COUPLING MICROWAVE POWER INTO ECR ION SOURCE PLASMAS AT FREQUENCIES ABOVE 20 GHZ

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Abstract

Electron Cyclotron Resonance (ECR) ion sources have been built to operate at frequencies from 5 GHz to 28 GHz and typically use a plasma chamber that serves as a multi-mode cavity. For small sources operating at 6 to 14 GHz cavity mode-like behavior has been reported. In these cavities the vacuum mode density is low enough that it may be that the RF power distribution can be understood in terms of excitation of a few modes. The large superconducting ECR ion sources, such as VENUS[1] operating at higher frequencies have a much greater mode density and very strong damping from plasma microwave absorption. In this type of source, how the RF is launched into the plasma chamber will strongly affect the microwave coupling and the chamber walls will be less important.

The VENUS source uses over-sized round waveguide excited in the TE_{01} to couple to the plasma, while most modern fusion devices use quasi-gaussian HE_{11} waves for injection into plasmas. In this paper we will describe the potential advantages of applying this technology to superconducting ECR ion sources as well as designs for doing so with VENUS.

INTRODUCTION

In an ECR ion source the microwave power couples to the electrons through electron cyclotron resonance heating. The electrons are confined by a solenoidal magnetic mirror in the axial direction and by a multipole field, typically a sextupole, in the radial direction. The combined magnetic fields produce a closed surface where electron cyclotron resonance frequency equals the applied microwave frequency. The coupling can be modeled in the case of very low plasma density and single particle models. [2,3] This is generally done by assuming a microwave field distribution that is independent of the plasma density. One approach used is to assume the microwave fields are those of an undamped microwave cavity and to then assume only a single mode is excited. [4] For a cylindrical cavity, the cavity modes can be calculated and the RF electric fields determined. The typical unloaded Q of such a cylindrical cavity with aluminum walls is in the range of 2000 to 4000. On the other hand the damping of the plasma can lower this Q_o significantly and this will decrease the RF stored energy and the resulting RF electric fields.

To date neither experimental measurements nor calculations using the best simulation codes can accurately predict the actual microwave field distribution or even the level of stored energy in a ECR ion source with plasma loading. It is difficult to probe either the plasma density or the RF field strength in an ECR ion source because if a probe is inserted into the chamber the hot electrons in the plasma will destroy it. With two microwave ports on the plasma chamber, both the reflected power on the input port and the transmitted out the second port can be measured. Since the stored microwave energy is proportional to the transmitted power, the relative stored energy versus time can be determined.[5] This was done with VENUS by injecting 18 GHz though the input port and detecting the transmitted power out the 28 GHz port. In Fig. 1 the time dependence of the reflected and transmitted microwave power is shown where the RF power is switched on at t equals 0 with zero plasma density in the chamber. The microwave fill time for the chamber is on the order of 1 μs while the plasma breakdown is on the order of 1 ms. At about 1 ms the plasma density increases rapidly and begins to load the cavity. At this point the transmitted power, which is proportional to the stored energy in the plasma chamber drops almost to zero as the plasma loading depresses it. At about 1.5 ms after some oscillations between the stored RF energy and the plasma density, the microwave fields reach a rough equilibrium. In the initial stage the empty plasma chamber acts as a high Q cavity (with a Q_o of a few thousand) and the high fields can produces a burst of hot electrons and ions in the preglow [6], but as the plasma loading builds up it drastically damps the RF stored energy by about 1/10 in this case. For CW operation, it is this reduced RF field

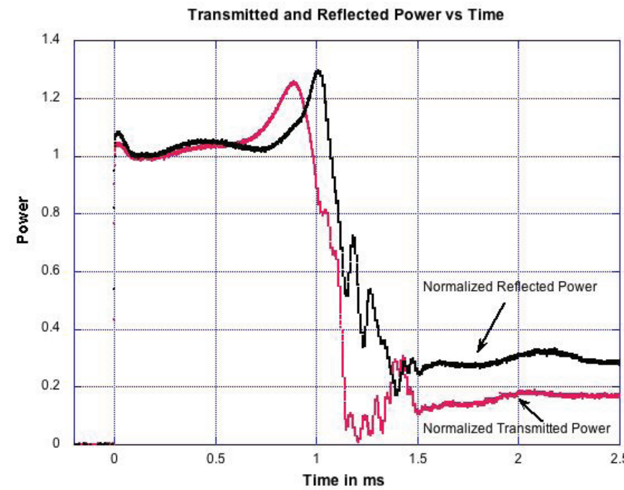

Figure 1: Time dependence of the reflected and transmitted 18 GHz power for the VENUS ECR ion source. At time t=0, the microwave power is switched on. As the plasma reaches maximum density at about 1 ms, the transmitted power decreases rapidly. Both reflected power and transmitted power are normalized to their initial values just after the power is switched on and before the plasma builds up.

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AN EXPERIMENTAL STUDY OF ECRIS PLASMA STABILITY AND OSCILLATION OF BEAM CURRENT*

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Abstract

The stability of ion beams extracted from ECR ion sources has been studied with the VENUS ion source at LBNL and the 14 GHz A-ECR at JYFL. Oscillations of the beam current in ~ kHz range are characterized with the Discrete Fourier transform. The effect of the ion source tuning parameters on the frequency and amplitude of the oscillations of various charge states is discussed. It was found that double frequency heating affects the oscillation frequency, the biased disc can be used to mitigate their amplitude, increasing B-minimum results to pronounced instabilities and operating the ion source with significantly higher mirror ratio than suggested by ECRIS scaling laws yields the most stable ion beams. It is argued that the observed beam current fluctuations are correlated with plasma processes.

INTRODUCTION

The stability of the ion beams extracted from ECR ion sources is important for accelerators, especially for high power linacs (e.g. FRIB) due to problems arising from fluctuating beam power and spill, medical applications (e.g. carbon therapy) and industrial applications. The stability of ion beams extracted from an ECRIS is determined by two factors; the long-term stability and rapid oscillations of the beam currents on a millisecond scale. This experimental study focuses on the fast oscillations presumably driven by plasma mechanisms.

EXPERIMENTAL RESULTS

The experiments were performed with the superconducting VENUS ECR ion source (see e.g. [1]) at LBNL and A-ECR type 14 GHz ECRIS at JYFL [2]. The temporal behavior of the beam currents for different charge states of oxygen (O^{2+} thru O^{7+}) was recorded with a resistor directly at the Faraday Cup. The VENUS microwave coupling system has both 18 GHz and 28 GHz waveguide antennas, which are used to inject power into the plasma chamber. The VENUS waveguide system has recently been reconfigured to measure cross coupling of 18 and 28 GHz with diode detectors as described in Ref. [3]. This feature was used for monitoring the 28 GHz power coupled out (transmitted) from the chamber through the 18 GHz waveguide port in order to correlate beam current fluctuations with properties of microwave-plasma coupling. The schematic of the experimental setup for VENUS is presented in Fig. 1. The setup used with the JYFL A-ECR is similar with minor exceptions. The beam stability data analysis procedure and experimental results are described hereafter.

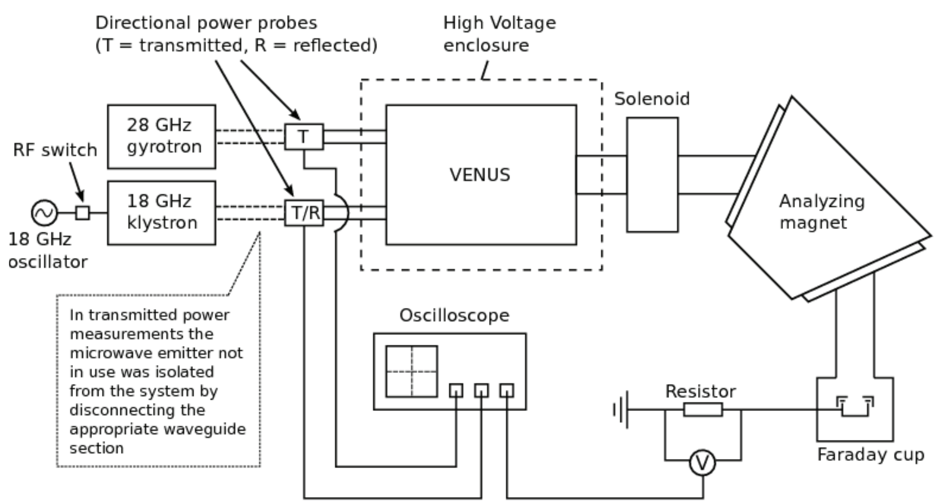

Figure 1: A schematic presentation of the experimental setup used with VENUS.

Data Analysis

The raw signals recorded from the Faraday cup in time domain were transformed to frequency domain with Discrete Fourier Transform (DFT) for further analysis. With VENUS the results were recorded with an oscilloscope (250 kHz sampling rate) and analyzed offline

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TWO-FREQUENCY HEATING TECHNIQUE FOR STABLE ECR PLASMA

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Abstract

Two frequency heating technique was studied to increase beam intensities for highly charged ions. The observed dependences on microwave power and frequency suggested this technique improves plasma stability but it requires precise frequency tuning. Although the mechanism is not clear, a high power travelling tube amplifier is promising for more improvement.

INTRODUCTION

In order to accelerate various ion species for basic experiments in e.g. biomedical and material science, physics and chemistry, two ECR ion sources and one PIG ion source are installed in the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS)[1]. Efforts to extend the range of ion species are continuously devoted, but more intense beams in excess of the present performance are desired for heavier ions like Xe or ions made from solid materials like Sn. In addition, a few carbon-ion radiotherapy facilities plan uses of some different ion species for fundamental researches. Since such experiments will be given a lower priority than the treatment, the diversion of existing hardware is expected. In the case of a typical hospital-specified facility, a charge-to-mass ratio as the injection condition into a linac is around 1/3. It means higher charge state ions are also required. For example, Ar^{13+} is required for some biological experiments.

Feeding RF power into an ECRIS at two frequencies was initiated by ECR pioneers Jongen and Lyneis in Berkeley, and some years later more successfully by Xie and Lyneis again in Berkeley[2]. So-called 'Two-frequency heating technique' has advantages; it is effective for any kinds of ion species, no modification of existing structure is necessary, and it is coexistent with almost other techniques. In early stages of our development, the enhancement of plasma region at different ECR zones was observed by the shapes of visible radiations[3]. The output currents had great dependence on additional microwave frequency[4]. However, the limited maximum power and bandwidth of an additional microwave constricted more detailed experiments.

A travelling wave amplifier system (TWT) recently has a capacity to feed larger power. A TWT with the frequency range from 17.75 to 18.25GHz and the maximum power of 700W was added to an 18 GHz ECR ion source called 'NIRS-HEC' with a krystron amplifier system (KLY) with a maximum power of 1500 W in 2007, then we studied the phenomena of two-frequency heating[5]. Table 1 shows maximum records of output currents of NIRS-HEC without two frequency heating technique. The underlined output currents were obtained with the afterglow technique. The output currents for ion species indicated in Italic have not routinely achieved the intensity requirement. The details of development on NIRS-HEC had been described in Ref. [6]

Table 1: Output Currents of the 18 GHz ECR Ion Source, NIRS-HEC Without Two Frequency Heating Technique

Ion	**Ar**		**Fe**	**Co**	**Ni**	***Ge***	***Kr***	***In***	***Xe***
m	40		56	59	58	74	84	115	132
q	8	13	9	9	10	28	15	20	21
I (eμA)	1100	20	<u>400</u>	160	<u>100</u>	*<u>50</u>*	*<u>200</u>*	*<u>140</u>*	*<u>200</u>*

DEPENDENCE ON MICROWAVE POWER

Dependence of Plasma Stability on Microwave Power

A beam intensity of highly charge state ions usually depends on the microwave power under a well-optimised condition. However, when the power increases, the plasma shows instability and it is difficult to keep. Figure 1 shows an example of plasma instability in the pulse shape of an extracted beam of Xe^{21+}. The left, centre, and right figures are obtained at the microwave power of 480, 720, and 960 W by KLY, respectively.

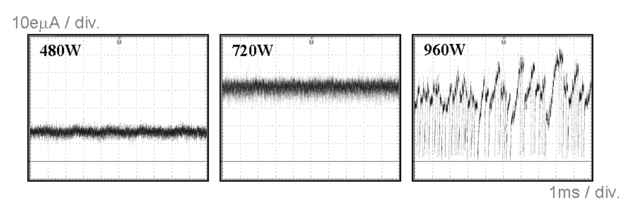

Figure 1: Example of plasma instability in the pulse shape of an extracted beam.

When an additional microwave is added in the above situation, the plasma instability is improved at larger microwave power obtained by the mixture of two different frequency microwaves.

Dependence of Beam Intensity on Microwave Power

Figure 2 shows the dependence of the beam intensity of Ar^{13+} on microwave power. A triangle, rectangle, and

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EXPERIMENTAL STUDY OF TEMPERATURE AND DENSITY EVOLUTION DURING BREAKDOWN IN A 2.45 GHz ECR PLASMA

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Abstract

An experimental study of temperature and density evolution during breakdown in off-resonance ECR hydrogen plasma by time resolved Langmuir probe diagnostic is presented. Under square 2.45 GHz microwave excitation pulses with a frequency of 50 Hz and relative high microwave power, unexpected transient temperature peaks that reach 18 eV during 20 μs are reported at very beginning of plasma breakdown. Decays of such peaks reach final stable temperatures of 5 eV at flat top microwave excitation pulse. Microwave coupling times are also measured in connection with plasma parameters evolution as function of duty cycles and incoming microwave power for two hydrogen working pressures.

INTRODUCTION

Understanding plasma physics processes during breakdown and decay in pulsed plasma sources is of special interest for many application fields as particle accelerator science, nuclear fusion reactors and plasma processing industry [1, 2]. An extensive research on this subject was conducted by different researchers with electrical probes, spectroscopy and radiation diagnostics under a wide range of parameters for different plasmas. Processes involved during breakdown should be determining for monocharged beam current optimization as well as the improvement of multiple charged ion production efficiency, both cases of great interest and under deep study in the ECRIS community [3, 4, 5]. In this work we present a study of breakdown process in off-resonance ECR hydrogen plasma by means of time-resolved Langmuir probe diagnostics and incoming and reflected microwave power measurements. The main goal is to improve our knowledge about evolution of plasma parameters during pulse mode operation helping to the design of ion sources at ESS Bilbao.

EXPERIMENTAL SETUP AND PROCEDURE

Measurements are made in a plasma reactor driven by a 3 kW adjustable output power magnetron of 2.45 GHz that is operated at 50 Hz in pulsed mode. Four coaxial coils with typical circulating currents of 10 amps produce an axial 120 mT off-resonance magnetic field. Such coils have a positioning mechanism to adjust the magnetic field distribution. On chamber diagnostic side a lid including pumping port, a fused silica observation window and a vacuum feed-through for probes are mounted. Such lid is placed where plasma electrode and extraction system would be placed in case of using this reactor as an ECRIS. Clearly our plasma reactor is an ECRIS reproduction without extraction electrodes. Fig. 1 shows a view of the experiment where the magnetic field system and diagnostic port side can be appreciated in first plane. The idea is to have a closed reproduction of ISHP ion source under development at ESS Bilbao [6] to use it as test bench for plasma research and optimization.

As is well-known in plasma community, Langmuir probes are used immersed in plasmas for acquiring characteristic I-V curves which permit to estimate plasma electron temperature and density. Time needed to make voltage sweep with acquisition of current values is always a limitation for time resolved measurements. However, several instrumentation companies have developed Langmuir probe systems that permit making transient studies of repetitive pulsed plasmas with some tens of ns resolution. These systems take first I-V point at one pulse; second one at following and so on, completing the voltage sweep in a predetermined number of pulses. In other words, each point at I-V curve belongs to different consecutive plasma pulses. When synchronization is carefully made checking during process if jitter is low enough, it is possible to have a good estimation of electron density and temperature at a precise predefined instant. In our case the system acquires an I-V point during 62.5 ns and after approximately 14.6 μs (time necessary for digitalizing and storing data) is ready to take

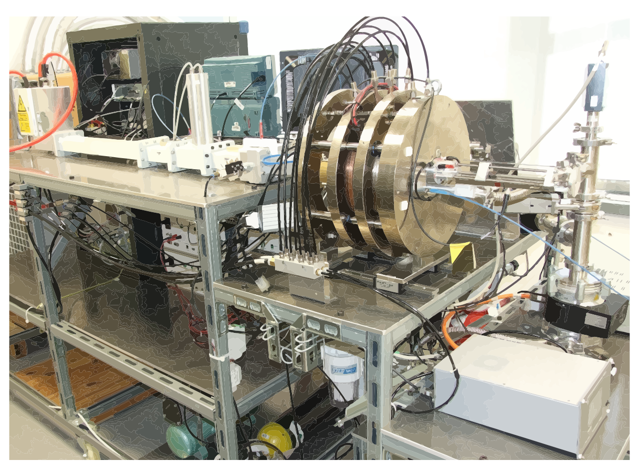

Figure 1: View of the experiment where the plasma reactor, magnetic coils and diagnostic port are shown in first plane.

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CONTROL OF THE PLASMA TRANSVERSAL LOSSES, CAUSED BY MHD INSTABILITIES, IN OPEN MIRROR MAGNETIC TRAP OF THE ECRIS: RECENT EXPERIMENTS ON SMIS 37 SETUP

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Abstract

This work is a continuation of the experiments described in [1, 2] and aimed at the investigation of the new conceptions of MHD stabilization of plasma in open axisymmetric traps, specifically, it is aimed at the investigation of the shear flow influence on the transport control in open mirror traps. As in previous experiments, shear flow was created by limiter-electrode with bias potential according to the vacuum chamber. Plasma density structure in radial and azimuthal directions was studied. Mode structure of the perturbations was investigated. Substantial sharp shift of the plasma density maximum to the system axis with bias potential growth was demonstrated. It was shown, that the value of the bias potential that corresponds to the plasma density profile shift grows with the magnetic field growth that can be interpreted as the electron temperature growth.

INTRODUCTION

Creation of the new generation of the ECR ion sources now is connected with an increase in the heating radiation frequency up to 56 GHz. In this case, the required value of the magnetic field in the trap can reach a value of 5 Tesla. The minimum B magnetic field configuration, which is traditional for the ECR ion sources, in the case of high values of the magnetic field is quite complicated, and now its creation requires a lot of efforts, whereas creation of a strong magnetic field in the axisymmetric magnetic trap is not a problem. That is why the stabilization of MHD perturbations in axisymmetric magnetic traps seems to be perspective. The advance in plasma stabilization using the shear flows achieved on the GDT (GasDynamic Trap, described in details in [3]) setup allows one to assume the same result in the case of the non-equilibrium plasma of the ECR ion sources. The essence of the method developed in Budker Institute consists in creation of a differential rotation zone at the periphery of the plasma column. It is obtained by the creation of the special (step-like) form of the radial profile of the plasma potential, which is achieved by using a system of special electrodes: radial limiters and bit-slice plasma receivers placed in the plasma expansion zone after the magnetic trap plug. This method now allows one to confine the plasma with $\beta \sim 0.6$ in the GDT in the stationary regime with a negligible level of the transverse losses.

In papers [1-2] mentioned method was for the first time tested for the plasma of the ECR discharge created by 37.5 GHz radiation (SMIS 37 setup, see Fig.1) in an axisymmetric magnetic mirror trap of multicharged ion source. A limiter with bias potential was set inside the vacuum chamber for plasma rotation. The limiter construction and the optimal value of the potential were chosen according to the results of the preliminary theoretical analysis. The increase in the limiter's potential up to the values of 70–100 V leads to a substantial (by approximately 3.5–4 times) increase in the entire amount of the ions leaving the trap through the magnetic plugs during one working pulse. That is the result of the increase in the plasma density and, probably, in the electron temperature in the trap. So, the confinement became better, which was interpreted as substantial suppression of the transverse losses. Measurements of ion spectra showed that the increase in the ion current couldn't be a result of additional flux of contaminations from chamber walls. Investigation of the time dependences of the ion current in the plasma decay regime demonstrated the decay time increase from 60 μs to 110 μs for the regime with improved confinement. This work is a continuation of the previous researches [1-2] and aimed on the further investigation of the shear flow influence on the transport control in open mirror traps of the ECR ion sources.

SMIS 37 EXPERIMENTAL FACILITY

The experimental investigations presented here were carried out on the SMIS 37 setup, which was described in details in [4]. The scheme of the setup is shown in Fig. 1. A gyrotron with the 100 kW power at 37.5 GHz, pulse duration up to 1.2 ms, and linear polarization of the radiation was used as an RF heating source. The plasma was confined in an axisymmetric open mirror trap. The pulsed magnetic field was created by two groups of solenoids. The duration of a current pulse with its form being close to a half-period of the sinusoid was 14 ms; the change in the value of the magnetic field during an RF pulse was less than 3%. The distance between the plugs was about 35 cm, and the mirror ratio was close to 5. The value of the magnetic-field intensity was 1.5-1.9 T at the

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SECONDARY-ELECTRON-ENHANCED PLASMA AS AN ALTERNATIVE TO DOUBLE/VARIABLE-FREQUENCY HEATING IN ECRIS

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Abstract

"Double Frequency Heating" (DFH) now has become the method of choice to optimize the output from the newest generation ECRIS installations. It was a challenge to compare this method with the comparatively cheap method of "metal dielectric" (MD) structure introduced into the plasma chamber, which has also proven to strongly enrich the plasma with electrons that are effectively trapped and heated. At the 14GHz ECRIS installation at Frankfurt, we have carried out a series of experiments using the two available RF-transmitters to launch two different frequencies into the IKF ECRIS. Due to restriction in the available frequency difference, the source could not be operated in real DFH-mode but was operated in "Frequency Tuning Mode" (FTM), for which also positive results are reported in literature. It turned out that the double RF-injection does not change the source performance substantially. The measured effects are in the order of 20% to 30% as reported elsewhere. In contrast to this, the enhancement gained by the MD method is much higher. The measured enhancement ratios even surpass those, reported for real double frequency heating.

INTRODUCTION

In order to increase the output, in particular of highly charged ions, from an ECRIS a number of techniques have been developed. One of these methods, DFH, is particularly suited for modern high power ECRIS installations with their ability to vary both the magnetic solenoid and multipole field of the source in a range appropriate to allow for resonance zones for both frequencies. First experiments with DFH were realized with second generation sources and were successful [1,2]. In order to apply DFH e.g. in a 14GHz source the RF-difference should be as large as 2 GHz. If the frequency difference is less than this value, one refers to this mode as "Frequency Tuning" (FT). Pioneering work on FT has been done by L. Celona, who developed FT as a powerful method to optimize the performance of electron cyclotron resonance ion source.[3]

At the 14GHz ECRIS of the Institut fuer Kernphysik Frankfurt (IKF), we have introduced the MD method to increase the output of highly charge ions from an ECRIS substantially [4,5]. The MD method is based on a development made at the Institute of Physics and Nuclear Engineering (INFIN), Bucharest, Romania.It consists in the production of metal-dielectric (MD) structures (Al-Al_2O_3 transitions) by a special electrochemical treatment of pure aluminium plates. The structures are characterised by high yields of secondary-electron emission under bombardment by charged particles (electrons/ions) from the plasma. The installation of MD-structures as wall coating into the plasma chamber therefore significantly enhances the density of plasma electrons n_e by injecting cold electrons to the plasma. At the same time the ion dwell times (ion confinement) are increased by blocking compensating wall currents, hence restoring the plasma ambipolarity. Due to this reduction in wall currents the method has also been shown to drastically reduce Bremsstrahlung radiation from the source, a limit that becomes more and more a problem in modern high power ECRIS devices.

In IKF we have two RF-transmitters available allowing to run the source in FT-mode. It therefore was a challenge to compare these two methods and in particular the possible benefit of FT-mode in an ECRIS with MD-configuration.

EXPERIMENT

The 14 GHz IKF ECRIS was operated in two different configurations, the standard (all stainless steel) mode of configuration, and the MD-mode, where the plasma chamber of the source was equipped with two MD-structures of 1 mm thickness. In MD-mode 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 stainless steel extraction electrode of the source. The emissive layers of both structures faced towards plasma.

Wave-guides for both available RF-transmitters have been launched to the injection plug of the source. The transmitters are a wider bandwidth TWT-amplifier and the narrow bandwidth Klystron-amplifier. In this configuration the minimum RF-difference of ~2 GHz, required for full DFH, could not be reached. Therefore the source was operated in FT-mode. The source geometries and the main electrical parameters were kept unchanged during all measurements. The extraction voltage was 15 kV and measurements were performed at RF power levels of 200 W to 1000 W. Tests were also performed up to 1500 W. Pure Argon was used as working gas. For the experiments reported here, the ion optical elements of the

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NEUTRAL GAS TEMPERATURE MEASUREMENTS OF A RADIO FREQUENCY MICRO-THRUSTER

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Abstract

A radio frequency (13.56 MHz) capacitively coupled cylindrical argon plasma discharge was analysed using optical emission spectroscopy (OES) for various powers and pressures in the ranges 5 W to 40 W and 0.5 Torr to 4 Torr. Trace amounts of nitrogen were added to the discharge to estimate the temperature of the neutrals using rovibrational band matching of the 2nd positive system of nitrogen. Comparing simulated computer generated spectra of these bands to experimentally measured spectra determined preliminary results for the rotational and vibrational temperatures of the nitrogen gas, from which the temperature of the neutrals was inferred by assuming the rotational temperature was the same as the neutral gas temperature.

INTRODUCTION

The development of increasingly smaller satellites and spacecraft has in turn developed a need for micro-thrusters that have low mass, volume and power consumption. Electric propulsion is favourable in such circumstances as the specific impulse is much higher than conventional chemical rockets [1]. Hall and gridded ion thrusters are current highly developed electric propulsion systems, however, these systems lose efficiency when scaled down [2]. Alternate options for electric micro-thrusters include resistojets and arcjets [1], hollow cathode thrusters [1,3] and radio frequency (RF) capillary discharge [4].

Another possible micro-thruster electric propulsion system consists of a capacitively coupled RF discharge (13.56MHz) within a tube with a 4.2mm inside diameter and 20mm length known as Pocket Rocket [5]. Gas, usually argon, is introduced to the system via an upstream plenum chamber with pressures around a few Torr. Electrodes placed around the Pocket Rocket tube create a cylindrical plasma discharge which is expanded into a vacuum. The discharge is weakly ionized (less that 1%) due to the higher pressures [6], therefore direct thrust from ion acceleration is negligible. However, the ions would typically reach a Bohm velocity in the order of 3000ms^{-1}, much greater than a typical thermal gas velocity of 300ms^{-1}. Charge exchange collisions between ions and neutrals may therefore result in neutral gas heating within the discharge and the thrust produced by the device will be increased over a cold gas thruster. Increased thrust from neutral gas heating makes Pocket Rocket a potentially viable micro-thruster for micro-satellites.

