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A.V.Philippov, G.D.Shirkov, N.A.Tokareva

MULTICOMPONENT CONSIDERATION
OF ELECTRON FRACTION
AND NUMERICAL SIMULATION
OF THE BREMSSTRAHLUNG EMISSION
FROM THE ECR SOURCE IN AFTERGLOW MODE

2000

Introduction

The development of physical model and mathematical simulation of the physical processes and numerical simulation of electron and ion accumulation and production in the electron cyclotron resonance ion source (ECRIS) is presented. This model is based on the processes connected with the elastic and inelastic collisions of the charged particles in the ECR plasma and the classical particle losses from the open magnetic trap [1], [2]. A new approach considers electrons in the ECR plasma as a multicomponent environment. There are three components introduced - primary cold electrons, hot electrons and superhot one. The electron density is determined from the new set of the balance equations for all electron components. The model includes appearance of electrons due to ionization of neutral atoms by electron impact, electron losses from the magnetic trap of the source, intercomponent transition of electrons due to RF heating. As a result both experimental and analytical electron distribution function can be approximated with a series of Maxwellian distributions with different temperatures and partial weights [3], [4]. The tests of the new model and code library have shown the qualitative accordance with the recent experimental data of RIKEN 18 GHz ECRIS [5]. The ECRIS is the most widely used source for highly charged ion production for accelerator and atomic physics applications [1], [2]. In the ECRIS plasma is confined in the open magnetic trap. The positively charged ions and electrons are generated from a neutral gas in the source chamber as a result of electron impact ionization. The free electrons released by ionization processes are heated by RF field and involved in the ionization process of neutral atoms and ions. Ions can be ionized until they will be lost from the ECRIS. The average ion charge in the ECRIS is determined by the density of the electron component and by the confinement time of the ions in the ECR plasma. The number of ions produced in the source also depends on the electron density. Particles are confined in ECRIS by magnetic field of the mirror configuration created by solenoid coils and multiple lenses. A permanent hexapole magnet is used for production of the longitudinal magnetic field with azimuthal variation to confine particle in radial direction. The axial configuration of the magnetic field is shown in Fig.1. [4]

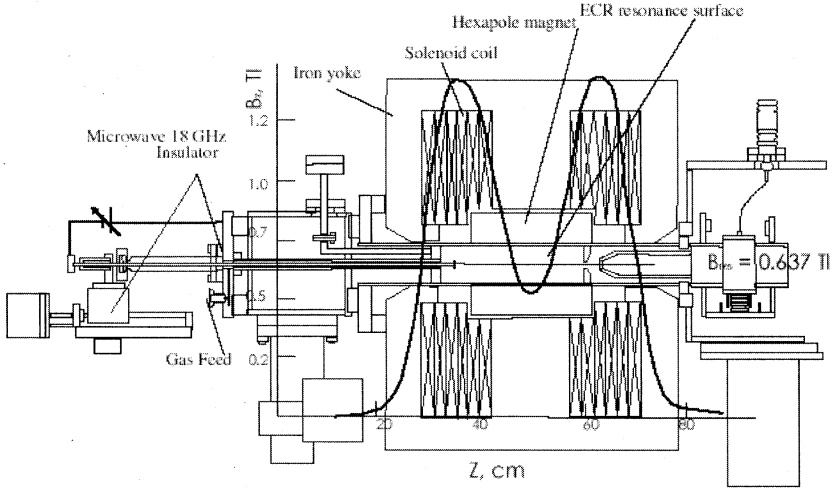


Fig. 1. Layout of RIKEN 18 GHz ECRIS and axial configuration of the magnetic field.

Balance equations

For physical modeling and numerical simulation of the processes in the ECR plasma the Classical model of ion confinement and loss [2] has been applied successfully during several last years. In this model ionization processes of neutral atoms and charge changing transitions in the ECR plasma with electron impact ionization can be described by a set of nonlinear differential balance equations for all ionic charge states and neutrals present in the ECR plasma. The balance equations are based on the Vlasov kinetic equations [1], [2].

