

FIRST RESULTS AT 24 GHZ WITH THE SUPERCONDUCTING SOURCE FOR IONS (SUSI)

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Abstract

The first commissioning results at 24 GHz of the Superconducting Source for Ions (SuSI) from Michigan State University (MSU) are reported. Although SuSI has been designed to operate primarily at 18 GHz, the superconducting magnet has been able to reach a field sufficient for operation at 24 GHz. Very exciting new results have been obtained during the commissioning of SuSI at 24 GHz for oxygen and argon. For oxygen 1.4mA of O^{7+} was measured when injecting 5.2 kW of microwave power. For argon, 220euA of Ar^{16+} was measured with 6kW injected. In most cases, the performances don't seem to saturate yet with the injected power. Some surprising observations were also made regarding the coupling of 18 GHz in parallel with the operation of the ion source at 24 GHz as well as the impact of the frequency on performances.

INTRODUCTION

The Electron Cyclotron Resonance (ECR) ion source SuSI is a fully superconducting ion source that has been operated at 18GHz for the last five years for injection into the Coupled Cyclotron Facility (CCF). Excellent performance have been reported with SuSI at this frequency for medium charge state ions of light to heavy ion beams [1] In particular after coupling as much as 3.4 kW using two klystrons, performances were found to be still limited only by the amount of microwave power available. Trying to push further the performances of SUSI a 24GHz gyrotron was installed and tested with the ion source. The choice of 24GHz was solely based on the maximum magnetic field that can be achieved with SuSI. Although, the superconducting magnet structure was initially designed to be compatible with operation up to 28 GHz, quenches of SuSI sextupole magnet have set a limit that in accordance with the field requirement in the high-B mode would correspond to a maximum frequency somewhat above 24 GHz [2]. Even so energizing the SuSI magnet requires a careful ramping of the current. First it is necessary to ramp both solenoids and sextupole coils together to avoid a quench. Second, it is also necessary to first ramp the current in the coils 10 to 15% higher than what is required for a given field configuration before ramping the current down to their nominal values. This procedure has been found to be very important to reach a stable operating point for extended period of time. Therefore to establish a stable field configuration for operation at 24 GHz does require to first push the current in the coils close to the known limits of the magnet. To be safe during the commissioning of the gyrotron, both axial and radial field were kept somewhat below the expected

high-B mode values for 24 GHz operation. For instance the radial field did not exceed 1.5 tesla. Likewise, the injection field was kept around 3 tesla most of the time. As a result, no quench occurred during the commissioning period. Some promising and exciting results at 24GHz have been obtained. After a technical description of the 24 GHz system, the ion source, experimental results will be presented and followed by a discussion.

24 GHZ SYSTEM

A 24 GHz gyrotron system was purchased from GYCOM, a Russia based vendor. Although rated for 10 kW, the maximum output power transmitted from the tube to a water-cooled load during the commissioning tests was 8.8kW which is more than sufficient for operation with the ion source. The high voltage power supply (HVPS) was directly purchased from a domestic supplier and a filter circuit added between the HVPS and the gyrotron. This filter includes a 50 nF capacitance that limits the ripple to less than 2% and a set of four 20 Ohm resistance used to limit the stored energy to a maximum of 5 Joules to protect the gyrotron tube. The 24GHz transmission line and RF coupling system to SuSI is similar to the one developed for the SECRAL source [3]. The 24 GHz microwave propagates in an over-moded circular waveguide. The initial TE02 mode produced by the gyrotron is converted to TE01 using a mode converter because of the low attenuation of this mode. Coupling with the ion source can cause unwanted modes to propagate back in direction of the gyrotron so that a mode filter is also included in the transmission line. Diagnostics at the exit of the gyrotron include an arc detector and a bi-directional coupler. Although the gyrotron tube and the ion source are under vacuum, the transmission line is simply left at atmospheric pressure filled with the air that was trapped during assembly of the waveguide A 10 kW rated, boron nitride window is used at each end to define the vacuum/air interface. Finally, a high voltage break rated for 50 kV was also provided by GYCOM. Because of space limitation, the gyrotron was installed in a room above the ion source and two 90-degree bend were added to the transmission line to connect the gyrotron to the ion source. Figure 1 shows a layout of the gyrotron and ion source together. All components of the transmission line are water cooled. The control system provided with the equipment include a PID loop to regulate the output power using the read-back signal from the bi-directional coupler. A few important features help protect the equipment. First, the circuit used with the arc detector can send a fast signal (<10us) to inhibit the HVPS. Second

PERIODIC BEAM CURRENT OSCILLATIONS DRIVEN BY ELECTRON CYCLOTRON INSTABILITIES IN ECRIS PLASMAS*

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Abstract

Experimental observation of cyclotron instabilities in electron cyclotron resonance ion source plasma operated in cw-mode is reported. The instabilities are associated with strong microwave emission and a burst of energetic electrons escaping the plasma, and explain the periodic oscillations of the extracted beam currents. The instabilities are shown to restrict the parameter space available for the optimization of high charge state ion currents.

INTRODUCTION

Plasma instabilities can be categorized to magnetohydrodynamic (MHD) instabilities driven by the topology of the magnetic field (see e.g. Ref. [1]) and kinetic instabilities triggered by the anisotropy of the electron energy distribution function (EEDF) (see e.g. Ref. [2]). The magnetic field topology of a minimum-B ECRIS is effective in suppressing MHD instabilities [3]. Due to the resonant interaction between the incident microwave radiation the EEDF of an ECRIS plasma is strongly anisotropic and is considered to consist of several ‘electron populations’ - cold, warm and hot electrons with average energies of 10 - 100 eV, 1 - 10 keV and 10 - 100 keV, respectively [4, 5]. Such non-equilibrium plasmas are prone to kinetic instabilities driven by the hot electrons whose transverse velocities $\vec{v} \perp \vec{B}$ dominate over the longitudinal velocities $\vec{v} \parallel \vec{B}$.

We have recently reported [6] an experimental observation of electron cyclotron instabilities in a minimum-B ECRIS plasma sustained by 14 GHz microwave radiation in cw-mode. The instabilities lead to ms-scale oscillation of the extracted beam current reported earlier in Refs. [7] and [8]. In this paper we present a review of earlier work [6] and provide new data explaining the nature of the instabilities.

THEORETICAL BACKGROUND

Electron cyclotron instabilities are driven by hot electrons interacting resonantly with electromagnetic plasma waves. Whistlers or slow extraordinary (Z-mode) waves propagating

to (quasi)parallel direction with respect to the external magnetic field, i.e. $\vec{k} \parallel \vec{B}$, can be excited inside the ECR-zone where the plasma oscillation frequency ω_{pe} can exceed the electron gyrofrequency ω_{ce} [9]. The (quasi)perpendicular extraordinary X- or Z-modes with $\vec{k} \perp \vec{B}$ can be excited when $\omega_{pe} < \omega_{ce}$ [10].

A characteristic feature of electron cyclotron plasma instabilities is the emission of microwaves. The energy of the microwave emission E_μ can be described by mode-dependent growth and damping rates γ and δ as

$$\frac{dE_\mu}{dt} \approx (\gamma - \delta) E_\mu. \quad (1)$$

The solution of the differential equation shows that the intensity of the microwave emission is an exponential function of the difference of the growth and damping rates, which depend on the mode of the microwave emission. Since the instabilities are triggered by the anisotropy of the EEDF, their (volumetric) growth rate is proportional to the ratio of hot and cold electron densities. The damping rate is determined by volumetric absorption of the wave energy by the collisional background plasma and external (wall) losses.

The balance equation [11] for the hot electron (number) density $N_{e,hot}$ can be written as

$$\frac{dN_{e,hot}}{dt} \approx -\kappa N_{e,hot} E_\mu + S(t) - L(t), \quad (2)$$

where κ is a coefficient [12] describing the amplification of the electromagnetic wave and corresponding decrease in the hot electron component due to direct energy loss, $S(t)$ is the source term of hot electrons, i.e. stochastic heating, and $L(t)$ is their loss term due to collisional velocity space diffusion, inelastic collisions and rf-induced pitch angle scattering [13, 14]. In quiescent steady-state ECRIS plasma the damping rate exceeds the growth rate and the source and loss terms of hot electrons cancel out. In unstable operation conditions $S(t) > L(t)$, which causes the anisotropy of the EEDF to increase until the condition $\gamma > \delta$ is met. At this threshold the hot electrons interacting with the resulting plasma wave emit microwave radiation and are expelled into the loss cone directly as a result of the interaction with the amplified plasma wave or shortly after the perturbation via stochastic cooling and/or collisional scattering. The increased flux of electrons from the trap results in a burst of wall bremsstrahlung. The process stabilizes the plasma due to reduced density of hot electrons. However, the instability

* Work supported by the EU 7th framework program ‘Integrating Activities - Transnational Access’, project number: 262010 (ENSAR), Magnus Ehrnrooth foundation, the Academy of Finland under the Finnish Centre of Excellence Program 2012–2017 (Nuclear and Accelerator Based Physics Research at JYFL) and researcher mobility grants 267174 and 267227, and the Russian Foundation for Basic Research grants 12-02-31206 and 13-02-00951.

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EMITTANCE MEASUREMENTS FOR RIKEN 28 GHZ SC-ECRIS

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Abstract

In 2012, intense beams of highly charged uranium ions (180 eμA for U³⁵⁺, 230 eμA for U³³⁺) were extracted from RIKEN SC-ECRIS. Following this success, an intense beam of U³⁵⁺ ions was used for the radioisotope beam factory (RIBF) experiment for a long period (about one month). It is obvious that production of high quality beams (characterized by smaller emittance and good stability etc) is also important for the RIKEN RIBF project. Therefore, in 2014, we systematically measured the emittance and beam intensity of highly charged uranium ions under varying conditions of magnetic field configuration, extracted beam intensity, beam stability etc. to obtain the optimal condition for the production of high-quality beams. In these experiments, we observed that the extent of emittance strongly depends on the magnetic field configuration, especially on B_{ext}.

INTRODUCTION

During the last several years, we have been working on increasing the intensity of highly charged uranium (U) ion beams and we have produced intense beams (~180 eμA for U³⁵⁺ and ~230 eμA for U³³⁺) using the sputtering method [1]. In 2013, we produced ~90 eμA of U³⁵⁺ for long-term usage in RIKEN radioisotope beam factory (RIBF) experiments. Consequently, in the course of the last several years, the intensity of U ion beams had dramatically increased. As an external ion sources for heavy ion accelerators, it is obvious that improving the quality of the beam characteristics, such as emittance and stability, is also important. Production of intense beams from the accelerator is key in producing intense RI beams, especially in the RIKEN RIBF project. For example, the overall design power of a U ion beam (beam intensity of 1 pμA) at the energy of 345 MeV/u is 82 kW. In this case, beam loss has to be minimized to avoid damaging the accelerator. It is obvious that the emittance of highly charged U ion beams should be sufficiently smaller than the acceptance of the accelerators of the RIKEN RIBF for safety acceleration. Therefore, to minimize the extent of emittance for intense beams of U ions, we intensively studied the effect of the ion source parameters on the emittance. As described in a previous paper [2], if the magnetic field distribution affects the ion dynamics and the trajectory of the extracted beams, it may also affect the emittance of highly charged heavy ions.

In this paper, we describe the experimental results regarding the effect of various ion source parameters (drain current, position of the beam extraction electrode,

and magnetic field distribution) on the emittance of highly charged U ion beams.

EMITTANCE MEASUREMENT FOR U ION BEAMS

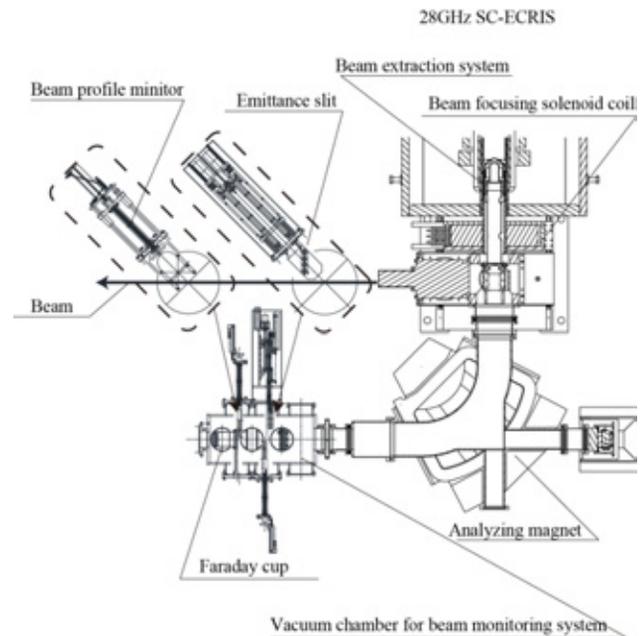


Figure 1: Schematic drawing of the beam extraction system of the ion source and Low energy line with beam-monitoring system.

The sputtering method was used for production of highly charged U ion beams. The method is described in detail in ref. [3]. The main feature of the ion source is that it has six solenoid coils for producing the mirror magnetic field. Using this configuration, one can produce so-called “flat B_{min}” [4] and classical B_{min}. In this experiment, the extraction voltage was fixed at 22 kV.

Figure 1 shows the schematic drawing of the beam extraction system of the ion source and the low-energy beam line (analyzing magnet and beam monitoring system). Emittance was measured using the emittance monitor, which consists of a movable thin slit (emittance slit in Fig. 1) and wires (beam profile monitor in Fig. 1). We also installed the beam slit and Faraday cup in the vacuum chamber of the beam monitoring system.

The root mean square (rms) emittance is defined as

$$\begin{aligned}\epsilon_{x-rms} &= \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \\ \epsilon_{y-rms} &= \sqrt{\langle y^2 \rangle \langle y'^2 \rangle - \langle yy' \rangle^2}\end{aligned}\quad (1)$$

FREQUENCY TUNING EFFECT ON THE BREMSSTRAHLUNG SPECTRA, BEAM INTENSITY AND SHAPE IN AN ECR ION SOURCE

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Abstract

The effect of the frequency tuning on bremsstrahlung spectra, beam intensity and shape in the 10 GHz, Nanogan ECR ion source have been investigated. The main aim of this work was to study the effect on a lower frequency type of ECR source where the separation between various modes in the cavity is much larger. The warm and cold components of the electrons were observed to be directly correlated with the beam intensity enhancement in the case of Ar⁹⁺ but not so for O⁵⁺. However, the warm electron component was much smaller than the cold component. The beam shapes of O⁵⁺ measured as a function of frequency showed a strong variation without hollow beam formation. Due to the use of an octupole magnetic structure in the Nanogan ECR source, the quadrupolar structure of the ECR surface is modified with the frequency tuning. In general, we have observed a strong absorption of microwave power at various frequencies whenever the reflection co-efficient showed a minimum value and the effect was seen stronger for the higher charge states. Details of the measurements carried out on the bremsstrahlung spectra, beam intensity and shape are presented together with the results of simulations.

INTRODUCTION

Experiments carried out using various ECR ion sources have shown that even a slight change in the frequency in the order of MHz strongly influences the beam intensities, shape, emittance, brightness and stability. The extracted currents are sensitive to small changes of less than 1 % in the rf frequency. This technique which has been called as the frequency tuning effect [1] was pioneered by the ECR group in Catania. Due to the remarkable change in the beam characteristics, the quality of the beam can be improved further. In the field of ECR ion source development, there is a constant endeavour to improve the beam quality and intensity. Earlier works using the frequency tuning effect have shown the influence on the beam characteristics [2-5] with a clear variation in the beam quality and intensity as a function of frequency. In a few of the experiments performed, the formation of hollow beam was observed just after source extraction before the solenoid focusing element [3]. Understanding of the bremsstrahlung spectrum of cold, warm, and hot electrons, and the electron distribution function are also necessary to study how characteristics of the beam are

influenced by the frequency tuning. S. Gammino *et al.* [6] have shown that the number of energetic electrons which populates the spectrum tail slightly changes when passing from one frequency to the other mostly because of variation in the warm population density. The slope of the bremsstrahlung spectra was observed to remain unchanged. But the experimental results shown in Ref. 7 did not show the trend where-in a large number of x-rays seemed to correspond to higher $\langle q \rangle$ and more intense beam current. For further understanding the frequency tuning effect on the beam characteristics and on the plasma conditions inside the cavity, it was felt necessary to study this effect on a lower frequency type of ECR ion source where the separation between various modes in the cavity is much larger than that of a source operating at a higher frequency. In hybrid modes, due to the superposition of two or more modes, it becomes difficult to explain how the electromagnetic fields can influence the production of beam intensities of highly charged ions. In this case, the measurement of the bremsstrahlung spectrum may give further information on the distribution of cold and warm electrons which can explain the probable ionization processes responsible for producing higher intensities of highly charged ions. At the Inter University Accelerator Centre, a compact, permanent magnet, 10 GHz Nanogan ECR ion source was used [8] to study the frequency tuning effect on the beam intensity, shape, and bremsstrahlung spectrum [9]. In order to further understand the frequency tuning effect on the beam characteristics, 3D simulations of the complete magnetic structure and of the electromagnetic fields for various modes in vacuum of the ECR cavity using CST Microwave Studio have been carried out [10]. To determine the shape of the beam at various tuning frequencies, the CST particle tracking solver was used under the combined influence of the confining magnetic fields and the electromagnetic fields of the cavity for specific modes. These simulations are compared to the beam shapes observed experimentally at various tuning frequencies. Presently, the simulation of one of the dominant modes of the cavity is compared with the observed beam shape at the corresponding frequency.

