

Numerical design and experimental characterization of an innovative ‘plasma-shaped’ cavity realized in AM for ECR Ion Sources

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Among the possible ways to improve the performance of Electron Cyclotron Resonance (ECR) ion sources, the redesign of the plasma chamber and microwave injection system plays a key role. The proposed innovative chamber design named IRIS (Innovative Resonator Ion Source) is derived from the typical six-branches-star density iso-surfaces of ECR ion sources plasmas, emulating the electron distribution as dictated by the confining B-minimum configuration. Its novel microwave launching system consists of a slotted waveguide that smoothly matches the cavity walls. Both the chamber and its microwave injection system have been designed using CST-Studio-Suite with the objective of increasing the power absorption into the plasma core, thereby maximizing the on-axis electric field. Particle-In-Cell simulations have confirmed the higher in-plasma energy deposition expected for IRIS compared to a conventional cylindrical cavity. The final prototype has been realized in Additive Manufacturing (AM) via Selective Laser Melting (SLM) technology, post-processed via Plasma Electropolishing (PEP), and eventually characterized in terms of S-parameters and on-axis electric field measurement using a bead-pull technique. Electromagnetic measurements have been performed, and results are presented, paving the way to routine operations in future ECR ion sources.

Introduction and motivation

Electron Cyclotron Resonance Ion Sources (ECRIS) are plasma-based ion sources where radiofrequency (RF) power is injected into a cylindrical chamber to sustain a magnetically confined plasma. Confinement is achieved via a magnetic system including solenoid coils and one hexapole in the so-called B-minimum configuration. Electrons are heated through RF at the resonance surface. ECRIS performance enhancement have relied on higher magnetic fields and thus operational frequencies, reaching technological limits due to complexity and cost [1]. A key issue in standard cylindrical plasma chambers for ECRISs is the formation of ‘hollow plasmas’, where the dense plasma core (plasmoid) shows a density depletion in the vicinity of the chamber axis [2]. This is caused by the cylindrical geometry, where excited electromagnetic (EM) modes are expressed in terms of Bessel functions (and their first derivatives), null the origin except the J_0 (J_1'). The resulting modes present electric field minimum on-axis, thereby reducing ionization efficiency and leading to

hollow ion beams formation (Fig.1) [3]. To address this, the IRIS (Innovative Resonator Ion Source) was developed featuring a twisted, star-shaped cavity that breaks the cylindrical symmetry and imitates the plasma shape, promoting modes excitation with on-axis electric field maximum. The plasma volume and, hence, the shape of IRIS are footprinted by particle in cell simulations of electrons in plasma [4]. Moreover, a novel radial microwave injection system can be used, consisting of a slotted waveguide, smoothly matched to the cavity walls [5].

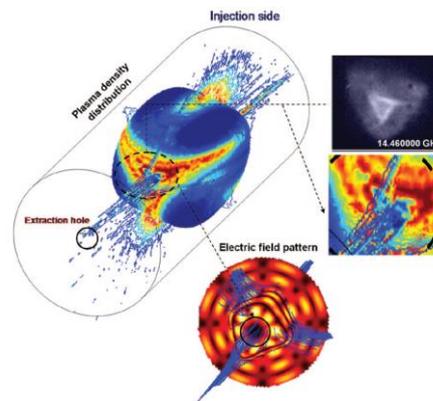


Figure 1. Simulation of an ECR plasma in a conventional cylindrical chamber. The low field amplitude on axis causes a density depression, resulting in a hollow ion beam (see the b/w insert, which shows an experimental image of a hollow Ar ion beam). Figure adapted from [3].

IRIS numerical simulations

Numerical simulations in CST Studio Suite and Ansys HFSS to study the IRIS cavity modes within the frequency range [14.5, 15.5] GHz. The scattering parameter $|S_{11}|$ was evaluated to assess injection waveguide-to-cavity coupling efficiency. Simulations demonstrated that the IRIS geometry supports more resonant modes than a standard cylindrical cavity and exhibits a better coupling. Field distribution analysis, on two selected modes, shows that the IRIS cavity concentrates EM fields on-axis much more than the cylindrical shape (Fig.2).