The balance equations are able to include all inelastic processes among particles in the source. The inelastic processes result in change of charge states of ions and neutrals. The elastic collision change the energy distributions and strongly influence on the confinement conditions and particle losses from the source. The contribution of each process depends on the plasma parameters and ions types. The balance equations take into account the ion and electron losses from the source as well.

In case of three electron components the ion balance equations have the following form:

$$\begin{aligned}
\frac{dn_0}{dt} &= v_0 \left(\frac{4}{D} + \frac{2}{L} \right) (n - n_0) + \left(v_{0,c}^{ion} n_{ec} + v_{0,h}^{ion} n_{eh} + v_{0,s}^{ion} n_{es} \right) n_0, \\
&\dots \\
\frac{dn_i}{dt} &= \left(v_{i-1,c}^{ion} n_{ec} + v_{i-1,h}^{ion} n_{eh} + v_{i-1,s}^{ion} n_{es} \right) n_{i-1} - \left(v_{i,c}^{ion} n_{ec} + v_{i,h}^{ion} n_{eh} + v_{i,s}^{ion} n_{es} + \frac{1}{\tau_i} \right) n_i, \quad (1) \\
&\dots \\
\frac{dn_z}{dt} &= \left(v_{i-1,c}^{ion} n_{ec} + v_{i-1,h}^{ion} n_{eh} + v_{i-1,s}^{ion} n_{es} \right) n_{z-1} - \frac{n_z}{\tau_i}.
\end{aligned}$$

Here D and L are the diameter and effective length of the source working region or plasma dimensions correspondingly. v_0 is mean velocity of the neutral particle and n is the density of neutral outside the plasma. n_0 , n_i are the densities of neutral particles and ions correspondingly. n_{ec} , n_{eh} , n_{es} are the densities of electrons, $v_{i,c}^{ion}$, $v_{i,h}^{ion}$, $v_{i,s}^{ion}$ are rate for single ionization processes. Indexes c, h, s, correspond to the cold, hot and superhot electrons. τ_i is the ion confinement time. The first term in the first equation of system (1) describes the injection of neutral particles inside of volume of the plasma source.

The set of equations (1) considers only single ionization processes. Other inelastic collision processes can be added [1], [2]. For example, if the electron densities of cold electron is relatively high, dielectronic recombination must be taken into account.

Ion confinement

Possible charge states of ions in the source are determined by the ion lifetimes and electron density. Therefore the ion confinement time τ_i is one of the fundamental values to describe the plasma parameters in the ECRIS. The ion confinement time τ_i can be defined according to Pastukhov theory for confinement of charged particles in the open magnetic trap [6]:

$$\tau_i = \left[RL \sqrt{\frac{\pi A m_u c^2}{2T_i}} + \frac{Gx}{(1+x)(v_{ii} + v_{in})} \right] \exp(x) \quad (2)$$

where $x = \frac{ie\Delta U}{T_i}$, $G = \frac{\sqrt{\pi} (R+1) \ln(2R+2)}{2R}$, R is the mirror ratio, A is atomic masses, m_u is the unified unit of atomic masses, c is the velocity of light, i is the

charge state number, e is the electron charge magnitude, ΔU is the depth of potential dip, T_i is the ion temperature. The values v_{ii} , v_{in} describe the collision rates among ions, and ions-neutral atoms correspondingly. There are the following formulas for this values [1], [2]:

$$v_{ii} = \frac{4\pi r_e^2 m_e^2 c^4 L_{ii}}{\sqrt{8m_e c^2 A T_i^3}} \sum_{k=1}^z k^2 n_k,$$

$$v_{in} = \frac{1.5 \cdot 10^{-9} n_0}{\sqrt[4]{A}},$$

where r_e is the classical radius of electron, m_e is the mass of electron,

$L_{ii} = 23.64 - \ln \sqrt{\frac{z n_e}{T_i^2}}$ is the Coulomb logarithm, n_0 is the density of neutral atoms, n_e

is the total electron density here. For a cylindrical working area the depth of the potential dip on the source axis can be determined by [1], [2]

$$\Delta U = \frac{\pi}{8} m_e c^2 r_e n_e D^2 f \left(1 + 2 \ln \frac{2L}{D} \right),$$

where

$$f = \frac{\sum_{i=1}^z i n_i - n_e}{n_e}$$

is the so called factor of plasma neutralization. The value of neutralization factor f determines the plasma potential and according to (2) regulates the ion confinement time τ_i .

