SOME CONSIDERATIONS ABOUT FREQUENCY TUNING EFFECT IN ECRIS PLASMAS*

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Abstract

In the recent past many experiments demonstrated that slight variations of the microwave frequency used for the ignition of ECRIS plasmas strongly influence their performances (frequency tuning effect) either in terms of extracted current, of mean charge state and of beam emittance. According with theoretical investigations, this phenomenon can be explained by assuming that the plasma chamber works as a resonant cavity: the excited standing waves, whose spatial structure considerably changes with the pumping frequency, globally influences either the energy absorption rate and the plasma spatial structure.

EXPERIMENTAL EVIDENCES

The experimental results collected during the last years in several laboratories (INFN-LNS, JYFL, GSI) have confirmed the validity of the Frequency Tuning Effect (FTE). Here we will report about two experiments with the ECR ion source of CNAO, Pavia, and with the CAESAR source of INFN-LNS (in this case we measured also the emitted X-rays at frequencies between 14.0 and 14.5 GHz). The experiments at CNAO evidenced the increase of the coupling efficiency with the RFQ: keeping constant all the other parameters, in Pavia the transmission was around 50-70%, while only a 30% of transmission was obtained at HIT with a "twin" accelerator and without FTE. Fig.1 shows the comparison between the extracted current and the reflection index. We can argue that resonant modes correspond to minima of reflection coefficient. Generally, the current signal is peaked on frequencies corresponding to modes (squared area b), because of the better coupling, but this is not a strict rule: in some cases (squared area a), although the matching of the microwave line with the source (cavity plus plasma) is optimal, and the extracted current remains low. Therefore we must distinguish between the microwave generator-to-plasma chamber coupling and the excited mode-to-plasma coupling. In the latter case, as formerly explained in [1, 2], the mode spatial structure plays the main role. According to simulations, the heating rapidity is strongly regulated by the electromagnetic field pattern over the resonance surface. This picture is not enough complete to describe all the consequences of the frequency tuning. Additional data information come from the data of Fig. 2.a and 2.b: from the X-ray measurements it follows that the high energy component of EEDF is not significantly affected by FTE (the magnetic field profile is the critical parameter, as demonstrated in [3]).

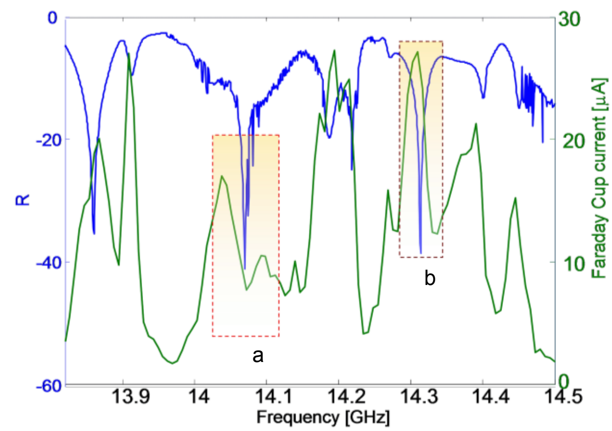

Figure 1: comparison between extracted current and reflection coefficient at different but close frequencies (test on the CNAO ECRIS).

Conversely the CSD (charge state distribution) reveals pronounced fluctuations for the highest charge states, as they are more sensitive to any change in heating rate. But the relationship between current and X-ray spectra is not straightforward. There are some frequencies (e.g. 14.38 GHz) which produce large amount of X-rays but relatively low currents and even a lower mean charge state. Considering the relation:

$$< q > \propto n_e \tau_i$$

being n_e the electron density and τ_i the ion lifetime, and assuming that the number of X-ray counts is somehow linked to the electron density, the results in Fig. 2 can be explained only by taking into account a possible influence of FTE on the ion dynamics (τ_i changes more than n_e).

