Electromagnetic Simulation of ‘plasma-shaped’ Plasma Chamber for Innovative ECRIS

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

(1) Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN-LNS), Via S. Sofia 62, 95123 Catania, Italy

(2) Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Legnaro (INFN -LNL), Viale dell’Università, 2, 35020 Legnaro PD, Legnaro, Padova, Italy

(3) Dipartimento di Ingegneria Elettrica, Elettronica e Informatica, Università degli Studi di Catania, Viale Andrea Doria 6, 95125, Catania, Italy

(4) Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, 44122 Ferrara, Italy

Introduction and motivation

- In the past years, several efforts have been dedicated to improve ECRISs performances (i.e. frequency tuning, TFH, innovative magnetic systems design).

- Operation at higher magnetic fields and microwave frequency is the most straightforward path to achieve higher source performance.

- Brute force approach, however, cannot be always used due to actual technological limits *(superconducting magnetic system complexity and cost, high magnets forces, hot electrons generations, plasma overheating, cooling, …)*.

➢ **New approach** to apply in order to **improve ECRISs performances without incur in actual technological limits?**

Improve source performances through plasma chamber re-design and microwave launch system optimization

Some reference about this talk topic

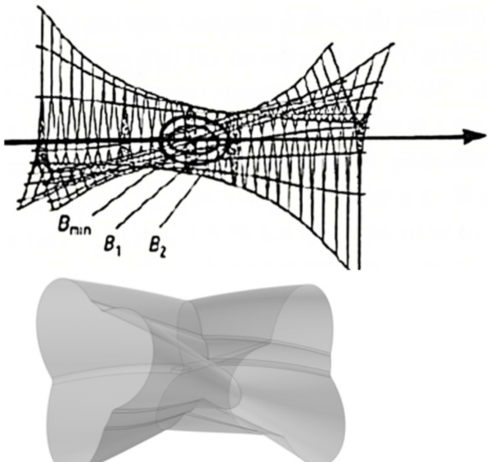
- **SERSE: demonstration of gyrotron mw transmission line + coupling system and description of the magnetic field requirements in order to obtain larger intensities and charges with ≥ 28 GHz frequency operation** (*D. Hitz, A. Girard, G. Melin, S. Gammino, G. Ciavola, and L. Celona, Review of Scientific Instruments **73**, 509 (2002)*).
- **SECRAL: production of beams of highly charged ions, in 18 + 24 GHz TFH operation, through the use of an optimized waveguide (Ø 20 mm) operating in the TE01 mode (gyrotron oscillator), with total power of 7.5 W** (*Zhao, H. W. et. al., "Intense highly charged ion beam production and operation with a superconducting electron cyclotron resonance ion source", Physical Review Accelerators and Beams, vol. 20, no. 9. 2017. doi: 10.1103/PhysRevAccelBeams.20.094801*).
- **VENUS: the microwave coupling scheme with the Ø 20 mm waveguide has been adopted and validated with the 28 GHz VENUS ion source at LBNL (***D. Z. Xie, W. Lu, J. Y. Benitez, C. M. Lyneis, and D. S. Todd, in Proceedings of the 22th International Workshop on ECR Ion Sources, Busan, S. Korea, 2016*).
- TE01 wave mode is used since losses along the waveguide are very low, due to almost zero electric fields at the inner surface and axis of the waveguide (reduced probability of electric breakdown due to the employed high power).
- **SECRAL II: implementation of a new mw coupling scheme based on the 'Vlasov launcher', a cylindrical waveguide with a shaped end able to radiate mw directly to the first ECR surface from cylindrically symmetric modes in circular waveguides (TE01)** (*J. W. Guo et. Al., Rev. Sci. Instrum. **91**, 013322 (2020)*).
- **HIISI: implementation of a new plasma chamber geometry that possesses reduced thickness at the hexapole magnetic poles, in order to enhance the radial magnetic field in the plasma loss area** (*H. Koivisto et. Al., Rev. Sci. Instrum. **91**, 023303 (2020)*).

➢ New **cavity resonator design:**

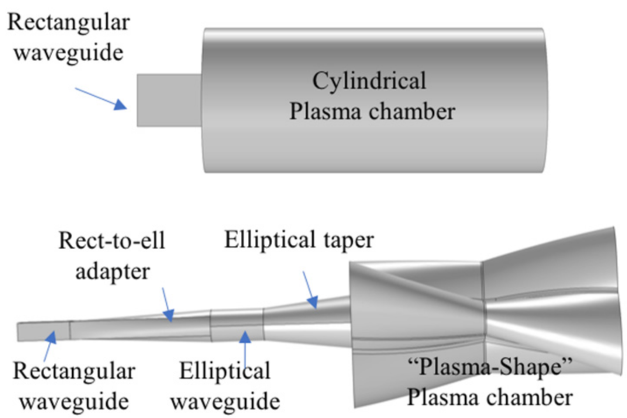
1. allows to **improve mode field distribution along the chamber axis**;
2. thus allows **better wave to plasma coupling**.

➢ **innovative microwaves injection system based on side-coupled slotted waveguides.**

ECRIS 2018: where were we…



Sext-in-Sol magnetic field structure



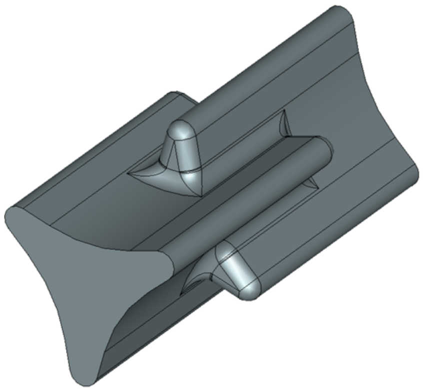
new-shaped" plasma chamber

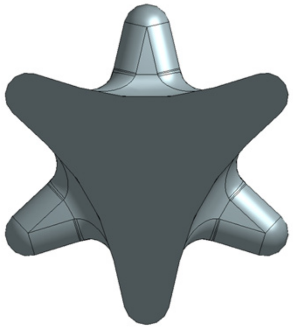
- The previous cavity geometry had been inspired by the typical star-shaped ECR plasma, determined by the twisted B-minimum magnetic field structure.