Multicomponent consideration of electron fraction of ECR plasma

The previous numerical simulation of the processes of ions accumulation and production in the ECRIS assumed that electrons have fixed energy. From physical point of view it will be much more realistic to assume the presence of several electron components with different temperatures [3], [4].

Electrons appear by electron impact ionization of the atoms and ions in the plasma. The energy of newly produced electrons corresponds to the energy of ionization and has a range of some tens or hundreds eV in dependence on ion types and dominant charge

state. A part of electrons crosses resonance surface in the source and undergoes the ECR heating. The energy of heated electrons is in keV region and reaches tens or hundreds keV according to X-ray measurement. In the modern ECRIS the average electron energy should be in the range of 5-10 keV to accumulate and produce intensive beams of highly charge ions. The rate of elastic electron scattering in the source is not as high as to slow and heavy ions to establish Maxwellian energy distribution. Therefore the energy distribution function of electrons should be rather complicated and not a smooth function of energy. It consists of a few components with very different energies. The cold electrons with energy below 100-300 eV are very effective in ionization of neutrals and low charged ion production but are not able to produce highly charged ions. After ECR heating the hot electrons with the energy of keV produce highly charged ions. The superhot electrons stabilize the plasma in general due to very good confinement condition.

Magnetic mirrors of the trap reflect the charged particles and confine the plasma in general. Only the particle 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 among charged particles change the direction of particle movement and therefore there is a continuous loss of electrons and ions from the source. The confinement time of charged particle in the open magnetic trap $\tau \propto \frac{1}{\nu}$, where ν is the total rate of elastic Coulomb scattering of the given particle. The rate of scattering depends on charge state z , mass m and particle energy E as [3], [4]:

$$\nu \propto \frac{z^2}{\sqrt{E^3 m}} \quad (3)$$

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 of plasma. If we suggest that the complete distribution function of electron energy is a superposition of l components of different

characteristic energies then the condition of plasma neutrality follows to the equations [3]:

$$\sum_{i=1}^z i n_i - \sum_{k=1}^l n_{ek} = 0 \quad (4)$$

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

The particle losses are determined by lifetime or confinement time of particles in the plasma and the time conservation of condition (4). In the static case is the cause of equal flows of ions and electrons from the plasma [3]:

$$\sum_{i=1}^z \frac{i n_i}{\tau_i} - \sum_{k=1}^l \frac{n_{ek}}{\tau_{ek}} = 0, \quad (5)$$

where τ_{ek} is the confinement times of electrons will be determined future.

The heated electrons have much more energy and less probability of scattering than the ions according to (3). The hot electrons and highly charge ions are accumulated in the center of plasma according to modern experimental data and theoretical models. It was shown [2], [7], that the high rate of the ion losses creates the negative potential dip in the center of plasma region. It regulates the ion losses and keeps the general plasma neutrality. On the other hand, the primary cold electrons have pure confinement conditions and could have a wider spatial distribution in comparison with ions and hot electrons. A simple estimation shown that the electron confinement time in the open magnetic trap of ECRIS is in the range of μ s or less for electrons with the energy about of hundreds eV. The probability to be heated with microwave power before loss for these electrons is too low, so there is no real chance to create the present dense and hot ECR plasma for highly charged ion production. Positive potential regulates the loss rate of primary cold electrons. The value of the potential must 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 few components: cold electrons primary of tens or hundreds

eV, a main component of hot electron 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 small negative dip ΔU in the plasma center confines positively charged ions. The superhot electrons have very good confinement conditions in the magnetic trap of the source (the confinement time is in the range of tens ms for energy region of hundreds keV) and stabilize plasma in general.

