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Experimental study of the dependence of beam current on injection magnetic field in 6.4 GHz ECR ion source

G S TAKI[1], P R SARMA[1], D K CHAKRABORTY[1], R K BHANDARI[1] and P K RAY[2]
[1]Department of Atomic Energy, Variable Energy Cyclotron Centre, Block-AF, Bidhan Nagar, Kolkata 700 064, India
[2]Bengal Engineering and Science University, Shibpur, Howrah 711 103, India
E-mail: gstaki@veccal.ernet.in

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Abstract. The ion current from an electron cyclotron resonance (ECR) heavy ion source depends on the confining axial and radial magnetic fields. Some efforts were made by earlier workers to investigate magnetic field scaling on the performance of the ECR source. In order to study the dependence of the ion current on the injection magnetic field in the 6.4 GHz ECR source, we have measured the current by varying the peak injection field and have inferred that the variation of the current is exponential up to our maximum design injection field of 7.5 kG. An attempt has been made to understand this exponential nature on the basis of ion confinement time.

Keywords. Electron cyclotron resonance ion source; mirror ratio; field scaling; ion confinement time; ion current.

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1. Introduction

A large number of electron cyclotron resonance (ECR) ion sources have been developed throughout the world in the last thirty years [1–6]. After the development of SUPERMAFIOS ion source by Geller [1], many modified sources have been constructed to improve the high charge state performance of the source and increase its efficiency. The most important parameters which affect production and stability of the source are the microwave frequency and power, and the confining mirror magnetic field. There are, of course, other parameters which play a role in the extraction process of the ions. Some of these parameters are the extraction potential, electrode configuration, etc. Apart from these, the magnetic field in the extraction area is also important.

The mirror magnetic field is required for confining the electrons of the plasma so that a lot of ionizations take place. The electrons gain energy at the resonant surface where resonance of microwave frequency and the electron rotation frequency occurs. It has been found that in general, the higher the magnetic field, the better is the performance [7]. Sources [8–14] having magnetic field much higher than the resonance field are called the high-B ECR ion sources.

Geller in 1987 outlined some classical empirical scaling laws to explain the experimental ion current data. In addition to the other laws, he gave the ion current production formula as [1]

$$I(q) \propto \omega^2 A^{-\alpha}, \tag{1}$$

where $I(q)$ is the ion current of charge state q, $\omega = 2\pi f$, where f is the microwave frequency, A, the atomic mass number and α an adjustable parameter varying from 0.5 to 1.

This relation shows that the extracted ion current follows a square law on the resonance frequency [15,16]. This is based on the important law of the dependence of plasma density on the microwave frequency. Since the resonance frequency is directly proportional to the resonance magnetic field ($B_{\rm res}$) one can infer that this law indicates that the ion current should be proportional to the square of $B_{\rm res}$.

$$I(q) \propto B_{\rm res}^2. \tag{2}$$

This equation shows a dependence of the ion current on the resonance magnetic field $B_{\rm res}$. However, there is experimental evidence that the ion current has a prominent dependence on the peak injection field. After the invention of high-B mode, Antaya and Gammino [11], working with a low frequency superconducting ECR source, experimentally showed that the mirror ratio should be much higher than that used till then. In general, the higher the confining magnetic field, the better is the performance of the source. Therefore, apart from the frequency scaling law, one needs to investigate the magnetic field scaling too. Hitz *et al* [17] and Gammino *et al* [4,18] studied the field scaling (both axial and radial) at a number of microwave frequencies. It was found that the ion current increases up to an injection mirror ratio of about 4 and then it saturates [4]. In a recent experiment, Nakagawa *et al* [19] showed that $B_{\rm min}$ can be optimized for maximizing the beam intensity while keeping $B_{\rm inj}$ and $B_{\rm ext}$ unchanged in an ECR ion source.