Previous experiments performed using a Langmuir Probe to determine the electron temperature of the Pocket Rocket discharge estimate the neutral gas temperature as 3200K at 10W and 1.5 Torr [6]. In the same paper, power coupling calculations relating the input power to discharge velocity estimated the neutral gas temperature for the same conditions much lower at 1430K.

To determine the temperature of the neutrals in the discharge, a non-invasive spectroscopy method was used where a small amount of nitrogen gas added to the discharge produces rovibrational spectral bands. The measured bands can be compared to simulated spectra to determine the rotational and vibrational temperature of the nitrogen molecules, from which the neutral gas temperature is inferred as the rotational temperature. This technique has been previously used to determine the temperature of similar discharges [7,8].

EXPERIMENTAL SETUP

The Pocket Rocket device, as shown in Figure 1(a) consists of a 4.2mm inside diameter, 1.3mm thick, 20mm long alumina tube. Argon gas is introduced to the system through an upstream plenum chamber with a diameter of 40mm and a length of 12mm. A 6mm wide copper electrode surrounds the tube at the midway point with two 3mm wide copper grounded electrodes placed either side at a distance of 3mm, creating a capacitively coupled discharge inside the tube. The discharge expands into a 750mm long, 50mm diameter evacuated glass tube which is itself attached to a vacuum chamber (160mm diameter, 300mm length) equipped with a primary rotary oil pump. A Convectron gauge measures the pressure in the upstream plenum, while a Baratron gauge measures the pressure in the vacuum chamber. The base pressure in Pocket Rocket is in the order of 10^{-3} Torr. Operating pressures measured in the plenum chamber ranged from 0.5 Torr to 4 Torr, resulting in vacuum chamber pressures approximately 2.2 times lower, from 0.2 to 1.8 Torr.

Power from an RF generator (13.56MHz) ranging from 5-40W is coupled to the system through a pi-matching network. The current and voltage supplied to the electrode are measured using a Rogowski coil and a 1/1000 high voltage probe respectively. In addition, a Bird power meter and standing wave ratio (SWR) meter are inserted between the RF generator and the matchbox to measure the forward and reflected power.

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DETAILED INVESTIGATION OF THE 4D PHASE-SPACE OF AN ION BEAM

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Abstract

A second order transfer matrix is calculated, which is used in the calculation of a 4D phase-space distribution of a 24.6 keV He^{1+} beam. The calculated distribution matches a 4D phase-space distribution measured with the KVI pepper pot emittance meter. The pepper pot emittance meter is installed in the image plane of a dipole magnet acting as a charge-state analyser directly downstream the KVI AECR ion source. From the second order transfer matrix simple analytical equations are derived by retaining the terms for angular coefficients. These simple equations describe the main features of the phase-space correlations in the image plane. The equations show also that the subset of the 4D phase-space distribution, selected by one pepper pot aperture, results in multiple beam-lets. Due to this successful matrix modelling we conclude that the 4D phase-space distribution measured is fully determined by the ion-optical properties of the magnet.

INTRODUCTION

At KVI we have investigated the low transmission efficiency of the low-energy injection beam line of the superconducting cyclotron AGOR. For this investigation a pepper pot emittance meter [1] has been developed. With such an instrument the 4D phase space distribution was measured of a 24.6 keV He^{1+} beam in the image plane of the dipole charge-state analyzing magnet of the AECR ion source. In the measured response distribution multiple beam-lets were seen. Using second order matrix calculations of the setup a method has been developed to describe the measured phase-space distribution in a simple way. In the section 'transfer matrix' the Taylor expansion into second order is presented which can be written as an second order matrix. In the section 'simplification' simple analytical expressions are derived which reproduce the main features of the correlations. In the section 'measurements' we shown that the simple expressions describe the distributions in the projections of the measured 4D phase-space.

TRANSFER MATRIX

For the determination of the second order matrix we use the COSY Infinity 9.1 [2] code. The code is based on the principle that Taylor expansion coefficients are calculated to describe the action of ion optical elements on the phase-space coordinates in a curvilinear coordinate system. The code includes the technique of differential algebra in the numerical integrations, which permits the computation of Taylor expansions coefficients into arbitrary order. With the code a second order expression (see Eq. 1) is derived which maps the 4D state vector (x, x', y, y') of the beam from point A in an object plane to a position B in the image plane.

$$\begin{aligned}\theta_1 &= (\theta|x)x_0 + (\theta|x')x'_0 + (\theta|y)y_0 \\ &+ (\theta|y')y'_0 + (\theta|xx)x_0^2 + (\theta|xx')x_0x'_0 \\ &+ (\theta|x'x')x'^2_0 + (\theta|xy)x_0y_0 + (\theta|x'y)x'_0\,y_0 \\ &+ (\theta|xy')x_0y'_0 + (\theta|x'y')x'_0\,y'_0 \\ &+ (\theta|yy)y_0^2 + (\theta|yy')y_0y'_0 + (\theta|y'y')y'^2_0\end{aligned} \quad (1)$$

In this expression the θ_1 can be replaced by the coordinate x_1, x'_1, y_1 and y'_1 in the image plane. The terms within the bracket are the expansion coefficients. The values of these coefficients are calculated with COSY Infinity 9.1 and are shown in Table 1. They depend on drift spaces, dipole geometry and fringe fields. The dimensions of the experimental setup and main features of the magnet are described elsewhere [3].

As initial conditions in the transformation, the ions start from a small point source (ø 2mm) in a virtual object plane under random angles r'_0 with the beam axis not exceeding 64 mrad. This angle r'_0 represents the initial transversal momentum of an ion.

$$r'^2_0 = x'^2_0 + y'^2_0 \quad (2) \qquad E_t = \tfrac{1}{2} m r'^2_0 \quad (3)$$

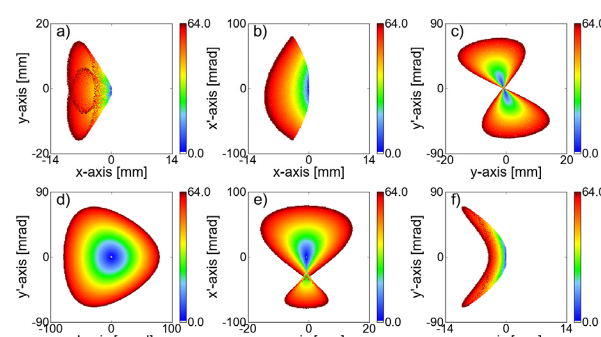

Figure 1: Calculated correlations of the initial transversal momentum r'_0 and the following combination of phase-space coordinates in the image plane: a) x-y, b) x-x', c) y-y', d) x'-y', e) y-x', e) x-y'. The colour code represents the initial transversal momentum r'_0.

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NEW EXTRACTION DESIGN FOR THE JYFL 14 GHz ECRIS*

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Abstract

A new extraction system has been designed and constructed for the JYFL 14 GHz ECRIS at the Department of Physics, University of Jyväskylä (JYFL). The goal of the new design was to improve the performance of the ion source and increase the transmission efficiency of the low energy beam transport and the accelerator by being able to handle higher beam currents, yield better beam quality and offer more tuning flexibility. The design is based on simulations with the IBSimu code. The suitability of the code for this task was verified by simulating the old extraction system resulting to good agreement between simulations and measurements. The new design, simulations and the first experimental results are presented.

INTRODUCTION

In order to improve the "ion source-to-target" performance at JYFL (Department of Physics, University of Jyväskylä), the low energy beam transport (LEBT) section of the beam line from the JYFL 14 GHz ECRIS [1] to the K-130 cyclotron will be upgraded in intermediate steps. The first section of the JYFL LEBT is presented in Fig. 1. Designing and constructing a new extraction system for the JYFL 14 GHz ECRIS is the first step of the project. This upgrade aims to make the ion source extraction more flexible and offer better ion beam starting conditions to facilitate further beam line modifications. Better beam quality and overall performance of the ion source, especially with high extracted total beam currents, are also desired.

SIMULATIONS

The new extraction system was designed by computer simulations with the IBSimu code [2] developed at JYFL. The code is capable of modeling extraction of multiple ion species in the presence of external magnetic field and strong space charge, which are the conditions normally present with ECR ion sources. However, the positive plasma model used by the code does not exactly match the complicated plasma conditions of ECR ion sources, a feature that has proven challenging for simulation codes. To study the feasibility of the code for ECRIS conditions the old extraction geometry was first modeled with IBSimu and the results were compared with measurements.

* This work has been supported by the EU 7th framework programme "Integrating Activities - Transnational Access", project number: 262010 (ENSAR) and by the Academy of Finland under the Finnish Centre of Excellence Programme 2006 - 2011 (Nuclear and Accelerator Based Physics Research at JYFL). VT acknowledges the support of the Ehrnrooth foundation.

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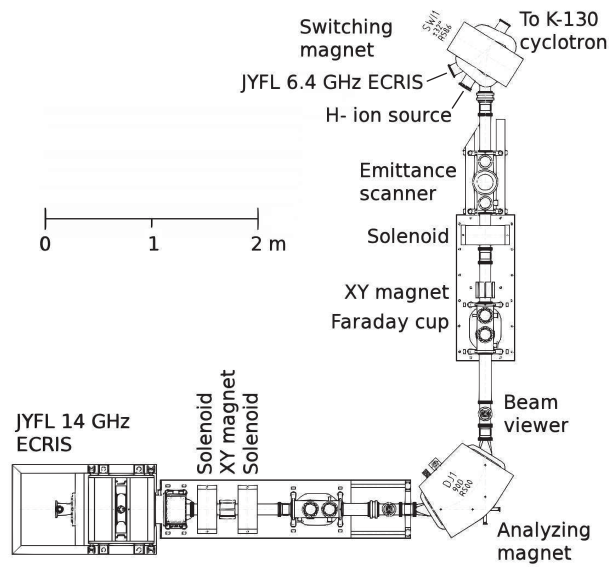

Figure 1: First section of the JYFL LEBT beginning from the JYFL 14 GHz ECRIS.

Old Extraction Design

Figure 2 shows simulation result of the original extraction geometry of the JYFL 14 GHz ECRIS with 1 mA of argon beam and optimum tuning. The beam includes charge states 1+ to 16+ with their ratios taken from measured charge state spectrum. Charge states 17+ and 18+ are omitted due to negligible beam currents. According to the simulations, the extraction system is barely able to handle the extracted beam. The outermost parts of the beam are collimated at the puller face and at the last grounded electrode of the Einzel lens. The beam exiting the extraction ($x = 0.525$ m in Fig. 2) is large, about 65 mm in diameter (FWHM of the profile) and rather divergent with maximum half-axis divergence of about 60 mrad. These values match well with the (64 ± 1) mm diameter and (60 ± 10) mrad half-axis divergence measured at the same location after the extraction with identical settings.

Increasing the current extracted from the plasma increases the simulated beam size due to space charge growth, leading to increased beam losses and a substantial drop in transmission through the extraction region (see Fig. 3). As a consequence, the total beam current leaving the extraction remains roughly constant at the level of $\sim$1 mA but the beam quality and profile are degraded. These results agree well with the experimental observation of degraded beam transmission with high total extracted currents in excess of 1 mA [3]. The collimation of the beam has been

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SPACE CHARGE COMPENSATION MEASUREMENTS OF MULTI-CHARGED ION BEAMS EXTRACTED FROM ECR ION SOURCES

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Abstract

In this contribution, we present measurements of the beam potential performed after the extraction region of ECR ion sources in dependence of the base pressure in the beam line and other parameters, e.g. total extracted current, using a Retarding Field Analyzer (RFA). If the beam current and the beam profile are known, it is possible to infer the level of space-charge compensation from the measured beam potential distribution. Preliminary results are discussed and compared to simulations.

INTRODUCTION

Space-charge compensation in beam lines due to the interaction of the beam with residual gas molecules is a well-known phenomenon for high current injector beam lines. When the beam interacts with the residual gas in the beam line, electrons are separated from gas molecules by charge-exchange processes and accumulate inside the beam envelope, while the ions created in the process are expelled by the positive beam potential. This lowers the space-charge potential of the beam and is called space-charge compensation or - neutralization. In [1], Soloshenko investigates the simple case of space charge compensation for the stable stationary beam. A steady-state is defined for the beam, where the rates of electrons created/entering the beam and leaving the beam are equal. Electrons captured inside the beam may gain enough energy to leave through Coulomb collisions with the beam ions themselves and through collective processes. Considering also the energy balance of the electrons, Soloshenko arrives at the following expression for the potential difference of beam center and and beam edge ($\Delta\phi = \phi_{center} - \phi_{edge}$):

$$\Delta\phi = \sqrt{3\mathcal{L}}\left(\frac{M}{m}\right)^{1/2}\left(\frac{\varphi_i}{V_0}\right)^{1/2} n_+^{1/2}\left(\frac{1}{n_0\sigma_e}+\frac{v_+\sigma_i r_0}{2v_i\sigma_e}\right)^{1/2}\cdot e$$

Where $\mathcal{L} = 2\pi\Lambda$ with Λ a Coulomb logarithm, r_0 the beam radius, φ_i the gas ionization potential, M the beam ion mass, eV_0 the beam ion energy, $v_{i/+}$ the plasma ion/beam ion velocities, $\sigma_{i/e}$ the ion/electron originating cross-sections and $n_{0/+}$ the residual gas/beam ion densities. By investigating the balance of the two terms in the sum he concludes that for low pressures we can expect a decrease in $\Delta\phi$ with increasing pressure, whereas for high pressure, $\Delta\phi$ reaches its minimum and becomes essentially independent of the pressure (see [1] for more details).

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In addition, ions hitting apertures, charged electrodes, ion optics elements and beam line coatings can influence the creation and loss of compensation electrons greatly and have to be taken into consideration.

For beam lines using mostly magnetic focusing elements and for pressure around 10^{-5} Torr, almost full compensation has been predicted [1] and observed [2]. However, due to the low pressure (typically 10^{-7} to 10^{-8} Torr) required for the efficient transport of high charge state ions, ion beams in ECRIS injector lines may be only partly neutralized and space charge effects may be present. With the dramatic performance increase of the next generation Electron Cyclotron Resonance Ion Sources it is possible to extract tens of mA of beams from ECR plasmas [3]. In this high current regime, non-linear defocusing effects due to the space-charge potential of the beam become more and more important. In order to develop a realistic simulation model for low energy beam transport lines, it is important to estimate the degree of space charge compensation along the Low Energy Beam Line (LEBT).

HARDWARE

ECR Ion Sources

This type of ion source is described in great detail elsewhere [4]. One point to be made, though, is that the plasma from which the ions are extracted is confined by a strong magnetic field, which is usually a superposition of a solenoid field (longitudinal confinement) and a sextupole field (radial confinement). For special applications, however, (e.g. high currents of protons) it is preferable to use only the solenoid magnets (e.g. LEDA source, see below). In this context it is important to mention that the sextupole field has great influence on the shape and behavior of the extracted beam. While beams from sources using only solenoids are typically radially symmetric (uniform or Gaussian beam profile), ECR beams from sources using sextupoles exhibit a triangular or star-shaped cross-section [5, 6]. The triangular shape and intrinsic sextupole moment of the beam has been subject to research for many years now and has to be taken into account when designing the LEBT of an ECRIS. It might also influence the measurement of beam neutralization with an RFA as will be seen later.

SuSI

The Superconducting Source for Ions is one of the injector sources of the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. As the name suggests, the magnetic fields are provided by a set of superconducting

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QUANTITATIVE DETERMINATION OF ^{146}SM/^{147}SM RATIOS BY ACCELERATOR MASS SPECTROMETRY WITH AN ECR ION SOURCE AND LINEAR ACCELERATION FOR ^{146}SM HALF-LIFE MEASUREMENT

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Abstract

The alpha-decaying ^{146}Sm nuclide is used for chronology of the Solar System and silicate mantle differentiation in planets. We performed a new determination of ^{146}Sm half-life by measuring ^{146}Sm/^{147}Sm alpha activity and atom ratios in ^{147}Sm activated via (γ,n), (n,2n) and (p,2$n\varepsilon$) reactions and obtained a value (68 Myr), smaller than that adopted so far (103 Myr), with important geochemical implications. The experiment required determination of ^{146}Sm/^{147}Sm ratios by high-energy (6 MeV/u) accelerator mass spectrometry to discriminate ^{146}Sm from isobaric ^{146}Nd contaminant. Activated Sm targets were dissolved, chemically purified and reconverted to metallic Sm. Sputter cathodes, made by pressing the Sm metal into high-purity Al holders, were used to feed the Argonne Electron Cyclotron Resonance (ECR) ion source. ^{146}Sm^{22+}, ^{147}Sm^{22+} ions were alternately injected and accelerated with the ATLAS linac by proper scaling of ion source and accelerator components. A tightly-fitted quartz cylindrical liner was inserted in the ECR plasma chamber to reduce contamination from the walls. ^{146}Sm ions were eventually counted in a gas-filled magnet and ^{147}Sm ions either measured as charge current or counted after proper attenuation.

INTRODUCTION

The extinct p-process nuclide ^{146}Sm ($t_{1/2}$= 103 ± 5 Myr [1,2]) was live in the early Solar System, as established through isotopic anomalies of its α daughter ^{142}Nd, first observed in meteorites [3]. The data have been used to estimate a time interval (≈ 70 Myr) between isolation of the Solar Nebula from the interstellar medium and the start of formation of the Solar System [4]. ^{146}Sm acts also as an important geochronometer for the early silicate differentiation in planetary bodies (meteorite parent bodies, Earth, the Moon and Mars, see [5] for a recent review of the field).

The ^{146}Sm half-life which is a crucial component in these applications has been measured four times with values of ~50 Myr [6], 74 ± 15 Myr [7] and 103 ± 5 Myr [1,2]. Considering the range of these values, we have performed a new determination of ^{146}Sm half-life [8] by measuring both the α activity ratio (A_{146}/A_{147}) and the atom ratio (N_{146}/N_{147}) in samples prepared from activated ^{147}S material. The half-life ($t^{146}_{1/2}$) is obtained through the expression

$$t^{146}_{1/2} = \frac{A_{147}}{A_{146}} \times \frac{N_{146}}{N_{147}} \times t^{147}_{1/2},$$

where $t^{147}_{1/2}$ denotes the α-decay half-life of naturally occurring ^{147}Sm ($t^{147}_{1/2}$ = 107 ± 0.9 Gyr, [9]). The ratio measurement eliminates most systematic α-activity uncertainties due to detector efficiency and geometrical acceptance. We focus in this contribution.on the use of the ECR ion source at the ATLAS facility for accelerator mass spectrometry (AMS) in order to measure N_{146}/N_{147} atom ratios. The high charge states produced in the ECR ion source allow us to accelerate Sm ions at energies of about 6 MeV/u with the ATLAS superconducting linear accelerator for unambiguous ion identification and also eliminates any stable molecules in the injected beam, two basic properties of AMS [10]. Ion identification was considered important in this experiment because of the need of ^{146}Sm discrimination against stable isobar ^{146}Nd.

EXPERIMENTAL SETUP

Samples of ^{146}Sm to be used in the AMS measurements were prepared from three different activations of enriched ^{147}Sm targets (^{147}Sm(γ,n)^{146}Sm, ^{147}Sm(p,2$n\varepsilon$)^{146}Sm and ^{147}Sm(n,2n)^{146}Sm, see [11,12] for details). Following the measurement of the α activity, the sources were dissolved and quantitatively diluted with high-purity ^{nat}Sm to obtain ^{146}Sm/^{147}Sm ratios in the range 10^{-7}-10^{-9}.

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INTEGRATION OF A THIRD ION SOURCE FOR HEAVY ION RADIOTHERAPY AT HIT

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Abstract

HIT is the first European hospital based facility for scanned proton and heavy ion radiotherapy. In 2009 the clinical operation started, since then more than 1000 patients were treated in the facility.

In a 24/7 operation scheme two 14.5 GHz electron cyclotron resonance ion sources are routinely used to produce protons and carbon ions.

In the near future a helium beam for regular patient treatment is requested. The modification of the low energy beam transport line (LEBT) for the integration of a third ion source into the production facility was done in winter 2011. For beam quality improvement with a smaller emittance at the same current we designed and tested a new extraction system at the testbench and equipped the source for protons and helium with this optimized system. This paper will present results of the LEBT modification and give an outlook to further enhancements at the HIT ion source testbench.

INTRODUCTION

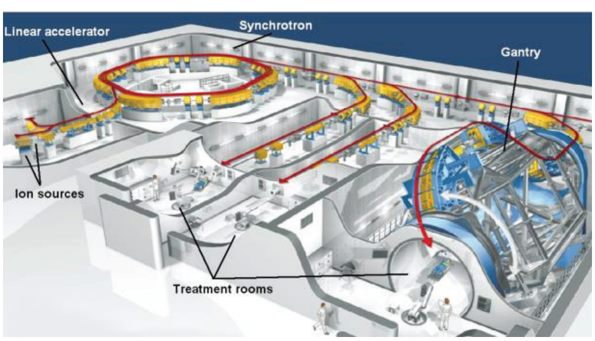

Figure 1: Overview of the HIT facility.

Since November 2009 more than 1000 cancer patients have been treated at HIT (see Fig.1) with carbon ions and protons [1, 2]. The increasing interest in the treatment with helium ions, especially for paediatric tumours [3], in addition with the requirement for fast switching between carbon ions, protons and helium ions triggered the design of a third independent spectrometer line and a new ion source.

LEBT MODIFICATION

The motivation for the new design of the LEBT beam line is based on the desire for higher beam brilliance and thus increased intensities for the upcoming clinical applications. The geometry of the available LEBT-room and the necessary space for a third source was an additional reason. Figure 2 and 3 is the status shown before winter 2011.

Figure 2: The existing low energy beam line (LEBT) before winter 2011.

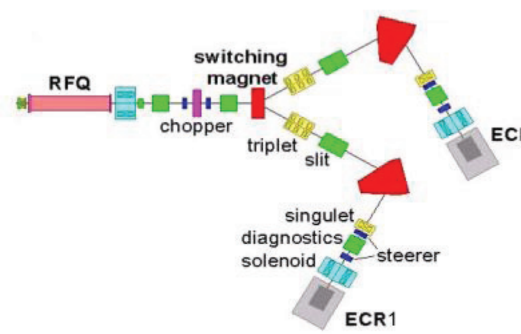

Figure 3: Schematic drawing of the LEBT before winter 2011.

The major improvement is motivated by the large emittance and the resultant poor transmission for the low LET beams especially protons through the LEBT.

TESTBENCH

To improve and test the possible LEBT setup with the requirement to integrate a third ion source in the production facility we build up a testbench with the following setup (Fig. 4): ECR ion source with extraction system (einzel lens), horizontal/vertical pair of steerers, 90° double focusing analyser dipole, beam diagnostics chamber with profile grid and Faraday cup, DC transformer, emittance measuring system (slit/grid) and Faraday cup. The emittance measurement analyser is a

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DESIGN OF A COMPACT ECR ION SOURCE FOR VARIOUS ION PRODUCTION

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Abstract

Carbon ion therapy facilities need not only carbon ions for medical use but also other ions for research. Ion source is required: 1) H to Fe ion production, 2) enough intensity of various ions for medical use and research, and 3) low cost. Our previous compact ECR ion sources (Kei series) are optimized for carbon ion production. In order to produce various ion beams, we design a new compact ECR ion source, named Kei3, based on previous Kei series. Manufacturing of the Kei3 will be finished in end of this year.

INTRODUCTION

Carbon ion radiotherapy is started in 1994 by the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS). The total number of patients reached to 6,500 and various types of tumor have been treated. NIRS carried out R&D studies for various components and designed a hospital-specified carbon ion radiotherapy facility [1]. The construction of the Gunma University Heavy Ion Medical Centre (GHMC [2]) was funded by the Japanese government and Gunma prefecture beginning in 2006, and construction started in 2007 at the Centre site in Maebashi, Gunma. The technologies concerned were transferred from NIRS to Gunma University. Gunma University already started a clinical trial since March 2010.

Compact ECR ion source with all permanent magnets, named Kei2, was developed for high energy carbon ion therapy facility at NIRS. Kei2 source was designed for producing enough intensity of carbon ion for medical treatment. A compact ECR ion source for GHMC, the KeiGM, is also based on the development of the compact ECR ion sources (Kei series) at NIRS [3]. These ECRISs are developed for production of C^{4+} ions for medical treatment. Table 1 shows beam intensity of H_3^+, $^{11}B^{4+}$, $^{12}C^{4+}$, $^{16}O^{6+}$, $^{40}Ar^{11+}$, and $^{56}Fe^{13+}$ ions by prototype Kei2 source at 30 kV extractions. Ion source parameters (microwave power and frequency, gas flow, biased disk voltage and position) were tuned for each ion. In the case of bigger q/A than 1/3, beam intensity was reached requirement value. However, in the case of smaller q/A than 1/3 and molecule ions, sufficient intensity was not obtained. Kei series were designed for production of C^{4+} ions. Therefore, it is difficult to produce enough intensity of heavier ions and molecule ions.

Some carbon ion radiotherapy facilities need to use H to Ne ion beam for biological experiment like irradiation of mouse, Ar and Fe beam for irradiation of cells and physical experiment. In order to produce various ion beams, we design a new compact ECR ion source, named Kei3. Kei3 is designed based on previous Kei series. Target ion species are molecule hydrogen to iron. Charge to mass ratio of ion is up to 1/3, because, we don't want to change the injector linac. Therefore, ion source has to produce H_3^+ to Fe^{19+} ions.

Table 1: Beam Intensity of Various Ions at Kei2

Ion	Required intensity [eμA]	Kei2 intensity [eμA]	Material
H_3^+	500	270	H_2 gas
$^{11}B^{4+}$	100	120	$C_2H_{12}B_{10}$
$^{12}C^{4+}$	200	680	CH_4 gas
$^{16}O^{6+}$	100	60	O_2 gas
$^{40}Ar^{11+}$		2.5	$Ar + O_2$ gas
$^{56}Fe^{13+}$		0.5	Metal iron +He gas

DESIGN OF THE KEI3

There are five important points for improvement from Kei2: 1) Same magnetic field and microwave system will be used for easy maintenance and the cost effectiveness, 2) Improve the vacuum in the plasma chamber and extraction region for production of heavier ion and increase the extraction voltage, 3) Movable beam extraction system for various extraction current densities, 4) Biased disk method and double frequency heating method for heavier ions, and 5) An evaporator and MIVOC method for production of ion from solid materials and metal. Figure 1 shows schematic drawing of Kei3 source. The Kei3 has an outer diameter of 280 mm and a length of 1120 mm. Kei3 consists of injection side vacuum chamber, permanent magnets and plasma chamber, and extraction side vacuum chamber with extraction system. The magnetic field was copied from Kei2 [4]. Magnetic field of upstream mirror peak, downstream peak and minimumB are 0.877 T, 0.579 T and 0.26 T, respectively. Based on experimental studies with a conventional 10 GHz ECR source [5] at HIMAC, the field distribution of the mirror magnet for compact source was designed so that a charge distribution of carbon ions was optimized at 4+. Radial magnetic field by hexapole magnet on the plasma chamber wall is 0.757 T.

