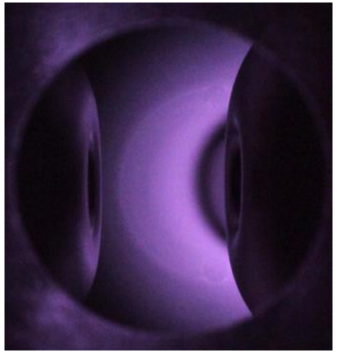
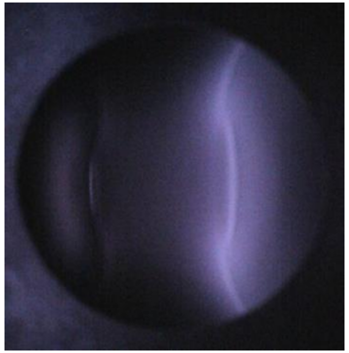
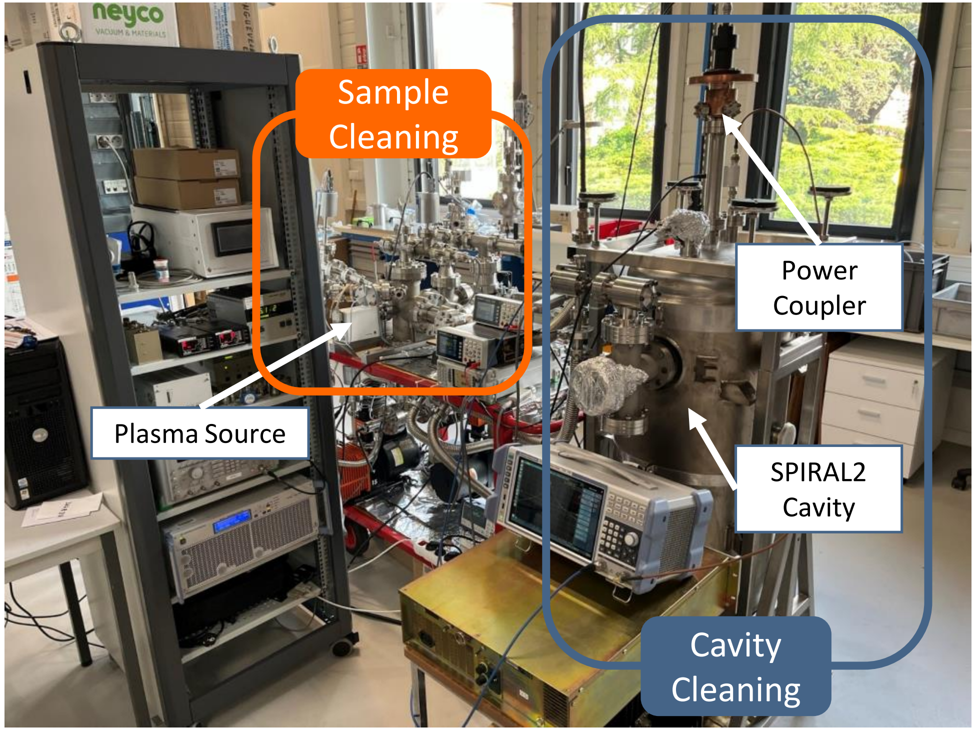
 

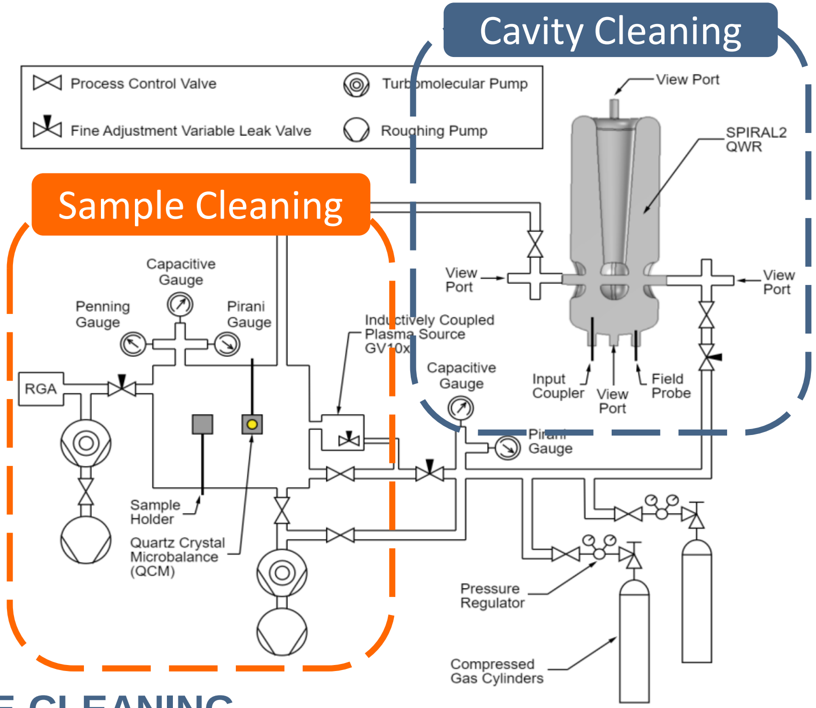
Overview of Plasma Processing Activities at IJCLab

TESLA Technology Collaboration Meeting
Fermilab
Dec 5-8, 2023

Camille CHENEY
PhD student

Our Plasma Cleaning Bench





- **SAMPLE CLEANING**
  - ICP plasma source (ibss Group GV 10x DS Ahser)
  - Quartz Crystal Microbalance (QCM) + Carbon coating
  - Removal rate measurements: varying gas mixture, pressure, gas flow, RF power
- **CAVITY CLEANING**
  - SPIRAL2 QWR cavity (with fundamental power coupler)
  - Study plasma ignition, plasma shape

IJCLab Plasma Processing Timeline

2021: THE BEGINNINGS

- Setting up a test bench

2022: FIRST EXPERIMENTS

- People involved:
  - Post-doctoral student (not full time)
  - MSc degree intern (5 months)
  - D. Longuevergne (supervisor)
- Removal rate measurements of carbon coating
  - Testing various gas mixtures
- First tests on a SPIRAL2 QWR
  - Fundamental mode
  - Custom length antennae

2023: MORE INVESTIGATIONS

- People involved:
  - Myself (5 months intern → full time PhD)
  - D. Longuevergne (PhD supervisor)
- SPIRAL2 QWR deeper study
  - Fundamental Power Coupler (FPC)
  - Higher Order Modes (HOM)
    - Coupling measurements
    - Plasma ignition/distribution study
    - **COUPLER BREAKDOWN**
      - Understand
      - Mitigate/delay

What is coupler breakdown?

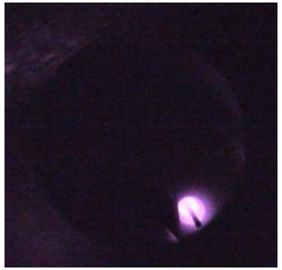
- **Definition:**
  - Phenomenon happening during plasma processing when plasma confines around the powered antenna (FPC or HOM coupler).
  - It appears above some RF power threshold.
- **Is it an issue?**
  - **YES (for HWRs and ellipticals)**
    - Sputtering of antenna material onto Nb = pollution (*Cf.* FRIB HWRs [1] and JLab elliptical [2])
    - Can damage isolating ceramic leading to vacuum leaks (*Cf.* IMP/CiADS HWRs [3])
  - **Maybe NO for QWRs (at least for plasma processing effectiveness)**
    - Field emission onset is delayed after processing, despite breakdown! (*Cf.* FRIB QWRs [1]) *"we did not observe damage to the coupler even after more than 10 hours of cumulative coupler plasma processing"*
    - No damage/sputtering observed for SPIRAL2 QWR as well
- **⚠ Must be avoided anyway, because it's very risky for cavity and coupler integrity**
- **Any explanation?**
  - Not yet fully understood
  - We have some hypothesis

[1] W. Hartung *et al.*, "Investigation of Plasma Processing for Coaxial Resonators"
[2] T. Powers *et al.* "Plasma Processing of SRF cavities"
[3] A.D. Wu *et al.*, "The Destructive Effects to the RF Coupler by the Plasma Discharge"

Coupler Breakdown: Every Resonator Suffer

QWR

SPIRAL2 88 MHz

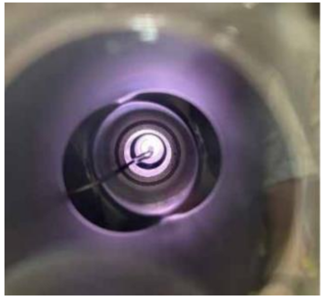


HWR

FRIB 322 MHz

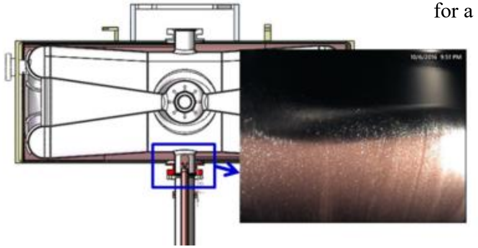
W. Hartung *et al.*, "Investigation of Plasma Processing for Coaxial Resonators"

