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# Plasma Processing to Reduce Field Emission in LCLS-II 1.3GHz SRF 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]

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19th International Conference on RF Superconductivity

July 5, 2019

- Introduction
- Plasma ignition in LCLS-II cavities
  - New method to control plasma ignition
  - RF measurements at different pressures with Neon and Argon
- Plasma cleaning test on 9 cell LCLS-II 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

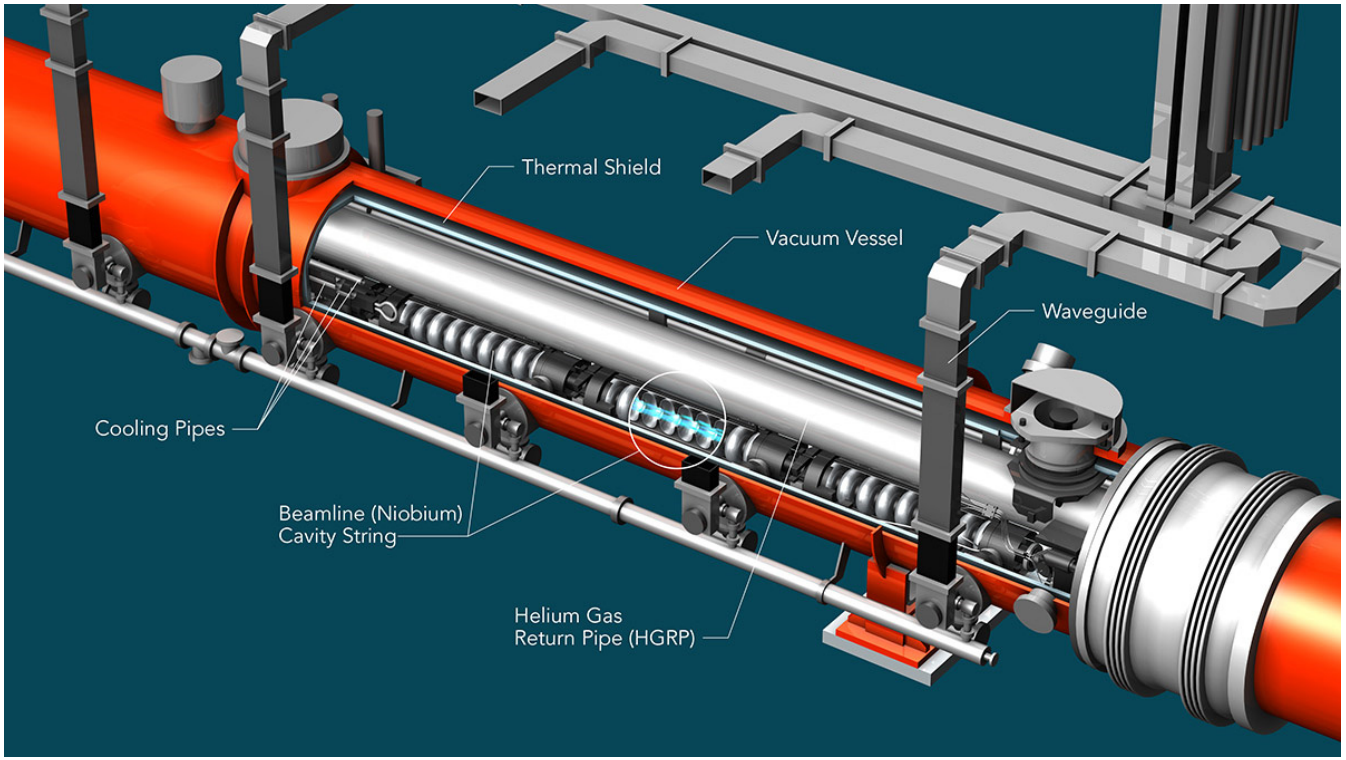
- Simulation for applicability of ORNL plasma processing to LCLS-II cavities
- Use the system to perform cleaning in the accelerator tunnel

OAK RIDGE National Laboratory

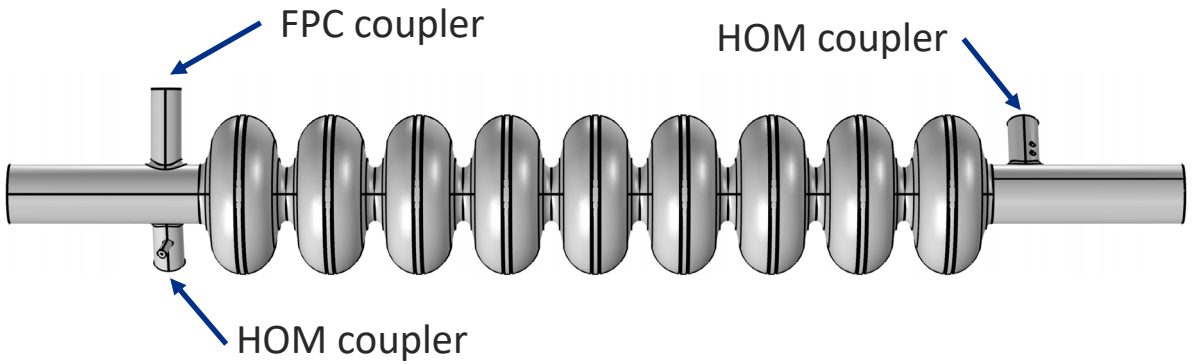
- Successful experience with plasma processing
- Guidance for design and sample studies for LCLS-II plasma cleaning

Project supported by DOE - Basic Energy Sciences (BES)

# In-situ plasma processing



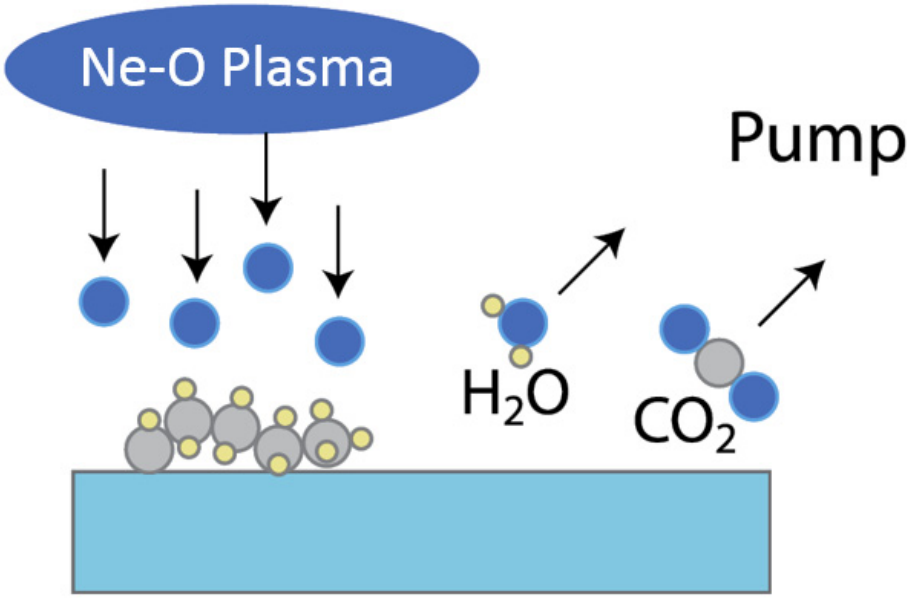

Procedure can be applied at room temperature in-situ in the cryomodules



# 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 Φ 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
Φ: 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

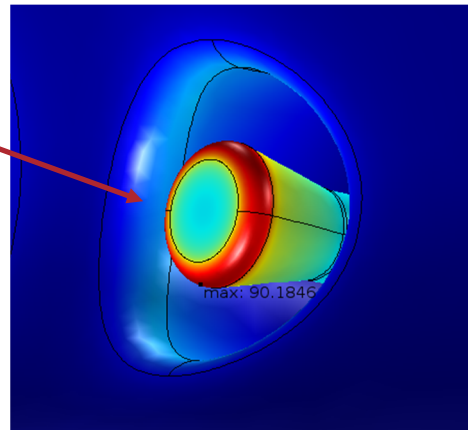
P. Berrutti, accepted for publication at J. Appl. Phys. 126 (2019)

# Field enhancement at LCLS-II FPC

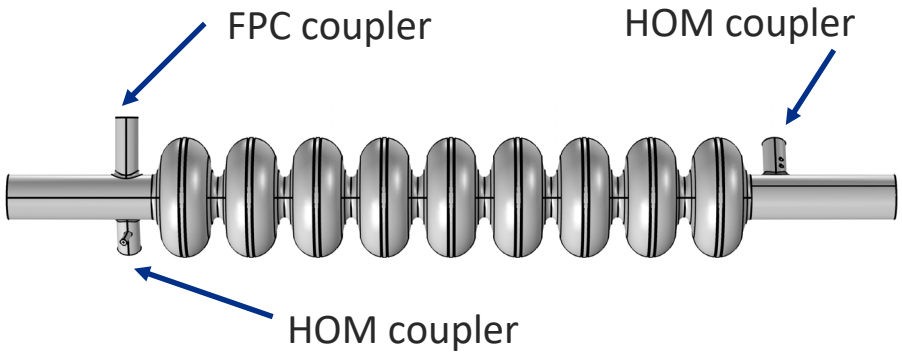
Due to geometry: intense field enhancement at the fundamental power coupler

| 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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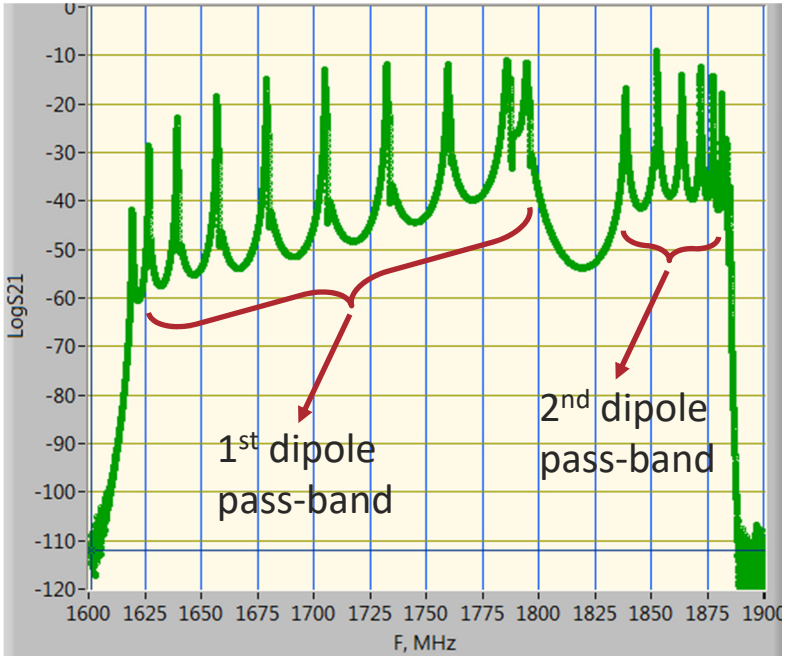
# Plasma ignition in LCLS-II cavities using HOMs

