A NEW SUPERCONDUCTING ECR ION SOURCE FOR THE FUTURE ACCELERATOR FACILITIES

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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 technology of copper coils and permanent magnets, and also with respect to the new projects of hybrid or fully superconducting magnets. 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: at CERN the program for the study of gluon-quark plasma requires ten times more Pb^{27+} ions than existing ion sources can provide in a pulsed mode. At GSI a comparable enhancement of the performances is also required, for many other elements (both pulsed and cw mode). The Rare Isotope Accelerator (RIA) project needs U^{30+} beam current much higher than ever achieved. 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 (fig. 1). Another requirement of the radioactive nuclear beam facilities which can be met by innovative ECRIS consists of an efficient charge breeding process ($1^+/N^+$) 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. High frequency operation of the source, cryogenic devices, sophisticated extraction systems, metallic element production systems have been developed in the frame of this project or they are under way. In particular, the problem of ion extraction and transport in the new sources is fundamental: as high currents are extracted it is necessary to optimise the design of the extraction system. This need was particularly evident after the tests carried out with a high frequency-high power (28 GHz-10kW) microwave transmitter coupled to the superconducting source SERSE at INFN-LNS. The results were outstanding and beam intensities never obtained before were measured [1]. 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]:

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

$$I^{q+} \propto f^2 M_i^{-\alpha} \qquad (2)$$

and the high B mode concept [1].

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

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 α is an adjustable parameter variable between 0.5 and 1, which takes into account the difficulty to ionize the heaviest ions, and B_{ECR} is the magnetic field corresponding to the ECR frequency.

The first proposal of a 28 GHz SERSE-like source was outlined in 1994 [4], but only four years later its design began. After the preliminary design of the magnets there was a pause due to the tests of SERSE at 28 GHz in 2000. In 2001 the basic design of the source was completed and submitted for funding, which has been allocated for 2002-2005. In the following the different technical issues are described, but it must be pointed out that some of them need a further R&D effort to optimise the source performance.

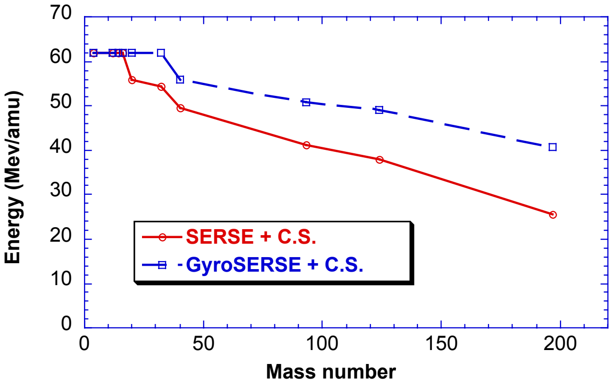

Figure 1: Maximum energies achievable from the K-800 superconducting cyclotron of INFN-LNS.

2 MAGNETS AND GENERAL DESIGN

The main features of the magnet design are given in tab. 1. Fig. 2 shows a model of the magnetic system, with the solenoids and the hexapole surrounded by an iron yoke. 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.

The magnetic field has a mirror maximum of 4.5 T at the injection and of 3.5 T at the extraction, a minimum variable from 0.4 to 0.8 T and a radial field of 3.0 T in order to work in High B mode, with a β value below 0.01. In these operating conditions the confinement time should be increased and the electron temperature should raise with the power, thus obtaining very high charge states. Following the scaling laws [3] we expected to obtain bare calcium nuclei and currents in the order of 1 eμA (the typical values injected into the CS) for beams such as Au^{50+}, Pb^{52+}, U^{58+} provided that the pressure in the chamber will be in the order of a few 10^{-8} mbar without plasma and of 10^{-7} mbar in operating conditions.

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 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. In addition, we are attentive to the breakthrough of new cryocooler technologies, such as pulse tube cryocoolers [5].Commercial high critical temperature superconducting current leads have been ordered for off-line tests to be carried out in summer 2002. This test is important for the definition of the final cryostat design.

