

RECENT RESULTS AND OPERATION AT 18 GHZ WITH SECRAL

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Abstract

An advanced superconducting ECR ion source SECRAL with 18GHz has been put into operation to provide highly charged heavy ion beams for HIRFL (Heavy Ion Research Facility in Lanzhou) cyclotron since May 2007. The paper will give an overview of recent operation status and test results for enhancing performance of the SECRAL ECR ion source. Detailed experimental results with an aluminium chamber, 14+18 GHz double frequency heating, emittance measurements, and bremsstrahlung measurements will be presented. Finally some upgrading program for SECRAL will be reported.

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STATUS REPORT AND RECENT DEVELOPMENTS WITH VENUS

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Abstract

Since the superconducting ECR ion source VENUS started operation with 28 GHz microwave heating in 2004 it has produced ion beam intensities such as 860 eμA of Ar¹²⁺, 200 eμA of U³⁴⁺, or with respect to high charge state ions, 270 eμA of Ar¹⁶⁺, 1 eμA of Ar¹⁸⁺ and .4 eμA of Xe⁴²⁺. In August of 2006, VENUS was connected to the 88-Inch Cyclotron as the third injector ion source extending the energy range and available heavy ion beam intensities from the 88-Inch Cyclotron. This paper will highlight recent developments and results.

In addition, the paper will discuss recent modifications to the VENUS superconducting lead design, which became necessary after an unexpected quench damaged a superconducting lead. Following a quench in January of 2008, the VENUS sextupole coils could not be energized. The lead quenched due to the loss of liquid helium in the upper cryostat. This resulted in localized heating, which vaporized a section of the lead wire. Analysis of the quench scenario, which is discussed in the paper, revealed design flaws in the original lead support and cooling design. The major undertaking of repairing the magnet leads and rebuilding the VENUS cryostat is described.

INTRODUCTION

The VENUS ECR ion source (shown in Fig.1) at the Lawrence Berkeley National Laboratory (LBNL) is a 3rd generation source. The fully superconducting magnet structure has been designed for optimum fields for operation using 28 GHz plasma heating frequency. As a prototype ECR ion source for the Facility for Rare Isotope Beams (FRIB) the emphasis of the R&D is the production

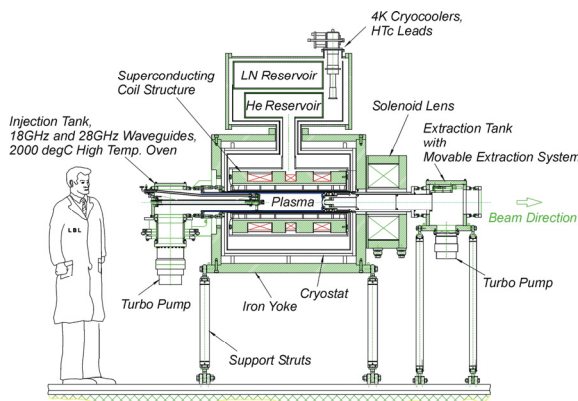


Figure 1: Mechanical layout of the VENUS ion source and cryogenic systems

of medium high charge states such as U³³⁺. As an injector into the 88-Inch Cyclotron the emphasis is on the production of high charge state ions. VENUS has been

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Superconducting ECRIS

operated routinely using 28 GHz as its main heating frequency since 2004 and has produced many record beams. Besides 28 GHz, 18 GHz can be injected as a second frequency for double frequency heating or used for single frequency heating ($B_{\text{ECR},18\text{ GHz}}=0.64\text{T}$). Table 1 shows a summary of the VENUS ECR ion source performance^[1-4].

Two main magnetic confinement and heating configurations are typically used in the VENUS ECR ion source. In the single frequency heated plasma mode a minimum B field of .64 to .75 T is used, which results in a shallow magnetic field gradient at the 28 GHz resonance zone. Up to 6.5 kW of 28 GHz power has been coupled into VENUS using this mode of operation. In the double frequency mode a minimum B field of .45 T is used. This field profile results in a combination of a shallow gradient (for 18 GHz heating) and a steeper gradient (for 28 GHz heating) at the resonance zone. Up to 9kW of combined 18 and 28 GHz power (a power density of about 1kW/liter for the about 9L big plasma chamber) has been coupled into the VENUS plasma chamber so far. The ion source performance continues to improve as we couple more power into the plasma chamber. For typical 28 GHz operation in single or dual frequency mode, the sextupole magnet is energized to produce slightly above 2 Tesla at the plasma chamber wall.

Table 1: Recent VENUS Results

VENUS 28 GHz or 18 GHz +28 GHz							
CS	¹⁶ O	⁴⁰ Ar	CS	⁸⁴ Kr	¹²⁹ Xe	²⁰⁹ Bi	²³⁸ U
6 ⁺	2850		25 ⁺	223		243	
7 ⁺	850		26 ⁺			240	
8 ⁺			27 ⁺	88		245	
12 ⁺		860	28 ⁺	25	222	225	
13 ⁺		720	29 ⁺	5	168	203	
14 ⁺		514	30 ⁺	1	116	165	
16 ⁺		270	31 ⁺		86		
17 ⁺		36	33 ⁺		52		205
18 ⁺		1	34 ⁺		41		202
			35 ⁺		28.5		175
			37 ⁺		12		
			38 ⁺		7		
			41 ⁺			15	
			42 ⁺				.4
			47 ⁺			2.4	5
			50 ⁺			.5	1.9

In September of 2006 the first ion beam from VENUS was injected and accelerated by the 88-Inch Cyclotron.

NEW 28GHZ SC-ECRIS FOR RIKEN RI BEAM FACTORY PROJECT

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Abstract

To increase the intensity of U ion beam for RIKEN RI beam factory project, we started to construct new SC-ECRIS. The main features of the ion source is as follows 1) the ion source has a large size of ECR surface 2) field gradient and surface size at ECR zone can be changed independently to study these effects on the ECR plasma. Six sets of solenoid coils and hexapole coil are used for making the magnetic field. The maximum magnetic field of RF injection side (B_{inj}), beam extraction side (B_{ext}) and radial magnetic field at the plasma chamber surface (B_r) are 3.8, 2.4 and 2.1T respectively. The construction began at Mitsubishi Electric Corporation in October 2007. After all the coils were wound and assembled, the excitation tests were performed in June 2008. After excitation test, we obtained the 85~90% of designed value. In the excitation test, we recognized that it is necessary to reinforce the structure at the coil ends of the hexapole. After the test, we started to modify the structure of the hexapole coil end. In September 2008, we will start the second excitation test.

INTRODUCTION

Since middle of 1990s, RIKEN has undertaken construction of new accelerator facility so-called Radio Isotope Beam Factory (RIBF) [1] and successfully produced 345MeV/u U beam (~4 nA on target) in 2007.[2] However, to meet the requirement of the RIBF (primary beam intensity of 1pμA on target), we still need to increase the beam intensity of the heavy ions. For this reason, we started to construct the new superconducting ECR ion source (SC-ECRIS) which has an operational frequency of 28 GHz.

Before construction, we intensively studied the effect of the key parameters (magnetic field, RF power, gas pressure bias disc etc) on the plasma and beam intensity for optimizing the structure of the ECRIS. During the investigation, we obtained several interesting results.[3-5] Based on these results, we designed the ion source and made a first excitation test of SC-coils.

In this paper, we report the structure, progress of the new RIKEN SC-ECRIS construction

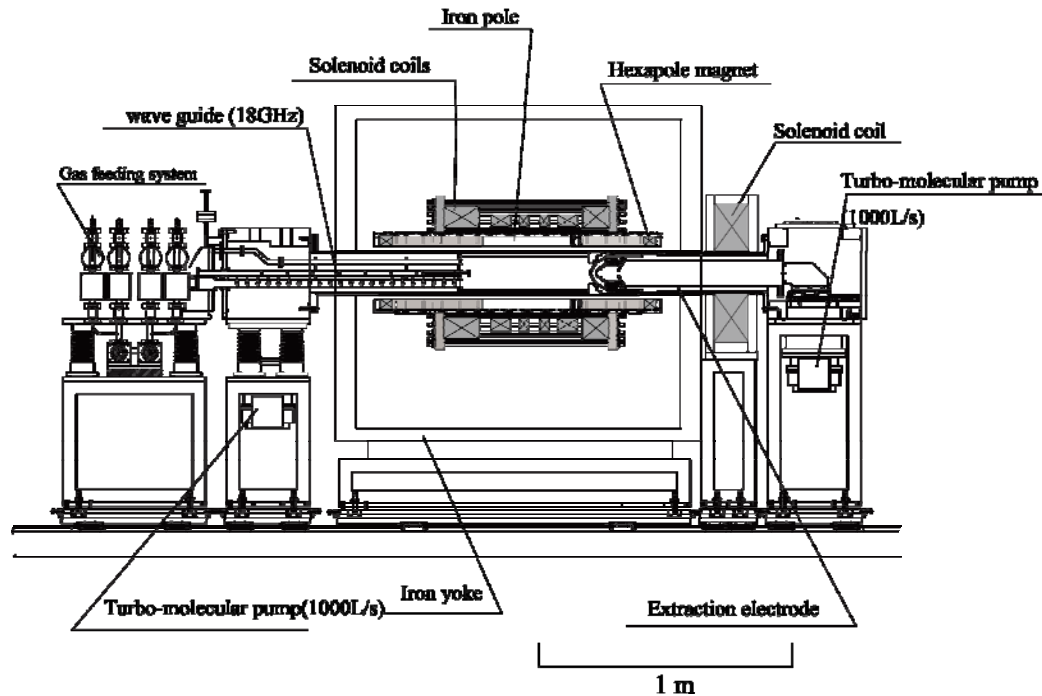


Fig.1 Schematic drawing of the RIKEN SC-ECRIS

CONTINUOUS AND PULSED OPERATION OF A HIGHLY EFFICIENT 18 GHz PLATEAU-ECRIS

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Abstract

A highly efficient 18 GHz Plateau-ECRIS (PECRIS V) has been developed. The magnetic field on axis has a flat plateau-minimum. Together with a very strong permanent magnetic hexapole it creates a large resonance volume. In this resonance volume electrons are electron-cyclotron-resonance-heated more efficiently than in standard ECRIS and the maximum density of the plasma is obtained near the axis from where ions are primarily extracted. The plasma chamber is designed as a microwave resonator with specific end-plates to achieve high microwave amplitudes on the axis in spite of the low microwave power of <500 W. Up to 4 microwave frequencies have simultaneously been used. By the use of several frequencies at, above, and below the plateau, we become less sensitive on density variations in the plasma. We also present a technique for the extraction of intense short pulses of highly charged ions. This technique temporarily reduces the magnetic field on the extraction side and is an interesting alternative to the afterglow, in particular for the highest charge states. The design and the highly efficient operation of PECRIS V may thus serve as guideline for the future conceptions of ECRIS.

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COMMISSIONING RESULTS OF THE 18GHZ FULLY SUPERCONDUCTING ECR ION SOURCE SUSI

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Abstract

The construction of SUSI the 3rd generation ECR ion source from NSCL/MSU has been completed. After an initial period marked by problems with its coil system, SUSI has now reached stable operation at 18GHz. Excellent performances have been obtained during the commissioning of the ion source for various elements including: ^{40}Ar , ^{129}Xe and ^{208}Bi . Some early results regarding beam transport are also discussed and in particular the choice of not using a focusing element between the ion source and the bending magnet.

INTRODUCTION

The coupled cyclotron at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) can accelerates heavy ion beams up to 200 Mev/u. This primary beam is then used to produce radioactive ion beams by fast fragmentation on a beryllium target. In order to respond to the experimental program in nuclear science, a wide range of primary beam has been developed since 2001 from ^{16}O to ^{238}U . Beams are initially produced by an ECR ion source and then transported at low energy before injection in the K500. Final acceleration is made into the K1200 and in recent years large gain in beam intensity have been achieved for most beams. In particular more than a 1kW of primary beam power can now be extracted from the K1200 for ^{48}Ca and ^{40}Ar . These gains in beam intensity were not achieved by increasing the ion current extracted from the ECR ion sources but instead reflect a strong effort to improve the beam transport in particular from the ECR to the K500 [1]. However it is clear and in particular for heavier ion beams, that the gains that can be ultimately achieved through the coupled cyclotron largely rely on the choice of the ECR ion source used to inject the beam. SUSI the most recent ECR ion source from NSCL is a fully superconducting ECR source designed to operate primarily at 18GHz. Large gains in beam intensity are therefore expected compare to our 6.4 GHz SC-ECR or 14GHz ARTEMIS. In addition a flexible axial magnetic field described previously [2] provides the capability to modify the length and the position of the resonant zone and also to adjust the gradient of the axial magnetic field near the resonance. Finally, the injection baffle can be moved providing an additional knob that allow for example to adjust the volume of the plasma chamber. These innovative features in the SUSI design should help to not only maximize the intensity of the extracted ion

beam current but more generally to optimize the brightness of the extracted ion beam.

MAGNET TESTS AND QUENCHES

However, to achieve an ion source with a flexible axial magnetic field requires the design and construction of a complicated coil system. The axial magnetic field of SUSI is defined using 6 solenoids. Two large solenoids at the injection with an outer diameter of 460mm, and four smaller ones with two at the extraction of the source plus an additional two more in the middle. These four smaller solenoids have an outside diameter of 400 mm and the two solenoids in the middle are running with opposite polarity. All six solenoids have an inner diameter of 300 mm and a length of 80 mm. A field of 2.6T/1.5T can be reached at the injection/extraction side by powering either coil with 290A/210A. The hexapole coils are also superconducting and are 743 mm long. The ends of the sextupole are far from the central field of the solenoids, to minimize the interaction forces. Based on a similar design developed at LBNL for the construction of VENUS, these coils were wound around a three-piece core, which includes a central piece made of steel to enhance the field. The sextupole coils can provide 1.5T at the plasma chamber walls with 390A.

All coils were wounded at NSCL and then tested individually. During these tests, the solenoids were taken beyond 400A without training. On the other hand the sextupole coils experienced a few training quenches but eventually reached more than 700A each. These current values are well beyond the values needed for operation of the ion source at 18GHz and in fact would correspond to the current needed to operate the ECR ion source with a 28GHz microwave frequency transmitter. After the tests with the individual coils were completed, the assembly of the full coil system took place. The sextupole coils were assembled around the bore of the helium vessel tube, banded together and then inserted into the solenoid bobbin. Bladders installed between each sextupole and inflated with an Indium alloy were used to restrain the sextupole coils from moving radially. A very detailed and complete description of the design, construction and assembly of the coils can be found elsewhere [3]. Once the assembly was complete the coil system was cooled down in a large Dewar and tested. Because the number of current leads on the Dewar was limited, only four solenoids plus the sextupole could be energized at any given time. Additionally, the two large solenoids at the injection were serially connected and depending on the

ION BEAM RESEARCH AND DEVELOPMENT WORK AT JYFL

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Abstract

During the last year the main focus of the JYFL ion source group has been on the studies of the beam transmission, time evolution of Bremsstrahlung (will be presented elsewhere in this same proceedings by T. Ropponen) and on the development of metal ion beams. Comprehensive studies of the beam transmission efficiency at the Department of Physics, University of Jyväskylä have shown several problems concerning the injection line of the K-130 cyclotron. The experiments have shown strongly non-uniform and elliptical beam shape, which limits the beam transmission efficiency. The durability of the inductively heated oven has successfully been improved and it has been tested with the 14 GHz ECRIS for the production of titanium and chromium ion beams. The intensity level of about 20 μA was reached for the medium charge states, which is adequate for most of the nuclear physics experiments at JYFL.

INTRODUCTION

According to operation experience with the K130 facility at JYFL (University of Jyväskylä, Department of Physics) the beam transmission efficiency decreases when the beam intensity extracted from the ECRIS increases [1]. In some cases the available beam intensity after cyclotron even decreased when the beam intensity from the ECRIS was increased. As a result of this behavior the beam transmission project was initiated in order to overcome the problem and to meet the beam intensity requirements. The extensive beam transmission measurements were started in 2007 with the beam line simulations in collaboration with NSCL/MSU. As a result of the simulations several bottlenecks concerning the beam transmission were found. As a next step the beam transmission experiments were started in order to confirm the results obtained by the simulations.

The most of the beams needed for the nuclear physics experiments are produced with the JYFL 14 GHz ECRIS. Figure 1 shows the beam line components used for the focusing and steering of the ion beams from the ECRIS to the cyclotron. In this case the beam is transported via three different dipole magnets: DJ1 is used as a mass spectrometer, SWI1 is used to select the ion source for the experiment (i.e. light ion source, 6.4 GHz ECRIS or 14 GHz ECRIS) and DI2, which is used to bend the beam into the vertical injection of the cyclotron. As the figure shows the focusing of the beam is carried out with solenoids, which generates different focus points for different q/m-ratios. The beam diagnostics includes Faraday cups, beam viewers and an Allison-type emittance scanner.

BEAM TRANSMISSION EFFICIENCY

The objective of the beam transmission experiments was to define the losses of different beam line sections

including the K130 cyclotron. The beam intensities were measured from several locations: FCJ2, FCI5, inflector, outer radius of cyclotron, after deflector and finally from PFC. The Faraday cup FCJ2 is located after the analysing magnet, FCI5 in the vertical beam line before the cyclotron injection and PFC is the first Faraday cup after the cyclotron.

Figure 2 shows the tendency of the transmission efficiency as a function of the beam intensity extracted from the 14 GHz ECRIS. Here the efficiency is calculated from the ion beam currents measured by FCJ2 after the first dipole magnet (DJ1) and by PFC after the cyclotron. The transmission studies were carried out using $^{40}\text{Ar}^{8+}$ ion beam, which corresponds to the q/m-ratio normally needed for the nuclear physics experiments. The voltage of 9.66 kV was used for the extraction of ion beam from the ECRIS and the beam current was varied by changing the microwave power. The experiments were carried out with the second harmonic acceleration.

According to the experiments the transmission efficiency decreases strongly when the beam intensity extracted from JYFL 14 GHz aECRIS increases. As Fig. 2 shows the total transmission efficiency has the value of about 15 % for the beam intensities less than 25 μA (drain current ≈ 0.5 mA). The efficiency degrades almost linearly when the beam intensity increases being only about 6 % for the beam intensities above 100 μA (drain current ≈ 1 mA or higher). The corresponding drain current of high voltage power supply is presented in the same figure. The drain current roughly corresponds to the total beam current extracted from the ECRIS if secondary electrons from the puller are excluded.

THE HIGH CHARGE STATE ALL-PERMANENT MAGNET ECRIS OPERATED ON 320 KV HV PLATFORM*

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Abstract

An all-permanent magnet ECR ion source named LAPECR2 (Lanzhou All-permanent magnet ECR ion source No. 2) has been built and tested at IMP. This ion source is designed and operated to produce intense ion beams of both low charge states (such as H⁺, He²⁺, Xe³⁺...) and high charge states (such as Ar¹⁴⁺, Xe³⁰⁺...) for the 320 kV high voltage (HV) platform at IMP. Many good results have been obtained on LAPECR2, such as 1 mA O⁶⁺, 130 eμA O⁷⁺, 166 eμA Ar¹¹⁺, 2 eμA Ar¹⁶⁺, 0.33 eμA Ar¹⁷⁺, 85 eμA Xe²⁰⁺, 24 eμA Xe²⁷⁺, 2 eμA Xe³¹⁺. This ion source was designed to fulfill the various requirements of all of the experimental terminals, such as the delivery of metallic ion beams. A high temperature micro-oven has been fabricated and installed on the source to produce stable metal vapor. This HV platform has been successfully biased to 390 kV without ion beam. And ion beams with the energy up to 340 keV/q have already been delivered to the successive experimental terminals. After a brief introduction of the source LAPECR2, the operation status on the HV platform is discussed. The typical performance of the source of both gaseous and some metallic ion beams will be given in this paper.

INTRODUCTION

As the most efficient machine to produce stable intense high duty factor high charge state ion beams, ECR ion sources have been widely adopted as the injectors of multiple charge state ion beams for different purposes [1]. With the development of the techniques of ECRISs, many high performance ECRISs have been built around the world, such as GTS [2], VENUS [3], SECRAL [4], etc. These ion sources can provide very intense high charge state ion beams for the successive accelerators or experimental terminals. Besides the demands of high performance room temperature or superconducting ECRISs, there is great demand of all permanent magnet ECRISs, because of their typical characteristics such as large electricity free, strong cooling water free, easy handling and operation, simple structure, etc. With the advancement of NdFeB techniques, high remanence and high coercivity materials are now commercially available, which enables the realization of high magnetic field with

comparably reasonable cost. The Nanogan series [5] and the BIE series [6] are all successful candidates of all permanent magnet ECRISs.

With the development of heavy ion beam associated research, we notice that there is an energy margin between the ion beams delivered by an ordinary ECRIS platform and the ion beams accelerated by SFC accelerator at IMP (K=69), which covers many interesting fields concerning heavy ion beams. To promote the studies in these fields, a 320 kV HV platform had been set up by the end of 2006. Five experimental terminals of this HV platform are dedicated to the research activities of highly charged ion physics, atomic physics, material physics, biophysics, and astrophysics respectively. These research activities inquire the platform to deliver ion beams of both light and heavy elements from low charge states to high charge states. Thus, the project of building a high performance all permanent magnet ECRIS LAPECR2 was started from the beginning of 2004. In this paper, the commissioning results of LAPECR2 and the operation status on the HV platform are presented.

LAPECR2 ION SOURCE

The physical goals of the 320 kV HV platform inquire that LAPECR2 should be a high charge state ECR ion source that can deliver both gaseous and metallic ion beams. This indicates that high B, high rf frequency and high rf power modes should be taken into consideration in this design. However, one of the biggest drawbacks of all permanent magnet ECRISs is the inflexibility of the magnetic field and insufficient field strength. Thus, the designed magnetic field configuration should be optimized for the desired operation mode. The latest semiempirical scaling laws of ECRIS [7] can be an important reference in the conceptual design. In our design, three big 24-segmented axial magnetic rings at the source injection side provide the injection magnetic field peak up to about 1.3 T, and three 24-segmented axial magnetic rings at the extraction side provide the extraction field up to about 1.1 T. A single central axial magnetic ring increases the B_{min} field up to 0.42 T. And the radial magnet is a 36-segmented Halbach structure hexapole which provides a 1.2 T radial field at the inner wall of a Ø67 mm ID plasma chamber. These key parameters are designed to optimize the operation of the source at 14.5 GHz. To have sufficient radial confinement to the plasma and also to keep the axial field high enough, the hexapole, one of the injection magnetic rings and also one of the extraction magnetic rings are specially shaped to satisfy the physical requirements (as shown in figure

* Work supported by National Scientific Fund for Outstanding Youth through the contract of 10225523 and National Natural Science Foundation of China for Young Scientists through the contract No. 10405026

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THE BIO-NANO-ECRIS PROJECT: A NEW ECR ION SOURCE AT TOYO UNIVERSITY TO PRODUCE ENDOHEDRAL FULLERENES*

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Abstract

We are developing a new electron cyclotron resonance ion source (ECRIS) for the synthesis of endohedral fullerenes, which have potential in medical care, biotechnology and nanotechnology. So this ion source is called Bio-Nano ECRIS. It has been reported that ions of fullerenes and carbons-loss fullerenes, such as C_{60}^+ , C_{58}^+ , ..., are easily produced in ECRISs. Such carbons-loss fullerenes might have an advantage for the production of various endohedral fullerenes. The Bio-Nano ECRIS is designed for the production of endohedral fullerenes. In this paper, the recent progress is briefly summarized; i) Bio-Nano ECRIS project, ii) design aspect of the Bio-Nano ECRIS, iii) results of the initial experiments on the production of the ions of fullerenes and carbons-loss fullerenes.

BIO-NANO ECRIS PROJECT

Endohedral fullerenes

Fullerenes have a unique type of inner empty space with their unusual cage-like structures [Fig. 1(a)]. A variety of atoms may reside in this space [1] and form endohedral fullerenes [Fig. 1(b)]. Endohedral fullerenes have novel physical and chemical properties that are very important for their potential applications such as magnetic resonance imaging agents, biological tracing agents, organic ferromagnets and superconductors etc.

Endohedral fullerenes are generally produced by arc discharge and laser vaporization methods [1]. These methods are originally for the synthesis of fullerenes. The soot, which contains fullerenes, is generated by arc discharge or laser vaporization of the pure graphite target. These methods are applied for the synthesis of endohedral fullerenes. By using the encapsulating elements-graphite mixed target in place of the pure graphite target, we can synthesize the endohedral fullerenes. However the atomic species and fullerene species, which can form endohedral fullerenes, are still limited for arc discharge and laser vaporization methods. For example, the production of iron-encapsulated fullerenes has not been successful so far. But it can be applied as magnetic resonance imaging agents. Thus, we aim the production of $Fe@C_n$ using the

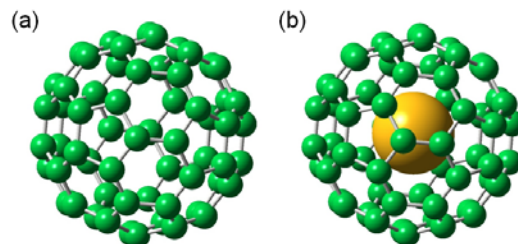


Figure 1: Illustration of (a) C_{60} molecule and (b) endohedral C_{60} molecule.