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:

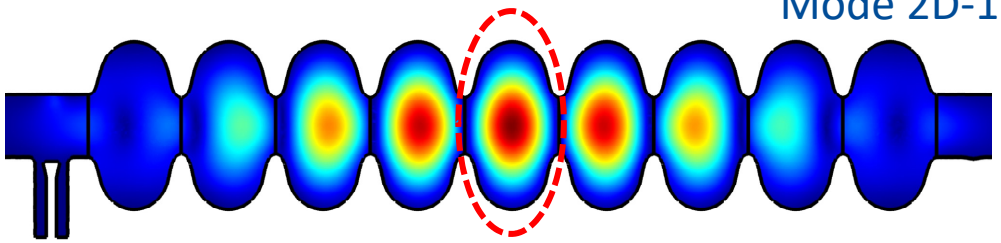
- Coupling factor: $0.01<\beta<1.17$
- Reflection coefficient $0.006<|\Gamma|^2<0.94$

- 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

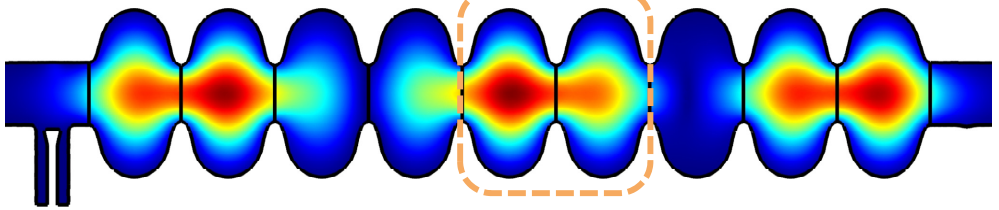
# Example of plasma transfer from cell #5 to #6

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.

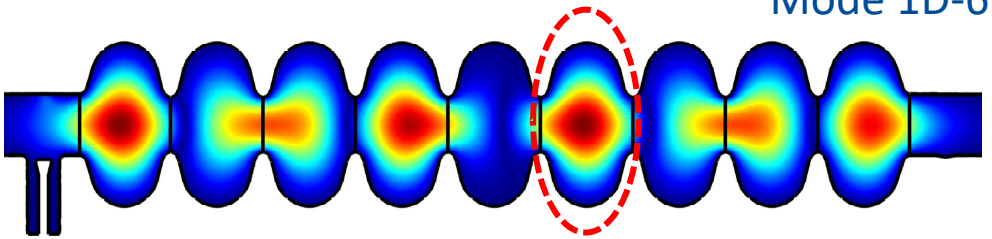
Mode 2D-1



Mode 1D-3



Mode 1D-6



P. Berrutti, B. Giaccone *et al.*, accepted for publication at Journal of Applied Physics –126, July 14 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

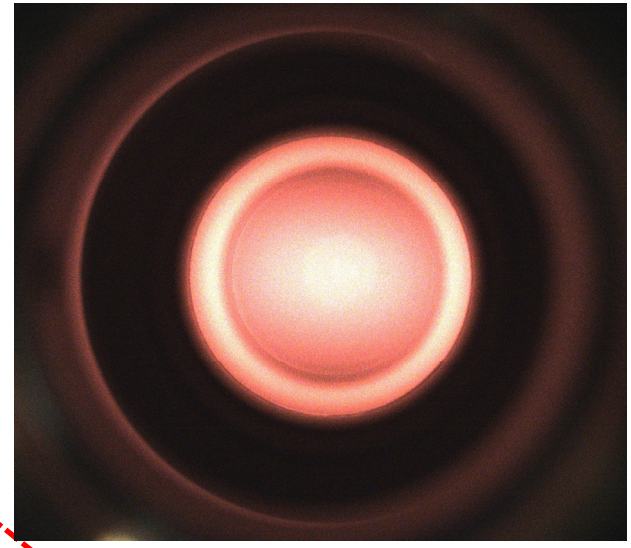
   $\delta\omega$ depends on:
   - Change in dielectric constant due to plasma ($\epsilon \propto \eta$)
   - Intensity of the electric field of the mode in the cell of ignition

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

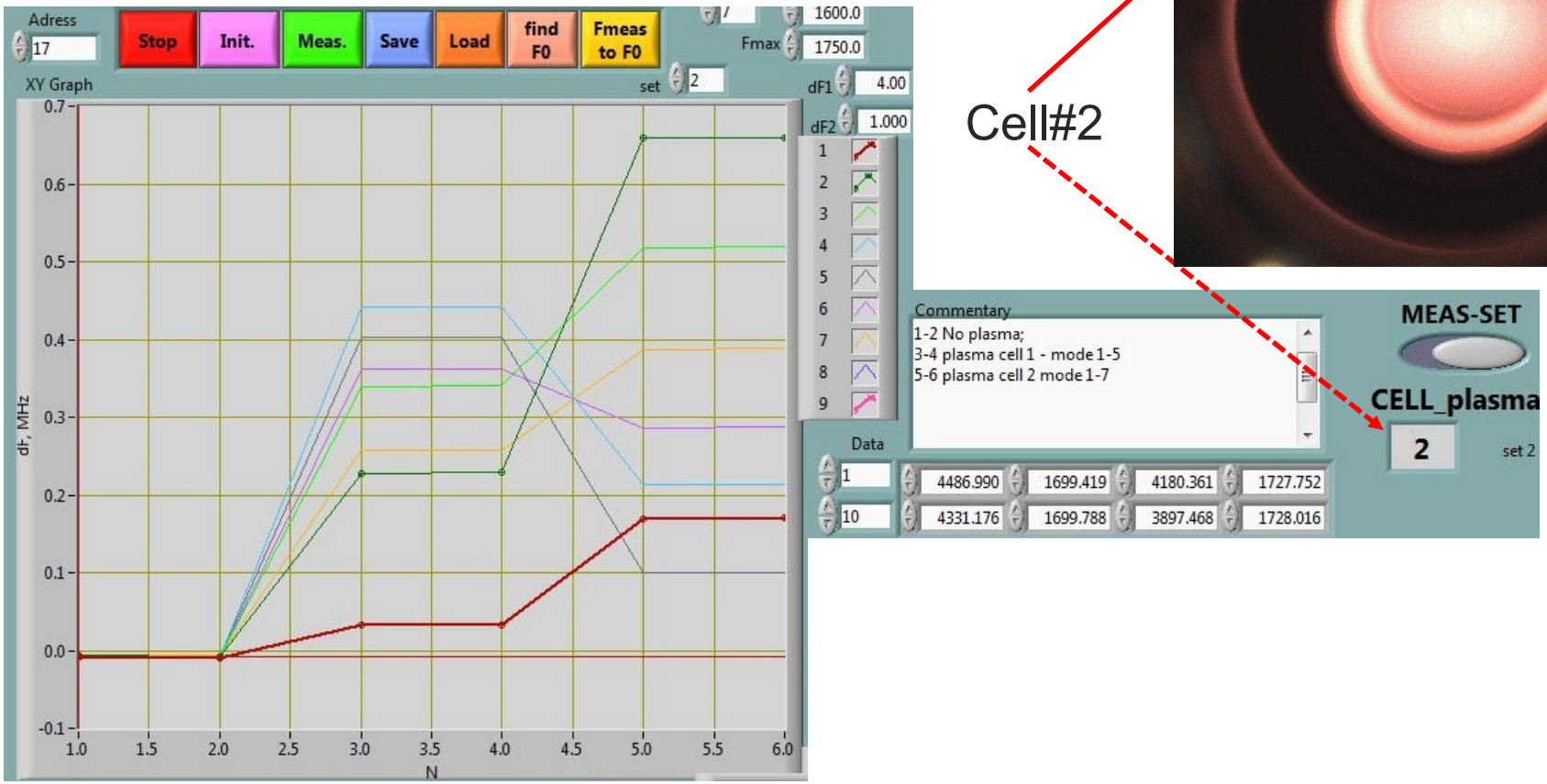
2. Measured $\delta\omega$ is compared with $\delta\omega$ calculated simulating the glow discharge in each cell of the cavity