ATLAS 172 MHz



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

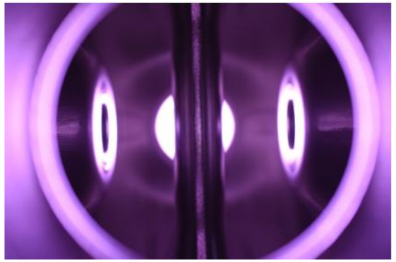
CiADS 162.5 MHz



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

Spoke

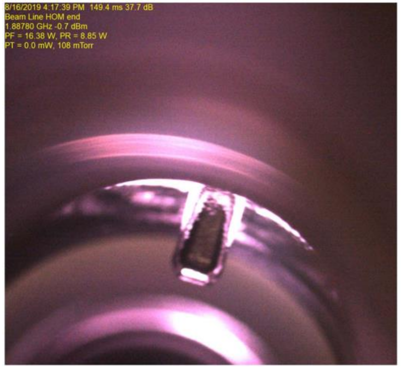
PIPII SSR1 325 MHz



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

Elliptical

CEBAF C100 1.5 GHz

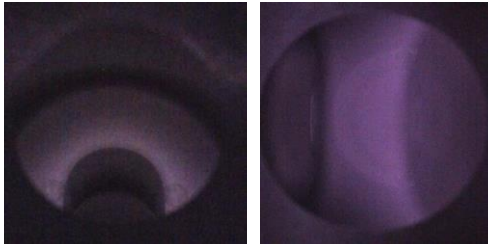


T. Powers *et al.* "Plasma Processing of SRF cavities"

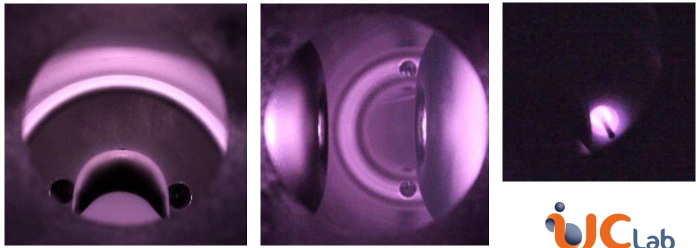
SPIRAL2 QWR Coupler Breakdown

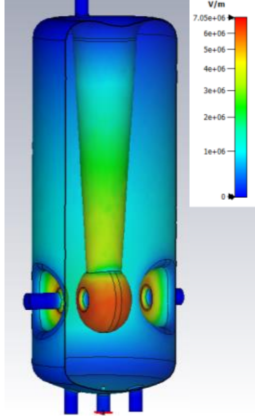
Increasing RF power

- **1st Regime: No plasma**
  - No ignition
  - “standard” behavior of an RF cavity
- **2nd Regime: Cavity plasma ignition**
  - Plasma ignites in the cavity volume
  - Plasma follows high E field regions



- **3rd Regime: Coupler Breakdown**
  - Plasma confines around the power coupler
  - **No visible traces of sputtering**





SPIRAL2 QWR
Mode 1 E field

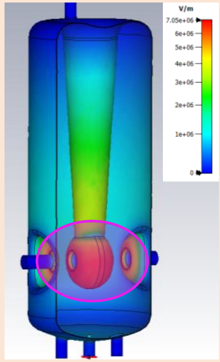
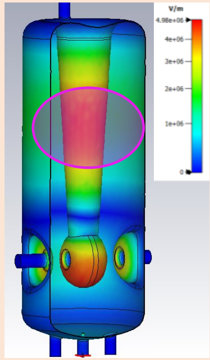
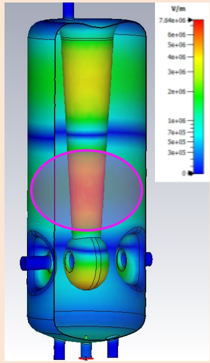
How to delay coupler breakdown? (1/4)

At IJCLab, we played on:

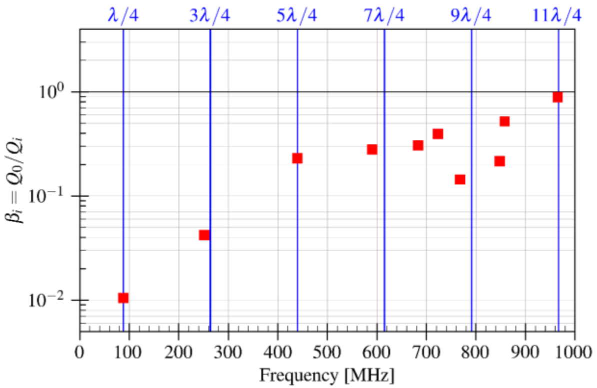
1. Frequency
2. Pressure
3. DC bias of the power coupler

How to delay coupler breakdown? (2/4)

1. FREQUENCY

	Mode 1 – 88 MHz	Mode 2 – 251 MHz	Mode 5 – 439 MHz
CST Microwave Studio E field surface plot Plasma location* *with RF power ramp			
Plasma ignited in the cavity volume **Ar/O_2(10%) 10^{-1} mbar**	P_{FWD}~[0.2 ; 3]W	P_{FWD}~[1 ; 30]W	P_{FWD}~[10 ; > 100]W

VNA input coupling measurements (with FPC)

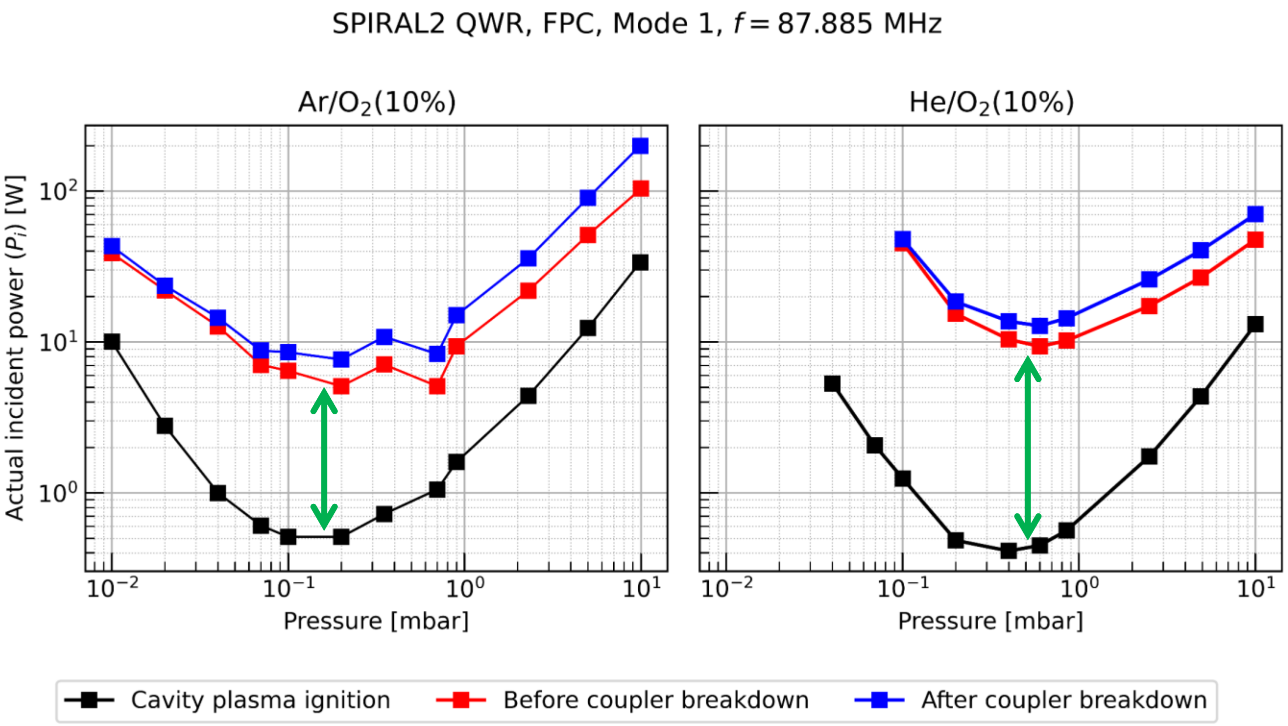


How to delay coupler breakdown? (3/4)

2. PRESSURE

- Both cavity and coupler ignition follow Paschen law
- He/O_2(10%) has the larger power margin between cavity plasma ignition and coupler breakdown

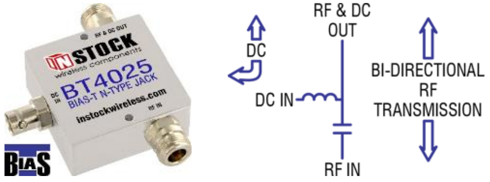
Gas	1st ionization energy
He	24.587 eV
Ar	15.759 eV
O	13.618 eV

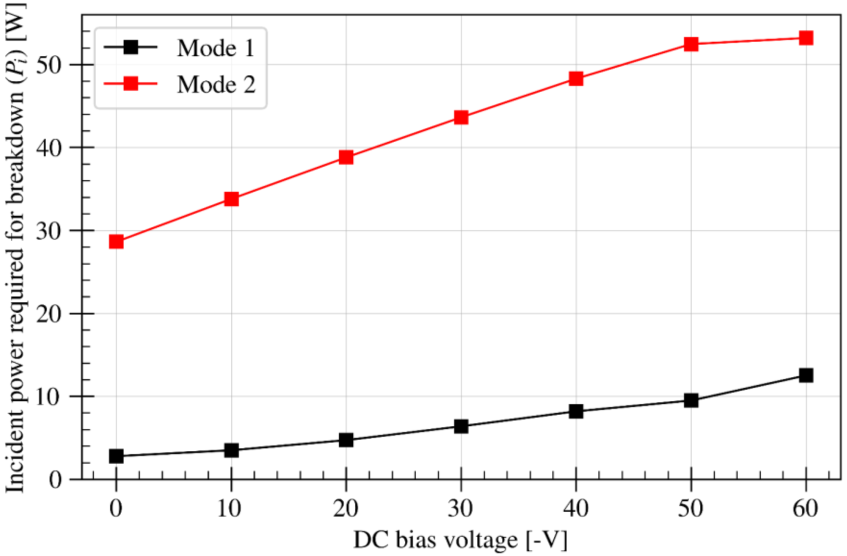


How to delay coupler breakdown? (4/4)

3. DC BIAS OF THE POWER COUPLER

- Negative DC bias applied to the power coupler
- The lower the V_{DC}, the higher the power required for breakdown
- Mode 5 is not showed due to bias tee power limitation (100W)
- On the contrary, positive bias tends to favor coupler breakdown





Summary

- Coupler breakdown is identified as the main risk and limiting factor of plasma processing
- We are studying coupler breakdown to understand what is causing it, and how to delay/avoid it
- Higher frequencies, as well as negative DC bias look favorable
- Coupler breakdown tends to follow Paschen law

- **FUTURE PLANS:**
  - Plasma computer simulations
  - Set up plasma diagnostics (Langmuir probe, OES)

Acknowledgments

- Vacuum people at IJCLab
- G. Curley and S. Guilet for their plasma expertise
- Plasma processing teams at Fermilab, FRIB, Jefferson Lab for useful discussions, information sharing, and suggestions
- Special thanks to T. Powers, T. Ganey, N. Raut and A-M. Valente Feliciano for welcoming me at Jefferson Lab

Thank you for your attention!

