Plasma processing development for SPIRAL2 quarter-wave resonators: experimental and simulation studies

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Outline

1. **Plasma processing overview**
2. **Plasma processing studies for SPIRAL2**
   - Overview of the experimental results
3. **Plasma modeling**
   - 2D axial symmetry assumption
   - Plasma fluid model
4. **Plasma simulation results**
   - Plasma parameters
   - Coupler breakdown mechanisms
5. **Comparison of experimental and simulation results**
6. **Conclusion & future plans**

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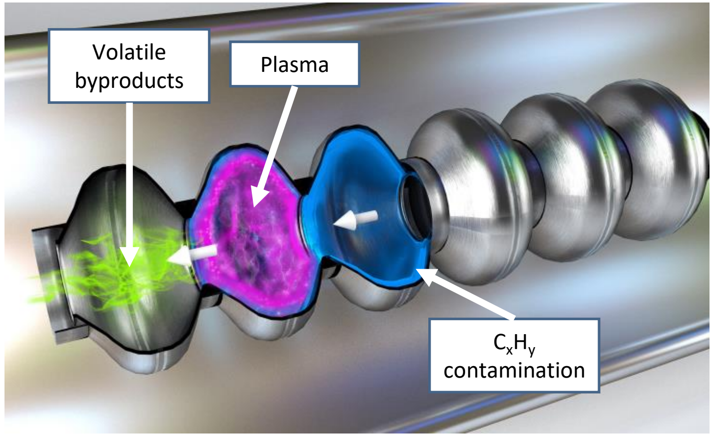
Plasma processing overview

- **WHAT?**
  - Recovery surface treatment
  - In-situ of the cryomodules
  - Used to mitigate field emission in SRF cavities
    - Caused by hydrocarbon pollution (C_xH_y)
- **WHEN?**
  - After a few years of operation
    - When cavity performances decrease due to increased field emission
  - In the future?
    - Before the accelerator commissioning
- **HOW?**
  - Bring the cavities back at room temperature
  - Put gas in the cavity
    - Gas mixture of noble gas (He, Ne, Ar) with a few % of O_2
  - Excite a resonant mode by providing RF power
    - Through fundamental power coupler (FPC) or HOM coupler
  - Plasma ignition
    - Typical processing time = 1 hour (can be repeated twice)

- **PLASMA PROCESSING MECHANISMS**
  - Plasma surface interactions
    - Chemical reactions
    - Low energy ion bombardment
  - Volatile byproducts are pumped out via the vacuum system



Artistic illustration represents the plasma processing technique
(Image credit: ORNL/Jill Hemman)

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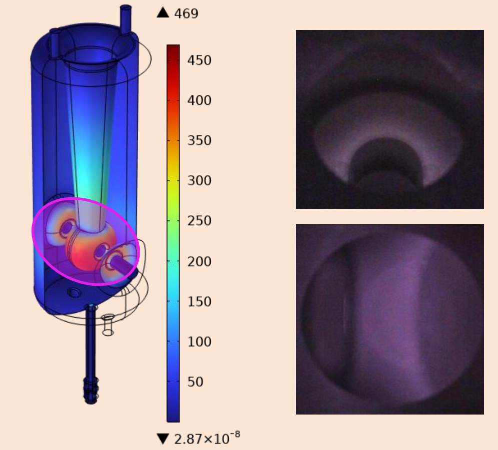
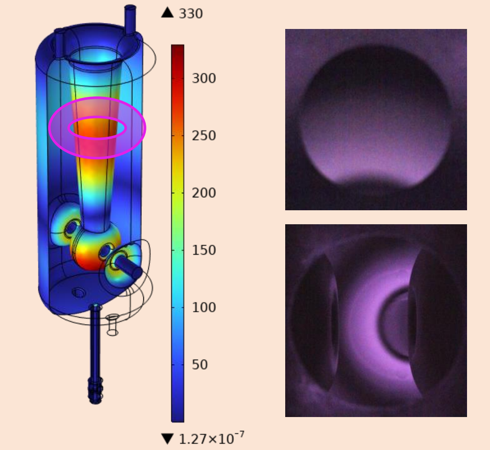
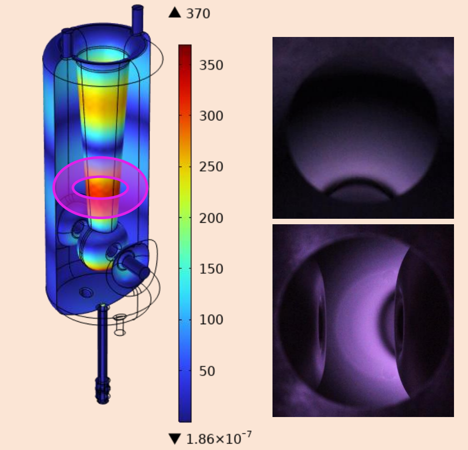
Plasma studies for SPIRAL2

	Mode 1 – 88 MHz	Mode 2 – 251 MHz	Mode 5 – 439 MHz
COMSOL E-field surface plot **Plasma location**			

- **Experimental conditions:**
  - Ar/O_2(10%)
  - P=0.1 mbar (=75 mTorr)

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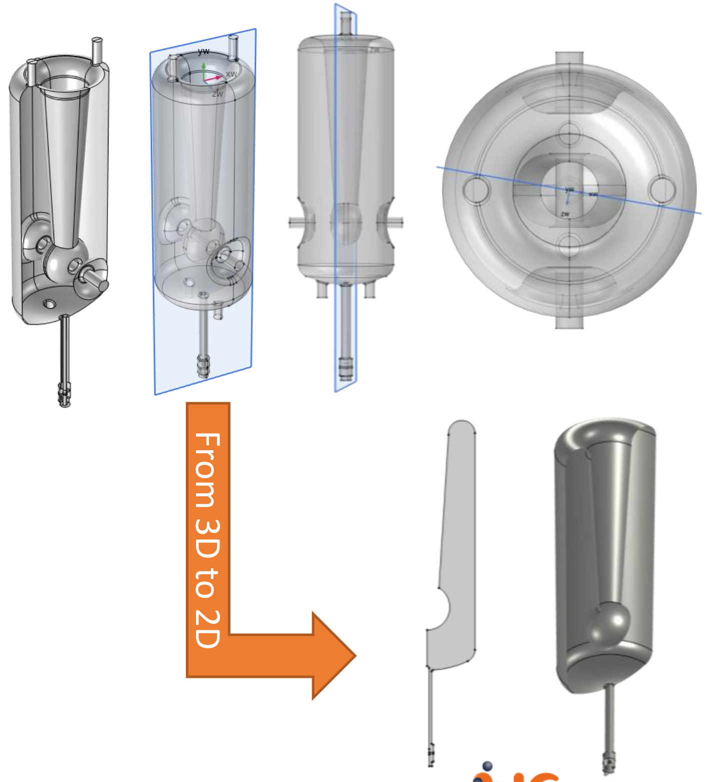
2D axial symmetry assumption

