Summary of the performances of the superconducting electron cyclotron resonance ion source at 14 GHz

P. Ludwig, F. Bourg, P. Briand, A. Girard, G. Melin, D. Guillaume, P. Seyfert, and A. La Grassa
Département de Recherche Fondamentale sur la Matière Condensée, Service des Ions, Atomes et Agrégats, Service des Basses Températures, CEA/Grenoble, 38054-Grenoble Cédex 9, France

G. Ciavola, S. Gammino, M. Castro, F. Chines, and S. Marletta
Istituto Nazionale di Fisica Nucleare, Laboratorio Nazionale del Sud, 95123 Catania, Italy

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This article deals with the most recent performance of the superconducting electron cyclotron resonance ion source (SERSE) working at 14 GHz with high magnetic fields after the required conditioning and optimization of several operating parameters. SERSE has now achieved an outstanding level of performance in delivering highly charged ion beams in argon and oxygen gases: the results obtained while operating in a stainless steel chamber and with an aluminum liner are shown and discussed. © *1998 American Institute of Physics.* [S0034-6748(98)03312-7]

I. INTRODUCTION

The superconducting electron cyclotron resonance ion source (SERSE) parameters and objectives have been extensively described in several publications.[1] The first operation of SERSE with reduced magnetic field coils was carried out early in 1997,[2] soon after a new coil system was installed. The characteristics of this new superconducting coil system and the preliminary SERSE results at full magnetic fields were recently presented.[3]

As compared to other existing electron cyclotron resonance ion sources (ECRIS), SERSE has two major differences, high magnetic field and large plasma chamber dimensions. The high magnetic field is expected to allow for high-density plasma confinement as well as high frequency operation. The high density plasma makes it easier to obtain highly charged ions, and should increase the extracted ion currents as well. The beneficial effect of large plasma chamber dimensions, although already encountered in a few ECRIS,[4] has not yet been fully exploited by working at magnetic field strengths as high as those of SERSE. This may have important consequences as shown and discussed below. SERSE has routinely run for a few months, and this article only concentrates on the operating conditions and performances during this period. The SERSE cryogenic system[2] worked quite reliably, with a total average liquid helium consumption of about 3.5 l/h, including the consumption of cryostat, helium line, current leads, and additional 500 liter reservoir.

II. OPERATING CONDITIONS AND PROCEDURE

The tests were not performed at the full capability of the coil system[3] in order to keep a safety margin with respect to quench occurrence, and to allow for magnetic field scans of both the axial and hexapole fields. The SERSE coil current settings which are generally used, and the resulting field configuration are given in Table I. Figure 1 shows the axial magnetic field profile. The axial walls of the plasma chamber were not exactly located at the axial field maxima (Fig. 1). On the injection side the chamber wall was initially positioned between the two mirrors in the decreasing magnetic field. On the extraction side the plasma electrode position was optimized on the basis of the largest extracted ion current, and positioned accordingly at a lower magnetic field than the maximum field (1.5 T).

When comparing SERSE to other sources, it is interesting to point out that the resonance zone volume of SERSE, presumably the rf power absorption volume, is small and does not scale like the plasma chamber volume. The chamber volume is close to the magnetic plasma confinement volume (see below) owing to the large dimension of the superconducting hexapole. In SERSE the rf power absorbed by the resonance zone volume is about twice as large as that of a high performance compact Caprice source,[5] but the electrons being heated in this volume may spread out in a larger volume. Other SERSE parameters worth mentioning are given in Table II.

The SERSE plasma chamber is pumped down by two 600 l/s units, at injection and at extraction. Two hundred and three 6 mm holes have been drilled in the wall at injection. Lately, large apertures were opened in the plasma electrode at extraction in order to improve the pumping speed during plasma conditioning; the pumping speed was also increased in the pipe that holds the biased electrode at injection to allow for electrode degassing. These improvements of the vacuum conditions proved to be absolutely necessary when optimizing the source on high charge state ions such as Ar^{16+} and Ar^{17+}. As mentioned above, the starting procedure of SERSE included first, an optimization of the plasma electrode position near the closed $|B|$ surface at the highest $|B|$ value ($\sim$1.37 T), contained completely within the plasma chamber. This gives the largest plasma confinement volume.[6]

