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A POSSIBLE OPTIMIZATION OF ELECTRON CYCLOTRON RESONANCE ION SOURCES PLASMA CHAMBERS

C. S. Gallo *, A. Galatà, INFN-Laboratori Nazionali di Legnaro, (Padova), Italy
D. Mascali, G. Torrisi, INFN-Laboratori Nazionali del Sud, Catania, Italy

Abstract

In the cylindrical resonant cavities of Electron Cyclotron Resonance Ion Sources (ECRIS), microwave fields are used to generate and sustain the plasma. Normally, resonant modes of a higher order than the fundamental one are excited, due to the high frequency used compared to the dimensions of the plasma chambers: this can lead to small electric fields on the resonant surface, translating in low electrons energy and poor source performances. In this paper, we propose a possible modification of the conventional plasma chambers, resulting from an electromagnetic study carried out on a Caprice-type full permanent magnet ECRIS. Such modification implies the excitation of a "length-independent" resonant mode, having an intense and homogeneous electric field on the plasma chamber axis. This characteristic makes the modification suitable to be applied to numerous ECR sources. The positive effect on the plasma electrons density distribution will be also shown.

INTRODUCTION

Electron Cyclotron Resonance Ion Sources (ECRIS) [1] are nowadays the most effective devices to produce high intensity continuous or pulsed beams of medium-high charge states. In such sources, a plasma is created and sustained through a resonant interaction between microwaves (typically at 14 or 18 GHz) and the electrons motion, and is confined by a particular multi-Tesla magnetic configuration called B-minimum structure, generated by superimposing the field created by two or more coils to the one generated by a hexapole. Considering the particular topology of the magnetic field, the resonant interaction takes place on closed egg-shaped surfaces, called resonance surfaces. The performances of these devices have been evolving during the years following the well known scaling laws [1], the High-B mode concept [2] and the ECRIS standard model [3]: this has involved the necessity to employ higher and higher frequencies and magnetic fields, that often implies the development of expensive and technologically complex devices. At the same time, different "tricks" were discovered and have been applied to boost their performances: in particular, the injection of two close or well separated frequencies [4, 5], as well as the fine tuning of a single frequency, known as frequency tuning effect [6]. The main aim of those tricks is to increase the electrons density and energy by optimizing the power absorption by the microwave field. In fact, the beam extracted from an ECRIS consists of those ions that flow from a portion of the resonance surface around the plasma chamber axis toward the extraction aperture, following the magnetic field lines: consequently, for any given operating frequency and magnetic configuration, it is mandatory to maximize the energy transfer to plasma electrons in that specific part of the resonance surface. For plasma chambers with cylindrical shapes, possible modes that show an intense electric field around the axis and are length-independent are, for example, the $TM_{0,n,0}$ modes: this paper describes a simple but effective modification to the plasma chamber geometry in order to excite the plasma through one of the above mentioned modes, so as to maximize the energy transfer to plasma electrons. The modification has been studied with the electromagnetic solver COMSOL Multiphysics®and validated by simulating the electrons dynamics under the calculated electromagnetic fields, using an ad-hoc code developed in MatLab®.

* carmelo.gallo@lnl.infn.it

SIMULATION DOMAIN

The geometry used to validate numerically the modification proposed in this paper is the plasma chamber of the ECRIS called LEGIS (LEGnaro ecrIS) and installed at Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali di Legnaro (INFN-LNL). It is a full permanent magnet source of the Supernanogan type built by the Pantechnik company, whose typical operating frequency is 14.428 GHz. The plasma chamber, made in aluminum, consists in a cylinder with a radius of 22 mm, a length of 128 mm and two holes, one of 24 mm in diameter at the injection side and the other of 7 mm in diameter at the extraction side: Fig. 1 shows the model implemented in COMSOL®, together with the radial microwave input through a rectangular WR62 waveguide located at 10 mm from the injection hole.

