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Enhancement of the electron confinement and temperature by means of the Two Frequency Heating in ECR Ion Sources plasmas

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Abstract. In the last years several experimental results have shown a substantial enhancement of the total current and of the mean charge state for the particles extracted from the ECR Ion Sources (ECRIS) when they are fed by means of two electromagnetic fields at different frequencies. Considerations about the effect of the superimposition of microwaves at different frequencies, as well as of the spatial distribution of the electromagnetic fields within the source chamber are given in this paper in terms of electron energy and confinement. On this purpose a series of simulations has been performed on the motion of a single particle subject to a confining magnetostatic field and to the electromagnetic modal field in the source cylindrical cavity.

Introduction. In all the experiments regarding ion production by means of the ECR (Electron Cyclotron Resonance) mechanism, a monochromatic electromagnetic wave in the microwave region is used to increase the electron energy and therefore to improve the plasma production. The use of two feeding electromagnetic waves at different frequencies and coupled to an ECR ion source chamber through two separate transitions in the source input flange has become advantageous and common during the last years. Many experimental results, in fact, seems to demonstrate that the ion source performances under these feeding conditions increase [1]. Other experimental results have also shown the high sensitivity of the source performances with respect to the frequency of the electromagnetic field excitation [2].

In a previous paper [3] we began to investigate the effect of the spatial distribution of the electromagnetic field, and of its variation even for small changes of the excitation frequency, on the motion of a single particle within the cavity where the plasma is generated. In this work we continue the theoretical analysis by evaluating also how two different modes excited in the source chamber may affect the motion of a charged particle there subject also to a confining magnetostatic field.

Source description and modelling. We consider for our study the SERSE source operating at Laboratori Nazionali del Sud in Catania [4], fed by a rectangular waveguide WR62 placed off-axis on the input circular flange of the chamber. We take into account, as chamber model, a closed cylindrical multimodal cavity with aluminium walls, having radius a = 6.5 cm and length l = 45 cm. Inside the cavity an electromagnetic stationary field is formed, and it can be expressed as sum of many eigenmodes therein excited. The cavity is sorrounded by a magnetic structure composed by an hexapole and three coils, producing a field of magnetic induction that can be modelled by the following expressions:

$$B_x = -B_1 x z + 2 S_{ex} x y\,;\; B_y = -B_1 y z + S_{ex}\left(x^2 - y^2\right);\; B_z = B_0 + B_1 z^2 \qquad (1)$$

where S_{ex} is a constant related to the hexapole field, B_0 and B_1 to the solenoids ones. This field configuration is suitable for the magnetic confinement of charged particles and it is called at *B-minimum.* The first step of the study regards the description of the ECR surface, i.e. the locus within the cavity of the points satisfying the equation $\omega = \omega_g = q\ B\ /\ m$. The derived equation for the surface is of the type $A_1\rho^4 + A_2\rho^2 + A_3 = 0$, where

$$A_1 = B_1^2 \cos^2\theta + S_{ex}^2 \sin^4\theta - B_1 S_{ex} \sin^2\theta \sin 2\theta \sin 3\phi;\quad A_2 = 2B_0 B_1 \cos^2\theta;\quad A_3 = B_0^2 - \left(\frac{m\omega}{q}\right)^2 \qquad (2)$$

An electron undergoes the strong excitation caused by the electromagnetic field on the points of this surface. The field evaluation on them is therefore indispensable. Let us write the equations of the modal field in the cylindrical resonant cavity in vacuum, without taking into account in this simplified approach the modes coupling and the angular modal degeneration due to the cylindrical symmetry. The equations (3) describe the fields related to the TM and TE modes respectively, where $x_{n\nu}$ and $x'_{n\nu}$ are the ν-roots of the Bessel function and its first derivative both of n order, μ is the magnetic permittivity, C_n is a constant related to the mode energy and ω_{res} is the mode resonant frequency.