We have carried out an experiment to study the dependence of the extracted ion current on the injection peak field B ($=B_{\rm inj}$) for our 6.4 GHz ECR source [6,14]. The maximum injection mirror ratio $B_{\rm inj}/B_{\rm res}$ is 3.3 and no saturation in ion current has been observed up to that field. We have found that the variation of current with the peak injection field can be described by an exponential function. We have made an attempt to understand this exponential nature on the basis of the field-dependent ion confinement time.

2. Experiment

Experiment was carried out using a 6.4 GHz VEC-ECR [6] ion source at Variable Energy Cyclotron Centre, Kolkata. This source underwent many modifications [14]

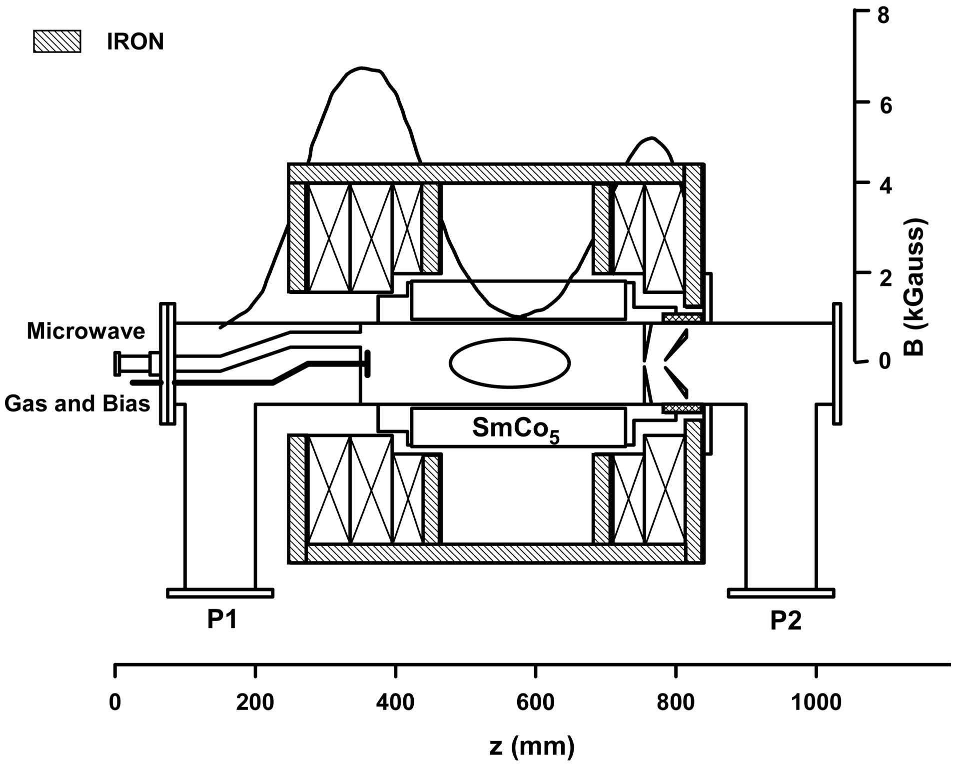

Figure 1. The 6.4 GHz ECR ion source at VECC, Kolkata.

for increasing the extracted ion current. The source is being routinely used for delivering heavy-ion beam to the K130 AVF cyclotron. Figure 1 shows the ECR ion source schematically.

Heavy ions are extracted from the VEC-ECR by an accel–decel extraction system through an 8 mm circular hole in the plasma electrode with the help of a modified Pierce-shaped stainless steel puller electrode. The puller is placed 30 mm away from the plasma electrode and has a 10 mm aperture at the centre. The plasma electrode is placed on the extraction mirror peak of 5.2 kG. The radial field created by $SmCo_5$ assembly on the chamber wall is 4.2 kG. As can be seen from figure 1, the mirror coils have separate iron return yokes and so the fields in the injection and extraction sides can be independently varied. The variation in the injection field has negligible influence on the extraction field. The injection peak field was varied in steps from 3.5 kG to 7.5 kG and ion current was measured for various q/A of oxygen, neon and argon. The other ECR discharge parameters, viz., microwave power, vacuum and gas flow were initially optimized for obtaining O^{7+} ions and subsequently were kept unchanged throughout the experiment. The charge states were separated by a magnetic analyzer and the ion current was measured in a Faraday cup.

