ECR ION SOURCES AND SCALING LAWS

S. GAMMINO, G. CIAVOLA

INFN - Laboratorio Nazionale del Sud, Via S.Sofia 44, 95123 Catania, Italy

The development of Electron Cyclotron Resonance (ECR) ion sources has been continuous during twenty years but the knowledge of the laws which determine their behaviour is not yet complete. In 1987 a list of tentative scaling laws was proposed by Geller and coworkers[1] and for a few years these semiempirical laws have been the guidelines for the design of new ECR sources and the improvement of the existing ones.
In order to prove or to reformulate these laws, we have made some systematic tests on the superconducting source SC-ECRIS at the National Superconducting Cyclotron Laboratory of the Michigan State University, devoted to the definition of the role of different parametres which determine the performance of ECR sources.
The results of such tests and the conclusions which we have drawn will be outlined, with particular attention on the role of the confining magnetic field.
A fundamental parameter appears to be the ratio of particle pressure to magnetic pressure, $\beta = n_e k T_e / (B^2/2\mu_0)$, which has been decreased in order to obtain a stable plasma, by increasing the confining field in each direction.

1 - Introduction

The Electron Cyclotron Resonance ion sources (ECRIS) have represented a real upgrading of the accelerator facilities, allowing to increase both the energy and intensity of the extracted beams.
Unfortunately there is no model which is able to predict, given the starting conditions, how to improve the charge state distribution (CSD) for every species of ion and every starting condition, even if a lot of work has been done[2,3,4,5].
The uncertainties on the starting conditions make almost impossible any representation of the plasma by means of a simple model and often the values of the microscopic parameters cannot be measured, because there is not enough clearance in ECR sources for plasma diagnostic devices.
The experience suggests that the electron density n_e and temperature T_e as well as the ion confinement time τ_i inside the plasma are the main parameters to describe the plasma, but in order to get a high intensity high charge state beam other items must be taken into account, as the microwave power P_{rf}, extractor shape and voltage V_{ex}, chamber pressure and volume, gas input and magnetic topology.

2 - Theoretical and semiempirical descriptions of ECR sources

The description of ECR plasmas and of the stripping process has been usually based on the sequential ionization[6] and on the batch model[2], which states that it is necessary to increase the quality factor $n_e\tau_i$ to obtain higher charge states.
However this model does take into account neither the recombinations nor the confinement losses and the role of electron temperature is somewhat neglected.
In 1987 a qualitative relationship between experimental data and macroscopical parameters was outlined by Geller[1], who suggested some semiempirical scaling laws which were able to explain the results of many existing ECR sources:

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

$$q_{opt} \propto \log \omega^{7/2} \qquad (2)$$

$$q_{opt} \propto P^{1/3} \qquad (3)$$

$$P_{rf} \propto \omega^{1/2} q^3 V \qquad (4)$$

$$I^{q+} \propto \omega^2 M_i^{-\alpha} \qquad (5)$$

where q_{opt} is the optimal charge state, B is the peak field of the magnetic trap, P_{rf} is the microwave power, $\omega = 2\pi f$, I^{q+} is the intensity of the charge state q, M_i is the ions mass and α is an adjustable parameter varyable between 0.5 and 1.
These laws worked fairly good to address properly the design of the next sources, but many other parameters (pressure in the plasma chamber, extraction setting, microwave injection) and some "tricks" (gas mixing, electron injection, wall coating, biased disk) which affect heavily the performance of ECR sources are not taken into account in such laws.
In 1990 the High B mode (HBM) for ECR ion sources was proposed, based upon a magnetohydrodynamical condition for a quiet plasma in magnetic traps[7,8]:

$$p_{particle} << p_{magnetic} \qquad (6)$$

where $p_{particle}$ is the pressure related to the momentum of charged particles in the plasma and $p_{magnetic}$ is the magnetic pressure. The particle pressure inside the plasma $p_{particle}$ is equal to $\Sigma n k T = \Sigma n_e k T_e + \Sigma n_i k T_i$ and $p_{magnetic}$ is defined as $B^2/2\mu_0$, then (being in ECRIS plasmas $T_e >> T_i$) the above formula may be rewritten:

$$\Sigma n_e k T_e << B^2/2\mu_0 \qquad (7)$$

It comes out that the magnetic field increase is effective either on electron density and on electron temperature and it is very beneficial for the ionization of the highest charge states. A rule of thumb suggests that $\beta = p_{particle}/p_{magnetic}$ should be lower than 0.01 to have a quiet plasma; in ECRIS working at 14.5 GHz this condition (for $n_e \approx n_{cutoff} \approx 2.5 * 10^{12}$ cm^{-3} and $T_e \approx 10$ keV) entails $B \approx 1.4$ T, whilst at 6.4 GHz a value of $B \approx 0.6$ T is high enough. Many sources are now operating in such a mode and the increase of magnetic field has been fruitful not only for the 6.4 GHz SC-ECRIS of the National Superconducting Cyclotron Laboratory at Michigan State University (where it was proved for the first time[9]), which improved its ion output by a factor 10 for the highest charge states, but also CAPRICE at Grenoble[10], the 6.4 GHz TAMU source[11], ECRIS2 at KVI[12], working with $\beta \approx 0.02$, have improved their CSD.

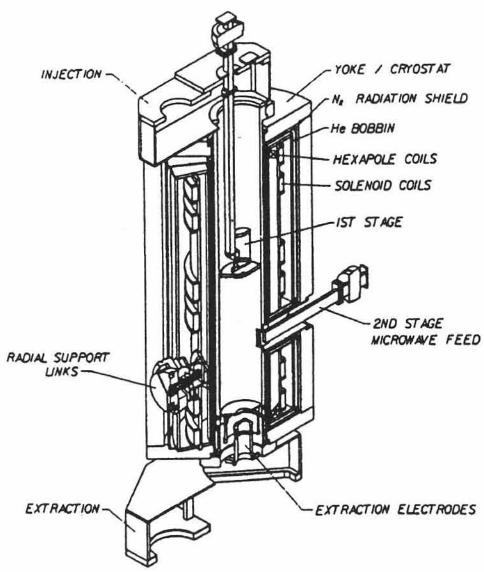

Fig. 1 - The source SC-ECRIS.

The main limit of the HBM description is the lack of a link with the neutral density n_0; it has been useful as indicator for the improvement of the plasma confinement, but it is far away to be a basis for a complete theoretical description.

In 1993 another simple model was proposed[13] which linked in a straightforward way the ECR ion source capability to get a certain charge state with its electron temperature T_e and its quality factor $n_e\tau_i$. This model shed some light on the behaviour of ECR sources, but unfortunately it links macroscopical parameters as the charge states to microscopical parameters as electron density and temperature and it is not able to explain the relationship with the other macroscopical parameters as pressure, rf power, volume, etc.

Recently the interest in theoretical descriptions has been increasing along with the computational capability to include a huge number of parameters and many authors[3,4,5] have developed codes which simulate the major parameters of the real ECR plasmas and which explain the most of the experimental data, even though the predictions are not always correct for each charge state and each CSD.

2.1 - Magnetic field scaling

In order to check the main arguments of the High B mode and to verify the validity of some of the scaling laws, a systematic set of tests has been carried out on SC-ECRIS[14]. The analysis of the ion outputs dependence on the magnetic field was carried out for the different directions, after that the experience of High B mode operation on SC-ECRIS supported the idea of an asymmetry in optimal confining trap.

In figgs. 2, 3, 4 the ion currents for some high charge states of Argon are reported for different values of B_1 (the axial field on the injection side), B_2 (the axial field on the extraction side), B_{rad} (the radial field).