# 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



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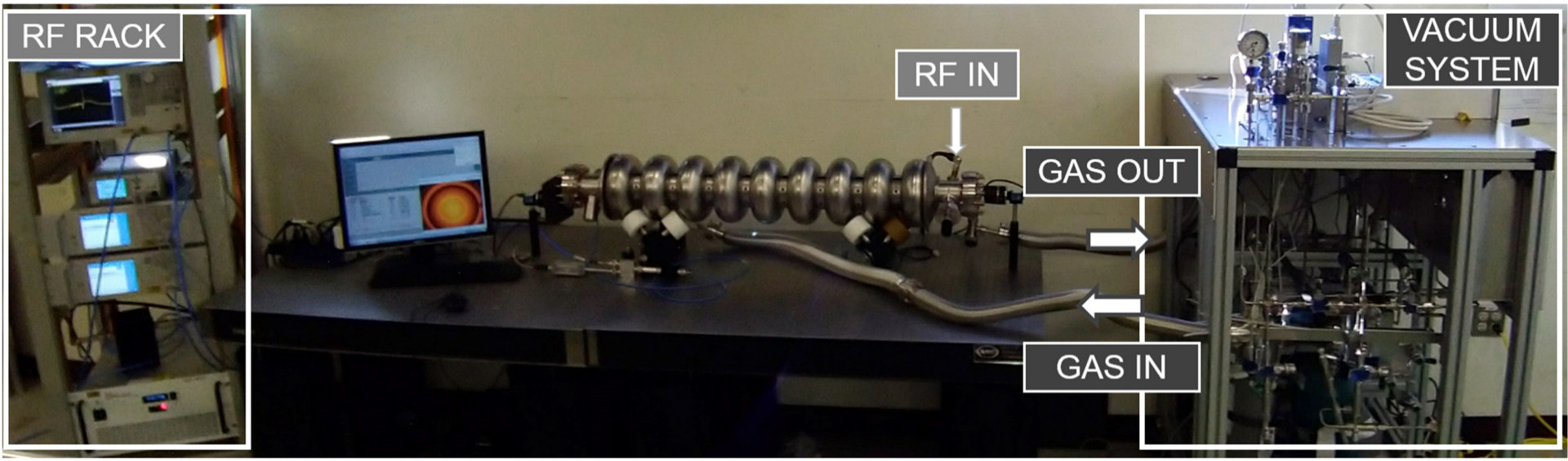
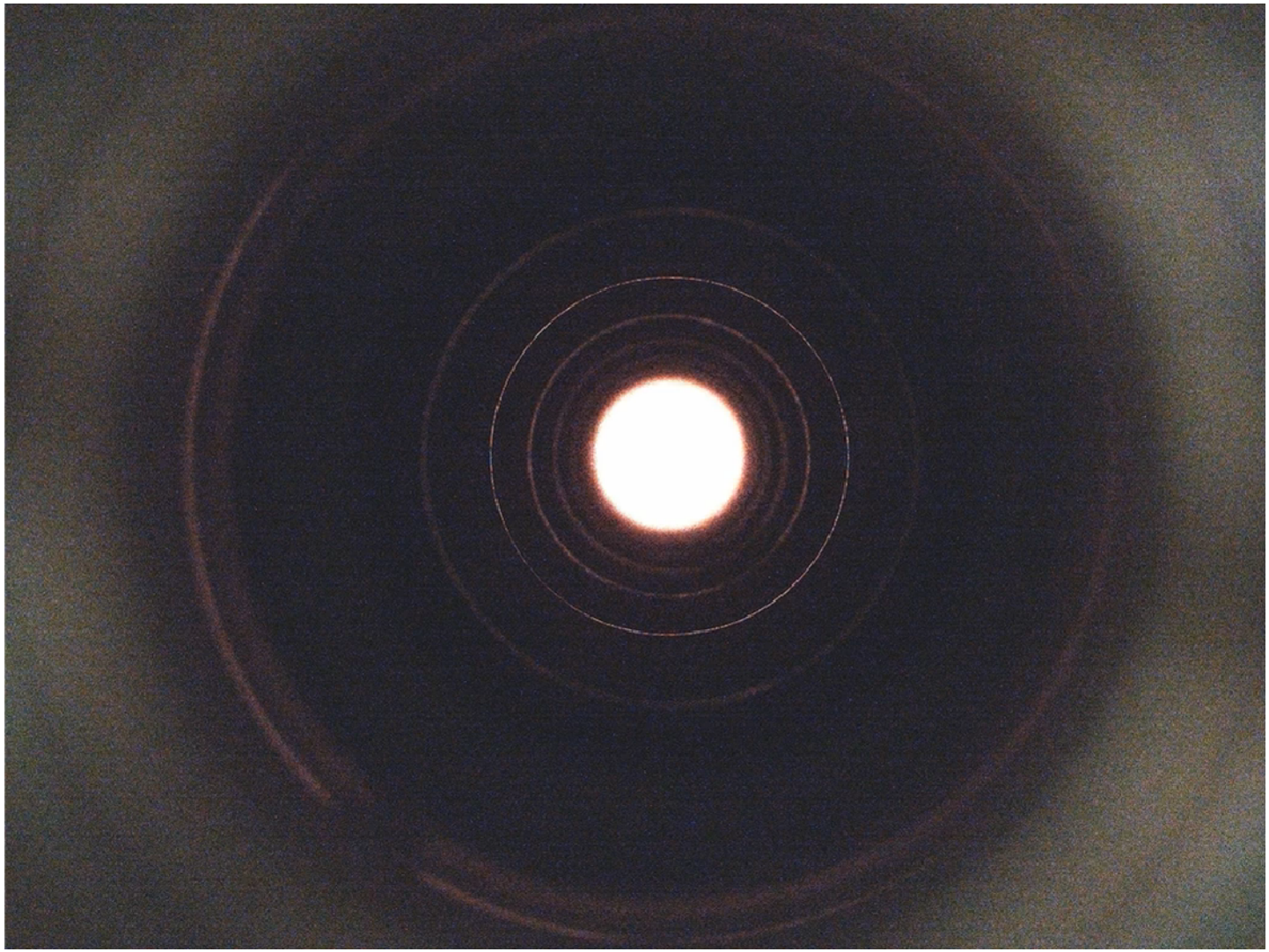
# Plasma cleaning apparatus




- 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

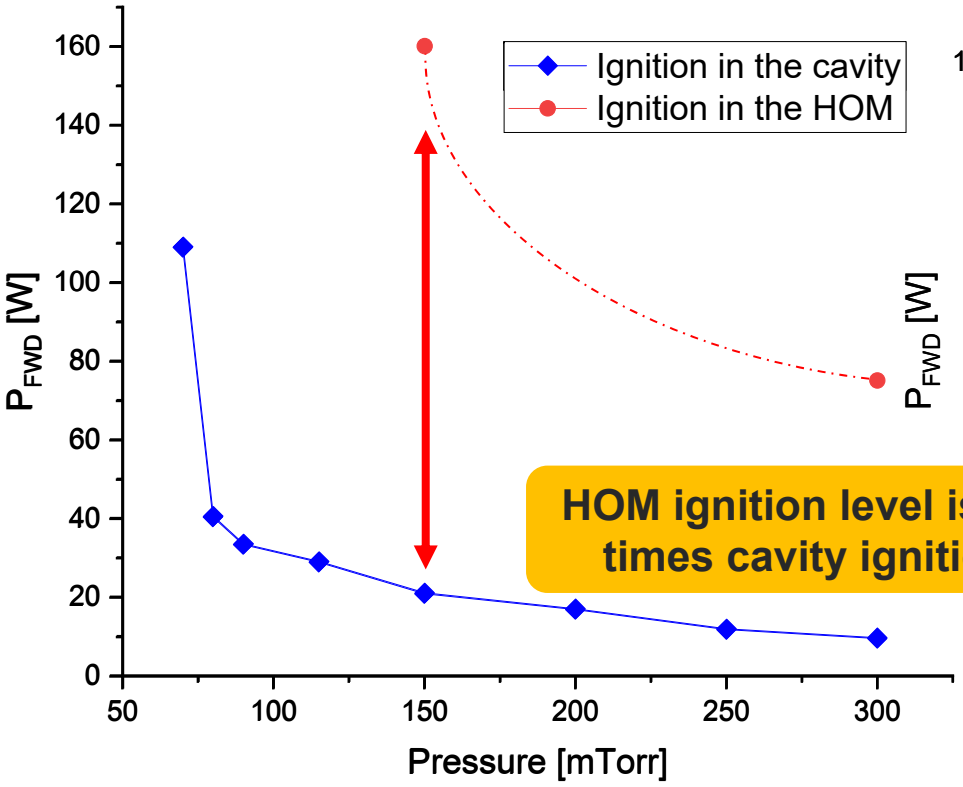
Example of Neon plasma ignition in each one of the 9 cells



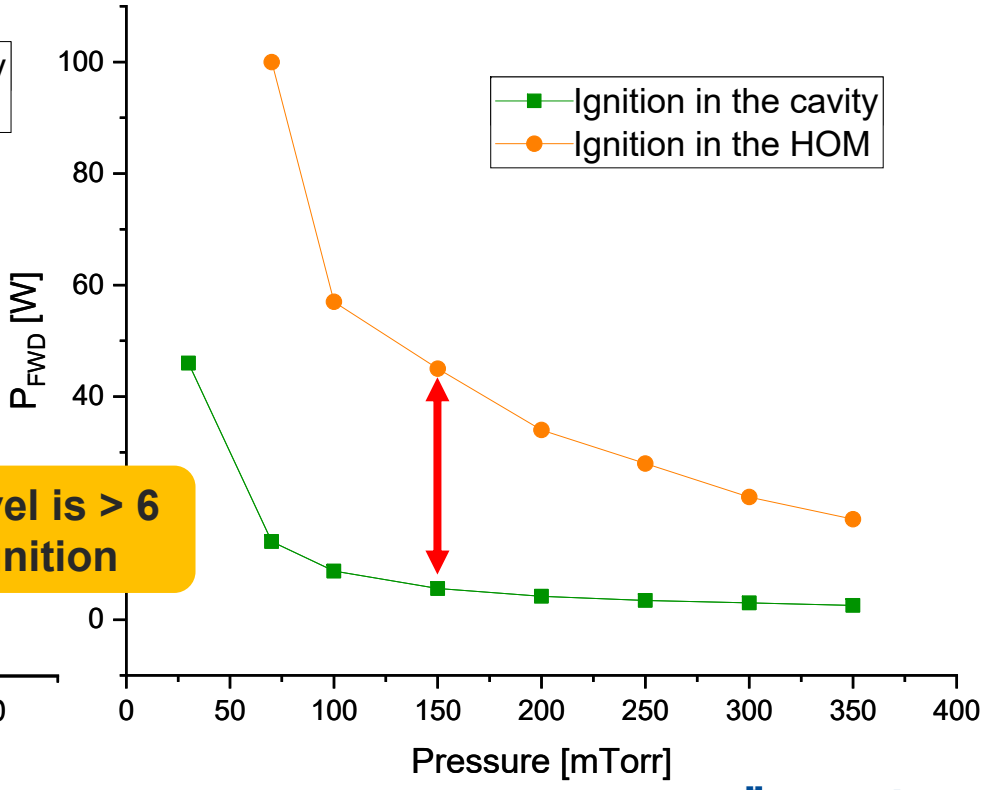
# Neon and Argon ignition curves

- 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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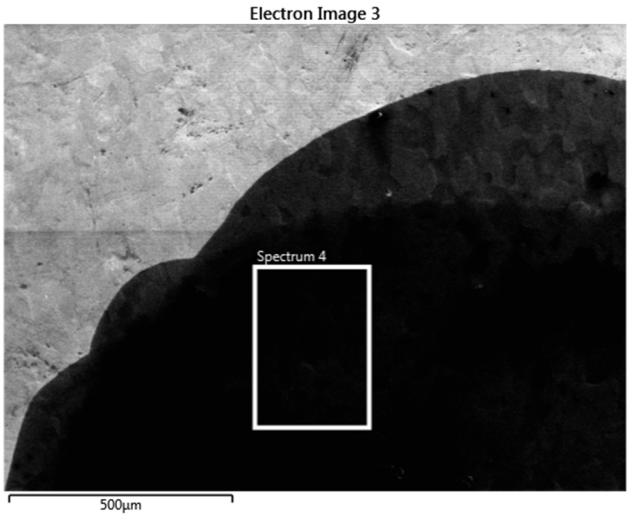
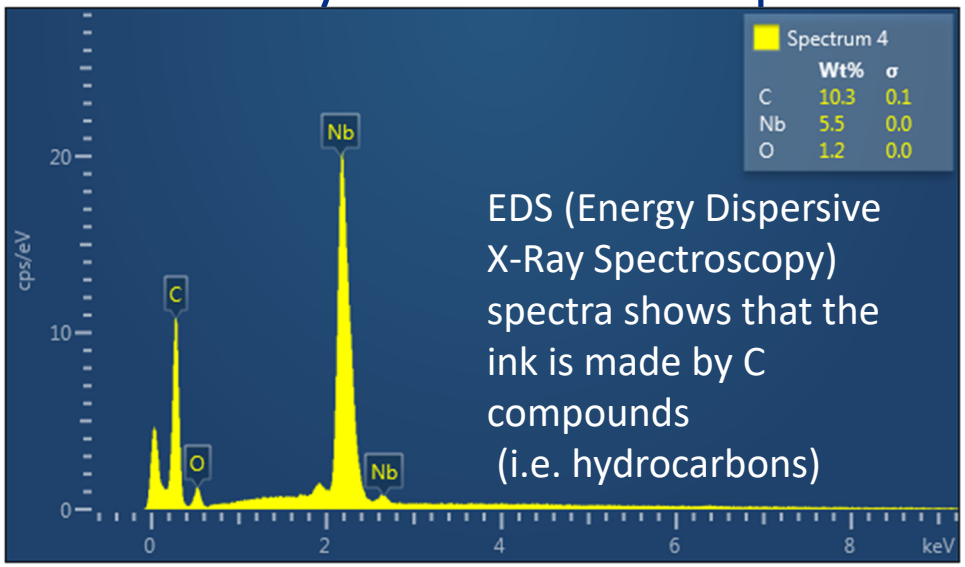
# Plasma processing studies in artificially contaminated cavity

