Slotted Antenna Waveguide for Microwave Injection in Ion Sources

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Introduction and motivation

- Microwave-to-plasma coupling in ECR Ion Sources is based up to now on the matching of a rectangular waveguide (positioned off-axis on the end-plate) of the cylindrical plasma chamber.

- In order to improve the ECR heating scheme (i.e. performances), some novel microwave launch models needs to be developed.

- We present the numerical modeling of an innovative microwave launching scheme in ECR ion sources that employs a slotted waveguide placed on the chamber side wall.

- The new launcher geometry presents some peculiar advantages with respect to the standard axial launcher:

1. **The number of modes inside the plasma chamber is greatly improved: this could lead to some advantages in terms of ion source frequency tuning;**

2. **This new solution also releases space on the end flanges of the plasma chamber for the necessary ancillary equipment while offering a distribute and more homogeneous power transfer to the plasma.**

Basics of Electron Cyclotron Resonance Ion Source (ECRIS)

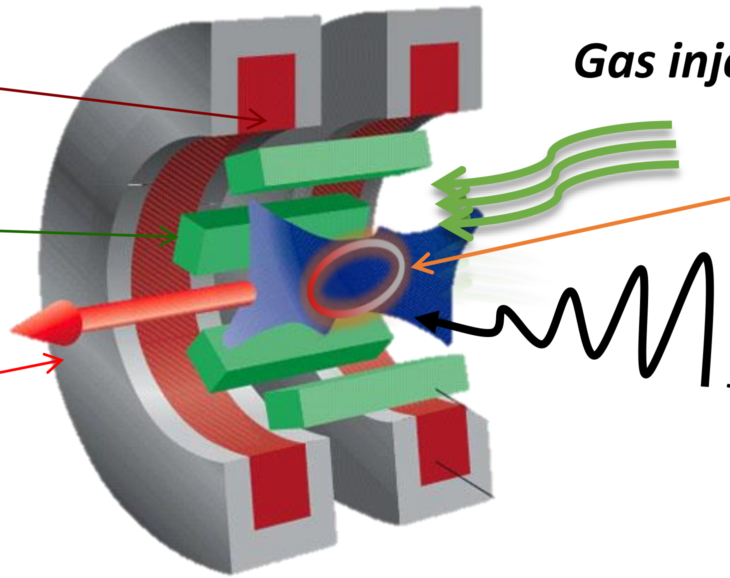
- The Electron Cyclotron Resonance Ion Sources (ECRISs) are nowadays the most effective devices to provide intense currents for highly charged ions devoted to particle accelerators for nuclear science and applications.

- In ECRISs, the main mechanism of microwave-to-electrons energy transfer is the Electron Cyclotron Resonance heating, when the electron cyclotron resonance frequency $\boldsymbol{f_{ce}} = \boldsymbol{eB_{ECR}/(2\pi m_e)}$ equals the frequency $\boldsymbol{f_{\mu wave}}$ of the injected microwaves ($\boldsymbol{m_e}$ and $\boldsymbol{e}$ are the electron mass and charge, $\boldsymbol{B_{ECR}}$ is electron cyclotron resonance field).

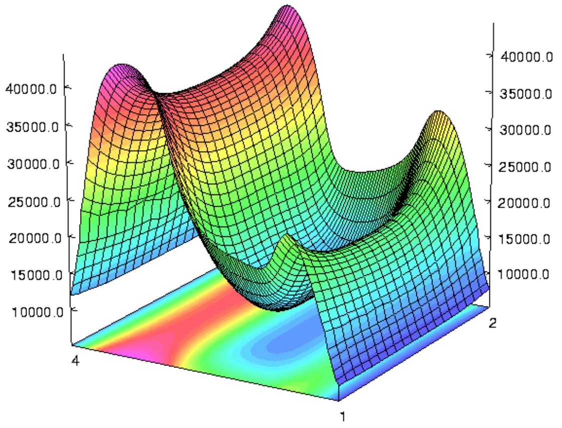
- The plasma is confined by a magnetic field in a so-called *minimum-B-configuration* (the value of the magnetic field has a minimum in the centre of the ion source and from there increases in all directions) which forces the electrons to gyrate around the magnetic field lines at the electron cyclotron frequency $\boldsymbol{f_{ce}}$.

- If a microwave radiation of the same frequency ($\boldsymbol{f_{\mu wave}} = \boldsymbol{f_{ce}} \sim \text{tens GHz}$) is feeding the plasma, electrons are resonantly (stochastically) heated from the right-hand circularly polarized wave. The ECR heating produces the plasma by electron-impact ionization and a beam of ions can be electrostatically extracted through a high voltage extraction aperture.

