PRODUCTION OF HIGH CURRENT-HIGH CHARGE STATES ION BEAMS WITH THE SUPERCONDUCTING ECR ION SOURCE SERSE

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Abstract

The superconducting electron cyclotron resonance (ECR) ion source SERSE, developed by INFN/LNS of Catania and CEA/DRFMC of Grenoble, have reached very high currents for beams of gaseous elements (e.g. 80 eµA of Ar^{14+} , 1 eµA of Ar^{17+}), equal or better to the best ones obtained by ECR ion sources. The performance have been obtained at 14 GHz for field of 1.1 to 1.4 T for the radial field and higher than 2 T for the mirror field, which is a check of the validity at 14 GHz of the High B mode concept, yet demonstrated at 2.45 GHz and 6.4 GHz.

The main features of the installation at the Laboratori Nazionali del Sud will be outlined in the following. At the end of this year SERSE will be coupled to the Superconducting Cyclotron, already operating with the radial injection from the Tandem. A significant increase in energy is expected, as well as an increase of the currents of about two order of magnitude, which will allow to operate the radioactive ion beam facility EXCYT.

1 HOW TO GET INTENSE BEAMS OF HIGHLY CHARGED IONS ?

Semiempirical scaling laws were proposed [1] to relate the ECR ion sources (ECRIS) performance to different parameters. Although the approximations made for these laws are quite rough, they put in evidence the importance of some parameters in ECRIS performance. For instance two of these laws link the optimum charge state (charge state of the highest current) to the rf frequency and to the field of the B minimum trap:

$$q_{opt} \propto \log \omega^{3.5} \quad (1)$$

$$q_{opt} \propto \log B^{1.5} \quad (2)$$

then a straightforward way to increase the average charge state of ion beams produced by ECRIS is to rise at the same time the microwave frequency and the magnetic field of the B minimum trap. A similar concept, called “High B mode” (HBM) [2], comes from the statement that the condition for a quiet plasma in a magnetic trap is:

$$n_e \, k \, T_e << B^2/2\mu_O \quad (3)$$

which means that the magnetic field increase is acting both on electron density and temperature. The experiments have confirmed that there is an increase of performance of ECRIS with the rise of magnetic confining field [3,4]. For the frequency of 14 GHz or higher, HBM operations are possible only with superconducting magnets. Unfortunately superconducting magnets require longer times for construction, higher investments, they are more complex and need some maintainance for cryogenics. These considerations have limited the use of superconducting magnets but the sources operating with superconducting magnets have also some advantages:

- the plasma chamber is bigger and wall recycling is less important, then the source is more stable;
- the capability to tune also the radial field makes easier the plasma optimization.

The original design of SERSE [2] was based on the assumption that the radial field should be pushed up to the maximum level achievable and the two field maxima of the axial profile should be higher than that level, but further experimental results [4] have shown that the axial confining field must be stronger on the injection side.

2 THE SUPERCONDUCTING ECR ION SOURCE "SERSE"

A schematic drawing of SERSE is shown in figure 1: the axial field is given by a set of three solenoid coils, the central one working with a reverse current; the hexapole is made of six flat race-track coils which are encased in a stainless steel supporting cylinder.

This superconducting coil system has the following characteristics for a typical high-B mode profile:

solenoid magnetic fields (max/min/max): 2.7/0.3/1.6 T,
hexapole maximum field : 1.54 T (design value: 1.4 T)
field uniformity : better than 2.8% (design value: 5%)
axial mirror to mirror distance: 52 cm
plasma chamber diameter: 13 cm
plasma chamber volume: 5.6 liter.

The resonance field B_{ECR} at 14 GHz is about 0.5 T and the ratio B/B_{ECR} is larger than three, which is a rule of thumb for good plasma confinement [4]. Microwaves are injected through two ports, each one for a maximum power of 2 kW, but the small dimensions of the plasma volume (the resonance zone axial length is 10 to 12 cm, the diameter at minimum axial field is 5 to 7 cm) have limited the power effectively coupled to the plasma to 2.5 kW at 14 GHz.

Considering that the average charge state of the beam depends on the power, the optimization of the microwave coupling is a critical issue and some developments are under way. Gas inputs for the main gas and the mixing gas are parallel to the waveguides. A biased electrode is mounted at the center of the injection section, to provide "warm" electron to balance the electron deficit of the ECR plasma. An accel-decel extraction system is used, with the intermediate electrode and the ground electrode movable with respect to the extraction electrode.

