SIMULATION OF MULTIPLY-CHARGED ION PRODUCTION IN DECRIS-14-2

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Numerical simulation of multiply-charged ion production in the Dubna Electron Cyclotron Resonance Ion Source (DECRIS) has been done on the basis of a simple balance model. The balance equations are presented. The gas mixing effect and thermal electrons are taken into account in the model. The simulation indicates that the support gas in the gas mixing effect results in an increase of thermal electrons. The calculated charge state distributions for argon and xenon are fitted by the experimental results from DECRIS-14-2 when oxygen is used as a support gas.

1 Introduction

A new ECR ion source DECRIS-14-2 (Dubna Electron Cyclotron Resonace Ion Source at 14 GHz) was constructed for the Cyclotron U-400M at FLNR, JINR. In order to improve the performance of this ion source and understand the physical processes inside the source, a theoretical investigation for multiply-charged ion production in DECRIS-14-2 was carried out. Following the pioneer work of Jongen [1], West [2] and Shirkov [3] for the calculations of charge state distribution in ECR ion source, a simple model and a computer code for simulation of multiply-charged ion production were developed. The gas mixing effect and the thermal electrons are taken into account in our calculation. The model, the main equations and the calculated results are presented. The theoretical simulation are fitted by the experimental results from DECRIS-14-2.

2 General Description of the Model and the Main Equations

2.1 Ion Confinement

We basically consider the ECR ion source as a mirror machine with hot electrons (a few keV), thermal electrons (a few tens eV), and cold ions (a few eV). Ion parallel confinement is dependent on the magnetic field configuration and potential. The central plasma in an ECR ion source should dip because of a relatively high density and relatively long confinement time of hot electrons in the central region. So ions are electrostatically confined in the space-charge electric field of the hot electrons, i.e., confined by a small negative potential dip $\Delta\phi$. The ion confinement time is calculated by taking into account the ion diffusion time, the scattering time and the time for the ions to overcome the potential dip $\Delta\phi$, i.e.[2],

$$\tau_i = (\tau_f + \tau_s) exp(\frac{\Delta\phi z_i}{T_{ion}}) \tag{1}$$

where $\tau_f = RL(\frac{\pi m_{ion}}{2T_{ion}})^{\frac{1}{2}}$,
$\tau_s = G(R)\tau_{si}\frac{\Delta\phi z_i}{T_{ion}}$

τ_i is ion confinement time. R is mirror ratio. $G(R)$ is a factor, here approximately equal to 2. L is effective plasma length. T_{ion} is ion temperature. τ_{si} is the ion scattering time. z_i is ion charge state.

2.2 Hot Electrons and Thermal Electrons

Hot electrons are created by ECR heating and confined magnetically in the minimum-B geometry of ECRIS. They move back and forth along the magnetic field lines and when crossing the resonance zone, they receive kicks of transverse energy from the rf electric field that helps trap them in the B_z mirror magnetic field, and eventually reach higher energies. We suppose the hot electron lifetime is basically determined by large angle scattering with the other electrons, the ions and the neutrals in the plasma, here including the ions and the neutrals of support gas, i.e.,

$$\tau_e^h = \frac{1}{\nu_{ee}} + \frac{1}{\nu_{e\Sigma i}} + \frac{1}{\nu_{e\Sigma n}} \tag{2}$$

where τ_e^h is the lifetime of the hot electrons, ν_{ee}, $\nu_{e\Sigma i}$,

$\nu_{e\Sigma n}$ are collision rates of electron-electron, electron-ion, and electron-neutral, which were quoted from Ref.[1,2].

Thermal electrons are produced mainly by the hot electron impact ionization. They are generally considered to be confined by a positive plasma potential. Collisions are very important for thermal electrons, and the effective lifetime for thermal electrons can be calculated by 90° Spitzer collisions and the plasma potential.

We assume that the hot electron density and the thermal electron density are uniformly distributed in the plasma. The quasineutrality for all ions and electrons throughout the plasma is required,

$$n_e^{th} = \sum_{i=1}^{imaxA} Z_i^A n_i^A + \sum_{i=1}^{imaxB} Z_i^B n_i^B - n_e^h \qquad (3)$$

Where n_e^{th} and n_e^h are the densities of thermal electrons and hot electrons. Z_i^A and Z_i^B are the ion charge state of main gas and support gas. n_i^A and n_i^B are the ion densities of main gas and support gas with charge state i.