Supplementary Material

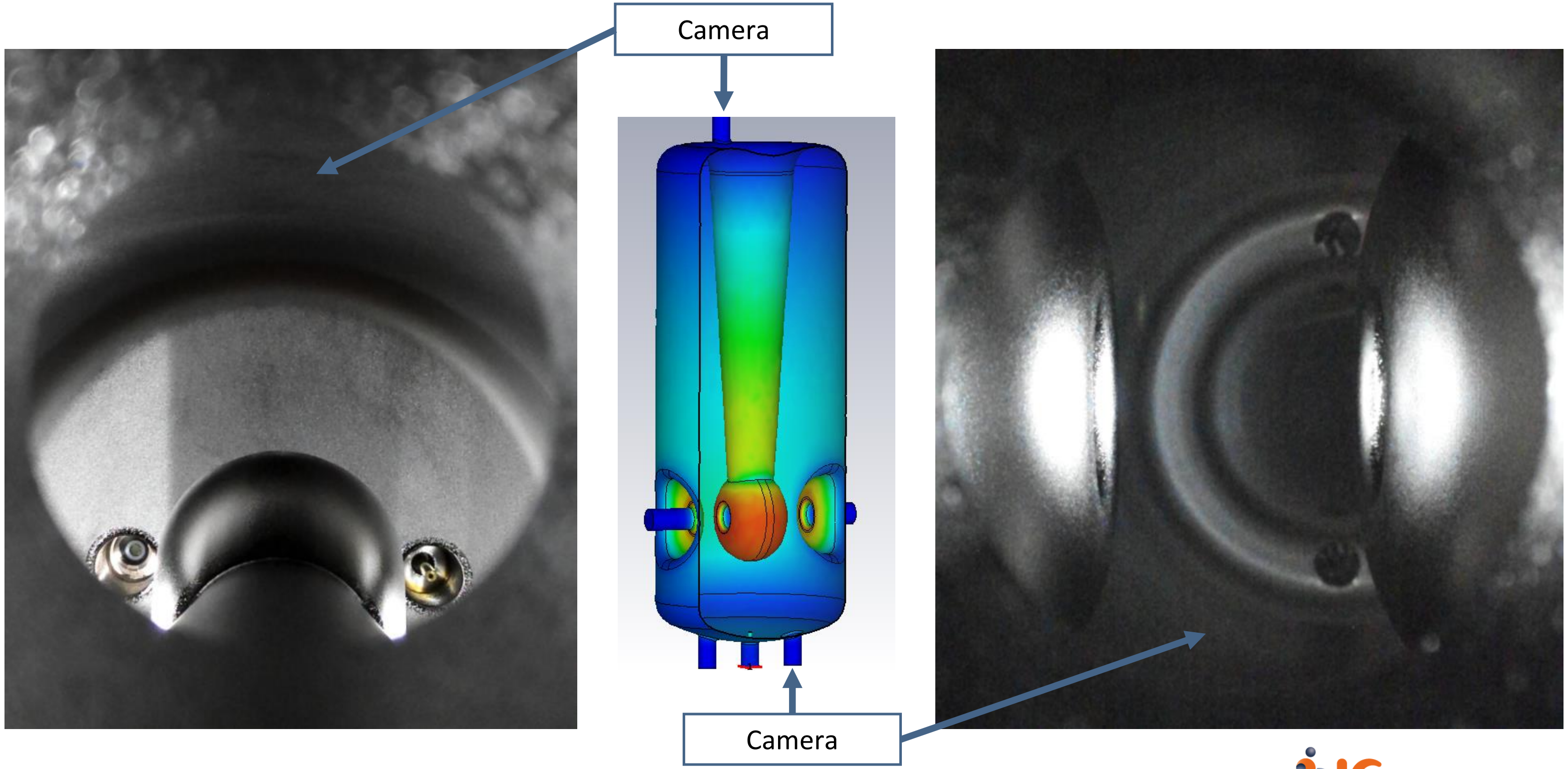
Just to be used to plasma pictures…

IDS U3-36L0XC

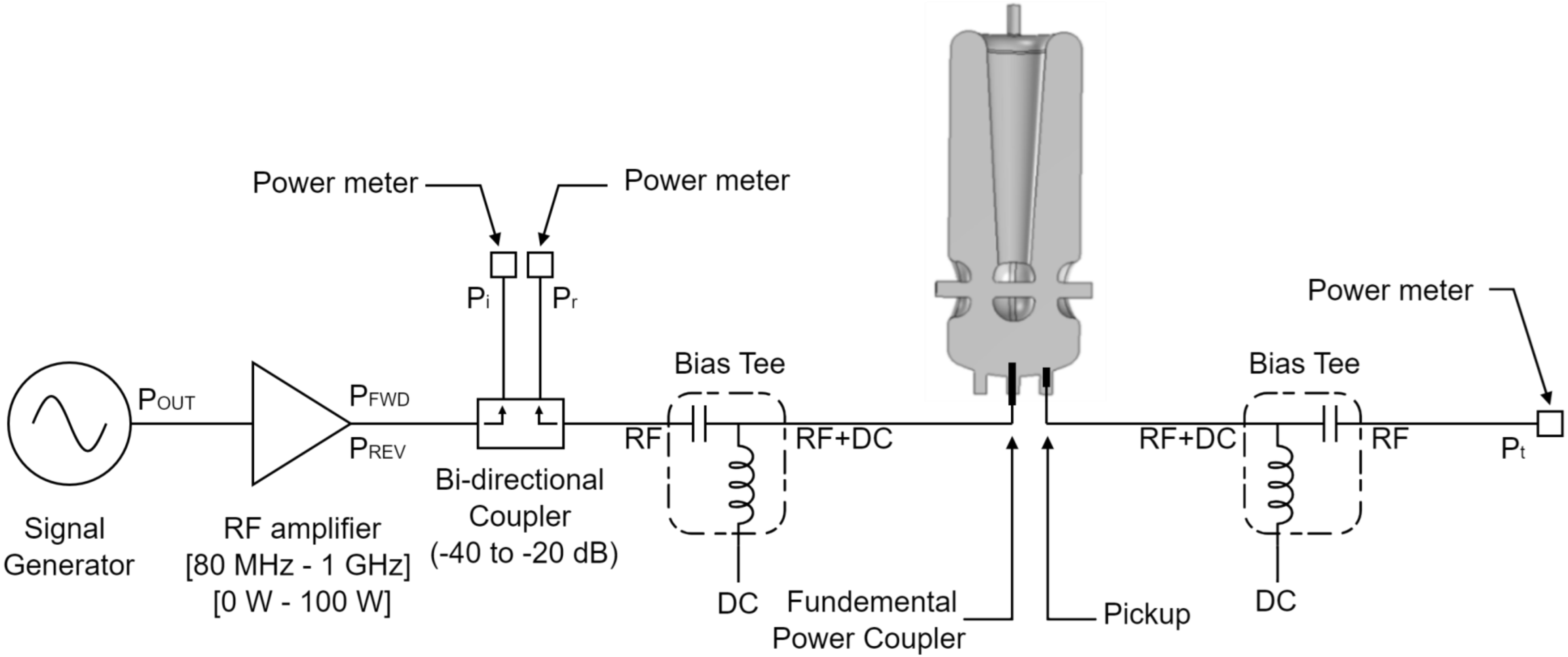
T_{expo} = [0.5 - 2] sec

(+) Cameras usable on the bench

(-) Not usable in the LINAC



RF setup



Power meter
Power meter
Pi
Pr
Power meter
Bias Tee
Bias Tee
POUT
PFWD
PREV
RF
RF+DC
RF+DC
RF
Pt
Signal Generator
RF amplifier
[80 MHz - 1 GHz]
[0 W - 100 W]
Bi-directional Coupler
(-40 to -20 dB)
DC
Fundemental Power Coupler
Pickup
DC

