# Field Emission Mitigation via Plasma Processing in 9-cell TESLA-type Cavities


**Bianca Giaccone[1,2]**, Martina Martinello[1], Paolo Berrutti[1], Dan Gonnella[3], Marc Doleans[4], Giulia Lanza[3], Anna Grassellino[1], Marc Ross[3]

[1]Fermilab, [2]Illinois Institute of Technology, [3]SLAC, [4]ORNL


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- Introduction
- Plasma ignition in 1.3GHz TESLA-shaped cavities
  - New method to control plasma ignition
  - RF measurements at different pressures with Neon and Argon
- Plasma cleaning test on 9 cell TESLA-shaped cavity with artificial contamination
- First RF results of plasma processing applied single cell and 9-cell cavities
    - Effect of plasma on N-doping
    - Effect of plasma on contaminated cavities
- Conclusions
  - Future work

# Collaboration for LCLS-II Plasma Processing

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- Adapt the ORNL plasma cleaning technique to LCLS-II cavities and cryomodules
- Provide a system capable of efficiently process LCLS-II cavities/cryomodules

SLAC NATIONAL ACCELERATOR LABORATORY

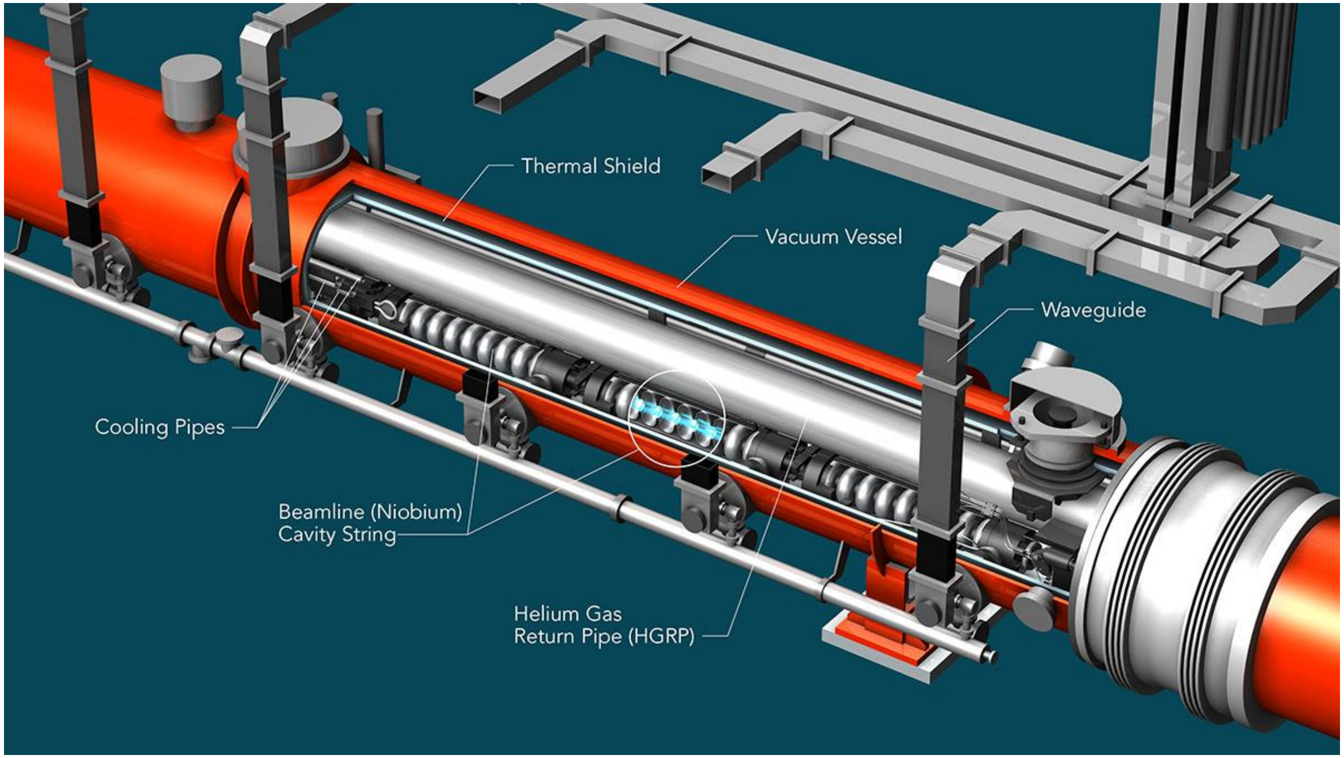
- Simulation for applicability of ORNL plasma processing to LCLS-II cavities
- Use the system to perform cleaning in the accelerator tunnel

OAK RIDGE National Laboratory

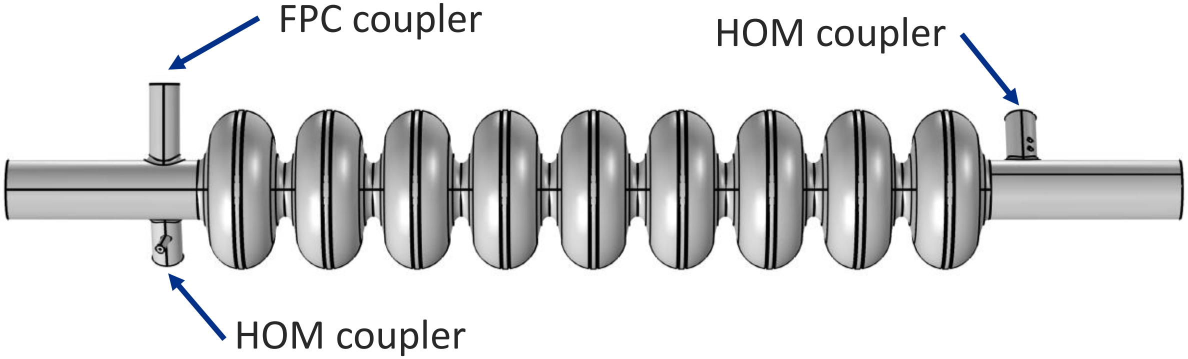
- Successful experience with plasma processing
- Guidance for design and sample studies for LCLS-II plasma cleaning

Project supported by DOE - Basic Energy Sciences (BES)

# In-situ plasma processing




Procedure can be applied at **room temperature in-situ** in the cryomodules

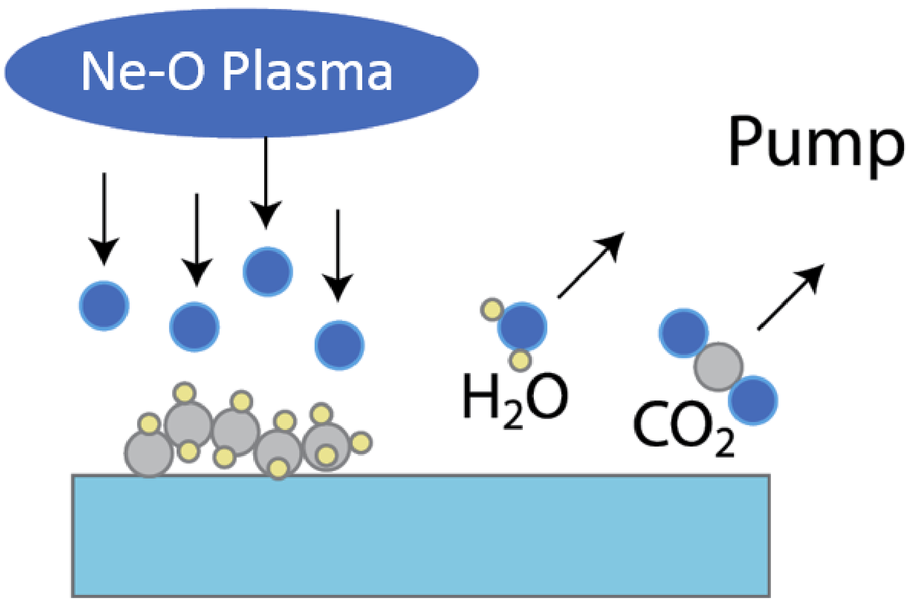


# Plasma Processing Methodology

- Reducing FE by **increasing work function** of cavity RF surface
  - Hydrocarbons and adsorbates lower work function of Nb
- Enabling operation at higher accelerating gradient

$$O_2 + C_xH_y \rightarrow CO + CO_2 + H_2O$$

**Increasing $\Phi$ by 10 % means increasing $E_{acc}$ of about 15 %**




$$j = \beta \frac{AE^2}{\Phi} e^{-B\frac{\Phi^{3/2}}{\beta E}}$$

$$dj = 0 \qquad \frac{dE_{acc}}{E_{acc}} \approx \frac{3}{2}\frac{d\Phi}{\Phi}$$

$J$: current density
E: surface electric field
$\Phi$: work function
$\beta$: enhancement factor (≈10 to 100)
A,B: constants

M. Doleans et al. NIMA 812 (2016) 50-59

# Plasma ignition in SRF cavities

Glow discharge is ignited one cell per time ⟶ necessary to:

- maximize E field in one cell
- select cell of ignition

**SNS method:** Dual Tone excitation to **ignite the plasma**

– Superposition of two frequencies of the fundamental pass-band to create an asymmetry and maximize the electric field in one cell to select it as cell of ignition

M. Doleans, J. Appl. Phys. 120, 243301 (2016)

**FNAL method:** Dual Tone excitation to **transfer the plasma**

– Ignition in central cell + superposition of higher order modes to move the plasma inside the cavity

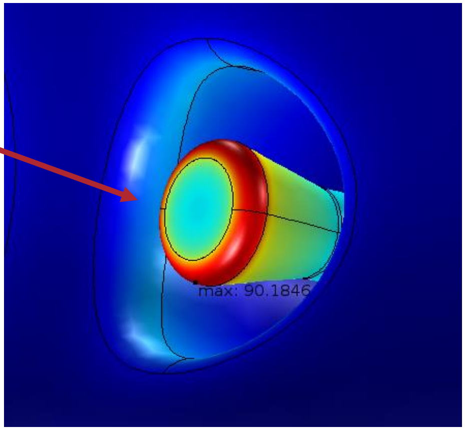
P. Berrutti, J. Appl. Phys. 126, 023302 (2019)

# Field enhancement at LCLS-II FPC

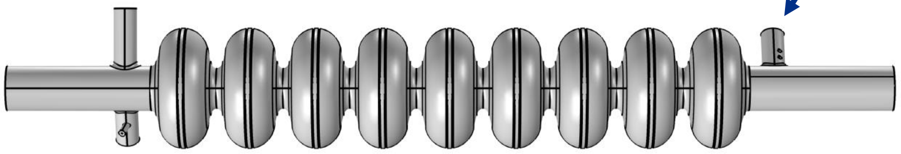
Due to geometry: intense field enhancement at the fundamental power coupler

| 9-cell plasma ignition | |
|---|---|
| Total $P_f$ [W] | 350 |
| $E_{coupler}$ [kV/m] | 90 |
| $E_{cavity}$ [kV/m] | 12 |

**Field enhancement at the coupler ≈ 7.5 (for SNS ≈ 3)**




Due to low coupling factor at room temperature less than 1% of the power is transmitted to the cavity ($Q_{Nb} = 1 \cdot 10^4,\ Q_{ext} = 3 \cdot 10^7$).




This could result in: **- no plasma ignition**
**- plasma ignition in the coupler**

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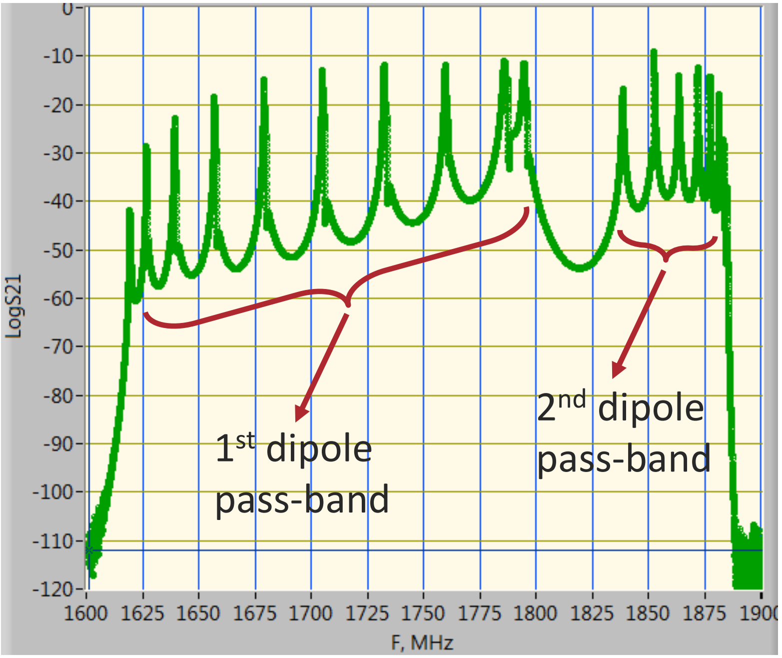
# Plasma ignition in TESLA-shaped cavities using HOMs

New idea: ignite the plasma using HOMs!




HOMs (higher order modes): good coupling at room temperature
Plasma can be ignited using **only few Watts!**

For the first two HOM pass-bands:

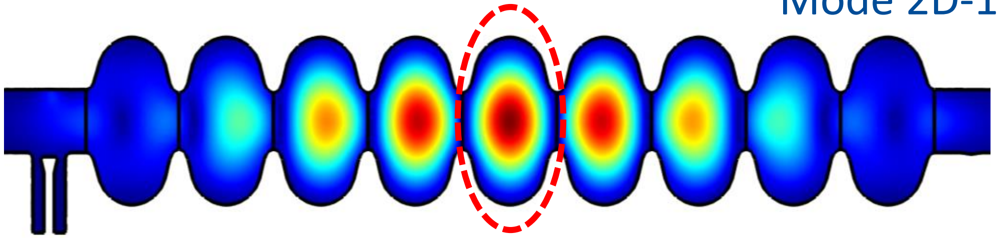
- Coupling factor: $0.01<\beta<1.17$
- Reflection coefficient $0.006<|\Gamma|^2<0.94$

- Plasma is ignited cell by cell, not in the entire cavity
- **Dual tone excitation to transfer the plasma:** using a superposition of HOMs it is possible to transfer the plasma through adjacent cells

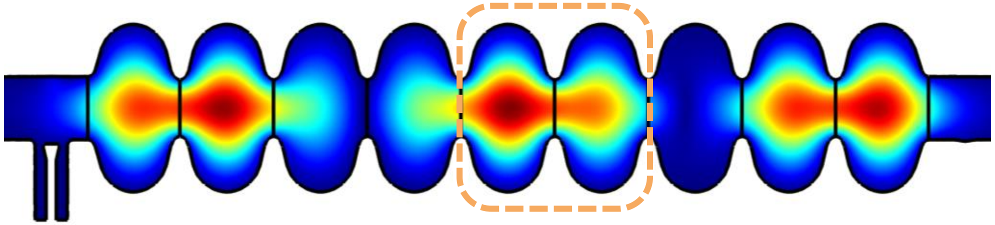
# Example of plasma transfer from cell #5 to #6

1. Cell #5 is ignited with mode 2D-1
2. Mode1D-3 is added to create asymmetry between cell #4 and cell #6
3. E field is still maximum in cell 5: Mode 2D-1 can now be switched off and the plasma remains ignited in cell #5
4. Add mode 1D-6 to 1D-3: E field is now maximum in cell #6, the plasma moves from 5 to 6
5. Switch off mode 1D-3, plasma remains ignited in cell #6.

