THE SUPERCONDUCTING ECR ION SOURCE SERSE: A TOOL FOR HIGHER ENERGIES AND CURRENTS WITH THE LNS SUPERCONDUCTING CYCLOTRON

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The superconducting ECR ion source SERSE has been developped by INFN/LNS, Catania and CEA/DRFMC, Grenoble, reaching very high currents for beams of gaseous elements (e.g. 225 eμA of O^{7+}, 200 eμA of Ar^{12+}, 1 eμA of Ar^{17+}). The best performances at 14 GHz have been obtained for fields as high as 1.1 to 1.4 T for the radial field and higher than 2 T for the mirror field, confirming the validity of the High B mode concept, yet demonstrated at 2.45 GHz and 6.4 GHz. The results of the tests and the main features of the installation at Laboratorio Nazionale del Sud will be outlined. The coupling of the source to the Superconducting Cyclotron (already operating with the radial injection from the Tandem) is scheduled for the end of this year. A significant increase in energy is expected as well as an increase of the currents extracted from the cyclotron of about two orders of magnitude, which will allow to operate the radioactive beam facility EXCYT.

1 The source design

The design of the electron cyclotron resonance (ECR) ion source SERSE [1] is based on the observation that high magnetic fields for plasma confinement are essential to obtain high electron density and temperature plasmas and to boost intensities and charge states of the ion beams [2,3]. Thus SERSE was designed to attain the highest magnetic field yet achieved for ECR ion sources (ECRIS), in order to work in the so-called high-B mode configuration (high mirror ratio minimum-B configuration) at frequencies of 14 and 18 GHz. The drawing of SERSE is shown in figure 1: the axial field is given by three solenoid coils, the central one working with a reverse current; the hexapole is made of six flat race-track coils encased in a stainless steel supporting cylinder. This superconducting coil system has the following characteristics in the high-B mode profile:

solenoid magnetic fields (max/min/max): 2.7/0.35/1.6 T,
hexapole maximum field : 1.54 T (design field : 1.4 T)
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 equal to 0.5 T and the ratio B/B_{ECR} results to be larger than three for all the directions, 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 was 10 to 12 cm, the diameter was 5 to 7 cm) limit the power which can be effectively coupled to the plasma to 2.5 kW for operation at 14 GHz.
The design of the source was completed in 1993 and in 1995 all the equipments were available, but unfortunately the performance of the magnet system was quite poor and the decision to order a new set of magnets led to a significant shift in the experimental programme.

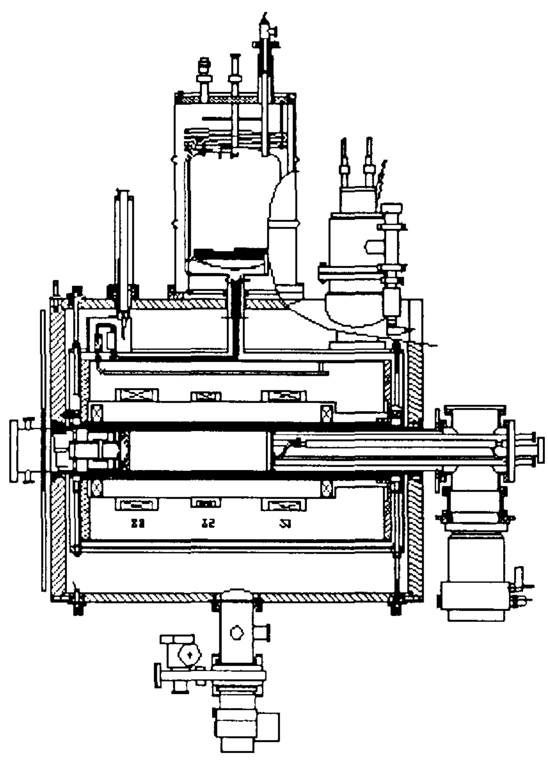

Fig. 1 - A sketch of SERSE.

During the second part of 1996, while the design and construction of new magnetic system was going on, however the first built magnets were mounted and SERSE was assembled for testing the whole source. Cooling of the cryostat from 300K to 4.2K was obtained in about one week and the total facility LHe consumption, i.e. cryostat with helium line and additional 500 liter LHe reservoir, was about 3.6 l/h in normal working conditions.