- **Why?**
  - Faster computations than with 3D geometry
    - Typical 2D computing time = a few 10s of minutes
    - Typical 3D computing time = several hours (5 to 24+)
      - Depends a lot on the CPU performance
  - Initial step toward a 3D model
- **How?**
  - Cut a slice from the 3D geometry
  - 2D slice + axial symmetry
- **Is it accurate?**
  - OK for RF parameters
    - f_0, Q_0 @300K, $\beta_{ext}=Q_0/Q_{ext}$ are very similar
  - OK for plasma
    - Plasma distribution is axisymmetric for mode 2 and 5
    - Almost axisymmetric for mode 1



Plasma modeling

Plasma model

- **Plasma fluid model**
  - COMSOL Multiphysics
  - Self-consistent model
    - Maxwell equations coupled with plasma equations
- **Hypothesis**
  - Simple plasma chemistry
    - 100% Ar
  - 2D axial symmetry
  - Maxwellian EEDF

Important plasma parameters to look at

- Electron density
  - $n_e\ [m^{-3}]$
- Mean electron energy
  - $\bar{\varepsilon}\ [eV]$
- Ionization rate
  - $R_e\ [m^{-3}s^{-1}]$
- RF power deposition
  - $RFPD\ [W.m^{-3}]$
  - $RFPD = \frac{1}{2} real\left(|\vec{J}| \cdot |\vec{E}|^*\right)$

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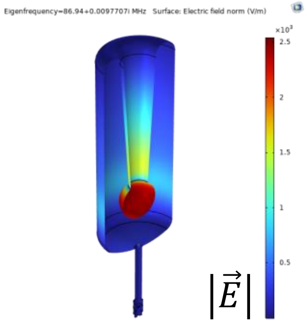
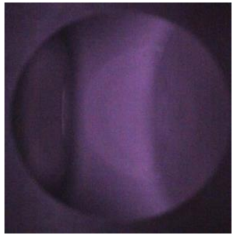
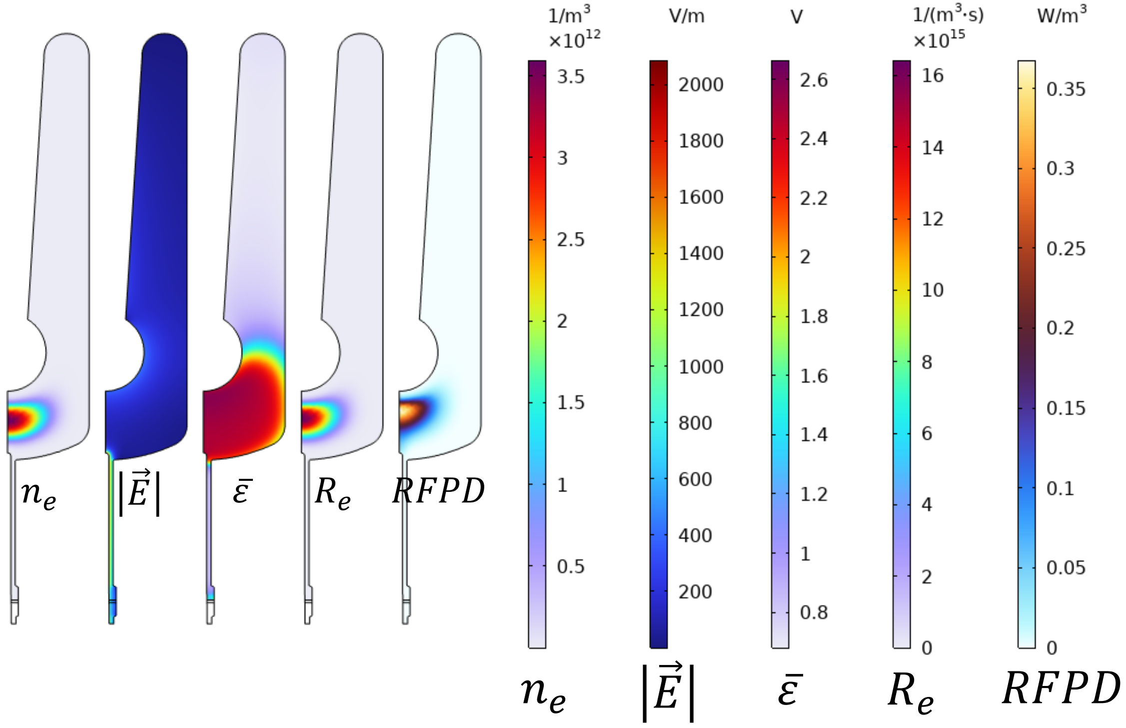
Mode 1 – 88 MHz, 0.3W, 0.1mbar