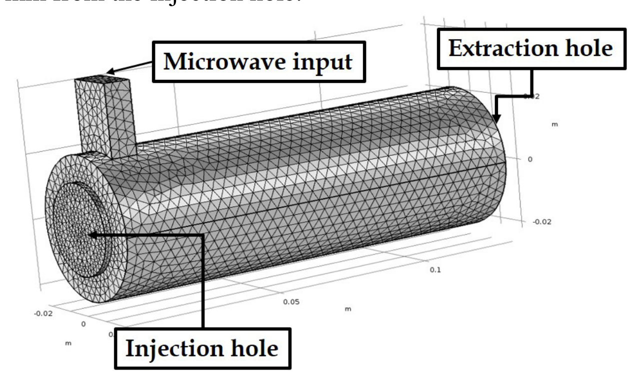

Figure 1: Model of the plasma chamber of the LEGIS source implemented in COMSOL®. Microwaves are injected through a radial rectangular WR62 waveguide. The extraction hole is not visible.

As a first step, the frequencies of the resonant modes $TM_{0,n,0}$ were calculated analytically for the present geom-

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etry considering n=1–3: the values obtained are 5.2 GHz (TM$_{0,1,0}$), 12.0 GHz (TM$_{0,2,0}$) and 18.8 GHz (TM$_{0,3,0}$). Unfortunately, none of those frequencies are compatible with the magnetic structure of the LEGIS source, projected to operate between 14 and 14.5 GHz. In order to make at least one the above mentioned modes suitable for the operation with our source, we considered a reduced plasma chamber radius of 18.3 mm, able to shift the frequency of the TM$_{0,2,0}$ mode at 14.4 GHz. The simulations shown in the following section concern the comparison of two structure: the present geometry of the LEGIS plasma chamber (present chamber) excited at the operating frequency of 14.428 GHz and its possible modification reducing the radius to 18.3 mm (modified chamber), excited with a TM$_{0,2,0}$ mode.

ELECTROMAGNETIC ANALYSIS

The electromagnetic analysis started with the study of the two structures with the Eigenmode solver, that is considering them as ideal cavities, with perfectly conducting boundaries and without any hole, and finding the resonant modes: the maximum element of the mesh size was set to 1.75 mm (about $\lambda_0/6$, where λ_0 is the vacuum wavelength), a good compromise between accuracy of the calculations and computational costs. For the present chamber, the resonant mode closest to the operating frequency is the TE$_{2,1,11}$ at 14.488 GHz, while for the modified chamber we focused on the TM$_{0,2,0}$ mode found at 14.395 GHz. The calculated electric field distribution for the two cases is shown in Fig. 2 it can be clearly seen that the TM$_{0,2,0}$ mode not only has a very intense electric field on the plasma chamber axis, but its maximum value is more than 50% higher compared to the TE$_{2,1,11}$. As a following step, the two holes at injection and extraction were included in the analysis of the two geometries: Fig. 3 shows the results. In both cases we observed a shift in the resonant frequency, in particular of -60 MHz for the present chamber and +37 MHz for the modified geometry, but the TM$_{0,2,0}$ still shows an intense electric field on axis (except for a small decrease close to the injection hole), and its maximum is now twice the one shown by the TE$_{2,1,11}$.

The analysis then moved to the Frequency domain solver, that is the study of the behavior of specific frequencies considering the real geometry and RF excitation port (holes and waveguide input): 14.428 GHz (TE$_{2,1,11}$ mode) and 14.432 GHz (TM$_{0,2,0}$ mode) were chosen for, respectively, the present chamber and the modified chamber. Perfectly conducting boundary was the boundary condition applied to the plasma chamber wall, while for the two holes the perfectly matched layer was chosen, so as to absorb all the outgoing wave energy without any impedance mismatch. The calculations started considering vacuum-filled cavities and 100 W of microwave power, with a mesh size of $\lambda_0/6$: the electric field distributions in logarithmic scale are shown in Fig. 4 for both frequencies. The effectiveness of the modification to the plasma chamber is evident: the TM$_{0,2,0}$ mode shows again a much higher electric field on