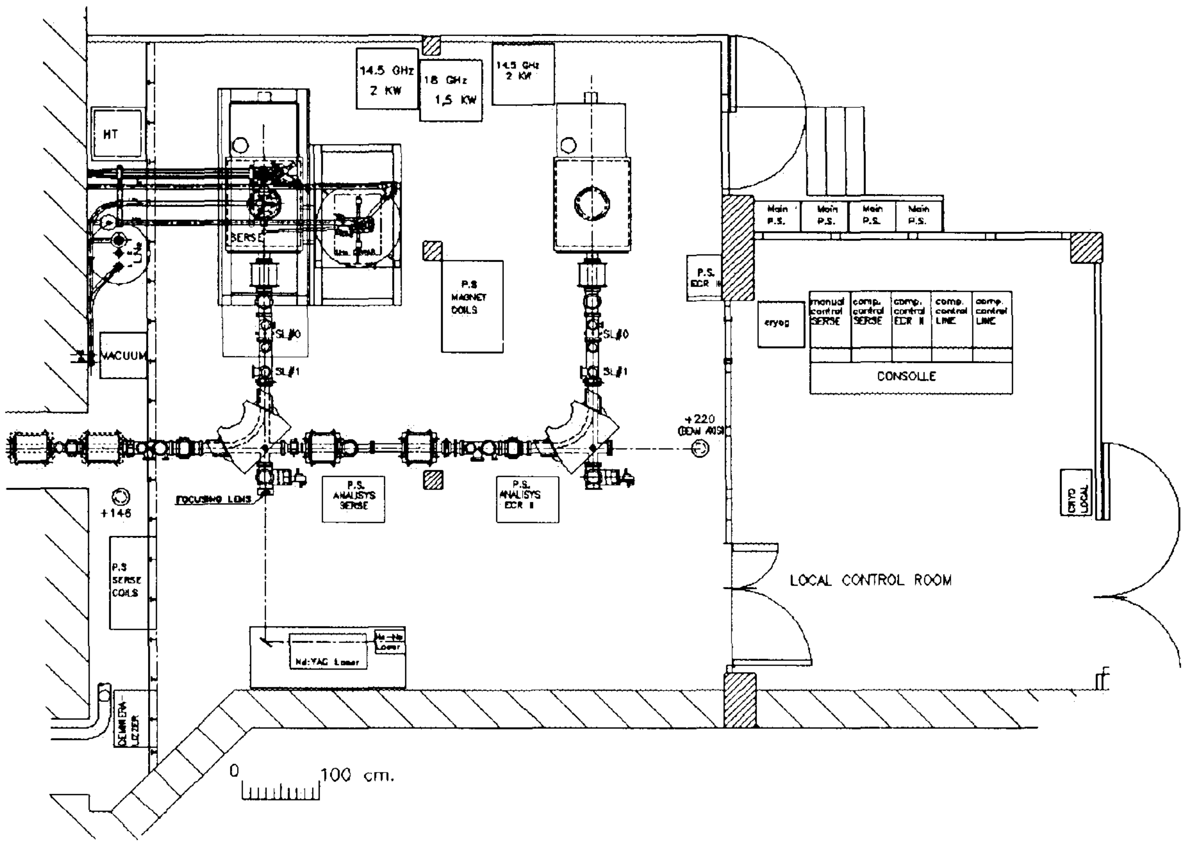

Fig. 2 - The ECR ion sources (ECRIS) room at LNS.

Some preliminary tests [5] were performed during the first months of 1997 at Grenoble with the same experimental setup as the one of the future installation at Catania, even for the extraction system and the beam line (fig. 2).

Because of a hexapolar magnetic field limited to 0.8 T and of a low mirror ratio, the absolute level of the performance was low either in terms of charge state and intensities, but these preliminary tests were useful to test the analysis section of the beam line, the microwave input system, the extraction system and all the ancillary equipment. The ECR plasmas were characterized by a high level of hard X-rays, as one would expect from poor magnetic confinement. In order to improve the confining field of the new system, calculation of magnetic field, forces and stresses on the system were performed [6] and it came out that the impossibility of reaching the highest required values of magnetic field was probably due to an insufficient stiffness of the coils support. The new superconducting magnets exceeded the design value after some training and the agreement with the specifications was good. Radial field uniformity was better than 2.8% (the design value was 5%). In August 1997 the new superconducting coil system was mounted in place of the old one inside the cryostat so that the tests of the whole source has been carried out in the testbench at Grenoble [7] with the highest magnetic fields so far realized in electron cyclotron resonance ion sources. The high field allows to obtain high electron density and temperature plasmas, needed for ion charge state upgrading, provided that vacuum is below 10^{-7} mbar inside the plasma chamber, in order to reduce the charge exchange limitation.