Bio-Nano ECRIS, where @ means that the atoms listed to the left of “@” are encapsulated into C_n , C_n means fullerenes or carbons-loss fullerenes.

Recently the organic chemical synthesis of $H_2@C_{60}$ has been reported by Komatsu et al. [2]. They demonstrated the synthesis of the open-cage C_{60} , which has a large orifice (13-membered ring), by an organic chemical reaction. And they synthesized open-cage fullerene incorporating hydrogen. They showed the availability of the open-cage fullerenes, which has a large orifice on their surface, for the production of endohedral fullerenes.

Fullerenes in ECRIS

Fullerene plasmas and beams have been produced in ion sources, such as electron impact, Nielsen-type, Nier-type, Kaufman-type, radio-frequency and ECR ion sources, for various scientific and practical reasons and purposes [3]. In particular, by using an ECRIS, collision reactions of fullerenes have been studied so far [4]. In an ECR plasma, fullerenes are ionized and fragmented; C_{60}^+ , C_{58}^+ , C_{56}^+ , ... are generated. Fullerene fragments (so-called carbons-loss fullerenes) are generated by eliminating C_2 units. We expect that carbons-loss fullerenes might have an orifice (7-membered ring or higher), even though such structure is unstable and transient. Therefore, carbons-loss fullerenes might have an advantage for encapsulating atoms into their inner spheres.

Our early study

In Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), the encapsulation of gas atoms into fullerenes in ECR plasma has been studied using the ATOMKI-ECRIS, which is designed for the production of multiply charged ions [5]. In 2006, a prototype magnetic structure (the ATOMKI-ECR-B,

* Part of this study has been supported by a Grant for the 21st Century Center of Excellence Program since 2003 and a Grant for the High-Tech Research Center Fund since 2006. Both funds were organized by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

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EXPERIMENTS WITH HIGHLY CHARGED IONS AT THE PARIS ECR ION SOURCE, SIMPA*

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Abstract

In this paper recent achievements will be reported at the SIMPA ion source in Paris that include the first use of an electrostatic ion trap for trapping highly charged ions on the beam line of an ECR ion source and electron temperature and density measurements with the help of the observation of the bremsstrahlung spectrum of the electrons in the ECR plasma of the source. Also a new vacuum double crystal spectrometer is under construction in our lab that will allow us to measure the very narrow inner shell transitions of highly charged ions produced in the ECR plasma and provide new x-ray standards with this method for the atomic physics community.

THE SIMPA ION SOURCE

The full permanent magnet “supernanogan” type Electron Cyclotron Resonance (ECR) ion source, SIMPA

(Source d’Ions Multichargés de Paris = Paris highly charged ion source) has been jointly operated by LKB (Laboratoire Kastler Brossel) and INSP (Institut des NanoSciences de Paris) since 2004. Since this time numerous projects have been started to use the extracted beam in atomic physics and surface physics experiments and the x-ray radiation of the ECR plasma for plasma and atomic physics investigations. The ion source has a fully permanent magnet setup with a microwave line of 14.5 GHz attached into the plasma chamber. The extraction is made possible by raising the whole ion source to a high voltage platform between 0 kV to 35 kV potential, leaving the beam line at ground potential. The beam line has a solenoid magnet for beam focusing. Charge state selection and scan is possible with a dipole magnet. Figure 1 shows a general setup of the SIMPA ECR ion source laboratory in Paris.

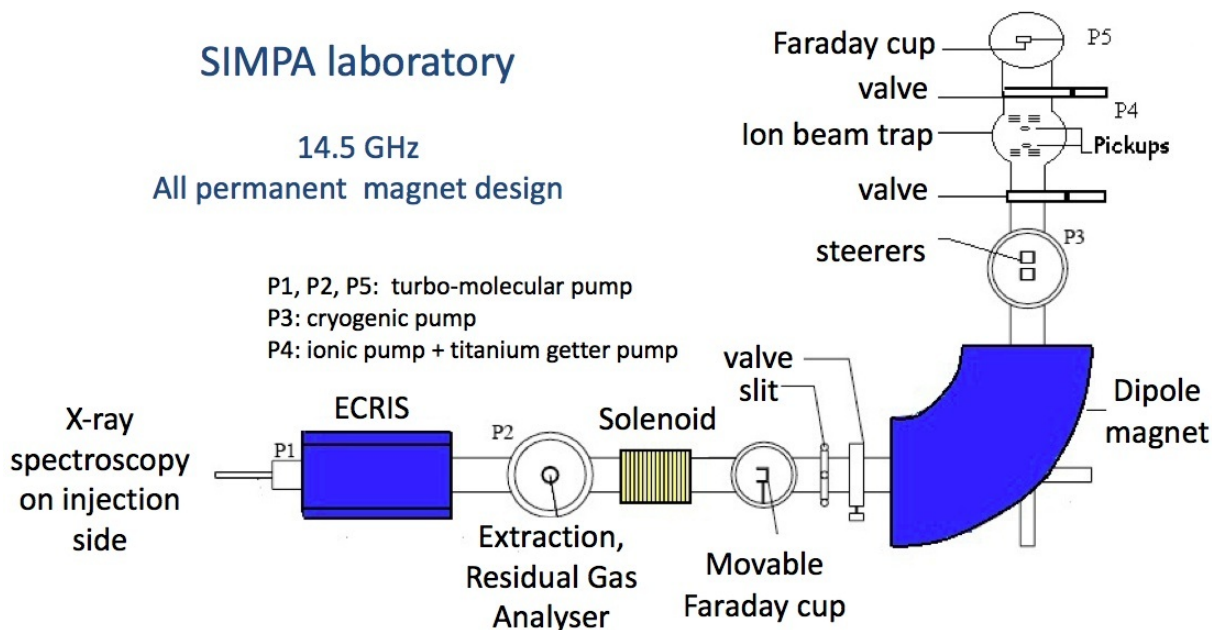


Figure 1: The SIMPA ECR Ion Source laboratory in Paris. The 14.5 GHz all permanent magnet SUPERNANOGAN type ECR ion source is connected to a beam line with a solenoid and dipole magnet feeding the ion beam trap. A Be window on the injection side allows x-ray spectroscopy

THE ELECTROSTATIC ION BEAM TRAP

The development and applications of ion traps and heavy-ion storage rings have a significant impact on many branches of physics. These devices enable the

storage of ions for a relatively long time, with meV to eV kinetic energies, in ion traps and to GeV kinetic energies, in heavy-ion storage rings. Ion traps are able to trap charged particles for a long time, and they have been successfully applied in several areas of physics. Recently,

ECRIS ON HIGH VOLTAGE PLATFORM FOR ENGINEERING AND MODIFICATION OF MATERIALS

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Abstract

An all permanent magnet electron cyclotron resonance ion source (ECRIS) along with the associated components like 10GHz UHF transmitter, vacuum pumps, vacuum gauges, vacuum pump controllers, gas handling systems with gas bottles, local command and controls systems, etc are set up on a 200kV platform for providing various ion beams having energy in the range of a few tens of keVs to a few MeVs. Understanding of charge transfer processes during collision with molecules and dissociation of molecules are discussed. The capability of ECRIS in producing multiply charged ions is being used for engineering and modification of materials. The beam currents available from the first few charge states are mainly used for these studies. The 10 GHz all-permanent-magnet ECR ion source on high voltage platform at Inter University Accelerator Centre (IUAC) has been in regular operation since 2000 for delivering various ion beams for research in materials science, atomic and molecular physics. The salient features of ECRIS based Low Energy Ion Beam Facility (LEIBF) at IUAC, operational experience of the ion source for producing some of the special beams and some of the experimental results are presented.

INTRODUCTION

To get the operational experience of ECR ion source [1] on high voltage platform and to provide the low energy ion beams from gaseous and solid species, the LEIBF [2] has been set up at IUAC. The most important feature of the facility (LEIBF) is that the ECR ion source and all its peripheral components including electronics (power supplies, RF power amplifier, etc.) and vacuum systems are placed on a high voltage (200 kV) platform. The various parameters of the source are controlled through fiber optics communications at 200 kV isolation. The regular operation of this facility provided us experience and expertise to design and build the world's first High Temperature Super-conducting ECR Ion Source (PKDELIS) [3] for use on a high voltage (400 kV) platform. The ion source has been tuned to get optimum intensities of gaseous, semi metallic and metallic ion beams which are being used for research in emerging fields like nano science and spintronics. To engineer the optical, electrical and structural properties of materials via ion implantation and ion irradiation, first few charge states of beam and moderate beam intensity ($\sim 1\mu\text{A}$) are mainly required. Nanostructured materials play an important role in technology as they exhibit different, and quite often, unique physical properties relative to their macroscopic counter parts. These composites have drawn a lot of attentions due to their applicability for fast

switching devices, single electron transistors, gas sensors and nano-electronics in one dimensional molecular wire. In comparison of other methods, ion implantation allows us to obtain well controlled nanostructures by choosing suitable ion implantation conditions and subsequent thermal annealing. In this paper, development of Ni and Si beams using ECR ion source and fabrication of their nanocomposites in different matrices are presented.

DEVELOPMENT OF NICKEL AND SILICON BEAMS

For the development of Ni beam, Metal Ions using VOLatile Compound (MIVOC) method was used. In order to get enough throughput required for high intensities of lower charge states, the pellet (6mm in diameter and 3 mm thick) of nickelocene was prepared and placed into the source inside the bias tube (a negatively polarized copper tube placed axially into the source from the injection side to reflect the electrons back into the ECR plasma to increasing electron density for ionization) for the development of the ion beams. A mesh of metal wires was used at the open end (towards the plasma) of the bias tube to avoid falling of the volatile compounds from the tube during initially pumping of the source for vacuum. With this technique, we got enough intensities (of the order of $1\mu\text{A}$) of the beams. The analysed charge state distribution (CSD) of Ni is shown in figure 1.

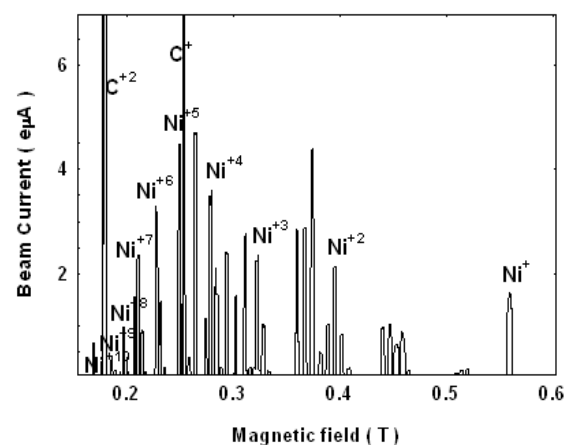


Figure 1: Charge state distribution of Ni optimized for +1 charge state

The optimized source parameters for the extraction of nickel beam are listed in table 1.

APPLICATION OF THE ATOMKI-ECRIS FOR MATERIALS RESEARCH AND PROSPECTS OF THE MEDICAL UTILIZATION*

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Abstract

In the ATOMKI ECRIS Laboratory long-term projects were initiated to use heavy ion beams and plasmas for materials research and to explore the possibility of industrial or medical applications of such ions. In the paper four applications are shown. (1) A new ECR-device was developed in collaboration with Japanese institutes to produce endohedral fullerenes, namely caged Fe in C₆₀. (2) Titanium bio-implants are covered with fullerene ions to form an intermediate layer between the metal and the organic tissues in order to shorten the time of the cell growth and to improve the properties of the connection. (3) Laser and electron irradiations showed that the structure and properties (volume, refractive index) of certain amorphous thin films can be effectively modified. We extend these investigations using heavy ion beams, focusing on the effect of the ion charge. (4) Highly charged slow ions were found to be efficiently guided by insulating nano-capillaries even at large tilt angles. This phenomenon is investigated for different kinds of capillary arrays and materials.

INTRODUCTION

In the history of the ECRIS workshops majority of the talks, posters and papers dealt with the technical features of ECR ion sources. During their operation lifetime most sources undergone several minor or major modifications or upgrades. The main goal is usually to increase the beam intensity and/or the charge of the extracted ions. Another large volume of the papers discussed the physics of the ion sources, both experimentally and theoretically. In these fields excellent results were achieved and presented in the ECR workshops and in ion source conferences.

Nowadays a continuously increasing demand is detected for the application of heavy ion beams in industry and medicine. The application of plasmas and ion beams produced by ECR ion sources is normally published in other conferences or in independent papers. These contributions usually do not show the details of the ion sources or the “beam-making” itself. However, a specific application of a heavy ion beam frequently requires the modification of the ion source itself or, at least, unusual plasma formation or ion extraction.

* This work was supported by the Hungarian National Science Foundation OTKA (Grant No's: K46454, K73703 and PD050000), the RET-GENOMNANOTECH project of the Debrecen University (4.3.3 and 4.2.1 sub-projects) and in part by the Bio-Nano Electronics Research Center (Kawagoe, Japan) and the National Institute of Radiological Sciences (NIRS, Chiba, Japan).

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In this paper we show a few possible, promising applications of heavy ion beams. Each of these projects just started at the ATOMKI ECRIS Laboratory, some of them in collaboration with other institutes. The first results already appeared, but the major achievements are expected within the next 1-5 years.

NEW MATERIALS IN ECR DISCHARGE

Fullerene plasmas and beams have been produced in ECR ion sources for various scientific and practical reasons and purposes [1]. High intensity singly and multiply charged beams are needed for collision experiments. The endo- and exohedral fullerenes are getting more and more important for materials research and, in some cases, for medical applications. Endohedral means that an alien atom or molecule is encapsulated inside the carbon cage. The most known endohedral fullerene is the N@C₆₀ molecule (here the @ sign means that the atom at left locates inside the molecule at right). It has been investigated to develop a sensitive indicator to measure molecular distortions, molecular motions etc. and in conjunction with quantum computing [2].

At the ATOMKI-ECRIS fullerene plasmas have been produced since 2000 by using filament ovens to evaporate fullerene. One of our goals has been the production of high intensity singly and multiply charged fullerene ion beams. Another research topic is the investigation of mixture plasmas (C₆₀ + X, where X is N, O, Fe or other atoms). In C₆₀+N mixture plasmas endohedral N@C₆₀ was observed in the beam spectra and in macroscopic quantity in the soot deposited on the wall of the plasma chamber [2].

The fullerene encapsulated iron would be another promising new material if one could produce it first in a beam then in bulk quantity. In the past years we made some efforts in this direction. The composition of C₆₀+Fe mixture plasmas was studied by extracting ions from it. The iron component of the plasma was obtained from ferrocene powder or using high-temperature filament ovens to melt pure iron rods [3,4]. These and other results and demands led us to a major modification of the ATOMKI-ECRIS. Since 2006 it has been operating in two modes (“A” and “B”) [5]. In “B”-mode the ion source is equipped with a large plasma chamber and a weak hexapole around it. This mode is specialized for the production of large-sized, low-ionized plasmas and provided the fullerene beams for a number of experiments.

The ATOMKI-ECRIS-B source was selected as a prototype for an other new ECRIS just built in Toyo

DEVELOPMENT OF ECR HIGH PURITY LINERS FOR REDUCING K CONTAMINATION FOR AMS STUDIES OF ^{39}Ar

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Abstract

The first application of ^{39}Ar Accelerator Mass Spectrometry (AMS) at the ATLAS linac of Argonne National Laboratory (ANL) was to date ocean water samples relevant to oceanographic studies using the gas-filled magnet technique to separate the ^{39}K - ^{39}Ar isobars. In particular the use of a quartz liner in the plasma chamber of the Electron Cyclotron Resonance (ECR) ion source enabled a ^{39}K reduction of a factor ~ 130 compared to previous runs without liners and allowed for our current lowest detection limit of $^{39}\text{Ar}/\text{Ar} = 4.2 \times 10^{-17}$ [1]. We are currently working on improving the AMS method for ^{39}Ar by following two development paths to allow for higher beam currents while lowering ^{39}K rates. The first option is to modify the design of the quartz liner to provide active water cooling. The second option is to use a thick walled liner of high purity aluminum constructed with an interference fit to the plasma chamber wall. The overall driving force for this AMS project is to search for a source of argon that has a low concentration of ^{39}Ar . Such a source of argon would be useful for new liquid argon detectors that are being developed for detecting dark matter WIMPs (Weakly Interacting Massive Particles).

INTRODUCTION

Commercial argon is obtained from the atmosphere and contains ^{39}Ar , which is produced by cosmic ray interactions with ^{40}Ar in the atmosphere. The ^{39}Ar decays by beta emission with an end-point energy of 560 keV and a half-life of 269 years. The atmospheric concentration of ^{39}Ar relative to ^{40}Ar is 8.1×10^{-16} ,

corresponding to a beta decay rate of ~ 1 Bq/kg of argon [2].

Argon can also be found as a trace component in gas that comes from deep underground wells. Shielded from cosmic rays it should have lower than atmospheric levels of ^{39}Ar though there are nuclear reaction mechanisms that can produce ^{39}Ar in underground sites. For example, the neutron induced reaction $^{39}\text{K}(n, p)^{39}\text{Ar}$ will occur if there is uranium and thorium together with potassium, since the alpha particles of the U and Th chains produce neutrons by (α, n) reactions on light nuclei [3, 4].

The challenges to detect ^{39}Ar at natural levels are great with $^{39}\text{Ar}/\text{Ar} (= 8.1 \times 10^{-16})$ being a thousand times smaller than that of $^{14}\text{C}/\text{C} (= 1.2 \times 10^{-12})$. One liter of "modern" ocean water, i.e. water in equilibrium solubility with the atmosphere, contains only ~ 6500 atoms of ^{39}Ar , requires very high overall detection efficiency [5].

Since argon does not form negative ions, tandem accelerators, the traditional AMS tool, are unsuitable and positive-ion accelerators must be used and a very high background of ubiquitous ^{39}K , the interfering stable isobar ($\Delta M/Q = 1.55 \times 10^{-5}$) must be separated.

The difficulty in this experiment is also evident in a mechanical sense. From ECR II to the spectrograph there is over 120m of equipment that must maintain relatively good stability for long periods of time (see figure 1). Factors that come into play range from: the output of the ion source, the tune of the beam provided by the accelerator, beam line elements like magnets that can drift

USE OF AN ECR ION SOURCE FOR MASS SPECTROMETRY

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Abstract

At ANSTO we have developed an Electron Cyclotron Resonance (ECR) ion source to investigate new concepts for mass spectrometers designed to measure isotopic ratios of elements such as carbon, nitrogen and oxygen. The low pressure ECR plasma presents particular challenges when used for mass spectrometry. The elements we are interested in measuring are typically present as residual gas in vacuum systems and hence we need to achieve ultra-high vacuum throughout our system. Also ECR plasmas generate highly reactive species of these elements which can then bond to internal surfaces. A number of measures have been taken to combat these difficulties. We have shortened the plasma bottle length to minimise the surface area. In making this change we have also discovered that the useful plasma volume is much less than expected. Originally the source was designed with a mirror ratio of around 2.1. With the restricted bottle size, our effective mirror ratio is 1.8 and yet the performance of the source is unaffected. This and other design modifications will be discussed.

INTRODUCTION

At ANSTO we are developing an Isotopic Ratio Mass Spectrometer (IRMS) system utilising an Electron Cyclotron Resonance Ion Source (ECRIS) [1]. The ECRIS properties have two main advantages over traditional systems based on electron impact ionization. Firstly the ionization efficiency which can be 2 orders of magnitude greater than electron impact ionization at converting the sample to an ion beam for measurement. Secondly the process of creating charge states greater than 1+ breaks up molecules which cause molecular interferences in mass spectrometry of the single charge state. For this reason our IRMS system typically makes measurements of 2+ charge state ions, and thus the name adopted for our system is the IRMS++.

Initial testing of the system has verified the ability of our ECRIS to generate 2+ and greater charge states free of molecular interference at a sample efficiency >10%. Other characteristics that are not desirable for the operation of a mass spectrometer have also been discovered. This has included high backgrounds, high levels of background beams and retention of the sample in the ion source (ion source memory effect). We describe below methods used to minimise these effects and modifications that have been made to the ion source to reduce them, while avoiding any negative impact on the performance of the ECRIS.

EXPERIMENTAL ARRANGEMENT

The configuration of the IRMS++ instrument developed at ANSTO is shown in Figure 1, including an electrostatic analyser which has been installed since the work shop report ref[1]. The system incorporates an in house developed cost effective ECR ion source to produce low to medium charge state ions. The source is described briefly below; a more detailed description of it can be found in a recent paper [2].

Microwave power to the ECR ion source is provided by a 100 watt microwave amplifier and oscillator, which is tuneable within 64 channels across a frequency range of 6.85 – 7.15GHz. The microwave generator is coupled to the ion source chamber via a wave guide. Normally the microwave generator is operates at 10-25W, and frequency of 7.115GHz.

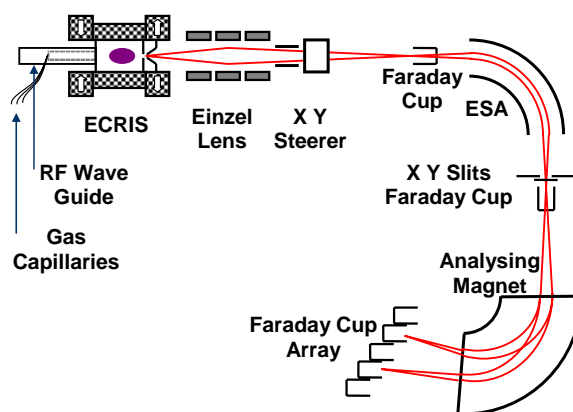


Figure 1: The configuration of the ANSTO IRMS++ instrument.

The magnet field is achieved by permanent magnets, consisting of 2 ring magnets to form the axial field, and a hexapole to form the radial field.

The plasma bottle is constructed from a 48mm ID closed end quartz tube, with the closed end transitioning to a 9mm OD tube as to deliver gas to the plasma chamber. The quartz plasma bottle is transparent to microwaves enabling the capping of the end, and provides electrical isolation to ground for the plasma electrode and the plasma itself. The support, and sample gases are delivered to the 9mm OD quartz tube via 3 polymer coated silica capillaries of different lengths and diameters, allowing delivery of gases from chambers at pressures ranging from 5 to 1000 Torr. These utilise the poor conductance to transition between laminar gas flow in the sample section, to molecular flow of the Ultra High

BEAM-PROFILE/-EMITTANCE MEASUREMENTS AT THE FRANKFURT ECRIS

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Abstract

The off-line analysis of the Frankfurt Emittance and Profile Monitor (FProM) has been improved to allow better (direct) access to the calibrated profile and emittance representations. With the new system profile and emittance scans can be performed and directly interpreted at measuring times of 2-3min per full scan. With this significantly improved working performance a series of measurements has been carried out, where we have pursued the issue of beam filamentation in the extraction region of the 14GHZ Frankfurt ECRIS. The new program development will be presented together with results from the measurements.

INTRODUCTION

The determination of the beam parameters distinctly beyond the mere measurement of extracted beam currents has become an important issue for the development of new ion sources. In particular the development of newest generation ECRIS sources with their extremely high magnetic fields, extending far into the extraction area, have to be based on detailed measurements not only the beam emittance but also of the lateral beam profile, in order to carefully tailor the beam transport system. We have upgraded the “Frankfurt online scanning system”, which initially was developed as a simple and easy to install monitor to control position and integrated lateral profiles of the beam from the Frankfurt 14Ghz ECRIS. This system had already been turned into an emittance / and profile monitor by adding an automated moving-slit system [1]. For a better usability of this system, an offline data-analysis system has been supplemented, which allows direct access to the normalized and calibrated beam profiles and emittance distributions. For the determination of Twiss parameters a converter allows the use of the EAS code [2] for further processing of the measured data.

THE FProM-SYSTEM

A detailed description of the scanner hardware is given in Ref. 1. The idea behind the scanning system is to shadow the current, measured in a (in principle in any) Faraday cup in the beam line by moving a trapezoidal Aluminium screen, mounted on a wheel which rotates around the Faraday cup. In this way the primitive function of the beam profile is measured in two orthogonal directions. Derivation of these two profiles delivers the lateral density distributions of the beam profile (x/y-profiles). A typical online screen of FProM is displayed in

Ion Beam Extraction and Transport

Fig. 1. In the left upper corner the original profile (primitive function) is displayed, whereas in the bottom windows the derivatives of the two slopes (rising and falling) are plotted, allowing the online control of form and position of the beam in the two orthogonal scanning directions. The panels in the upper right of the screen are controls for the stepping motors of altogether 3 moving slit systems, which can be added to the hardware in order to transform the scanner into a high resolution profile and emittance monitor. In this way up to 3 systems can be controlled by the online program.