The extraction electrode (extraction hole is 8 mm in diameter) was at first positioned at the maximum axial magnetic field (1.6 T), and lately moved by 3 cm inside the plasma chamber, closer to the resonance zone, where the field is about 1.4 T. The voltage of the source was 20 kV during the tests here reported, but we have been able to operate the source at higher voltage, above 25 kV.

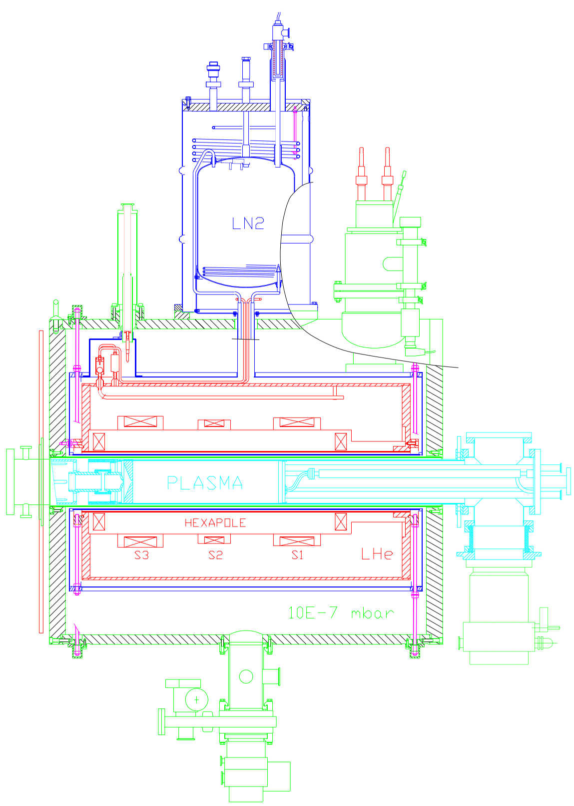

Figure 1: A cut view of SERSE.

3 TESTS OF SERSE AT 14 GHZ AND NEAR TERM DEVELOPMENTS

The superconducting coil system [5] has been assembled inside the cryostat during the summer 1997 and the tests of the source has been carried out in the testbench at Grenoble [6].

The conditioning of the source chamber was slow and the SERSE base pressure, still improving, is today in the high 10^{-8} mbar range at injection, and in the low 10^{-7} mbar range at extraction/beam line. The pumping is obtained through two 600 l/s turbomolecular pumps, at the injection (almost 200 holes are drilled in the flange) and at the extraction, where some apertures have been drilled to guarantee an appropriate pumping.

Since the first days of operations in High B mode, the source demonstrated to be able to produce a plasma with very high electron density and temperature, with a charge state distribution (CSD) peaked on 9^+ for pure Argon [6].

After some weeks of operations (8 to 10 hours a day) the source performance was close to the expectations [7] for 14 GHz single frequency operations, corresponding to a plasma density of 1 to 2 * 10^{12} cm^{-3} and an electron temperature between 5 and 10 keV.

Fig. 2 shows one of the best results obtained for pure Oxygen; it is remarkable that the amount of O^{7+} is almost equal to the amount of O^{5+} and that fully stripped oxygen current is at least 40 eμA, which to the goal set by the EXCYT project [8]. Fig. 3 and 4 show the best CSD yet obtained for Argon, optimizing respectively the charge states 11^+ and 16^+, with increasing amount of oxygen as mixing gas. In tab. 1 the best results for Argon and Oxygen are summarized and compared to the ones obtained by the best operating ECRIS. Only the source of LBL and RIKEN (which use respectively the double frequency effect and 18 GHz microwave) have comparable results.

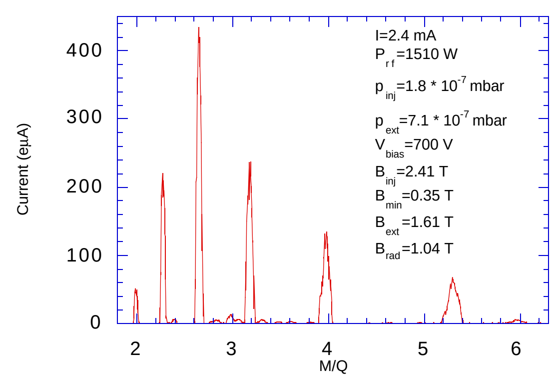

Fig. 2 - A CSD for pure oxygen.