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CHARGE-BREEDING AT THE TEXAS A&M UNIVERSITY CYCLOTRON INSTITUTE *

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Abstract

The Cyclotron Institute of Texas A&M University is currently involved in an upgrade that is intended to produce beams of radioactive ions suitable for injection into the K500 superconducting cyclotron. As an integral part of this upgrade an electron-cyclotron-resonance ion source (CB-ECRIS) has been specially constructed for charge-breeding. This CB-ECRIS incorporates a hexapole of the Halbach style. Since radial injection of microwave power is ruled out, this presents special problems for the axial injection of low-charge-state ions for charge-breeding. In preparation for the injection of radioactive ions, low charge-state rubidium ions have been successfully charge-bred and subsequently accelerated by the cyclotron.

INTRODUCTION

Reference 1 gives a complete description of the Texas A&M upgrade. As part of the upgrade the K150 cyclotron has been re-commissioned to use as a driver for the production of radioactive ions. The primary method is to first stop radioactive products from beam-target collisions in a helium-filled cell and then to transport them as low-charge-state ions. For products resulting from K150 light-ion beams, Texas A&M is developing a suitable light-ion guide (LIG). For products resulting from K150 heavy-ion beams, a heavy-ion guide (HIG) based on the ion-guide program at Argonne National Laboratory is also being developed. These low-charge-state ions will be injected into an ECR ion source (CB-ECRIS) for charge-breeding to higher charge states. A beam of ions of one selected charge-state will then be transported to the injection line of the K500 superconducting cyclotron and finally accelerated by the K500. Figure 1 illustrates the scheme including the driver K150 cyclotron.

CHARGE-BREEDING

Charge-breeding of ions injected into an ECR ion source presents special problems. The goals are first efficiency and second fast breeding times, holding radioactive species in mind. Efficiency depends upon, among other things, matching the injected beam to the optical acceptance of the source. Also, as when in our case injection occurs opposite to extraction in the ECRIS, efficiency depends upon minimizing losses due to charge-bred ions lost to extraction back along the injection path. For acceptable efficiencies optical matching and minimizing losses must be made compatible.

*Work supported by U. S. Dept. of Energy Grant DE-FG02-93ER40773

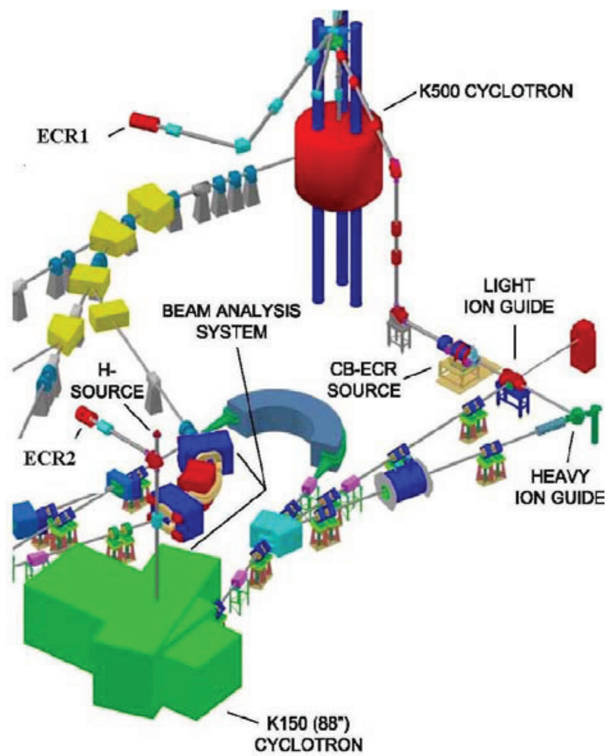

Figure 1: Layout of the Texas A&M Radioactive Beam Facility.

CB-ECRIS

The 14.5 GHz CB-ECRIS was designed and built by Scientific Solutions of San Diego, California with a Phase I and a Phase II Small Business Innovative Research grant from the U. S. Department of Energy [2] and first operated in 2009 [3]. The 9 cm ID, aluminum plasma chamber is surrounded by a Halbach style, NdFeB, permanent-magnet hexapole with a peak field of 1.1 Tesla at the inner wall. The two copper axial coils are encased in steel yokes and are capable of producing peak confinement fields of 2.5•B(ECR) at 500 A of excitation.

Injection of Singly-Charged Ions

At present an aluminosilicate ion gun manufactured by HeatWave Labs, Inc. for the production of a low intensity beam of singly charged alkali ions is being used to test charge-breeding. In the injection path are an electrostatic x-y steerer [4], an Einzel lens, a Faraday cup, a grounded, funnel-shaped tube and a separately biased tube

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DESIGN OF THE AISHA ION SOURCE FOR HADRON THERAPY FACILITIES

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Abstract

Different facilities for hadrontherapy have been built or designed in the recent past and Italy is present in the field either with synchrotron-based and with cyclotron-based facilities. For both types of accelerators the availability of high brightness multiply charged ion beams is essential and R&D efforts in this subject are increasing. At CNAO, proton and carbon ion beams will be accelerated up to 400 AMeV by a synchrotron and the beam injection is guaranteed by two identical ECR sources of the SUPERNANOGAN family modified according to the specifications we set. Optimisation of beam emittance and intensity is of primary importance to obtain the necessary current in the RFQ-LINAC and future facilities may require much better performances in terms of beam brightness than the ones provided by such commercial ECRIS. A hadron therapy center is going to be built in Catania and the R&D related to the injector has already started within the frame of a collaboration between the Sicilian Authority and INFN. The design of a relatively compact ECR ion source operating at 18 GHz, named AISHa, has been completed recently and the construction will start at the end of 2012.

INTRODUCTION

The AISHa ion source has been designed by keeping in mind the typical requirements of hospital-based facilities, where the minimization of the mean time between failures (MTBF) is a key point together with the maintenance operations which should be fast and easy. Therefore, a so-called 3rd generation ECR ion source is not suitable, being quite complex for unskilled operators.

The new AISHa source is designed to be an intermediate step between the 2nd generation ECRIS (unable to provide the requested current and/or brightness) and the 3rd generation ECRIS (too complex and expensive).

It is intended to be a multipurpose device, operating at 18 GHz instead of 14 GHz in order to achieve higher plasma densities. It should provide enough versatility for future needs of the hadron therapy, including the ability to run at larger microwave power to produce different species and higher charge states than it is now for C^{4+}. At the same time, the electrical power to be installed for its operation will be kept below 50 kW, for possible installation on high voltage platforms. This demand implies also the simplification of all ancillary systems including an oven for metallic ion beams, which is interesting for new beam for hadrontherapy and for other applications.

The AISHa source is funded within the framework of the program of Sicilian Government named PO FESR 2007-2013 and a pool of Sicilian SME is associated with INFN for this project. The source is potentially interesting for the hadrontheraphy center to be built in Catania (call in progress) and for the CNAO (Pavia), which is the only operational Italian center for deep hadrontherapy at this date. In fact, it aims to offer treatments with active scanning both with proton and carbon ion beams, accelerated up to 400 MeV/amu by a synchrotron. Actually, at CNAO two ECR sources of the SUPERNANOGAN type (built by the Pantechnik company according to specifications set by INFN) are used. The factory tests confirmed the fulfilment of the specifications in terms of beam current and emittance. A further increase of accelerator reliability involves the improvement of the beam brightness, which can be achieved with the design and construction of this new ECR ion source.

MECHANICAL DESIGN AND BEAMLINE

The plasma chamber design is particularly important because its dimensions determine the plasma dynamics and the microwave coupling, while on the other way its larger dimensions may increase dramatically the construction costs. Since highly charged ions are not required to be produced (highest charge state requested do not exceed 6^{+}), the source can be designed with a short plasma chamber.

This will also reduce the number of high energy electrons, with a general improvement of source stability and reliability. Mechanics is essential for reliable operations; the perfect water-cooling permits to avoid hot spots which deteriorate the vacuum, making the beam less stable and the emittance larger and variable with the time.

The plasma chamber will be stainless steel made and it should operate at a maximum power rate of 2 kW by using double wall water-cooling . The insulation will be adapted to 40 kV operation by means of a 4 mm thick PEEK tube surrounding the hexapole, keeping magnets and yoke at ground potential. Polishing of any surface is requested in order to avoid sparks. This value of insulation will permit to adapt the AISHa source to other facilities (e.g. the high voltage platform for INFN-LNL). A new type of dc break has been designed to permit reliable operation even at 40 kV. The layout of the source is shown in Fig. 1.

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OPERATIONAL EXPERIENCE WITH THE GTS-LHC ION SOURCE AND FUTURE DEVELOPMENTS OF THE CERN ION INJECTOR

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Abstract

Since 2010 the GTS-LHC source delivers lead ions for heavy ion physics at the LHC. Several modifications allowed the improvement the source reliability and the beam stability. The attempts to improve the beam intensity were less successful. The different modifications and actual performance figures will be presented in this paper.

In addition to the heavy ion physics program of the LHC new ion species will be requested for different experiments in the future. The fixed target experiment NA61 requires primary argon and xenon beams. And a future biomedical facility asks for light ions in the range helium to neon. Approaches to prepare these beams and to modify the ion injector towards a light ion front end are presented.

INTRODUCTION

The GTS-LHC source was installed and commissioned in 2005. It delivered the Lead ion beam needed for the commissioning of the heavy ion injector chain: Linac3 - Low Energy Ion Ring (LEIR) - Proton Synchotron (PS) – Super Proton Synchotron (SPS). For the very first setting up of LEIR also an oxygen ion beam was used.

In 2010 and 2011 the LHC used the lead beam for heavy ion collisions at a momentum of 1.38 A TeV/c. In parallel NA61 used the beam for fixed target physics [1].

HEAVY ION OPERATION

The GTS-LHC ECR Ion Source was built by CEA, Grenoble, and installed at Linac3 in 2005. It uses three warm electromagnet solenoids to generate a minimum B configuration, and a permanent magnet hexapole for radial plasma confinement. The source is injected with 14.5 GHz microwaves, typically using 10 Hz repetition cycles of 50 ms pulse length. Lead is introduced through a resistively heated micro-oven and mixed with oxygen gas. The source uses the afterglow technique to increase the intensity of high charge state ions for injection into the LEIR synchrotron, extracting Pb^{29+} with a voltage of 18.8 kV. More information can be found in [2]

The GTS-LHC source and Linac3 were running about 26 weeks in 2011. Most of the time was used for setting up the injector chain. 778 hours beam time was taken for physics. During the physics period a total of 45 hours were needed for two oven refills and 2.4 hours the source was down due to failures. Since then the oven refills could be optimized. Now it takes in average 8-10 hours from the stop of the source until a stable beam is available again.

For the year 2011 several improvements on the source were done:

- The gas injection feedback loop was sensitive to the microwaves injected into the source. This has been improved with a different gauge type (IMR265 by Pfeiffer) installed close to the gas injection valve that could be used for the feedback loop (see Figure 1). This eliminated the sensitivity to the microwave and in addition it smooths out any (fast) pressure fluctuations in the source.

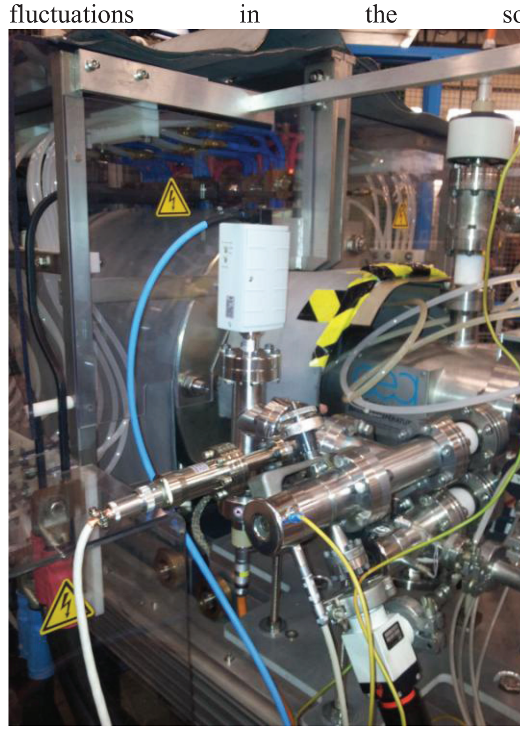

Figure 1: Gas injection with new gauge (in the center of the picture) for gas injection feedback loop.

- The electrical connection of the intermediate electrode failed regularly in previous years. The connection wire had a direct view of the beam, and the kapton insulation was eroded over some period which resulted in a short circuit. An additional insulation with a kapton tubing and a shielding with a wire mesh (braid) was made (see Figure 2), and inspection after the run showed no damage this time.

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DESIGN OF WEB-BASED INTERFACE TO RIKEN 28 GHZ SUPER-CONDUCTING ECR ION SOURCE AND THE FUTURE PLAN

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Abstract

A new RIKEN 28GHz superconducting ECR ion source (28GHz-ECRIS) was constructed in 2009 in order to increase the intensity of Uranium ion beam for RIKEN RI beam factory project (RIBF) [1]. For effective and stable operation of the 28GHz-ECRIS, its operational software should have a user-friendly man-machine interface. The ECRIS control system was constructed with the Experimental Physics and Industrial Control System (EPICS) as well as RIBF control system. As a result, it was successful to provide the useful software, such as the operation GUI panels, the XY chart application, and the data acquisition system in EPICS-based system. On the other hand, to keep beam quality from 28GHz-ECRIS for a long beam service term, it should be possible to operate the 28GHz-ECRIS by members of the ion source team at any time. In order to relieve concern in the overseas business trip of members, we designed a real-time web-based client operational software using WebSocket, which is a new protocol presented by Internet Engineering Task Force (IETF) [2].

INTRODUCTION

The control system for RIKEN 28GHz-ECRIS was built with using EPICS which is the same as that for RIKEN RIBF [3]. The TCP/IP network was used for the communication with between local controller and client system. For manipulation of the main parameters of the ion source (gas pressure, current of the super-conducting solenoid coils, etc), F3RP61-2L was adopted, which was manufactured by Yokogawa Electric Corporation and was a CPU module of FA-M3 Programmable Logic Controller (PLC) without a ladder program. As the Linux runs on the F3RP61-2L, it can work as an EPICS Input/Output Controller (IOC). Similarly, the vacuum control system and beam diagnostic system were constructed by using EPICS, and Linux-based IOCs connected with N-DIMs, which were developed originally in RIKEN, over the Ethernet. On the other hand, for the 28GHz-ECRIS operational software, two Microsoft Windows XP PCs were used both in RIKEN linear accelerator (RILAC) and RIBF cyclotron control rooms. The PCs, in which X Window System is installed, have six displays using a multiple-display environment. And the web-based system is used for reading and writing of electric-log book and data archive viewer system for 28GHz-ECRIS.

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MAIN CONTROL PANEL

The main panel to manipulate the gas pressure, extraction voltage, power supplies of the magnets and the X-Y plot of the spectrum of charge state distribution were developed with using the EDM [4]. EDM is one of the motif-based display managers provided by EPICS collaboration in order to develop the client operational software with GUI. The main panel GUI and plotter GUI are shown in Fig. 1 and 2, respectively. We adopted the Cygwin-X as an X-server, because the EDM is displayed on the X-window system.

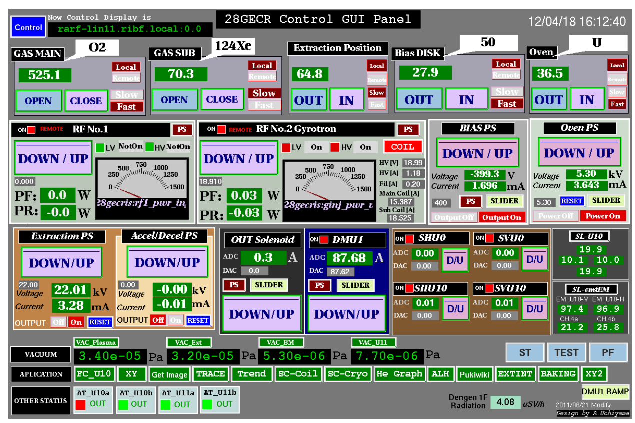

Figure 1: Main control panel constructed with EDM for 28GHz-ECRIS.

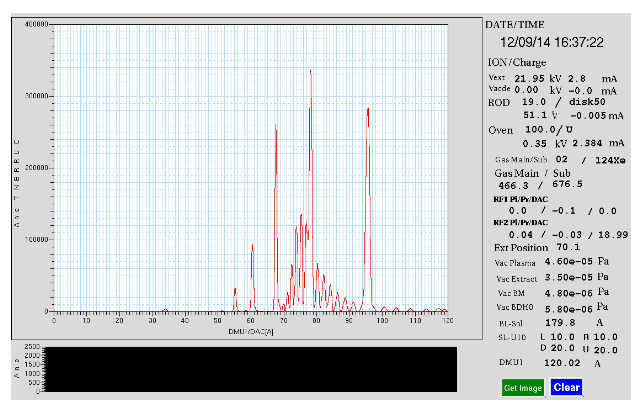

Figure 2: XY plotter chart constructed by using EDM for 28GHz-ECRIS operation.

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DEVELOPMENT OF INTENSE PROTON ECR ION SOURCES AT IMP*

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Abstract

Since 1997, there have been two ECR ion sources for producing intense proton beam developed at Institute of Modern Physics (IMP). In 1999, a high current 2.45 GHz ECR proton source for Lanzhou university neutron generator, was constructed and tested at IMP. A mixed ion ($H_1^+ + H_2^+ + H_3^+$) beam current of 110 mA with CW mode was delivered from a single aperture of 6mm diameter with microwave power of 600W at the extraction voltage of 22 KV. Recently a new pulsed proton source has been designed and built at IMP for the CPHS (Compact Pulse Hadron Source) facility in Tsinghua University. Till now the commissioning of this source has been finished for 60mA pure proton beam with 50keV energy at Tisinghua University. The long time running stability and beam emittance have been tested and the results are well up to the requirements of CPHS. In this paper, the design of the proton ion source and the LEBT for the Chinese ADS project is also discussed.

INTRODUCTION

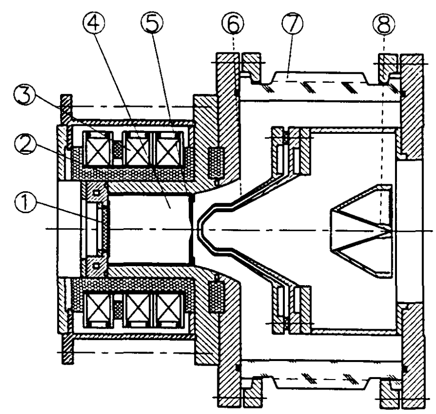
As an effective candidate, light ion Electron Cyclotron Resonance (ECR) source is always chosen to be the injector for proton accelerators. Different to the high charge state ECR ion source, which has more complicated magnetic field configuration and is driven by more than 10 GHz microwave with up to even more than 10kW power, the light ion ECR source is only considered by the simple axial magnetic field distribution and fed with 2.45 GHz microwave from magnetron of no more than 2kW power. Either electro-magnet or permanent magnet could be adopted to form the magnetic field. The ion source with all permanent magnet is very suitable to work on high voltage platform.

Today more and more proton accelerators have been, is and will be constructed for scientific research, industrial application and cancer therapy. High performance proton source is needed to satisfied different requirements. In china, there are some proton accelerator projects, such as Compact Pulsed Hadron Source (CPHS) project of Tsinghua University [1] and the china accelerator drive system (ADS) called for by Chinese Academy of Science (CAS) [2]. IMP undertook the task of proton source and LEBT for these two projects.

FIRST PROTON SOURCE AT IMP

1997, we started the research of producing high intensity proton beam from a compact ECR source for Lanzhou university neutron generator [3]. Fig.1 shows the source structure with the extractor and a near faraday cup. The necessary magnetic field is mainly formed by a set of permanent magnet rings of NdFeB material. The outer jacket of the source is made of iron to return the path of magnetic field. In order to get a better result, three auxiliary coils, which are water-cooled in directly through the copper sheets on the surface, are used to tune the magnetic field precisely in a small range. The water-cooled plasma chamber is made of copper with both diameter and length of 70mm. The ion extraction and beam pre-focusing are realized by a three-electrode system whose tips are made of TZM alloy. The gaps are 6mm and 3mm in the accelerating and decelerating regions respectively.

With a very simple microwave feeding system, a mixed ion ($H_1^+ + H_2^+ + H_3^+$) beam current of 110 mA with CW mode was delivered from a single aperture of 6mm diameter with microwave power of 600W at the extraction voltage of 22 KV.



1. Microwave window;
2. Permanent magnets;
3. Coils;
4. Plasma chamber;
5. Plasma electrode;
6. Accel-decel electrodes;
7. Ceramics;
8. Faraday cup

Figure 1: Layout of papers.

PROTON SOURCE FOR CPHS

In 2009 a new project for the construction of a Compact Pulsed Hadron Source (CPHS) was approved on Tinghua University [1], which consists of a proton linear accelerator, a neutron target station, and beam lines for neutron and proton applications. In this system, a high intensity current ECR proton source and a low energy

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BEAM EXPERIMENTS WITH THE GRENOBLE TEST ELECTRON CYCLOTRON RESONANCE ION SOURCE AT ITHEMBA LABS

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Abstract

At iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) a new electron cyclotron ion source (ECRIS) was installed and commissioned. This source is a copy of the Grenoble Test Source (GTS) for the production of highly charged ions. The source is similar to the GTS-LHC at CERN and named GTS2. A collaboration between the Accelerators and Beam Physics Group of CERN and the Accelerator and Engineering Department of iThemba LABS was proposed in which the development of high intensity Argon and Xenon beams is envisaged. In this paper we present beam experiments with the GTS2 at iThemba LABS, in which the results of CW, pulsed and afterglow operation are compared.

INTRODUCTION

iThemba LABS is administered 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 figure 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 three external sources [1]. In 2006 the decision was made that, due to the requirements of nuclear physics for new ion species and higher particle energies, a new ECRIS should be procured. A source, based on the design of the Grenoble Test Source (GTS) [2], which is similar to the GTS-LHC at CERN, has been constructed and installed. 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 that was designed and constructed by Grand Accelerator National d'Ions Lourds (GANIL) [3] and originally built for the Hahn-Meitner-Institute (HMI) in Berlin [4], with its beam line elements, was donated to iThemba LABS and is in operation since 2009.

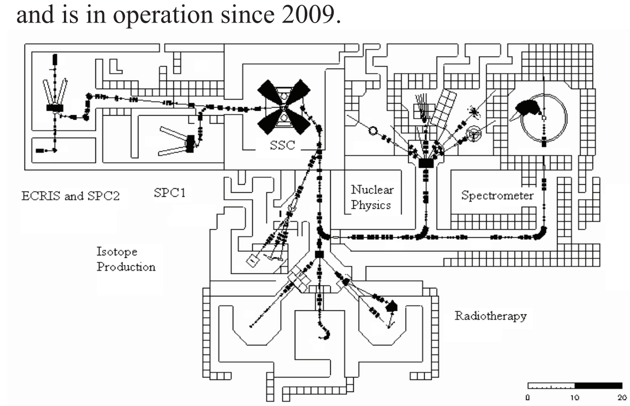

Figure 1: Layout of the iThemba LABS facility

The NA61 experiment at CERN studies the production of quark-gluon plasma. The light ion beam for the reaction is produced via the fragment method in which the primary lead beam hits a target which releases the secondary beam of lighter ion fragments. For experiments with heavier ions like Argon which are planned for 2014, a direct beam from the SPS is needed [5]. This beam is to be produced in the GTS-LHC and injected into LINAC3 which operates at a pulse length of 200 μs with a maximum repetition frequency of 5 Hz. Direct injection into the RFQ requires $^{40}Ar^{11+}$ ions from the source with a source potential of 9.6 kV.

THE GTS2 ECRIS

The coils, the permanent magnet assembly, the plasma chamber and all mechanical parts of the GTS2 were manufactured by different companies in Europe, which were also involved in manufacturing the GTS-LHC. For the vacuum system of the source three 700l/s turbo pumps (one at injection and two at extraction), one 70l/s turbo pump for the oven system and two dry roughing pumps are used. The longitudinal magnetic field is produced by three coils, namely the injection-, centre-, and extraction coil. The power supplies for the injection- and extraction coil can deliver 1300 A at 60 V leading to a maximum B-field of 1.6 T. A 600 A bipolar power supply is connected

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INSTALLATION AND OPERATION OF A 28 GHz GYROTRON FOR THE RIKEN SUPERCONDUCTING ECR ION SOURCE

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Abstract

We introduced a 28 GHz gyrotron with a maximum output power of 10 kW as a microwave source for the RIKEN superconducting ECR ion source. In its first test, large power ripples were observed in the output microwaves, and its operation was difficult at a power less than 1 kW. These ripples could be reduced by increasing the electric capacitance in the rectified circuit of the cathode power supply. In October 2011, the ion source could be continuously operated with the 28 GHz gyrotron for two months, and it supplied U and Xe beams to the experiments at the RI-Beam Factory. In this period, we observed fluctuations of 20-30% in the beam current from the ion source, which were correlated with the RF power. As a result of these investigations, the cause of these fluctuations was found to be attributed to the current in the solenoid coil of the gyrotron. These fluctuations could be reduced to within 7-8% of the total RF power by exchanging the solenoid power supply with new one with a current stability of less than 1×10^{-5} per day.

INTRODUCTION

At the RI-beam factory (RIBF) at RIKEN, all atomic elements up to uranium can be accelerated to an energy of 345 MeV per nucleon by a cascade of a heavy ion linac and four ring cyclotrons. Experiments in nuclear physics using secondary beams produced from these intense primary beams are being performed intensively. Because U beams have a large cross-section to generate many isotopes of interest, an increase in the beam intensity is of great need. In order to increase the intensity of U^{35+} used for beam acceleration at the RIBF, we have been developing a superconducting 28 GHz ECR ion source [1, 2]. This ion source uses a 28 GHz gyrotron. The gyrotron is produced by Mitsubishi Electric Corporation and has a maximum output power of 10 kW. The first test at the RIKEN site was performed with a dummy load in September 2010, and after improvement to its power supply, the superconducting ECR ion source was operated with the gyrotron in April 2011. Moreover, the 28 GHz ion source supplied U and Xe beams to the RIBF experiment successfully for two months from October to December of 2011 [3].

