

A NEW APPROACH TO THE MODELLING OF THE PLASMA DYNAMICS IN ECR ION SOURCES

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Abstract

The trend of Electron Cyclotron Resonance Ion Sources (ECRIS) to use higher frequencies and magnetic fields is driven by the need to make larger beam currents and higher charge states available for nuclear physics accelerators. Anyway, because of the limits imposed by the magnets' and microwave generator's technology, any further increase of performances requires a detailed investigation of the plasma dynamics. The experiments have shown that the current, the charge states and even the beam shape change by slightly varying the microwave frequency ("frequency tuning effect" – FTE). The plasma dynamics in ECRIS have been studied by means of single particle and PIC simulations, that explain the FTE in terms of the wave field distribution over the ECR surface. The presence of high energy electrons observed in different 2nd and 3rd generation ECRIS has been also explained in terms of the diffusion in the velocity space above the stochastic barrier. Other methods used to improve the ECRIS performances, e.g. the two frequency heating with an adequate phase relation between the two waves, can be better exploited by using the predictions of the simulations here described.

INTRODUCTION

ECRIS plasmas are generated through the interaction of microwaves with gas or vapours contained in a cylindrically shaped metallic cavity in presence of a magnetostatic field. The magnetic field has the double role to create the condition for the so-called Electron Cyclotron Resonance (i.e. when $\omega_{RF} = qB/m$) and to confine the plasma with long ion lifetimes, thus allowing the formation of highly charged ions. At power, magnetic fields and microwave frequencies used up to now all the ECRIS obey to the so called Standard Model: the extracted current strongly increases with the microwave frequency, but only if the confinement is adequate [1]. The scaling law concerning the microwave power and the ECR heating process (ECR-H) was not confirmed in all the cases because the relation between the power and the magnetic field is not simple; the problem of the wave energy transmission into the plasma may be divided into two parts: the first is connected to the microwave generator-waveguide-plasma chamber coupling, while the second one regards the wave-plasma interaction that cannot be described by simple analytical relations [2]. For the wave-plasma interaction two types of numerical simulations have been implemented: single particle (MonteCarlo) and PIC simulations. The MonteCarlo approach has been used in order to describe the

electromagnetic field propagation inside the plasma chamber of the SERSE ion source and the following interaction with plasma electrons. The resonant modes existing in the plasma chamber have been determined. In addition the SERSE magnetic field has been approximated by the following expressions:

$$B_x = -B_1xz + 2Sxy$$

$$B_y = -B_1yz + 2S(x^2 - y^2)$$

$$B_z = -B_0 + B_1z^2$$

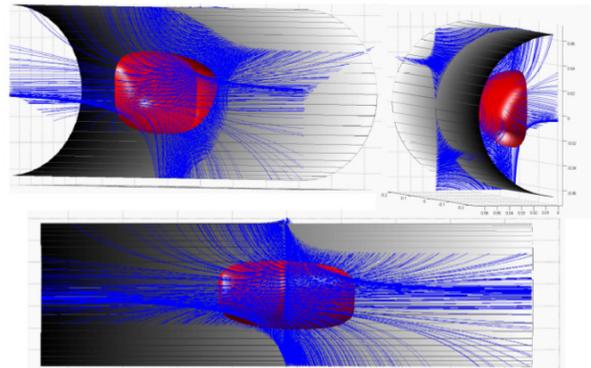


Figure 1: Magnetic field lines (in blue) of the SERSE source minimum-B field. In red the egg-shaped ECR surface; in grey the plasma chamber.

In order to understand how different patterns of electric field in the plasma chamber affect the electron heating, the evolution of the electron energy is followed through many crossing of the resonance region. We can simulate the energy absorption process of the electrons but not the following build-up of the different ion charge states, because a collisionless plasma is used, for sake of simplicity. The electrons follow a Maxwell-Boltzmann distribution at the beginning of the simulation. The model cannot give quantitative predictions on the final energy of the electrons subject to different electric field shapes, but it is aimed to comparative results, which are able to inform about the most effective mode to heat the plasma. PIC simulations have been carried out with a code developed at Kurchatov Institute of Moscow, Russia [3], solving the Maxwell equations in a self-consistent way. Reliable simulations are time expensive, so at first we looked for a collisionless plasma in axially symmetric mirror trap in 2D R-Z approximation. No ionization was taken into account.

EXPERIMENTAL BASIS

Several experiments have shown that small changes of the microwave frequency strongly change the extracted currents and the achievable charge states, according to FTE, and they also influence the ion beam formation mechanism, as strong variations of the beam shape and brightness have been observed [4]. Figure 2 demonstrates that the use of broadband microwave generators, like TWTs (that permit to tune the frequency) fully exploits the RF power injected into the plasma chamber, increasing the ECRIS performances with respect to the use of klystron generators [5].