EXPERIMENTAL SET-UP

A 10 GHz fully permanent magnet, Nanogan ECR ion source was powered by a wide-band (8–18 GHz) travelling wave tube (TWT) amplifier manufactured by Amplifier Research, U.S.A [11]. A Rhode and Schwarz signal generator was used to vary the frequency and in the case of our experimental study, the frequency was chosen

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EMISSION SPECTROSCOPY DIAGNOSTIC OF PLASMA INSIDE 2.45 GHz ECR ION SOURCE AT PKU*

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Abstract

The 2.45 GHz permanent magnet electron cyclotron resonance ion source (PMECR) at Peking University (PKU) can produce high current hydrogen molecular ions H_2^+ and H_3^+ under different conditions, but the physics processes and plasma characteristics within the discharge chamber are not very clear until now. Langmuir probe, laser detachment, absorption spectroscopy and optical emission spectroscopy are common approaches for diagnosing the plasma. Among those methods, optical emission spectroscopy is a simple *in situ* one without disturbing the plasma. To better understand the plasma producing processes, a new ion source with transparent quartz discharge chamber was designed at PKU so that plasma diagnostic can be performed through directly detecting the light generated within ECR zone by fibre optics. A collisional radiative (CR) model is used to calculate plasma parameters like electron density n_e and electron temperature T_e for non-equilibrium plasma in ECR ion source.

INTRODUCTION

High current hydrogen molecular ion source for the generation of both H_2^+ and H_3^+ ions is developing at PKU as they can be potentially applied in high current linac, cyclotron or medical synchrotron[1][2]. The 2.45 GHz ECR ion source at PKU, which can produce more than 100 mA proton, was chosen as the device for obtaining molecular ions. Studies on the inner dimension of source chamber, operation pressure, microwave power and also pulsed duration indicated some promising results that pure 40 mA H_2^+ and 20 mA H_3^+ ions could be generated with both species fractions approximating 50% by only tuning the operation parameters[3][4]. Besides, a 2.45 GHz microwave driven negative ion source developed at PKU got some promising results that more than 15 mA H^- ions was extracted in pulsed mode recently[5]. These experimental results make us want to know more about the plasma behaviours which are very important in the generation and destruction of H_2^+ , H_3^+ and H^- inside the source. Obviously, the pressure inside discharge chamber will influence electron temperature which determines the cross-sections of many interaction processes, and RF-power will also contribute a lot to electron density. It will be better to figure out the relation of these parameters with plasma characteristics, so diagnosis was introduced for getting more information about crucial plasma parameters in ECR ion source such as electron density, electron temperature etc.

*Work supported by NSFC NO. 11175009 and 91126004.
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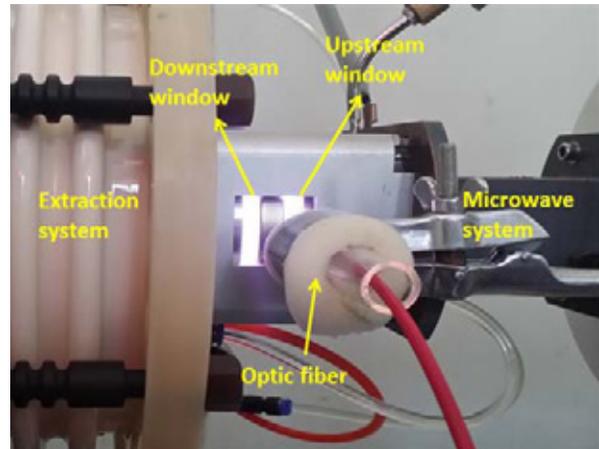


Figure 1: Photo of the ion source with transparent window.

Langmuir probe is a commonly used method to diagnose plasma inside ECR plasma. R. Gobin *et al.*, at CEA/Saclay utilized Langmuir probe to measure electron temperature for the development of H^- ion source, and the measured T_e was 6.7 eV before the microwave-break grid and 3.5~5.3 eV behind the grid[6]. But as they indicated, the Langmuir probe was sometimes hard to interpret under strong RF power and magnetic field environment, and it could only indicate some trends inside ECR plasma[7]. Recently, laser detachment method and absorption spectroscopy method have been developed, but the facilities are complicated and hard to realize with ECR ion source. By comparison, optical emission spectroscopy method is a simple and non-invasive approach to diagnose the plasma by analysing the light emitting from ECR cavity with optic fiber, high revolution spectrometer and auxiliary noble gas[8]. For this reason, a new ion source with transparent quartz chamber was designed and constructed so that the light from plasma could be seen from outside without disturbing the vacuum. The diagnostic method and preliminary results will be presented in this paper.

EXPERIMENTAL SETUP

The ion source is a permanent magnet ECR ion source named PMECR IV (Patent Number: ZL 201110026605.4). For diagnosing the plasma, the discharge chamber is made of quartz which has a high transmissivity for 400~800 nm light [9]. The magnetic field is provided by three NdFeB rings which are separated by non-magnetic metal gaskets. Based on above designs, the light from plasma can be detected through gaps between magnetic rings as shown in Fig.1. There are two positions where diagnosis can be carried out. One is located at ECR zone

SIMULATION OF THE CERN GTS-LHC ECR ION SOURCE EXTRACTION SYSTEM WITH LEAD AND ARGON ION BEAMS

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Abstract

A comprehensive study of beam formation and beam transport has been initiated in order to improve the performance of the CERN heavy ion injector, Linac3. As part of this study, the ion beam extraction system of the CERN GTS-LHC 14.5 GHz Electron Cyclotron Resonance Ion Source (ECRIS) has been modelled with the ion optical code IBSimu. The simulations predict self-consistently the triangular and hollow beam structures which are often observed experimentally with ECRIS ion beams. The model is used to investigate the performance of the current extraction system and provides a basis for possible future improvements. In addition, the extraction simulation provides a more realistic representation of the initial beam properties for the beam transport simulations, which aim to identify the performance bottle necks along the Linac3 low energy beam transport. The results of beam extraction simulations with Pb and Ar ion beams from the GTS-LHC will be presented and compared with experimental observations.

INTRODUCTION

Linac3 delivers the heavy ion beams for the CERN experimental programme and is the first section of the LHC (Large Hadron Collider) heavy ion injector chain. The subsequent accelerator chain utilizing the heavy ions from Linac3 is comprised of LEIR (Low Energy Ion Ring), PS (Proton Synchrotron), SPS (Super Proton Synchrotron) and ultimately the LHC.

The heavy ion beams are produced with the GTS-LHC 14.5 GHz room temperature ECR ion source [1] at an initial energy of 2.5 keV/u. The beams are accelerated with an RFQ to 250 keV/u, followed by an Interdigital-H Drift Tube Linear Accelerator (IH-DTL) to reach the final Linac3 output energy of 4.2 MeV/u. Downstream from the IH-DTL the beam is transported through a carbon foil stripper and a filter line to produce and separate the desired ion species for LEIR injection.

The GTS-LHC is based on the original Grenoble Test Source (GTS) developed at CEA [2, 3]. It has been used predominantly in afterglow mode to produce intense lead ion beams with $^{208}\text{Pb}^{29+}$ being the ion of choice since 2007. The normal operation is performed with 10 Hz repetition rate and 50 ms RF heating pulse length. A 200 μs long ion beam pulse is selected from the ~ 1 ms afterglow peak exhibited by the lead beam and accelerated at up to 5 Hz repetition rate through Linac3. Finally, the beam is stripped to $^{208}\text{Pb}^{54+}$ for LEIR injection. Following the beam develop-

ment and testing performed in 2013 [4], the GTS-LHC will deliver $^{40}\text{Ar}^{11+}$ beam for fixed target experiments in 2015.

As a part of the LHC luminosity upgrade for ions, a comprehensive study of Linac3 beam formation and transport has been initiated. The first part of this study includes detailed modelling of Linac3 beam dynamics with simulations, starting from beam extraction from the GTS-LHC. The extraction simulations serve two distinct purposes. Firstly, a reliable modelling of the beam transport along Linac3 requires realistic initial beam definitions, which recreate the characteristic properties of ECRIS beams that are observed experimentally. With a realistic model of Linac3 the factors limiting the beam transport performance can then be identified and possibly remedied. Secondly, the optimization of the beam extraction itself has the potential to yield performance improvement.

The current state of beam dynamics studies is presented for Pb and Ar beams. The Ar beam has been chosen due to its availability for measurements in 2014 during the injector chain commissioning and preparation for the 2015 physics experiments.

EXTRACTION SIMULATIONS

Extraction Simulation Settings

The GTS-LHC ion beam extraction has been modelled with the ion optical code IBSimu [5]. The code provides good capabilities to simulate multispecies extraction from plasma in the presence of strong magnetic fields and space charge, conditions which are closely associated with ECR ion sources. Although the nonlinear positive plasma model used by the code [6] considerably simplifies the complex ECRIS plasma conditions, previous studies have shown that IBSimu is a powerful tool in modelling ECRIS extraction systems [7].

The GTS-LHC extraction geometry, presented in Fig. 1, includes a plasma electrode, an intermediate electrode and a grounded electrode, forming a triode extraction system. Downstream from the electrodes the extraction region opens into a vertical cylindrical pumping chamber, followed by a beam pipe section with an inner diameter of 65 mm. The simulations have been performed in 3D with coordinate x denoting the optical axis and z and y the transverse directions. The 3D magnetic field map of the GTS-LHC was calculated with Cobham Opera 3D simulation software [8] and it includes the solenoid and the permanent magnet hexapole fields. In addition, the field of the first beam line solenoid downstream from the extraction region is included in the simulations. The resulting longitudinal magnetic field pro-

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HIGH CURRENT PROTON AND DEUTERON BEAMS FOR ACCELERATORS AND NEUTRON GENERATORS

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Abstract

This paper presents the latest results of high current proton and deuteron beam production at SMIS 37 facility at the Institute of Applied Physics (IAP RAS). In this experimental setup the plasma is created and the electrons are heated by 37.5 GHz gyrotron radiation with power up to 100 kW in a simple mirror trap fulfilling the ECR condition. High microwave power and frequency allow sustaining higher density hydrogen plasma (n_e up to $2 \cdot 10^{13} \text{ cm}^{-3}$) in comparison to conventional ECRIS's or microwave sources. The low ion temperature, on the order of a few eV, is beneficial to produce proton beams with low emittance.

Latest experiments at SMIS 37 were performed using a single-aperture two-electrode extraction system. Experiments with hydrogen and deuterium show possibility of beams formation with currents up to 550 mA at high voltages below 45 kV with normalized rms emittance lower than $0.2 \pi \cdot \text{mm} \cdot \text{mrad}$. Such beams have a high potential for application in future accelerator research.

Also in frames of the present paper it is suggested to use such an ion source in a scheme of D-D neutron generator. High current gas-dynamic ion source can produce deuteron ion beams with current density up to $700\text{-}800 \text{ mA/cm}^2$. Generation of the neutron flux with density at the level of $7\text{-}8 \cdot 10^{10} \text{ s}^{-1} \text{ cm}^{-2}$ could be obtained in case of TiD_2 target bombardment with deuteron beam accelerated to 100 keV. Estimations show that it is enough for formation of epithermal neutron flux with density higher than $10^9 \text{ s}^{-1} \text{ cm}^{-2}$ suitable for boron neutron capture therapy. Important advantage of described approach is absence of Tritium in the scheme.

EXPERIMENTAL SETUP

The experimental research presented in this work was carried out on the SMIS 37 shown schematically in Fig. 1 [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 for plasma production and heating. 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 -to-plasma coupling system shown on the left in Fig. 1. 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. 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. Hydrogen and deuterium were used as a working gas. Its inlet into the source was realized through an opening incorporated with the microwave coupling system. The delay between gas injection and subsequent microwave pulse ($300\text{-}3000 \mu\text{s}$) as well as the gas pulse duration (about 5 ms) were adjusted for each experimental condition in order to maximize the beam current and optimize the temporal shape of the extracted current pulse.

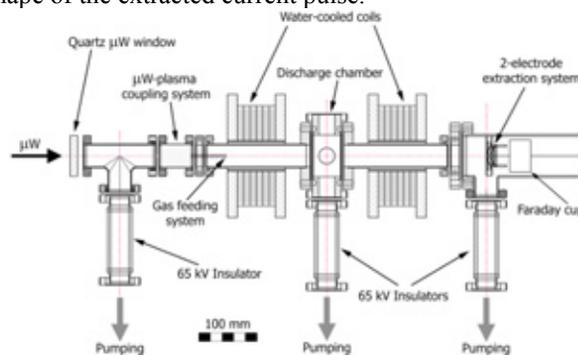


Figure 1: SMIS 37 experimental setup.

The ion extraction and beam formation were realized by two-electrode, i.e. single gap plasma electrode - puller electrode system. Diameters of the holes in plasma electrode and puller were of 10 mm and 22 mm respectively. The plasma electrode was placed 10 cm downstream from the magnetic mirror to limit the extracted ion flux as described in [2], which helps improving the beam transport through the puller.

The maximum available extraction voltage was 45 kV. A Faraday cup was placed immediately behind the puller electrode to measure the total beam current passing through the extractor.

EXPERIMENTAL RESULTS

The use of powerful millimeter wave radiation allows to significantly increase the plasma density in the discharge compared to traditional ECR sources (the density scales with the square of the radiation frequency). In our experiments with 37.5 GHz gyrotron frequency the plasma density could be higher than 10^{13} cm^{-3} [3]. High value of plasma density N_e in combination with quite low ion life-time τ (but still enough for 100% ionization degree) provides high density of ion flux from the trap $\sim N_e \tau$. In our experiments the total plasma (ion) flux

OPTIMIZATION OF LOW-ENERGY BEAM TRANSPORT *

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Abstract

Transport of low-energy heavy-ion beams from an Electron Cyclotron Resonance Ion Source to an accelerator often suffers from significant emittance increase caused by aberrations of ion-optical elements in the beam transport line. In this paper we use a combination of four-dimensional phase-space measurements and simulations to study beam transport through an analyzing magnet. It is shown that large second-order aberrations of the magnet lead to a five-fold increase of the beam emittance. Several mitigation strategies are investigated, i.e. adding compensating hexapoles or extra focusing elements between ion source and magnet. The best solution is to use a focusing solenoid between ion source and magnet. Using a compensating hexapole is not recommended, since it introduces significant third and higher-order aberrations.

INTRODUCTION

Low-energy heavy-ion beams extracted from Electron Cyclotron Resonance Ion Sources (ECRIS) have relatively large beam diameters and divergences because the extraction occurs in a decreasing magnetic field. Such beams are therefore very sensitive for ion-optical aberrations in the bending and focusing elements of the beam transport line leading to emittance blowup and beam losses. To give some typical numbers¹, injector ECRIS's have beam emittances in the range of 20-100 mm mrad for low to medium charged ions. The geometrical acceptance of a cyclotron is typically 100-200 mm mrad. However, measured emittances in low-energy beam lines are often in the range of 100-300 mm mrad taking into account the phase space cut-offs by beam limiters. This results in low transport and injection efficiencies [2–4]. There is thus much room for improvement. These issues are particularly relevant for very high-intensity beams where beam losses might lead to damage, or for very low-intensity beams where one cannot afford to lose any ions.

This paper presents methods to determine the beam emittance and ion-optical aberrations quantitatively and discusses possible ways to minimize the emittance blowup caused by these aberrations. The motivation for this work was to better understand beam transport in the low-energy beam transport (LEBT) line of the AGOR facility at KVI-CART [5, 6]. The measurements and simulations have been done with a mono-component 25 keV He⁺ beam only for the first part of this LEBT line consisting of an ECRIS and a charge-state analyzing magnet, but it is straightforward to

include more ion-optical elements. Regarding the simulations to minimize the ion-optical aberrations of the dipole magnet a 21 keV H⁺ beam is used. The paper is organized in three sections. The first section describes the experimental and computational methods that have been used. The second section presents and discusses several ways to minimize ion-optical aberrations. The last section finishes with the conclusions.

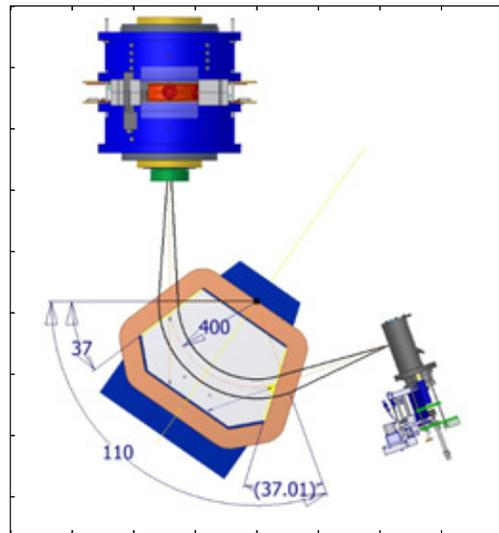


Figure 1: ECR ion source, charge-state analyzing magnet and a pepper-pot emittance meter.

