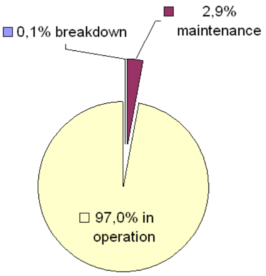

Figure 2: operation-statistic of the two ion sources at HIT, since summer 2007.

CEA/SACLAY LIGHT ION SOURCES STATUS AND DEVELOPMENTS

R. Gobin*, G. Adroit, G. Bourdelle, N. Chauvin, O. Delferrière, Y. Gauthier, P. Girardot, F. Harrault, C. Marolles, C. M. Mateo, S. Nyckees, B. Pottin, Y. Sauce, F. Senée, O. Tuske, T. Vacher, C. Van Hille, CEA/Saclay, DSM/IRFU/SACM, F- 91191-Gif/Yvette, France

Abstract

After several years of high intensity light ion beam production with the SILHI source, CEA Saclay is now involved in the construction of different injectors dedicated to large infrastructures like IFMIF or Spiral 2. Other installations are also interested by high intensity ion sources. Such machines plan to produce and accelerate proton or deuteron beams in pulsed or continuous mode. The SILHI source, based on ECR plasma generation, already demonstrated its performance in both modes.

As a consequence, at present time the construction of 2 new injectors for Spiral 2 and IFMIF (source and low energy beam lines) is in progress at CEA/Saclay. This article will report on the status of both installations. It will also point out on ongoing developments. Such developments are mainly done with the new BETSI test bench operating for several months.

INTRODUCTION

In the beginning of the 90s, Chalk River (Canada) laboratory group demonstrated the production of intense single charge light ion beams with ECR sources operating at low frequency (i.e. 2.45 GHz). At CEA/Saclay, the SILHI source developments started in the middle of the 90,s. Since 1997 more than 100 mA proton or deuteron beams are routinely produced in pulsed or continuous mode with this source [1]. To optimize the beam transport in the low energy beam line, the extraction system was carefully designed and space charge compensation studies were undertaken. Moreover, to comply with new infrastructure requests, specific source designs have been performed.

As a consequence, permanent magnet sources have been developed to fit in with the 5 mA deuteron beam expected production in continuous mode for Spiral 2 [2]. Then, to answer the IFMIF (International Fusion Material Irradiation Facility) high intensity deuteron beam request (125 mA) [3], a copy of the SILHI source with a 4 electrode extraction system has been proposed. Table 1 summarizes the Spiral 2 and IFMIF requested characteristics at the injector and RFQ interface.

Such proposals were accepted and now both injectors for Spiral 2 and IFMIF are presently under construction at CEA/Saclay, as reported in the following sections. In parallel, the SILHI installation is used for optical diagnostic improvements or tests dedicated to the mentioned projects.

As reported in the last section, new developments have been undertaken towards beam profile reconstruction using tomography technique. It is also planned to install a new solenoid on the BETSI ion source test bench, in order to allow molecular ion focusing in front of the analyzing dipole.

All this work is performed within the PROFIIL (Plateforme de Recherche et d’Optimisation des Faisceaux Intenses d’Ions Légers) platform.

Table 1: Spiral 2 and IFMIF requests at the RFQ entrance.

Requests	Unit	Spiral 2	IFMIF
Particle type		(H^+), D^+	D^+ , (H_2^+)
Intensity	mA	0.15 to 5	140
Energy	keV	(20), 40	100
Emittance	π.mm.mrad	0.1	0.2
D^+ fraction		99	99
Mode		CW and pulsed	CW and pulsed

SPIRAL 2 INJECTOR CONSTRUCTION

Several years ago, permanent magnet source has been developed to produce several mA of H^+ or D^+ beams [4]. So, the Spiral2 ion source, presently installed at CEA/Saclay (Fig. 1) is also based on the ECR heating plasma, with a permanent magnet induced magnetic field. Magnet rings are composed of several individuals magnets glued together in an aluminum shell. Magnetic orientation follows the source axis. Shielding plates are positioned in order to concentrate the magnetic flux on source axis and to reduce fringe field which avoids Penning discharges inside the accelerating column. The resonant zone (of 87,5 mT) for plasma heating is located near the ridged transition-plasma chamber interface.

Extraction column is composed of 5 electrodes and is not water-cooled. The gaps are optimized for the lowest extraction RMS emitance: calculations were made for 10 mA of proton beam at 20 keV and also 10 mA of deuteron beam at 40 keV.

At end of 2009 the ion source has been tested with hydrogen gas injection in the plasma chamber, in pulsed and CW mode. The extracted ion beam was collected just at the end of the accelerating column in a Faraday cup equipped with an electron repeller electrode. A total beam of 12 mA has been extracted from the ion source without any characterization. Figure 2 presents repetitive 8 mA

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*rjgobin@cea.fr

SHEATH FORMATION OF A PLASMA CONTAINING MULTIPLY CHARGED IONS, COLD AND HOT ELECTRONS, AND EMITTED ELECTRONS

H.J. You[#], National Fusion Research Institute, Daejeon, Republic of Korea

Abstract

A model of sheath formation was extended to a plasma containing multiply charged ions (MCIs), cold and hot electrons, and secondary electrons emitted either by MCIs or hot electrons. In the model, modification of the "Bohm criterion" was given; thereby the sheath potential drop and the critical emission condition were also analyzed.

INTRODUCTION

It is quite well known since Geller's remarks [1] that ion confinement is an important factor in an electron cyclotron resonance ion source (ECRIS). Particularly, it has been pointed out that the ion confinement is closely related to the plasma potential, since many empirical techniques (wall coatings, secondary electron materials, electron injection and biased disks, and gas mixing) were found to lower plasma potential [2]. In this sense, the detailed sheath formation is very important in understanding how multiply charged ions (MCIs), bulk (cold and hot) electrons, and secondary electrons (either by MCIs and bulk electrons) are contributing to the plasma potential (sheath potential drop). The present study was motivated by the fact that the secondary electron yields are strongly dependent on the charge state of the ions and on the incident energy of electrons; secondary electron yield γ_j by ion bombardment is almost linearly proportional to the charge state j, so that the ratio γ_j/j reaches around unity for Ar^{8+} ion [3], and secondary electron yield γ_e by electron bombardment is typically larger than 0.5 for the incident energy larger than 100 eV [4]. Therefore, the contributions of the secondary electron emissions on the sheath formation would be severe if the charge state of ions and/or the energy of electrons are high.

MODEL

We consider an unmagnetized plasma composed of different MCIs, cold and hot electrons, and emitted electrons from the wall. The wall is located at x=0 and is contact with plasma, which is assumed to be zero. The electric field is also zero there. The wall potential V_W is negative with respect to the plasma potential V_S. We assume bi-Maxwellian electrons (cold and hot electrons), which has two different electron temperatures. The secondary electrons are assumed to be emitted from the wall with the same initial velocity v_{em}. The above all considerations are illustrated in Fig. 1.

The potential profile $V(x)$ in the sheath is obtained by solving Poisson's equation,

$$\frac{d^2V(x)}{dx^2} = -\frac{1}{\varepsilon_0}\left[\sum_j e_j n_j(x) - en_e(x)\right], \qquad (1)$$

where $n_e(x) = n_{ec}(x) + n_{eh}(x) + n_{em}(x)$, and n_j, n_{ec}, n_{eh}, and n_{em} are the densities of j-charged ions, cold electrons, hot electrons, and emitted electrons from the wall surface, respectively.

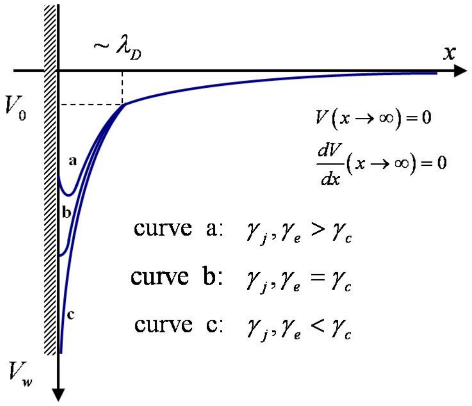

Figure 1: Sheath model & potential variations in front of the wall surface which emits electrons.

The behaviour of the j-charged ions can be described by continuity equation and momentum equation, therefore yielding following equation [5]

$$dn_j/dV = n_j e_j / m_j v_j^2, \qquad (2)$$

where m_j and v_j are the mass and velocity of j-charged ion.

