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Electromagnetic Simulation of Unconventional Resonant Cavities for Magnetoplasmas

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Outline

1. Introduction to ECR;
2. Unconventional resonant cavities for magnetoplasmas of ECRIS;
3. Case study;
4. Systems simulations;
5. Results;
6. Conclusion.

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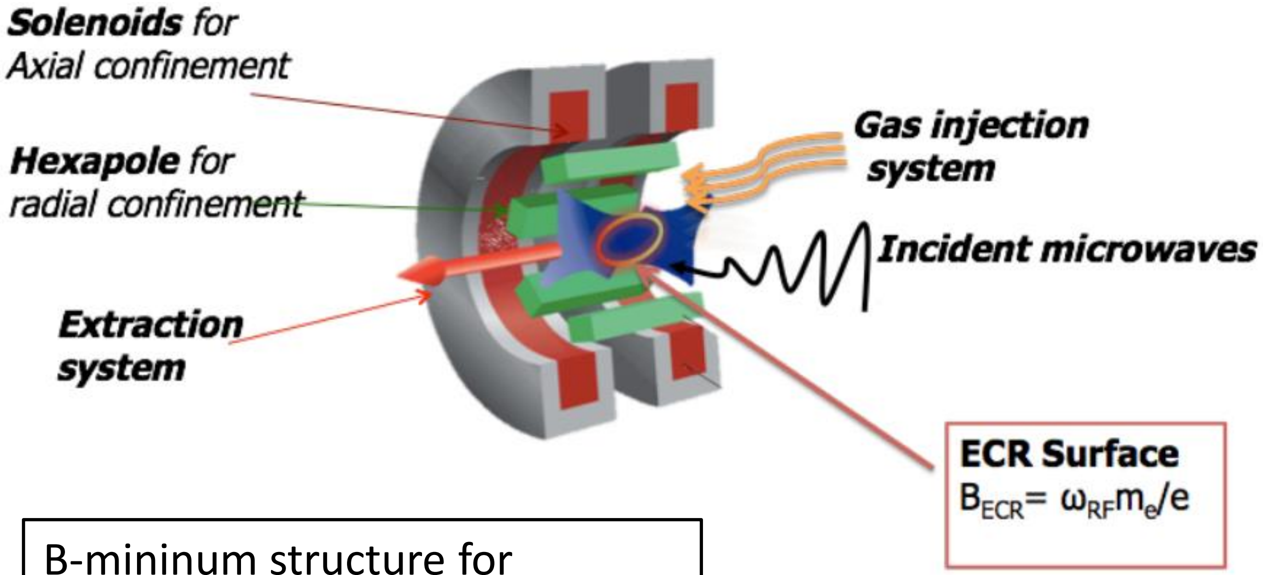
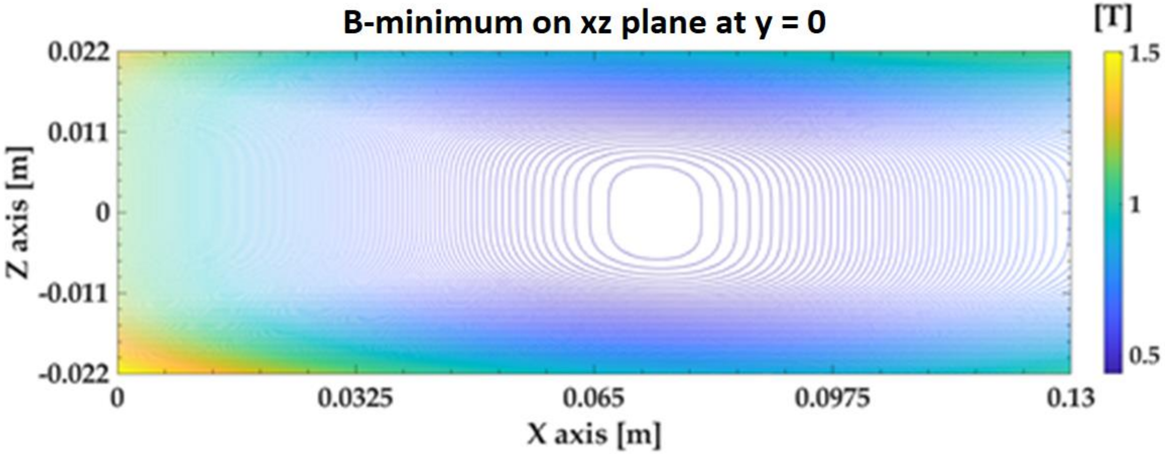
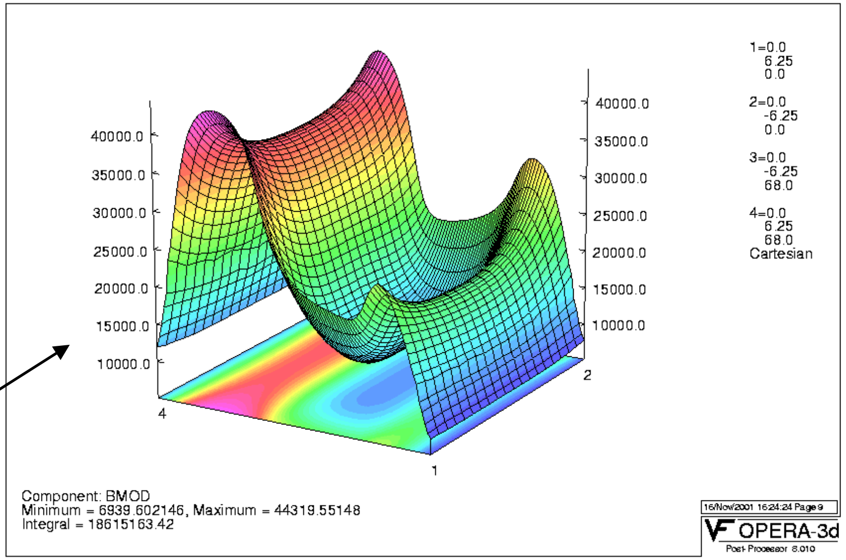
Magnetically confined Plasmas







B-mininum structure for electrons and ions confinement.