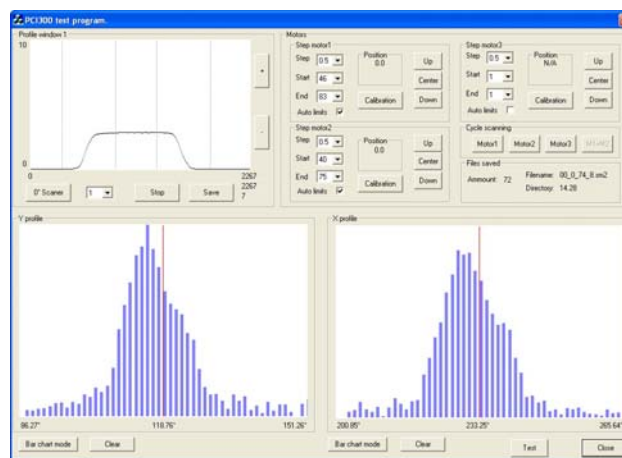


Figure 1: on line screen of the Frankfurt Profile and Emittance Monitor (FProM)

Altogether three such systems have been installed in Frankfurt now, two in the ECRIS beam line (one at 0°; one at the injection into the RFQ). The third system has been installed in the injection line to the new Frankfurt Low Energy Storage Ring (FLSR) in order to match the injected beam to the ring acceptance. All systems are equipped with at least one slit system, the ECRIS 0° beam monitor has two slit systems allowing to measure emittances in both lateral directions (x-x' and y-y'). Additionally, by controlling the joint movement of such a pair of orthogonal slits, the 4-dimensional information (x,x',y, y') can be measured like in a “pepper pot” measurement. Since the two orthogonal directions are scanned by only one rotating shadow, the scanning edges of the shadow have to be oriented at 45° to the axis of rotation. This implies that a mounting of the system e.g. into a spare port opposite to the mounting flange of the Faraday cup, which normally is mounted in a way that it is aligned to the accelerator based x or y direction, results

CONCEPTUAL DESIGN OF A SPUTTER-TYPE NEGATIVE ION SOURCE BASED ON ELECTRON CYCLOTRON RESONANCE PLASMA HEATING

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Abstract

A design for a negative ion source based on electron cyclotron resonance plasma heating and ionization by surface sputtering is presented. The plasma chamber of the source is an rf-cavity designed for TE₁₁₁ eigenmode at 2.45 GHz. The desired mode is excited with a loop antenna. The ionization process takes place on a cesiated surface of a biased converter electrode (cathode). The ion beam is further “self-extracted” through the plasma region. The magnetic field of the source is optimized for both, plasma generation by electron cyclotron resonance heating, and beam extraction. The source can be used for a production of a variety of negative ions ranging from hydrogen to heavy ions. The potential users for the source concept range from large scale accelerator facilities, utilizing H⁻ ion beams, to dc tandem accelerators for heavy ions. The benefits of the source concept compared to widely used filament- and inductively coupled rf-driven sputter-type sources are the lack of consumable parts and low neutral pressure minimizing the stripping losses of negative ions. In this article we will focus on the H⁻ production scenarios with the novel source. The benefits and drawbacks of higher frequency operations are also discussed.*

INTRODUCTION

The focus of the H⁻ ion source development program at Los Alamos Neutron Science Center (LANSCE) has recently been on improving the performance of the filament-driven surface conversion ion source (see for example ref. [1]) and developing an rf-driven surface conversion ion source operated with helicon wave mode [2]. The main problems associated with these ion sources are the presence of consumable parts and high neutral gas pressure causing stripping losses, respectively.

In this article we propose a design for a novel H⁻ ion source based on electron cyclotron resonance plasma heating and surface ionization. The source is expected to operate within a neutral gas pressure range of 0.1-1 mTorr i.e. order of magnitude lower than the helicon discharge [2]. This helps to mitigate the H⁻ losses due to collisions with neutrals and reduces the volume formation of H⁻ preventing undesired increase of emittance, sometimes observed with surface converter ion sources [1].

* Work supported by the US Department of Energy under contract DE-AC52-06NA25396

PHYSICS ASPECTS OF H⁻ ION BEAM PRODUCTION

Modern H⁻ ion sources are based on two important ion formation processes, the volume [3] and the surface [4] production. The relative importance of these processes depends on the detailed design of the ion source.

The volume production of H⁻ is generally accepted to be due to dissociative attachment (DA) of low energy electrons to rovibrationally (v'') excited molecules. Two electron populations are needed in order to optimize the volume production process: hot electrons (few eV) creating the excited molecular states i.e. $e_{hot} + H_2 \rightarrow e + H_2^{v''}$ ($v'' > 5$) and cold electrons (less than 1 eV) responsible for dissociative attachment i.e. $e_{cold} + H_2^{v''} (v'' > 5) \rightarrow H + H^-$. Therefore, the ion sources based on this process are typically optimized by separating the plasma chamber in two parts by a filter (electrostatic or magnetic) decoupling the plasma heating zone from the H⁻ production zone (see for example ref. [5]).

The surface production mechanism in negative ion sources is so-called resonant tunneling ionization: the electron affinity level of a hydrogen atom adsorbed on a metal surface shifts and broadens. If the electron affinity level shifts below the Fermi energy of the (cesiated) metal surface, electrons have a finite probability to tunnel through the potential barrier forming an H⁻ ion when the surface is subjected to heavy ion (Cs) bombardment [7].

The work function of the surface affects the probability of the electron tunneling, which is the other beneficial effect of cesium i.e. Cs deposition lowers the work function. If the bias-voltage of the converter electrode is on the order of hundreds of volts (like in the case of LANSCE converter source) the sputtering of the metal becomes an important issue. This aspect favors the use of converter materials such as molybdenum and rhenium with low sputtering yields under proton bombardment.

In a converter-type ion source the H⁻ ions created on the cesiated surface have to propagate through the plasma in order to become extracted from the ion source. Three types of loss processes of H⁻ due to collisions with other particles within the propagated distance need to be considered:

(1) $H^- + e \rightarrow H + 2e$: The H⁻ mean free path can be calculated from the electron mean free path by taking into account the average velocities (energies) of the particles,

$$\lambda_{H^-} = \sqrt{\frac{m_e E_{H^-}}{m_{H^-} E_e}} \lambda_e. \quad \text{This equation was used for}$$

estimating the H⁻ losses due to collisions with electrons for the proposed ion source design.

STATUS OF NEW ELECTRON CYCLOTRON RESONANCE ION SOURCES AT ITHEMBA LABS

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Abstract

iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) is a multi-disciplinary accelerator facility. One of its main activities is the operation of a separated-sector cyclotron (SSC), which provides beams of various ion species at energies ranging from 5 to 220 MeV/amu. These beams are used for fundamental nuclear physics research in the intermediate energy region, radioisotope production and medical physics applications. During the last 16 years the heavy ion beams at iThemba LABS were produced in a 10 GHz Minimafios Electron Cyclotron Resonance Ion Source (ECRIS). In 2006 the decision was made that, due to the requirements of nuclear physics for new ion species and higher particle energies, a new 3rd generation ECRIS should be procured. Therefore a source, based on the design of the Grenoble Test Source (GTS), is under construction. It is a room temperature source that uses two microwave frequencies, 14.5 GHz and 18 GHz, to deliver highly-charged ions of sufficient intensity to be accelerated in the separated-sector cyclotron to energies in the GeV range. At the same time a 14.5 GHz ECRIS4 with its beam line elements that were designed and constructed by Grand Accelerator National d'Ions Lourds (GANIL) and originally built for the Hahn-Meitner-Institute (HMI) in Berlin was donated to iThemba LABS and has recently been installed. The status of the projects and future plans will be discussed.

INTRODUCTION

iThemba LABS is operated by the National Research Foundation (NRF) of South Africa. It provides accelerator and ancillary facilities for: research and training in the physical, biomedical and material sciences; treatment of cancer patients with energetic neutrons and protons and related research; production of radioisotopes and radiopharmaceuticals for use in nuclear medicine, industry and related research. At the heart of the iThemba LABS accelerator complex is the variable-energy, separated-sector cyclotron, which provides beams with a maximum energy of 200 MeV for protons. Beams are directed to vaults for the production of radioisotopes, proton and neutron therapy and nuclear physics experiments as shown in Fig. 1. Light ions, pre-accelerated in the first solid-pole injector cyclotron (SPC1) with a K-value of 8 are used for therapy and radioisotope production. For radioisotope production and neutron therapy a high-intensity 66 MeV proton beam is used, while a low-intensity 200 MeV beam is used for proton therapy. The second solid-pole injector cyclotron

(SPC2) with a K-value of 10 is used for pre-acceleration of light and heavy ions as well as polarized protons from the two external sources shown in Fig. 2. With the 3:1 available RF frequency range and the different harmonic numbers that can be used, the particle energy of all three cyclotrons can be varied over a wide range for a large variety of ion species. Beams are delivered to the different user groups for 24 hours per day and seven days per week. The 66 MeV proton beam is available for radionuclide production and neutron therapy from Mondays until midday on Fridays. Patients are treated during daytime and between treatments the beam is switched to the radionuclide production vaults within seconds, and the intensity increased to 250 μ A. During weekends a 200 MeV beam is used either for proton therapy or nuclear physics research using beams of light and heavy ions, as well as polarized protons [1, 2].

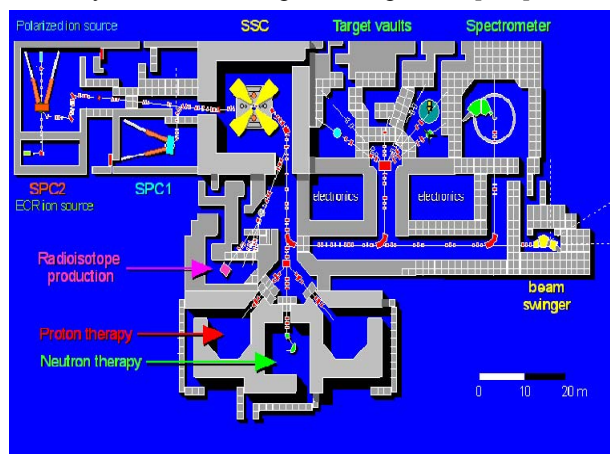


Figure 1: Layout of the accelerators at iThemba LABS.

ACCELERATORS AT ITHEMBA LABS

The Injector Cyclotron for Heavy Ions

The solid pole injector cyclotron SPC2 with a K-value of 10 has four radial magnet sectors and an extraction radius of 48.6 cm. Beams are accelerated with two 90°-dees operated at a maximum voltage of 60 kV. The RF-system can be tuned over the frequency range 8.6 MHz to 26 MHz with movable short-circuit plates in quarter-wave transmission lines. Harmonic numbers 2 and 6 are used. The beam is extracted with an electrostatic channel and two active and one passive magnetic channel. The ion sources are external and the beam is injected axially with three spiral inflectors corresponding to the three orbit geometries that are being used. At present heavy ions with mass numbers up to that of xenon are delivered by our

FIRST BEAM OF THE 2.45 GHZ VERSATILE ION SOURCE (VIS) FOR HIGH POWER PROTON ACCELERATORS

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Abstract

The Versatile Ion Source (VIS) is a permanent magnet version of the TRIPS source with a simplified and robust extraction system. It operates up to 80 kV without a bulky high voltage platform, producing multi-mA beams of protons and H^2+ . The description of the source design and the preliminary performance will be presented. An outline of the forthcoming developments is given, with particular care to the use of a low loss dc break and to the use of a travelling wave tube amplifier to get an optimum matching between the microwave generator and the plasma.

**PAPER NOT
RECEIVED**

MEASUREMENTS OF X-RAY SPECTRA ON ECR-II*

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Abstract

FAR-TECH, Inc. has been developing an inexpensive and robust X-ray spectral diagnostic for monitoring electron cyclotron resonance ion sources (ECRIS). To this end, FAR-TECH, Inc. has recently performed extensive measurements of X-ray emission from the ECR-II device in the ATLAS facility at Argonne National Laboratory. We find that both the intensity and the shape of the observed spectra are highly correlated with the charge state distribution (CSD) of ions extracted from the ECR-II plasma as measured by a Faraday cup (FC).

INTRODUCTION

X-ray measurements provide much useful information about ECRIS plasmas. The intensity, width, and energy shift of the *K* and *L* lines provide information about the species present in the plasma and their charge states. The bremsstrahlung continuum provides information about the electron distribution function (EDF). The EDF determines both the ionization rates as well as the particle confinement time, thus determining the CSD. This information can be of great use in improving ECRIS modeling codes. In addition, X-ray measurements are non-invasive and can be made without taking the beam offline. However, many X-ray detectors, such as crystal spectrometers [1] or CCD cameras [2] are expensive (~\$100K) and/or difficult to use and maintain. In addition, many detectors have limited energy range (< 20 keV) [2], which is insufficient for measuring the bremsstrahlung spectra, where photon energies can be over 100 keV. Therefore, FAR-TECH, Inc. has been developing an inexpensive, robust X-ray diagnostic tool for ECRIS plasmas.

EXPERIMENTAL SETUP

The X-ray measurements described here were performed using an Amptek XR-100T-CdTe detector [3]. The CdTe diode has a detection efficiency of over 20% from 2 to 200 keV and an energy resolution of 600 eV at 60 keV. The detector was controlled using an Amptek PX4 digital pulse processor. The detector and controller together cost only \$10K.

The detector was installed on the ECR-II device [4] at the ATLAS facility at Argonne National Laboratory. The detector was installed inside the vacuum chamber through a side port so as to have a view across the plasma transverse to the axis of the device, as shown in Figure 1. The port is located at the midplane of the plasma, where the X-ray detector can view the plasma through apertures

between the hexapole magnets. Considerable care was taken ensure that only X-rays generated by collisions in the plasma would be detected, and not X-rays generated by electron collisions with the walls of the device. Lead shielding and two, 2 mm thick, tungsten collimator plates separated by a tungsten spacer blocked all line-of-sight X-rays except those passing through the collimator holes. The holes in the collimator plates (100 μm and 200 μm) are small enough that the solid angle viewed by the detector passes through apertures on either side of the plasma chamber without intersecting it. Thus, only X-rays generated in the plasma pass through the collimator holes.

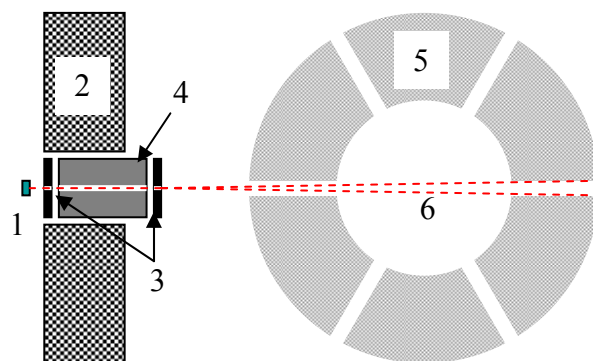


Figure 1: Experimental setup of the X-ray diagnostic. (Not to scale.) Device axis is perpendicular to the page. All components shown are in vacuum. (1) CdTe detector (2) Lead shielding (3) Collimator plates (4) Tungsten spacer (5) Plasma chamber (6) Viewing solid angle

The X-ray measurements presented here were performed on argon plasmas. Unless otherwise stated, the operating parameters were RF frequency $\omega_{RF} = 14$ GHz, minimum magnetic field $B_{min} = 3080$ G, argon pressure $p = 8 \times 10^{-8}$ torr, and RF power $P_{RF} = 300$ W. The charge state distribution (CSD) of extracted ions was measured with an analyzing magnet and Faraday cup. The RF frequency at 14 GHz is resonant with the electron cyclotron motion at a magnetic field of $B_{ECR} = 5000$ G, so $B_{min}/B_{ECR} = 0.62$.

Typical acquisition times for X-ray spectra were 20 minutes for $\sim 10^6$ counts. Figure 2 shows a typical raw spectrum acquired on ECR-II. Characteristic K_{α} and K_{β} ($K_{\alpha/\beta}$) lines for different species visible to the detector are easily seen. Lead is in the shielding, tungsten is in the collimator, and CdTe is in the detector itself. The argon $K_{\alpha/\beta}$ line disappears if a different working gas is used, which shows that it comes from the plasma and is not an artifact of the detector.

Most of the X-ray counts come from the bremsstrahlung continuum. Our measurements showed a broad peak in the continuum around 120 keV, similar to

*This research was performed under a U.S. DOE SBIR grant and the Office of Nuclear Physics under contract # DE-AC02-06CH11357.

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HIGH ENERGY COMPONENT OF X-RAY SPECTRA IN ECR ION SOURCES

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Abstract

The 88-Inch Cyclotron at LBNL is home to three powerful ECR ion sources, which operate at a range of heating frequencies from 6.4 GHz for the ECR to a combination of 18GHz and 28GHz for the VENUS superconducting ECR. Over the last few years we have investigated the production of x-rays from ECR ion sources with the goal of improving the understanding of the electron energy distribution within these sources. By measuring the spectral temperatures (defined as the reciprocal of the slope of the semi-logarithmic plot of the x-ray energy spectra) and using them as relative indicators of the electron temperatures, different plasma conditions and tuning parameters can be evaluated. A comparison of the axial x-ray spectra measured with the 6.4GHz ECR ion source to spectra obtained using the 18 and 28GHz VENUS source at equivalent power densities is presented. In addition, the paper discusses the experimental setup and analysis of the x-ray measurements. In particular, we discuss how to remove artifacts from the energy spectra resulting from the interaction of x-rays with the detector in order to accurately represent the x-rays emitted from the source.

INTRODUCTION

Lawrence Berkeley National Lab (LBNL) has three electron cyclotron resonance ion sources (ECRIS): LBNL-ECR, AECR-U, and VENUS, which operate at frequencies of 6.4GHz, 10 & 14GHz, and 18 & 28 GHz, respectively. This wide range of operating frequencies presents a unique opportunity to examine how various plasma parameters scale with frequency.

Several interactions lead to the emission of bremsstrahlung by electrons, in the form of x-rays. For example, electrons colliding with ions and electrons which are lost from the plasma and collide with the plasma chamber wall radiate x-rays due to their sudden deceleration. Studying the radiated x-ray spectra is a step towards our ultimate goal of determining the electron energy distribution function (EEDF).

The difficulty preventing one from making direct conclusions of the EEDF from an x-ray spectrum is that the detected spectrum does not directly reflect the energy of the electrons in the plasma and the spectra emitted by such a distribution. The detected spectrum is a result of many parameters. For example, the detector, a thallium-activated sodium iodide (Na(Tl)) scintillator, reacts

differently to photons depending on their energy and the dimensions of the scintillator itself. Correcting the detected spectra so that they more accurately represent the emitted spectra is crucial in our attempt to characterize the plasma electrons. In addition the bremsstrahlung coming from the walls must be separated from the bremsstrahlung coming from the electron-ion collisions inside the plasma, since we want to measure the EEDF of the confined plasma and not the EEDF of the electrons lost to the walls. Therefore, specific collimation of the emitted x-rays is necessary in order to minimize the amount of wall bremsstrahlung visible to the detector.

The data presented in this paper include bremsstrahlung measurements from the VENUS ion source when using 18GHz and 28GHz heating and bremsstrahlung measurements from the LBNL-ECR ion source using 6.4GHz heating, both emitted axially and observed through the extraction aperture. The emitted x-rays are collimated and then detected with a NaI(Tl) scintillator. The specific collimation, which controls the region visible to the detector, and its significance, is discussed as well as the response of the NaI(Tl) detector to the x-rays and the correction applied. Finally, a preliminary comparison is made between the LBNL-ECR and VENUS bremsstrahlung emitted at equivalent plasma power densities and similar collimation geometries.

EXPERIMENTAL SETUP

Collimation and Detector

The experimental setup and collimation geometry for both VENUS and LBNL-ECR spectra were designed to minimize background radiation from other sources such as the nearby AECR-U. Despite the effort to shield the detector from the AECR-U's x-rays, background measurements showed that the background was minimized but not completely eliminated. Figure 1 shows the significance of the background for LBNL-ECR spectra at low power, at which the x-ray intensity is relatively low in comparison. Note, in particular, for a spectrum taken at a low power of 115W, as shown, the counts are only a factor of ~2 greater than the background.

ECR

The experimental setup of the LBNL-ECR and NaI detector is shown in Figure 2. The collimation consists of

PERMANENT MAGNET MICROWAVE-DRIVEN ION SOURCE FOR NEUTRON GENERATION

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Abstract

The basic principle of a neutron generator is to bombard an ion beam of either deuterium or tritium onto a target, where neutrons are produced via the D/T reactions. Compared with RF-driven and Penning Ion Sources commonly used in neutron generators, the 2.45 GHz ECR ion source has the advantages of high power efficiency, high fraction of atomic ions, low gas pressure. For portable application, the ECR source can be built with permanent magnets to minimize size. Results published by Gobin(*) and Song(**) using permanent magnets have shown current densities more than that required in neutron generator applications. In our study, we are trying to simplify the coupling between the magnetron and the plasma chamber in order to achieve either improved system efficiency or compactness. For example, in one case, a pyrex tube is inserted at the end of a wave guide as the plasma chamber. In another case, the plasma chamber has the same cross-sectional dimension as the wave guide for matching the producing of a slit beam. Results such as the current density, ion species, and plasma density profile inside the plasma chamber, as functions of microwave power and gas pressure will be presented.

**PAPER NOT
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EXPERIENCE AT THE ION BEAM THERAPY CENTER (HIT) WITH 2 YEARS OF CONTINUOUS ECR ION SOURCE OPERATION

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Abstract

Radiotherapy with heavy ions is an upcoming cancer treatment method with to date unachieved precision. It associates higher control rates particularly for radiation resistant tumour species with reduced adverse effects compared to conventional photon therapy. This paper will provide an overview about the project, with special attention given to the two 14.5 GHz electron cyclotron resonance (ECR) ion sources. The HIT ECR ion sources are routinely used to produce a variety of ion beams from proton up to oxygen. The runtime of these two sources are 330 days per year, our experience with two years of continuous operation will be presented, with special emphasis on stability and breakdowns of components. In addition, an outlook of further planned developments at the HIT ECR ion sources will be given.

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 radiological university hospital in Heidelberg (Radiologische Universitätsklinik Heidelberg, Germany).

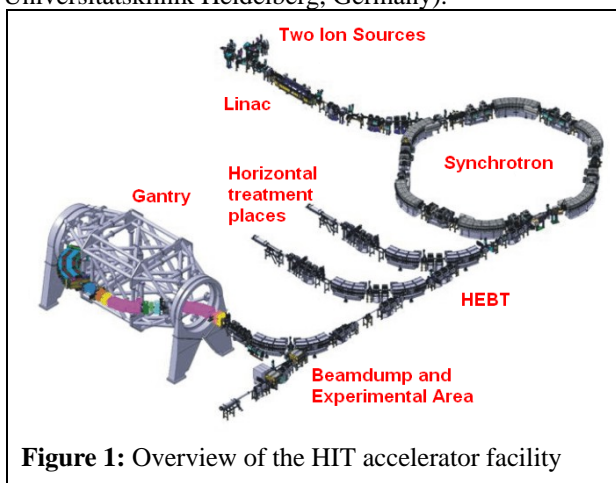


Figure 1: Overview of the HIT accelerator facility

Over the last two years the HIT accelerator [2,3] was commissioned by GSI Darmstadt [4,5,6], while the technical systems were operated under the responsibility of the HIT operating team. In parallel the implementation of the medical equipment took place.

The acceptance tests with beam started in 2006, when sources, low energy beam transport system (LEBT) and the linear accelerator (LINAC) were commissioned [4], followed by synchrotron [5] and high energy beam transport system (HEBT) in 2007 and 2008. The first turn in the synchrotron was achieved in February 2007, the

first beam in the treatment place was seen in March 2007. Beam performance for protons and carbons had reached a level enabling patient treatment at the two fixed beam patient treatment places by December 2007, at the experimental area by April 2008. Gantry commissioning started at January 2008 [6].

The beam production at HIT consists of two 14.5 GHz permanent magnet ECR ion sources from PANTECHNIK [7]. The 7 MeV/u injector linac [3] (Figure 2) comprises of the LEBT, a 400 keV/u radio frequency quadrupole accelerator (RFQ) [8,9], and a 7 MeV/u IH-type drift tube linac (IH-DTL) [3,8,9].

