Extraction from ECR ion sources: a new way to increase beam brightness

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EXTRACTION FROM ECR ION SOURCES: A NEW WAY TO INCREASE BEAM BRIGHTNESS

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Abstract

One of the goals of work on ion sources is to provide the highest beam intensity in the smallest emittance. As computer power has increased so rapidly over the last few years, it is now possible to simulate the extraction from the ECR ion sources with greater accuracy, taking into account the physics of the several processes involved in the beam creation. In the last section of their paper, R. Leroy and co-workers [1] showed experimentally that the intensity of a beam can be improved significantly by biasing the plasma electrode. The idea was to use the isolated plasma electrode as a "biased disk". We have calculated the influence on the extracted ion trajectories of this additional potential (from 0 V down to -60 V). The simulations have been computed for the MONO1000 [2] and SUPERSHyPIE [3] ion sources. All the simulations showed an increase of the beam brightness with more or less important gain depending on the extraction voltage and the extraction conditions. A recent experiment performed on the MONO1000 ECRIS has confirmed the feasibility of this method: a gain of around 40% in terms of emittance has been obtained on an $^{84}Kr^{1+}$ beam.

Introduction

This work was performed in the framework of the ITSLEIF [4] network. One of the tasks deals with the improvement of the ECR ion source extraction. The goal is to get higher intensity in a smaller emittance for multi-charged ions of low energy (1–25 keV/q) used in the different facilities of the network. In previous work [1], Leroy and co-workers measured the evolution of the Ar^{4+} current with the polarisation of the plasma electrode at different bias of the coaxial tube. Each time, a maximum value of the current was obtained for a biased plasma electrode between -14 and -30 V. One of the major results was: "the plasma potential of the source is decreased when the coaxial tube voltage is increased". We have used this technique to investigate the extraction zone and the effect of this polarisation on the plasma electrode. Figure 1 shows the effect for negative potentials. This small polarisation will slightly modify the electric field lines in the extraction zone such that the divergence of the beam will be decreased. But at the same time ions from the edges of the beam will not be extracted. So to get a measurable effect, the emittance reduction should be larger than the diminution of the extracted ion current. The relevant parameter in this process is the brightness of a beam. We will use the equation (1) where I_{beam} represents the beam current and ε_x and ε_y the emittances of the beam in the respective transverse planes of the beam propagation. In the following, we will deal only with geometric emittances.

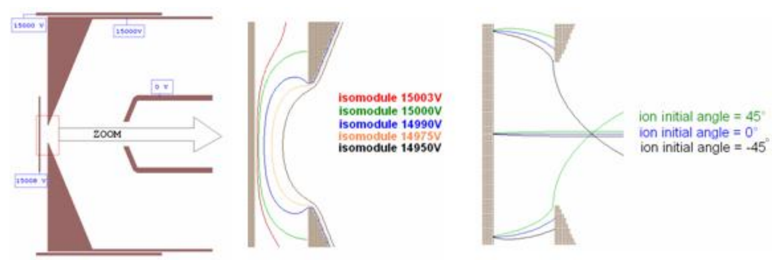
$$B = \frac{2I_{beam}}{\pi^2 \varepsilon_x \varepsilon_y} \qquad (1)$$

The results will be shown by the relative brightness:

$$B_{rel} = \frac{B(V_{pe})}{B(V_{pe} = 0\text{V})} \qquad (2)$$

In the equation, V_{pe} corresponds to the difference between the voltage applied to the plasma electrode and the voltage applied to the ECRIS body: in our case this value will be negative and varies from 0 V down to -60 V. In this paper, V_{pe} = 0 V corresponds to the usual extraction case.

a)



b)

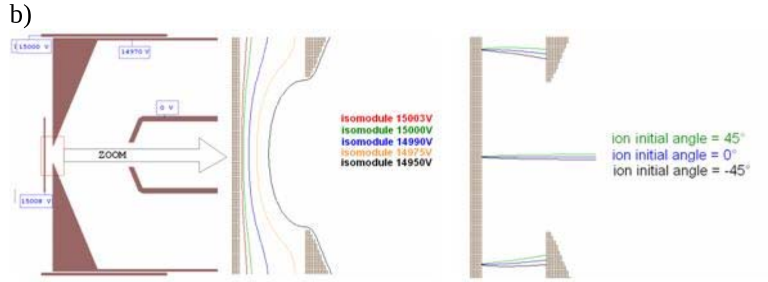


Figure 1: Principle of the technique; case a) corresponds to a plasma electrode at source potential while b) corresponds to a plasma electrode biased at -30 V relative to the source potential.

