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Electromagnetic simulation of unconventional resonant cavities for magnetoplasmas

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Abstract

The design of resonant cavities, aimed at obtaining a desired electromagnetic field configuration, must take into account the geometry and the coupling between the cavity itself and the transmission line delivering the electromagnetic power to the structure. The design issues are even more challenging when the cavity is filled with an inhomogeneous and anisotropic medium. In this paper, we present an electromagnetic analysis, carried out by multiphysics simulations with COMSOL Multiphysics® and MatLab®, of conventional (cylindrical) and unconventional geometries for resonant cavities containing magnetically confined plasmas. The study has been applied in particular to Electron Cyclotron Resonance Ion Sources, with the aim at improving their performances.

1 Introduction

The Electron Cyclotron Resonance Ion Sources (ECRIS) [1] are nowadays the most effective devices that can feed the particle accelerators continuously and reliably way, providing high current beams of low and medium charge state ions and lower, but still important, beam current for highly charged ions. In such sources, a plasma is generated inside a high vacuum chamber and confined using a particular magnetic configuration called "B-minimum" structure. It is generated by the superposition of a hexapolar magnetic field (generating a radially varying field) and a mirror magnetic trap, that is a set of two or three coils (generating the axial magnetic field); the resulting magnetic field has the characteristic of growing from the center towards the periphery of the plasma chamber, and confines the plasma in the typical "star-shaped" structure [2]. The plasma is generated and sustained by microwaves (usually between 14 and 28 GHz) through a resonant interaction, called Electron Cyclotron Resonance, between a wave of frequency ν_{MW} and the cyclotron motion of the electrons in the magnetic field at an angular frequency ω_c: the condition for the resonance to take place requires identical frequencies $\nu_{MW} = \omega_c/2\pi$; considering the topology of the magnetic field, this condition depends on the local magnetic field and is met on the points of a closed "egg-shaped" surface, usually called ECR-resonance surface [3]. Being the plasma an anisotropic medium for wave propagation, the outcome of the resonant interaction depends on various parameters like the microwave frequency, the propagation with respect to the magnetic field and the plasma density [4]. Energetic electrons, generated by the ECR resonance, can create highly charged ions through stepwise ionizations: as a consequence, the higher the desired charge states q+ the higher has to be the time spent by the ion inside the plasma. The performances on an ECRIS, in terms of extracted beam current and charge states produced, strongly depend on the plasma density and energetic content that, in turn, depend on the electromagnetic field distribution excited inside the plasma vacuum chamber working as a resonant cavity. To be compatible in terms of overlap and shape with the cylindrical symmetry imposed by the magnetic system, usually the plasma chambers are multimodal cavities of a cylindrical shape: in this paper, we investigate the possibility to employ unconventional geometries with the aim at improving the microwave-to-plasma coupling, and so the ECRIS' performances. To this scope, we carried out an electromagnetic analysis, by joining COMSOL Multiphysics® and MatLab®, for studying resonant cavities containing magnetically confined plasmas. The physics case considered in this study is a real ECRIS, the one called "CAESAR" and installed at INFN-LNS [5], whose operating frequency is 14.5 GHz: to have the possibility of a direct comparison with experimental evidence we considered first its classical cylindrical vacuum chamber. Then, we designed a new geometry for an innovative resonator ion source, hereafter referred to as IRIS, that follows the shape imposed to the plasma by the magnetic field: both geometries are shown in figure 1.

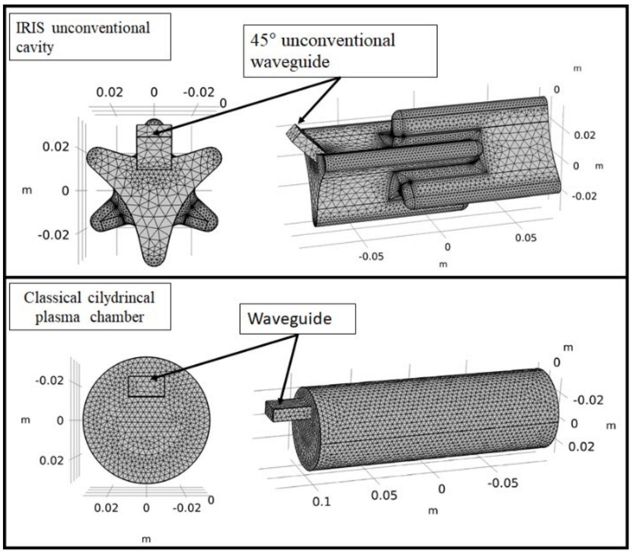

Figure 1. Model of the IRIS unconventional chamber (top); the classical cylindrical CAESAR cavity (bottom) implemented in COMSOL®.

