IL NUOVO CIMENTO **44 C** (2021) 149
DOI 10.1393/ncc/i2021-21149-7

Communications: SIF Congress 2020

Electromagnetic simulations of plasma chambers in ECR ion sources: Unconventional designs and microwave injection

C. S. Gallo(1)(2)(*), O. Leonardi(3), G. S. Mauro(3), A. Pidatella(3), F. Russo(3), G. Sorbello(3)(4), G. Torrisi(3), A. Galatà(1) and D. Mascali(3)

(1) *INFN, Laboratori Nazionali di Legnaro - Legnaro PD, Italy*
(2) *Dipartimento di Fisica e Scienze della Terra, Università di Ferrara - Ferrara, Italy*
(3) *INFN, Laboratori Nazionali del Sud - Catania, Italy*
(4) *Dipartimento di Ingegneria, Università degli Studi di Catania - Catania, Italy*

received 14 January 2021

Summary. — 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 inside Electron Cyclotron Resonance Ion Sources (ECRIS). 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 inside ECRIS. 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 or, in general, magnetic traps.

1. – Introduction

Electron Cyclotron Resonance Ion Sources (ECRIS) [1] are the most effective device to produce and inject multiply charged ion beams inside particle accelerators. In such sources, a plasma is created and sustained inside a cavity (called plasma chamber) through a resonant interaction between microwaves (typically between 14 and 28 GHz) and electrons moving in a particular magnetic configuration called B-minimum structure. Energetic electrons are thus created and produce ionization of a background gas. The magnetic field is generated by superimposing the one created by two or more coils (generating the axial magnetic field) and the one generated by a hexapole (generating a radially varying field): the overall effect is a magnetic field that increases going from the centre towards the periphery of the plasma chamber and can confine a plasma impressing the typical "star-shaped" structure. The resonant interaction, called Electron Cyclotron Resonance (ECR), takes place in those points of plasma chamber where the microwave frequency equals the electrons Larmor frequency: considering the particular magnetic structure, such points form an egg-shaped surface, usually called resonance surface. The performances of an ECRIS could be improved by several means: first of all the use of

(*) E-mail: `carmelo.gallo@lnl.infn.it`

higher and higher frequencies and magnetic fields, which often implies the development of expensive and technologically complex devices. Other methods consist in optimizing the energy transfer to plasma electrons by microwaves: several techniques have been developed so far, like the two frequency heating (TFH) [2], the two close frequency heating (TCFH) [3], or the frequency tuning [4]. All the above-mentioned techniques are applied to plasma chambers of cylindrical shape. This paper presents an innovative approach consisting of the modification of the plasma chamber geometry to produce an intense electromagnetic field in those points where the ECR resonance takes place. The proposed geometry reflects the shape impressed on the plasma by the external magnetic field and has been numerically studied by joining COMSOL Multiphysics®, for the electromagnetic calculations, and MatLab®, to implement the 3D dielectric tensor of the plasma.

2. – Simulation domain

To benchmark the improvements brought by the proposed geometry, hereafter called IRIS, we used the ECR ion source CAESAR, installed at INFN-LNS [5], as physic case: its operating frequency is around 14.50 GHz and the plasma chamber has a conventional cylindrical shape. Both geometries are shown in fig. 1: CAESAR has a plasma chamber with a radius of 32.5 mm and a length of 200.0 mm, with an injection in the direction parallel to the cavity axis for the microwaves through a rectangular WR62 waveguide. IRIS reflects the shape impressed to the plasma by the magnetic field and the microwaves injection waveguide has been tilted 45 degrees to the plasma chamber axis. Both geometries have been implemented in COMSOL Multiphysics® using a non-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 intensifies due to the ECR resonance. The boundary conditions applied to the plasma chamber wall were Perfectly Conducting Boundary and the initial value of the electric fields was set to zero in all the volume of the simulation.