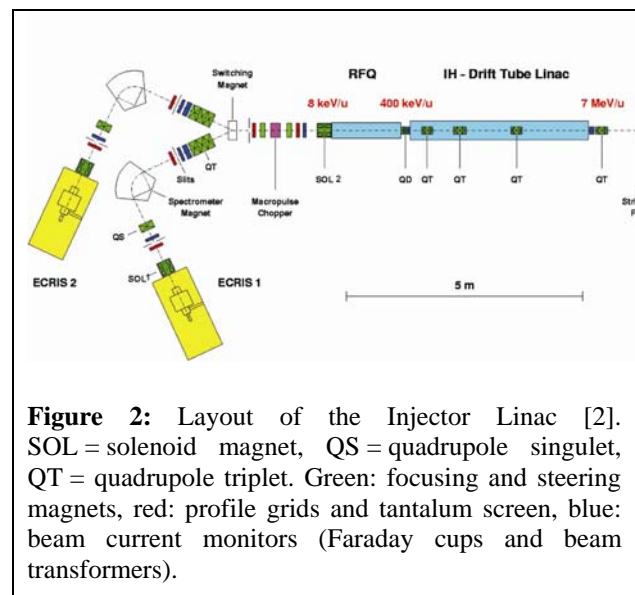


Figure 2: Layout of the Injector Linac [2]. SOL = solenoid magnet, QS = quadrupole singlet, QT = quadrupole triplet. Green: focusing and steering magnets, red: profile grids and tantalum screen, blue: beam current monitors (Faraday cups and beam transformers).

The linac beam is injected in a compact 6.5 Tm synchrotron [10] 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 beam is distributed by the high energy beam transport line (HEBT) to the four beam stations. There are two horizontal fixed beam stations for patient treatment. In station three the beam is guided along an isocentric gantry. The fixed beam station for quality assurance is dedicated to development and research activities. All places are fully equipped for a 3D rasterscan volume conformal irradiation.

The maximum available beam intensity at the patient treatment place are $8 \cdot 10^7$ ions/s for carbon and $3.2 \cdot 10^9$ ions/s 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

First experience with the operation of the GTS-LHC ion source at 18 GHz

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Abstract

The GTS-LHC ion source delivers the heavy ion beam, in preparation for the ion collision experiments at CERN. The source was operating up to now with a microwave frequency of 14.5 GHz, in the afterglow mode, for the commissioning of the injector chain of the LHC. Tests have been made with injection of microwaves at 18 GHz, and the first results and experience are presented in this paper.

INTRODUCTION

Within the last years the ion injector chain for the Large Hadron Collider (LHC) was successful commissioned [1] with the so called “early” beam. This beam is ready to be used for the first heavy ion experiments at the LHC.

The goal of the frequency change was to ease the operation and have some margin for the “nominal” beam.

The main difference from the source and linac point of view between the “early” and the “nominal” beam is the number of shots need to be stacked in the following machine (Low Energy Ion Ring - LEIR). An increased intensity from the source reduces the number of shots necessary and simplifies the operation of LEIR.

OPERATION AT 14.5 GHz

For standard operation the source has used a microwave frequency of 14.5 GHz up to now[2]. All the commissioning of the ion injector chain for the LHC was done in this operation mode.

For the injection of the beam into the next synchrotron (LEIR) a flat top of approximately 200 μ s is needed. The source pulses at 10 Hz with 50% duty factor for the microwave heating and is tuned in an afterglow-mode of operation.

Beam intensity in an individual charge state is measured from the source using Faraday Cup 2 (see Fig. 1). For operational optimization of the source for the linac, it is critical to optimize firstly in Faraday Cup 3, after the RFQ. It is often the case that the optimization of beam on Faraday Cup 2 can be far from the best optimization on Faraday Cup 3 (even after thorough tuning of the intermediate elements). Finally the

real figure of merit is the beam intensity from the full Linac, into the final stripped ion (see also [3]).

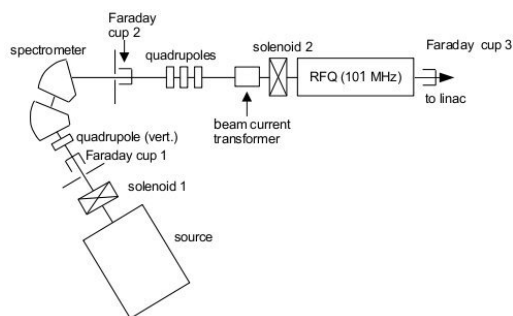


Figure 1: Sketch of the Low Energy Beam Transport (LEBT) of Linac3.

At the end of the linac, after a stripper and a spectrometer, the current is measured with a beam transformer.

Due to a better understanding and a careful tuning the source performance could be increased over the last years from around 100 $e\mu$ A of Pb^{29+} to presently $\sim 131 e\mu$ A measured after the RFQ. This results at the end of Linac3 in a maximum current of $\sim 31 e\mu$ A of Pb^{54+} .

Figure 2 shows a charge state distribution when the beam was optimised into Faraday Cup 2. This was a peak performance, and did not deliver the maximum performance from the linac.

Typical conditions for operation at 14.5 GHz are: RF power of 540 W, bias disk voltage of -390 V (pulsed during the afterglow), extraction voltage of 18.52 kV, average drain current of 1.7 mA and solenoid settings of 1260 A/370 A/1200 A (injection/central/extraction coil) leading to a $B_{max} = 1.3$ T at extraction.

Under this conditions a stable beam can be delivered for a period of up to two weeks. Then the oven has to be refilled. The overall intensity variation is in the range of 10%. The source has to be fine tuned several times per day to keep this level.

OPERATION AT 18 GHz

For the ECR ion sources several scaling laws are known and well tested [4]. One of them predicts that the extracted current for a certain charge state is proportional to the square of the frequency ($I_q \propto \omega^2$). If

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PRODUCTION OF MULTI-CHARGED IONS FOR EXPERIMENTAL USE AT HIMAC

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Abstract

Since 1994, heavy-ion radiotherapy using carbon ions is successfully carried out with the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS). HIMAC is dedicated to radiotherapy, but it has as a second essential task to operate as a users facility. In that scope it accelerates many ion species for basic experiments in e.g. biomedical and material science, physics and chemistry. In order to serve all HIMAC users at best, the extension of the range of ion species is an important subject in ion source development at HIMAC. Several developments on the 18GHz ECR ion source (called NIRS-HEC) are now in progress. In order to increase the beam intensity for heavier ions, additional microwave power is applied at a different frequency by a traveling wave tube amplifier. Various compounds are employed for the production of metallic ions by the metal ion volatile compound (MIVOC) technique. Results of recent developments are reported.

INTRODUCTION

Status of heavy-ion radiotherapy

Heavy-ion radiotherapy has physical and biological advantages over other types of radiation therapies. The physical advantage is a localized dose distribution just on a tumor in a human body. The biological advantages are a large relative biological effectiveness (RBE) due to the high linear energy transfer (LET), a small oxygen enhancement ratio (OER), and a small dependence on the cell cycle. Although LBL carried out pioneering trials in the 1970's – 1980's[1], it was not completed clinically. In order to verify the effectiveness and safety of heavy-ion radiotherapy clinically, the first medical dedicated heavy-ion accelerator in the world, named HIMAC, started operation at the National Institute of Radiological Sciences (NIRS) in 1993[2]. Over 4000 cancer patients have already been treated since 1994. These clinical results have clearly verified the advantages of heavy-ion therapy. The detailed results, i.e. a 5-year survival ratio, a local control ratio, grading of any side effect, and so on, are given in reference [3].

Based on 10 years-experience at HIMAC, a hospital-specified facility optimized for carbon ions has been designed[4]. The prototype injector, which consists of an

Status Reports

ECR ion source (called Kei2[5]), a RFQ linac, and an IH linac[6], has been successfully developed at NIRS. Thus, in co-operation with NIRS, Gunma University has been constructing the carbon-therapy facility since April 2006. The first clinical trial is scheduled for FY2009.

Motivation of developments for ion sources

HIMAC is dedicated to radiotherapy, but - as mentioned above - it has as a second essential task to operate as a users facility. In that scope it accelerates - during evening, night and weekend- various ion species for basic experiments. Two ECR ion sources and one PIG ion source are installed in HIMAC at present. A 10 GHz ECR ion source, so called NIRS-ECR, has satisfied the medical requirements[7]. A PIG ion source[8] produces ion species from solid materials by the sputtering technique. Other ion species are supplied using the 18 GHz ECR ion source, so-called NIRS-HEC[9,10]. In order to serve all HIMAC users at best, the extension of the range of ion species is an important subject in ion source development at HIMAC. The requirement for ion sources is to produce ions with a charge-to-mass ratio over 1/7 and an injection energy of 8 keV/n. The present records of beam intensities are summarized in Table 1. However, more ion species and higher intensities for heavier ions are still required. Developments for ion sources are in progress.

Table 1: Records of beam intensities without afterglow

* E:NIRS-ECR, H:NIRS-HEC, P:NIRS-PIG

Ion	Output (eμA)	*	Ion	Output (eμA)	*	Ion	Output (eμA)	*
H ₂ ⁺	3000	P	Ne ³⁺	6000	P	Ti ¹⁰⁺	50	H
He ⁺	6000	P	Mg ⁴⁺	400	P	Fe ⁹⁺	400	H
B ²⁺	150	P	Si ⁵⁺	250	H	Co ⁹⁺	170	H
C ²⁺	470	E	Cl ⁶⁺	400	H	Ge ¹⁴⁺	50	H
N ³⁺	1050	H	Ar ⁸⁺	1100	H	Kr ¹⁵⁺	205	H
O ³⁺	930	H	Ca ⁶⁺	250	P	Xe ²⁰⁺	95	H

Scope of the developments

In order to increase the NIRS-HEC beam intensity, the optimization of the extraction configuration was most

RECENT DEVELOPMENT OF 18 GHZ SUPERCONDUCTING ECRIS AT RCNP

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Abstract

The upgrade program of the AVF cyclotron is in progress since 2004 at the cyclotron facility of the RCNP, Osaka Univ., in order to improve the quality, stability and intensity of accelerated beams. A 18 GHz superconducting ECRIS has also been installed to increase beam currents and to extend the variety of ions, especially for highly charged heavy ions which can be accelerated by RCNP cyclotrons. The mirror magnetic field is produced with four liquid-helium-free superconducting coils and the permanent magnet hexapole is of Halbach type with 24 pieces of NEOMAX-44H material. The production development of several ion beams has been performed since 2006. Operational tests for beam intensity optimization have been done for ^{12}C , ^{16}O , ^{18}O , ^{15}N , ^{40}Ar , ^{86}Kr and so on. The MIVOC method for Boron ions has been developed as well.

**PAPER NOT
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Ion beam production from rare isotopes with GSI ECR Ion Sources

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Abstract

ECR ion sources (ECRIS) of CAPRICE-type, working at 14.5 GHz, are in use at the High Charge State Injector (HLI) of the accelerator facility at GSI for beam production and at a test bench for development work. The ECRIS is mostly used to produce ion beams from rare isotopes because of its high efficiency and low material consumption. Depending on their material properties beams of rare isotopes are produced from gases, gaseous compounds, solid materials or solid compounds. Gases can be used directly, while solids have to be transformed into the gaseous state for the ECR plasma which is achieved by using resistively heated ovens. As enriched materials are produced by isotopic separation processes their composition including contamination by impurities can be of importance for the handling in the evaporation process and can be detrimental for the beam user if the ion beam contains additional ion species. Characteristics and suitable treatment of materials and production processes are described. Experimental investigations with different sample materials and operational experiences are reported.

INTRODUCTION

Two preaccelerators are providing ion beams for the heavy ion Universal Linear Accelerator (UNILAC) at GSI which in turn delivers the ion beam to an experimental area with high duty cycle (pulses of typ. 5 ms length, 50 s⁻¹ repetition frequency) and to the Heavy Ion Synchrotron (SIS) with low duty cycle (pulses of typically 300 μs length, 1 s⁻¹ repetition frequency). The High Charge State Injector (HLI) is mainly used for the high duty cycle operation. In this mode the CAPRICE type ECR ion source (ECRIS) at the HLI is working in DC mode [1]. The appropriate input velocity for injection into the preaccelerator and the maximum mass/charge ratio of 8.5 determines the choice of ion charge state and extraction voltage, respectively. Typical ion charge states are Mg⁵⁺, Ni⁹⁺, and Xe¹⁸⁺. The respective extraction voltages are between 5 kV and 22 kV. The basic demand to the operation of the ECRIS at the accelerator is to provide a great variety of ion species in stable and reproducible long time operation. These requirements are well fulfilled for the operation with gases. For non gaseous elements which are more than 85% of all elements sometimes gaseous compounds of the desired element can be used. In all other cases the solids must be transformed into the gaseous state

at a suitable vapor pressure in the order of 10⁻³ mbar.

At GSI the oven technique has been preferred because it resembles closely the operation with gases. So it provides higher intensities in comparison with sputtering and lower contaminations compared to the MIVOC method (Metal Ions from Volatile Organic Compounds).

Many experiments at GSI request beams of specific isotopes which require highly enriched isotope materials. For rare isotopes the ECRIS is favorable due to its low material consumption and its high efficiency of conversion of sample material into the ion beam. Fig. 1 shows a statistical overview of the ion species produced for accelerator beam times from 2002 until August 2008. Without taking into account the C²⁺ beam time for cancer therapy the proportion of isotopically enriched sample material is exceeding 80 %.

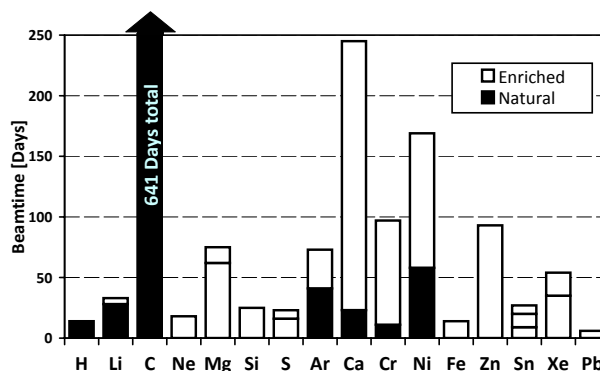


Figure 1: Ion beams produced for accelerator beam times from 2002 to August 2008.

ENRICHED MATERIALS

Natural sample material can be easily obtained in the desired forms and with high chemical purity. For isotopically enriched materials the enrichment processes as well as additional chemical treatments can result in different material properties compared to natural materials. These can be chemical composition including impurities, mechanical and structural characteristics. E. g. metal powders have a huge internal surface facilitating oxidation or hydration processes which are detrimental for the evaporation.

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PERMANENT MAGNETS UNDER IRRADIATION AND RADIOACTIVE ALKALI ION BEAM DEVELOPMENT FOR SPIRAL 1

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Abstract

Up to now, eighteen Target Ion Source Systems (TISSs) have been built and used for the production of radioactive ion beams on SPIRAL 1 facility, based on the Isotope-Separator-On-Line (ISOL) method. The TISSs are composed of thick carbon targets and of fully permanent-magnet Electron Cyclotron Resonance Ion Sources (ECRISs) of the Nanogan III type. After irradiation and a decay period of two years, the irradiated TISSs are dismantled and if their magnetic fields are still suitable, the ECRIS are used with a new target. Thereby thirty-two runs have been performed using new or renewed TISSs. After irradiation, the measured magnetic field sometimes reveals magnet damage. Our experience is reported here. In the second section, we present the progress on the NanoNaKE setup, which aims to extend the radioactive ion beams in SPIRAL 1 to the alkali elements, by connecting a surface-ionization source to the Nanogan III ECRIS via a compact 1+ ion beam line. The main issues and difficulties are discussed and the preliminary solutions are described.

INTRODUCTION

The use of high-energy fragmentation as well as the ISOL methods for exploring the structure of nuclei far from the stability has become one of the major activities at GANIL (*Grand Accélérateur National d'Ions Lourds*). The ISOL method, used in SPIRAL, provides radioactive ion beams, with subsequent acceleration by a K=265 cyclotron CIME, (*Cyclotron d'Ions à Moyenne Energie*).

Three cyclotrons are used to produce the primary beam which bombards the target of the TISS (Figure 1) placed in a heavily shielded cave. Exotic nuclei produced by nuclear reactions are released from the high temperature target (2000°C), effuse through a cold transfer tube up to a multi-charged ECR ion source. After extraction from the ECRIS at low energy (≤ 34 q.keV), the beam of interest is selected by a magnetic spectrometer ($m/\Delta m = 250$) and injected into CIME. The exotic beams can be accelerated in an energy range of 1.7 to 25 MeV/u and, after extraction, the proper magnetic rigidity is selected by GANIL's modified alpha spectrometer and directed to one of the existing experimental areas.

Two kinds of carbon target are used for the radioactive ion beam production, one dedicated to the production of He isotopes, the other to heavier gaseous element up to Krypton. The restriction to gaseous elements is provided

Radioactive Ion Beams

by a cold transfer tube, situated between the target cavity and the source chamber. Available intensities are given on the GANIL web site [1]

PERMANENT MAGNETS UNDER IRRADIATION

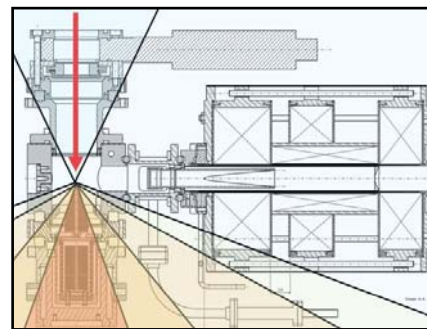


Figure 1: angular distribution of neutrons downstream from the target

The carbon target is placed close to the permanent magnets of the ion source (Nanogan III), which can then be damaged by neutron irradiation, leading to losses in axial and radial confinement of the source. For this reason, after a radioactive decay period of some years, the irradiated TISSs are placed in a glove box and dismantled. The target part is discarded as nuclear waste, and the magnetic field of the ion source is measured: if it is still acceptable, the ion source is reassembled with a new target.

During recent years, magnetic measurements have revealed more and more damage. Among the eighteen TISSs constructed since 2001, two types of degradation have been observed:

(a) Degradation of the injection magnet (close to the target):

Figure 2 shows an example of the decrease of the axial magnetic field on the injection side, with no modification at the opposite (or extraction) side.

Measurements all around the injection magnet (Figure 3) show an average loss of magnetic field of about 20%, with a maximum of 40% on the target side.

OPERATIONS OF KVI AECRIS AT AGOR SUPERCONDUCTING CYCLOTRON FACILITY

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Abstract

We present the status of ECRIS operation in KVI. Our work is mainly focused on improving the beam intensity and quality of highly charged ions for injection into the AGOR cyclotron. The main request was for Ne^{6+} ions to produce short-lived ^{21}Na for fundamental physics studies. Typical beam intensities are $350\text{ e}\mu\text{A}$. Several other ion beams were produced, e.g. C^{2+} , C^{4+} , C^{6+} and F^{4+} . Overall performance of the source met the user requirements. We recently started again with Pb ion production, resulting in $25\text{ e}\mu\text{A}$ of Pb^{27+} . Source output was gradually optimized, mainly by installing stainless steel screens at the injection and extraction sides of the ion source. A two-frequency heating system ($14.5 + 12.5\text{ GHz}$) has been installed and the first results will be presented.

**PAPER NOT
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OPERATIONAL EXPERIENCE WITH THE 18 GHz HTS-ECRIS, PKDELIS*

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Abstract

The high temperature superconducting electron cyclotron resonance ion source (HTS-ECRIS), PKDELIS was installed at IUAC in the beginning of 2005. There were some initial problems with one of the two cryo-coolers for the axial HTS coils and vacuum related problems at the intermediate location for test run. These were rectified subsequently. X-ray Bremsstrahlung measurements are carried out systematically to develop deeper understanding of the ECR plasma production processes. The source and low energy beam transport (LEBT) system are planned to be re-installed on a high voltage platform in the new beam hall III to prepare for injection into high current injector of the superconducting linear accelerator. Recent results of the PKDELIS and operational experience will be reported.

INTRODUCTION

At the Inter University Accelerator Centre, New Delhi, the accelerator augmentation programme involves the development of new accelerators for further boosting the beam energies to above 5 MeV/u (above Coulomb barrier) around mass 100 a.m.u. With the existing tandem accelerator, it was realised that the beam currents and mass range available were not sufficient for most of the experiments in nuclear physics and related areas. The tandem-LINAC combination in parallel with a high current injector was proposed to meet the above design goal [1]. An alternate high current injector was proposed based on a reasonable high performing electron cyclotron resonance ion source capable of delivering higher beam currents and covering a wide mass range [2]. In this paper, the operational experiences of the HTS-ECRIS PKDELIS at ground potential (presently) is described. This kind of source was designed for operation on a 400 kV high voltage platform to inject beams with initial velocities at 1 % of the velocity of light and further accelerate to ~ 8 % of the velocity of light before injection into the superconducting linear accelerator. In the near future, the source and low energy beam transport section will be finally shifted for installation on a high voltage platform to prepare for injection into the superconducting linear accelerator. The new beam hall III construction is complete and various beam hall utilities are nearing completion.

HTS-ECRIS PKDELIS

The HTS-ECRIS PKDELIS is designed for operation at two frequencies, viz. 14.5 and 18 GHz. Further description of the source can be found in earlier publications [3]. The test bench results of the source at Pantechnik, France during the end of 2003 gives more information about the beam currents of various ions extracted which are required for the high current injector [4]. Later, the source was initially installed at our centre at a test set-up position in the beginning of 2005. The source commissioning was delayed due to various problems that are described below.

Cryo-cooler cool down issues

During initial start-up, we had problems with the extraction cryo-cooler which eventually could not cool down the coil to ~ 20 K. This limited the source start-up and delayed the source commissioning. Initially it was thought that that due to the leak in the helium line, the cooling efficiency reduced. After re-charging the line (adding more helium), the cooling did not improve. It was further thought that the helium was contaminated. The helium was completely removed and re-charged again which still did not improve the situation. Since the extraction cryocooler was generating a much feebler sound when compared to the normal operating injection cryocooler which had a loud tapping sound, it was decided to open up the cold head section to investigate further. It was found that the bottom flange was not properly fastened to the piston and this impeded the motion and resulted in poor performance. This was rectified and the efficiency of the cooling improved. The vacuum on the injection side of the source was also poor leading to lower charge states. After these problems were rectified in the beginning of 2007, a wireless control system for operating the source in the middle of 2007 was implemented. The source was finally commissioned during the end of 2007.

Wireless control system

After experiences with other accelerators using fibre optic cables for source control especially in high voltage environments, using a wireless communication would appear to be better in terms of minimising the source downtime especially for running round-the-clock experiments. A wireless control system was developed based on MODBUS RTU on RS 485. Using 2.45 GHz radio modems, and PLC's for interlocking purposes, a

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MICROWAVE POWER SAVING AND REDUCED BREEMSTRAHLUNG EMISSION FOR A HIGH CHARGE STATE ION PRODUCTION IN AN ECRIS EQUIPPED WITH MD STRUCTURES*

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Abstract

Metal dielectric structures (MD), installed in the plasma chamber of the Frankfurt 14GHz electron cyclotron resonance ion source (ECRIS), have been used to significantly reduce the level of microwave power, necessary to create comparable ion intensities as for the standard operation of the Frankfurt ECRIS. The measurements indicate that the RF-power may be reduced by a factor of 2-3 to obtain the same output of high argon charge states as in the standard source with stainless steel plasma chamber. This reduced level of microwave power also leads to a much lower level of X-ray emission from the source.

INTRODUCTION

The performance of an electron cyclotron resonance ion source (ECRIS) may be expressed in terms of the „quality factor” $QF = n_e \cdot \tau_i$, where n_e is the density of the plasma electrons and τ_i , the ion dwell time in the plasma. Basically all methods and scaling prescriptions for the optimization of an ECRIS act on one or both of the above factors. One consequent approach is the continuous increase of the microwave power and frequency to enhance the density and energy of the plasma electrons. In modern constructions (e.g. 4th generation ECRIS) this usually goes along with a continuous increase of the plasma volumes, which now have several times the volumes used e.g. in the 14GHz sources of the second generation. Special effects like gas mixing, isotope effect or wall coating also base on the optimization of the above two factors. Approaching the 4th generation of ECRIS's now with microwave powers of tens of kW at frequencies as high as 28-30GHz, reveals unexpected technical problems which set serious constraints to the continually scaling of e.g. the frequency as suggested by the above formula. Only one of these limits is the massive heat load transferred by the Bremsstrahlung radiation into the plasma chamber walls and into the superconducting structure of the magnetic trap. Superconducting technology has become necessary to fulfill both, the resonance condition but also the need for very high mirror ratios for the effective electron confinement.

In this article we report on a method to significantly reduce this production of Bremsstrahlung radiation or alternatively to substantially improve the performance of existing sources of the 2nd and 3rd generation. This method is based on a development made at the Institute of Physics and Nuclear Engineering, Bucharest, Romania, ECRIS Plasma Physics and Techniques

and consists in the production of metal- dielectric (MD) structures (Al-Al₂O₃ transitions) by a special electrochemical treatment of pure aluminum plates. The structures are characterized by high yields of secondary electron emission under bombardment by charged particles (electrons and ions from the plasma), which serves to significantly enhance n_e by sending cold electrons to the plasma, when MD-layers are introduced as wall coating into the plasma chamber⁽²⁾. Additionally, facing the plasma as insulators, the MD structures substantially increase the ion dwell times (ion confinement) by blocking compensating wall currents, hence restoring the plasma ambipolarity. The degree of this restoration depends on the actual configuration of MD-coverage of the plasma chamber walls and can be almost complete even if only part of the chamber is covered by the MD structure⁽¹⁾.