Electron confinement

In accordance with above consideration the electron confinement time is determined by the electron collision frequency in the plasma. The potential dip ΔU as well as the main plasma potential U do not influence on the confinement conditions of electrons of keV and higher energies. It means that for the hot and superhot electrons the known expression should be used to evaluate the confinement time [1], [2]:

$$\begin{aligned}\tau_{eh} &= \frac{1.48 \left(\ln R + \sqrt{\ln R} \right)}{\nu_{eh}}, \\ \tau_{es} &= \frac{1.48 \left(\ln R + \sqrt{\ln R} \right)}{\nu_{es}}.\end{aligned}\tag{6}$$

The quantity ν_{eh} , ν_{es} are the electron collision rate for the hot and superhot electron components correspondingly with all kinds of particles (electron, ions and neutrals) in the plasma:

$$\begin{aligned}\nu_{eh} &= \nu_{ehh} + \nu_{ehc} + \nu_{ehs} + \nu_{ehi} + \nu_{ehn}, \\ \nu_{es} &= \nu_{eses} + \nu_{esec} + \nu_{eseh} + \nu_{esi} + \nu_{esn},\end{aligned}$$

where ν_{ehh} , ν_{ehc} , ν_{ehs} , ν_{ehi} , ν_{ehn} describe the all collision rates among hot electrons and all kinds of particle (hot, cold and superhot electrons, ions and neutral atoms), ν_{eses} , ν_{esec} , ν_{eseh} , ν_{esi} , ν_{esn} describe the all collision rates among superhot electrons and all kinds of particle (superhot, cold and hot electrons, ions and neutral atoms).

The determination of the confinement time of cold electrons not so evident. But the work Pastukhov [6] 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. The expression (2), that we used 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 cold electrons in ECRIS, we have [3], [6]:

$$\tau_{ec} = \left[RL \sqrt{\frac{\pi m_e c^2}{2T_{ec}}} + \frac{Gx}{(1+x)(v_{eci} + v_{ecn})} \right] \exp(x), \quad (7)$$

with $x = \frac{eU}{T_{ec}}$, v_{eci} describe the all collision rates among cold electrons and ions, v_{ecn} describe the all collision rates among cold electrons and neutral atoms, U is the plasma potential, T_{ec} is the temperature of the cold electrons.

If equations (4), (5) is excluded from the considerations, a further equation for the determination of the electron density is added to obtain a closed set equation. It is convenient to use the balance equation for electron component. For the case of three different electron components this must be three equations for each individual component. If we assume that the cold electrons are formed in the result of the ionization of neutral atoms or ions and that they are transformed in hot electrons after microwave heating and that hot electrons transformed in superhot electrons during the hot electron confinement time, it follows that:

$$\begin{aligned} \frac{d n_{ec}}{d t} &= \sum_{i=1}^{z-1} v_{i-1, c}^{ion} n_{i-1} n_{ec} + \sum_{i=1}^{z-1} v_{i-1, h}^{ion} n_{i-1} n_{eh} + \sum_{i=1}^{z-1} v_{i-1, s}^{ion} n_{i-1} n_{es} - \frac{n_{ec}}{\tau_{ch}} - \frac{n_{ec}}{\tau_{ec}}, \\ \frac{d n_{eh}}{d t} &= \frac{n_{ec}}{\tau_{ch}} - \frac{n_{eh}}{\tau_{hs}} - \frac{n_{eh}}{\tau_{eh}}, \\ \frac{d n_{es}}{d t} &= \frac{n_{eh}}{\tau_{hs}} - \frac{n_{es}}{\tau_{es}}, \end{aligned} \quad (8)$$

with τ_{ec} , τ_{eh} , τ_{es} as life time of the cold, hot and superhot electrons in the plasma correspondingly, which determine the rate of the electron loss from source and τ_{ch} , τ_{hs} as characteristic time for heating of the cold electrons with low energy and characteristic time for the hot electrons, during this time hot electrons transform into superhot with high energy.

