60 GHz ECR ION SOURCES*

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Abstract

Electron Cyclotron Resonance Ion Sources (ECRIS) deliver high intensities of multicharged heavy ions to accelerators; nowadays the evolution of science requires extremely intense ion beams. Since 1987, semi empirical scaling laws state that the ECR plasma density, in a minimum-B magnetic field configuration, varies like the square of the electromagnetic waves (EM) frequency or of the resonant magnetic induction. The present most performing ECRIS are operated at 28 GHz. In order to significantly increase the ion beam intensities, the use of EM with frequencies of the order of 60 GHz is evaluated worldwide. Conceptual studies based on superconductors are performed and different magnetic configurations accepting such a high ECR frequency are proposed by several groups. Since 2009, LPSC collaborates with IAP-RAS (Russia) and LNCMI (CNRS) and has built the first ECRIS with a topologically closed 60 GHz ECR resonance zone, using radially cooled polyhelices. Unique ion beam intensities have been extracted from this prototype, like 1.1 mA of O^{3+} through a 1mm hole representing a current density of 140 mA/cm^2. The worldwide high frequency ECRIS research status is presented along with a focus on the present LPSC-IAP-LNCMI strategy.

ECRIS STATE OF THE ART

The production of intense multi charged heavy ion beams is performed worldwide with Electron Cyclotron Resonance Ion Sources (ECRIS) using a minimum-B magnetic field to confine the ECR plasma. It is generated by the superimposition of an axial field, produced by at least two solenoids, with a hexapolar radial field produced by permanent magnets or superconducting coils. Until now, the ECRIS development and optimization has been driven by scaling laws [1] specifying semi-empirical values for the optimal magnetic induction on the peak fields of the axial mirror and the radial field at wall. This magnetic field insuring the plasma confinement has to be much higher than the ECR magnetic field value B_{ECR}:

$$B_{ECR} = \frac{\omega_{\mu w} \times m_e}{e}, \quad (1)$$

where $\omega_{\mu w}$ is the frequency of the microwaves (μw), m_e and e, the mass and the charge of the electron. Following the scaling laws, the axial magnetic induction on the axis of an ECRIS, at the injection side, has to be of the order of three to four times B_{ECR}, and the radial magnetic field has to be at least twice this value inside the plasma chamber. Presently, the highest μW frequency injected into a minimum-B ECRIS is 28 GHz [2–6] ($B_{ECR} = 1$ T), that means 3 to 4T for the axial field on the axis and more than 2T for the hexapolar radial field. In such an ECRIS, it is considered that the plasma density is close to the critical one, this assumption allows to say that the plasma density varies like the square of $\omega_{\mu w}$ or B_{ECR}.

These ECRIS, using NbTi superconductors to provide the appropriate magnetic induction, are called 3rd generation ones. Their performances are excellent and more or less in the same range, they produce about 800 to 1400 μA of Ar^{12+} (see previous references for various ion beam data). However their cost is high (a few M€), the development time is long (~5 years) and their construction process presents non negligible risks of failure. The new generation accelerator facilities requiring higher intensities of highly charged heavy ions, a strong research and development activity is necessary to define the so-called 4th generation ECRIS (higher ECR frequencies in the range 40-60 GHz). Such ECRIS are expected to operate with a plasma density up to four times higher than the present 3rd generation. However it necessitates the doubling of the magnetic field induction. A 60 GHz ECRIS magnet, featuring a 3 to 4 T hexapole with a 7T injection peak field requires the use of Nb3Sn superconductor technology [7]. The construction of Nb3Sn magnet is very difficult and risky, because once reacted, the Nb3Sn cable is very brittle. So far, no one has built such a prototype. Experimental research and development activities on ECRIS have reached a bottle neck. We will describe in the next paragraphs the different options evaluated worldwide for ~ 60 GHz ECRIS.

