Electron Cyclotron Resonance Sources of Multicharged Ions: State of the Art, Recent Developments and Prospects

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Abstract

The improvement of the Electron Cyclotron Resonance Ion Sources (ECRIS) essentially relies on the technology and the plasma physics. The main trends of efforts at Grenoble are: high magnetic field ECRIS, permanent magnet only built ECRIS, basic research on plasma physics involved in multicharged ion production. Here the recent results are discussed as well as the orientations and prospects.

1 INTRODUCTION

For almost 20 years the Grenoble laboratory [1] has developed the ECR ion sources (ECRIS) of multiply charged ions, both for small and large scale experiments. Although their performances keep regularly improving, they reach so high a level that significant improvements get less easy to achieve, in spite of the so numerous laboratories involved in this task. The present article does not give a full scope of the possibilities of the ECRIS, only few of them will be considered, we rather analyze the present state of the art of ECRIS, giving the main trends and looking forward to the prospects that seem really worth noticing today.

2 PRESENT STATUS AND PERFORMANCES OF THE ECRIS

2.1 Magnetic Configurations

So far only little work has been done on the magnetic configurations being used: most sources kept the initial design of the mirror field created by a pair of coils, combined with a radial multipolar field, usually hexapolar and created by permanent magnets, large enough to maintain within the source a closed $e|B|\ /m_e = \omega_{rf}$ surface [1]. This criterion not fully understood makes the sources working better, because it likely optimizes the coupling of the rf wave with the electrons, thus maximizing their density for ionization. The possibility of varying the currents in the coils provides a fine tuning, always necessary to increase the extracted currents, and explained by the discrete structure of the rf fields [2]. There is an open question: is this today magnetic structure really unique and the best one?

2.2 Best data and performances

It is usual to compare the absolute extracted currents (in $e\mu$A) of the different ECRIS, their dimensions being quite close to each other and the rf power in the range of a few hundreds W ($\leq$1 kW) because increasing too much the rf power makes them running unstable. It is also usual to utilize a carrier gas together with the main element to be produced: the density of this carrier gas is dominant with respect to that of the other element [3].

The figure 1 gives for argon and uranium as examples, the best absolute results so far obtained in continuous mode of operation at different frequencies [4] [5] [6].

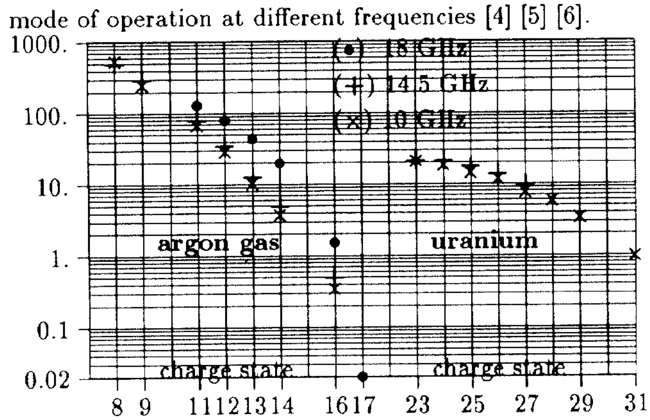

Figure 1: Extracted ion currents ($e\mu A$) from [4] [5] [6].

The same behavior is observed for other elements. These data are somewhat puzzling as the predicted scaling $\max(I_q) \sim \omega_{rf}^2$ or $\sim B^2$ is not really observed. This frequency scaling [1] was suggested by the statement that the maximum electron density of the plasma n_e—and consequently the maximum extracted ion currents, was limited in such a way that

$$\omega_{pe} = \left(\frac{n_e e^2}{m_e \epsilon_0}\right)^{1/2} \simeq 2\pi.9000\sqrt{n_e} \leq \omega_{rf}\ (2\pi\mathrm{Hz},\ \mathrm{cm}^{-3})\ , \tag{1}$$

because of the rf field penetration in the plasma. The results at 10 GHz and 14.5 GHz apparently do not follow the above statement, but both sources at 10, 14.5 and 18 GHz are high magnetic field sources ($|B_{max}| \geq 1.0$ T). Note that for metals the results are strongly dependent of the metal vapor diffusing system in the source [7].

