A study on Vacuum Aspects of Electron Cyclotron Resonance Ion Source Plasma

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Abstract: The electron cyclotron resonance (ECR) ion source is special type hot plasma machine where the high temperature electrons co-exist with multiply charge state ions and neutrals. A few years ago 6.4 GHz. ECR ion source (VEC-ECR) was developed indigenously at VECC. This multiply charged ion source is being used continuously to inject heavy ion beams into the cyclotron. Vacuum plays the major role in ECR ion source. The water cooled plasma chamber is made from an oxygen free high conductivity copper billet to meet the suitable surface condition for vacuum purpose. The entire volume of the ion source is pumped by two 900 l/s special type oil diffusion pumps to achieve 5x10^{-8} Torr. Usually main plasma chamber is pumped by the plasma itself. Moreover a few l/s additional pumping speed is provided through extraction hole and pumping slot on the extraction electrode. A study has been carried out to understand the role of vacuum on the multiply charged heavy ion production process. Considering the ion production and loss criteria, it is seen that for getting Ar^{18+} better vacuum is essential for lower frequency operation. So, an ECR ion source can give better charge state current output operating at higher frequency and stronger confining magnetic field under a specific vacuum condition. The low pressure condition is essential to minimize charge exchange loss due to recombination of multiply charged ions with the neutral atoms. A fixed ratio of neutral to electron density must be maintained for optimizing a particular charge state in the steady state condition. As the electron density is proportional to square of the injected microwave frequency \(n_e \propto f^2\), a particular operating pressure is essential for a specific charge state. From the study, it has been obtained that the production of Ar^{18+} ions needs a pressure \(\sim 9.6 \times 10^{-8}\) Torr for 6.4 GHz. ECR ion source. It is also obtained that an ECR ion source, works at a particular vacuum level, can give better charge state production performance, if it operates at higher frequency and stronger magnetic confinement.

1. DESCRIPTION OF VEC-ECRIS
The present VEC-ECRIS is a single stage high magnetic field ion source with a biased electron repeller placed on the axis, near the injection mirror point [2]. The supply of cold electrons and use of low mass mixing gas improve the source performance and stability. High-B VEC-ECR has only two sets of coils with individual iron return yoke [figure 1]. This topology facilitates with an easy tuning of the source and has negligible influence of the injection field on the extraction area due to an excellent isolation between the mirrors. \(B_{\text{min}}\) field is reduced but the peak fields are increased to 7.2 and 5.5 K-gauss corresponding to mirror ratios to \(R_1=6.4\) and \(R_2=5\) respectively.
The main plasma chamber is made out of oxygen free high conductivity copper billet. It has inner diameter 108 mm and length 345 mm to form a multimode microwave cavity. The chamber is water-cooled and carries 305 mm long rare earth sextupole magnet bars externally. The injection and extraction chambers are pumped by two 900 l/s diffusion pumps. These are electrically isolated by ceramic tubes of low out-gassing rate and provided with a specially designed high voltage corona shield to avoid contamination by oil vapour fragmentation components. In VEC- ECR, base pressure of 1x10^{-7} Torr in injector stage and ~5x10^{-8} Torr in extraction chamber have been routinely obtained.

2. Successive ionization process

In ECRIS multiply charged ions (MI) are obtained by successive ionization process. When a sufficiently energetic electron collides with a neutral molecule ionization takes place. The ionization may happen basically by two processes, single impact and successive ionization. But it has been observed from theoretical as well as experimental value of the single impact ionization cross section is much lower than the value of successive ionization cross section (figure 2).

The successive or stepwise ionization process needs a considerable amount of time to attain a specific charge state. So the low charge state ion should be confined for a time which is longer than the ionization time. During this period ion may encounter a few collisions with cold electrons or low charge state ions, which eventually leads to ion loss.

![Figure 1. ECR ion source schematic](image)

![Figure 2. Comparison of single-impact ionisation cross-section against electron energy (argon)](image)

![Figure 3. Recombination coefficients in oxygen .The effect of dielectronic collision.](image)
3. LOSS PROCESSES AND HIGH CHARGE STATE PRODUCTION CRITERIA IN SUCCESSIVE IONIZATION PROCESS

Our present interest is to understand the different recombination processes occurring during ionization. The loss processes are basically either by electron-ion collisions or ion-ion/ion-neutral collisions.

3.1 Recombination of multiply charged ions with electrons

Recombination of multiply charged ions with electrons is basically two types. One is radiative recombination and other is dielectronic recombination. From the theoretical calculation by using Mac whirter formula [3] for successive ionization the radiative recombination coefficient $\alpha_r$ has a value of the order of $10^{-13}$ cm$^3$s$^{-1}$. It can be estimated from the equation as follows:

$$\alpha_r = 5.2 \times 10^{-14} \left( \frac{\ell}{\Lambda} \right) z \left[ 0.43 + \frac{1}{2} \log \frac{\ell}{\Lambda} + 0.47 \sqrt{\Lambda} \right]$$

(1)

with $\Lambda = \frac{T_e}{(IP)_z}$ where $T_e$ and $IP$ electron temperature and ionization potential in electron volts. $\ell$ denotes azimuthal quantum number.

