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.
**Introduction of ECRIS**

**Magnetically confined Plasmas**

- **Solenoids** for Axial confinement
- **Hexapole** for radial confinement

**ECR Surface**

\[ B_{ECR} = \frac{\omega_{RF} m_e}{e} \]

- **B-minimum structure** for electrons and ions confinement.

- **Magnetic mirror** for axial confinement.

**B-minimum on xz plane at y = 0**
Introduction of ECRIS

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*

\[ \frac{B_{\text{max}}}{B_{\text{ECR}}} > 2 \]

**2000** ECRIS standard model

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

Techniques to increase the ECR ion source performances

- **Frequency Tuning**
  - CAPRICE source @ GSI*

- **SUPERNANOGAN @ CNAO**
  - *G. Ciavola et al., proc. EPAC08

- Two Frequency Heating

- Two Close Frequency Heating

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*G. Ciavola et al., proc. EPAC08

*L. Celona et al., Rev. Sci. Instrum. 79, 023305 (2008).*
Unconventional resonant cavities for magnetoplasmas of ECRIS

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

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

Operational parameters of the CAESAR Source
Case study

Current CAESAR cavity

Extraction hole
RF Injection
Resonance cavity
Aluminium cylinder
Plasma
Injection hole
Extraction system

Cavity dimensions:
\[ \phi = 63.5 \text{ mm}; \quad L = 200.0 \text{ mm} \]

The working frequency, after frequency tuning, is: \[ f = 14.5 \text{ GHz} \]
Full anisotropic dielectric tensor for magnetized inhomogeneous and anisotropic plasma computed in

\[ n_{\text{halo}} = 2.5 \times 10^{15} \text{m}^{-3} \]
\[ n_{\text{plasmoid}} = 2.5 \times 10^{17} \text{m}^{-3} \]

Plasmoid/halo structure

Solution of Maxwell’s equations in

Electromagnetic field in ECRIS Plasma

Systems simulations: numerical approach

Fully 3D dielectric tensor

\[ \bar{\varepsilon} = \varepsilon_0 \bar{\varepsilon}_r = \varepsilon_0 \left( \bar{\varepsilon} - i\bar{\varepsilon}_0 \right) = \varepsilon_0 \left( \frac{\bar{\varepsilon}}{\bar{\varepsilon}_0} - \frac{1}{\bar{\varepsilon}_0} \right) \]

Solution of the wave equation

\[ \nabla \times \nabla \times E - \frac{\omega^2}{c^2} \bar{\varepsilon}_r \cdot E = 0 \]
Modification of the plasma chamber geometry

CAESAR plasma chamber

Mesh definition in COMSOL

Innovative “star-shaped” geometry: IRIS

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.”

Reflects the shape of the plasma due to the magnetic structure

Italian patent pending n. 10202000001756
Modification of the plasma chamber geometry

First step: Eigenmode solver

CAESAR plasma chamber

Innovative “star-shaped” geometry: IRIS

Electric field

\[ f_{TM0,3,8} = 14.053 \text{ GHz} \]

\[ 10 \times \log_{10}(E) \]

\[ 10 \times \log_{10}(E) \]

\[ f_{TM2,2,9} = 14.022 \text{ GHz} \]
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
As can be seen, in the case of IRIS, microwaves are better matched to the cavity in almost all the considered frequency range.

S11 on the WR62 waveguide input
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

\[
\tilde{\varepsilon} = \varepsilon_0 \varepsilon_r = \varepsilon_0 \left( \tilde{\varepsilon} - i\tilde{\sigma} / \omega \right) = \varepsilon_0 \left( \tilde{I} - \frac{\tilde{\sigma}}{\omega \varepsilon_0} \right)
\]

Plasmoid/halo structure

\[ n_{\text{halo}} = 2.5 \times 10^{15} m^{-3} \]

\[ n_{\text{plasmoid}} = 2.5 \times 10^{17} m^{-3} \]
Modification of the plasma chamber geometry

Third step: Frequency domain solver in presence of a plasma

CAESAR plasma chamber

Innovative “star-shaped” geometry: IRIS

Power (100 W) for both waveguides @ 14 GHz

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.
Calculations of the $|S_{11}|$ in the presence of a magnetized plasma show an even more evident improvement by employing the proposed new geometry IRIS.
Power absorption from the plasma

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

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 range frequency

Operating CAESAR frequency @ 14.5 GHz
Conclusion

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!