Magnetic mirror for axial confinement

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Magnetic system and frequency roles

- ***1987*** **Geller's scaling laws:**

$$I \propto \omega^{2} M^{-1}$$

$$q_{opt} \propto \log(B^{1.5})$$

- ***1990 High B-mode concept (Ciavola & Gammino)***

It doesn't conflict with Scaling Laws, but it limits their efficiency to high confined plasmas ***14GHz, 18 GHz, 28GHz confirmations***

$$\frac{B_{\max}}{B_{ECR}} > 2$$

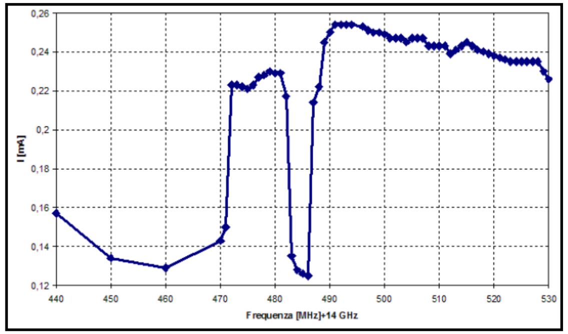
- ***2000 ECRIS standard model***

$$\begin{cases} B_{inj} \approx 3\, B_{ECR} & or\ more\ if\ possible \\ B_{rad} \geq 2\, B_{ECR} & (on\ plasma\ chamber\ wall) \\ B_{ext} \approx B_{rad} & competitive\ process... \end{cases}$$

Techniques to increase the ECR ion source performances

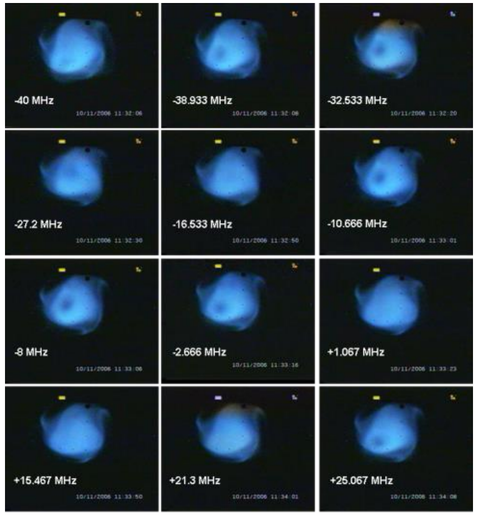
Frequency Tuning*

SUPERNANOGAN @ CNAO*



*G. Ciavola et al., proc. EPAC08

CAPRICE source @ GSI*



*L. Celona et al., Rev. Sci. Instrum. **79**, 023305 (2008).

Two Frequency Heating

Two Close Frequency Heating

Alternative approach

Electromagnetic study to optimize the geometry of the plasma chamber

↓

Maximization of the electromagnetic power absorption in specific zones on the resonance surface from which ions are extracted.

↓

Boost of the ion source performances for the same input microwave power!!

Case study

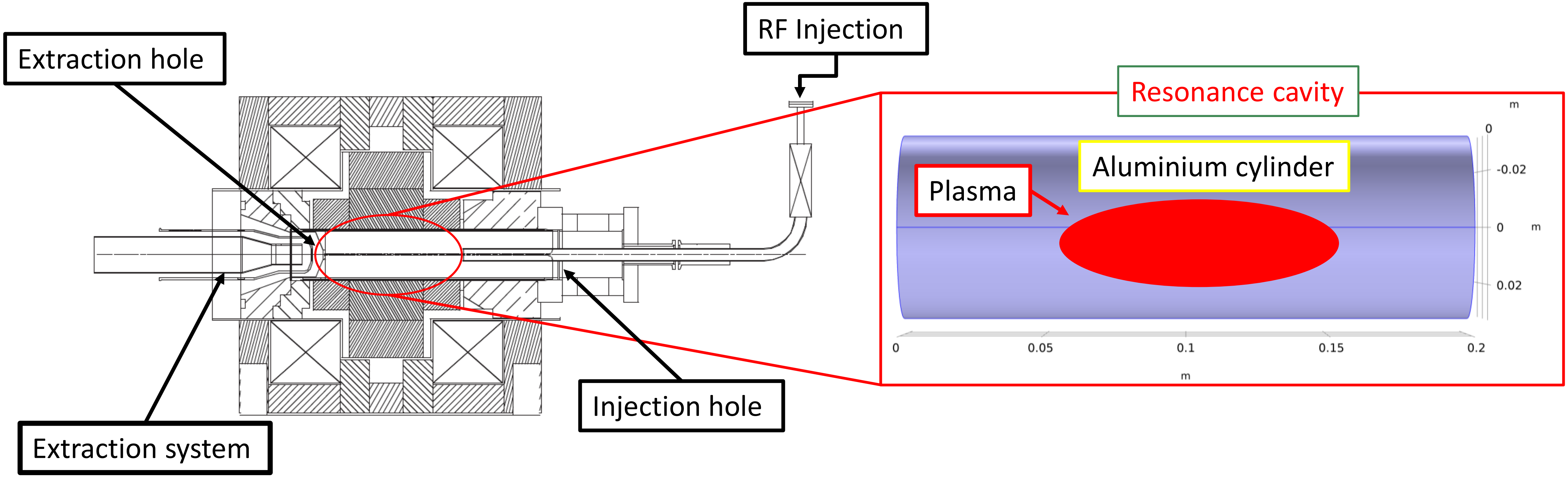
CAESAR Source @ INFN-LNS

Produce heavy ion beams in a very wide range of mass: from hydrogen to lead

Operating frequency	14 and 18 GHz
Maximum radial field on the wall	1.1T
Maximum radial field on the wall	1.1 T
Maximum axial field (injection)	1.58 T
Maximum axial field (extraction)	1.35 T
Minimum axial field	0.4 T
Hexapole	NdFeB made 1.1 T
Extraction	Accel-Dec, 30kV/12kV Max
Plasma chamber	St. steel or Al made

Operational parameters of the CAESAR Source

Current CAESAR cavity

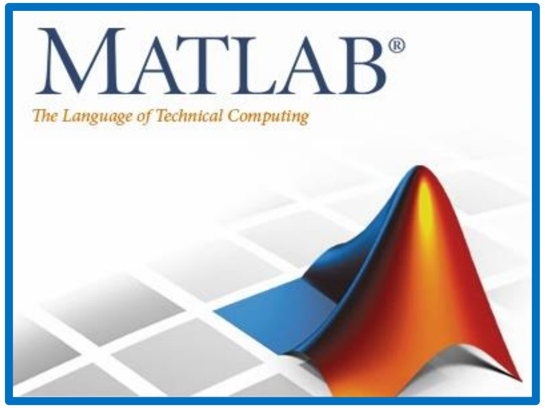


Cavity dimensions:
ϕ = 63.5 mm;
L = 200.0 mm

The working frequency, after frequency tuning, is: f = 14.5 GHz

Systems simulations: numerical approach

Full anisotropic dielectric tensor for magnetized Inhomogeneous and anisotropic plasma computed in