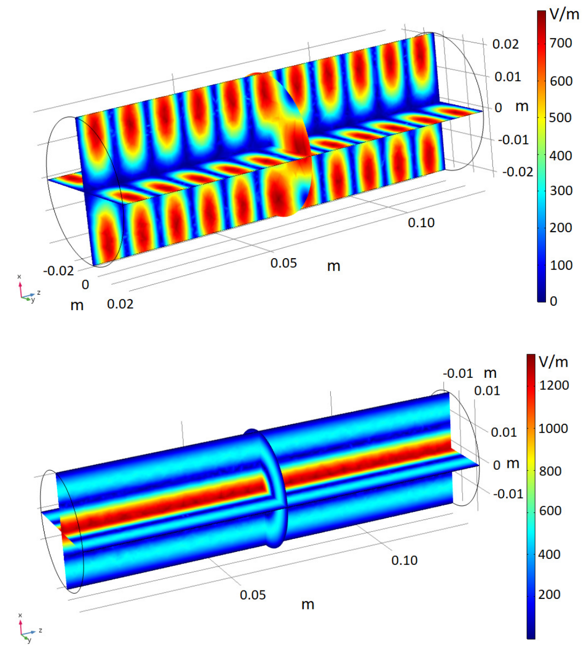

Figure 2: Electric field distribution calculated through the COMSOL®eigenmode solver: the present chamber with the TE$_{2,1,1}$ mode (top), the modified chamber with the TM$_{0,0,2}$ (bottom).

the plasma chamber axis, especially toward the extraction side, and in general a higher electric field compared to the TE$_{2,1,1}$ mode. After the vacuum-filled geometry simulations we included the plasma through the full-3D dielectric tensor, computed by MatLab®for each mesh point given by COMSOL®following the same approach used in [7]:

the plasma was described through the plasmoid/halo scheme [8], considering a dense plasma inside the resonance surface with $n_{plasmoid}=2.5\cdot10^{17}$ m^{-3}, and a rarified halo outside with $n_{halo}=n_{plasmoid}/100$. This time the mesh size used was not uniform, reaching $\lambda_0/10$ around the resonance surface. The results of the calculations for both frequencies are showed in Fig. 5 and summarized in Table 1: the power absorption at the resonance surfaces is evident in both cases but the modified geometry shows a higher electric field in a zone around the axis, especially at the extraction side. Table 1 shows that the modified geometry not only gives a better matching for the microwaves, but also a higher power ab-sorbed by the plasma (around 30% more compared to the present geometry). The difference in the amplitude of the electric field produced in the two analyzed cases is even more evident by looking at Fig. 6, showing the modulus of the electric field on the plasma chamber axis. For the present geometry (top part), the electric field at the resonances is not really different compared to the rest of the plasma chamber, while for the modified geometry (bottom part) two very high peaks are visible in correspondence of the resonances, with an absolute value three times higher compared to the present geometry.

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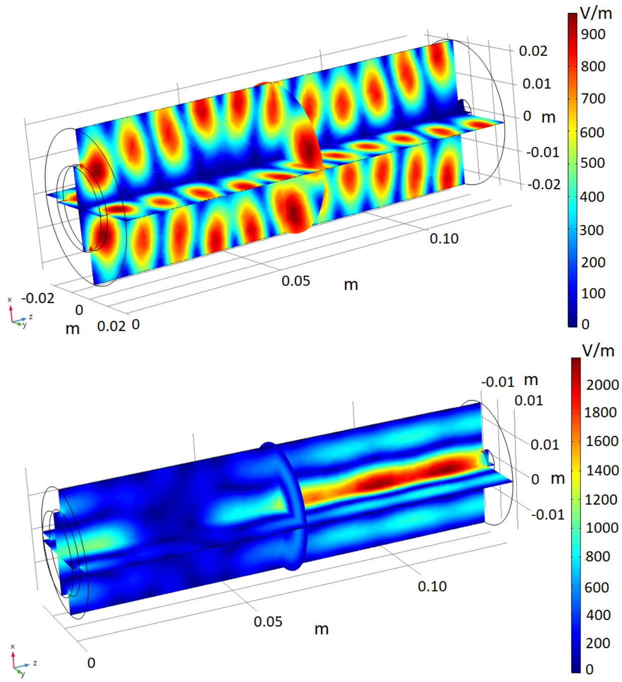

Figure 3: Electric field distribution calculated through the COMSOL®eigenmode solver including the injection and extraction holes: the present chamber with the $TE_{2,1,11}$ mode shifted at 14.428 GHz (top); the modified chamber with the $TM_{0,2,0}$ shifted at 14.432 GHz (bottom).