28 GHz GYROTRON

The newly developed 28 GHz superconducting ion source uses a gyrotron microwave source. Figure 1 shows the schematic drawing of this gyrotron, and its parameters are listed in Table 1. Electron beams produced from a magnetron-type electron gun are injected into an open

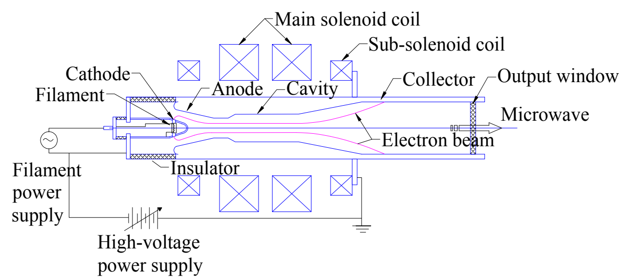

Figure 1: Schematic drawing of the 28 GHz gyrotron.

Table 1: Parameters of the Gyrotron

frequency	28±0.1 GHz
Mode	TE02
Electron beam voltage (max.)	22 kV
Electron Beam current (max.)	1.6 A
Input power (max.)	60 kW
Main Solenoid current (typ.)	195 A
Sub Solenoid current (typ.)	18.5 A
Output power (max.)	10 kW

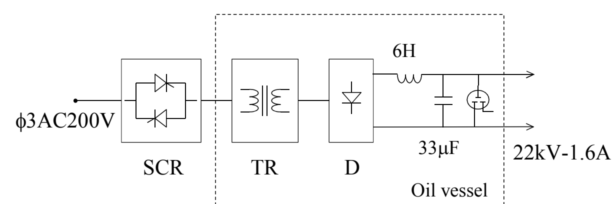

Figure 2: Electric circuit of the cathode power supply.

resonator along solenoid fields, producing 28 GHz microwaves by electron cyclotron resonance in the cavity. The maximum acceleration voltage and current of the electron beams are 22 kV and 1.6 A, respectively. The gyrotron uses cathode and filament power supplies along with two dc power supplies for the solenoid coils, as shown in Fig. 1. Figure 2 shows a diagram of the electric circuit of the cathode power supply. The AC input power is controlled with thyristors at low voltage, and it is rectified into direct current after it is boosted up with a transducer. The cathode power supply also has a protection circuit with a three-gap device in order to protect the gyrotron from an arc event. The output RF power is controlled by the current and voltage of the electron beam. Figure 3 shows the relationship between the cathode voltage and the RF power for a fixed beam current of 1.2 A. The RF power was measured from the temperature rise of a dummy load. Each point in Fig. 3

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DECRIS-5 ION SOURCE FOR DC-110 CYCLOTRON COMPLEX RESULTS OF THE FIRST TESTS

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Abstract

The project of the DC-110 cyclotron facility to provide applied research in the nanotechnologies (track pore membranes, surface modification of materials, etc.) has been designed by the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research (Dubna). The facility includes the isochronous cyclotron DC-110 for accelerating the intensive Ar, Kr, Xe ion beams with 2.5 MeV/nucleon fixed energy. The cyclotron is equipped with system of axial injection and ECR ion source DECRIS-5, operating at the frequency of 18 GHz. The main parameters of DECRIS-5 ion source and results of the first tests are presented in this report.

INTRODUCTION

The project of the DC-110 [1] cyclotron facility to provide applied research in the nanotechnologies (track pore membranes, surface modification of materials, etc.) has been designed by the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research (Dubna). The cyclotron has 2m pole diameter, and to provide the energy of 2.5 Mev/nucleon the accelerated ions should have the mass to charge ratio about of A/Z = 6.6, that is 40Ar6+, 86Kr13+ and 132Xe20+. The parameters of the source are determined mainly by required intensity of the 86Kr13+ and the 132Xe20+ ion beams at the level of 200 eμA and 150 eμA correspondingly. The prolonged beam stability (few hours) is also important during the track pore membrane irradiation.

In recent years ECRIS has made considerable progress with the continuing increase of extracted ion beam intensity in which the fully superconducting ECRIS and hybrid ECRIS take the leading role. At the same time a room temperature ECRIS has the advantages of easy operation and lower cost in comparison to a SC ECRIS but with lower performance. Taking into account the operating conditions and that the production of very high charge states is not required the use of RT ECRIS in our case is more preferable.

A room temperature (RT) ECRIS consists of a set of water cooled resistive solenoids and a permanent sextupole magnet. To meet the requirement of an optimum 3D confinement magnetic field configuration the GTS-type [2] magnetic structure was chosen. This kind of magnetic structure provides a high enough level of an injection magnetic field keeping the reasonable ac power consumption.

DESCRIPTION OF THE SOURCE

The new 18 GHz RT ECRIS DECRIS-5 was constructed and built at FLNR JINR, Dubna, Russia. The magnetic structure of the source is composed by three independent copper coils. The injection and extraction coils are enclosed in soft iron yokes. By adding an iron plug at the injection side, which is situated directly inside the discharged chamber, the injection magnetic field can be effectively increased. At full excitation of the injection solenoidal coil, the injection magnetic field can be as high as 2.25 T. The calculated axial magnetic field distribution and the scheme of the magnetic structure are shown in the Fig.1 and Fig.2 correspondingly. The maximal current of the power supplies for the injection and extraction coils is 1200 A, for the middle coil – 800 A. The power consumption of the coils is about of 150 kW.

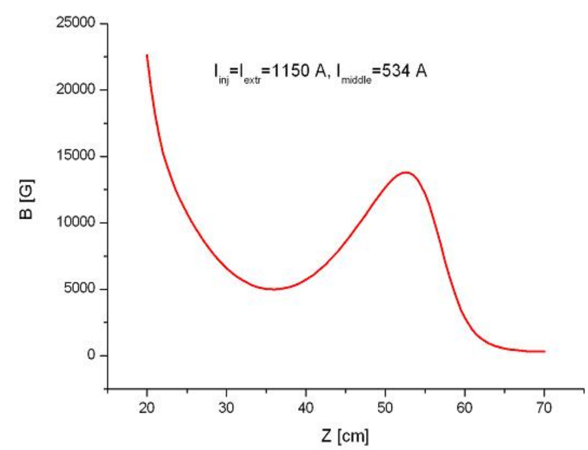

Figure 1: The axial magnetic field distribution.

The new hexapole for DECRIS-5 ion source (Fig.3) for radial confinement of plasma has a Halbach structure. It consists of 36 permanent-magnet identical trapezoidal sectors with the corresponding easy axis direction. In order to obtain a smooth magnetic field distribution along the pole an each sector was made from the whole piece of the magnetic material. This technology allows to eliminate some failings in magnetic field distribution near permanent magnet junctions. The inner diameter, the outer diameter, and the length of the hexapole are 86 mm, 230 mm, and 300 mm, respectively. Fig.4 shows the measured radial magnetic field strength on the plasma chamber wall in front of each pole. The comparison between radial field distributions of sectional hexapole for

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RECENT DEVELOPMENTS AND ELECTRON DENSITY SIMULATIONS AT THE ATOMKI 14.5 GHz ECRIS

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Abstract

The 14.5 GHz ECR ion source of ATOMKI is a standard, room-temperature ECRIS for plasma diagnostic studies, for atomic physics research and also serves as a low-energy particle source with wide range of elements for surface treatments. Recently the original NdFeB hexapole was exchanged by a new one and, consequently, new iron plugs were calculated, designed and installed at the injection side of the source. The resulted stronger magnetic trap has shown significant effect on the beam intensities and on the charge states distributions. The new magnetic configuration was re-calculated by the TrapCAD code developed by our group. The spatial positions and energy structure of 3 million electrons were calculated. A post-simulation energy filtering carried out on the non-lost (plasma) electrons reveals numerous interesting and important information in 3D.

INTRODUCTION

The 14.5 GHz ATOMKI ECR ion source celebrates its 20 years anniversary in 2012 because the basic financial contract was signed in 1992. The first plasma was generated in 1996 and the ion source delivers beams since 1997. During the past two decades continuous technical developments characterize the source itself and its surroundings called ECR Laboratory [1].

In a recent paper the status in 2011 and the special features of our ECRIS were shown in full detail [2]. Since then the magnetic trap was significantly strengthened by exchanging the hexapole magnet and the iron plugs. The computer control system was also changed and the new one is being tested and developed promisingly. All these technical upgrades are summarized in the first part of this paper.

The new magnetic trap significantly changed the structure of the magnetic field inside the plasma chamber. The magnetic system was re-calculated and then the electron cloud in the new trap was simulated by our TrapCAD code [3, 4]. Meanwhile TrapCAD itself was also slightly upgraded. The results of the simulation are shown in the second part of the paper.

UPGRADED MAGNETIC TRAP

The mechanical, electrical and microwave structures of the ATOMKI-ECRIS are not fixed: depending on the actual experiment they have several configurations. In Fig. 1 the basic (most frequent) setup is shown. The magnetic trap consists of two identical room-temperature solenoid coils with 5 cm thick iron yoke and of a permanent magnet hexapole. The coils-generated axial magnetic field peak values are 0.95 Tesla at both sides without the optional soft iron plugs at the injection side.

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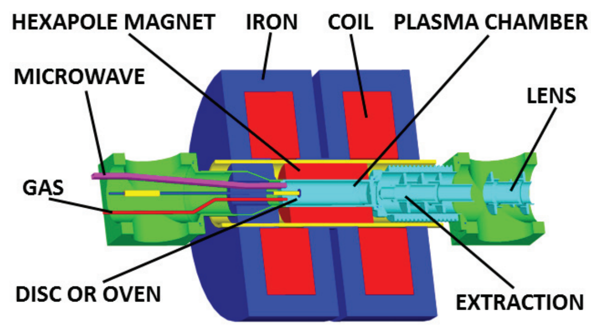

Figure 1: The most frequent mechanical and magnetic configuration of the ATOMKI-ECRIS.

In 2012 the 15 years old hexapole was exchanged by a new one. Table 1 summarizes the geometrical and magnetic features of the original and new hexapoles. The radial pole field of the old hexapole at the plasma chamber internal wall (R=29 mm) was 0.95 Tesla at the beginning and this value gradually decreased between 1996 and 2007 year by year by a yearly factor of about 2%. In 2008 however, a sudden and still un-understable big decrease occurred resulting a much weaker magnetic field strength of 0.7 Tesla at R=29 mm. Between 2008 and 2012 the ECRIS mainly operated at lower frequencies with the weakened hexapole in order to reach an acceptable mirror ratio. In 2012 the hexapole was exchanged by a new one. Its external diameter could be enlarged by a small re-designing of the surrounding pieces. Now the magnetic field in the plasma chamber is about 1.2 Tesla i.e. much stronger than ever it was with the old hexapole.

When the new hexapole was installed the soft iron magnetic plugs at the injection side had to be re-designed, manufactured and installed. The goal of this change was double. We wanted to increase the peak magnetic field at the injection side inside the plasma chamber as high as possible. The second gal was to minimize the force to the plugs and thus to minimize the opposite direction force to the basic structure of the ion source. Both goals were achieved and now the peak axial magnetic field at the injection side is almost 1.3 Tesla while it remained less

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NUMERICAL MODELING OF ION PRODUCTION IN ECRIS BY USING THE PARTICLE-IN-CELL METHOD

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Abstract
To better understand the physical processes in ECRIS plasmas, we developed a Particle-in-Cell Monte-Carlo Collisions code that simulates the ionization and diffusion dynamics. The ion production is modelled assuming that the ions are confined by a ponderomotive barrier formed at the boundary of the ECR zone. The main features of ECRIS performance are reproduced, such as the saturation and decrease of highest charge state currents with increasing gas pressure, as well as response to an increase of injected RF power.

INTRODUCTION

The ponderomotive force plays an important role in the ECRIS plasmas [1]. Electrons are partially expelled by a gradient of the microwave electric field from a thin layer around the ECR zone, giving rise to a positive potential that confines the ions. The height of this ponderomotive barrier (PB) is difficult to estimate: it depends on the power density of the microwave radiation, on the gradient of the magnetic field at the resonance, on the plasma density and other factors. Taking the PB height as a free parameter in our calculations, we suppose that it goes to zero when the plasma density approaches the cut-off value because of reflections of the microwaves from the ECR zone boundary and absorption in the plasma.

The ECRIS plasma potential is experimentally known to be positive and around 20-50 V. Roughly half of the potential drop from the plasma to the walls occurs in a thin sheath area (extending a few Debye lengths from the walls), the remaining drop is in a pre-sheath further inside the plasma. The extension of the pre-sheath is unknown, but we here assume that it is located between the ECR zone and the wall sheath. Then, neglecting the PB width, the PB mimics the potential dip, often assumed to be a reason for ion confinement in ECRIS.

The PB confinement of the plasma is accompanied with the gas-dynamics confinement, where the ion pressure gradients govern the rate of ion diffusion to the walls and to the extraction area [2]. The length of the ion production volume defines the ion confinement times, which were found to be linear proportional to the ion charge state [2]. Here we present numerical simulations of the ECRIS plasma combining both confinement models.

CODE DESCRIPTION

The main features of our PIC-MCC code have been described elsewhere [2]. The calculations were done for neon as a feeding gas; the magnetic field and geometry of the source are those of the KVI-AECRIS [3]. The magnetic fields were calculated with POISSON-SUPERFISH, the hexapole component was calculated analytically, neglecting edge effects.

The elastic ion-ion collisions are modelled using the energy-and-momentum conserving Takizuka-Abe scheme [4], the rates of charge-transfer collisions and elastic collisions between ions and neon atoms are adopted from [5] with linear scaling of the rates as a function of the ion charge state (Z). The charge-transfer reactions for the multiply charged ions result in Coulomb repulsion of the colliding particles and we estimate the Q-value of these reactions to be 10 eV independent of the charge state. Then, even if the rates are relatively small ($\sim3\times10^{-10}\times Z$ cm^3/sec) compared to the ionization and ion loss rates, and the neutral density in the chamber is much smaller than the plasma density, the influence of these collisions on the plasma behaviour is not negligible.

Heating due to electron-ion collisions is modeled by kicking the ions at each computational step in a random direction with the velocity diffusion coefficient corresponding to an electron temperature T_e of 1 keV. The ionization rates are calculated according to [6]. The recombination processes can be neglected in our conditions because of their low rates for this T_e.

The static electric field inside the ECR zone is set to zero, and arbitrary set to 1 V/cm along the magnetic field lines outside the zone. The pre-sheath electric field can be varied in a wide range without changing the computational results, as long as there is no backward influence of the pre-sheath area on the main production volume, but the ions are just moving toward the chamber walls and into the extraction aperture.

When hitting the walls, the ions are neutralized and scattered back with an angular distribution according to the cosine-law and with a Gaussian distribution of energies (FWHM=10 eV, peak energy of $10\times Z$ eV [7]). In collisions with the walls, the neutralized particles loose their energy with a thermal accommodation coefficient taken from [8] for Ne on an Al surface. For initial energies above a few eV, this coefficient is relatively high (~0.5) while it goes to almost zero for energies in the meV range. The result is that the kinetic energies of the neutral atoms inside the source chamber are quite high (~0.25 eV) and are in the same range as the ion temperatures in the plasma.

When a computational macro-particle hits the extraction aperture (of 0.8 cm diameter), it is injected back into the volume from the injection side with an energy taken from a Maxwell-Boltzmann distribution at room temperature. The total number of computational macro-particles is conserved. Calculations are done until a steady state is reached. Transient processes are not properly calculated in such a scheme. In equilibrium, the

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PROTON BEAMS FORMATION FROM DENSE PLASMA OF ECR DISCHARGE SUSTAINED BY 37.5 GHZ GYROTRON RADIATION

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Abstract

Formation of hydrogen ion beams with high intensity and low transverse emittance is one of challenging tasks determining success in the field of accelerator research for last tens of years. Now there are a few modern projects like ESS and IFMIF whose requirements for the ion beam could not be fulfilled with the most advanced proton (or deuteron) sources.

Present work is devoted to experimental investigation of proton beams production from dense plasma (Ne>1013 cm-3) of ECR discharge sustained by 37.5 GHz, 100 kW gyrotron radiation at SMIS 37 facility at IAP RAS. Extraction systems with different configuration were used. It was demonstrated that ultra bright proton beam with 4,5 mA current and 0.1 π·mm·mrad normalized emittance (corresponding brightness is 45 A/(π·mm·mrad)2) can be formed with single-aperture (1 mm in diameter) extraction.

For production of high current beams a 13-hole extractor was used. 200 mA and 1.1 π·mm·mrad normalized emittance proton beam was obtained. A possibility of further beam parameters enhancement by developing of extraction system and its power supply is discussed.

INTRODUCTION

Operation of modern high power accelerators often requires production of intense beams of hydrogen ions. H+ (proton) beams are utilized or envisioned for use in linear accelerators e.g. the future European Spallation Source under design [1], H- ions are favored in applications based on charge exchange injection into storage rings or circular accelerators, e.g. the US Spallation Neutron Source [2] and some special applications such as the IFMIF project [3], require D+ (deuteron) ion beams. Requirements for the brightness of such beams grow together with the demand of accelerator development and arising experimental needs. New facilities aiming at outperforming the previous generation accelerators are usually designed for higher beam currents. Enhancing the hydrogen beam intensity and maintaining low transverse emittance at the same time is, however, becoming increasingly difficult. The most modern accelerators require hydrogen ion beams with currents up to hundreds of mA (pulsed or CW), and normalized emittance less than 0.2-0-3 π·mm·mrad [1, 3] to keep the beam losses at high energy sections of the linac below commonly imposed 1 W/m limit.

This paper is devoted to investigating the generation of high current proton beams at SMIS 37 facility [4] at the Institute of Applied Physics (IAP RAS). SMIS 37 has been constructed for production of high current beams of multicharged ions. However, due to the substantial potential exhibited by the setup, we found it reasonable to test its capabilities for proton beam production.

SMIS 37 EXPERIMENTAL FACILITY

The experimental research presented in this work was carried out on the SMIS 37 shown schematically in Fig. 1. A gyrotron generating a Gaussian beam of linearly polarized radiation at the frequency of 37.5 GHz, with the power up to 100 kW, and pulse duration up to 1.5 ms was used as a source of pulsed microwave radiation. The microwave radiation is launched into the plasma chamber through a quasi-optical system consisting of 2 mirrors, quartz (vacuum) window and a special μW-plasma coupling system shown on the left in Fig. 1. The setup has been designed for efficient transport of the radiation avoiding parasitic resonances and plasma flux impinging the quartz window. A simple mirror trap was used for plasma confinement. The magnetic field in the trap was produced by means of pulsed solenoids, spaced 15 cm apart. The current pulse with the shape close to half period of a sinusoid had the duration of 11 ms with the magnetic field variation during the microwave pulse being less than 3%. Magnetic field in the mirror was varied from 1.4 to 4 T (ECR for 37.5 GHz is 1.34 T). Ratio of the maximum and minimum magnetic fields of the trap was equal to 5 (i.e. Bmax/Bmin). The hydrogen inlet into the source was realized through an opening incorporated with the microwave coupling system.

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EFFECT OF SOURCE TUNING PARAMETERS ON THE PLASMA POTENTIAL OF HEAVY IONS AND ITS INFLUENCE ON THE LONGITUDINAL OPTICS OF THE HIGH CURRENT INJECTOR

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Abstract

Plasma potentials for various heavy ions have been measured using the retarding field technique in the 18 GHz High Temperature Superconducting ECR ion source, PKDELIS [1]. The influence of various source parameters viz., RF power, gas pressure, magnetic field, negative DC bias and gas mixing on the plasma potential is studied. It is observed that the plasma potentials are decreasing for increasing charge states and a mass effect is clearly observed for the ions with similar operating gas pressures. In the case of gas mixing, it is observed that the plasma potential minimises at an optimum value of the gas pressure of the mixing gas and the mean charge state maximises at this value. The energy spread arising from the plasma potential influences the longitudinal optics of the High Current Injector in terms of increased phase spread which deteriorates the transmission through the RFQ. Details of the measurements carried out as a function of various source parameters and its impact on the longitudinal optics are presented.

INTRODUCTION

Plasma potentials are one of the important figures of merits of an ion source and depicts the degree of stability of a plasma. The ion source stability is one of the main criteria for application in accelerators an ion implanters, besides other applications. In the context of electron cyclotron resonance ion sources, the improved stability results from a lower plasma potential and determines a good confinement of the plasma resulting in a higher mean charge state distribution [2]. On the other hand, if the plasma potential is high, sputtering to the wall is highly probable that results in an unstable plasma. Therefore, the confinement properties of the plasma are worsened and the resulting charge state distribution is a lower mean charge state. The main goal is to tune the source such that that plasma potential is as low as possible, which manifests itself in a stable operation mode. Measurement of plasma potentials is therefore important to get an idea of the source operating conditions. This in turn can be used to infer another important figure of merit called the 'energy spread'. A quick online estimate would suffice to further improve the source tuning and especially for delivering beams to experiments which require good timing information. The importance of the plasma potential shows up in the estimation of the energy spread which is crucial for timing measurements in nuclear physics experiments and other experiments where the pulse width of the bunched beam is of extreme importance. At the Inter University Accelerator Centre, a High Current Injector (HCI) is being installed for delivering a wider mass range of ions with relatively higher beam intensities into the superconducting linear accelerator (SC-LINAC) than what is presently available from the Pelletron-SC-LINAC combination Fig. 1. Due to the wide available mass range, there is a wider charge state distribution and the energy spread of the ion beam will depend on the charge state being delivered. In our earlier experiments, the emittance of various ion beams from an ECR ion source were measured [3] to obtain inputs in the design of beam transport and to match the acceptances of the downstream radio frequency quadrupole (RFQ) and drift tube LINAC (DTL) accelerators of the high current injector being developed [4]. For subsequent acceleration through the RFQ and DTL, the dc beam from the ECR needs to be pulsed and the longitudinal emittance depends on the energy spread of the beam. Due to the pulsed nature of the beam, the timing resolution is very important for various experiments. Since a significant energy spread can influence the longitudinal optics, it was felt necessary to measure the plasma potentials for various ions and its dependence on source tuning parameters. O.Tarvainen et al.,[6] have measured plasma potentials using the retarding field technique and observed the plasma potentials to increase with RF power and gas pressure and the values changed when the negative DC bias was varied. They [7] also measured the effect of the gas mixing technique on the plasma potential, energy spread and emittance of the beam under various source conditions. They estimated that the energy spread due to the plasma potential can influence the emittance of the beam to several tens of percent in the bending plane of the dipole magnet. In Ref 8., they compared the measured values of the emittance and plasma potential using single frequency and double frequency heating modes. In this study we carried out a systematic measurement of the plasma potential and the worst possible energy spread to study the influence on the longitudinal optics. Various methods have been used in the literature to measure the plasma potential. We have used the retarding field method and the instrument used is similar to the one used by the Jyvaskyla group [6] and is described in detail in [12]. In

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THE EINZEL LENS LONGITUDINAL CHOPPER

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Abstract

This paper describes the Einzel lens beam chopper that has been newly developed for the KEK digital accelerator (DA) project. Function of beam chopping is added to the Einzel lens used as a transverse focusing device for a low energy ion beam. Its idea and operational chopping performance are discussed in details.

INTRODUCTION

The KEK digital accelerator (DA) is a small-scale induction synchrotron without a high-energy injector [1]. The concept of an induction synchrotron was experimentally demonstrated in 2006 [2] by utilizing the KEK 12 GeV Proton Synchrotron. Instead of an RF cavity, an induction cell is employed as the acceleration device. It is simply a one-to-one transformer, which is energized by a switching power supply generating pulse voltage. Two types of induction cells for acceleration and confinement are employed. An injected beam pulse is captured by the barrier bucket and accelerated with pulse voltages. It is a crucial point of the induction synchrotron that voltage timing is controlled by a gate signal of solid-state switching elements based on bunch signals detected at the bunch monitor. This operational performance enables acceleration of ions from extremely low velocities, and is the reason why the DA does not require a high-energy injector. It is understood from these properties that the DA is capable of accelerating any species of ion, regardless of possible charge state.

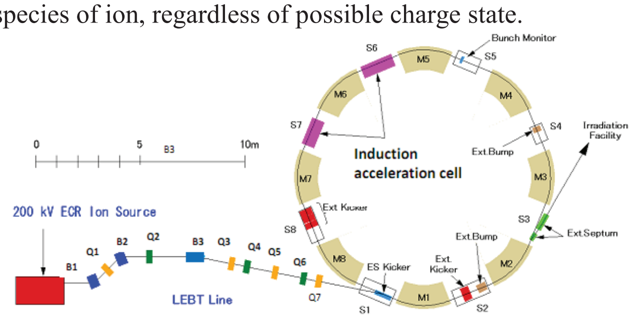

Figure 1: Outline of the KEK Digital Accelerator.

In the KEK DA, schematically shown in Fig. 1, a 5 msec long ion beam is created in the electron cyclotron resonance ion source (ECRIS) and chopped by the newly developed Einzel lens chopper in 5 μsec and post-accelerated in the acceleration column attached with the 200 kV high-voltage platform (HVP), after which it propagates through the low-energy beam transport line (LEBT) to be injected into the ring with the electrostatic injection kicker. The electrostatic kicker voltage is turned off before the injected beam pulse completes a single turn in the DA ring, which is a rapid-cycle synchrotron. The injected beam is captured with a pair of barrier voltage pulses and accelerated with pulse voltages.

The single turn injection scheme limits on the maximum beam length. On the other hand, beam production in most of ion sources requires a finite time period due to a principle mechanism of plasma formation. A beam chopper which can provide a desired pulse length is indispensable. In this paper, its main argument will be focused on how a necessary beam length can be generated and key features of its operational performance are summarized.

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ACCELERATOR COMPLEX

Permanent Magnet ECRIS [3]

The ECRIS is embedded on the DC 200 kV HVP. In order to minimize the consumed electric power and avoid troublesome of water cooling on the high voltage platform, the permanent magnet ECRIS being operated in the pulse-mode (10 Hz and 2-5 msec) has been developed. This ECRIS driven by a 9.35 GHz TWT with a maximum output power of 750 W is capable of producing from hydrogen ion to Argon ion, which are extracted at 10 kV. The HVP including the Einzel lens chopper and the post-acceleration column is schematically shown in Fig.2.

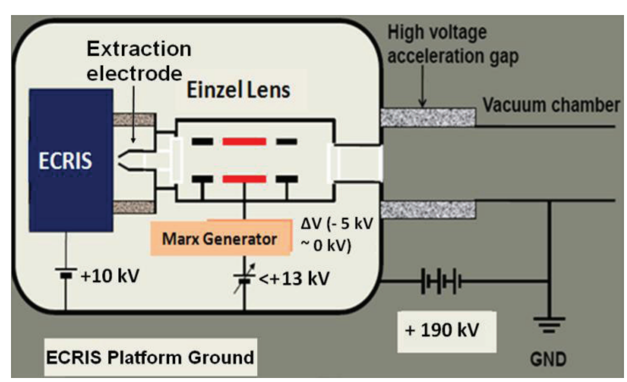

Figure 2: Schematic of the HVT and its contents.