In the following sections we present the beneficial effects of the idea, and not absolute values. First we will present calculations done with a singly charged ECRIS

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called MONO1000 [2] and the first experimental results performed with this source. In the next section, we will present simulations done for a multicharged ECRIS named SUPERSHyPIE [3].

Simulations: general issue

In reference [5], C. Pierret and co-workers have already described the tools used for the extraction simulations. The RADIA [6] module which runs with the Mathematica program was used for calculating the magnetic field, especially in the extraction zone. For the trajectory calculations, the SIMION3D [7] and CPO [8] codes are used. With the first of these, the space-charge effect is not really effective but it is fast enough to perform many calculations and hence to get results for several configurations. The second reproduces the space-charge effect correctly (see the reference [5]) but it is slower. It will be used to re-compute solutions obtained from the SIMION3D calculations, with more accuracy. In these calculations, the space-charge compensation effect is not included. For both cases, the extraction is made in the following manner: the ions are generated on a plasma surface at the source potential added to the plasma potential. One way to get closer to a realistic spatial and energy distribution of the generated ions to be extracted, would be the application of a plasma simulation code (e.g. TrapCAD [9,10]) as pre-processor for the extraction calculations. For each case the ion distribution used is in accordance with the results from the reference [5]. The energy of the ions is 0.1 and 1 eV for MONO1000 and SUPERSHyPIE respectively. The angle of emission of the ion is within the range of 90°. No energy dispersion has been taken into account. The results of the simulation reflect the total beam extracted (summed over all charge states) and for the beam located in the middle of the puller electrode.

The singly-charged case: MONO1000 ECRIS

As this source is an axisymmetric source without a hexapole and a singly charged one, it is a simple case to simulate and test the technique described above.

Simulations

The MONO1000 ECRIS is mainly a singly charged ion source that can produce multicharged ions. It comprises a double ring of permanent magnets with the same magnetic field orientation and without a hexapole. It works with 2.45 GHz RF signal injected into the source via a coaxial wave-guide.

As it is a axi-symmetric source, the ion distribution is assumed to have the same symmetry. Moreover, a random ion distribution is generated a few mm from the plasma electrode and only the singly charged ions have been treated, which is a fairly good reproduction of reality. The plasma potential has been taken to be 8 V. In this case, the diameter of the plasma electrode is 7 mm and for the puller electrode it is 10 mm. The plasma electrode is located in a magnetic field of around 0.2 Tesla.

Figure 3 shows the relative brightness calculated with both SIMION3D and CPO codes applied to an Ar^{1+} extracted beam. Both curves increase with the diminution of the V_{pe} voltage without getting a plateau.

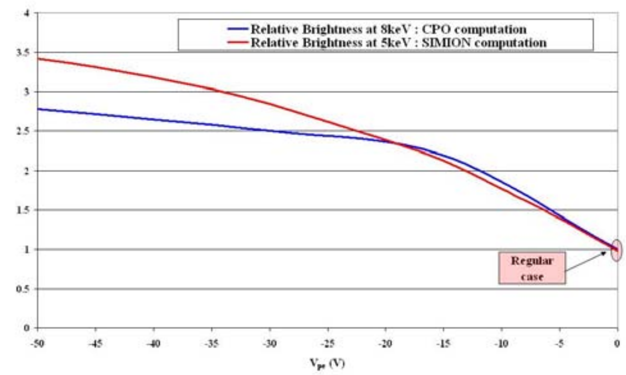

Figure 2: Relative brightness of an extracted Ar^{1+} beam at low energy calculated with the SIMION3D code (red) and with CPO (blue)

