

ELECTROMAGNETIC SIMULATION OF “PLASMA-SHAPED” PLASMA CHAMBER FOR INNOVATIVE ECRIS

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Abstract

The plasma chamber and injection system design play a fundamental role in ECRISs with the aim to obtain an optimized electromagnetic field configuration able to generate and sustain a plasma with a high energy content. In this work we present the numerical study and the design of an unconventionally-shaped cavity resonator that possesses some key advantages with respect to the standard cylindrical cavities, usually adopted in ion sources setups. The cavity geometry has been inspired by the typical star-shaped ECR plasma, determined by the magnetic field structure. The chamber has been designed by using the commercial softwares CST and COMSOL, with the aim to maximize the on-axis electric field. Moreover, a radically innovative microwaves injection system, consisting in side-coupled slotted waveguides, has been implemented, allowing a better power coupling and a more symmetric power distribution inside the cavity with respect to the standard rectangular waveguides. This new “plasma-shaped oriented” design could relevantly improve the performances of the ECRISs while making more compact the overall setup.

INTRODUCTION AND MOTIVATION

Microwave-to-plasma coupling in ECR Ion Sources is based on the matching of the injection waveguide to the plasma-filled cavity. The variation in the performances in terms of extracted current and charge states has been explained by taking into account the different patterns that the electromagnetic field assumes on the resonance surface [1, 2]. In the past years, various approaches to enhance ion source performances through an optimization of the plasma chamber shape [3] or through the use of improved microwave injection systems, have been studied and presented [4–7]. This paper describes the numerical modeling of a novel microwave cavity for plasma confinement whose geometry has been determined by the electron trajectories as they move under the influence of a B-minimum magnetic field. The new cavity shape promotes the excitations of electromagnetic modes that show a field maximum at its center; this could result in an increase of the power absorbed by the plasma and prevent the formation of the typical hollow plasma observed experimentally and demonstrated by numerical simulation [8]. Furthermore, due to the less occupied

radial volume, the employment of the presented cavity allows more space for the mid coils and thus a finer tuning of the confining magnetic field could be possible. The second part of the work describes an innovative microwave launching scheme that employs a slotted waveguide placed on the chamber outer wall. This radically new solution greatly improves the number of modes that can be efficiently coupled into the cavity, together with an improved electric field symmetry along the cavity axis. Moreover, the new microwave launch system allows more space on the end flanges of the plasma chamber that can be employed by other ancillary equipment, while offering a distributed and more homogeneous power transfer to the plasma compared to the classical axial injection scheme through rectangular waveguide.

PLASMA SHAPED CAVITY AND AXIAL MICROWAVE INJECTION

The presented “plasma-shaped” cavity is visible in Fig. 1, along with its dimensions. For the future experimental test on the CAESAR ECRIS setup [9], we set the cavity diameter d and length L equal to 48.5 mm and 150 mm respectively. The cavity geometry has been inspired by the typical star-shaped ECR plasma and is determined by the twisted B-minimum magnetic field structure [10] and also takes into account the electrons trajectories as they move under the influence of the magnetic field.

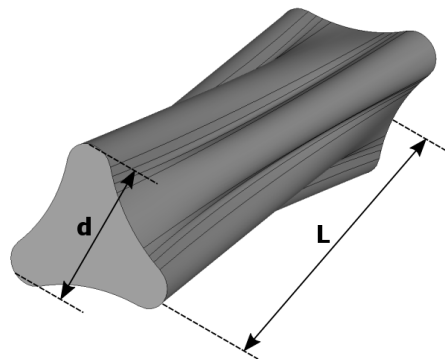


Figure 1: 3D model of the presented “plasma-shaped” cavity with its fundamental dimensions.

In order to study the new cavity driven behaviour, it has been connected to an axial feeding waveguide. Using the

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commercial simulator CST Studio Suite, its S-parameters have been calculated and compared to those of a cylindrical cavity with diameter $d = 63.5$ mm and length $L = 150$ mm (CAESAR cavity dimensions), fed by the same feeding configuration. The two geometries are visible in Fig. 2. In particular, both structures: a) consists of a vacuum solid with lossy metal boundary conditions, b) have been fed through a standard WR62 waveguide and c) have been simulated using the same mesh quality (curvature tolerance, number of mesh refinement steps, etc).