The installation of this high performance ECR ion source at LNS will enhance not only the currents extracted from the LNS Superconducting Cyclotron [8] (one to two orders of magnitude), but also the maximum beam energies.

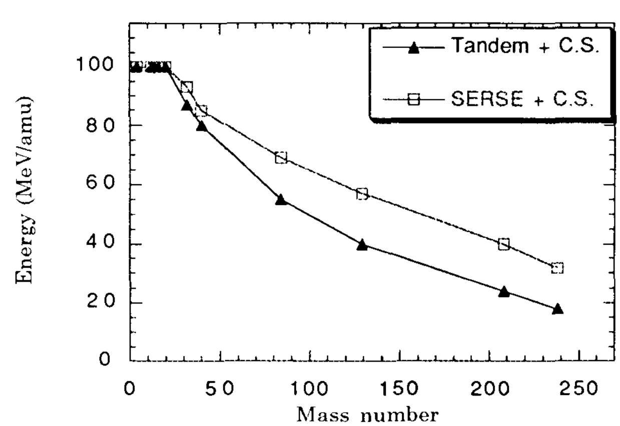

Fig. 3 - The maximum beam energy of the Superconducting Cyclotron.

For the heaviest ions, the maximum design energy is limited by the charge state of the ions injected into the Cyclotron, then the increase of the charge state of the injected ions is very effective. In fig. 3 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.

2 The source tests

The tests were carried with an extraction voltage of 20 kV, but the capability to operate the source up to 26 kV was verified, this voltage being adequate for the injection of the most beams in the cyclotron (maximum voltage will be about 30 kV). A ϕ=30 mm biased electrode has been used (voltage ~ 600 V, currents ~ 1-2 mA).
The conditioning of the source chamber has been slow up to now 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 and in the beam line. The pumping is obtained through two 600 l/s turbomolecular pumps, at the injection and at the extraction. In order to improve the pumping speed, a 1000 l/s turbomolecular pump will be mounted soon in a volume where charge exchange processes significantly affect the beam and depress the current of fully stripped or H-like ion beams.
The extraction electrode ($\phi_{extraction}$ = 8 mm) 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. 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 [7]. After some weeks of operations (8 to 10 hours a day) the chamber conditioning was sufficient to let the source behave according to the expectations for 14 GHz single frequency operation. Fig. 4 shows one of the best results obtained for pure Oxygen; it is remarkable that the current of fully stripped oxygen is at least 40 eμA, close to the goal set by the EXCYT project [9]. Fig. 5,6,7 show some of the best CSD yet obtained for Argon, optimizing respectively the charge states 11^+,12^+,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 ECRIS. It comes out that the source has comparable results to the sources of LBL and RIKEN, which respectively use the double frequency effect and 18 GHz injection, and better than the other 14 GHz ECR ion sources. 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 Grenoble testbench, with an Al liner insider the plasma chamber. The average production rates for high charge state beams of Argon was 60 to 80% of those obtained with the stainless steel chamber, but when the rf power was increased up to 2 kW, the performance fastly deteriorate of a factor two.

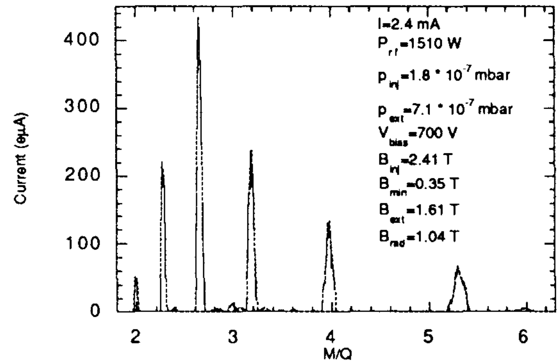

Fig. 4 - A CSD for pure oxygen.

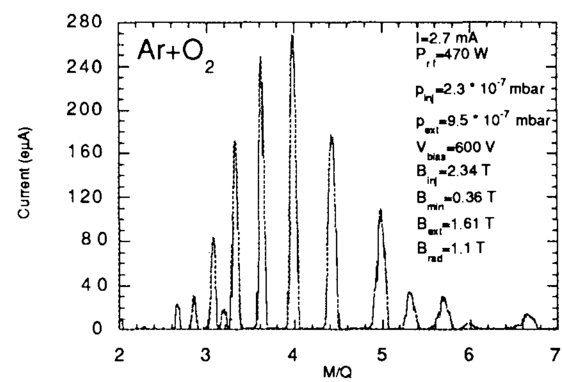

Fig. 5 - A CSD for argon, optimized for 11^+.