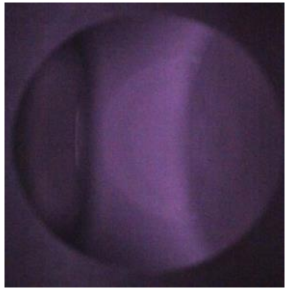


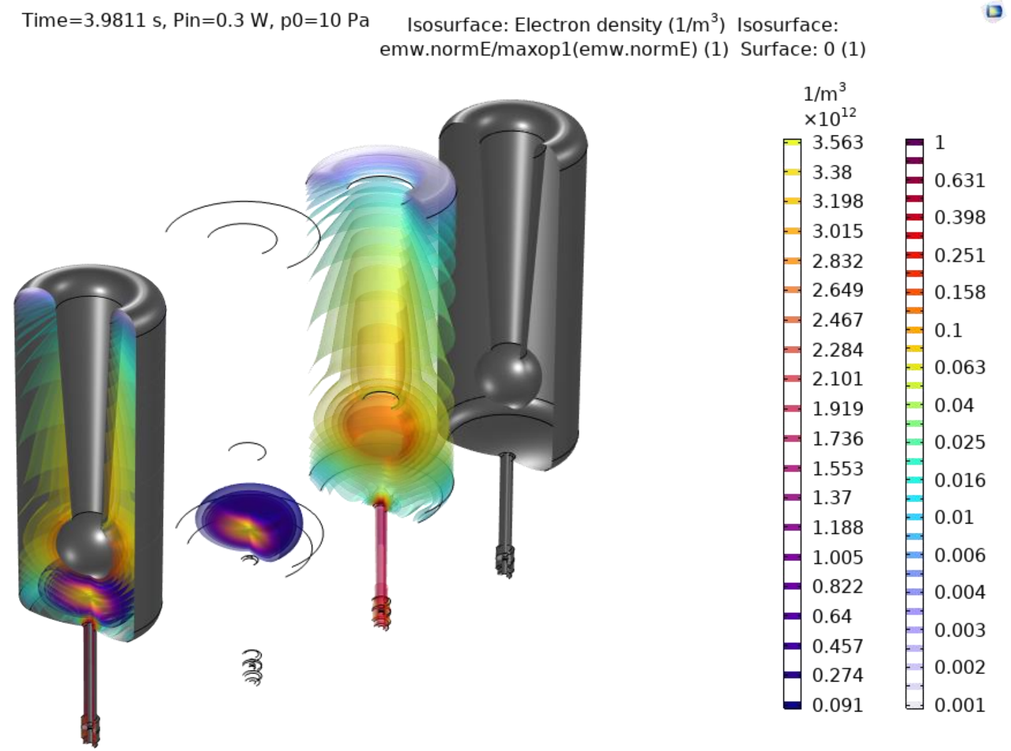




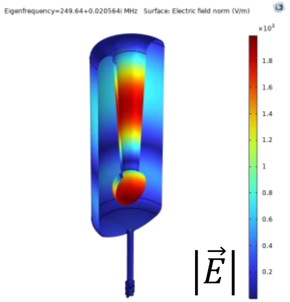
- Plasma location is following observations but looks underneath the central conductor
- **Expectations:** plasma around the central conductor and focused in the accelerating gaps

