THIRD GENERATION ECR ION SOURCES

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Abstract

A new electron cyclotron resonance ion source (ECRIS) running at high frequency has been designed in collaboration between INFN–LNS and CEA– Grenoble. The source, named GyroSERSE, aims to the production of highly charged ions (up to 55^+ or 60^+) at intensities so far never obtained and of medium charge states at high intensities (≈1 emA). Both goals are of paramount interest for future accelerators and require high-frequency superconducting ECR ion sources. This means a significant step to achieve with respect to the existing technology. The expected performances of the new source are presented, as estimated from ECRIS scaling laws and demonstrated recently by experiments performed with SERSE at 28 GHz [1,2]. The technological aspects related to high-frequency operation and to cryogenic systems are briefly discussed, thus showing that this kind of source is as versatile as the sources of the previous generation but it shows performances typically ten times higher.

1 INTRODUCTION

At many large accelerator facilities there is a strong need of higher injection currents of highly charged ions, up to 1 mA for heavy ions with charge states above 25^+ (both pulsed and cw mode). At INFN-LNS the ultimate goal for nuclear science is to produce between 0.1 and 0.5 eμA of U^{60+} (cw mode) and other heavy ions to increase the energy of the beam extracted from the superconducting cyclotron (the advantage of coupling a 3rd generation ECRIS to an accelerator is clearly shown in fig. 1). A similar advantage can be obtained by any other accelerator facility based on a linac or a cyclotron.

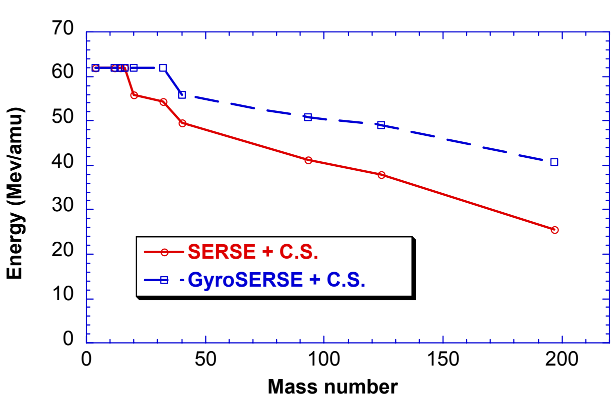

Figure 1: Maximum energies achievable from the K-800 superconducting cyclotron of INFN-LNS.

Another requirement of the future RNB facilities based on a linac or cyclotron post-accelerators is to have an efficient charge breeding process ($1^+/N^+$ transformation) in order to obtain high charge states ($Q>20^+$) with a high ionisation efficiency (>20%) on a single charge state.

In 1999 a research project called "Innovative ECRIS" was established to meet all these requirements. Some tests were carried out with a high frequency-high power (28 GHz - 10 kW) microwave transmitter coupled to the superconducting source SERSE at INFN-LNS [1,2]. The results were outstanding and beam intensities never obtained before were measured. Anyway we perceived that with an adequate source design more intense beams can be obtained. The successful exploitation of the SERSE source at 28 GHz opened the way to the GyroSERSE source, a high confinement superconducting source optimised for 28 GHz and designed following the scaling laws [3]:

$$q_{opt} \propto \log B^{3/2} \quad (1)$$

$$I^{q+} \propto f^2 M_i^{-1} \quad (2)$$

and the high B mode concept [4].

$$B/B_{ECR} > 2 \quad (3)$$

where q_{opt} is the optimal charge state, B is the peak field of the magnetic trap, f is the microwave frequency, I^{q+} is the intensity of the charge state q, M_i is the ions mass and B_{ECR} is the magnetic field corresponding to the ECR frequency. The expected performances of GyroSERSE are shown in fig.2: we are confident that the increase of both the quality factor $n_e\tau_i$ (electron density and confinement time) and the electron temperature T_e will enhance the production of high charges.

2 MAGNETS AND GENERAL DESIGN

The features of the magnet design are given in tab. 1., where the relevant parameters are described: in particular, the radial field above 3T can be obtained by means of a special cos(θ) design. Fig. 3 shows a model of the magnetic system, with the solenoids and the hexapole surrounded by an iron yoke and followed by the focusing solenoid which is the first element of the beamline. The mechanical constraints have obliged to choose a well larger inner bore than for SERSE, because of the boundary conditions for the hexapole (the stored energy exceeds 300 kJ). The plasma chamber inner diameter is 180 mm, 50 mm larger than the one of SERSE.

Fig. 4 shows the B-mod lines in the plasma chamber, featuring a value of the last closed surface of about 3 T. Then the magnetic field will permit to operate in High B mode, with a β value below 0.01, at any frequency between 28 and 37 GHz.