Input coupling factors measurements

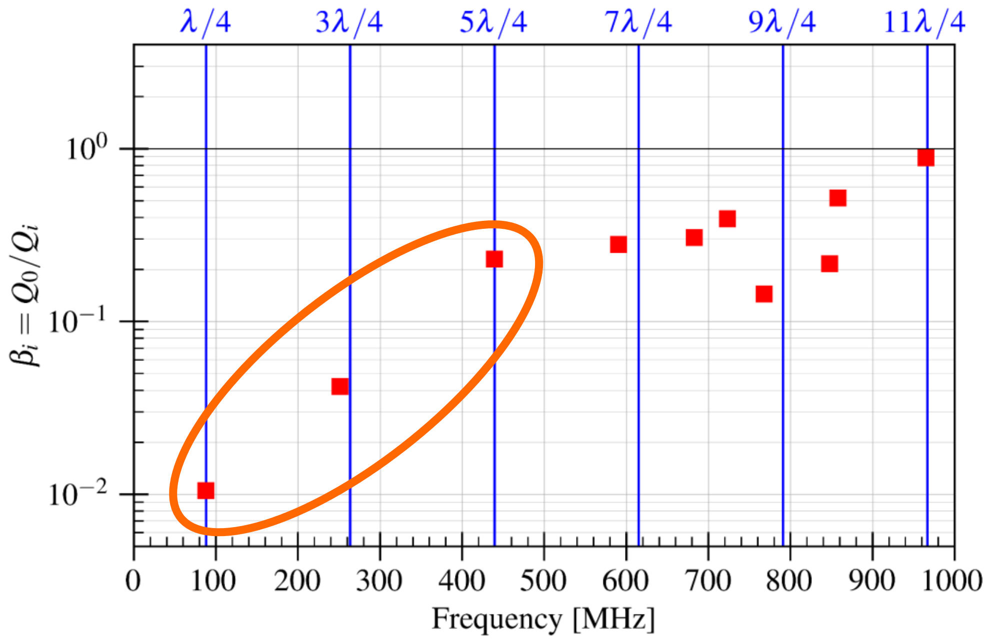
Coupler-to-cavity coupling

- Coupling = optimal when cold
- Room temperature coupling = weak

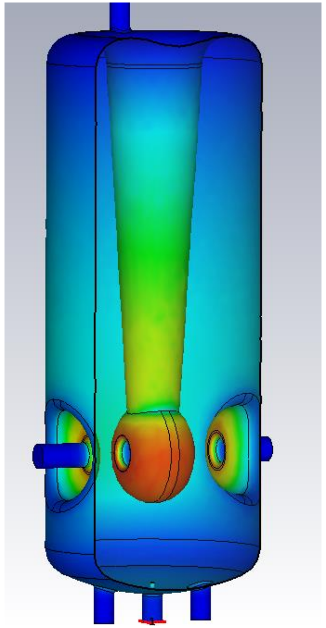
- Bad coupling: $\beta \rightarrow 0$
- Good coupling: $\beta \rightarrow 1$

→Coupling increases when frequency increases

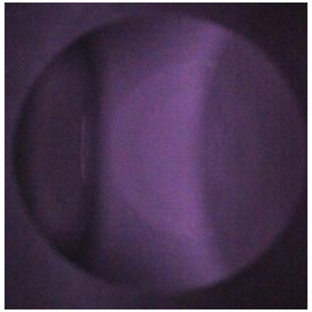
→Advantageous to use HOMs



Fundamental mode – 88 MHz



Electric field distribution (CST Microwave Studio)



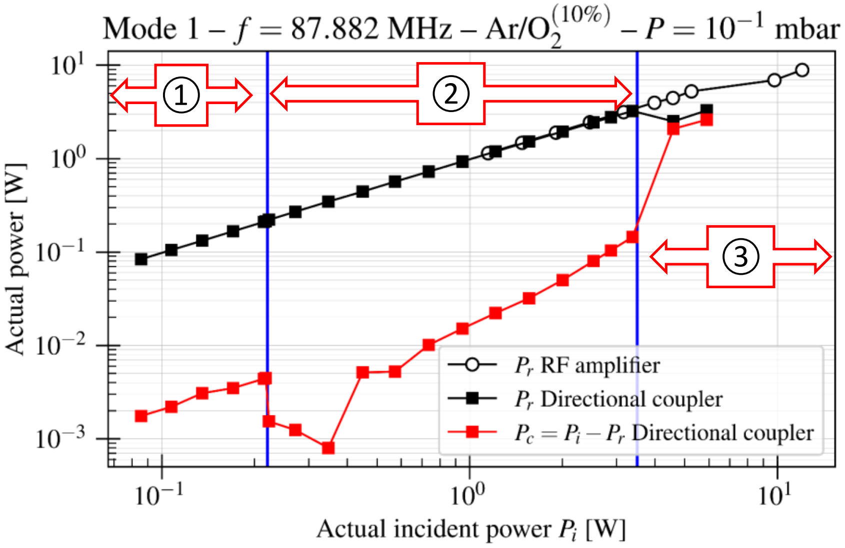
Pictures of the plasma

For all the following tests:

- $P = 10^{-1}$ mbar
- $Ar/O_2(10\%)$

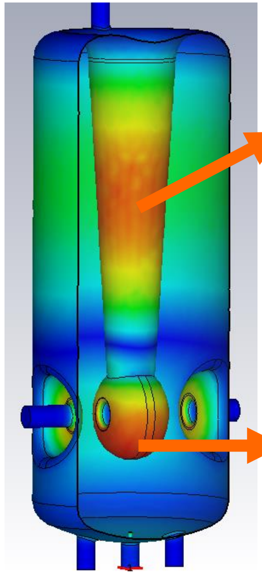
- Plasma ignition even with weak coupling
- Plasma ignites where the electric field is strong

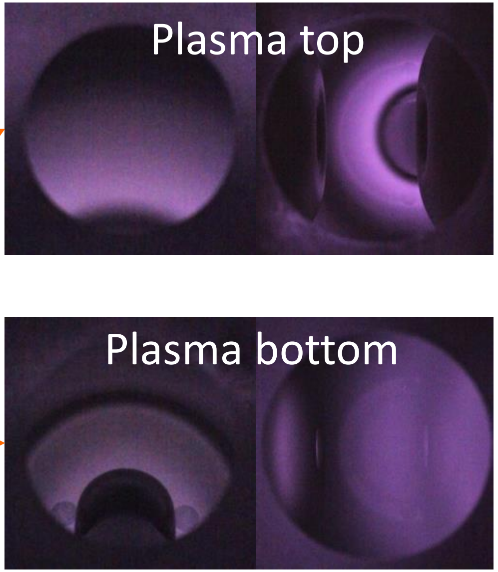
- 3 regimes can be identified



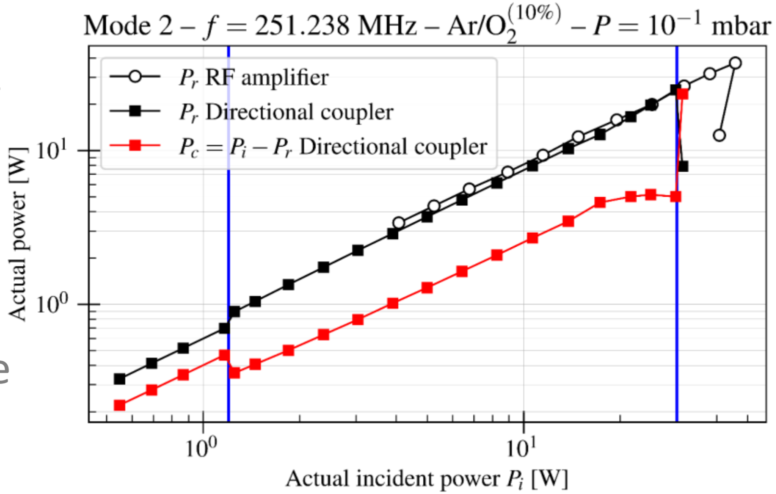
RF power measurements

Mode 2 – 251 MHz

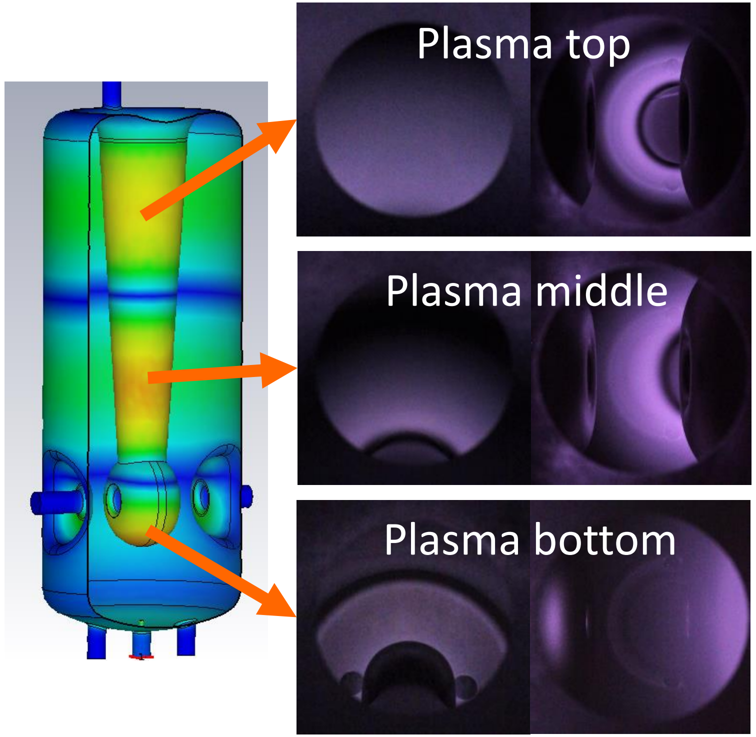




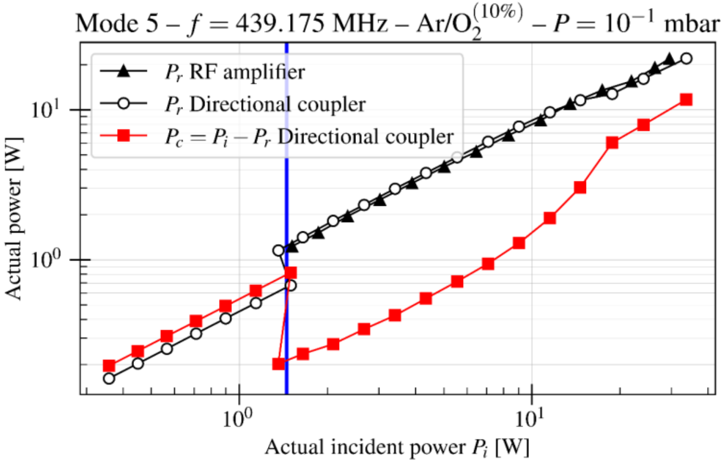
- Ignition possible in one of the 2 high field zones
- Ignition always on top with RF power ramp
- Bottom ignition possible with RF power pulse