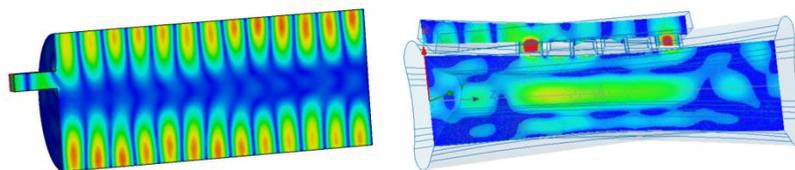


Figure 2. Comparison of the electric field configuration for a cylindrical cavity excited axially and IRIS. Excited modes: (left) cylindrical cavity, $f_0 = 14.45$ GHz, (right) IRIS cavity, $f_0 = 14.72$ GHz.

Prototype realization and post-processing

The complex geometry of the IRIS cavity precludes realization through conventional machining techniques. The prototype was fabricated using additive manufacturing by Laser Powder Bed Fusion (LPBF) technique. The 3D model was optimized for printing at a 45° orientation to minimize support structures while the external shape ensures that each layer forms a connected surface to minimize defects while cooling. The prototype, visible in Fig.3, was built using 316L

steel powder with an EOSint M280 printer.



Figure 3. IRIS prototype realized in additive manufacturing.

Post-processing has then been performed to remove support structures, polishing flanges, and preparing for experimental testing. Plasma Electrolytic Polishing (PEP) was employed to decrease the surface roughness: in order to avoid breakdowns and any worsening of the modes' coupling factors). PEP reduces surface roughness through anodic dissolution combined with plasma discharge within the vapour-gas layer of a salt-based electrolyte. Simulations were used to optimize material removal without impacting on EM properties, resulting in an optimal value of 50 μm .

Experimental Validation

Experimental validation has been carried out to: a) compare the experimental vs simulated mode distribution, by using a Vector Network Analyzer and b) measure the on-axis electric field profile of selected modes through the bead-pull technique, based on the Slater's theorem [6]. Fig.4(left) shows that numerical and experimental $|S_{11}|$ are in good agreement. The baseline offset is probably due to non-uniform wall polishing after the PEP treatment. Fig.4(right) shows, for the mode at $f_0 = 14.64$ GHz, the comparison between the simulated and the measured on-axis electric field profile: a good agreement between the two profiles can be observed, with minor deviations likely due to bead-induced perturbations in low-field areas. Importantly, high-field regions overlap the ECR surface (dashed lines), which is a satisfactory outcome validating the IRIS design and realization.

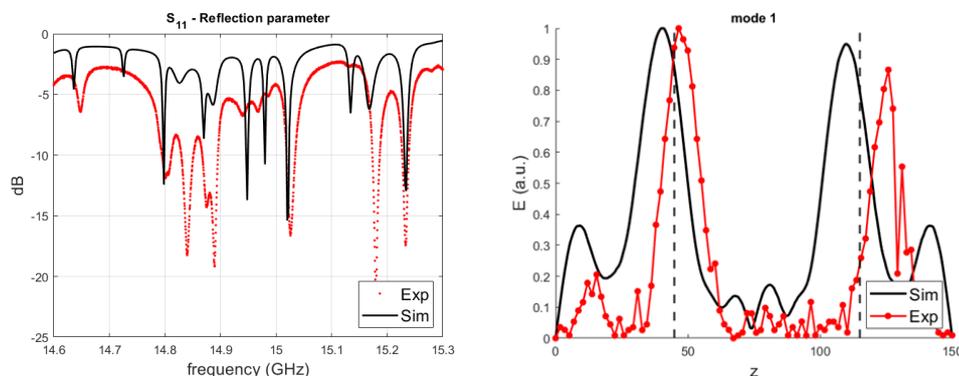


Figure 4. (Left) Comparison of the reflection parameter S_{11} in the simulation (black) and reality (red) and (right) the axial electric field for a selected mode.

Conclusions and perspectives

The IRIS concept has been successfully validated through EM simulation, manufacturing, and

experimental testing. This new cavity allows more modes with on-axis electric field maximum. The new diffractive microwave injection system further improves on-axis power deposition. The fabrication and post-processing workflow demonstrated the viability of complex geometries for high-frequency plasma applications. Future work will focus on building a "hot" prototype with integrated cooling channels (COMSOL Multiphysics simulations are ready). Particle-in-Cell plasma simulations are ongoing in order to compare electron heating in cylindrical vs IRIS shapes.

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