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Plasma ion dynamics and beam formation in electron cyclotron resonance ion sources[a)]

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In electron cyclotron resonance ion sources it has been demonstrated that plasma heating may be improved by means of different microwave to plasma coupling mechanisms, including the "frequency tuning" and the "two frequency heating." These techniques affect evidently the electron dynamics, but the relationship with the ion dynamics has not been investigated in details up to now. Here we will try to outline these relations: through the study of ion dynamics we may try to understand how to optimize the electron cyclotron resonance ion sources brightness. A simple model of the ion confinement and beam formation will be presented, based on particle-in-cell and single particle simulations. © *2010 American Institute of Physics.* [doi:10.1063/1.3292932]

I. INTRODUCTION

Experimental data collected in the past ten years feature a strong dependence of the electron cyclotron resonance ion sources (ECRIS) performances on the microwave frequency used for plasma heating: substantial variations in the extracted current and mean charge state have been detected; the data recently collected at GSI (Gesellschaft für Schwerionenforschung, Darmstadt, Germany) (Ref. 1) demonstrate that the frequency tuning also affects the beam shape and brightness. Therefore we need to find a model which explains the influence of microwave frequency on both particles dynamics. Single particle and particle-in-cell (PIC) simulations are particularly useful for the electron dynamics: magnetostatic and electromagnetic fields can be taken into account and the plasma heating at different input power and for different electromagnetic modes excited inside the plasma chamber can be simulated. In Ref. 2, the main results concerning the electron dynamics are reported: the variation in the performances in terms of charge states and extracted current was explained by taking into account the different patterns of the electromagnetic fields on the resonance surface. Collisionless electron and ion dynamics are simulated by means of single particle and PIC techniques, and this is their main limitation. In fact, ions are collisional in the dense and hot plasma located inside the ECR surface. Monte Carlo simulations try to simulate collisions in ECR plasmas, paying particular attention to the ion dynamics in presence of self-generated electrostatic fields, which will be described in details in the following pages.

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II. THEORETICAL MODEL

ECRIS plasmas are generated through the resonant interaction of microwaves with gas or vapors contained in a cylindrical metallic cavity. A magnetostatic field creates the condition for the so-called ECR (when $\omega_{RF}=qB/m$) and confines the plasma in order to ensure long ion lifetimes (required for highly charged ions production). As first approximation we can study only the electron motion in presence of the electromagnetic wave and of the magnetostatic field (*single particle approach*). We consider the plasma chamber as a resonant cavity, and we calculate the resonant modes excited at a given frequency.[2]

Figure 1 shows the magnetostatic field lines and a characteristic electromagnetic field distribution over the resonance surface when the $TE_{4\ 4\ 23}$ resonant mode is excited into the cavity of the SERSE ion source operating at INFN-LNS of Catania. The magnetic field can be calculated by means of analytical approximations, which reproduce the minimum B field structure.[2] We assumed that the electrons follow a Maxwell–Boltzmann distribution at the beginning of the simulation, with $T_e=100$ eV. The reciprocal electron-ion interactions are not taken into account. Electrons are considered collisionless (this hypothesis is reasonable for times shorter than 50–100 ns). The evolution of the electron energy is followed through many crossing of the resonance region.

More exhaustive information on the plasma particles dynamics can be obtained by means of *PIC simulations*: in this case electrons and ion dynamics are simultaneously investigated by solving the Maxwell equations in a self-consistent way. To reduce simulation times we looked for a collisionless plasma in axially symmetric mirror trap. The KARAT code[3] was used, simulating plasmas with initial temperatures $T_i=T_e=1-2$ eV.

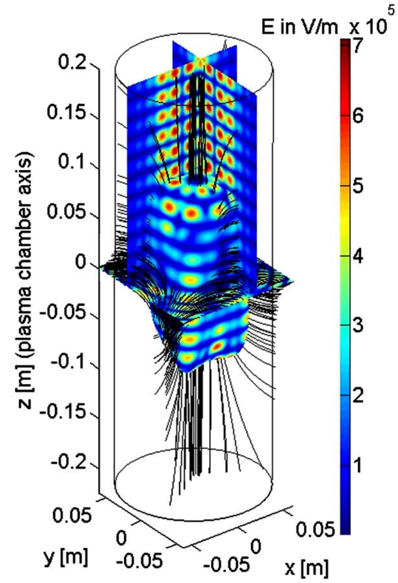

FIG. 1. (Color online) Typical electromagnetic field distribution inside the plasma chamber over two longitudinal planes and, in particular, over the resonance surface, for the $TE_{4\ 4\ 23}$ resonant mode. The magnetic field lines are also shown. The geometrical and magnetic properties of the SERSE source have been used.