Two 14 GHz transmitters were used, one for each rf power launching waveguide. The rf power was equally dis-

TABLE I. SERSE magnetic field and ECR (at 14 GHz) parameters: solenoid coil current settings, injection coils I_{inj}, central coil I_{cent}, extraction coils I_{extr}; corresponding axial magnetic field extrema, B_{inj}^{Max},B_{cent}^{min},B_{extr}^{Max}; hexapole coil current range I_{hexa}, corresponding radial magnetic field range at chamber wall ($\phi = 13$ cm) B_{hexa}; axial distance between axial magnetic field maxima L_{MM}, axial distance between walls L_{ww}; plasma chamber volume V_{pc}; axial magnetic fields at chamber walls $B_{inj}^{wall}/B_{extr}^{wall}$; ECR surface axial length and radial diameter L_{ecr}/Φ_{ecr}; maximum rf power at 14 GHz so far used P_{rf}.

$I_{inj}/I_{cent}/I_{extr}$ (A)	I_{hexa} (A)	L_{MM} (cm)	V_{pc} (cm^3)	L_{ecr}/Φ_{ecr} (cm)
117/−132/126	100–110	52	5600	8/5.5
$B_{inj}^{Max}/B_{cent}^{min}/B_{extr}^{Max}$ (T)	B_{hexa} (T)	L_{ww} (cm)	$B_{inj}^{wall}/B_{extr}^{wall}$ (T)	P_{rf} (kW)
2.4/0.45/1.5	1.2–1.3	42	2.2/1.4	≤2

tributed by the two inputs. During plasma operation, the reflected power was minimized by slightly changing the operating frequency of the corresponding line by a few tens of MHz, while staying in the klystron bandwidth. After opening to atmosphere, several days of wall conditioning and biased electrode degassing were usually necessary before achieving normal source operation at low pressure ($\sim 2\times 10^{-7}$ mbar). This conditioning period was carried out with oxygen plasma at progressively increasing input rf power. Highly charged ion production would not be possible without this conditioning. As compared to other nonsuperconducting high performance ECRIS,[5] SERSE has a much larger plasma chamber surface to condition and clean up. In spite of its likely higher plasma density, and its larger $|B|$ plasma confinement surfaces, the particle flux, both electrons and ions, impinging on the SERSE walls may be smaller than that of high performance existing ECRIS.

Normal source operation with highly charged ion production was only possible with convenient biasing voltage applied on the cylindrical electrode at injection (see Table II). SERSE has no specific first stage, or any other external source of electrons to boost the density buildup. Source tests described below were performed only in gases, oxygen and argon, with a stainless steel plasma chamber, and with an aluminum liner inserted within the stainless steel chamber.

III. OPERATION IN STAINLESS STEEL PLASMA CHAMBER

One of the first observed remarkable feature of SERSE, was its capability of delivering highly charged ions at the

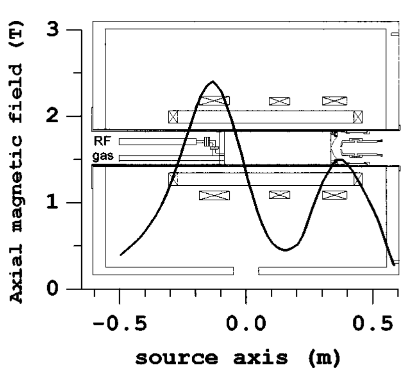

FIG. 1. SERSE axial magnetic field and location of plasma chamber during these tests; horizontal axis origin is at cryostat midplane.

TABLE II. Other SERSE parameters: extraction voltage V_{extr}, plasma electrode/puller electrode diameters Φ_{plas}/Φ_{pull}, diameter/intensity/voltage $\Phi_{elec}/I_{elec}/V_{elec}$ of biased electrode (on axis at injection), rf power launching systems at injection (off-axis waveguides), base/working pressures P_b/P_w.