$$\begin{cases} E_\rho = -\dfrac{a r \pi}{x_{n\nu} l} C_n J'_n\left(\dfrac{x_{n\nu}\rho}{a}\right)\cos n\phi \sin\dfrac{r\pi z}{l} \\ E_\phi = \dfrac{n r \pi a^2}{\rho l x_{n\nu}^2} C_n J_n\left(\dfrac{x_{n\nu}\rho}{a}\right)\sin n\phi \sin\dfrac{r\pi z}{l} \\ E_z = C_n J_n\left(\dfrac{x_{n\nu}\rho}{a}\right)\cos n\phi \cos\dfrac{r\pi z}{l} \end{cases} \qquad \begin{cases} E_\rho = \dfrac{\mu\,\omega_{res}\, a^2}{x'^2_{n\nu}}\dfrac{n}{\rho} C_n J_n\left(\dfrac{x'_{n\nu}\rho}{a}\right)\sin n\phi \sin\dfrac{r\pi z}{l} \\ E_\phi = \dfrac{\mu\,\omega_{res}\, a}{x'_{n\nu}} C_n J'_n\left(\dfrac{x'_{n\nu}\rho}{a}\right)\cos n\phi \sin\dfrac{r\pi z}{l} \\ E_z = 0 \end{cases}$$

TM modes TE modes (3)

In Fig. 1 we show the cavity structure together with the plotting of the distribution of the electromagnetic field on the resonance surface for modes at different characteristic frequency.

It is clearly shown that when the frequency of the incoming excitation wave is varied also of very small fractions the field distribution on the resonance surface change remarkably. In the case when the source excitation consists of two electromagnetic fields at different frequencies two resonance surfaces exist. In this context we operated to resolve numerically the particle motion equations and to evaluate the trajectory of the electrons and their confinement.

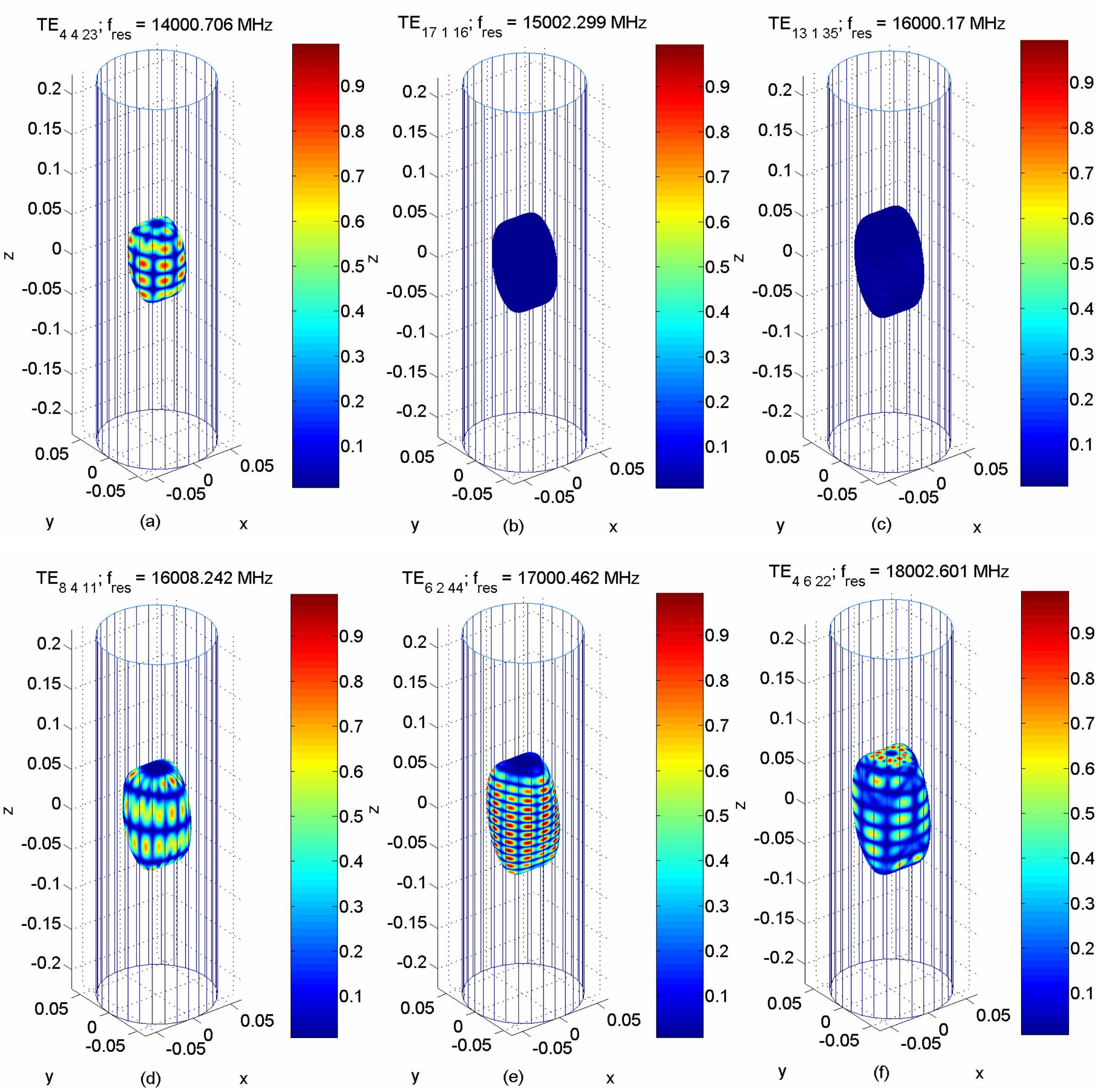
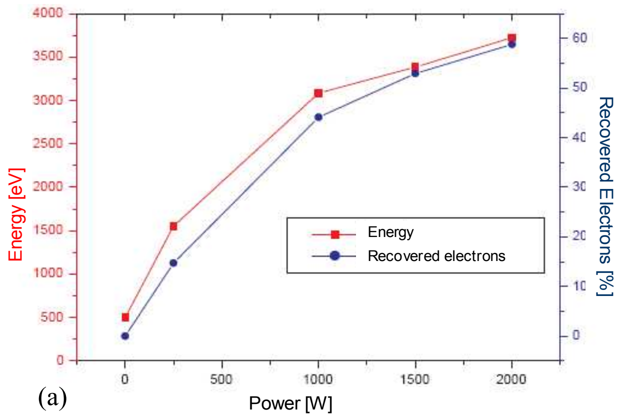