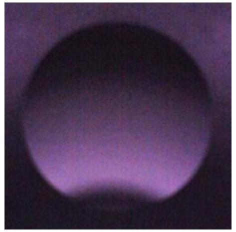
Mode 1 – 88 MHz, 0.3W, 0.1mbar

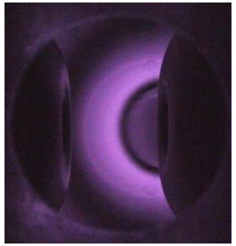


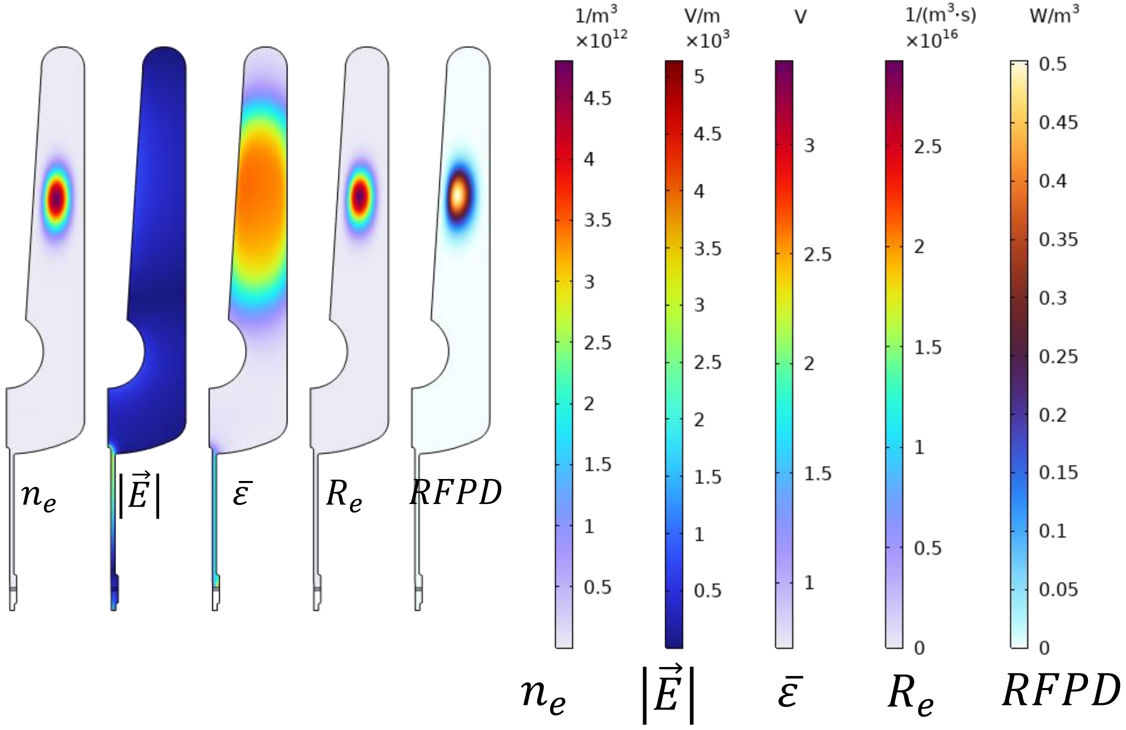


Mode 2 – 251 MHz, 2W, 0.1mbar



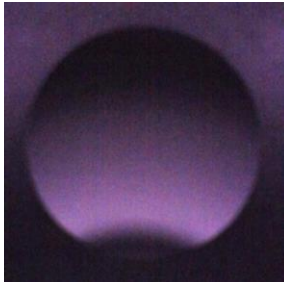


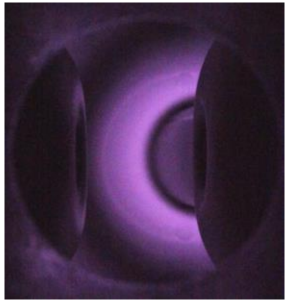


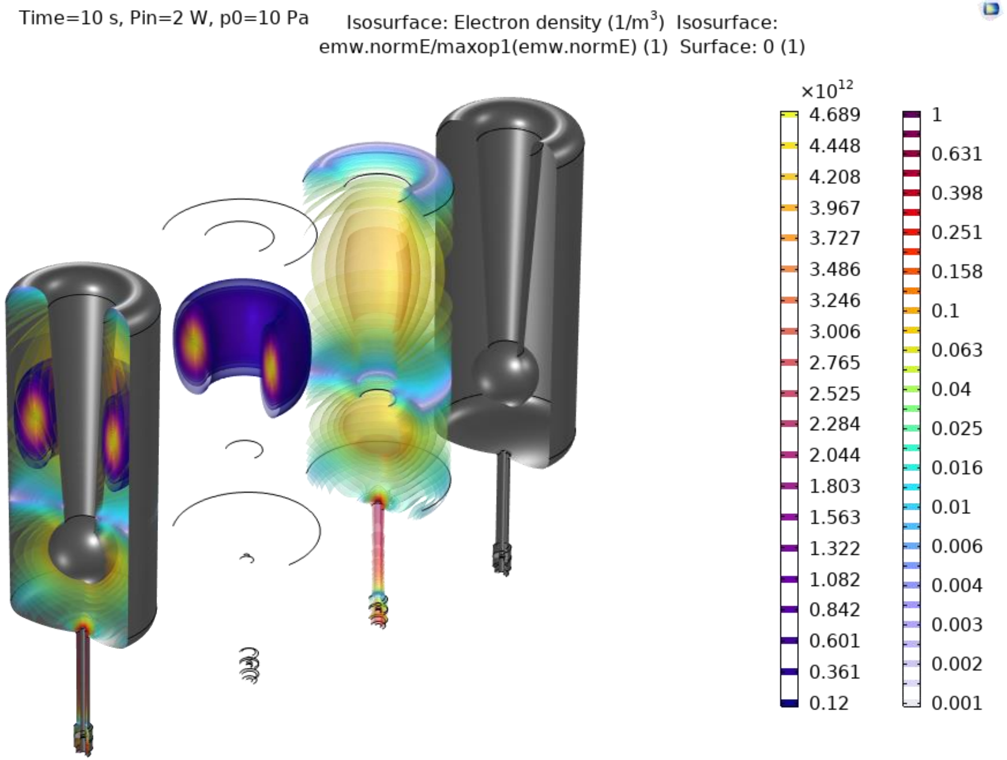


- Plasma location is following observations
  - Plasma torus in the upper part of the cavity

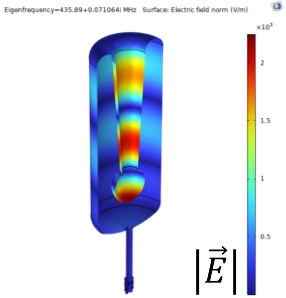
Mode 2 – 251 MHz, 2W, 0.1mbar

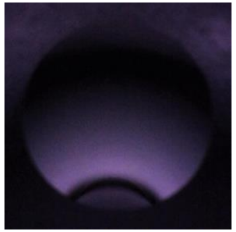


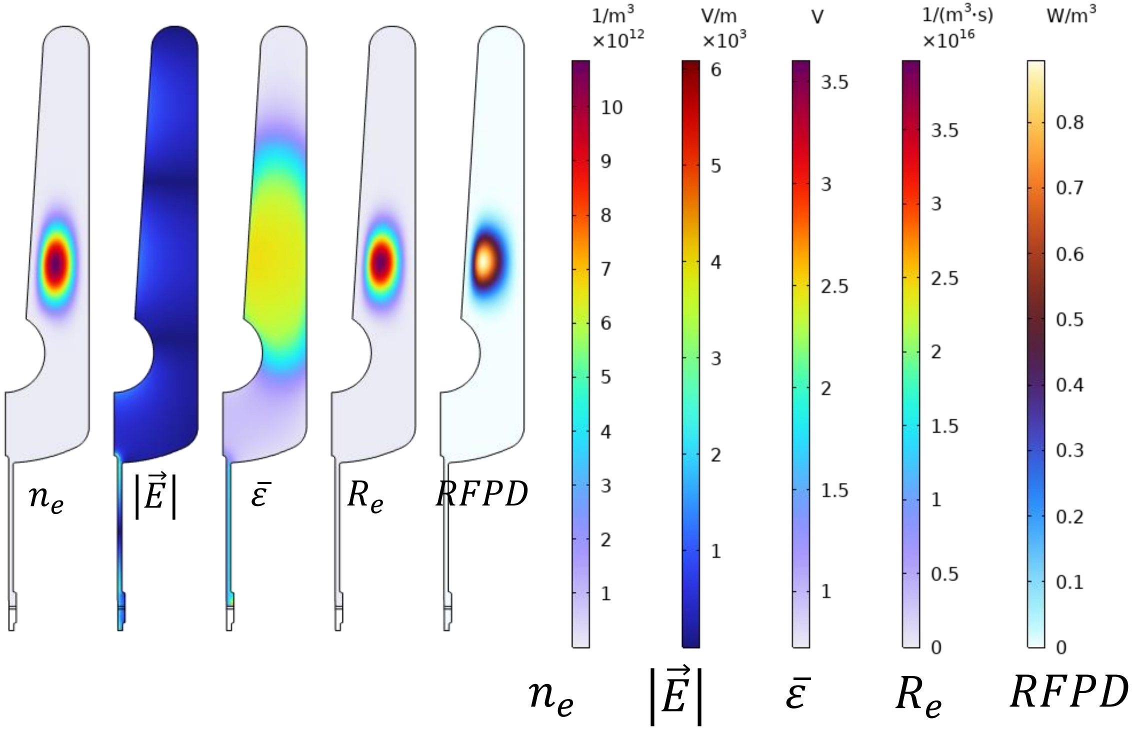




Mode 5 – 439 MHz, 1.5W, 0.1mbar

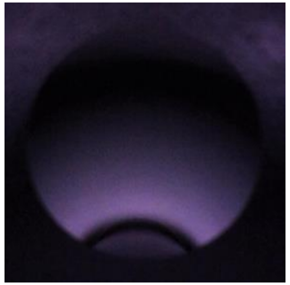


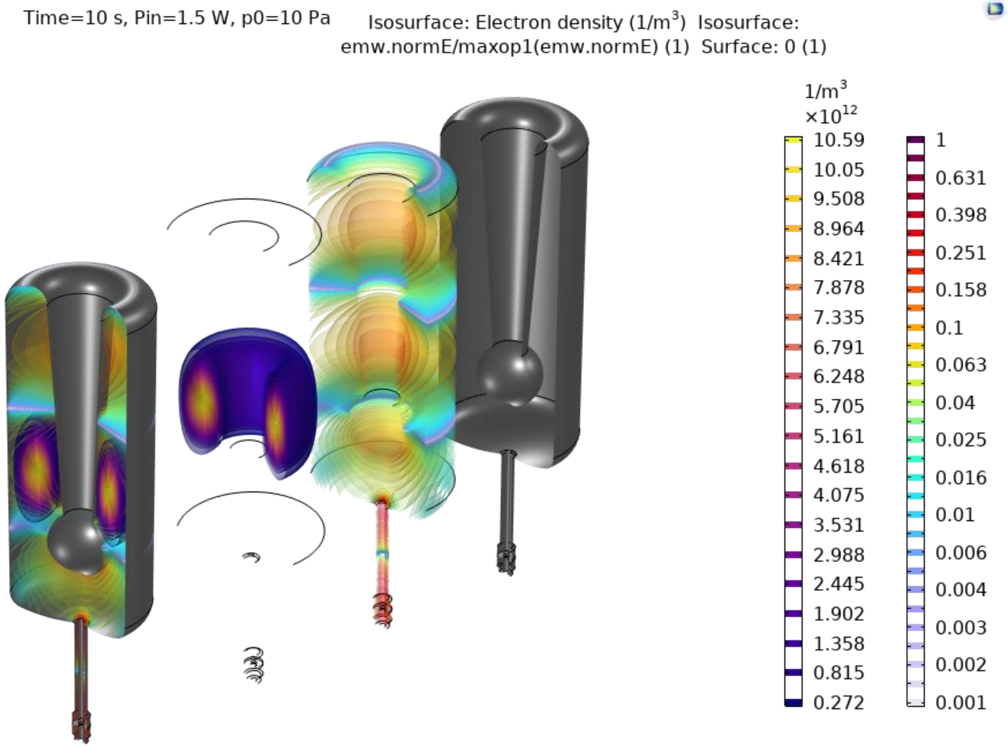




- Plasma location is following observations
  - Plasma torus in the middle part of the cavity