MAGNETIC FIELD CONFIGURATIONS FOR ~60 GHz ECRIS

A few groups in the world began to evaluate and design the next generation ECRIS. The Lawrence Berkeley National Laboratory in USA and Institute of Modern Physics at Lanzhou in China worked on the optimization of the present magnetic structures associating superconducting solenoids and hexapole using either NbTi or Nb_3Sn or both material [7, 8], and they show the difficulty to build such systems. Some other original minimum-B magnetic structures issued from fusion devices are proposed too, like the ARC-ECRIS source [9, 10], consisting in a 'yin-yang' coil creating magnetic field inductions and mirror

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ratio very close to classical ECRIS ones. It is interesting to note that the use of NbTi for such a coil may allow the injection of 60 GHz microwaves in a minimum-B structure. A more recent publication [11] proposes to make a rather sophisticated toroidal ECRIS (56 GHz) with a twisted hexapolar field along the torus and a radial extraction. The configuration studied is based on the use of high currents flowing through solid material and coils (3.5 MA and 300 kA for the generation of toroidal and poloidal fields respectively). A lot of modelling work needs to be performed to evaluate the potential of such a device and the realization could be a technical challenge.

In the frame of the European Isotope Separation On-Line project, and later in EUROnu (Beta Beams) [12], P. Sortais, proposed the concept of a “60 GHz ECR – duoplasmatron” [13], to ionize and bunch, with high efficiency, a continuous flux of radioactive atoms and provide an intense pulsed ion beam with the time structure suitable for the CERN accelerator facility. In the frame of a collaboration between LPSC and the high magnetic laboratory in Grenoble (LNCMI), we designed and built a cheap prototype (~150 k€) [14]. It uses high field magnets techniques (radially cooled copper polyhelices), to establish a magnetic field for a 60 GHz ECRIS. This first configuration is a spindle cusp with a closed resonance zone at 2.14 T (Fig. 1). It is a minimum-B structure; iso-B surfaces are slightly deformed ellipsoids centered on the null value.

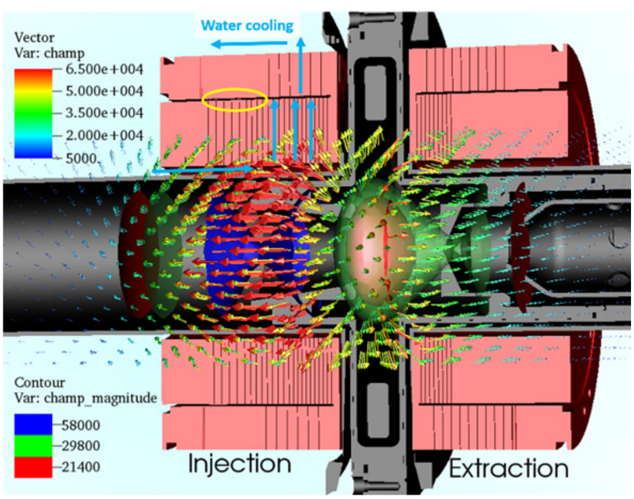

Figure 1: Simulated magnetic field with a 2.14 T quasi ellipsoidal surface at the center, 6T at the injection, 3T at the extraction, and 4T at the radial cusp.

MAGNETIC FIELD MEASUREMENTS

LNCMI High Magnetic Field Facility

The high magnetic field laboratory LNCMI in Grenoble, is equipped with 4 AC/DC convertors delivering 16 kA each, and a maximum voltage of 400 V (maximum available power is 24 MW). It provides high magnetic fields up to 36 T for fundamental physics and applications. A group of the laboratory performs research and development for the generation of high magnetic fields with resistive and superconducting magnets [15]. Our prototype has been designed to deliver its maximum magnetic field (7T at the injection) for an intensity of 30 kA. It is thus possible to use only two of the LNCMI convertors connected in parallel which allows more flexibility for the experiments planning. However, in such a situation, the extraction magnet is connected in series with the injection one, depriving us of an independent tuning of the magnetic field on each coil.

Magnetic Field Measurements at 26 kA

The magnetic field of the prototype was previously measured for an intensity of 15 kA allowing an operation at 18 GHz [16]. For an operation at 60 GHz it has been decided to operate the magnets up to 26 kA.

To validate the operation at such intensity, the prototype was connected to four 7.5 kA water cooled cables.

The intensity was ramped in successive cycles from zero to a maximum value increased at each ramp. During a ramp, the voltage was monitored and fitted. At the next ramp, the experimental voltage was compared to the fit of the previous one. In case of a significant voltage deviation, the procedure was stopped, due to a possible problem with the magnet. During the procedure, at 21 kA, the monitoring system measured an irreversible drop of about 8% of the resistance of the helices at the injection side. As a reminder, the width of the slits between each winding and the electric insulation are held by numerous small insulator strips glued in an oven with a special epoxy resin. The prototype disassembly showed short circuits between a few windings of the internal helix ‘compensated’ by the ungluing of the insulators at the basis of the helix (Fig. 2).