Basics of Electron Cyclotron Resonance Ion Source (ECRIS)



- The plasma **electrons** are heated resonantly with microwaves @ **ECR**
- The plasma **Ions** remain **cold**



Minimum-B magnetic field structure

ECR Plasma key parameters

$n_e \sim 10^{12}$ cm^{-3}

$T_e \sim$ tens keV - $T_i \sim$ few eV

$\tau_{ion} \sim$ ms

High Charge State Ion Sources

Driven by the need to use high charge states to increase the final energy for the **accelerator**

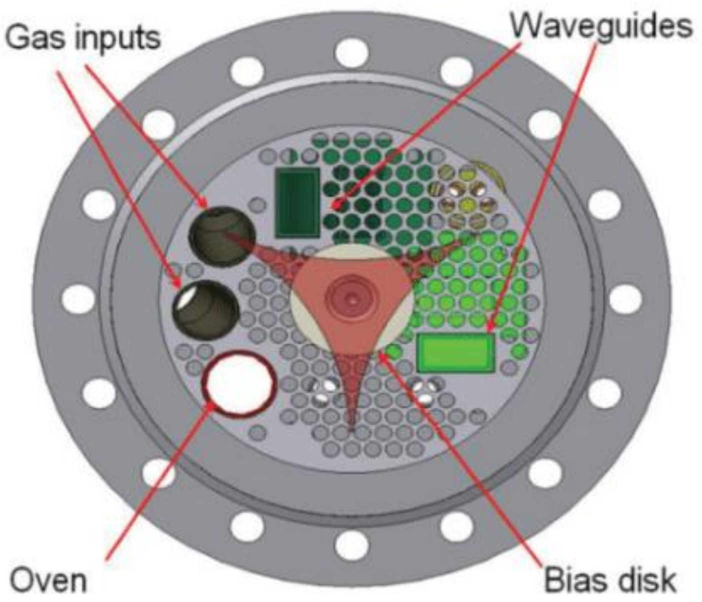
Microwave coupling in ECRISs

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

1. Higher frequency and higher microwave power (up to the the onset of plasma instabilities).

2. double (or triple) frequency heating to improve plasma stability and source performances. The limiting factor on the number of microwave heating frequencies is the available space for waveguide feedthroughs at the injection flange.

3. off-axis microwave coupling placed in-between plasma flutes to increase the coupling efficiency.



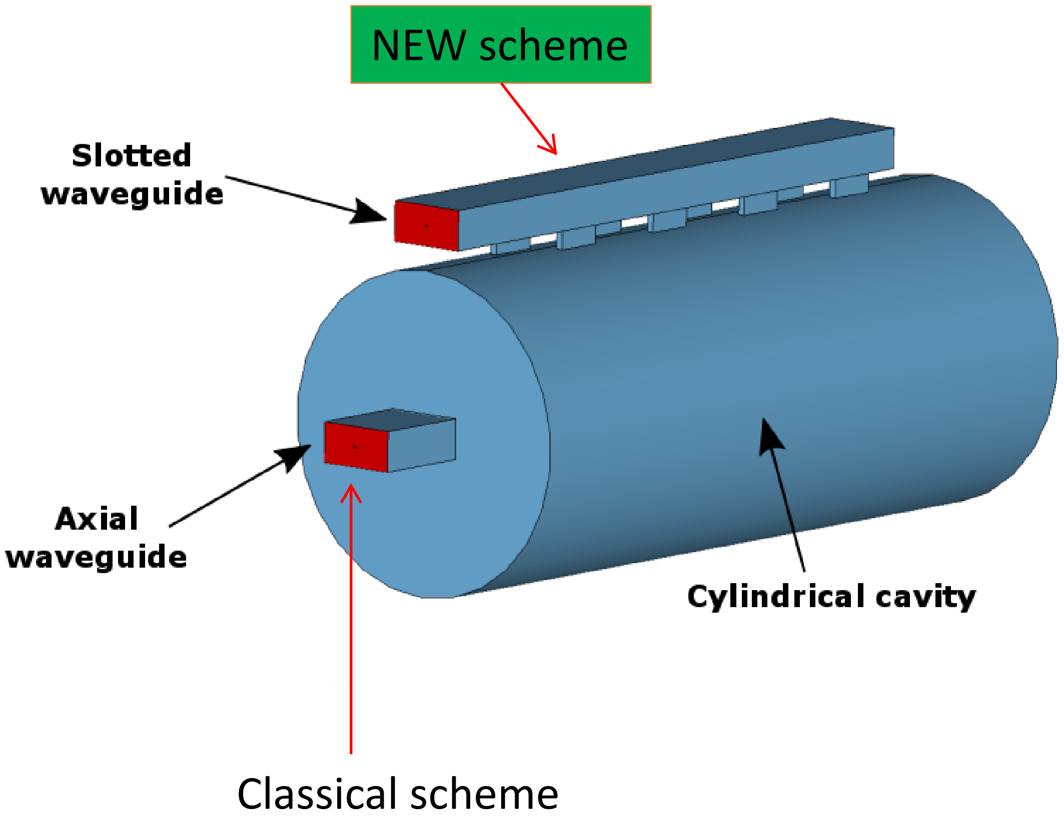
ECR ion source injection flange typical layout.