These results would indicate that so far the maximum electron density the source can hold, has not yet been reached, and that actually some progresses are feasible. It is clear that the high magnetic field ECRIS work better, they are more stable with higher performances. The intrinsic effect of the rf power—heating the electrons, is certainly dependent of the magnetic field gradients, but it is not clear whether it has some importance in limiting the electron density.

2.3 Additional injection of electrons

Injecting electrons along the main axis of the magnetic configuration, where the multiply charged ions are expected to lie, improves the observed extracted current of ions. As a result of the charge neutrality equation,

$$n_e = \sum_{1}^{q_{max}} n_q q \ , \qquad (2)$$

the higher the electron density n_e, the higher the density n_q of ions of charge state q. This is illustrated by the figure 2: a negatively biased probe reduces the plasma electron losses and/or provides new electrons from secondary emission of impinging plasma particles [8].

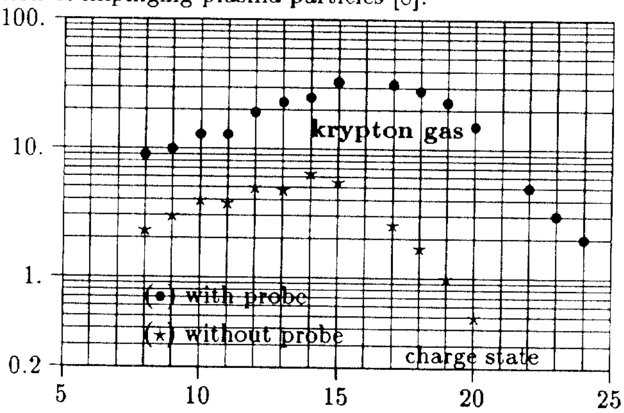

Figure 2: Enhanced ion currents (eμA) by a biased probe [8].

Similar results have been achieved by using a low voltage electron gun on the main axis [9]. Note that only off-axis rf wave launching allows this kind of improvement to be set up, it cannot be easily done in ECRIS using rf coaxial feeders, such as Caprice [4] and ECR4 [5]. Another way of injecting additional electrons is the use of a convenient coating on the ECRIS walls, e.g.ThO_2 [1] or SiO_2 [9]: these coatings create new electrons by secondary emission.

Once again these effects show that increasing the electron density in the ECRIS, and then the extracted ion currents, is not limited.

2.4 A few ECRIS physics considerations

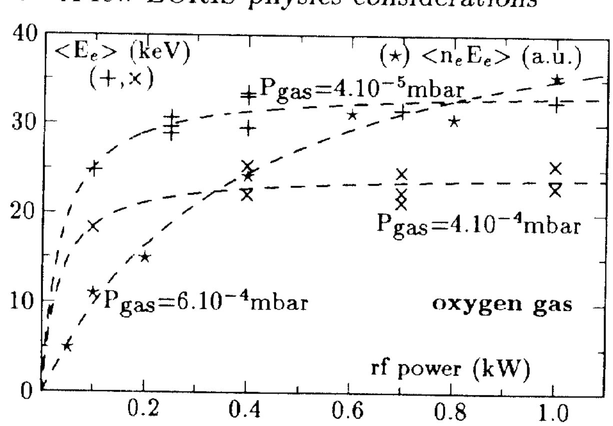

Figure 3: Mean electron energy in ECRIS from [10].

Together with the development of high performance ECRIS, the activity on the ECRIS at Grenoble is partly devoted to the ECRIS fundamental physics aspects. A better understanding of the physics of ECRIS is one of the most important conditions of future developments and improvements. The figure 3 shows the behavior of the mean electron energy averaged over the electron distribution [10]. Surprisingly the main effect of the rf power is to increase the electron density rather than the energy, the latter being essentially controlled by the neutral pressure.