Torrisi et. Al., Non-conventional microwave coupling of RF power in ECRIS plasmas, AIP Conference Proceedings 2011, 020014 (2018); doi: 10.1063/1.5053256

Evolution of the proposed structure: overview

<u>Additive manufacturing process</u> → **Almost no limit to realizable shapes**





- **Cavity geometry improvement**: take into account the **electrons trajectories** as they move **under** the influence of the **magnetic field**.

- **RESULT**: **plasma cavity with minimized volume** → determined by the **maximum space occupied by electrons** inside ECR plasma.

- In order to employ the new cavity with the INFN LNS CAESAR ion source setup, further <u>mechanical and e.m. tuning have been performed</u>.

Evolution of the proposed structure: overview

- New approach:

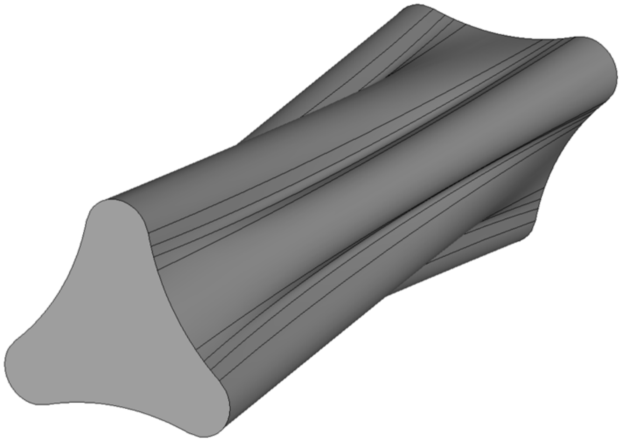
➢ **<u>force the mode generation only in the 'magnetic confinement space';</u>**

➢ **<u>finely tune the structure (or the injection system) in order to obtain modes with field maximum along the cavity axis.</u>**

- Advantages over the classic cylindrical plasma cavity:

1. excitation of modes with **electric field maximum along the chamber axis → Improved performances**

2. **Less occupied volume**: **magnetic field** profile could be **improved** (more room for the mid-coil (s), etc).



Innovative Resonator Ion Source: **IRIS**
Italian patent pending n. 102020000001756

Axial waveguide injection: cylindrical vs. 'plasma-shaped' cavity (1/2)

- The presented structure has been studied by the use of the commercial e.m. simulator CST.

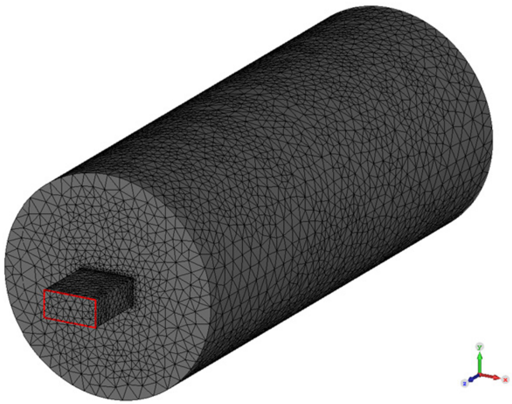
- Results in terms of S-parameters have been compared to those obtained with a standard cylindrical plasma chamber.

- Both structures:

1. consists of a **vacuum solid with lossy metal walls**.

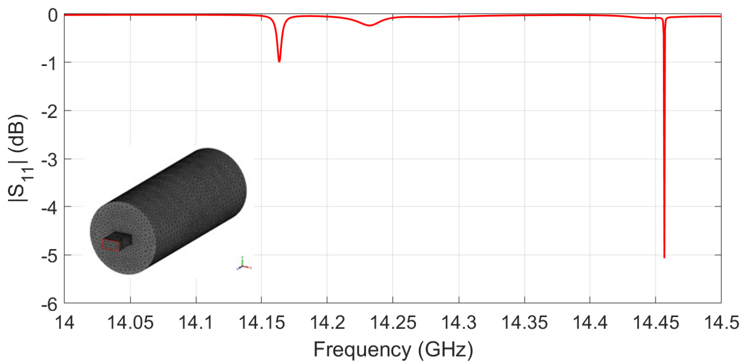
2. have been fed through a **standard axial waveguide** (WR62).

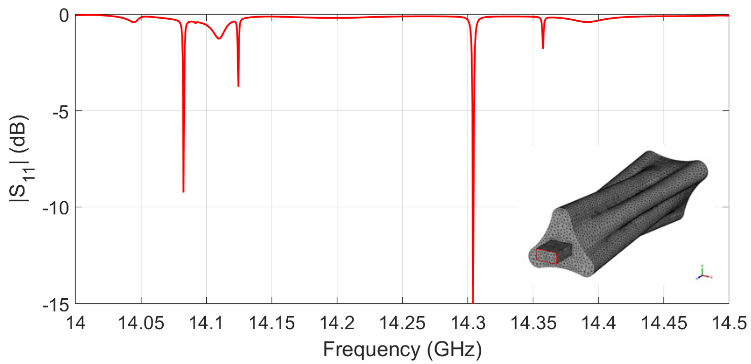
3. have been simulated using the **same mesh quality** (curvature tolerance, number of mesh refinement steps, etc).

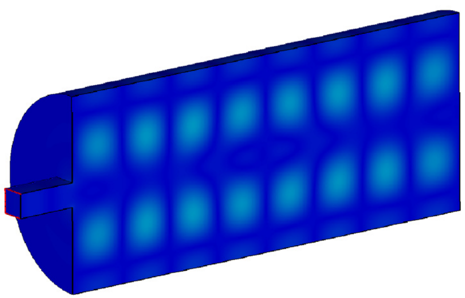


Axial waveguide injection: cylindrical vs. ‘plasma-shaped’ cavity (2/2)

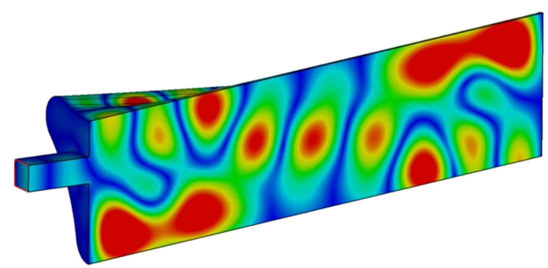
- The performances of both structures have been observed in terms of S-parameters in the band of [14; 14.5] GHz.
- **<u>Number of modes</u>** and **<u>mode adaptation</u>** have been chosen as the main quality parameters.