Einzel Lens

The Einzel lens is located just after the ECRIS extraction electrode. Its middle electrode is sustained at an optimized voltage, which gives over-all transverse

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EXPERIMENTAL RESULTS: CHARGE-STATE- AND CURRENT-DENSITY DISTRIBUTIONS AT THE PLASMA ELECTRODE OF AN ECR ION SOURCE

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Abstract

We have measured the current-density distribution (CDD) in very close vicinity (15 mm downstream) of the plasma electrode of our hexapole-geometry electron-cyclotron-resonance ion source (ECRIS). For this, we equipped our 3D-movable puller electrode with a customized Faraday Cup (FC) inside. To achieve high spatial resolution we reduced the aperture of the puller electrode to only 0.5 mm. Thus, the source-region of the extracted ion beam is limited to a very small area of the plasma electrode's hole (d = 4 mm). The information about the charge-state distribution (CSD) and the current density in the plane of the plasma electrode is conserved in the ion beam and was scanned by remotely moving the small-aperture puller electrode (incl. FC) across the aperture of the plasma electrode. From additional m/q-measurements for the different positions we can deduce that different ion charge-states are grouped into bloated triangles of different sizes but with the same orientation in the plane of the plasma electrode with the current density peaking at the centre. This confirms simulations by various groups as well as some emittance measurements, but adds spatial resolution for the different charge-states.

INTRODUCTION

To further understand the processes within the plasma of ECR ion sources various groups have developed simulation tools to predict different plasma parameters or to benchmark them against existing ion sources. The parameters of importance usually are the extractable current, the achievable charge states, and the emittance of the beam at the extraction. The simulations also show the spatial arrangement of the different ion species and charge states. Here, the highly charged ions are concentrated closer to the axis of symmetry than the lower-charged ion species, but always arranged in characteristically shaped triangular stars [1, 2, 3] (if operated with a hexapole for radial plasma confinement). As a result the highly charged ions are expected to have a lower emittance. This was substantiated by emittance measurements using a bending magnet for ion separation [4, 5]. Unfortunately, using this technique the spatial information is lost. Therefore, we use a different approach to determine the spatially resolved CSD in the plane of the plasma electrode by experiment: We use our 3D-movable puller electrode to record the profile (or CDD) of the extracted beam at a distance of only 15 mm to the plasma electrode. Knowing the total CSD of the extracted beam and the axial magnetic fields we can conclusively show (by now for charge states 2+ to 4+) that the different charge states are grouped into triangular structures with the same orientation but different sizes in the plane of the plasma electrode. The current density peaks at the center.

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BEAM PROFILE MEASUREMENTS CLOSE TO THE EXTRACTION

To measure beam profiles at a distance of only 15 mm (!) downstream of the plasma electrode we take advantage of our 3D-movable puller electrode to scan the plasma electrode's aperture. It is equipped with a customized FC. The aperture which spatially limits the measured ions has a diameter of only 0.5 mm. The dimensions of the plasma electrode and the plasma chamber are shown in fig. 1. The geometrical dimensions of the FC and the use of a negatively biased repeller guarantee the suppression of secondary electron escape. Beam profiles have been aquired for two different source settings. By adding helium into the plasma chamber we changed the ion composition and the pressure inside the ECR zone. Therefore, we separate between the settings RG (residual gas at 5E-7 mbar) and RGHe (helium added until 1E-6 mbar) in the following paragraphs. The resulting beam profiles are shown in fig. 2. The figure shows the CDD for both settings (RG left and RGHe right) in the plane of the puller electrode at comparatively high resolution. The x- and y-axes denote the position in the plane of the plasma electrode with the origin being at beam center. The colour bars indicate the measured current densities. For both measurements we see similar tendencies: Areas with similar current densities can be grouped into bloated triangular-like structures with different orientations and sizes overlapping each other. The

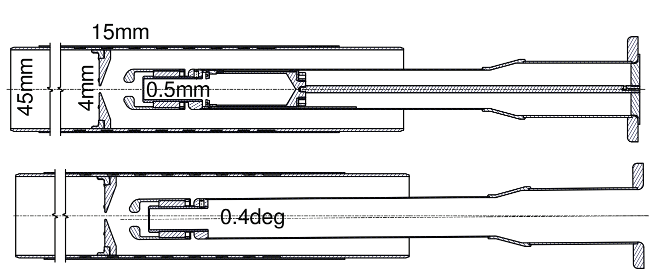

Figure 1: CAD-drawings of the plasma chamber, the plasma electrode, and the puller electrode for different settings: (1) central with implemented FC, (2) at the outmost position without the FC. Here the puller electrode is tilted by 0.4 °. The resulting shift is 2 mm.

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ION BEAM EXTRACTION FROM MAGNETIZED PLASMA

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Abstract

By increasing the total extracted ion current, the optimization of the extraction system becomes more important for any ion source because of the space charge effect. Several attempts have been made in the past to simulate the extraction from an Electron Cyclotron Resonance Ion Source (ECRIS) in a correct way. Most of these attempts failed, because they were not able to reproduce the experimental results. The best model up to now is given by the following procedure:

- Tracing the magnetic field lines through the extraction aperture, looking where these field lines are coming from.
- Using these coordinates of the magnetic field line as starting points for ions to be extracted.
- The initial current of each trajectory is determined by theoretical assumptions about the plasma or by a plasma simulation.
- Childs law is applicable locally only in direction of the magnetic field, if no emission limited flow is present.

INTRODUCTION

This model assumes that ions travel through the plasma only influenced by the magnetic field. The positive ions inside the plasma chamber are assumed to be space charge compensated to a very high degree because of the presence of cold electrons, resulting in a small plasma potential. Collisions are neglected for the path of the ion, as well as diffusion effects inside the plasma. The radius of gyration for cold electrons is well within the μm range, and so the radius of gyration for ions is below the mm range. This is a necessary precondition to define the ECRIS plasma to be magnetized. The assumption that diffusion processes are playing also a minor role is supported by the experimental experience that plasma etching occurs only at places in the plasma chamber pronounced by the magnetic structure. The visible traces inside the plasma chamber and on both end plates of the plasma chamber (injection side plate and plasma electrode) are sharply limited. These effects confirm the validity of the model. Furthermore, with that model we are able to reproduce experimental results which we have obtained with viewing targets[1]. The different spatial distribution of starting conditions generates ions with different $\int Bds$ after extraction, which also degrades the beam quality.

BASIC PRINCIPALS

General Plasma Characteristics

Due to the condition of charge neutrality for any plasma, the number of electrons n_e and the number of ions $n_{i,a}$ with charge state a can be estimated by:

$$\frac{n_e - \sum_{a=1}^{qmax} a \cdot n_{i,a}}{n_e} << 1 \quad (1)$$

The Debye shielding is deduced by solving Poisson's equation in a spherical coordinate system with the assumption, that there is no angular dependency[2]. This assumption is of not correct because of the magnetic field. If there would be no magnetic field, λ_D is given by:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k T_e}{n_e e^2}} = 7.43 \cdot 10^3 \sqrt{\frac{T_e[eV]}{n_e[m^{-3}]}} \quad (2)$$

where k is Boltzman's constant, $T_e$is the electron temperature, respectively T_i the ion temperature, e the electron charge, and ε_0 the dielectric constant. The formulation of the Debye length λ_D is valid only, if the number of particles N_D within a sphere with radius λ_D is $>> 1$.

$$N_D = n_e \frac{4}{3}\pi(\frac{\varepsilon_0 k T_e}{n_e e^2})^{3/2} = 1.72 \cdot 10^{12} \frac{T_e^{1.5}[eV]}{\sqrt{n_e[m^{-3}]}} \quad (3)$$

This condition is fulfilled if we assume a typical particle number of $n_e = 10^{15..18} m^{-3}$, and a Debye length in the range of μm to mm, which means that the required conditions for a plasma are satisfied. However, the Debye length within the magnetic field is not isotropic any more. Equ. 2 might be valid in the direction of the magnetic field, but not perpendicular to it.

If dynamic shielding is investigated, the plasma frequency ω_p comes into consideration. For electrons it follows:

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}} = 56.5\sqrt{n_e[m^{-3}]} \quad (4)$$

The plasma frequency for ions with mass m_i and density $n_{i,\alpha}$ is derived by the same procedure as for electrons with mass m_e. Because the plasma frequency for ions is lower by the factor of $\sqrt{\frac{m_i}{m_e}}$, this frequency is not of importance for screening. Only electromagnetic fields with frequencies above the plasma frequency ω_p should be able to penetrate the plasma and to propagate through the plasma.

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STATUS OF THE SEISM EXPERIMENT*

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Abstract

LPSC Grenoble has developed the first and unique confinement structure in the world that allows a closed 60 GHz ECR zone, using advanced magnet technology from Grenoble High Magnetic Field Laboratory (LNCMI). The magnetic structure was validated for 28 GHz resonance and a closed 1 T iso-B surface was measured. Discrepancies between calculated and measured field maps were extensively studied in order to determine a working range for 28 GHz plasma tests. A whole test bench, including high pressure water for helix cooling, intense currents (up to 15 kA) for helix powering and a beamline with mass separation is under construction at LNCMI. This contribution presents the status of the experiment.

SEISM MAGNETIC STRUCTURE

Initial Design

The SEISM prototype is based on a magnetic cusp, designed to reach 7 T at the injection, 3.5 T at the extraction and 4.5 T on the radial mirror [1]. A short axial mirror length (100 mm) is possible thanks to the use of polyhelix resistive coils developed by LNCMI Grenoble. Magnetic field measurements [2] confirmed that this configuration could produce a closed 1 T iso-B surface (see Fig.1), thus allowing the resonance at 28 GHz.

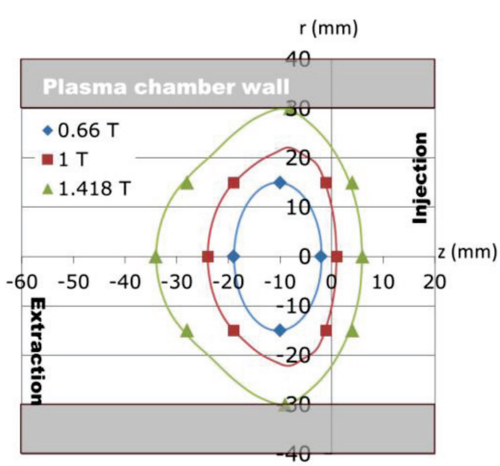

Figure 1: Iso-B map in the prototype at 15000 A.

However, one observed that the resonance zone had a 9 mm shift towards the extraction that remains unexplained. This shift was carefully investigated, as well as the consequences for the source design and operation.

Investigation of the Magnetic Shift

First, an independent measurement based on the magnetic field flux variation was performed with a 0.1 mm step along the central axis at low current (146 A). A 6 mm shift was found.

Then, both injection and extraction water tanks containing the helices were taken apart and their dimensions were checked with CAO drawings. No assembly error was found.

Finally, a new measurement was performed at low current (50 A and 100 A) after assembling the source parts between the tanks, and a 5 mm shift was found. This 5 mm shift is consistent with 2D simulations performed with FEMM software.

Consequences for the Source Design

Magnetic field configuration provides crucial information for the design of the plasma chamber and of the microwave injection.

Concerning the plasma chamber, such displacement of the magnetic field centre may cause energetic electrons crossing the resonance zone to hit and damage the plasma chamber walls. In the present case, plasma chamber dimensions are already constrained by the magnetic structure assembly. A solution was investigated to adjust the current ratio between injection and extraction coils in order to centre the resonance zone. For $I_{inj}/I_{ext}=0.8$, the cusp point is centred (see Fig. 2), which corresponds to 15 kA maximal intensity delivered by LNCMI power supplies on extraction coils and 12 kA on injection coils for 28 GHz resonance. In order to allow more flexibility on the coils current for the first beam tests, one decides to start with a 18 GHz plasma, which we expect to confine more.

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DESIGN OF NEW 18 GHZ ECRIS FOR RIKEN RIBF

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Abstract

In RIKEN Radio Isotope Beam Factory (RIBF), we plan to install a new 18 GHz electron cyclotron resonance ion source (ECRIS), which supply an intense beam of highly charged heavy ions into the RIKEN linear accelerator (RILAC). By equipping the RILAC with two ion sources, we expect to be able to develop new beams while producing a beam for experiments at RIBF. Based on the structure of existing 18 GHz ECR ion source which have been developed at RIKEN, this ion source has the following additional features: (1) Three solenoid coils have been installed to enable B_{ext} to be adjusted while B_{min} is fixed at an optimum value. (2) A variable frequency RF power source has been adopted. Therefore, further enhancement of the beam intensity is expected because the frequency band that is suited to the size of a plasma chamber can be selected. (3) The structure of the chamber has been improved to simplify maintenance work.

INTRODUCTION

For RIKEN Radio Isotope Beam Factory (RIBF) project [1], we constructed and developed several high-performance electron cyclotron resonance ion sources (ECRISs) [2–5]. One of the ion sources is the RIKEN 18GHz ECRIS used as an external ion source for the RIKEN linear accelerator (RILAC) [5]. The main role of the ion source is to produce an intense beam of multi-charged medium-heavy ions (e.g., $^{40}Ar^{8+}$ $^{48}Ca^{10+}$, $^{70}Zn^{15+}$, $^{84}Kr^{18+}$) for the RIKEN RIBF and the super-heavy element search experiment. For this purpose, we have improved performance using various methods [5]. However, we recently needed to develop new beams to meet the requirements for new beams and to extend the irradiation time (longer than one month) of the heavy ion beam, particularly the metallic ion beam, on target for the RIBF. To meet these requirements, we needed a new ion source. By equipping the RILAC with two ion sources for the RILAC, we could develop new ion beams while producing a beam for the experiment. Furthermore, when faced with problems of the ion source during beam production for the experiment, we can immediately switch to another ion source for producing the beam. This means that we can extend irradiation time by using two ion sources. For these reasons, we started to design and construct the new 18 GHz ECRIS as an additional external ion source for the RILAC.

In the present paper, we describe the structure of the new 18 GHz ECRIS. We present the structure of the solenoid coils used for producing a magnetic mirror along the axis and a hexapole magnet, the design of the plasma chamber, and the traveling wave tube (TWT) amplifier for producing 18 GHz microwaves, in the following sections.

SOLENOID COILS AND HEXAPOLE MAGNET

Figures 1 (a) and (b) show schematic drawings of the new 18 GHz ECRIS. It consists of three solenoid coils that produce a mirror magnetic field along the axis. Figure 2 shows a typical magnetic field distribution along the axis. The main parameters of the solenoid coils are listed in Table 1. By using this magnet system, one can independently control the magnetic mirror ratio and B_{min}. As described in several papers [4, 6, 7], beam intensities of highly charged heavy ions are strongly dependent on B_{min}. The optimum value of B_{min} for maximizing the beam intensity is nearly constant (70%~80% of B_{ecr}) for the high-performance ECRIS [4]. This may be due to the effect of the magnetic field gradient and the ECR zone

Table 1: Specifications of the Mirror Coil

	Solenoids I & III	Solenoid II
Number of turns	296	60
Maximum current	660 A	300 A
Maximum voltage	105 V	10 V
Maximum intensity of the mirror magnetic field	>1.3 T	
Minimum intensity of the mirror magnetic field	<0.5 T	

Table 2: Specifications of the Hexapole Magnet

Material	Nd-B-Fe permanent magnet
Inner diameter	85 mm
Outer diameter	186 mm (magnet only), 210 mm (including a holding jacket)
Length	250 mm
Number of divisions	36
Magnetic field intensity	~1.3 T at the surface of the cylinder with the size of 79 mmϕ × 150 mm

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RECENT RESULTS OF PHOENIX V2 AND NEW PROSPECTS WITH PHOENIX V3*

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Abstract

The 18 GHz PHOENIX V2 ECRIS is running since 2010 on the heavy ion low energy beam transport line (LEBT) of SPIRAL2 installed at LPSC Grenoble. PHOENIX V2 will be the starting ion source of SPIRAL 2 at GANIL. The status and future developments of this source are presented in this paper. Recent studies with Oxygen and Argon beams at 60 kV have demonstrated reliable operation at 1.3 emA of O^{6+} and 200 eμA of Ar^{12+}. Metallic ion beam production has been studied with the Large Capacity Oven (LCO) developed by GANIL and 20 eμA of Ni^{19+} have been obtained. In order to improve further the beam intensities for SPIRAL2, an economical upgrade of the source named PHOENIX V3 has been recently approved by the project management. The goal is to double the plasma chamber volume from 0.6 to 1.2 liter by increasing the chamber wall radius, keeping the whole magnetic confinement intensity unchanged. The PHOENIX V3 magnetic design is presented along with a status of the project.

PHOENIX V2 RECENT RESULTS

The PHOENIX V2 source is an evolution of the former PHOENIX V1 source used to study intense pulsed afterglow Lead beams for the LHC [1,2,3]. Major improvement of V2 with respect to V1 are a higher voltage withstanding (60 kV) and a higher radial magnetic confinement (1.35 T instead of 1.2 T at plasma chamber wall); the drawback being a lower chamber volume (0.7 liter instead of 1.2). Information on the 3 PHOENIX version layout is reported in the next section for completion. PHOENIX V2 was installed at LPSC on the SPIRAL2 LEBT from December 2009 until June 2012 and allowed the successful beam line commissioning. Production tests of A/Q=3 beams have been performed with gas and metals in collaboration with IPNL and GANIL. The table 1 summarizes the results obtained. The beam results increased recently by 30% after the discovery and the fixing of a wrong mechanical part machining in the plasma chamber water flow circuit. Once fixed, the water flow reached its nominal value and the source immediately accepted much more RF power to produce further high charge states ions. The Fig. 1 presents a Ni spectrum obtained with the GANIL LCO. [4] The Ni consumption was 0.2 mg/h and beam featured stable behaviour for several hours. One should note the excellent charge state distribution peaked on the 19+ which was unexpected for such a compact source. The 20 μA Ni^{19+} was obtained at the upper LCO operation temperature and no intensity saturation was observed. So a higher Ni^{19+} current should be reached with 2 ovens set in parallel or a larger oven. Unfortunately, the 32 mm source radius is too small to allow this. The key to understand this high charge state distribution is likely the pressure decrease in the plasma chamber induced by the Ni vapor (Getter effect). Indeed, the plasma chamber is only pumped through the plasma electrode. The vapor to ion yield was measured to be ~10%. The LCO is located off axis with an angle that optimizes the vapor solid angle intersection through the ECR plasma.

Table 1: Intensities Produced by PHOENIX V2

Ion	Charge state	Intensity [μA]
He	2+	2400
O	6+	1300
	7+	250
Ar	12+	205
	14+	50
Ni	19+	20
	20+	11.5
	21+	5

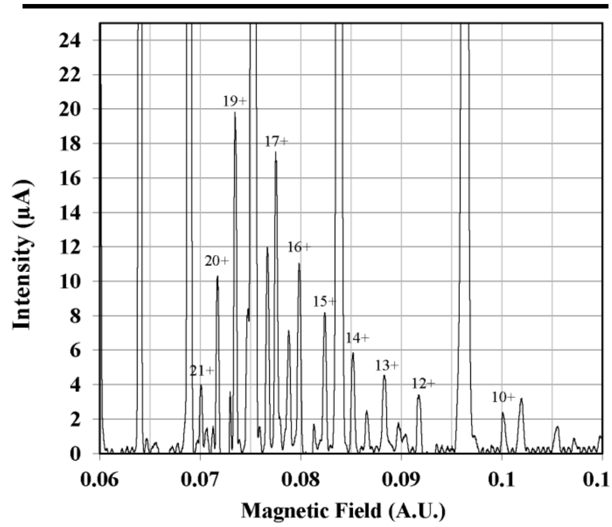

Figure 1: Nickel spectrum obtained with PHOENIX V2.

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RELATIONSHIP OF PERFORMANCE AND RF MODES IN ECR ION SOURCE

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Abstract

The performance of El ectron Cyclotron Resonance (ECR) ion source depends on the operation frequency, the magnetic mirror field, the hexapole fields, the m irror ratio, the ECR zone. We studied the relationship of performance and operation frequency in ECR ion source. The performance (beam intensity of Ar^{9+} ion) was measured according to change of frequency from 9.7 to 11.7 GHz in fixed magnetic field of a new ECR (FM-ECR) ion source. We measured resonant frequencies of plasma chamber of th e FM-ECR ion source in condition of no plasma (current of mirror coils is zero). The data of intensity of Ar^{9+} related to measured resonant frequencies. Their resonant modes were checked with a 3D electromagnetic simulator. As a result, it becam e clear that the performance of the i on source depends on electric field distribution of the RF resonant mode.

INTRODUCTION

We studied new ECR (Electron Cyclotron Resonance) ion source for production of full stripped heavy ion. This type ECR i on source is operated by high e nergy electron which is acce lerated by sa me principle of frequency modulated (FM) Cyclotron. Thi s ion source is named FM-ECR ion source. In experiment with this ion source, we fund that current of higher charge state ions depends on frequency of micro-wave. This phenomena is not so good for production of high energy electron in the FM-ECR ion source by input micro-wave power depending on frequency. Therefore an aim of FM-ECR ion source was not succeeded. Then, measurement of fre quency dependence for production of high charge ion started with the FM-ECR ion source. Performance of ECR ion sources depends on the operation frequency, the magnetic field, the hexapole field, the mirror ratio, the magnetic profile and the length, surface and volume of ECR zone . Characteristic of RF modes in ECR ion source were not studied before for very complex mode. Simple RF modes were studied previously by LBL and C atania [1-3]. The relationship of frequency tuning and RF mode are studying several in stitute [4-6]. We studied relation of between currents of high charge ion and frequency of RF mode using the FM-ECR ion source.

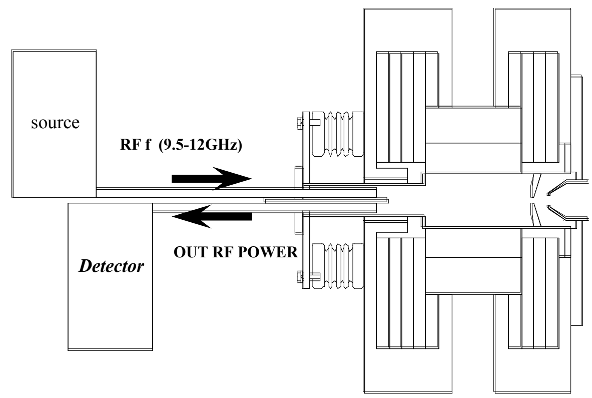

Figure 1: Experimental Apparatus and FM-ECR ion source.

Table 1: Main Parameters of FM-ECR Ion Source

	HiECR (Previous)	Present Status
Microwave Power source		
Frequency (GHz)	10-18	10-12
Power (W)	250	100/250
RF injection port	1	2
Diameter (mm) of Plasma Chamber		
RF injection side	38	
Extraction side	72	
Length (mm)		
RF injection side	77.5	
Extraction side	173.5	
Total length	251	
Hexapole Magnet		
Field on chamber (kG)	11.4	
Material	42N	
Inner diameter (mm)	76-82	
Length (mm)	145	
Mirror Field		
Maximum field on axis (kG)	9.6	7.8
Maximum coil current (A)	600	425
Maximum power (kW)	60	30

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PLASMA INSTABILITY IN THE AFTERGLOW OF ECR DISCHARGE SUSTAINED IN A MIRROR TRAP

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Abstract

The investigations of plasma decay in ECR heated discharges confined in a mirror magnetic trap is actively studied subject for many years. The motivation of this work is to study plasma instabilities causing perturbations of ion current during the plasma decay.

Present work is devoted to time-resolved diagnostics of non-linear effects observed during the afterglow plasma decay of an 14 GHz Electron Cyclotron Resonance Ion Source (ECRIS) at JYFL operated in pulsed mode. Plasma instabilities causing perturbations of extracted ion current during the decay were observed and studied. It is shown that these perturbations are associated with precipitation of high energy electrons along the magnetic field lines and strong bursts of bremsstrahlung emission. The effect of ion source settings on the onset of the observed instabilities was investigated. Based on the experimental data and estimated plasma properties it is assumed that the instabilities are of cyclotron type. The conclusion is supported by a comparison to another type of plasma devices (SMIS 37, IAP RAS) exhibiting similar characteristics but operating in a different plasma confinement regime.

INTRODUCTION

A number of studies have been devoted to the investigations of plasma decay in ECR heated discharges confined in a mirror magnetic trap (e.g. refs. 1-4). The motivation of this work is to study plasma instabilities causing perturbations of ion current during the plasma decay. The initial transient peak observed during the afterglow plasma decay has been successfully utilized for injection to circular accelerators of heavy particles[5]. The ejection of multicharged ions during the plasma decay is related with its strong nonequilibrium state. ECR plasma heating results to complex non-equilibrium velocity distribution of electrons. In addition, the electron and ion components of plasma are confined in the magnetic trap differently due to significant difference of collision rates. Plasma non-equilibrium state continues to grow after switching off the microwave pulse due to loss cone scattering depending on electron energy, which in particular can cause instabilities described e.g. in Refs. 6-9. Strongly non-equilibrium velocity distribution of electrons confined in mirror magnetic trap can be found in Earth's magnetosphere10 as well as in plasma generators driven by high frequency microwave radiation. Thus, the investigations described in the present paper have rather wide range of applications. The main focus of this work is determining the reasons of apparent perturbations of ion current extracted from plasma during the afterglow of ECR discharge. It is obvious that these perturbations are related to plasma instabilities. The temporal correlation of these perturbations and peaks of bremsstrahlung emission was suggested in ref. 11. Bremsstrahlung and characteristic X-rays are produced by collisions of fast electrons in plasma and with vacuum chamber walls, the latter being the dominant process. Ejection of electrons from the plasma to the walls is evidently related with changes in confinement of fast electrons whose lifetime in quiescent plasma amounts to seconds. Ejection of fast electrons (> 100 keV) from a mirror trap in afterglow mode has been studied in refs. 7 and 12. It was demonstrated that as a result of development of cyclotron instability fast electrons interacting with electric field of plasma waves could enter the loss cone and abandon the trap. The instantaneous current of such electrons, expelled in bursts of less than 200 ns, can be substantial. It is hypothesized in this paper that ion current perturbations, peaks of bremsstrahlung radiation and ejection of fast electrons from the trap are consequences of a single phenomenon, and are related with the evolution of cyclotron instability in strongly non-equilibrium plasma in afterglow of ECR discharge. To confirm this hypothesis a detailed study of temporal behavior of extracted ion currents, bremsstrahlung emission and fast electrons expelled from afterglow plasma was carried out.