In this way, MD structures allow operation of the source at lower working pressure and RF powers. The reduction of the working pressure is very important to minimize charge exchange and electron recombination in the plasma and in the extraction region. The MD-ECRIS gives much better results than using gas mixing⁽⁴⁾. It is an additional advantage of the use of MD structures that the extraction of distinctly different charge states (e.g. Ar⁵⁺, Ar¹⁰⁺, and Ar¹⁵⁺) from one source tuning is not excluded like in the case of gas mixing.

In the present experiment we focus on the possibility to utilize MD structures to extract essentially the same ion-beam intensities like in the standard ECRIS, however, at a strongly reduced level of RF power. This, of course, means also a significantly reduced level of emission of X-rays with important consequences for the lifetime of ECRIS components, for safety considerations and, quite generally, for the feasibility of improvements.

EXPERIMENTAL PROCEDURE

The experiment was performed at the 14 GHz IKF ECRIS of the Institut für Kernphysik, Frankfurt/Main, Germany (IKF). The plasma chamber of the source was equipped with two MD-structures of 1mm thickness. One structure (MD-liner) was installed in the stainless steel plasma chamber symmetrically with respect to the hexapole magnet for the radial plasma confinement. It covered the radial walls at a length of 150 mm (i.e. roughly 3/4 of the whole radial plasma chamber walls). The other structure (MD-electrode) covered the entire

OPTIMIZATION OF GASDYNAMIC ECR ION SOURCES

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Abstract

The current work is a continuation of the study of gasdynamic ECR ion sources (ReGIS). The main difference of these sources from classical Geller ECR ion sources is the use of the quasi-gasdynamic regime of plasma confinement in magnetic traps. A possibility of ion beam formation in REGIS with total current of 100 mA and higher was demonstrated in *. Such currents are attained due to small longitudinal lifetime in the quasi-gasdynamic regime of confinement. A drawback of ReGIS is low average ion charge. In the current work possible ways of increasing ion charge are demonstrated. Based on the model described in ** a magnetic trap is optimized and microwave radiation power required for producing a preset average charge is analyzed. The computations are compared with data of experiments. A variant of a magnetic trap and microwave pump designed to obtain pulsed beams of Ar+5 and Xe +15 ions with currents of tens of MA was proposed.

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HIGH INTENSITY HELIUM BEAM AT CEA/SACLAY

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Abstract

The Spiral 2 injector will be first built, installed and tested at CEA Saclay before its transfer to Caen. The RFQ has been designed to accelerate different particles: protons, deuterons and $q/A = 1/3$ heavy ions. The A-Phoenix ion source developed and tested at LPSC Grenoble will be directly transferred to Ganil. So to test the $q/A = 1/3$ ions acceleration with the RFQ built at Saclay, the light ion ECR source has been thought capable to produce 3He^+ ions. Moreover, high intensity 3He ion beam accelerator applications are possible in other domains such as astrophysics or neutrino factory. The SILHI source has been fed with natural helium (4He) gas for several hours. Beam intensity as high as 20 mA (870 Am-2 through 4.8 mm diameter aperture) has been extracted from the source with 85 keV energy. Extensive experiments will be done with the 9 mm diameter nominal plasma electrode to characterize the He^+ extracted beam. With the same extracted beam density, total beam intensity in the range of 100 mA seems reachable. In addition, simulations of the beam extraction will be done to estimate possible electrode modifications in order to improve the beam transport.

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MODELING ECRIS PLASMA USING 2D GEM* (GENERAL ECRIS MODEL)

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Abstract

The GEM 1D code [1] is developed by FAR-TECH, Inc. to model the plasmas in ECRIS devices using experimental knobs such as the magnetic field, rf power and frequency, and the geometry of the device. The code models EDF (electron distribution function) by solving Fokker-Planck equation, ions as fluid and neutrals by particle balancing. It has been extended to include 2D (axial and radial) spatial features such as 2D ECR heating and ion radial diffusion. The convergence and consistency of the code have been studied. It is parallelized using the MPI technique to boost the calculation speed. Results of the GEM 2D simulation and comparisons of GEM 2D with GEM 1D results and experimental measurements will be presented. The predicted hollow profile of ECRIS plasma is consistent with experimental observations.

INTRODUCTION

GEM 2D is extended from an advanced ECRIS modeling code, GEM 1D, which has been developed by FAR-TECH to predict axial steady-state ECRIS plasma profiles and charge state distribution (CSD) of output beam self-consistently using experimental knobs as input, such as rf power, rf frequency, gas pressure, and device configurations. GEM 1D calculates non-Maxwellian EDF (electron distribution function) of hot electrons using a bounce-averaged Fokker-Planck code [2] and solves the flow of the cold ions using 1D ion fluid code. It has obtained some numerical results consistent with experiments. However, the further applications of GEM to beam capture [3] and beam extraction simulation require GEM to be extended to 2D to acquire both axial and radial profiles of the plasma parameters. Also, 2D models can simulate the complicate magnetic field in ECRIS and ECR heating zone more accurately. This paper presents the modeling theories of GEM 2D and the results of the simulation of a typical ECRIS device, ECR-I in ANL [4]. The comparisons with GEM 1D results and experimental data will also be presented and discussed.

DESCRIPTION OF GEM 2D MODELS

GEM-1D simulates the dynamics of an ECRIS plasma along the field lines but assumes the plasma is uniform in the radial direction. GEM 2D is extended from GEM 1D by adding a radial dimension to GEM 1D's numerical models. It can predict ECRIS plasma in both radial and axial directions by a combination of 2D physical models including 2D magnetic field and ECR heating modeling, bounce-averaged Fokker-Planck EDF modeling and 2D ion fluid modeling. In the following discussion, we will

use ECR-I at ANL as the standard device for the simulation. The typical operation parameters are listed in table 1.

Table 1: Operating parameters for ECR-I

Parameters	Typical Values
Plasma	Oxygen
Length	29 cm
Radius	4 cm
Gas pressure	1.2e-7 Torr
rf power	323W
rf frequency	10 GHz
B field ratio	4.5 and 3

2D modeling of the Magnetic field and ECR resonance surface

The magnetic field on ECR-I is a typical minimum-B structure which is composed by a mirror field and a hexapole field. The full 3D ECR resonance surface is a football shape structure [5] which depends on z , r , θ in cylindrical coordinate. For 2D simulations, the magnetic field is azimuthally averaged to eliminate θ dependence. The radial grids are tied onto the flux surfaces that are evenly distributed on the mid-plane and then extended to the whole chamber along the field lines (Fig 1a). The axial profiles of the field strength on the field flux surfaces are plotted in Fig. 1b. Note that the field strength increases with radius. This is because while we average over the hexapole variation in the direction of magnetic field, the magnitude of the hexapole field strength is still included in GEM-2D. This allows a proper calculation of the ECR resonance zone.

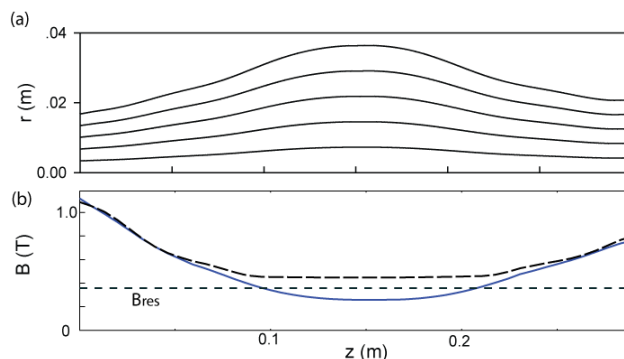


Figure 1: a) Radial grids that are tied onto the magnetic

WALL DISTRIBUTION OF IONS EXTERNALLY INJECTED FOR CHARGE –BREEDING IN ECRIS

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Abstract

We have investigated the ion loss distribution in an electron cyclotron resonance (ECR) ion source. The ions, radioactive and singly charged ^{111}In , were injected into the ECR ion source (ECRIS) for breeding their charge states at the Tokai Radioactive Ion Accelerator Complex (TRIAC). The residual radioactivity on the wall of the ECR plasma chamber of the source was measured, giving a two-dimensional distribution of the ions failed to be re-extracted during charge breeding. The distribution was decomposed, according to azimuthal symmetry, into three components, asymmetric, 120-degree symmetric, and isotropic ones, whose origins were quantitatively discussed for clarifying ion-losses in the course of charge breeding in ECRIS.

INTRODUCTION

The radioactive ion beam (RIB) facility TRIAC [1] has been jointly constructed under the collaboration between KEK and JAEA and operated for experiments since November, 2005. The facility is based on an isotope-separator on-line (ISOL) technique. The radioactive nuclei are produced by means of proton-induced fission of ^{238}U or heavy-ion reactions with the primary beams from the JAEA tandem accelerator. The produced radioactive nuclei are singly ionized and mass-separated by the JAEA-ISOL [2]. They are fed to the 18 GHz ECR ion source for charge breeding (KEKCB), where the singly charged ions are converted to multi-charged ions with the mass-to-charge ratio (A/q) of around 7. The charge-bred radioactive ions are extracted again and fed to the post-accelerator [3] for further acceleration.

Several RI beams as well as stable ion beams have been successfully charge-bred to $A/q \sim 7$. Recently, we have accelerated to 178keV/A the medium-mass charge-bred radioisotopes of Kr and In. The acceleration of RI beams charge-bred by ECRIS was the first time over the world. Details on the charge breeding experiments for the KEKCB can be found elsewhere [4].

In charge breeding experiments using KEKCB at TRIAC, we observed large differences in charge breeding gaseous and non-gaseous ion species, i.e. in the injection optics and the resultant charge breeding efficiencies [5]. In order to understand the differences we investigated

how the ions, which were externally injected to the ECR plasma of KEKCB for breeding their charge states but failed to be re-extracted, were distributed on the wall (surface) of the plasma chamber.

EXPERIMENT

For the measurement of ion distribution on the wall of the plasma chamber, we injected into KEKCB and charge-bred radioactive singly-charged ^{111}In ions with a half-life of 2.8 days. After charge breeding, we measured the distribution of the ^{111}In by detecting the residual activity on the wall of the chamber. We here just introduce the experiments for measuring the residual activity since detailed experimental procedures for charge breeding can be found elsewhere [5].

As shown in Figure 1, after charge breeding, we removed the inner tube (a 350mm-long cylindrical tube with a diameter of 76mm) from the plasma chamber and measured two γ -rays emitted from ^{111}In (after beta-decay to ^{111}Cd) deposited on the wall of the inner tube by a Ge(Li) detector. In front of the Ge(Li) detector, a 20mm-thick lead shield with a hole of 20 mm in diameter was placed as a collimator. In addition, we placed a cylindrical lead block inside the inner tube to prevent γ rays from the opposite side of the tube. By changing the azimuthal angle and longitudinal position on the inner tube, around and along the axis of injection and extraction in a cylindrical coordinate, the measurements were performed at several tens of points on the tube. (Lower part of Figure 1 and Figure 2)

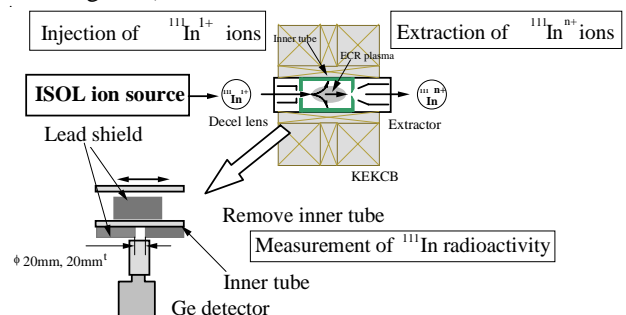


Figure 1: Experimental set-up for charge breeding and measuring the residual radioactivity of ^{111}In on the surface of the inner tube.

NEW SPINDLE CUSP ZERO-B FIELD FOR ECR ION AND PLASMA SOURCES

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Abstract

A traditional ECR ion source (ECRIS) or plasma source use magnetic min-B field for plasma containment and energizing electrons based on the principle of the ECR process. A cusp field produces modified min-B or zero-B field. A new cusp magnetic field (NCMF) configuration with symmetric field at the cusp positions, corresponding to a given RF frequency confirming the standard model of ECR Ion Source, is simulated to contain large volume high density plasma for producing beam for low or high charged ion. The magnetic field increases along and across the magnetic lines of force starting from zero at the centre and maximum value at the periphery. The cusp field with convex lines of force towards the plasma is ideal for confining it as drift of the particles take place either in the azimuth or towards the low field region at the centre. Non-adiabatic behaviour of electrons at the centre can be either tackled by gas-dynamic confinement at high density or exploited to generate more secondary electrons. Confinement feature of the field is assessed by electron simulation. A new technically viable cusp ECRIS has a bright prospect ahead as it is simple, stable, compact and cost-effective compared to the traditional ECRIS.

INTRODUCTION

Geller's group pioneered constructing ECRIS like MAFIOS and its variants [1-3] at Grenoble in 1970's and later. The ECR plasma and its property have been described well by him [4] in terms of confinement of plasma, ECR heating and techniques to improve working of an ECRIS. A minimum-B field was produced employing axial field and radial magnetic field for confining plasma quiescently. The cold electrons with some initial kinetic energy gyrate about a magnetic line of force, that is magnetic line of force (MLF) with f_G (gyro-frequency) $\propto B$ (magnetic field). At resonance condition, $f_G \approx f_{RF}$, electrons get energy from the RF wave.

The main motivating factors of the present study are i) to study the possibility of more confinement of electrons and ii) to construct a simple, compact and cost-effective ECRIS to alleviate some of the problems of traditional ECRIS like complicated magnet system, small plasma volume, limited injection and extraction regions etc.

Earlier the classical CMF was used to design an ECR ion source (ECRIS) [5] because of its inherent plasma confining nature. But it had a little success because of huge loss of plasma at the cusp (mainly ring cusp, RC) positions owing to insufficient and asymmetric magnetic field. The CMF has been reconfigured here adopting a simple, novel and cost-effective technique to shrink the loss area [6]. It helps to achieve high value of $n_e \tau_i$ for

generating intense HCI beam. The variation of plasma pressure, $P_{par} = n_e k_B T_e$, along the MLF depends on the magnetic pressure, $P_B = B^2 / (2\mu_0)$. The gravitation-like inward force because of the curvature of MLF's produces a MHD-stable configuration.

DESIGN SCHEME TO PRODUCE NCMF

A classical CMF can be produced using either a pair of coaxial coils carrying opposite current or a single ring of radially magnetized permanent magnet. The field does not rise along the radius at the mid-plane as rapidly as along the central axis. But rise in field in both the direction in new improved CMF (NCMF), on the average, is equal. The field is zero at the centre and is weak in a small region around it. The deduced vector potential in eq. (1) represents the NCMF and can be used to visualize the field line distribution and calculate the field components in the cylindrical co-ordinates.

$$A_\theta(r,z) = g r z + b r z^3 + c r^3 z + C \quad (1)$$

$$B_r(r,z) = -g r - 3b r z^2 - c r^3 \quad (2)$$

$$B_z(r,z) = 2g z + 2b z^3 + 4c r^2 z \quad (3)$$

Where constants $g = (11B_0)/(14L)$, $b = (-2B_0)/(7L^3)$, $c = -(3/4)b$ and $C=0$ (say). A NCMF of any dimension, L and maximum field, B_0 can be evaluated. The absolute NCMF for $B_0=40$ kG and $L=16$ cm is plotted in Fig. 1 using eqs. (2) and (3).

The magnet geometry consists of yoke, end-plugs and centre disk of highly permeable material in addition to coil pair or PM ring to generate NCMF. There is no limitation to magnet size and field strength in case of using coils to produce NCMF. Application of PM discards the power supplies, major cooling system etc. It can be used to produce NCMF for high-B mode cusp ECRIS of as high as 18 GHz RF frequency [7]. The calculated field can be realized feeding proper geometry similar to Fig. 2 in a field computing code [8, 9].

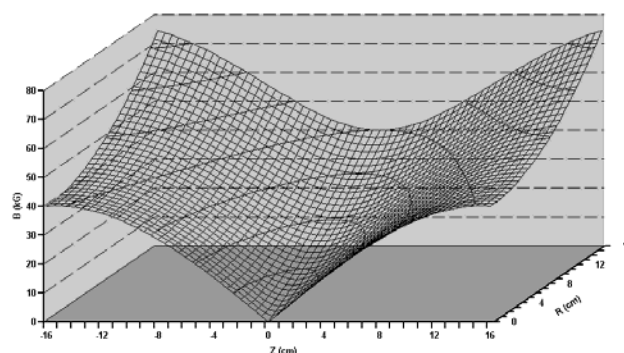


Figure 1: Plot of absolute field due to NCMF

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HIGH-RESOLUTION BEAM-PROFILE MEASUREMENTS WITH A FARADAY-CUP ARRAY

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Abstract

The division of extraterrestrial physics at the University of Kiel is establishing a solar wind and supra-thermal particle laboratory which will be used mainly for three reasons: the calibration of space instruments dedicated to measure the solar wind and/or supra-thermal particles, the research of space weathering of dust particles and to study fundamental plasma physics. The laboratory will be able to generate a well-defined and highly charged ion beam at energies from 1 to 450keV/q. Both, calibration of space instruments and dust particle bombardment, need accurate values for the main beam parameters such as current, position, and profile. While the total current is measured by a single Faraday cup (FC), position and profile of the ion beam are acquired by an array of 44 tiny (0.3 mm diameter) Faraday-Cups (FCA) moving through the beam. This allows high resolution of beam current and position, as well as high durability since beam-currents from several hundred pA to a few mA and an incident beam power up to 40W are expected. Here, we present the basics of the detectors hard- and software design in addition to some first results of measurements.

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CONCEPTUAL DESIGN OF A 56 GHZ ECR ION SOURCE MAGNET STRUCTURE

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Abstract

The development of a 4th Generation ECR ion source, which could operate at 56 GHz twice that of 3rd Generation sources, presents several technical challenges.* The greatest challenge is to produce a magnet structure with sufficient field strength to adequately confine the plasma. A design study is underway to determine the feasibility and engineering issues associated with a magnet structure that could produce 8 T at injection, 6 T at extraction and 4 T radially. The initial analysis shows that peak fields in the superconductor would be roughly 12 to 14 T and this is above B_{c2} for NbTi but less than B_{c2} for Nb₃Sn. We are evaluating two possible designs; the classic design, where the sextupole coils are placed inside the solenoids and the inverted design where the sextupole is placed outside the solenoid magnets. The preliminary results of the ongoing study are being presented and discussed.

**PAPER NOT
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GASDYNAMIC ECR SOURCES OF MULTICHARGED IONS

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Abstract

A new type of pulsed sources of multicharged ions (MCI), namely, a gasdynamic ECR source is proposed. Its main difference from the classical ECR ion sources is a different, quasi-gasdynamic regime of plasma confinement in a magnetic trap. Plasma was produced and heated by radiation of a pulsed gyrotrons with the frequencies of 37.5 and 75 GHz in magnetic traps of various configurations. Plasma confinement in quasi-gasdynamic regime under such conditions was studied. It was demonstrated that with such a confinement regime it is possible to generate multicharged ions and create intense (more than 1 A/cm²) ion fluxes through the trap plugs. Creation of intense plasma fluxes allows one to extract high-current MCI beams of high brightness. Transverse homogeneity of a plasma flux makes it possible to use a multi-aperture extraction system for the formation of broad intense MCI beams. MCI beams with current up to 150 mA and normalized emittance lower than 1 π -mm-mrad were produced. Comparison of results of calculations and data of experiments shows that they are in a good agreement, which allows us to predict creation of a new type of ECR source.

INTRODUCTION

The recent experimental and theoretical research carried out at the Institute of Applied Physics (IAP RAS, Nizhniy Novgorod, Russia) resulted in development of a new type of pulsed ECR sources of multicharged ions – gasdynamic ECR ion sources (ReGIS). It will be demonstrated that such sources are capable of generating high-current and high-brightness ion beams with a moderate ion charge.

The ideas underlying development of such sources were borrowed from the field of classical ECR sources of multicharged ions (we will refer to them as to the Geller ECR ion sources (GECRIS)) [1], as well as from investigations of fusion mirror traps (FMT) [2]. The ReGISs differ from the Geller sources by the mechanism of plasma confinement in a magnetic trap. It is the quasi-gasdynamic mechanism [3] similar to that used in FMT. The principal distinction from FMT is strong nonequilibrium of confined plasma (the temperature of the electrons is much higher than the temperature of the ions), which is typical of GECRIS.

REGIS PRINCIPALS

A possibility of realizing two different (classical and quasi-gasdynamic) regimes of confinement of nonequilibrium plasma in open magnetic traps at

powerful ECR heating by millimeter wave radiation was demonstrated in [3]. The great majority of modern ECR sources of MCI operates in the regime of classical plasma confinement in a trap. Ion confinement in this case is determined by ambipolar potential distribution in the trap [4]. In a mirror trap, electrons get into a loss cone either as a result of collisions with ions or with each other, or due to quasi-linear diffusion in velocity space due to intense ECR heating [5]. With increasing plasma density the transition from the classical to the quasi-gasdynamic regime of plasma confinement was observed in experiments [3]. The mechanism of plasma confinement in a trap changes for the values of the plasma such that the velocity at which the loss cone is filled in by electrons in velocity space is higher than the velocity of plasma escape from the trap. The loss cone is filled in, the electrons are confined in the trap by ambipolar potential, and plasma losses are determined by gasdynamic ejection of ions. This regime of confinement of nonequilibrium plasma with filled loss cone is called a quasi-gasdynamic regime. The transition to this regime of plasma confinement is inevitable when its density is increased [6]. The plane of plasma parameters divided into characteristic regions for the two regimes of plasma confinement with characteristic regions for classical and gasdynamic ECR ion sources is presented in fig. 1.

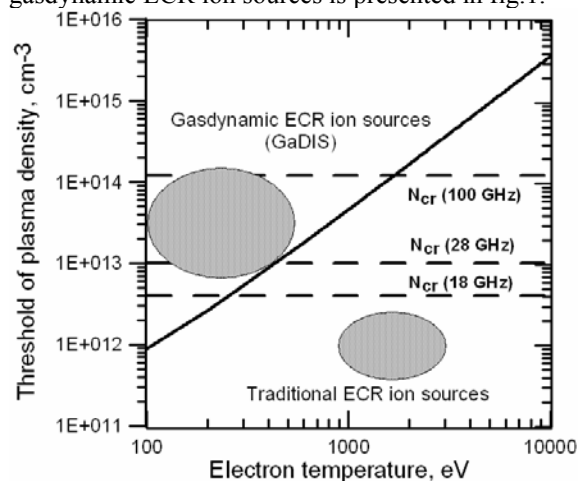


Fig. 1. The border between the two regimes of plasma confinement.

In quasi-gasdynamic regime plasma life time can be roughly determined as $\tau = \frac{R \cdot L}{2 \cdot V_s}$, where R is the mirror

ratio and L is the length of the trap and V_s is the ion-sound velocity. Thus, in the quasi-gasdynamic regime plasma lifetime is determined only by ion-sound velocity and

A 60 GHZ ELECTRON CYCLOTRON RESONANCE ION SOURCE FOR PULSED RADIOACTIVE ION BEAM PRODUCTION

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Abstract

The efficient production of short pulses of radioactive ion beams is a key point of the long term CERN beta-beam project. A strong R&D effort in the field of ion sources is required to reach this challenging objective. A summary of the pulsed beta-beam ion source specification is proposed. A discussion follows on the ion source technologies suitable for this demanding project. The proposed solution foreseen (a 60 GHz ECRIS), uses a cusp magnetic configuration based on water cooled copper coils. The 3D magnetic field structure, along with the mechanical design status is presented. An experimental test with an aluminium prototype shows a good agreement with simulation and validates the design.

THE BETA-BEAM PROJECT

The neutrino physicist community is currently discussing the next generation neutrino beam factory. Nowadays, several projects are still under competition. The Beta-Beam is a project studied by the CERN [1]. The baseline scenario is to generate, ionize, and then accelerate Radioactive Ion Beams (RIB) $\sim 5 \times 10^{13}/s$ ^{18}Ne or ^6He to high energies (with a Lorentz factor $\gamma > 100$). These nuclei which undergo a β decay are stored in a long race track decay ring to produce intense neutrino beams (see Figure 1, blue arrows). The goal of these beams is to study the neutrino oscillations properties and give constraints on the mixing angle θ_{13} .