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Solution of Maxwell's equations in

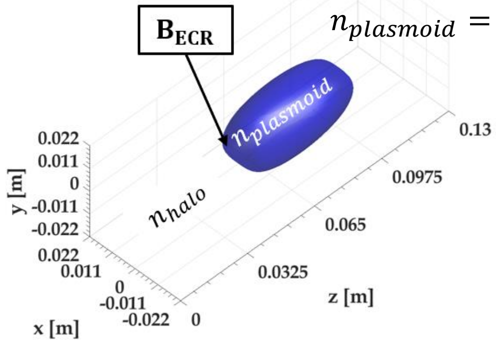
=

Electromagnetic field in ECRIS Plasma

Plasmoid/halo structure

$n_{halo} = 2.5 * 10^{15} m^{-3}$

$n_{plasmoid} = 2.5 * 10^{17} m^{-3}$



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Fully 3D dielectric tensor

$$\overline{\overline{\epsilon}} = \epsilon_0 \overline{\overline{\epsilon}}_r = \epsilon_0 \left(\overline{\overline{\epsilon'}} - i \overline{\overline{\epsilon''}} \right) = \epsilon_0 \left(\overline{\overline{I}} - \frac{i \overline{\overline{\sigma}}}{\omega \epsilon_0} \right)$$

$$= \epsilon_0 \begin{bmatrix} 1 + i \frac{\omega_p^2}{\omega} \frac{a_x}{\Delta} & i \frac{\omega_p^2}{\omega} \frac{c_z + d_{xy}}{\Delta} & i \frac{\omega_p^2}{\omega} \frac{-c_y + d_{xz}}{\Delta} \\ i \frac{\omega_p^2}{\omega} \frac{-c_z + d_{xy}}{\Delta} & 1 + \frac{i \omega_p^2}{\omega} \frac{a_y}{\Delta} & i \frac{\omega_p^2}{\omega} \frac{c_x + d_{yz}}{\Delta} \\ i \frac{\omega_p^2}{\omega} \frac{c_y + d_{xz}}{\Delta} & i \frac{\omega_p^2}{\omega} \frac{-c_x + d_{zy}}{\Delta} & 1 + i \frac{\omega_p^2}{\omega} \frac{a_z}{\Delta} \end{bmatrix}$$

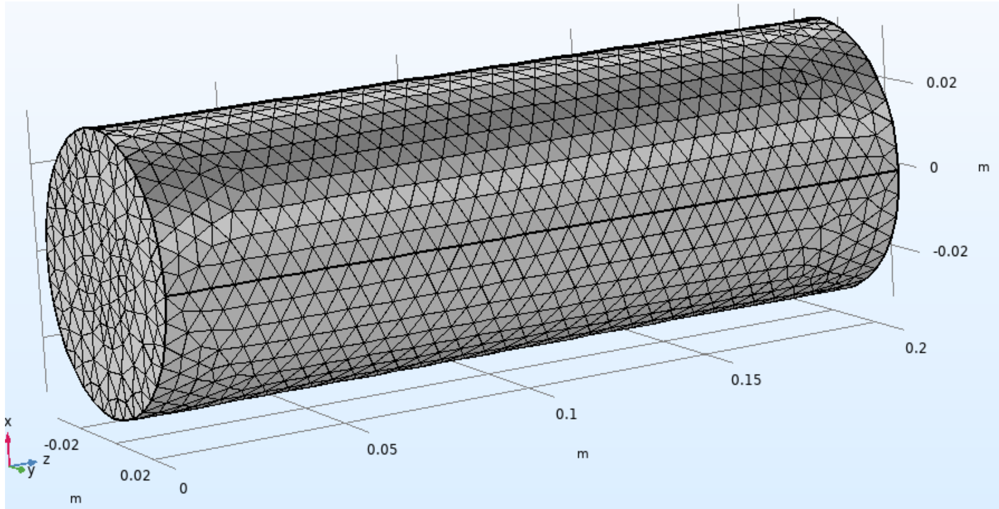
=

Solution of the wave equation

$$\nabla \times \nabla \times \boldsymbol{E} - \frac{\omega^2}{c^2} \overline{\overline{\epsilon_r}} \cdot \boldsymbol{E} = 0$$

Modification of the plasma chamber geometry

CAESAR plasma chamber

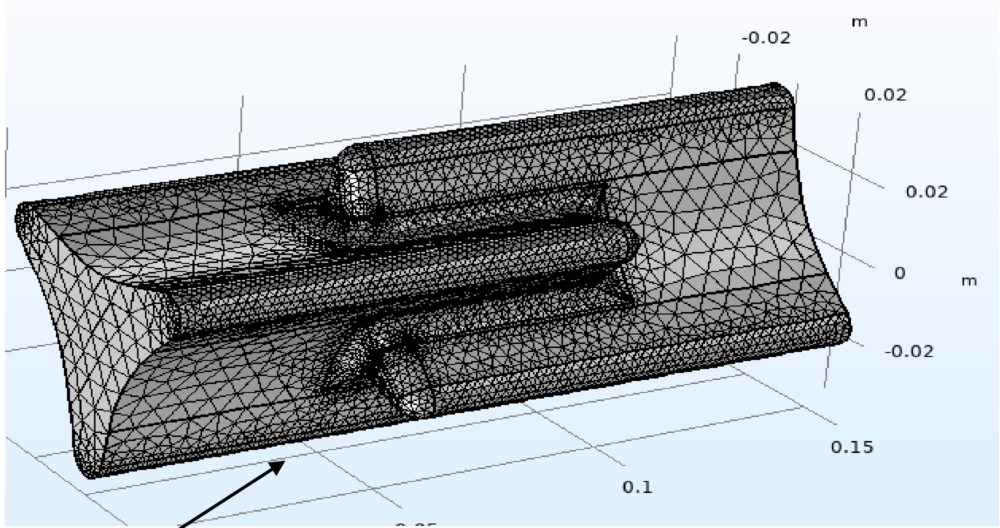


Mesh definition in COMSOL

The maximum element of the mesh size was set to 1,75 mm (about $\lambda_0/6$)

The lossy cavity walls are modelled via the appropriate "impedance boundary condition."