Bad mode coupling to the cavity.



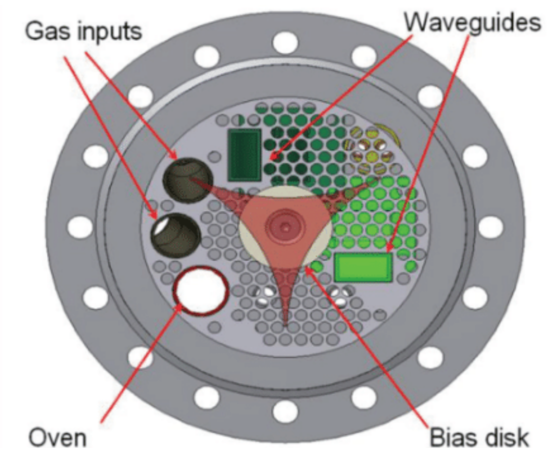
Better coupling plus mode with intense electric field at the cavity center.

How can we improve axial symmetry?

'Classical' injection waveguide launch scheme

The coupling of microwaves to the plasma has been improved up to now in different ways:

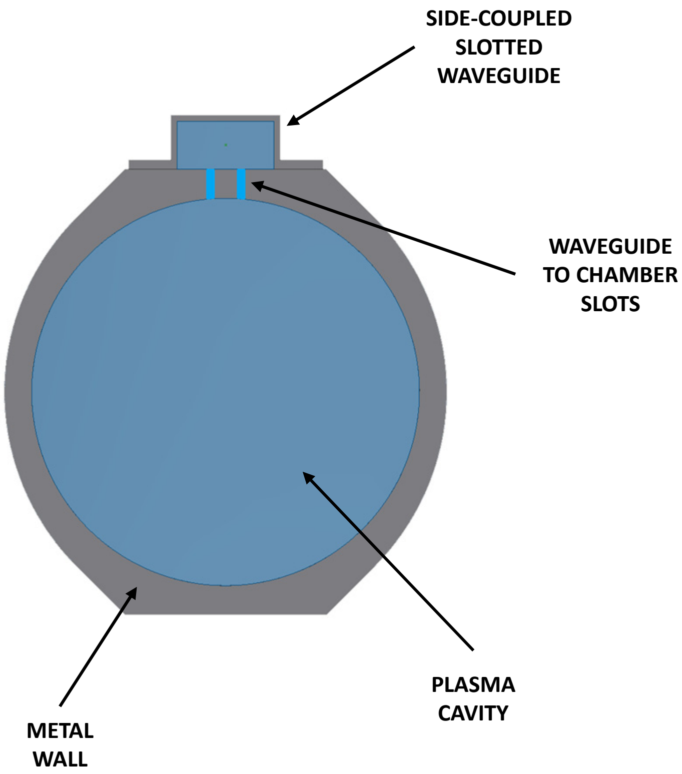
1. Higher frequency and higher microwave power;
2. double (or triple) frequency heating to improve plasma stability and source performances;
3. off-axis microwave coupling placed in-between plasma flutes to increase the coupling efficiency.



Slotted waveguide launch scheme

- Proposed structure:

innovative microwave launching scheme that employs a slotted waveguide placed on the chamber side wall.

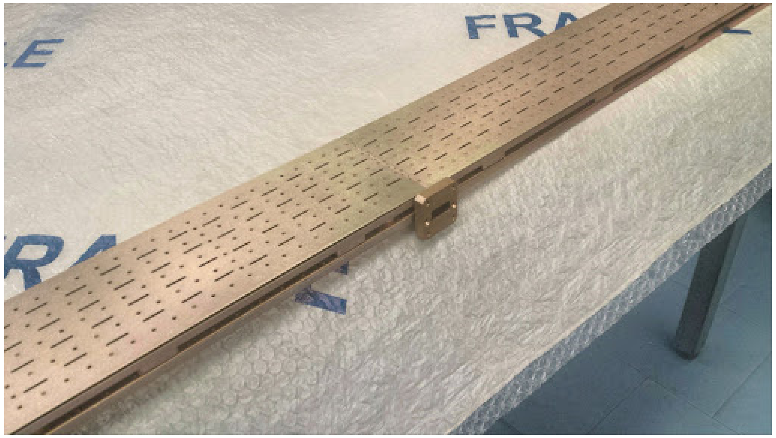


Slotted waveguide antenna design (1/4)

- Initial study of the slotted waveguide as a stand alone antenna (free-space operation).

- Slotted waveguides advantages:

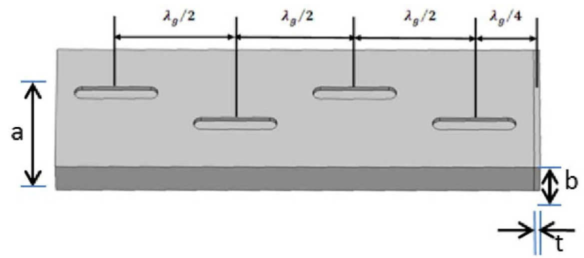
1. low-profile design requirements;
2. mechanical robustness;
3. good efficiency;
4. relative ease of realization;
5. wide operational frequency bandwidth.