This conclusion is confirmed by the other experimental data, which show how the frequency tuning affects the beam shape and emittance. At GSI [4] and JYFL in 2009 hollow beams have been obtained for some values of frequency, although no remarkable variations in the output current were observed. A plausible hypothesis is that cavity modes affects also the spatial plasma distribution, and consequently the ion dynamics, as discussed in [5]. Further confirmations come from the last experiment carried out at JFYL, focused on the beam transmission through the cyclotron, which varied even when the source output current did not change [6].

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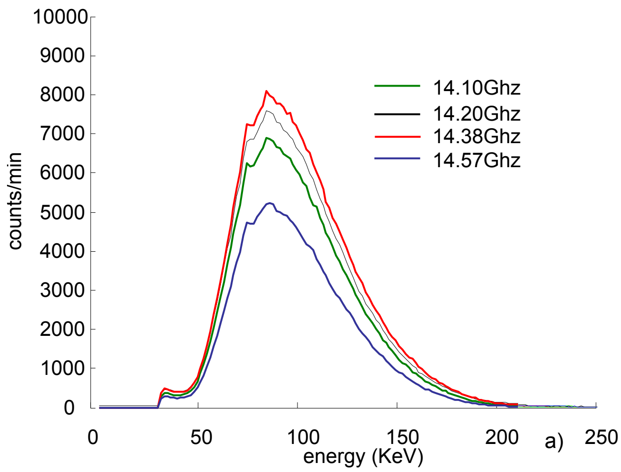

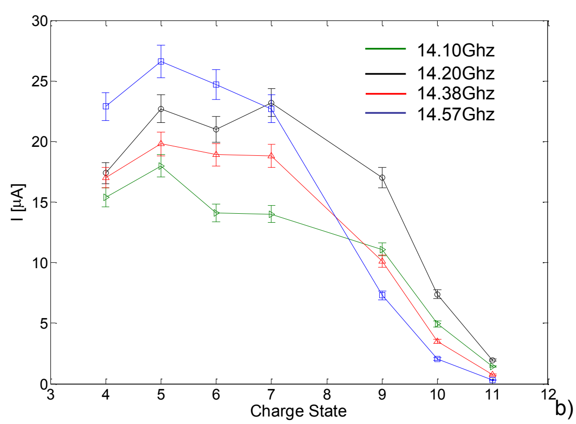

Figure 2: X-ray spectra (above) and CSDs (below) at different frequencies as measured with the CAESAR source.

THEORETICAL APPROACH

To reduce the calculation times for fully 3D collisional simulations of ECRIS plasma we can split the electron and ion dynamics, looking separately to their time evolution by using a Monte-Carlo (MC) collisional approach. 2D PIC simulations follow the electrostatic reciprocal interactions between electrons and ions on long timescales but assuming a collisionless plasma, and they can be used for a preliminary determination of plasma spatial distribution. In a fully 3D MC simulation the B-min field can be correctly reproduced, in Cartesian coordinates, by using the following formulas:

$$B_x = -B_1 xz + 2Sxy$$

$$B_y = -B_1 yz + 2S(x^2 - y^2)$$

$$Bz = \begin{cases} -B_0 + B_{inj} z^2 & \forall z < 0 \\ -B_0 + B_{ext} z^2 & \forall z > 0 \end{cases}$$

A SERSE-like device has been implemented in our code, with a plasma chamber length of 45 cm, and radius 6.5 cm. The magnetic field for 14 GHz (B_{ext}=1.2 T, B_{inj}=2.2 T, B_{min}=0.3 T, B_{hex}=1.2 T) is correctly reproduced with B_0=0.3 T, B_{inj}=25 T/m^2 , B_{ext}=36.5 T/m^2 and S=360. According to PIC calculations, because of the interaction with the electromagnetic field, working as an additional confinement tool, the ECRIS plasma separates into a high density plasma inside the resonance volume, and a lower density plasma in the outer resonance region. This situation can be adequately reproduced by the following formula for electron density [7]:

$$n_{ECRIS}(x,y,z) = 0.3 n_{cutoff} + \Sigma_i h n_{cutoff} \exp\left\{ -\frac{\left[B_{tot}(x,y,z) - (B_{ECR} - ki)\right]^2}{k^2} \right\}$$

which was used as input parameter for MC simulations. B_{tot} is the total magnetic field, h and k are two constants which ensure that the plasma density rapidly falls at the resonance plasma boundary in a few mm layer. This density is introduced into the following relation to calculate the collision probability, once known the characteristic time of Spitzer collisions for particles moving at velocity v:

$$P(t) = 1 - \exp\left(-\frac{t}{\tau_{coll}}\right) \qquad \tau_{coll} = \frac{M_{i,e}^2 2\pi\varepsilon_0^2 v_{i,e}^3}{n_e z^4 e^4 \ln\Lambda}$$

where z is the ion charge state (it is z=1 for electrons) and ln Λ the so called Coulomb logarithm. The MonteCarlo hybrid code solves the relativistic Landau equation [8] for electrons and a non relativistic equation for ions:

$$\frac{d\vec{v}}{dt} = \frac{q}{M}\left[\vec{v} \times \vec{B} + \vec{E}_s\right] \qquad (i)$$

$$\frac{d\vec{v}}{dt} = \frac{q}{m}\left(1 - \frac{v^2}{c^2}\right)^{3/2}\left[\vec{v} \times \vec{B}_S + \vec{v} \times \vec{B}_{em} + \vec{E}_{em} - \frac{1}{c^2}\left(\vec{E}_{em} \cdot \vec{v}\right)\vec{v}\right] \qquad (e)$$

where E_s is the electrostatic field over the resonance surface (from PIC simulations it is around $V=20\ V$). This potential is perturbed by eventual fluctuations of the electron density [5].

The crucial assumption of our model is that the source chamber works as a resonant cavity even when filled by the plasma, which just shifts the resonance frequencies proportionally to the electron density, and introduces an absorption term in the eigen-field equation of the cavity. Experiments performed so far demonstrate that mode patterns still persist in high density absorbing plasmas [9].

MAIN RESULTS

Simulations are coherent with experiments: MC hybrid calculations make evident that the local absorbed power is much lower than the input one. The electromagnetic field was then calculated according to eigen-mode allowed in the aforementioned cylindrical chamber, with a field strength corresponding to a RF power of 1000W and Q=20000 [10]. The six first order differential equations which come out from either electron and ion vectorial equations of motion are solved by means of the 4th and 5th order Runge-Kutta routine implemented in MATLAB with time precision δt = 10^{-12} s (δt=10^{-9} s for ions), corresponding to about 10 points per gyroperiod. The trajectories of particles are followed for a fixed time interval Δt, after which the check of the collisions is done. If collisions are found, the velocity vector is rotated of 90° and the calculus restarts from this new coordinate.

Particles impinging on chamber walls are immediately removed from the calculation. Fluxes of electrons and ions, during their motion along the magnetic field, are stored with mm precision in a 3D array, which permits to visualize any density accumulation.