Experimental results and numerical simulation

Recently, time resolved X-ray experiment in the afterglow operation source regime have been performed at RIKEN 18GHz ECRIS [5] in order to study of X-ray emission of

high energy electrons from the source. The discrimination level of X-ray registration was at 50 keV and the duration of time gate was 10 ms.

The afterglow enhancement of Ar ion currents and the bremsstrahlung emission for same operation conditions and time scale are presented in Fig.2 [5]. The Figures 2 (a) and (b) show the oscillograms for Ar^{9+} and Ar^{6+} output currents correspondingly. The current of Ar^{9+} has a decay time of a few ms and it is nearly tripled during the afterglow. The current Ar^{6+} has a decay time about ten ms and has a very small enhancement during the afterglow. The Figures 2 (a) and (b) show that the saturation time of the currents in the heating stage are about 50-60 ms for the Ar^{9+} and 30 ms for the Ar^{6+} .

The pulse of X-ray emission presented in Fig.2 (c) has a different behavior in comparison with ion currents during the afterglow. The increasing of X-ray emission does not stop at first 100 ms and it has at least two very different decay times in afterglow. The first decay time is very short (a few ms) but the pulse of X-ray emission has a very long tail. The decay time of this tail, according to the Fig.2 (c) is not less than 100 ms. It means that a part of high energy electrons is alive in the plasma during a few hundred of ms after switching off the RF power. This phenomenon is very important for the ECR plasma understanding. It was concluded that the production of large continuous ionic currents requires the building up of a satisfying hot electron component to confine them. The major aim is to enrich this component as much as possible in order to get large ionic population inside the plasma by production of the bigger potential dip ΔU for the ion confinement. The drop of electron component at the RF power switching off is beneficial for expulsion of the ions.

Formally the problem of calculation of density distribution of multicharged state of condition in ECR plasma mathematical is completely determined and is reduced to the decision of a complete Kochi problem (1)-(8) for set of self-consistent kinetic equations with initial condition of ions, neutral atoms, and three electronic components. However, its real solution requires a series of physical and mathematical simplifications, and also reasonable combination of analytical and numerical methods [8], [9].

The computers codes realizing the model (1)-(8) were developed and tested simulation and interpretation of time-resolved X-ray experiments at the RIKEN 18 GHz ECRIS [5] in the afterglow operation regime.