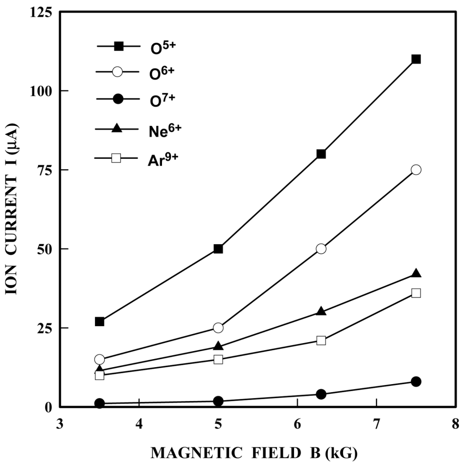

Figure 2. Extracted ion current from 6.4 GHz VEC-ECR source for different charge states of various species.

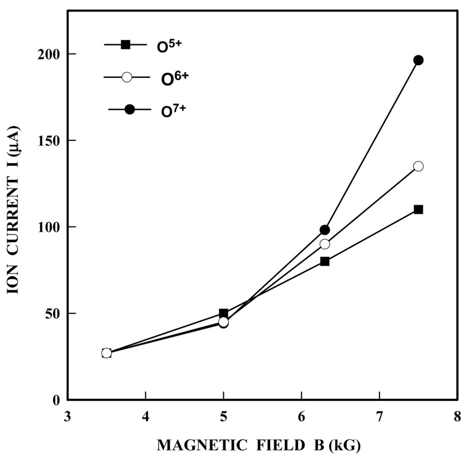

Figure 3. Comparison of the normalized curves for the oxygen ions showing steepness of the curves.

3. Experimental result and analysis

The peak injection field was the only parameter that was varied in the experiment. The extraction peak magnetic field remained unchanged at 5.2 kG. The radial field produced by the permanent $SmCo_5$ magnets was also constant. Figure 2 shows the extracted current as a function of the peak injection field for various charge states of oxygen, neon and argon. It is seen that the extracted current increases sharply with the injection field B.

For a better visualization of the sharpness of the increase, we have normalized the curves for oxygen ions at 3.5 kG. It is seen that for O^{7+} the curve is steeper than those for O^{5+} and O^{6+} (figure 3). The apparent flatness of the curve for O^{7+} in figure 2 is obviously due to the comparatively small intensity.

A number of relations have been used for fitting the experimental curves. A power law and two exponential relations have been explored. The curves have been found to be steeper than the power law. An exponential curve, viz.,

$$I(q) = a\frac{\exp(pB)}{B} \tag{3}$$

has been found to give a good fit. Here a and p are parameters independent of the field B. The parameter p markedly depends on q/A. As the number of experimental points is small for each curve, we have adopted the following procedure for deciding between the various forms of relations. The form of relation will be the same for all the five curves in figure 2, only the fitted parameters will be different. So we can write

$$I_1(q_1)I_2(q_2)\ldots I_N(q_N) = a_1a_2\ldots a_N\frac{\exp\left[(p_1+p_2+\cdots+p_N)B\right]}{B^N}, \tag{4}$$

Table 1. Exponent p for different fits (for various charge states).

Ion	q/A	Power law, B^p	$\exp(pB)$	$\exp(pB)/B$
O^{7+}	0.438	2.58	0.504	0.695
O^{6+}	0.375	2.49	0.415	0.605
O^{5+}	0.313	1.85	0.354	0.544
Ne^{6+}	0.300	1.70	0.327	0.517
Ar^{9+}	0.225	1.60	0.312	0.503
χ^2/ν		0.57	0.040	0.046

where the subscripts indicate various charge states and N is the number of curves. Writing

$$I_1(q_1)I_2(q_2)\ldots I_N(q_N) = I^N,$$

$$a_1a_2\ldots a_N = a^N,$$

$$p_1 + p_2 + p_3 + \cdots + p_N = Np, \tag{5}$$

eq. (4) becomes the same as eq. (3). This procedure is equivalent to taking the geometrical average of the ion current values. When five curves of different charge states are merged to one curve, the fitting becomes more accurate statistically.