EXPERIMENTAL AND COMPUTATIONAL METHODS

Experimental setup

The first part of the LEBT line includes an ECRIS, charge-state analyzing magnet and a pepper-pot emittance meter (see Fig. 1). The ECRIS is of the AECR-type with two room temperature solenoids and an open NdFeB permanent hexapole magnet. The plasma is heated with 14 GHz microwaves with a maximum power of 2 kW and the source can be biased with respect to ground up to a maximum voltage of 34 kV. Ions are extracted with an accel-decel lens system consisting of a plasma electrode with a 8 mm extraction aperture followed by shielding and ground electrodes. Charge-state selection of the extracted beam is done with an unclamped double-focusing analyzing magnet with a bending radius of 400 mm, bending angle of 110° and pole face

* Work supported by university of Groningen (RuG).

¹ All quoted beam emittances are understood to be 4-rms emittances according to the definition of Lapostolle [1].

COMBINATION OF TWO ECRIS CALCULATIONS: PLASMA ELECTRONS AND EXTRACTED IONS

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Abstract

In strongly magnetized ECRIS plasmas collisions do not influence the path of the charged particle. Electrons and ions can move more freely only along a magnetic field line compared to the transverse direction. Therefore, extraction simulation requires that the trajectories of charged particles have to be traced through the plasma chamber instead of starting at the plasma boundary. In previous simulations the particle density at the beginning of the trajectory deep inside the plasma has been unknown. Now the full 3D electron tracking within the plasma chamber has been combined with the generation of initial ion starting conditions including particle density for ion tracking. The TrapCAD code has been used to determine the electron spatial distribution in a certain energy window. The idea is that at the places where the electron reaches a specific energy, an ion trajectory can be started. The magnetic field has been modeled with OPERA, whereas for solving the electric potential and the particle tracking the computer code KOBRA3-INP has been used. First results will be shown and discussed. The number of affecting parameters on the operating conditions of the ion source may lead to a multi-dimensional optimization space for simulation.

MOTIVATION

Several attempts have been done in the past to simulate the extraction of ions from an Electron Cyclotron Resonance (ECR) Ion Source (ECRIS). Most of these attempts gave only partial results or even failed, because they were not able to reproduce the experimental results. In early simulations the ions started from outside the plasma or just at the plasma boundary. Later models tried to include the effect of the non-cylindrical magnetic field [1]. One of the recent and best models up to now is given by the following procedure: tracing magnetic field lines through the extraction aperture, looking where these field lines are coming from, and using the coordinates of the magnetic field line as starting points for ions to be extracted [2]. This means magnetized ions are considered.

It is also well-known that energetic plasma electrons are strongly tighten to the magnetic field lines. The question is whether we can use the coordinates of these electrons by simultaneously using the field lines? A simulation study of ECRIS plasma electrons revealed that in certain cases the positions of the electrons inside the plasma chamber may correspond to the positions of the highly charged ions [3]. The study was built on direct experimental results: on visible-light photos and on energy-filtered X-ray photos of argon plasmas.

In this paper we make an attempt to combine the two methods: a plasma electron cloud is simulated in a given ECRIS configuration and the coordinates of these electrons are used to be the starting positions of ions to be extracted. During the extraction procedure the fully 3D magnetic field structure of the ECRIS (inside and outside the plasma) is taken into account.

THE ECRIS CONFIGURATION

For the simulations of plasma electrons and ions to be extracted the CAPRICE-type ECR ion source operating at GSI was selected. The technical details of this ECRIS are described elsewhere [4]. It has a relatively short plasma chamber in a strong magnetic trap (created by two room-temperature coils and by a NdFeB-magnet hexapole) operating on 14.5 GHz microwave frequency (even it is suitable to operate at different frequencies) [4]. The simulation of electron movement requires the knowledge of magnetic field values in a fine 3D mesh. Because ECRISs have certain symmetries, for this pre-calculation a real 3D code was not necessary. Instead, the 2D PoissonSuperfish code (version 6.15) has been used [5]. For the calculation the exact geometry of the GSI-CAPRICE with typical coils currents used for highly charged ion production were applied (see Table 1).

Table 1: Input parameters for Superfish calculations

Parameters for calculation	Value
Plasma chamber length:	187 mm
Plasma chamber diameter:	63 mm
Injection coil current:	1100 A
Extraction coil current:	1100 A
Hexapole materials (VACODYM):	745HR/655HR
Mesh size for the coils system:	0.5 mm
Mesh size for the hexapole system:	0.2 mm

Figure 1 and 2 show the result: the geometries of the axial and radial magnetic traps and the relevant magnetic field distributions. Throughout with Superfish and TrapCAD calculations in this paper the axis of the plasma chamber is marked by z and the radial distance is marked by r . The calculated magnetic curves correspond well (inside the plasma chamber) with measurements carried out by the GSI team earlier. The curves show the minimum and maximum values of the magnetic field

PRODUCTION OF METALLIC STABLE ION BEAMS FOR GANIL AND SPIRAL2*

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Abstract

GANIL has been producing many stable beams for nearly 30 years. Constant progress has been made in terms of intensity, stability and reliability. The intensity for some stable metallic beams now exceeds or approaches the μA level at an energy up to 95 MeV/u: 1.14 μA for ^{36}S (65% enriched) at 77 MeV/u, 0.35 μA for ^{58}Ni (63%) at 74 MeV/u. The presentation highlights recent results obtained with ^{50}Ti using the MIVOC (Metallic Ions from Volatile Compounds) methods on the ECR4 ion source. The Titanium beam was produced using the organo-metallic compound Titanocene : Cp^*TiMe_3 . The synthesis of this metallocene compound has been successfully performed by the IPHC-Strasbourg from isotopically enriched ^{50}Ti metal. Two tests have been done with the natural Titanocene (^{48}Ti) to validate the new compound, and to qualify the intensity and beam stability. The good results obtained led us to program the Physics experiment in 2013, September and we have produced a very stable $^{50}\text{Ti}^{10+}$ beam at an intensity of 20 μA for 300 hours. The Spiral 2 facility, currently of installation, will provide gaseous and metallic stable ion beams. The ion source choice for the commissioning of the stable beams $Q/A=1/3$ is the ECRIS PHOENIX V2. This ECRIS has been designed by LPSC Grenoble and several tests of stable metallic beams have been realized in this laboratory. The results for Nickel ($^{58}\text{Ni}^{19+}$) and calcium ($^{40}\text{Ca}^{16+}$) are given.

PRODUCTION OF NEW METALLIC BEAM FOR GANIL: ^{50}TI

Introduction

The study of a Titanium beam production started in 2011 with the ion source ECR4 by using the MIVOC method (Metal Ions from Volatile Compounds). This method was originally introduced at the University of Jyväskylä in Finland [1, 2, 3] and is routinely used at GANIL for the production of Ni and Fe beams, either using natural or isotopically enriched samples.

Thanks to the synthesis of the MIVOC compound Titanocene by B.GALL's team (IPHC-Strasbourg), an isotopically enriched $^{50}\text{Ti}^{10+}$ beam was successfully delivered for physics experiment (E656-J.PIOT) in October 2013, during 15 days.

*Work partially funded by EU Grant Agreement 283745

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Titanocene

The MIVOC method is based on the of the ECR ion source plasma feed by a controlled flow of organo-metallic compound. Such molecules are produced out of enriched material of desired element through dedicated chemistry. Nevertheless, only organo-metallic compounds with high enough vapour pressure can be used for MIVOC beams. It is for example the case for Fe, Ni and Mg where MIVOC method is widely used. Special care has to be taken to handle some of these compounds which are toxic.

With a melting point at 1660 °C for its metal form, titanium is typically a candidate to MIVOC method. Several years of developments were required to fully overcome the problematic of production and handling of this element. Several compounds were synthesized at IPHC Strasbourg and tested at University of Jyväskylä to successfully produce a MIVOC beam of titanium. Finally, first isotopically enriched MIVOC beam of titanium was obtained and accelerated in fall 2011 by the $K = 130$ MeV cyclotron of the University of Jyväskylä. The Compound was produced with a quite high efficiency by a two-step chemistry starting with TiCl_4 92.57 % enriched ^{50}Ti element, then going to $\text{C}_5(\text{CH}_3)_5\text{Ti}(\text{CH}_3)_3$ via $\text{C}_5(\text{CH}_3)_5\text{TiCl}_3$. A beam intensity of 19.4 μA was extracted for titanium-50 at 11^+ charge state from the JYFL 14 GHz ECR2 ion source. This very stable beam – either on short and long time scale - was used for a three week experiment dedicated to the first prompt spectroscopy of a super-heavy element: ^{256}Rf ($Z=104$) [4].

Following this success, this compound was tested in GANIL Caen in collaboration with IPHC Strasbourg.

Transfer of the Synthesis in the MIVOC Chamber

Like the majority of organo-metallic compounds, the Titanocene is very air and moisture sensitive. The transfer of the synthesis in the MIVOC chamber is thus done under inert atmosphere (Argon). We used a portable glove bag (see Fig.1) for the sample manipulation. A special infra-red light has been used.

STATUS REPORT AT THE HEIDELBERG ION-BEAM THERAPY (HIT) ION SOURCES AND THE TESTBENCH

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Abstract

Since October 2009 more than 2000 patients were treated at HIT. In a 24/7 operation scheme two 14.5 GHz electron cyclotron resonance ion sources are routinely used to produce protons and carbon ions for more than 8000 hours per year. The integration of a third ion source into the production facility was done in summer 2013 to produce a helium beam. This paper will give a status report of the ion source operating experience and statistics and will summarize the enhancement activities, which were undertaken at an in-house ion source testbench.

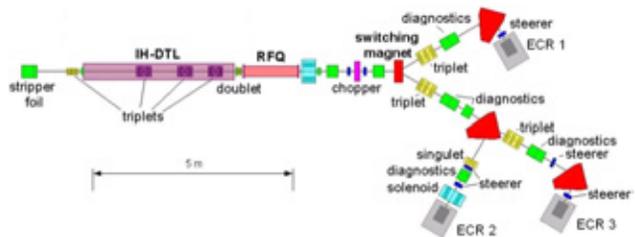


Figure 2: Low energy beam line (LEBT) and the linear accelerator (LINAC).

INTRODUCTION

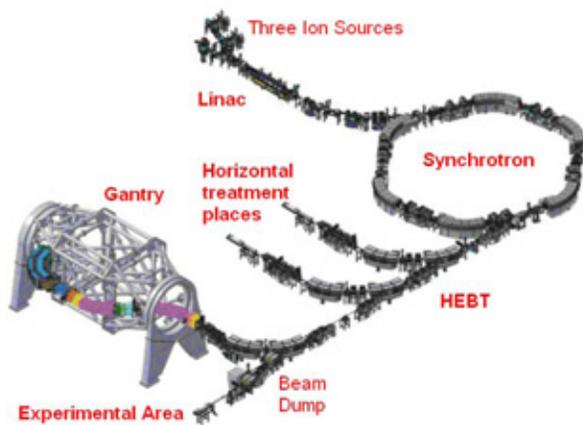


Figure 1: Overview of the HIT facility.

The beam production at HIT consists of two ECR Supernanogan ion sources [1] for the routine operation of proton and carbon beams at 8 keV/u; a third Supernanogan ion source is integrated (see ECR3 in Figure 2) for ion species like helium and oxygen for experiments at the experimental area (see Figure 1) and for the therapy in the future.

The compact 217 MHz linear accelerator (LINAC) consists of a radio frequency quadrupole accelerator (RFQ) and an IH-type drift tube linac (IH-DTL) with the end energy of 7 MeV/u for all ions; a foil stripper directly located behind these cavities produces fully stripped ions (see Figure 2).

A synchrotron of 65 m circumference accelerates protons, helium, carbon and oxygen to predefined end energies e.g. for carbon ions from 89 to 430 MeV/u in 255 steps.

OPERATION EXPERIENCE

During the last years of operation mainly carbon ions were used by 58 %, followed by hydrogen (39 %), helium (2 %) and oxygen (1 %). The continuous operation runtime of the two sources are about 340 to 360 days per year in a 24h-operation! The operation-statistics since 2008 of the accelerator is shown in Figure 3. The sources in 2013 are in operation for 358 days per year, 7 days for planned maintenance shifts and 4 hours in 2013 are the “off time”. The “off time” between 2008 and 2010 is caused by multiple RF amplifiers breakdowns [2].

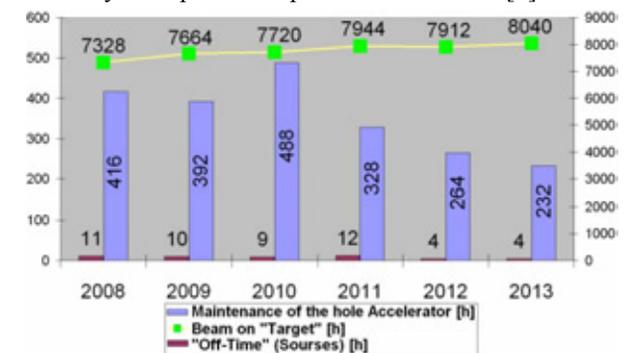


Figure 3: operation-statistic of HIT (2008- 2013).

The peak of the ion source “Off-Time” in 2011 is caused by numerous failures of the extraction system. The pollution of the extraction ceramic led to sparks in that region and generated an isolator ceramic replacement about every 3 weeks. This unfavorable situation could be remedied by the new construction and installation of the extraction system in winter 2011 at the therapy sources.

Since this time we do not have any insulator ceramic contaminations and no “hardware” problems with the sources. These replacements ensure an off time of just 4 hours per year (2012 and 2013). These 4 hours per year of “not usable” and instable therapy beam are used e.g. to find new and stable setting parameters, can be bridged by

DIRECT INJECTION OF INTENSE HEAVY ION BEAMS FROM A HIGH FIELD ECR ION SOURCE INTO AN RFQ

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Abstract

Beam intensities achievable from high performance ECR sources for highly charged ions are limited by the high space charge. For high performance ECR sources, the stray magnetic field of the source can provide focusing against the space charge blow-up of the beam when used with the Direct Plasma Injection Scheme (DPIS) developed for laser ion sources. A combined extraction/matching system has been designed for direct injection into a radio frequency quadrupole (RFQ) accelerator, allowing a total beam current of 12 mA for the production of highly charged $^{238}\text{U}^{40+}$ (0.49 mA) to be injected at an ion source voltage of 60 kV. In this design, the features of IGUN have been used to take into account the rf-focusing of an RFQ channel (without modulation), the electrostatic field between ion source extraction and the RFQ vanes, the magnetic stray field of the ECR superconducting solenoid, and the defocusing space charge of the ion beam. The RFQ has been designed to suppress most of the charge states extracted from the ECR, acting as a filter for the desired $^{238}\text{U}^{40+}$. This reduces the transport problem for the beam line as well as reduces the emittance for the transmitted charge states.

INTRODUCTION

High performance superconducting electron cyclotron resonance (ECR) ion sources such as the 28 GHz VENUS [1], the 24 GHz SECRAL [2] and the 28 GHz source at RIKEN [3] operate at higher frequencies than older sources and hence have higher plasma densities and magnetic fields. A new design study of a 56 GHz source by the ECR ion source group at Berkeley shows that the source can have even higher plasma densities, since the density scales as the square root of the operating frequency [4]. A new type of ECR source has been proposed recently by D. Z. Xie [5] for operation at 50 GHz. Considering the frequency scaling from 28 GHz to 56 GHz and without an increased volume of the plasma chamber, the heavy ion beam of U^{40+} produced earlier by the VENUS source [1] at an intensity of 12 μA can be extracted with an intensity of possibly as much as 0.49 mA at the higher 56 GHz operating frequency. The extraction of these intense highly charged heavy ion beams poses several problems. Generally, accel-decel extraction systems coupled to ECR ion sources have shown inherent problems extracting intense beams of highly charged ions due to sparking at the high voltages

required and the poor vacuum conditions, which also limits the extraction of intense beams of highly charged ions. Hence, this type of extraction system generally fails due to problems with the high voltage power supplies. This eventually keeps the ion source from functioning smoothly and increases the downtime of the accelerator. In the applications of laser ion sources, with their much higher plasma densities, severe problems of handling intense beams due to sparking and/or beam loading are avoided by using an ingenious technique, the so-called Direct Plasma Injection scheme (DPI) [6]. This technique was utilized for transporting intense beams directly into a radio frequency quadrupole (RFQ) accelerator using the combined focusing of the gap between the ion source and the RFQ vanes (or rods) and the focusing of the rf fields from the RFQ penetrating into this gap. In this scheme, the plasma expands to the entrance of the RFQ, where the electrons are deflected by the fringe field of the RFQ and only the ions get trapped by the RFQ focusing field. Hence, space charge effects are completely controlled, with the great advantage being the ability to transport very intense beams. This technique was experimentally demonstrated for the acceleration of carbon (C^{3+} , C^{4+} , C^{5+}) and aluminum (Al^{9+}) ions with beam intensities greater than 60 mA [7].