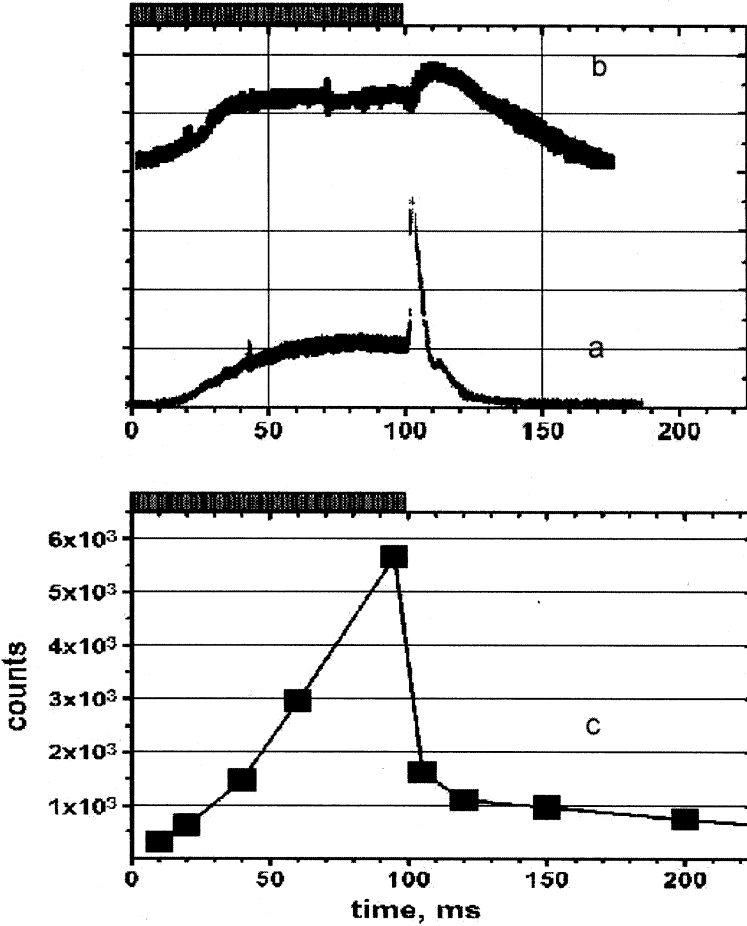


Fig.2 Currents Ar^{9+} (a), Ar^{6+} (b) and X-ray count rate (c) as a function of time.

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 about tens of keV of the used X-ray detector.

The numerical simulation of Ar ion production and bremsstrahlung in the afterglow regime of ECRIS operation in the RIKEN 18 GHz ECRIS was carried out. The ECR plasma were presented as three electrons component with different energies according to above consideration: the cold electron component with energy of a few hundreds eV (10%), the main hot electron component with energy of ten keV (80%) and the superhot electron component with energy of hundred keV (10%). The total electron density was it the range of $1-1.5 \cdot 10^{12} \text{ cm}^{-3}$ to obtain the charged state distribution and ion output current in the best coincidence with experimental values. The results of calculations are presented in Figures 3 - 5 [10].

The Figures 3 - 4 [10] show output currents of all Ar ions charge states. The current of Ar^{6+} has a decay time about ten ms and a small enhancement during the afterglow. The current of Ar^{9+} has less decay time in comparison with Ar^{6+} and it has double during afterglow. The general behavior of these curves is very similar to the experimental results presented in Figures 2 (a) and (b).

The Fig.5 [10] shows the bremsstrahlung emission of superhot electrons during the afterglow. The presented bremsstrahlung is almost the same as it is shown in the experimental curve in Fig.2 (c). The increasing X-ray emission does not stop at first 100 ms and it has at least two very different decay times of a few ms and about hundreds ms.

The calculations give the understanding of this phenomenon. The confinement times of cold and hot electrons are about a few ms. The confinement time of superhot electrons is in range of tens or hundreds ms and the process of superhot electron formation and accumulation is relatively slow. The period of 100 ms is not enough for complete accumulation of the superhot electron component and the bremsstrahlung is not saturated enough at 100 ms in Fig.5 [10] as well as it is in Fig.2 (c). Thus, after switching off the RF power, the process of hot and superhot electron creation is stopped. All hot electrons are lost during a few ms according to the corresponded confinement time. A most part of ions is pushed out from the source producing afterglow. It is visible in the afterglow and the first stage of bremsstrahlung decay in Figures. But the superhot electron component is conserved in the source due to very good confinement conditions in the magnetic trap. Some ion losses increase the

confinement time of superhot electrons up to 100 ms and even more due to the reduction of collision frequency with accumulated ions. These superhot electrons generate some low charged ions and secondary cold electrons and produce bremsstrahlung emission during all their lifetime of a few hundreds of ms.