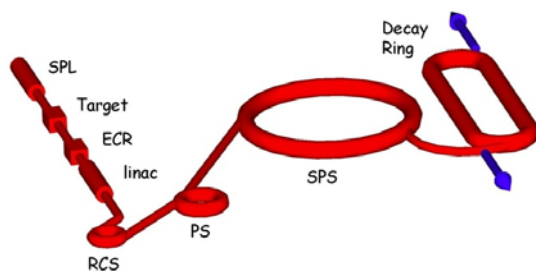


Figure 1: Baseline scenario of the beta-beam accelerator.

The radioactive elements are expected to be produced in the future EURISOL facility. The primary beam, delivered by a proton LINAC, induces nuclear reactions in a set of target stations. Radioactive Gases effuse from

the target to the ion source through a high conductance cooled pipe to filter gas and condensable contaminants. The ion source should bunch the beam in order to inject ions as efficiently as possible in the 3 synchrotrons rings included in the project.

SPECIFICATIONS FOR THE PULSED ION SOURCE

Pulsed Ion beam Current specifications

Consider an ideal source able to ionize the RIB of interest with 100% efficiency. If the ion extraction is performed in continuous working (CW) operation, the $5 \times 10^{13}/s$ ^{18}Ne flux would result in a 8 μA extracted CW beam. Such ionic intensity is very easy to extract from a classical Electron Cyclotron Resonance Ion Source (ECRIS). The Beta-Beams pulse width at the source extraction is expected to be $< 50 \mu\text{s}$, with a frequency repetition rate $f=1/T$ ranging within the 10 to 25 Hz range. The highest peak current, derived from these values is $\sim 16 \text{ pA}$. Moreover, other gases will be extracted from the target and ionized in the source. Thus, an unknown number of contaminants will be added to the peak current.

High radioactivity environment constraints

The ^{18}Ne and ^6He half lives $T_{1/2}$ are respectively 1.67s and 0.807s. The time for a radioactive atom to exit the target and reach a classical ion source located several meters away already approximately reduces the initial atoms flux by a factor 0.4. A key parameter for the project is to design an efficient ion source located as close as possible to the target in order to minimize the radioactive decay losses. Moreover, the source should hold radiation damages for a long time (~ 1 month). Consequently, the ion source mechanical parts shall not contain permanent magnets, plastic gaskets; even radiation damage on glass fibre may cause problems. Due to the high radiation level, the maintenance of the ion source will not be possible and its cost per unit will have to be moderate, since it may be necessary to change it periodically.

MICROWAVE SOURCES FOR 3-rd AND 4-th GENERATIONS OF ECRIS

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Abstract

Recent results in the development of the electron cyclotron resonance ion sources (ECRIS) have proven the potential of the operating frequency for the production of high-intensity multicharge ion beams. The next ambitious steps are discussed today which include further increase in frequency up to 60 GHz, use of broadband microwave sources, and two- or three-frequency heating. Microwave sources capable of meeting the needs of the next generation of ECRIS are considered here based on many-year experience of the Institute of Applied Physics in the design and fabrication of high-power millimeter-wave equipment and achievements of other research groups. Different varieties of gyro-devices producing broadband radiation (multi-frequency or fast-swept in time) with CW or average power of order of 10-15 kW and the center frequency within the range 24-60 GHz are discussed.

INTRODUCTION

The progress in the development as well as the domain of operating parameters for any microwave power source are strongly stimulated and dictated by the applications. For example, gyrotrons with frequencies of 140 GHz and 170 GHz, and CW power of megawatt level have been developed for thermonuclear fusion installations (tokamaks, stellarators); amplifiers having broad frequency band, pulsed power of order of 100 kW and center frequencies lying in the transparency windows of the atmosphere (e.g. 35 GHz and 94 GHz) were worked out for radars. The electron cyclotron resonance ion sources are a relatively new line of application based on the use of moderate microwave power (on the order 10 kW) at frequencies of tens GHz. A significant improvement of ECRIS performance parameters upon a transition to the frequency of 28 GHz has been prove recently by experimental results obtained at several facilities. According to current concepts, further progress in ECRIS operating characteristics can be achieved using microwave sources of higher frequency and such additional options as fast frequency sweeping (with a sweep time less than 10^{-4} s within a frequency band of few percents) or multi-frequency generation or generation of CW signal with a broadband spectrum [1, 2].

It is generally recognized that the only microwave sources capable of delivering CW or average power on the order of 10 kW in the frequency range of tens GHz are vacuum electron devices based on the cyclotron resonance maser (CRM) instability and using low-relativistic electron beams (particle energy of about tens keV), often called gyro-devices. The operation of these high-power coherent radiation sources (gyro-devices) is based on the interaction of the electrons gyrating in the external magnetic field with a fast electromagnetic wave under the cyclotron resonance condition: $\omega - h\nu_{\parallel} \approx n\omega_H$,

where ω and h are the frequency and the axial wavenumber of the wave, v_{\parallel} and ω_H are the axial velocity and the cyclotron frequency of the electrons, n is the cyclotron harmonic number. The interaction of electrons with fast electromagnetic waves propagating in the cavities and waveguides with smooth metal walls is the distinguishing feature of gyro-devices as opposed to conventional slow-wave electron devices. Since no periodic structure is employed, enhanced power handling capability exists in gyro-devices.

Formally, the orbital bunching of gyrating relativistic electrons has much in common with bunching of linear electron beams being used in ordinary ("O" type) devices. Therefore each CRM has its "O" type analog: monotron, klystron, travelling-wave-tube (TWT), backward-wave oscillator (BWO). The differences in operation principles of these gyro-devices can be seen from the dispersion diagram shown in Fig. 1. This diagram will be discussed later in more detail as applied to each type of gyro-device.

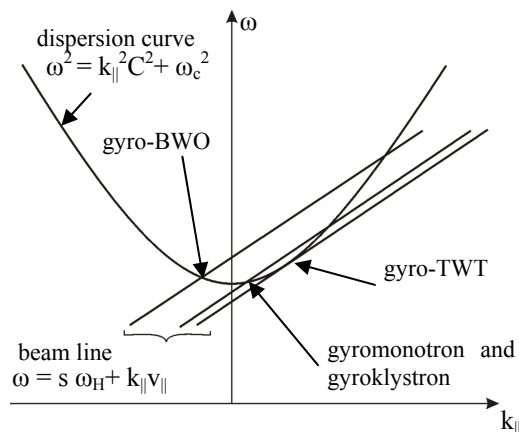


Figure 1: Dispersion diagram showing the operating point for gyro-devices: ω_H – electron cyclotron frequency, ω_c – the cutoff frequency of the waveguide mode, k_{\parallel} – axial wave number, v_{\parallel} – axial velocity of electron beam.

A review of the experimental results obtained during last two decades shows that gyro-devices are capable of meeting the requirements imposed by the next generation of ECRIS. Here, the general concepts of various gyro-devices are briefly introduced. Examples of last experimental achievements obtained in application-driven developments are presented to illustrate the feasibility of custom-made gyro-device based systems for ECRIS.

GYROTRON (gyro-MONOTRON)

The feasibility of implementing fixed-frequency gyrotrons for a customer-ordered frequency and power of 10-15 kW in both CW and pulse regimes is beyond question today and gyrotrons operating at frequencies of 28, 37 and 75 GHz are already used in some ECRIS

ON THE OBSERVATION OF STANDING WAVES IN CYLINDRICAL CAVITIES FILLED BY MICROWAVE DISCHARGE PLASMAS*

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Abstract

A set of measurements has been carried out at INFN-LNS on a plasma reactor used for environmental applications with the aim to characterize it in terms of possible excited resonant modes inside the cavity with and without plasma.

The results have put in evidence that resonant modes are excited inside the cavity and standing waves are formed even in presence of a dense plasma. The measurement of the eigen-frequency shift, which occurs after the plasma ignition, has been carried out, for several values of pressure and power.

The changes in plasma shape, density and electron temperature have been also monitored for different operating conditions by means of a Langmuir Probe.

Such measurements are also relevant for the ECR Ion Sources, as they confirm that the variation of their performances with the frequency can be explained by considering that resonant modes are excited inside the plasma chamber even in presence of a dense plasma.

INTRODUCTION

Many experiments in the last years have shown that significant improvements of ECRIS performances are obtainable by means of a multi-frequency heating of ECR plasmas. On the other hand, it has been demonstrated that a substantial increase of the extracted currents is achieved also by slightly varying the microwave frequency even in the case of single frequency heating [1,2]. This “frequency tuning effect” has been verified experimentally for different ion sources, and in particular some tests carried out on a CAPRICE source at the GSI testbench by sweeping the microwaves in a range of ± 40 MHz around 14.5 GHz, have also shown a dependence of the beam intensity distribution from the microwave frequency feeding the plasma chamber [2].

This means that an improvement of the coupling and of the heating phenomena is achieved by properly tuning the frequency of the microwaves. At the same time, from the observations in [2] we can also state that the beam formation process and the beam shape are strongly affected from the frequency variations.

The explanation of these results is strictly linked to the electromagnetic field pattern inside the chamber: in particular, the ECRH and the ionization process change with the electromagnetic field distribution and with its value over the resonance surface. Such distribution cannot be simply determined even supposing the plasma

chamber as a cylindrical cavity air filled. In fact, the microwave feeding wavelength is usually much lower with respect to the plasma chamber dimensions; therefore the first resonant frequency of the plasma chamber in vacuum conditions is very far from the operating one (e.g.: for the SERSE source the first resonant frequency is at 1.39 GHz, while the operating frequency is within the 14-18 GHz range). Consequently, the electromagnetic field pattern at the operating frequency is the result of the superposition of the different modes excited in the chamber, each one weighted by its coupling factor.

When the plasma is triggered its presence changes the electromagnetic properties of the whole structure; the previous observations suggest that an electromagnetic modal structure is present in the source even in presence of plasma. In this case, a different electromagnetic field pattern can be produced if the frequency is slightly changed, determining a different efficiency of the plasma heating and of the ionization process [3].

In order to study the evolution of the modes in the plasma chamber when the plasma is created, we exploited a plasma reactor in use at LNS for environmental purposes. This choice has the great advantage with respect to an ECR ion source to have different ports for diagnostics and also to have the possibility to monitor the plasma properties by means of a Langmuir probe (LP).

PLASMA REACTOR DESCRIPTION

The plasma reactor operating at LNS is based on the same physics principles of the Microwave Discharge Ion Sources, that generally are used for industrial applications or as proton sources in nuclear physics. The plasma chamber is a stainless steel cylinder 268.2 mm long, with a radius of 68.5 mm. A magnetic system which consists of three NdFeB permanent magnets rings generates an off-resonance magnetic field along the plasma chamber axis. In the injection side the flanges for the pumping and for the gas injection are located together with a WR284 rectangular waveguide operating in the TE₁₀ dominant mode and placed on the cavity axis. In the opposite side DN 40 and DN 25 flanges are used to connect the plasma diagnostics devices such as: mass spectrometer, optical window (to be used for plasma observation and for optical spectroscopy), microwave probes and the Langmuir probe (see figure 1). The microwaves are generated by a Magnetron operating at 2.45 GHz with a 300 W cw of maximum power. A rotative pump is used for vacuum (pressures in the order of a few 10^{-2} mbar are usually obtained).

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Broadband Excitation of ECR Plasmas*

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Abstract

Scientific Solutions developed an rf source capable of producing a variety of rf spectra for excitation of ECR plasmas at 2.45, 6.5, 14.5, 18.0 and 28.0 GHz. This device replaces the crystal oscillator in the rf chain and is essentially a software-defined radio transmitter that allows the user to select from a variety of different rf spectral patterns via an Ethernet link. Two specific patterns were chosen for our initial series of tests: 1) a simultaneous multimode pattern comprised of n rf-modes within a specified bandwidth and 2) a “chirp” spectral pattern comprised of n discrete frequencies where the chirp bandwidth, slew direction, and slew rate are user-selectable. In either case “ n ” is a user-defined value between 1 and 1024. This paper describes the design of the rf circuit and its theory of operation. Initial results of our tests with the 6.4 and 14.5 GHz ECR sources at Texas A&M University and with the AECR-U at the Lawrence Berkeley National Laboratory are also presented.

BACKGROUND

ECR sources depend on coupling energy into plasma electrons via the electron-cyclotron resonance. Plasma electrons transiting the resonance region inside the source absorb energy from the radio-frequency field. The change in electron energy is determined by the magnitude of the rf field in the resonance zone integrated over the time required to transit the zone. The effective width of the resonance zone is derived from the gradient of the magnetic field (dB/dz) and the bandwidth of the rf energy. Therefore to increase the volume of the resonance zone, we need to decrease the field gradient or increase the rf bandwidth. The question addressed here is: given a constant field gradient, which is more efficient in transferring rf energy to plasma electrons: 1) high peak rf power with a narrow resonance zone, or 2) lower peak power with a wider zone?

Kawai et. al. reported on experiments using an rf noise source to increase the rf bandwidth.[1] These experiments showed marginal improvement of ion current in a “plateau” style ECR source, but did show enhanced operational stability compared with single-frequency excitation. More recent experiments with a minimum-B

*This material is based upon work supported by the U.S. Department of Energy under Award Number DE-FG02-04ER84166. The views and opinions of authors

expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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configuration ECR source [2] demonstrated significant benefits of broadband excitation in producing Ar^{11+} ions with 400 W of rf power.

A possible reason for the lack of improved ion current in the first case is that noise sources have no coherence between adjacent frequency “bins.” Therefore an electron transiting one frequency bin has a 50% probability of encountering the opposite phase in the adjacent bin, thereby decelerating the electron instead of continuing to accelerate it. Generating an rf spectrum in a coherent manner populates adjacent frequency bins with phase-related rf energy. Hence a modulated rf source may provide just the coherence needed to improve the rf coupling efficiency. The trick lies in discovering the optimal modulation scheme(s).

RF MODULATOR AND KLYSTRON DRIVER CIRCUIT

To investigate broadband radio frequency (rf) excitation of ECR plasmas, we utilized a software-defined radio transmitter (RF Injection Device or RID) originally developed for another application. This device, created to automatically analyze resonant frequency spectra between 100 MHz and 1 GHz, was modified to produce a variety of user-selectable spectra in the 1-2 GHz band. The baseband rf signal from the modified RID is passed through an Analog Devices AD8349 quadrature modulator that provides complete control of the rf waveform within a 20 MHz bandwidth centered around the operating frequency. The output waveform of the AD8349 is frequency multiplied into the range of interest using a variety of multiplier chains and amplifier circuits as illustrated in figure 1. The exact configuration of the multiplier chain depends on the target frequency range. The AD8349 actually supports much wider bandwidth. However we restricted the baseband frequency range to 20 MHz in order to keep the frequency-multiplied bandwidth within a reasonable range so as not to stress the klystron amplifiers typically used for ECR heating.

The operation of the RID is controlled by an embedded Xilinx processor connected via Ethernet to the user’s computer running the interface control panel. Because the frequency synthesis is under complete software control, we can easily adjust the operating frequency, the bandwidth, and fill factor (i.e. the mode spacing) up to the limits of the AD8349.

As shown in figure 1, the output spectrum of the RID is frequency multiplied in a variety of circuits whose configuration depends on the desired operating frequency (figure 1). Note that the operating bandwidth of the

THREE-DIMENSIONAL SIMULATION OF ELECTRONS AND IONS IN ECRIS

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Abstract

Electron-Cyclotron-Resonance-(ECR)-Heating (ECRH) is known to produce non-equilibrium plasmas with the total non-Maxwellian energy in the electrons while the ions stay below 1 eV. Theories based on Maxwell distributions are thus unable to correctly describe ECR-Ion Sources (ECRIS). Particle In Cell (PIC)-techniques are feasible only with significant approximations in the extremely complicated magnetic structure of an ECRIS. This is the reason to concentrate all efforts on the calculation of various electron distributions in an ECRIS taking into account all three-dimensional static fields, dynamic microwave fields, and all collisions of the electrons. To this end the Boris-algorithm is introduced which is shown to be very efficient and precise for all conditions in an ECRIS including the resonance transitions. The electron distributions clearly show the low efficiency of ECRH in a standard ECRIS with a central minimum of the axial magnetic field compared to the high ECRH-efficiency in a plateau-ECRIS with a flat central minimum. A non-relativistic version of the code is used to demonstrate the positive effects of ion-CRH on the confinement of the ions with far reaching consequences.

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RECEIVED**

TOWARDS KINETIC MODELING OF ION TRANSPORT IN AN ECRIS PLASMA

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Abstract

Next generation heavy ion beam accelerators require intense, high charge state ion currents of exotic materials. ECRIS devices can generate these currents however detailed kinetic simulations are needed to optimize the loading of these materials into the plasma. Full Particle-In-Cell simulations of the plasma are highly challenging due to the large discrepancy between length and time scales. However separation of time-scales provides a means of making progress. Electrostatic simulations on ion timescales, though demanding, are capable of modeling the kinetic behavior of the ions. Similarly, electromagnetic simulations on electron time scales can provide the non-thermal kinetic properties of the electron population. In this work, we treat the electrons as a simplified fluid for the longer time-scale evolution of the ions. We characterize and diagnose the electron distribution for use in the ion simulations. Ionization and recombination processes are then modeled in a hybrid fluid-electron / kinetic-ion formulation using the prescribed electron distribution as one of the interaction partners. Progress in the electrostatic modeling of the ion dynamics is also presented.

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RECEIVED**

STATUS OF FAR-TECH'S ELECTRON-CYCLOTRON-RESONANCE CHARGE-BREEDER SIMULATION TOOLSET; MCBC GEM AND IONEX *

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Abstract

The status of FAR-TECH's electron-cyclotron-resonance charge-breeder simulation toolset (MCBC, GEM and IonEx) is described. FAR-TECH, Inc. has been building a suite of comprehensive numerical tools for end-to-end Electron Cyclotron Resonance (ECR) charge breeding (CB) modeling [1]. They consist of the Monte Carlo Beam Capture (MCBC) code [2,3], the Generalized ECRIS Modeling (GEM) code [3,4], and the Ion Extraction (IonEx) code [6,7]. We present the main progresses since our last status presentation [1]. This progress includes upgrades in GEM to 2D and IonEx to 3D.

INTRODUCTION

In ECR "charge breeders" a beam of low (+1 or +2) charged ions is injected into an ECRIS plasma and charge bred to produce higher charge-state ions. The charge breeders are particularly useful for radioactive ion beam (RIB) production. Future large, expensive ion sources will require modeling and diagnostics for optimal and efficient design.

FAR-TECH, Inc. has been building a suite of comprehensive numerical tools for end-to-end Electron Cyclotron Resonance (ECR) Charge Breeder (CB) Ion Source (IS) modeling [1]. The tool consists of three modules, each representing distinctive physical processes. First, the Monte Carlo Beam Capture (MCBC) code [2,3] traces injected ions until they are captured by being slowed down to a speed less than the background ion thermal speed, lost to the walls, or pass through the extraction holes. Second, the Generalized ECRIS Modeling (GEM) code [4,5] calculates the charge state distribution (CSD) of an ECR ion source plasma including the captured injected beam ions. Finally, the Ion Extraction (IonEx) code [6,7] calculates extracted ion trajectories utilizing the phase space ion distributions obtained from GEM. The link between MCBC and GEM are in place, and the link between GEM and IonEx will be carried out in the near future.

Since our last status report [1], our main progress has

been with GEM2D and IonEx upgrades. The 2D (r,z) spatial extension of GEM from 1D (z) allows more realistic modeling of the rf resonance, which is a key ingredient for ECRIS performance. Through GEM2D, the ellipsoidal shaped rf resonance surface can be modeled. For typical ECR plasmas GEM2D simulations indicate hollow profiles of electron density and temperature, consistent with experimental observations at ATOMKI [8], resulting in hollow profiles of extracted ion sources [9]. As for IonEx, while a user-friendly GUI is being built, a 3D spatial extension is being made. IonEx utilizes a meshfree technique, which uses points or nodes not cells, and an innovative meshfree technique called PICOP (particle-in-clouds-of-points) [6], not PIC (particle-in-cell). Generation and adaptation of points are easier than those of meshes and particularly for handling a complicated geometry and highly non-uniform problems (e.g., multi-scale problems like a plasma meniscus).

Next, we present a summary of these three modules.

SUMMARY OF MCBC, GEM, IONEX MODULES

As presented previously, GEM models ECR ion source plasmas by fluid ions and bounce averaged Fokker Planck electrons [5,10]. The MCBC code simulates beam slowing down dynamics in a plasma due to Coulomb collisions, and atomic processes which includes ionization due to hot electrons and charge exchange. MCBC provides ion source profiles to GEM, which in turn provides ion flux profiles to IonEx. Next we briefly describe the status of each of these modules.

MCBC

The full 3D3V Monte Carlo particle tracking code models Coulomb collisions, and atomic processes in a plasma. The Coulomb collisions are implemented by the Boozer model [11], after modifying the collision formula to ECR plasmas. The modified Boozer model and atomic processes modeled in the code can be found in our previous paper [1].

GEM

We made improvements in two main areas with GEM. The first area is in the convergence of the GEM1D code using the up-wind scheme for the ion continuity equations. The second area is the extension of GEM to 2D. The 2D modeling allows for the resonant layer to be at finite radius as well as at finite axial locations. As rf heating is a main ingredient for producing ECR plasmas,

* Contributed paper, the 18th ECRIS Conference, Chicago, IL, September 2008. This research was performed under a U.S. DOE SBIR grants.

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Time Evolution of Endpoint Energy of Bremsstrahlung Spectra and Ion Production from an Electron Cyclotron Resonance Ion Source

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 O. Tarvainen, Los Alamos National Laboratory
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Abstract

Electron cyclotron resonance ion sources (ECRIS) [1] are used to produce high charge state heavy ion beams for the use of nuclear and materials science, for instance. The most powerful ECR ion sources today are superconducting. One of the problems with superconducting ECR ion sources is the use of high radio frequency (RF) power which results in bremsstrahlung radiation adding an extra heat load to the cryostat. In order to understand the electron heating process and timescales in the ECR plasma, time evolution measurement of ECR bremsstrahlung was carried out. In the measurements JYFL 14 GHz ECRIS was operated in a pulsed mode and bremsstrahlung data from several hundred RF pulses was recorded. Time evolution of ion production was also studied and compared to one of the electron heating theories. To analyse the measurement data a C++ program was developed. Endpoint energies of the bremsstrahlung spectra as a function of axial magnetic field strength, pressure and RF power are presented and ion production timescales obtained from the measurements are compared to bremsstrahlung emission timescales and one of the stochastic heating theories.

DATA ACQUISITION SYSTEM AND DATA ANALYSIS

In order to study the time evolution of bremsstrahlung radiation JYFL 14 GHz ECRIS was operated in pulsed mode. The trigger signal for the RF pulse (leading edge) was synchronized with the data acquisition system. The duration of RF pulses launched into the plasma chamber was set to 1.76 seconds with 5.92 seconds off-time between consecutive pulses. The TTL type reference signal controls the RF switch which has a switching time of 40 ns (0–100%) and provides timing signal for both the digital oscilloscope (used to record ion beam currents) and the digital signal processing unit (TNT2) [2]. The RF switch controls the 14 GHz oscillator signal to the klystron and a germanium detector was used to measure the radial bremsstrahlung spectra. TNT2 unit generates the data in binary format and a computer is used to store the data. Energy resolution of the germanium detector was 4.2 keV at peak energy of 444 keV and 7.4 keV at 1048 keV of ^{152}Eu (shaping time was set to 2.0 μs).

The effect of the lead shielding around the collimator was also studied. It was noticed [3] that while adding

shielding around the lead collimator changed the count rates and also the shape of the bremsstrahlung spectra the timescales remained the same. The size of the collimator hole (from 0.5 mm² to 4 mm²) was not affecting the spectra and had a insignificant effect on the count rate which means that most of the bremsstrahlung events do not come through the collimator but around it.

Data analysis was done with a self-written C++ program. While the TNT2 unit discarded ADC overflows on-the-fly everything else was left untouched in the raw data. Pile-up events are rejected during the data sorting. Typical measurement time per one set of ECR parameters was 90 minutes resulting in data from over 700 RF pulses. To analyze the data 680 RF pulses are used in every data set i.e. bremsstrahlung data of 680 different RF pulses are combined in order to obtain enough statistics. Data from a background measurement is used during the data processing and the background spectrum is subtracted from the measurement data. The data sorting code produces a significant amount of data files. Both RF on and RF off phases are analysed and, for example, spectrum data is written with 2 ms time step (if the first 1500 ms of the RF pulse is used 750 spectra are produced for both RF on and RF off phases) and total count rate data integrated over the whole energy spectrum (from 15 keV to 600 keV) is generated throughout the whole length of the RF pulse. Typically a 1 GB of ASCII data is sorted in about 30 seconds. However, because the code also generates figures of all the sorted data as well as gif animations (time evolution of the bremsstrahlung spectrum in 2 ms steps) the sorting time per one data set can be significantly increased. A typical time to sort all the 21 data sets that were recorded during the measurements is between 9 and 10 h (Intel C2D E6600, 3 GB RAM). Using parallel computing to analyze the data would be relatively easy, however, the creation of animations can take 3 GB of memory, or even more, depending on the settings of the analysing program meaning that a normal desktop computer does not have enough memory to run parallel data analysing. Rejection of bad RF pulses has also been coded into the analyse program. This ensures that possible incomplete or erroneous RF pulses are discarded from the final analyse. The code has been written for *Unix/Linux* environments and requires *Gnu Scientific Library (GSL)*, *Gnuplot* and *Convert* in order to generate the graphs and animations.