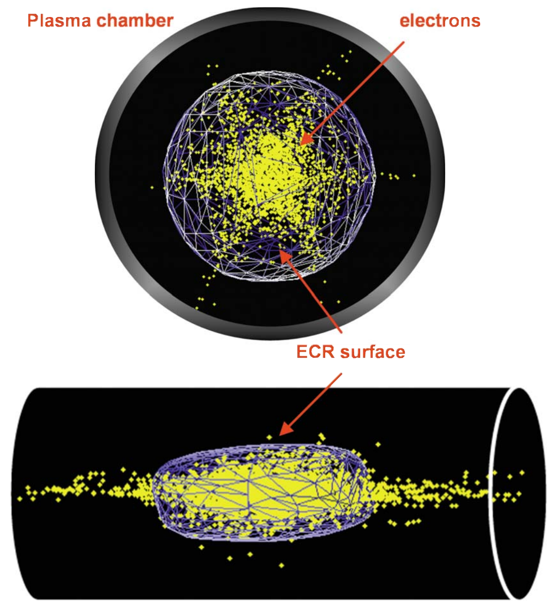

FIG. 2. (Color online) Simulated electrons inside the SERSE plasma chamber after 50 ns; the egg-shaped ECR surface is also shown.

In order to follow the ion dynamics over a large timescale, i.e., till the beam formation, the collisions are crucial: the single particle approach can be improved by introducing Coulomb collisions. The resulting model is a *hybrid approach*: the collisionless long timescale phenomena are determined through the PIC simulations. Once determined, the steady state structures of electron density distribution and the self-generated electrostatic potentials, the ion dynamics are simulated by taking into account the ion-ion collisions (the most frequent ones) and the possible effects of the magnetostatic field. Initially the ions are mainly located inside the ECR surface and their motion is calculated by solving the equation

$$\frac{d\vec{v}}{dt} = \frac{q}{M}[\vec{v} \times \vec{B} + \vec{E}_s] \tag{1}$$

for times comparable with the real lifetimes of ions in modern ECRIS (0.1–10 ms). In Eq. (1), q and M are the ion charge and mass, respectively, B is the magnetic field, and E_s are plasma self-generated electrostatic fields (e.g., due to plasma potential or other inner fields, as discussed below). The initial ion velocity distribution is Maxwellian, with $T_i = 1-20$ eV (according to experimental data and PIC simulations). Collisions are checked by comparing numbers randomly extracted after fixed time intervals (1 ns) in the range 0–1 with the ion-ion collision probability

$$P(t) = 1 - \exp\left(-\frac{t}{\tau_{\text{coll}}}\right), \tag{2}$$

where[4]

$$\tau_{\text{coll}} = \frac{M^2 2\pi\varepsilon_0^2 v_i^3}{n_e z^4 e^4 \ln \Lambda} \tag{3}$$

is the mean time between two collisions. In Eq. (3), v_i is the ion velocity, z is the ion charge state and $\ln \Lambda$ is the so-called Coulomb logarithm. If the randomly extracted number is lower than $P(t)$, a new casual direction is assigned to the scattered ion, ensuring that the total energy remains the same (electrostatic scatterings are elastic collisions).

III. SINGLE PARTICLE AND PIC RESULTS

Simulation results about electron heating have been published in Refs. 2 and 5. Here we focus our attention on the plasma confinement (plugging) inside the resonant surface. Single particle simulations demonstrated that after 50 ns more than 78% of particles still contained inside the plasma chamber are effectively confined inside the ECR surface. A typical situation is shown in Fig. 2. The SERSE source typical setup, in terms of rf power *(1500 W)*, magnetic field (B_{inj}=2.1 T, B_{min}=0.4 T, B_{ext}=1.7 T, B_{hex}=1.2 T), and microwave frequency *(18 GHz)* has been simulated. The largest part of particles is well confined inside the egg-shaped resonant surface. Fluxes of escaping electrons are evident only along the chamber axis because of the low electromagnetic field in this region (see Fig. 1).