Mode 5 – 439 MHz, 1.5W, 0.1mbar





Summary

- Plasma distribution is quite similar for simulations and observations
  - Although less true for mode 1
- Plasma simulations give us orders of magnitude of plasma parameters
- Plasma simulations allow us to understand the plasma mechanisms inside the cavity

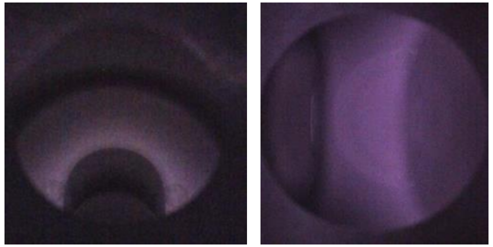
Outline

SPIRAL2 QWR Coupler Breakdown

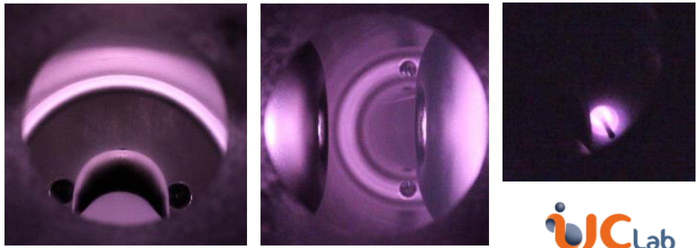
Increasing RF power

- **1st Regime: No plasma**
  - No ignition
  - “standard” behavior of an RF cavity

- **2nd Regime: Cavity plasma**
  - Plasma ignites in the cavity volume
  - Plasma follows high E field regions



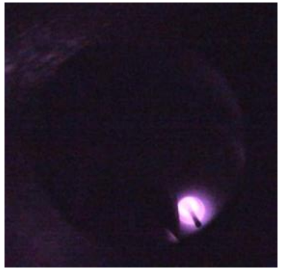
- **3rd Regime: Coupler Breakdown**
  - Plasma confines around the power coupler
  - 2nd to 3rd regime transition is very brutal
  - Must be avoided: copper can be sputtered!



Coupler Breakdown: Every Resonator Suffer

QWR

SPIRAL2 88 MHz

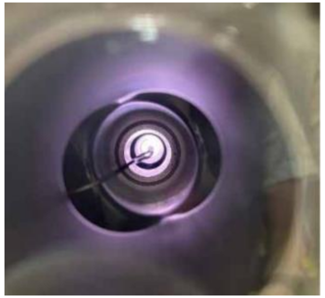


HWR

FRIB 322 MHz

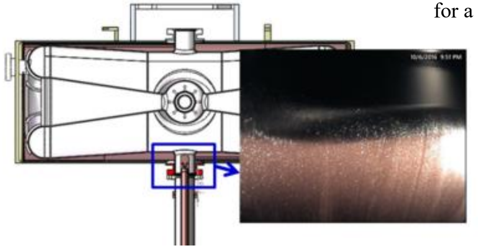
W. Hartung *et al.*, "Investigation of Plasma Processing for Coaxial Resonators"

ATLAS 172 MHz



M.E. McIntyre *et al.*, "Plasma Processing: Ignition Testing and Simulation Models for a 172 MHz HWR Cavity"

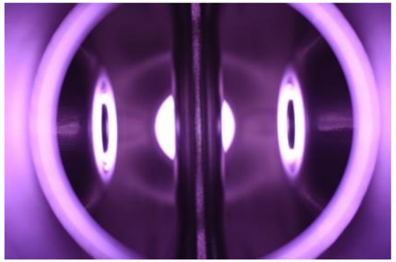
CiADS 162.5 MHz



A.D. Wu *et al.*, "The Destructive Effects to the RF Coupler by the Plasma Discharge"

