MULTICOMPONENT CONSIDERATION OF ELECTRON FRACTION OF ECR SOURCE PLASMA

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The development of model of electron and ion accumulation and production in the ECR ion source is presented. New equations represent electrons in the ECR plasma as a multicomponent media. In the result any kind of experimental or analytical electron distribution function can be approximated with a series of Maxwellian distributions with different temperatures and partial weights. A main positive plasma potential with negative potential dip is introduced into consideration. This potential regulates the loss rate of primary cold electrons from the plasma volume and completes the total picture of ECR plasma behavior. The first test of new model and code with recent experimental data of RIKEN 18 GHz ECR source has shown some new opportunities for investigators to study the ECR ion sources.

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 [1, 2]. The report presents the development of physical model of electron and ion production, confinement and loss in the ECR ion source.

The ECR source is an open magnetic trap for the plasma confinement. Special coils create an axial field with strong magnetic traps on of the axis ends. A permanent multipole magnet is used for production of the longitudinal magnetic field with azimuthal variations. Positively charged ions and electrons are generated from the neutral gas in the source chamber as the result of electron impact ionization. Electrons are heated by radio frequency (RF) microwave field operated with the frequency of electron Larmor rotation of the longitudinal magnetic field in the trap. Ions extraction is performed through a hole with negative potential applied to extraction gap. The increase of the degree of ionization in the ion source is the result of step-by-step ionization during the ion confinement time. The mean ionization degree depends on the electron density, electron energy distribution and ion lifetime in the source.

Processes of ion accumulation and production in the plasma 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 [2]. 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. [2, 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 [3, 5, 6]. 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 present model assumes that an electron energy distribution is the Maxwellian energy distribution with electron temperature for the most effective and exact reproduction of experimental charge state distributions (CSD) of extracted ions. This is one of the main disadvantages of present model because the Maxwellian distribution is a simple but a very rough approximation for the electron energy distribution function.

Basement and New Approach

Electrons appear in the process of electron impact ionization of the atoms and ions in the plasma. The energy of newly produced electrons corresponds to the energy of ionization and have a range of some tens or hundreds eV in dependence on ion types and dominant charge states. A part of electrons crosses the resonance surface in the source and undergo the ECR heating. The energy of heated electrons is in the keV region and reaches tens or hundreds of keV according to X-ray measurement [7-9]. The average or effective electron energy should be in the range of 5-10 keV in the modern ECR sources to produce existed intensive beams of highly charge ions according to numerical simulation of ion accumulation and production [10]. The rate of electron elastic scattering in the ECR source is not very high to establish the Maxwellian energy distribution in opposite to slow and heavy ions. Therefore the energy distribution function of electrons should be rather complicated and not a smooth function of energy. It could consist at least of two or three components with very different energies. The cold electrons with energy below 100-300 eV are very effective in neutral ionization and low charged ion production but not able to produce highly charged ions. Hot electrons after ECR heating with the energy of keV produce highly charged ions. Superhot electrons stabilize the plasma due to very good confinement conditions.

Magnetic mirrors of the trap reflect the charged particles and confine the plasma in general. Only the particles with velocity vectors in a small solid angle along the trap axis can be lost from the plasma. In the static case the elastic Coulomb collisions between the charged particles change the direction of particle movement and therefore there is a continuous loss of electrons and ions from the source through the loss cone. The confinement time of charged particle in the open magnetic trap $\tau \propto \nu^{-1}$, where ν is the total rate of elastic Coulomb scattering of the given particle. The rate of scattering deepens on charge state *Z*, mass *m* and particle energy *E* as

$$\nu \propto Z^2 / (E^{3/2} m^{1/2}) \qquad (1)$$

Therefore low energy electrons and ions have very high rate of elastic scattering and very low confinement conditions in opposite to electrons of keV and more energy.

Positive ions neutralize the space charge of electrons to prevent the appearance of high electrical and magnetic fields in the plasma. One can consider the plasma as neutral or quasineutral in every point of its volume. If one suggests that the complete electron energy distribution function is a superposition of electron components of different energies then the condition of plasma neutrality follows to the equation

$$\sum_{i=1}^{Z} i\, n_i - \sum_{k=1}^{l} n_{ek} = 0 \qquad (2)$$

here n_i are densities of ions with different charged states *i*, *Z* is the maximum charge of ions in the plasma, n_{ek} are densities of one of *l* electron components. If there is a mixture of ions of different elements in the plasma, then it is necessary to sum up all ion species.