In the case of new ECR ion sources, the development of higher operating frequencies in superconducting ECR ion sources will result in higher plasma densities. Therefore, much higher beam intensities will not only be possible by using extraction voltages higher than the 30 kV in use today in most ECR sources, but also by changing the extraction electrode aspect ratio. Operating at these higher extraction voltages will however result in operating the accel-decel systems at relatively higher voltages, increasing the probability of sparking. In order to circumvent this problem in conventional ECR ion source extraction systems, a proposed solution is to couple an RFQ directly to a high performance ECR ion source using the laser ion source DPI scheme. For high performance ECR sources that use superconducting solenoids, the stray magnetic field of the source can be used in the DPI scheme to provide more focusing to overcome the space charge blow-up of the beam [8]. In the present study, the RFQ has been designed to suppress most of the charge states extracted from the ECR, acting as a filter for the desired $^{238}\text{U}^{40+}$. This reduces the transport problem for the beam line as well as reduces the emittance for the transmitted charge states.

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CURRENT DEVELOPMENTS FOR INCREASING THE BEAM INTENSITIES OF THE RIKEN 18-GHz SUPERCONDUCTING ECR ION SOURCE

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Abstract

The RIKEN 18-GHz superconducting ECR ion source (18-GHz SC-ECRIS) and the RIKEN AVF cyclotron function as the light-ion injector at the RI Beam Factory (RIBF) as well as being used for low-energy nuclear physics experiments and additional RI production. We are currently trying to measure and improve the beam quality of the 18-GHz SC-ECRIS because the beam intensities are lower than those obtained from the other injector using the RIKEN Linear Accelerator (RILAC). In order to improve our understanding and to increase the beam intensities, we are developing the simulation of the low energy beam transportation and an online emittance meter based on the pepper-pot method. We have tested a prototype emittance meter and confirmed an analysis procedure to deduce the emittance from the measured data.

INTRODUCTION

Since the RIKEN AVF cyclotron was constructed in 1989, it has been used as an injector for the RIKEN ring cyclotron (RRC). It has been used as stand-alone experiments related to low-energy nuclear physics and RI production. Since April 2009, the AVF injection mode started in the RIKEN RI Beam Factory (RIBF), where the cascaded chain of AVF, RRC, and Superconducting Ring Cyclotron (SRC) has provided light ion beams such as D, ^{14}N , and ^{18}O ions. The RIKEN 18-GHz superconducting ECR ion source (18 GHz SC-ECRIS) is one of three ion sources used for the AVF cyclotron as shown in Fig. 1. One of the current problems in the AVF injection mode is that the beam intensities are significantly lower than those obtained with the RIKEN Linear Accelerator as the injector (the RINAC injection mode), as show in Table 1. In order to increase the beam current of the AVF injection mode, a comprehensive understanding of the behavior of the ion beam not only around the extrac-

Table 1: Beam intensities achieved from SRC.

Beam	Energy / A (MeV)	Intensity (pnA)	Injector
^{18}O	230	400	AVF
^{18}O	250	200	AVF
^{18}O	345	1000	RILAC

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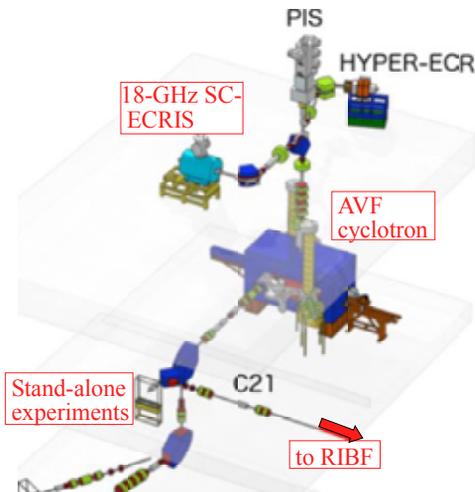


Figure 1: Schematic view of the RIBF injector apparatus with the 18-GHz SC-ECRIS.

tion area of the ion source but also for the low energy beam transport (LEBT) to the AVF cyclotron is necessary. To this end, we have started developing simulations to elucidate the ion trajectory through the LEBT and an online emittance monitoring system based on the pepper-pot method [1]. The current status of the 18-GHz SC-ECRIS is also discussed.

APPARATUS

The 18-GHz SC-ECRIS is one of the ion source for the AVF cyclotron. At present, the 18-GHz SC-ECRIS mainly provides light-ion beams generated from gaseous elements, e.g. D^+ , $^{12}\text{C}^{4+}$, $^{18}\text{O}^{6+}$, $^{40}\text{Ar}^{11+}$ ions and so on. The dimensions of the SC-ECRIS and LEBT are shown in Fig. 2. The specifications of the 18-GHz SC-ECRIS are given in Table 2. The length and diameter of the plasma chamber are 70 mm and 378 mm, respectively. The plasma chamber is encapsulated by a hexapole permanent magnet of which the magnetic field is ~ 1.1 T at the surface. A set of superconducting solenoids is used to achieve the minimum- B condition. A moveable biased disc with a diameter of 30 mm is installed, to which a negative voltage of a few hundred volts with respect to the plasma chamber can be applied to increase the multi-charged ion flux. A 750-W TWTA (XTRT-750DBS, Comtech Xicom Technology, Inc) is installed to generate the 18-GHz microwaves that induce the ECR heating. The multi-charged ions are extracted and accelerated towards a grounded extraction electrode by applying a high voltage,

DEVELOPMENT OF AN INTERFACE AND DIAGNOSTIC SYSTEM FOR THE ECR ION SOURCE AT KBSI

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Abstract

A 28 GHz superconducting ECR (electron cyclotron resonance) ion source was recently developed at KBSI (Korea Basic Science Institute) to produce a high current and high charge state ions [1]. The condition of the ion beam extracted from the ion source should be analyzed by a diagnosis tool after accelerating and focusing process. For this, we developed an ion beam diagnostic system composed of a slit, a wire scanner, a view screen and a faraday cup. The interface of the diagnostic system was designed so as to achieve stable operation of the ECR ion source. The information obtained from the diagnostic system can be used as a reference in studies of the optimum beam conditions needed to adjust the extraction parameters. The details of the diagnostic system and initial test results will be reported.

INTRODUCTION

A heavy ion accelerator using fast neutrons was developed for the radiography facility at KBSI. A 28 GHz superconducting ECR (electron cyclotron resonance) ion source was employed for a high current ion beam to meet the requirements needed for generating fast neutrons. The key part of heavy ion accelerator system is comprised of the 28 GHz ECR ion source, an LEBT (low energy beam transport) system with a series of electromagnets (a dipole, two quadrupoles and three solenoids), RFQ (radio frequency quadrupole) for ion beam acceleration from 12 keV/u to 500 keV/u and DTL (Drift Tube linear accelerator) for acceleration up to 2.7 MeV/u. The layout is shown in figure 1. Neutron imaging is planned to be generated by the reaction of an accelerated lithium beam and a hydrogen target.

The figure 2 shows the components of the LEBT system, which are a dipole magnet, three solenoids, two quadrupoles and the diagnostic system. Ion beams extracted from the ECR ion source are transported to the RFQ entrance via the LEBT system. After analysing the process at the dipole magnet, we prepared a diagnostic chamber to obtain the beam profile, the transverse emittance and the intensity of the beam current at this location. Inside of the diagnostic chamber, we installed

horizontal and vertical slits, a wire scanner, the screen monitor and the faraday-cup. The slits and wire scanner permit us to select the desired beam and to measure the transverse emittance. The screen monitor and wire scanner are utilized to identify the horizontal and vertical profiles of the ion beam. The faraday-cup provides information regarding the beam intensity as an electrical current.

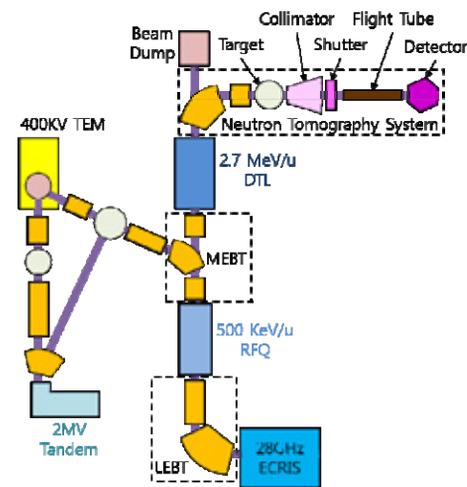


Figure 1: The layout of the KBSI accelerator.

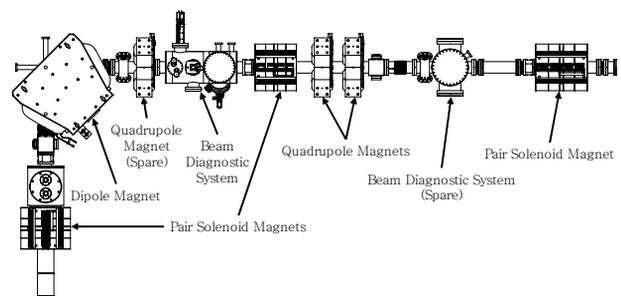


Figure 2: Schematic diagram of the LEBT system.

Simulations of the ion beam optics were carried out using the TRANSPORT code. The basic parameters used in this simulation are listed in Table 1.

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PRODUCTION AND ACCELERATION OF TITANIUM-50 ION BEAM AT THE U-400 CYCLOTRON*

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Abstract

The production of Ti-50 ion beam with ECR ion source using MIVOC method is described. The experiments were performed at the test bench with the natural and enriched compounds of titanium $(\text{CH}_3)_5\text{C}_5\text{Ti}(\text{CH}_3)_3$. The compounds were synthesized in collaboration with IPHC (Strasbourg) group. In the experiments at the test bench the beam currents of Ti^{5+} - 80 μA and Ti^{11+} - 70 μA were achieved at different settings of the source. After successful tests two 3 weeks runs with Ti-50 beam were performed at the U-400 cyclotron for the experiments on spectroscopy of super heavy elements. The intensity of the injected beam of $^{50}\text{Ti}^{5+}$ was about of 50-60 μA , during experiment the source have shown stable operation. The compound consumption rate was determined to be about of 2.4 mg/h, corresponding to ^{50}Ti consumption of 0.52 mg/h.

INTRODUCTION

In recent years, the reactions ^{48}Ca with ^{238}U , $^{242,244}\text{Pu}$, ^{243}Am , ^{245}Cm and ^{249}Cf were used to synthesize new super heavy elements with $Z = 114-116$ and 118. In the frame of these experiments a technique for producing of metallic ^{48}Ca was developed, optimization of operation mode of ECR ion source was performed in such a way that the necessary intensity of $^{48}\text{Ca}^{5+}$ ions was achieved with maximum efficiency ionization [1]. The methods of collection and recovery of expensive isotope also were developed. The complex of these studies made it possible to conduct long-term experiments on the synthesis of super heavy elements with high efficiency using of the working substance.

The most heavy target, with which it is possible to carry out experiments on the synthesis of super heavy elements in heavy-ion reactions is ^{249}Cf , so further progress in the area of the elements with $Z > 118$ requires the production of intense beams of accelerated neutron-enriched isotopes such as ^{50}Ti , ^{58}Fe , ^{64}Ni and others. The use of each new isotope for production of the accelerated beam requires investigations directed on optimization of the ECR source operation mode and development of technique for material feed into the source.

Several methods for production of ions of solids from ECR sources have been developed. Solid material can be evaporated by resistor or inductive oven, which is inserted into source chamber [2,3].

Refractory metals can be sputtered by plasma ions [4]

or inserted into the plasma and heated by energetic plasma electrons ("insertion technique") [5,6].

The other possibility for production of ions of solids is the feeding of the plasma with an organometallic compound through the Metal Ions from Volatile Compounds (MIVOC) method [7].

PRODUCTION OF TITANIUM ION BEAM

The experiments on production of Ti ion beams were carried out at many laboratories with the use of different methods.

The production of Ti ion beams by evaporation from the resistor oven was studied at GSI [8]. The evaporation of pure titanium requires the temperature between 1750 °C and 1800 °C. During the experiments with HTO more than 50 μA of $^{50}\text{Ti}^{8+}$ were produced with high level of beam stability. The oven life time of 6 days was obtained.

The experiments on production of Ti ion beams by evaporation from the induction oven were carried out at ANL [9]. The beam of $^{50}\text{Ti}^{12+}$ with the intensity of 5.5 μA was produced during seven days.

The MIVOC method was first adopted for production of Ti ion beam by JYFL group [10]. Commercially available $(\text{CH}_3)_5\text{C}_5\text{Ti}(\text{CH}_3)_3$ compound was used as a working substance. In the case of $^{48}\text{Ti}^{11+}$ ion beam the intensity of 45 μA was produced.

The consumption of the compound was measured to be 47 mg giving the value of 0.22 mg/h for the consumption of titanium. The ion beam was very stable during the period of 282 h. So, from the point of view beam intensity, stability, reliability and material consumption the MIVOC method seems very promising for providing ^{50}Ti ion beam for long term (several months of non-stop operation) experiments on synthesis of super heavy elements.

The compound is sensitive to air, moisture, temperature and light that needs cautious handling when loading the material for use. The synthesis of this compound is rather complicated especially with the use of enriched titanium which is available in a small, about 1 g, quantity.

Test Experiments

First time the ^{50}Ti ion beam was accelerated at the U-400 cyclotron in 2005. The task was to provide about of 30 enA of ^{50}Ti beam at the target for experiments on the fission physics. Due to the moderate requirements for the intensity it was decided to use TiCl_4 which has a vapor pressure of about 10 torr at room temperature that is sufficient for feeding of the ECR source with working substance. The natural TiCl_4 (5.2 % of ^{50}Ti) was used. The glass ampule with TiCl_4 was connected to the standard

*Work supported by Russian Foundation for Basic Research under grant number 13-02-12011

MODERNIZATION OF THE MVINIS ION SOURCE

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Abstract

The mVINIS Ion Source was designed and constructed jointly by the team of specialists from the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research (JINR), Dubna, and the Laboratory of Physics, Vinča Institute of Nuclear Sciences, Belgrade. It was commissioned in 1998. From that time, it has been widely used in the field of modification of materials with different kinds of multiply charged ions. Recently, we decided to modernize this electron cyclotron resonance (ECR) ion source in order to improve its operation capability. Our main goal was to enhance the basic construction of the source in order to improve the production of multiply charged ion beams from gaseous and solid elements. We changed the shape of the plasma chamber and consequently reconstructed the magnetic structure. Also, we improved the construction of the injection chamber. Besides, we decided to refurbish its major components that have been in operation for quite a long time (the vacuum pumps, microwave generator, control system etc.). These improvements have resulted in a substantial increasing of the ion beam intensities, especially in the case of high charge state ions.

INTRODUCTION

The mVINIS Ion Source was designed and constructed jointly by the team of specialists from JINR, Dubna, and the Vinča Institute, Belgrade. This is a CAPRICE type ECR ion source [1], where the axial confinement of plasma is obtained by two solenoid coils with an iron yoke. The cone-shaped rings around the plasma chamber are used to increase the axial magnetic field peaks and fix their positions. The radial confinement of plasma is performed by a NdFeB permanent hexapole magnet with the Halbach type structure. The operating frequency of the source is 14.5 GHz. A detailed description of the components and performances of mVINIS have been published elsewhere [2, 3]. It was commissioned in 1998. From that time, it has been widely used in the field of modification of materials with different kinds of multiply charged ions. During the 15 years of operation, we have noticed some disadvantages, which are listed below.

- The use of the microwave coupling system having the standard waveguide connected with a coaxial line through a non-regular element (the injection cube) causes big losses of the microwave power. As a result, we have a strong heating on the injection side of the source and an

uncontrolled outgasing. A special tuning mechanism for the coupling system is also required.

- The manufacturing of the water cooled plasma chamber is complicated and expensive (the variable diameter double-wall chamber requires the welding of parts made of copper and stainless steel).
- There is no room to install some additional elements inside the chamber because the injection part of the chamber is used as a coaxial waveguide.
- The only place to introduce a micro-oven to evaporate solid substance is the internal conductor of the coaxial line. It is also used as a bias electrode and has to be insulated from the plasma chamber. As a result, the oven power supply should be also insulated. The size of the oven is strongly restricted by the diameter of the internal conductor of the coaxial line.
- The position of the micro-oven is exactly on the axis of the ion source. The interaction of the oven with plasma causes an additional oven heating. As a result, the oven temperature depends on the source regime. In order to minimize this effect, the fine tuning mechanism is required to define the optimal position of the oven.

MODERNIZATION OF THE ECR ION SOURCE

We decided to enhance the basic construction of the ECR ion source in order to solve the above mentioned disadvantages and improve the production of multiply charged ion beams from gaseous and solid elements. We changed the shape of the plasma chamber and consequently reconstructed the magnetic structure. Also, we improved the construction of the injection chamber.

First of all, we made a decision to increase the internal diameter of the plasma chamber from 64 mm to 74 mm to provide enough room for the installation of all the required elements. As a consequence, this should also increase the plasma volume and ion lifetime, which will enable one to obtain higher charge state ion beams and higher beam intensities. Such a reconstruction required some changes in the magnetic structure and introduction of a completely new injection chamber.