Spoke

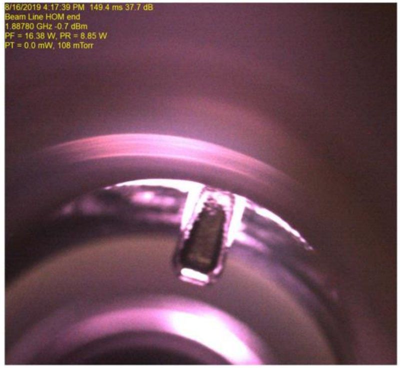
PIPII SSR1 325 MHz



P. Berurtti., "Plasma Cleaning at FNAL: LCLS-II HE vCM Results and Ongoing Studies on Spoke Resonators"

Elliptical

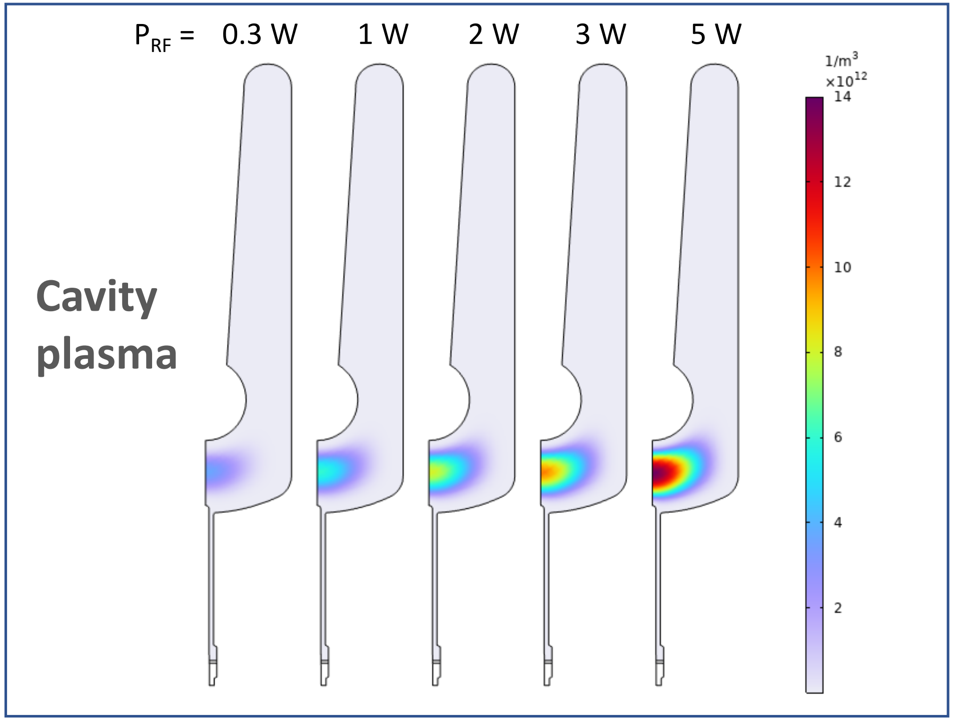
CEBAF C100 1.5 GHz

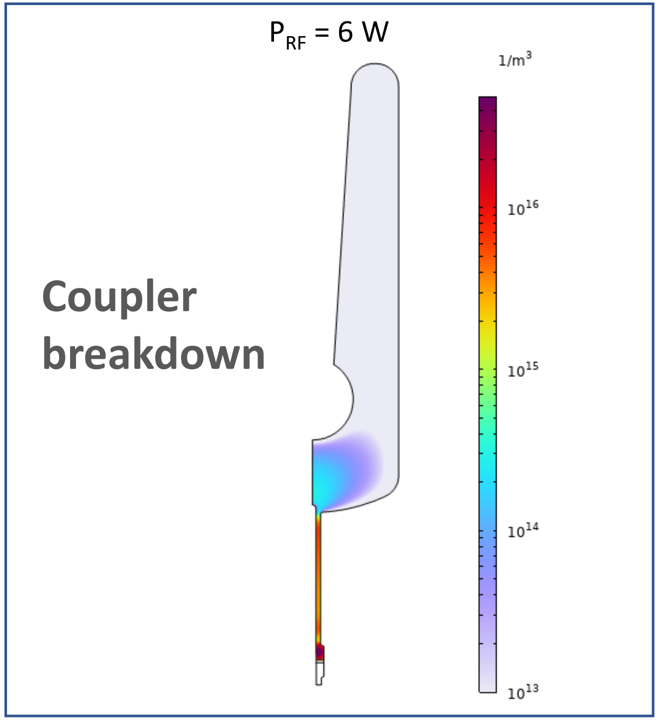


T. Powers *et al.* "Plasma Processing of SRF cavities"

Mode 1 – Coupler breakdown

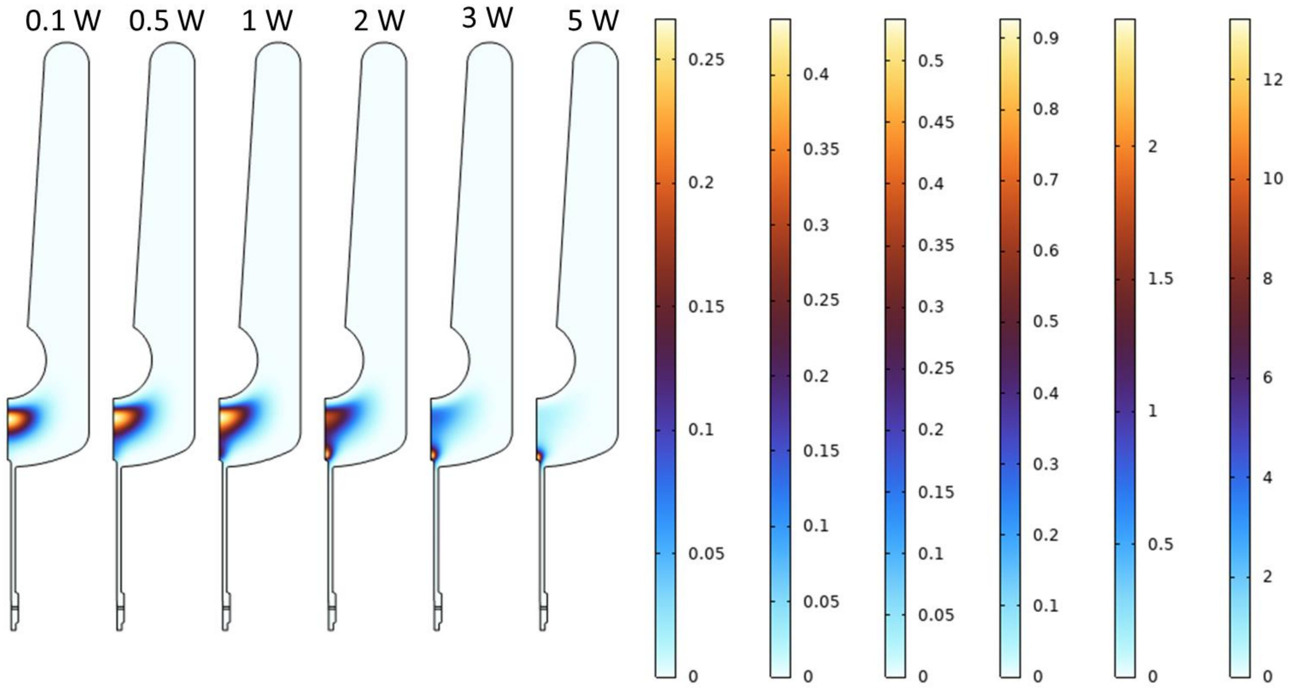
Electron density [m^{-3}] **VS** RF power [W]