The particle losses are determined by lifetimes or confinement times of particles in the plasma. The time conservation of condition (2) in the static case is the cause of equal flows of ions and electrons from the plasma:

$\sum_{i=1}^{Z}$ **Error!** - **Error!Error!** = 0 (3)

with τ_i being confinement times of ions and τ_{ek} electron confinement times, correspondingly. These values will determined later in this paper.

The heated electrons have much more energy and less probability of scattering than the ions according to (1). Hot electrons and highly charge ions accumulated in the plasma center according to the modern experimental data and theoretical models. It was shown [5, 6] that the high rate of ion losses creates the negative potential dip in the plasma central region. This regulates the ion losses and keeps the general plasma neutrality. From the other hand, the cold primary electrons have pure confinement conditions and could have a wider spatial distribution in comparison with ions and hot electrons. A simple estimation shows that the electron confinement time in the open magnetic trap of ECRIS is in the range of µs or less for electrons with energy of about 100 eV. Therefore these electrons have very low probability of microwave heating before loss from the plasma and there is no real chance to create the present dense and hot ECR plasma for highly charged ion production. A positive potential is necessary to prevent the high rate of cold electron losses. The value of this potential should be comparable with the characteristic energy of this electron component.

Thus, the complete physical picture could be the follow. The electrons have a complicate distribution of a number components: cold primary electrons of tens or hundreds eV; a main electron component of keV energy to produce highly charged ions and, according to the experimental data, a component of superhot electrons of tens or hundreds keV. The mirror configuration of magnetic field confines the hot and superhot electrons. The positive potential *U* regulates the rate of cold electron losses and a small negative dip ΔU ($\Delta U << U$) in the plasma center confines the positively charged ions (Fig.1). All of this in total should to satisfy the conditions of plasma neutrality (2) and equal flows (3). The superhot electrons have very good confinement conditions in the magnetic trap of source (the confinement time is in the range of tens ms for the energy region of hundred keV) and stabilize the plasma in general.

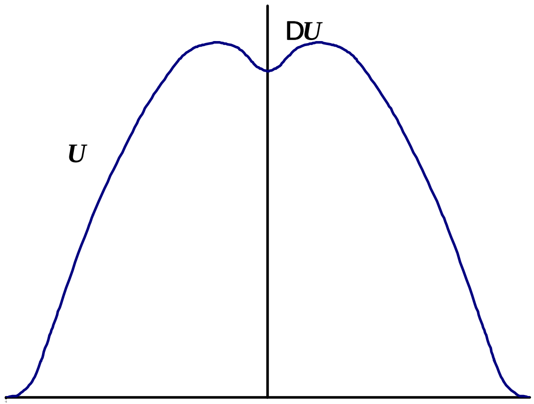


Figure 1. Plasma potential *U* with potential dip ΔU

Let we consider the confinement of ions and different electron components in this configuration of electrical potential and magnetic trap. We assume here that the main particle losses are along the axis due to the strong axial magnetic field.

It was shown [5, 6], that ions have Maxwellian energy distribution with the temperature T_i in the plasma due to the intensive elastic Coulomb collisions. All ions have equal temperature but different charge states of *i* have different values of the potential barrier $ie\Delta U$ and different rates of losses from the source. The confinement times for ions τ_i can be defined according to the Pastukhov theory for confinement of charged particles in the open magnetic trap [4]:

τ_i = [$R\, l$ **Error!** + **Error!**] $exp(x)$, (4)

with $x = (ie\Delta U/T_i)$ and $G = \{ (\sqrt{\pi}\,(R + 1)\, ln(2R + 2))/2R\}$. Here *AM* ion mass, *R* mirror ratio, *l* is effective plasma length. The rates of ion-ion scattering ν_{ik} and ion-neutral scattering ν_{i0} are given in the Ref. [3, 6], for example. The first value is much higher than the second one in the brackets of equation (4) for the actual ECR source conditions.

