MODELING OF ION PRODUCTION IN ECR ION SOURCES

G. Shirkov, JINR, Dubna, Russia

Abstract

Main statements of the physical model of ion accumulation and production in the ECR are presented. This model based on the balance equations and charged particle confinement in the open magnetic trap. Results of simulation with the library of computer codes based on the used model have a good qualitative and quantitative coincidence with existent experimental data and enable one to estimate electron density and effective energy in the source plasma. Several examples of recent numerical simulation of experimental distributions of ion charged states are presented.

1 INTRODUCTION

The electron-cyclotron resonance (ECR) ion source is the most widely used source for the highly charged ion production for accelerator and atomic physics applications. The report presents the results of numerical investigations on the production of different ions with the aim to study the plasma parameters in the ECR ion source. The library of computer codes based on the “Classical model of ion confinement and losses” [1, 2] was used for numerical simulations. The adjusting of input parameters for calculations to compare the calculated charged state distribution (CSD) of output ions with the experimental data has been used to obtain some understanding of the physics of the ECR plasma [2, 3]. This way was used for the estimation of density and average effective energy of electron component of the plasma.

2 BASEMENT AND FRAMES OF MODEL

Processes of ion accumulation and production in the plasma and of ECR ion sources can be described with a set of nonlinear differential balance equations for all densities of ionic charge states, electrons and neutrals existing in the source. The balance equations take into account all inelastic processes between particle and ion losses from the source. The inelastic processes (ionization, electron capture, recombination, etc.) change the charge states of ions and ionize neutrals. The complete set of balance equations for all possible charge states with taking into account single and double ionization and charge exchange processes between neutrals and ions is used in the model and given, for example, in Ref. [1, 3]. Often the ECR source is used as a continuous working device and all the processes in the source are stationary. In this case the set of differential equations transforms into a set of nonlinear algebraic equations.

The balance equations take into account ion losses from the plasma volume. The Pastukhov theory [4] for the plasma confinement in the open magnetic trap was applied in the model to determine the rate of ion losses. The distribution function of ion energies is assumed to be Maxwellian, as the result of high rate of elastic collisions in the plasma. The ion temperature (average energy) is determined from the balance equation of ion energy in the plasma. An additional balance equation for density of electron component describes the electron production and losses in the plasma and results in a complete set of equations for all plasma components.

The mechanism of radio frequency (RF) electron heating using electron-cyclotron resonance conditions in the plasma is not completely clear and the electron energy distribution function is still unknown. But the input RF power determines the main average plasma parameters (the plasma density and electron energy) and usually is registered during the source operation.

The complete set of mathematical equations links up all parameters of the plasma and it is able to determine the electron density and all ion species densities as well as the densities of ionic currents through the axial ends of the source for given dimensions of the plasma volume and longitudinal distribution of magnetic field. The density of neutral gas outside the plasma and electron temperature only are used as input parameters for numerical simulations. In the case of a mixture of two elements in the source the relation between neutral densities of these two elements is used as a third input parameter.

The physical model and mathematical equations introduced in Ref. [1, 2] are able to describe qualitatively and simulate quantitatively the processes of ion accumulation and production in the static and pulsed regimes of the ECR source operation. Unfortunately, there are no date about experimental values of the electron energy and density. But the input RF power is a very important parameter to compare the experimental data with the result of calculations. In particular, the CSD strongly depends on RF power and one can assume that the effective electron density and energy are functions of the RF power [5]. Thus the experimental CSD and RF power are criterions for the fitting and they could be used for the estimation of the electron energy and density derived from the simulation.

3 NUMERICAL SIMULATION OF CSD

The influence of gas mixing on the density of plasma was studied in numerical investigations on oxygen ion production in the CAPRICE ion source of Grenoble [6]. Figure 1 shows the CSD of pure oxygen plasma (series 1, 2) and in the mixture with helium (series 3, 4). Series 1 and 3 correspond to the experimental data [7], 2 and 4 are calculated CSD here. The electron temperature T_e = 2 keV and density of neutral oxygen n_O = 2.2 10^{10} cm^{-3} were chosen in these calculations to give the best agreement with experimental data. The calculated electron density are n_e=9 $10^{11}cm^{-3}$ for series 2 and n_e=2.5 $10^{12}cm^{-3}$ for series 4.

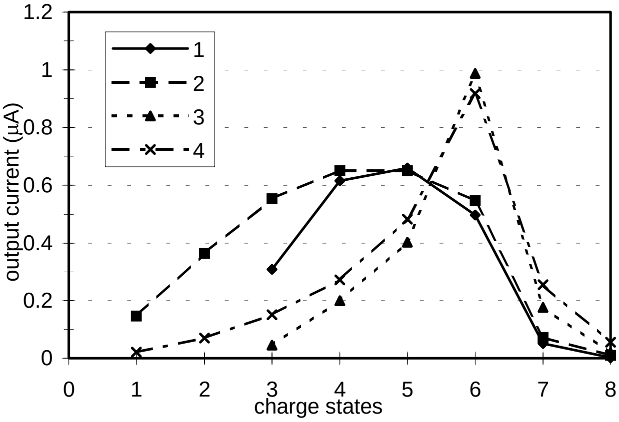

Figure 1: Experimental data [7] (series 1,3) and calculated CSD (series 2,4) in the CAPRICE ion source. Series 1,2 - pure oxygen; series 3,4 - oxygen-helium mixture.