The existence in the ECRIS of so hot an electron energy, which meets the requirements of high states of ionization, makes to some extent the ECRIS behavior similar to that of the EBIS, although at a much higher density of particles. The ions get confined in the space charge well $\Delta\phi$ of the magnetically trapped hot electrons. This is evidenced by the transient enhanced current of high charge q ions at the rf turn-off in the afterglow (see fig. 4). As the hot electron population collapses, being no longer sustained by the rf field, the confined ions leave the trap: the amplification factor of the extracted currents is found compatible with the expected electrostatic ion confinement factor [6],

$$\exp\left(q\,|\Delta\phi|\,/kT_i\right) \sim 2-5 \text{ depending upon q.} \qquad (3)$$

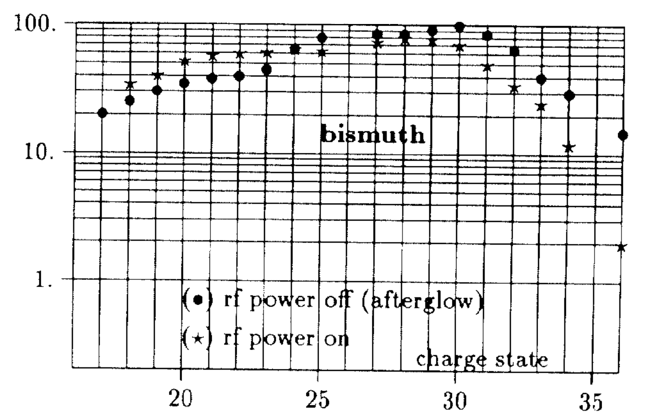

Figure 4: Enhanced ion currents (eμA) in afterglow from [8].

This phenomenon is interesting of itself to obtain very high ion currents of high charge states q in short pulses ($\sim$ 1 ms at a few Hz), and is well suited to synchrotron injectors (100 eμA of Bi^{30+} are obtained).

Thus the investigations of the ECRIS physics do open new areas and do allow the ECRIS to run with improved possibilities.

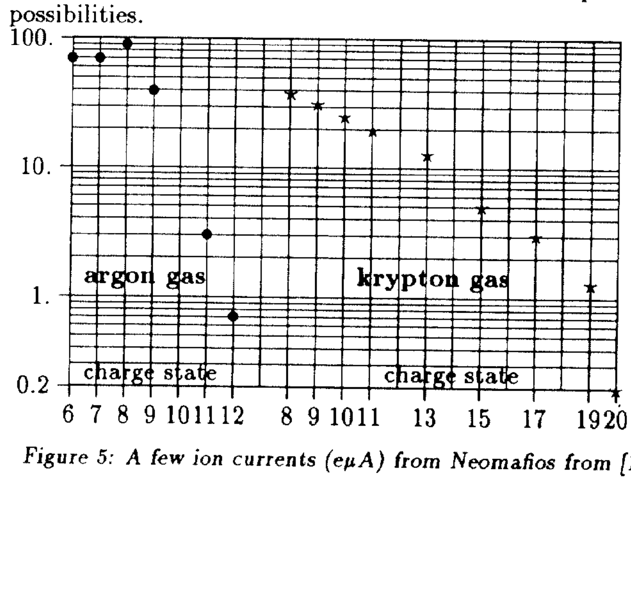

Figure 5: A few ion currents (eμA) from Neomafios from [11].

2.5 *All permanent magnets built ECRIS*

They are really worth mentionning because of their advantages, however at the cost of limited performances. Both the axial and the radial magnetic fields are obtained only with permanent magnets. The loss of one degree of freedom, i.e.the axial field tuning, is compensated by a reduced power consumption—that of the rf generator, a few kW, instead of a few tens of kW. This advantage together with their high flexibility and simplicity, make them quite attractive to high voltage platform accelerators. Some of the 10 GHz Neomafios source results are shown in figure 5: this source equips two important facilities in Japan [11].

3 PROSPECTS FOR ECRIS

New areas of ECRIS development and research need to be explored in order to reach higher performances for multiply charged ion beams both in intensity and charge states. Although no evident breakthrough may be foreseen, the following trends of efforts are worth considering: (i) the high technology ECRIS with high magnetic fields, (ii) the physics of ECRIS, i.e. the new developments, ideas and measurements carried out in order to improve the understanding of the ECRIS physics.