EXPERIMENTAL SETUP

The experimental data were taken using the JYFL 14 GHz ECRIS[13]. The source uses an Nd-Fe-B permanent magnet sextupole arrangement and solenoid coils forming a minimum-B structure for confinement of the plasma. The strength of the sextupole field on the wall of the plasma chamber is 0.95 T. Plasma electrons are heated by 50 - 800 W of microwave power at 14.085 GHz. Typical operating neutral pressures are in the 10^{-7} mbar range. The main parts of the setup are a 14 GHz klystron amplifier with a rise and fall times of < 10 μs and < 40 μs, a fast RF-switch with a rise time of 40 ns controlling the incident power, dedicated electron detector with attenuating foils mounted downstream from the plasma electrode, Germanium x-ray/gamma ray detector equipped with a lead collimator structure, TNT2 digital signal processing unit[14]. The Ge-detector arrangement is suitable for studying the temporal behavior of

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EMITTANCE MEASUREMENT FOR U ION BEAMS PRODUCED FROM RIKEN 28 GHZ SC-ECRIS

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Abstract

In order to investigate the ion optical parameters of the beam line of a new injector system for RIKEN RIBF, we measured the emittance of heavy ion beams from the RIKEN 28 GHz SC-ECR ion source. In the test experiments, we observed that the emittance of the U^{35+} beam was ~100π mm-mrad (4 rms emittance). The emittance with 28 GHz was almost the same as that with 18 GHz and independent of the injected RF power. The size of the emittance increased with the decreasing charge state. We also observed that the brightness of the U^{35+} ion beam increased with the increase in the negative bias voltage of the disc installed in the plasma chamber.

INTRODUCTION

At RIKEN, we commenced the construction of the new superconducting electron cyclotron resonance ion source (SC-ECRIS), which has the optimum magnetic field strength for the operational microwave frequency of 28 GHz to produce an intense beam of highly charged heavy ions for RIKEN RI beam factory project [1]. In the spring of 2009, RIKEN SC-ECRIS produced the first beam with 18 GHz microwaves [2]. Since then, we have conducted various test experiments with the aim of increasing the beam intensity of highly charged heavy ions [2]. In 2010, we started the injection of 28 GHz microwaves into the ion source and produced intense Xe and U ion beams [3]. For the external ion source of the heavy ion accelerator, it is important to not only increase the beam intensity but also improve the beam quality (emittance, brightness, etc.). Accordingly, several laboratories have systematically studied the effect of the main parameters (magnetic field distribution, gas pressure, RF power, etc.) of the ECRIS on the emittance. A simple method to increase the beam intensity is the "biased disc" method [4]. We employed this method and successfully increased the beam intensity of highly charged heavy ions [2]. Although it is natural to assume that a negatively biased disc would affect the beam quality, few experiments have so far been conducted for understanding the effect of a biased disc on beam quality. Hence, we started studying the effect of the biased disc.

In this paper, we report the experimental results of emittance measurements for the U ion beam produced from the RIKEN 28 GHz SC-ECRIS. The effect of a biased disc on the emittance is also described.

RIKEN 28 GHZ SC-ECRIS

The detailed structure and performance of the RIKEN SC-ECRIS with 28 GHz microwaves have been described in Refs. [2, 3]. Using six solenoid coils, RIKEN SC-ECRIS can produce various magnetic field distributions on the axis, which are both of the classical B_{min} and the so-called "flat B_{min}" [5]. The microwaves were generated by the 28 GHz gyrotron (Max. power of 10 kW) and injected into the RIKEN 28 GHz SC-ECRIS.

EXPERIMENTAL RESULTS AND DISCUSSION

In this experiment, the maximum mirror magnetic field strength at the RF injection side (B_{inj}), minimum strength of mirror magnetic field (B_{min}), the maximum mirror magnetic field strength at the beam extraction side (B_{ext}), and radial magnetic field strength at the inner wall of the plasma chamber (B_r) were fixed to 3.3, 0.6, 1.8, and 1.8 T, respectively, with 28 GHz microwaves. The extraction voltage was 22 kV. To produce a U ion beam, we used the sputtering method. Figure 1 shows the schematic illustration of the RF injection side of the plasma chamber. The sputtering voltage and the position of the U rod (L) were optimized to maximize the beam intensity of highly charged U ions. The typical sputtering voltage and L were 5 kV and ~140 mm, respectively. Figure 2 shows the typical charge distribution of the highly charged U ions. The RF power was ~1 kW.

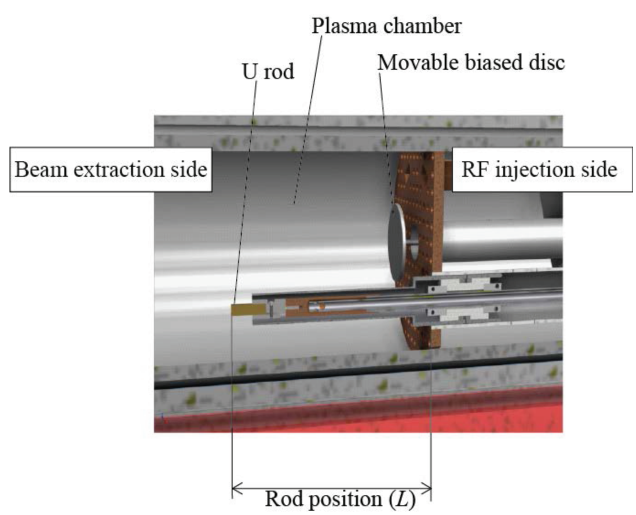

Figure 1: Schematic illustration of the RF injection side of the plasma chamber.

The root-mean-square (rms) emittance is defined as

$$\varepsilon_{x-rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$
$$\varepsilon_{y-rms} = \sqrt{\langle y^2\rangle\langle y'^2\rangle - \langle yy'\rangle^2}.$$

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DEVELOPMENT UPDATE OF THE LECR4 ION SOURCE – DRAGON AT IMP*

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Abstract

A room temperature ECR ion source, LECR4-DRAGON to operate at 18 GHz, is under development for the SSC-LINAC project at IMP. In comparison to other room temperature ECRISs, a unique feature of the LECR4-DRAGON is its plasma chamber of ID 126 mm that is the biggest chamber for a room temperature ECRIS and the same as the superconducting ECR ion source SECRAL. Because of the project funding agency requires study a different magnet cooling scheme, solid quadrate copper coils cooled by medium evaporation at about 50 ^{0}C are to be used to produce a maximum axial magnetic field of about 2.5 T at injection and 1.4 T at the extraction, which are similar to SECRAL operating at 18 GHz. Furthermore, a large bore non-Halbach permanent sextupole with staggered structure has been under fabrication which can produce a radial magnetic field reaching 1.5 T at the plasma chamber wall for operation at 18 GHz. The progress updates and discussions of this ion source will be presented.

INTRODUCTION

The LECR3 source, a room temperature ECRIS [1], is operating at IMP since 2003 and it has been delivering the most of light ion beams for the SSC cyclotron and CSR, whereas the SECRAL [2] ECR ion source has been mainly providing the highly charged heavy ion beams. To meet the demands of intense medium charge state heavy-ion beams, a research program, collaborating with IEE- Beijing, had been started two years ago. The goal of this program is to produce intense medium charge state heavy-ion beams with a room temperature ECR ion source, meanwhile testing an evaporative cooling technology [3] for potential applications to accelerator magnets. In comparison to a superconducting ECR ion source, a room temperature ECR ion source has the advantages of lower cost and easier operation but with lower performance due to the limitations on the magnetic field and ac power consumption. To date, all the room temperature ECR ion sources are built with a small plasma chamber of inner diameter less or equal to 80 mm producing a radial field of about 1.2 to 2.0 T [4]. The small plasma chambers are not optimal as evidenced by some outstanding SC ECRISs [2, 5] at about the same field profile with larger plasma chambers (ID > 120 mm). Thus a larger bore sextupole magnet has been chosen for the LECR4-DRAGON with its axial magnetic field modelling the SECRAL field profile operating at 18 GHz: 2.5 T at the injection and 1.3 T at the extraction region with a radial field of 1.4 T at the plasma chamber walls. The unique feature of LECR4-DARGON is that the solenoid magnet coils are fully immersed in and cooled with a 47.7 ^{0}C evaporative medium. Figure 1 shows the mechanical layout of the LECR4-DRAGON while Fig. 2 showing the computed axial magnetic field profile.

* This collaboration project was supported by the Research Foundation of Chinese Academy of Sciences.

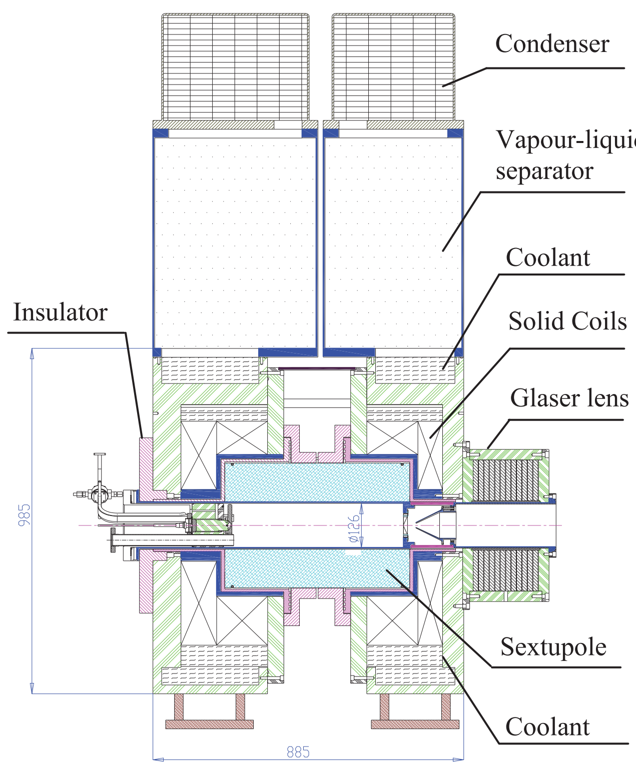

Figure 1: A schematic cross-section view of the LECR4-DRAGON. No mechanical pumping at the injection side for simplicity but may be added in the future.

Evaporative Medium Cooled Solenoid and Prototype Experiments

Institute of Electrical Engineering of Chinese Academy of Sciences (IEE) has been researching the evaporative

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ADVANCED INJECTION SYSTEM OF LIGHT IONS (AISLI) FOR DIELECTRIC WALL ACCELERATOR*

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Abstract

Dielectric wall accelerator (DWA) is a kind of acceleration system with high electric field gradients up to 400 MV/m and very compact dimension, for example ϕ 30 mm x 50 mm, which has the ability to accelerate the particles with any charge to mass ratio. To demonstrate the high gradient tiny acceleration system, a compact injector is required, which should deliver a 50 mA/40 keV pulsed H^+ converging beam to the entrance of DWA. Based on the experimental results obtained on the test bench, a six electrodes injector was developed at Peking University (PKU). In this paper we will describe the preliminary experimental results as well as the details of the new compact injector which named as Advanced Injector System of Light Ions (AISLI).

INTRODUCTION

Dielectric wall accelerator (DWA) is a new acceleration concept that can generate an extremely high gradient up to several hundred MV/m for a short pulse beam with any charge to mass ratio particle [1]. As mentioned in literature [2], a compact proton injector capable of delivering sub-ns proton bunches, and high gradient insulators (HGI) with high surface breakdown strength are two of the five essential elements to make a proton DWA accelerator compact. Sitting the HGI in oil tank is a solution to increase the HGI surface breakdown strength. A space between the proton injector and HGI for adaption is needed. To better understanding the DWA concept, a ϕ 30 mm x 50 mm HGI will be used to demonstrate its acceleration ability. Beam need for this HGI demonstration is a 50 mA/40 keV converging square pulse proton beam. Its repeat frequency is 50 Hz. The width of each pulse is 200 ns. Besides, the injector should be a very compact one so that it can match DWA's tiny features with reasonable dimension. Parameters of the injector are listed in table 1.

To meet the requirement of the tiny DWA, a 20 cm long proton injector including 8 cm adaption space for ion tank are developed at Peking University (PKU). It consist of on a permanent magnet 2.45 GHz Electron Cyclotron Resonance Ion Source (PMECRIS) [3] and an electrostatic focusing LEBT based on the preliminary experimental results obtained on PKU LEBT test bench. This injector is named as Advanced Injection System of Light Ions (AISLI). In part II, we will present the preliminary experimental results based on PKU ion source test bench. In part III we will give a description of AISLI, emphases are located on PBGUNS code simulation, methods for the beam producing, beam focusing, pulse shape controlling. At the end of this paper we will give a summary and anticipation.

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Table 1: Proton Injector Key Performance Parameters Required by DWA

Peak Current	mA	50
Energy	keV	40
Emittance	π mm.mrad	≤0.2
Radius at entrance of HGI	mm	5
Frequency	Hz	50
Pulse width	ns	200
Space for adaption	mm	80

PRELIMINARY EXPERIMENT ON PKU ION SOURCE TEST BENCH

General Consideration

A proton injector is a facility to generate plasma, create an expected ion beam and transport it into accelerator. The core of it is an ion source and a low energy beam transport part (LEBT).

There are more than 50 kinds of ion source around the world. Scientists at LLNL chose a spark source to produce proton beam for their DWA [2]. At PKU a permanent magnet 2.45 GHz Electron Cyclotron Resonance Ion Source (PKU PMECRIS) has been chosen. This is not only because researchers at PKU are skillful on this kind of ECRIS [3-5], but also because the unique feature of it, high ion beam density, high reliability, ability to operate both in CW mode and in pulsed mode, good reproducibility and low maintenance and long lifetime. Because of those characteristic, 2.45 GHz ECRIS is popular as a high current ion source in the world [6-10]. By using permanent magnet to replace the solenoid, the ECR ion source body is about 100 mm, and even smaller.And accessories to support source operation on high voltage platform become less. This will benefit the miniaturization the whole injector.

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METAL ION BEAM PRODUCTION WITH IMPROVED EVAPORATION OVENS

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Abstract

Most of the ion beams delivered by the ECR ion sources at the GSI accelerator facilities are produced from materials in the solid state, which must be transformed into the gaseous state to feed the plasma. The well established method of thermal evaporation has been used by means of two types of resistively heated ovens for metals and solid compounds. The main goal of development is to improve their versatility in terms of lifetime, durability, efficiency, and extended temperature range. Recent investigations and developments include the use of alternative materials for oven components. The main focus has been on the further development of the high temperature oven. A modular construction with improved mechanical dimensional accuracy for more precise and easier mounting has been established. Its optimization for stable long time operation has been continued leading to a lifetime of 6 days for evaporation of Ti at 1750°C. Furthermore the temperature limit could be extended to 2300°C. In addition to the improvements in evaporation technology the technique of microwave frequency tuning could be successfully applied for metal ion operation leading to enhanced ion beam intensities.

INTRODUCTION

A great variety of ion species is required at the GSI heavy ion accelerator facility. More than 85% of the natural elements are solid at room temperature and must be transformed into the gaseous state to feed the plasma. Several methods like thermal evaporation, plasma heating, ion sputtering, laser ablation or producing metal ions from volatile organic compounds (MIVOC) can be applied. At GSI the evaporation technique using ovens has been preferred because it resembles closely the operation with gases [1]. It has been used for two decades to produce ion beams from many different materials with the CAPRICE type ECR Ion Source (ECRIS). The basic requirements of operation are long time stability, long operation periods without maintenance, constant beam parameters and low material consumption when using rare isotope materials. According to semi-empirical scaling and experimental experience a vapour pressure of about 10^{-3} mbar is suitable for evaporation into the plasma and to extract stable ion beams of sufficient intensity.

STANDARD OVEN

The resistively heated standard oven (STO, Fig.1) is mostly used for the production of metal ion beams in routine operation with the ECRIS at GSI. The STO is optimized for temperatures between 300°C and 1500°C.

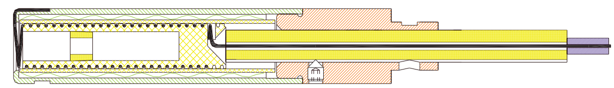

Figure 1: STO - GSI standard oven (yellow: Al_2O_3; green: Ta; orange: Mo; violet: CuBe2)

For $^{54}Cr^{8+}$ it was investigated whether the lifetime of the oven can be increased by increasing the initial amount of ^{54}Cr sample material. It turned out that the lifetime increases with the charge to some extent, however, the material consumption also increases. It became evident that an optimum charge of sample material exists giving the best compromise between oven lifetime and material consumption. The overall consumption of ^{54}Cr sample material was 4 mg/h on average with a range of fluctuation between 2 mg/h and 6 mg/h for the particular charges. Figure 2 shows a typical mass/charge spectrum of the extracted ion beam. Besides ^{54}Cr and He (auxiliary gas) it shows a very low amount of contaminations and confirms the very high degree of enrichment of the ^{54}Cr material.

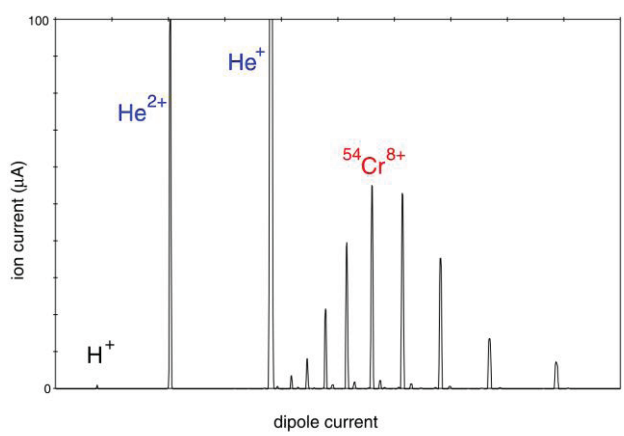

Figure 2: Typical mass/charge spectrum of ^{54}Cr.

TITANIUM BEAM WITH STO

The investigations on the development of a ^{50}Ti beam for experiments of the Super Heavy Element (SHE) program were extended by exploring 3 alternative approaches. Besides thermal evaporation of titanium with the STO another type of resistively heated oven was investigated. This type of oven had been developed for the thermal evaporation of materials at very high temperatures (HTO, Fig. 3) [1].

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EXPERIMENTAL STUDIES ON THE ALISES ION SOURCE AT CEA SACLAY

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Abstract

The ALISES ion source was originally designed to reduce beam emittance at RFQ entrance by shortening the length of the LEBT. A wide opened magnetic coil at ground potential produces the fringe field needed for the ECR heating at 2,45 GHz frequency. The first part will describe the commissioning of the source: Penning discharges inside the accelerating column make the high voltage power supply collapse. Experimental tests with kapton films while discharges occur and simulations with the OPERA-3D code have shown great similarities to detect the location of those discharges and allow us to make the ion source work. The second part of this paper will present the result of low intensity light ion beam production versus the plasma chamber length and radius. Those very preliminary tests give us indications to reduce the ion source dimensions.

INTRODUCTION

At CEA Saclay, light ion sources are generally designed for accelerator purpose. Since mid-90's ECR ion sources have been developed for high intensities: the SILHI source produces up to 100 mA of proton or deuteron beams routinely [1] for the IPHI accelerator and the IFMIF ion source [2] producing up to 120 mA of deuteron is under commissioning. Recently the need of smaller size ion sources had increased, capable to deliver 50 mA of proton beams with the lowest emittance. In order to work on this need, an internal R&D work was scheduled on several years to study several criterions: what are the relevant parameters that can reduce the size of an ion source?

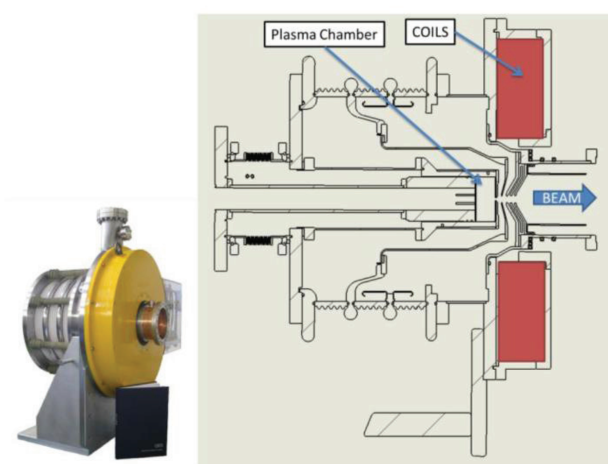

Figure 1: ALISES Ion Source, extraction side.

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This paper will show the first experimental results of the ALISES ion source installed on the BESTI test bench [3] and how we solved partially Penning discharges inside the source. The second part will show the preliminary results at low bias voltage for low extracted currents when changing the plasma chamber length and diameter.

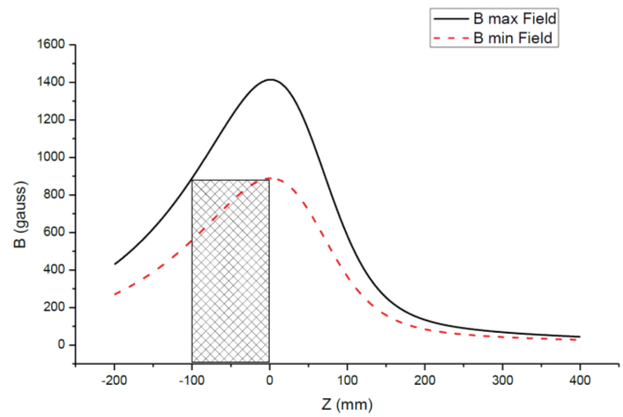

Figure 2: Fringe field of the source coil. The dash zone represents the plasma chamber

COMMISSIONING

The ALISES ion source has been described in ref [4] and [5]. This source is not intended to be a small size source but allows us to test several size parameters in order to miniaturize the next generation of ion sources. The ALISES concept consists in reversing the position of the insulating structure with the magnetic field generation material (coils or permanent magnets), in order to shortened the LEBT and keep the extracted beam focalized at source exit.

The commissioning of the ion source was made in several steps. First we applied 50 kV of bias voltage on the source body and the puller electrode independently in order to detect some grounding problem or sparking. No sparking was detected on either electrode. For the second step, we switched off all HV power supplies of the source and switched on the magnetic field of the source coil in order to produce the 875 Gauss resonance zone at 100 mm behind the plasma electrode. With a 3 sccm of H_2 gas and 300 W of HF power delivered by the magnetron, a pink colored plasma was observed through a window along the LEBT axis, characteristic of the hydrogen Balmer lines.

When the electric and magnetic field were simultaneously on, the HV power supplies dropped down

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A MULTI-SAMPLE CHANGER COUPLED TO AN ECR SOURCE FOR AMS EXPERIMENTS*

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Abstract

A project using Accelerator Mass Spectrometry (AMS) at the ATLAS facility to measure neutron capture rates on a wide range of actinides in a reactor environment is underway. This project will require the measurement of a large number of samples previously irradiated in the Advanced Test Reactor at Idaho National Laboratory. The AMS technique at ATLAS is based on production of highly-charged positive ions in an electron cyclotron resonance ion source (ECRIS) followed by acceleration in the ATLAS linac. The sample material is introduced into the plasma via laser ablation. This should limit the dependency of material feed rates upon the source material composition as well as minimize cross-talk between samples. A new multi-sample changer has been constructed allowing rapid changes between samples. The sample changer has 20 positions and is capable of moving from one sample to the next in one minute.

INTRODUCTION

Accelerator mass spectrometry (AMS) is a sensitive technique for accurately measuring quantities of long-lived, rare isotopes in the presence of more abundant ones using very small amounts of material. The material of interest is introduced into the ion source of an accelerator, ionized, accelerated, and separated by electromagnetic means. Accelerators offer an advantage over conventional mass spectrometers owing to the total elimination of molecular interference due to the dissociation of the molecules in the ion source plasma. By accelerating the mass of interest to energies of a few MeV/U, it is often possible to use differences in rates of energy loss to separate the isobar constituents into their exact elemental groups resulting in a complete atom-by-atom unique identification over much of the periodic table [1, 2].

AMS often has a limited amount of material that can be provided for the measurement with sample sizes of at least a few mg mass required to be able to handle and control the delivery of the ions into the plasma (and hence to the detector). Also for oven evaporation or even sputtering, the form of the source material determines how easily this material can be introduced into the plasma. So in many AMS cases the success of the project can hinge on the choice of the material chemical form and either the dilution methods employed or the pre-AMS chemical separation techniques used to enrich the element of interest.

Oven evaporation and sputtering can indiscriminately deposit material into the source resulting in an accumulation of material on the source walls. This can lead to sample 'cross-talk' and elevated backgrounds. For many AMS experiments, it has been necessary to develop liners to shield the source plasma from the wall contaminations [3]. This can form the ultimate limitation to AMS sensitivity either because of an inability to discriminate isobar members adequately or due to sample cross-talk.

In an effort to reduce both the cross-talk problem and allow the use of small samples with minimal chemical processing and dilution, the laser ablation technique is being employed to introduce the sample material into the source in a very controlled and precise manner. Laser ablation was first developed at ATLAS [4, 5] and used as a plasma diagnostic tool and has since been used by a number of other labs to explore the coupling of laser produced ions into an ECR source [6, 7]. The controlled release of materials into the plasma by well-focused laser light will eliminate the significant material accumulation often seen in the region of the oven throat or beside the sputter samples. The inefficient and indiscriminate injection of material into the source using the sputter or oven methods reduces the total sensitivity of the AMS method and is a major source of cross-contamination between samples.

THE ANL ECR ION SOURCE

ECR2 is a room temperature ion source based upon the A-ECRU design [8] with the plasma excited with multiple frequencies between 10 and 14 GHz and a typical bias voltage of 14 kV. The source has radial access utilized for material introduction as well as pumping to the plasma region. Due to source space considerations as well as the desire to have the ablated material traverse as much of the plasma as possible, it was decided to pursue an axial ablation geometry. In this geometry the laser is mounted off of the source high voltage platform at ground potential. The beam is directed up to the high voltage platform through large diameter insulting pipes. The ablation sample is introduced on the injection side of the source with the laser beam entering the vacuum system through a port on the 0º line. The laser enters the ion source plasma chamber through the extraction aperture and strikes the target (Fig. 1).

For the initial on-line tests, the ablation sample was mounted on a simple linear motion feed through. The optimum ablation position during source operation was determined by varying the sample position and observing the intensity of the beam of interest. However, for the experimental program, a large number of sample positions were required with the ability to cycle rapidly between them.