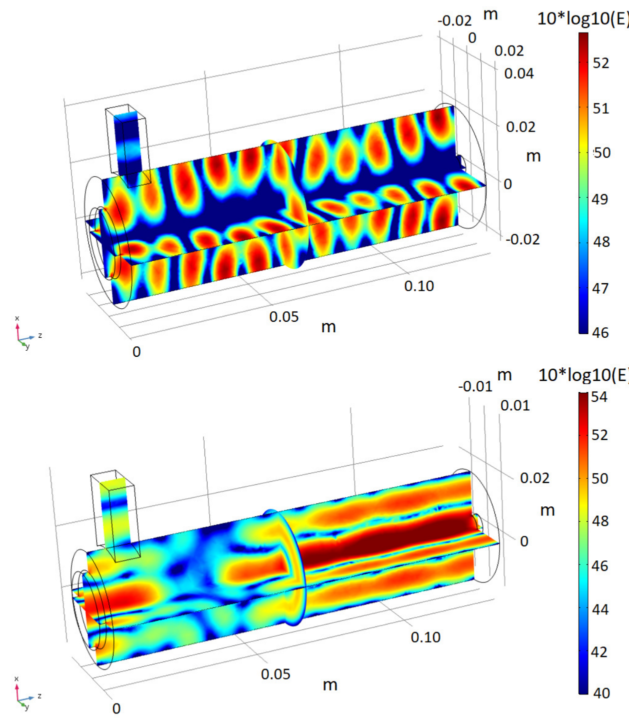

Figure 4: Electric field distribution in logarithmic scale calculated through the COMSOL®frequency domain solver: 14.428 GHz for the present chamber (top), 14.395 GHz for the modified chamber (bottom).

Table 1: Comparison between the two simulated geomteries including the plasma.

	Present Geometry	**Modified Geometry**
Frequency [GHz]	14.428	14.432
Simulated power [W]	100	100
Matched power [W]	69.2	91.7
Plasma absorption [W]	64.5	84.4

ELECTRONS DYNAMICS

The electromagnetic fields calculated for the two geometries were used to simulate the electrons dynamics, using a MatLab®code derived directly from the one developed by the INFN ions source group for ions [9]. With such a code we simulated the motion of 100000 electrons, whose starting conditions are located inside the resonance surface, with a time step $T_{step}=10^{-12}$ s and a total simulation time $T_{span}=4{\cdot}10^{-5}$ s: the calculations included both electromagnetic and magnetostatic fields, as well as electron-electron collisions and relativistic effects. By using an ad-hoc routine, the code stores particles positions at each time step in a 3D matrix reflecting the domain of the simulation divided in cells of 1 mm^3, creating an "occupation" map directly correlated to the electrons spatial density distribution. The projection on the xz plane of the maps for the two geometries is shown in Fig. 7: the present geometry is characterized by low field intensities in the near-axis region, which have been demonstrated to be prone for hollow-plasma generation, i.e. the plasma density is low where the electromagnetic field intensity is low as well. The electromagnetic simulations here performed, instead, is promising for a better RF power deposition in the axial region, allowing the formation of a denser and more uniform plasmoid.

CONCLUSIONS AND PERSPECTIVES

The electromagnetic study proposed consists of a cheap and effective modification of the plasma chamber geometry of the ion source LEGIS installed at INFN-LNL, to optimize the electromagnetic coupling to the plasma. The modification was validated by electromagnetic calculation carried out including the plasma through its 3D dielectric tensor, and the electrons dynamics under the resulting electromagnetic field, the magnetostatic field of the magnetic trap and electron-electron collisions. The $TM_{0,2,0}$ mode is able to create an intense electric field on the chamber axis, about three times higher compared to the one created by the $TE_{2,1,11}$ mode, leading to a higher power absorbed in the plasma volume and the formation of a much denser plasma. In principle such modification could be applied to similar geometries of any length. Such calculations will be verified in the next future by comparing the ion output of the LEGIS source before and after the proposed modification.