Figure 1: *Normalized field distribution on the relative resonance surface for modes at different frequencies, within the cylindrical cavity.*

Simulations results. We first considered the case of the single $TE_{4\,4\,23}$ mode excitation in the cavity (Fig. 1a). The Fig. 2a shows the trend of the electron energy and the role of the electromagnetic field in the confinement of the electrons that otherwise would escape from the plasma (*recovered electrons*). The two plots in Fig. 2a have a very similar behaviour and they tend to saturate for high powers.



(a)

	14 GHz 300 W	18 GHz 1000 W	18 GHz 2000 W	(14+18) GHz (1000+300) W
Confined Fraction	0.671	0.725	0.868	0.895
Energy [keV]	1.5509	1.0141	1.2612	1.9589

(b)

Figure 2: *(a) Electron energy and number of recovered electrons for different values of the incoming wave power; (b) Data for different power and frequencies of the excitation.*

We performed the same simulations by considering the excitation of the mode $TE_{4\ 6\ 22}$ only (Fig. 1f, with resonant frequency close to 18 GHz), with 1000 W power. The effects of the spatial distribution of the electromagnetic field on the ECR phenomena are clearly shown in the table of Fig 2b, with respect to the case when the single $TE_{4\ 4\ 23}$ mode is excited with 300 W power, in terms of electron confined fraction and energy after a given simulation time, large enough to allow an effective interaction between electron and microwaves. The numerical study has dealt also with the case of two electromagnetic waves at different frequencies supplying respectively the mode $TE_{4\ 6\ 22}$ with 1000 W power together with the $TE_{4\ 4\ 23}$ one with 300 W power. In this case we have two resonance surfaces and therefore it may happen that the electrons that hardly interact with the first can have interaction with the second, and vice versa. The electron energy and the confined electron fraction are increased even with respect to the single $TE_{4\ 6\ 22}$ mode excitation at 2000 W power. According to Fig. 2a, the electron energy may be doubled, in the single mode case, by triplicating the power, whereas by using two frequencies we increase the total power of the 30% only. Further studies and simulations are now in progress, together with a better description of the microwave fields within the source chamber, to get more details about the ECR processes and about their dependence on the feeding electromagnetic waves.

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