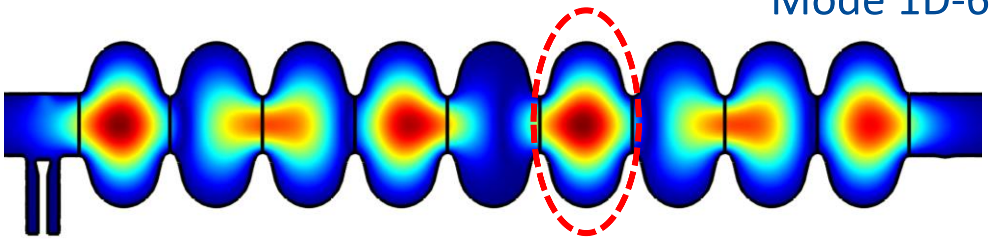
Mode 2D-1



Mode 1D-3



Mode 1D-6



P. Berrutti, B. Giaccone et al., J. Appl. Phys. 126, 023302 (2019)

# Cell of ignition: detected with frequency shift measurements

Method to locate the cell where plasma is ignited without use of cameras:

1. The **frequency shift $\delta\omega$** of the first dipole pass-band due to plasma ignition is **measured**

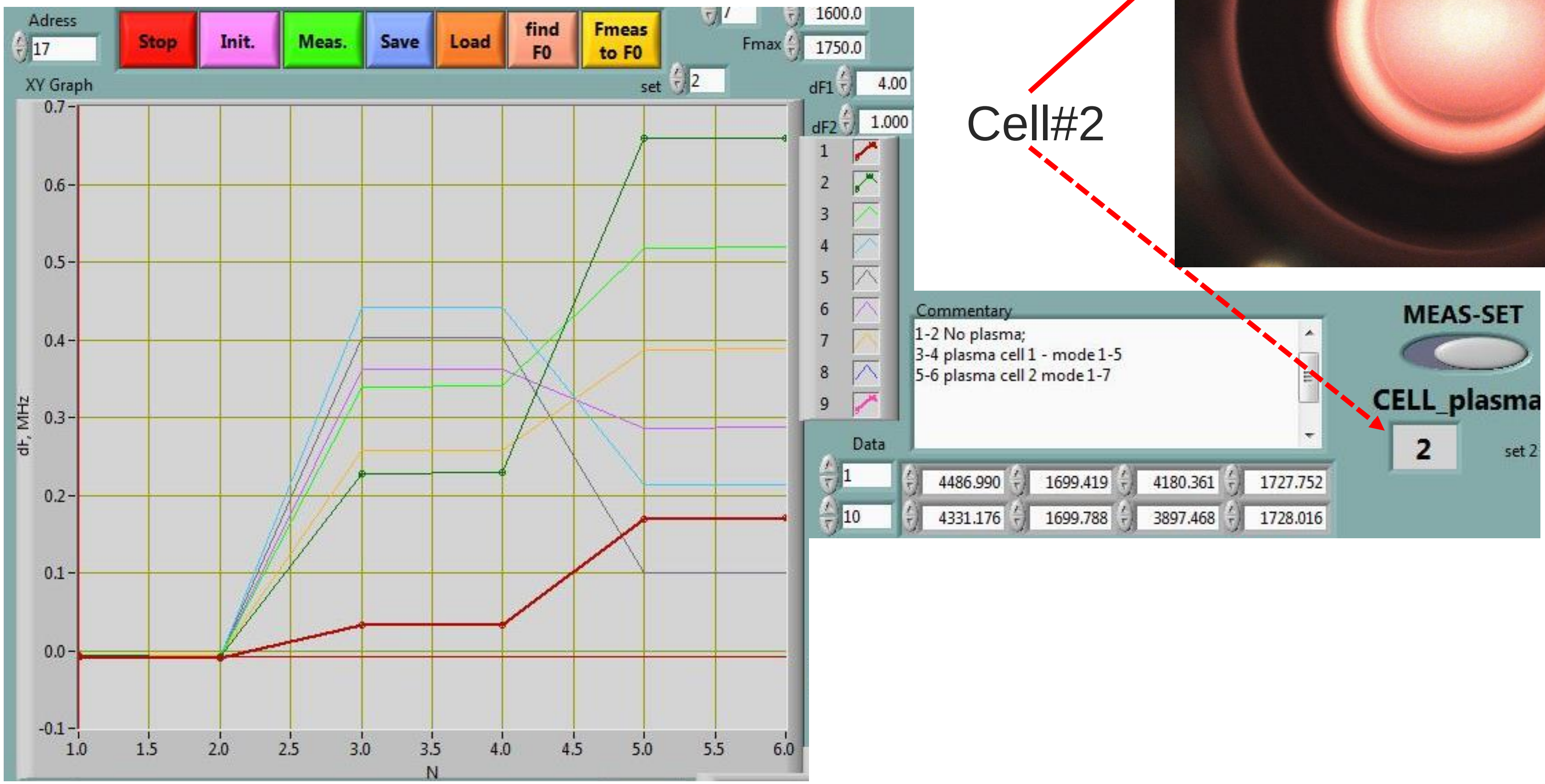
   $\delta\omega$ depends on:
   - Change in **dielectric constant** due to plasma ($\epsilon \propto \eta$)
   - **Intensity** of the **electric field** of the mode in the cell of ignition

$$\frac{\delta\omega}{\omega} \approx \frac{1}{2}\frac{\iiint_{plasma} \eta E^2 dV}{\iiint_{cavity} E^2 dV}, \qquad \eta = \frac{\omega_{plasma}^2}{\omega_{RF}^2}$$

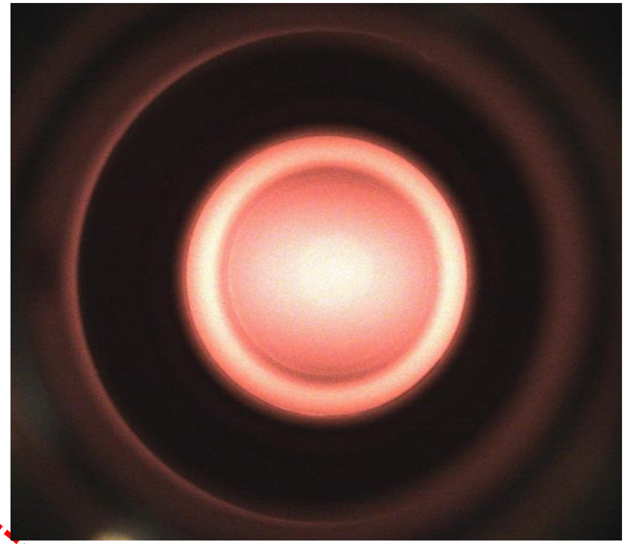
2. Measured $\delta\omega$ is compared with $\delta\omega$ calculated simulating the glow discharge in each cell of the cavity

# Cell of ignition: detected with frequency shift measurements

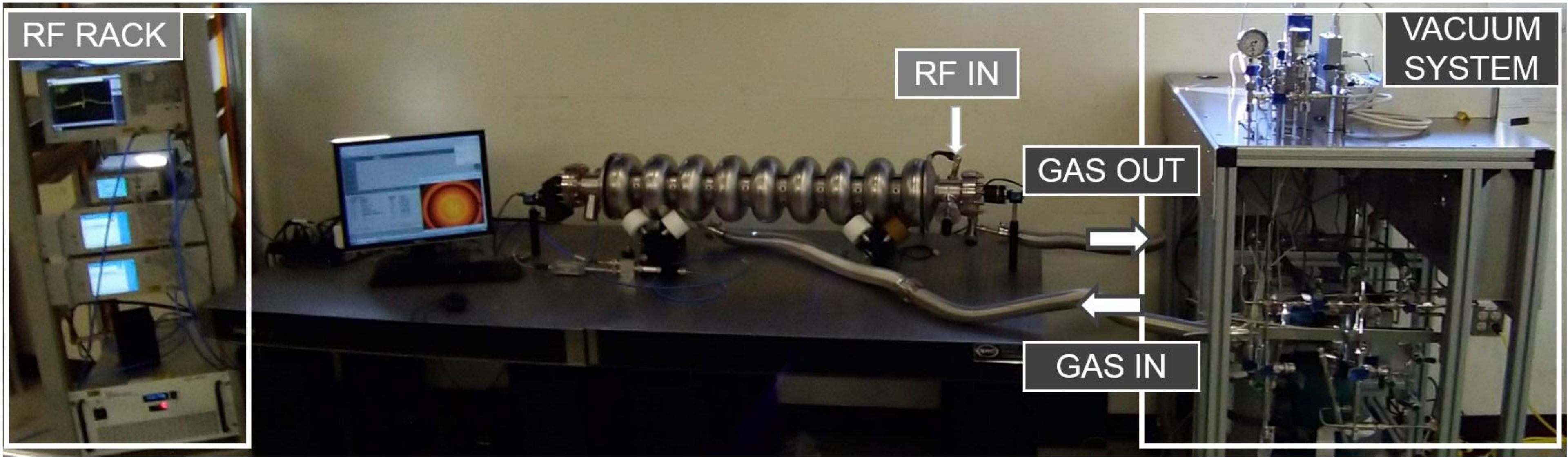
Developed a Labview program that measures $\delta\omega$ and compares it to simulated $\delta\omega$ and **identifies cell of ignition**




Cell#2

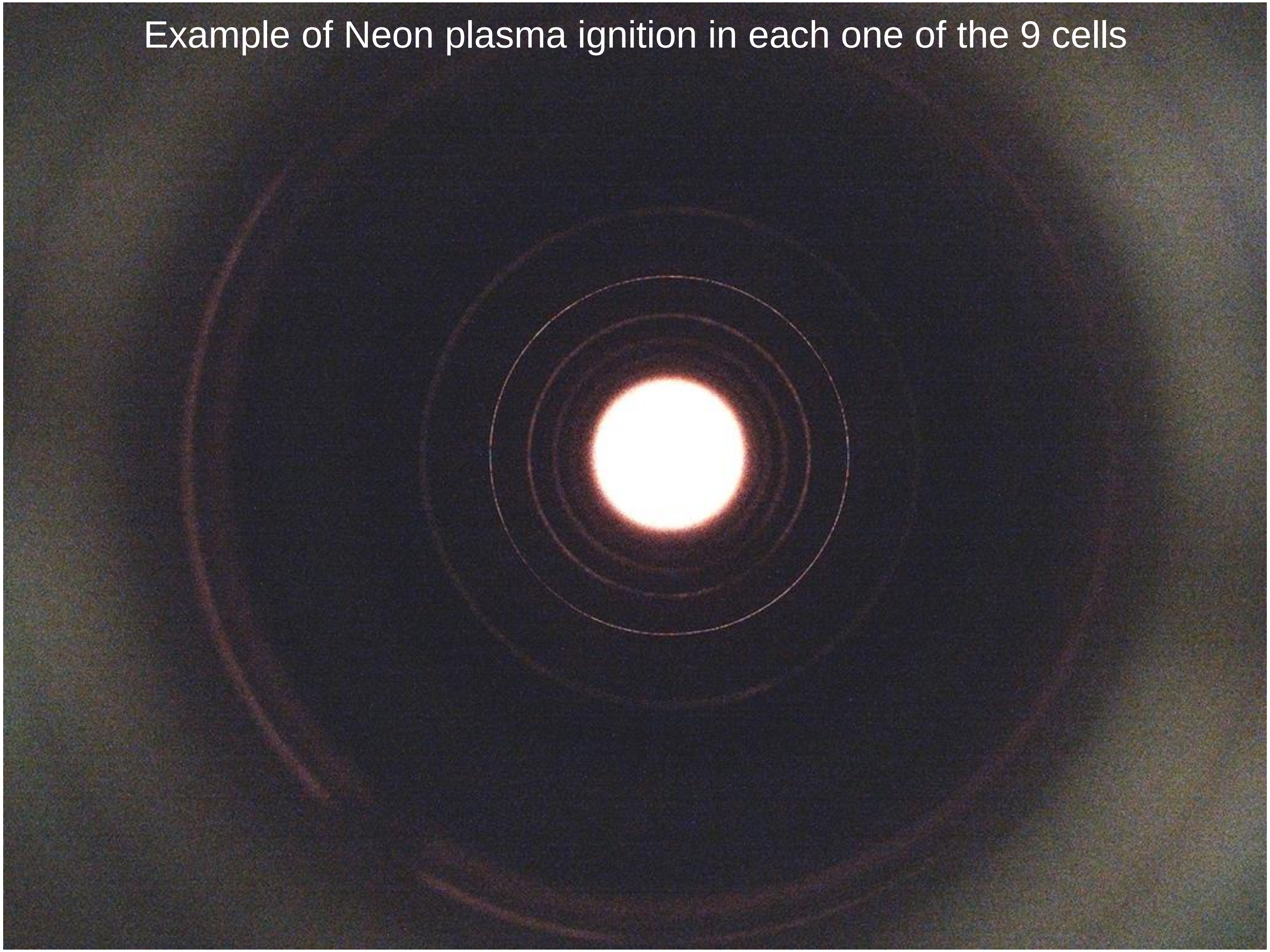


# Plasma cleaning apparatus




- Cleaning is performed at room temperature with 75-200 mTorr of Ne-$O_2$
- Cavities are assembled with valves on both end sides, for injection and evacuation of the gas
- Neon and Oxygen are sent to the cavity mixed (few % of $O_2$)
- RGA is used to analyze by-products

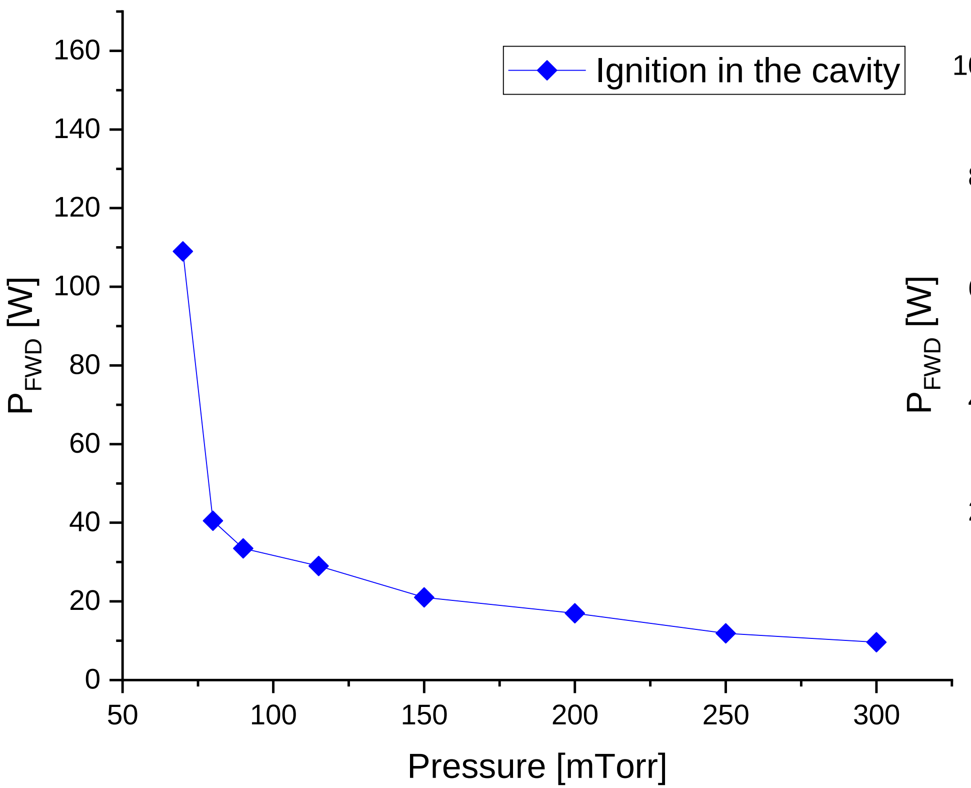
# RF measurements: cavity backfilled with Neon or Argon



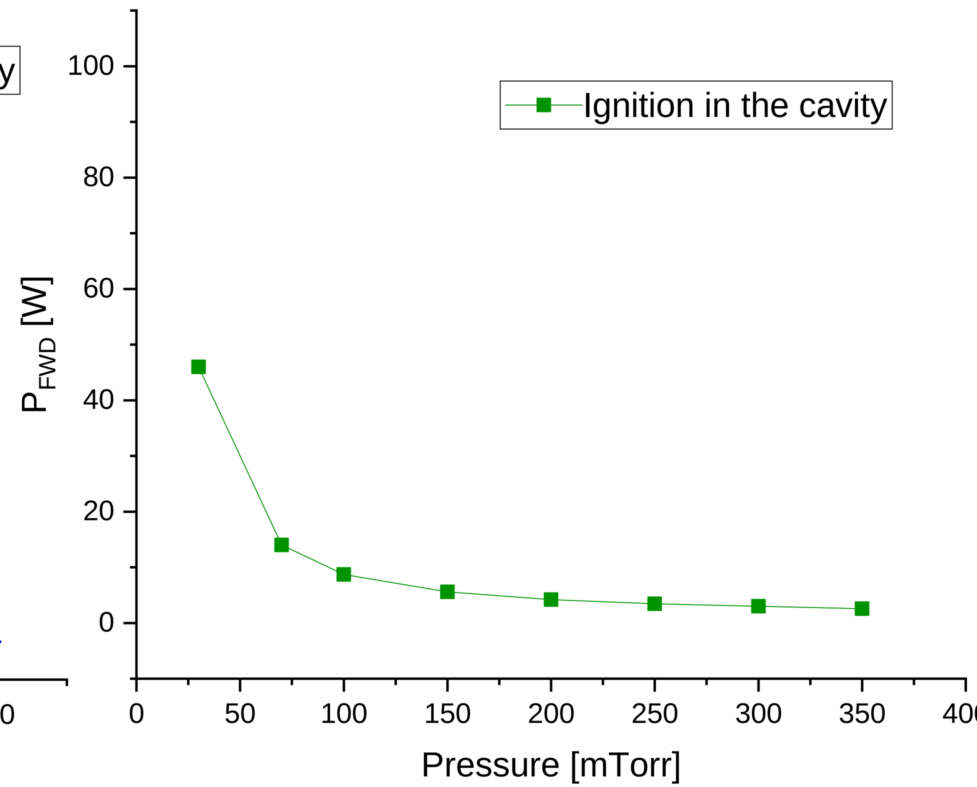
# Neon and Argon ignition curves

- Plasma ignition as a function of pressure monitored for both Neon and Argon
- Verified that the risk of igniting the plasma at the HOM coupler is negligible