3.1 *High magnetic field ECRIS*

This obviously refers to the superconducting sources. A 0.7 T superconducting source has been successfully working for many years at 14.4 GHz in Jülich [12]. The MSU superconducting source recently reached the highest ECRIS magnetic fields so far: 1.4 T radially and 2.2 T axially [13]. It will be possible in this source to study the scaling of the ECRIS at different rf frequencies far beyond the existing levels, since the upper limit of the resonance frequency is in the range 28–35 GHz of gyrotron tubes. Today the source is going to work at 14.5 GHz: this achievement looks quite exciting and promising to the ECRIS community. Following the MSU enterprise, a joint venture LNS-Catania/DRFMC-Grenoble will soon start the design and the building of a new superconducting source for the LNS cyclotron [14].

3.2 *ECRIS physics studies*

A strong program of research and studies of the ECR plasmas and the multicharged ion production has begun in Grenoble. It involves the development of plasma and atomic physics diagnostics in order to measure the main plasma parameters, and the investigation of new magnetic configurations. Today a specific facility having the required flexibility has just started running. It aims at featuring the multicharged ions, as well as exploring new regimes of interest for ECRIS, and many other basic studies such as emittance characterization. This ambitious program, a long task requiring difficult measurements, interpretations, and comparisons with numerical codes, will hopefully give new orientations to the ECRIS.

4 CONCLUSION

The analysis of the today ECRIS results makes it realistic to think of enhanced performances. There are clearly experiments showing that the maximum extracted ion currents are not yet achieved. Whether these improvements rely on the hot electron density increase, on the magnetic field confinement capability, or eventually on some limitations related to the ECR plasma physics, has to be established. There are several promising prospects now under way, on one hand as far as the technology is concerned, the superconducting ECRIS, on the other hand as to the ECRIS physics understanding, the systematic studies undertaken in specific facilities. Both approaches should bring up new informations, a necessary condition of further ECRIS improvements.

5 REFERENCES

[1] R. Geller, "ECRIS Sources...", Europhys.News,vol. 22, pp. 8–11, 1991; "ECRIS...", Annu. Rev. Nucl. Part. Sci., vol. 40, pp. 15–43, 1990.

[2] M. Delaunay et al., "Exploration axiale du plasma RCE...", N. I. M. , vol. A305, pp. 223–231, 1991.

[3] M. Delaunay, "Influence of ionization cross-sections on the gas mixing...", in the ICIS 91 Conf. Proceedings, Bensheim, Germany, Oct. 1991 (to be published in Rev. Sci. Instr., 1992).

[4] B. Jacquot and M. Pontonnier, "La source Caprice 10 GHz...", N. I. M. , vol. A287, pp. 341–347, 1990; ibid. vol. A295, pp. 5–11, 1990; in 10th Int. Workshop ECRIS Proceedings, Knoxville, Tennessee, Nov. 1–2 1990, pp. 133–155.

[5] P. Sortais et al., "Results of the new ECR4 14.5 GHz...", in 10th Int. Workshop ECRIS Proceedings, Knoxville, Tennessee, Nov. 1–2 1990, pp. 35–46.

[6] G. Melin et al., "Some particular aspects of the physics...", Rev. Sci. Instr., vol. 61, pp. 236–238, 1990; and other unpublished data.

[7] R. Geller et al., "Metal ion production in ECRIS", ibid. ref. [3].

[8] G. Melin et al., "Recent developments and future projects on ECR ion sources...", ibid. ref. [5], pp. 1–15.

[9] Zuqi Xie et al., "Enhanced ECR ion source...", Rev. Sci. Instr., vol. 62, pp. 775–778, 1991.

[10] C. Barué et al., "Hot electron studies in the Minimafios ECR ion source", ibid. ref. [3].

[11] P. Ludwig et al., "The 10 GHz Neomafios upgraded ECR ion source", ibid. ref. [3].

[12] H. Beuscher, "Status of ECR source development...", ibid. ref. [5], pp. 121–131.

[13] T.A. Antaya, "A review of studies...", Journal de Physique, vol. C1–50, pp. 707–726, 1989; and private communication.

[14] G. Ciavola, S. Gammino, "A superconducting ECR source for the LNS", ibid. ref. [3].