One should keep in mind that in this process of clubbing the curves together, some of the information about the individual curves are lost. But one can make more accurate inference about the common feature (the form of the relation, in this case) of the curves. We point out the similarity between this method and the technique of maximum likelihood [20] of statistical analysis where one multiplies the individual probabilities and then maximizes the product.

Figure 4 shows the comparison between the fits for all the ions taken together. As explained in the previous paragraph, the experimental points shown in figure 4 are the geometrical averages of five different ion current values. As indicated by the χ^2-values (table 1), the exponential fits are much better than the power-law fit. Compared to the χ^2-value for the power law fit, the χ^2-values for both the exponential fits are much smaller and are more or less the same. However, theoretical considerations described in the discussions led us to prefer the $\exp(pB)/B$ fitting. When the curves are fitted individually we find that the parameter p strongly depends on the q/A of the ions (figure 5). Table 1 shows the values of p for various ions.

4. Discussions

We have experimentally found an exponential dependence of the extracted ion current on the injection magnetic field in our range of measurement. Another feature observed by us is that the exponent of this dependence markedly varies with the q/A of the ions.

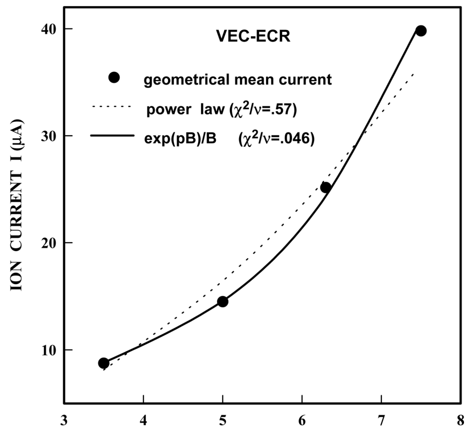

Figure 4. Comparison between various fits to the ion current data. The solid circles are the geometrical means of the current values shown in figure 2.

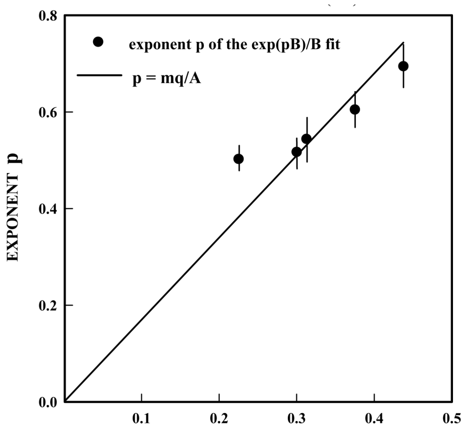

Figure 5. Dependence of the exponent p in the $\exp(pB)/B$ fit (table 1) on q/A. The error bars show the standard error in the fit parameter.

We have made an attempt to understand the observed exponential dependence of the ion current on the injection field B in the following manner. The extracted ion current depends on the ion production inside the source. Following Geller [21] and Hitz *et al* [22] the dependence of the extracted ion current on the ion density $N(q)$, its confinement time τ_q and the volume $V_{\rm res}$ of the resonance zone is given by

$$I(q) \propto \frac{qN(q)V_{\rm res}}{\tau_q}. \tag{6}$$

Ion density $N(q)$ is an increasing function of τ_q and is almost exponential (as indicated by Hitz *et al* [17,22]) and therefore for a fixed resonance volume one arrives at the following explicit relationship between the ion current and τ_q.

$$I(q) \propto \frac{\exp(k\tau_q)}{\tau_q}, \tag{7}$$

where k is a constant. This shows that the current increases almost exponentially as the confinement time increases. It is to be noted that the above equation suggests that for very small confinement time also the ion current is large, but this is not actually so, as the ion confinement time should be larger than the ionization time. Therefore the singular behaviour of eq. (7) is of no concern to us.