The densities of cold and hot electrons are assumed to obey the Boltzmann relation,

$$n_{ec}(x) = n_{ec0}\exp(\psi), \quad n_{eh}(x) = n_{eh0}\exp(\psi). \qquad (3)$$

Here $n_{ec}(x)$ and $n_{eh}(x)$ are the cold and hot electron densities at x from the sheath edge, and n_{ec0} and n_{eh0} are the cold and hot electron densities at the sheath edge. The dimensionless potential ψ and the ratio (θ) of cold and hot electron temperatures (T_{eh}, T_{ec}) are defined in the following way:

$$\psi = -e\left(V_0 - V(x)\right)/kT_{ec}, \quad \theta = T_{eh}/T_{ec}. \qquad (4)$$

Therefore, ψ is a negative dimensionless potential measured with respect to the potential at the sheath edge.

[#] hjyou@nfri.re.kr

CHARACTERIZATION OF THE MICROWAVE COUPLING TO THE PLASMA CHAMBER OF THE LBL ECR ION SOURCE

C. Lyneis , J. Benitez, D. Leitner, J. Noland, M. Strohmeier, LBNL, Berkeley, CA, USA
H. Kovisto, O. Tarvainen, Department of Physics, University of Jyväskylä, Finland

Abstract

The characteristics of the microwave coupling of the 6.4 GHz LBL ECR ion source were measured as a function of frequency, input power, and time dependence. The time dependence of the plasma diamagnetism and plasma loading of the ECR chamber were compared. The cavity modes in the LBL ECR plasma chamber are fairly widely spaced which makes it possible to locate frequencies, where a single RF mode is predominately excited. For one of these modes we were able to demonstrate that with no plasma in the cavity it is over-coupled. As the power is increased, the plasma density and the plasma loading both increase and the cavity becomes under-coupled. The experiments demonstrate that even for this low frequency, low plasma density source, the plasma loading strongly lowers the Q and the RF stored energy as the plasma builds up.

INTRODUCTION

The LBL ECR plasma chamber, which has a diameter to wavelength ratio of only 2, is not as over moded as many higher frequency ECR ion sources. This makes it possible to locate frequencies, where a single RF mode is predominately excited. In Table 1 the mode distribution between 6.2 and 6.5 GHz for the source is shown. This is approximate since it is based on a model with cylindrical geometry and the LBL ECR has a sextupole shaped chamber.[1] Using model calculations and accounting for dipole and multi-pole modes there are about 94 modes between 6 and 7 GHz or an average mode spacing of 10 MHz. In contrast a large high frequency source such a VENUS at 28 GHz has a mode spacing of roughly 26 kHz, which means no possibility to see quasi single mode excitation.

Table 1: Calculated Modes in the LBL ECR Plasma Chamber

Mode	Frequency in GHz
$TM_{01,16}$	6.236
$TE_{4,1,9}$	6.317
$TM_{0,2,8}$	6.325
$TE_{1,2,9}$	6.330
$TE_{3,1,13}$	6.339
$TE_{2,1,10}$	6.353
$TE_{0,1,14}$	6.362
$TM_{1,1,14}$	6.362
$TE1_{,1,17}$	6.374
$TM_{0,2,9}$	6.496
$TE_{4,1,10,}$	6.507

The LBL ECR can be analyzed as a transmission line terminated by a single port resonant cavity. The measurable variables are the frequency, incident power level, and the reflected signal. In this analysis, we treat the case of a single mode cavity or, equivalently, a multi-mode cavity where the modes are sufficiently separated with respect to their frequency response that they can be treated as a single mode cavity over a small delta in frequency.[2] This approximation works best at zero or low plasma densities in the source when the cavity Q is high. At higher plasma densities where the plasma loading increases the modes overlap and the approximation breaks down.

In a single port cavity the incident and reflected power can be measured. These data can be used to compute the adsorbed power and the coupling coefficient, β, which can be expressed as

$$\beta = \frac{\sqrt{P_i} \mp \sqrt{P_r}}{\sqrt{P_i} \pm \sqrt{P_r}} \tag{1}$$

where P_i is the incident power and P_r is the reflected power. The choice of sign depends on whether the cavity is under coupled (upper sign) or over coupled (lower sign).

The coupling coefficient can be written alternatively as

$$\beta = \frac{Q_0}{Q_{ext}}, \tag{2}$$

where Q_{ext} is the external Q-value of the cavity. For a single mode Q_{ext} is a constant dependent on the geometry of the coupling port and the electromagnetic distribution of the mode. In this paper, the calculation of the Q_0 includes all of the power adsorbed inside the cavity, whether it is due to the resistive walls or plasma adsorption.

The electromagnetic energy stored in the cavity (EM-fields), U, can be calculated from

$$U = \frac{Q_0 P_a}{\omega} = \frac{Q_{ext}}{\omega}\beta P_a, \tag{3}$$

SOME CONSIDERATIONS ABOUT FREQUENCY TUNING EFFECT IN ECRIS PLASMAS*

D. Mascali, S. Gammino[#], L. Celona, G. Ciavola, INFN-LNS and CSFNSM, Catania, Italy
L. Neri, R. Miracoli, N. Gambino, G. Castro, INFN-LNS and Università di Catania
F. Maimone, GSI, 64291 Darmstadt, Germany and Univ. of Catania, D.M.F.C.I, Catania, Italy

Abstract

In the recent past many experiments demonstrated that slight variations of the microwave frequency used for the ignition of ECRIS plasmas strongly influence their performances (frequency tuning effect) either in terms of extracted current, of mean charge state and of beam emittance. According with theoretical investigations, this phenomenon can be explained by assuming that the plasma chamber works as a resonant cavity: the excited standing waves, whose spatial structure considerably changes with the pumping frequency, globally influences either the energy absorption rate and the plasma spatial structure.

EXPERIMENTAL EVIDENCES

The experimental results collected during the last years in several laboratories (INFN-LNS, JYFL, GSI) have confirmed the validity of the Frequency Tuning Effect (FTE). Here we will report about two experiments with the ECR ion source of CNAO, Pavia, and with the CAESAR source of INFN-LNS (in this case we measured also the emitted X-rays at frequencies between 14.0 and 14.5 GHz). The experiments at CNAO evidenced the increase of the coupling efficiency with the RFQ: keeping constant all the other parameters, in Pavia the transmission was around 50-70%, while only a 30% of transmission was obtained at HIT with a "twin" accelerator and without FTE. Fig.1 shows the comparison between the extracted current and the reflection index. We can argue that resonant modes correspond to minima of reflection coefficient. Generally, the current signal is peaked on frequencies corresponding to modes (squared area b), because of the better coupling, but this is not a strict rule: in some cases (squared area a), although the matching of the microwave line with the source (cavity plus plasma) is optimal, and the extracted current remains low. Therefore we must distinguish between the microwave generator-to-plasma chamber coupling and the excited mode-to-plasma coupling. In the latter case, as formerly explained in [1, 2], the mode spatial structure plays the main role. According to simulations, the heating rapidity is strongly regulated by the electromagnetic field pattern over the resonance surface. This picture is not enough complete to describe all the consequences of the frequency tuning. Additional data information come from the data of Fig. 2.a and 2.b: from the X-ray measurements it follows that the high energy component of EEDF is not significantly affected by FTE (the magnetic field profile is the critical parameter, as demonstrated in [3]).

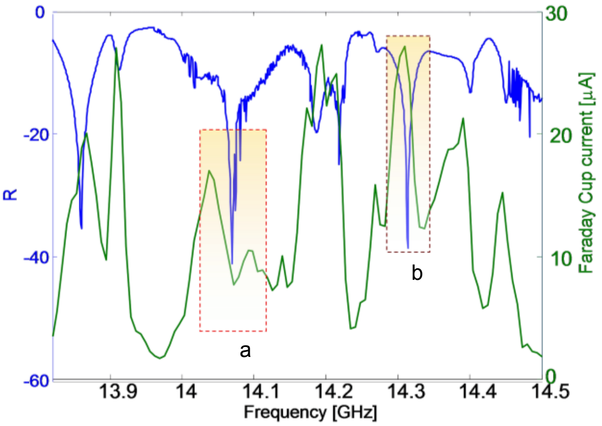

Figure 1: comparison between extracted current and reflection coefficient at different but close frequencies (test on the CNAO ECRIS).

Conversely the CSD (charge state distribution) reveals pronounced fluctuations for the highest charge states, as they are more sensitive to any change in heating rate. But the relationship between current and X-ray spectra is not straightforward. There are some frequencies (e.g. 14.38 GHz) which produce large amount of X-rays but relatively low currents and even a lower mean charge state. Considering the relation:

$$< q > \propto n_e \tau_i$$

being n_e the electron density and τ_i the ion lifetime, and assuming that the number of X-ray counts is somehow linked to the electron density, the results in Fig. 2 can be explained only by taking into account a possible influence of FTE on the ion dynamics (τ_i changes more than n_e).