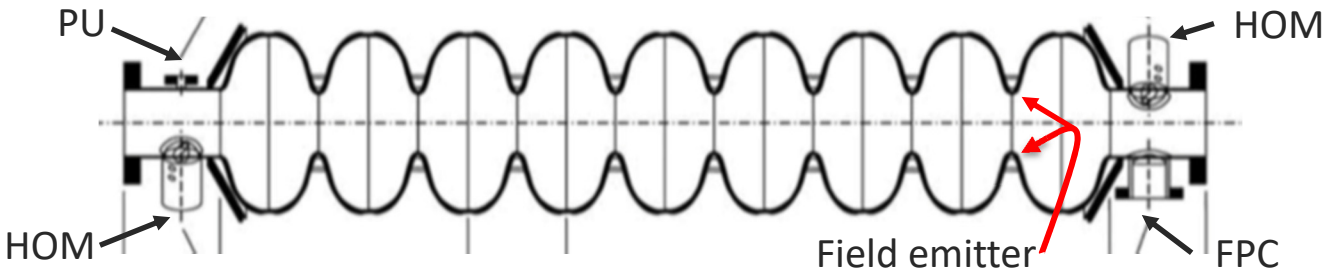
- 1st test goal: remove hydrocarbon contamination with plasma cleaning

- 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



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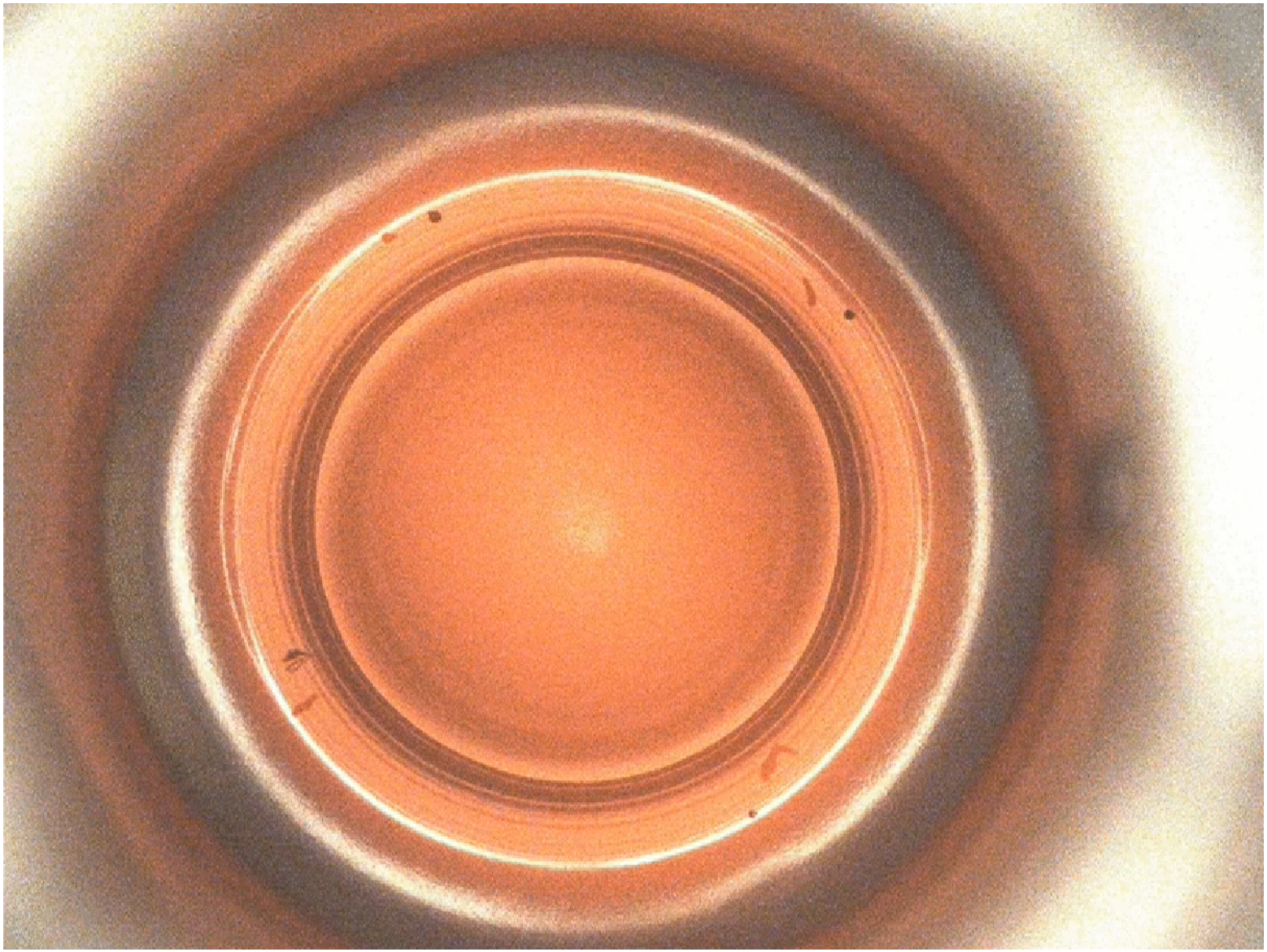
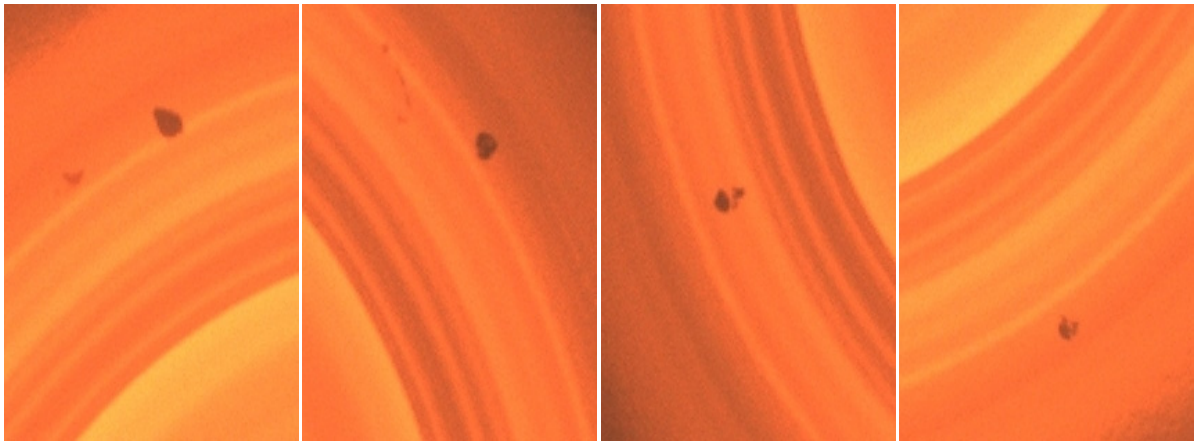
# Contaminated cell (#1) has been processed for ≈ 19 hours total