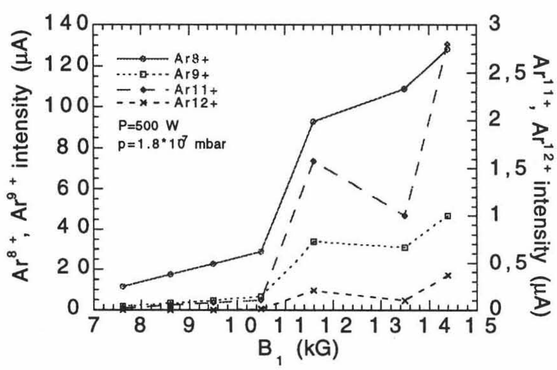

Fig. 2 - The current of high charge states for Argon vs. B_1.

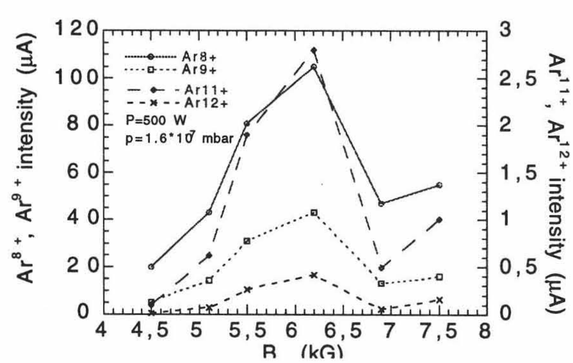

Fig. 3 - The current of high charge states for Argon vs. B_2.

For the radial field and for the axial field on the injection side the ion currents of high charge states increase with the confining field but not steadily and the logarithmic curves hardly fit their behaviour.

The experiments have also shown an optimal value for the axial field on the extraction side, because for higher field the

process of confinement is competitive with the extraction process, and even though more high charge states are created inside the plasma, they are not efficiently extracted.
In fig. 5 the extracted currents of O^{3+} and O^{7+} are plotted vs. the radial field, showing that the medium and low charge states as O^{3+} are not affected by the variation of the radial field.

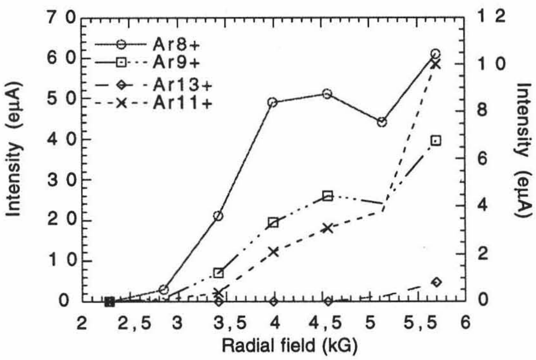

Fig. 4 - The current of high charge states for Argon vs. B_{rad}.

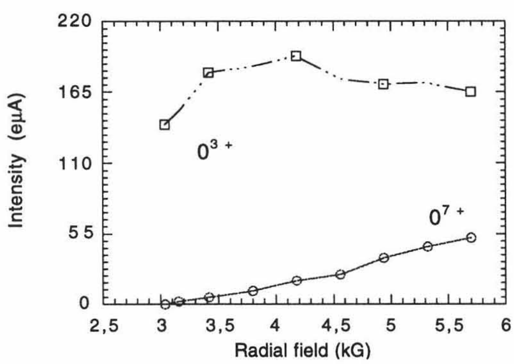

Fig. 5 - Measured current of O^{3+} and O^{7+} vs. B_{rad}.

2.2 - Rf power scaling

According to the scaling law (4), for a source like 6.4 GHz SC-ECRIS with a large volume, the needed power should be about 4 kW, instead of the 800 to 900 Watts usually needed. This example shows that it is not possible to extend the validity of this law to a wide number of sources, each one with its peculiar waveguide to chamber coupling and its peculiar plasma absorption.
A more general relationship may be the following:

$$P_{rf} = n_e\, k\, T_e\, V/(\tau_e \eta_{ECRH}) \qquad (8)$$

where the overall ECR heating efficiency is given by the product of the efficiencies related to the waveguide, to the coupling between waveguide and plasma chamber and to the plasma absorption. It is clear that often just a small amount of the power supplied by the generator is really coupled to the plasma and it is used to increase the electron temperature and to ionize more.