The additional confinement provided by the electromagnetic field is due to the rapid increase in the electron perpendicular velocity (with respect to the magnetic field lines), which expels the particle from the mirror loss cone. Many of the low energy electrons reach energies on the order of keVs after a single resonance crossing, then they begin to oscillate in the mirror, turning at the resonance value of the magnetic field. This mechanism has been observed also by PIC simulations: a steady state structure of the electron density appears after few tens of nanoseconds and lasts for times longer than tens or even hundreds of microseconds. The inner resonance plasma reaches densities at least three times larger than the outer one. Hence the plasma can be divided in two parts: the primary plasma (PP) inside the ECR surface surrounded by a secondary plasma (SP) at lower density and temperature. This characteristic plasma distribution influences the ion dynamics. PIC simulations put in evidence that

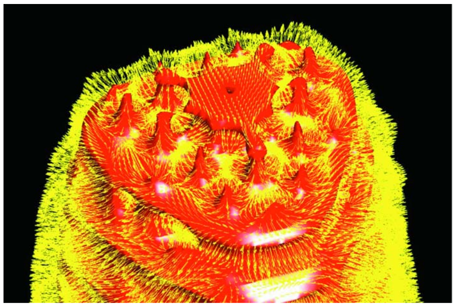

FIG. 3. (Color online) Partial view of a corrugated isodensity surface, that one closest to the ECR region; the electrostatic field vectors, that are perpendicular to the isodensity surface everywhere, have also been plotted.

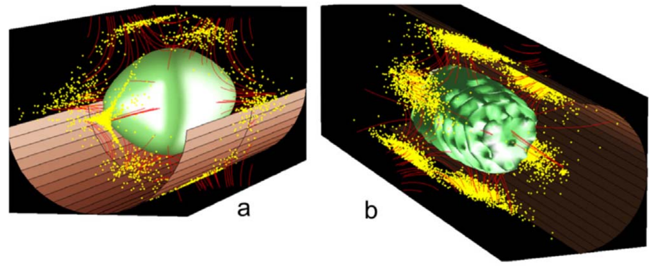

FIG. 4. (Color online) Ions impinged on the chamber walls in case of (a) smooth and (b) strongly corrugated isodensity surfaces. The structure of the magnetic field is represented by the field lines.

ions are accelerated when they cross the PP to SP boundary. This means that a positive potential exists over the resonance surface (we name it V_{PP}). The currently accepted model for ion confinement is based on the internal potential dip due to the well confined hot electrons. In PIC simulations there are no evidences about inner resonance accelerations: the potential shape is flat inside the PP and it rapidly decreases when passing from PP to SP. The ion confinement is ensured by the electron confinement through the ambipolar diffusion mechanism.

If the plasma was excited by plane waves the isodensity surfaces should coincide with the closed, egg-shaped surfaces at constant magnetic field. This would be true also over the resonance surface, being uniform the magnetic and electromagnetic contributions to the electron confinement. Therefore even the positive potential between the PP and SP should be uniform, and everywhere perpendicular to the ECR surface. Indeed in ECRIS the peculiar pattern of the electromagnetic field influences the self-generated, ambipolar electrostatic field structure through the influence on electron confinement: this means that the PP isodensity surface is corrugated, i.e., the isodensity and constant B field surfaces no longer coincide. At first approximation the corrugation reproduce the electromagnetic field pattern, so it changes with the pumping rf frequency. PP-SP boundary electric fields are still everywhere perpendicular to the isodensities surfaces, and the mutual orientation of the electrostatic vectors' directions and magnetic field lines changes continuously from one point to another of the PP surface; this basically leads to the scattering of ions crossing the PP-SP plasma boundary. Figure 3 shows in red the corrugated isodensity surface in proximity of the ECR zone, and in yellow the orientation of the electrostatic field vectors.

IV. ION COLLISIONAL DYNAMICS

By means of the hybrid model described in Sec. II we simulated the ion motion in presence of the above mentioned scattering electric fields [Fig. 4(b)], compared with the case of a smooth potential over the PP surface [Fig. 4(a)]. Strongly corrugated surfaces may be generated by $TE_{n,m,r}$ or $TM_{n,m,r}$ modes with high values of the triplet of integer numbers n, m, r: this triplet determine the number of maxima and minima of the electromagnetic standing waves excited inside the cavity at a given frequency (Fig. 1).