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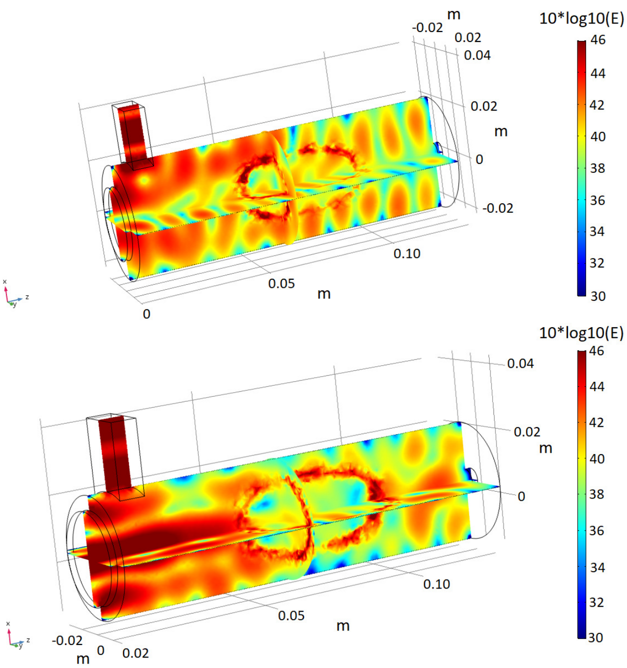

Figure 5: Electric field distribution in logarithmic scale calculated through the COMSOL® frequency domain solver and including the plasma: 14.428 GHz for the present chamber (top); 14.395 GHz for the modified chamber (bottom).

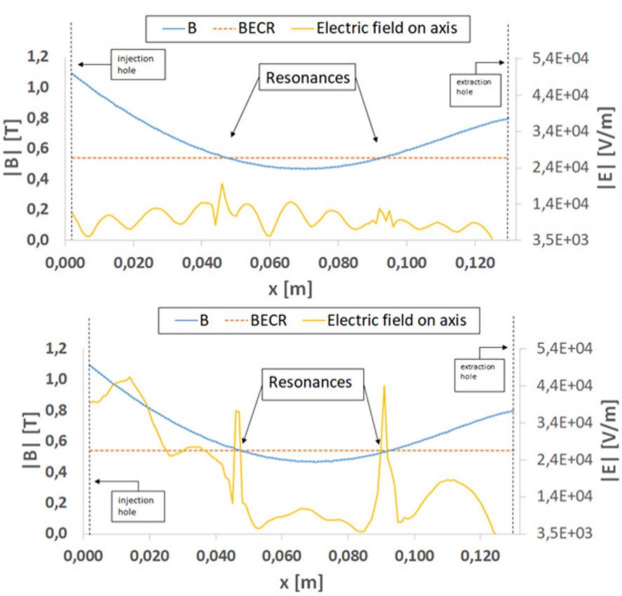

Figure 6: Modulus of the electric field on the plasma chamber axis: present geometry (top), modified geometry (bottom). The points corresponding to the two resonances are indicated by arrows.

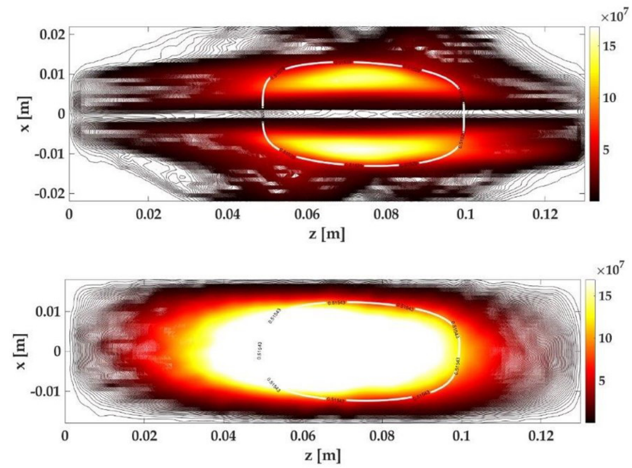

Figure 7: Projection on the xz plane of the occupation maps: present geometry (top) and modified geometry (bottom). The points corresponding to the resonance are indicated by the white dashed lines.

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