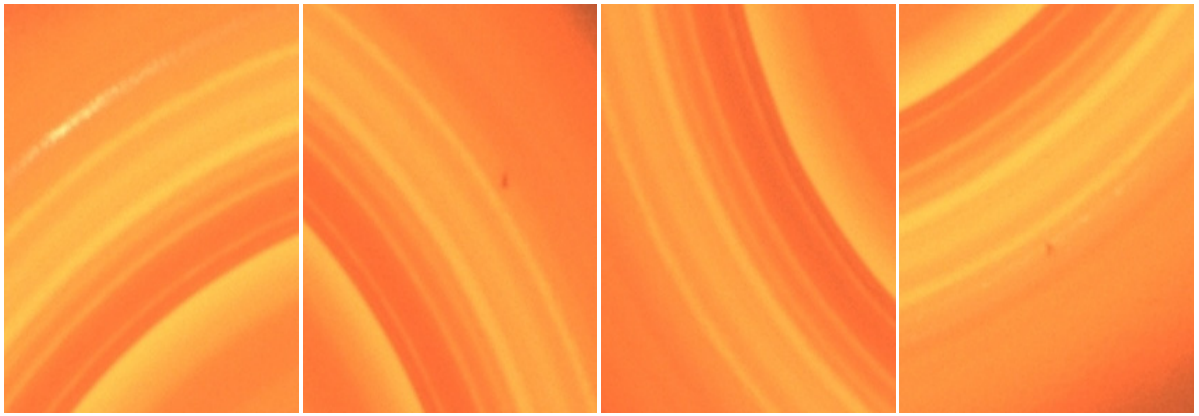


Initial state

After 5h of plasma cleaning



After 19h of plasma cleaning



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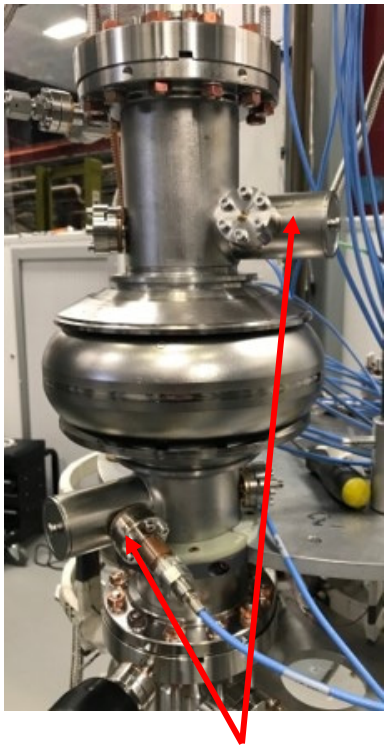
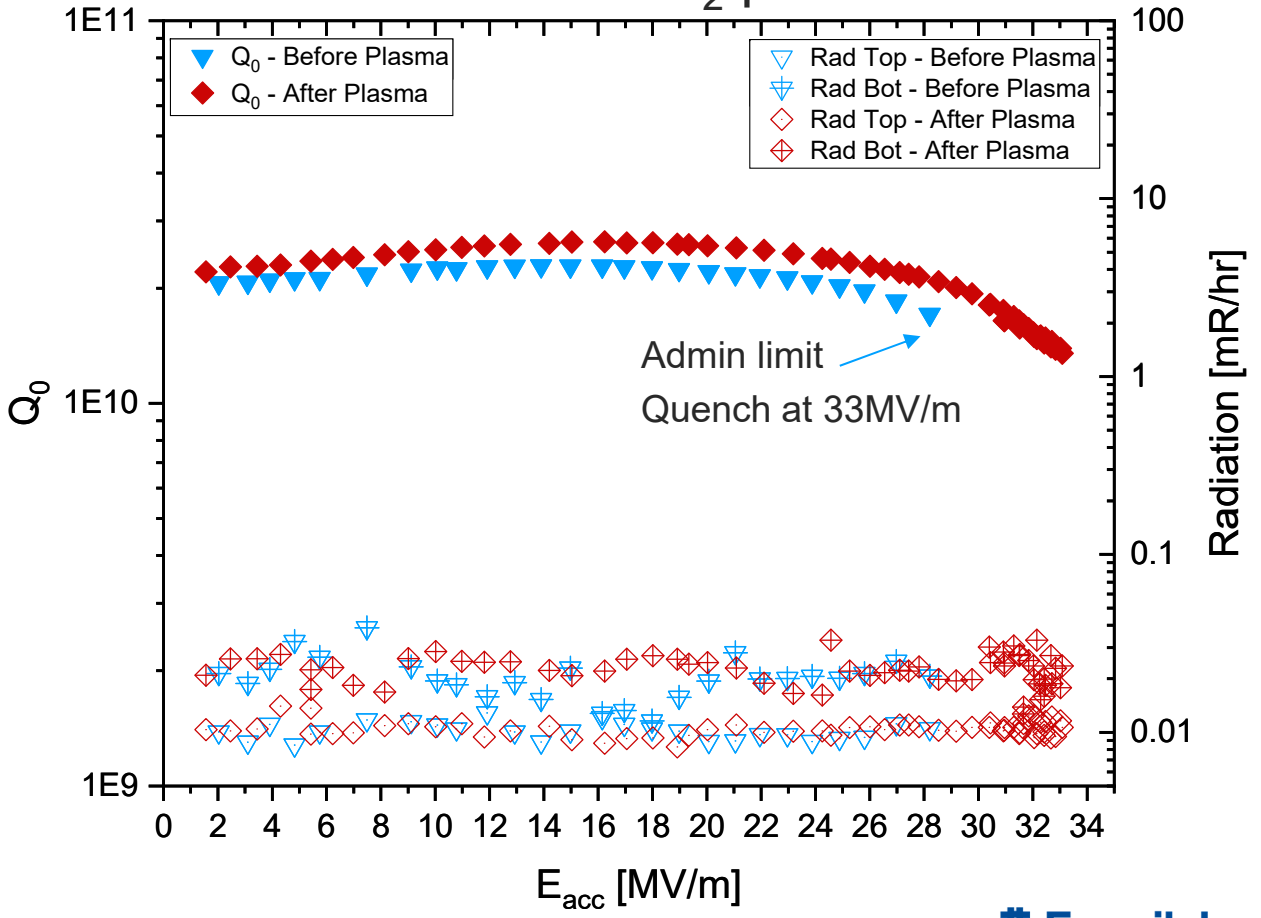
# N-doped single cell: RF results before and after plasma processing

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

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



HOM couplers



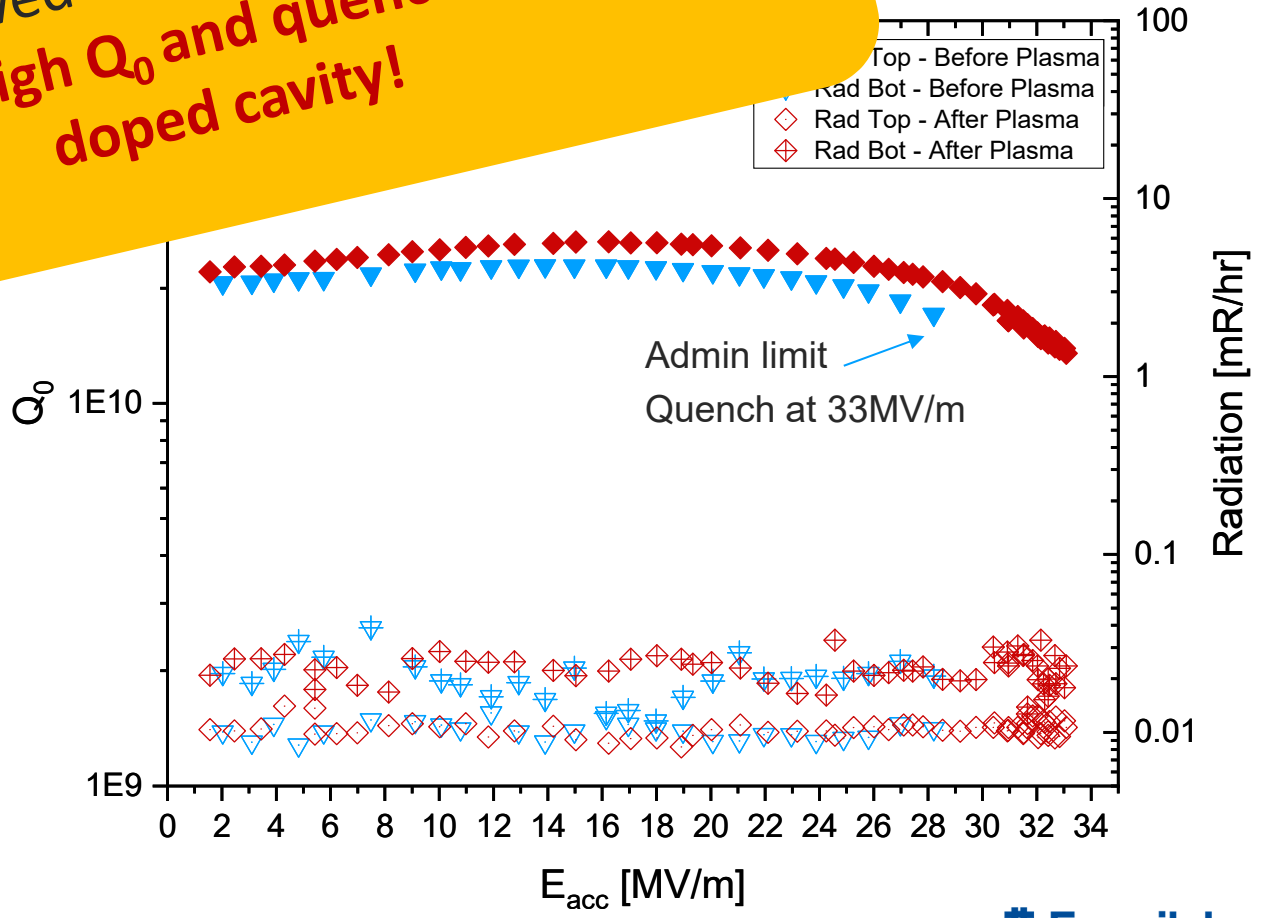
# N-doped single cell: RF results before and after plasma processing

Scope: study effect of plasma p… …rs on N-doped cavities

- N-d… …ma.

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

HOM couplers



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# Studies of plasma processing in Contaminated cavities

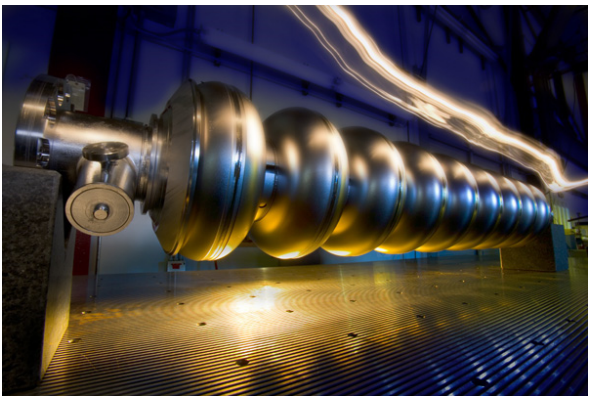
Plasma processing applied in some field emitting/contaminated cavities:

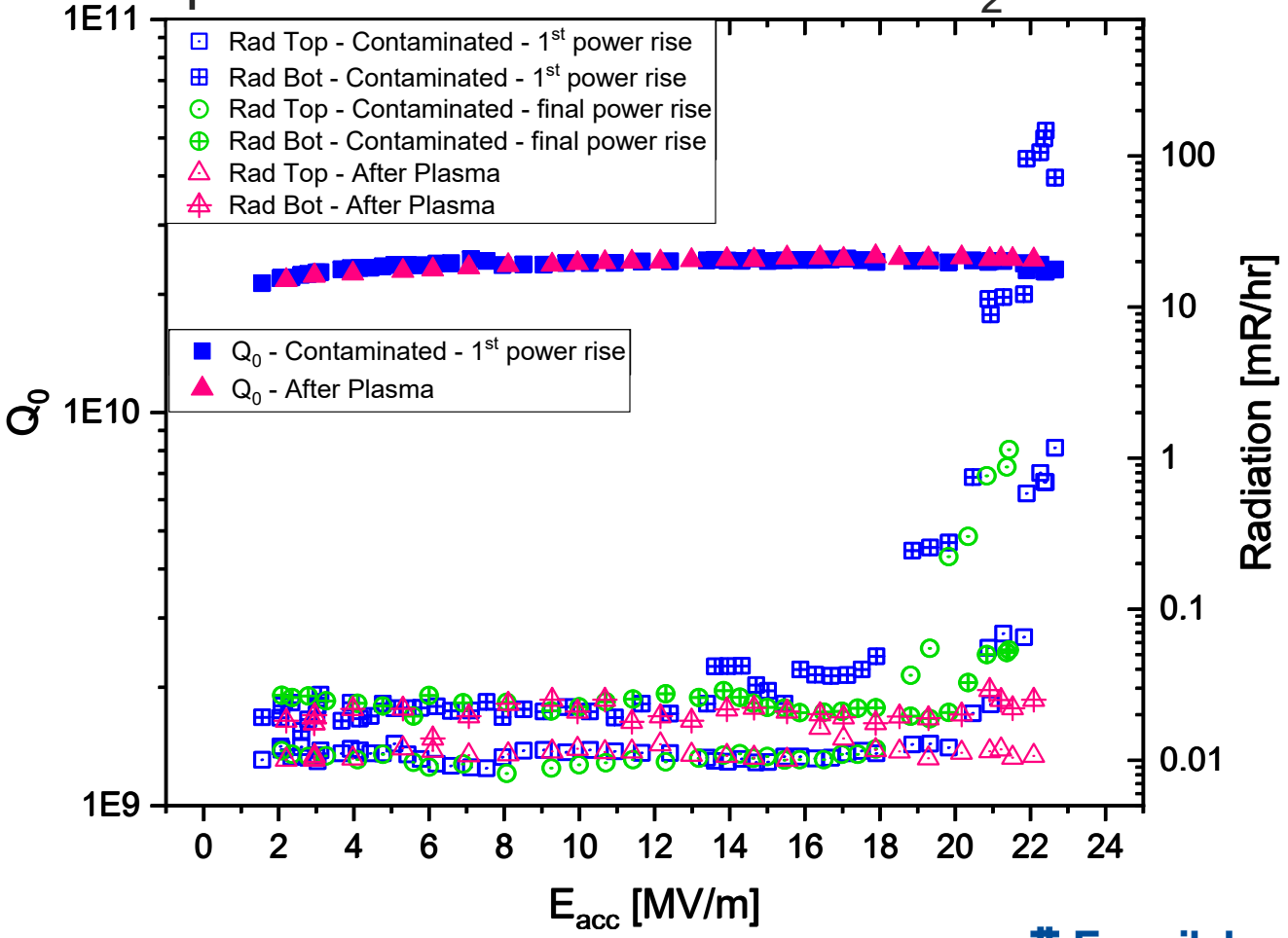
- Vacuum failure: simulation of a vacuum failure in clean-room to introduce some field emitters
- Carbon contamination: introduction of some carbon contamination on the iris of the cavity
- Naturally FE cavities: plasma processing applied on a naturally field emitting cavities, as received from the vendor