Slotted waveguide antenna design (2/4)

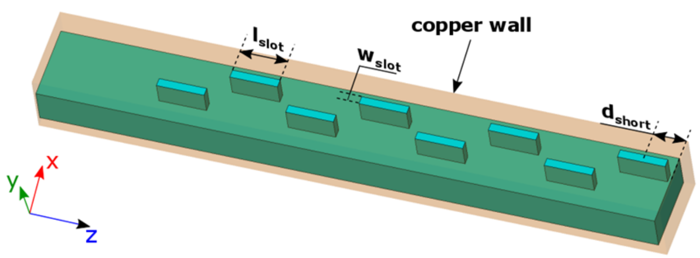
The general rules for the slotted waveguide antenna project are:

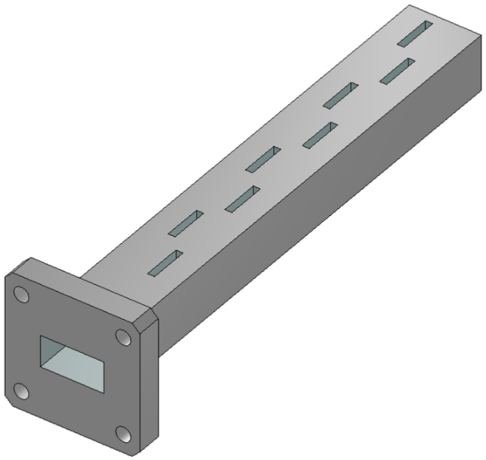
1. the center of the first slot on the waveguide aperture size should be placed at a distance $\frac{\lambda_g}{4}$ from it;
2. the center of the last slot should be placed at a distance $\frac{\lambda_g}{4}$ from the metallic wall that closes the waveguide;
3. the distance between the centers of two consecutive slots should be equal as $\frac{\lambda_g}{2}$;
4. the slot length should be equal at $\frac{\lambda_0}{4}$, where λ_0 is the free space wavelength, while the slot width should be much smaller with respect to λ_0.



Slotted waveguide antenna design (3/4)

- Slotted waveguide antenna can be finely tuned through the electromagnetic simulator.
- For the antenna realization, a standard WR62 waveguide has been used (a = 15.8 mm, b = 7.9 mm).
- The presented antenna works in the band [14.2; 15.25] GHz with central frequency 14.7 GHz.





Slotted waveguide antenna design (4/4)

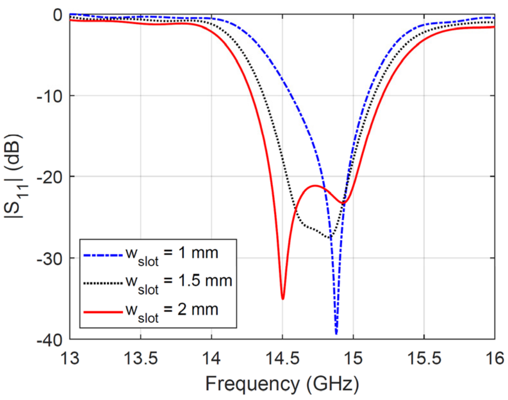
- Number of slots limited by the impedance bandwidth of the slotted waveguide antenna.

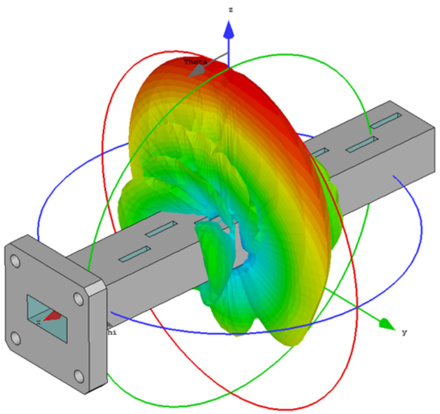
- Antenna efficiency is directly proportional to the number of slots and increases with these.

- **OBJECTIVE**: maximize $|S_{11}|$ impedance bandwidth and obtain uniform radiation pattern.

- **TRADEOFF**: eight slots have been used.

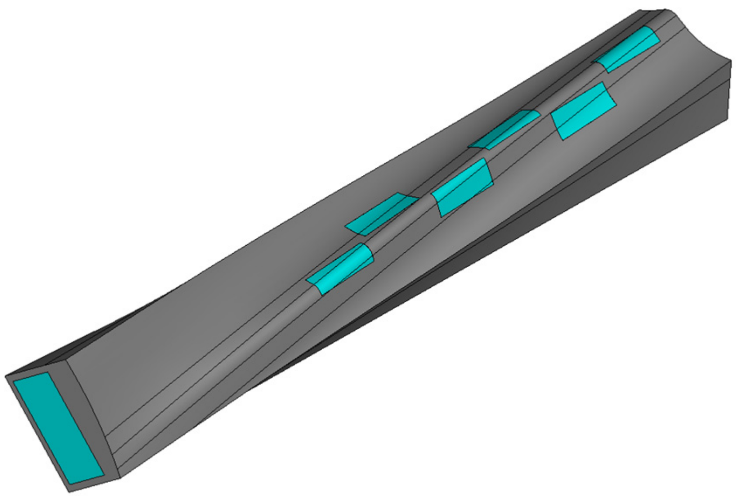
- Critical parameter: width of the slots. A good compromise between impedance bandwidth and antenna efficiency is $w_{slot} = 2\ mm$.

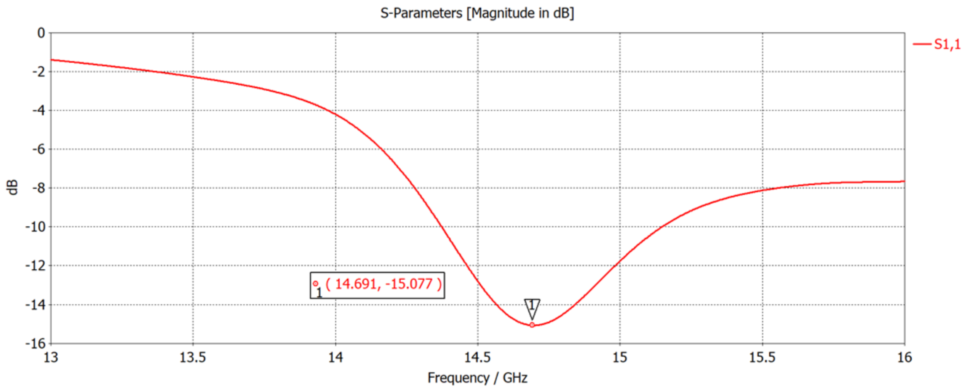




Twisted slotted waveguide antenna design

Good performances obtained for the twisted-slotted case.