The results presented in Fig. 1 [6] demonstrate the temperature reduction (ion cooling) of oxygen ions and increasing of plasma density in the oxygen-helium mixture.

For several years the 18GHz ECR ion source at RIKEN has been constantly improved by an optimization of each component. The source runs at 18 GHz and is able to produce ions of different gases and metals [8]. Numerical investigations presented on the production of Kr and Xe ions have been carried out to study the plasma parameters in dependence on the input RF power and peculiarity of the gas mixing effect [5].

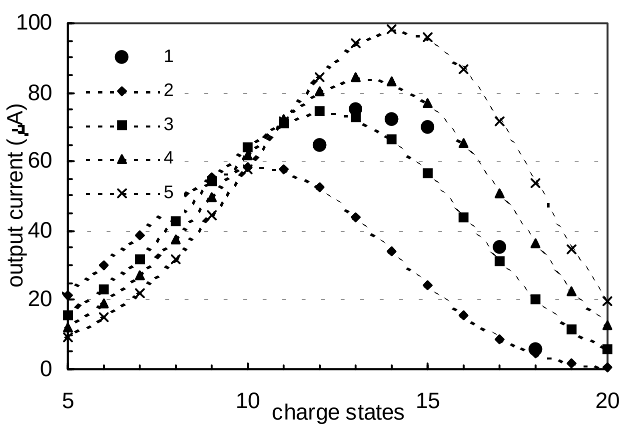

Figure 2: Dependence of CSD on the relation of neutral Kr to O_2. The experimental CSD (1) has Kr:O_2 as 1:2 and P = 520 W. The calculated electron densities and input RF powers are: Kr:O_2 as 1:0 (2) - n_e=0.56 10^{12}cm^{-3}, P=90W; 1:1 (3) - n_e=1.0 10^{12}cm^{-3}, P=260W; 1:2 (4) - n_e=1.5 10^{12} cm^{-3}, P=500W; 1:4 (5) - n_e=2.4 10^{12}cm^{-3}, P=1060W.

Figure 2 [5] presents the dependence of output CSD on the relation of gas pressures of neutral Kr to O_2 in the source chamber. Figure 3 [5] shows the dependence of main plasma parameters on the input RF power. The calculated CSD of Xe ions optimized for the best coincidence with experimental points.

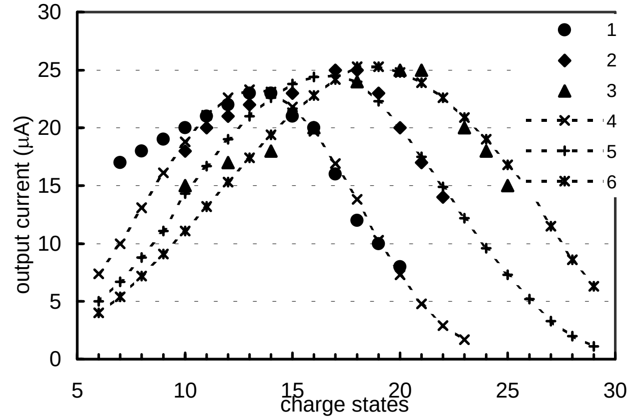

Figure 3: Experimental CSD (1, 2, 3) of Xe ions at 100W, 300W, 400W RF powers and calculated Xe CSD (4, 5, 6) for T_e=2.2keV, n_e=0.48 10^{12}cm^{-3}, P=120W; T_e=4.5keV, n_e=0.78 10^{12}cm^{-3}, P=290W; T_e=6.0keV, n_e=1.1 10^{12}cm^{-3}, P=560W.

SERSE is the new Superconducting ECR ion source of INFN-LNS [9]. It was designed and constructed by INFN-LNS, Catania and CEA - DRFMC, Grenoble, tested in Grenoble and mounted in Catania in the middle of 1998. SERSE is an ECR source with magnetic field up to 2.7 T and field mirror ratio up to 7. The combination of two or three 14GHz/18GHz RF generators for the plasma heating will provide the input RF power up to 4 kW. It has a large plasma chamber with the length in the order of 50 cm and diameter of 13 cm. All these characteristics provide unique conditions to produce highly charged ions for the injection into the INFN-LNS cyclotron. The production of oxygen and argon ions was studied during the first tests of SERSE in Grenoble [10].