# Simulated vacuum failure: RF results before and after plasma processing

Scope: study the removal of natural contamination

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





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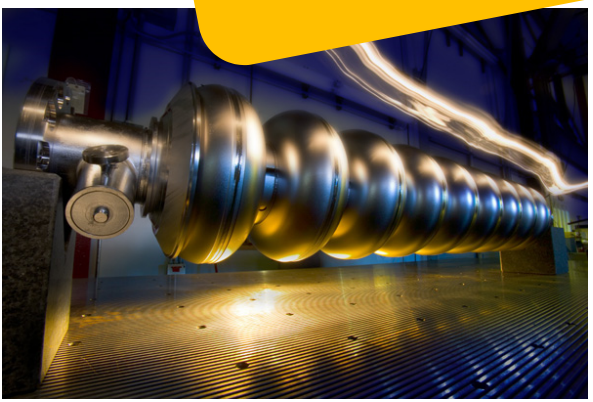
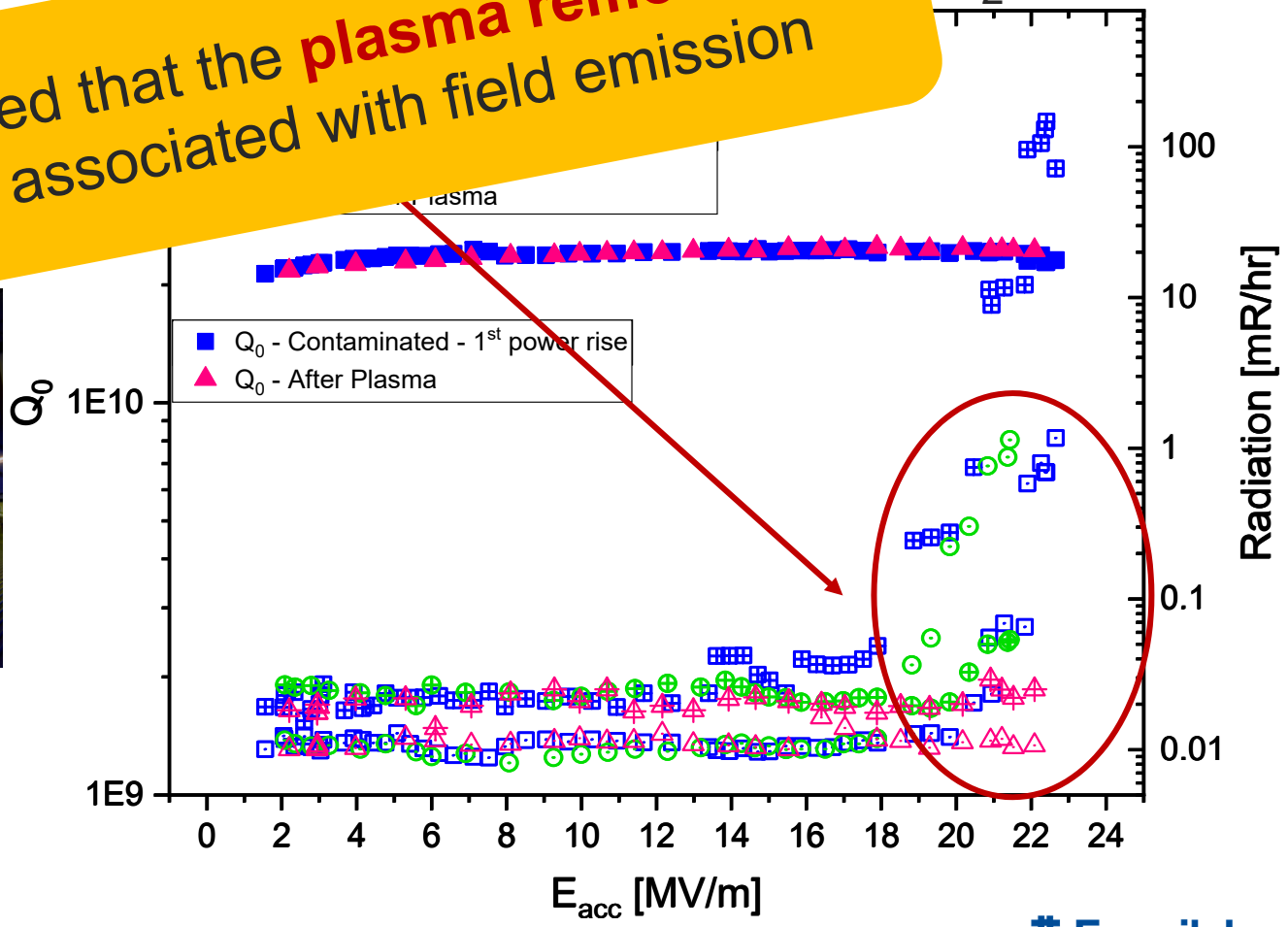
# Simulated vacuum failure: RF results before and after plasma processing

Scope: study the removal of natural contami

- 9-cell cavity: each cell pr $O_2$ plasma

RF test showed that the **plasma removed** the **radiation** associated with field emission





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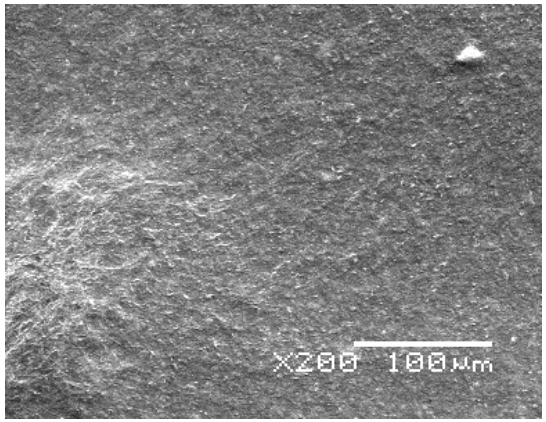
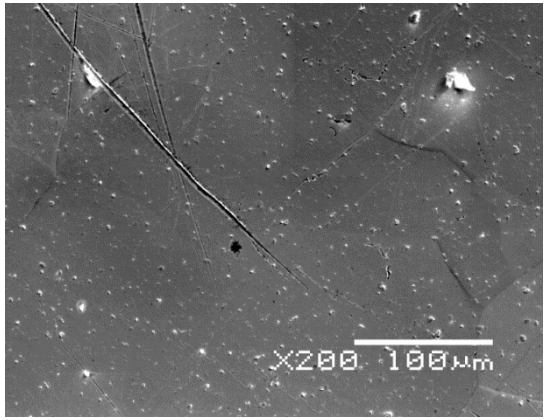
# Controlled introduction of carbon contamination