Innovative "star-shaped" geometry: IRIS



Reflects the shape of the plasma due to the magnetic structure

Italian patent pending n. 102020000001756

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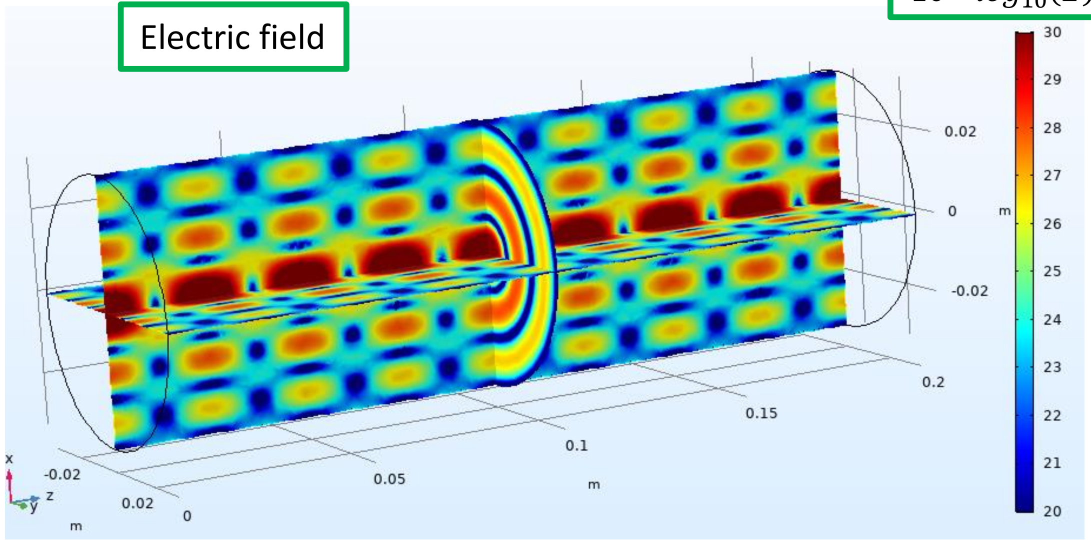
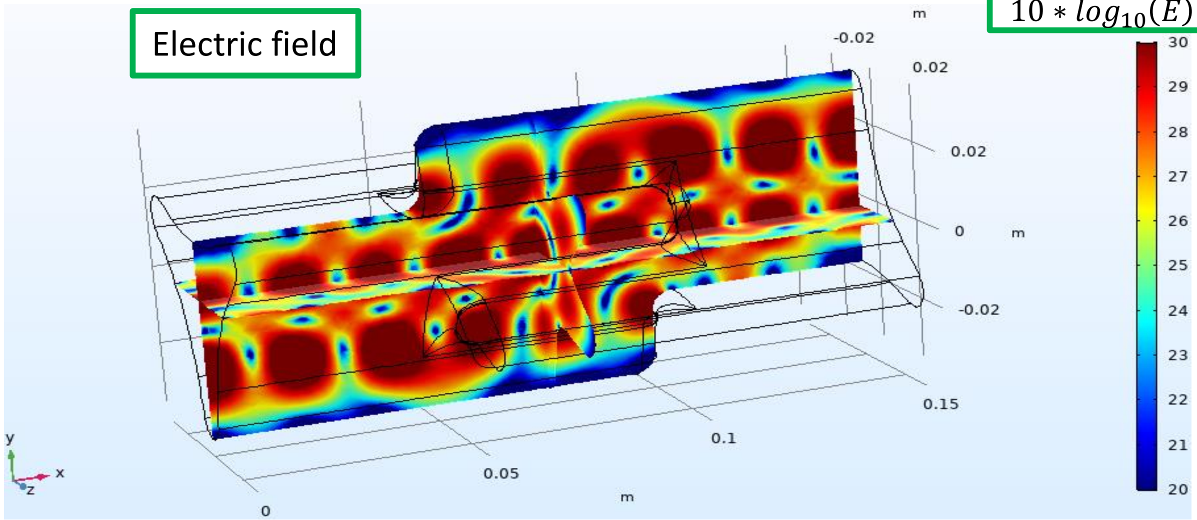
Modification of the plasma chamber geometry

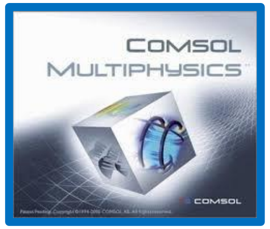
First step: Eigenmode solver

CAESAR plasma chamber



Innovative “star-shaped” geometry: IRIS





$f_{TM_{0,3,8}}$ = 14.053 GHz

$f_{TM_{2,2,9}}$ = 14.022 GHz

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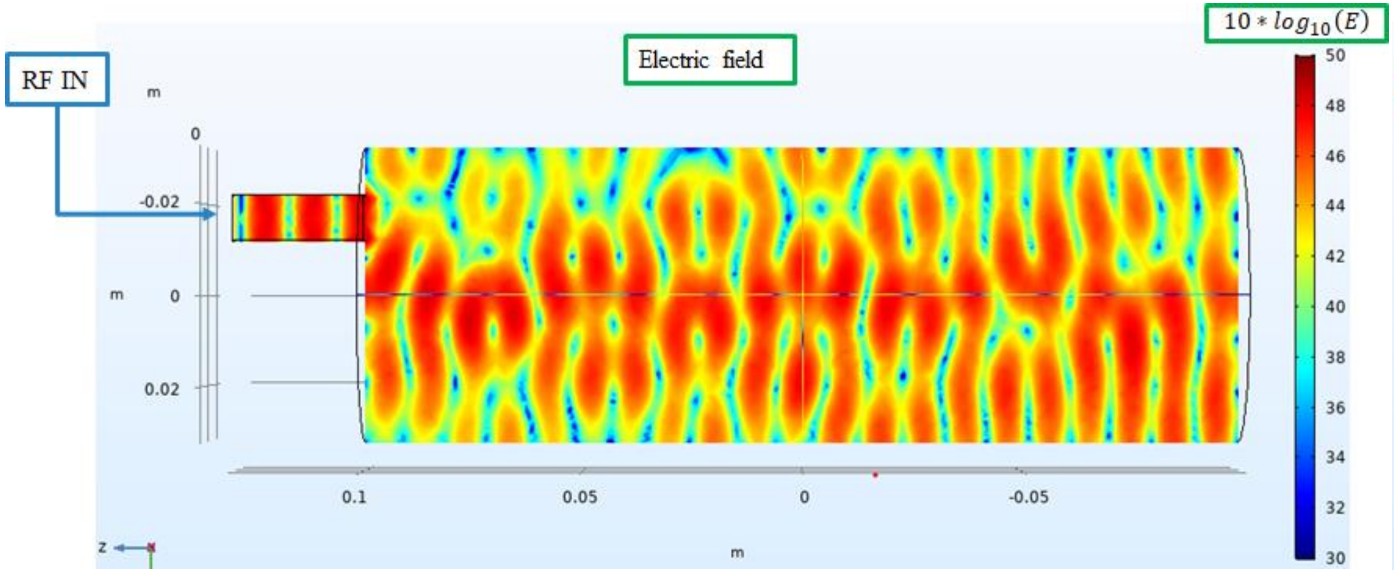
Modification of the plasma chamber geometry