This conclusion is confirmed by the other experimental data, which show how the frequency tuning affects the beam shape and emittance. At GSI [4] and JYFL in 2009 hollow beams have been obtained for some values of frequency, although no remarkable variations in the output current were observed. A plausible hypothesis is that cavity modes affects also the spatial plasma distribution, and consequently the ion dynamics, as discussed in [5]. Further confirmations come from the last experiment carried out at JFYL, focused on the beam transmission through the cyclotron, which varied even when the source output current did not change [6].

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[#] davidmascali@lns.infn.it

STUDIES OF THE ECR PLASMA IN THE VISIBLE LIGHT RANGE

S. Biri[1#], R. Rácz[1, 2,], J. Pálinkás[1, 2]
[1]Institute of Nuclear Research (ATOMKI), Hungary, H-4026 Debrecen, Bem tér 18/c
[2]University of Debrecen, Hungary, H- 4010 Debrecen, Egyetem tér 1.

Abstract

High resolution visible light (VL) plasma photographs were taken at the ATOMKI-ECRIS by an 8 megapixel digital camera. Plasmas were generated from gases of He, methane, N, O, Ne, Ar, Kr, Xe and from their mixtures. The analysis of the photo series gave many qualitative and numerous valuable physical information on the nature of ECR plasmas. It is a further challenging task to understand the colors of this special type of plasmas. The colors can be determined by the VL electron transitions of the plasma atoms and ions. Through the examples of He and Xe we analyze the physical processes which effect the characteristic colors of these plasmas.

INTRODUCTION

ECR plasmas can experimentally be investigated by two significantly different ways. Small-size electrostatic electrodes (Langmuir-probes) give local information on certain plasma parameters (density, potential) [1]. The other method is based on the fact that the plasma emits radiation in the infra-red (IR), visible light (VL), ultra-violet (UV) and X-ray (XR) regions of the electromagnetic spectrum. The main drawback of this method is that the recorded information always corresponds to integration or superposition over a specific line-of-sight in the plasma volume. In spite of this, the analysis of photos and spectra in any of these regions has shown that spatial imaging gives important and new insight into the plasma structure. XR-photons come from the walls of the plasma chamber or from the highly charged plasma ions. VL-photons however dominantly originate from atoms and low-charged ions excited by the cold electrons. Thus studying VL plasma photographs transforms information mainly on the spatial position and density distribution of the cold electrons.

As a continuation or supplement of our earlier successful X-ray studies [2] we made series of high-resolution VL plasma photos and movies in the ATOMKI ECRIS Laboratory. In [3] the effect of the basic setting parameters (gas pressure, magnetic field, microwave power) to the shape, color and structure of Ne, Ar and Kr plasmas were studied. In [4] the shape and intensity distribution of the VL-plasmas are compared with computer simulations and with XR-photos. The results and information presented in these two papers improve the understanding the ECRIS plasma. In the present paper a study is given on the colors of the ECR plasmas.

EXPERIMENTAL SETUP

The technical details and the application fields of the ECR ion source of ATOMKI are shown elsewhere [5, 6]. The homepage of the ECR Laboratory [7] stores also lots of information and photos. The ATOMKI-ECRIS had to be partly re-constructed in order to take direct photos from the injection side. The extraction optical system was removed. The beamline was closed with a quartz vacuum window to observe the plasma in-situ. A mirror was placed at a distance of 100 cm from the plasma chamber in 45° angle in order to set the observers and the camera at a safe perpendicular 40 cm distance from the mirror and from the axes of the ion source. Two microwave amplifiers (14.3 GHz klystron and 8-12 GHz TWT) were connected to be used simultaneously or individually. The axial magnetic field was usually set 80% of its maximum value in order to form closed resonance zones in a wide range of frequencies so the typical peak values of the magnetic field were 0.88 Tesla. The pressure (measured in the injection box) was (2…5)*10^{-5} mbar when only one gas was injected. This pressure value is more than one order of magnitude higher than the optimal one for the production of highly charged ions, but corresponds to produce high current, singly charged beams by this ion source.

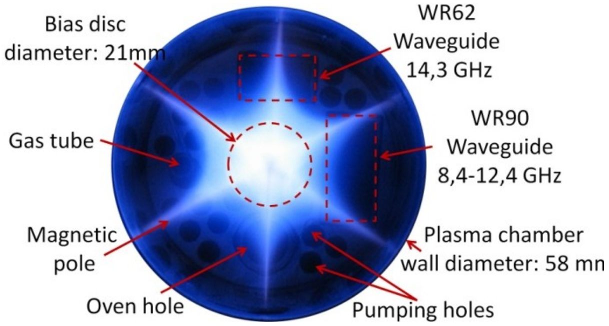

Figure 1. Typical axial image of the plasma. (Kr gas, microwave: 8.4 GHz, 10Wr, 2*10^{-5} mbar pressure) Plasma chamber, waveguides, bias disc, gas tube, oven hole, pumping hole can be seen.

When looking in the plasma chamber of an ECRIS the axial image of the plasma (Fig. 1.) in conformity with experimental setup can be seen. The photographs were taken by an 8 megapixel Canon digital camera. The ECR plasma is not an ideal photo model: its longitudinal length is about 20 cm, it is partly transparent and diffuse. To take systematically photo series we had to set manually the camera parameters. The typical exposure time was between 0.8 and 4 sec. Iris value was set to the maximum

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[#]biri@atomki.hu

BREMSTRAHLUNG AND ION BEAM CURRENT MEASUREMENTS WITH SuSI ECR ION SOURCE *

T. Ropponen[†], D. Cole, G. Machicoane, A. Stolz, L. T. Sun, L. Tobos
National Superconducting Cyclotron Laboratory, Michigan State University

Abstract

The Superconducting Source for Ions (SuSI) [1] at the National Superconducting Cyclotron Laboratory at Michigan State University is a fully superconducting 3rd generation ECR ion source currently operated with two 18 GHz klystrons. The axial magnetic field is generated by six solenoid magnets which allow to control the magnetic field characteristics, such as resonance locations, mirror ratios and magnetic field gradients, almost independently. In this paper we will focus on the measurements done with different collimation geometries and we will show results comparing FlatB and normal Bmin operation. We will also discuss about the effect of different magnetic field gradients while keeping the length of the plasma and value of $B_{\min}$ as constants.

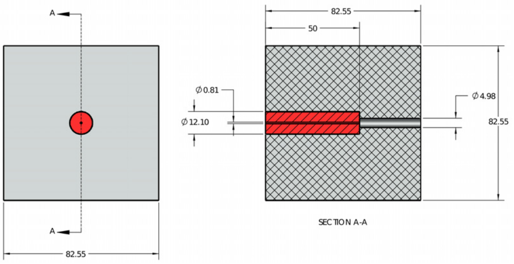

Figure 1: Cross-section view of the collimator structure. Both collimators that were used in the setup are identical. Lead is marked with gray color and tungsten insert with red. Dimensions are given in inches.

MEASUREMENT SETUP AND MAGNETIC FIELD PROFILES

The bremsstrahlung measurements presented in this paper are steady state high energy measurements. The bremsstrahlung events were recorded axially through the diagnostic port of the analyzing magnet using an Ortec p-type germanium detector. A small solid angle for the detection of bremsstrahlung was achieved using two collimators separated by 445 mm. Each collimator was made of lead for the outer parts and tungsten for the inserts. The layout of the collimator structure is presented in figure 1. The area at the extraction aperture of SuSI that was seen by the detector was about ⌀ 7 mm while SuSI plasma electrode has an opening of ⌀ 10 mm. In addition to these two collimators the existing lead shielding in the ECR area was put to use in order to decrease the amount of scattered radiation. First, a stand-alone lead shielding plate (25 mm of Pb, 6 mm of steel) positioned between the two collimators was used during the measurements. Second, the ECR area is confined using several large lead panels (13 mm of lead, 6 mm of steel) and one was positioned between the second collimator and the Ge detector. A 5 mm hole was drilled through both the shielding plate and the lead wall panel to allow the radiation to reach the detector. The distance from the plasma electrode to the detector was about 3.2 m. Figure 2 presents the general layout of the measurement setup.

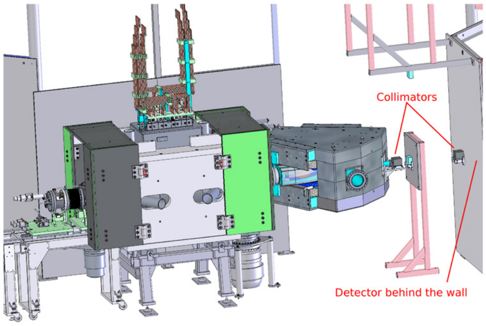

Figure 2: Layout of the measurement geometry. The first collimator is located next to the bending magnet flange (glass window) and the second one is attached to the ECRIS room wall. The stand-alone Pb shield is seen between the collimators. The detector was located behind the wall and was shielded with Pb blocks in order to decrease the background levels.