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ION CYCLOTRON RESONANCE HEATING IN A PLATEAU-ECRIS

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Abstract

It is shown why static or low frequency electric fields perpendicular to the magnetic field can penetrate into a magnetized plasma of high density. A configuration of electrodes is chosen for the application of radio-frequency electric fields to heat by ion-cyclotron-resonance (ICR) Ar($q+$), H-, and He-ions in PECRIS V with a magnetic plateau and a great resonance volume. It is shown that all ions ICR-heated in this resonance volume gain rotational energy $E(\text{rot})$ and stay thus better confined leading to a drop so that their extracted currents. $E(\text{rot})$ of these ions thermalizes while they are further ionized by electron collisions so that the extracted currents of Ar($(q+n)+$)-ions do show a considerable increase with $2 < n < 7$. The extracted currents of the two ICR-heated light ions do show only drops which will be discussed in detail. As proof of their gain of $E(\text{rot})$ the energy gain of extracted He-ions has been measured. The ICR-heating of multi-charged ions may thus be a technique to considerably improve the currents of the highest charge states.

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STUDY OF THE DEPENDENCE OF ECR ION CURRENT ON PERIODIC PLASMA DISTURBANCE*

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Abstract

In a recent work we observed the existence of periodic current bursts from an ECR ion source when a biased disc is used for enhancing the extracted beam current. It was concluded that the current per burst in the source remains essentially constant. When the disc bias voltage is increased, the burst frequency increases, and so does the total current. The increase in ion current has been found to be proportional to the charge state. However, in the case of protons a different trend is observed. In this work we have studied the periodic bursts in the proton current in order to understand the difference in the behaviour of current jump in protons and heavy ions.

In order to understand the aspects of the ion current enhancement by using a biased disc, we have tried to explore the time characteristics of the ion beams of various charge states. In an earlier work we measured the time spectra of neon ions, and observed the presence of periodic ion bursts [9]. The burst frequency varied with the disc bias voltage, and the ion current showed a good positive correlation with the burst frequency.

For investigating this feature further, we have measured and analyzed the time spectra of various ion species of high and low charge states. Spectra have been measured at a number of disc bias voltages and microwave power levels. Above a threshold microwave power, there is a consistent presence of ion bursts.

INTRODUCTION

ECR ion sources are used in accelerators and various other laboratories for producing ion beams. In many applications it is needed to produce highly charged heavy ion beams. However, in general, the higher the charge state, the lower is the ion current. A number of techniques are employed to enhance the ion current. Often a lighter gas is added to the sample gas which reduces the ion temperature thereby increasing the retaining time. Ion current increases in this process [1]. Supply of low temperature electrons to the main stage plasma is another method. In this process the plasma becomes more stable, as a result of which the ion confinement time increases. Wall coating [2], use of an electron gun [3], and the insertion of a biased disc [4-6] are the methods of the electron supplying technique.

When a negative potential is applied to the disc, the electron density increases and thus increases the ion current [7]. Another explanation by D. Meyer [8] suggests that with the application of a negative potential on the disc, the plasma potential decreases and the plasma becomes more stable. With a stable plasma, production of high charge state ions increases.

EXPERIMENT

Experiments were performed with VEC-ECR source [10] for oxygen ECR plasma with helium as mixing gas. The source pressure was kept at 1.8×10^{-7} Torr. An aluminium biased disc of 3cm diameter was placed on the axis at the injection mirror point. Bias voltage was varied in steps from 0 to -55 Volt.

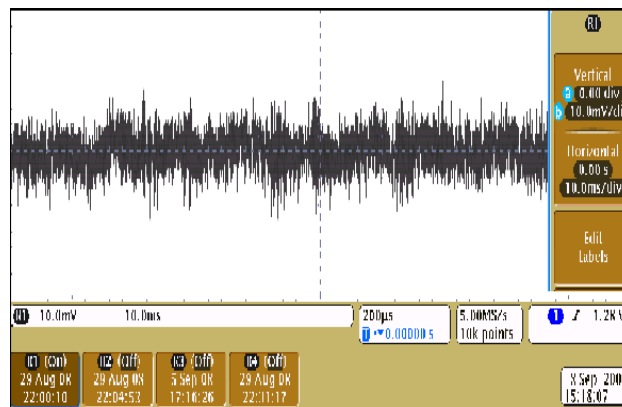


Figure 1: Time spectrum of O^{6+}

In the present experiment, a Faraday cup, located just beyond the image slit of the 90° analyzing magnet in the beam line, measured the ion current. Spectra for

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EFFECTS OF ROLL ANGLES ON HALBACH ARRAY EFFICIENCY

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Abstract

The Halbach Array was first described by Mallinson in 1973 (IEEE Transactions on Magnetics, 9, 678-682, 1973). Named after Klaus Halbach, the Berkeley physicist who first applied Halbach arrays in the construction of wigglers, Halbach Arrays have seen increased use in applications that require high weight to magnetic field efficiency. Since magnet geometry is often dictated by the application, weight, and/or cost requirements, the progression of the angular orientation (roll angle) of the array is a frequent target for optimizing array performance. The effect of different roll angles of a magnet system is studied here on a canonical linear array modeled with two different magnet alloys – one high-energy, low-coercivity alloy, and one high-coercivity alloy. All models studied are comprised of square cross-sections. The integrated flux on each side of the array is compared for efficiency, while the half-maximum distances are compared for projection strength. To validate the model results, the candidate arrays are physically constructed, measured and compared to the modeled outcomes.

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GYROTRON INTRODUCTION FOR ECRIS 2008

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Abstract

Gyrotrons are proving to be very reliable sources of high power at frequencies in the range of 28 to 170 GHz, where other sources are very limited in power capability. As a specific example for ECRIS applications, a 10 kW, 28 GHz CW gyrotron has made possible significant increases in the ion currents generated by the Venus ion source at the Lawrence Berkeley Laboratory [1]. In this paper we briefly discuss the physics and engineering aspects of the gyrotron oscillator, point out some of the issues that require special treatment in the control system and power supplies for it, review related gyro-devices, and present important applications.

INTRODUCTION

The history of gyrotrons goes back to the 1950s. The basic idea of a cyclotron resonance interaction was recognized by a number of people. Particular recognition should be given to Russian scientists under the leadership of A. V. Gaponov [2]. A more recent detailed review of gyro-devices is given in [3].

Figure 1 shows specific CPI gyrotrons and other selected gyrotron sources in a plot of average power output versus wavelength. They occupy an empty region between lasers and conventional vacuum electron devices (VEDs) like klystrons, traveling-wave tubes, and magnetrons. The domain of solid-state devices is similar to conventional VEDs but at lower power level. A more detailed listing of gyrotrons worldwide can be found in [4].

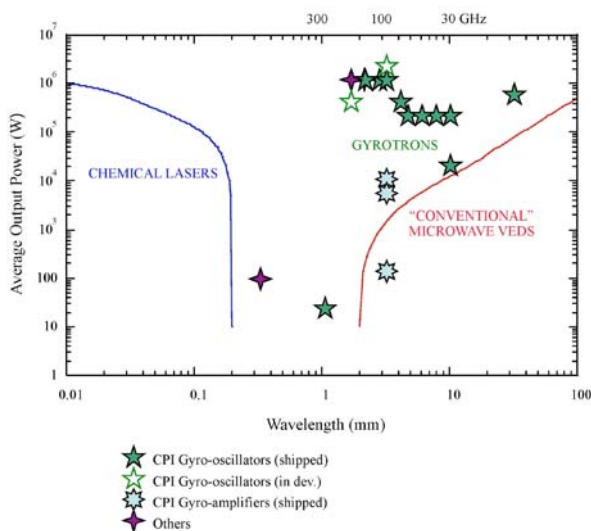


Figure 1: The role of gyrotrons in frequency-power parameter space

BASICS OF THE GYROTRON INTERACTION

Gyrotrons make use of the strong coupling that takes place between an electron moving in a circular orbit perpendicular to a dc magnetic field and an electromagnetic field in the plane of the orbit which has a frequency near the cyclotron resonance frequency of the electron.

The left side of Figure 2 shows 8 electrons at some initial time distributed equally around the orbit center. The electron in position 7 sees a maximum decelerating force, and the one at 3 sees maximum accelerating force. One half cycle later the field has reversed polarity and 7 has moved half way around the orbit and again is decelerated. Likewise 3 is again accelerated. At 1/4 and 3/4 cycle times the electric field is zero and only magnetic forces exist.

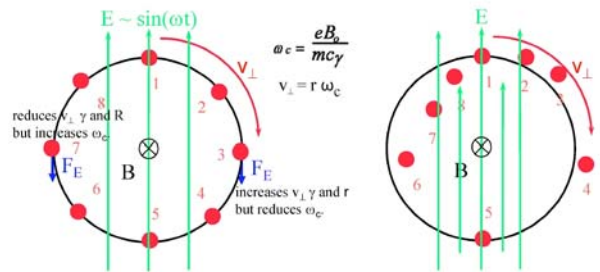


Figure 2: Electrons at cyclotron resonance with a time-varying electric field

The right side of Figure 2 shows the situation an integral number of cycles later, when the cumulative forces have produced a bunching in the rotational phases of the electrons. In this case there is no net energy loss of the electrons because equal numbers have been accelerated and decelerated. If, however, we have a slight difference between ω and ω_c , we can arrange for the bunch to form in a region of decelerating force, and the loss of electron energy will cause the electric field to grow.

To create a gyrotron we introduce a microwave resonator to define a volume for the fields and create an electron beam where all electrons have the same transverse component of velocity, v_{\perp} , and a small component of axial velocity so that the electrons are removed from the cavity before they slip further into a phase to gain energy back.

IN MEMORY OF RICHARD GELLER

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Abstract

Reviews the life of Richard Geller.

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REFLECTIONS ON THE LIFE OF RICHARD GELLER

T. Lamy, LPSC, Grenoble

Abstract

A review of the life of Richard Geller.

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NEW CONFIGURATION AND RESULTS WITH THE LPSC CHARGE BREEDER

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Abstract

A 1+ thermo ionization source has been used to produce Sodium and Rubidium beams in order to compare the PHOENIX charge breeder capture efficiency for different ion masses but with the same beam optics. Yields of 1.9% for $^{23}\text{Na}^{6+}$ and 3.5% for $^{85}\text{Rb}^{15+}$, with charge breeding times of 8,6 ms/charge and 4,7 ms/charge respectively, have been measured. 1+ and n+ emittance measurements are presented along with the capture sensitivity to different parameters (DeltaV plots). Technical modifications have been performed to the charge breeder: replacement of the plasma chamber to allow a double frequency operating (14 + 18 GHz), modification of the injection magnetic plug to reinforce the axial magnetic field and correct its dissymmetry in the 1+ beam deceleration zone, insulation improvement to allow 60 kV operation for the SPIRAL2 project. First charge breeding experimental results at 14 and 18 GHz in the new configuration are presented and discussed for Rb beams.

INTRODUCTION

Improvement of ECR charge breeding characteristics (efficiency yield, charge breeding time, emittance) will immediately benefit to the physics performed with accelerated Radioactive Ion Beams (RIB's) allowing higher intensities (and/or brilliance) available to the experiments. There are two ways to reach such improvements: either to increase the 1+ beam capture efficiency, either to use the known methods that improve the intensity and charge state distributions delivered by Electron Cyclotron Resonance Ion Sources (ECRIS). The work presented here is intended to act on both ways.

RUBIDIUM AND SODIUM RESULTS

The experimental setup has already been extensively described [1] and will not be detailed here. A 1+ beam is produced, characterized, and then multi ionized into the charge state breeder, the n+ beam extracted is then characterized too. The three characteristics measured are efficiency, charge breeding time and emittance.

Rubidium

A 20 keV - 80 nA beam is produced with a thermo ionization source and injected into the PHOENIX charge breeder. Figure 1 shows the emittance plots for the $^{85}\text{Rb}^{1+}$ (left) and $^{85}\text{Rb}^{15+}$ (right) ion beams, on the latter the emittance scan excursion allows to see peripheral beams of higher and lower Q/A beams (Q and A being the charge and the mass of the ions respectively). The emittance values are $2 \pi.\text{mm.mrad}$ and $13.5 \pi.\text{mm.mrad}$

for the 1+ and 15+ beams respectively. However, when measuring emittances of different n+ ion beams, we always measure the same value, we suspect wrong entrance and exit angles with the n+ spectrometer. This can be clearly seen on the n+ picture, the emittance of the beams is strongly decreasing for increasing exit angles (yellow lines). With the present exit angle, we think the n+ emittance is overestimated by a factor 2 at least. So, the n+ beam line has to be realigned in order to measure the real emittance of the source.

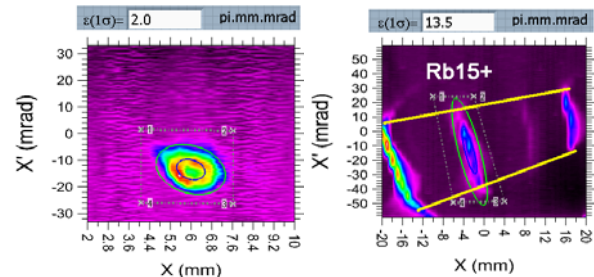


Figure 1: $^{85}\text{Rb}^{1+}$ and $^{85}\text{Rb}^{15+}$ emittances

Despite this problem, we have measured the transmission of the beam line to be 100% and we can then measure the charge breeding efficiency (1+→15+) which is $\eta = 3.6\%$ (result of the same order than in other laboratories, for example: [2], [3]).

The charge breeding time for this efficiency tuning was $\tau_{\text{obt}} = 70$ ms. Such a result has to be compared to ones which were obtained in previous experiments ($\eta = 5\%$, $\tau_{\text{obt}} = 225$ ms). The charge breeder tuning (RF power, buffer gas flux and magnetic confinement) may give either low efficiency and fast process or higher efficiency but longer charge breeding time. In the context of radioactive ions the tuning will therefore be a compromise depending on the half life of the radioactive decay process.

Sodium

A 20 keV - 170 nA $^{23}\text{Na}^{1+}$ beam is produced with the same thermo ionization source as the one used for rubidium production, and injected. The emittance values for the $^{23}\text{Na}^{1+}$ injected and the $^{23}\text{Na}^{7+}$ produced are $1 \pi.\text{mm.mrad}$ and $15.6 \pi.\text{mm.mrad}$ respectively (Figure 2). The efficiency yield was 1.4 % and 1.9 % on the $^{23}\text{Na}^{7+}$ and $^{23}\text{Na}^{6+}$ respectively, with a charge breeding time of 52 ms for the 6+. In the case of light ions the tuning may be hard to find due to the capture sensitivity to the potential difference between the 1+ and the n+ sources (ΔV). However it seems that the ΔV width decreases for increasing charges, but not the potential value of the highest efficiency (Figure 3).

STATUS OF THE ECRIS CHARGE STATE BREEDING PROJECT AT TRIUMF

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Abstract

Efficient and fast charge state breeding is an important parameter for the acceleration of radioactive ions at ISOL facilities. Most on-line ion sources produce only singly charged ions but efficient accelerators require high charge states. Tests of an ECRIS as charge breeder (14 GHz PHOENIX from Pantechnik) have been performed on a test bench at TRIUMF mainly focussing on the optimization of the efficiency and breeding time. After this the source has been moved on-line to the ISAC facility. Mass separated beams of radioactive ions from the on-line ion sources can be directed into the source as well as ions from a Cs test ion source. The latter will be used for commissioning the system and setting up and optimizing the performance of the source as well as the transport of the highly charged ions to the accelerator. A summary of the results obtained at the test bench and first results from the on line commissioning will be presented.

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INITIAL RESULTS OF THE ECR CHARGE BREEDER FOR THE 252CF FISSION SOURCE PROJECT (CARIBU) AT ATLAS

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Abstract

The construction of the Californium Rare Ion Breeder Upgrade (CARIBU), a new radioactive beam facility for the Argonne Tandem Linac Accelerator System (ATLAS), is in progress. The facility will use fission fragments from a 1 Ci ^{252}Cf source; thermalized and collected into a low-energy particle beam by a helium gas catcher. In order to reaccelerate these beams, the existing ATLAS ECR1 ion source has been redesigned to function as a charge breeder source. An additional high voltage platform has been constructed to accommodate a low charge state stable beam source for charge breeding development work. The design features and initial results of this charge breeder configuration will be discussed.

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Design of a Charge-Breeder Ion Source for Texas A&M University*

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Abstract

Scientific Solutions designed and fabricated a 14.5 GHz charge-breeder ECR source for the Texas A&M University Cyclotron facility. This charge-breeder source was designed as a charge-breeder from the start rather than as a conversion of an existing ECR system. In addition, the overall system was designed to be modular so that various components can be easily substituted to facilitate technology developments. This paper details the overall design, the design constraints, and reviews specific performance requirements that resulted in this particular system design.

BACKGROUND

The purpose of this project was to provide a test bed for developing technology and techniques specific to charge-breeder electron-cyclotron resonance (ECR) ion sources. Unlike “primary” ECR sources where the unionized elemental feedstock is introduced into the source as neutral atoms, a charge-breeder is designed for injection of short-lived radioactive ions. Because these exotic ions are produced in nuclear reactions, the number of ions is always severely limited. Therefore the overall efficiency of the charge-breeder source is extremely important. The source efficiency is the product of the injection efficiency, the ionization efficiency, the ion extraction efficiency, and the effective dwell time in the source. This project not only created a charge-breeder system for producing the highly charged ion species needed for nuclear physics experiments, but one that could be used as a test bed for testing and developing additional techniques and technologies.

DESIGN RULES

Once the choice of operating frequency is made, the design of the magnetic circuit is the next most important feature. The optimal magnetic field profile of a high charge-state ECR ionizer was determined primarily through trial-and-error over the last ten to fifteen years. [1-4] The preferred field profile has a peak magnetic field at the beam extraction point approximately equal to twice the ECR resonant field, B_{ECR} , (~ 2.79 GHz/kGauss). The minimum magnetic field should be in the range of $0.8 \cdot B_{\text{ECR}}$. [5] The peak magnetic field at the end opposite extraction has been the subject of more discussion. [6] Some argue that $2 \cdot B_{\text{ECR}}$ is adequate while others claim improved performance with fields up to $5 \cdot B_{\text{ECR}}$. Such high fields are generally obtained by inserting steel plugs into the bore of the solenoid magnet. However it is not possible to reach $3 \cdot B_{\text{ECR}}$ or higher without blocking a substantial part of the bore of a conventional copper-coil

solenoid magnet. Blocking the bore blocks injection of ions. This conflict represents a major incompatibility between charge-breeders and primary ECR sources.

The bore of the solenoid is the next most important parameter in the overall system design (after the magnetic field profile). The bore should be as large as possible to maximize the diameter of the plasma chamber. However the sextupole magnet surrounding the plasma chamber pushes this critical dimension to values larger than can be excited by room-temperature copper coils when the ID of the plasma chamber exceeds 9 cm. As discussed below, 8” (20 cm) is the largest bore compatible with 14.5 GHz operation, a strong sextupole magnet, and copper coils.

The sextupole magnet plays an extremely important role in the confinement and stabilization of the plasma. To minimize electron loss to the interior walls of the plasma chamber, the sextupole should have a field magnitude of at least $2 \cdot B_{\text{ECR}}$ at the interior surface.

We chose a 24-block Halbach ring configuration [7] because this design makes the most efficient use of expensive permanent magnet material and provides the highest magnetic field strength available per unit mass of magnet block. The Halbach configuration rotates the magnetization vector at three times the rotation angle around the cylinder. This rotation effectively cancels the magnetic field outside the cylinder while doubling the interior field strength. The peak field at the inner wall of the plasma chamber of $2.2 \cdot B_{\text{ECR}}$. This radial field is significantly stronger than most primary ECR sources and is expected to significantly improve the performance.

Note that the cylindrical Halbach array completely surrounds the plasma chamber and permits no radial access. However a charge-breeder system should not require peripheral components, such as ovens or sample insertion ports. Therefore not having radial access should not be a disadvantage.

The ion injection system is comprised of a pair of electrostatic lenses and the beam extraction system is a relatively conventional “puller” assembly with an added electron trap to prevent electrons from backstreaming into the ion source.

DESIGN FEATURES

This charge-breeder design has a number of features that facilitate maintenance and repair, protect critical components, promote long operational lifetime, and enable technology development. These features include 1) no water-to-vacuum joints, 2) cooling channels between the plasma “cusps” and the sextupole magnet, 3) ample vacuum pumping of interior rf waveguides, 4) modular design with replaceable components, 5) mounting of solenoids and charge-breeder system on ball-bushing rails.

*This material is based upon work supported by the U.S. Department of Energy under Award Number DE-FG02-04ER84166. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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

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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 ($^3\text{He},d$) 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 of 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	4×10^4
^{50}Mn (0.28s)	45	1×10^5
^{54}Co (0.19s)	45	4×10^4
^{64}Ga (2.63m)	45	2×10^5
^{92}Tc (4.25m)	35	2×10^5
^{106}In (6.20m)	28	4×10^5
^{108}In (58.0m)	28	2×10^5
^{110}In (4.9h)	26	4×10^5

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 $^{27}\text{Al}(p,n)^{27}\text{Si}$) 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 non-selective device, meaning that all ions, singly and possibly doubly charged, as well

MISTIC: RADIATION HARD ECRIS

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Abstract

The ISAC RIB facility at TRIUMF utilizes up to $100 \mu\text{A}$ from the 500 MeV H^- cyclotron to produce RIB using the ISOL method. At the moment, a hot surface, a laser and a FEBIAD ion source are used to produce RIB. These ion sources are not suitable for gaseous elements like Ne, C, O, N and F which are key nuclei in nuclear astrophysics research at TRIUMF. However, these elements can be ionized efficiently by an ECRIS. By combining a high frequency electromagnetic wave and a magnetic confinement, the ECRIS can produce high energy electrons essential for efficient ionization of these elements. To this end, a prototype ECRIS called MISTIC (Monocharged Ion Source for TRIUMF and ISAC Complex) has been built at TRIUMF using a design similar to the one developed at GANIL [1]. Conventional ECRIS cannot be used at ISAC because of the high radiation field created when high energy proton beam impinges the target. In order to achieve a radiation hard ion source, electromagnetic coils replace the permanent magnets. Preliminary tests for Ne, Kr and Xe showed that MISTIC is very stable over a large range of frequencies, magnetic field configurations and pressures.

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EMITTANCE MEASUREMENTS OF ION BEAMS EXTRACTED FROM HIGH-INTENSITY PERMANENT MAGNET ECR ION SOURCE*

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Abstract

A pepper-pot – scintillator screen system has been developed and used to measure the emittance of DC ion beams extracted from a high-intensity permanent magnet ECR ion source. The system includes a fast beam shutter with a minimum dwell time of 18 ms to reduce the degradation of the CsI(Tl) scintillator by DC ion beam irradiation and a CCD camera with a variable shutter speed in the range of 1 μ s to 65 s. On-line emittance measurements are performed by an application code developed on a LabVIEW platform. The sensitivity of the device is sufficient to measure the emittance of DC ion beams with current densities down to about 100 nA/cm². The emittance of all ion species extracted from the ECR ion source and post-accelerated to an energy of 75-90 keV/charge have been measured downstream of the LEBT. As the mass-to-charge ratio of ion species increases, the normalized RMS emittances in both transverse phase planes are reduced from 0.5-1.0 π mm-mrad for light ions to 0.05-0.09 π mm-mrad for highly charged ²⁰⁹Bi ions. The dependence of the emittance on ion's mass-to-charge ratio follows very well the dependence expected from beam rotation induced by decreasing ECR axial magnetic field. The measured emittance values can not be explained by only ion beam rotation for all ion species and the contribution to emittance of ion temperature in plasma, non-linear electric fields and non-linear space charge is comparable or even higher than the contribution of ion beam rotation.

INTRODUCTION

During the last few years it became evident that ion beams extracted from ECR ion sources have complicated structure of both spatial and phase space distributions [1]. The ion motion in the horizontal and vertical planes is strongly coupled due to the magnetic field configuration inside the source and extraction region. Slits and Alison type emittance scanners, which were widely used previously, can not provide full information about such distributions. A pepper pot emittance probe is the most suitable device to study 4-D ion beam emittance. Another significant advantage of the pepper pot probe is the very short time of measurements. 4-D emittance data can be obtained in less than 1 s on-line, allowing ECR ion source tuning to minimize the emittance of extracted ion beams. Different scintillators were used previously to measure the emittance of intense ion beams extracted from pulsed ion sources [2, 3]. However, there are almost no data on

emittance measurements of DC ion beams with moderate intensities typical for ECR ion sources using a pepper pot coupled to a scintillator probe. The main challenge is the choice of the viewing screen to provide high sensitivity, long life time, linearity and wide dynamic range of measurements. In most cases these parameters are unknown or not well known.