3. – Electromagnetic analysis

The electromagnetic analysis started with the study of the two structures with the eigenmode-domain solver, which is considering them as ideal cavities, without any hole, and finding the resonant modes close the operative frequency (14.5 GHz). The resonance mode, close to the operative frequency, is the $TM_{3,2,3}$ modes for the CAESAR chamber and the $TE_{4,2,5}$ modes for the IRIS geometry. The analysis then moved to the frequency-domain solver, which is the study of the behaviour of specific frequencies considering both geometries. The electromagnetic analysis consisted of comparing the fields generated

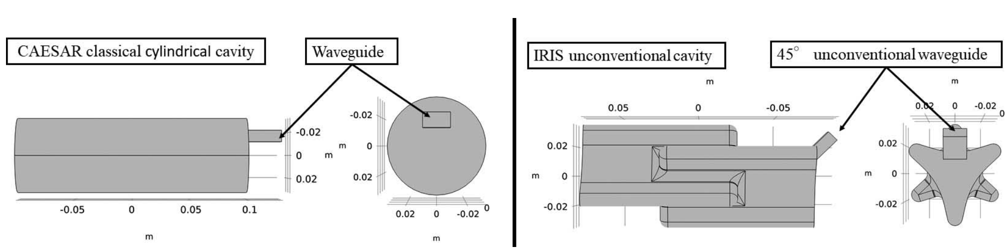

Fig. 1. – The conventional plasma chamber of the CAESAR source (left); the proposed unconventional geometry of IRIS (right).

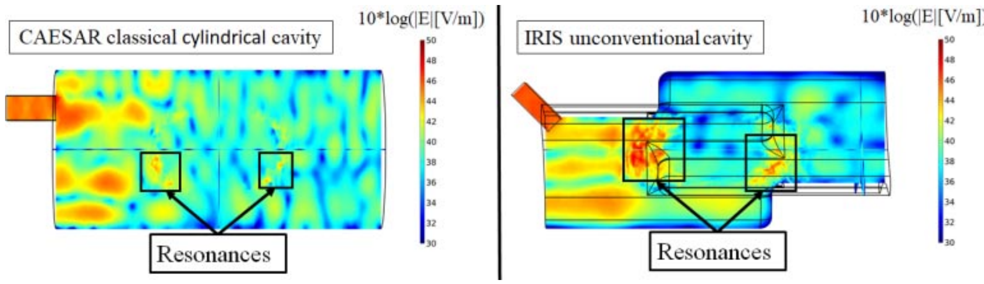

Fig. 2. – Electric field distribution, at 14.5 GHz, in 10 logarithmic scales, calculated through the COMSOL Multiphysics® frequency domain solver and including the plasma through MatLab®, inside the CAESAR (left) and IRIS plasma chamber (right).

inside the two geometries at 14.5 GHz, considering a microwave power of 100 W. The plasma was described following the plasmoid/halo scheme [6, 7], which is a dense core (the plasmoid), concentrated inside the resonance surface and a rarified halo outside. The value of the density in the two regions was chosen as $n_{plasmoid} = 2.5 \times 10^{17}\,\mathrm{m}^{-3}$ and $n_{halo} = 2.5 \times 10^{15}\,\mathrm{m}^{-3}$: the plasma has been implemented in the electromagnetic solver through its 3D dielectric tensor calculated with MatLab®. The parameters taken into consideration were the electric field distribution, the microwave power matched to the cavity (the difference between the simulated power and the power reflected at the waveguide input) and the one absorbed by the plasma. Figure 2 shows the electric field distribution in log scale for the two geometries: it can be seen how the IRIS geometry can create a much higher electric field in those points corresponding to the ECR resonance around the plasma chamber axis. The effect is even clearer looking at fig. 3, showing the modulus of the electric field along the plasma chamber axis, where the ECR resonance takes place in two specific points: the CAESAR geometry (left part of fig. 3) does not show a real intensification of the electric field at the resonances, compared to the rest of the plasma chamber, while for the IRIS geometry (right part) we can observe two evident intensifications. In particular, the absolute value of the electric field in those two points is, respectively, six and four times higher compared to the CAESAR geometry. Table I summarizes the results about the power coupled to the cavity and then absorbed by the plasma: this last parameter has been calculated through the volume integral of the total dissipated power inside the chamber. It can be seen that the amount of power transferred to the plasma chamber is comparable in the two cases, but in the case of the IRIS geometry it is almost totally absorbed by the plasma (around 20% higher power absorbed compared to the conventional geometry).