Curve of plasma ignition using **Neon**




Curve of plasma ignition using **Argon**



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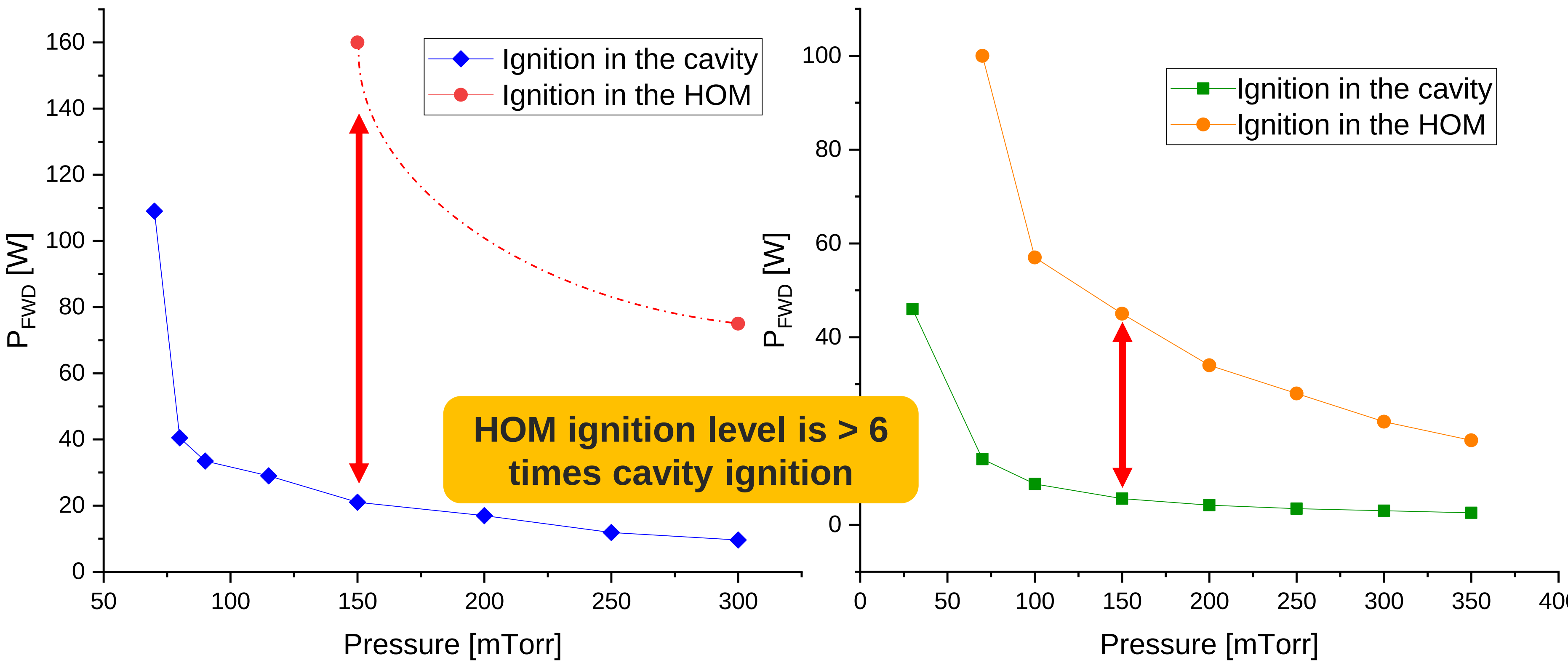
Curve of plasma ignition using **Neon** Curve of plasma ignition using **Argon**



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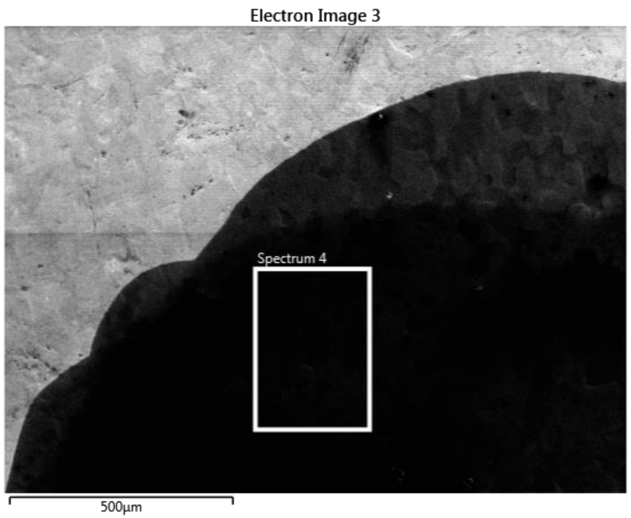
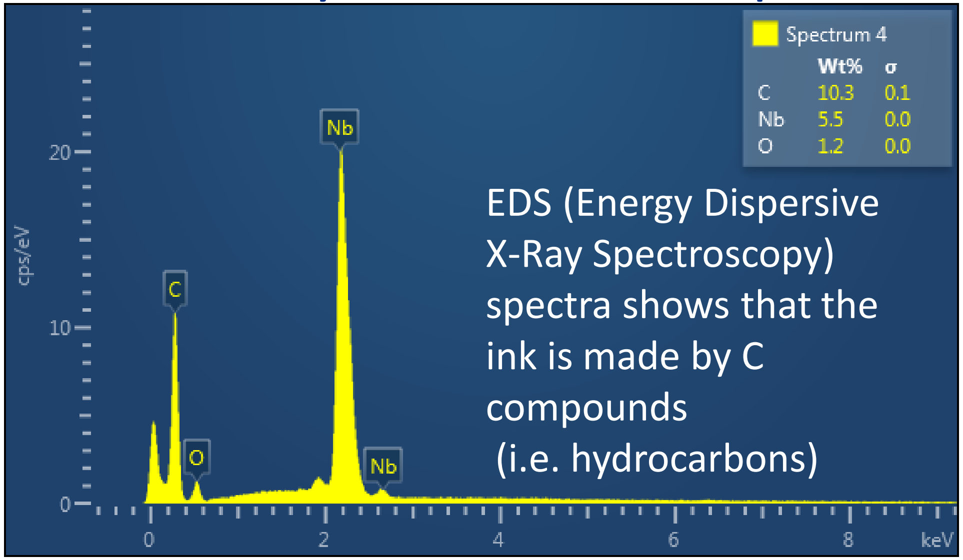
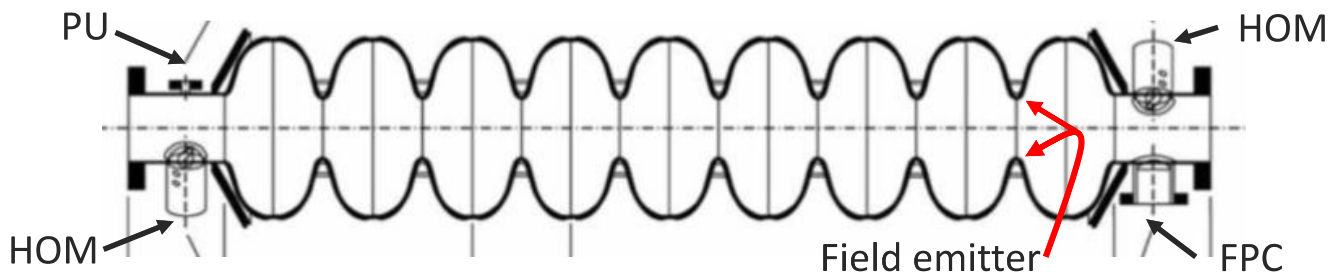
# Plasma processing studies in artificially contaminated cavity

- 1st test goal: remove hydrocarbon contamination with plasma cleaning
- We draw 8 “dots” with both red and black permanent markers around the iris of the first cell of a 9-cell LCLS-II cavity

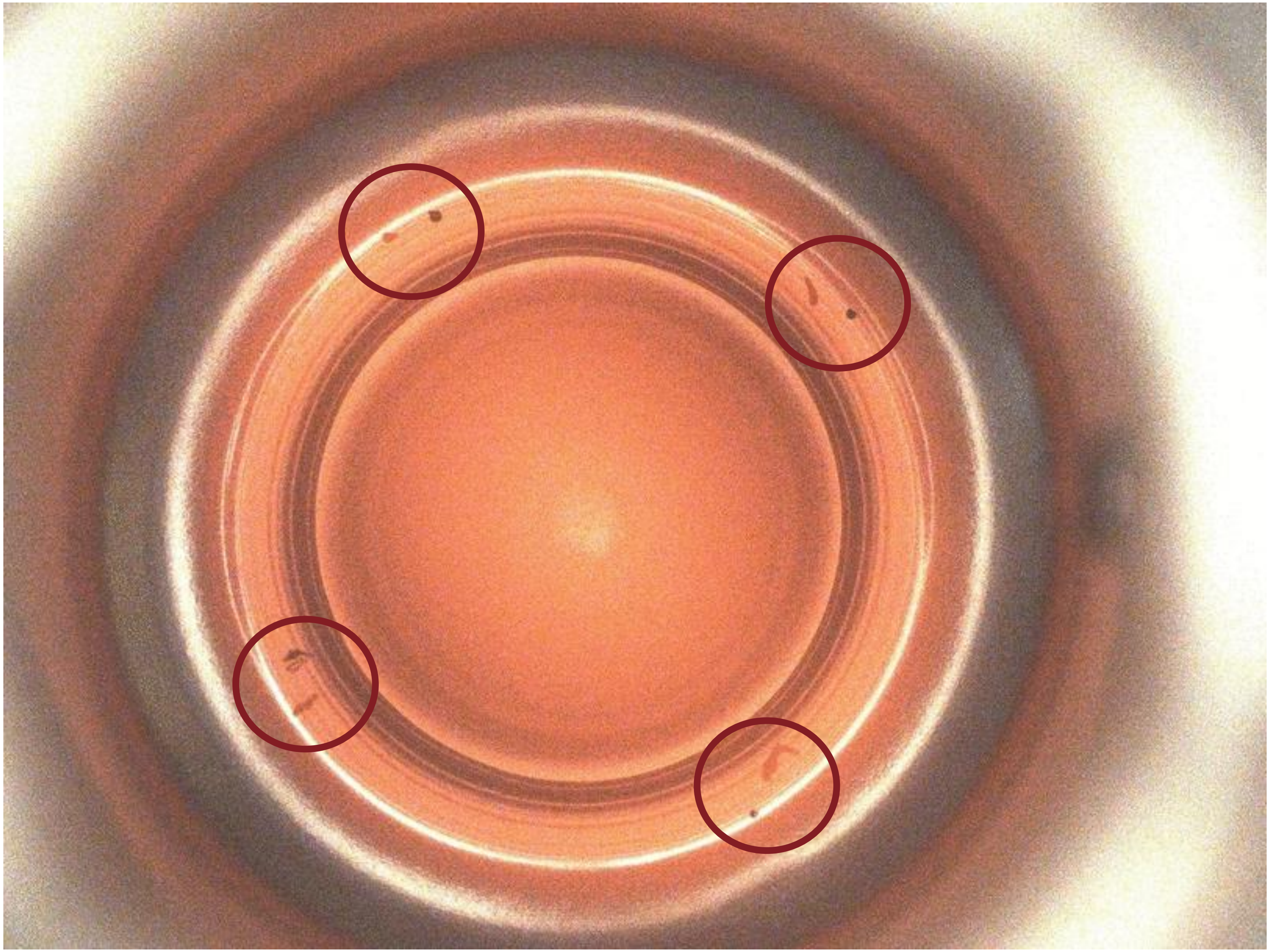



EDS analysis of black Sharpie ink



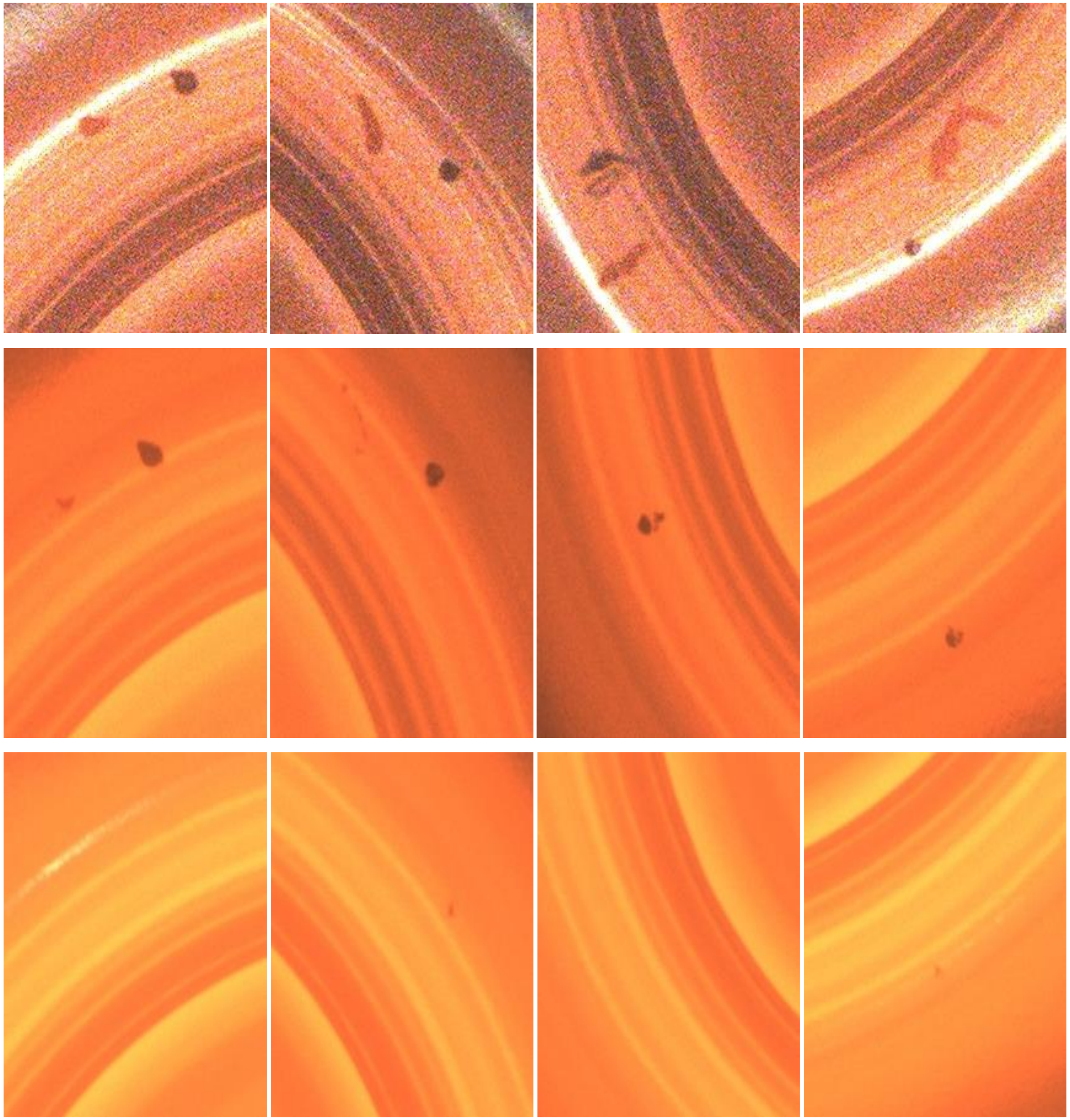
# Contaminated cell (#1) has been processed for ≈ 19 hours total