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OPTIMIZATION OF THE NEW SC MAGNETIC STRUCTURE DESIGN WITH A HYBRID MAGNET*

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Abstract

In the development of the next generation Electron Cyclotron Resonance Ion Source, so far either a set of full NbTi or Nb_3Sn magnets has been proposed to construct the magnet system. However, the single set of NbTi magnets may not be the optimum in terms of the field strength and configuration. An optimization of the new SC magnetic structure [1] with a hybrid magnet (NbTi and Nb_3Sn) is being investigated. With the hybrid magnet and other minor changes the optimized new magnetic system is capable of producing field maxima of 9.0 T on axis and 4.1 T at the plasma wall, which are about 30 and 5 percent higher than the new SC magnetic structure to be built with a set of full NbTi magnets. In addition, the axial length of the optimized magnetic structure has been slightly shrunk resulting in a less bulky system. This new magnetic field profile is high enough for operation frequency up to 56 GHz. The design features and the preliminary stress analysis of the optimized new SC magnetic structure will be presented and discussed.

INTRODUCTION

The significant performance enhancement of Electron Cyclotron Resonance Ion Source (ECRIS) in the last decade has demonstrated that operating with higher-field and higher-frequency remain to be the most effective and straightforward path to further improve the ECRIS performance [2-4]. To meet the increasing ion beam demands from the accelerators worldwide under construction or design, the next generation ECRISs of much higher-field and higher operating-frequency have been proposed to be built with either a set of full Nb_3Sn or a set of full NbTi magnets. As a continuation of the classical magnet structure, a set of full Nb_3Sn magnets would yield field maxima of 8.0 T on axis and 4.0 T at the plasma chamber walls [5]. The newly proposed magnetic structure (MK-I) would produce 7.0 T and 3.9 T with a set of full NbTi magnets, and 12.0 T and 6.0 T with a set of full Nb_3Sn magnets, respectively [1]. However, there are many uncertainties of the Nb_3Sn magnet to be used in ECRIS and which need thoroughly addressed before an ECRIS of Nb_3Sn can become a reality. On the other hand, the NbTi magnet has been fully proven its reliability in the present generation ECRISs, but the configuration of maximum fields of 7.0 T and 3.9 T may not be very satisfactory to support operations up to 56 GHz. Development has demonstrated that higher magnetic fields is the needed basis for a next generation ECRIS to achieve higher performance [6]. Therefore building an ECRIS with a set of full NbTi magnet may not be the best option in the near future and an exploration of any possible optimizations on the magnet system would greatly benefit the development.

*Work supported by China Nature Science Foundation under Contract No. 10921504

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A HYBRID MAGNET WITH THE NEW MAGNTIC STRUCTURE

Fabrication of a Nb_3Sn solenoid coil nowadays is a pretty straightforward process. In reference to the case of a set of full NbTi magnets (NbTi-I) with the MK-I magnet structure [1], the hybrid magnet (Hybrid-I) described here is such a set of magnets that injection solenoid is fabricated of Nb_3Sn wires but keep the rest coils of NbTi wires, as indicated in Fig. 1.

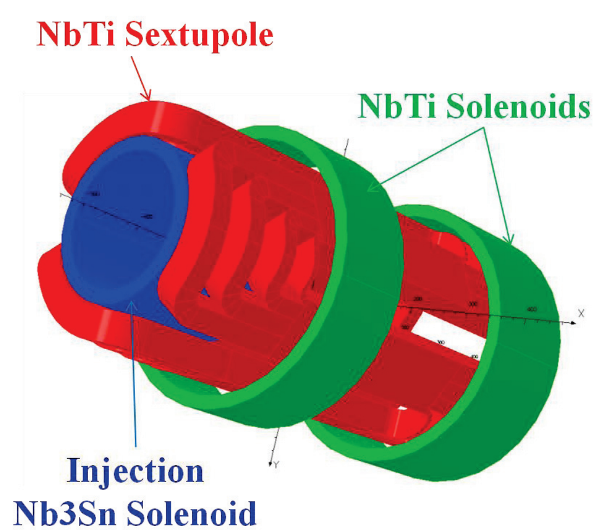

Figure 1: The hybrid magnet in the MK-I magnet structure in which the injection solenoid is made of Nb_3Sn wires and the rest of NbTi wires.

Other Optimizations

Since the Nb_3Sn wires can carry higher currents than the NbTi wires, thus the following optimizations are also exercised:

- Thinning the solenoid coil by keeping the outer diameter constant but increasing inner diameter by 24 mm so that there will be more space for inserting more injection components;

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CURRENT DEVELOPMENTS OF THE VENUS ION SOURCE IN RESEARCH AND OPERATIONS *

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Abstract

The VENUS ion source functions as a research and development tool in the ECR community as well as an injector for LBNL's 88-Inch cyclotron. In order to meet the needs of both the ECR community and users at the 88-Inch cyclotron, technology such as ovens and a sputter probe have been developed for introducing metals into the plasma. Using a modified high temperature oven, VENUS has produced 450eμA of $238U^{33+}$ and 400eμA of $238U^{34+}$, twice the required Uranium beam current needed for FRIB. In addition, after upgrading its high voltage capabilities VENUS produced 11emA of $4He^{2+}$, a capability that remains unparalleled by other ECR ion sources. In addition to its recent record high intensities VENUS is also being developed to deliver low intensity, ultra high charge state ions for the cocktails beams, where many species are produced simultaneously for use by the BASE Facility. $124Xe^{43+}$ is now in regular production for the 16MeV/u cocktail, and development of $209Bi^{56+}$ for the 10MeV/u cocktail is in progress and has been accelerated through the 88-Inch cyclotron. This paper presents the latest work towards integrating the VENUS ion source into our research and operational goals.

INTRODUCTION

During the last two years a lot of effort has gone into the integration of VENUS into the operation of the 88-Inch cyclotron as well as a continued effort to use it to push the limits of ECR's. To meet the needs of the 88-Inch cyclotron users VENUS should provide intense medium charge state beams for studies involving low-cross section reactions as well as several low intensity medium and high charge state ions simultaneously for the cocktails. A low temperature oven has been developed and work with the high temperature oven continues for the production of intense metal ion beams. To produce a variety of low intensity beams development of a sputter probe has begun and initial results are presented. In order to continue to explore the limits of ECR ion production capability we continue to work to make improvements. In this paper we discuss improvements in the VENUS high voltage capability as well as potential improvements to be made in the VENUS plasma chamber. The mechanical layout and specifics of the VENUS ECR ion source have been discussed at length previously and as such will not be done so here [1,2]. Table 1 provides key specifics.

* This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.
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Table 1: Key Parameters of the VENUS ECR Ion Source

VENUS Key Parameters	Values
Maximum 18GHz/28GHz Power	2,000W/10,000W
Maximum INJ/ /EXT Fields	4.0T/3.0T
Maximum RADIAL Field at wall	2.2T
Superconductor	NbTi
Coil Structure	Sextupole in Solenoid
Plasma Chamber Volume	9L
Plasma Chamber Diameter/Length	14.4cm/50cm

SPUTTER PROBE DEVELOPMENT

A sputter probe being developed for use in VENUS is intended to be used to produce metal beams for the cocktails used by the chip testers at the BASE Facility [1]. Cocktail beams consist of ions from up to 14 different elements with similar mass-to-charge, M/Q, ratio which are all extracted from the ion source and delivered to the cyclotron simultaneously. The 88-Inch cyclotron then selects the ion to deliver to the user. Each ion has a different range or penetration depth and will deliver a different amount of energy to the tested part.

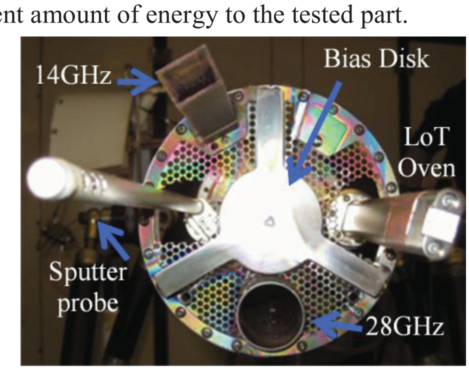

Figure 1: The VENUS injection is shown with the sputter probe and low temperature oven.

The sputter probe, shown in Figure 1, is inserted axially on a water-cooled support tube and a moveable bellows. The intention is to get the sputter probe, made to hold three metal samples, as close as possible to the plasma in order to take advantage of the high ion density regions since it is biased negatively from 0 to-3000V. Because it is inserted axially, placing the sputter probe at the maximum radial position closest to the wall will allow us to insert it further along the chamber in between the plasma flutes. Figure 2 shows the initial results when sputtering ^{181}Ta. At -2000V, 16eμA of 29+ was obtained.

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RECENT THE RIKEN 28 GHZ SC-ECRIS RESULT

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Abstract

Highly charged uranium (U) and xenon (Xe) ion beams were produced by the RIKEN superconducting electron cyclotron resonance ion source (SC-ECRIS) using 28 GHz microwaves. The beam intensity of Xe^{25+} was about 250 eμA at an RF power of 1.7 kW. The sputtering method was used to produce a highly charged U ion beam. The beam intensity is strongly dependent on the rod position and sputtering voltage. We obtained ~60 eμA for the U^{35+} ion beam at an RF power of 2 kW.

INTRODUCTION

In the last decade, facilities for the production of radio isotope (RI) beams have been constructed worldwide.[1–4] In these facilities, intense heavy ion beams are needed to produce intense radioisotope (RI) beams. To meet this requirement, several super-conducting electron cyclotron resonance ion sources (SC-ECRISs) have been constructed to produce intense highly charged heavy ions. [5–8]

At RIKEN, we started to construct the new SC-ECRIS, which has an optimum magnetic field strength for 28 GHz microwaves to produce intense highly charged heavy ion beams for the RIKEN RI beam factory project [1]. In the spring of 2009, the RIKEN SC-ECRIS produced its first beam using 18 GHz microwaves.[5] In 2010, 28 GHz microwaves were injected into the new SC-ECRIS and obtained highly charged Xe ion beam. Since then, we have conducted various experiments and modifications to increase the beam intensity. In this paper, we present the modification of the ion source and recent results for highly charged U and Xe ion production.

RIKEN SC-ECRIS

The detailed structure and performance were described in Ref. 5. The RIKEN SC-ECRIS can produce various on axis magnetic field distributions using 6 solenoid coils, which include both the classical B_{min} and the so-called "flat B_{min}"[9]. The liquid He vessel for the ion source is cooled by two refrigerators, (a Gifford-McMahon refrigerator (maximum cooling power of ~1 W) and a Gifford-McMahon + Joule-Thomson refrigerator (maximum cooling power of ~4 W)).

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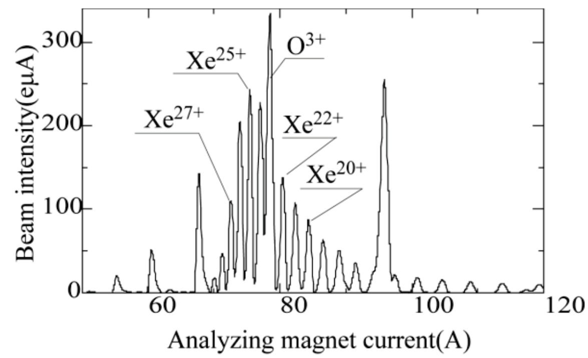

Figure 1: Charge state distribution of highly charged Xe ions at an RF power of 1.7 kW. The ion source was tuned to produce a Xe^{25+} ion beam.

RESULTS AND DISCUSSION

Xe Beam Production

In this test experiment, the maximum strength of the mirror magnetic field at the microwave injection side (B_{inj}), the radial magnetic field strength at the inner surface of plasma chamber (B_r), and the maximum strength of the mirror magnetic field at the beam extraction side (B_{ext}) were fixed to 3.2 T, 1.85 T, and 1.8 T, respectively. The extraction voltage was 22 kV, And the typical gas pressure was ~5 × 10^{-5} Pa. Figure 1 shows the charge distribution of highly charged Xe ions. The ion source was tuned to produce Xe^{25+} ions. Figure 2 shows the beam intensity of Xe^{25+} as a function of RF power.

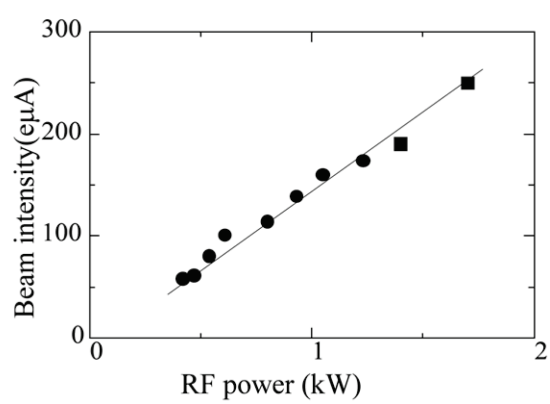

Figure 2: Beam intensity of Xe^{25+} ions as a function of RF power.

The beam intensity increased linearly and we obtained

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OPERATION OF AN ECRIS CHARGE STATE BREEDER AT TRIUMF

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Abstract

After initial commissioning of the charge state breeder for radioactive ions at the TRIUMF/ISAC facility further tests on the performance of the system have been done., One of the major problems found was the high background of stable ions from the ECR source. The main source of those is the residual gas and sputtered material from the plasma chamber wall and from the surrounding electrodes. Although, their intensity is small it can be orders of magnitude more than the intensity from the radioactive ions. Therefore, the original stainless steel plasma chamber of the Pantechnik PHOENIX ECR source has been exchanged to aluminium with a pure aluminium coating, all electrodes for injection and extraction of the ions have been replaced with aluminium and the iron joke at the extraction side, which is part of the vacuum system in the PHOENIX source has been coated as well. This combined effect has reduced the amount of background ions substantially. Together with some beam purification in the accelerator chain the background could be reduced to a level acceptable for experiments with radioactive ions. A low transport efficiency of ions with very high charge states can be explained by to charge changing collisions with residual gas

INTRODUCTION

Radioactive ions are produced at the ISAC facility at TRIUMF by bombarding solid targets with protons at 500 MeV and up to a current of 100 μA. The products diffuse out of the hot target into an ion source, are extracted at an energy of several 10 keV and mass separated. With ion sources robust enough to operate in this environment at high temperature and high radiation fields mainly singly charged ions are produced. The ions can be used directly in low energy experiments or they can be injected into a post accelerator for high energy experiments. The post accelerator at ISAC consists of a room temperature radio frequency quadrupole (RFQ) accelerator, a room temperature drift tube linear accelerator (DTL) and a superconducting linear accelerator (SClinac). The acceptance of the RFQ allows the injection of ions up to a mass to charge ratio of 30 amu/e at an energy of 2 keV/amu. It accelerates the ions to 150 keV/amu. The following accelerator sections can accelerate ions with a maximum mass to charge ratio of 7 amu/e. That means for most ions an increase in charge state is necessary. This is usually done by stripping in thin carbon foils after the RFQ. If ions with a mass greater than 30 amu are to be accelerated their charge state has to be increased already before the RFQ and in order to avoid further losses due to the stripping the mass to charge ratio should be below 7 amu/e. A modified charge state breeder PHOENIX electron cyclotron resonance (ECR) ion source from PANTECHNIK has been chosen as it is well adapted to the continuous mode of operation of the rest of the systems. The source has been installed and commissioned in 2010 and first results have been reported [1].

RESULTS

Already in the first experiments two problems have been found. It is the low transmission for very high charge state ions and the background from stable elements.

Charge Exchange

A reason for the low transmission is charge exchange along the beam transport. This process has been investigated earlier with the ECR source being installed at a test facility. Cross sections for the charge exchange in the relevant energy range from 10 -18 q keV have been determined for different ions with charge states up to 24+ [2]. In order to measure the charge state dependence of the transport efficiency $^{40}Ar^{7+}$, $^{56}Fe^{10+}$ and $^{133}Cs^{23+}$ have been selected after the charge breeder. They have been accelerated through RFQ and DTL and the total transmission has been determined. All those ions have a mass to charge ratio close to 5.7 amu/e, so possible mass dependencies in the accelerator are minimized. Table 1 gives the transmission for the different ions together with a theoretical transmission. It assumes charge exchange only in the low energy part with an average pressure of $2 \cdot 10^{-7}$ T over 25 m and 70% transmission of the accelerator. Cross sections from [2] have been used. Although, for the lowest charge state the measured value is close to the theoretical expectation for the higher charge states the transmission is less. This indicates that for those charge states charge exchange processes have to be considered as well for higher energies.

Figure 1 shows a beam profile from a $^{133}Cs^{23+}$ beam measured after an electrostatic bender in the low energy section. One can see that in the horizontal bending plane the beam splits in 3 components in this case: the main beam with charge 23+ and two more components with charge 22+ and 21+ respectively. The centre of the beam has been moved off the centre of the beam line for this picture.

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LPSC PHOENIX ECR CHARGE BREEDER BEAM OPTICS AND EFFICIENCIES

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Abstract

The PHOENIX ECR charge breeder characteristics (efficiency and charge breeding time) were measured at CERN-ISOLDE and at the Laboratoire de Physique Subatomique et de Cosmologie (LPSC), they were considered as sufficient to allow its setup on various facilities (TRIUMF - Canada / GANIL - SPIRAL2 and SPIRAL1 – France / SPES/INFN). The developments performed at the Argonne National Laboratory (ANL) have shown that the ECR charge breeder efficiencies could be much higher than the ones obtained with the LPSC PHOENIX, without major differences between the two devices. We have tried to study the possible reasons of such different results in order to improve the PHOENIX charge breeder characteristics. The transmission value of the n+ beam line has been measured to be as low as 30%. Emittances of the total beam extracted from the source and of some analysed beams (after the magnetic spectrometer) have been measured and will be presented. Simulations have shown a too low vertical acceptance at the center of the magnetic spectrometer. Simulations and experimental results will be presented, they show how an additional Einzel lens, inserted just before the dipole, has drastically improved the beam transmission. The impact of this new beam transport on charge breeding efficiencies will be presented.

ANL AND LPSC CHARGE BREEDERS CHARACTERISTICS

The ANL charge state breeder has been extensively described in [1]. It is a modified ECRIS allowing the injection and slowing down of an ion beam close to the axis, through a 25.4 mm internal diameter movable transfer tube. Like performed at LPSC, the injection plug has been modified in order to symmetrize the magnetic field at the injection side [2]. The recent configuration and results are presented in [3]. The pressure in this charge state breeder is about $2x10^{-8}$ mb, the axial magnetic field values at the injection, in the middle plane and at the extraction of the source, are respectively B_{inj} = 1.16 T, B_{min} = 0.27 T and B_{ext} = 0.83T.

Concerning the LPSC PHOENIX charge state breeder a few modifications have been performed since 2008. For example, the plasma chamber was modified in order to have the possibility to insert a liner (no internal diameter change) and has been equipped with two waveguide ports. The magnetic field, at the injection, has been slightly increased and fully symmetrized by the addition of iron parts around the plasma chamber [4]; finally, the grounded transfer tube has been removed allowing a more stable operation of the source. The pressure at the injection is about $6x10^{-7}$ mb and the axial magnetic field values are equal to B_{inj} = 1.21T, B_{min} = 0.42T and B_{ext} = 0.82T.

Both the ANL and LPSC charge breeders have two waveguide ports, at ANL the plasma is excited by a 2kW, 10.44GHz klystron plus a 500W, 11 to 13GHz TWTA. At LPSC we use a 2kW, 14GHz klystron and performed experiments (in collaboration with the INFN Laboratori Nazionali di Legnaro, Padova-Italy) with an additional 500W, 13.75 to 14.5 GHz TWTA [5].

This description of the two charge breeders shows that their characteristics are very close, some results presented in 2011 by both laboratories [3], [6] are compared in Table 1 below.

Table 1: Some Performances of the ANL and LPSC Charge Breeders

Laboratory	Ion	Yield (%)	Global yield (%)
ANL	$^{129}Xe^{25+}$	13.4	64
LPSC	$^{132}Xe^{18+}$	6.31	Not measured
ANL	$^{85}Rb^{19+}$	13.7	77
LPSC	$^{85}Rb^{15+}$	6.5	32

We can see that the performances of the ANL charge breeder are much better in term of yields and charge states. Unfortunately, the final number of radioactive ions being the convolution between the charge breeding time and the efficiency, it is difficult to make a valuable comparison due to the lack of data concerning charge breeding times. However, the difference in the yields results is sufficient to expect an improvement of the characteristics of the LPSC charge state breeder. The next paragraphs of this publication will discuss the LPSC charge breeder setup characteristics.

N+ BEAMS CHARACTERIZATION AND BEAM LINE OPTICS AT LPSC

Extraction Conditions and Beam Line

A photo of the PHOENIX charge breeder extraction beam line is shown Fig. 1. The extraction holes diameters of the source are 8 mm for the plasma electrode and 18 mm for the puller, the distance between them is 42mm. The n+ ions are extracted at 20 kV, they enter a 120° magnetic spectrometer through a beam line equipped with

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DESIGN STATUS OF ECR ION SOURCE AND LEBT FOR FRIB*

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Abstract

The Facility for Rare Isotope Beams (FRIB) at Michigan State University will provide intense beams of rare isotopes for research in nuclear physics, nuclear astrophysics and study of fundamental interactions. A Superconducting linac will accelerate the primary beam to energies beyond 200 Mev/u and is designed to reach a maximum beam power close to 400kW on the fragmentation target. In the case of Uranium about 13.3 pμA of U33+ are needed from the ion source to reach this maximum beam power on target. An ECR ion source operating at 28 GHz and based on the VENUS ion source developed at Lawrence Berkeley National Laboratory (LBNL) is currently being designed to meet the project intensity requirement and is presented in this paper. Although the intensity requirement from the ion source are very high for the FRIB project, new results have been obtained recently with VENUS that demonstrate that this ion source can actually produce close to 13pμA of U33+ within the emittance required by the accelerator. In addition an achromatic Low Energy Beam Line (LEBT) capable of transporting concurrently two charge states will be used to transport and accelerate the ion beam coming from the ion source.

INTRODUCTION

Michigan State University has been selected to build the Facility for Rare Isotope Beams (FRIB) in 2008 by the US Department of Energy (DOE). The FRIB driver accelerator consists of two Electron Cyclotron Resonance (ECR) ion sources located on a high voltage platform that will provide a large range of elements from Oxygen to Uranium at an initial energy of 12 keV/u, an achromatic low energy beam transport, a Radiofrequency Quadrupole (RFQ), a first linac segment with Quarter-wave Resonators (QWR) of β=0.041 and 0.085 accelerating the beam up to 20 MeV/u, a liquid lithium based stripper to reach higher charge states followed by two other linac segments with Half-wave Resonators (HWR) of β=0.29 and 0.53 accelerating the beam above 200 MeV/u. The third linac segment could be used for a future energy upgrade of the facility to 400MeV/u. The linac will be located about 10 meters underground and following the different linac segments a beam delivery system will transport the accelerated beam to the target. This latter is followed by a fragment separator that merges with the existing nuclear experimental areas of the NSCL laboratory. The facility is also designed to allow for the future implementation of an ISOL option. Figure 1 below show a section view of the driver linac with the different segments. The FRIB driver accelerator is described in more details in other publications [1]

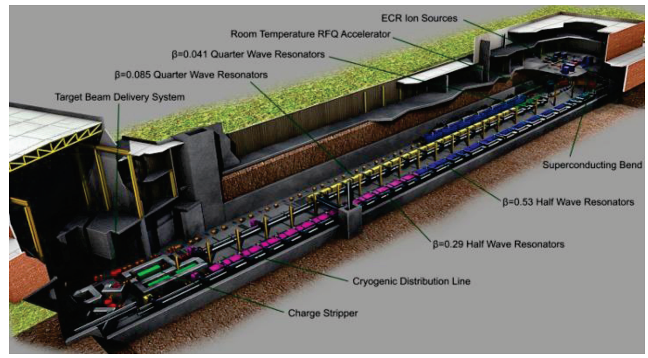

Figure 1: Layout of the FRIB driver linac. Ground level is shown in green at the top.

FRIB ECR ION SOURCES

To limit machine downtime during ion source development or possible breakdown, two ECR ion sources will be implemented for FRIB. Each source is located above ground primarily for radiation safety reasons. FRIB won't operate at full power initially but instead the accelerator will be first commissioned at low beam power and later followed by an operational phase where the beam power will be gradually ramped up to the maximum design value. Intensity required from the ion source during the commissioning will be much lower and a simpler source can be used during that phase. ARTEMIS-B developed in 2005 for offline development [2] and based on the design of the AECR-U of LBNL is available and will be sufficient for the commissioning need of the accelerator. Although, ARTEMIS-B was originally built to be operated vertically, the design has been recently modified to position the ion source horizontally. A temporary deck has been built as well as a new stand to support the ion source. Over the next year, the source will be reassembled and tested in this new orientation. Because, the ion source will be operated on a high voltage platform, the power supplies used for the solenoid coils have to be replaced with ones that are more efficient in order to be compatible with operation on the high voltage platform. The NdFeB based hexapole magnet of ARTEMIS-B will be also upgraded with a materials grade that has a higher energy product to increase the radial field.

The second ion source will be a high performance superconducting ECR ion source capable to operate at 28 GHz and based on the ion source VENUS developed at LBNL. The magnet system follows the conventional design of the sextupole inside the solenoids. The VENUS

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PERFORMANCE OF ANL ECR BREEDER WITH LOW MASS BEAMS

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Abstract

The CAlifornium Rare Isotope Breeder Upgrade (CARIBU) is a new radioactive beam facility for the Argonne Tandem Linac Accelerator System (ATLAS). The facility utilizes a ^{252}Cf fission source coupled with an electron cyclotron resonance (ECR) ion source to provide radioactive beam species for the ATLAS experimental program. The californium fission fragment distribution provides nuclei in the mid-mass range which are difficult to extract from production targets using the isotope separation on line (ISOL) technique and are not well populated by low-energy fission of uranium. To date the charge breeding program has focused on optimizing these mid-mass beams, achieving high charge breeding efficiencies of both gaseous and solid species including 14.7% for the radioactive species $^{143}Ba^{27+}$. In an effort to better understand the charge breeding mechanism, we have recently focused on the low-mass species sodium and potassium which up to present have been difficult to charge breed efficiently. Unprecedented charge breeding efficiencies of 10.1% for $^{23}Na^{7+}$ and 17.9% for $^{39}K^{10+}$ were obtained injecting stable Na^+ and K^+ beams from a surface ionization source.