Mode 5 – 439 MHz

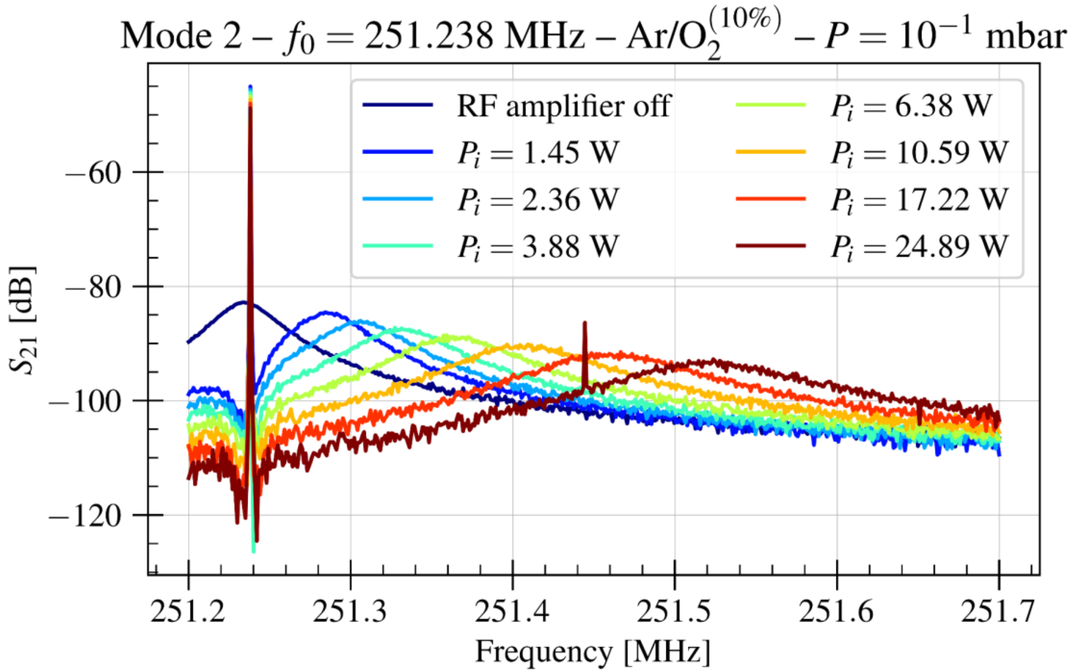


- Ignition possible in one of the 3 high field zones
- Ignition always in the middle with an RF power ramp
- Top and bottom ignition possible with RF power pulse



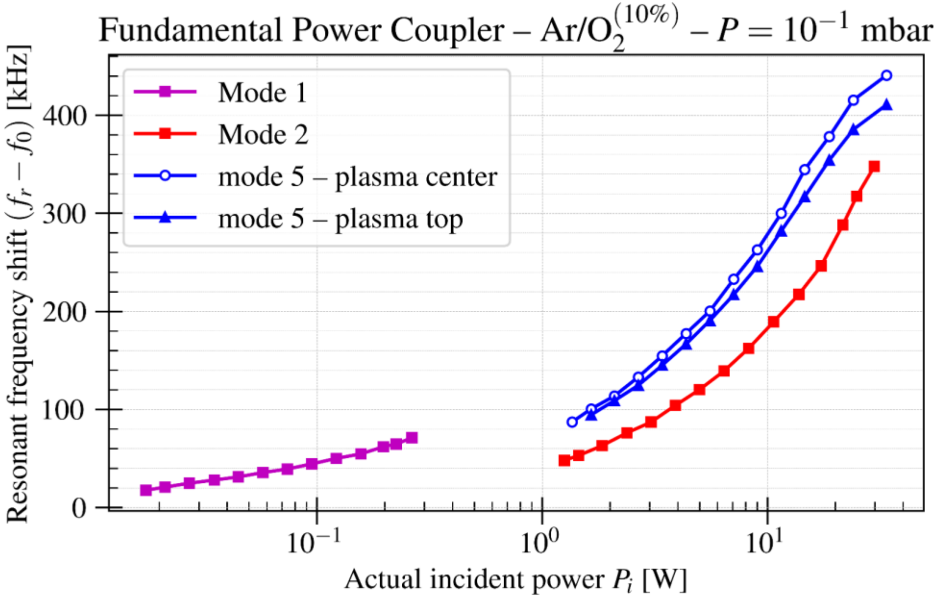
Resonant frequency shift

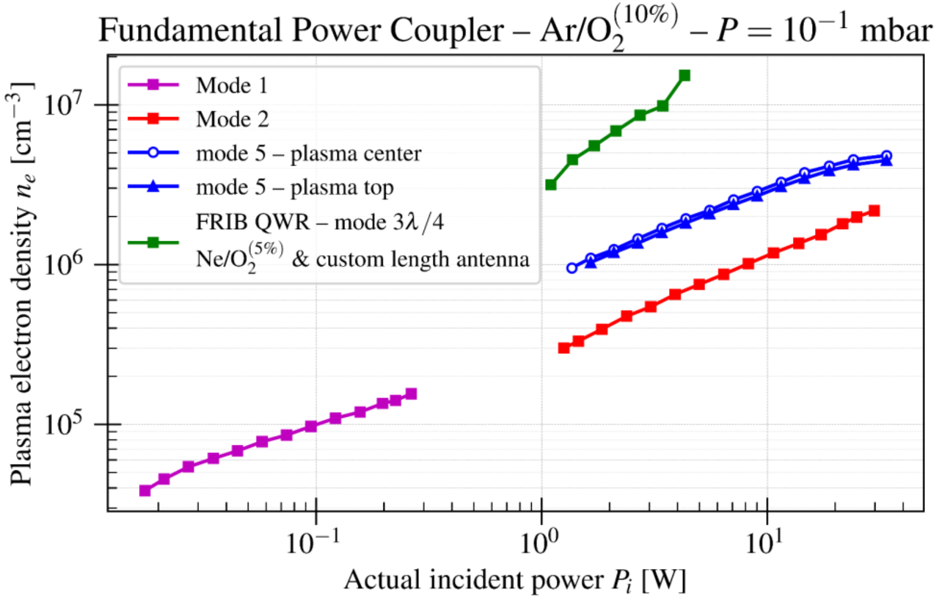
- f_0 = Resonant frequency without plasma
- Resonant frequency increases when plasma is ignited
- When trying to follow resonant frequency at constant power, the shift still increases until catch up
- If driving over resonant frequency, plasma turns off



Electron density measurement

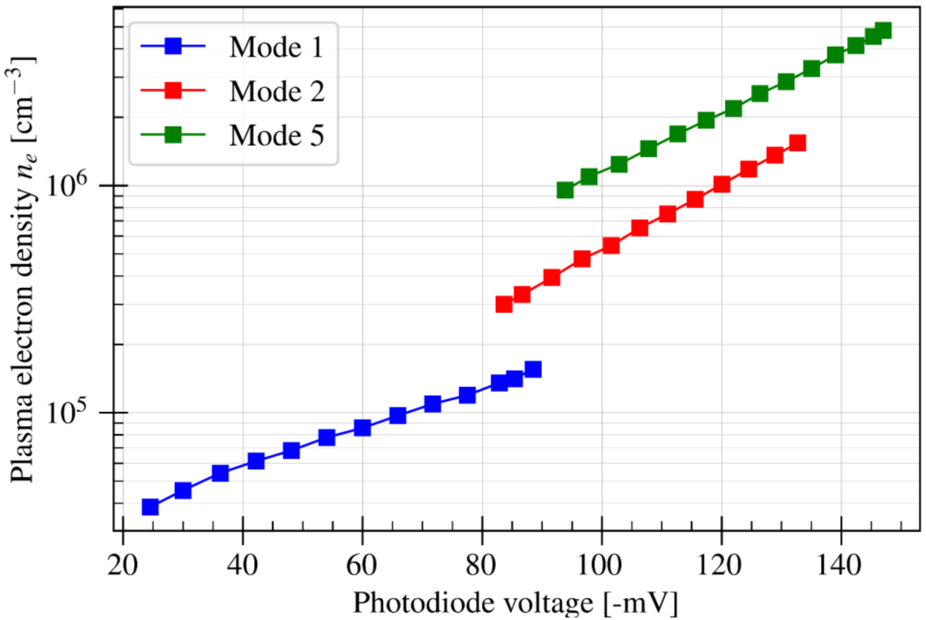
$$n_e = 4\pi^2 \frac{m_e \epsilon_0}{e^2} \left(f_r^2 - f_0^2 \right) \left[m^{-3} \right]$$ comes from: $$\omega_{p,e} = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}} \, [\mathrm{rad/s}]$$