The applied numerical approach is the following: as a first step, we studied the resonant modes of both vacuum and plasma filled cavities, by using the COMSOL Multiphysics® eigenmode solver. The same simulation was, then, repeated in the frequency domain, considering the external coupling i.e. the microwaves injected through rectangular waveguides into the empty cavity. Finally, both cavities have been studied by including the presence of plasma through its 3D dielectric tensor, whose matrix elements are calculated by MatLab® in each mesh point and used by COMSOL®. The comparison regarded not only the coupling between the cavities and the waveguides but, also, the total power absorbed by the plasma.

2 Simulation domain

Details about the geometries adopted in the presented numerical simulations are shown in figure 1 (conventional and unconventional geometry). The cylindrical plasma chamber of the CAESAR ion source has a radius of 32.5 mm and a length of 200 mm. Microwaves are off-axially injected from the endplate of the cylinder through a rectangular WR62 waveguide. While the unconventional IRIS cavity consists of two “three-brunches” stars rotated of 60° one concerning the other, that overlap in the middle of the plasma chamber. In this case, the waveguide has been positioned tilted 45-degree respect the cylinder longitudinal axis also to optimize the available space on the injection endplate flange (see figure 1). The code implemented a not uniform mesh size, with a maximum element size of $\lambda_0/6$ (where λ_0 is the vacuum wavelength) and a minimum of $\lambda_0/10$ in those points where the electric field intensity is higher due to the ECR resonance. The mesh size was chosen finding a compromise between the accuracy and computational costs.

3 Electromagnetic analysis

The electromagnetic analysis started with the computation of the resonant modes of both cavities with the Eigen mode solver, focusing on the range 14-16 GHz. As expected, both geometries behave as multimodal cavities, allowing 116 resonant modes in the considered frequency range for IRIS cavity and 154 resonant modes for the classical chamber. As an example, figure 2 shows the electric field distribution, in 10 logarithmic scales, for two resonant modes: for CAESAR, the $TM_{0,3,8}$ at 14.053; for IRIS, a resonant mode at 14.022 GHz similar to the TM2,2,9 for a cylindrical resonator with the same overall dimensions
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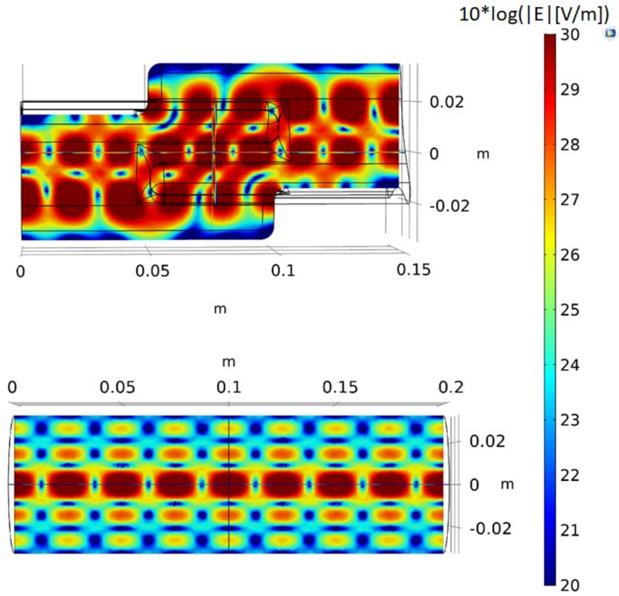

Figure 2. Electric field distribution in 10 logarithmic scale calculated through the COMSOL® eigenmode solver: 14.022 GHz for the IRIS chamber (top), 14.053 GHz for the CAESAR chamber (bottom).

After the Eigen mode analysis, the analysis moved to the Frequency domain solver, that is the study of the electromagnetic field distribution for specific frequencies. The analysis has been really extensive: in fact, we simulated 200 frequency in the range 14-16 GHz, injected through a rectangular WR62 waveguide with a power P = 100 W. The calculated electric field distribution, in 10 logarithmic scales, at 14 GHz is shown in figure 3 where we can see an intense electric field in the IRIS chamber, respect the field inside the CAESAR cavity.