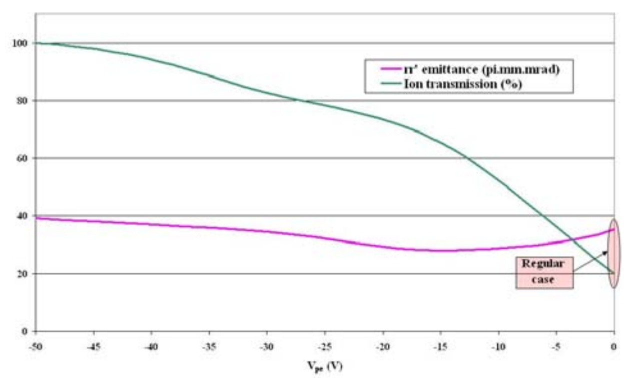

Figure 3: Ion transmission and emittance of an extracted Ar^{1+} beam at high energy (15 keV)

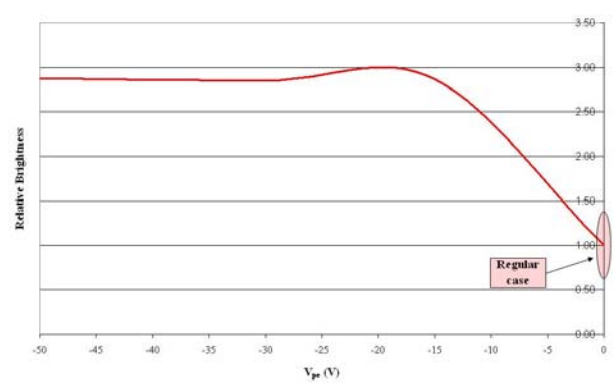

Figure 4: Relative brightness of an extracted Ar^{1+} beam at high energy (15 keV) calculated with the CPO code

Both curves are similar down to -20 V but below this SIMION3D overestimates the relative brightness compared to the CPO code, which should give more realistic results. For a higher energy, e.g. 15 keV, the emittance of the beam and the ion transmission as well as the relative brightness are shown in figures 4 and 5. The ion transmission increases with reducing V_{pe} voltage while the emittance curve has a minimum value for V_{pe} = -15 V. The combination of these two parameters (ion transmission and emittance) is summarized with the curve displayed in figure 4. In this higher-energy case , the relative brightness increases up to a maximum and then hits a plateau which corresponds to the increase of the ion transmission and the emittance in the same range. In essence, the use of this bias plasma electrode improves the brightness of the beam. The next step is the comparison of this technique with the experiment.

Experiment

An experiment has been done to confirm or invalidate the method explained above. The MONO1000 ECRIS was used used with a simple test bench composed of an extraction box, a double focusing analyse dipole with a Br_{max} of 0.244 T.m, a faraday cup and an emittance meter of the type describes in reference [11]. This device can measure the emittance in both transverse planes of the

a) b)

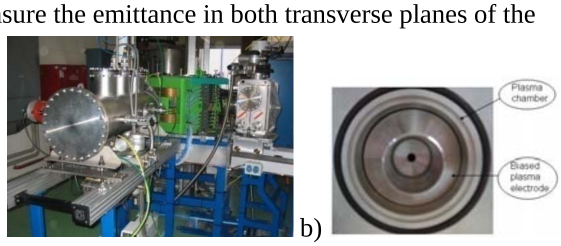

Figure 5: a) The test bench, and b) the extraction system with insulated plasma electrode.

beam. It is located beyond the analysing dipole and we focused our measurement on a specific beam: $^{84}Kr^{1+}$ in this case. Within the extraction box, there is an einzel lens and the plasma electrode is movable.