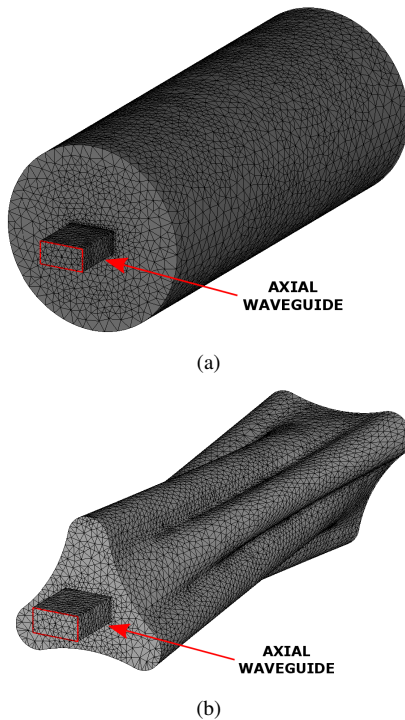


Figure 2: (a) standard cylindrical cavity and (b) “plasma-shaped” cavity models. Applied mesh and axial feeding waveguides are visible.

The performances of both structures have been observed in terms of S-parameters in the frequency range 14-14.5 GHz. Figure 3 shows the $|S_{11}|$ curve for the considered geometries. From the plots it can be seen that in the case of cylindrical cavity the modes inside the considered frequency range are not well adapted (i. e. not optimal power transfer from the feeding waveguide to the cavity). However, in the case of the “plasma-shaped” cavity, more modes are present inside the considered bandwidth and in particular the mode at the frequency of 14.304 GHz has the best coupling (≈ -15 dB). Moreover, the electric field is much more intense than the cylindrical case’ one, as can be seen in Fig. 4.

SLOTTED WAVEGUIDE ANTENNA DESIGN

In order to improve the microwave-to-cavity coupling and at the same time have a more uniform and symmetric axial electric field distribution, a slotted waveguide

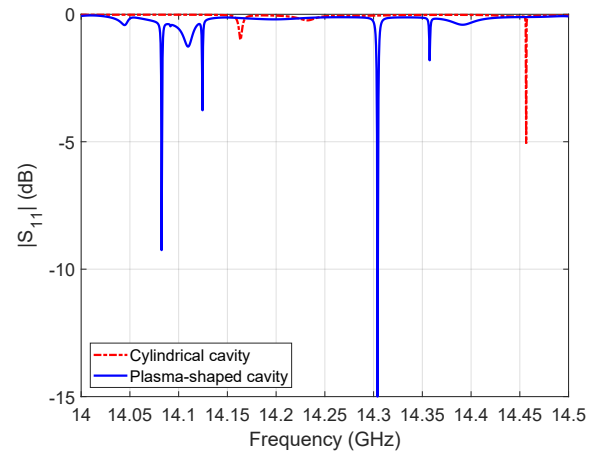


Figure 3: $|S_{11}|$ curve, inside the operational bandwidth of 14-14.5 GHz, for the standard cylindrical cavity and the “plasma-shaped” one.

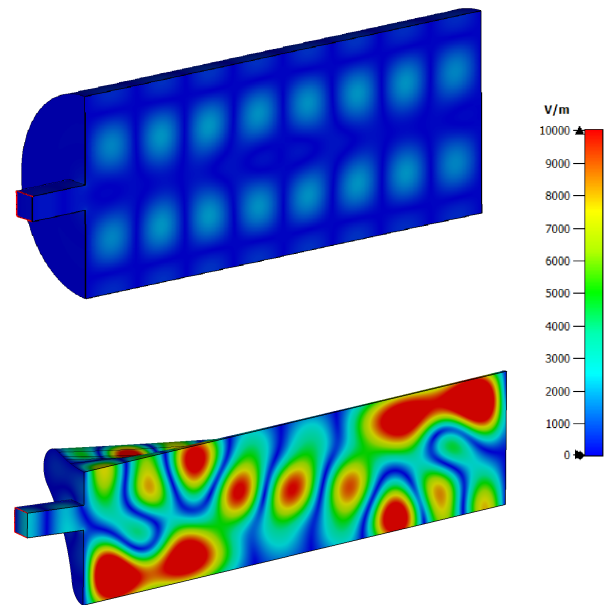


Figure 4: Electric field module plot on cavities slice: cylindrical cavity ($f_0 = 14.457$ GHz) vs. plasma-shaped cavity ($f_0 = 14.304$ GHz). The field has been normalized to the maximum value of 10 kV/m.