LEGIS FACILITY FOR STUDY OF REACTOR STEELS RADIATION RESISTANCE

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Abstract

Considerable efforts have been drawn to adapt heavy ion beams imitation experiments for investigation of radiation stability of materials in nuclear industry, mainly structural materials - steels. Formation of defect structure in the steel using the neutron flow from the nuclear reactors is fraught with many difficulties such as a long-term session of exposure and induced radioactivity in the irradiated samples. Heavy ions instead could provide a versatile tool to induce a precise damage in material under controlled condition. The LEGnaro ECR Ion Source (LEGIS) installed on a high voltage platform (up to 300 kV) allows for the unique possibility of a program for reactor steels investigation by several heavy ion beams. The sample irradiation up to hundreds of dpa (displacement-per-atom) in less than an operation day can be provided by beams of different ions ranging from hydrogen to the iron with different energies. The investigation program and details of experimental facility are presented and discussed in the following.

INTRODUCTION

Nowaday, due to the active development of nuclear power engineering, an actual issue is the investigation of new structural materials for the active zone of nuclear reactors. The exploitation properties degradation of reactor materials is mainly initiated by local structure faults that appear under the influence of high energy particles. Microstructure alterations in materials can be observed both at the grain scale and at the atomic level. Examples of negative macroscopic consequences of these processes are irradiation swelling, embrittlement, irradiation induced growth, and a number of other changes in material properties (see, for instance, [1, 2]).

To characterize structural materials and evaluate their residual operation period, accumulation of corresponding damaging doses under conditions close to real ones is required. It takes too much time and it is not always justified. For example, the accumulation of a dose of ~100 dpa (displacement-per-atom) upon neutron irradiation is achieved for several years even in fast fission reactors. An accelerator-based neutron source is under developing in framework of IFMIF project. It aims at constructing quite an intense (about 10^{17} s^{-1}) 14 MeV neutron source facility, in order to test materials which are foreseen to be employed, as critical components in the future fusion reactors. But even after the IFMIF facility starts operation the test procedure will take significant amount of time and, besides, neutron irradiation leads to a

high induced radiation activity of materials, which significantly complicates further investigations.

In structural materials for nuclear reactors, radiation defects are formed, first of all, due to elastic collisions with neutrons. They are generated non uniformly, in cascades of atom-atom collisions.. A neutron with energy of 1 MeV transfers about 70 keV to a primary knocked on atom (PKA) of iron, which is the main chemical element of steels. It is assumed that a PKA with an energy more than 50 keV creates subcascades with an average energy of about 20–30 keV. Low energy ions can simulate PKAs similar to those formed upon neutron reactor irradiation and, correspondently, can simulate cascades that are typical of neutron irradiation. Therefore, over a long period of time, there have been developed methods of express analysis of materials (imitation experiments) with the use of ion beams [3–10].

The LEGnaro ECR Ion Source (LEGIS) installed on a 300 kV High Voltage Platform (HVP) enables the allows for the possibility of a program for reactor steels investigation by several heavy ion beams. The sample irradiation up to hundreds of dpa in less than an operation day can be provided by beams of different ions ranging from hydrogen to the iron with different energies. The continuous beam generated by an ECR source provides many advantages for the imitation experiments. First of all it allows controlling the heating of the samples. Therefore the temperature dependence for irradiation swelling and embrittlement can be investigated in temperature range typical for fusion and fission reactors. Since beams from an ECR can be widely varied in intensities, in addition to investigation of defect generation dependence on the dose, the investigation of the dose accumulation velocity that influence on the defect generation can be carried out as well. Even if it is impossible now to provide at the existing lay-out the simultaneous irradiation of samples by two beams (iron and hydrogen or helium), it is possible to provide mix irradiation by those beams just by selecting the different ion by means of a bending dipole without stopping the ECR operation.

Therefore the developing of imitation experiments with the LEGIS source at LNL provides the good experimental base for material radiation resistance investigation. Those investigations, which are under developing in collaboration with ITEP and MEPhI (Moscow) will be the first step (so called express-analysis) for materials developed for future reactors before their tests at the IFMIF-EVEDA facility.

The experimental lay-out including the target assembly as well as the beam dynamics simulation throughout of

ISBN 978-3-95450-158-8

A MICROWAVE ION SOURCE FOR PULSED PROTON BEAM PRODUCTION AT ESS-BILBAO

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Abstract

Ion Source Hydrogen Positive (ISHP) is a microwave discharge installed at ESS Bilbao in Spain. This source will be employed in future application of high proton current in the field of research projects and for industrial processes. ISHP produces over 30 mA of pulsed proton beam by operating at 2.7 GHz. The magnetic field is produced by two independently movable coil pair and the extraction system is composed of a plasma electrode at high voltage platform potential, two ground electrodes and a negatively biased screening electrode inserted between the ground electrodes. The last three electrodes are contained in the extraction column, and can be moved as a group by stepper motors, to change the distance between the plasma electrode and first ground electrode. Measurements with different extraction system setups will be described to show the improvement of the beam intensity and beam emittance.

INTRODUCTION

The microwave discharge ion sources for proton production are widely employed in many areas of the research and for a growing number of industrial application, because they have many advantages in terms of compactness, high reliability, reproducibility, and low maintenance. These sources are used to work at low frequency and they require only an axial magnetic field distribution in order to dissociate the H_2 molecules and to produce high proton beams. At ESS Bilbao there is a very versatile proton source, ISHP that is able to support a wide variety of experiment. In fact the source can work for different values of duty cycle and for each configuration it's possible to optimize the magnetic confinement by changing the solenoid position and coils current. Moreover it's possible to change the distance between the plasma electrode and the puller electrode, adapting the beam dynamics with the extraction voltage and plasma conditions.

PROTON SOURCE

ISHP is composed by a water-cooled, cylindrical plasma chamber, made of copper 97 mm in length and 80 mm in diameter. A RF generator produces continuous or pulsed signal at the resonant frequency of 2.7 GHz, the microwaves, then, are amplified by a 2 kW, S-band satellite communications Klystron. The RF chain is, also, composed of a circulator with a water load to protect the klystron from excessive

reflected power, a triple stub tuner placed between two directional couplers, is used to match plasma impedance with that of the waveguide. The tuner is composed of three rods that can penetrate inside the waveguide allowing to match the plasma load to impedance of the power transmitter system to transfer the maximum power [1, 2]. The microwave line also comprises a quartz RF window acting as a vacuum seal, a E-plane bend and a coupler, that is a double ridge stepped waveguide transition. The last one is a matching transformer which couples the rectangular waveguide to the plasma chamber and concentrates the electromagnetic field increasing plasma density [3].

The extraction system is composed of a plasma electrode at high voltage platform potential, two ground electrodes, and a negatively biased screening electrode (repeller) inserted between the ground electrodes. The last three electrodes are contained in the extraction column, and can be moved as a group by stepper motors, to change the distance between the plasma electrode and first ground electrode. In this way it can be possible to optimize the beam focusing for different experimental set-ups in terms of extraction voltage, plasma parameters, and beam current. The plasma electrode has 7.5 mm diameter aperture, and is made of copper plated pure iron. The ion source, the microwave line, and their complementary components are installed on a 75 kV high voltage platform.



Figure 1: Layout of ISHP source: the klystron, the RF chain and components, and the plasma chamber are installed on a high voltage platform.

Magnetic System

At 2.7 GHz the resonant field (B_{ECR}) is 0.964 T. The B_{ECR} is provided by two movable solenoids, shown in fig-

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METALLIC BEAM DEVELOPMENT WITH AN ECR ION SOURCE AT MICHIGAN STATE UNIVERSITY (MSU)*

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Abstract

Electron Cyclotron Resonance (ECR) ion sources have been used at MSU to provide metal ion beams to the coupled cyclotron facility (CCF), and in the future, for The Facility for Rare Isotope Beams (FRIB). The challenges of metallic beam production with ECR are in production, efficiency, stability and contamination. Future facilities such as FRIB will add the challenge of intensity. We report development of two rare earth metals and the conversion from the oxidized state into metal. The enriched isotopes of ¹⁴⁴Sm, and ¹⁷⁶Yb are commonly available in the sesquioxide form which is unsuitable for use in our standard ovens. We report here results from the off-line chemical reduction of samarium, and ytterbium oxides into metal. We were able to demonstrate efficiencies of up to 90% throughout the conversion process. The samples were then run on our ECR ion sources to confirm the products of the reduction. In addition we report the development of cadmium metal by passing vapor through over 3/4 m of heated stainless steel tubing and observed 4.3 eμA of Cd²⁰⁺ with an average consumption of 1 mg/hr.

INTRODUCTION

The Coupled Cyclotron Facility (CCF) at Michigan State University provides the nuclear science community with beams of rare isotopes produced by fast fragmentation. All rare isotopes produced through CCF operation have been obtained from about 30 primary beams (from Oxygen to Uranium) accelerated to an energy range of 80 to 160 MeV/u. To enhance the yield of rare isotopes, the primary beam is generally a separated isotope with either the largest or the smallest neutron excess available. So far the primary beam list has never included rare earth elements. Specifically of interest for the nuclear science community are ¹⁴⁴Sm, and ¹⁷⁶Yb, for good production of proton rich and neutron rich elements respectively. Initial production of the ion beam is done using an ECR ion source. Normal operation of an ECR relies on feeding the plasma with the vapor of the element to be ionized. A practical problem with rare earth elements is that they are naturally found in an oxidized form that would require extremely high temperature to reach a decent vapor pressure (range of 10⁻² to 10⁻³ mbar) for operation with an ECR. Therefore, we need to efficiently convert the available rare earth oxide into metal before using them with an ECR ion source.

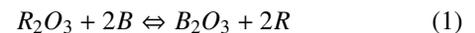
* This work was supported by Michigan State University and the National Science Foundation: NSF Award Number PHY-1102511.

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Also of interest are primary beams of ⁸²Se, ¹⁰⁶Cd, and ²⁰⁴Hg. Due to the relatively high volatility of these metals [1], it may be possible to control the flow of vapor into our plasma chamber with a simple setup that positions the sample outside the ion source and uses a variable leak valve and a heated transfer line to transmit the vapor to the plasma chamber. This was demonstrated recently in the case of mercury [2] where transfer of the vapor to the chamber and ionization by the ECR plasma lasted for about 150 hours.

CHEMICAL REDUCTION OF RARE EARTH SESQUIOXIDES

The chemical separation of metal oxides were investigated for the purpose of reducing calcium carbonate and calcium oxide (quicklime) into metal, and our procedure for the chemical conversion of the rare earth oxides is largely based on techniques developed for the benefit of the experimental program at NSCL. The rare earth metals (including scandium and yttrium) will readily oxidize into the sesquioxide, R₂O₃ [3], wherein R represents a rare earth element. The process to convert from the sesquioxide of samarium and ytterbium is known [4], and is reversible.



Metal B is the reagent to the reaction, and R is a rare earth metal. The chemical conversion will proceed in both directions if the temperature is sustained and the supply of materials allows. Extraction of a metal from the mixture occurs by diffusion with one metal leaving the mixture at a larger rate than the other. The reagent B is chosen to have a negligible vapor pressure in both elemental and oxide forms at the reaction temperature, to ensure minimal evaporation. According to [4] the oxides of ytterbium and samarium will undergo reactions with lanthanum reagent at 1350 °C and 1200 °C respectively. In the case of ytterbium sesquioxide the reduction-distillation will proceed at a temperature far below the oxide melting point. Furthermore, samarium and ytterbium metals are relatively stable in atmosphere unless heated in excess of 200 °C [5] and allowed for handling of pure metal samples in atmospheric conditions.

Procedure

Our experimental set-up is constructed of two basic parts, the oven which heats the oxide-reagent mixture and collector plates which captures metal vapor diffusing from the oven. The chemical conversions were performed in a vacuum chamber that could reach pressures of about 10⁻⁷ mbar.

IMPROVEMENT OF BEAM INTENSITIES FOR ION BEAMS WITH CHARGE-TO-MASS RATIO OF 1/3 WITH THE TWO-FREQUENCY HEATING TECHNIQUE

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Abstract

In order to increase the beam intensities of ions with a charge-to-mass ratio of about 1/3 like Ar^{13+} and Fe^{18+} from an electron cyclotron resonance ion source (ECRIS), a technique was tested to feed multiple microwaves with different frequencies, the so-called two-frequency heating technique. Our group studied the improvements when the two frequencies are close together each with a power of more than 1kW using an 18GHz ECRIS installed in the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS). The intensities of highly charged ions of C, Ar, Fe and Ni were increased successfully.

basic research in these countries, there are occasionally requirements to produce various other ion species. Since the injector design is fixed for the acceleration of ions with a charge-to-mass ratio of about 1/3, the performance of the Kei-series does not satisfy such requirements. We developed a new compact ECRIS, named Kei3, for ion species between He^+ and Si^{9+} [5]. Kei3 is now under commissioning. However, production of highly charged ions like Ar^{13+} or Fe^{18+} will not be possible with that source. So we tested the ion production with charge-to-mass ratio of 1/3 by an 18GHz room-temperature ECRIS, named NIRS-HEC. In order to improve the intensity, we fed RF power into an ECRIS at two frequencies, the so-called two-frequency heating technique.

INTRODUCTION

Although the best ion species for heavy ion radiotherapy principally depends on the type and location of a tumor, a carbon ion beam was finally chosen at the Heavy Ion Medical Accelerator in Chiba (HIMAC) due to its better biological dose distributions than helium or neon for the typical depth and thickness of a tumor. Presently, seven carbon-ion radiotherapy dedicated facilities are operated worldwide. Four of the seven facilities are located in Japan. For the production of the carbon ions, ECRISs have been developed and utilized because its lifetime is longer than other types of ion sources. The ion sources satisfy medical requirements at each facility[1].

The Gunma University Heavy-ion Medical Centre (GHMC)[2], the Saga Heavy Ion Medical Accelerator in Tosu (SAGA-HIMAT), and the Ion-beam Radiation Oncology Centre in Kanagawa (i-ROCK, under construction), are facilities specific for carbon-ion radiotherapy exclusively. One ECRIS was installed in each facility. Compact ECRISs, named Kei-series, were developed[3] to reduce the size, initial construction cost, and electric power consumption. 'KeiGM', and 'KeiSA', were manufactured with minor modifications of the magnetic configuration and the high voltage insulation. Typically, the ECRIS has to deliver C^{4+} ions at 30 kV extraction voltage with current of at least 200 μA [4]. KeiGM and KeiSA satisfy the requirements. At GHMC were during 20130 hours of operating time three serious failures which interrupted the patient treatment and Saga-HIMAT had no failures during 7200 hours.

Recently, several countries made plans to construct such a carbon-ion radiotherapy facility. However, in order to carry out biological experiments to encourage

TECHNICAL METHOD

18GHz NIRS-HEC ECRIS

In order to extend the range of available ion species for HIMAC, NIRS-HEC was designed to reach a high extraction voltage and a high magnetic field with normal conducting magnets. For the production of intermediate charge-state ions, optimization of the extraction configuration is most effective. The extraction electrode is electrically isolated from the ground and a high voltage power supply on the source potential safely applies the extraction voltage between the plasma electrode and the extraction electrode independent of the source potential. The position of electrode can easily be changed. With these two parameters extraction configuration can be optimised. The maximum voltage between plasma and extraction electrode is 60 kV. The maximum mirror fields at the injection and at the extraction side are 1.3 and 1.2 T, respectively. NIRS-HEC supplied various ion species since 1996[6].

For a carbon-ion radiotherapy facility, NIRS-HEC has some drawbacks. Its initial construction cost is two or three times higher than Kei-series. Electric power consumption is huge. However, due to its vertical beam extraction, the footprint including an analyzing magnet system is not so different from Kei-series shown in Figure 1. In addition, NIRS-HEC has a long lifetime even for 'dirty conditions' like carbon depositions. NIRS-HEC is usually operated over a half year without $\#$ maintenance during which the vacuum chamber is not exposed to atmosphere. All operation parameters are set by a remote control system and are able to restore by a software. The failure rate is also low. These performances are suitable for a medical facility.

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ECR ION SOURCE DEVELOPMENTS AT INFN-LNS

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Abstract

At INFN-LNS, ECRIS development during the '90s permitted to optimize the K-800 Cyclotron performances: SERSE and CAESAR have well supported Nuclear Physics research, since then. For the new needs of the facility, further improvements are required and they are here described. Activities recently started, aimed to the production of multicharged ion beams and to the production of intense light ion beams with different schemes of plasma generation.

Technological developments led the AISHa source design, in order to adapt a high performance ECR ion source to hospital facilities needing multiply charged ion production with high reliability and brightness, easy operations and maintenance. The realization of a proton source, called PS-ESS, and of its LEBT line for the Linac of the European Spallation Source in Sweden is one of the major activities at INFN-LNS. Other developments are ongoing on high charge state and high intensity beam production: a major update is going to be finalized on SERSE cryogenic system and on CAESAR injection side; at Vancouver, the VIS source is used for producing multi-mA beams of H_2^+ for a high-current cyclotron; a new flexible plasma trap is under test for fundamental research about innovative plasma heating methods.

INTRODUCTION

During the '90s different ion sources have been built at INFN-LNS, two for the production of highly charged heavy ions to be accelerated by the K-800 Superconducting Cyclotron [1,2] and one for the high intensity proton beam injector for the TRASCO/ADS projects [3]. The SERSE source have been working for about 15 years, but during the last three years a shortage in the availability of LHe from the main liquefier has blocked its operation for many months per year. The performances of the second source, CAESAR, have been acceptable for the Cyclotron needs, but the fact that it was the only source has made impossible to proceed to further optimization, after that the injection part has been totally redesigned.