The collimators were aligned through the injection flange using a laser and ^{133}Ba and ^{152}Eu sources were used for energy and relative efficiency calibration. Energy resolution of the setup was 2.14 keV at 80.997 keV, 2.97 keV at 443.965 keV and 6.15 keV at 1085.842 keV. Measurement time was fixed to 30 min per set and typical count rates at the detector varied between 2 kHz and 75 kHz. Background radiation has been subtracted from the data presented in this paper.

The measurements were conducted using analog NIM, CAMAC and VME electronics. The electronics is divided into two branches — the so-called slow branch for energy and the fast branch for timing information. Due to this arrangement, the system is capable of detecting pile-up events. Shaping time of the linear amplifier was set to 3 μs and the signal width was roughly 6 μs. When two or more

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[†] ropponen@nscl.msu.edu

MAXIMUM BREMSSTRAHLUNG ENERGY VERSUS DIFFERENT HEATING LIMITS*

H. Koivisto#, V. Aho, V. Toivanen, O. Tarvainen, P. Jones, J. Saren, P. Peura JYFL, Jyväskylä, Finland

Abstract

A comprehensive set of bremsstrahlung measurements has been performed at JYFL (University of Jyväskylä, Department of Physics) in order to understand the parameters affecting the heating of electrons. In order to extend the understanding of electron heating, a new set of measurements with the JYFL 6.4 GHz ECRIS has been conducted to study the parameters affecting the maximum bremsstrahlung energy. During the work the effects of microwave power and magnetic field were studied. The analysis of the experimental data focuses in comparing the results with theoretical stochastic electron heating limits.

INTRODUCTION

In addition to the high requirements for the magnetic fields in 3rd generation superconducting ECR ion source the total microwave power fed into the plasma chamber can be even 10 kW. Consequently, these operation conditions results in intensive bremsstrahlung emission, which gives an extra heat load to the cryostat. It has been attempted to decrease the load by increasing the x-ray shielding as has been done for example for VENUS at LBNL, Berkeley using 2 mm tantalum sheet. However, due to the very limited space the thickness of the shielding must be small and thus practically transparent to the high-energy part of photon spectrum.

Experiments studying the parameters affecting the bremsstrahlung emission have been performed in several laboratories. In addition, different simulation codes have been developed to model the electron heating process. The research work has clearly shown that the magnetic field structure has a strong effect on the energy of the bremsstrahlung emission. It is explained that this is due to the lower magnetic field gradient in the heating zone, which improves the heating efficiency. As an example, the measurements at Berkeley showed that the end-point energy of the photon emission almost doubled when the B_{min} of the VENUS was increased from 0.44 T to 0.64 T having total microwave powers of 8.8 kW and 6 kW, respectively [1]. It has also been shown that the microwave power increases both the end-point energy and especially the yield of the photon emission. The build up of hot electron population in ECRIS plasma has been studied also by S. Gammino et al. [2] using Canobbio theory where maximum energy W_{max} can be expressed as $W_{\max}(eV) = 1.5 \cdot 10^9 (E(V cm^{-1})/\omega_0)^{2/3}$. In this equation E is the electric field, ω_0 the microwave frequency and it is assumed that the ECR heating takes place in a so-called low gradient regime.

These problems and observations gave a motivation to study the bremsstrahlung emission of an ECRIS also at JYFL. The objective of the work is to study parameters affecting the high-energy bremsstrahlung radiation. This work includes developing a hybrid simulation code [3], time resolved bremsstrahlung experiments (see e.g. [4]), and as a recent effort studying the parameters affecting the end-point energy of photon emission in continuous operation mode. In this article we present some results obtained when the ion source parameters affecting the end-point energy of bremsstrahlung radiation in steady state conditions have been varied. The results were compared to a stochastic heating limit theory in order to get more insight in the possibilities affecting the production of bremsstrahlung.

STOCHASTIC HEATING LIMITS

The ECR heating is considered to be stochastic if the phase between the electron and the wave is random in consecutive passes of resonance regions. When the electron gains energy the time between the successive passings of the resonance region decreases resulting to eventual loss of phase randomization, i.e. heating is not stochastic anymore. However, the energy can be increased even further until so-called adiabatic heating limit is reached. In this work the maximum bremsstrahlung energy produced by the JYFL 6.4 GHz ECRIS has been compared to the stochastic heating theory presented in ref. [5]. The theory states that the stochastic heating limit can be expressed as

$$W_s = 0.2\left[m_e L\left(1+\frac{l^2}{L^2}\right)\right]^{1/4} l\omega^{1/2}(eE)^{3/4} \qquad (1)$$

where E is the electric field of the microwaves at the resonance, $\omega = 2\pi f$ (f is the microwave frequency), m_e the mass of the electron, e is the unit charge, L is a parameter, which can be calculated from the axial magnetic field profile ($B = B_{\min}(1+z^2/L^2)$), where the resonances are at $z = \pm l$. Here B_{min} is the minimum magnetic field and z the axial distance from this minimum. Adiabatic heating limit is defined to be $W_a = 5W_s$. With the aid of equation (1) the effect of electric field E (related to microwave power), gradient of the magnetic field B, microwave frequency f and axial distance l of resonance points (from B_{min}) on the adiabatic and stochastic limits can be studied. The *gradB* has been calculated from the magnetic field profile equation shown above. In this consideration the relativistic effect, power absorption and mode structure behaviour are neglected.

Figure 1 shows the adiabatic heating limit as a function of the electric field of microwaves at the resonance. The calculations correspond to typical operation parameters of

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*Work supported by the Academy of Finland and Magnus Ehrnrooth foundation.

hannu.koivisto@phys.jyu.fi

COMMISSIONING OF THE ECRIS CHARGE STATE BREEDER AT TRIUMF

F. Ames, R. Baartman, P. Bricault, K. Jayamanna, TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T 2A3, Canada
T. Lamy, LPSC UJF-CNRS/IN2P3-INPG, 53 Rue des Martyrs, 38026 Grenoble, France

Abstract

Radioactive isotopes produced at the ISOL facility ISAC at TRIUMF are usually extracted as singly charged ions from the target ion source system. If the mass of these ions exceeds A=30 their acceleration requires breeding to highly charged ions. A modified version of an electron cyclotron ion source (ECRIS) charge state breeder (14.5 GHz PHOENIX from Pantechnik) has been installed and a first on-line test resulting in the successful acceleration of $^{80}Rb^{14+}$ has been performed already in 2008. During the radioactive beam time periods of 2009 and 2010 further measurements with stable and radioactive ions from different target ion source combinations have been performed to further commission the system. Breeding efficiencies of several percent in the maximum of the charge state distribution have been achieved. A major problem for experiments using those beams is the background from residual gas and other ions, which are also produced in the ECR charge state breeder and which result in similar mass to charge ratios than the radioactive isotope.

INTRODUCTION

At the ISAC radioactive ion beam facility at TRIUMF radioactive ions are produced by bombarding solid targets with up to 100 µA of protons from TRIUMF's 500 MeV cyclotron. The target material is operated at high temperature to allow fast diffusion and effusion of the reaction products into an ion source. Mainly singly charged ions are extracted [1]. The desired isotopes are separated with a magnetic mass separator and the ion beam can be transported to low energy experiments at an energy of several 10 keV or injected into a post accelerator for serving high energy experiments. The intensity of the radioactive ion beam covers a broad range from single ions for the most exotic ones up to about 10^9 per second for isotopes close to stability. The acceptance of the post accelerator allows a maximum A/q value of 30. However, this applies only to the first accelerator stage, a 4 rod radio frequency quadrupole (RFQ), which accelerates to 150 A keV. The following drift tube and superconducting cavity sections are able to accelerate ions up to 5 A MeV. They require $A/q<7$. Up to now this has been achieved by a stripping foil after the RFQ. If additional losses from this stripping process, which becomes less efficient for heavy ions, are to be avoided the charge breeding should directly lead to $A/q<7$.

Charge state breeding with an ECRIS has been chosen because of its capability to work efficiently in a continuous mode and because of the high charge capacity, which allows the charge state breeding of high intensity ion beams.