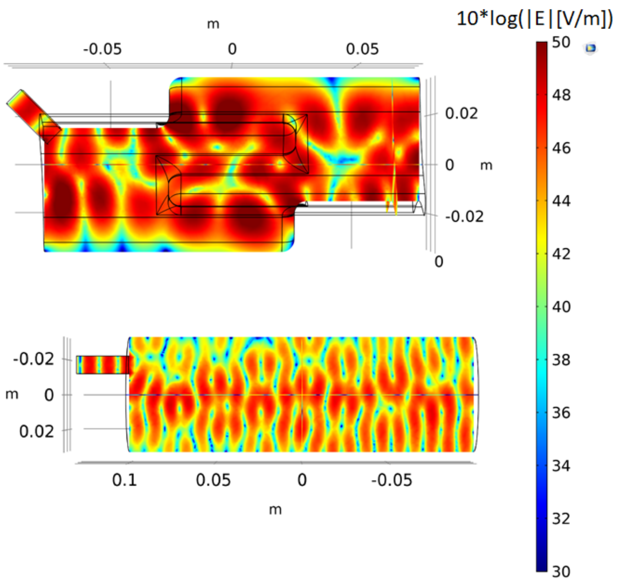

Figure 3. Electric field distribution in 10 logarithmic scales calculated through the COMSOL® frequency domain solver: 14 GHz for the IRIS chamber (top), the same frequency for the CAESAR chamber (bottom).

A quantitative figure of merit of the coupling between a transmission line and a resonant cavity is given by the S_{11} parameter: its analysis for all the simulated frequencies is shown in figure 4 for both the geometries. As can be seen, in the case of IRIS, microwaves are better matched to the cavity in almost all the considered frequency range.

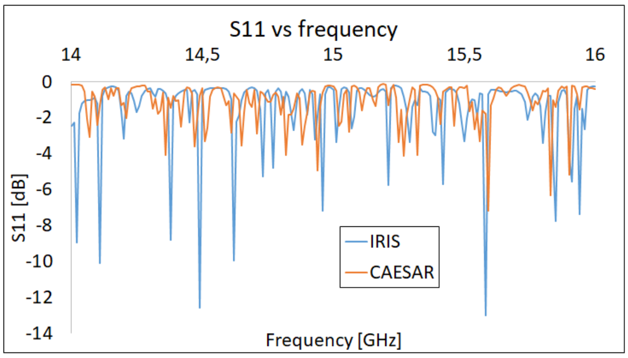

Figure 4. Coefficient of reflection S11 on the port of the W62 waveguide, calculated through the COMSOL®.

Finally, we simulated the presence of plasma through its fully-3D dielectric tensor. Its nine matrix elements have been calculated by MatLab® for each mesh point given by COMSOL® (for more details, see [6]). The plasma was implemented considering a plasmoid/halo scheme [7], i.e. subdividing the chamber volume into two regions one consisting in a dense core, called plasmoid, and enclosed inside the resonance surface, with a density $n_{plasmoid} = 2.5 * 10^{17} m^{-3}$, and a rarefied halo outside, with $n_{halo} = 2.5 * 10^{15} m^{-3}$. As an example, the electric field distribution (in 10 logarithmic scales) at 14 GHz is shown in figure 5: for both cases, the intensification of the electric field at the resonance is clearly visible, but for the IRIS geometry the area where this effect takes place is much wider. This could translate in a higher power transferred to the plasma for a given input power in the cavity, thus increasing the plasma energetic content.

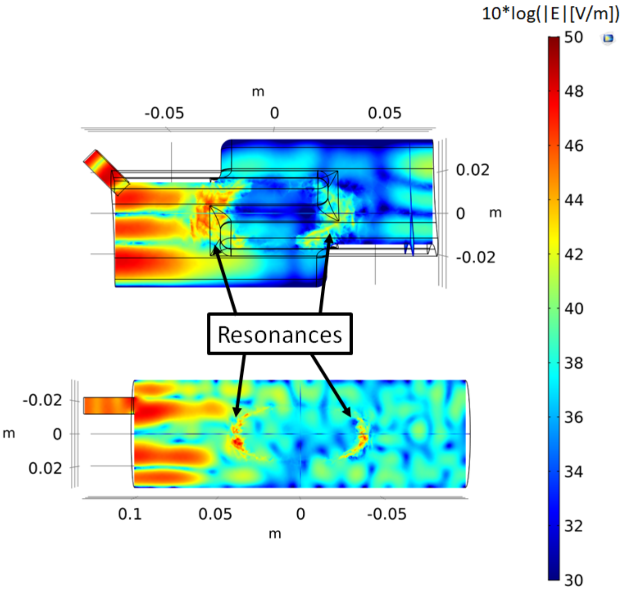

Figure 5. Electric field distribution in 10 logarithmic scales calculated through the COMSOL® frequency domain solver and including the plasma by MatLab®: 14 GHz for the IRIS chamber (top), the same frequency for the CAESAR chamber (bottom).