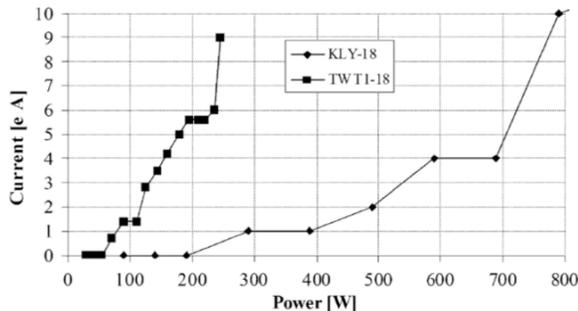


Figure 2: O^{8+} current extracted from the SERSE ion source for different values of the RF power, from a TWT or a klystron generator.

Experiments also demonstrated that a strong variation of the ECRIS performances occurs as a consequence of the magnetic gradient variation at the resonance surface. Some interesting results have been obtained in experiments with the SERSE source at INFN-LNS and with the VENUS source at LNBL. In the latter case [6] the current of the higher krypton charge states is maximized for $B_{min}=0.717$ T. For extremely low and extremely high mirror ratios the CSD (charge states distribution) shifts toward 24^+ or lower charge states [6]. Being the RF power fixed, this phenomenon is related to the magnetic field gradient only. In addition, the experimental data demonstrated that the high energy X-rays counts integrated over different energy ranges increase with the B_{min} field. The amount of electrons above 800 keV increases of about one order of magnitude passing from $B_{min}=0.72$ to $B_{min}=0.85$ T. In the same interval the current of highly charged ions decreased abruptly. Hence the CSD trend and the production of high energy electrons are strictly connected. It is reported in literature [7] that the warm electrons temperature corresponds to $3 \div 5I_z$, where I_z is the ionization potential of the charge state on which the CSD is peaked. Experimentally we observe that by varying B_{min} and B_{ext} the CSD has a maximum for 25^+ only in a restricted range of mirror ratios. We may assume that the heating mechanism up to high energies subtracts energy to the warm electrons. ‘‘Gentle’’ gradients of the axial magnetic field boost the production of very high energy electrons (up to 2 MeV), and then of high energy X-rays, limiting

the exploitation of the ECRIS performances. Additional evidences that low mirror ratios favourite the heating up to extremely high energies come from figure 3: the energy required to produce MeV-electrons is not available for the heating process from low energy states (cold electrons) to the warm population (i.e. those electrons with high ionization cross section).

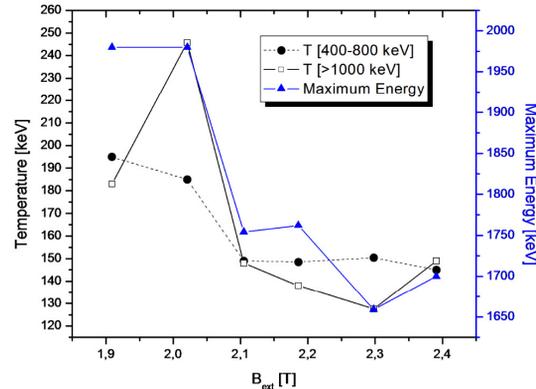


Figure 3: Hot electron temperature calculated by means of the plasma emitted X-ray spectra [8] compared with the maximum detected energy.

THEORY AND MODELLING

The experimental data above reported triggered the activity of modeling towards an improved description of the wave-particles interaction [9]. The different location of maxima of the electromagnetic field in the plasma chamber involves a different heating for different modes, as confirmed by the single particle simulations. For example, the mean energy achieved by the electrons after 50 ns using the $TE_{1,1,42}$ mode is five times higher than the energy attainable with the $TE_{4,4,23}$ mode (20 keV the former, about 5 keV the latter) [9]. In addition, the TE modes allow to reach higher energies than TM modes, because of their transversal electric field. These results explain the strong variation of the extracted current observed in figure 2.

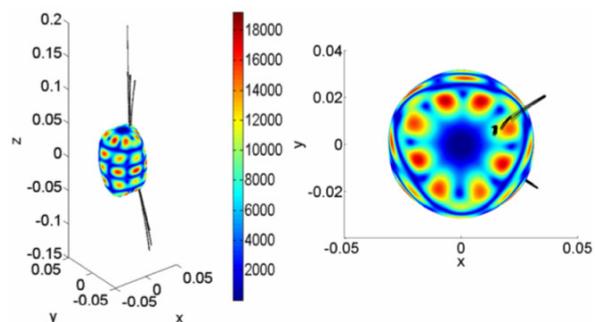


Figure 4: Electron trajectories in a min-B magnetic field configuration and electromagnetic field pattern over the ECR surface.