V_{extr} (kV)	Φ_{plas}/Φ_{pull} (cm)	$\Phi_{elec}/I_{elec}/V_{elec}$ (cm/mA/V)	rf launching	P_b/P_w (mbar)
20–25	0.8/1.7	3/≤2/≤600	2×WR62	$5\times 10^{-8}/2\times 10^{-7}$

very beginning of plasma operation: Ar^{16+} ion current was already about 1 $e\mu$A, while the current distribution peaked on Ar^{11+} ion current. Then these highly charged ion currents kept regularly increasing during the conditioning period. It is important to notice that the results presented below were obtained only after a limited period of about two months. A fully conditioned source was never actually achieved because frequent vacuum breaks back to atmospheric pressure for various optimizations were still necessary.

The results given in Table III are the best measured extracted ion currents, while separately optimizing the different charge states. Oxygen was used as a mixing gas when maximizing the argon ion currents. For oxygen ions the data presented were obtained while working in pure oxygen gas. Figure 2 shows an argon ion current distribution measured when optimizing highly charged argon ion currents (Ar^{16+}), while source conditioning was presumably advanced, the magnified detail shows the presence of Ar^{17+} ion current. Figure 3 shows an oxygen ion current distribution measured when optimizing O^{7+} ion current. Other presentations of Figs. 2 and 3 in logarithmic scale (Figs. 4 and 5), show the absolute currents of all extracted ions existing in SERSE plasma; here overlapping oxygen and argon ion currents, i.e., of same m/q, have been interpolated.

Besides the outstanding level of highly charged ion currents, specifically those of Ar^{16+} and Ar^{17+}, these distributions reveal an unusual behavior with respect to nonsuperconducting high performance existing ECRIS when optimized for Ar^{16+} ions:[5] (i) high performance existing ECRIS have argon ion current distributions peaking on charge 10/11 (most abundant ion current), SERSE argon ion distributions peak on charge 12/13; (ii) mixing gas ion currents (e.g., oxygen ion currents in argon ion current distributions) are usually by far dominant with respect to highly charged argon ion currents in existing ECRIS, here in SERSE they are not, but are about the same amplitude or even lower, e.g., O^{5+} in Figs. 2 or 4.

IV. OPERATION WITH AN ALUMINUM LINER

Aluminum coatings and aluminum plasma chambers as well have proved to be very efficient in boosting the extracted multicharged ion currents from ECRIS.[5] The forma-

TABLE III. Best separately optimized ion currents of argon and oxygen ions in $e\mu$A (stainless steel plasma chamber).

Ar^{11+}	Ar^{12+}	Ar^{13+}	Ar^{14+}	Ar^{16+}	Ar^{17+}	O^{6+}	O^{7+}
257	200	122	80	17	1	430	225