2.3 - Volume scaling

The idea that the higher volume helps the production of intense currents (even if the CSD is not too different from the one of similar sources with smaller volume) has been often proposed, but the nice results obtained with small sources as MINIMAFIOS or CAPRICE always put in discussion this proposition. In 1993 different authors reinforced the idea[15,16] of this scaling and some experimental results were also interpreted as a confirmation. To test on SC-ECRIS the effectiveness of large plasma volumes we fixed the plasma cross section by leaving constant the hexapolar field and the mirror maxima and we changed only the longitudinal dimension of plasma so that the volume roughly scales with the plasma length L_p, defined as the distance between the points on the axis where $B=B_{ECR}$. In fig. 6 the currents of high charge states of Argon are plotted vs. L_p, showing for all of them an optimal value around $L_p \sim 10$ to 12 cm. These results are in disagreement with the volume scaling, even if it needs to be considered that our attention was focused on the study of highly charged ions, for which confinement time and electron temperature are the most important parameters; their effect may hide the effect of volume scaling that seems to be more effective on the lowest charge states.

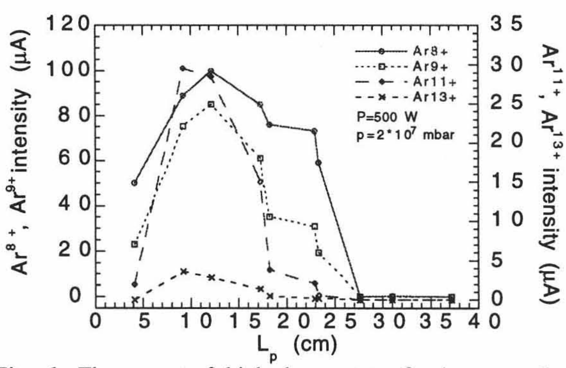

Fig. 6 - The current of high charge states for Argon vs. L_p.

2.4 - The frequency scaling

A particular relevance among the different scaling laws has been always given to the frequency scaling. Plasma theory says that electron density in a plasma has a cutoff which scales as the square of frequency:

$$n_{cutoff} = \varepsilon_0\, m_e\, \omega^2 / e^2 \qquad (9)$$

This formula is valid for a plasma which is not subject to magnetic field, which is not the case for ECR sources.

Otherwise recent theoretical and experimental developments[17] have suggested that the scaling may be effective only if the confining field is high enough to support a higher cutoff electron density.

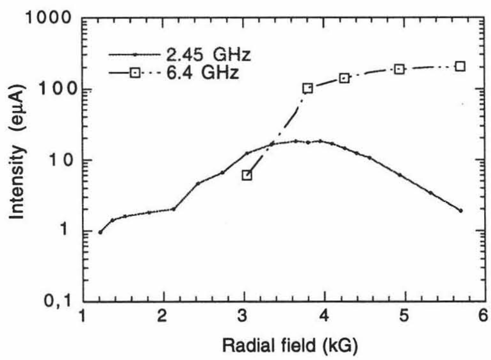

Fig. 7 - O^{6+} current vs. B_{rad} at 2.45 GHz and 6.4 GHz.

In fig. 7 this trend is shown by plotting the extracted current of O^{6+} vs. B_{rad} for the frequencies of 2.45 and 6.4 GHz. Not only the increase in current is well higher than that foreseen by the law (5) but it is also evident an increase of more than one order of magnitude with the magnetic field, up to a level where the current saturates; as foreseen in ref[17] the value of the saturation field increases with the frequency and the frequency increase is useful only if the magnetic field is high enough.