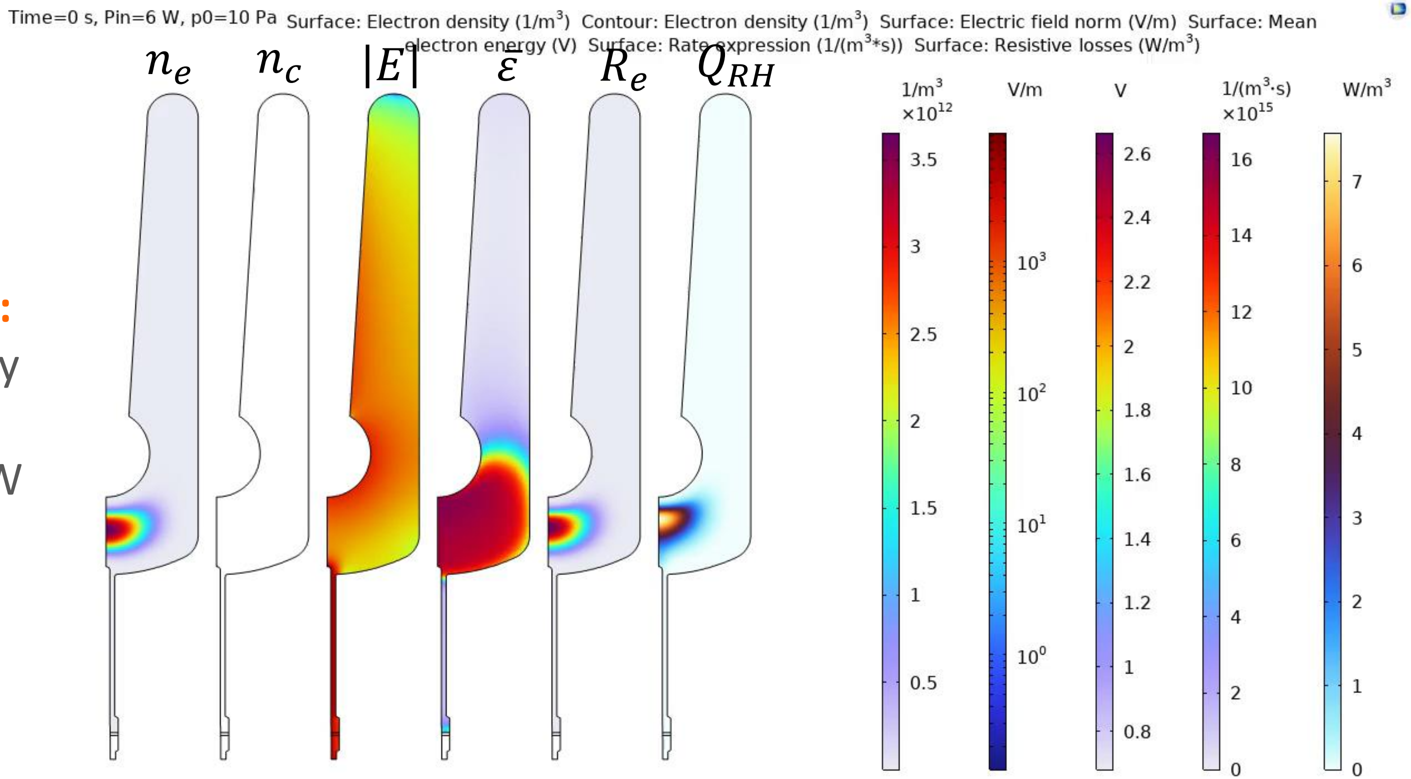
Mode 1 – Coupler breakdown

Power deposition [W.m^{-3}] **VS** RF power [W]



- When the RF power increases, the power deposition increases
  - And changes location
- At high power, most of the power is deposited on the coupler tip
- This leads to electron heating, and consequently ionization in this region

Mode 1 – Coupler breakdown



Initial conditions:

- Plasma already ignited (5W)
- RF power = 6W

Coupler breakdown timeline

Turn up RF power

More power transferred to electrons

n_e increases

Dielectric constant is modified

Cavity becomes out of resonance “Plasma detuning”

Electric field distribution changes

High electric field mainly in the coupler region

Electrons are heated in the coupler tip region

Electrons become hot enough to ionize the gas in the tip region

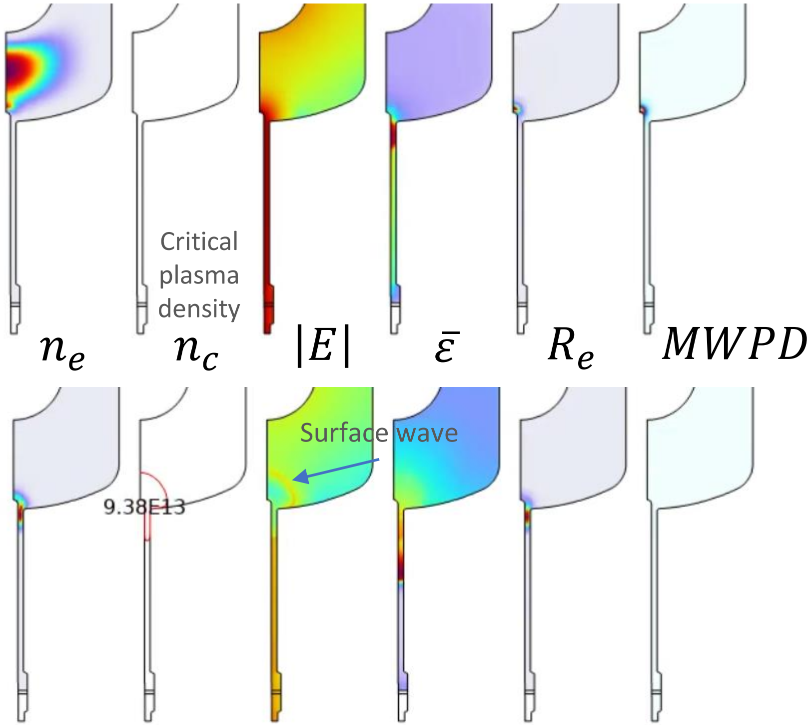
An over-dense plasma ignites around the coupler

E field almost vanishes in the cavity volume due to the plasma screening

Transition to surface wave plasma = RF power deposition highly localized to the contour of critical density

Just before coupler breakdown (t=3.3884E-04 s)

Just after coupler breakdown (t=3.4674E-04 s)



Same mechanisms for mode 2 and 5

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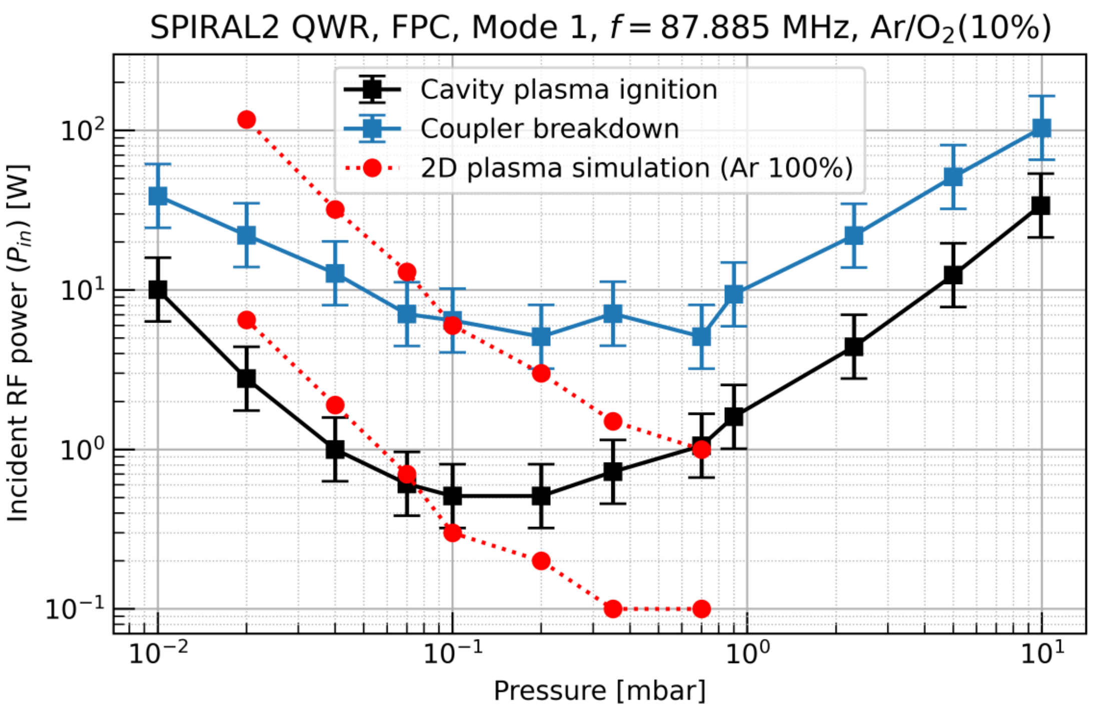
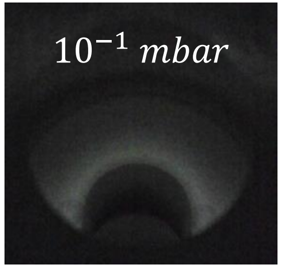
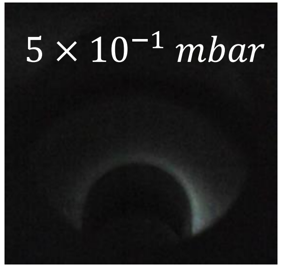
Mode 1 – Ignition and breakdown curves