The coils of the magnetic system will be wound from NbTi superconducting composites and cooled by immersion in a liquid helium bath. The electrical connection to the power supply at room temperature will be made by high critical temperature superconducting currents leads. The use of cryocoolers will permit to operate the cryostat without external supply of liquid helium. Robust and reliable cryocoolers for the liquid helium temperature range are commercially available nowadays. Owing to their limited cooling capacity, however, more than one machine may be necessary for the present application.

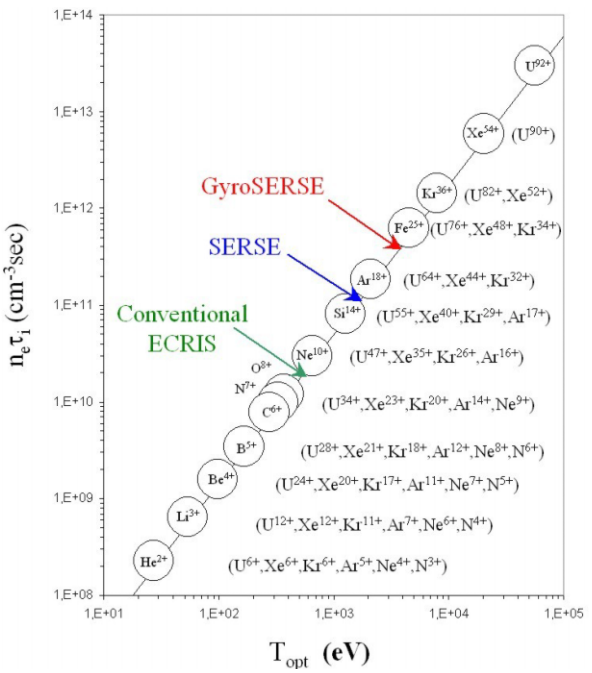

Figure 2: The Golovanivsky plot describes the ionization capability of a source in terms of the quality factor $n_e\tau_i$ and of the electron temperature T_e (charge states corresponds toa currentvalue of 1eμA).

Maximum field at injection	**4.5 T**
Minimum field	**0.4 T**
Maximum field at extraction	**3.5 T**
Hexapolar field on the wall	**3.0 T**
Cryostat length	**2150 mm**
Warm bore diameter	**194 mm**
Hexapole inner diameter	**216 mm**
Iron yoke thickness	**45 mm / 70 mm**
Maximum coil current	**340 A**

Table 1: The design features of GyroSERSE magnets.

2.1 The mechanical design

The large dimensions of the plasma chamber will allow to obtain a very good pumping speed, as it is for SERSE, which has a residual gas pressure of 10^{-8} mbar. As the radial pumping is not possible, the pumping will be performed only through 2 mm diameter holes drilled in the injection flange and in the outer part of the extraction electrode, to prevent microwave leaks. A 5 mm double wall water-cooled stainless steel chamber will be able to dissipate a maximum power of 10 kW. High Voltage (50 kV) insulation will be provided by a 3 mm thick polyetherethercheton (PEEK) between the chamber and the cryostat. The length of the plasma chamber will be about 650 mm and the volume will be larger than 16 liters, well higher than any other existing source. In fig.5 the sketch of the GyroSERSE is presented.

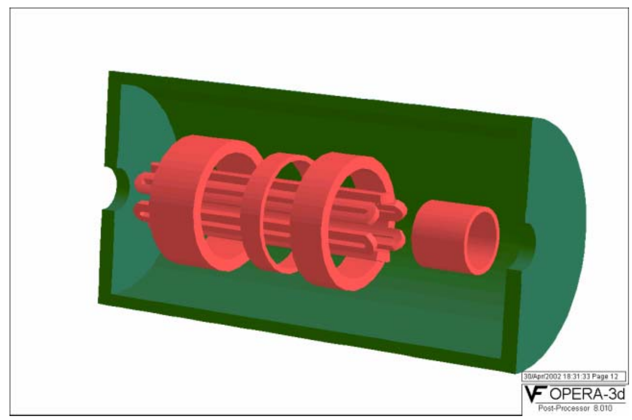

Figure 3: The OPERA-3D model of the magnetic system.