Innovative proposed structure: overview

We present a geometry composed of:

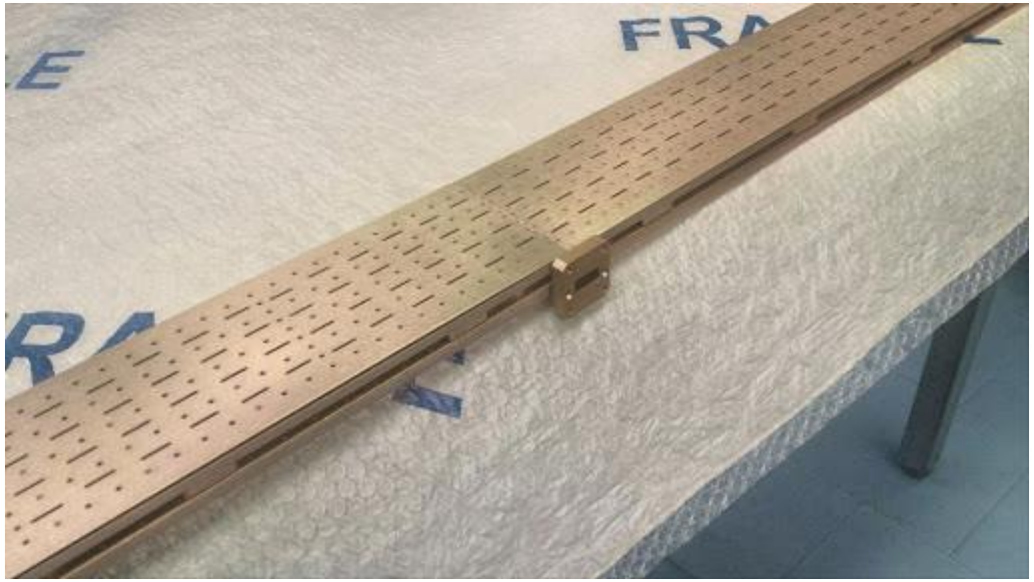
1. a cylindrical cavity of diameter *D = 63.5 mm* and length *L = 150 mm* (typical dimensions for an ECRIS plasma chamber);

2. two rectangular WR62 waveguides for microwave injection: a regular standard axial waveguide and the new proposed **side coupled waveguide**, running along the chamber outer wall, that is coupled to the cavity through several **slots**.



Slotted waveguide antenna design (1/4)

- Slotted waveguides have found many applications in radar and communication systems due to their low-profile design requirements, mechanical robustness, good efficiency, relative ease of realization and wide operational frequency bandwidth.



http://www.4and4eight.com/products/slotted-waveguide-arrays

Slotted waveguide antenna design (2/4)

- We started with the design of a slotted waveguide antenna working in free space.

- The guided wavelength for the TE_{10} mode of the rectangular waveguide is:

$$\lambda_g = \frac{c}{f}\frac{1}{\sqrt{1-c/(2af)}}$$

- The general rules for the slotted waveguide antenna project are:

1. the center of the first slot should be placed at a distance $\frac{\lambda_g}{4}$ from the waveguide input aperture;

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 to $\frac{\lambda_g}{2}$;

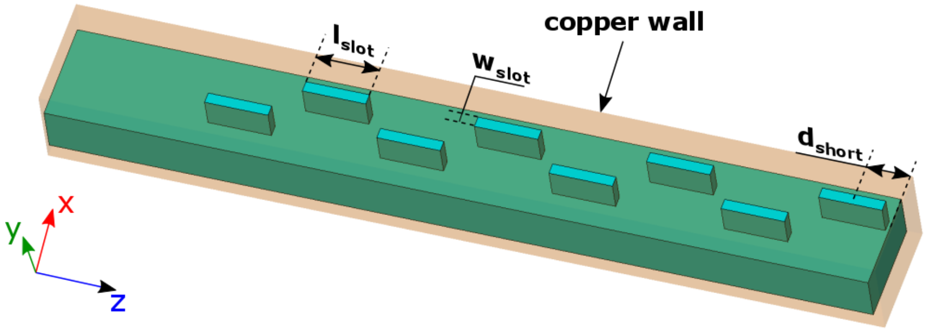
4. the slot length should be equal to $\frac{\lambda_0}{4}$, where λ_0 is the free space wavelength, while the slot width should be much smaller with respect to λ_0.