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

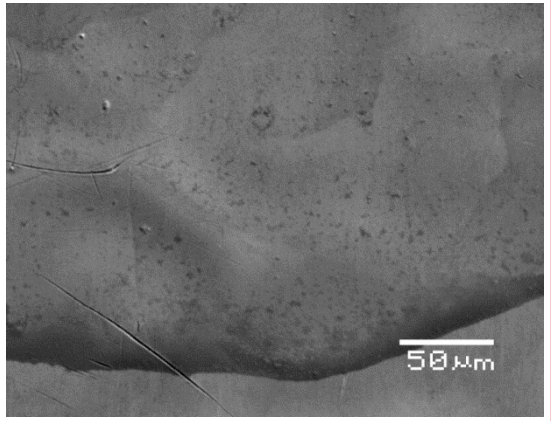
Pure Aquadag



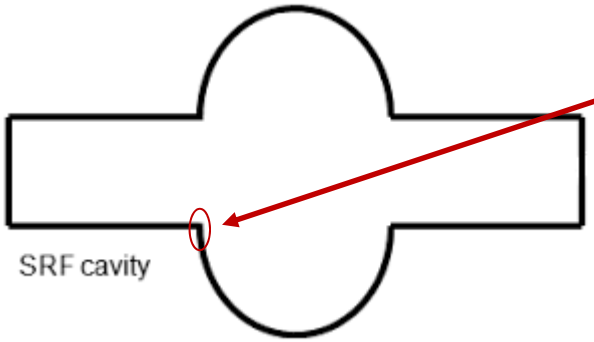

$10^2$ times diluted Aquadag




$10^4$ times diluted Aquadag



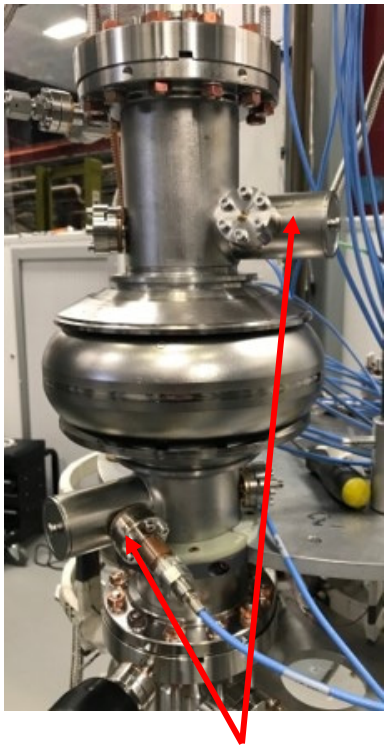

**Chosen concentration**



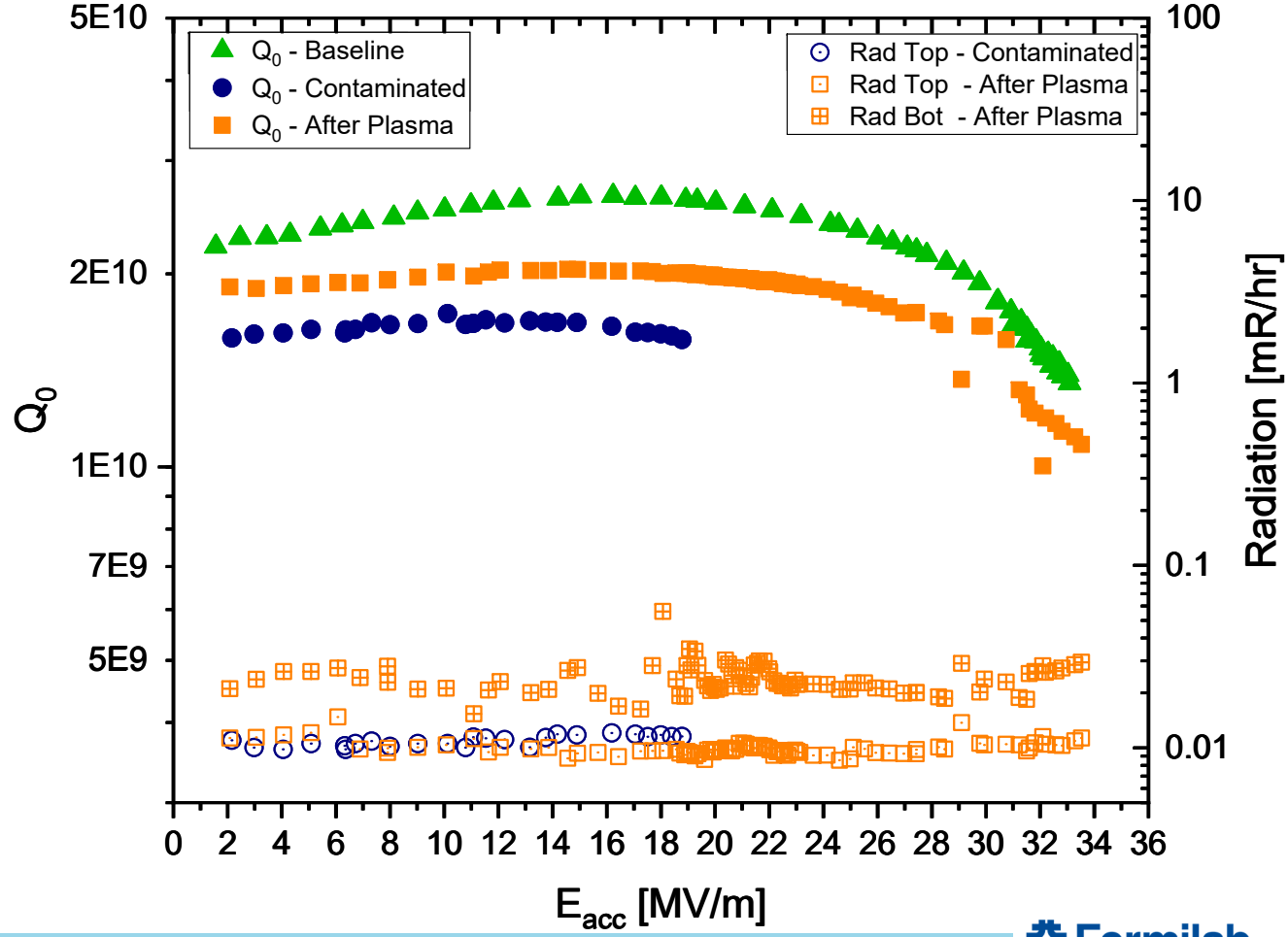
# Carbon contamination: RF results before and after plasma processing

Scope: study the removal of Carbon contamination

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



HOM couplers

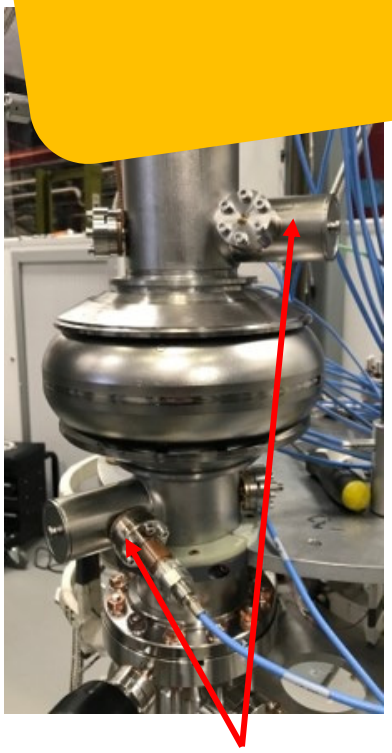


# Carbon contamination: RF results before and after plasma processing

Scope: study th

- lasma.

RF test showed that the **plasma** removed the contamination **restoring** the **initial accelerating field**



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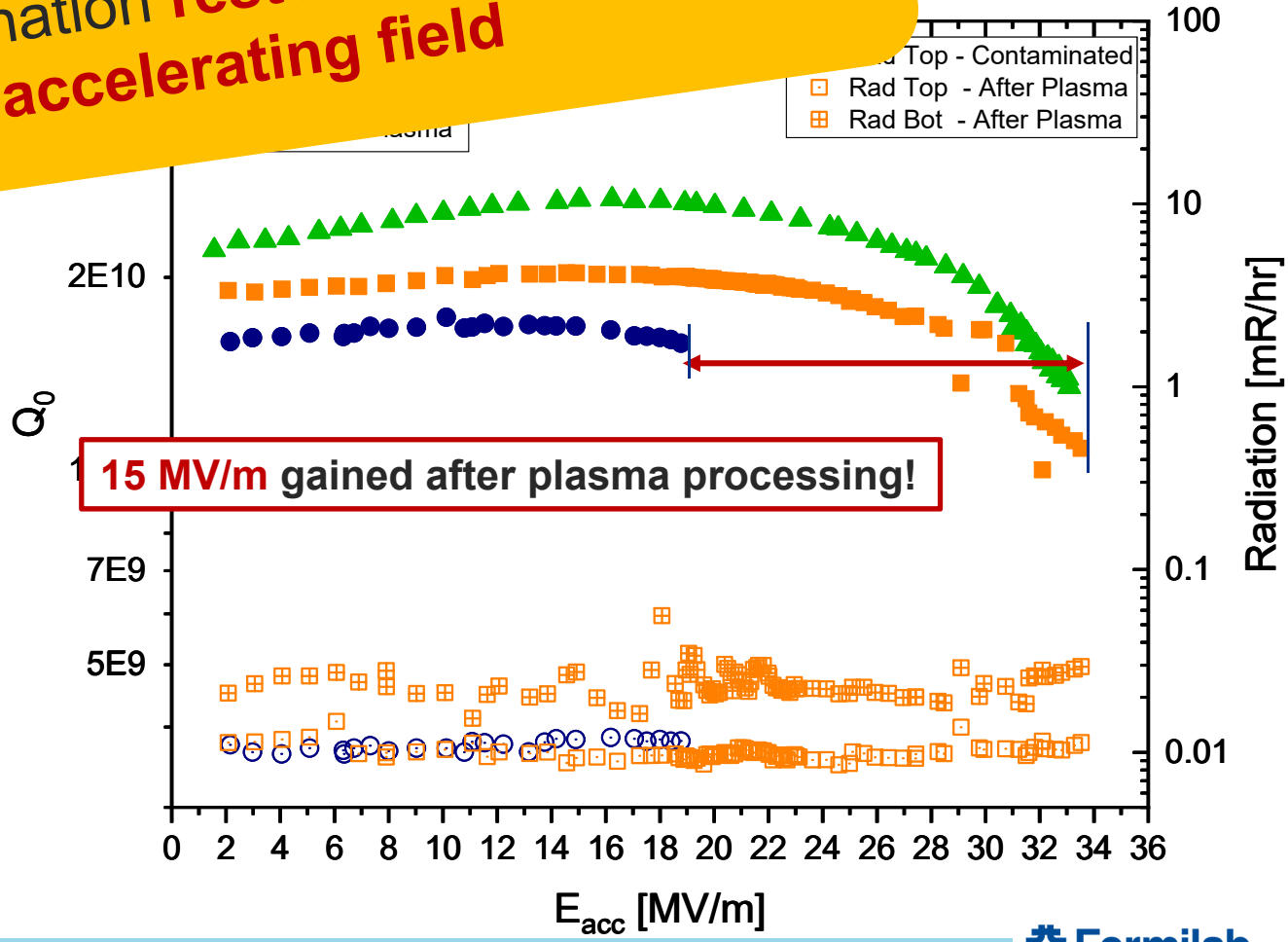




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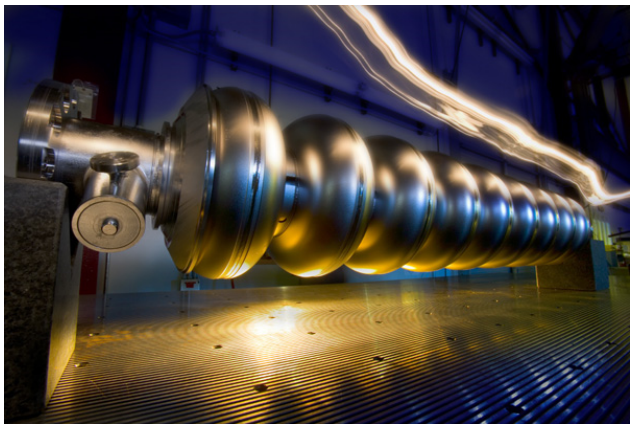
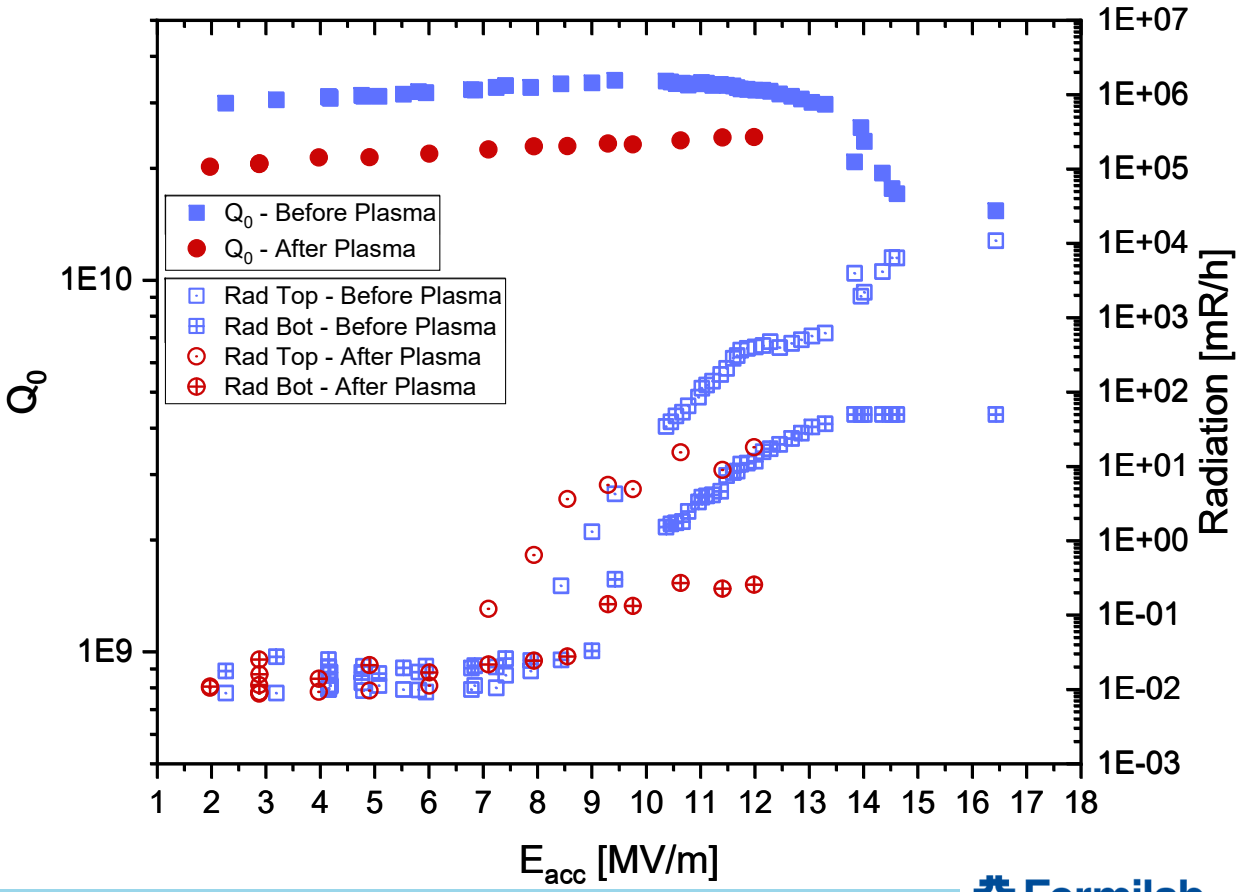
- **Naturally FE cavities: plasma processing applied on a naturally field emitting cavities, as received from the vendor**

