Comparison of the charge state distributions of electron cyclotron resonance ion sources working in high *B* mode at different frequencies

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The behavior of the two superconducting electron cyclotron resonance ion sources of Michigan State University-National Superconducting Cyclotron Laboratory and of INFN-Laboratori Nazionali del Sud, operating respectively at 6.4 and 14 GHz is compared in this note. The charge state distributions present a similar shape, when both the sources are optimized for the production of high charge state ions. The beam intensity is roughly proportional to the square of the frequency which may be explained by the difference in plasma density. © *1998 American Institute of Physics.* [S0034-6748(98)03808-8]

The role of some key parameters for the production of high charge states in electron cyclotron resonance ion sources (ECRIS), such as the electron density and temperature or the ion lifetime, has been tested by many experiments and the so called ''scaling laws'' [1] have been discussed extensively during the last 10 years.

We have participated in the debate[2] with some comments and experiments, in the framework of the current models, with particular attention to the concept of the high *B* mode,[3] which outlines a particular mode of operating the ECRIS, with the magnetic confining field much higher than the resonance field $B_{\mathrm{ECR}}=2\pi m f/e$.

In a plasma stable from a magnetohydrodynamical point of view, with a plasma density limited by the cutoff density, the high *B* mode[2] concept suggests that an increase of magnetic field is useful until the density approaches the cutoff density. If this plasma density is obtained, a further increase of magnetic field is not effective, except in the case where even a higher frequency is used (which leads to higher cutoff density). Thus, by doubling the frequency and magnetic field (provided that rf power and pressure are not limiting factors for the production of high charge states), one could gain an increase in plasma density of a factor of 4 and a boost of extracted current of high charge state ion beams. Obviously, the real plasma modeling is somewhat more complicated than that proposed by the scaling laws and by the high *B* mode concept, because the interplay between frequency, magnetic field, ion lifetime, electron density, and temperature is not simple and these concepts are then only useful as a guideline.

The high *B* mode has been successfully demonstrated on the superconducting ECR ion source SC-ECRIS at the National Superconducting Cyclotron Laboratory of the Michigan State University, operating at 6.4 and 2.45 GHz,[4,5] but no extension was possible to higher frequencies because of the low hexapolar field achievable by this source.

Recently another superconducting ECR ion source, SERSE,[3,6] has been built for the axial injection of the superconducting cyclotron at the Laboratorio Nazionale del Sud in Catania and its magnetic field is high enough to attain high *B* mode operation at 14 and 18 GHz (maximum radial field is 1.5 T, maximum axial field is 2.7 T).

Considering that the magnets and the plasma chamber of SERSE are similar to the ones of SC-ECRIS, a similar set of operational parameters was obtained in the experiment described here, except for the plasma density, which is much higher in the case of SERSE, because of its higher frequency.

For SC-ECRIS at 6.4 GHz the best results, in terms of high charge state production, were obtained for a microwave power of more than 1200 W coupled to a plasma volume of a few tens of cm^3, with a small amount of the main gas with respect to the support gas, a pressure in the low 10^{-7} mbar and a value of confining field 2.5× the resonance field for the hexapole and about 5× the resonance field for the mirror. In this case the charge state distribution for argon (Fig. 1) had a maximum on the state of 12^+ and the amount of 16^+ was remarkable.

When we operate SERSE at 14 GHz under similar conditions (Fig. 2), with a pressure in the chamber on the order of 2×10^{-7} mbar, the charge state distribution (CSD) is close to the one in Fig. 1, except for a broader maximum between states 11^+ and 14^+, and the amount of 16^+ is very

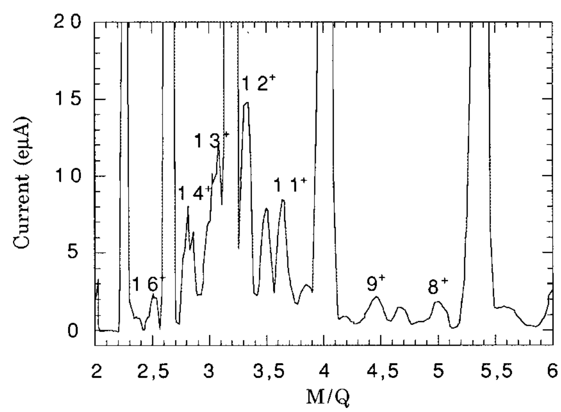

FIG. 1. Charge state distribution for argon beams obtained with the source SC-ECRIS of MSU-NSCL.

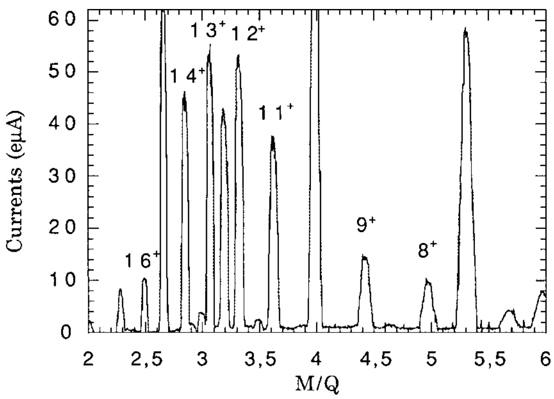

FIG. 2. Charge state distribution for argon beams obtained with the source SERSE of INFN-LNS.

high. In Table I the relevant source parameters are reported for both the experiments.

It must be pointed out that the distance of the resonance points on the exis (i.e., the points where $B_{\mathrm{mirror}}=B_{\mathrm{ECR}}$) was in both cases only 10 cm, which is an indication of the poor validity of volume scaling in ECR ion sources.[4]

The main difference between the CSD in the two experiments concerns the absolute level of the current obtained, which is a factor 4–6 higher in the case of SERSE at 14 GHz compared to SC-ECRIS at 6.4 GHz. This value may be originated by a much higher value of the cutoff density, which in simple models is expected to scale as the square of the frequency ($n_{\mathrm{cutoff}}^{\mathrm{SERSE}}=4.78n_{\mathrm{cutoff}}^{\mathrm{SC\text{-}ECRIS}}$). According to the high B mode, it appears that in both cases highly confined ECR plasmas were produced, with a similar value of electron temperature, but with a plasma density quite different. The base pressure inside the plasma chamber may have limited the fraction of fully stripped and H-like ions, which should increase significantly according to the ''batch model'' [7] if the electron temperature and ion lifetime are about the same in the two sources.

A clearcut experiment will be carried out in the future, when the source SERSE will be operated with a 18 GHz generator, in which case the plasma density should be about 60% higher and then an increase of current of the same order of magnitude is expected. A systematic study of the effect of continuously variable frequency and magnetic field will be done as soon as a variable frequency generator in the range 8–18 GHz becomes available at LNS.

TABLE I. Comparison of relevant parameters of SC-ECRIS and SERSE in the experiments reported here.

	SC-ECRIS	SERSE
Frequency (GHz)	6.4	14
Radial field (T)	0.57	1.2
Axial field (T)	1.2	2.3
Microwave power (W)	1270	1450
Pressure in the chamber (mbar)	1.8×10^{-7}	2.3×10^{-7}
Main gas	argon	argon
Gas mixing	with oxygen	with oxygen
Extraction hole diameter (mm)	8 mm	8 mm
Transmission	90%	85%
Faraday cup suppression	yes	yes

The results reported in Fig. 1 have been obtained in collaboration with the Ion Source Group of the MSU-NSCL. The results reported in Fig. 2 have been obtained in collaboration with the CEA-DRFMC-SI2A and CEA-DRFMC-SBT.

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