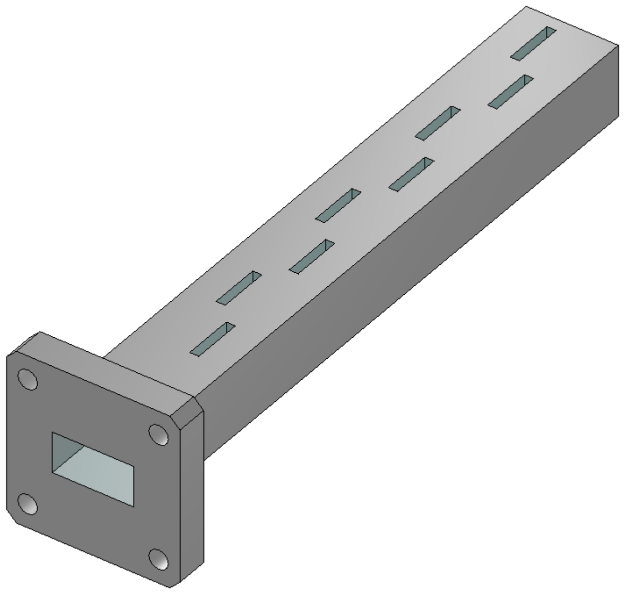
Slotted waveguide antenna design (3/4)

- The exact slotted waveguide antenna dimensions can be finely tuned by the use of the electromagnetic simulator.

- For the antenna realization, a standard WR62 waveguide has been used (input aperture dimensions: a = 15.8 mm, b = 7.9 mm).

- The presented antenna, designed with the use of CST Microwave Studio, works in the band [14.2; 15.25] GHz with central frequency 14.7 GHz.





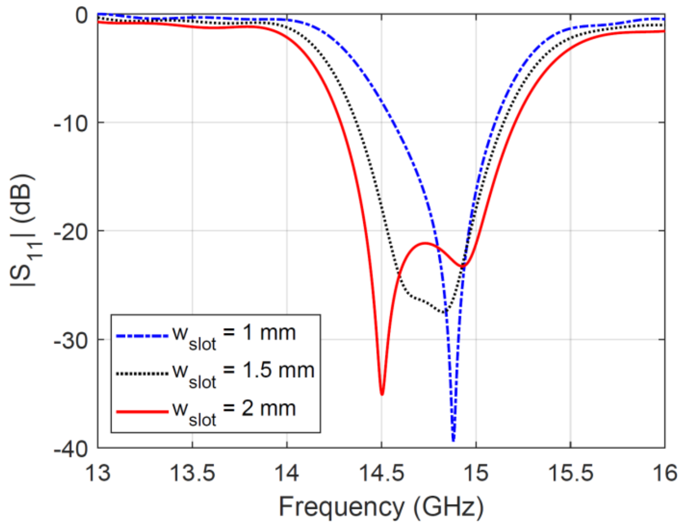
Slotted waveguide antenna design (4/4)

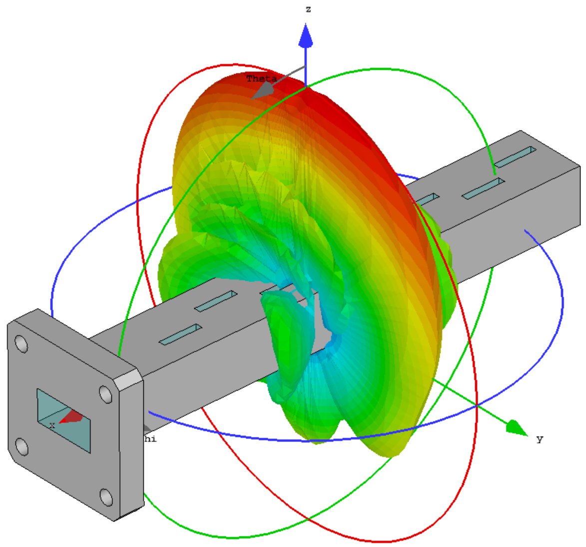
- The number of slots that can be arrayed in a single waveguide antenna is limited. The impedance bandwidth of the slotted waveguide antenna narrows rapidly with an increasing number of elements.

- On the other hand, the antenna efficiency is directly proportional to the number of slots and increases with these.

- With the objectives to maximize the $|S_{11}|$ impedance bandwidth and to obtain an almost uniform radiation pattern we have chosen to implement eight slots.

- Another critical parameter that can affect the impedance bandwidth is the width of the slots. A good compromise between impedance bandwidth and antenna efficiency has been found when w_{slot} = 2 mm.





Side coupling scheme vs. axial coupling scheme (1/2)

- The next step considers the coupling of the slotted waveguide to the employed plasma chamber.

- The cylindrical cavity has been simulated considering two microwave launch geometries:

1. **standard** axial launch with a rectangular WR62 waveguide;
2. launch along the chamber outer wall by the use of the **slotted waveguide**.