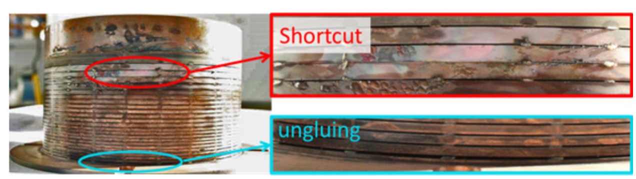

Figure 2: Internal injection helix defaults observed at 21 kA during the first test to reach 26 kA.

The analysis of the problem has shown that the water cooling channel design was at stake. In the magnet tank, cold water is introduced in the inner coils diameter. It then flows radially through the thin slits between the coil turns. On the top left of Fig. 1, the water path is shown in cyan, the position of the short circuit in yellow. The number of slits is much higher in the inner helix than in the outer one, creating a water speed decrease on the inner helix rear part and a subsequent overheating. The problem was solved by machining supplementary axial slits in the inactive part of the outer coil, taking care to minimize the effect on the electrical current path (Fig. 3).

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Figure 3: Perpendicular slits machined in the internal injection helix.

After this modification, the source was successfully operated up to the full current (26 kA) for hours. Let us remark that this result is important for the high field magnets technology, some windings having the highest ever reached current density in a radially cooled helix (600 A/mm^2). This validation allowed us to measure the magnetic field of the source. We can see on Fig. 4 the plot of the axial magnetic field on the axis, for three different intensities (10, 20, and 26 kA). These results are in full agreement with the simulations performed and allow a satisfying operation of the source at 60 GHz.

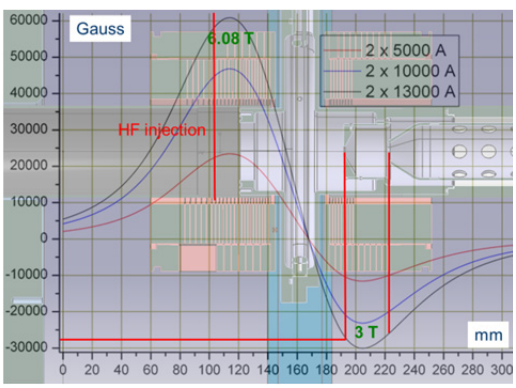

Figure 4: Magnetic field measurements at 10, 20 and 26 kA, superimposed on a cut view of the source.

60 GHz GYROTRON AND BEAM LINE

Gyrotron Setup

A pulsed 60 GHz - 300 kW gyrotron has been designed, constructed, and tested, by the GYCOM Company and the IAP-RAS in Nizhny Novgorod (Russia) in the frame of an International Science and Technology Center contract, funded by LPSC-CNRS and the European Community. Presently the μw pulse width can be varied from 50μs to 1 ms and the repetition rate can reach 2Hz at full power, 5Hz at 100 kW. Let us note that by means of some modifications and by the change of high voltage power supplies, this gyrotron could be operated in CW up to a power of 15 kW.

The gyrotron was setup at LNCMI at the end of 2012, its main components can be seen Fig. 5, more details can be found in [17]. The electromagnetic waves are launched as a quasi-Gaussian beam, vertically polarized. A dedicated microwave launching system has been designed by I. Isotov (IAP-RAS) to optimize the power density on the resonance surface. It has been realized at LPSC.

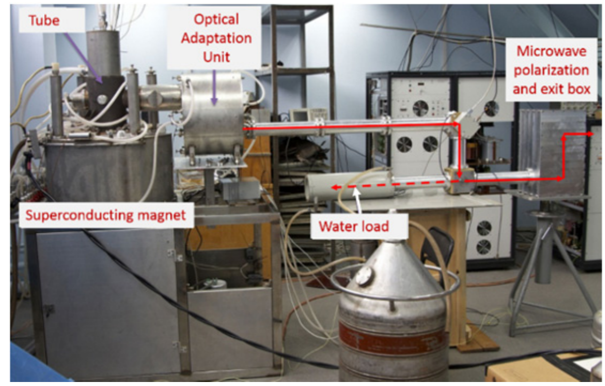

Figure 5: 60 GHz, 300 kW pulsed gyrotron.