CCP: $n_0 \propto \omega^2 V_0$

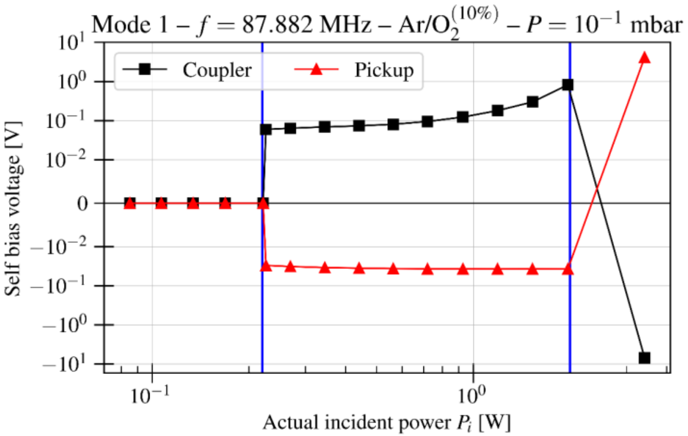
Photodiode measurements

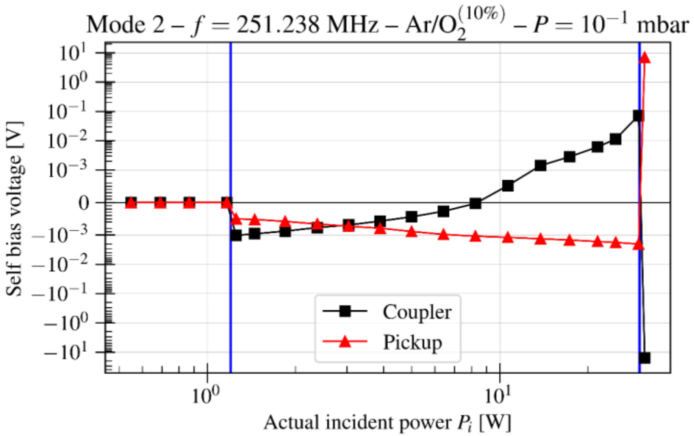


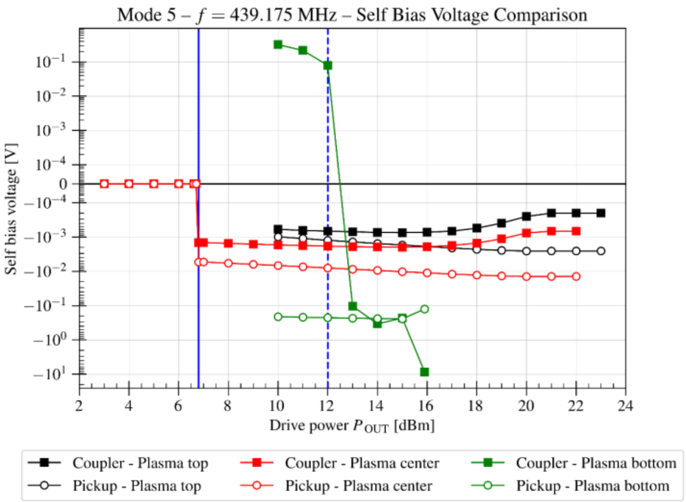
- Photodiode voltage is proportional to the electron density

- $V \propto e^{n_e}$

Self-bias voltage measurements







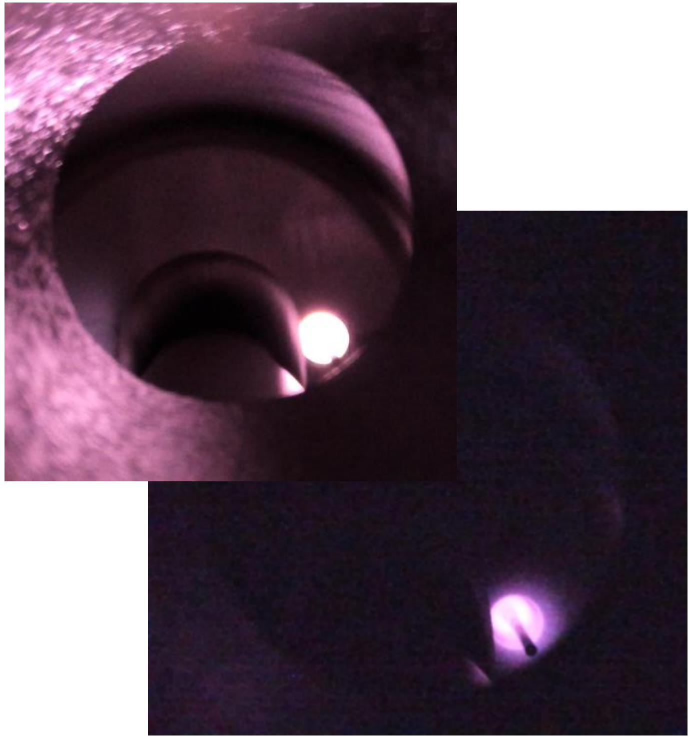
- 3 regimes can be distinguished as well
- Mode 5: self-bias voltage indicates plasma location

Coupler ignition issue (3rd regime)

- **Description**
  - Appears at relatively high power,
  - Plasma confinement around the power coupler

- **Problem**
  - Sputtering of Cu on top of Nb
  - Cu is not superconducting
  - Creation of electron emitting sites

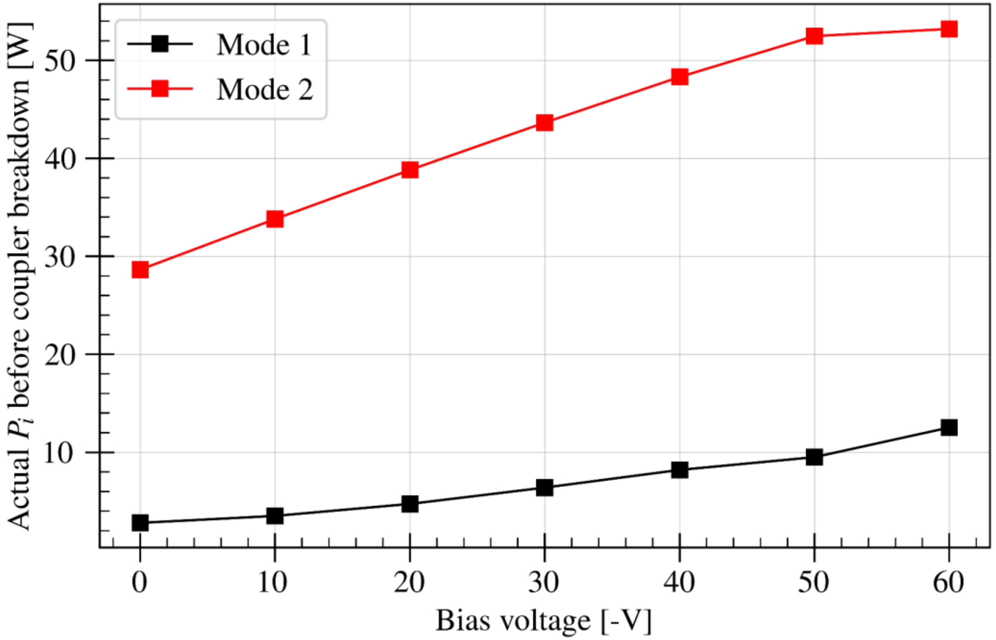
- **Hypothesis on its origin**
  - Self-bias of the power coupler
    - Due to electrodes surface area difference
    - Explained by current continuity



What happens if the bias voltage is forced?

- Negative bias voltage applied to power coupler
  - ➢ Using a bias tee

- **Bias voltage delays coupler ignition!!**
  - ➢ **Promising**



Summary on promising HOMs

PROS

Mode 1

- LINAC frequency
- Plasma in field emission zones
- Always ignites at the same location

Mode 2 & 5

- Upper part of the cavity processing
- Delayed coupler ignition
- Always ignites at the same location with RF power ramp
- Higher electron density

CONS

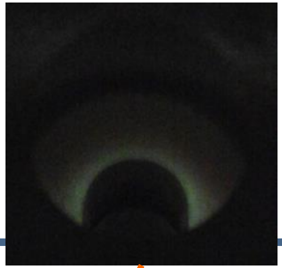
Mode 1

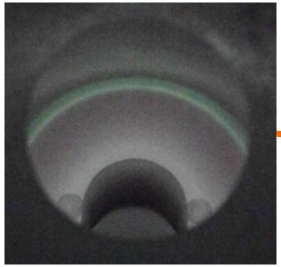
- Coupler ignition < 10 W
  - Restricted window
    - Mode 1 [0.1 - 3] W
    - Mode 2 [1 - 30] W
    - Mode 5 [2 - 50] W