2.3 The neutrals in the plasma

In the plasma of an ECR source, there is a continuous burn up of neutrals through electron impact ionization, as well as through charge exchange with ions.The distribution of the neutral density in the plasma of a real ECR ion source is quite inhomogenous. The neutral density outside the confined plasma, especially near the wall, is much higher than that inside the confined plasma. However, considering calculation simplicity, we assumed the neutrals inside and outside the plasma are kept in uniform distribution respectively. It is also assumed that a dynamic equilibrium exists between the neutral density outside the plasma and the neutral density inside the plasma. In the calculation of neutral density inside the plasma, we only consider single step ionization, single step charge exchange, and the neutral flux entering into and leaving out of the plasma. It should be underlined here that the charge exchange between the ions of main gas and the neutrals of support gas, the ions of support gas and the neutrals of main gas play an important role in determining the ion charge state distribution and the neutral density inside the plasma.

The change rate of neutral density inside the plasma for main gas A can be written as

$$\begin{aligned}\frac{dn_{npl}^A}{dt} = {} & \nu_0^A n_0^A + n_1^A < \sigma_{ex}^{AB} v_i^A >_{1\to 0} n_{npl}^B - \\ & n_e^h < \sigma_i^A v_e^h >_{0\to 1} n_{npl}^A - \\ & n_e^{th} < \sigma_i^A v_e^{th} >_{0\to 1} n_{npl}^A - \\ & \sum_{i=2}^{imaxA} n_i^A < \sigma_{ex}^{AA} v_i^A > n_{npl}^A - \\ & \sum_{i=2}^{imaxB} n_i^B < \sigma_{ex}^{BA} v_i^B > n_{npl}^A - \nu_0^A n_{npl}^A \qquad (4)\end{aligned}$$

Where ν_0^A is the rate of the neutral flux entering into (leaving out of) the plasma. n_0^A is the neutral density outside the plasma for main gas A. n_{npl}^A and n_{npl}^B are the neutral densities inside the plasma for main gas A and support gas B. σ_{ex}^{AB}, σ_{ex}^{AA}, σ_{ex}^{BA} are the charge exchange cross sections between the ions of main gas A and the neutrals of support gas B, the ions of main gas and the neutrals of main gas, the ions of support gas and the neutrals of main gas respectively. v_i^A and v_i^B are the thermal velocities for main ions and the ions of support gas. v_e^h and v_e^{th} are the thermal velocities for the hot electrons and the thermal electrons.

At an equilibrium of stationary state, $\frac{dn_{npl}^A}{dt} = 0$.

Interchanging the symbol A and B in eq.(4), we can get an equation of the neutral density inside the plasma for support gas B.

2.4 Balance Equations for the Ion Charge State Distribution

Positive ions in ECR ion source are produced mainly by successive electron impact ionization from neutral to maximum charge state. In Present model, all the multiple processes, such as multiple ionization and charge exchange, are negligible.The most important and effective contribution to the reduction of a given charge state is charge exchange between ions and neutrals. However, at the higher charge states, we have to take into account radiative recombination resulting from the thermal electrons. The ions and the neutrals of support gas take part in all the same processes as those of the main gas. The interaction between them is nothing more but elastic collisions and charge exchange. The balance equations for the ions of support gas and main gas are treated separately.

For the ions of main gas A with charge state i ($1 < i < imax - 1$), the equilibrium equation that we wish to solve is described by

$$\begin{aligned}\frac{dn_i^A}{dt} = {} & \frac{v_i^A}{L} n_i^{0A} + n_e^h < \sigma_i^A v_e^h >_{i-1,i} n_{i-1}^A + \\ & n_e^{th} < \sigma_i^A v_e^{th} >_{i-1,i} n_{i-1}^A + \\ & n_{npl}^A < \sigma_{ex}^{AA} v_i^A >_{i+1,i} n_{i+1}^A + \\ & n_{npl}^B < \sigma_{ex}^{AB} v_i^A >_{i+1,i} n_{i+1}^A + \\ & R_{i+1,i}^A n_{i+1}^A - n_e^h < \sigma_i^A v_e^h >_{i,i+1} n_i^A - \\ & n_e^{th} < \sigma_i^A v_e^{th} >_{i,i+1} n_i^A - \\ & n_{npl}^A < \sigma_{ex}^{AA} v_i^A >_{i,i-1} n_i^A -\end{aligned}$$

$$n_{npl}^{B} < \sigma_{ex}^{AB} v_i^A >_{i,i-1} n_i^A - R_{i,i-1}^{A} n_i^A - \frac{n_i^A}{\tau_i^A} \quad (5)$$

Where $R_{i+1,i}^{A}$ the rate of radiative recombination from charge state $i+1$ to i. $\frac{n_i^A}{\tau_i}$ indicates the ion flux out of the plasma. $\frac{v_i^A}{L} n_i^{0A}$ the input ion flux from the first stage. n_i^{0A} is the density of main ions from the first stage.

