FIELD SCALING LAW FOR ION CURRENT IN ECR SOURCE

G.S. Taki†, P.R. Sarma, D.K. Chakraborty, R.K. Bhandari
Variable Energy Cyclotron Centre, Block-AF, Bidhannagar, Kolkata-700064, India
P.K. Roy, Bengal Engineering College (DU), Shibpur, Howrah, India

Abstract

The ion current in Electron Cyclotron Resonance (ECR) heavy ion source depends on various source parameters. In order to study the scaling of the ion current with the magnetic field, we have measured the current by varying the magnetic field and have shown that the variation of the current is exponential which is steeper than the power law.

INTRODUCTION

A large number ECR ion sources have been developed throughout the world in the last thirty years [1-5]. After the development of SUPERMAFIOS ion source by Geller [6] many modifications have been made to improve the high charge state performance of the source and increase the efficiency. The most important parameters which effect 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 role in the ion extraction process. Apart from these, the magnetic field in the extraction area also is important.

The mirror magnetic field is required for confining the electrons of the plasma. The electrons gain energy at the resonant surface where resonance of microwave frequency and the magnetic field occurs. Recently it has been found that the higher the magnetic field, the higher is the production of high charge states. Such sources having magnetic field much higher than the resonant field are called the high-B ECR ion sources [7-10]. In 1987, R. Geller outlined some classical empirical scaling laws to explain the experimental data on ion current. He indicated that [11],

$$I(Z) \propto \omega^2 A^{-\alpha} \propto B^2{}_{res} A^{-\alpha} \qquad (1)$$

where $I(Z)$ = ion current of charge state Z

$\omega = 2\pi f$, f = microwave frequency

A = atomic mass number

α = a parameter varying from 0.5 to 1.

This relation shows that the extracted ion current follows a square law on the resonance magnetic field B_{res}. This is based on the important law of the dependence of plasma density on the microwave frequency. This has been verified by others also[12]. However, after the invention of high-B mode, Antaya and Gammino, working with a low frequency superconducting ECR source [7,8], experimentally showed that the mirror ratio has no saturation value. The higher the confining magnetic field (B), the better is the performance. Therefore, apart from the frequency scaling law, one needs to investigate a magnetic field scaling law too. We have carried out an experiment to find out an empirical relation between the extracted ion current and the injection peak mirror field (B). We have found that the variation of the current with the peak injection field is an exponential function and is much steeper than the square law indicated by Geller. We have analyzed the data of MSU ion source also and have seen a similar exponential trend. An attempt has been made to explain this exponential nature on the basis of the electrostatic trap potential $\Delta\phi$ created by the mirroring electrons in underdense plasma.

EXPERIMENT

We carried out the experiment using the 6.4GHz VEC-ECR [5] ion source at Variable Energy Cyclotron Centre, Kolkata. This source underwent many modifications [13] for increasing the extracted ion current. 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 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. This peak field is suitable for axial high-B mode operation in combination with the radial field of 4.2 kG created by $SmCO_5$ assembly on the chamber wall. The injection peak field was varied in steps from 3.5 kG to 7.5 kG and ion current was measured for various Z/A of oxygen, neon and argon. The other ECR discharge parameters i.e., microwave power, vacuum and gas flow were initially optimized for obtaining high charge state ions and subsequently were kept unchanged throughout the experiment. The charge states were separated by a magnetic analyzer and the ion current were measured in a Faraday cup.

RESULT AND ANALYSIS

As we could not vary the radial field (produced by the permanent $SmCO_5$ magnets), we kept the extraction peak magnetic field constant. Only the peak injection field was the parameter which was varied. Fig. 1 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 rapidly with the injection field B.

†gstaki@veccal.ernet.in

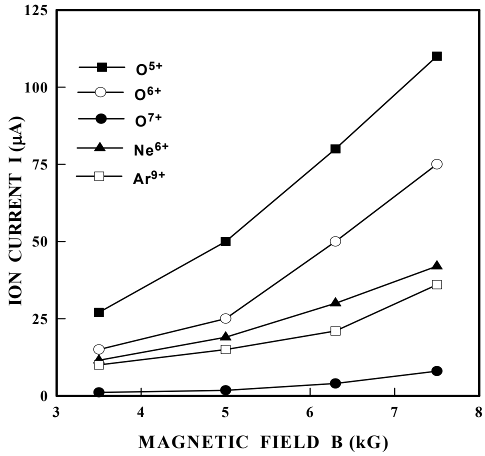

Figure1: Extracted ion current for different charge states

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 and an exponential law viz.,

$$I(Z) = a\frac{\exp(pB)}{B} \tag{2}$$

has been found to be give a good fit. Here a and p are parameters independent of field B. The parameter p markedly depends on Z/A. For improving the statistical accuracy of the fit we have combined the experimental data for all the ions and charge states.

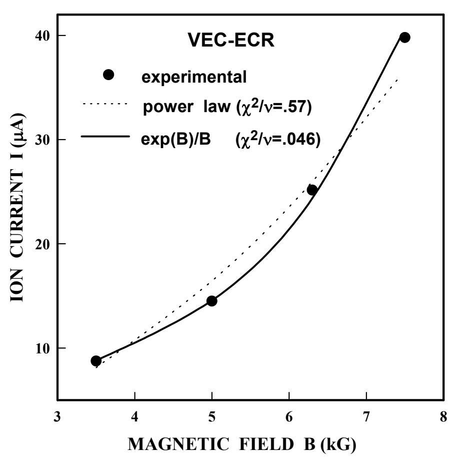

Figure 2: Comparison between various fits.