Initial state

After 5h of plasma cleaning

After 19h of plasma cleaning





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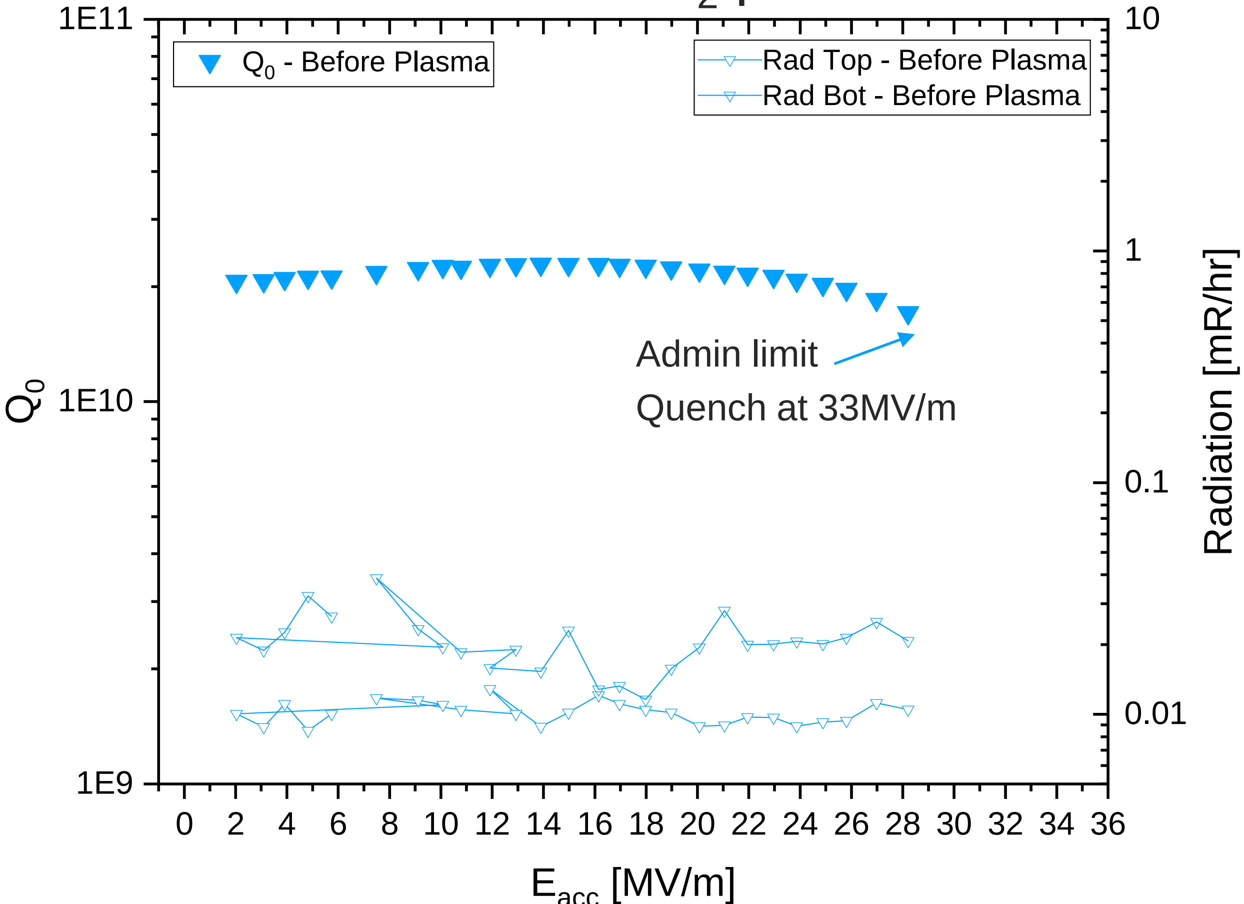
# N-doped single cell: RF results before and after plasma processing

Scope: study effect of plasma processing on Q-factors on N-doped cavities

- N-doped cavity processed for 16h with Ne-$O_2$ plasma.

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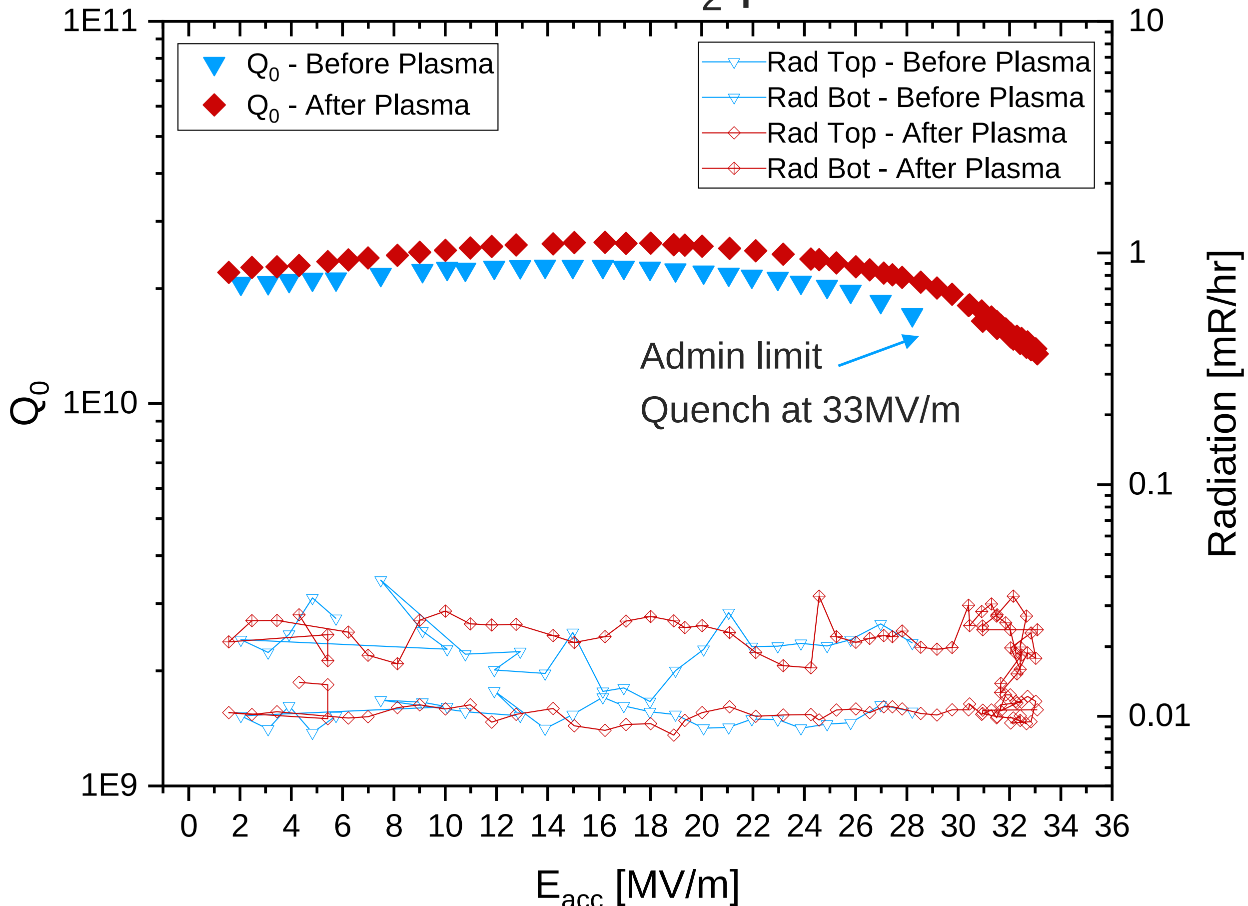
HOM couplers



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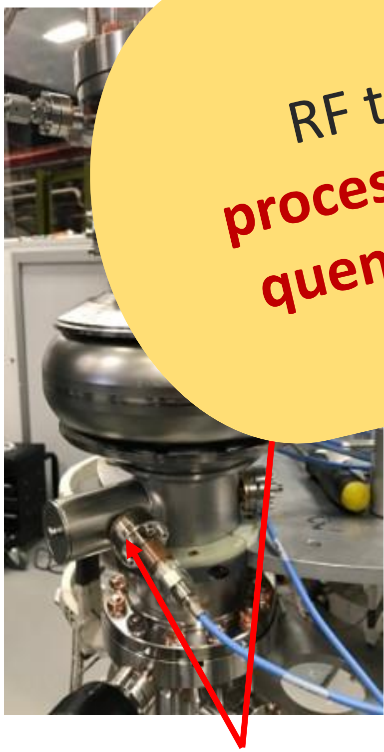
Scope: study effect of plasma processing on Q-factors on N-doped cavities

- N-doped cavit... $O_2$ plasma.

RF test proved that **plasma processing preserves high $Q_0$ and quench field in N-doped cavity!**



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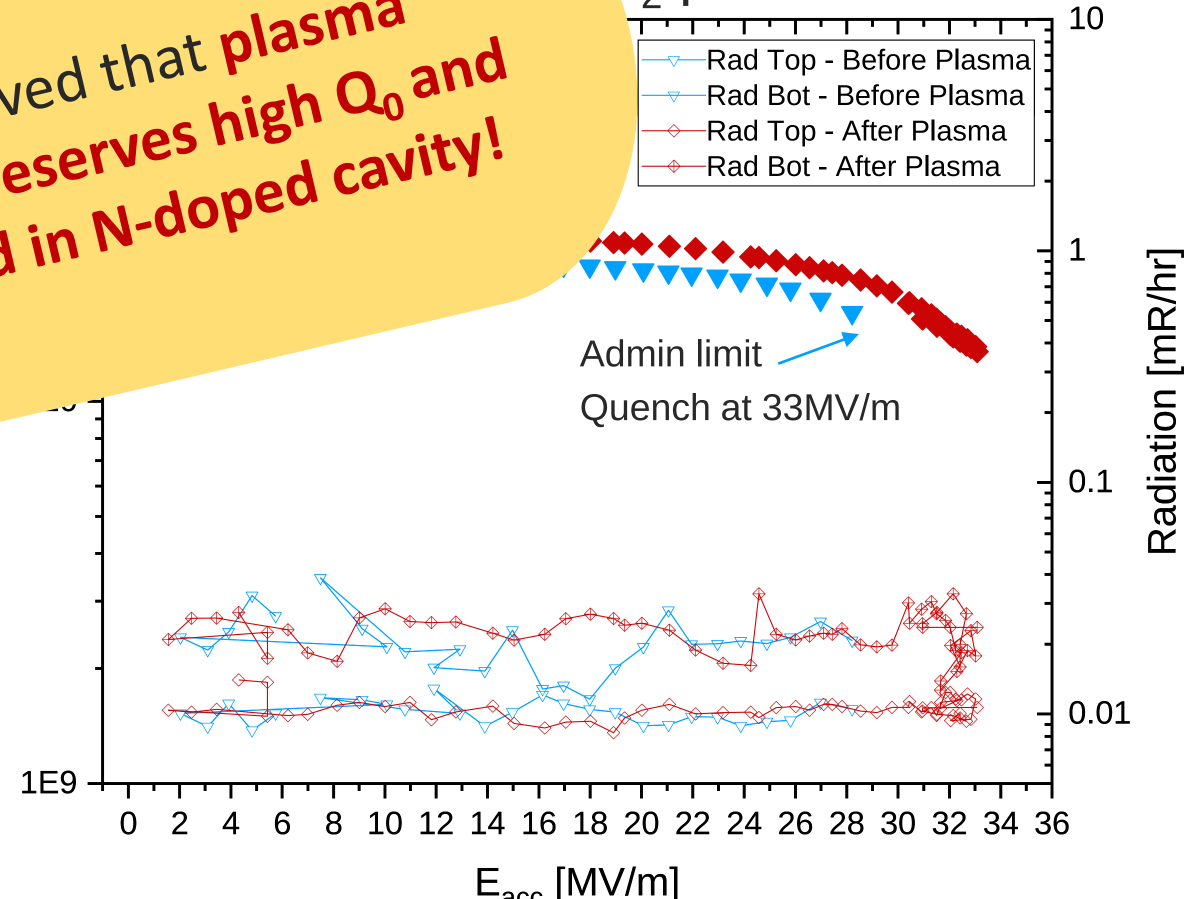

# Studies of plasma processing in Contaminated cavities

Plasma processing applied in some field emitting/contaminated cavities:

- Carbon contamination: introduction of Aquadag contamination on the iris of the cavity
- Naturally FE cavities: plasma processing applied on a naturally field emitting cavities, as received from the vendor
- Vacuum failure: simulation of vacuum accident to ATM to introduce field emitters
  - Inside Clean room
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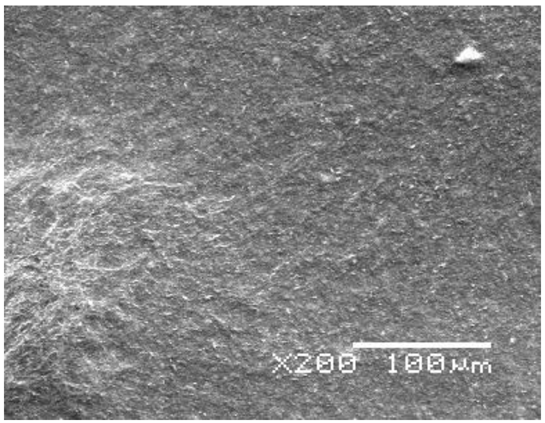
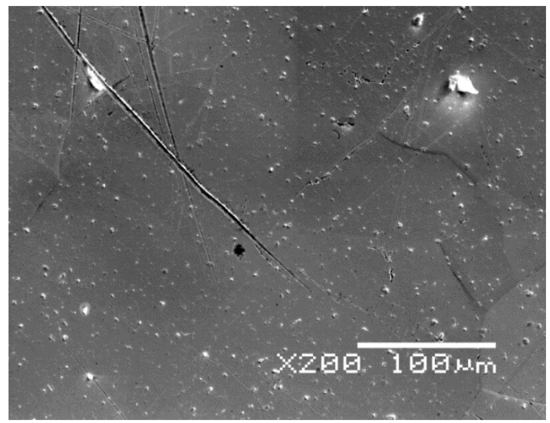
# Controlled introduction of carbon contamination

- Small drop of Aquadag (carbon-based conductive paint) introduced using a clean Nb wire at the iris of a single-cell cavity

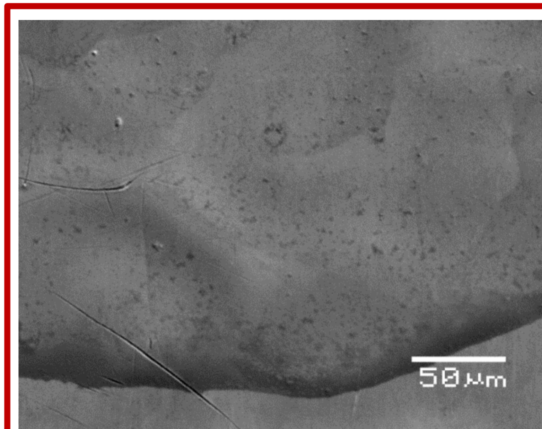
Pure Aquadag



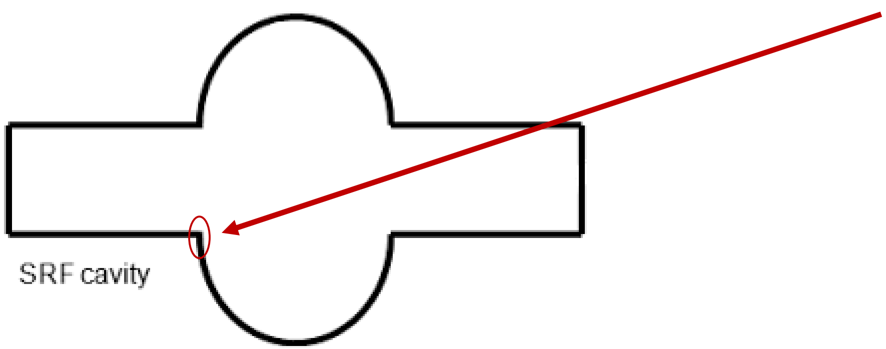

$10^2$ times diluted Aquadag




$10^4$ times diluted Aquadag




**Chosen concentration**

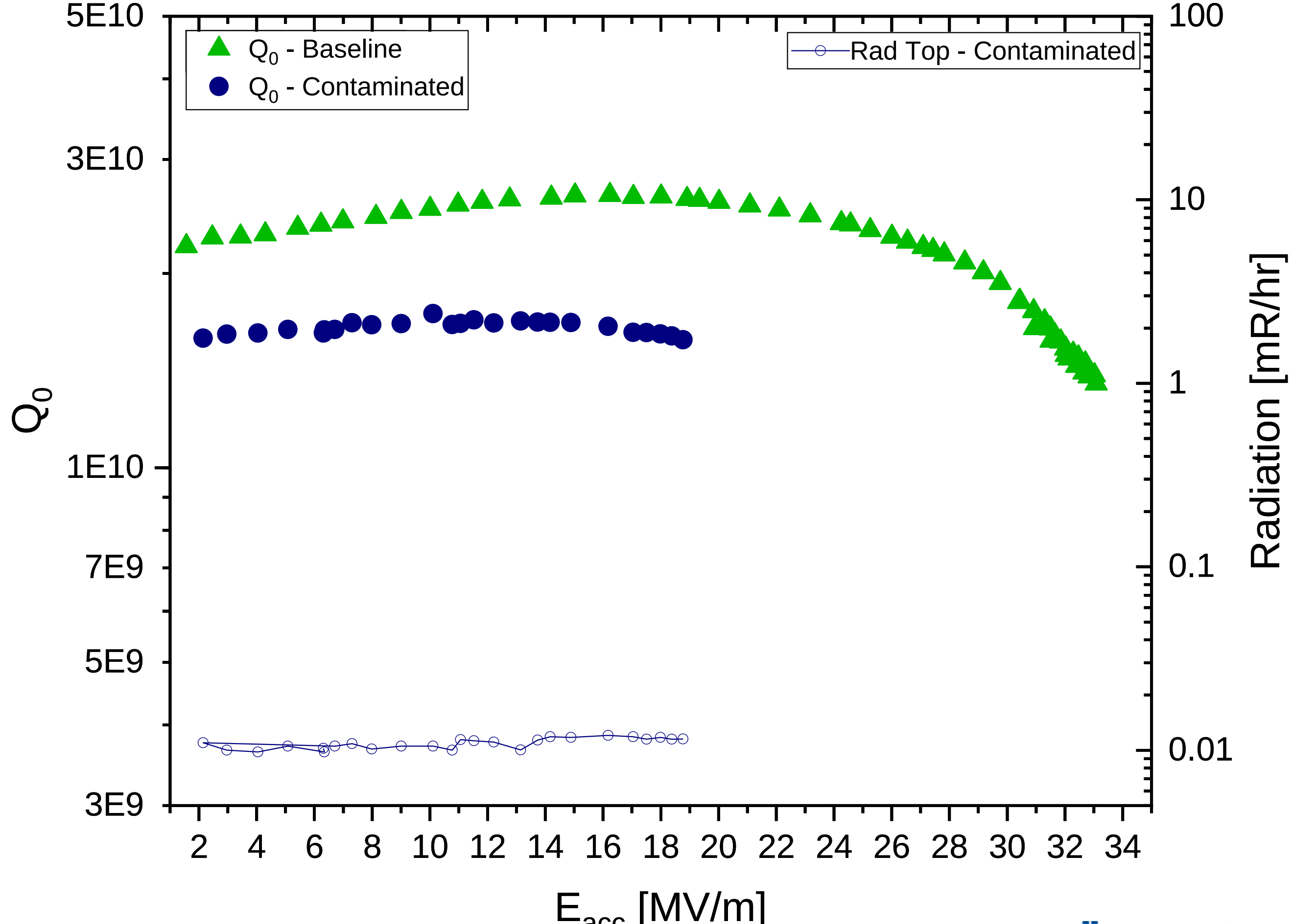


# **Carbon contamination**: RF results before and after plasma processing

Scope: study the removal of Carbon contamination

- Single cell cavity processed for 17h with Ne-$O_2$ plasma.