SET – UP OF THE SYSTEM

A modified version of a 14.5 GHZ PHOENIX booster from Pantechnik has been installed in a shielded area directly after the mass separation of the radioactive ions. They can be directed to the charge breeder source via a movable electrostatic deflector. The PHOENIX source is operated at a high voltage close to the one of the on – line ion source, so that singly charged ions are decelerated and stopped in the plasma. After extraction of the highly charged ions they are accelerated again to ground potential and separated according to their mass to charge ratio with a combination of a magnetic and electrostatic sector field. This combination assures the separation of scattered and charge exchanged ions out of the beam and thus, guaranties higher beam purity. The mass resolving power ΔM/M of the system is better than 1/100. A small surface ion source for Cs ions in front of the charge breeder source allows for the set-up and tuning of the charge breeder independent from the on-line target ion source system. A more detailed description of the set-up can be found in [2] and [3].

COMMISSIONING RESULTS

The installation has been finished already in 2008 and a first test, cumulating in the first successful acceleration of charge bred radioactive ions ($^{80}Rb^{14+}$) has been performed in November 2008. Results have been already reported in [3]. Final commissioning took place during the beam time periods of 2009 and the beginning of 2010.

With the test ion source a breeding efficiency of 3.5% for Cs^{21+} has been achieved. This is the same as the maximum value, which has been reached before when the source was installed on a test bench [3]. A variety of stable and radioactive ions from different target ion source combinations have been injected and efficiency and charge state distributions have been measured. In order to determine the breeding efficiency for the stable isotopes, current measurements before the charge state breeder and after the A/q selection have been performed. For the radioactive species the beam has been sent first directly to a detection station in the ISAC experimental hall. In this detection station ions can be implanted into a tape, which is surrounded by detectors for α, β and γ radiation. After a measurement the tape can be transported behind a lead shield leaving a fresh spot for a new measurement. After the intensity of the singly

RECENT PERFORMANCE OF THE ANL ECR CHARGE BREEDER*

R. Vondrasek, R. Scott, R. Pardo, A. Kolomiets, ANL, Argonne, IL 60439, U.S.A.

Abstract

The construction of the Californium Rare Ion Breeder Upgrade (CARIBU) [1], a new radioactive beam facility for the Argonne Tandem Linac Accelerator System (ATLAS), is complete and the project is now in the commissioning phase. The facility will use fission fragments, with charge 1+ or 2+, from a 1 Ci ^{252}Cf source; thermalized and collected into a low-energy particle beam by a helium gas catcher. An existing ATLAS ECR ion source was modified to function as a charge breeder in order to raise the ion charge sufficiently for acceleration in the ATLAS linac. A surface ionization source and an RF discharge source provide beams for charge breeding studies. An achieved efficiency of 11.9% for ^{85}Rb^{19+}, with a breeding time of 200 msec, and 15.6% for ^{84}Kr^{17+} has been realized. Both results are with the source operating with two RF frequencies (10.44 + 11.90 GHz). After modification to the injection side iron plug, the charge breeder has been operated at 50 kV, a necessary condition to achieve the design resolution of the isobar separator.

ECR CHARGE BREEDER

The charge breeder is a room temperature ECR ion source with an open structure NdFeB hexapole with a wall field of 0.86 T [2]. The open hexapole structure allows for pumping through the six 17 mm x 41 mm radial slots, resulting in a source pressure of 2×10^{-8} mbar without plasma and 8×10^{-8} mbar with plasma. The pressure in the extraction region is typically 4×10^{-8} mbar. The source is capable of accepting multiple frequencies with the RF launched through the hexapole radial slots. This scheme allows a large amount of iron to be retained on the injection side of the source resulting in a high magnitude and symmetric axial field. The low charge state ions are introduced into the plasma through a stainless steel tube mounted on a linear motion stage which has a 30 mm range of travel. This allows the deceleration point of the low charge state ions to be adjusted on line without disturbing the source conditions.

Injection Region Modifications

For the isobar separator to achieve the required resolution of 1:20,000, beam extraction from the gas catcher must occur at 50 kV. Hence, the high voltage isolation of the source was upgraded to allow 50 kV operation. However, penning discharges in the injection region occurred at 30 kV bias. An iron plug in this region was modified to increase the gap size from 6.5 mm over a 100 mm length to 10.8 mm at a discrete location as shown in Fig. 1. After several weeks of conditioning, the source operates reliably at 50 kV.

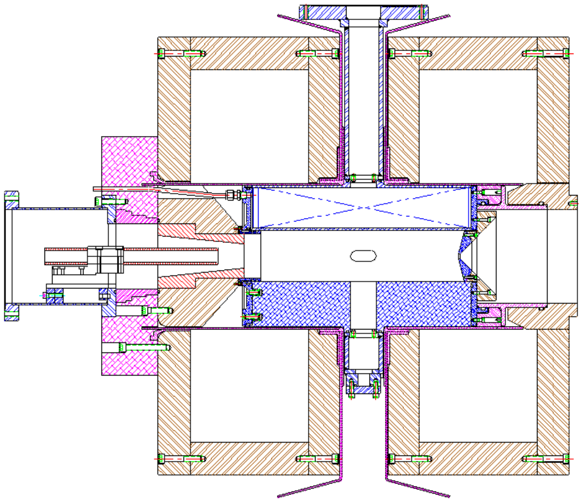

Figure 1: Schematic of the ANL ECR charge breeder. The 1+ beam is injected from the left via the transfer tube. The iron plug which was modified is highlighted with diagonal red. The radial slots where the RF is launched are visible on the source mid-plane.

CHARGE BREEDING RESULTS

The 1+ beam is mass analyzed and injected into the ECR source via a grounded transfer tube. The ions decelerate into the plasma region where a sub-set of them are ionized and captured by the plasma [3].

It was observed that the tune of the 1+ injection line was critical for breeding efficiency. For beams from elemental solids, the optimum injection channel was extremely narrow with a high degree of sensitivity to the entrance einzel lens. With gaseous elements, the einzel lens setting was not as critical, but steering constraints remained very stringent. The position of the transfer tube was also found to be an important variable. A summary of achieved charge breeding efficiencies is given in Table 1. The breeding time was measured by pulsing the incoming 1+ beam and measuring the n+ response time.

Table 1: Summary of charge breeding results.

Ion Species	n+ Charge State	Efficiency (%)	Breeding Time (msec)
Kr-86	17+	15.6	-
Rb-85	19+	11.9	200
Xe-129	25+	13.4	~250
Cs-133	20+	2.9	-

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FINE FREQUENCY TUNING OF THE PHOENIX CHARGE BREEDER USED AS A PROBE FOR ECRIS PLASMAS

Lamy Thierry, Angot Julien, Marie-Jeanne Melanie, Medard Jerome, Sortais Pascal, Thuillier Thomas, LPSC - UJF - CNRS/IN2P3 - INPG, Grenoble, France
Galata Alessio, INFN-Legnaro National Laboratories, Legnaro, Italy
Koivisto Hannu, Tarvainen Olli, University of Jyväskylä, Department of Physics, Jyväskylä, Finland

Abstract

Fine frequency tuning of ECR ion sources is a main issue to optimize the production of multiply charged ion beams. The PHOENIX charge breeder operation has been tested in the range 13.75 – 14.5 GHz with an HF power of about 400 W. The effect of this tuning is analyzed by measuring the multi-ionization efficiency obtained for various characterized injected 1+ ion beams (produced by the 2.45 GHz COMIC source). The 1+/n+ method includes the capture and the multi ionization processes of the 1+ beam and may be considered as a plasma probe. The n+ spectra obtained could be considered, in first approach, as an image of the plasma of the charge breeder. However, in certain conditions it has been observed that the injection of a few hundreds of nA of 1+ ions (i.e.: Xe^+) in the plasma of the charge breeder, is able to destroy the charge state distribution of the support gas (i.e.: up to 40 % of O^{6+} and O^{7+} disappears). The study of this phenomenon will be presented along with plasma potential measurements for various charge states. This study may help to understand the creation (or destruction) of highly charged ions inside an ECRIS.

INTRODUCTION

When we inject a characterized 1+ ion beam into a plasma, then extract and analyse all the ion species from it, one may expect some information about the characteristics of this plasma : its ability to capture 1+ ions and its ability to multi ionize the 1+ ions injected (i.e. plasma temperature and density). The 1+/n+ method developed for radioactive ion beams could be considered as a kind of non perturbative probe because the number of ions injected is exactly known (1+ beam intensity measurement), and extremely low with respect to the initial number of ions present in the plasma. In this paper, we propose to check the validity of these assumptions, by using fine frequency tuning of the microwaves injected to modify the characteristics of the ECR plasma, and by measuring the plasma potential to quantify the plasma characteristics variations.