- The numerical study has been divided into three steps:

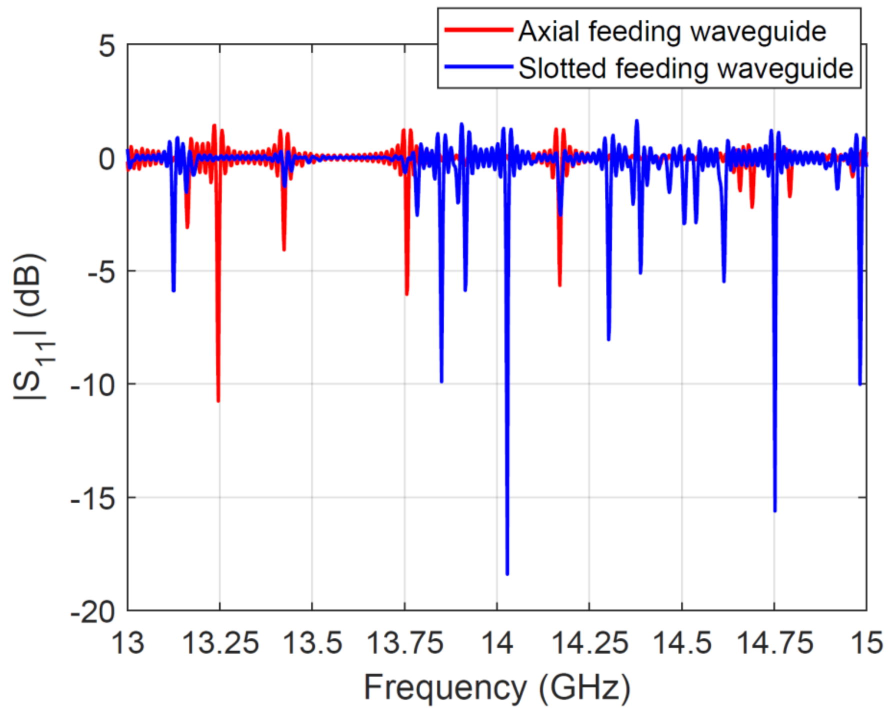
a) simulation of the cylindrical cavity with only the presence of the launch axial waveguide;

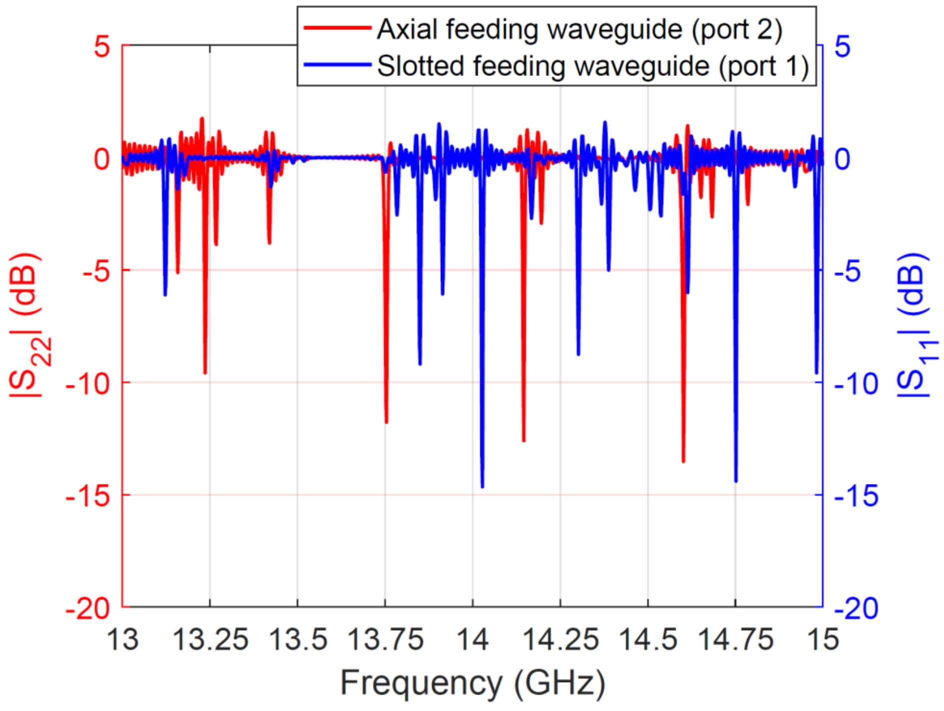
b) simulation of the cylindrical cavity with only the presence of the launch side coupled slotted waveguide;

c) simulation of the cylindrical cavity with the presence of both launch geometries (two ports simulation).

Side coupling scheme vs. axial coupling scheme (2/2)

The previously described steps have been simulated through the full wave software CST and the results have been analyzed.





Steps a) and b): it is found that the slotted waveguide launch scheme excites a **larger** number of modes inside the cavity with respect to the axial launch scheme. Advantage in single frequency operation of the ion source, when the frequency tuning effect is applied.

Step c): both waveguides have been fed through two waveguide ports. The modal distributions inside the band of interest remains almost the same. The two launch schemes do not interfere with each other.

