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General review of recent developments for ECR ion sources

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General review of recent developments for ECR ion sources

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Abstract

In this paper we will recall the main characteristics of ECR discharges for the production of multicharged ions and we will show basic limitations of ECRIS performances using the elementary zero dimension ionisation equilibrium model. Then we will present main domains where the ion source characteristics are the limiting factor for the applications. The improvement of the technology of compact ECR ion sources dedicated to applications in special environments like on line isotopic separators or high voltage platforms will be discussed. Finally we will describe advanced ion sources projects for future production of very highly charged ions generally connected to superconducting devices.

1 Introduction

ECR ion sources are now used for very different purposes. A lot of devices are designed with various performances, technologies, volumes and costs [1]. For accelerator applications the problem consists in reaching the highest Q/A as possible with a current in the range of μAp even with metallic ions [2]. For atomic physics it is to produce very specific ions generally He-like or fully stripped ions [3]. For THT applications the problem is the power consumption of devices and for on line production it is the gas efficiency of the discharge. In order to know what could be connections between ion source technologies and performances, we will make a very rough description of ionisation process for ECR devices. Then we will try to compare the results obtained with most advanced machines like AECS at Berkeley, MSU-SC at Lansing or ECR4 at GANIL. We will finish by a rapid description of new devices and compare their specificities to existing machines.

2 Ionisation equilibrium and ECRIS functioning points

In order to compare functioning points of different sources we can write elementary equations of ionisation equilibrium. If sources are tuned for similar performances it is possible to find sets of parameters that can describe relative evolution of discharge characteristics from a source to another one. We must not forget these equations consist in a very rough description of diffusion process since a zero dimension model neglecting any differential diffusion of ions during escape of the magnetic structure and of course during beam formation and transport. We neglect also any inhomogeneity of density and temperature. Nevertheless this model has been already extensively used in order to test different simulation of plasma parameters [4][5][6][7][8].

Balance equations of the density n_i of ions in the charge state i for steady state of ions production are :

$$\frac{dn_i}{dt} = n_e n_{i-1} \langle \sigma_{i-1 \rightarrow i}^{ioni} \nu_e \rangle + n_0 n_{i+1} \langle \sigma_{i+1 \rightarrow i}^{exc} \nu_e \rangle - n_i n_e \langle \sigma_{i \rightarrow i-1}^{exc} \nu_e \rangle - n_e n_{i+1} \langle \sigma_{i+1 \rightarrow i}^{ioni} \nu_e \rangle - \frac{n_i}{\tau_i} = 0$$

Density of the state i is a balance between creation, by ionisation of the state $i-1$ and charge exchange of the state $i+1$, and losses of the state i by ionisation, charge exchange and diffusion over a time τ_i . Main parameters of the ionising plasma n_e , $f(v_e)$, τ_i and n_0 are chosen arbitrary in order to define what could be regimes of ionisation (parametric model).

n_e the electronic density is fixed at 10^{12} cm^{-3} assuming a saturated density with value closed to the cut off density around 10 GHz [9]. $f(v_e)$ the electronic speed distribution function is a maxwellian distribution or a sum of a maxwellian and a gaussian distribution (centred around high electronic energy (keV) and with a width of several keV). The gaussian part of the distribution simulates the effect of strong ECR heating.

In order to simplify systematic study of charge state distribution (CSD) as a function of confinement time τ_i we have used an elementary collisional diffusion process with $\tau_i = K_{diff} z^2$ (s). So we neglect by this way any potential distribution inside the plasma. n_0 the neutral density is fixed 10^{10} cm^{-3} assuming a residual pressure in the plasma around 10^{-6} mbar . Ionisation cross section is a Lotz formulae fitted on compilation of ionisation cross section measurement [10]:

$$\sigma_i^{ioni} = A_i^{ioni} \log(E_e / E_i^{ioni}) / E_i^{ioni} E_e$$

Charge exchange cross section is the well known semi empirical Muller-Salzborn formulae:

$$\sigma_{i,i-1}^{exc} = A^{exc}_i / (E_0^{ioni})^3$$

(with A_i^{ioni} ionisation constant, E_0^{ioni} ionisation potential of the neutral and E_e electronic energy)