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 solenoids currents	**200 A**
Maximum coil current	**340 A**

Table 1: The design features of GyroSERSE

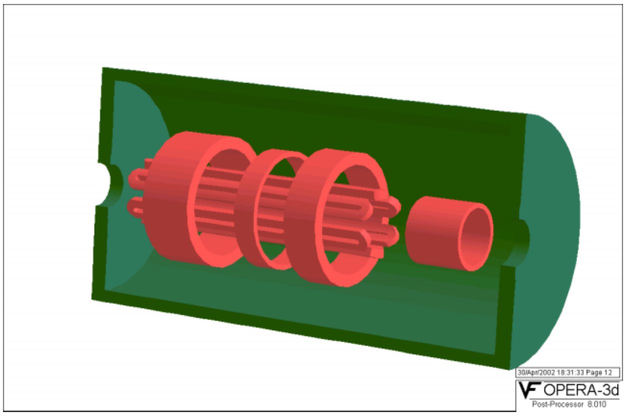

Figure 2: The OPERA-3D model of the magnetic system.

In the meantime, a relevant change to the cryostat design was proposed and studied, i.e. the insertion of the focusing solenoid inside the cryostat, which is expected to simplify the transport process and the beamline itself.

The preliminary studies of forces and stresses did not reveal any risk connected to the mutual solenoids' interaction, as the strength of the focusing solenoid is small with respect to the main ones. Evaluation of different options (1.8 K cooling, Nb_3Sn conductors, etc.) was performed, but we concluded that the advantages do not compensate the risks and the larger costs.

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 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.

A high voltage test bench with a simplified copy of the plasma chamber and of the cryostat will be manufactured in the coming year, in order to optimize the reliability at high voltage, above 40 kV (as reference, the SERSE source is not able to operate above 30 kV).

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. The microwaves emitted from a 28 GHz-10 kW gyrotron through a circular wave guide (TE_{02} mode) will pass through some components added to protect the gyrotron from any reverse power. The arc detector is used for the sparks on the rf window; the mode filter stops any other mode than TE_{02}; a mode converter is used to transform the microwaves from TE_{02} to TE_{01}: this, in addition to oversized circular waveguides reduces the losses. A 90° bend with corrugated walls prevents mode conversion; a dc break is placed just before the source to insulate the waveguide up to 30 kV and a water-cooled sapphire rf window is placed at the entrance of the source to separate the waveguide from the vacuum. A mechanical compensator is used to counteract thermal expansion. A bidirectional coupler measures the incident and reflected power in the TE_{02} mode. 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 were injected in the ECR plasma; the maximum observed reverse power was less than 150 W, which enabled a safe operation of the gyrotron. [1]

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 [6]. 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; a value of 150π mm mrad has been used as starting condition for the preliminary beamline simulations here described. Higher extraction voltage than 40 kV may further decrease the emittance. The analysis beamline design has started from the following assumptions: the focusing solenoid (fig.2) should be as close as possible to the extractor; 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; 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 will 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 (fig. 3): the beam envelope plot in x- and y- direction and some xy phase space plots at different locations (source, entrance and exit of the dipole magnet and exit slit) are shown. 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 [6].

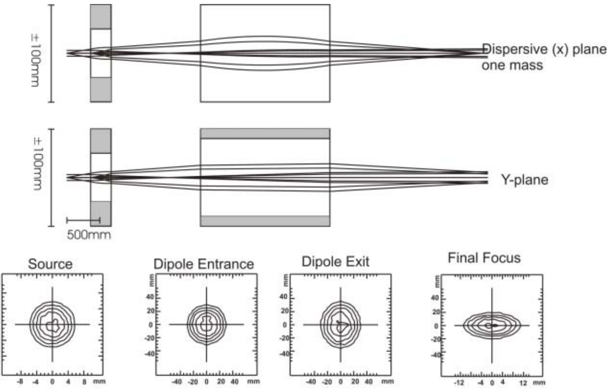

Figure 3: The GyroSERSE analyzing beam line using only one solenoid.

4 ACKNOWLEDGEMENTS

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