THE 1+ COMIC SOURCE

The availability of a reliable ion source to produce cw 1+ ion beams in the range of 100 nA up to 1 µA with good stability is crucial for the 1+/n+ method in order to have a rather confident experimental simulation of low intensity radioactive ion beams and enough signal to have a precise measurement of the n+ efficiency yield. The microwave coupling of the ultra compact 2.45 GHz COMIC ion source developed at LPSC [1] has been particularly optimized, so the necessary HF power for the ignition and the maintaining of the plasma is extremely low (from 100 mW to 5 W depending on the pressure) and can be delivered by a solid state amplifier (see Fig. 1) leading to an extremely stable operation.

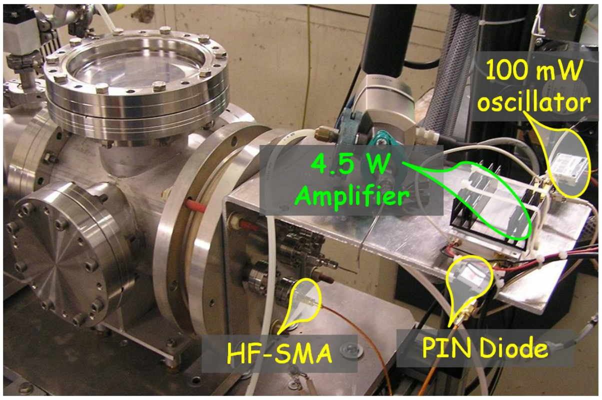

Figure 1: HF circuit of the COMIC Source on the 1+/n+ test stand.

LOW INTENSITY 1+ BEAM INJECTION INTO A PLASMA

Experiment

Oxygen gas is injected to produce the plasma in the PHOENIX charge breeder. The ions extracted from this plasma are analysed in a magnetic spectrometer and the intensities are plotted on Fig. 2 (blue spectrum). In this spectrum, 267 µAe (i.e. 110 µAp) are extracted from the source. Then, a 500 nA $^{132}Xe^+$ beam produced by the COMIC source is injected into the charge breeder. The capture is optimized and a second spectrum is performed (red spectrum on Fig. 2). In this second spectrum, the multicharged oxygen ion intensities are lower: the sum of the peaks is 234 µAe, equivalent to 103 µAp. Considering that about 50 % of the $^{132}Xe^+$ has been captured by the plasma, we can deduce that the 0.25 µA of $^{132}Xe^+$ has destroyed 7 µAp of multicharged oxygen ions, in other words one Xe ion destroys about thirty oxygen ones.

PRELIMINARY RESULTS OF SPATIALLY RESOLVED ECR ION BEAM PROFILE INVESTIGATIONS[*]

L. Panitzsch, M. Stalder, R.F. Wimmer-Schweingruber, CAU, Kiel, Germany

Abstract

The profile of an ion beam produced in an Electron Cyclotron Resonance Ion Source (ECRIS) can vary greatly depending on the source settings and the ion-optical tuning. Strongly focussed ion beams form circular structures (hollow beams) as predicted by simulations [1] and observed in experiments [2] and [3]. Each of the rings is predicted to be dominated by ions with same or at least similar m/q-ratios due to ion-optical effects. To check this we performed a series of preliminary investigations to test the reqiured tuning capabilities of our ion source. This includes beam focussing (A) and beam steering (B) using a 3D-movable extraction. Having tuned the source to deliver a beam of strongly focussed ions of different ion species and having steered this beam to match the transmittance area of the sector magnet we also recorded the ion charge state distribution of the strongly focussed beam profile at different, spatially limited positions (C). The preliminary results will be introduced within this paper.

EXPERIMENTAL SETUP

Within this section a short overview of the ECR ion source including the beam line and the profile measuring device, the Faraday Cup Array (FCA), will be given.

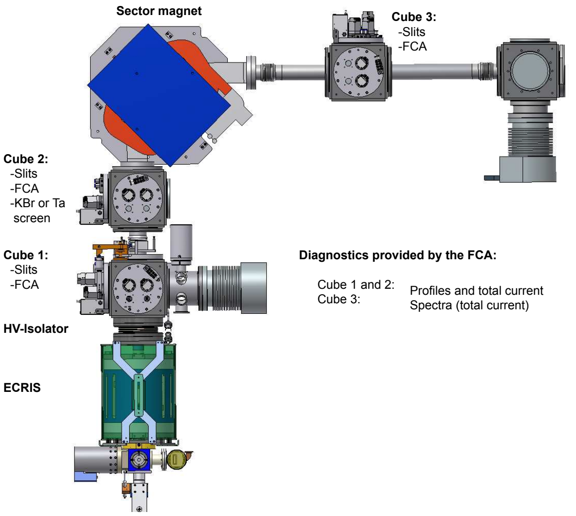

Figure 1: overview of the setup

ECRIS and beam line

The ion source we use to generate the ion beam is an all-permanent magnet ECR ion source. One special feature of this source is the extraction electrode that is movable in three dimensions, along the beam axis and perpendicular to it. After the extraction the ions pass two cubes providing access to the beam (see figure 1). The cubes are equipped with slits to limit the beam and with a profile-measuring device described in the following subsection. A 90° sector magnet is used to separate the ions according to their m/q-ratio. Sweeping the magnetic field we are able to record m/q-spectra using the detector placed in the third cube along beam line.

The tuning of the source was similar during all tests. At a comparatively high pressure in the vacuum chamber of 10^{-5} mbar we axially guide microwaves at a power of 50 W into the plasma.

Faraday Cup Array (FCA)

In order to monitor the ion beam from the source to the experimental chamber we have developed a new kind of beam profile monitor. Its working principle is based on the well-proven Faraday cup (FC). Having arranged a total number of 44 tiny (Ø = 0.3 mm) FCs to an array and driving this arrangement through the beam we record the position and the current for each tiny cup in a repetitive measurement. This allows the reconstruction of the beam profile. We have combined this detector with a standard FC to be able to also determine the total beam current. This detector is characterized by its sensitivity in combination with high durability. The spatial arrangement of the tiny cups allows the detection of profile-structures on mm-scale in a large range of current densities. More detailled information can be found in [4]. A CAD-view of the detector is presented in figure 2.

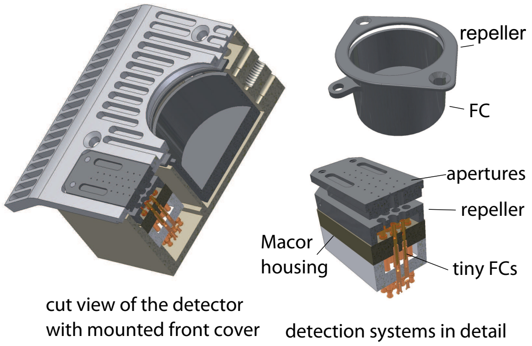

Figure 2: different CAD-views of the FCA

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A CORRECTION SCHEME FOR THE HEXAPOLAR ERROR OF AN ION BEAM EXTRACTED FROM AN ECRIS

P. Spädtke*, R. Lang, J. Mäder, F. Maimone, J. Roßbach,
K. Tinschert, GSI Darmstadt

Abstract

The extraction of any ion beam from ECRIS is determined by the good confinement of such ion sources. It has been shown earlier, that the ions are coming from these places, where the confinement is weakest. The assumption that the low energy ions are strongly bound to the magnetic field lines require furthermore, that only these ions starting on a magnetic field line going through the extraction aperture can be extracted. Depending on the setting of the magnetic field, these field lines may come from the loss lines at plasma chamber radius. Because the longitudinal position of these field lines depends on the azimuthal position at the extraction electrode, the ions are extracted from different magnetic flux densities. Whereas the solenoidal component can only be transferred into another phase space projection, the hexapolar component can be compensated by an additional hexapole after the first beam line focusing solenoid. The hexapole has to be rotatable in azimuthal direction and moveable in longitudinal direction. For a good correction the beam needs to have such a radial phase space distribution, that the force given by this hexapole acts on the aberrated beam exactly in such a way that it create a linear distribution after that corrector.

INTRODUCTION

The ion beam extracted from an ECRIS suffers from the magnetic field designed for a good confinement of the plasma. Both magnetic field components, the solenoidal part and the hexapolar part have influence on the properties of the ion beam. Whereas the error caused by the solenoidal component can only be shifted between different projections of the 4d-phase space[1, 2], the negative influence of the hexapole should be possible to be removed. The solenoidal component will stay with the beam, because ions are born within the plasma where the magnetic flux density is high, and therefore $\int \vec{B}ds \neq 0$ which is responsible for twisted trajectories. The experimental evidence for the density structure within the beam has been demonstrated by viewing targets and by emittance measurements with a suitable device[3, 4], showing a typical behavior for all ECRIS beams[5]. This can be explained when ions are extracted only on magnetic field lines going through the extraction hole[6]. A picture behind a pepper plate shows also experimental evidence of a certain structure, see Fig. 1.