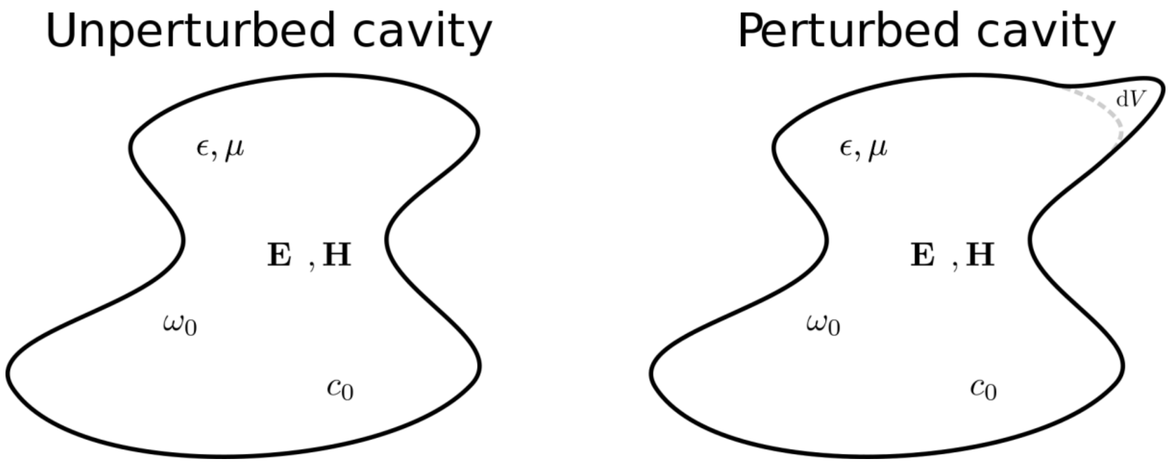
Field measurement in cavities: Slater perturbation method

- For a cavity on resonance, the stored electric and magnetic energies are equal.

- If a small perturbation is introduced into the cavity (for example by changing its shape), this will produce an unbalance in the electric and magnetic energies, and the resonant frequency will shift to restore the balance.

$$\frac{\Delta\omega_0}{\omega_0} = \frac{\int_{\Delta V}(\mu H^2 - \epsilon E^2)\mathrm{d}V}{\int_V(\mu H^2 + \epsilon E^2)\mathrm{d}V} = \frac{\Delta U_m - \Delta U_e}{U}$$

- Slater perturbation theory provides the basis for field measurement in cavities.



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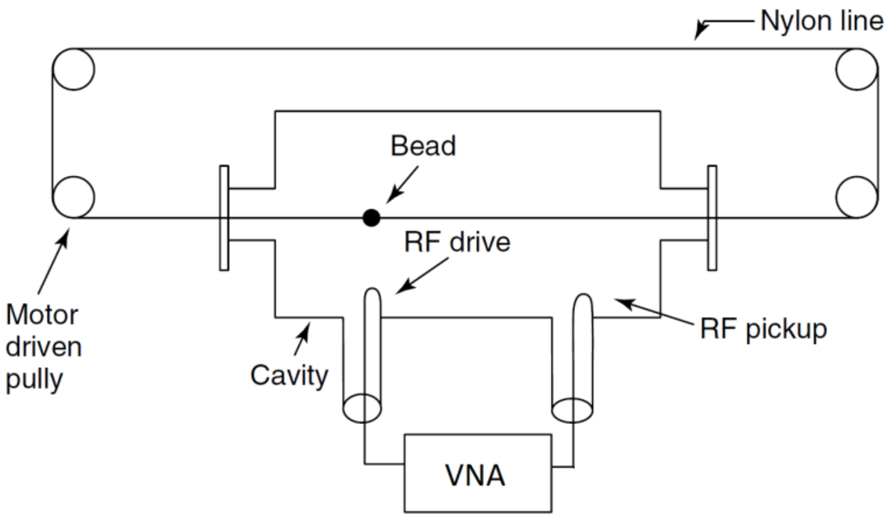
Electric field measurement through the bead-pull technique (1/2)

- In manufacturing or tuning single or multicell cavities it is required to investigate the field profile inside them.

- The field can be sampled by introducing a perturbing object (a small bead made of dielectric or metallic material), pulled along the RF cavity through a non-conducting wire, and measuring the change in resonant frequency at each position.

- The frequency shift will be proportional to the electromagnetic field at each bead sampled point.



$$\frac{\Delta\omega_0}{\omega_0} = -\frac{3\Delta V}{4U}\left[\frac{\epsilon_r - 1}{\epsilon_r + 2}\epsilon_0 E^2 + \frac{\mu_r - 1}{\mu_r + 2}\mu_0 H^2\right]$$

ΔV is the bead volume, U is the stored energy inside the cavity, |E| and |H| are the electric and magnetic field of the mode being considered.

Electric field measurement through the bead-pull technique (2/2)

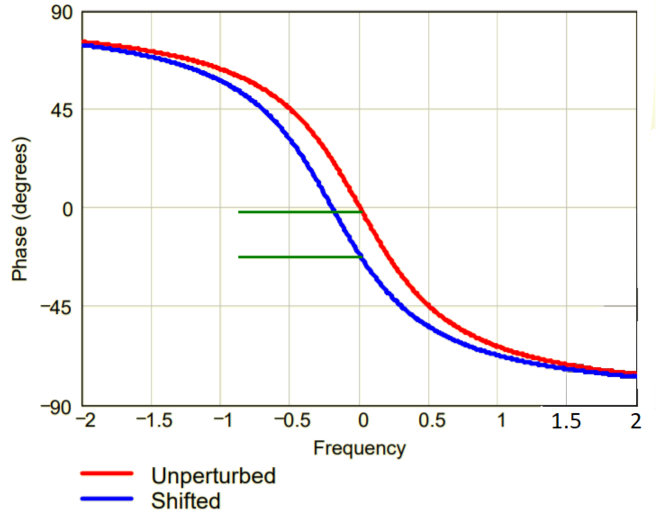
- For small perturbations, shifts in the peak of the cavity response are hard to measure.