The electron density cannot be considered as a variable dependent only from the frequency, but it depends from the interplay with frequency, magnetic field and electron temperature. By increasing B, n_e approaches n_{cutoff} and the CSD is the one corresponding to the maximum electron temperature achievable in the plasma. If $n_e \approx n_{cutoff}$ the magnetic field increase is not more useful and frequency must be risen for further enhancement. In particular, by increasing both frequency and magnetic field[10] a very relevant increase of n_e and T_e have been obtained.

This may be also explained in terms of the parameter $\beta = (n_e k T_e) / (B^2/2\mu_0)$[17].

If the frequency of a source with $\beta \approx 0.01$ is increased, plasma behaviour is worse because β increases with the electron density and the particle pressure is not compressed anymore by the magnetic field; the loss rate from the plasma increases and the electron temperature decreases, depressing the high charge states production. If β is decreased below 0.01 once again because of better trap confinement, high charge states are obtained, provided that the pressure is low enough to make negligeable the recombinations due to interactions with neutral atoms. These discussions can be summarized by the following formula:

$$\beta \approx 0.01 \Rightarrow n_e \approx n_{cutoff} \qquad (10)$$

3 - Conclusions

The experiments hereabove reported have shown that it is not possible to determine simple scaling laws which have clear-cut effects on the source output. The interdependence of many parameters is so complicate that positive results can be only obtained by computer calculations where all the different contributions should be included.

However the codes may profit of these experiments, which may be finally summarized in the following statements:

- the ratio between the radial field and the resonance field should be very high, about three or four;
- the axial field at the injection must be as high as possible, in order to close the loss cone;
- the axial field at the extraction should be optimized around the value of the radial field, so that the escape of plasma on the wall is not favoured with respect to the beam extraction;
- the frequency should be increased, provided that a high magnetic confinement is maintained;
- the CSD improves with the microwave power, but the amount of power that can be coupled to the plasma increase with the confining field and decrease with the base pressure.

Acknowledgements

The discussions with R. Geller, A. Drentje, G. Melin, T. Antaya and the contributions by P. Briand, R. Harkewicz, K. Harrison, A. Srivastava are gratefully acknowledged.

References

1. R. Geller et al., Proc. of the 8th Workshop on ECRIS, East Lansing (1987) 1
2. S. Bliman, N. Chan-Tung, Journ. of Plasma Physics (8/1979)
3. G. Shirkov, Proc. of the 6th Int. Conf. on Ion Sources, Whistler (Canada), Sept. 1995, to be published
4. V. B. Kutner et al., Proc. of the 6th Int. Conf. on Ion Sources, Whistler (Canada), Sept. 1995, to be published
5. P. Sortais, Proc. of the 6th Int. Conf. on Ion Sources, Whistler (Canada), Sept. 1995, to be published
6. W. Lotz, Zeit. fur Phisik 216 (1968) 241
7. S. Gammino, G. Ciavola, LNS internal report 90/4
8. G. Ciavola, S. Gammino, Rev. Sci. Instr. 63(4), 1992, 2881
9. T. A. Antaya, S. Gammino, Rev. Sci. Instr. 65(5), 1994, 1723
10. G. Melin et al., Proc. of the 6th Int. Conf. on Ion Sources, Whistler (Canada), Sept. 1995, to be published
11. D. May, private communication
12. A.G. Drentje et al., KVI annual report (1994), 92
13. T. Antaya, Proc. of the 11th Workshop on ECRIS, Groningen (1993) 37
14. S. Gammino et al., to be published on Rev. Sci. Instr.
15. G. D. Alton, Rev. Sci. Instr. 65(4), Apr. 1994, 775
16. D. Hitz et al, Proc. of the 11th workshop on ECR ion sources, Groningen (1993) 91
17. S. Gammino et al., to be published on Plasma Sources Science & Technology