The eq.(5) is only strictly valid for the ions $1 < i < imax - 1$. The single charged ions in ECR ion source are involved in a different processes. The resulting equation for the single charged ions of the main gas A is given by

$$\begin{aligned} \frac{dn_1^A}{dt} = & \frac{v_i^A}{L} n_1^{0A} + n_e^h < \sigma_i^A v_e^h >_{0,1} n_{npl}^A + \\ & n_e^{th} < \sigma_i^A v_e^{th} >_{0,1} n_{npl}^A + \\ & n_{npl}^A < \sigma_{ex}^{AA} v_i^A >_{2,1} n_2^A + \\ & n_{npl}^B < \sigma_{ex}^{AB} v_i^A >_{2,1} n_2^A + \\ & \sum_{i=2}^{imaxA} n_i^A < \sigma_{ex}^{AA} v_i^A >_{i,i-1} n_{npl}^A + \\ & \sum_{i=2}^{imaxB} n_i^B < \sigma_{ex}^{BA} v_i^B >_{i,i-1} n_{npl}^A - \\ & \frac{n_1^A}{\tau_1^A} - n_e^h < \sigma_i^A v_e^h >_{1,2} n_1^A - \\ & n_e^{th} < \sigma_i^A v_e^{th} >_{1,2} n_1^A - \\ & n_{npl}^B < \sigma_{ex}^{AB} v_i^A >_{1,0} n_1^A \end{aligned} \quad (6)$$

At equilibrium, $\frac{dn_i^A}{dt} = \frac{dn_1^A}{dt} = 0$.

For the ions of support gas, we only need interchange the symbol A and B.

The main equations in present work are solved as a set of nonlinear algebraic equations by an iterative numerical method. The iterative numerical procedure is dependent on the self-consistent determination of the thermal electron density and the plasma potential dip by means of Newton-Raphson method [2]. We take a Maxwell-Boltzman distribution for the electron energy, and Lotz formula [4] for the electron impact ionization cross section. The ionization potential and subshell binding energies are taken from Ref.[5]. The approximated formulas for charge exchange cross sections which involve the same and different species are used from Ref.[6].

The extraction current of the main ions from an ECR ion source can be expressed as

$$I_{ex} = \eta e n_i^A Z_i^A LS/\tau_i^A \quad (7)$$

Where η is the percentage that the ions with charge state Z_i^A could be really extracted from the source. e is the electric charge. L is the effective plasma length. S is the extraction area.

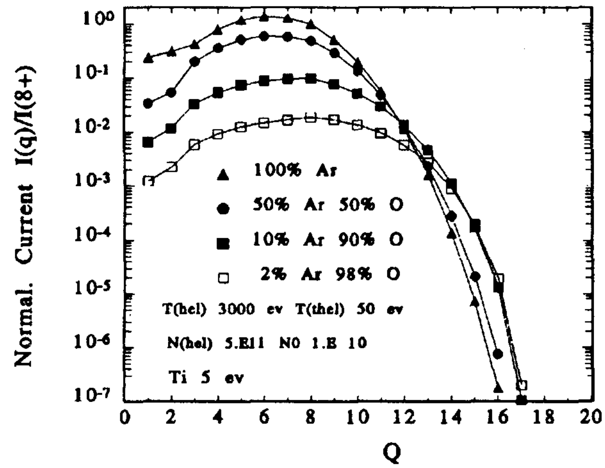

Figure 1: Charge state distribution for different mixing ratios betweeen the main gas and the support gas . All the ion currents are normalized to the currents of A_r^{8+} without support gas.

3 Calculation Results

We present the main calculation results in the equilibrium state of argon plasma mixed with oxygen. The code was written such that it can bee run with and without gas mixing. The code input parameters are neutral densities of main gas A_r and support gas O_2 outside the plasma (n_0^A, n_0^B), hot electron density n_e^h and temperature T_e^h, thermal electron temperature T_e^{th}, ion temperature T_i, mirror ratio R, source dimensions, and atomic physics data for main gas and support gas. The typical range of input parameters is from the operation experiences of DECRIS-14-2 : $n_e^h = 10^{11} \sim 1.5 \times 10^{12} cm^{-3}$, $T_e^h = 1 \sim 20keV$, $T_i = 3 \sim 20eV$, $T_e^{th} = 20 \sim 100eV$, $n_0^A + n_0^B = 10^9 \sim 10^{11} cm^{-3}$, $R = 2$, mirror to mirror length $L = 20cm$, diameter of the plasma chamber $D = 7.cm$. The running of the code is quite dependent on a good match among those input plasma parameters, otherwise the code would fail to reach a self-consistent convergence in the calculation of thermal electron density and the plasma potential dip.