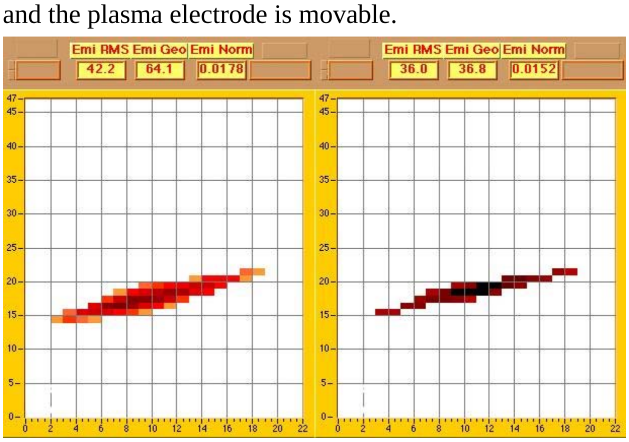

Figure 6: Vertical emittance of the $^{84}Kr^{1+}$ beam with V_{pe} = 0 V (left) and with V_{pe} = -30 V (right)

During the experiment, the total extracted current was 0.5 emA. The Kr gas was injected through a calibrated leak of 2.2 pμA value. All the atoms injected are ionized so there is 2 eμA of $^{84}Kr^{1+}$ and 0.4 eμA of $^{84}Kr^{2+}$. The source extraction was set to 7 kV to enable comparison for low-energy extraction. The source was tuned to get the maximum current of the $^{84}Kr^{1+}$ – in this case 2 eμA – and hence the emittance was recorded for different values of the V_{pe} without modifying the source parameters. Figure 6 shows emittances recorded and analysed after applying such a threshold, the emittance corresponds to 63% of the total current of $^{84}Kr^{1+}$ (in our case 1.26 eμA). The reduction of the emittance is evident from comparison of the case with V_{pe} = 0V and the case with V_{pe} = -30V. The gain, in terms of emittance reduction, is 42.6%. Figure 7 is a summary of the data recorded.

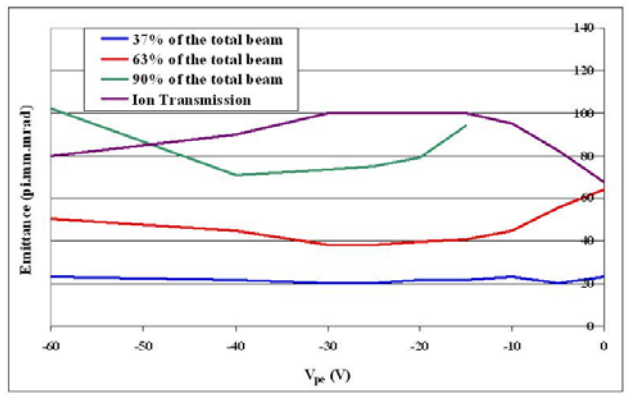

Figure 7: Emittance and ion transmission of the $^{84}Kr^{1+}$ beam asa function of V_{pe}.

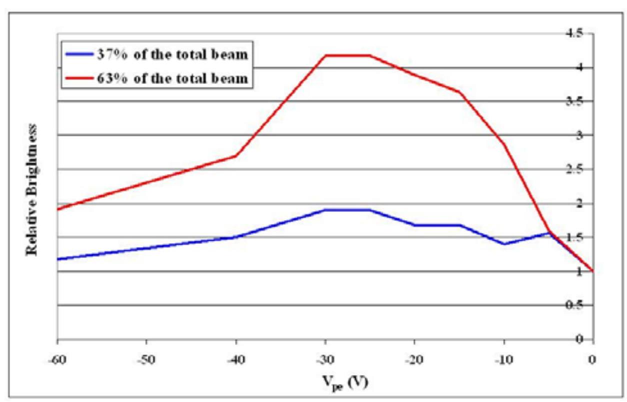

Figure 8: Variation of the relative brightness of the $^{84}Kr^{1+}$ beam with V_{pe}.

Each percentage curve corresponds to the values of an emittance for that percentage of the total beam. The blue curve is related to the core of the beam. It is slightly affected by the negative bias of the electrode plasma because in this region we can assume that the beam is a little divergent. The green curve corresponds to nearly the whole beam. In this case the negative bias modifies the emittance appreciably so as to give a real reduction for a value around -30 V. The figure 8 shows the experimental result but in terms of relative brightness. Only the curves for 37% and 63% are displayed because it was not possible to get the emittance value at V_{pe} = 0V and for the 90% case. Again, a real improvement of the relative brightness of the beam for the value around -30 V can be seen. The enhancement is higher because a larger part of the beam is involved, so the negative bias can reduce the larger ion angles.