Confinement time of ions depends upon the magnetic field configuration of the source. For understanding this dependence of the confinement time on the magnetic field we have done a Monte Carlo simulation study of the survival of ions in an ECR magnetic trap. This magnetic trap consists of the solenoidal magnetic field having peaks on the injection and extraction sides and also the sextupolar radial and azimuthal field.

An ion of a given charge state and mass with an initial velocity in any direction gyrates and moves in the trap field for a long time (compared to the rotation time period) and ultimately moves out of the trap to get lost on the chamber wall. Apart from the magnitude of the magnetic field and the charge-to-mass ratio, the confinement time depends on the initial magnitude and direction of the velocity, and, of course the starting position of the particle.

In a real situation, the charge state of an ion undergoes a change inside the source due to ionization. To keep the simulation simple, we have studied the confinement time for fixed charge states. However, we have repeated the study for various charge-to-mass ratios independently. This will allow us to have a rough estimate of the effect of the magnetic field on the confinement time. We have done the study for various magnitudes of the peak injection field.

We have written a FORTRAN code where the initial position coordinates and the velocity components are chosen at random by the Monte Carlo method. This is important because when ions are initially generated by energetic electron collision these parameters may be assumed to be random. In our simulation the ions are tracked at time intervals of 10 nsec (which is much smaller than the typical rotation time period of an ion) until the ion goes out of the chamber region. For the fixed coil geometry the field is calculated for various combination of currents in the solenoid coils with the help of the POISSON code and the sextupolar field is superimposed on it. The peak extraction field and its position has been kept constant. One then calculates the confinement time in the field so obtained. A large number of ions (around 10^5) are tracked and the average confinement time is found out.

Figure 6 shows the variation of the average confinement time as the peak injection field is varied. The extraction peak field is kept at 5.2 kG and the sextupolar field at the chamber wall is 4.2 kG. The calculated data have been fitted with a line which passes through the origin. The fit shows that one can take the confinement time to be proportional to the injection field.

Figure 7 shows the dependence of the average confinement time on the charge-to-mass ratio of the ions. Here also we find that the confinement time comes out to be nearly proportional to the charge-to-mass ratio. For higher $B_{\rm inj}$ there is a small departure from linearity. One can add a constant term in the relation between τ_q and $B_{\rm inj}$ to take this into account. However, this term comes out to be quite small compared to the linear term, and for the sake of simplicity we have retained only the linear term. Therefore eq. (7) becomes

$$I(q) \propto \frac{\exp(mBq/A)}{Bq/A}, \tag{8}$$

where m is a constant. Equation (8) is same as equation (3) for a fixed q/A. The above equation shows that the exponent p (vide eq. (3)) has a dependence on the ratio of the charge state and the mass of the ions (q/A). In our experiment we see a similar dependence as shown in figure 5. One should note that ions undergo some amount of heating in the plasma. We have not considered this in our simulation as the conclusions drawn from figures 6 and 7 remain the same for all the energies, but only the scale of confinement time changes.

To see whether we can draw similar conclusions for any other source, the curves of SC-ECR [7] at NSCL in Michigan State University have been examined. Figure

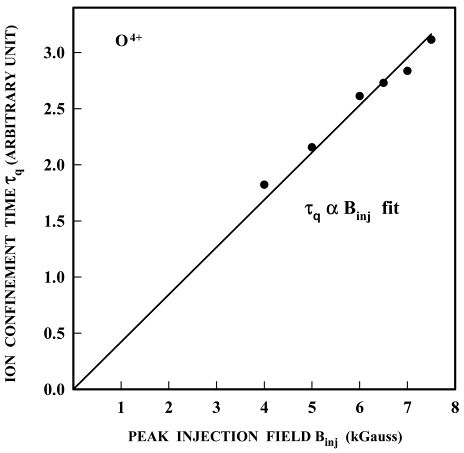

Figure 6. Variation of the calculated average confinement time of O^{4+} ions on the peak injection field. The line is a fit passing through the origin.