HOM couplers



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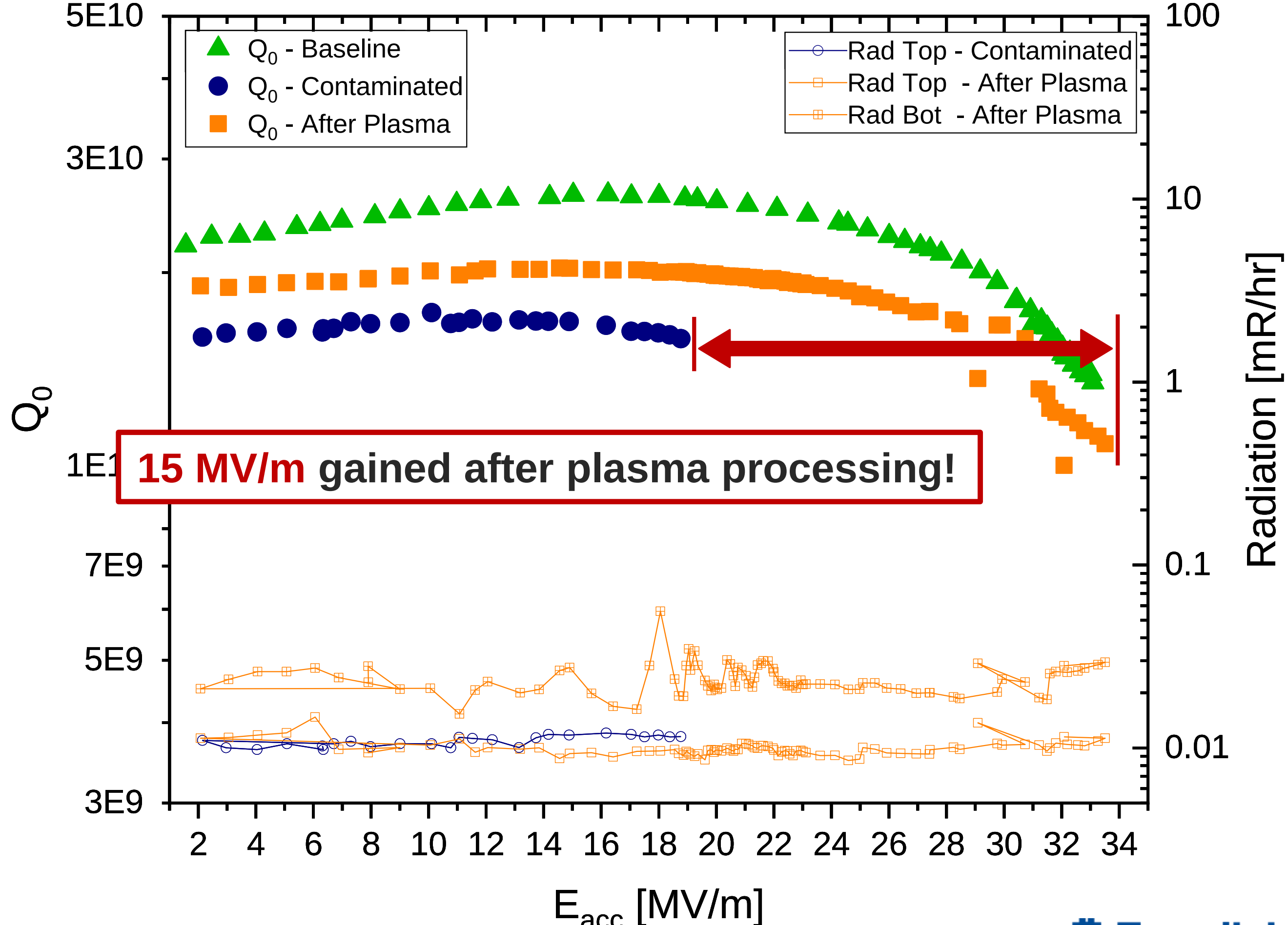




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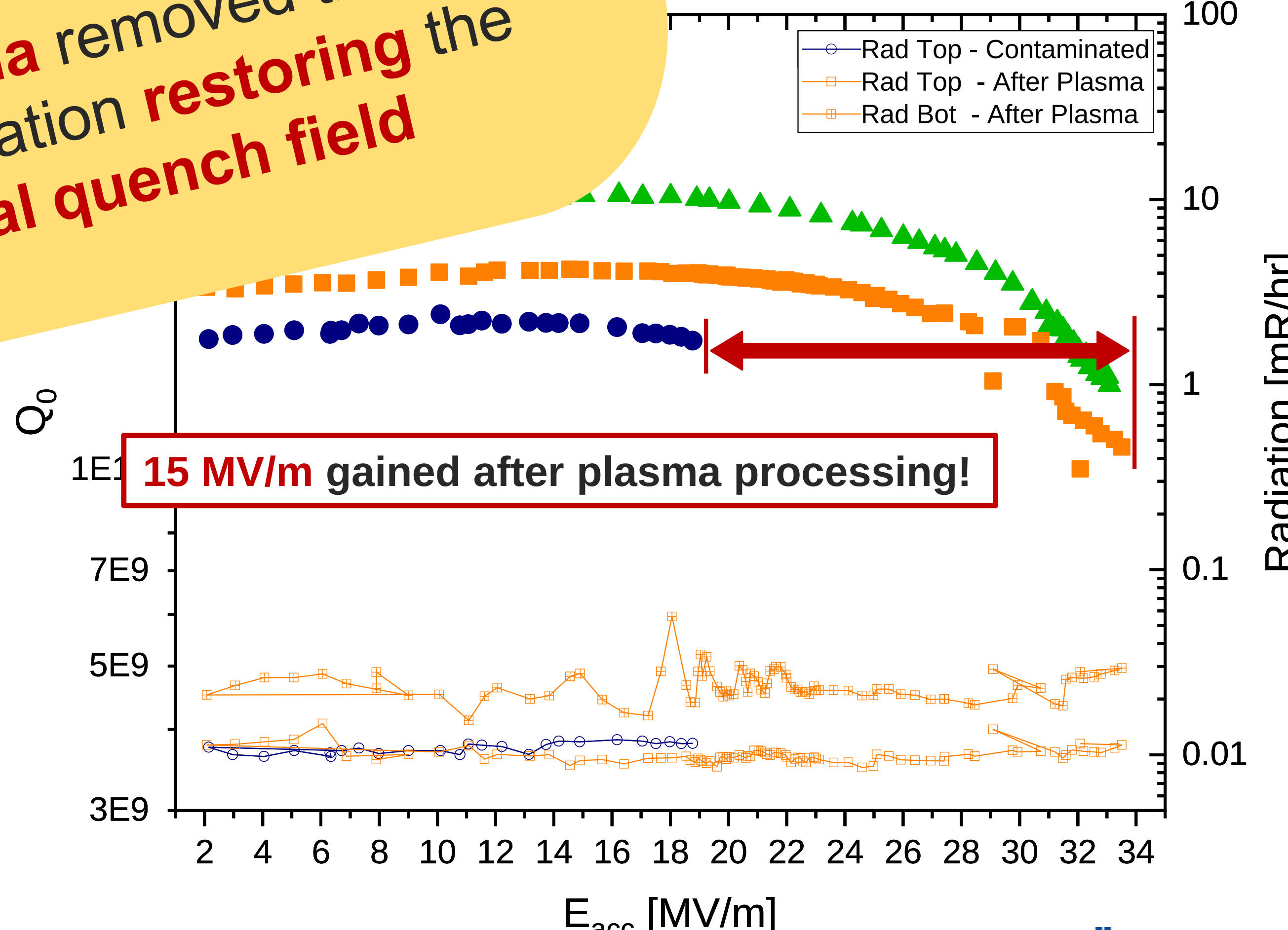
- Single cell … ith Ne-$O_2$ plasma.

**Plasma** removed the contamination **restoring** the **initial quench field**

HOM couplers




**15 MV/m gained after plasma processing!**

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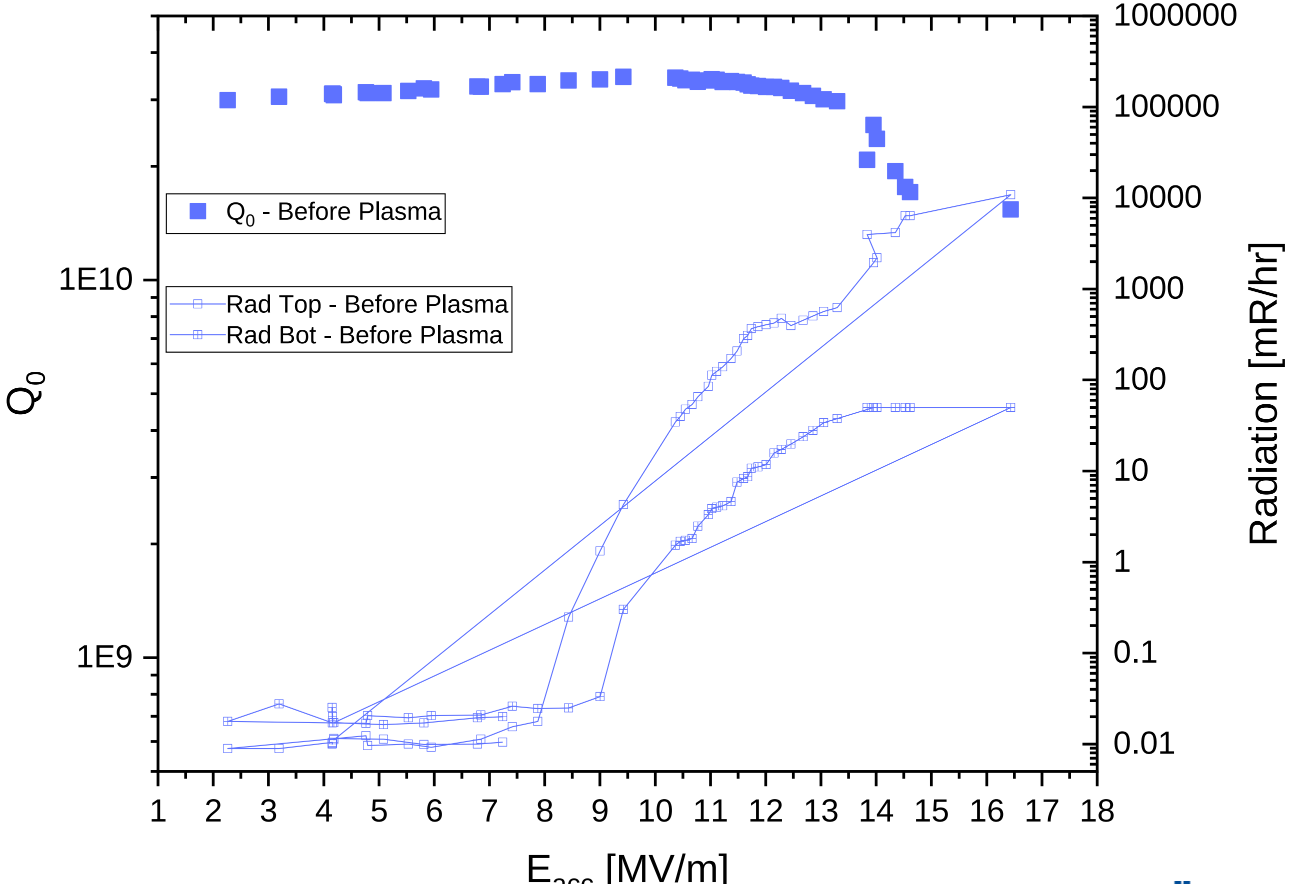
# **Naturally Field Emitting cavity:** RF results before and after plasma processing (1)

Scope: study the effect of Plasma processing on natural field emission

- 9-cell cell cavity, each cell processed for <2h with Ne-$O_2$ plasma.



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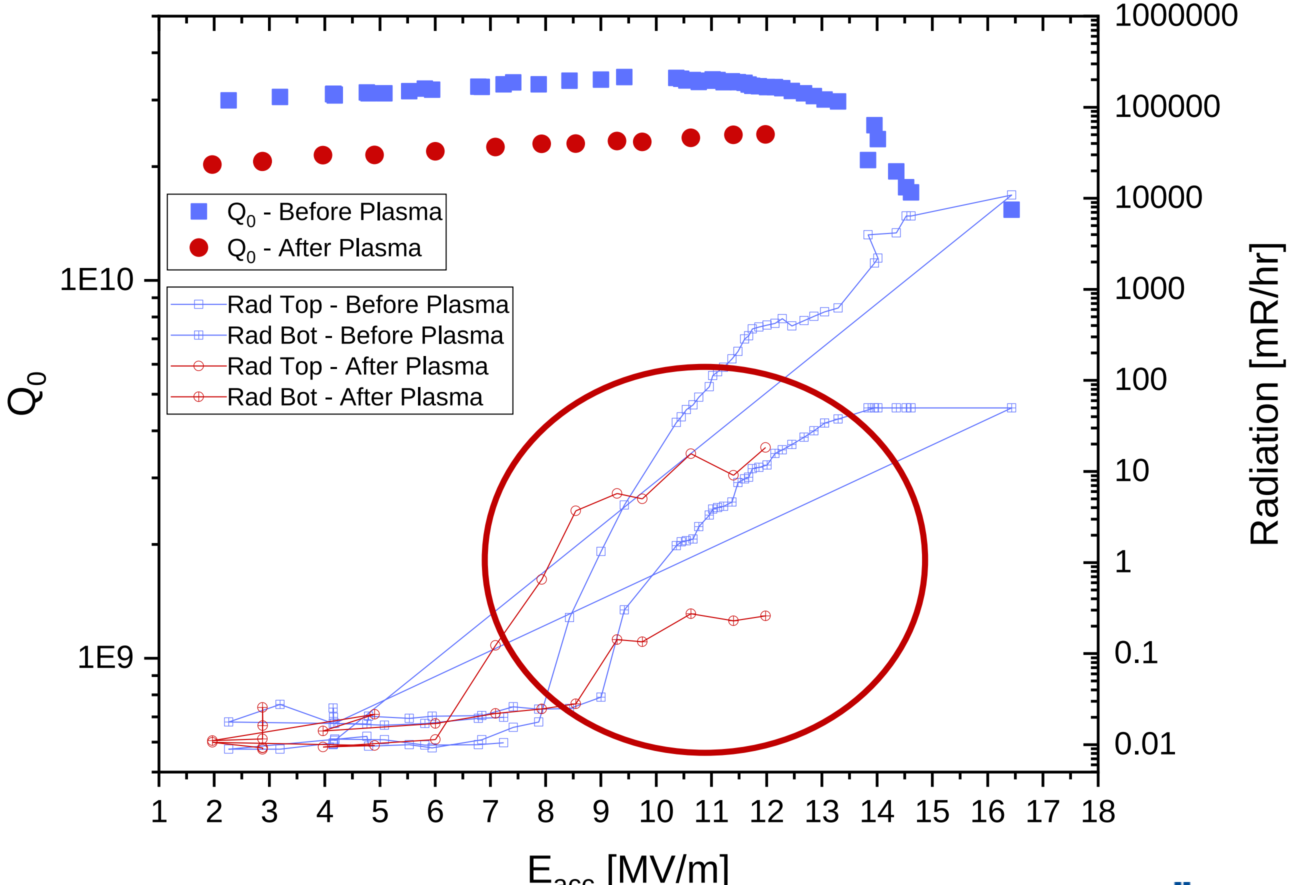