The multicharged case: SUPERSHyPIE ECRIS

The SUPERSHyPIE ECRIS is mainly a multicharged ion source that can produce beams with a high charge state, such as O^{8+}, Ar^{17+}, Xe^{30+} [4]. After the promising result obtained with the singly charged ECRIS, it was encouraging to apply this technique to a multicharged ECRIS. Many simulations have been done but only that concerning a real case will be presented: it is the case of a plasma for producing Ar^{q+} beam with O_2 as a support gas.

Simulations

The SUPERSHyPIE ECRIS runs with a RF frquency of 14.5 GHz. It is composed of a combination of coils and permanent magnets and a hexapole for the axial and radial magnetic components, respectively. The scheme is the same as that discussed above: the ions are generated few mm from the plasma electrode (diameter of 13 mm) at the source potential added to the plasma potential of 8 V. Hence there is the puller electrode with a flat nose and a diameter of 20 mm. The plasma electrode is located in a

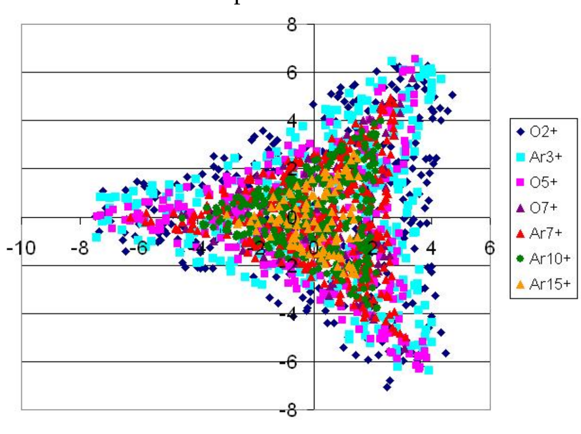

Figure 9: Initial ion distribution representing a real spectrum measured with the SUPERSHyPIE ECRIS

magnetic field of around 1 Tesla. Clearly the ion distribution should follow the shape of the plasma due to the total magnetic structure (star structure) and the charge distribution which has been chosen following the results in the reference [11]: the higher the charge, the more concentrated are the ions. Moreover, macro ions have been created in order to avoid slowing down the CPO calculation by gathering charges (table 1). The result of the ion distribution is shown in the figure 9. The star is within a 15-mm diameter circle. The calculations have been done using 15 kV of extraction.

Table 1: Average charge distribution

Average charge	Included charges	Equivalent intensity (emA)
O^{2+}	1,2,3	2,235
O^{5+}	4,5,6	2,369
O^{7+}	7,8	0,061
Ar^{3+}	1,2,3,4,5	0,231
Ar^{7+}	6,7,8	0,325
Ar^{10+}	9,10,11,12	0,938
Ar^{15+}	13,14,15,16	0,108

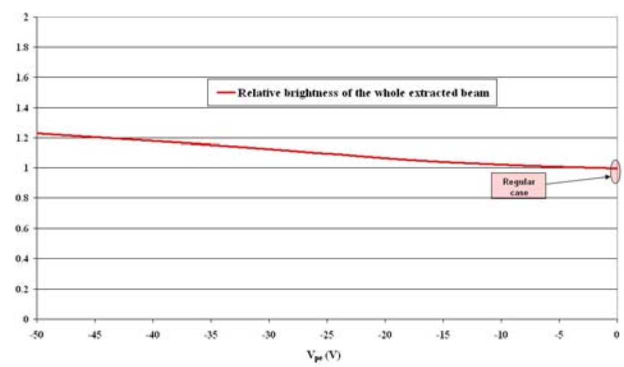

Figure 10: Relative brightness of an extracted beam (realistic case) at high energy (15 keV) calculated with the CPO code

voltage and with the CPO code. Figure 10 shows the relative brightness for the whole extracted beam (i.e. O^{q+} and Ar^{q+} beams). Again, there is an increase but much smoother compared with the MONO1000 case and with a