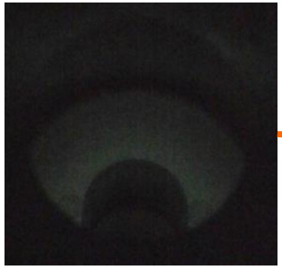
Mode 2 & 5

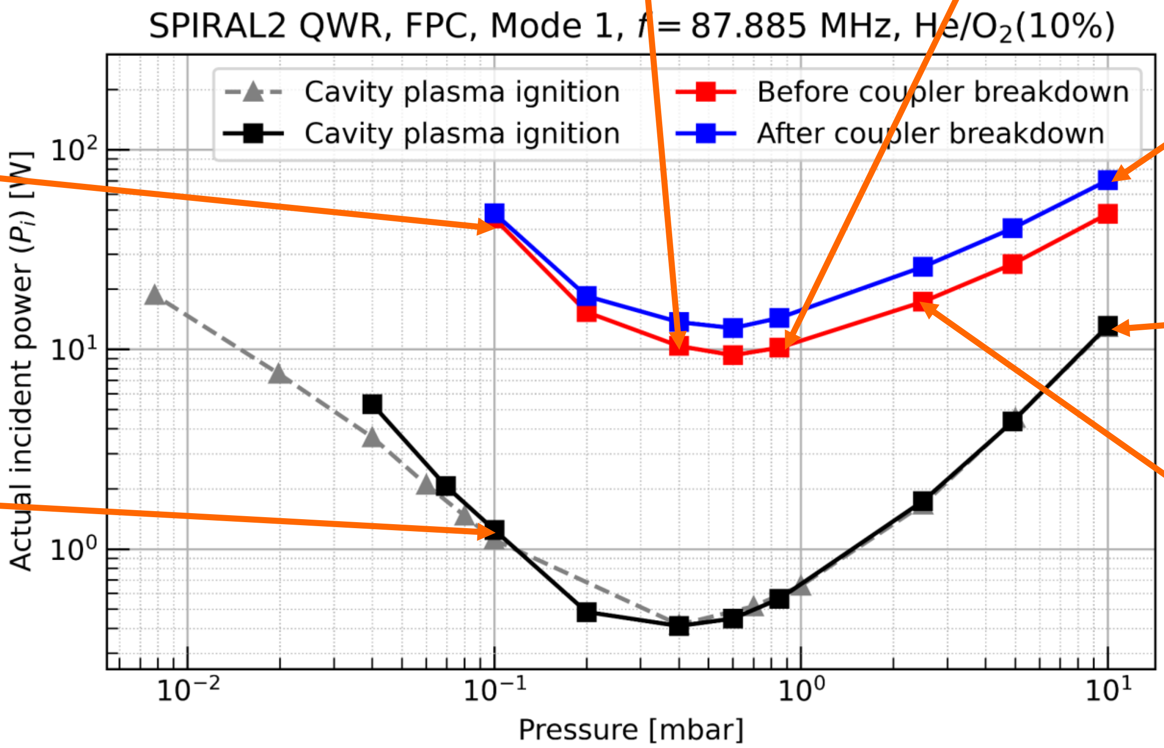
- Not the LINAC frequency
- Maybe not so efficient for treating field emission (no experimental proof yet)

He/O_2(10%)

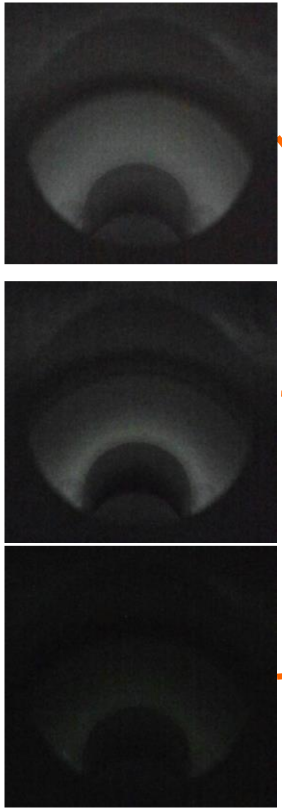


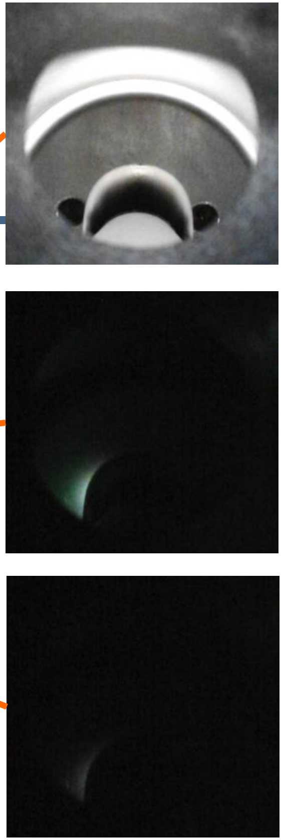


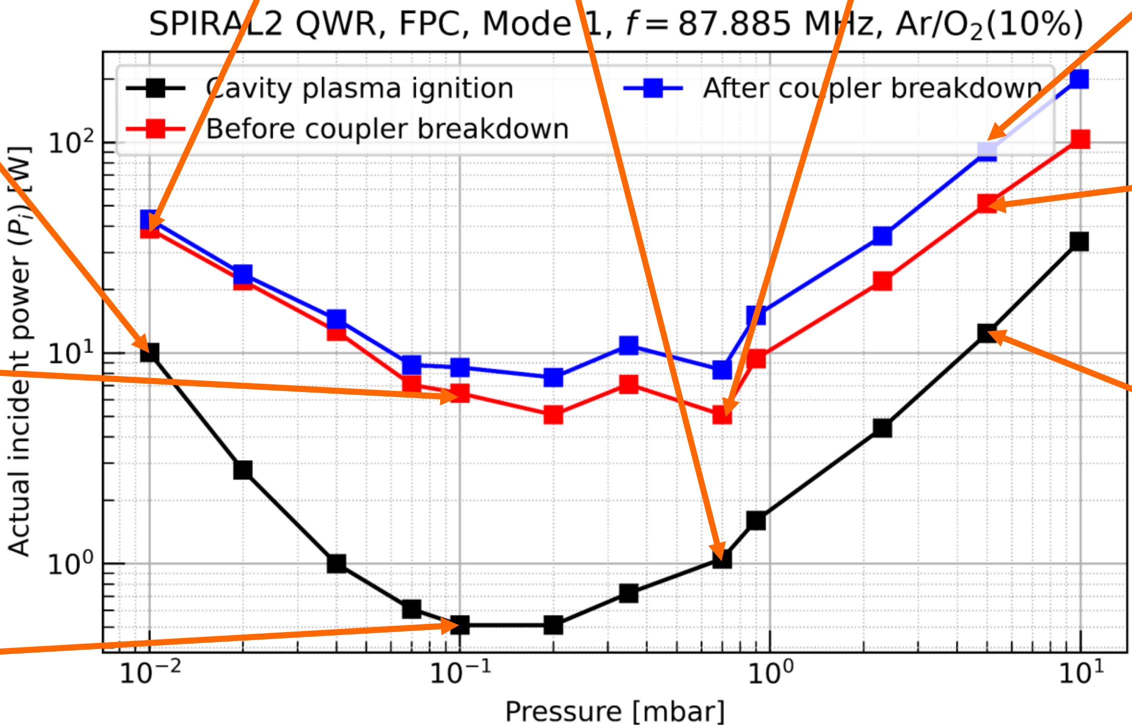



SPIRAL2 QWR, FPC, Mode 1, f = 87.885 MHz, He/O2(10%)
Cavity plasma ignition
Cavity plasma ignition
Before coupler breakdown
After coupler breakdown
Actual incident power (Pi) [W]
Pressure [mbar]
10^2
10^1
10^0
10^-2
10^-1
10^0
10^1

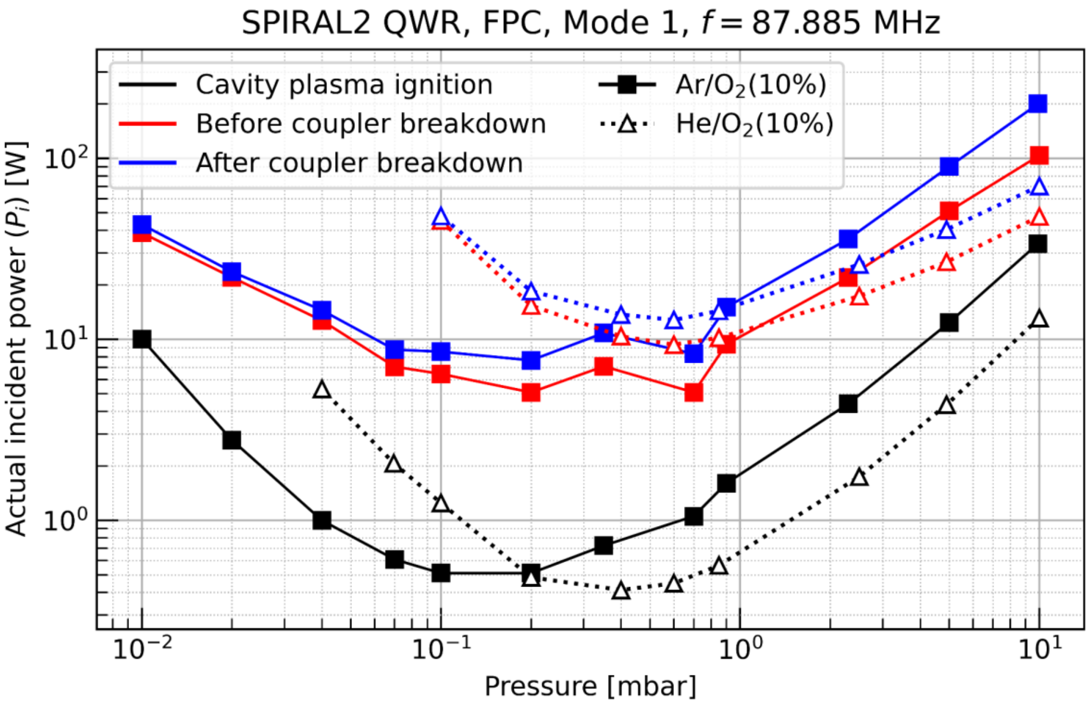
$Ar/O_2(10\%)$






SPIRAL2 QWR, FPC, Mode 1, f = 87.885 MHz, Ar/O2(10%)
Cavity plasma ignition
Before coupler breakdown
After coupler breakdown
Actual incident power (Pi) [W]
10^2
10^1
10^0
10^−2
10^−1
10^0
10^1
Pressure [mbar]