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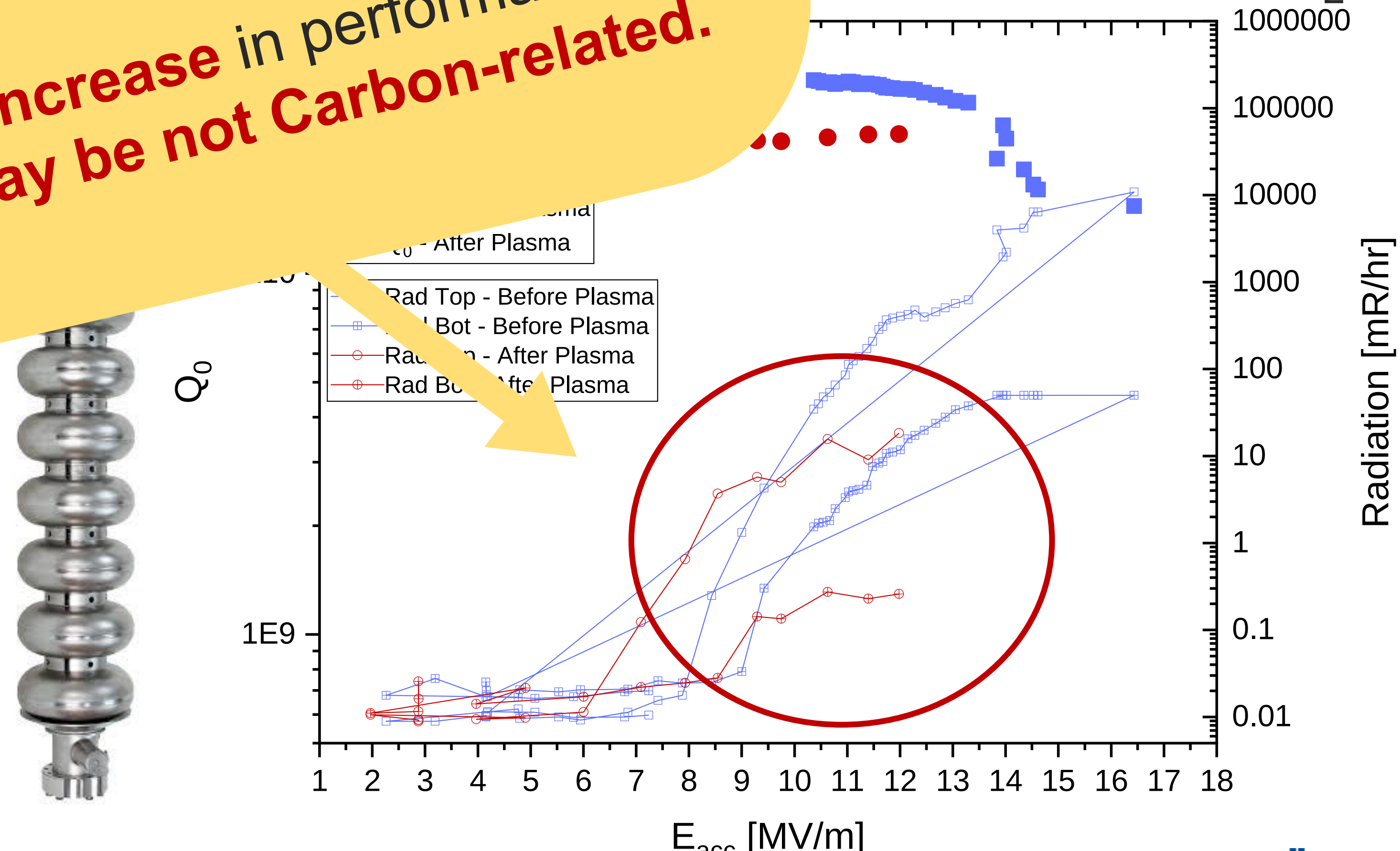
- 9-cell ... d for <2h with Ne-$O_2$

NO increase in performance.
FE may be not Carbon-related.



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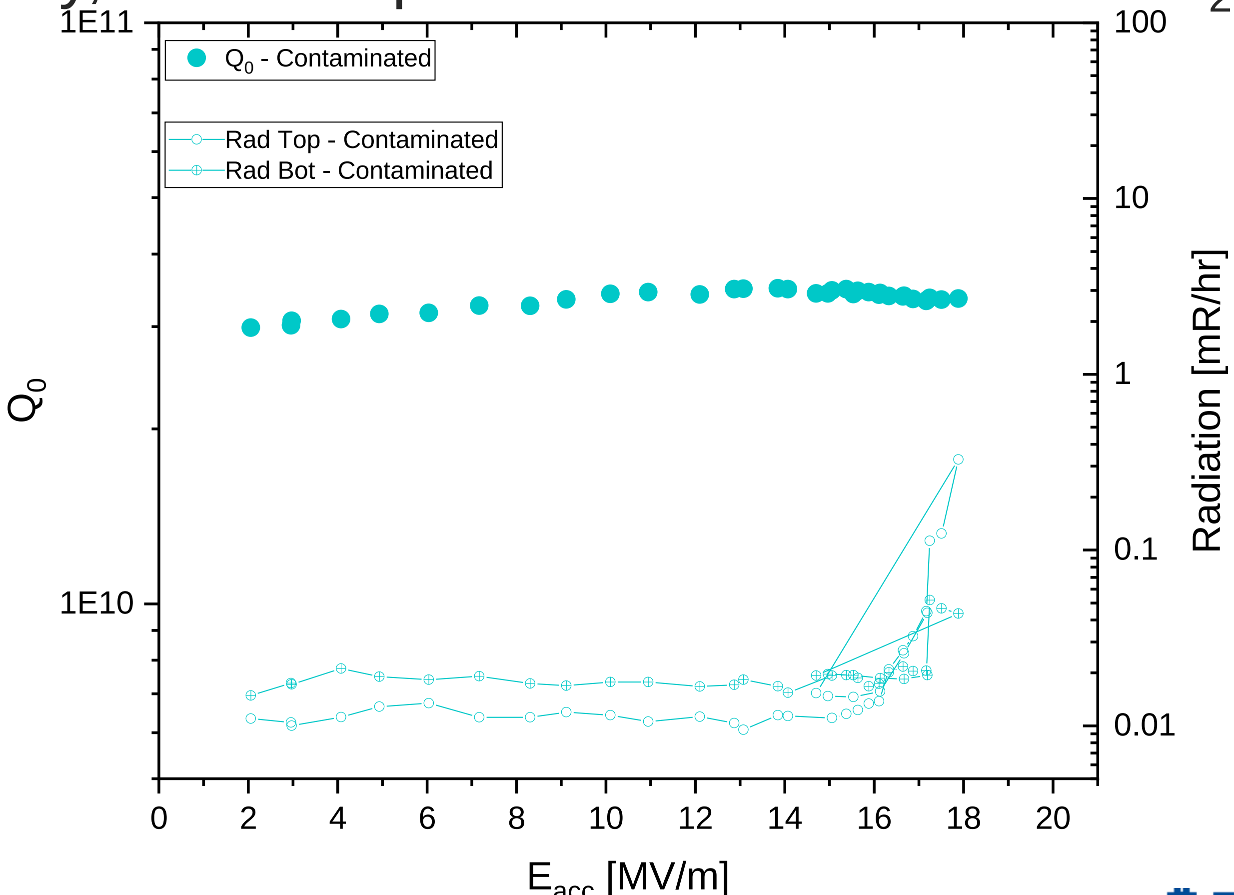
# **Naturally Field Emitting cavity:** RF results before and after plasma processing (2)

<u>Scope</u>: study the effect of Plasma processing on natural field emission

- 9-cell cell cavity, each cell processed for <2h with Ne-$O_2$ plasma.



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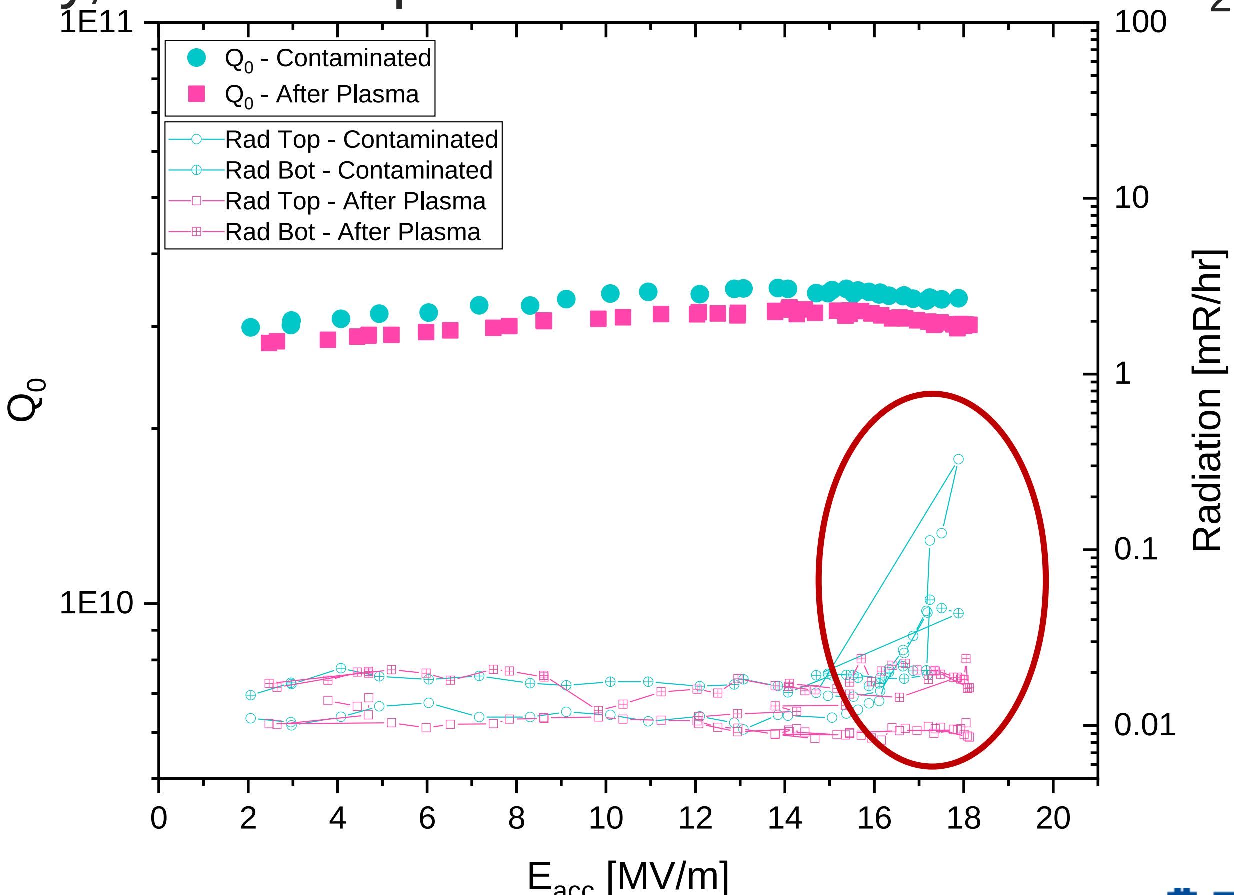




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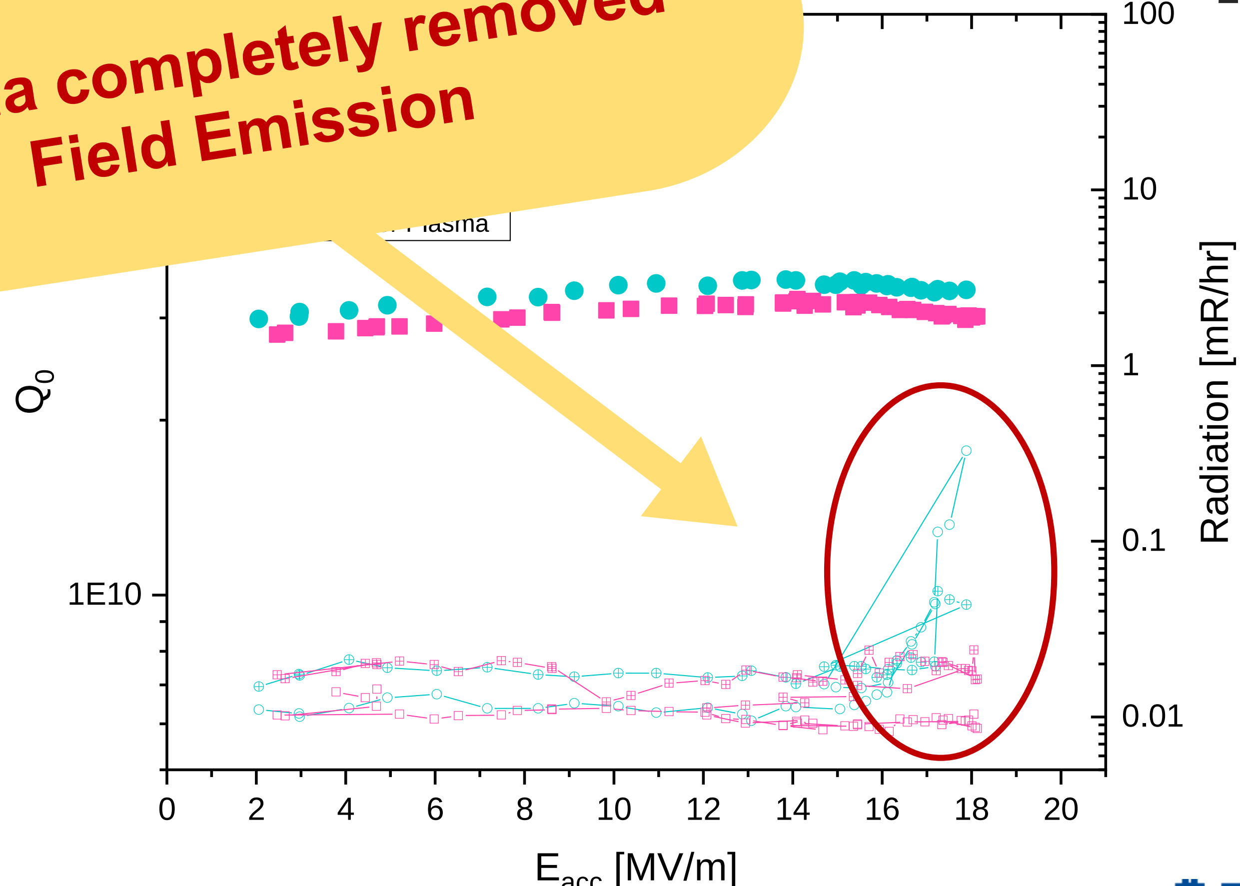
Scope: study the effect of Plasma processing on natural field emission

- 9-cell cell cavit… <2h with Ne-$O_2$ pla…

**Plasma completely removed Field Emission**



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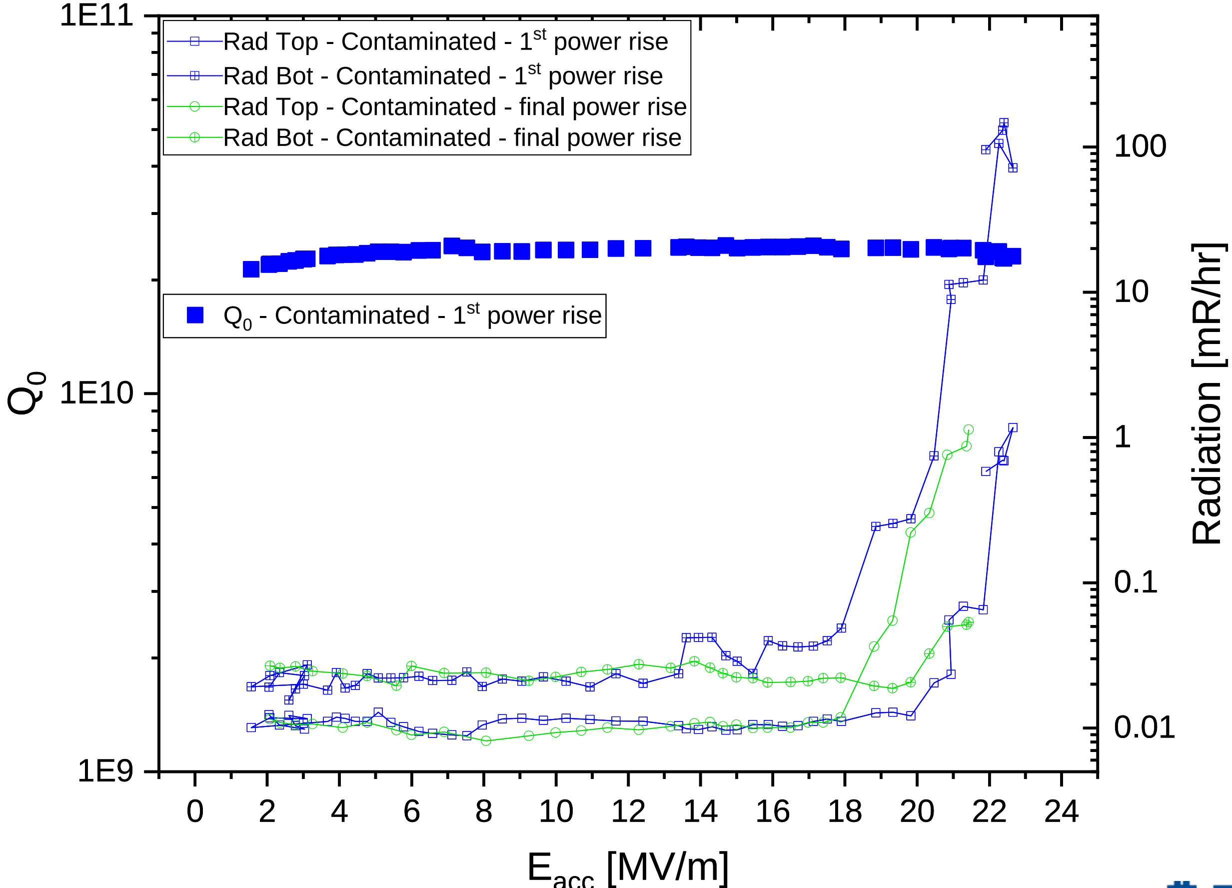
# **Simulated vacuum failure in clean room:** RF results before and after plasma processing

Scope: study the effect of plasma on natural contamination due to venting

- 9-cell cavity: each cell processed for <2h with Ne-$O_2$ plasma.