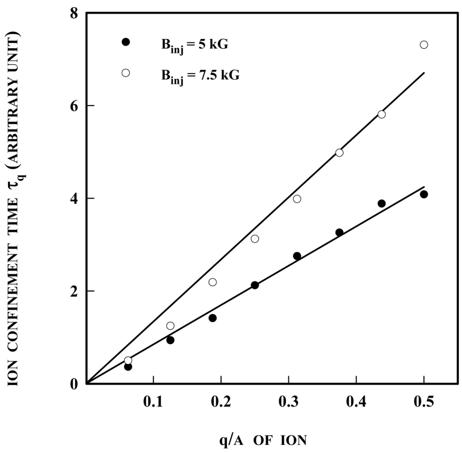

Figure 7. Dependence of the average confinement time of ions on charge-to-mass ratio.

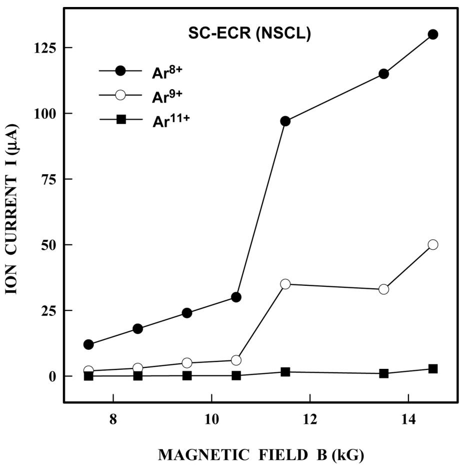

Figure 8. Variation of ion current in SC-ECR [7] of NSCL.

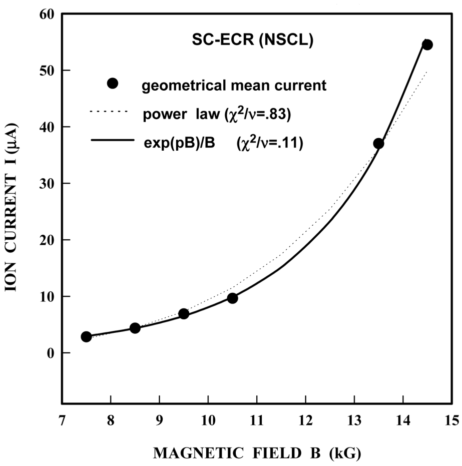

Figure 9. Comparison between various fits for SC-ECR of NSCL. The solid circles are the geometrical means of the current values shown in figure 8.

8 shows the plot of the current for various charge states of argon as a function of the magnetic field. We have not included the curve for Ar^{12+} in figure 8 as the current for Ar^{12+} is very low in comparison to that for other charge states and uncertainty arises in deciphering the current values from the graph. Figure 9 shows the fitting for argon ions extracted from SC-ECR. Here also exponential fit is better. The derived exponents (p) are, however, different in this case. In figure 8, the current

is consistently large at an injection field of $B_{\mathrm{inj}} = 11.5$ kG for all the curves. We observe that this is the field where SC-ECR is operated normally and the source is well-optimized at this field. This may be the reason why the extracted ion current is abruptly large at that field. In fitting the curve in figure 9 we have ignored this point at $B = 11.5$ kG because the goodness of the fit increases by a large factor in this process.

In this work we have studied the magnetic field dependence of ion current for our ECR ion source. The frequency scaling of Geller is quite satisfactory when one compares two sources of different frequencies. But for high-B mode ECR sources, field scaling is very important. Our analysis shows that the ion current increases with the injection field almost exponentially up to a mirror ratio of 3.3 for our source.