In the recent past, the requests have been more and more relevant either in terms of beam current and in terms of highly charged ion beams from metallic samples, so the decision to update the existing hardware to fulfil the new needs and to improve the two sources has been taken and the first steps have been done; the update operations of the SERSE and CAESAR sources will be completed in 2015. The major changes to the SERSE design will concern the cryostat, that will be operated in stand-alone

mode. After this major improvement, a new commissioning phase is to be started, in order to increase the beam current out of the K800 Superconducting Cyclotron. This phase will involve the LEBT revision with the increase of on-line beam diagnostics.

The changes to the CAESAR source are of four types: i) increase of maximum frequency to 18 GHz, ii) update of the control system to decrease the EMI and the related electronics failures, iii) implementation of a compact oven and iv) increase of the injected microwave power.

All these improvements will be even more remarkable if the proposal of the refurbishment of the 20-years-old cyclotron will be funded: in that case the demand of high brightness heavy ion beams will further increase of a factor 10 to 100, in order to support the future studies on double beta decay.

In the meantime, new projects have been started: the AISHa source for hadrontherapy facilities is designed for high brightness multiply charged ion beams with high reliability, easy operations and maintenance.

AISHa has been designed to meet the above cited requirements by means of high field He-free superconducting magnets, while the radial confinement will be provided by a Halbach-type permanent magnet hexapole structure. The source will take profit of all the know-how acquired in the years by the INFN-LNS ion source team. After the prototype, now under construction at INFN-LNS in the frame of a partnership with three Italian SME, a second copy will be built for CNAO and discussion for a third one started.

Another project is going to start as an advanced design study, in the frame of an European collaboration aimed to the construction of a high intensity heavy ion beams accelerator in Huelva, Spain [4]. For this project the design study will be focused on an updated version of AISHa, named ASIA.

On the side of high current proton beams source, following the successful experience of TRIPS and VIS sources, the high intensity proton source named PS-ESS is under construction for the European Spallation Source; it is designed to meet the request of an accelerator chain deemed to produce 2 GeV - 62.5 mA beams, 4% duty cycle. Another activity in this field is the one under way at Best Cyclotron Company, Vancouver, where the VIS source is in use to produce multi-mA beams of H_2^+ for the injection in a high-current cyclotron. Though it is a proof-of-principle experiment, a new customized microwave injection system and plasma chamber for enhanced H_2^+ production has been studied and constructed. The new setup after some off-line tests at INFN-LNS has been moved to Vancouver and in the next month will be tested.

STATUS REPORT OF SECRAL II ION SOURCE DEVELOPMENT *

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Abstract

For a new injector linac project launched at IMP, a superconducting ECR ion source SECRAL II is now under construction. This ion source is a duplicated one of SECRAL I which is operated routinely for HIRFL facility at the frequency of 18-24 GHz. SECRAL II is designed to be operated at the frequency of 28 GHz, which needs slightly higher radial field at the plasma chamber wall. The fabrication of the cold mass was started at early 2013, and it has been completed in May 2014. The engineering design of the whole superconducting magnet has also been finished and ready for fabrication. After a brief introduction of the recent results obtained with SECRAL I ion source, this paper will present the cold mass test results and the cryogenic system design of SECRAL II magnet. The test bench design will be also discussed.

INTRODUCTION

As an indispensable machine to provide intense highly charged ion beams, ECR ion sources have been used as the ion beam injectors at IMP for over 20 years. At IMP, the national laboratory accelerator facility is HIRFL (Heavy Ion Research Facility in Lanzhou) as shown in Fig. 1, which is mainly composed of one K69 cyclotron SFC, one K450 cyclotron SSC, RIBLL1 for radioactive beam production, cooler storage rings CSRm and CSRe, and the radioactive beam line RIBLL2 to connect the two rings [1, 2]. The HIRFL facility can work with several schemes for experimental researches. The 50 years old K69 cyclotron can work standalone for nuclear, atomic physics and material research purposes with the beam species from H to U. When the K69 and K450 cyclotron work with a coupling scheme, the HIRFL facility can deliver tens of MeV/u CW heavy ion beams. For the operation of HIRFL-CSR, two injection schemes are now available: one is the direct injection of high Q/M heavy ion beam from SFC with the energy of several MeV/u, and the other one is the injection of the beam delivered by SFC + SSC working with a coupling mode. When utilizing the standalone injection scheme with SFC, it is very hard to deliver sufficiently high current with the necessary beam energy, especially in terms of high Z ion beams. By utilizing the coupling scheme of SFC + SSC to do beam injection for CSRm, beam energy is guaranteed, but as a cause of very low coupling efficiency between the cyclotrons, the output beam intensity is far below the injection needs of CSRm, especially for the very heavy

ion beams such as Bi, U, and etc. The HIRFL-CSRm is designed to be able to accumulate and accelerate very heavy ion beam such as U with the beam intensity of several 10^9 ppp, which is about 2 orders higher than the present performance. The barrier is the non-optimal injection scheme. A project proposal has been recently issued to build a dedicated injection linac injector for CSRm so as to boost the performance by ~ 2 orders for heavy ion beams. For this injector linac (called CSR-Linac), a high performance state of the art ECR ion source is needed to provide the needed intense high Q/M heavy ion beams. SECRAL II project is therefore initiated.

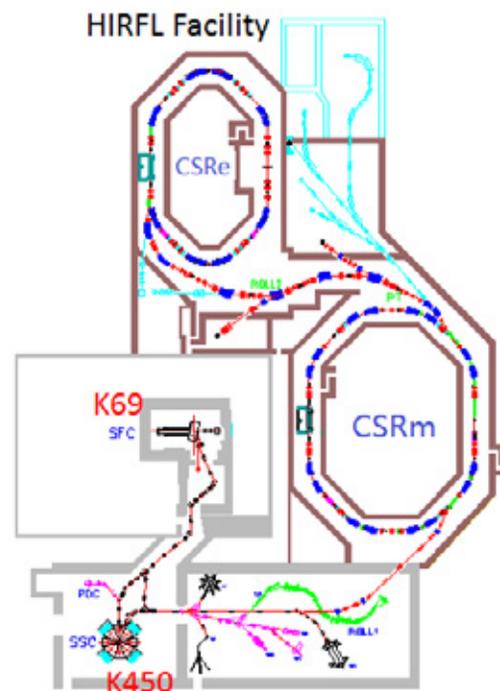


Figure 1: Layout of HIRFL facility.

SECRAL I was connected to the injection line of HIRFL complex in 2007 and had been in service for more than 17,000 hours for routine operation. It has been the main working horse for the facility, especially in terms of very heavy ion beams operation. In case of any severe problem with the ion source, HIRFL facility would lose most of its performance and capacity. As a contingency plan, SECRAL II project was proposed. Combined with the CSR-Linac project, SECRAL II project serves a dual purpose.

*Work supported by the 100 Talents Program of the CAS (No. Y214160BR0), NSF (contract No. 11221064) and MOST (contract No. 2014CB845500).
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HIISI, NEW 18 GHZ ECRIS FOR THE JYFL ACCELERATOR LABORATORY*

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Abstract

At the end of 2013 the Academy of Finland granted an infrastructure funding for the JYFL Accelerator Laboratory in order to increase beam intensities for the international user community. The primary objective is to construct a new high performance ECR ion source, HIISI (Heavy Ion Ion Source Injector), for the K130 cyclotron. Using room temperature magnets the HIISI has been designed to produce about the same magnetic field configuration as the superconducting ECRIS SUSI at NSCL/MSU for 18 GHz operation. An innovative structure will be used to maximize the radial confinement and demagnetization safety margin of the permanent magnets. The sextupole magnet is separated and insulated from the plasma chamber providing two advantages: 1) the permanent magnet can be cooled down to -10°C to increase its coercivity and 2) at the same time to reach slightly higher radial field on the inner surface of the plasma chamber. Comprehensive simulations were performed with the radial heat load to analyse and address all the heat loads and temperature distribution on the permanent magnet. This information is crucial to define the maximum plasma heating power and the grade of the permanent magnets. In this article the magnetic field design of HIISI and detailed innovative scheme for sextupole magnet will be presented.

INTRODUCTION

Figure 1 shows the xenon ion beam intensities produced by high performance ECR ion sources. GTS [1], operating at 18 GHz frequency, is the best performing ECR ion source using room temperature magnets (resistive coils and permanent magnet sextupole), while VENUS [2] and SUSI [3] are fully superconducting ECR ion sources. The same performance level has also been achieved by fully superconducting SECRAL [4]. Although the great performance of superconducting ion sources meets and exceeds our goals, their construction costs greatly exceeds the available funding for the new

JYFL ECR ion source leading to the choice of a room-temperature magnet ECRIS.

From the ion source performance point of view the most challenging requirement for HIISI is the production of highly charged heavy ion beams. For example, an intensity of about 10 nA for Xe^{44+} ion beam is needed to guarantee the requested beam energy and particle flux after the K130 cyclotron. This requirement is shown in Figure 1 by a red circle, which is beyond the performance of any present room-temperature magnet ECR ion source. The development of this new ECR ion source HIISI will enhance the high quality nuclear physics research at JYFL and potential for exciting discoveries in the future.

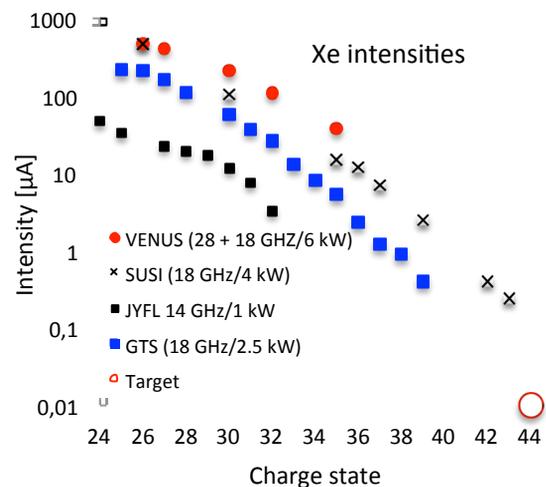


Figure 1: Intensities of Xe ion beams produced by different ECR ion sources. The red circle indicates the beam intensity of Xe^{44+} ion beam to be produced with the new ECRIS operated at 18 GHz.

MAGNETIC FIELD STRUCTURE

As Figure 1 shows, the performance of SUSI exceeds the desired intensity of Xe^{44+} ion beam when operated at 18 GHz with the microwave power of 4 kW. The magnetic field configuration of SUSI for the production of Ar^{12+} and Xe^{35+} ion beams are listed in Table 1 indicating that the intensive highly-charged ion beams can be produced with the magnetic field strengths in the range of: 2.5 – 2.8 T (B_{inj}), 1.2 – 1.5 T (B_{ext}), 1.1 – 1.35 T (B_{rad}) and about 0.45 T (B_{min}). All these field strengths agree well with the empirical source design criteria [5]. The

ISBN 978-3-95450-158-8

* This work has been supported by the EU 7th framework programme Integrating Activities - Transnational Access, project number: 262010 (ENSAR), the Academy of Finland under the Finnish Centre of Excellence Programme 2012- 2017 (Nuclear and Accelerator Based Physics Research at JYFL) and under the Finnish Research Infrastructure (FIRI) Programme of the Academy of Finland.
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THE INSTALLATION OF THE 28GHZ SUPERCONDUCTING ECR ION SOURCE AT KBSI

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Abstract

In 2009, a 28 GHz superconducting electron cyclotron resonance (ECR) ion source was developed to produce high currents, diverse heavy ion charge state for the compact heavy ion linear accelerator at KBSI (Korea Basic Science Institute). The aim of this study was to generate a high current, and fast neutrons for interacting a heavy ion with the proton target. The fabrication of the key parts, which are the superconducting magnet system with the liquid helium re-condensed cryostat, the 10 kW high-power microwave considering for optimum operation at the 28 GHz ECR Ion Source, were completed in 2013. The waveguide components were connected with a plasma chamber including a gas supply system. The plasma chamber and ion beam extraction were inserted into the warm bore of superconducting magnet. In this paper, we present the current status of the installation of an ECR ion source and report on the test results for ECR plasma ignition.

INTRODUCTION

The compact linear accelerator employing the 28 GHz ECR ion source was developed at KBSI [1]. The practical purpose of the KBSI accelerator is to produce fast neutrons for the high-resolution radiography technology. We have been fabricating a 28 GHz superconducting ECR ion source to deliver high intensity beams of highly charged heavy ions into the radio frequency quadrupole

(RFQ) and the drift tube linear accelerator (DTL). To fulfill this target, accelerated ${}^7\text{Li}$ ions need to interact with a hydrogen gas jet at an energy of a few MeV/u, which then generate high-intensity fast neutrons at forward angles. The 28 GHz superconducting ECR ion source was developed in 2009. The design of each component of the ECR ion source was completed in 2010. The individual components were assembled in 2011. Very recently, a 28 GHz superconducting ECR ion source has been installed, as shown in Figure 1. In this article, we present information regarding the components required for the ion source in details, and the experimental setup for the first plasma ignition.

THE SUPERCONDUCTING MAGNETS

The superconducting magnet system is comprised of 3 mirror solenoid coils and a hexapole magnet [2, 3]. The inside diameters of the hexapole magnet and solenoid coils are 207 mm and 442 mm, respectively. Two kinds NbTi superconducting wire was used for the magnet system. A higher current density NbTi wire was selected for the winding of hexapole magnet, respectively. The copper/NbTi ratios were 4.9 for the solenoid coils and 2.32 for the hexapole magnet. The superconducting magnets have an operating margin of about 30% away from the critical current, according to the design values. Figure 2 shows a schematic drawing of the superconducting magnet system.

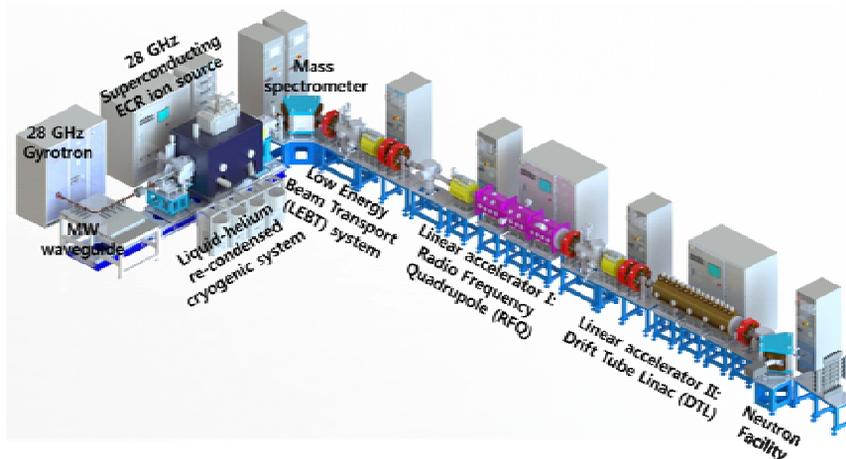


Figure 1: Schematic view of the heavy ion accelerator with the 28 GHz superconducting ECR ion source.

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ISBN 978-3-95450-158-8

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Status reports and new developments

FIRST COMMISSIONING RESULTS OF AN EVAPORATIVE COOLING MAGNET ECRIS-LECR4*

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Abstract

LECR4 (Lanzhou ECR ion source No.4) is a room temperature ECR ion source, designed to produce high current, multiple charge state ion beams for SSC-LINAC project at IMP. The ion source has been optimized to be operated at 18 GHz. A unique feature of LECR4 is that all of its axial solenoid coils are fully immersed in a special coolant and cooled by evaporative cooling technology when excited. At design currents, the coils can produce peak mirror fields on axis 2.5 Tesla at injection, 1.3 Tesla at extraction and 0.5 Tesla at minimum-B. The nominal radial magnetic field is 1.0-1.1 Tesla at plasma chamber wall, which is produced by a Halbach structure 36-segmental hexapole magnet. Recently, the project has made significant progress. In January 2014, the first plasma at 18 GHz was ignited. During the ongoing commissioning phase with a stainless steel chamber, tests with ion beams: Oxygen, Argon, Xenon and Bismuth have been conducted. Some intense ion beams have been produced with microwave power less than 1.6 kW, such as 1.97 emA of O⁶⁺, 1.7 emA of Ar⁸⁺, 1.07 emA of Ar⁹⁺, 290 euA of Xe²⁰⁺ and so on.

INTRODUCTION

A room temperature ECR ion source named LECR4 (Lanzhou ECR ion source no.4) was designed and built at Institute of Modern Physics (IMP) to meet the demand of intense multiple charge state ion beams for SSC-LINAC project [1]. The other purpose of the LECR4 project is to test an evaporative cooling technology for its application to accelerator magnet. SSC-LINAC is a new CW heavy ion LINAC used as the injector for the Separated Sector Cyclotron (SSC) at IMP. The SSC-LINAC consists of an ECR ion source, low energy beam transport (LEBT), a 4-rod RFQ, medium energy beam transport (MEBT) and IH-DTL, as shown in Figure 1. The required ion species are from Carbon to Uranium. According to the demand, traditional room temperature ECR ion sources with operation microwave frequency 14- 18 GHz were considered. According to Prof. Geller's famous scaling laws, we know that higher magnetic fields and higher frequencies will increase the performance of ECR ion source. Following these guidelines, many high performance room temperature ECR ion sources like AECR-U [2], RIKEN 18 GHz [3], IMP-LECR3 [4] and GTS [5] have been built. All these ECR ion sources need high pressure de-ionized water

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

system to cool the high current axial mirror field magnet coils. Recently, with advances in evaporative cooling technology at Institute of Electrical Engineering of Chinese Academy of Science (IEE, CAS) [6], a de-ionized water free room temperature ECR ion source with new cooling technology is possible. IEE institute has been researching the evaporative cooling technology since 1958. Up to now, this technology has been applied in many high-power, high current density devices, such as Three Gorges Power Station. According to careful simulation and prototype experiments [7], the final design of ECR ion source (named LECR4) was completed in 2012. About one year later, the source body assembly was fabricated at IMP. In October 2013 the axial magnet reached 100% of the design fields. The first beam of LECR4 was extracted and analyzed in February 2014. The ion source commissioning of intense multiple charge state ion beams was performed from February 2014 to July 2014. The first test with RFQ was performed on 4th April 2014. The preliminary results will be presented in this paper.