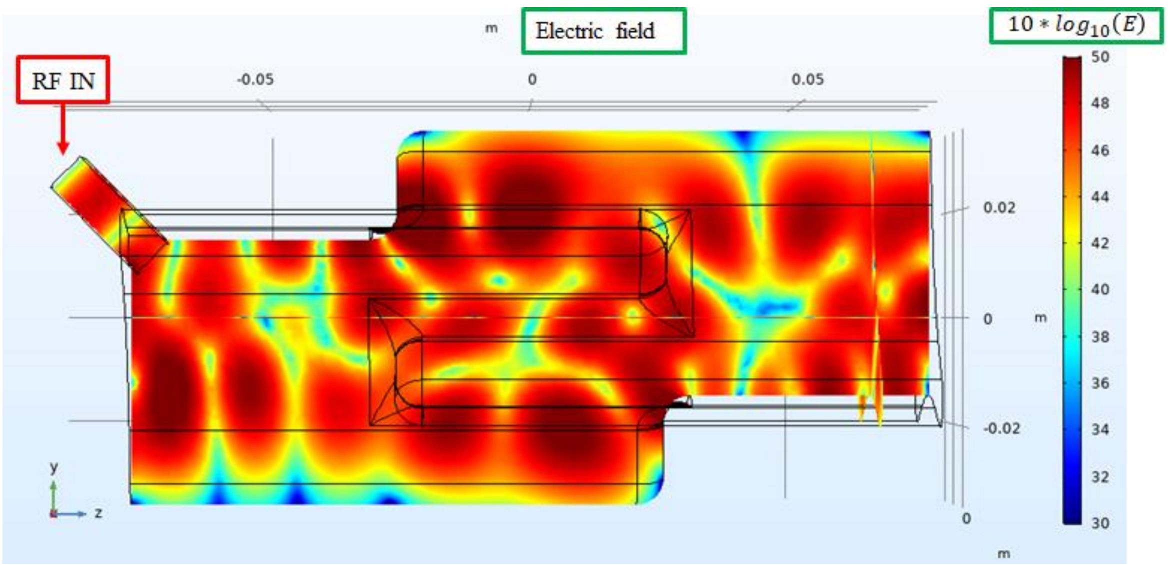
Second step: Frequency domain solver in vacuum

Power (100 W) for both waveguides @ 14 GHz

CAESAR plasma chamber

Innovative "star-shaped" geometry: IRIS





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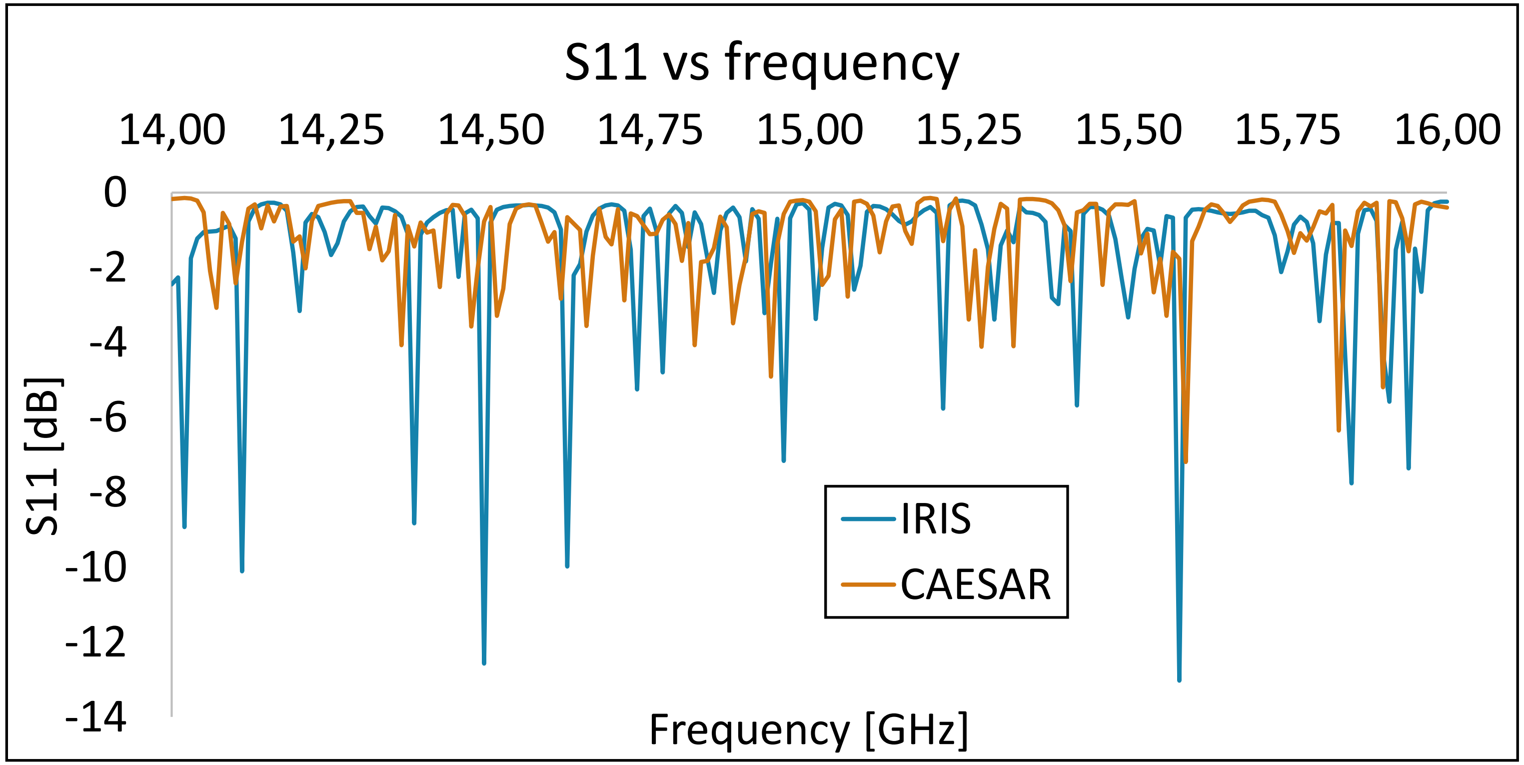
S11 on the WR62 waveguide input

As can be seen, in the case of IRIS, microwaves are better matched to the cavity in almost all the considered frequency range.