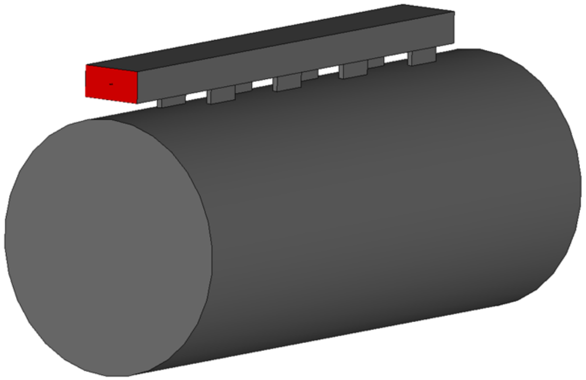


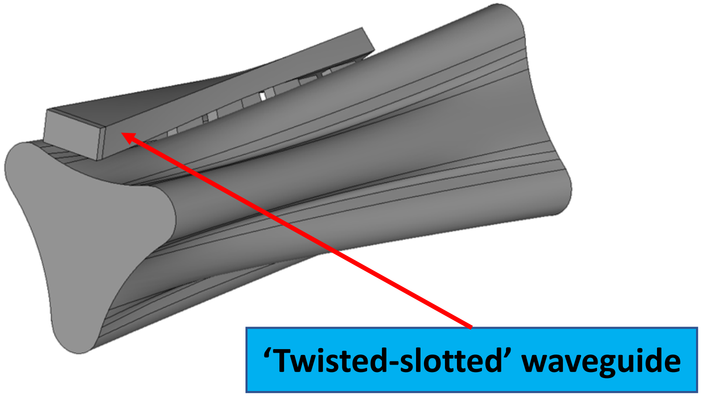


NOTE: antenna models can be scaled up (or down) at any desired frequency.

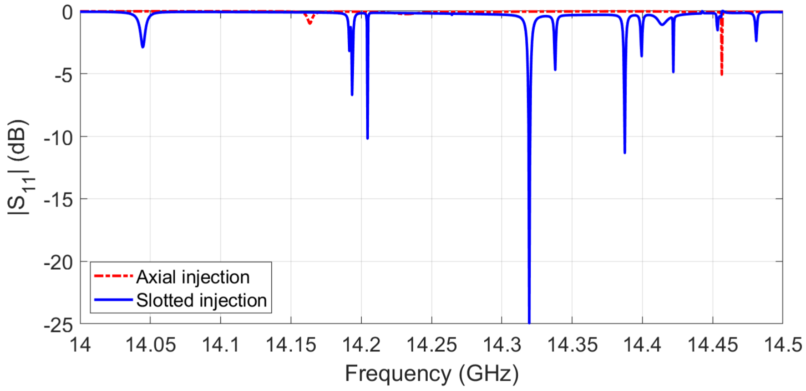
Side-coupled waveguide injection: cylindrical vs. 'plasma-shaped' cavity (1/2)

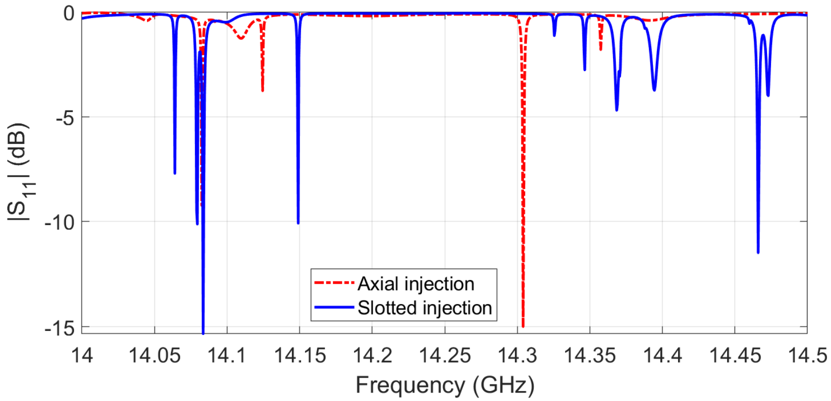
- **Next step**: coupling of the slotted waveguide to the employed plasma chambers.
- Cylindrical and 'plasma-shaped' cavities have been simulated with a side-coupled slotted waveguide.
- 'Plasma-shaped' cavity employs a twisted-slotted waveguide.

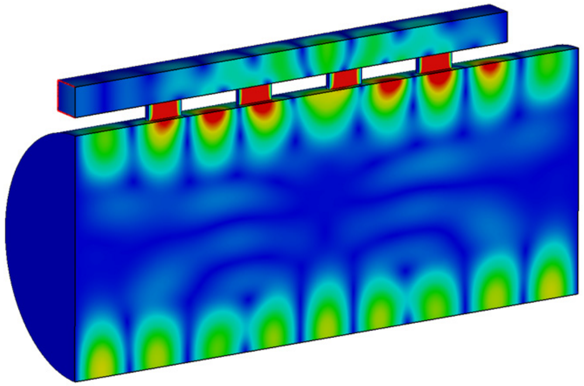


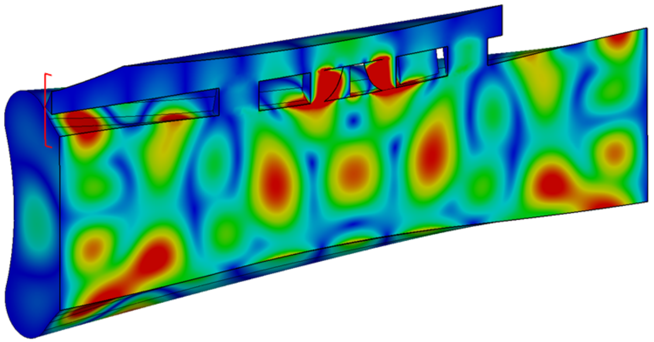


Side-coupled waveguide injection: cylindrical vs. ‘plasma-shaped’ cavity (2/2)









More modes coupled inside the cavity and better wave-to-cavity match BUT predominance of modes with off-axis electric field maximum.