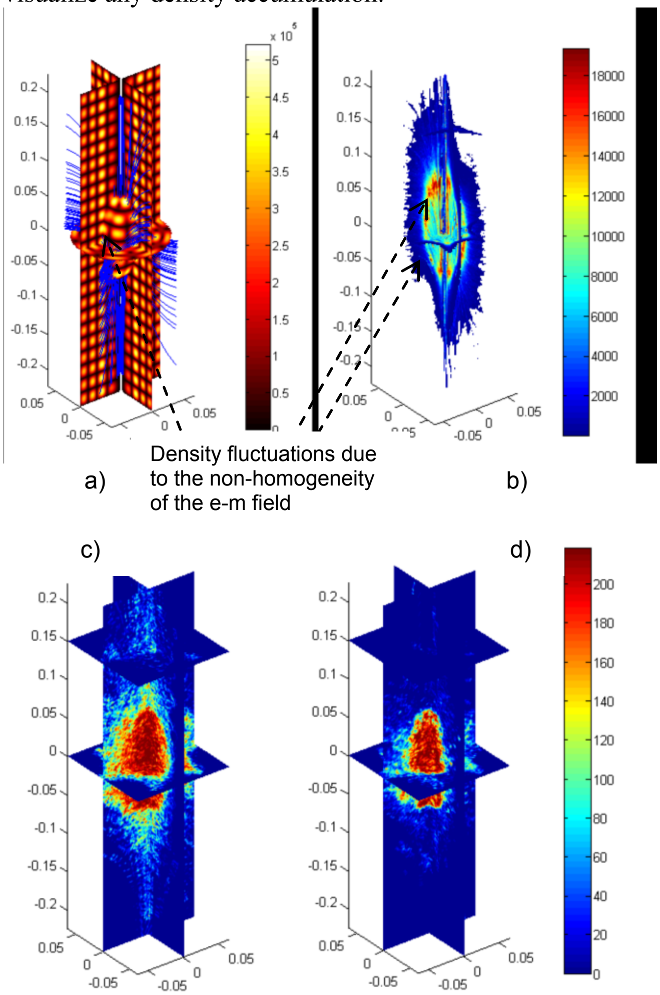

Figure 3: a) pattern of the electromagnetic field for 1000 W, TE4 4 23 mode, Q=2·104. b) longitudinal and transversal slices of electron density distribution (a.u.); c) d) comparison between simulated ion distributions (a.u.) for Ar plasma, with 1<q<4 (c), and 5<q<8 (d).

The most important results are shown in Fig. 3. MC hybrid approach reveals the existence of a strong non-homogeneity in plasma distribution: the largest part of electrons is well confined inside the resonance surface during the first 5 μs of life, confirming the results of 2D PIC simulations. Neither collisions are able to destroy the characteristic structure of plasma density, nor reciprocal electrostatic interactions among electrons and ions are able to do it, as observed in PIC simulations. MC show also that the density concentration in proximity of the resonance depends on the mode pattern (see Fig. 3.a) and b)), as well as the energy deposition into the plasma. Because of this additional effect of electromagnetic field on confinement and plasma structure, ions are partially reflected, partially accelerated when passing from inner resonance plasma to the outer one, fitting the shape of the electron density distribution. Ions are dynamically confined by collisions in the inner resonance-high density plasma; in the outer-resonance plasma, because of the lower density, the number of collisions drastically decreases and the ions feel the magnetostatic field. Localization of density perturbs the ion trajectories and the plasma surface corrugation scatters the ions along their path towards the extraction hole. According to the charge state, ions are then more or less scattered laterally or along the chamber axis, as confirmed by figures 3c) and 3d) (lower charge states are less confined). Simulations put also in evidence a depletion of plasma density in the near axis region: this may be at the basis of hollow beams. The only way to reduce the around axis accumulation of plasma, flattening the density, is the excitation of modes with maxima even in the region close to x=y=0.

In conclusion, simulations show that the different modes regulate the electron diffusion from cold to warm population, affecting the ionization efficiency; this is not sufficient to have high currents, because the ion scattering may make more rapid the losses of plasma particles, thus decreasing τ_i. Therefore the quality factor Q decreases although n_e remains about unchanged. In these cases also the emittance worsens. A proper handling of FTE may restore the conditions of good axial confinement, removing the hollow shape of extracted beam [6], and positively affecting the emittance. Hence FTE is a powerful technique to boost the performance of existing source without any large investments. Further efforts will be devoted to simulation methods, in order to self-consistently determine the dynamics of electron and ion density structures over very long timescales; more accurate predictions on ion beam properties will be possible.

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