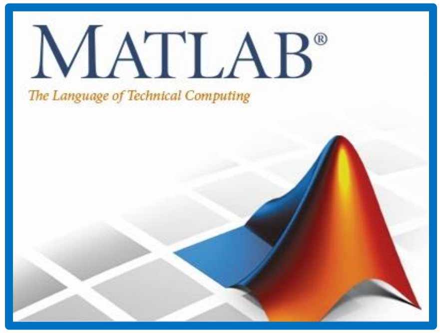
Modification of the plasma chamber geometry

Third step: Frequency domain solver in presence of a plasma

Meshing the integration domain: tetrahedrons size is reduced in the proximity of the ECR surface, accounting for resonance. The maximum element of the mesh size was set to 1,75 mm (about $\lambda_0/6$). The minimum as set to $\lambda_0/10$.

The lossy cavity walls are modelled via the appropriate "impedance boundary condition."

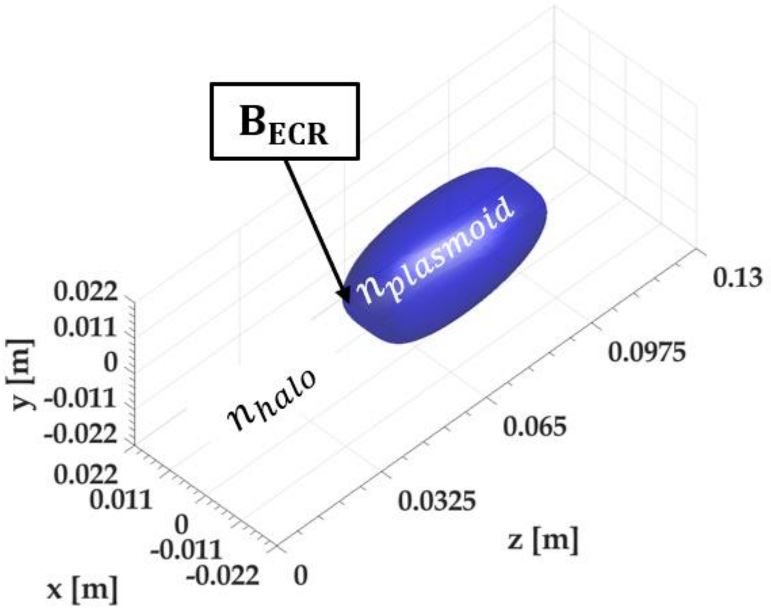
The inner cavity volume is filled by lossy plasma characterized by dielectric tensor.



Fully 3D dielectric tensor

$$\bar{\bar{\epsilon}} = \epsilon_0 \bar{\bar{\epsilon}}_r = \epsilon_0 \left(\bar{\bar{\epsilon'}} - i \bar{\bar{\epsilon''}} \right) = \epsilon_0 \left(\bar{\bar{I}} - \frac{i \bar{\bar{\sigma}}}{\omega \epsilon_0} \right)$$

$$= \epsilon_0 \begin{bmatrix} 1 + i \frac{\omega_p^2}{\omega} \frac{a_x}{\Delta} & i \frac{\omega_p^2}{\omega} \frac{c_z + d_{xy}}{\Delta} & i \frac{\omega_p^2}{\omega} \frac{-c_y + d_{xz}}{\Delta} \\ i \frac{\omega_p^2}{\omega} \frac{-c_z + d_{xy}}{\Delta} & 1 + \frac{i \omega_p^2}{\omega} \frac{a_y}{\Delta} & i \frac{\omega_p^2}{\omega} \frac{c_x + d_{yz}}{\Delta} \\ i \frac{\omega_p^2}{\omega} \frac{c_y + d_{xz}}{\Delta} & i \frac{\omega_p^2}{\omega} \frac{-c_x + d_{zy}}{\Delta} & 1 + i \frac{\omega_p^2}{\omega} \frac{a_z}{\Delta} \end{bmatrix}$$



Plasmoid/halo structure

$$n_{halo} = 2.5 * 10^{15} m^{-3}$$
$$n_{plasmoid} = 2.5 * 10^{17} m^{-3}$$

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Modification of the plasma chamber geometry

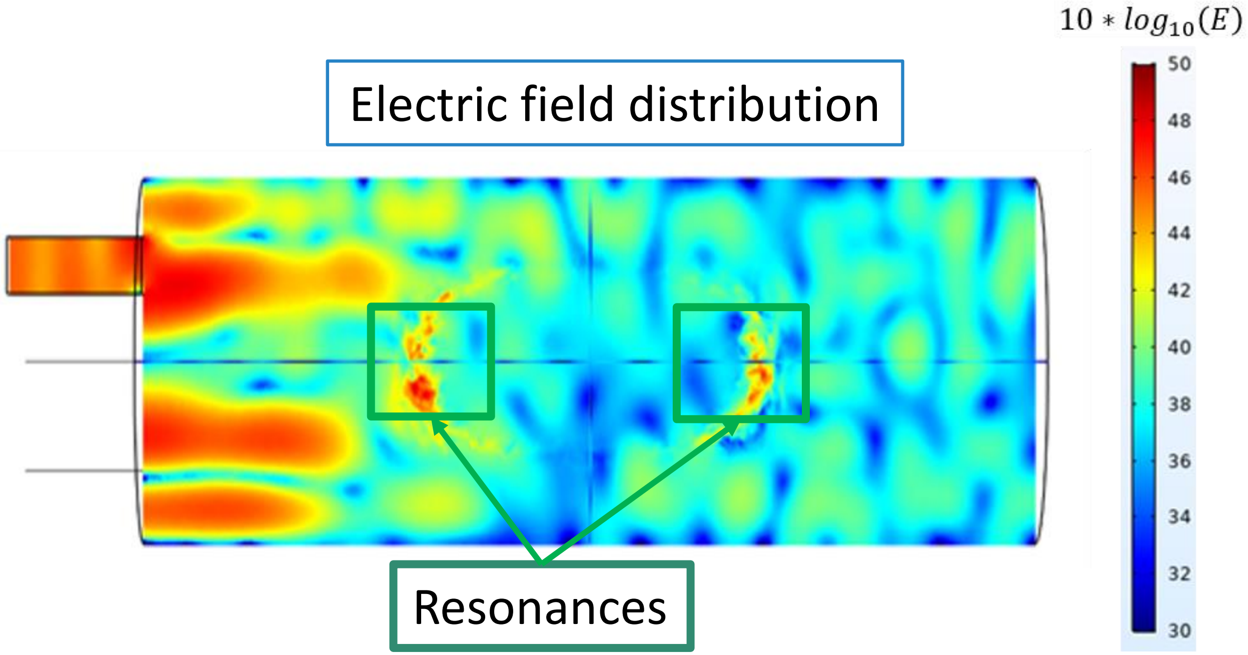
Power (100 W) for both waveguides @ 14 GHz