Dielectronic recombination constant has been evaluated by different author and for very specific cases $\alpha_d > \alpha_r$, though it is not always negligible for very high charge state $z$. Generally all the recombination process look marginal in ECRIS plasma with $T_e > 1000$ eV which is the typical electron temperature for a B-min ECR ion source. Hence loss process for the electron-ion recombination or electron pick up can be ignored. The coefficients determined by other workers, for different loss processes are shown in figure 3. The figure clearly shows that for one keV electron, the combined loss coefficient increases for high charge states. But the overall value can be neglected.

3.2 Recombination of multiply charged ions with neutral atoms and low charged state ions

Let us we consider the recombination of multiply charged ion with neutral. The process may be expressed by the following equation:

$$A^{z+} + B^0 \rightarrow (AB)^{z+} \rightarrow A^{(z-1)+} + B^+$$

From the consideration of the Chbisovs formula the scattering cross section ($\sigma_x$) can be calculated as:

$$\sigma_x = 1.7 \times 10^{-15} z \text{ cm}^2$$

(2)

This is essential to find out neutral to electron density ($n_0/n_e$).

From the knowledge of charge transfer and stepwise ionization criterion, the upper limit of neutral density $n_0$ is obtained in the plasma for specified electron density [3].

$$\frac{n_0}{n_e} \leq 10^4 \xi \sqrt{\frac{T_e^{\text{op}}}{T_e}} z \frac{1}{A^{1/2} z^{-1}}$$

(3)

where $n_e = n_{ce} = 1.24 \times 10^8 f^2$

(4)

From these equations we can calculate the operating vacuum of the discharge chamber after knowing the neutral density ($n_0$). The equation (4) can also be used for any charge state $z$ at for particular electron density($n_e$) which is $4.91 \times 10^{11}$ cm$^{-3}$ for 6.4 GHz ECR ion source. This number is known as critical density ($n_{ce}$) and for the ionization of hydrogen like ions $\xi = 1$. To produce Ar$^{18+}$ from ion sources operating at different frequencies ($f$), the maximum value of electron density, neutral density and operating pressure can be calculated as shown in Table 1.
The results show the allowable neutral density is increasing with operating frequency. The higher is the operating frequency comparatively less will be the vacuum requirement figure 4. The ECR ion source operating at higher frequency obviously has the confining magnetic field higher than the other. So, in case of ECR ion source, the high frequency operation is always beneficial.

**Table 1**

| Frequency (GHz.) | Electron density (n_e) | Neutral density (n_0) | Pressure (Torr) |
|------------------|------------------------|-----------------------|-----------------|
| 2.45             | 7.023x10^10            | 5x10^8                | 1.41x10^-8      |
| 6.4              | 4.91x10^11             | 3.4x10^9              | 9.58x10^-8      |
| 10               | 1.2x10^12              | 8.34x10^9             | 2.35x10^-7      |
| 14.5             | 2.52x10^12             | 1.75x10^10            | 4.93x10^-7      |
| 18               | 3.88x10^12             | 2.69x10^10            | 7.58x10^-7      |
| 30               | 1.08x10^13             | 7.5x10^10             | 2.11x10^-6      |

**Table 2**

| Charge State | N (µA) | O (µA) | Ne (µA) | Ar (µA) | Kr (µA) | Xe (µA) |
|--------------|--------|--------|---------|---------|---------|---------|
| 4+           | 130.0  |        |         |         |         |         |
| 5+           | 86.0   | 120.0  |         |         |         |         |
| 6+           | 31.0   | 75.0   | 45.0    |         |         |         |
| 7+           | 12.0   | 25.0   |         |         |         |         |
| 8+           | 10.0   |        |         |         |         |         |
| 9+           | 1.5    | 41.0   |         |         |         |         |
| 11+          |        | 11.0   |         |         |         |         |
| 12+          |        | 6.5    |         |         |         |         |
| 13+          |        |        | 45.0    |         |         |         |
| 14+          |        |        | 20.0    |         |         |         |
| 15+          |        |        | 10.0    |         |         |         |
| 17+          |        |        | 9.0     |         |         |         |
| 18+          |        |        | 8.5     |         |         |         |
| 19+          |        |        | 6.5     |         |         |         |
| 20+          |        |        | 1.5     | 4.1     |         |         |
| 21+          |        |        |         | 2.6     |         |         |
| 22+          |        |        |         | 3.6     |         |         |
| 23+          |        |        |         | 2.5     |         |         |
| 24+          |        |        |         | 2.2     |         |         |
| 25+          |        |        |         | 1.2     |         |         |
| 26+          |        |        |         | 1.9     |         |         |
| 27+          |        |        |         | 2.0     |         |         |
| 28+          |        |        |         | 1.1     |         |         |
| 29+          |        |        |         | 1.0     |         |         |
| 30+          |        |        |         | 0.9     |         |         |
| 31+          |        |        |         | 0.7     |         |         |
With improvement of the base vacuum ($5 \times 10^{-8}$ Torr), ion current output data (TABLE 2) of 6.4 GHz VEC-ECR ion source shows an enhanced high charge state production performance with superior charge state distribution and it can be observed that the charge state distribution is appreciably superior than the similar type of sources operating at other laboratories.

7. References

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