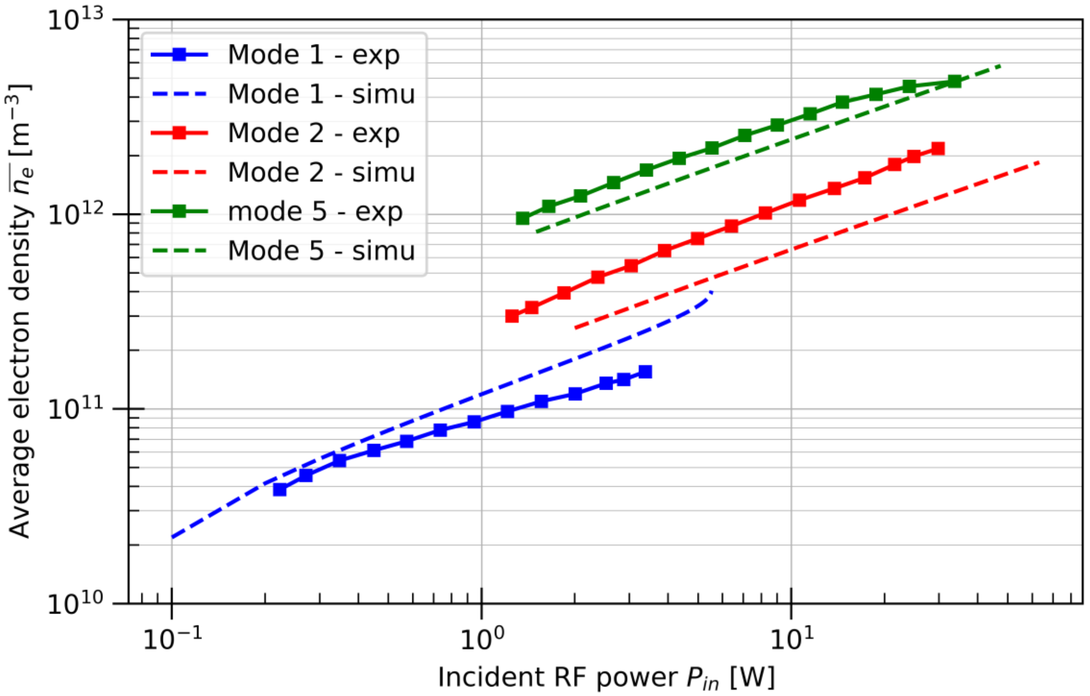
- 2D simulations are in good agreement with experimental measurements at 10^{-1} mbar
  - Relatively large deviation elsewhere
- For $P > 5 \times 10^{-1}\ mbar$ the 2D axisymmetry assumption doesn't reflect experimental observations anymore
  - The plasma is no longer distributed uniformly around the symmetry axis





Average electron density $\overline{n_e}$

- **Experimental data**
  - $\overline{n_e} = 4\pi^2 \frac{m_e \varepsilon_0}{e^2}(f_r^2 - f_0^2)$
  - f_r is the shifted resonance frequency due to plasma
  - f_0 is the resonance frequency without plasma
- **Numerical simulation**
  - $\overline{n_e} = \frac{1}{V}\iiint n_e \, dr \, d\theta \, dz$
  - V is the cavity volume



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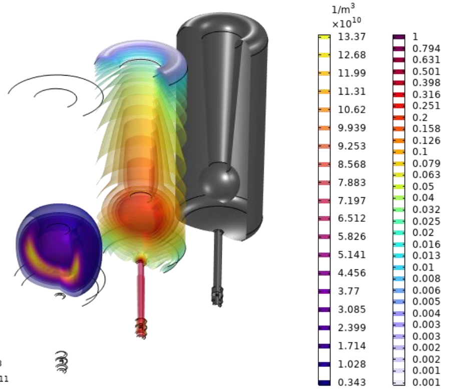
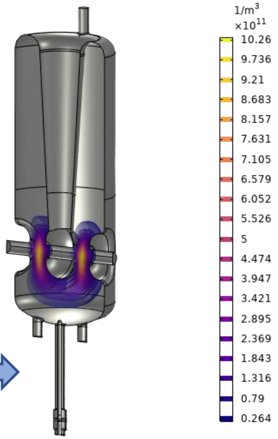
Conclusion & future plans

- **Plasma model limitations**
  - 2D axial symmetry assumption
  - Plasma location for mode 1
    - Most likely due to the Maxwellian EEDF hypothesis
  - Our case = very specific plasma parameters
    - Low density, intermediate frequency range (usually 13.56 MHz or 2.45 GHz)
    - Almost no literature available

(2D) Mode 1 with a computed EEDF using the Boltzmann two-term approximation



- **Future plans**
  - Plasma diagnostics
    - Langmuir probe
      - Measured parameters: n_e, V_p, T_e, EEDF
    - Optical Emission Spectroscopy (OES)
      - Measured parameters: species concentration
  - Use diagnostics data as model input parameters
  - 3D plasma simulations for more accuracy



(3D) Mode 1 with a computed EEDF using the Boltzmann two-term approximation

Special thanks

- **Jefferson Lab's plasma processing team**
  - For the technical training on their plasma test bench, and discussions
  - For the plasma simulation training with COMSOL Multiphysics

- **CEA, FRIB, Fermilab, Argonne and Brookhaven plasma processing teams**
- **Plasma expertise from LPP and INSP (CNRS laboratories)**
  - For the useful discussions, information sharing, and suggestions

- **The IJCLab vacuum team**
  - For the technical support