Tab. 1 - SERSE results compared with those obtained by some other ECR ion sources (*High B mode, § two frequencies, #no gas mixing)

Ion	Sc-Ecr* 6.4 GHz	Caprice 14 GHz	AECR§ 14 GHz	SERSE* 14 GHz	RIKEN 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	

Another explanation may be found in the distance between the chamber wall and the plasma, because of the size of the source, but the deterioration of currents with the power can be explained only by the outgassing. Unfortunately we should interrupt these tests, because of a small leak in the cryostat, which appeared during the mounting and which had to be fixed before the transfer of the source to LNS.

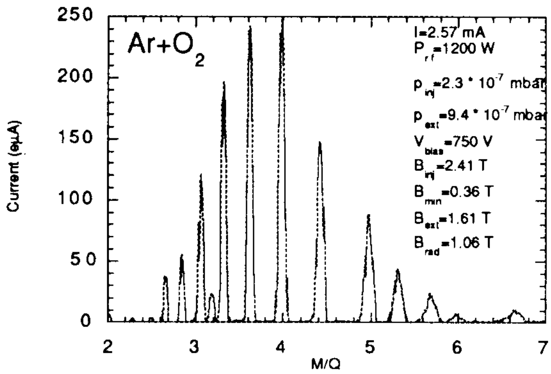

Fig. 6 - A CSD for argon, optimized for 12$^+$.

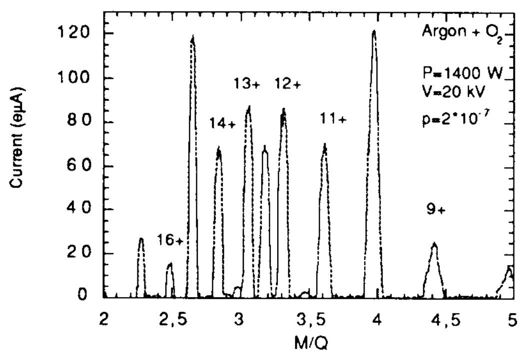

Fig. 7 - A CSD for argon, optimized for 16$^+$.

3 The installation at LNS

The transfer of the source at LNS has been carried out in May 1998 and it is now located in an area adjacent to the Cyclotron vault, to be shared with another conventional CAPRICE source under construction. The constraints of this room have largely complicated the installation, especially because of the short distance between the aperture towards the cyclotron vault (where the beam line is positioned) and the ceiling. This aperture fixes the height of the source axis to a level 2.2 m above the floor, then only 2.1 m are available for the source, resulting in significant limitations to the cryogenics supplies, which has been addressed with non standard design of many components.
The superconducting coils power supplies, the two 14 GHz and the 18 GHz rf generators, the HV supplies and all the other equipments are located around the source.
The liquid helium coming from the LNS liquifier plant is transferred to the LHe dewar close to the source by means of a dedicated transfer line, which allows a continuos refilling.
The beam extracted from the source SERSE is focused by a solenoid and analyzed by a 90° dipole magnet (ρ=500 mm, gap=60 mm) before entering in the axial injection beamline, now under construction [10, 11].

4 Future prospects

Considering that the magnetic system allows to operate the source at field level about 30% higher than we have done for the above tests, it can be convenient to operate the source at higher frequency and a 18 GHz-1500 W generator is already available. Double frequency operation will be carried out, by injecting 18 GHz on one port and 14 GHz on the other port, as it has been done for AECR at Lawrence Berkeley National Laboratory [12]. Moreover the use of overdense plasmas and of Laser Ion Sources as injector of charged ions in the ECR plasmas should let us to be able to accelerate within a few years fully stripped beams up to Z>30.
A high temperature oven [13], yet tested off-line, is able to attain 2000°C with an evaporation rate of 10^{13}-10^{15} atoms/sec, in line with the neutrals rate needed by ECRIS
We expect that these upgrading will allow to SERSE to further increase its high charge states currents, and to be an invaluable tool for the production of fully stripped light ions, until the completion of third generation ECRIS, now in the design phase at the Laboratori Nazionali del Sud and at the Lawrence Berkeley National Laboratory.

Acknowledgements. We thank A. Carbonaro, E. Messina, A. Pagano, F. Speziale, the LNS Technical Division, J.M. Matthonet, J.P. Arnaud, P. Dalban, L. Guillemet, A. La Grassa and the Cryogenics Group of SBT for the support.

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