More modes coupled inside the cavity and better wave-to-cavity match PLUS possibility to obtain modes with predominant axial field maximum.

Conclusions

- **An innovative, 'plasma-shaped' cavity resonator to be employed in ECRISs has been presented.**

- Advantages with respect to the classic cylindrical cavity:

a) modes with a predominance of electric field on axis can be (relatively) easily excited;
b) more space is available for the surrounding magnetic system (i.e. axial coils).

- **A novel microwave launching scheme for ECRIS plasma chambers, based on slotted waveguides placed along the chamber outer wall, has also been studied.**

- Advantages with respect to the axial waveguide launch scheme:

a) number of modes coupled into the cavity is greatly improved: advantage in single frequency tuning operations;
b) more symmetric field and homogeneous power distribution from the multiple radiating waveguide slots;
c) possibility to have more space available on the injection flange for other ancillaries;
d) potential capacity to handle higher input power with multi-branch slotted waveguide system.

Perspectives

- **Short term** perspectives (next months):

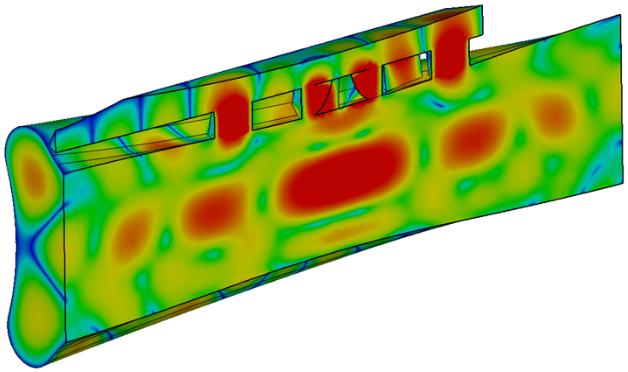
1. tuning of the side-coupled injection system in order to obtain improved mode profiles;
2. realization and experimental characterization of 'cold' models (antennas, cylindrical cavity + slotted waveguide).

- **Mid term** perspectives (next year):

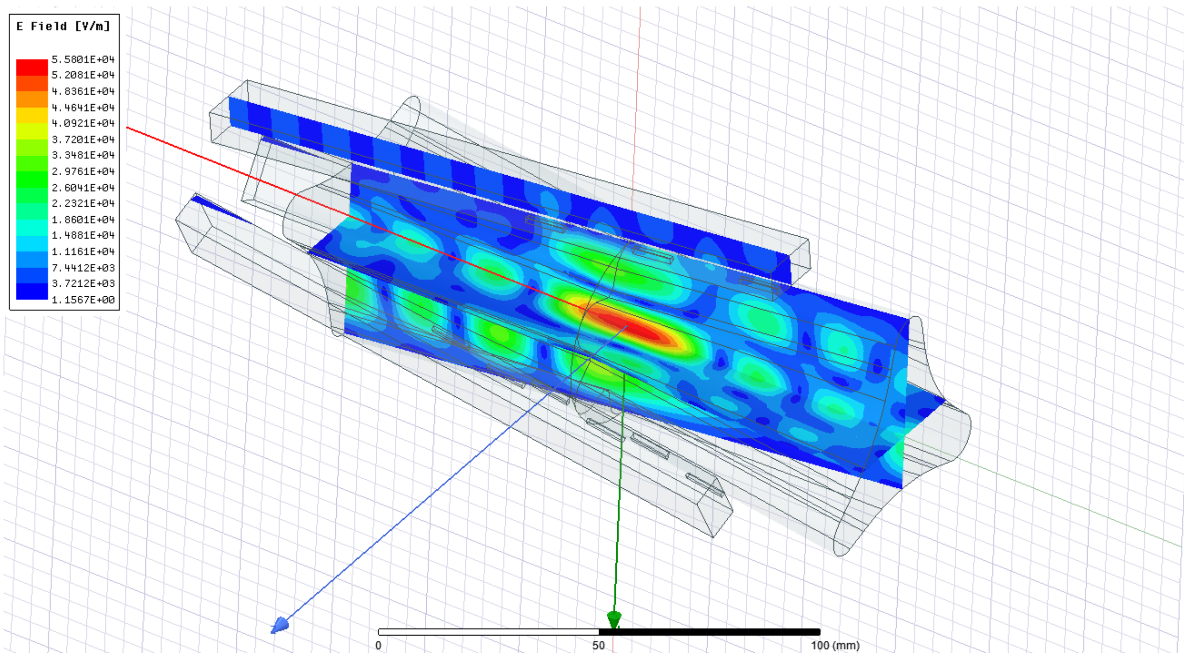
1. realization of the plasma chamber plus side-coupled injection system with additive manufacturing technique;
2. prototype test by using LNS CAESAR ion source setup.

- **Long term** perspectives:

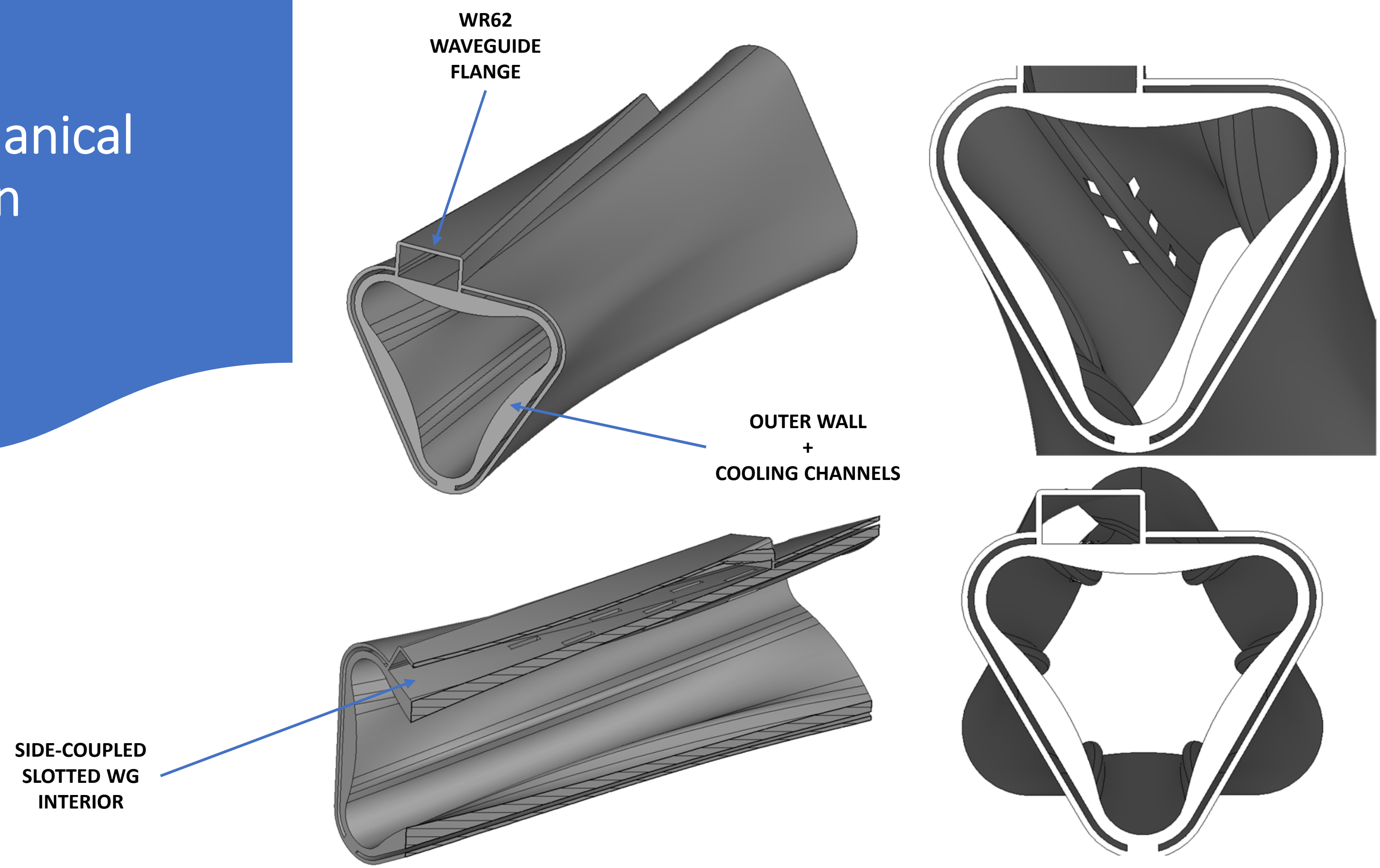
1. study of a less invasive superconducting hexapolar structure employable with the IRIS plasma chamber;
2. study of a radially-symmetric multi slotted waveguide injection system (splitter) for higher input power.