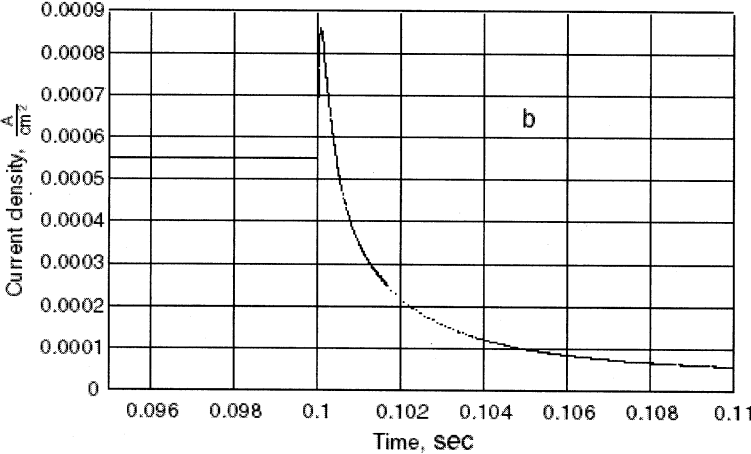
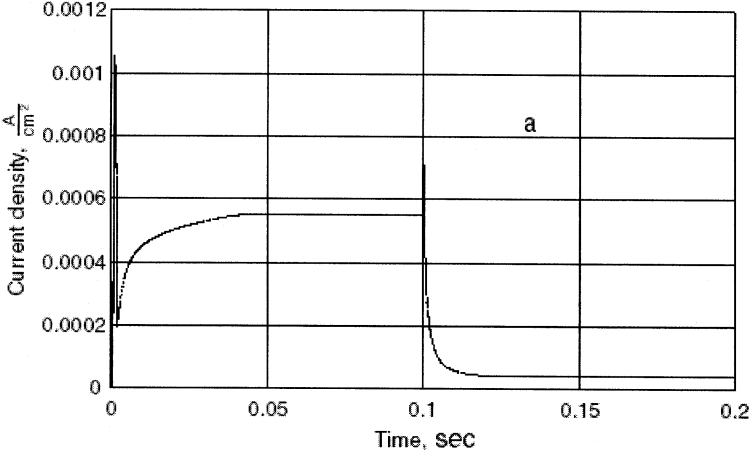


Fig.3 The output current of Ar^{6+} (a) during afterglow (zoom in b) as a function of time.

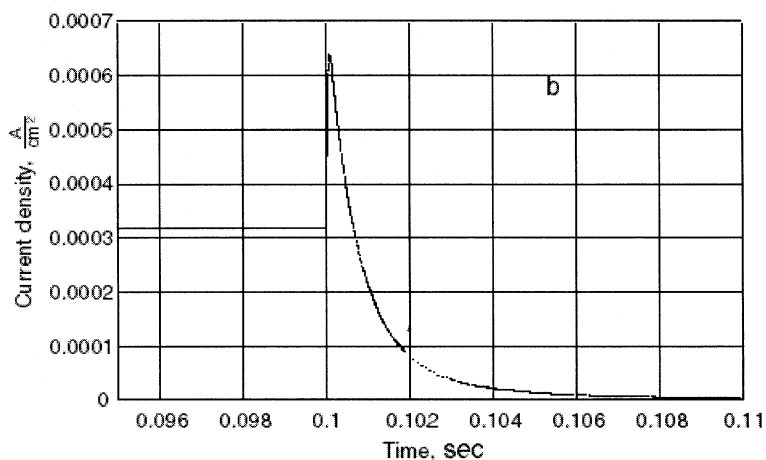
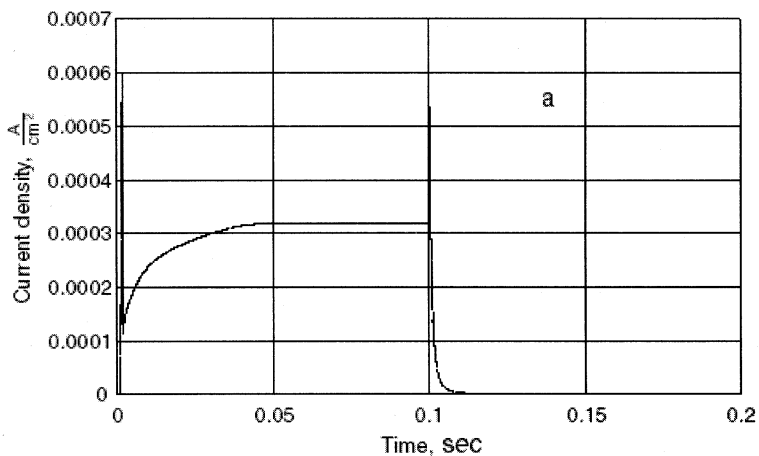


Fig.4 The output current of Ar^{9+} (a) during afterglow (zoom in b) as a function of time.