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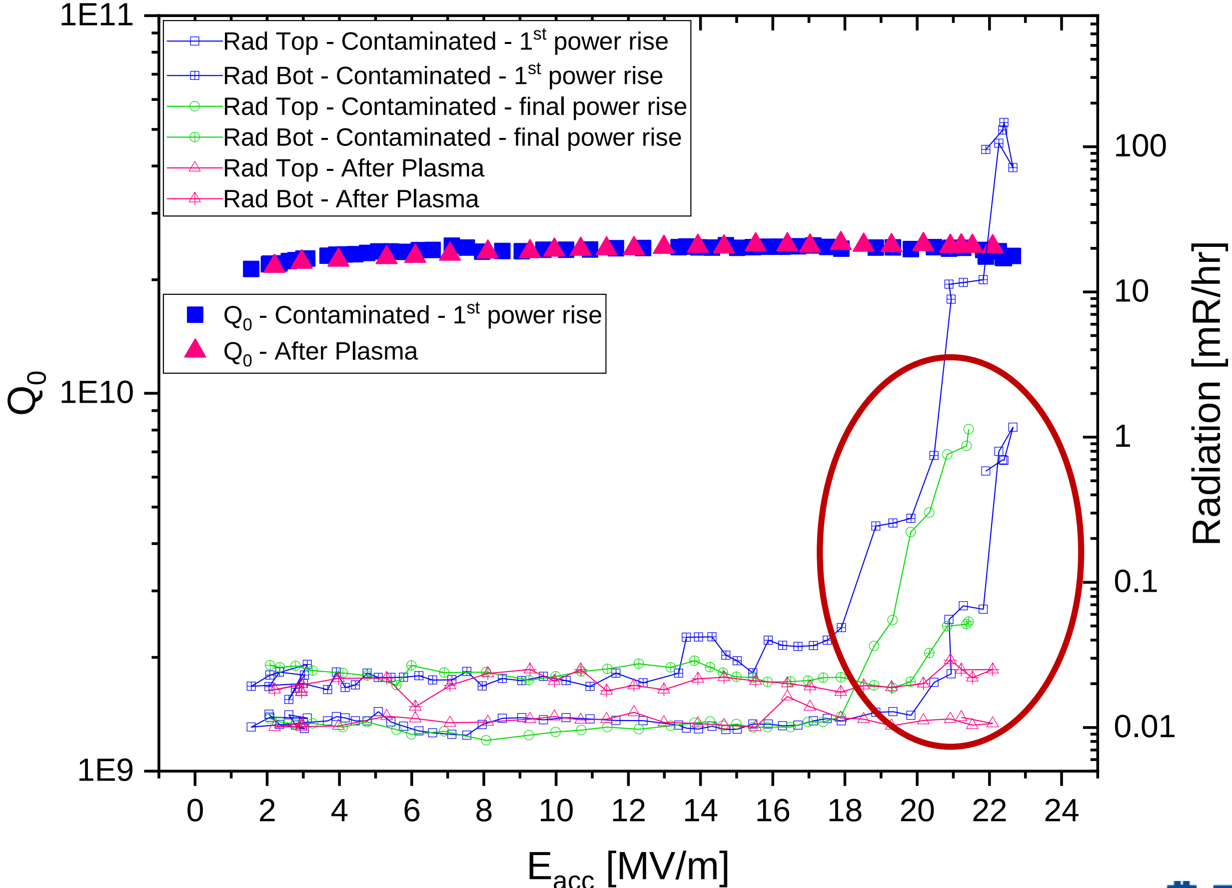
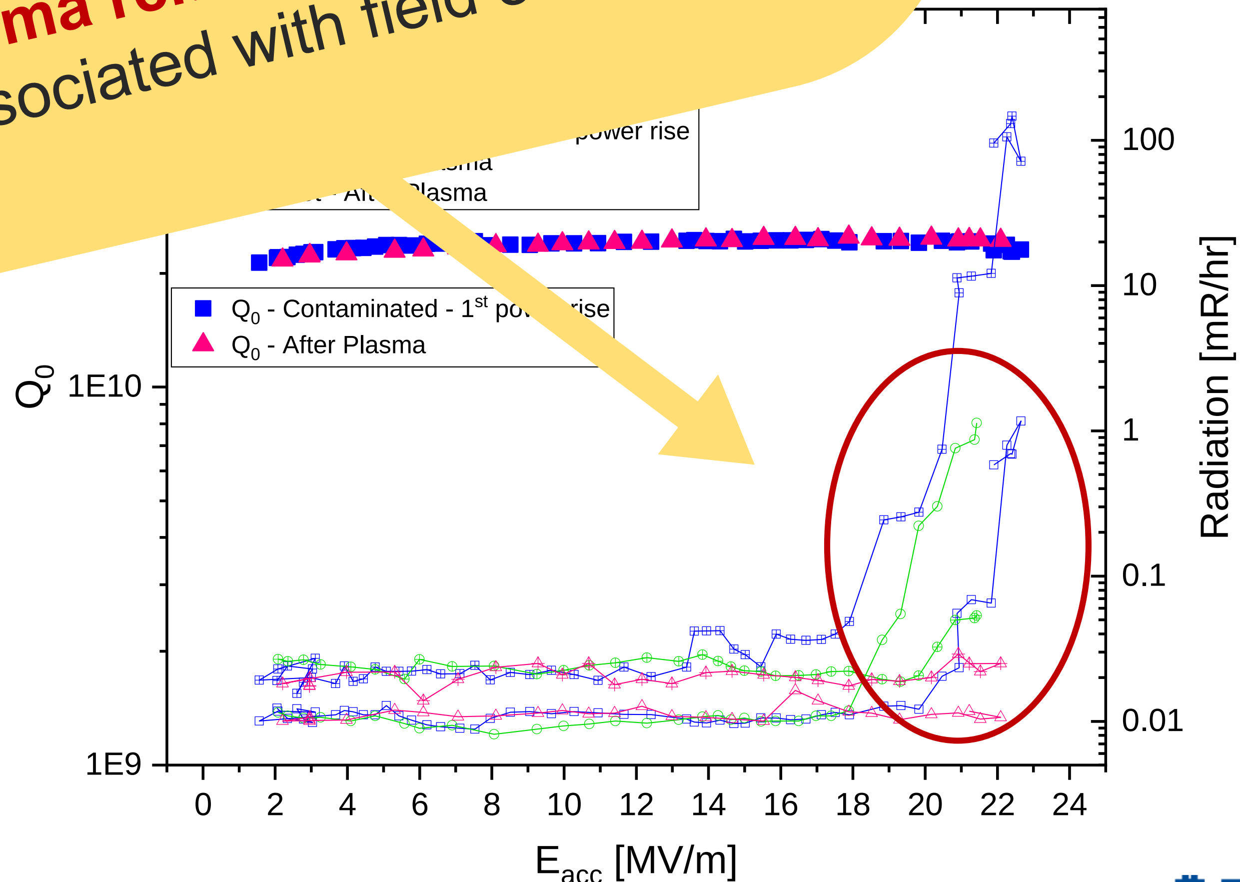


# **Simulated vacuum failure in clean room:** RF results before and after plasma processing

Scope: study the effect of … ntamination due to venting

- 9-c … Ne-$O_2$ p…

**Plasma removed the radiation associated with field emission**



# Studies of plasma processing in Contaminated cavities

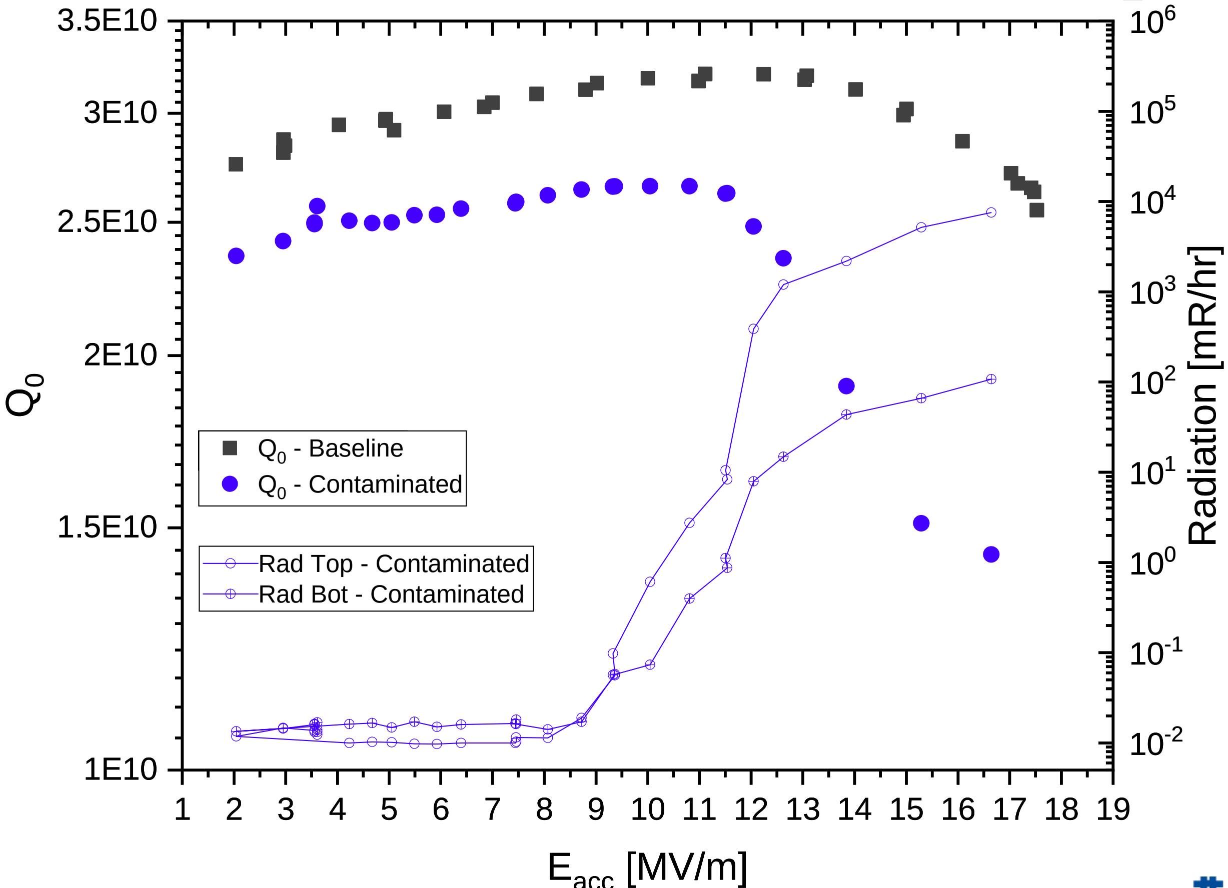
Plasma processing applied in some field emitting/contaminated cavities:

- Carbon contamination: introduction of Aquadag contamination on the iris of the cavity
- Naturally FE cavities: plasma processing applied on a naturally field emitting cavities, as received from the vendor
- **Vacuum failure: simulation of vacuum accident to ATM to introduce field emitters**
  - Inside Clean room
  - **Outside Clean room**

# **Simulated vacuum failure outside clean room:** RF results before and after plasma processing

<u>Scope</u>: study the effect of plasma on natural contamination due to venting

- 9-cell cavity, each cell processed for <2h with Ne-$O_2$ plasma.



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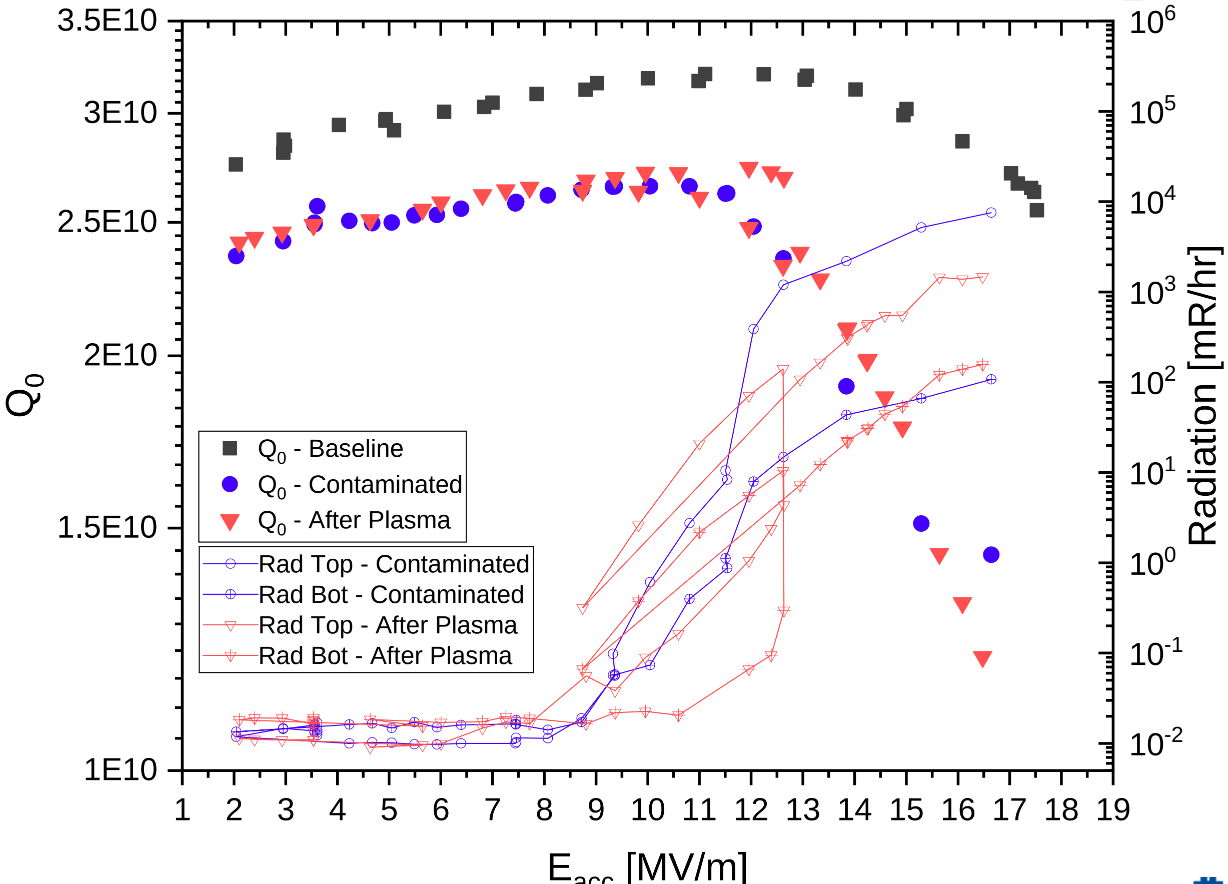
# **Simulated vacuum failure outside clean room:** RF results before and after plasma processing

Scope: study the effect of plasma on natural contamination due to venting

- 9-cell cavity, each cell processed for <2h with Ne-$O_2$ plasma.



