URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Geometry optimization of ECRIS plasma chamber

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Abstract

In the cylindrical resonant cavities of Electron Cyclotron Resonance Ion Sources (ECRIS) microwave fields are used to generate and sustain the plasma. The design of resonant cavities and the related microwaves injection lines play a key role in the creation of intense electromagnetic fields, to generate and sustain the magnetized plasma. This paper presents an innovative geometry, as an alternative to the conventional cylindrically shaped plasma chamber, whose aim is the improvement of the microwave-to-plasma coupling, and the consequent optimization of the on axis electric field. The geometry has been numerically validated by joining COMSOL Multiphysics®, for the calculation of the electromagnetic fields and MatLab® to implement the plasma through its 3D dielectric tensor. The results are very promising and could be applied to any ECRIS.

1 Introduction

There are many ways to create ion beams but the Electron Cyclotron Resonance Ion Sources (ECRIS) [1] are the most effective device to produce high intensities of medium-high charge states. In such sources, a plasma is created and sustained inside a plasma chamber, working as a resonant cavity, where the interaction between microwaves and electrons through the electron cyclotron resonance determines the stability of the plasma and the output of the ion source, in terms of intensity and charge states produced. The electrons are magnetically confinement by an axial magnetic field (generated by two or more coils) and a radially varying field (generated by a hexapole). The superposition of these two fields is called "B-minimum" configuration and can confine a plasma, impressing the typical "star-shaped" structure. Considering the particular topology of the magnetic field (the intensity increases going from the centre of plasma chamber towards the periphery), the resonant interaction, called Electron Cyclotron Resonance (ECR), takes place in specific points forming an egg-shaped surface, called resonance surface. Many techniques have been developed so far to improve the performances of the ECRIS: first of all the use of higher and higher frequencies and magnetic fields, that often implies the development of expensive and technologically complex devices. Another possibility is the injection of two close or well-separated frequencies (respectively TFH [2] and TCFH [3]), as well as the fine-tuning of a single frequency, known as frequency tuning effect [4]. The main aim of those techniques is to increase the electrons density and energy by optimizing the power absorption by the microwave field. Another way is the modification of the plasma chamber geometry to produce an intense electromagnetic field in those points where the ECR resonance takes place. This paper presents the optimization of the innovative geometry presented to the in a previous work [5]. In that case, the geometry consisted of two “three-branches” stars rotated of 60° one concerning the other, that starting from the extremities of the plasma chamber overlap in the middle point. This geometry will be identified as IRIS-OLD in the following. Its evolution, object of the present paper and identified as IRIS-NEW, differs from the previous version for two main reasons:
1) the new geometry has fewer edges, so it is easier to be machined through 3D printing;
2) the new shape allows a further increase of the electric field in the centre of the plasma chamber.
The geometry has been studied with the electromagnetic solver COMSOL Multiphysics® for simulating the electromagnetic fields, and MatLab® to implement the 3D dielectric tensor of the plasma. The CAESAR setup, an ECRIS installed at INFN-LNS [6], whose operating frequency is 14.5 GHz, has been used to compare the results obtained. The geometry of CAESAR consists of a classical cylindrical plasma chamber: its geometry and those of the two versions of IRIS (OLD and NEW) are shown in Figure 1.

2 Simulation domain

CAESAR has a classical cylindrical plasma chamber with a radius of 32.5 mm and a length of 200.0 mm and an axial injection for the microwaves. The two versions of IRIS reflect the shape impressed to the plasma by the magnetic trap. The microwaves injection waveguide has been tilted of 45 degrees respect to the plasma chamber axis. The IRIS-NEW geometry differs from the previous version for the fact that the three branches of both stars extend all along the plasma chamber. Furthermore, the volume occupied

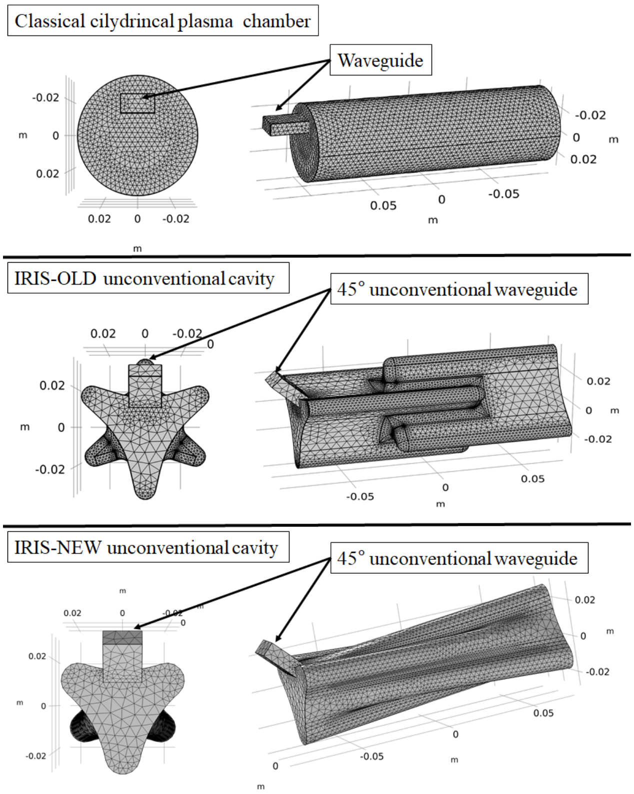

Figure 1. Model of the classical cylindrical CAESAR cavity (top); the IRIS-OLD unconventional chamber (middle) and the IRIS-NEW unconventional chamber (bottom) implemented in COMSOL Multiphysics®.