has been employed as the microwave injection system and its behaviour has been numerically characterized. Slotted waveguides find many applications in radar and communication systems due to their low-profile design requirements, mechanical robustness, good efficiency, relative ease of realization and wide operational frequency bandwidth [11–13]. The first step has been the design of a slotted waveguide antenna operating in free space. Defining the guided wavelength for the TE_{10} mode of the rectangular waveguide as $\lambda_g = \frac{c}{f} \frac{1}{\sqrt{1-c/(2af)}}$, where f is the operational frequency and a is the waveguide large side, the

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guidelines for the design of a slotted waveguide antenna can be found [14, 15]. In the numerical optimization of a slotted waveguide antenna, particular attention must be paid to its critical parameters, and in particular: the distance between the center of the last slot from the closing metallic wall or d_{short} , the width and length of the slots, w_{slot} and l_{slot} respectively. In general, the impedance bandwidth results inversely proportional to the slot number [16]. However, using a low number of slots has a negative impact on the efficiency, so a trade-off for this parameters needs to be chosen depending on the required performances. The antenna shown in Fig. 5 has been optimized through the use of CST. The operational bandwidth is 14.2-15.25 GHz with central frequency 14.7 GHz. We chose to employ eight slots with the scope to maximize the $|S_{11}|$ impedance bandwidth and to obtain an uniform radiation pattern. This value has also been chosen considering the available space along the cavity outer wall, equal to 150 mm. A tuning of the slot width or w_{slot} , a critical parameter that can affect the impedance bandwidth [16], has been performed: the calculated $|S_{11}|$ is shown in Fig. 6 for different slot width values. A good compromise between impedance bandwidth and efficiency has been found when $w_{slot} = 2$ mm.

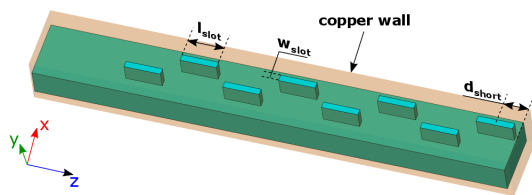


Figure 5: Slotted waveguide antenna model and fundamental parameters: slot length l_{slot} , width w_{slot} and distance from the short circuit d_{short} . The structure consists of an air volume enclosed into a copper block (orange object). The antenna is fed through a waveguide port, not visible in the figure.

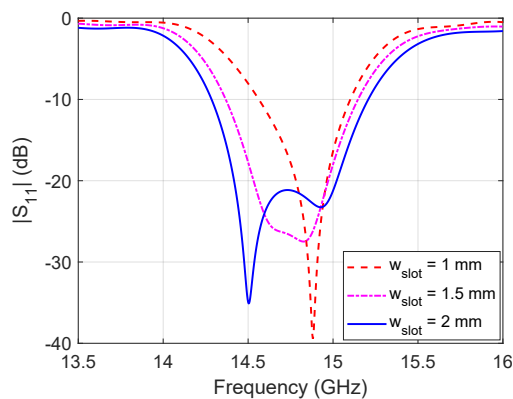


Figure 6: $|S_{11}|$ vs. slot width w_{slot} : it can be seen that this parameter affects the impedance bandwidth.

SLOTTED WAVEGUIDE INJECTION SIMULATIONS

The final step has been the coupling of the slotted waveguide to the cavities, as visible in Fig. 7. In the case of the “plasma-shaped” cavity, the slotted waveguide has also been twisted in order to follow the outer wall shape. Figure 8 shows the $|S_{11}|$ curves for both cavities with the

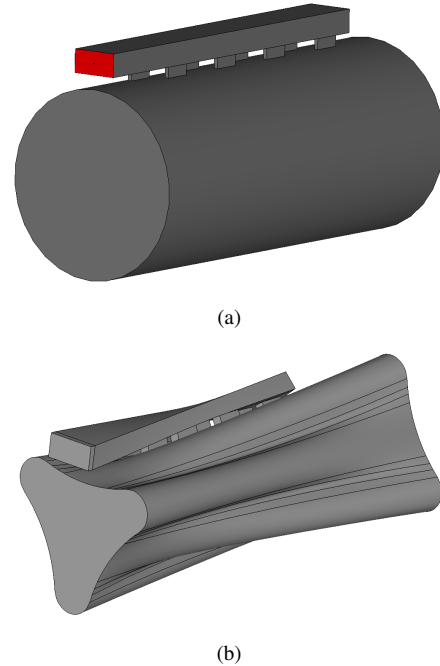


Figure 7: (a) standard cylindrical and (b) “plasma-shaped” cavities together with the adopted slotted waveguide microwave injection system. In (b) the slotted waveguide has also been twisted in order to follow the cavity profile.