INTRODUCTION

The development of ECR charge breeders is being pursued by many groups [1-8] with a particular concern being the efficient charge breeding of light ion species which up to present has been problematic [9,10]. The GANIL ion source group is pursuing a new 1+ to n+ charge breeding system for the SPIRAL project utilizing an ECR ion source with the efficient charge breeding of light nuclei being of high importance. Previously confined to gaseous elements, new versatile 1+ sources will be used to extend the range of elements available for post-acceleration to condensable elements. During on-line tests with such ion sources, radioactive isotopes of 9 new elements have already been ionized: isotopes of the alkali (Li, Na, K, Rb) metallic (Al, Fe, Cu, Mn) and halogen (Cl) elements were all produced from the FEBIAD ion source except for the alkali ion Li which was only surface ionized. While the new 1+ sources allow for the production of a wider range of elements, achieving a high charge breeding efficiency in the ECR remains a critical step. With this in mind, a new ECR charge breeder is being designed for the SPIRAL upgrade. The future ECR charge breeder will be based on an upgrade of an existing Phoenix ECR ion source which was formerly tested at ISOLDE, CERN [11,12]. The upgraded charge breeder will include a number of modifications inspired from the Argonne National Laboratory (ANL) ECR charge

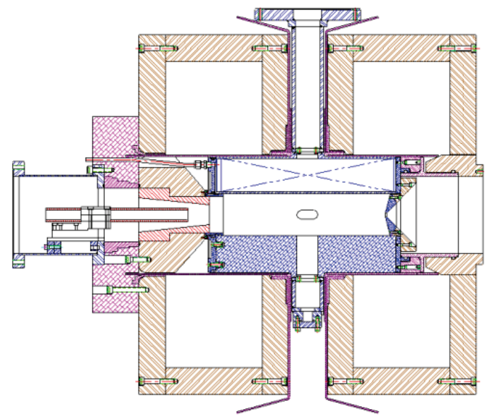

Figure 1: Schematic of the ANL ECR charge breeder. The 1+ beam is injected from the left through the grounded stainless steel tube. The tapered iron plug is highlighted with diagonal red hatching. The radial slots where the RF is launched are visible on the source mid-plane.

breeder: the injection of two RF frequencies (one fixed 14 GHz and one variable 8-18 GHz); complete cylindrical symmetry at the injection side; on-line adjustment of the grounded tube position; and a vacuum level around a few 10^{-8} mbar.

THE ANL ECR CHARGE BREEDER

In its final configuration, the CARIBU facility [13] will use a 1 Ci ^{252}Cf source to produce fission fragments which will be thermalized and collected by a helium gas catcher into a particle beam with a charge of 1+ or 2+. An ECR ion source functions as a charge breeder (ECRCB) [14,15] in order to raise the ion charge sufficiently for acceleration in the ATLAS linac.

The charge breeder is a room temperature ECR operating at 10-14 GHz with an open-structure NdFeB hexapole (see scheme in Fig. 1). The six radial ports which are each 17 x 41 mm in size act as pumping channels resulting in a plasma chamber pressure of 5 x 10^{-8} Torr. They also serve to introduce the RF and support gas into the plasma chamber. This eliminates the need for cut-outs in the injection side iron plug and results in a large peak and highly symmetric axial magnetic field where the ions enter the plasma. This scheme differs from other ECR charge breeders in existence which are closed hexapole devices with axial RF injection. For the ANL ECRCB, the low charge-state ions are introduced into the plasma through a grounded stainless steel tube mounted on a linear motion stage. The stage has a 30 mm range of

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

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Abstract

At CEA/Saclay, IRFU institute is in charge of the design, construction and characterization of the 140 mA continuous deuteron Injector for the IFMIF project. This injector is composed of the source and the low energy beam line (LEBT) with its own diagnostics. The Electron Cyclotron Resonance (ECR) ion source operates at 2.45 GHz and the 2 m long LEBT is based on 2 solenoids. Krypton gas injection in the beam line is foreseen in order to reach a high level of space charge compensation for the beam matching at the RFQ entrance. During the last months hydrogen beam has been produced in pulsed and continuous mode and the beam diagnostics have been installed and commissioned. Recently a 125 mA-100 keV pulsed deuteron beam has been produced with a 1% duty cycle. In this article, the high intensity proton and deuteron beam characterization will be presented.

INTRODUCTION

For several decades numerous HPPA (High Power Proton Accelerator) projects are based on high intensity beam interaction with different targets, either for industrial applications or research facilities. Even if the IFMIF (International Fusion Materials Irradiation Facility) machine [1], dedicated to irradiation materials for future fusion reactors will accelerate deuteron instead of protons, this project is also ranked in the HPPA family.

The aim of the IFMIF machine is to produce a high flux of neutrons with energy spectrum comparable to next fusion reactors like DEMO. To reach this goal, the IFMIF layout is based on 2 deuteron accelerators able to simultaneously produce 125 mA at 40 MeV. The 2 combined beams will impact a liquid lithium target flowing down in front of the test cells where future studied materials will be installed for neutron irradiation.

The total power delivered in continuous mode by the accelerators at the target interaction will be 10 MW. Nevertheless, despite such high beam power, the maintenance of the machine leads to imperative very low beam losses. One could consider this machine as the accelerator of all the records: the highest intensity, the highest beam power, the highest space charge and the longest RFQ.

That is why a prototype is presently under construction. This prototype consists of only the front end of one of both accelerators made of the ion source with its associated LEBT, a 10 meter long RFQ operating at 176 MHz and a first cyomodule with 8 HWR superconducting cavities. This cryomodule will allow reaching about 9 MeV beam energy.

Table 1: Summary of the IFMIF Injector Requested Parameters at the RFQ Entrance Flange

Requirements	Target value
Particles	D+
Output energy	100 keV
Output D+ current	140 mA
D+ fraction	99 %
Beam current noise	1 % rms
Normalized rms transverse emittance	0.25 π mm mrad
Duty factor	CW
Beam turn-off time	< 10 μs

To reach the requested beam intensity and considering a RFQ transmission of about 92 %, the deuteron beam at the RFQ entrance should reach a minimum of 140 mA with 100 keV energy. Table 1 summarizes the injector requests. Such demands are very challenging and push to a design based on the SILHI source operating at CEA/Saclay for more than 10 years [2]. A LEBT (Low energy Beam Transport) follows the source and will allow matching the beam at the entrance of the RFQ. As a consequence, like for other HPPA, while designing an injector, one has to consider the ion source, the extraction system and the LEBT as a whole [3].

ION SOURCE AND LEBT DESIGN

The source design is based on a 2.45 GHz frequency magnetron which transfers the RF power to the plasma chamber via waveguides and a RF window. A 3 step ridged transition located between the window (protected behind a bend to avoid backstreaming electron damages) and the plasma chamber. A boron nitride disk, located at the end of the ridged transition determines the barrier between the waveguide and the plasma chamber. The cylindrical plasma chamber, made of water cooled copper, is 90 mm inner diameter and 100 mm long. A second

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ALL PERMANENT MAGNET ECR ION SOURCE DEVELOPMENT AND OPERATION STATUS AT IMP

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Abstract

All permanent magnet ECR ion sources have many advantages over traditional ECR ion sources composed of several axial room temperature solenoids and one permanent magnet hexapole magnet, which make them the first choice for many heavy ion facilities and platforms. At IMP, three all permanent magnet ECR ion sources have been built for different applications, i.e. the very compact ECR ion source LAPECR1 for intense mono or multi charge state ion beams' production, the LAPECR2 ion source installed on the 320 kV high voltage multidisciplinary platform, and the LAPECR3 ion source dedicated to C^{5+} beam production for the cancer therapy facility. In this paper, after a general discussion of the ion sources' design, the applications and the operation status of the IMP all permanent magnet ECR ion sources will be presented.

INTRODUCTION

Been widely used as Multiple Charge Ion (MCI) beam provider, ECR ion source is one of the best devices that can produce intense MCI beams. ECR ion source is actually a magnet field confined plasma machine, where the ion beams can be extracted. The confinement magnetic field is normally a so-called nested min-B magnetic field which is a superposition of radial multipolar field and axial mirror field. Generally, the axial field is supplied by superconducting magnet solenoids, room temperature magnet solenoids, or permanent magnet rings, while the radial field is supplied by either superconducting sextupole coils or Halbach structure permanent magnet hexapole [1] (other hexapole structures are also used). The different combination of the types of radial and axial field magnet gives the different species of ECR ion sources, i.e. fully superconducting ECR ion sources, such as VENUS [2] and SECRAL [3], hybrid ECR ion sources, such as SHIBA [4] and A-PHOEBIX [5], classical room temperature ECR ion sources, such as AECR-U [6] and GTS [7], and all permanent ECR ion sources, such as the Nanogan sources [8] and the BIE sources [9]. The first very successful modern ECR ion source, the so-called Caprice source [10], is a room temperature ECR source, which is still widely used in many labs. Fully superconducting ECR ion sources can provide the beam intensities and charge states that can't be met by other types of ECR sources, but based on the applications, all the four types of ECR ion sources can find the users if only the application needs can be met. All permanent magnet ECR ion sources have their special features and merits that make them extremely suitable for industrial applications and small experimental platform setup: (1) very compact device, (2) easy maintenance, (3) easy to operate, (4) low electricity consumption, (4) no needs for large volume LCW (Low Conductivity Water), and (5) most important of all, cost saving. But there also several intrinsic disadvantages of this type of devices mostly because of the all permanent magnet structure, such as: (1) inflexibility of the magnetic field, (2) low magnetic field strength and small plasma chamber size, and (3) therefore moderate MCI beam intensity.

IMP/CAS is an institute dedicated to nuclear physics and the associated multidisciplinary physics studies. The accelerator facility development is based on these needs and requirements. Three all permanent magnet ECR ion sources have been successively built at IMP for the facility's needs. The structure and the parameters will be discussed in the following content.

LAPECR1 SOURCE

Small experimental lab needs very compact experimental setups. This is the original reason to build the LAPECR1 source to deliver intense mono charge state ion beams, low intensity MCI beams and even some molecular ion beams. Table 1 gives the main parameters of this ion source. This ion source is designed with a very compact size which makes the source body weighs only 25 kg that can be easily moved around by an adult. Despite of the compactness, the source is equipped with a Ø40 mm ID plasma chamber that enables the direct microwave power feeding with a WR62 rectangular waveguide to simplify the injection plug structure. Iron plugs at both the injection and extraction sides have been incorporated to enhance the mirror peaks. The source is designed and operated at 14.5 GHz.

HIRFL accelerator needs intense proton and H_2^+ beams for ion beam injection. The room temperature LECR3 ion source, which is mostly used to deliver intense MCI beams like C^{4+}, Ar^{8+}, Kr^{18+}, Xe^{20+} and etc., can't be operated at the source potential higher than 25 kV, therefore a simple setup that can deliver intense proton or H_2^+ beams at the source potential of ~35 kV is proposed. In this project, LAPECR1 is floated on a G10 insulator plate which is covered with a plexiglass box. Because of the simple structure of LAPECR1, this setup composes a small HV platform that can be biased to more than 36 kV.

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LASER ABLATION OF ACTINIDES INTO AN ELECTRON CYCLOTRON RESONANCE ION SOURCES FOR ACCELERATOR MASS SPECTROSCOPY

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Abstract

A project using accelerator mass spectrometry (AMS) is underway at the ATLAS facility to measure the atom densities of transmutation products present in samples irradiated in the Advanced Test Reactor at INL. These atom densities will be used to infer effective actinide neutron capture cross-sections ranging from thorium to californium isotopes in different neutron spectra relevant to advanced fuel cycles. This project will require the measurement of many samples with high precision and accuracy. The AMS technique at ATLAS is based on production of highly-charged positive ions in an ECRIS followed by injection into a linear accelerator. We use a picosecond laser to ablate the actinide material into the ion source. We expect that the laser ablation technique will have higher efficiency and lower chamber contamination than sputtering or oven evaporation thus reducing 'cross talk' between samples. The results of off-line ablation tests and first results of an accelerated beam generated by the laser coupled to the ECR will be discussed as well as the overall project schedule.

INTRODUCTION

Advanced nuclear fuel cycles are currently under evaluation in order to assess their potential to cope with new requirements of radioactive waste minimization, optimization of resource utilization and reduced risk of proliferation. This assessment should account for several key features of the fuel cycle, such as irradiated fuel processing, innovative fuel development and fabrication, waste characterization and disposal. In some cases, the impact of nuclear data and of their associated uncertainties can be crucial in order to assess further exploration. The need for accurate data has been pointed out in recent studies devoted to Generation-IV systems, see e.g. [1]. The very high mass actinides can play a significant role in the feasibility assessment of innovative fuel cycles. As an example, the potential build-up of ^{252}Cf when recycling all transuranics in a light water reactor, leads to increased neutron emissions that could impact the fuel fabrication process [2]. As a consequence, the poorly known nuclear data of higher mass transuranics need to be significantly improved.

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

The MANTRA (Measurements of Actinides Neutrons Transmutation Rates with Accelerator mass spectroscopy) project objectives are to obtain valuable integral information about neutron cross sections for actinides that are important for advanced nuclear fuel cycles. The proposed work takes advantage of two experimental facilities: the neutron irradiation capabilities of the Advanced Test Reactor (ATR) at the Idaho National Laboratory and the Accelerator Mass Spectrometry (AMS) capabilities of the Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory [3].

In this paper we will concentrate on the requirements of the AMS program and the novel aspects, specifically the laser ablation, that is implemented at the ECR ion source to carry out this research project. The requirements placed on the AMS measurements to be performed at ATLAS are quite challenging. These challenges include high-precision isotope ratio measurements, minimization of cross-talk between samples, efficient use of milligram samples, and the processing of an unprecedented number of samples for a facility as complex as ATLAS. Unique element (Z) identification is desirable, but is not expected to be possible except for specific cases.

The measurement configuration for ATLAS uses the ECR-II ion source [4], significantly modified as discussed below, as the source of ions. After acceleration and deceleration (increasing the accelerator m/q resolution but keeping the ion energy within acceptance range of analytical elements) in the ATLAS linac to approximately 1 MeV/u, the actinide ions of interest are counted in the focal plane of the Fragment Mass Analyzer (FMA) [5].

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ECRISs AT GANIL TODAY AND TOMORROW

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Abstract

GANIL (Grand accélérateur National d'Ions Lourds) uses ECRISs for producing stable and radioactive ions for more than 20 years. Two ECR4 type ion source (IS) deliver intense multi-charged stable ion beams of gaseous and metallic elements feeding cyclotrons for post acceleration to energies up to 100 A.MeV. A full permanent magnet ECRIS is also employed for producing multi-charged radioactive ion beams in the frame of SPIRAL 1 (Système de Production d'Ions Radioactifs Accélérés en Ligne, part 1). For atomic and material physic experiments, a high performance ECRIS labeled GTS developed at CENG/ Grenoble (France) is currently used to deliver high intensity, high charge state and low energy ion beams. To extend the range of radioactive ion beams available at GANIL, two ISOL (Isotope Separator On Line) projects are underway (SPIRAL1 upgrade and SPIRAL 2). In the frame of these projects, radiation hard singly-charged ECRIS, Q/A=1/3, 1/6 ECRISs, 2.45 GHz deuteron ECRIS and permanent magnet target ion source system (TISS) using an ECRIS are under development in parallel. A review of the main uses, current developments and performances obtained or expected with ECRISs at GANIL are presented. Locations of all the setups mentioned below are indicated in Figure 1.

INTRODUCTION

In 1982, GANIL delivered its first stable ion beam at high energy, using Penning Ion Gauges (PIG) as injectors for cyclotrons. For reasons of short lifespan, the PIG Ion Sources (IS) were frequently replaced (every ~40 hours), reducing the available time for operation. In 1985, a 10 GHz ECRIS named MINIMAFIOS [1] and developed by R. Geller was installed as one of the two injectors. Its advantages were higher lifespan, intensities and stability. Three years later, it was replaced by a 10 GHz CAPRICE [2] ECRIS, allowing an enlargement of the beam range in term of charge states and elements, stretched to metallic elements. In 1991, PIGs are definitely abandoned. The second injector of GANIL is equipped with a 14 GHz ECR4 [3] type IS placed at 100 kV. Its commissioning in 1993 showed an important increase of beam intensities for gas and metallic elements compared to the ones obtained with CAPRICE. A gain of ionization efficiency was also observed using a micro-oven for several metallic elements. Finally, CAPRICE was replaced by an ECR4 IS in 1995.

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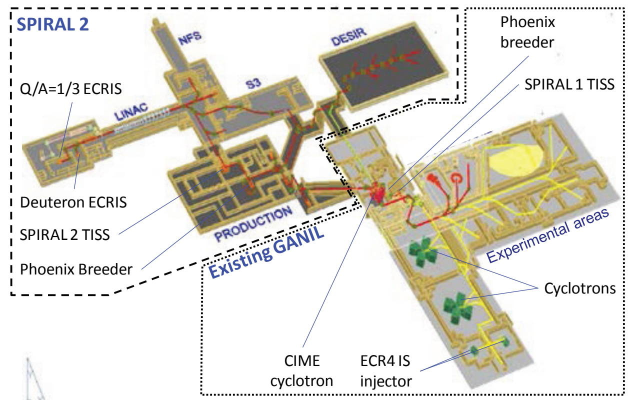

Figure 1: Schematic of the GANIL today and by 2020. Yellow lines: stable ion beams at GANIL. Red lines: SPIRAL 2 ion beam lines.

In 1994, GANIL decided to extend its range of ion beams to radioactive ones using the isotope separator on line (ISOL) method. The studies of SPIRAL 1 facility are undertaken and the first radioactive ion beam is delivered in 2001. Radioactive isotopes are produced in the target and ionized by an original permanent magnet ECRIS (NanoGan III [4]), designed to cope with the numerous constraints inherent to the generation of radioactivity. Ions emerging from the TISS are mass to charge separated and injected in the post-accelerator cyclotron CIME [5] to reach energies up to 25 A.MeV.

The increasing demand of radioactive ion beams encouraged GANIL to extend its range of available beams [6]. In 2006, the construction of a second radioactive ion beam facility (SPIRAL 2) was officially decided at GANIL. Beams of short lived heavy radioactive ions will be produced in flight by the S3 facility [7]. Longer lived isotopes will be produced by ISOL method in the production cave containing a TISS. Two production methods will be used:

- fission of uranium induced by neutrons, these latter being produced in a graphite converter on which a deuteron beam impinges,
- reaction of heavy ions on target material. Two ECRISs are chosen as injectors for the LINAC post-accelerator: an existing 2.45 GHz ECRIS delivering up to 5 mA of deuterons developed at

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STATUS OF ECR ION SOURCES FOR CARBON-ION RADIOTHERAPY IN JAPAN

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Abstract

For the five Japanese carbon-ion treatment facilities the carbon beams are being produced with ECR ion sources of two types, both developed at NIRS. These sources satisfy all medical requirements. A study has been initiated for understanding the performance deterioration following long periods of carbon operation.

HISTORY AND GEOGRAPHY

Presently in Japan five carbon-ion radiotherapy (C-RT) facilities are situated. The Heavy Ion Medical Accelerator in Chiba (HIMAC), the Hyogo Ion Beam Medical Centre (HIBMC) and the Gunma University Heavy-ion Medical Centre (GHMC) are already under operation. Over 1100 patients have been treated by three facilities in 2011. The Saga Heavy Ion Medical Accelerator in Tosu (SAGA-HIMAT) and the Ion-beam Radiation Oncology Centre in Kanagawa (i-ROCK) are under construction.

The HIMAC project at the National Institute of Radiological Sciences (NIRS) was promoted by the Japanese government as a research project under the first “Comprehensive 10-year Strategy for Cancer Control [1984-1993].” HIMAC is the first medical dedicated carbon facility in the world[1], and has successfully treated close to 7000 patients with 140-400 MeV/u carbon beams since 1994. The clinical result at HIMAC clearly shows the effectiveness and safety of C-RT[2], therefore the newer Japanese facilities have chosen carbons as well for treatment, all being produced in ECR ion sources.

HIBMC is the first proton and carbon combined facility, and was mainly funded by a local government. In order to reduce the running cost and the risk of interruption due to troubles, two ECR ion sources with the same structure are utilized to produce proton and carbon ions. HIBMC is also the first commercial C-RT facility with the permission under the Japanese regulation law of medical instruments, and start the treatment since 2001.

Under the third 10-year Strategy [2004-2013], the government promotes development of downsizing technologies. NIRS designed a hospital-specified C-RT facility and developed prototypes of various components. The feature of the design is an exhaustive optimisation for treatment by carbon beams[3]. This realized a cost-effective and reliable facility’s design. The ECR ion source was also renewed under this concept. GHMC was constructed as a demonstration facility by the government, and start the treatment since 2010[4].

Table 1 shows existing and planned ECR ion sources for C-RT in Japan. Type N, H, and K mean NIRS-ECR, NIRS-HEC and Kei-series described in the next section. Figure 1 shows their locations. SAGA-HIMAT is funded by a consortium of a local government and private companies[5]. i-ROCK belongs a local government.

Table 1: Chronology of ECR Ion Sources at Carbon-Ion Radiotherapy Facilities in Japan

Name	Type	Facility	Launch
NIRS-ECR	N	HIMAC	1993
NIRS-HEC	H	HIMAC	1997
ECR1	N	HIBMC	1999
ECR2	N	HIBMC	1999
KeiGM	K	GHMC	2009
Kei2	K	HIMAC	2010
KeiSA	K	SAGA-HIMAT	*2012(plan)*
?	K	iROCK	*2015(plan)*

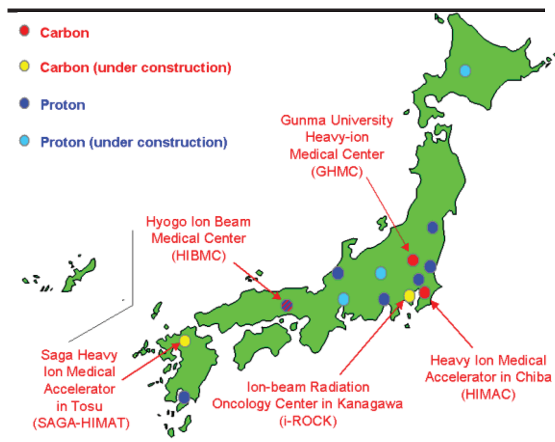

Figure 1: Geographical distribution of carbon-ion radiotherapy facilities in Japan.

DESCRIPTION OF SOURCES AND THE STATUS OF OPERATION

Four types of ion sources have experiences of C-RT; a 10GHz ECR ion source called 'NIRS-ECR', an 18GHz ECR ion source called 'NIRS-HEC', and ‘Kei-series’, and finally one PIG ion source called ‘NIRS-PIG’, which for the production of carbon ions, NIRS-PIG at HIMAC is being used temporally only[6]. The main purpose of NIRS-HEC is to produce heavier ions like Fe for

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ECRIS RELATED RESEARCH AND DEVELOPMENT WORK AT JYFL AND SOME FUTURE PROSPECTS*

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Abstract

Since the last ECR workshop the JYFL ion source group has focused on 1) development of metal ion beams, 2) ion beam formation and transport, 3) plasma studies and 4) photoelectric effect in ion sources. The MIVOC method and sputtering technique were further studied in order to produce intensive titanium ion beams. As a result, an intensive $^{50}Ti^{11+}$ ion beam was successfully produced with the MIVOC method. An improvement in ion beam transport of the JYFL K130 cyclotron facility was achieved as a result of the work performed on ion beam formation. This work will be described in more detail elsewhere in these proceedings (see V. Toivanen et. al). The plasma research can be divided into plasma breakdown processes, plasma and ion beam instabilities, afterglow processes and plasma-wave coupling. The afterglow and instability experiments will be presented elsewhere in these proceedings (see. V. Skalyga et. al. and O. Tarvainen et. al.). In addition, studies involving in the photoelectric induced electron emission and charge exchange reactions will be briefly discussed.

METAL ION BEAM PRODUCTION

The metal ion beams and their production techniques can be considered as one of the key factors in nuclear physics laboratories using stable isotopes. Also at JYFL increasing requirements towards the availability of some refractory elements, like Ti, Zr and Mo has been expressed. In the following the development work for the sputter and the MIVOC technique will be presented.

Sputtering Technique

The sputter technique makes it possible to produce ion beams from the elements exceeding the capabilities of high temperature ovens. The efficiency of the method depends on the mass of projectile, its energy, angle of incident and naturally the sputter yield of the material to be sputtered. Unfortunately, the sputter yield tends to be low in the case of refractory elements, as is demonstrated in Table 1. However, the method still offers the intensities not available using the other methods. The method was first adopted at ANL, and since that it has been used in several laboratories on a day-to-day basis (see for example ref. [1,2]).

At JYFL the sputter technique has mainly been used for the production of Zr ion beams. Recently, strong effort has been made to produce ^{50}Ti ion beams by placing enriched ^{50}Ti powder into a small hole drilled in a metallic titanium rod [3]. This hole, including the enriched material, is placed to the spot where the sputtering mainly takes place. A test sample (with natural abundances) was exposed to plasma via radial port of the JYFL 14 GHz ECRIS. During the tests up to 20 µA of $^{48}Ti^{11+}$ beam was extracted from the ion source. Unexpectedly, the titanium ion beam remained even if the sputter voltage was set to zero. This indicated that the power was coupled directly to the sample causing vigorous heating and consequently the evaporation of titanium. The substantial evaporation of titanium requires the temperature of about 1800˚C. At this temperature a remarkable fraction of heat losses are caused via thermal radiation. This generated a strong heat load on the adjacent permanent magnets.

After the sputter experiment a clear degradation of source performance was noticed. The measurement of hexapole magnets confirmed that magnetic field was decreased approximately by 10 % close to the radial port used for the experiment. The destroyed hexapole was replaced and more efficient cooling scheme to minimize the heat load of the permanent magnets was designed. The sputter experiments will be continued with the new cooling scheme during the last quarter of 2012.

Table 1: Sputter yield Y for some elements. The yield is calculated for Oxygen or Argon projectiles at 1000 eV. Values calculated with Simple Sputter Yield Calculator (http://www.iap.tuwien.ac.at/www/surface/sputteryield)

Element	Y (with O)	Y (with Ar)
Ag	1.8	3.7
Ni	0.9	1.7
Mo	0.4	0.9
Pb	2.3	4.9
Ti	0.4	0.7
Zr	0.4	0.8

MIVOC Method

The MIVOC method [4] is very efficient in the case of some metal ion beams like Fe, Ni and Ti. As an example, in the case of $^{48}Ti^{11+}$ion beam the intensity of 45 µA was produced using (trimethyl)pentamethylcyclopentadienyl-titanium)compound [5]. However, for the nuclear physics experiment at least 40 pnA of accelerated ^{50}Ti ion beam was needed. In order to meet this intensity requirement the afore-mentioned compound has to be synthesized using the enriched ^{50}Ti isotope. After an intensive development work the compound needed for the nuclear physics experiment was successfully synthesized by the Strasbourg group and subsequently tested using the JYFL 14 GHz ECRIS [6]. The $^{50}Ti^{11+}$ beam produced with the

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