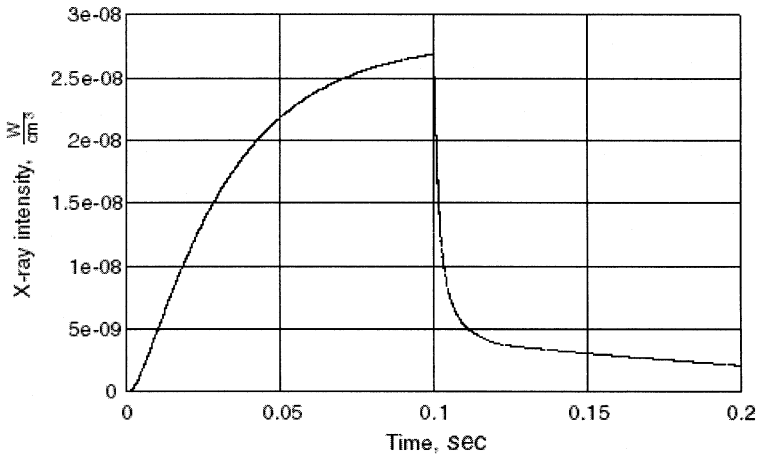


Fig.5 Calculated bremsstrahlung emission of superhot electrons during the afterglow.

Conclusions

The principal conclusions of the analysis performed above are the following: the electrons have a complicate distribution of a few components: the cold primary electrons of tens or hundreds eV; the main electron component of keV energy to produce highly charged ions and, according to the experimental data [5], the component of superhot electrons of tens or hundreds keV.

The obtained results of numerical simulations of Ar ion production and bremsstrahlung in the afterglow regime of ECRIS operation are conformed with the experimental data [5]. The representation of electrons in ECRIS as a multicomponent media of different energies makes it possible to explain and simulate the phenomenon of long bremsstrahlung (100-300 ms) in afterglow regime of the ECRIS operation at RIKEN [5]. It shown that a superhot electron component with energy of hundred keV is responsible for this long time X-ray emission from ECRIS. This gives a new step in understanding of plasma and highly charged ion production in the ECRIS.

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Филиппов А.В., Ширков Г.Д., Токарева Н.А.

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Многокомпонентное представление
об электронной составляющей и численное моделирование
рентгеновского тормозного излучения ECR-источника
в режиме после высвечивания

Представлено развитие физической модели и математического моделирования некоторых физических процессов накопления ионов и электронов в источниках ионов на электронно-циклотронном резонансе (ECRIS). Новые уравнения основаны на представлении об электронах в ECRIS как многокомпонентной среде. Предполагается наличие трех электронных компонент в ECR-плазме, а именно: компоненты первичных холодных электронов, компоненты горячих электронов и компоненты сверхгорячих электронов. Плотность электронов определяется на основе новой системы уравнений баланса для всех электронных компонент. Модель описывает появление электронов в результате ионизации нейтральных атомов электронным ударом, электронные потери из магнитной ловушки источника ионов, а также трансформацию электронных компонент в результате высокочастотного нагрева. Приведено сравнение результатов новой модели с экспериментальными данными, полученными на 18 ГГц ECR-источнике ионов в RIKEN (Япония).

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Philippov A.V., Shirkov G.D., Tokareva N.A.

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Multicomponent Consideration of Electron Fraction
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The development of physical model and mathematical simulation of the physical processes and numerical simulation of electron and ion accumulation and production in the electron cyclotron resonance ion source (ECRIS) is presented. A new approach considers electrons in the ECR plasma as a multicomponent environment. There are three components introduced: primary cold electrons, hot electrons and superhot one. The electron density is determined from the new set of the balance equations for all electron components. The model includes appearance of electrons due to ionization of neutral atoms by electron impact, electron losses from the magnetic trap of the source, intercomponent transition of electrons due to RF heating. The tests of the new model and code library have shown the qualitative accordance with the recent experimental data of RIKEN 18 GHz ECRIS.

The investigation has been performed at the Laboratory of Particle Physics, JINR.

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