Third step: Frequency domain solver in presence of a plasma

CAESAR plasma chamber

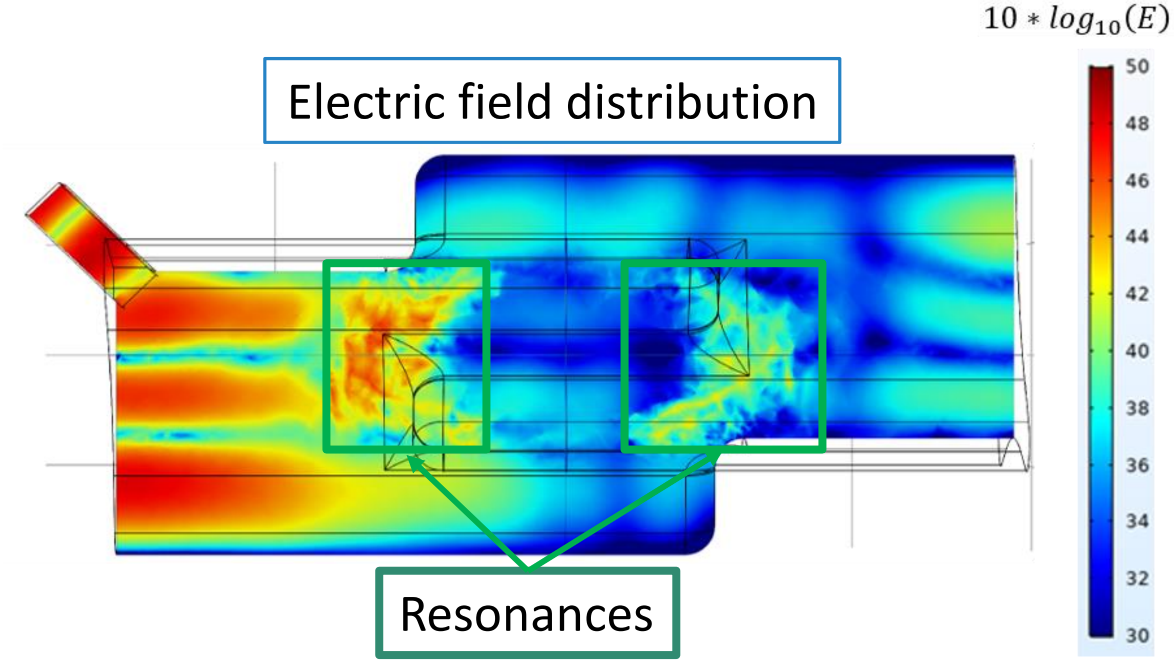
Innovative "star-shaped" geometry: IRIS

Electric field distribution



Resonances

Electric field distribution



Resonances

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.

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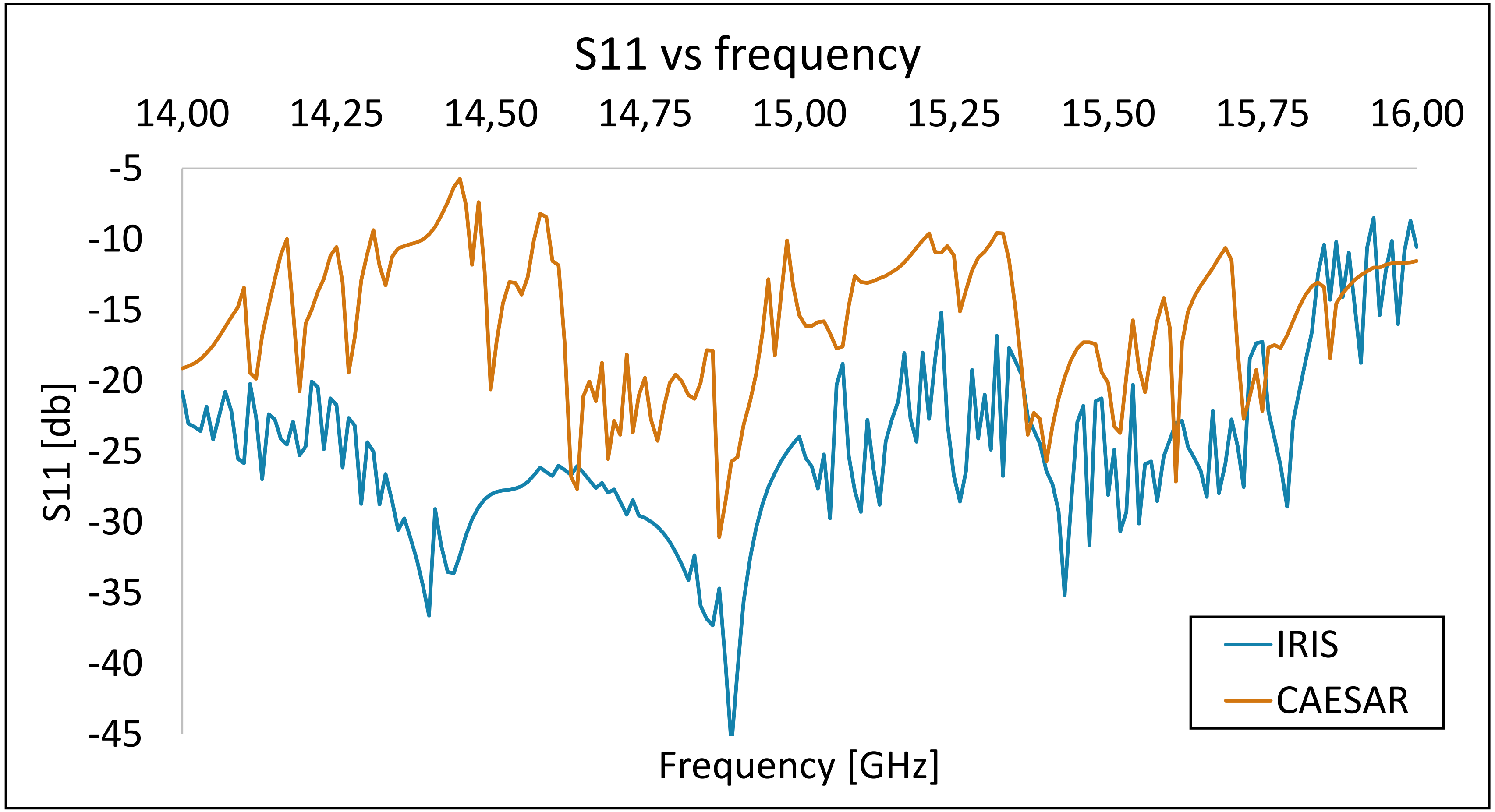
S11 on the WR62 waveguide input