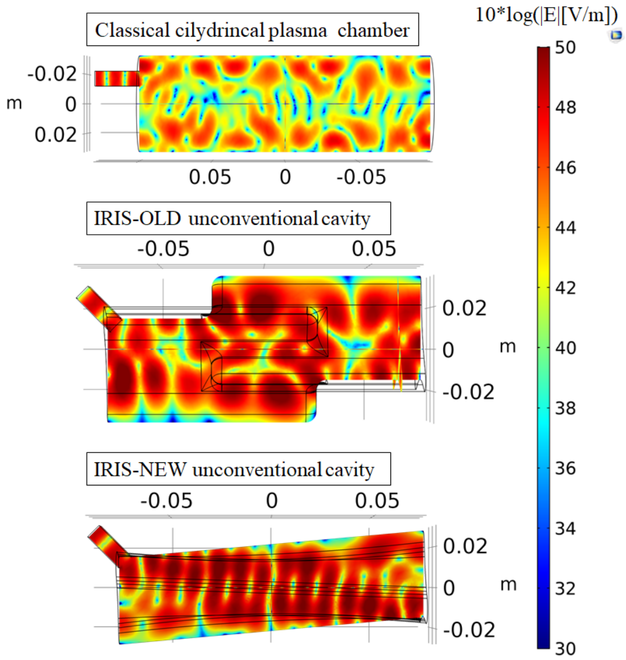

Figure 2. Electric field distribution, in base-10 logarithm, calculated through the COMSOL Multiphysics® frequency domain solver: the CAESAR chamber (top), the IRIS-OLD cavity (middle) and the IRIS-NEW chamber (bottom) at 14.5 GHz frequency.

in the middle of the plasma chamber is less, thus allowing more space for the magnetic structure, with the possibility of a finer tuning of the magnetic field. The simulations were implemented with a not uniform mesh (see figure 1), 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 intensifies. The boundary condition applied to the plasma chamber wall was PEC, to absorb all the outgoing wave energy without any impedance mismatch.

3 Electromagnetic analysis

As described in [5], the electromagnetic analysis started with the study of the three geometries (CAESAR, IRIS-OLD and IRIS-new) with the Frequency-domain solver, that is the study of the behaviour of specific frequencies considering the resonant cavity and the waveguide RF excitation port. The analysis has been really extensive: in fact, we simulated 100 frequencies in the range 14 - 15 GHz with a power P = 100 W. This range of frequencies was chosen considering a range of +/- 500 MHz to the CAESAR operating frequency of 14.5 GHz. Figure 2 shows the electric field distribution, in base-10 logarithm, at 14.5 GHz: we can observe a wider area showing intense electric fields for IRIS-NEW on-axis of the plasma chamber compared to the previous geometries. Using MatLab® with COMSOL Multiphysics® we included the plasma through its full-3D dielectric tensor for each mesh point given by COMSOL®, following the same approach used in [7]. The plasma was described through the plasmoide/halo scheme [8], considering a dense plasma inside the resonance surface with $n_{plasmoid} = 2.5 * 10^{17}\ m^{-3}$, and a rarefied halo outside with $n_{halo} = n_{plasmoid}/100$. Figure 3 shows the electric field distribution in log scale for the two geometries at the frequency of 14.5 GHz. The power absorption at the resonance surfaces is evident in all the cases but the IRIS geometries show a higher electric field in a zone around the axis, especially around the plasma chamber axis. That is because the new geometry allows increasing the electric field in the centre of the plasma chamber instead of on the walls of the cavity.
The reflection parameter S11 indicates the coupling between a transmission line and a resonant cavity. Figure 4 compares the results obtained with CAESAR and the two IRIS geometries. For both IRIS plasma chambers, microwaves are better matched to the cavity in the entire frequency range. In particular, for IRIS-NEW the S11 coefficient doesn't show any dependence from the frequency. Moreover, in the new shape, the S11 is almost always under -30 dB, that is coupling at 99.9 %. Another fundamental parameter to be analyzed is the power absorbed by the plasma. COMSOL Multiphysics® calculates the volume integral of the total dissipated power inside the chamber, whose results are compared in Figure 5 for the three geometries. It can be seen that with IRIS-NEW the amount of power transferred to the plasma chamber is higher in the entire