- Phase shift caused by the movement of the bead through the cavity is much easier to measure.

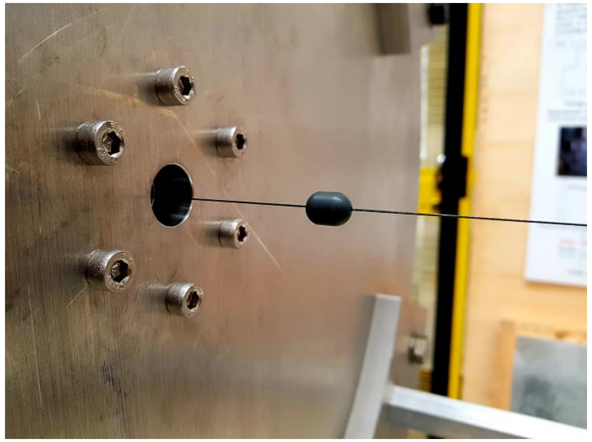
- Considering a spherical or cylindrical perturbator, the electric field can be related to phase shift $\Delta\Phi(z)$ introduced by the perturbator movement along the cavity axis *z* by using Slater theorem:

$$E(z) = \sqrt{\frac{\Delta\phi(z)}{2Q_L} \frac{U}{\epsilon_0 \pi r^3} \frac{\epsilon_r + 2}{\epsilon_r - 1}}$$

Q_L = cavity loaded quality factor, U = cavity stored energy, r = perturbator radius.



https://uspas.fnal.gov/materials/08UMD/SRF/Bead-Pulling.pdf



Dielectric bead for field measurement at the input flange of a RF cavity.

Simulation of the bead-pull measurement

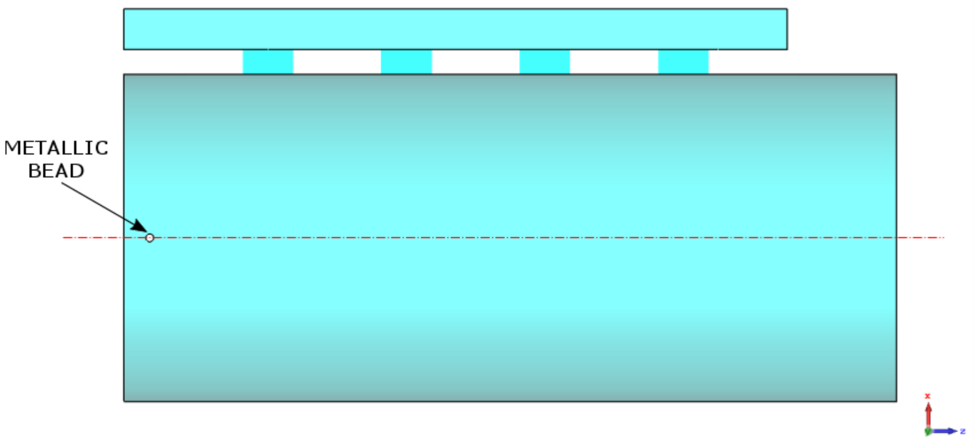
- It is useful to evaluate the electric field profile for a selected mode by using the Slater perturbation method.

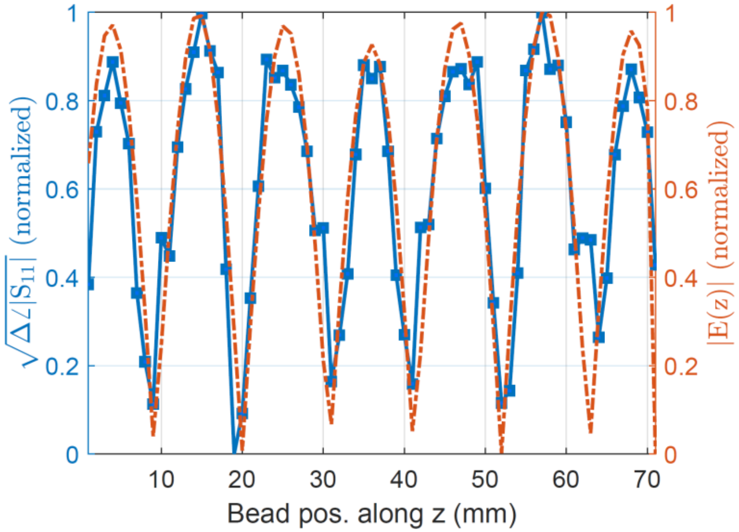
- Using the slotted waveguide feeding scheme, a mode at (unperturbed) frequency f = 14.612 GHz with a predominant electric field along the cavity *z* axis has been chosen as the objective of the full wave simulation.