Keeping the total neutral density outside the plasma and the other parameters constant, we calculate the charge state distributions with different mixture ratio between main gas A_r and support gas O_2, as shown in Fig.1. We can see from Fig.1 that support gas O_2 does shift the CSD to the higher charge state, meanwhile, the

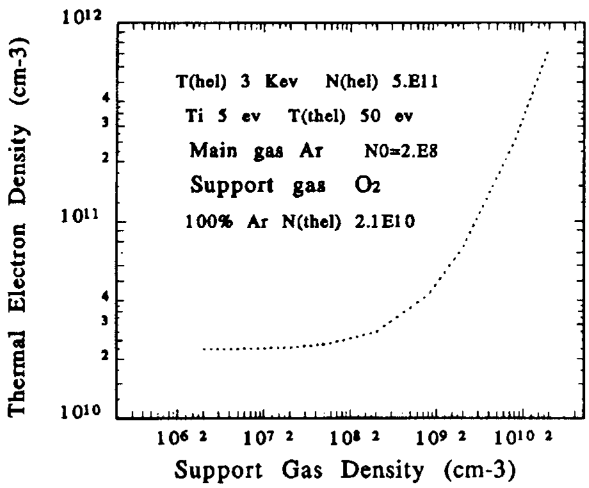

Figure 2: Dependence of the thermal electron density on the support gas density

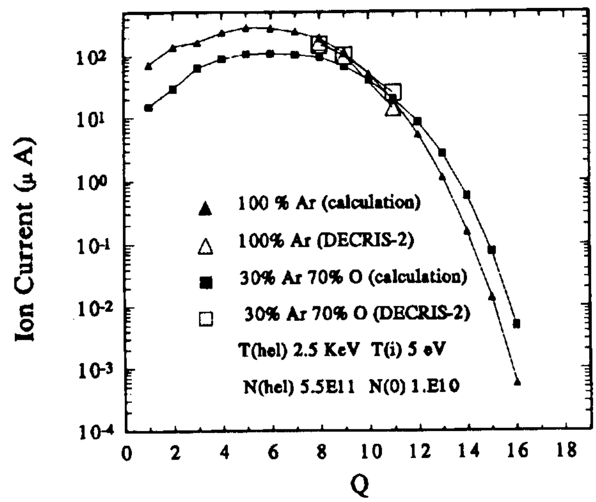

Figure 3: Comparison between the calculated charge state distributions and the experimental measurements from DECRIS-14-2 for argon mixed with oxygen.

currents of lower charge state are depressed. With increasing the support gas O_2 percentage (decreasing the main gas A_r percentage), this effect is more obvious. But when support gas O_2 is dominant up to 98%, only very high charge states benefit from the presence of the support gas O_2.

Making the neutral density of the main gas A_r constant, and varying the neutral density of the support gas O_2 step by step, we find that the thermal electron density keeps rising with increase of the support gas density, as shown in Fig.2.

The calculated charge state distribution of argon plasma mixed with oxygen is fitted with the experimental results from DECRIS-14-2 , as shown in Fig.3. In order to make a good fittings with the experimental data, in the calculation both the electron density and electron temperature are little bit low because the experimental results were obtained with rf power less than 250 W. We can see the calculation is in a good agreement with the experimental results.

4 Conclusion

A simple model for simulation of multiply-charged ion production in ECR ion source was developed. The model is able to calculate the charge state distributions with the gas mixing , in which the effect of thermal electrons is considered. The calculation finds that the support gas might cause increase of thermal electrons. The charge state distributions of argon plasma mixed with oxygen for different mixing ratios are fitted with the experimental results from DECRIS-14-2, and a good agreement was found. The further effort will be focused on the effect of magnetic field to the charge state distribution.

Reference

[1]. Y.Jongen, *Proceedings of Workshop on ECR Ion Sources and Related Topics*, Darmstadt, 213, 1993.

[2]. H.I.West, *Lawrence Livermore National Laboratory*, UCRL-53391, 1982.

[3]. G.Shirkov, *Rev. Sci. Instrum. Vol.63* , 2894, 1992.

[4]. W.Lotz, *Z. Physik Vol.220* , 466, 1969.

[5]. T.A.Carlson, et al, Atomic Data, Vol.2 , 63, 1970.

[6]. A.Muler, et al, Phys. Letters, 62A , 391, 1977.