Fig.2 shows the comparison between the fits. As indicated by the χ^2-values (Table 1), The exponential fits are much better than the power-law fit. The fit with exp(B) is marginally better than that with exp(B)/B. But we prefer the latter because of theoretical considerations described in the discussions. When the curves are fitted individually we find that the parameter p strongly depends on the Z/A of the ions. Table 1 shows the values of p for various charge states.

Table 1: Exponent values for various charge states

Ion	Z/A	Power	exp(B)	exp(B)/B
O^{7+}	.4375	2.58	.504	.695
O^{6+}	.3750	2.49	.415	.605
O^{5+}	.3125	1.85	.354	.544
Ne^{6+}	.3000	1.70	.327	.517
Ar^{9+}	.2250	1.60	.312	.503
χ^2/ν		0.57	0.040	0.046

DISCUSSIONS

We have made an attempt to understand the exponential variation 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. D. Hitz et al. [14] suggested that the ion current depends on the ion confinement time τ_z and is given by

$$I(Z) \propto A\frac{\exp(k\tau_z)}{\tau_z} \tag{3}$$

where k is a constant. Because of the influence of an electrostatic trap $\Delta\phi$ created by the mirroring electrons in underdense plasma, the ion confinement time follows the following model [15]

$$\tau_z = nB\exp\left(Z\frac{\Delta\phi}{KT_z}\right) \tag{4}$$

where K=Boltzman constant, T_z= ion temperature and n is a constant factor. Combining the above two equations, the ion current comes out to be

$$I(Z) = a\times\exp\left[nBe^{mZ/A}\right]\Big/\left[Be^{mZ/A}\right] \tag{5}$$

Here a, n and m are source parameters dependant on the average radius and length of the plasma, the field B_{min}, ion temperature etc.

The above equation shows that the exponent p (vide eqn. (2)) has a dependence on the ratio of the charge state and the mass of the ions Z/A. In our experiment we see such dependence as shown in Table 1. This is shown in Fig.3 also. For finding out the form of this dependence we have fitted a power law and an exponential law to the data. The exponential form gives a better fit, as indicated by the value of the χ^2 per degree of freedom. This agrees with eqn.(5) where see the exponent as n exp(mZ/A). We have examined the curves of SC-ECR [16] at NSCL in Michigan State University to see whether we can draw similar conclusions for that source.

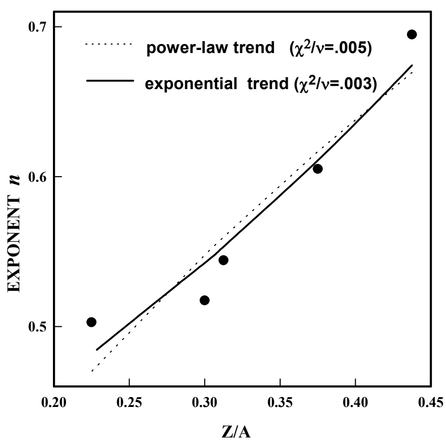

Figure 3: Dependence of exponent on charge state

Fig.4 shows the plot of the current for various charge states of oxygen as a function of the magnetic field. Fig.5 shows the fitting for oxygen ions extracted from SC-ECR. Here also exponential fit is better. The derived source parameters are, however, different in this case.

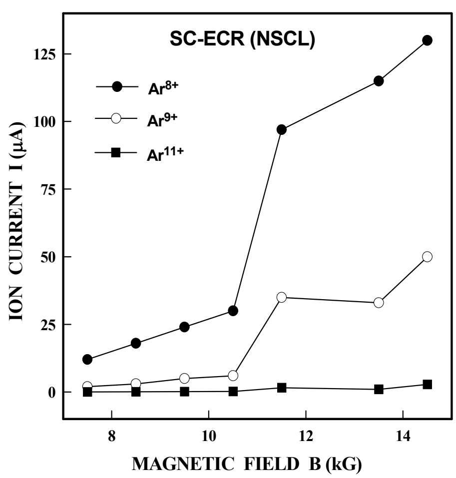

Figure 4: Variation of ion current in SC-ECR of NSCL

In this work we have made an attempt to find a magnetic field scaling law for ECR ion sources. The frequency scaling law of Geller is quite satisfactory when one compares two sources of different frequencies. But for high-B mode ECR sources, field scaling law is very important. Our analysis shows that the ion current increases almost exponentially when the injection field is increased. This also means that one can obtain large current of high charge state ions even if the microwave frequency is comparatively lower. Srivastava and Briand also drew a similar conclusion [17]. We point out that the magnetic field scaling is stronger than the frequency scaling as the former is an exponential law and the latter is a power law. Another observation we make is that magnetic field scaling is stronger for higher values of the charge-to-mass ratio.

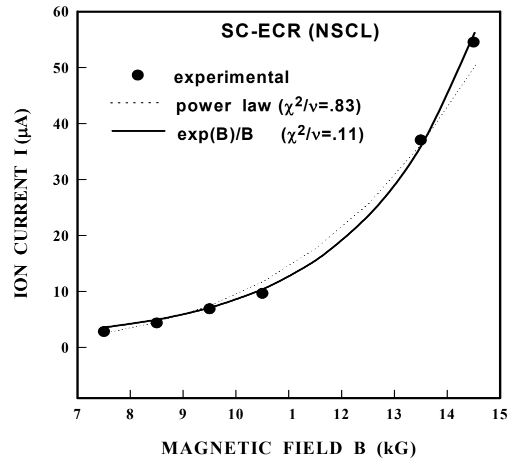

Figure 5: Various fits for SC-ECR of NSCL

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