Calculations of the|S11| in the presence of a magnetized plasma show an even more evident improvement by employing the proposed new geometry IRIS.



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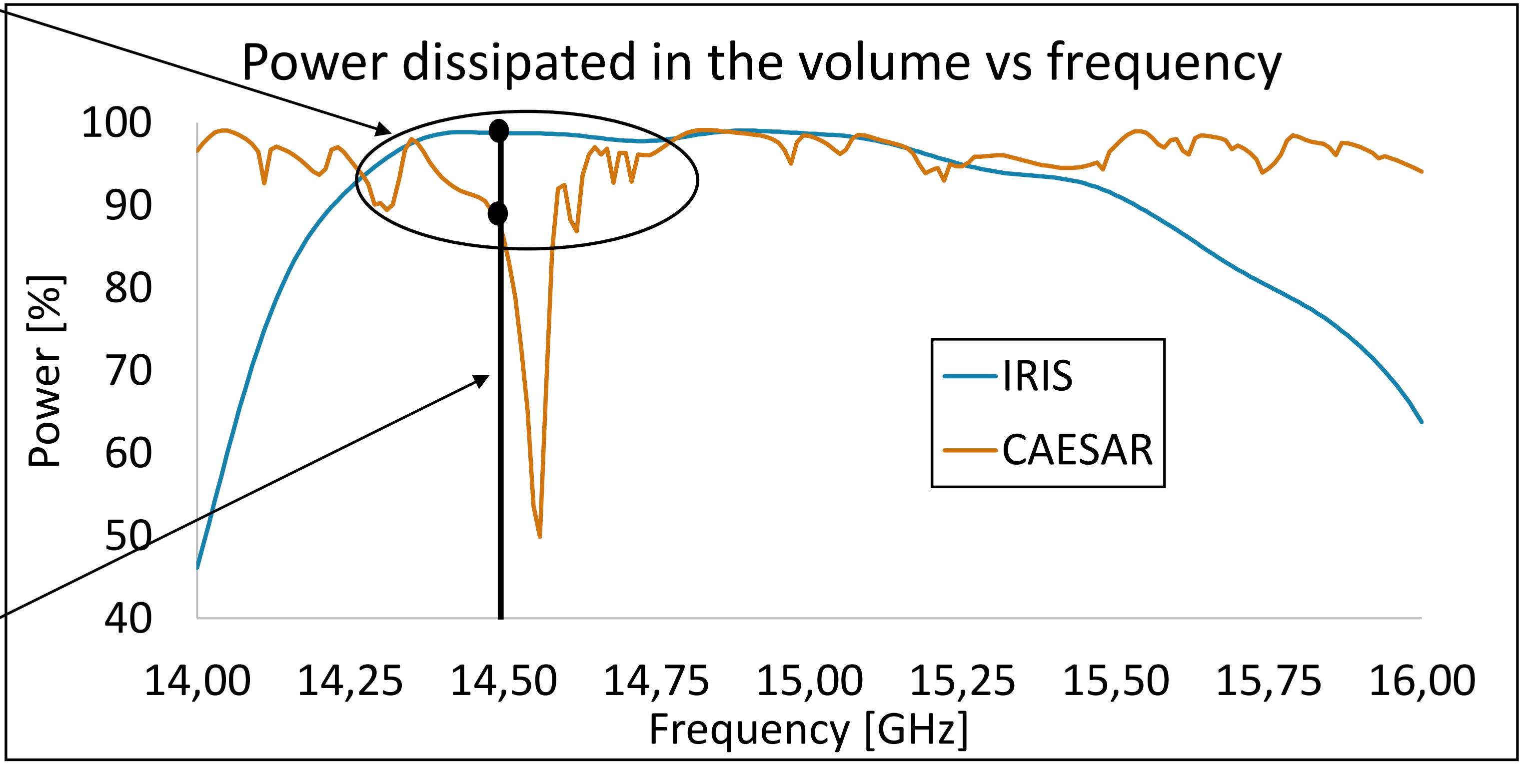
Power absorption from the plasma

The power absorption is calculated through the volume integral of the total dissipated power inside the chamber.

Operating CAESAR range frequency

The results show that the IRIS geometry produces a higher and almost flat power absorption coefficient over a wide frequency range around the CAESAR operating frequency. This could translate in an easier tunability and higher flexibility of the ion source.

Operating CAESAR frequency @ 14.5 GHz



Conclusion

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We presented an electromagnetic study of an unconventional resonant cavity for magnetically confined plasmas whose performances have been compared with the classical cylindrical geometry of the CAESAR ion source, installed at INFN-LNS.

The proposed could boost the ion source performances and increase its flexibility by:

- Coupling a higher microwave power to the plasma.
- Ensure a high microwave power absorption in a wider frequency range.

The design study has been completed and now we are in the engineering phase, which is considering Additive Manufacturing for the realization of a first prototype: tests on materials and first items will start soon at INFN-LNS

Thank You for your attention!