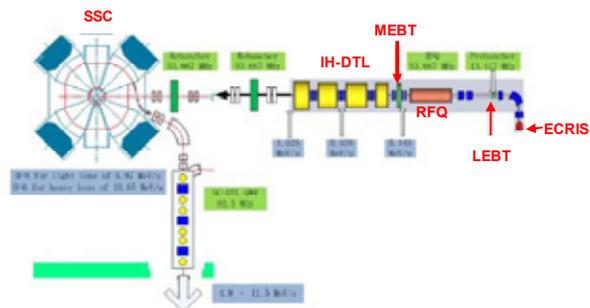


Figure 1: General view of the SSC_Linac.

LECR4 ION SOURCE

Figure 2 shows the layout of LECR4 and its beam transport line. There is no vacuum pump at the injection side for simplicity. The detail design of LECR4 ECR ion source can be found in the reference paper [8]. The features of LECR4 are following:

- LECR4 is the first ECR ion source using evaporative cooling technology in the world. All the coils are fully immersed in a special coolant, named ZXB-21. Its boiling temperature is 47.7 degree in a standard atmospheric pressure. Solid square copper wires (3.32 mm×5.77 mm with insulation) are used to wind the solenoid coils. The maximum exciting current is 300 A, that means an average current density about 12 A/mm², slightly higher than using

DEVELOPMENT OF THE MAGNETIC SYSTEM FOR NEW DECRIS-PM ION SOURCE

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Abstract

Super-heavy-element factory is under development at the Flerov Laboratory for Nuclear Reactions, JINR, Dubna. The factory will include DC-280 cyclotron, which will be equipped with two 100 kV high voltage platforms. All-permanent magnet ECRIS will be installed on one of the platforms. The request for the source is a production of medium mass ions with $A/q=4\div7.5$ such as $^{48}\text{Ca}^{8+}$. Results of the detailed design of a magnetic structure for DECRIS-PM will be presented.

INTRODUCTION

One of the basic scientific programs which are carried out at the FLNR is a synthesis of new elements requiring intensive beams of heavy ions. To enhance the efficiency of experiments for next few years it is necessary to obtain accelerated ion beams with the following parameters:

Ion energy	4÷8 MeV/n
Ion masses	10÷238
Beam intensity (up to A=50)	10 μA
Beam emittance	≤ 30 π mm×mrad
Efficiency of beam transfer	> 50%

These parameters have formed the base for the new cyclotron DC-280 [1]. The basic design features of the DC-280 cyclotron project are shown in Table 1.

Table 1: DC-280 Cyclotron - Basic Technical Parameters

Parameter DC280	Goals
High energy of the injected beam (up to 100 kV)	Shift of the space charge limits by a factor of 30
Large gap in a centre	Space for a long spiral inflector
Low magnetic field	Large starting radius. Good orbit separation. Low deflector voltage
High acceleration rate	Good orbit separation.
Flat-top system	Effective capture. Single orbit extraction. Beam quality.

The axial injection system of the DC-280 cyclotron will include two high voltage platforms which will allow for efficient injection of ions from helium to uranium with an atomic mass to charge ratio in the range of 4÷7. Each HV-platform will be equipped with the low power consuming ECR ion source. For production of ions with the medium masses (from He to Kr) the all permanent magnet (PM)

ECR ion source will be used. In this paper we report the design of the magnetic system of the new DECRIS-PM ion source.

MAGNETIC STRUCTURE DESIGN

Many good performance all-permanent magnet ECRISs have been built around the world: NANOGAN series [2], BIE series [3], LAPECR2 [4] and others. The main advantages of all permanent magnet ECRISs are low power consumption, low pressure in the cooling water system, simplified operation, etc. However there are few significant drawbacks of all permanent magnet ECRISs. First of them is the fixed distribution of the magnetic field and comparatively low field strength. Thus, the designed magnetic configuration should be optimized for the desired operation mode from the very beginning. Another drawback is strong mechanical force acting on the individual parts of the system. As a result the correction of the magnetic field after the assembly of the magnetic system is practically impossible without the degaussing of it.

Some deviations from the required field distribution can occur for many reasons. The magnetic material itself has scatter in parameters of up to 5%. Furthermore, the magnetic rings that form the axial magnetic field consist of several blocks. In calculations of the magnetic field it is almost impossible to take into account the influence of gaps between individual blocks. Fig. 1 illustrates this problem. The figure shows the distribution of the magnetic field in front of one of the hexapole poles which is made of five blocks of identical magnetic material. With the gaps of about 0.1 mm the oscillations in the magnetic field measured at a distance of 3 mm from the pole are around 10%.

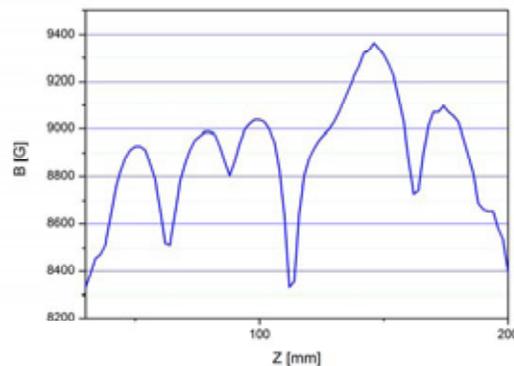


Figure 1: Measured magnetic field distribution along the hexapole pole.

THERMAL DESIGN OF REFRIDGERATED HEXAPOLE 18 GHZ ECRIS HIISI

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Abstract

A project is underway for constructing a new 18 GHz ECR ion source HIISI at University of Jyväskylä. An innovative plasma chamber structure with grooves at magnetic poles for larger chamber radius at poles. The hexapole will be reffridgerated to sub-zero temperatures to boost the coercivity and the remanence of the permanent magnet material and to allow the use of high remanence, low intrinsic coersivity permanent magnet materials. The hexapole structure is insulated from high temperature solenoid coils and plasma chamber by vacuum. The thermal design of the structure has been made using a thermal diffusion code taking in account radiative, conductive and convective heat transfer processes. The heat flux distribution from plasma has been estimated using electron trajectory simulations. The electron simulations are verified by comparing the distribution to plasma chamber patterns from 14 GHz ECR. Thermal design efforts are presented together with an analysis of the demagnetizing H-field in the permanent magnets.

INTRODUCTION

A project is underway for constructing a new 18 GHz ECR ion source HIISI at the University of Jyväskylä. The minimum-B magnetic field configuration is created by normally-conducting solenoid coils and permanent magnet 24-segment Halbach-array hexapole. See figure 1 for a schematic presentation of the ion source and the magnetic field. An innovative plasma chamber structure with grooves at magnetic poles is being studied [1]. This allows large chamber radius at the poles, leading to the pole field necessary according to the scaling laws while using less permanent magnetic material than a conventional design would. The smaller radius between the poles makes space for chamber water cooling. The hexapole will be reffridgerated to sub-zero temperatures to boost the coercivity and the remanence of the permanent magnet material. The hexapole structure is insulated from high temperature solenoid coils and plasma chamber by vacuum. See figure 2 for a cross section view of the ion source. The overall design of the ion source is presented elsewhere in detail [1], while this paper concentrates on the thermal modelling and engineering choices of the plasma chamber and the reffridgerated hexapole and the analysis of the demagnetizing H-field in the permanent magnet structure.

ELECTRON TRAJECTORY SIMULATIONS

An estimate of the heat flux distribution from the ion source plasma to the plasma chamber wall is needed for

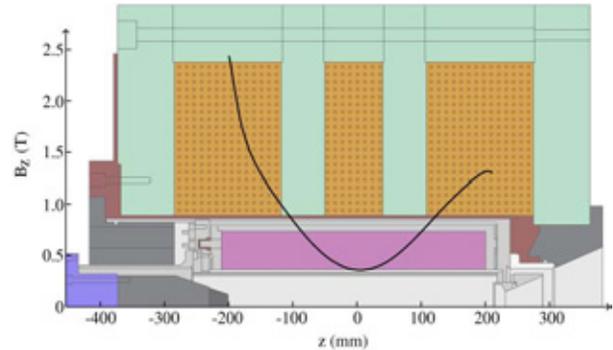


Figure 1: Schematic presentation of the 18 GHz ECRIS HIISI with the axial magnetic field overlaid.

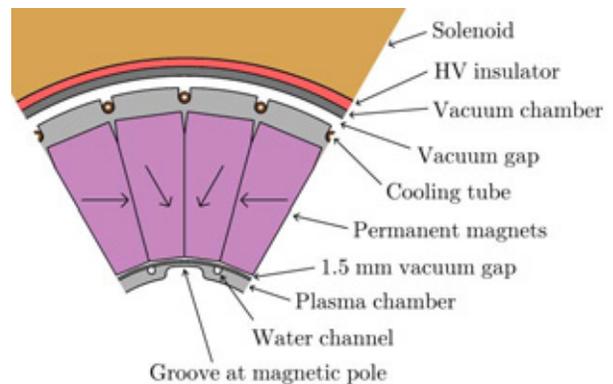


Figure 2: Cross section of the 18 GHz HIISI showing part of the reffridgerated 24-segment Halbach permanent magnet hexapole and the vacuum gaps insulating it from the plasma chamber and the solenoid coils. The plasma chamber is grooved to increase the radius at the pole.

credible thermal studies of the plasma chamber and the permanent magnets. A computer code was devised for this purpose. The code tracks single electron trajectories in the ion source magnetic field using relativistic energy-conserving leapfrog-type Boris algorithm [2]. Electric fields and plasma processes are not considered. The particles are launched isotropically from random locations full-filling the condition $B < B_{\text{ecr}}$, where B_{ecr} is the resonance field for relativistic electrons with kinetic energy E . Thus, the simulated trajectories can be thought to represent electron trajectories after a collision process in the plasma. If the particle is in the loss-cone it will escape the magnetic bottle in a finite time and contribute to the heat flux on the plasma chamber. Otherwise it will remain confined in the plasma.

EXPERIMENTAL ACTIVITIES WITH THE LPSC CHARGE BREEDER IN THE EUROPEAN CONTEXT*

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Abstract

One of the Work Packages of the "Enhanced Multi-Ionization of short-Lived Isotopes at EURISOL" NuPNET project focuses on the ECR charge breeding. The LPSC charge breeder is used for experimental studies in order to better understand the fundamental processes involved in the 1+ beam capture by a 14 GHz ECR plasma. Some improvements, like symmetrisation of the magnetic field at the injection side and higher pumping speed, have been carried out on the PHOENIX charge breeder. The impact of these modifications on the efficiencies and charge breeding times are presented. In the same time, the new LPSC 1+ source developments performed in order to ease the efficiency measurements with various elements are presented.

CONTEXT

In Europe, several high energy radioactive ion beams (RIB's) facilities are under design, construction, or upgrade. At CERN (Geneva, Switzerland), the HIE-ISOLDE project (which uses an EBIS as a charge breeder) has the objectives to increase the energy and the beam intensity of the REX-ISOLDE facility by 2017 [1]. At GANIL (Caen, France), the SPIRAL2 phase2 aiming to produce high energy intense RIB's has been stopped for the moment; however, an upgrade of the SPIRAL1 facility will allow the delivery of new light condensable elements, by 2016, using a modified PHOENIX ECRIS charge breeder whose initial version was developed at LPSC [2].

At the 'Laboratori Nazionali di Legnaro' (Legnaro, Italy) of the Istituto Nazionale di Fisica Nucleare (INFN), the SPES facility (Selective Production of Exotic Species) [3] is under construction; its completion is foreseen in 2017. It will deliver mainly heavy radioactive ions up to an energy of 11 MeV/u, and will be equipped with a LPSC PHOENIX ECRIS charge breeder [4].

For long term science with accelerated radioactive ion beams, the EURISOL project aims to produce high intensities (10 to 100 times higher than the present facilities under construction) and should be equipped with an EBIS and an ECRIS charge breeder. ECR charge

breeders with their high intensity acceptance, their fully cw or pulsed operation, are suitable to increase the charge state of the monocharged radioactive ions, as a beam line component located far from the highly radioactive environment of the production targets. LPSC, where ECR charge breeding has been first developed, has taken the responsibility of the design, the construction, and of the experimental qualification of European charge breeders.

Within the same time, the laboratories, authors of this publication, have gathered their research and development activities related to charge breeding in a collective project named 'Enhanced Multi-Ionization of short-Lived Isotopes at EURISOL (EMILIE)', funded by the European Research Activities - NETWORK for Nuclear Physics Infrastructures (NuPNET).

LPSC ACTIVITIES RELATED TO ECRIS CHARGE BREEDERS

SPIRAL2

A detailed mechanical design of the ECR charge breeder has been performed including the modifications studied at LPSC (for example, the suppression of the grounded tube for the slowing down of the 1+ beam). The definition of the operating conditions have been characterized on the LPSC test bench allowing the highest efficiencies maintaining a short charge breeding time (typically 10 ms per charge). The radioactive environment has been taken into account by optimizing the troubleshooting procedures of contaminated parts, allowing to respect the "As Low As Reasonably Achievable" principle. For the moment the SPIRAL2 phase 2 project has been suspended, so the LPSC charge breeding activities for this project, too.

SPIRAL1 Upgrade

The SPIRAL1 facility, after its upgrade including a modified ECR PHOENIX charge breeder, will have to deliver new light condensable radioactive elements. In this context, we have performed experiments with the original charge breeder to compare the charge breeding efficiencies of carbon ions when injecting either $^{13}\text{C}^+$, $^{13}\text{CO}^+$ or $^{13}\text{CO}_2^+$ beams extracted from the miniaturized 2.45 GHz COMIC [5] source (see Fig. 1). The detailed

*Work supported by the ERA-NET NuPNET

INVESTIGATION ON THE ORIGIN OF HIGH ENERGY X-RAYS OBSERVED IN THIRD GENERATION ECRIS

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Abstract

The operation of third generation ECR ion source heated with 24 or 28 GHz microwave frequency shows a high energy x-ray spectrum with a characteristic temperature much higher than the one observed at the usual heating frequencies (14-18 GHz). The behaviour of the x-ray spectrum is studied based on the review of a set of data previously done at LBNL [1]. The data reviewed shows that the hot x-ray temperature scales with the ECR frequency. The experimental data is compared with the prediction of a simple model of ECR heating developed for this purpose. A formula to estimate the ECR resonance thickness is calculated. The model explains nicely the experimental x-ray temperature variation when the central magnetic field of the ECRIS is changed. It demonstrates that such a magnetic field variation does not change the electron confinement time and that the change of the x-ray spectrum temperature is due to the change of the ECR zone thickness. The only way for the model to reproduce the fact that the x-ray temperature scales with the ECR frequency is to assume that the electron confinement time scales (at least) with the ECR frequency. This result brings new credit to the theoretical prediction that the hot electron RF scattering is decreasing when the ECR frequency increases.[2,3] The spatial gyro effect, which can be considered as another possible origin of the very hot x-ray produced in ECRIS is recalled for convenience in this paper.

VENUS EXPERIMENTAL DATA

Extensive experimental x-ray measurements have been carried out on several third generation ECR ion sources. This paper focuses on data formerly measured with the VENUS ion source at LBNL. [1] The data considered in this paper is the one comparing the x-ray spectrum produced at 18 GHz and 28 GHz with a homothetic magnetic field (*i.e.* scaling the ECR frequency) and for 2 values of the axial median magnetic field intensity (B_{min}):

- steep Gradient configuration when $B_{min} \sim 0.47 B_{ecr}$
- shallow Gradient configuration when $B_{min} \sim 0.47 B_{ecr}$

The axial magnetic field configuration associated to these four tuning is shown on Figure 1. The red and blue plots respectively stand for 28 and 18 GHz operation. Solid lines are for shallow gradient, while dashed lines are for steep gradient. The magnetic calculation have been carried out with RADIA.[4] The VENUS radial magnetic field is considered to reach 2.1 T at wall (radius 70 mm) for the 28 GHz operation and 1.35T for the 18 GHz operation.

The experimental x-ray spectrum plotted in [1] have

been fitted with the usual Boltzmann temperature profile:

$$\frac{dN}{dE} \sim N_0 e^{-\frac{E}{kT}} \quad (1)$$

The fits are plotted on Figure 2, and the spectrum temperatures calculated are summarized in the Table 1. The same convention of color and line style is used in Fig. 1 and 2 for convenience.