Figure 1 a : Te = 100 eV (maxwellian)

Figure 1 b : Te = 300 eV (maxwellian)

Figure 1 c : Te = 1000 eV (maxwellian)

Figure 1 d : Te = 10000 eV (maxwellian)

7E+10 6E+10 5E+10 4E+10 3E+10 2E+10 1E+10 0E+0

Figure 1 : Density (cm^{-3}) charge state distribution of Argon as a function of the confinement time of ions and for maxwellian distribution of electronic energy

We can see (fig. 1) systematic CSD of Argon for lifetime of ions between 10 μs to 10 ms (1^+) and for maxwellian distribution of electronic energy at 100, 300, 1000 and 10000 eV.

At very low temperature (fig. 1 a) we see very clearly saturation for Ar^{8+} (E_i^{ioni} 148 eV) over a long range of confinement time. It is only after a very long time that we observe the opening of the L shell of Ar due to the small part of high energy electrons of the 100 eV distribution.

Figure 2 : Width of the charge state distributions of Ar as a function of the confinement time of ions and for maxwellian distribution of electronic energy

With 300 eV of temperature (fig. 1 b) we begin to open the M shell even for low lifetime and then it is possible to reach K shell for long lifetime after a regular increase of the $\langle Z \rangle$ of the CSD (defined as $\sum q_i n_i / \sum n_i$).

At 1 KeV (fig. 1 c) we begin to observe an important effect : for long lifetimes of course we saturated the Ar¹⁶⁺ density (E_i^{ioni} 918 eV) but for low lifetimes and with high average electronic energy we observe a widening of the CSD. It is due to the fact that production rates are relatively poor for any charge states: electron energy is too high for very low charge state and confinement time is too low for high charge state. These very wide CSD from Ar⁵⁺ to Ar¹⁵⁺ are probably characteristic of numerous ECR discharges.

Then at 10 KeV (fig. 1 d) we observe an extreme sensitivity of the $\langle Z \rangle$ with the confinement time and in this case we can open the K shell of Ar and so centered the distribution on Ar¹⁸⁺. This type of tuning is more closed to the EBIS one where confinement time and electronic energy can be chosen arbitrary and independently of other parameters. Unfortunately CSD centered on Ar¹⁶⁺ or more has never been observed in an ECRIS.

In order to get a best feeling of the effect of lifetime limitations, we can see (fig. 2) the dependence of the width of the CSD (width of the electrical currents). This one is defined here as the number of ions produced with relative currents above 10% of the maximum current of the CSD.

We can see that widths greater than 10 charges can be observed only for lifetime corresponding to diffusion constants below some 10^{-4} (we can observe CSD with more than 12 charges in a source like ECR4). By this way we can also get a lower limit to the temperature to some hundreds of eV (for a maxwellian distribution). Consequently, the width of the CSD can be used as a rough diagnostic of the confinement limitation of the discharge.

Figure 3 : $\langle Z \rangle$ of the charge state distributions of Ar as a function of the confinement time of ions and for maxwellian distribution of electronic energy

Now we can compare this functioning point with the $\langle Z \rangle$ of the extracted CSD. This one is also an easy measurable parameter of the experimental CSD. For a window of lifetime and temperature given by the width, we can use the $\langle Z \rangle$ corresponding to this CSD and then deduce a more precise value of the confinement time.

We can also observe that for diffusion constant below some 10^{-4} and for temperature above 300 eV, the evolution of $\langle Z \rangle$ is very sensitive to variation of the confinement

time. It means that even for a small variation of the confinement time we can observe a significant variation of $\langle Z \rangle$ so of the source performances. It is probably the reason why ECRIS performances can sometimes be very sensitive to different tricks of tuning like electron gun, biased potential and support gas effects, even if they induce small variations of ionisation equilibrium parameters [11]. Before comparing experimental CSD to theoretical one we will at once recall main characteristics of most advanced machines for production of highly charged ions.