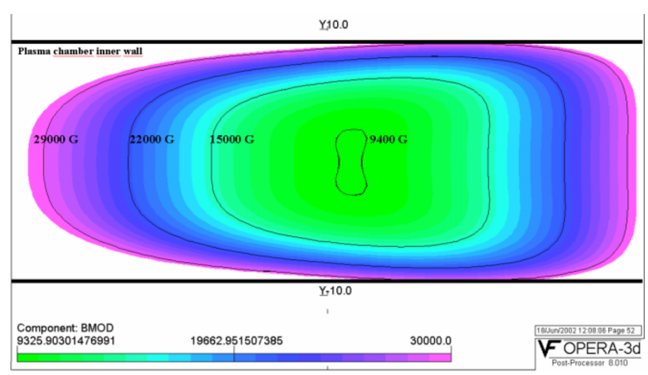

Figure 4: The B-mod lines.

2.2 The microwave injection

The behaviour of the 28 GHz rf coupling to the plasma was tested during the SERSE 28 GHz experiment and a new transmission line [1] based on the concepts used in the domain of magnetic fusion was designed for that purpose. The same design with minor modifications may be applied to GyroSERSE. A 28 GHz 10 kW gyrotron (TE_{02} output mode) will be used, with a transmission line similar to the one used for the SERSE 28 GHz experiment. It appears that the dc-break plays the role of an additional mode filter since only TE_{0n} modes are transmitted through this device. Higher-order reflected modes, if any, are dissipated in the line so that only a small fraction of the total reflected power returns to the gyrotron. The mode filter damps the residual reflected modes. During the experiment 2 to 6.5 kW (up to 4 kW in cw mode) were injected in the SERSE plasma; the maximum observed reverse power was less than 150 W, which enabled a safe operation of the gyrotron [1].

In the case of GyroSERSE the optimum power must be much higher. The optimum power for the ECRIS is given by the formula:

$$P_{RF} = n_e kT_e \ V / (t_e h_{ECRH})$$

where $h_{ECRH} = P_{absorbed} / P_{RF} = h_{waveguide} h_{coupling} h_{plasma}$.
As the volume of the plasma will be higher than the SERSE one, but the confinement time and the density will be both higher, we believe that 6 kW or more will be necessary to optimise the operation of the source.

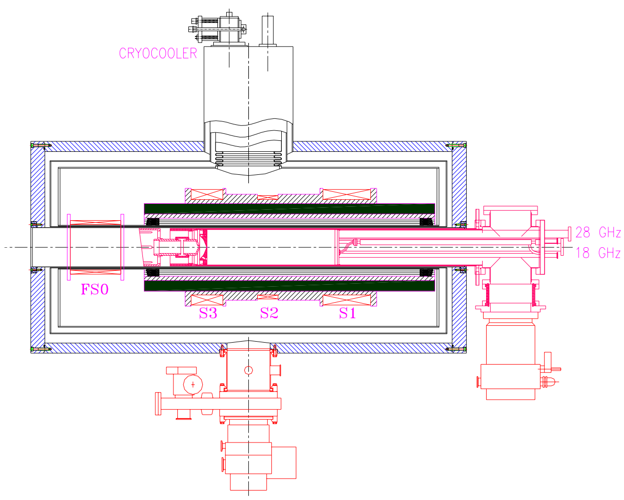

Figure 5: The GyroSERSE source.

3 EXTRACTION OPTICS AND LEBT

Simulations with KOBRA3D code have been carried out which confirmed that the large magnetic field (3.5 T) at the extraction may cause some emittance increase [5]. The triode topology was chosen for its simplicity and effectiveness. The distances and the shape of the electrodes have been optimized for high charge state extraction. Ray tracing of ion trajectories has been performed up to 10 cm downstream of the extraction aperture. The emittance values range between 120 and 200 π mm mrad at 40 kV extraction voltage; a value of 150π mm mrad has been used as starting condition for the preliminary beamline simulations here described. An extraction voltage higher than 40 kV may further decrease the emittance. The analysis section of the beamline has been designed following the assumption that the focusing solenoid should be as close as possible to the extractor; moreover the solenoid should not be used to shrink the ion beam to a narrow focus; the analysis magnet should have a large curvature radius to have a good mass selection and a large gap to keep the beam losses small and the beam pipe should have a diameter of 160 mm to avoid beam losses and to provide a good vacuum conductance.

Some alternative designs have been considered, because the GyroSERSE source may be built for different laboratories under different site constraints.

The simplest design is based on a single solenoid that matches the beam to the analyzing magnet. The solenoid is embedded in the cryostat 35 cm away from ion formation electrode and it is 300mm long. The 90° dipole magnet (bending radius of 1200 mm, mass resolving power M/ΔM>120) has an air gap of ±80 mm and field boundaries inclined by 26° in order to achieve x and y focussing; the distance between the solenoid and the entrance slit of the separator is 300 mm and the distance between the entrance slit and the dipole entrance is 1000 mm. The distance to the final focus is 2300mm.

Other design options based on a combination of one solenoid and four quadrupoles are described in [5].

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