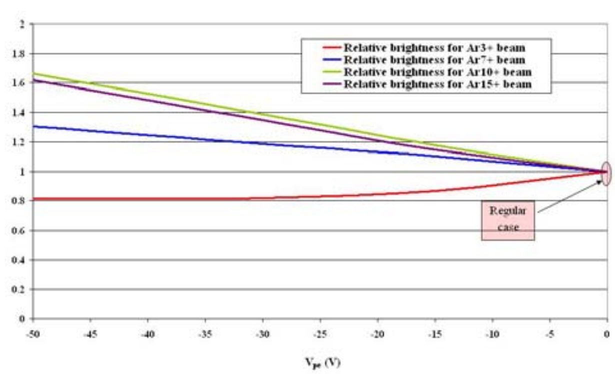

Figure 11: Relative brightness of the Ar^{q+} extracted beams at high energy (15 keV) calculated with the CPO code.

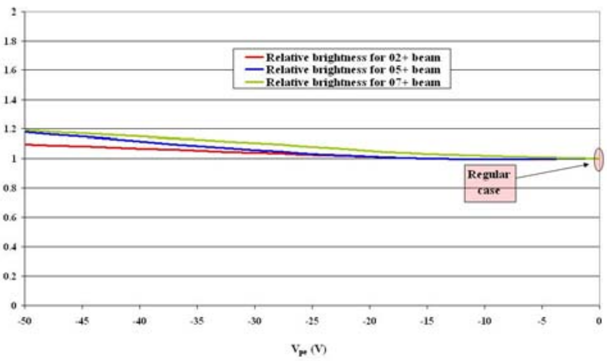

Figure 12: Relative brightness of the O^{q+} extracted beams at high energy (15 keV) calculated with the CPO code.

lower gain. Looking at the O and Ar beams, the results are somewhat different. For the Ar beams (figure 11), the method is unfavourable for the lower charge (3+) but positive for the others. This could be explained by the magnetic field gradient which is really strong (19 Tesla/m). For such low charge states, the new effect cannot compensate for the increase of the emittance due to this high gradient. For the O beams (figure 12), the method is favourable for all the charge states.

a) Discussion

We have shown that biasing the plasma electrode negatively over a small range of *V* works. The assumption that it is possible to modify the electric field lines in the extraction region slightly and hence to increase the brightness of a beam has been proved experimentally. Clearly, all the curves do not give the required gain but they encourage us to believe that this method could significantly improve the brightness of the beams extracted from ECR ion sources

The experiment has only been done for one case: low extraction voltage and for a singly charged extracted beam. It should also be done for a higher voltage (e.g. for 15 kV extraction voltage) and especially for other masses. Our measurements have been done after the analysing dipole. For the calculation of the relative brightness, it has been assumed that the vertical and horizontal emittances are equal which is not true due to the horizontal dispersion from analysing dipole. The relative brightness should be deduced from the measurements of the emittances in the both transverse plane but this was made impossible for us due to a failure in the movement of the horizontal slit set.

After the encouraging calculations done for the multi-charged case, measurements should be also performed in order to confirm this method applied to such an ECRIS. For this purpose, a new extraction box will be installed on the SUPERSHyPIE bench in order to be able to bias the plasma electrode, and also to move it. A movable plasma electrode experiment was already reported at the ATOMKI-ECRIS [12], however that electrode was not biased. We plan to apply the method described in this paper at the ATOMKI source in 2009. At GANIL, the experiment is scheduled for the first half of 2009 but not with the SUPERSHyPIE ECRIS. The GTS [13] ECRIS, which will be mounted at the beginning of 2009, will be our multicharged ECRIS to test this technique.

Finally, simulations should be continued to fit the experimental data and to provide the right ion distribution which characterises an ECRIS, and to allow us to predict the emittance and brightness of a beam extracted from an ECRIS.

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