3 High $\langle Z \rangle$ tuning of advanced ECRIS : ECR4, AECS and MSU-SC

3.1 Technical descriptions

Except the MSU superconducting source, most of present high performance ECRIS are based on the concept of CAPRICE and Minimaños devices initially developed by B. Jacquot and R. Geller in Grenoble since 1983 [12],[13]. The basic idea consists in designing a simple and reliable machine in which, for a fixed ECR frequency, we try to optimise the magnetic structure and the functioning frequency in order to improve the production of highly charged ions.

Figure 4 : Schematic view of the ECR4 14.5 GHz GANIL ion source

With ECR4 which is a CAPRICE type machine [14], it is the smallest high performance machine. This one is built around a 6.6 cm in diameter and 20 cm in length plasma chamber. This characteristic has been at once used in order to minimize the volume to be magnetized because the first prototype was dedicated to its implantation on a high voltage platform (50 KW for 1.1 T of axial field). Latest version ECR4-M could work with mirror field up to 1.6 T for a functioning at 18 GHz but presently we have only 14.5 GHz tuning [15]. The length of the mirror is smaller than the length of the hexapole so it is a well defined 1.1 T module line that reaches the radial wall of the plasma chamber. The main characteristic of the source except its coaxial UHF injection is probably the very high magnetic gradient and consequently a very small resonance area limited to some centimeters only (fig. 7).

The LBL AECS has a general structure quite similar to the Minimaños one [16][17]. The length of the magnetic structure is roughly 2 times longer than ECR4 and the diameter of the plasma chamber is 7.5 cm. The source works

with a high hexapolar field so the value of the module of the magnetic field at the radial wall of the plasma chamber is quite similar to the ECR4 one (fig. 7). The UHF injection is a direct axial injection in the area of the maximum of the axial field. The source is operational since 1990 and is characterised by the use of different tricks for the improvement of performances. An electron gun placed on the axis of the source has shown an improvement of performances by a factor 2 [16], and recently [18], the use of two heating frequencies 10 and 14.5 GHz has induced the same improvement.

Figure 5 : Schematic view of the AECR 14.5 GHz LBL/Berkeley ion source

Initially studied to test the ECR frequency scaling law, the super conducting source from MSU-NSCL, designed by T. Antaya and R. Geller [19], after a long time of technological development, gives very good results at the frequency of 6.4 GHz. The source works with a large plasma chamber ($\varnothing$ 14 cm and L 60 cm).

Figure 6 : Schematic view of the MSU superconducting 6.4 GHz ion source

The magnetic structure is only limited by magnetic forces between hexapolar and axial coils, which allows to define a very large range of minimum $|B|$ structure (tuning of the

hexapolar and axial magnetic field). By using coils with current in opposition, it is very easy to define a very high mirror ratio both on radial and axial fields(fig. 7).

The optimized profile shows a general structure very similar to the CAPRICE one: a very high magnetic field in the area of the UHF injection (mirror ratio 7!). The minimum field is very closed to the resonant field (0.23T) and the extraction field is lower than the injection one and closed to the value of the maximum radial field (0.6T).

Figure 7 : Magnetic mirror fields for ECR4, AECR and MSU-SC devices

	Nanogan II	ECR4	AECR	MSUSC
f ECR (GHz)	10-18	14.5	14.5+10	6.4
B max (T)	0.95	1.2	1	1.2
B min (T)	0.36	0.4	0.36	0.18
L mirror (cm)	15	17	30	35-60
$\varnothing$ chamber(cm)	3.6	6.6	7.5	14
L chamber(cm)	17	20	30	60
Volume (cm ⁻³)	173	684	1325	6900

Table 1 Main source characteristics

We must observe that this machine works with a minimum $|B|$ structure roughly 10 times bigger in volume than with ECR4 14 GHz source. It means that the 6.4 GHz results have been obtained with an absolute value of the mirror field similar to a compact source one, but with wave/cavity, wave/plasma and stability conditions totally different, so the exact role of the frequency scaling in ECR devices is not quite clear [20].

3.2 Ar¹⁶⁺ currents : experimental production and simulation

In order to compare functioning points of these three ion sources, we have drawn (fig. 8) real spectra extracted from sources when these ones are tuned to produce the best Ar¹⁶⁺ current as possible. The three sources use a little bit less than

1 KW of UHF power and the extraction voltages are in the range of 10 to 15 KV.

The three sources produce very similar currents of Ar^{16+} but in spite of it, spectra extracted are drastically different. Nevertheless since the production of an extremely charged ion like Ar^{16+} demands the best ionising parameters, the three spectra are probably comparable and characteristic of the source properties.