# Simulated vacuum failure outside clean … results
before and after plasma proces…

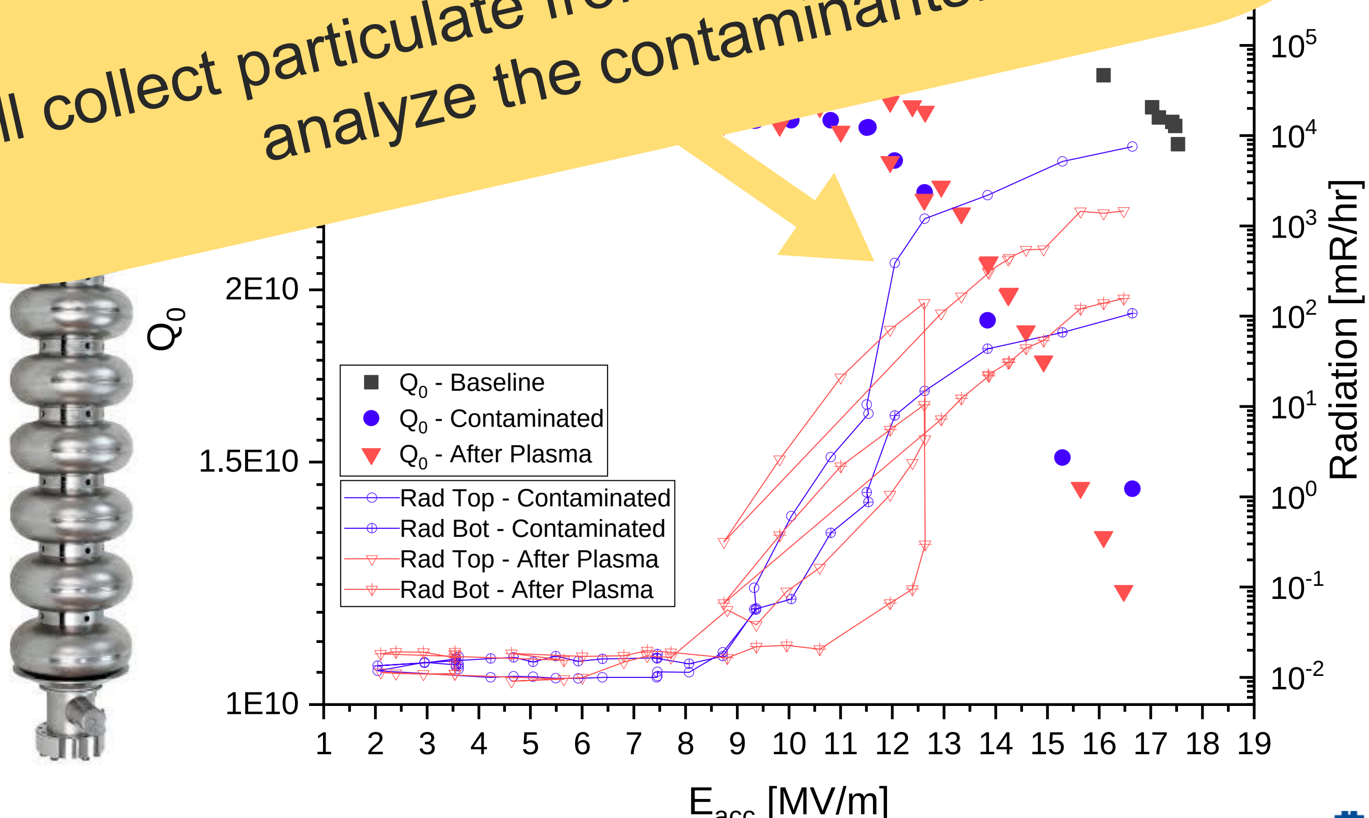
Scope: study the eff…
due to v…

- C…

**Only moderate reduction in radiation.**

Repeated the experiment on 3 cavities with similar results.

Will collect particulate from cavity inner surface to analyze the contaminants.



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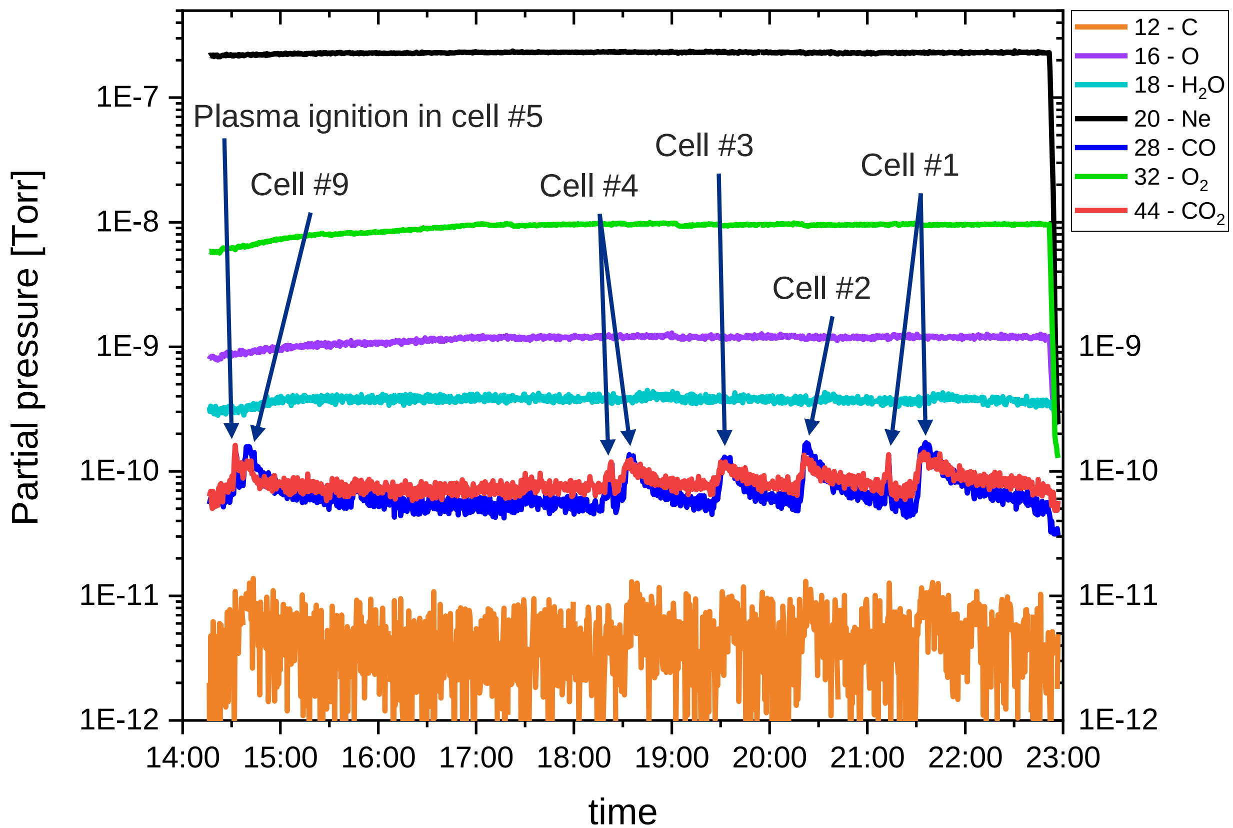
# Example of Residual Gas Analyzer spectrum

- RGA spectrum measured during first day of plasma processing on 9-cell cavity

- Peaks in C, CO, $CO_2$ indicate when the glow discharge is transferred to a new cell
- Carbon-related peaks decrease to background level in ≈30min



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- Introduction
- Plasma ignition in 1.3GHz TESLA-shaped cavities
  - New method to control plasma ignition
  - RF measurements at different pressures with Neon and Argon
- Plasma cleaning test on 9 cell TESLA-shaped cavity with artificial contamination
- First RF results of plasma processing applied single cell and 9-cell cavities
  - Effect of plasma on N-doping
  - Effect of plasma on contaminated cavities
- **Conclusions**
  - **Future work**

# Conclusions

- **HOMs ignition method: substantially reduces $P_{FWD}$** and enables the procedure on 9-cell TESLA-shaped cavities
  - Developed procedure to **locate plasma** in the cavity for in-situ application
- Studied different pressures and gases: identified optimal pressure range for adequate plasma control
- Viewport cavity: very successful ⟶ **hydrocarbon contamination removal** using Ne-$O_2$ glow discharge.
  - Developed a first recipe in terms of pressure, $O_2$%, plasma density and duration.
- **N-doped cavity:** Plasma processing preserved High Q & quench field
- **Contaminated cavities** treated with plasma processing and RF tested before and after:
  - **Carbon contaminated cavity**: **gradient successfully recovered**
  - **Natural FE**: **1 out of 2** showed **removal of FE**
  - **Vacuum failure simulation**:
    - Inside clean room: **FE successfully removed**
    - Outside clean room: repeated on 3 cavities, showed **moderate increase in performance**

# Future work

- Cavities exposed to simulated vacuum failure: collect and analyze particles that are still present after plasma cleaning
- Continue plasma process and cold-test 9-cell 1.3GHz TESLA-shaped cavities to acquire statistics on effectiveness in terms of field emission reduction
- Use viewport cavity with controlled, visible and reproducible carbon contamination to optimize processing parameters:
  - Pressure
  - Duration
  - $O_2$ concentration
  - Plasma density



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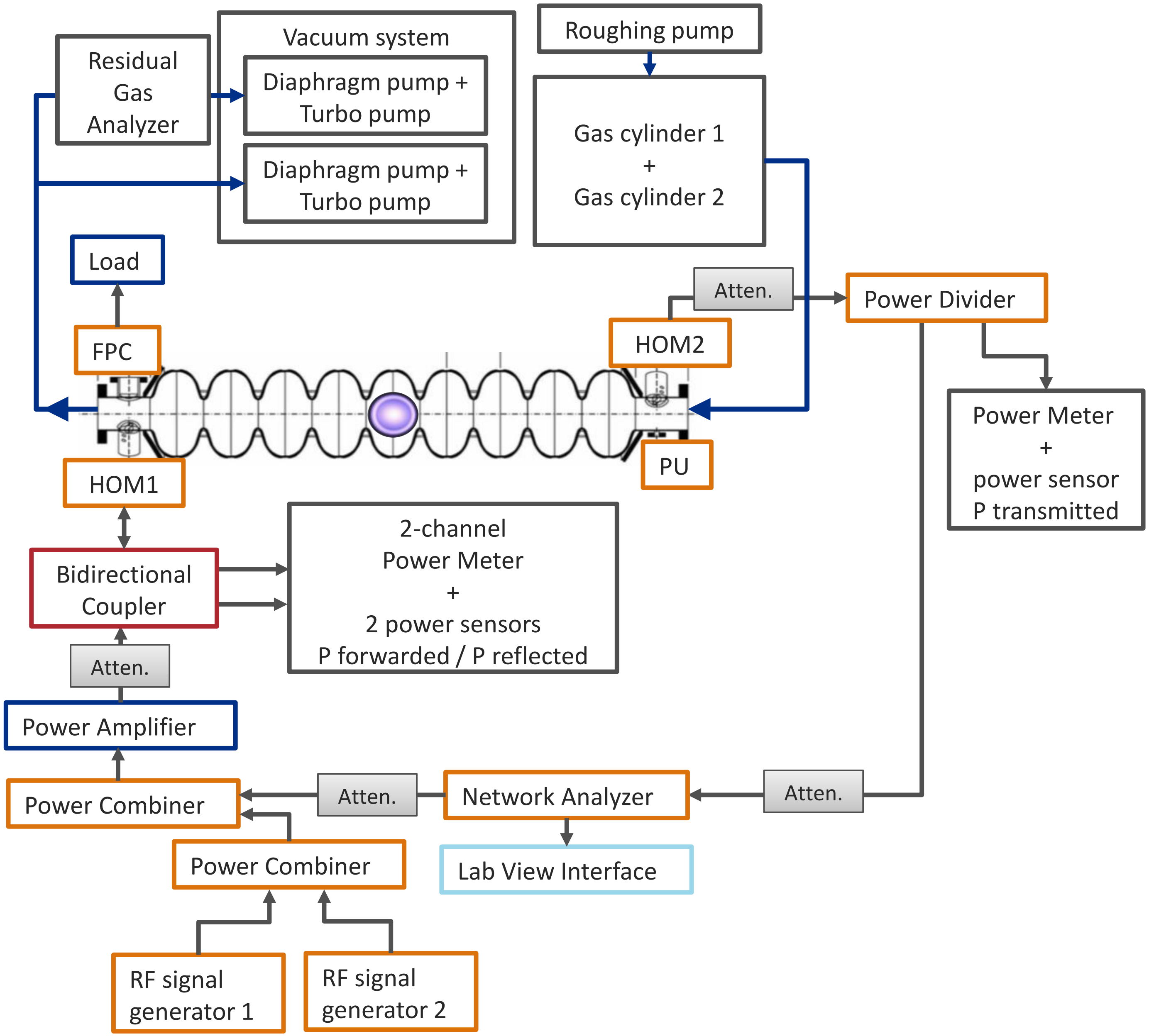
Thank you!

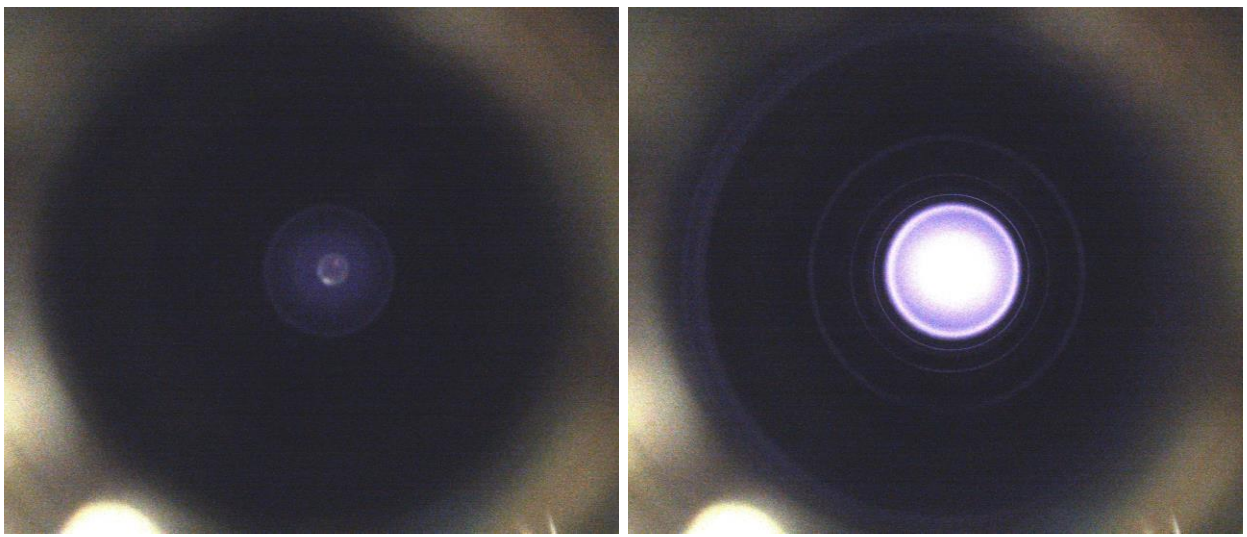

Residual Gas Analyzer
Vacuum system
Diaphragm pump + Turbo pump
Diaphragm pump + Turbo pump
Roughing pump
Gas cylinder 1 + Gas cylinder 2
Load
FPC
Atten.
Power Divider
HOM2
Power Meter + power sensor P transmitted
PU
HOM1
2-channel Power Meter + 2 power sensors P forwarded / P reflected
Bidirectional Coupler
Atten.
Power Amplifier
Power Combiner
Atten.
Network Analyzer
Atten.
Power Combiner
Lab View Interface
RF signal generator 1
RF signal generator 2

# RF measurements: Tuning of plasma intensity

Both detection and tuning are related to $\delta\omega$ of the eigenfrequencies caused by the plasma

$$\frac{\delta\omega}{\omega} \approx \frac{1}{2} \frac{\iiint_{plasma} \eta E^2 dV}{\iiint_{cavity} E^2 dV}, \qquad \eta = \frac{\omega_{plasma}^2}{\omega_{RF}^2}$$

Mode 1-5 cell #5



To tune the intensity can be varied:

- $P_{FWD}$
- $\omega_{RF}$

sent to the cavity

$\Delta f_{max} \approx$ 15-20MHz

# Single cell – plasma ignition – N-doping test