slotted waveguide microwave injection system. From the plot it is immediately evident that the use of the new injection system results in a higher number of modes that are coupled inside the cavities with respect to the standard launch with an axial waveguide; this result could potentially improve ion source performances when applying the frequency tuning technique [17]. Figure 9 shows the electric field plot, at the frequency of 14.466 GHz, for the “plasma-shaped” cavity with the slotted waveguide injection. It can be observed that the field has a maximum at the cavity center and that the field profile has been symmetrized along the cavity axis with respect to the one of Fig. 4, evaluated inside the cavity with the axial waveguide injection. It has to be pointed out that, for the same slotted waveguide injection configuration, the cylindrical cavity presents a predominance of modes with off-axis electric field maximum. The symmetric field leads to a homogeneous power distribution from the multiple radiating waveguide slots to the cavity, with a potential advantage relative to the power absorption from the plasma. Moreover, the use of the slotted waveguide could in principle lead to an increase of the total employable power by creating

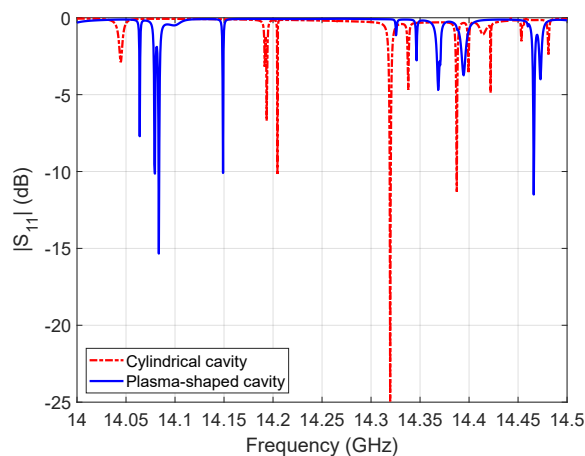


Figure 8: $|S_{11}|$ curve, inside the operational bandwidth of 14-14.5 GHz and with the slotted waveguide microwave injection system, for the standard cylindrical cavity and the “plasma-shaped” one.

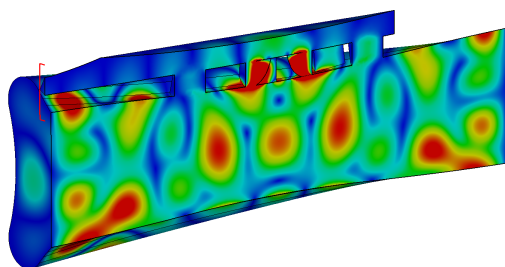


Figure 9: Electric field module plot at the frequency of 14.466 GHz for the “plasma-shaped” cavity with the slotted waveguide injection.

a splitted-injection system composed of multiple slotted waveguides placed radially with respect to the cavity [18].

CONCLUSION AND PERSPECTIVES

In this work, the numerical study of an innovative plasma cavity geometry, inspired by the typical star-shaped ECR plasma, has been presented. The new geometry presents some key advantages with respect to the classical cylindrical cavity; in particular, it is able to excite electromagnetic modes with electric field maximum located near the cavity axis, where the maximum of the resonant absorption takes place. In order to obtain a more symmetric field profile and an homogeneous power transfer to the plasma, a novel microwave injection setup based on a slotted waveguide has been introduced instead of the standard axial waveguide setup. Numerical results show that the new injection system greatly improves the excited modes inside the frequency band of interest, which could be useful in ion source frequency tuning operations. Moreover, the use of the “plasma-shaped” cavity in conjunction with the slotted waveguide results in the symmetrization of the excited modes: this could allow a more uniform power transfer to the plasma when a mode with electric field maximum along the

cavity axis is excited, as in the case of the presented geometry. The innovative cavity geometry plus the new microwave injection system solution also releases space from the main injection flange exploitable for other ancillaries.

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