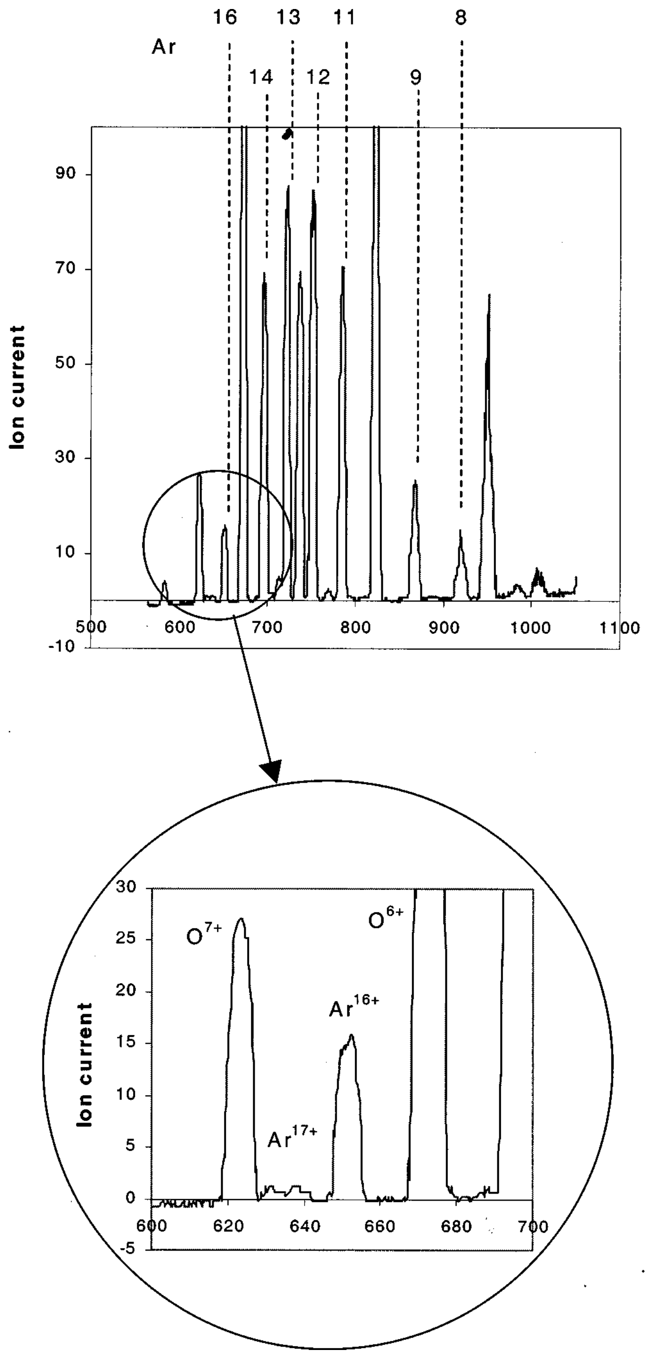

FIG. 2. SERSE argon ion current distribution when optimizing Ar^{16+} ion current, with oxygen as a mixing gas, in stainless steel plasma chamber, the magnified detail shows the Ar^{17+} ion current peak; ion currents are in $e\mu A$, horizontal scale is the analyzing magnetic field in gauss.

tion of Al_2O_3 coating on the walls is likely increasing the yield for secondary electrons under the impact of impinging plasma particles, which may in turn increase the electron density and the source performance. Therefore a 1-mm-thick aluminum liner was introduced into the SERSE stainless steel plasma chamber, as a solid aluminum chamber mockup. The liner was strongly tightened on the stainless steel walls to secure its cooling. Conditioning with pure oxygen plasma to allow for aluminum oxide formation was performed continuously for about a week, and operation with argon resumed for only a few days. Soon after, SERSE shutdown

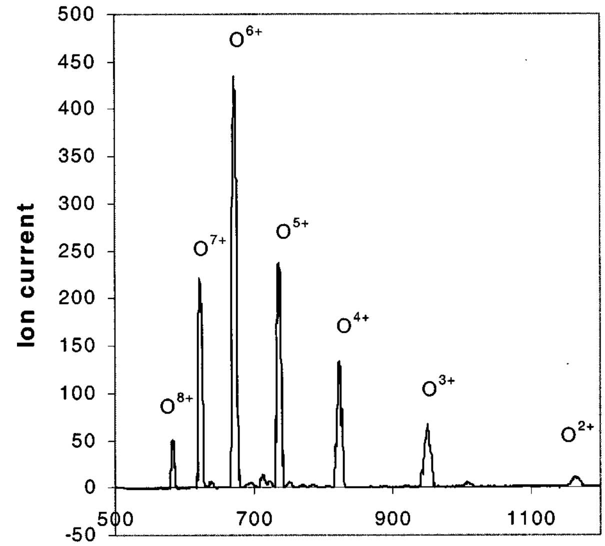

FIG. 3. SERSE oxygen ion current distribution when optimizing O^{7+} ion current, no mixing gas, in stainless steel plasma chamber; ion currents are in $e\mu A$, horizontal scale is the analyzing magnetic field in gauss.

occurred before transfer to Catania. The ion currents delivered by SERSE (see Fig. 6) did not even reach those obtained with the stainless steel plasma chamber. These results are not at all definitive because of the following reasons: (i) the operation with aluminum liner did not last enough time to achieve the aluminum conditioning (formation of Al_2O_3 coating not complete)?, (ii) aluminum conditioning was not actually possible because of the plasma chamber/liner dimensions too large with respect to the ECR plasma position, as already mentioned above?, (iii) the aluminum liner was not tightened enough to the stainless steel chamber for its efficient cooling, and liner degassing was too important to allow for highly charged ion production without charge exchange? The latter reason is the most likely. Therefore these tests with aluminum should resume later with a longer conditioning period.