Our study was limited to a mirror ratio of 3.3 and we can not conclude whether the current trend remains exponential beyond that ratio. Gammino and others have shown that ion current gets saturated when the injection mirror ratio is too large [4,12,17]. Various factors are thought to contribute to this limitation. Charge exchange loss is one important factor [4]. Another factor is the density limitation of hot electrons. For increasing the ion current it is important to have a high electron density. Even if the injection field is increased beyond a limit, the electrons tend to escape radially and also through the extraction side crossing over to the electrostatic potential. This is a saturating factor [23].

References

[1] R Geller, *Electron cyclotron resonance ion sources and ECR plasmas* (IOP Publishing, Bristol, 1996) p. 395

[2] A G Drentje, *Rev. Sci. Instrum.* **74**, 2631 (2003)

[3] D Hitz, A Girard, K Serebrennikov, G Melin, D Cormier, J M Mathonnet, J Chartier, L Sun, J P Briand and M Benhachoum, *Rev. Sci. Instrum.* **75**, 1403 (2004)

[4] S Gammino and G Ciavola, *Rev. Sci. Instrum.* **71**, 631 (2000)

[5] T Nakagawa, T Kageyama, M Kase, A Goto and Y Yano, *Jpn. J. Appl. Phys.* **32**, L1335 (1993)

[6] D K Bose, G S Taki and R K Bhandari, *Ind. J. Phys.* **66B**, 629 (1992)

[7] S Gammino, G Ciavola, T Antaya and K Harrison, *Rev. Sci. Instrum.* **67**, 155 (1996)

[8] D Hitz, F Bourg, M Delaunay, P Ludwig, G Melin, M Pontonnier and T K Nguyen, *Rev. Sci. Instrum.* **67**, 883 (1996)

[9] H Koivisto, P Heikkinen, V Hänninen, A Lassila, H Leinonen, V Nieminen, J Pakarinen, K J Ranttila Ärje and E Lieukkonen, *Nucl. Instrum. Methods in Phys. Res.* **B174**, 379 (2001)

[10] Z Q Xie and C M Lyneis, *Rev. Sci. Instrum.* **67**, 886 (1996)

[11] T A Antaya and S Gammino, *Rev. Sci. Instrum.* **65**, 1723 (1994)

[12] S Gammino, G Ciavola, L Celona, M Castro, F Chines and S Marletta, *Rev. Sci. Instrum.* **70**, 3577 (1999)

[13] S Biri and J Vámosi, *Rev. Sci. Instrum.* **69**, 646 (1998)

[14] G S Taki, D K Chakraborty and R K Bhandari, *Pramana – J. Phys.* **59**, 775 (2002)

[15] S Gammino and G Ciavola, *Rev. Sci. Instrum.* **69**, 3081 (1998)

[16] S Gammino and G Ciavola, *Proceedings of the 14th Int. Conf. on Cyclotron and their Application* (Cape Town, 1995) p. 377

[17] D Hitz, A Girard, G Melin, G Ciavola, S Gammino and L Celona, *Rev. Sci. Instrum.* **73**, 509 (2002)
[18] S Gammino, G Ciavola, L Celona, D Hitz, A Girard and G Melin, *Rev. Sci. Instrum.* **72**, 4090 (2001)
[19] T Nakagawa, T Aihara, Y Higurashi, M Kidera, M Kase, Y Yano, I Arai, M Imanaka, S M Lee, G Arzumanyan and G Shirkov, *Rev. Sci. Instrum.* **75**, 1394 (2004)
[20] P R Bevington and D K Robinson, *Data reduction and error analysis for the physical sciences* (McGraw-Hill, New York, 2003) ch. 10
[21] R Geller, *Electron cyclotron resonance ion sources and ECR plasmas* (IOP Publishing, Bristol, 1996) p. 370
[22] D Hitz, A Girard, G Melin, S Gammino, G Ciavola and L Celona, *Proceedings of the 15th workshop on ECR ion source* (Univ. of Jyväskylä, Finland, 2002)
[23] A Girard, D Hitz and G Melin, *Rev. Sci. Instrum.* **75**, 1381 (2004)