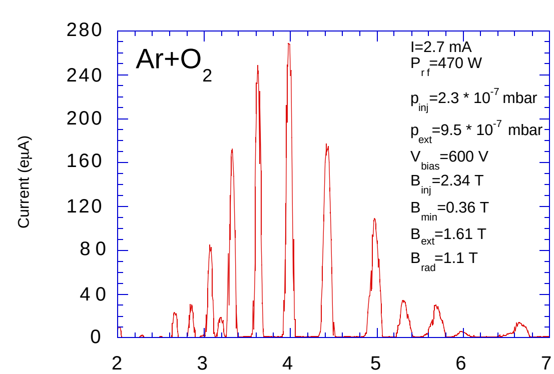

Fig. 3 - A CSD for argon, optimized for 11^+.

Table 1 - A comparison of the SERSE performance with the results obtained by some other ECR ion sources (*High B mode, § two frequencies, #no gas mixing)

Ion	Sc-Ecr	*Caprice	AECR§	SERSE*	RIKEN
	6.4 GHz	14 GHz	14 GHz	14 GHz	18 GHz
O^{6+}	930	1130	1150	430 #	
O^{7+}	205	180	306	225 #	
Ar^{11+}	200	190	270	257	300
Ar^{12+}	125	100	192	200	180
Ar^{13+}	67	40	120	122	
Ar^{14+}	36	17	77	80	90
Ar^{16+}	2.5	1	21	17	18
Ar^{17+}			1.35	1	

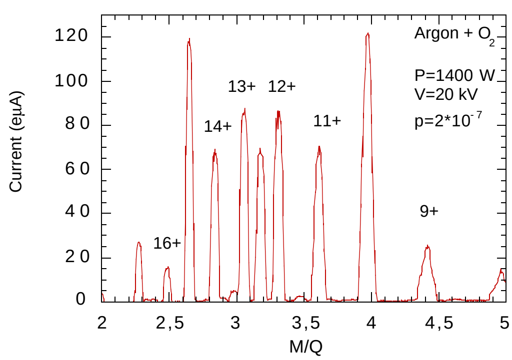

Fig. 4 - A CSD for argon, optimized for 16^{+}.

The pressure appears now to be the main limiting factor for the production of highly charged ions. Outgassing is not negligeable and it can explain the poor results of the tests which has been carried out during last two weeks of tests in the testbench, with an Al liner inside the plasma chamber. The intensities of high charge state beams of Argon was 60 to 80% than the ones with the stainless steel chamber reported in tab. 1 and the performance deteriorate with the increase of the rf power.
In February 1998 we had to stop the source tests, because of a small leak in the cryostat current leads, which appeared during the mounting of the magnets and which was fixed before the transfer of the source to LNS.
The transfer has been carried out in May 1998 and the cooldown at LNS has been completed at the beginning of June. The operation of the source at LNS has just begun and the first weeks will be devoted to the repetition of the tests carried out in the Grenoble testbench. With respect to the testbench, some improvements are already available:
- the LHe refilling will be done automatically from the LNS liquifier plant;
- the source can be operated at 14 GHz and at 18 GHz (single frequency or two frequencies operations [9];
- a high temperature (2000°C) oven will be used for metallic ion production [10];
- a 1000 l/s pump will be mounted at the extraction, to limit charge exchange effects on fully stripped ion beams.
The installation of SERSE at LNS will significantly enhance the currents extracted from the Superconducting Cyclotron [11] (one to two orders of magnitude) and the maximum beam energies. In fig. 5 the maximum energies obtainable with the radial injection are compared with the one expected with the axial injection, by extrapolation of the data yet measured during the source tests.

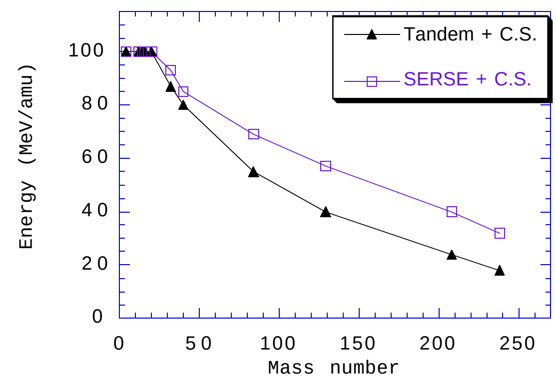

Fig. 5 - The maximum beam energy of the LNS Superconducting Cyclotron.

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