4. – Conclusions and perspectives

This work presented an alternative way to boost the performances of ECRIS, by optimizing the geometry of the plasma chamber. It has been demonstrated that the proposed IRIS geometry has a better RF power deposition in the direction parallel to the cavity axis. Even though the power transferred to the plasma chamber is similar in the two geometries, a higher electromagnetic field can be produced on the resonance surface. This leads to a higher power absorbed by the plasma for the same input power, compared to the conventional cylindrical geometries. These results open the way to a

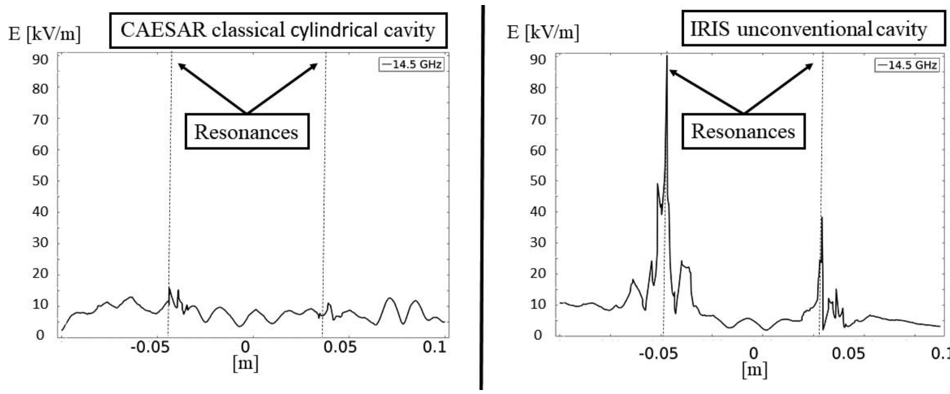

Fig. 3. – Modulus of the electric field along the plasma chamber axis: CAESAR geometry (left), IRIS geometry (right). The points corresponding to the two resonances are indicated by arrows.

Table I. – *Comparison at 14.5 GHz between the two simulated geometries including the plasma.*

	CAESAR	IRIS
power simulated [W]	100	100
power matched [W]	84.6	89.4
power plasma absorption [W]	68.9	82.1

new field for ion sources and magnetic trap optimization: the construction of a prototype and its test at INFN-LNS is foreseen for the next future, to validate the calculations' results.

* * *

The authors wish to thank the 3rd 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 No. 102020000001756). The authors wish also to thank Eng. L. Ferrari for his support in producing the 3D model of the IRIS plasma chamber.

REFERENCES

[1] Geller R., *Electron Cyclotron Resonance Ion Sources and ECR Plasmas* (IOP, Bristol) 1996.
[2] Xie Z. Q. and Lyneis C. M., *Rev. Sci. Instrum.*, **66** (1995) 4218.
[3] Rácz R. *et al.*, *JINST*, **13** (2018) C12012.
[4] Celona L. *et al*, *Rev. Sci. Instrum.*, **79** (2008) 023305.
[5] Celona L. *et al*, *ECR ion source developments at INFN-LNS, 21st International Workshop on ECR Ion Sources, Niznhy Novgorod, Russia, 24–28 August 2014* (oral talk) `http://accelconf.web.cern.ch/AccelConf/ECRIS2014/html/author.htm`.
[6] Galatà A. *et al*, *Rev. Sci. Instrum.*, **87** (2016) 02B505.
[7] Ivanov A. A. and Wiesemann K., *IEEE Trans. Plasma Sci.*, **33** (2005) 1743.