Hence the frequency tuning effect is connected with the different electromagnetic modes. It is known that the

electrons move along the field lines, which cross the ECR surface only in particular regions, as shown in figure 4. If in the crossing regions the electric field associated with the electromagnetic wave is high enough, the heating is very rapid and a great amount of electrons gain within few tens of ns the energy necessary to ionize the atoms. The simulations explain also the two frequency heating. Electrons passing across the double resonance have a high probability to be strongly accelerated and confined by the electromagnetic field, especially when the two frequencies differ few MHz and if they have the right phase relationship. Single particle simulations also help to explain the origin of the high energy electrons in ECRIS, mostly generated in presence of “gentle” gradients, while for larger gradients their amount is modest [6].

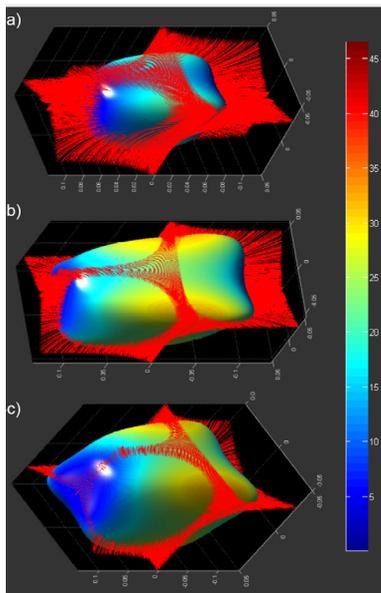


Figure 5: Distribution of the magnetic field gradient over the resonance surface of the VENUS source for $B_{hex}=2.0$ T and $B_{min}=0.65$ and 0.85 (figures a) and b)) and for $B_{hex}=1.7$ T and $B_{min}=0.65$ T (figure c)).

The gradient over the entire ECR surface has been considered for the data reported in [6, 9]. Experimentally, electrons above the so-called adiabatic barrier [10] are mainly produced for higher B_{min} . Comparing the figures 5a) ($B_{min}=0.85$ T) and 5b) ($B_{min}=0.65$) it can be noticed that the global gradient distribution is mostly affected by B_{min} , whereas it is less influenced by B_{hex} (fig. 5c)). The same occurs for B_{mj} , so we may conclude that the global reduction of the gradient triggers the heating mechanism able to produce ultra-hot electrons.

PIC simulations have been also employed for the investigation of the ultra-hot electrons formation. The numerical results put in evidence that an extremely rapid heating up to a characteristic energy $E_s \sim 8-20$ keV occurs after about 80 ns [10]. E_s corresponds to a sort of intermediate boundary for the heating: after the electrons have reached E_s , a slow diffusion in velocity space occurs, till the absolute stochastic barrier $E_b \sim 70-75$ keV

(about 2 ms are needed); according to the model in [10], E_b is the maximum achievable energy for the single particle. Anyway the simulations demonstrate that a very slow heating above the absolute stochastic barrier occurs (after 25 ms electrons with a relativistic factor $\gamma \sim 1.5$ were observed). Simulations confirmed that the number of such high energy electrons increases for lower mirror ratios and for resonances close to the magnetic field minimum value, as experimentally observed. This is a key point for the design of future ECRIS. Simulations also permit to imagine a simple model for the beam formation mechanism, which is based on the existence of two different plasma regions: primary and secondary plasma. The ions are accelerated outwards from the ECR surface by an accelerating electrostatic field, which is perturbed by the electromagnetic field, according to a pattern like the one shown in figure 4. This perturbation leads to the scattering of the ions which are forming the beam in proximity of the extraction hole, thus changing the shape of the ion beam, as observed in [4]. This model is particularly interesting as it links the beam shape variation to the frequency tuning, in perfect agreement with the experimental evidences [4].

CONCLUSIONS

The numerical simulations demonstrated that in order to suppress the amount of high energy electrons a properly tailored magnetic field profile is needed: the position of the ECR affects the electron temperature. In order to optimize the heating rapidity, alternative schemes like frequency tuning effect and two frequency heating [2] will be crucial for future ECR ion sources, that should feature a high gradient of the magnetic field. Further theoretical investigations are under way to better understand the ion dynamics and the beam formation mechanism, being the beam brightness a key parameter for the accelerators injectors.

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