The results in terms of the $|S_{11}|$ are confirmed also when including the magnetized plasma in both cavities: in figure 6, it can be observed that when the cavities are filled with a plasma, the improvement of the S_{11} given by the proposed new geometry is even more evident than the empty-cavities case.

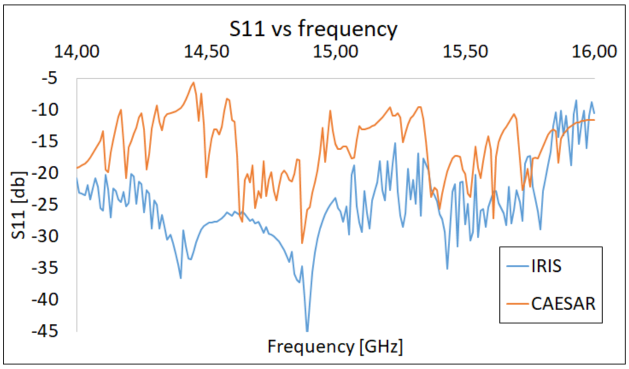

Figure 6. Coefficient of reflection S11 on the port of the W62 waveguide, calculated through the COMSOL® including the plasma by MatLab®.

A fundamental parameter that directly influences the plasma energetic content is the overall power absorption: it has been calculated for both geometries through the volume integral of the total dissipated power inside the chamber. The results are shown in figure 7: it can be seen that, except for the extremes of the considered frequency range, the IRIS geometry produces a higher power absorption coefficient that is almost flat over the frequencies. High and flat power absorption in a wide frequency range means easier tunability and higher flexibility of the ion source. It is worth noting the huge difference slightly above 14.5 GHz, i.e. very close to the CAESAR operating frequency.

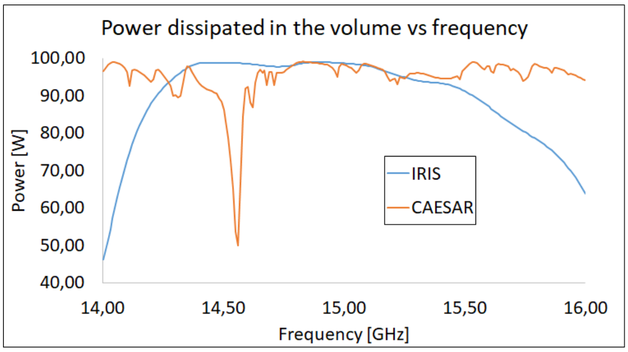

Figure 7. Comparison between power absorbed by the plasma in the CAESAR and IRIS chamber, calculated through the COMSOL® including the plasma by MatLab®.

For the sake of completeness, we calculated also the power loss on the wall of the cavities: results are shown in figure 8. Even if the losses are, in general, low, we can observe that with the new geometry they practically disappear, being always below the 2% of the total injected power.

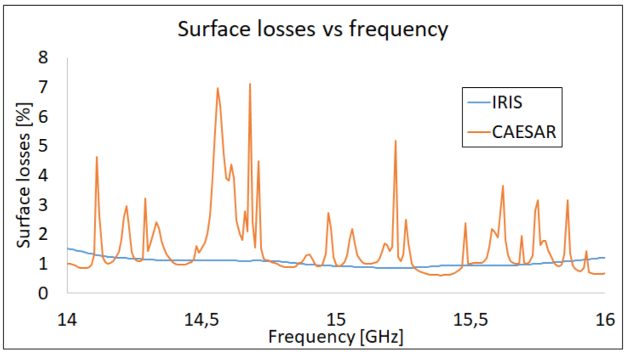

Figure 8. Comparison between power losses on the walls of the cavities in the CAESAR and IRIS chamber, calculated through the COMSOL® including the plasma by MatLab®.

4 Conclusions and perspectives

In this paper, we presented an electromagnetic study of an unconventional resonant cavity for magnetically confined plasmas. The comparison with the classical cylindrical geometry of the CAESAR ion source, installed at INFN-LNS, revealed that, by employing the proposed innovative geometry, it could be possible to boost the ion source performances by increasing the plasma energetic content for the same input microwave power. This would be obtained not only thanks to a higher microwave power that is effectively coupled into the plasma but also, in particular, to a higher microwave power absorbed by the plasma in a wider frequency range. As a further step, the design of the innovative geometry will be refined, to build a prototype to be tested at INFN-LNS.

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