The idea of compensation relies on the assumption that it is possible to set the ion beam profile within the known field of a hexapole in such a way that the actual field reverse the aberration of the incoming beam. For the compensation it is essential that the ion beam can be matched in phase space relative to the hexapole position. The orientation of the hexapole correction needs to be variable as well.

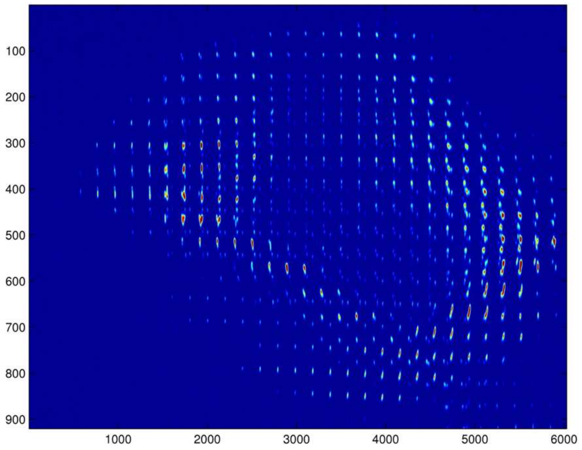

Figure 1: Beam spots behind a pepper plate. The ^{40}Ar^{8+} beam is extracted in cw-mode by a single hole of an accel-decel extraction system with 15 kV/-2kV. Both axis are scaled in pixel.

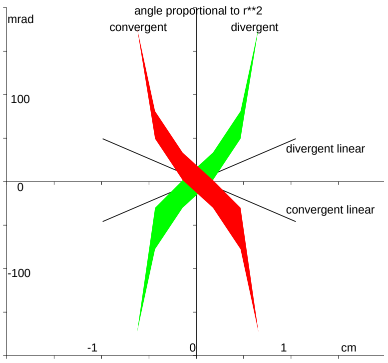

Figure 2: Both possible beam emittance orientations to remove the hexapolar error: divergent emittance in green, and the convergent emittance in red.

If the angle of the radial profile increases with r^2 as shown in Fig. 2, a hexapolar field can be used to change it to a linear distribution again. Such a setting should be possible to create by the help of the focusing force of the solenoid and its distance to the hexapolar field. However, this model assumes linear optic without any coupling. If the radial position of a trajectory changes within the compensation hexapole, the integral focusing force will apply. To minimize possible errors, the hexapole field should be as short as possible. The effective length has to be chosen such that the device can be designed with normal con-

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* p.spaedtke@gsi.de

KINETIC PLASMA SIMULATION OF ION BEAM EXTRACTION FROM AN ECR ION SOURCE

S.M. Elliott, Thin Film Consulting, Longmont, CO 80501 U.S.A
J. Simkin, Cobham Technical Services, Vector Fields Software, Oxford, OX5 1JE, UK
E.K. White, Thin Film Consulting, Longmont, CO 80501 U.S.A.

Abstract

Designing optimized ECR ion beam sources can be streamlined by the accurate simulation of beam optical properties in order to predict ion extraction behavior. The complexity of these models, however, can make PIC-based simulations time-consuming. In this paper, we first describe a simple kinetic plasma finite element simulation of extraction of a proton beam from a permanent magnet hexapole electron cyclotron resonance (ECR) ion source. Second, we analyze the influence of secondary electrons generated by ion collisions in the residual gas on the space charge of a proton beam of a dual-solenoid ECR ion source. The finite element method (FEM) offers a fast modeling environment, allowing analysis of ion beam behavior under conditions of varying current density, electrode potential, and gas pressure.

INTRODUCTION

The first simulation reported here represents proton extraction from a hexapole ECR ion source similar, but not identical, to an existing 10 GHz source [1], [2] and with a magnet system for higher frequency operation. The v14 SCALA/TOSCA 3d FEM software [3] is used for reasonably fast prediction of ion beam formation with automatically generated secondary charged particles from gas in the ionization chamber. A second model of a dual-solenoid ECR ion source [4] is used to simulate space charge beam compensation with gas secondary electrons.

PART 1: KINETIC PLASMA SIMULATION

The simulation includes space charge interactions of electrons and ions in the ionization chamber of a hexapole ECR ion source with a solenoid magnet lens (Fig. 1), extracting a proton beam from the plasma volume. The simulation predicts a three spoke ion beam cross-section.

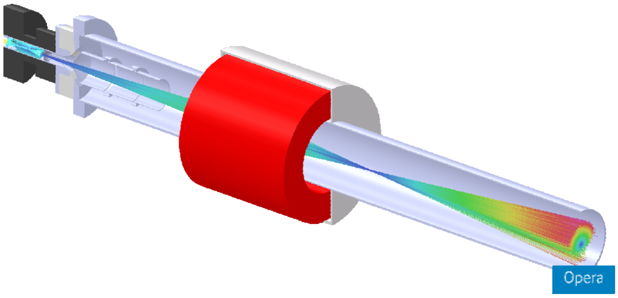

Figure 1: Source geometry with solenoid lens.

The source is composed of a magnet system and ionization chamber. An extractor is held at -10 kV. An einzel lens is also included (Fig. 2).

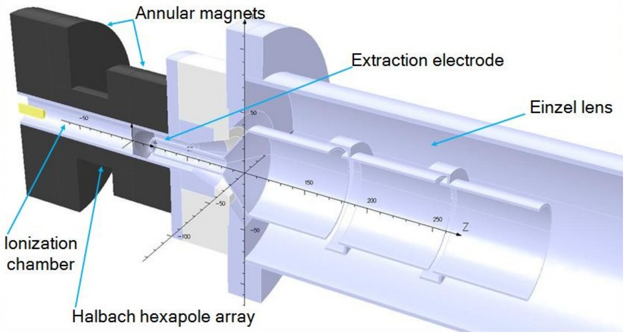

Figure 2: Source and einzel lens.

SIMPLE PLASMA SIMULATION

A small current of ions launched from the ECR surface initializes emission of volume secondary electrons and ions. The plasma fills the magnetic volume in the ionization chamber. Electrons and ions can be given energy and angular distributions, energy and current loss and scattering may be calculated, and surface secondary particles may be added as well.

RESULTS

The minimum B axial magnetic field is simulated with non-linear magnetic materials and has a minimum of about 0.47 T on axis (Fig. 3).

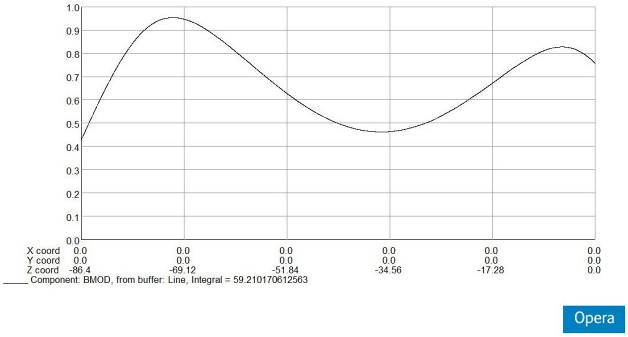

Figure 3: Ionizer on-axis magnetic flux density.

The space charge distribution in the ionization chamber is inhomogeneous due to the magnetic field (Fig. 4).

DIPOLE MAGNET OPTIMIZATION FOR HIGH EFFICIENT LOW ENERGY BEAM TRANSPORT*

S. Saminathan[†], J.P.M. Beijers, J. Mulder, V. Mironov, and S. Brandenburg
Kernfysisch Versneller Instituut, University of Groningen, Groningen 9747AA, The Netherlands

Abstract

Losses in the low-energy beam transport line from the KVI-AECRIS to the AGOR cyclotron are estimated to be around 50 %. Numerical simulations of beam extraction and transport have been performed up to the image plane of the analyzing magnet. The simulations show overall good agreement with measurements of beam profiles and emittances. It was found that the beam losses are caused by a too small gap of the analyzing magnet. This magnet also suffers from large second-order aberrations causing a significant increase of the effective beam emittance in both horizontal and vertical directions. We show that by increasing the magnet gap and suitably modifying the pole surfaces the beam losses can be suppressed and the second-order aberrations significantly reduced. This results in a substantially lower effective emittance of the transported beam.