Radially-symmetric microwave injection system

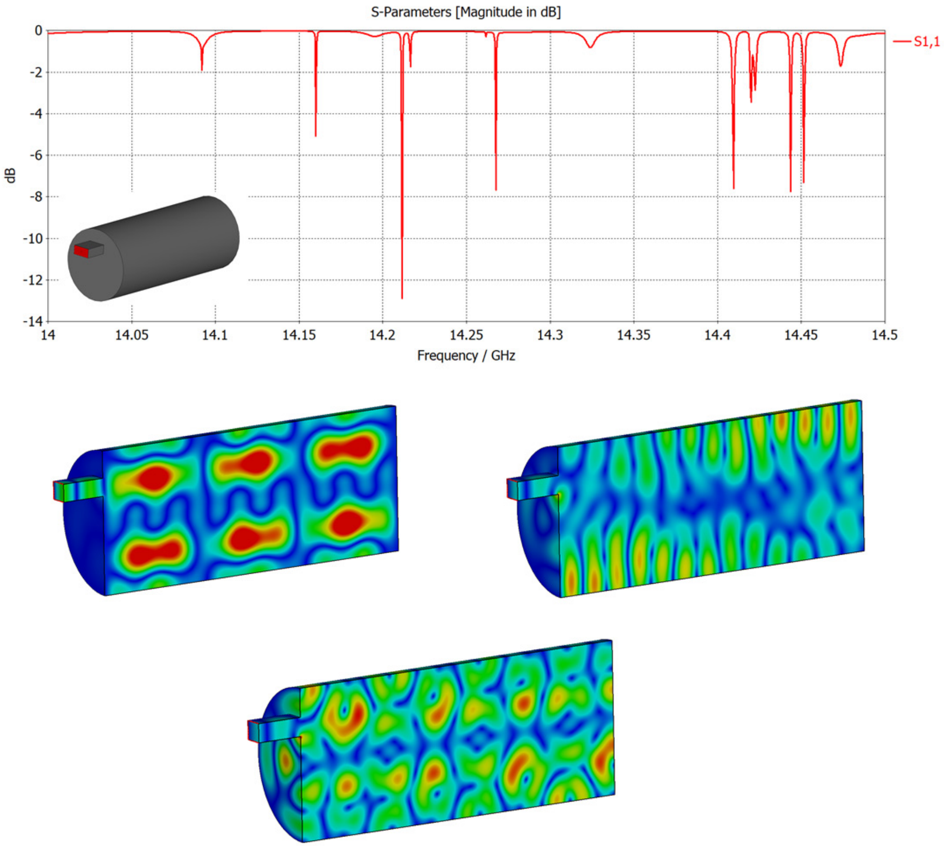


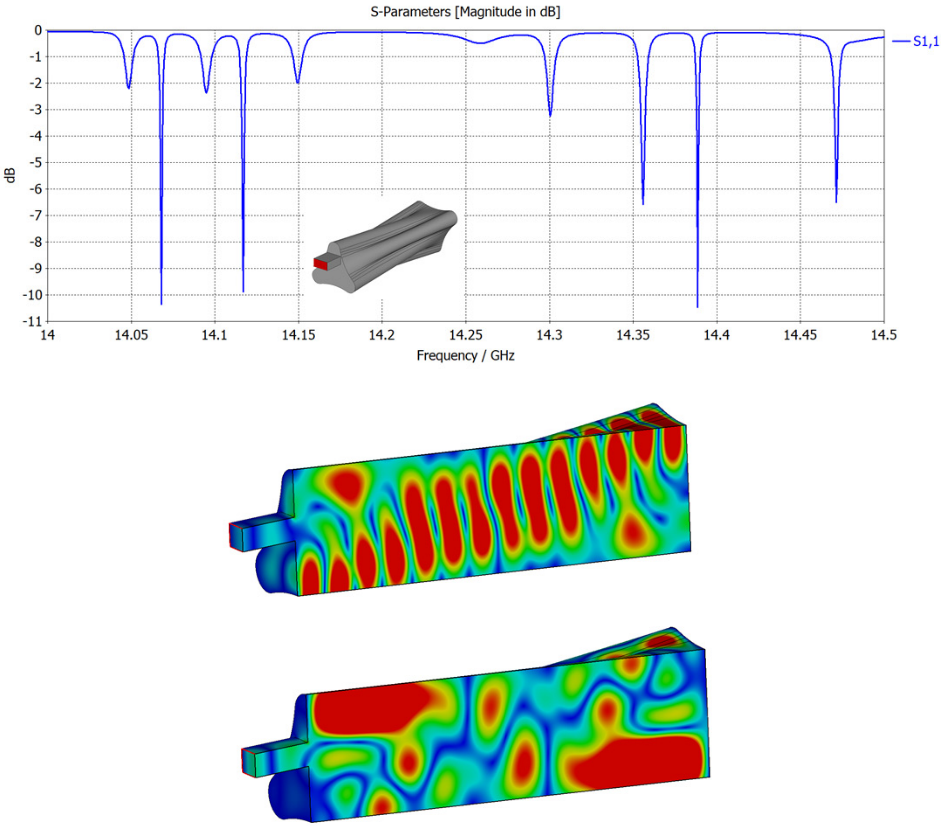
Mechanical design

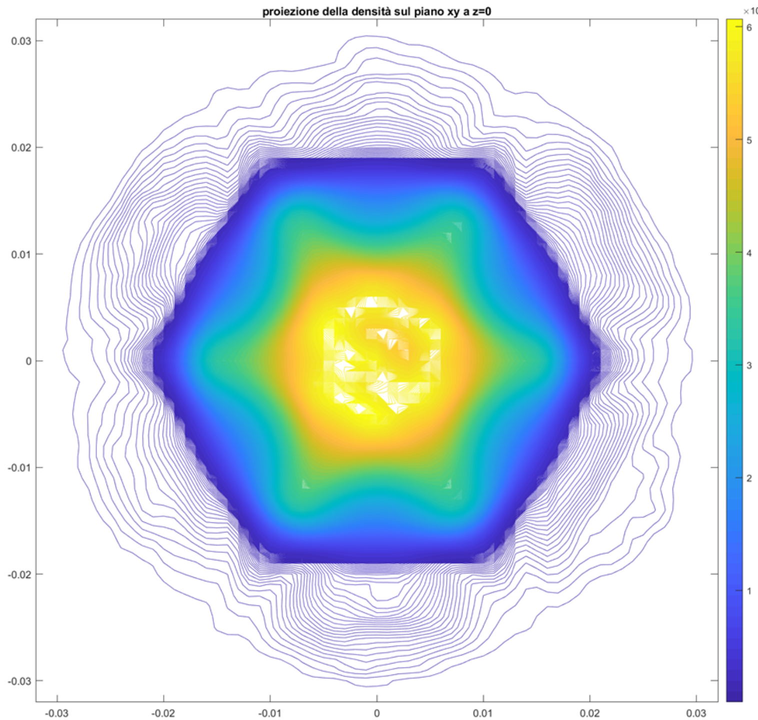


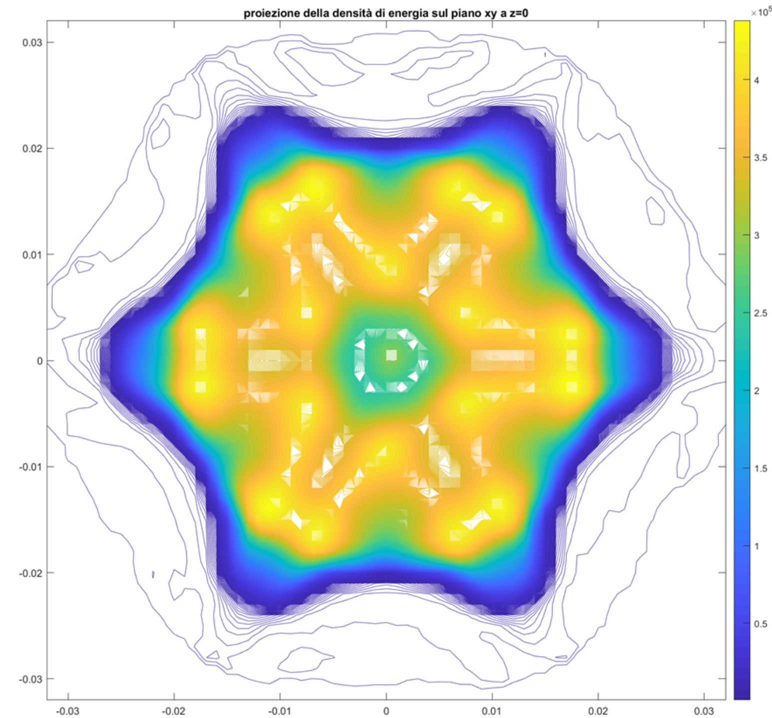
Thank you!

Shifted axial waveguide injection









A. Pidatella (INFN-LNS): Progress in self-consistent modeling of time-and-space dependent phenomena in ECRIS plasma.