The potential dip ΔU as well as the main plasma potential *U* don't influence on the confinement condition of electrons of keV and higher energies. It means that for these electrons the known expression should used for the confinement time determination. It was shown [4] that in this case the time of electron confinement can be evaluated as

$$t_{eh} = 1.48 * (lnR + \sqrt{lnR}) / n_{eh} \quad (5)$$

In this relation n_{eh} is the frequency of electron collisions with all kinds of particles (electrons, ions and neutrals) in the plasma:

$$n_{eh} = n_{eeh} + n_{eih} + n_{e0h}$$

The index "*h*" here means hot or superhot electrons. The determination of electron scattering rates was made in the Refs. [5, 6], for example.

The determination of confinement times of cold electron is not so evident. But the fundamental work of Pastukhov [4] was developed for the plasma confinement in the open magnetic trap for nuclear fusion. This plasma originally has hot ions for the nuclear fusion and relatively cold electrons. And the expression (4), that we use to apply for the ion confinement now, was found firstly for cold electrons in the nuclear fusion trap. Thus we can take it also for the cold electrons in the ECR source.

t_{ec} = [*R l* **Error!** + **Error!**] *exp(x),* (6)

with $x = (eU/T_{ec})$ and the index "*c*" for cold electrons here.

Expressions (4) – (6) determine the confinement or life times for all ion and electron components in the ECR plasma. Balance conditions (2) and (3) could be used for the determination of plasma potential U and potential dip DU. The complete set of traditional balance equations for all ion, neutral and electron components with equations (2) – (6) is a new approach in the numerical simulation of ion accumulation and production in the ECR plasma. New equations make it possible to represent electrons in the ECR plasma as a multicomponent media. Any kind of experimental or analytical electron distribution function can be approximated now with a series of Maxwellian distributions with different temperatures and partial weights. Two plasma potentials describe the ECR plasma much more accurately from the physical point of view.

Numerical Simulation

The new model and equations were used in a new version of computer codes for numerical simulation. The physical problem of ion accumulation and production in the ECR ion source is described with a set of nonlinear algebraic equations in the static case. Different iterations methods are used to solve the problem [11]. A practical solving of the nonlinear algebraic set has many difficulties to find a good first approximation for iteration process and with convergence of iterations. Naturally the new equations and conditions, the new plasma potential dramatically increase the difficulties to solve real problems of ion accumulation in the numerical way. Nevertheless a new version of computer codes for numerical simulation was developed and tested in simulation and interpretation of last experimental results at RIKEN 18 GHz ECR source [12].

The influence of biased electrode on Xe ion production was studied at RIKEN ECR ion source [9]. Ion charge state distributions (CSD) and X-ray Bremstrahlung emission were registered in dependence on electrode position and voltage. It was found that the biased electrode with negative voltage on the source axis results the generation of superhot electron components with energy of 100 –200 keV. One set of the experimental series is presented in Fig. 2. The following conclusions about presented experimental data in Fig. 2 have been made in the result of analysis of X-ray Bremstrahlung emission from the source:

- Series a (the biased electrode voltage $V = 0$) - the electron distribution function has not electron components with energy higher than 20 - 30 keV;
- Series b ($V = -20$) - the electron distribution function has an electron component with energy of about 80 keV;
- Series c ($V = -70$) - the electron distribution function has an electron component with energy of about 40 keV and a component with energy of about 200 keV.

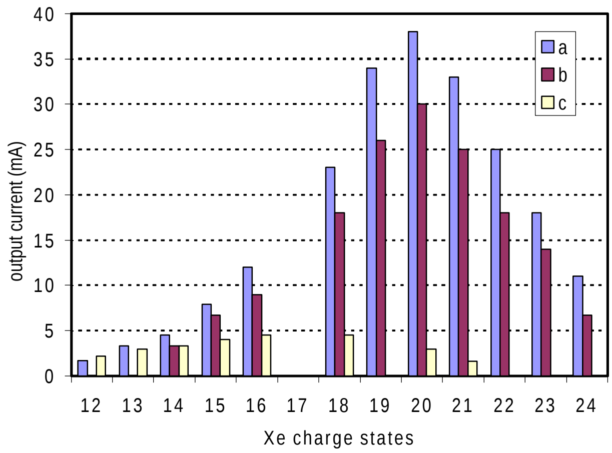


Figure 2. The experimental CSD of Xe ion. The electrode voltage $V = 0$ (a), -20 V (b) and –70 V (c).

Unfortunately there is not any information about the main core of electron distribution function and cold electrons due to the low registration effectiveness for energies less than 20-30 keV of the used X-ray detector.