With the MSU SC source the total current of Ar extracted from the source is very low, but the $\langle Z \rangle$ (11.6) is very high and Ar^{16+} current is not a negligible part of the total current (3% of extracted particles). With ECR4 the Ar^{16+} current is only two times less but the current of Ar^{8+} is 50 times higher and the $\langle Z \rangle$ is reduced to 9.3. In this case Ar^{16+} represents only 0.12 % of the extracted particles. With AECR we observe the exact intermediate situation : $\langle Z \rangle$ is 11.2 and Ar^{16+} current represents only 1 % of the argon distribution.

Very probably, we are in front of a basic contradiction of multicharged ion production. We know that the $\langle Z \rangle$ of the discharge is proportional to the $n_e \tau_i$ product, but the current extracted from the source is inversely proportional to the confinement time τ_i . So with a large and well optimised source it becomes more and more difficult to extract high currents of very highly charged ion, but these currents are extracted with a very good $\langle Z \rangle$. In a quite small device, in spite of a reduced $\langle Z \rangle$ the current of Ar^{16+} is remained at a reasonable value but mixed with large currents of low charge state ions. The AECR source is probably a good compromise for the production highly charged ions.

Figure 8 : Ar currents extracted from ECR4, AECR and MSU-SC devices during Ar^{16+} optimisation

We can test this effect by using the ionisation equilibrium model. By drawing charge state distributions of currents and assuming these ones are proportional to the $q_i n_i / \tau_i$ values, it is possible to fit experimental distributions (fig. 8).

We can find good fit of the three distributions, by using very similar electronic speed distributions (from 200 eV to 250 eV for the maxwellian component with some % of "gaussian" electrons in the range of 1 keV). In this case diffusion constants of $1.5 \cdot 10^{-4}$ (s) for ECR4, $2.7 \cdot 10^{-4}$ for

AECR and $8.3 \cdot 10^{-4}$ for MSU SC can explain the evolution of CSD.

Maybe the interpretation of performances just as a variation of the confinement time is a little bit too simple. In fact the density may change and a description as a function of the $n_e \tau_i$ product would be more precise. But in any case it seems that we are in front of a choice between the improvement of the $n_e \tau_i$ product (only τ_i if the density is saturated) that increases the $\langle Z \rangle$ and the minimization of τ_i that increases extracted currents.

Figure 9 : Simulated and extracted Ar currents for ECR4, AECR and MSU-SC devices

4 New and advanced devices

Devices that we have previously described are used for accelerator applications. They are generally used as primary injector for large accelerators. Since now some years, demands appear for the use of ECRIS in very special environnement like on-line isotopic separators or high voltage platforms [21]. In this case the most important aspect is the simplification of the technical environnement (minimisation of volume, weight, electrical and UHF consumption).

Figure 10 : Schematic view of NANOGAN II ion source with the target box and extraction insulation valves.

With classical coils the electrical consumption depends drastically of the volume to be magnetized, so if we can reduce the volume of the minimum |B| structure the choice of

permanent magnets is very interesting to minimize the electrical consumption.

It is the reason why a new family of devices called NANOGAN has been developed for production of multicharged radioactive ions. The latest version is now the NANOGAN II machine.

The source has a general structure very similar to the first NANOGAN prototype [21], but built around a $\varnothing$ 40 mm magnetic structure. The maximum of the amplitude of the field reaches 0.91 T that defines the magnetic mirror suitable for functioning around 14 GHz. Extraction system (with 1 or 2 electrodes) will be removable inside the pumping box in order to close two extraction valves for radioactive contamination control (fig. 10). The total weight of the source is 60 Kg and the total electrical consumption is below 1 KVA.