- A small metallic spherical bead of diameter 1.4 mm has been moved along the cavity axis for a distance of 140 mm, with a step of 2 mm, and the $|S_{11}|$ of the mode of interest has been acquired at each step.

- The electric field can be related to the phase shift at each position of the metallic bead, as:

$$|E| \sim \sqrt{\Delta\angle|S_{11}|}$$





Electric field obtained with the bead-pull simulation (blue curve) vs. electric field profile evaluated along the cavity axis through a standard simulation (orange curve). Curves are normalized to the maximum value.

Conclusions

- A novel microwave launching scheme for ECRIS plasma chambers, based on the use of a slotted waveguide placed along the chamber outer wall, has been presented.

- The **slotted waveguide** has firstly been studied as an antenna in free space, with the objective to study its behaviour against its fundamental design parameters.

- Subsequently, the slotted waveguide has been jointed to a cylindrical plasma chamber and the modal distribution has been evaluated and compared to the case of a standard axial launch scheme.

- The use of the side coupled launch scheme greatly improves the number of modes that can be coupled into the plasma chamber: this could be an advantage in single frequency tuning operations, in order to improve the performances of the ECRIS.

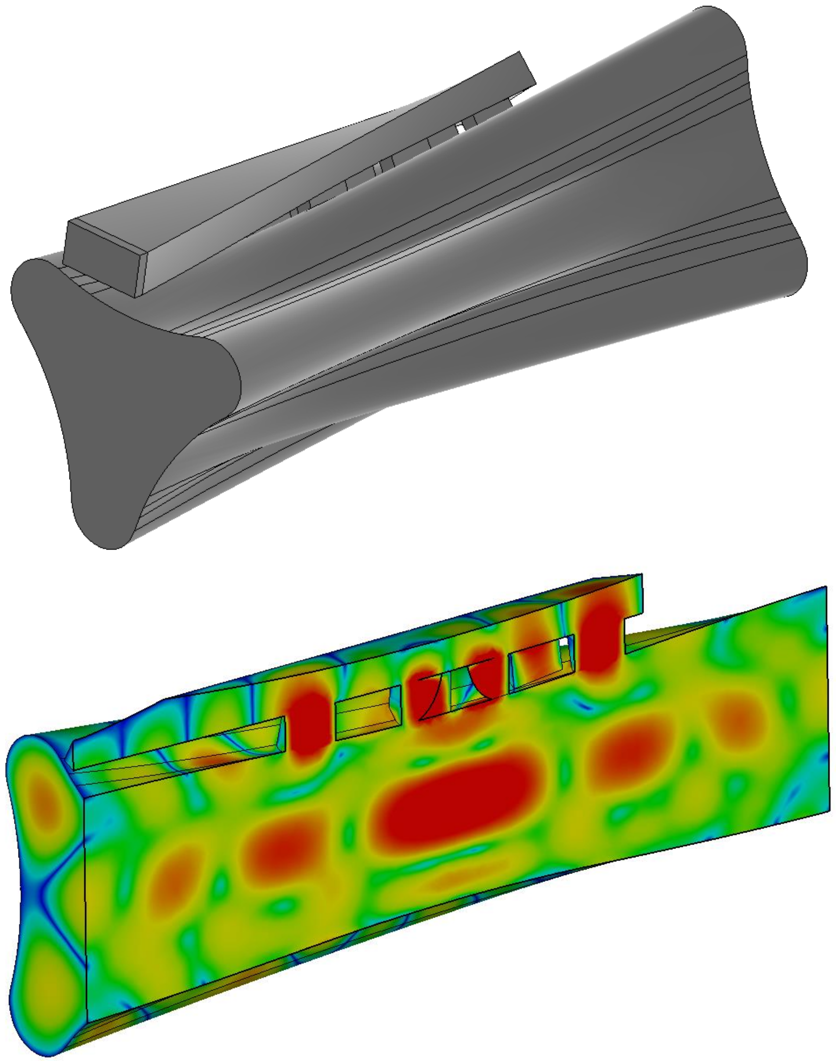
- Other advantages with respect to the standard axial launch scheme are a) more symmetric power distribution from the multiple radiating waveguide slots and b) the possibility to have more space available on the injection flange for other ancillaries.

Perspectives

- The presented side-coupled microwave injection system can be implemented in conjunction with an unconventionally-shaped cavity resonator, inspired by the typical star-shaped ECR plasma, determined by the magnetic field structure.

- Simulations show that this innovative design could improve ECRISs performances because of the ability to maximize the on-axis electric field with respect to a standard cylindrical cavity, while at the same time being more compact with respect to the latter.

Italian patent pending n. 102020000001756



Innovative 'plasma-shaped' plasma chamber with a 'twisted' side-coupled injection system.

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