Our first tests of a pepper pot coupled to a CsI (TI) crystal [4] show that the sensitivity of the probe is high enough to measure emittance of DC ion beams with energy 75 keV per charge state for a variety of ion species from protons to heavy ions with current densities even below 1 μ A/cm². The simple COHU 2600 [www.cohu.com] monochrome CCD camera with shutter speed 60 frames per second has been used in these measurements. It is obvious that the sensitivity can be significantly enhanced using a CCD camera with longer integration time and higher gain. In this paper we describe recent developments of the pepper pot emittance probe based on a CsI (TI) scintillator. A fast in-vacuum shutter with a minimum dwell time of 18 ms was employed to reduce the scintillator degradation by DC ion beam irradiation. A PC connected IMI TECH IMB-147FT 12-bit Firewire Monochrome [www.imi-tech.com] digital CCD camera with shutter speed variable in the range of 1 μ s to 65 s and adjustable gain was used to acquire and save pepper pot images. On-line emittance measurements were performed by an application code developed on LabVIEW [www.ni.com] platform. The linearity of the emittance meter was studied. The emittance meter was used to measure the emittances of all ion species extracted from the high intensity permanent magnet ECR ion source.

EXPERIMENTAL SETUP

The structure of the pepper pot emittance meter is shown in Fig. 1.

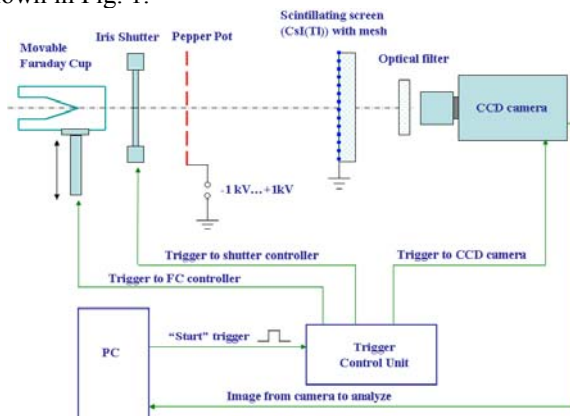


Figure 1: Emittance meter structure.

*This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

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COMPARISON BETWEEN AN ALLISON SCANNER AND THE KVI-4D EMITTANCE METER*

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INTRODUCTION

The demand for intense highly-charged ion beams at the AGOR facility has triggered a study to improve the beam-line transport efficiency. In the framework of this study an emittance meter (KVI-4D) to measure the 4D phase-space of a beam has been developed. The device is also intended for use at GSI with the MS-ECRIS, which is being built in the framework of the EURONS-ISIBHI project.

The demand for intense beams is pushing the development of ECR ion sources to areas where the formation of ion beams in the extraction region is affected by the strong fringe field of the solenoids and extracted intense beams are influenced by space charge effects. With the KVI-4D emittance meter we hope to gain more understanding of beam formation and transport and thus to improve overall efficiency.

In the following we will describe the design and the main parameters characterizing the instrument. Measurements will be presented where we compare data taken with an Allison [1] scanner and with the KVI-4D [2] emittance meter for the same beam. An exploration of the 4D phase-space data shows how beam filamentation can be investigated.

THE MEASUREMENT CONCEPT AND MAIN CHARACTERISTICS

The emittance meter has been designed to analyze a low-energy ion beam at the image plane of an analyzing magnet. At the image plane, the beam has an estimated maximum waist of 5 mm in the horizontal direction and a beam size of 40 mm in the vertical direction. The corresponding divergences are about +/-50 mrad and +/-6 mrad respectively. The instrument is design such that it is able to accept beams with a power up to 150 W.

To measure the emittance in four dimensions the pepper pot method [3, 4] has been adopted. Implementation of this principle led to the basic design of a tantalum pepper pot plate (see Fig.1) with a thickness of 25 μm , machined with an array of 20 μm diameter holes with a pitch of 2 mm. Each hole position is accurately defined in the y-direction. The plate is mounted at a distance of 59.3 mm from a MCP-based position-sensitive

detector which has been described in [2]. The pepper pot plate is stepped with a translation device in the x-direction through the beam. The accuracy of this movement is less than a micrometer. Images are recorded at each step and contain a row of spots in the y-direction. Each spot covers 500-3000 pixels of the CCD. Each pixel is defined accurately in a second coordinate system. By scanning a single row of holes over the beam area, overlap of the spots in the x-direction, where the divergence is large, is impossible. In the y-direction the divergence is much smaller, so that no overlap occurs for the 2 mm hole pitch, small compared to the 40 mm beam size.

From the measured positions of the ions and the exact position of the pepper pot plate we can reconstruct the rectilinear flight path of the particles and thus also the angular coordinates x' and y' . A 4D dataset $\rho(x,y,x',y')$ can be constructed that contains an intensity value proportional to the number of detected particles within a 4D volume-element dx, dy, dx', dy' at the phase-space position x, y, x', y' .

The dataset ρ can now be used to construct the various phasespace projections: $x-x'$ (see Eq.1); $y-y'$ and also $x-y', y-x'$ by integrating over the other dimensions.

$$\rho(x, x') = \iint \rho(x, y, x', y') dy dy' \quad (1)$$

By integrating over specific intervals of the other dimensions more detailed information can be obtained. An example of this will be discussed below.

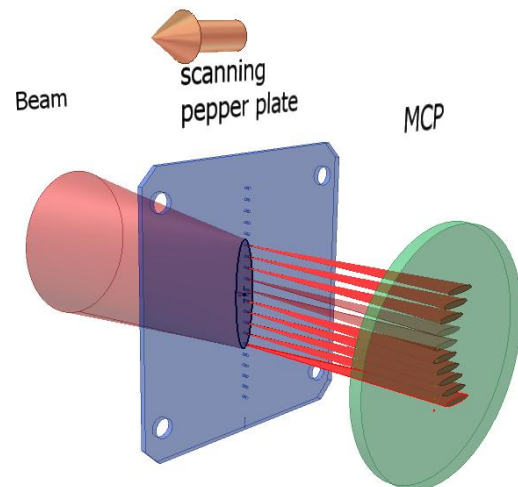


Figure 1: measurement concept of the KVI-4D emittance meter

* This work has been supported by the University of Groningen and by the European Union through EURONS, contract 506065. It has been performed as part of the research programme of the "Stichting voor Fundamenteel Onderzoek der Materie" (FOM), with support of the "Nederlandse Organisatie voor Wetenschappelijk Onderzoek" (NWO).

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A METHOD OF TUNING ECRIS BEAM TRANSPORT LINES FOR LOW EMITTANCE*

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Abstract

Heavy-ion beams from an ECR-type ion source have been shown to be structurally complex and to have a strong cross-correlation associated with their formation in and extraction from a high magnetic field with a strong sextupole content [1].

The emittances of such beams tend to be unavoidably large (compared to low magnetic field source types) yet because of cross-correlations, resistant to improvement by normal collimation methods [2].

Recent developments with beam from the 14 GHz room temperature ECRIS at the NSCL indicate that careful beam line tuning to pass specific parts of the beam structure can allow greatly reduced 4-dimensional emittances without losing a disproportionate amount of the total intensity.

INTRODUCTION

The National Superconducting Cyclotron Laboratory (NSCL) consists of two cyclotrons in series (the K500 and K1200) [3] which accelerate beams provided by one of two ECR Ion Sources. The primary source is ARTEMIS-A (Advanced Room Temperature Ion Source), which is a modification of the Berkeley AECR source and runs at 14 GHz using permanent sextupole magnets, radial ports and room temperature solenoids. A duplicate source, ARTEMIS-B, has been constructed and is installed on a separate test stand.

The primary operational mode of the accelerators is as a driver for operation of the A1900 particle separator, where stable-nuclei beams of 120-170 MeV/u are impacted on a solid target, with the resulting nuclear fragments collected, purified, and sent as a beam of exotic nuclei to the experimental areas.

MOTIVATION

Generally, from the point of view of the experimental program, the highest possible intensities are desired. The shielding of the production target area would allow for beams of up to 4 kW beam power. Presently, for some beams, final output is limited by the beam intensity from the ion sources. For others, beam powers are limited to about 800 W by losses and resulting heating of extraction elements in the cyclotrons. When the new high intensity ECRIS, SUSI, comes on line in 2009, the loss issue will become more pressing.

An important constraint on any solution to running with higher intensities is that the facility operates by user demand with a run of any particular beam seldom lasting

more than a few days. The list of beams available for nuclear science contains 22 different stable isotopes [4]. This great variety of beam types and the short run times requires that tunes also be repeatable, reliable, and quick to optimize.

EXPERIENCE

From nearly the beginning of coupled cyclotron operation in 2001, it was clear that an increase of beam current from the source and subsequent injection did not lead to increased K500 output and overall transmission efficiencies were low. Simple collimation (apertures and a small (8 mm diameter) plasma chamber extraction hole) improved the situation but the resulting beam images seen on phosphor-coated plates inserted into the injection beam line had many undesirable features such as large variations in intensity within the image. Considerable effort on improving injection beam line performance was undertaken, including a major change from magnetic to electrostatic focusing in the initial part of the line and a higher-quality analysis magnet [5, 6]. Better performance through the cyclotrons was achieved as the emittance of the low-energy beam injected into the K500 was reduced.

Artemis-B Beam Tests

In August 2007, the Artemis-B test stand was configured to explore the possibility of making a full 2nd order correction of aberrations in the extracted ECRIS beam due to the sextupole radial confinement field.

The beam line with relevant devices is shown in Figure 1. An electrostatic double-doublet system (DDS) consisting of four quadrupoles and one octupole served as the focusing elements before the 90 degree analysis magnet. Vertical and horizontal steering control is done by offsetting the plate voltages of the first and fourth quadrupoles. A sextupole magnet, rotatable about the beam line axis, was placed between the DDS and the analysis magnet. Calculations had shown that with the DDS set to give a π phase-advance (essentially, a focus) between the source sextupole and the external sextupole, the desired correction could be achieved. An Allison-type scanner was used to measure beam emittances. However, since it is a 2-dimensional device, to achieve some gauge of the higher-order nature of the beam, a pepper-pot-like plate was made to insert into the beam after the analysis magnet, followed by a field-free drift and a viewer plate. (An uncorrelated beam will project an image of the grid hole unchanged except for size, depending on the optical conditions.) The test stand configuration is shown in Figure 1 and the beam used was $^{40}\text{Ar}^{7+}$ with an extraction voltage of 20 kV.

*Supported under National Science Foundation Grant PHY-0110253

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Low Energy Beam Transport for Ion Beams created by an ECRIS

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Abstract

It has been shown previously that the emittance of an ion beam, extracted from an Electron Cyclotron Resonance Ion Source (ECRIS) is determined by magnetic field, applied electric potentials, geometry, and particle density distribution together with the initial properties of these particles[1],[2].

The model used for computer simulation seems to fit the experimental results: ions are extracted from the ion source if they are created (started) at places where magnetic field lines are going through the extraction aperture. Furthermore, the absolute value of magnetic flux density relative to the flux density at the extraction aperture defines, whether this ion can be extracted or not.

Due to coupling between the different subspaces of phase space because of the magnetic field, several assumptions used for beam transport issues are not valid any more: for example, two-dimensional emittance does not stay constant in every case; the six dimensional phase space does.

With increasing extracted ion currents, space charge compensation of the extracted beam becomes an important issue. The beam itself will create secondary particles which can serve for space charge compensation. This compensation will build up in a relatively short time, depending on the pressure, as long no leakage is present within the beam line.

ION BEAM EXTRACTION

Electron cyclotron resonance ion sources (ECRIS) are used more often, especially since several improvements of this type of ion source had increased the available intensities even for higher charge states. Nevertheless, extraction and beam transport is only partially comparable to the case of ion beam extraction not influenced by magnetic fields. It seems that the starting conditions of the ions within the plasma are essential for the process of beam formation. Because of the low ion temperature which is in the low eV range and the high magnetic flux density up to several T, the Larmor radius of ions is in the sub-mm range. Therefore, ion-ion collisions are minor important for the path of the ion. The magnetic field lines going through the extraction aperture show the possible path for the ions to be extracted. If the magnetic flux density is increasing along the field line, particles will transform energy in direction of the field line into rotational energy perpendicular to the field line and visa versa. Only if it is possible to create ions at these locations or to transport them to these places with a certain

magnetic flux density, the ion can be extracted. The magnetic flux density in the plane of extraction is therefore a good approximation for the minimum required flux density from which ions can be extracted. This surface is shown in the following 2D-cuts for different ECRIS types, see Figures 1, 2, 4 - 10. Together with the information where the magnetic field lines going through the extraction aperture are coming from, the possible extraction area can be determined. It is assumed that the plasma generator is able to produce particles in the required charge state at these locations.

The model has been tested for different existing ion sources, and for ion sources which are still under design or in construction, and it has been found that the actual magnetic setting has to be taken into account, instead of using the design values only.

CAPRICE

This source, used at the accelerator facility at GSI, has been investigated together with the technique of viewing targets, to proof our estimates about beam extraction. The ion source has two normal conducting coils for the mirror trap and a hexapole, made of permanent magnets. Using different materials for these permanent magnets, we have tested three differently strong hexapolar fields: 0.8 T, 1.0 T, and 1.2 T, measured at the inner diameter of the plasma chamber. Whereas the transverse magnetic flux density is fixed when the hexapole has been installed, the mirror field for both mirror coils is variable up to 1.2 T on axis, see Fig. 1. Plasma heating is done by a 14.5 GHz klystron. By changing the mirror field on injection side or extraction side, the origin of extracted ions can be changed from the back side of the source to the radial location of the loss lines, starting at injection side and reaching the center between both coils, see as example Fig. 7 for the MS-ECRIS. Because the allowed starting conditions are determined by the magnetic settings, it is important for ECRIS extraction simulation to include the different possible magnetic fields.

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This commercially available ion source[3] is easier to simulate, because the magnetic flux density is frozen due to the only use of permanent magnets, which might be a disadvantage on the other side. The magnetic flux density has been calculated using the PANDIRA code[4], which calculates the rotational symmetric mirror field. Because of the usage of permanent magnets, the longitudinal field

IMPROVED ECR EXTRACTION AND TRANSPORT SIMULATIONS USING EXPERIMENTALLY MEASURED PLASMA SPUTTERING

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Abstract

Simulations of beam extraction across a plasma sheath in an ECR ion source are critically dependent upon ion density distributions at the plasma extracting face; however, these distributions have not been measured experimentally. We present a new method of defining the initial distributions for simulation based upon the measurement of biased disc sputter marks. Multi-species beam extraction and transport simulations using these initial conditions will be compared with beam imaging and emittance measurements from the superconducting ECR VENUS at several positions along the beam line illustrating this simple model's ability to reproduce measured beam characteristics such as beam hollowing even though the triangular distributions at plasma extraction are of nearly constant density. The various possible sources of the beam hollowing observed both in simulation and experiment will be discussed. In addition, we will present a generalized method to define the initial distribution at extraction using only magnetic field line tracing and extracting aperture geometry.

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THREE DIMENSIONAL SIMULATION OF ION BEAM EXTRACTION FROM AN ECR ION SOURCE

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Abstract

Accurate prediction of ECR ion extraction behavior is important for high current density operation and subsequent beam transport calculations. In this paper we review the combined electric and magnetic space charge beam simulation of ion beam formation from an ECR ion source with a multi-electrode extraction system. Included in the simulation is the influence of secondary charged particles generated by ion collisions in the residual gas on the space charge in the beam. The self-consistent space charge simulation uses a finite element method with mixed linear and quadratic elements, magnetic fields incorporating non-linear magnetic materials, a plasma free surface emission model, and the generation of secondary charged particles by sampling of the primary beam trajectories. This method is useful for predicting the ion beam behavior from the ECR ion source under conditions of varying current density, electrode potential, and background gas pressure, including the behavior of suppressed electron flow and the influence of magnetic fields.

INTRODUCTION

This simulation represents an electron cyclotron resonance (ECR) ion source for producing a proton beam. The source is similar to a CEA-Saclay ECR source [1], though with a much higher magnetic field. New Vector Fields SCALA software [2] simulation capabilities permit fast prediction of ion beam formation with automatically generated secondary charged particles from background gas. The model is used for a space charge simulation of ECR extraction system with an accel-decel extraction system from a plasma free surface in combined electric and magnetic fields. The simulation includes beam neutralization from gas secondary electrons.

MODEL

The finite element model is composed of a three-electrode accel-decel extraction system and two solenoid magnets with non-linear magnetic materials (Fig. 1). The ion source dimensions are as follows:

Extraction aperture diameter	3.0 mm
Accel and decel aperture diameters	4.0 mm
Extractor-accel gap	12.5 mm
Accel-decel gap	1.5 mm
Ion beam drift space length	84.0 mm
Solenoid coil center spacing	100.0 mm
Magnet pole inside diameter	150.0 mm

The magnetic field model is analyzed first and the magnetic field information added to the electrostatic space charge database before solving.

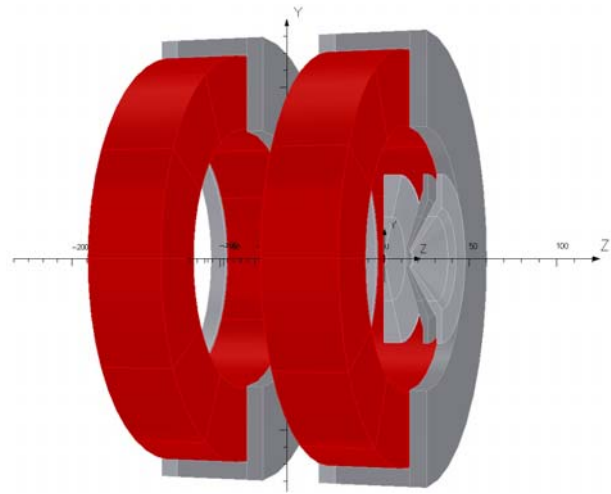


Figure 1: Source geometry with non-linear magnetic materials.

The model incorporates mixed linear and quadratic tetrahedral elements of varying size (Fig. 2).

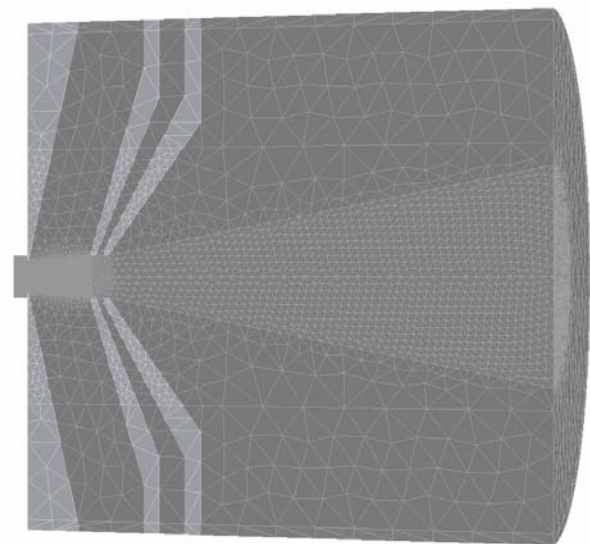


Figure 2: Tetrahedral mesh.

EXTRACTION FROM ECR ION SOURCES: A NEW WAY TO INCREASE BEAM BRIGHTNESS

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Abstract

One of the goals of work on ion sources is to provide the highest beam intensity in the smallest emittance. As computer power has increased so rapidly over the last few years, it is now possible to simulate the extraction from the ECR ion sources with greater accuracy, taking into account the physics of the several processes involved in the beam creation. In the last section of their paper, R. Leroy and co-workers [1] showed experimentally that the intensity of a beam can be improved significantly by biasing the plasma electrode. The idea was to use the isolated plasma electrode as a “biased disk”. We have calculated the influence on the extracted ion trajectories of this additional potential (from 0 V down to -60 V). The simulations have been computed for the MONO1000 [2] and SUPERSHyPIE [3] ion sources. All the simulations showed an increase of the beam brightness with more or less important gain depending on the extraction voltage and the extraction conditions. A recent experiment performed on the MONO1000 ECRIS has confirmed the feasibility of this method: a gain of around 40% in terms of emittance has been obtained on an $^{84}\text{Kr}^{1+}$ beam.

Introduction

This work was performed in the framework of the ITSLEIF [4] network. One of the tasks deals with the improvement of the ECR ion source extraction. The goal is to get higher intensity in a smaller emittance for multi-charged ions of low energy (1–25 keV/ q) used in the different facilities of the network. In previous work [1], Leroy and co-workers measured the evolution of the Ar^{4+} current with the polarisation of the plasma electrode at different bias of the coaxial tube. Each time, a maximum value of the current was obtained for a biased plasma electrode between -14 and -30 V. One of the major results was: “the plasma potential of the source is decreased when the coaxial tube voltage is increased”. We have used this technique to investigate the extraction zone and the effect of this polarisation on the plasma electrode. Figure 1 shows the effect for negative potentials. This small polarisation will slightly modify the electric field lines in the extraction zone such that the divergence of the beam will be decreased. But at the same time ions from the edges of the beam will not be extracted. So to get a measurable effect, the emittance reduction should be larger than the diminution of the extracted ion current.

* Work supported by the ITS-LEIF project (RII3 – 026015)

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The relevant parameter in this process is the brightness of a beam. We will use the equation (1) where I_{beam} represents the beam current and ε_x and ε_y the emittances of the beam in the respective transverse planes of the beam propagation. In the following, we will deal only with geometric emittances.

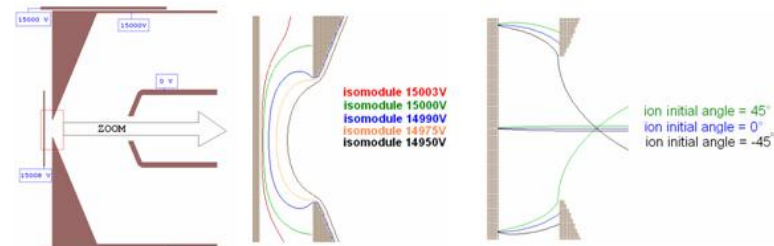
$$B = \frac{2I_{\text{beam}}}{\pi^2 \varepsilon_x \varepsilon_y} \quad (1)$$

The results will be shown by the relative brightness:

$$B_{\text{rel}} = \frac{B(V_{\text{pe}})}{B(V_{\text{pe}} = 0\text{V})} \quad (2)$$

In the equation, V_{pe} corresponds to the difference between the voltage applied to the plasma electrode and the voltage applied to the ECRIS body: in our case this value will be negative and varies from 0 V down to -60 V. In this paper, $V_{\text{pe}} = 0$ V corresponds to the usual extraction case.

a)



b)

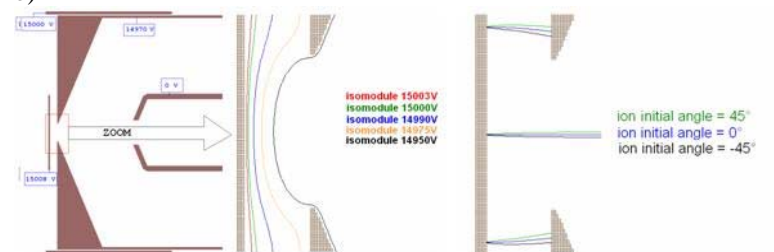


Figure 1: Principle of the technique; case a) corresponds to a plasma electrode at source potential while b) corresponds to a plasma electrode biased at -30 V relative to the source potential.

In the following sections we present the beneficial effects of the idea, and not absolute values. First we will present calculations done with a singly charged ECRIS

RECOMBINATION OF ANALYZED MULTIPLE-CHARGE STATE HEAVY-ION BEAMS EXTRACTED FROM AN ECR ION SOURCE

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Abstract

A prototype injector capable of producing multiple-charge-state heavy-ion beams has been constructed at ANL. The injector consists of an ECR ion source, a 100-kV platform and an achromatic Low Energy Beam Transport (LEBT) system. Several charge states of bismuth ions from the ECR have been extracted, accelerated to an energy of 1.8 MeV, separated and then recombined into a high quality beam ready for further acceleration. This technique allows us to double heavy-ion beam intensity in a high-power driver linac for a future radioactive beam facility. Another application is in post-accelerators of radioactive ions based on charge breeders. The intensity of rare isotope beams can be doubled or even tripled by the extraction and acceleration of multiple charge state beams. Experimental results of multiple-charge state beam studies will be reported.

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CONCLUDING REMARKS

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Abstract

Concluding presentation for the workshop

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