V. COMMENTS AND PROSPECTS

With respect to other ECRIS, the unusual behavior of SERSE argon ion current distributions, i.e., the position at

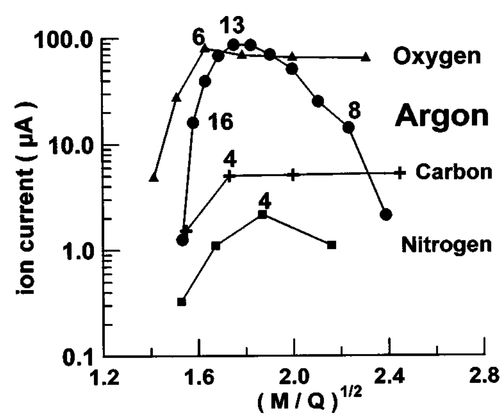

FIG. 4. Logarithmic representation of Fig. 2 showing all extracted ions of SERSE plasma.

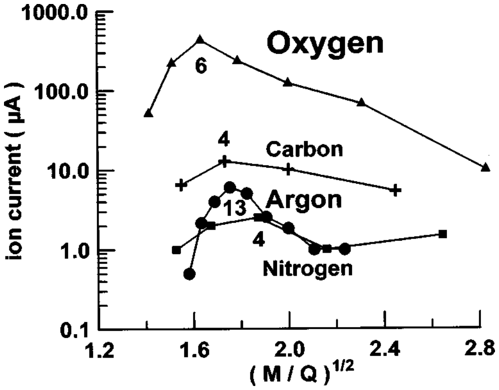

FIG. 5. Logarithmic representation of Fig. 3 showing all extracted ions of SERSE plasma.

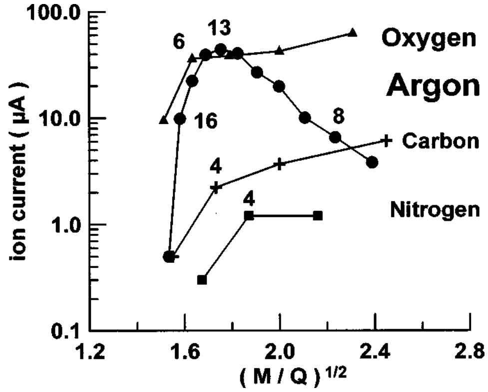

FIG. 6. SERSE extracted ion currents, argon main gas, oxygen mixing gas, aluminum liner.

high charge state (12/13) of the peak of the distribution (Fig. 2), is interesting to analyze. It has been shown[6] that this peak establishes at charge state for which ionization time and ion confinement time are close to each other. Both short ionization times and large ion confinement times lead to shift this peak towards higher charge states. Therefore this effect observed on SERSE data may indicate a large electron density (short ionization times), and large ion confinement times. The SERSE high magnetic field may actually confine a larger electron density than any other ECRIS. Both SERSE plasma density and dimensions may allow for large ion confinement times. Note also that charge exchange losses are likely very small in SERSE.

The SERSE ion current distribution width in charge state is smaller than that of other existing ECRIS, for instance Caprice,[5] when optimized for the same high charge state ions (here Ar^{16+}). This interesting feature may have some application in the production of radioactive multicharged ions (higher production efficiency of some charge states).

It is clear that the high magnetic fields of SERSE, both axial and hexapole fields, were of paramount importance to obtain the high level of performance presented in this article. However, at this high magnetic field once a highly charged ion current was optimized after playing with pressure, mixing gas amount, and biased electrode voltage, the improvement that was expected by slightly increasing the magnetic field was not very important. It is likely that the full benefit of a magnetic field increase would be obtained by increasing the rf frequency correspondingly. This is why further tests of SERSE in view of new improvements will be carried out with double frequency 14/18 GHz operation and/or single frequency 18 GHz operation.

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