Simulations put in evidence that in the case of a smooth potential a large fraction of ions arrive on the extraction flange, forming a marked three cusp shape [Figs. 4(a) and 5(a)]. A uniform potential of 60 V has been considered in this case, according to PIC calculations. Because of the uniform ambipolar electric field, which in turn produces low ion scattering, beams can be bright and mostly populated by highly charged ions. Particles at low charge state, in fact, have lifetimes long enough to be ionized many times; once generated, highly charged ions are guided by the magnetic field when traveling in the SP (neither scattering fields nor collisions exist because the ions are accelerated up to 100–500 eV, depending on charge state): they "remember" the magnetic field near the extraction hole and the extracted beam has the characteristic three cusp shape experimentally observed in Ref. 1 [Fig. 5(c)].

In case of strongly corrugated isodensity surfaces we assumed V_{PP} in the 30–100 V range, with marked distortions in order to exaggerate the ion scattering. This strong scattering shortens the ion lifetime (especially for the highest charge states) of a factor 10: the ions collide with the chamber walls laterally, as shown in Figs. 4(b) and 5(b). Only a reduced fraction of particles reach the extraction side, forming a diffuse triangular area near the extraction hole. In this way the beam will be characterized by low brightness and it will be mostly populated by ions at low charge states.

Therefore the shape of the PP surface, which in turn depends on the excited electromagnetic mode, influences the

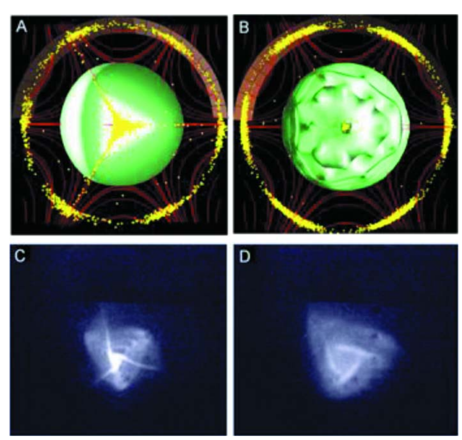

FIG. 5. (Color online) (a) and (b) Front view of the ions positions after 100 μs; the plastic chamber walls, the resonance surface, and the magnetic field lines are shown with the same perspective. (c) and (d) Extracted beam shape experimentally observed at two different microwave frequencies in the case of the CAPRICE ion source operating at GSI, Darmstadt (Ref. 1).

ion motion up to the extraction region, where the ion beam is formed. This explains the different shapes of the extracted beam experimentally observed in Figs. 5(c) and 5(d), obtained at two different microwave frequencies.

Between the two extreme conditions here described there are several intermediate cases, all of them depending on the particular pattern of the electromagnetic field affecting the isodensity surface corrugation, and then finally the ion scattering and the beam formation mechanism.

Note that although single particle calculations feature a strong radial electron confinement, in some conditions the existence of these nonuniform, large self-generated electrostatic fields deconfines ions mainly radially, thus limiting the plasma lifetime and the source performances. The actual lifetime of both the species, ions and electrons, is then regulated by these two conflicting mechanisms, provided that the plasma quasineutrality condition is continuously preserved by the ambipolar diffusion process.

Lateral ion losses are confirmed also by observation of gold depositions on the plasma chamber walls in case of gold plasmas. Clear strips are evident on the lateral surface of the cylinder. A similar effect was also observed in ECRIS operating as charge breeders, under some operative conditions.[6]

V. CONCLUSIONS AND PERSPECTIVES

The reciprocal interaction between electrons and ions has been described through a model which conjugates PIC and single particle simulations. The basic assumption is the creation of electromagnetic patterns over the resonance surface. Not only the frequency tuning influence on the plasma heating is based on this hypothesis, but also the effect of frequency tuning on the ion dynamics and beam formation, which is mediated by the electrons through the formation of PP corrugated isodensity surfaces. More detailed simulations will be performed, including ionization collisions, in order to fully describe the ion dynamics from ion creation to beam generation. Our final goal is the optimization of the beam brightness and emittance through the investigation of the beam formation mechanism just before the extraction hole.

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