Beam Line Setup

The experiment is located in a dedicated room at LNCMI, with a floor having a limited weight resistance, preventing us from setting up a high acceptance magnetic spectrometer. Due to our present budget constraints, we have not yet implemented a beam line and diagnostics suitable to the full characterization of intense ion beams. The beam line is equipped with two faraday cups, the first on the axis of the extraction, the other after a 60 mm gap magnetic spectrometer. A general view of the experiment is shown Fig. 6. The gyrotron system is easily tuned from a user-friendly interface; the operation of the helices is controlled from a dedicated rack and supervised by an adapted LNCMI automated system.

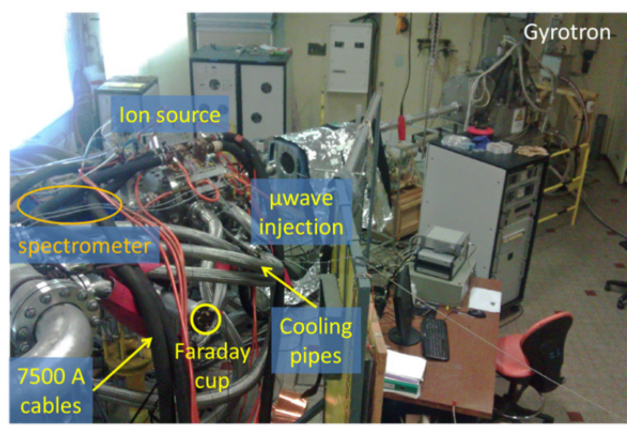

Figure 6: Overview of the beam line setup at LNCMI.

FIRST 60 GHz ECR PLASMA AND ION BEAMS

The plasma chamber and the microwave injection system are at high voltage with a Peek insulation allowing operation up to 30 kV. The microwaves are optically injected through a quartz window into the microwave adaptation system under vacuum. The source was operat-

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ed with oxygen in order to analyse all the charge states extracted at 20 kV with the available dipole. In order to limit the space charge effect, ions were extracted through a 1mm diameter hole in the plasma electrode. Oblique holes were present on the plasma electrode to enhance source pumping. The first experiments consisted in measuring the total current extracted from the ion source.

High Voltage Dependence of the Total Current Extracted

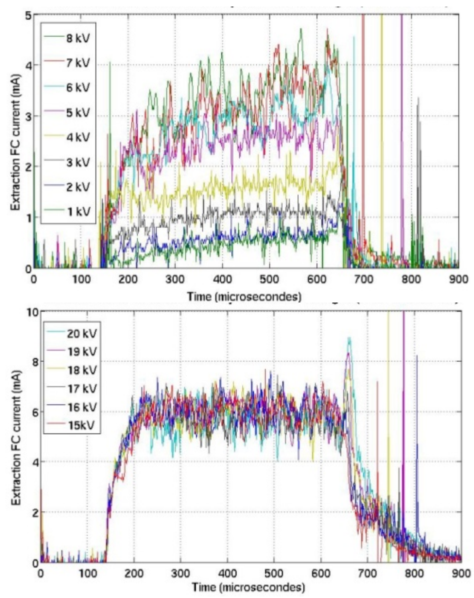

Figure 7: Total ion current intensity extracted on the axis of the source for extraction voltages from 1 to 8 kV (top) and 15 to 20 kV (bottom).

The initial pressure in the beam line is 2.3x10^{-06} mbar, oxygen gas is injected to reach 1.1 E-05 mbar. The current in the helices is set to 22 kA (~5T at the injection), the gyrotron power is adjusted to 80 kW to limit X-ray emission from the plasma, and the pulse duration is set to 500 µs. The ignition of the plasma is immediate, and this remark can be generalized for any tuning parameters. The total current is measured in the faraday cup on the axis of the extraction. Two sets of measurements are shown in Fig. 7: in the ranges from 1 to 8 kV, and from 15 to 20 kV. One can see the intensity gain during the µw pulse when increasing the extraction high voltage (~270 µA/kV) in the lower range. In the upper range there is no more gain for extraction voltages higher than 15 kV during the µw pulse, giving indication that the beam was fully transported up to the first faraday cup. However, an afterglow signal appears and its intensity increases with the high voltage, higher voltage will be required to transport the full afterglow intensity. The plateau signals are relatively stable and reach about 6 mA which means an ion beam current density of 760 mA/cm^2 (for other tunings, 900 mA/cm^2 was observed). During the afterglow this value increases up to 1.1 A/cm^2. The peaks appearing after the classical afterglow are much shorter in duration, seem to be reproducible, and represent an ion beam current density of 1.8 A/cm^2.