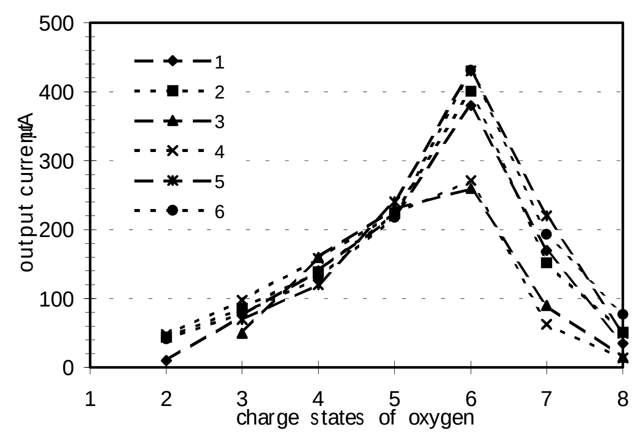

Figure 4: Comparison of experimental (1,3,5) and calculated (2,4,6) CSD of oxygen. Pure oxygen:(1) - W=1.5kW; (2) - N_e=1.2 10^{12}cm^{-3}, T_e=5keV, W=1.4 kW. Oxygen : argon mixture: (3) - P=1.5kW; (4) (8:3 of neutrals), N_e=1.2 10^{12}cm^{-3}, T_e=5keV, P=1.6kW. Optimized for O^{7+}: (5) - P=1.5kW; (6) - N_e=1.4 10^{12}cm^{-3}, T_e=6keV, P=1.7kW.

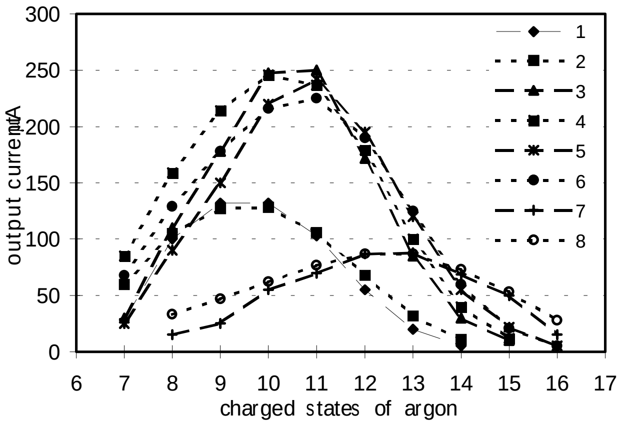

Figure 5: Comparison of experimental (1,3,5,7) and calculated (2,4,6,8) CSD of argon. Pure argon (1) - P=1.09kW; (2) - N_e=1.0 10^{12}cm^{-3}, T_e=6keV, P=1.0kW. Argon : oxygen, (3) - optimized for Ar^{11+}, P=0.47kW; (4) - 6:1 of neutrals, N_e=1.7 10^{12}cm^{-3}, T_e=7keV, P=1.7kW; (5) - optimized for Ar^{12+}, P=1.2kW; (6) - 6:1 of neutrals, N_e=1.8 10^{12}cm^{-3}, T_e=8keV, P=1.9kW. (7) - optimized for Ar^{15+}, P=1.4kW; (8) - 3:2 of neutrals, N_e=2.0 10^{12}cm^{-3}, T_e=13keV, P=1.8kW.

Figures 4 and 5 present the comparisons between experimental and calculated CSD of different regimes of production of oxygen and argon ions [11]. One can see that the general behavior and absolute values of calculated CSD are in a good coincidence with the experimental dots, except the value of input power for the experimental CSD optimized for Ar^{11+} (curve 3 in Fig. 5) which is well lower than for the optimization of the higher charge states. The optimization for Ar^{15+} (curves 7 and 8 in Fig. 5) gives relatively high values of plasma density and electron temperature and demonstrates high source performances: N_e = 2 10^{12} cm^{-3} (about the “cut off” of electron density for the RF frequency of 14GHz) and T_e = 10 - 13 keV.

4 DISCUSSIONS AND CONCLUSIONS

The obtained results of CSD simulations qualitatively agree with the experimental data. It means that the model accounts the most important physical processes in the plasma in the right way.

The quantitative coincidence here is not bad too but the numerical comparison of calculated and experimental results should be careful because of its dependence on the accuracy of used cross sections in calculations, and all other limitation of the model [1-3]. But all of these factors are able to change the results of CSD calculation in several tens of percents but not in an order of magnitude. The results of calculations are very sensitive to the variation of input parameters [5, 6, 11]. All these factors make one able to estimate the effective electron energy and density with the accuracy in the range of 20 - 30 %. It is very important because these values are unknown in the real experimental conditions. However, the input RF power is one of the most significant parameters in the ECR source that is under current control and adjusted during the source operation. All of these make it possible to use this way of numerical modeling to predict general possibilities of ECR source to produce highly charged ions.

But the present model, based on the balance equations for ionic charge states, assumes the homogeneous ion and electron densities in the plasma or beam volumes. This model does not take into account the real spatial distribution of electric and magnetic fields as well as field boundary conditions. Thus, this model is a rough and able to describe the only general effects in ion sources.

But one should has the detailed notion of the plasma structure, field and particle distributions, especially at the stage of design, tuning or optimization of an experimental set up. There is a number of very important effects connected with local particle generation or shape of field distributions in the plasma. A new project based on the finite particle or particle-in-cell method for the multicomponent ECR plasma was proposed to avoid the limitations of the present model [12]. This new numerical model will be used to study the detailed plasma and beam characteristics, the distribution function of particles, the ion transitions from one charge state to another one, elastic collisions of particles in the presence of nonlinear self and external fields.

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