INTRODUCTION

The low-energy beam transport (LEBT) line connecting the electron cyclotron resonance ion source (ECRIS) with the AGOR cyclotron at KVI, Groningen suffers from undesired beam losses of up to 50%. A program has therefore been initiated to improve the transport efficiency of the beam line. We started with a detailed simulation of beam extraction from the ECRIS and transport of the beam through the 110° analyzing magnet. The simulations have been bench marked against measurements of the full 4D emittance of the beams in the image plane of the analyzing magnet with a pepperpot [4] emittance meter and measurements of beam profiles at the source exit. The simulations clearly show that the analyzing magnet is the cause of significant beam losses. In addition, aberrations caused by the magnet's fringe fields lead to a large increase of the effective beam emittance. The next step was to start an improvement program of the ion-optical properties of the analyzing magnet. By increasing the magnet gap and modifying the shape of the pole faces of the analyzing magnet its ion-optical properties can be greatly improved leading to an increase of the beam transport efficiency of the LEBT line.

The paper is organized as follows. First we will present a detailed discussion of the beam extraction and transport simulations and comparison with the emittance measurements. Then the first results of the work on the improvement of the analyzing magnet will be presented and discussed. The paper ends with a summary and outlook.

BEAM TRANSPORT

The ECRIS and the 110° analyzing magnet are shown in Fig. 1. The ECRIS is an ion source of the AECR type of LBNL, Berkeley with the Al plasma chamber built by the Jyväskylä group [1]. More details of our source are given in Refs. [2] and [3]. The analyzing magnet is an unclamped double focusing magnet with straight 37° tilted edges and a vertical gap of 67 mm. The dipole bends the beam over 110° with a bending radius of 400 mm. Two BaF_2 viewing targets have been installed, i.e. VT1 located directly behind the extraction system and VT2 located close to the image plane of the analyzing magnet. Later the viewing target VT2 has been replaced by a pepperpot emittance meter [4]. There are no optical elements between ECRIS and analyzing magnet.

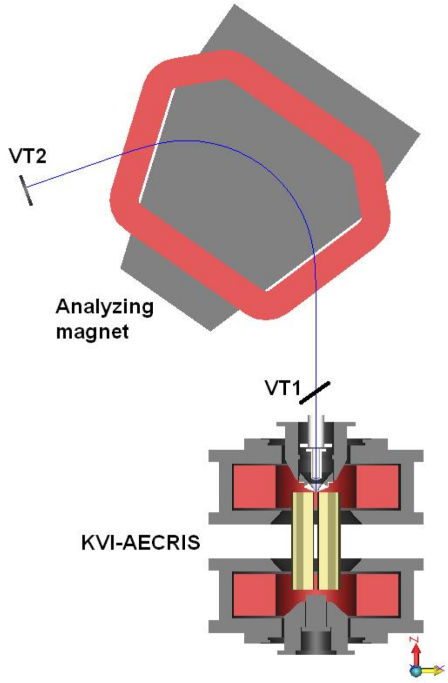

Figure 1: The KVI ECRIS and the 110° analyzing magnet.

Several computer codes have been used in the simulation process including an ECRIS simulation code PIC-MCC [5], and the particle tracking codes LORENTZ-3D [6] and

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[†] saminathan@kvi.nl

MODELING ECRIS USING A 1D MULTIFLUID

Michael Stalder[#], CAU, Kiel, Germany

Abstract

The Department of Experimental and Applied Physics (IEAP) at the University of Kiel (CAU Kiel) is establishing a solar wind laboratory for the calibration of space instrumentation. The main item of this facility is a 11GHz (Plateau) ECR ion source. It can be operated at two different radial magnetic confinements, using a set of permanent magnets in either hexapole or dodekapole arrangement. While beam focussing by moving the extraction along the beam line to match the ion beam into the analysing magnet is well known, little is known about beam steering by moving the extraction in the plane perpendicular to the beam line. For the hexapole-configuration we will present our results about the feasibility of ion beam focussing and steering using a 3D-movable extraction. The beam profiles of these measurements will be recorded in comparatively high resolution with a Faraday cup array (see paper doi: 10.1063/1.3246787). This method will be shortly introduced within this talk, as well.

Paper not received

[#] michael.stalder@gmmx.net

CLOSING REMARKS FOR ECRIS'10

T. Nakagawa, RIKEN, Japan

Abstract

The scientific topics of the ECRIS10 Workshop are introduced. New results presented by a selection of authors during the sessions are summarized.

INTRODUCTION

ECRIS'10, the 19th ECRIS workshop, was held in Grenoble, France, from the 23rd through the 26th of August 2010 with 100 participants. It is well known that Grenoble is the Mecca for ECRIS, as it has already played host two previous times (1982 and 1988). The programs this year covered the foremost topics related to the design and operation of ECR ion sources, including status reports, new developments, radioactive ion beam production, plasma physics and plasma diagnostics, beam extraction and transport, and applications. In this workshop, we found several clear trends in the development of ECR ion sources: 1) intense beam production for secondary beams (including radioactive beams); 2) pulsed mode operation for beta-beam projects; 3) new applications; and 4) plasma diagnostics, beam extraction, and transportation. Several highlights in these trends are presented in this short report.

TOPICS

Several facilities using ECR ion sources for radioactive beams are currently in operation. Requirements in this field lead us to employ higher magnetic fields and microwave frequencies to increase the beam current of ions in a medium charge state such as $U^{33\text{–}35+}$. H. W. Zhao demonstrated the effect of the microwave frequency (18 and 24 GHz) on the intensity of beams of highly charged heavy ions with SECRAL. D. Leitner presented the excellent results of VENUS after the re-commissioning. The NSCL team reported the excellent results of their 18 GHz ECR ion source (SuSI) and the requirements of the ECR ion source for the FRIB project. The experimental results of these ion sources clearly show that the beam intensity is not saturated at the highest RF power (~0.7 kW/L). This indicates that there is some scope to increase the beam intensity. The NSCL team made systematic bremsstrahlung and ion beam current measurements to examine the production mechanisms of highly charged heavy ions in the ion source. For the first time, they experimentally demonstrated the effect of the field gradient at the resonance zone on the beam intensity and bremsstrahlung X-rays.

For fourth-generation designs, the technical challenges in attaining the optimum magnetic field strength at 56 GHz were independently proposed by D. Leitner and Z. Q. Xie on the basis of their own concepts. Two Korean teams proposed and designed a new 28 GHz SC-ECRIS for the Korean Rare Isotope Beam Accelerator (KoRIA) project and a compact heavy ion linear accelerator facility.

ECR ion sources are used for the production of other secondary beams. A 2.45 GHz ECR ion source is used to produce thermal neutrons for a neutron imaging facility in Peking University. The CEA and CNRS have undertaken a research and development program on very high beam power accelerators, such as the Accelerator Driven Transmutation of Waste, a new generation of exotic ion facilities, and neutrino and muon production. The CEA is also involved in projects such as the European Spallation Source and IFMIF.

Utilizing metallic particles of rubidium, the charge breeder CARIBU (ANL) project has reached an extraction efficiency of 11.9% from an ECR ion source. Multiple-frequency operations also exhibit the potential to increase the beam intensity for the charge breeding system. The TRIUMF team achieved high-efficiency charge breeding for radioactive ions (1.4% efficiency for $^{124}Cs^{20+}$, 1.7% efficiency for $^{76}Rb^{15+}$, and 6.2% for $^{74}Kr^{15+}$). T. Lamy reported that grounded tube removal is very promising for charge breeding. In the SPIRAL project, a new multi-charged ion source, based on an asymmetric magnetic structure, was both proposed, and designed by L. Maunoury.

An intense short-pulse beam plays a crucial role in the Beta-Beam project. For meeting the requirements, the IAP-RAS and LPSC teams both experimentally and theoretically investigated the mechanisms behind the preglow of a multi-charged heavy ion beam from an ECR ion source. They reported that the effective generation in the short preglow peak is possible under powerful heating at a high frequency. In the study of the time evolution of plasma potential, O. Tarvainen concluded that the plasma potential is higher during the plasma build-up and decay compared with that under steady-state conditions; however, the processes explaining the potential fluctuations are different for preglow and afterglow. For realization of the intense short-pulse beam for the Beta-Beam project, a 60 GHz ECR ion source (megawatt-class) was proposed and tested in Grenoble.

ECR ion sources have several advantages as ion sources for trace element analysis (high ionization efficiency, production of stable plasma under the very low gas pressure ($<10^{-6}$ Torr), long plasma confinement for multi-charged ion production, etc.). Recently, the ANSTO ECR ion source was successfully used for measuring the isotopic ratios of elements such as carbon, nitrogen, and oxygen. An ECR ion source was successfully used as an ion source for AMS at Argonne to detect the noble gas elements (^{39}Ar, ^{81}Kr). R. Pardo proposed a new plan for laser ablation of actinides into an ECR ion source for AMS. P. Sortais fabricated a very small ECR ion source