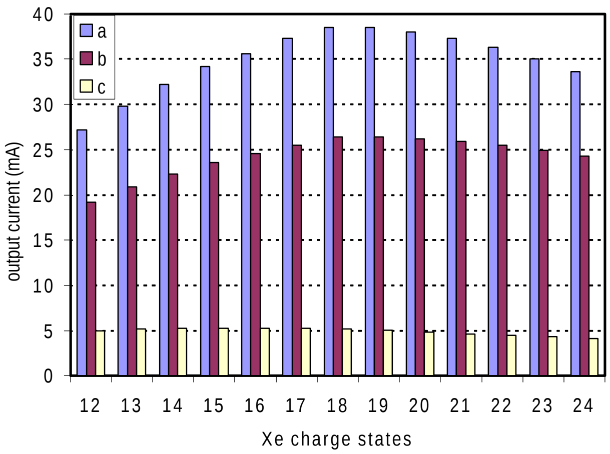
Note here: the source extraction and analyzing systems were optimized to Xe^{20+} and the spectrum shapes do not represent the actual behavior of the CSD at the extracted source hole.

The numerical simulation of Xe ion production in the RIKEN source was carried out for the xenon-oxygen mixture. The results of calculations are presented in Figure 3. The electron temperature of main electron component was chosen $T_e = 10$ keV and the total electron density was in the range of 1 – 2 10^{12} cm^{-3} to obtain the CSD and ion output current in the best coincidence with experimental values. An ellipsoid shape with the large axis of 20 cm and small axis of 5 cm was used for the plasma volume according to the distribution of magnetic field and ECR surface in the RIKEN source.

The energy and partial density of superhot electron components were chosen according to the analysis of experimental data. The following distributions were used to represent the experimental series:

a) 10keV – 100%,
b) 10keV – 70%, 80keV – 30%,
c) 10keV – 70%, 40keV – 20%, 200keV – 10%.

Figure 3. Calculated CSD of Xe ions.



Series a: eU/T_i = 0.08; N_e : 10keV – 100%
Series b: eU/T_i = 0.09; N_e : 10keV – 70%; 80keV – 30%
Series c: eU/T_i = 0.125; N_e : 10keV – 70%; 40 keV – 20%; 220keV – 10%

We did not consider here the cold electron component and main plasma potential *U* correspondingly because we had not any experimental information about electron energy distribution in the low energy region. The above electron energy distribution were fixed in calculations and the potential dip was calculated using the conditions of the plasma neutrality (2) and (3). We followed the relation eDU/T_i for this purpose which is responsible for the ion confinement in general according to (4). The calculations give the following values for eDU/T_i: Series a – 0.08, b – 0.09, c – 0.125. Results of calculations for Series b and c give lower extraction currents of Xe ions but higher in 1.5-2.0 times currents of oxygen ions in coincidence with experimental data.

The obtained results of numerical simulation of Xe CSDs qualitatively agree with the experimental data. Taking in to account that the source extraction and analyzing systems were optimized to Xe^{20+} only, the general behaviors of calculated and measured CSDs are in the coincidence. It means that the model accounts the most important physical processes in the plasma in the right way.

The peculiarity of calculated results and, according to this, difference among presented experimental results is qualitatively clear. The superhot electrons have very good confinement conditions and long lifetimes in the magnetic field with trap configuration. The presence of superhot component requires of dipper negative well *DU* for better ion capture to regulate the plasma neutrality. As the result, the Xe ion output decreases (highly charged ions have higher potential barrier in this case) but the output of oxygen ions increases correspondingly because they have the same temperature but lower charge states. The average charge state of xenon ions increase inside the plasma according to calculations but average charge state of output current remains approximately the same or even becomes lower due to difficulties with the highly charge ion extraction.

Conclusions

The development of physical model and mathematical simulation methods of electron and ion accumulation and production in the ECR ion source is a new step forward in the understanding of the ECR ion source. New equations make it possible to represent electrons in the ECR plasma as a multicomponent media. Any kind of experimental or analytical electron distribution function can be approximated now with a series of Maxwellian distributions with different temperatures and partial weights. Two plasma potentials describe the ECR plasma much more accurately from the physical point of view. The first test of new model and code has shown some new opportunities for investigators to study the ECR ion sources.

Acknowledgements. The author would like to express his recognition and gratitude to Prof. Y.Yano for the support of these investigations and to Dr.T.Nakagawa for the fruitful discussions.

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