Ar8+	140
Ar9+	60
Ar11+	10
Ar12+	4
Ar13+	1
Xe17+	17
Xe22+	5
Xe25+	1

Table 2 : preliminary results (μ Ae) obtained with NANOGAN II 14.5 GHz (150 W of UHF power)

We can see (Table 2) preliminary results obtained with the NANOGAN II source presently limited to a functioning up to 150 W of UHF power only. Ar performances show that in a device four times smaller in volume than ECR4 and forty times than MSU SC it is possible to maintain the level of the 1 μ Ae current on the charge state 13⁺ (16⁺ on high performance machines).

Figure 11 : Sketch of SERSE the superconducting ECR source developed by DRFMC Grenoble/INFN Catania

Concerning large devices a new machine, called SERSE is under construction at Grenoble for the INFN in Catania where it will be possible to investigate "high |B| mode" at 14.5 GHz with an axial magnetic field tunable up to 2.2 T (fig 11) [22]. This device with a plasma chamber volume closed to the MSU-SC one, will can reach a magnetic field

roughly two times higher. It will be probably very useful for production of very high $\langle Z \rangle$ spectra.

5 Conclusion

We have now a wide range of ECR devices with various technology depending of the nature of performances for production of multicharged ions. Nevertheless it does not seem that ECRIS have reached any fundamental limitations so optimization of plasma parameters, specially the density, could drastically improve performances even if lifetime decreases due to collisional processes.

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References

- [1] M. Segikuchi, theses proceedings
- [2] B. Wolf, theses proceedings
- [3] H. Winter, theses proceedings
- [4] Y. Jongen, LC-8003, Louvain-la-Neuve, Belgium, (1980)
- [5] H. West, UCRL-53391, LLNL, USA, (1982).
- [6] S. Bliman, N. Chang-tung, J. Physique, Paris, 42, (1981), 1247
- [7] P. Sortais, Note PADSII n° 586, Grenoble, France, (1986)
- [8] G. Shirkov, CERN PS94-33 (HI), (1994)
- [9] G. Melin et al; Proc. 5th Int. Conf. on Ion Sources, Beijing, China, 1993, Rev. Sci. Instrum. 65 4 (1994) 1057.
- [10] H. Tawara, T. Kato, M. Ohnishi, IPPM-AM-37, Feb. 85, Nagoya, Japan (1985).
- [11] C.M. Lyneis et al., Proc. 10th Int. Work. on ECRIS, Knoxville, USA, 1990, Oak Ridge Nat. Lab. CONF 9011136, (1991) 22.
- [12] B. Jacquot, R. Geller, Proc. Intern. Conf. on Electron Cyclotron Resonance Ion Sources and their Applications, East Lansing, USA, 1987, NSCL Report MSUCP-47,254.
- [13] R. Geller, B. Jacquot, P. Sortais, N.I.M., A243, 1986, 224-229.
- [14] P. Sortais et al., Proc. 10th Int. Work. on ECRIS, Knoxville, USA, 1990, Oak Ridge Nat. Lab. CONF 9011136, (1991) 35.
- [15] R. Leroy et al., Proc. 12th Int. Work. on ECRIS, Riken, Japan, 1995, to be published
- [16] C.M. Lyneis, X.Q. Xie, Proc. 11th Int. Work. on Electron Cyclotron Resonance Ion Sources, Groningen, 1993, KVI-Report 996, (1993) 127.
- [17] C.M. Lyneis, X.Q. Xie, Proc. 12th Int. Work. on ECRIS, Riken, Japan, 1995, to be published
- [18] C.M. Lyneis, X.Q. Xie, LBL-36393, UC-413, Nov. 1994, U.S.A.
- [19] C.M. Lyneis, T.A. Antaya ; , Proc. 3th Int. Conf. on Ion Sources, Berkeley, USA, 1989, Rev. Sci. Instrum. 61 1 (1990) 221.
- [20] G. Ciavola, S. Gamino, T. Antaya, K. Harrison, Proc. 12th Int. Work. on ECRIS, Riken, Japan, 1995, to be published
- [21] P. Sortais et al., Proc. 12th Int. Work. on ECRIS, Riken, Japan, 1995, to be published
- [22] G. Ciavola, S. Gamino, P. Briand, G. Melin, P. Seyfert, Proc. 5th Int. Conf. on Ion Sources, Beijing, China, 1993, Rev. Sci. Instrum. 65 4 (1994) 1057.