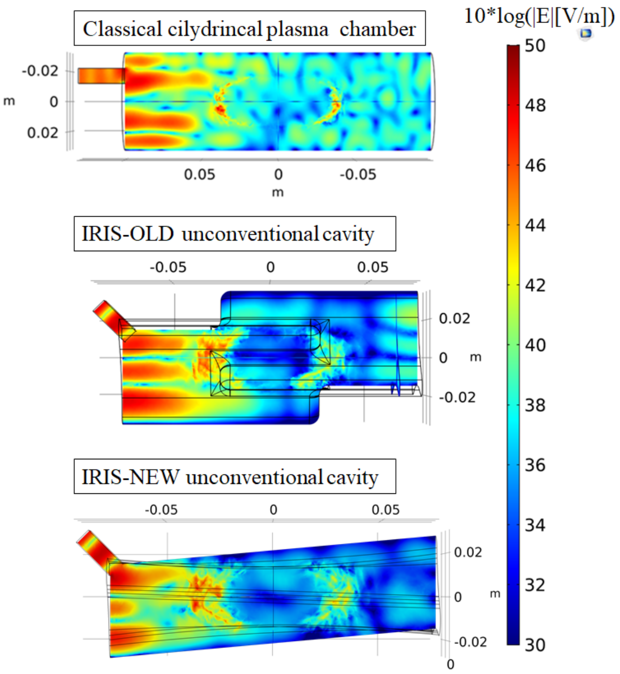

Figure 3. Electric field distribution, at 14.5 GHz, in base-10 logarithm, calculated through the COMSOL Multiphysics® frequency domain solver and including the plasma through MatLab®, inside the CAESAR (top), the IRIS-OLD cavity (meaddle) and IRIS-NEW plasma chamber (bottom).

frequency range considered, thus filling the gap between CAESAR and IRIS-OLD at lower frequencies.

4 Conclusions and perspectives

This paper presented an electromagnetic study of an unconventional resonant cavity for ECR Ion Sources. The results of the simulations show an improvement of IRIS-NEW geometry respect the classical plasma chamber CAESAR and the first IRIS chamber shape, allowing a better coupling between the waveguide and the plasma chamber and a higher power absorbed by the plasma in a wide frequency range. The presented study opens the way to a new design for the plasma chambers of ECR Ion Sources. A further improvement of the microwave injection system is presently under evaluation. Subsequential, the engineering phase for the realization of a prototype will start with the first real measurement tests at INFN-LNS.

5 Acknowledgements

The authors wish to thank the 3th Nat. Comm. of INFN, under the PANDORA Gr3 Grant, for the financial support. Part of this work has been carried out within the Grant73/IRIS project, also supported by INFN (Italian patent pending n. 102020000001756). The authors wish also to thank Eng. L. Ferrari for his support in producing the 3D model of the IRIS plasma chamber.

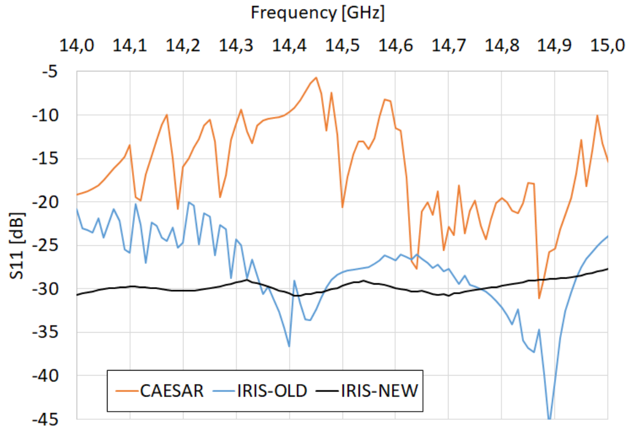

Figure 4. Coefficient of reflection S11 on the port of the WR62 waveguide, calculated through the COMSOL Multiphysics® including the plasma by MatLab®, for CAESAR, IRIS-OLD and IRIS-NEW geometry.

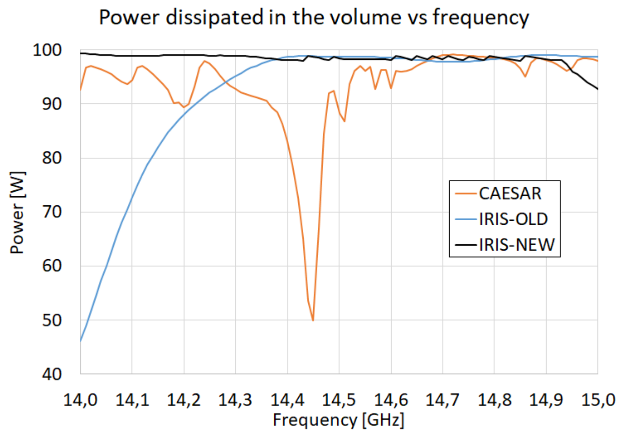

Figure 5. Comparison between power absorbed by the plasma in the CAESAR, IRIS-OLD and IRIS-NEW plasma chamber, calculated through the COMSOL Multiphysics® including the plasma by MatLab®.

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