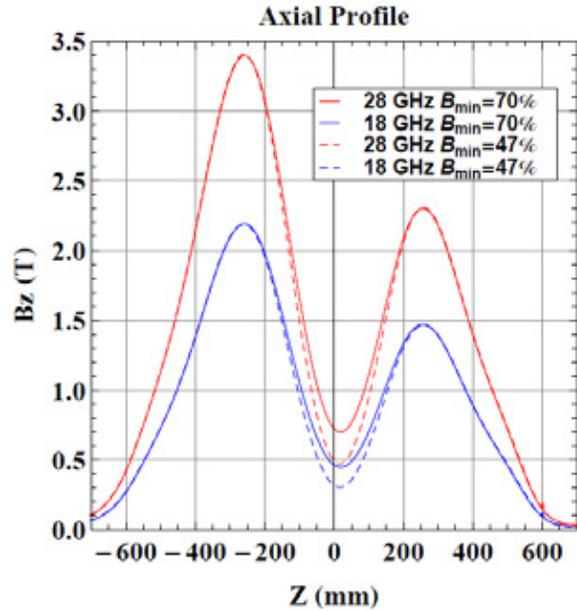


Figure 1: Axial magnetic field profiles used to study the x-ray spectrum dependence for 2 ECR frequencies and 2 B_{min} values.

Table 1: Experimental x-ray spectrum temperatures

f_{ECR}	Gradient type	kT
18 GHz	Steep	$47.7 \pm 2 \text{ keV}$
18 GHz	Shallow	$91.2 \pm 2 \text{ keV}$
28 GHz	Steep	$72.7 \pm 2 \text{ keV}$
28 GHz	Shallow	$139.5 \pm 2 \text{ keV}$

DATA ANALYSIS

A way to compare these spectrum is to normalize their values at the energy $E=0$ and consider that an individual x-ray population at a given dN/dE value undergoes an energy boost from E_1 to E_2 when the magnetic gradient changes from steep (kT_1) to shallow (kT_2), or when the frequency is changed from 18 to 28 GHz (with an appropriate homothetic magnetic field). This implies that:

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BORON ION BEAM PRODUCTION WITH THE SUPERNANOGAN ECR ION SOURCE FOR THE CERN BIO-LEIR FACILITY

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Abstract

To deliver B^{3+} ions for medical research the compounds decaborane and m-carborane were tested using the metal ions from volatile compounds (MIVOC) method with the Supernanogan 14.5 GHz ECR ion source. Using decaborane the source delivered less than $10 \mu A$ intensity of B^{3+} and after operation large deposits of material were found inside the source. Using m-carborane $50 \mu A$ of B^{3+} were delivered without support gas. For m-carborane, helium and oxygen support gasses were also tested, and the effects of different source tuning parameters are discussed. The average consumption of m-carborane was $0.1 \text{ mg}/\mu Ah$ over all operation.

INTRODUCTION

Over the last fifty years the field of ion beam therapy has developed from its first tests at the Lawrence Berkeley National Laboratory to, amongst other things, a powerful tool for the treatment of cancer tumours [1]. While the majority of treatments are conducted with protons, heavier ions provide different radiobiological properties and could be more useful in some cases [2]. Different ion species may hold specific advantages for treatment however, a comprehensive study of different viable species has not been completed. Ion beam therapy has been pioneered using carbon ions while helium, boron, lithium, oxygen and other light ion species require further studies to determine their radiobiological properties. No facility currently existing has been designed to deliver this range of ions from protons to neon exclusively for medical research. After discussion at CERN with many representatives of the radiobiological community a strong desire for such a facility has been expressed. Such a facility would allow for fundamental research in this field with new ion species, delivery techniques, and diagnostic tools [3].

The ion injection chain for the LHC starts with a 4.2 MeV/u ion Linac, followed by the Low Energy Ion Ring (LEIR) where the beam is multi-turn injected, and its emittance reduced with an electron cooling scheme. The ions then continue to the LHC through the PS and SPS synchrotrons. The energy range of LEIR (as the LHC lead injector it accelerates Pb^{54+} to 72 MeV/u) does not match the 430 MeV/u carbon beams that are delivered at for medical treatment, however with upgrades to the machine this should be achievable [4]. In the period between LHC fills, it could be envisaged to use LEIR for the delivery of different ion types. Regardless of how the beam is acceler-

ated for injection into LEIR, an ion source is needed. The chosen source must be capable of delivering most of the ions from protons to neon. The Supernanogan is a commercial, permanent magnet, 14.5 GHz ECR ion source currently being used at Heidelberg Ion Therapy Center, the Centro Nazionale di Adroterapia Oncologica (CNAO) and MedAustron to deliver carbon and protons [1]. The Supernanogan is capable of being operated with a micro-oven and gas mixing [5]. Of the ions up to neon, four ions present difficulties for producing ion beams. Beryllium, boron, lithium, and fluorine have not been routinely delivered from ECR ion sources and so production techniques for these ions require verification. Boron was selected to be investigated first using the Helmholtz-Zentrum Supernanogan, Berlin [6].

EXPERIMENT SETUP

Previously boron has been produced using the MIVOC technique at the University of Jyväskylä [7] and at the Flerov Laboratory for Nuclear Reactions (FLNR) in Dubna [8]. Both experiments used the same compound, m-carborane $C_2H_{12}B_{10}$, to deliver between $100 - 200 \mu A$ of $^{11}B^{3+}$. For this work a second compound, decaborane, was also chosen as an alternative source of boron material in case problems arose with m-carborane. The relevant properties of decaborane and m-carborane are given in Tables 1 and 2.

Table 1: M-carborane Properties.

Property	Value
Atomic Formula	$C_2H_{12}B_{10}$
Mass Ratio	24 : 12 : 110
Melting Point	546 K
Vapor Pressure	0.05 mbar (at 300 K)
Phase at 300 K	Crystalline Solid

Table 2: Decaborane Properties.

Property	Value
Atomic Formula	$H_{14}B_{10}$
Mass Ratio	14 : 110
Melting Point	373 K
Boiling Point	486 K
Vapor Pressure	0.269 mbar (at 300 K)
Phase at 300 K	Crystalline Solid

APPLICATION OF AN ECR ION SOURCE FOR IONIC FUNCTIONALIZATION OF IMPLANT MATERIALS ON THE NANOSCALE

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Abstract

Surface modification by variously charged heavy ions plays an increasingly important role since functionalization of surfaces and/or deeper layers at micro- and nanoscopic scale can be biologically useful for materials of medical implants. The functionalized surfaces have a huge potential in the field of nanotechnology, sensor devices as well.

Our group explores the physical and biological effect of such treatments. In the recent phase of the research work the implantation of titanium and zirconium-dioxide samples by calcium, gold and silicon ions is required.

The 14.5 GHz Electron Cyclotron Resonance Ion Source (ECRIS) of Atomki - a classical room-temperature ion source - was used in this study as an ion implanter to deliver low energy particles from wide range of elements.

A new vacuum chamber and a sample holder for effective irradiation and the production of the beam itself were developed. The technical details of the irradiation and the first result of the physical investigations are described in this paper.

INTRODUCTION

Plasma processing is a frontier technology and discipline born out of the need to control a group of parameters in materials processing unattainable by strictly chemical process. Materials treated by the plasma, or by the ions of the plasma have a huge area of the possible application field e.g. industry and biomedicine. The field is multidisciplinary involving and combining plasma physics, atomic and molecular physics, surface science and (depending on the final aim of the process) biomedical and engineering disciplines.

Plasmas and ion beams provided by an ECR ion source have some unique future which makes it one of the best candidates to carry out such surface treatment experiments. Due to the high gas efficiency, ECRISs can produce ion beams from a variety of materials, even from

solid. By changing the extraction voltage of the source and/or of the charge state distribution (CSD) of the plasma the implantation depth of the ions into the materials can be varied easily. Usually it must be around 10 nm, which is available applying standard terminal voltage. Last but not least there is another remarkable advantage: as an additional irradiation parameter the effect of the charge state of the ions can also be investigated.

The Atomki ECRIS [1,2] is highly suitable device for this task, because it is an independent ion source (there is no post acceleration) offering beam time more freely. Furthermore, the modularity of the source opens the possibility to change the configuration within reasonable time.

MOTIVATION

Our main efforts have been and steel are being made to accelerate and increase bone formation around dental and orthopaedic implants and to improve lifetime and mechanical stability. Modification of the medical implant and material surfaces by variously charged ion beam extracted from ECR ion source are investigated. We have started three subtopics (A-B-C) aiming different goals and requiring different irradiation conditions and ion beams. In the recent phase of the research work the implantation of titanium (the surface is always oxide) and zirconium-dioxide (ceramic) samples by calcium, gold and silicon ions is required. Those attributes are listed in the table 1 and the topics are described shortly below.

Table 1: This table shows the three subtopics started in the Atomki ECR Laboratory

	A	B	C
Target material	TiO ₂	TiO ₂	ZrO ₂
Beam	Au	Ca	Si

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A POINT-LIKE SOURCE OF EXTREME ULTRAVIOLET RADIATION BASED ON NON-EQUILIBRIUM DISCHARGE, SUSTAINED BY POWERFUL RADIATION OF TERAHERTZ GYROTRON*

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Abstract

It is proposed in this paper to use discharge plasma supported by terahertz radiation as a source of EUV light for high-resolution lithography. In this report we discuss the experimental investigation of two types of EUV sources based on discharge, supported by powerful gyrotron radiation. Following investigation results are described:

-a series of experiments that demonstrate the generation of EUV light from the vacuum-arc discharge plasma in tin vapor in the magnetic trap heated by gyrotron radiation with a frequency of 75 GHz under electron cyclotron resonance (ECR) conditions;

-a numerical modelling of the plasma emissivity in the EUV range, depending on the parameters of the heating radiation is performed;

-experimental studies of EUV emission from plasma discharge sustained by strong terahertz powerful radiation in inhomogeneous gas flows are started.

INTRODUCTION

Today micro- and nano- electronics industry requires a source of extreme ultra-violet (EUV) radiation with a wavelength of 13.5 ± 1 % nm for high resolution projection lithography. The power of the source must be at a level of 1 kW at the size of the emitting region of less than 1 mm.

One of the most promising sources of EUV light is considered to be a source that uses a pulsed CO₂ laser radiation focused on a specially formed stream of droplets of tin with dimensions of the order of 0.1 mm [1]. However, along with tangible achievements in these light sources have a number of fundamental flaws that do not allow us to consider the problem of creating a EUV light source to be solved.

We propose to use discharge plasma supported by terahertz radiation as a source of EUV light for high-resolution lithography. In this report we discuss the experimental investigation of two types of EUV sources based on discharge, supported by powerful gyrotron radiation. Following investigation results are described:

- a series of experiments that demonstrate the generation of EUV light from the vacuum-arc discharge plasma in tin vapor in the magnetic trap heated by gyrotron radiation with a frequency of 75 GHz under electron cyclotron resonance (ECR) conditions;

- a numerical modelling of the plasma emissivity in the EUV range, depending on the parameters of the heating radiation is performed;

- experimental studies of EUV emission from plasma discharge sustained by strong terahertz powerful radiation in inhomogeneous gas flows are started.

ELECTRON CYCLOTRON RESONANCE HEATING EXPERIMENTS

The experimental scheme is following: tin ions injected into the magnetic trap from a vacuum-arc discharge. Low-pressure discharge sustained in a magnetic trap by the high-power millimetre-wave radiation (200 kW @ 75 GHz) under ECR conditions. Multiply charged ions are efficiently generated and excited in such a discharge and emit line radiation in the desired wave-length range [2]. Experimental layout is in the Fig. 1.

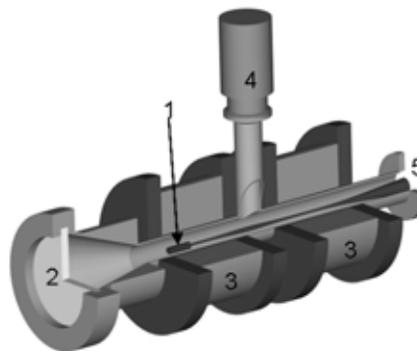


Figure 1: Experimental setup 3d-scheme. 1 – plasma generator, 2–window for microwaves, 3 - coils, 4 – EUV detector, 5 – flange for plasma analysis or EUV detector.

The charge state distribution of tin ions achieved in these experiments is shown in Fig. 2. A radiation power of 50 W in a wavelength range of $13.5 \text{ nm} \pm 1\%$ and an efficiency of about 1% for the conversion of the microwave radiation absorbed in the plasma to the extreme ultraviolet radiation were achieved in the experiments.

NUMERICAL SIMULATION

The efficiency of the source of the EUV radiation was estimated as follows. The system of the rate equations for the densities of the charged particles in various ionization states was solved. The initial mean charge of the tin ions in the injected beam was 2. The microwave-radiation

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CLOSING REMARKS FOR ECRIS'14

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Abstract

A scientific overview of the ECRIS14 workshop is proposed in this paper. The workshop content demonstrated that the ECR community is still very active and that research is of high interest for future accelerator projects. A selection of new results and development presented during the workshop is proposed.

INTRODUCTION

The XXIst ECR Ion Source conference was hosted by the Institute of Applied Physics of the Russian Academy of Science in Nizhny Novgorod, Russia, from August 24th to August 28th 2014. The number of attendees was 60. The workshop atmosphere was relaxed, studious and suitable to discussion. Many new ion sources have been presented, many new developments were announced and interesting new results shown. The paper proposes selected highlights from the workshop. Because it is not possible to present every single contribution, the author apologises for those works which are not mentioned there.

NEW RESULTS

The know-how on the use of high ECR frequency in superconducting ECR ion sources keeps on improving with new results from MSU, IMP Lanzhou and RIKEN.

At IMP Lanzhou, impressive high intensities Bi beams were produced: 710 μA of Bi^{30+} (1.4 kW 18 GHz+4.7 24 GHz), 100 μA of Bi^{41+} and 10 μA of Bi^{50+} .

The RIKEN 28 GHz SC-ECRIS, demonstrated the production of high intensity U beam using the sputtering method: 225 μA of U^{33+} and 180 μA of U^{35+} .

At MSU, the commissioning of SUSI started at the 24 GHz frequency. 860 μA of Ar^{12+} , 530 μA of Ar^{14+} have been obtained (with 5.5 kW of RF power). It is noticeable that these intensities are equivalent to the records of VENUS (LBNL) obtained at 18+28 GHz, with quite a different plasma chamber volume (7.6 litre for VENUS and 3.5 for SUSI). Another insight from MSU studies is that beam intensities obtained at high power 18 GHz compare with the ones obtained with a pure 24 GHz frequency. The so-called "ECR frequency scaling law" implying a current extracted proportional to the frequency to the square is not quite observed here. Results look like the higher intensities obtained with the 24 GHz emitter for Ar^{11+} to Ar^{14+} could be due to the higher RF power available rather than the frequency change, since the current gain per RF power is very similar for both frequencies. Nevertheless, a net gain in current performance at 24 GHz has been obtained for high charge state (Ar^{16+}). A last interesting information from SUSI comes from the plasma chamber return temperature which

happens to be higher at 24 GHz than at 18 GHz for the same RF power level.

At LPSC Grenoble, the first 60 GHz high power pulses have been injected into SEISM, a room temperature magnetic CUSP having a closed ECR resonance. Record beam current densities have been measured up to 600 mA/cm^2 (5 mA extracted from a $\varnothing 1$ mm extraction electrode). Another very interesting point is that intense afterglow peaks of low charge states have been observed. This implies that such a simple axisymmetric structure features non trivial plasma confinement properties: interesting physics is hidden behind.

NEW DEVELOPMENTS

This workshop edition featured many new ion sources projects or major upgrades of existing ones. Because the detailing all the contributions would be too long to be included in these closing remarks, the reader is invited to look into the proceedings for uncovered new developments.

First ECRIS Plasma and Commissioning

The commissioning of the ECRIS-LECR4 at Lanzhou gave excellent results at 18 GHz : 1.9 mA O^{6+} ; 1.7 mA Ar^{8+} , 0.29 mA Xe^{20+} with a radial magnetic intensity at wall of 1T only. The source uses a set of original evaporative cooling coils to generate its axial magnetic field.

The KBSI team of Busan presented the first plasma of their new 28 GHz SC-ECRIS dedicated to the production of Li beam. The SC solenoids reached their nominal current design, while the hexapole coils reached 83% of design so far. Further training of the hexapole is planned.

The Fraunhofer Institute and the Dreebit company presented the development of an original ECR ion source including an inverted cylindrical sputter magnetron to produce intense 1^+ aluminum beams for ion implantation.

New ECRIS Project

IMP CAS is building an upgrade of the SECRAL source named SECRAL II, to be operated at 18+28 GHz. The source has an upgraded cryogenics. The cold mass has been built and the coils ramped together to 90% of the design within 8 quenches.

IMP CAS presented the HIAF accelerator complex project requiring the challenging production of pulsed U^{34+} with a peak intensity of 1.7 mA and a duration of 400 μs . The design of a 4th generation high frequency ECR is under progress in the institute to tackle this objective.

INFN-LNS team reported the design of a new hybrid ion source named AISHa dedicated to hadrontherapy. The source features a permanent hexapole and a set of 3 He-free coils. The talk also included the presentation of

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