MULTICHARGED ION BEAMS EXTRACTED FROM THE 60 GHz ION SOURCE

3D Spectra

Afterglows being seen in the total ion beam intensity extracted, it is interesting to analyse the different Q/A intensities as a function of time. Fig. 8 shows such measurements, the colour is the intensity, the X-axis is the magnetic field of the spectrometer, and the Y-axis is the time. In order to maximize the afterglows, the extraction high voltage was set to 22 kV. The charge states from 2+ to 5+ are clearly observed. The black and white spectra on the right of the Fig. 8 are a cut view, at a specific time (horizontal yellow line), during the pulse. It is striking to see that during the plateau, the 2 to 4+ beams have about the same intensity. We can see too that the afterglows appear at different times, the 5+ being measured about 15 µs before the 1+ (not seen on the figure). If we only take into account the extraction voltage, the 5+ should appear about 90 ns before the 1+. This time difference appears to be physical and a plasma phenomenon is possibly the cause. Further analysis is required.

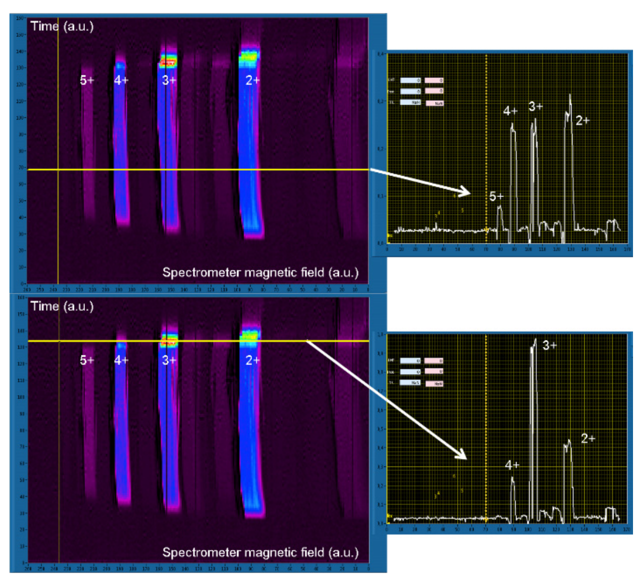

Figure 8: Multicharged oxygen ions spectrum, time evolution of the charge state distribution.

Oxygen 3+ Afterglow Intensity

The analysis of O^{3+} pulses at different extraction voltages show a remarkable stability of the signals (Fig. 9). At 25 kV, through the 1mm hole we have an afterglow of 1.1 mA (the maximum among the different charge states), reaching about 4 times the plateau intensity, so

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140 mA/cm^2. Further afterglow current increase is expected at higher voltage.

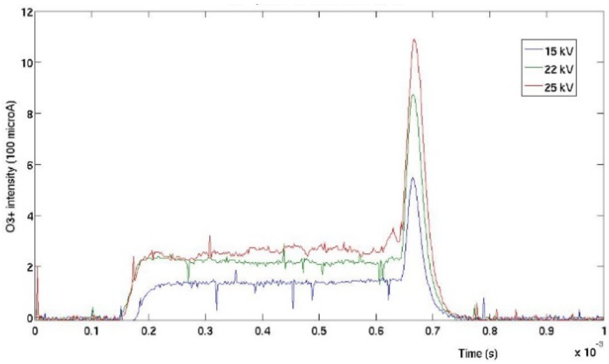

Figure 9: O^{3+} afterglows extracted at 15, 22, and 25 kV

CONCLUSION

The first results obtained during a one week experiment with our 60 GHz ion source showed unique features: extremely high intensities are extracted, presence of afterglows peaks proving electron confinement as predicted in [18]. The next steps will be to vary the length of the magnetic trap, then to test its properties as a magnetic bottle. In the future, we plan to improve the beam line transport, study plasma characteristics obtained with different magnetic structures in a European context. A dedicated experiment to study the transition between gasdynamic and Pastukov confinement is also planned by enhancing the control of the ion source pressure. This research may help to the definition of the 4th generation ECRIS.

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