Ar/O_2 VS He/O_2



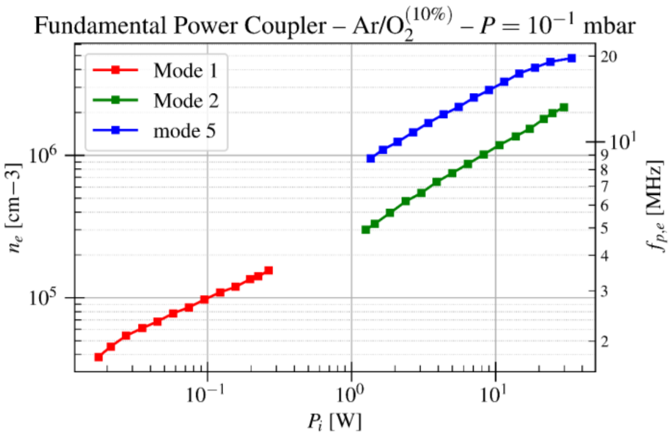
SPIRAL2 QWR, FPC, Mode 1, f = 87.885 MHz
Cavity plasma ignition
Before coupler breakdown
After coupler breakdown
Ar/O2(10%)
He/O2(10%)
Actual incident power (Pi) [W]
Pressure [mbar]

Coupler breakdown: some hypothesis

1. Plasma frequency related breakdown

- **Hypothesis:** at a certain power level, plasma density is high enough such that plasma frequency is bigger than the drive frequency. Then the RF wave cannot penetrate the bulk plasma anymore, leading to an E field distribution change, such that it confines the plasma around the powered antenna.
- **Problem:** in our case, plasma frequency calculated from electron density measurements shows that $f_{p,e}$~10 MHz which is way below f_{drive}~100 MHz. Then the RF wave can still pass through the plasma

- **Cut-off frequency & critical density**
  - $\omega_{p,e} > \omega$ = evanescent wave in the plasma
  - $n_c = \frac{\epsilon_0 m_e}{e^2}\omega^2$
  - At 88 MHz, $n_c = 9.6 \times 10^7$ [cm^{-3}]
  - At 251 MHz, $n_c = 7.8 \times 10^8$ [cm^{-3}]
  - At 439 MHz, $n_c = 2.4 \times 10^9$ [cm^{-3}]



Coupler breakdown: some hypothesis

2. Secondary electrons related breakdown (γ-mode transition)

- **Literature:** "Another interesting issue is related to higher-pressure operation, in which secondary electrons emitted from electrodes may play a role in the ionization processes and in the electron power balance." From P. Chabert, & N.S. Braithwaite "*Physics of radio-frequency plasmas*" pp. 166
- Copper: $1 \leq \text{SEY} \leq 2.5$ at low energy (< 500 eV)
- **Hypothesis:** Above a certain power threshold, secondary electrons can play a role near the power coupler, leading to plasma ignition around it. Then blocking RF wave propagation to the cavity volume.
- **Problem:** "In typical etching plasmas, with pressures around a few Pa and frequencies above 13.56 MHz, secondary electrons are usually not dominant, unless they are deliberately enhanced." From P. Chabert, & N.S. Braithwaite "*Physics of radio-frequency plasmas*" pp. 170, 171
    - Enhanced by the self-bias voltage????
    - Could explain why forced negative bias is efficient!! Repelling electrons

V. Baglin *et al.* "The secondary electron yield of technical materials and its variation with surface treatments"

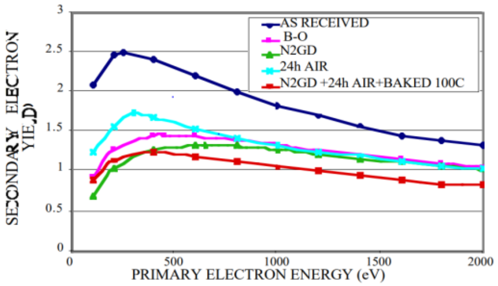


Figure 7: S.E.Y. of copper after various surface treatments

Coupler breakdown: some hypothesis

3. **Self-bias voltage related breakdown**
   - **Hypothesis:** While increasing the power, the power coupler becomes self-biased due to asymmetric electrode surface area. When the self-bias voltage is high enough, the plasma jumps from the volume to the power coupler where it confines.
   - **Problem:** “With hands” explanation, no literature

Coupler breakdown: some hypothesis

4. CCP discharge mode transition breakdown

- From P. Chabert, & N.S. Braithwaite “*Physics of radio-frequency plasmas*”. Chapter 1.4 Radio-frequency plasmas: E, H and W-mode. pp. 14, 15, 16, 17
  - “The E-mode forms a low-density plasma – the H-mode does not take over until the plasma density achieves sufficient conductivity for the electromagnetic mechanism to predominate”
  - “Studies have also shown that CCPs may also experience mode transitions (from E to H) if they are driven at high frequency because of an induced field parallel to the electrode.”

- **Hypothesis:** Is coupler breakdown an E-H mode transition?
- **Problem:** E-H mode transition is described as a “smooth” transition. However, in our case, this is not smooth at all.

Coupler breakdown: some hypothesis

E and H mode in CCP at VHF

6.2 Electromagnetic regime at high frequency
6.2.3 The general CCP at VHF

As in inductive discharges, when the power deposited by the inductively coupled current is larger than the power deposited by current that is driven by the electrostatic field, the discharge can be said to be in the H-mode. In the other limit, the discharge is in the E-mode. In this section it will be shown that CCPs at VHF can undergo E to H transitions. pp. 202

At low voltage, capacitive heating dominates (E-mode) whereas at high voltage the inductive heating takes over (H-mode), such that the discharge experiences an E–H transition as the voltage is raised. Unlike in inductive discharges, the transition is smooth and is not clearly defined. For the sake of simplicity, one can define the E–H transition as the condition $P_{ind} = P_{cap}$.
The E–H transition does not occur at a specific electron density, but also depends on the frequency. To analyse the role of the driving frequency, one has to remember that the voltage and the current are not radially uniform because of the standing wave effect. The voltage is maximum in the centre, where the current is zero, and decreases with radius. The radial position where the voltage reaches its minimum (and the current its maximum) will be denoted r = r1 in the following. The standing wave effect is weak if r1 >> r0, and strong if r1 ≤ r0 pp. 209

Coupler breakdown: some hypothesis

1.4 Radio-frequency plasmas: E, H and W-modes

The efficiency with which power is coupled from the power supply into the charged particles and the plasma uniformity both strongly depend on the design of the RF excitation.

Coupler breakdown: some hypothesis

VHF frequency & electromagnetic model

6. Multi-frequency capacitively coupled plasmas
Section 6.2 addresses the case of excitation by a single very high frequency in the electromagnetic regime, that is when the wavelength of the RF excitation is comparable with, or less than, the size of the electrodes. pp. 177

6.2 Electromagnetic regime at high frequency
The electrostatic model cannot be used for a CCP at an arbitrarily high excitation frequency in pursuit of higher electron density since nonuniformities arise when the excitation wavelength λ becomes comparable to the electrode radius, and the plasma skin depth δ becomes comparable to the electrode spacing. These conditions define the change-over from an electrostatic to an electromagnetic regime. pp. 187

Self-bias

According to the literature, we find that:

- “In an RF coaxial capacitively coupled plasma, a DC self-bias potential is established across the inner electrode sheath due to the surface area difference between the inner and outer electrodes.”
- “In CCP when one electrode has a smaller area than the other, to maintain current continuity, the smaller area electrode acquires a negative dc voltage (self-bias).”
- “The negative self-bias potential on the inner electrode plasma sheath provides higher energy to ions bombarding the inner electrode compared to the outer electrode, making it challenging to etch the outer electrode without applying a positive DC bias to the inner electrode.”
- “An additional DC current is needed to bring the negative self-bias potential at the inner electrode to zero or a positive value, which can be achieved by an external DC power supply.”
- “The DC coupling allowed a DC current to flow to the powered electrode and to expand the plasma structure to the whole chamber. In the case of low RF power without DC bias, the plasma is confined to the inner electrode, as similarly observed for planar geometry.”

Self-bias

J. Upadhyay et al. ; "*Effect of self-bias on cylindrical capacitive discharge for processing of inner walls of tubular structures—Case of SRF cavities*." AIP Advances 1 August 2018; 8 (8): 085008. https://doi.org/10.1063/1.5045692

Upadhyay, J., et al. *"Plasma processing of large curved surfaces for superconducting rf cavity modification."* Physical Review Special Topics-Accelerators and Beams 17.12 (2014): 122001. https://doi.org/10.1103/PhysRevSTAB.17.122001

Upadhyay, J., et al. *"Self-bias Dependence on Process Parameters in Asymmetric Cylindrical Coaxial Capacitively Coupled Plasma."* arXiv preprint arXiv:1506.05167 (2015). https://doi.org/10.48550/arXiv.1506.05167

Soni, Kunal et al. "Experimental and numerical characterization of a radio-frequency plasma source with a DC-grounded electrode configuration using a quarter-wavelength filter." Plasma Physics and Controlled Fusion 63 (2021): n. pag. https://doi.org/10.1088/1361-6587/abdbd1

SPIRAL2 B type cryomodule