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

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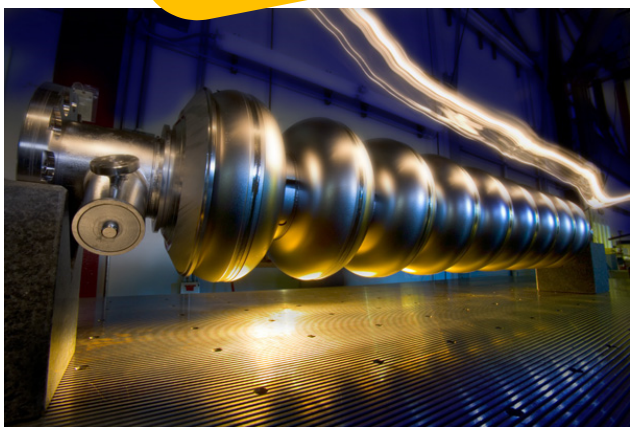
# Naturally Field Emitting cavity: RF results before and after plasma processing (2)

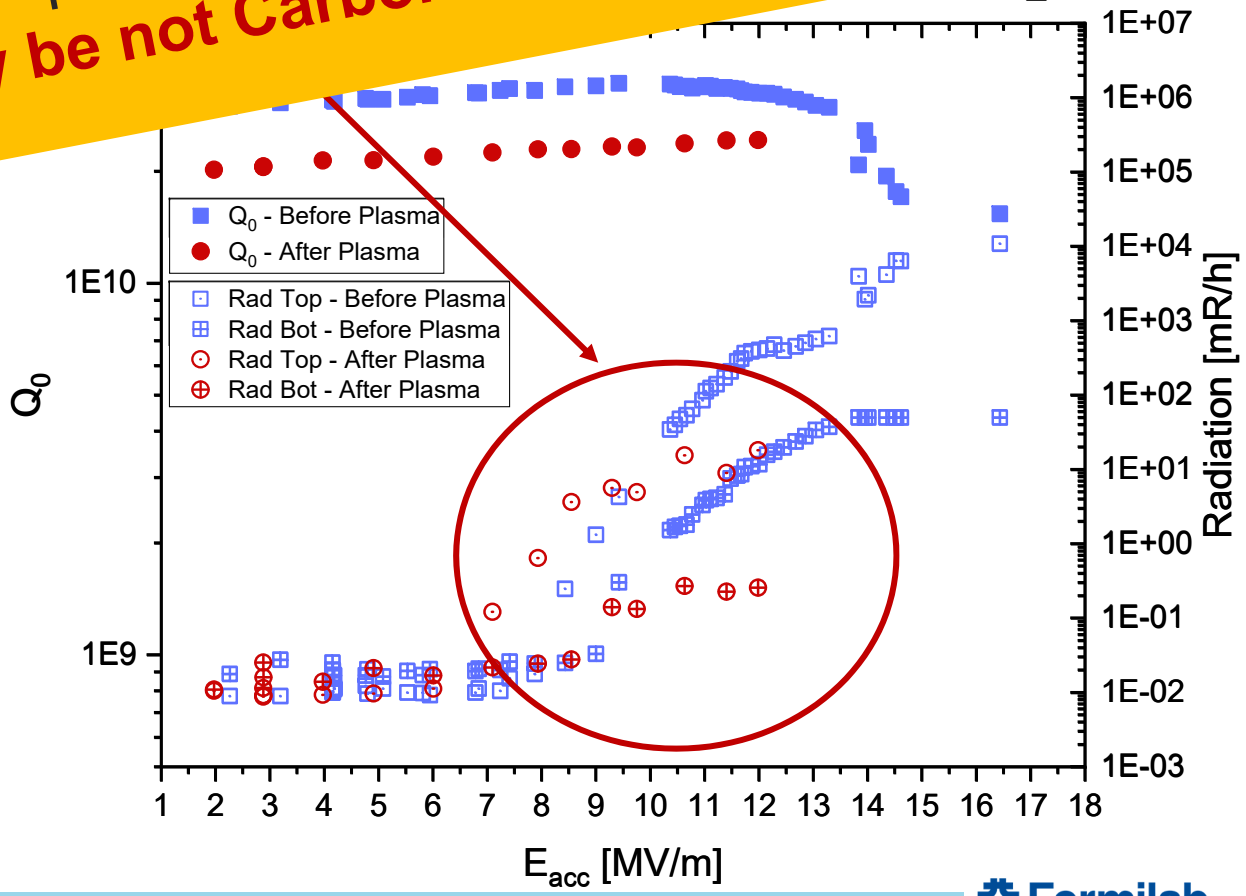
Scope: study the effect of [illegible] field emission

- [illegible] $O_2$ p[illegible]

After plasma RF test shows **NO increase** in performance.

**FE may be not Carbon-related.**





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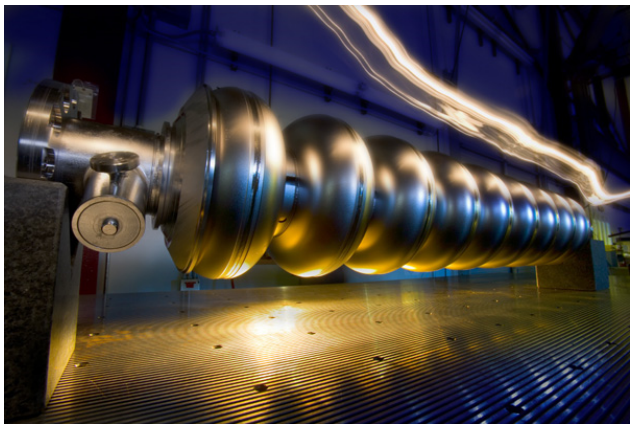
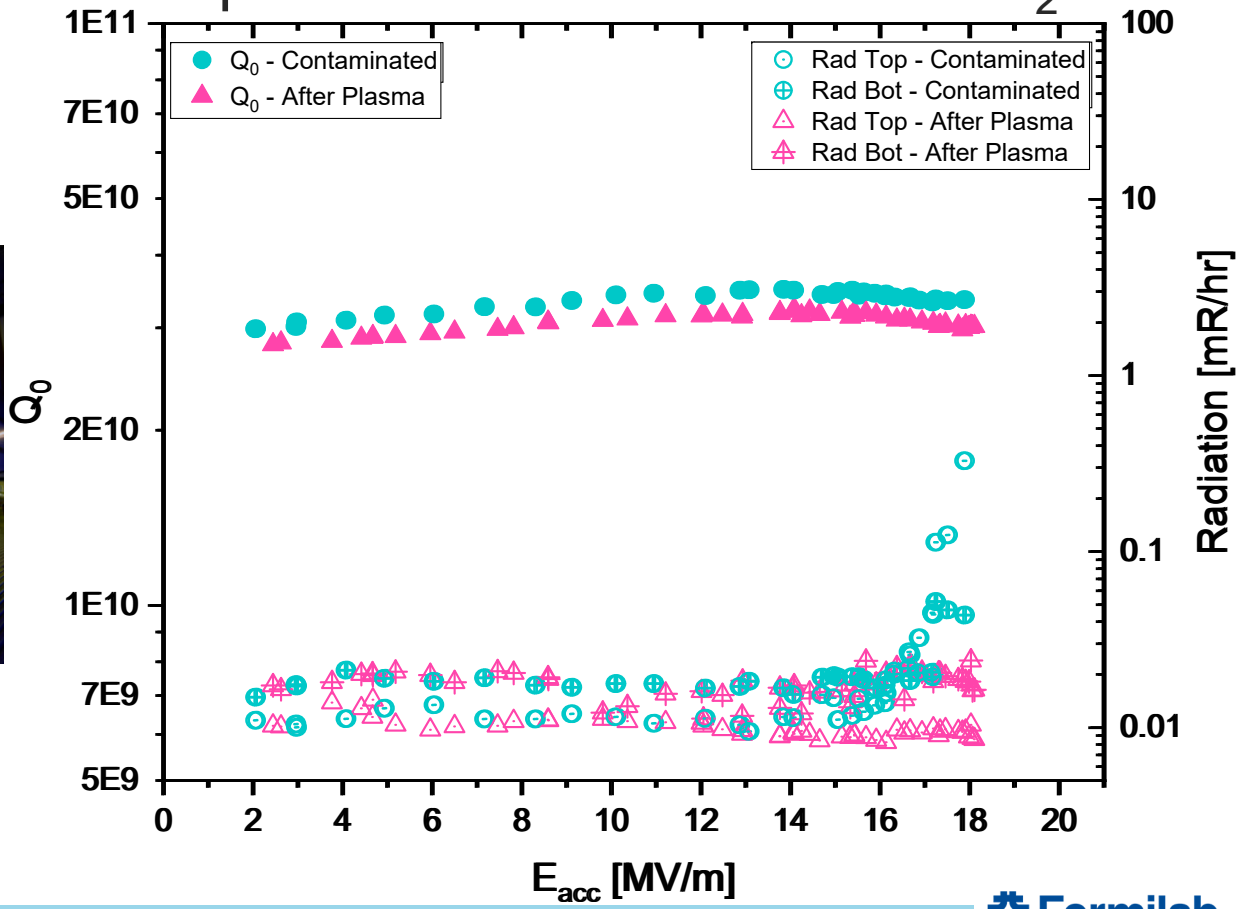
# Naturally Field Emitting cavity: RF results before and after plasma processing (1)

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.



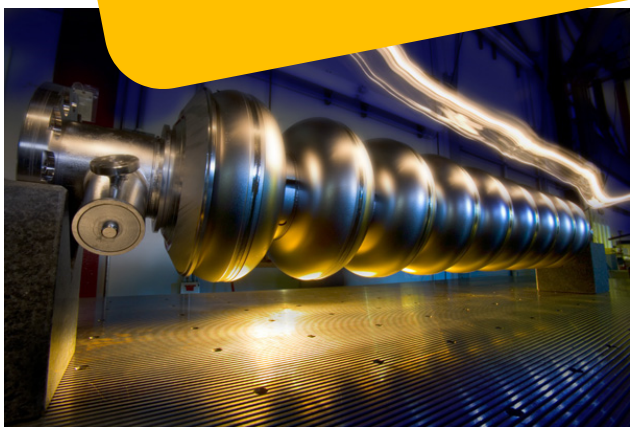


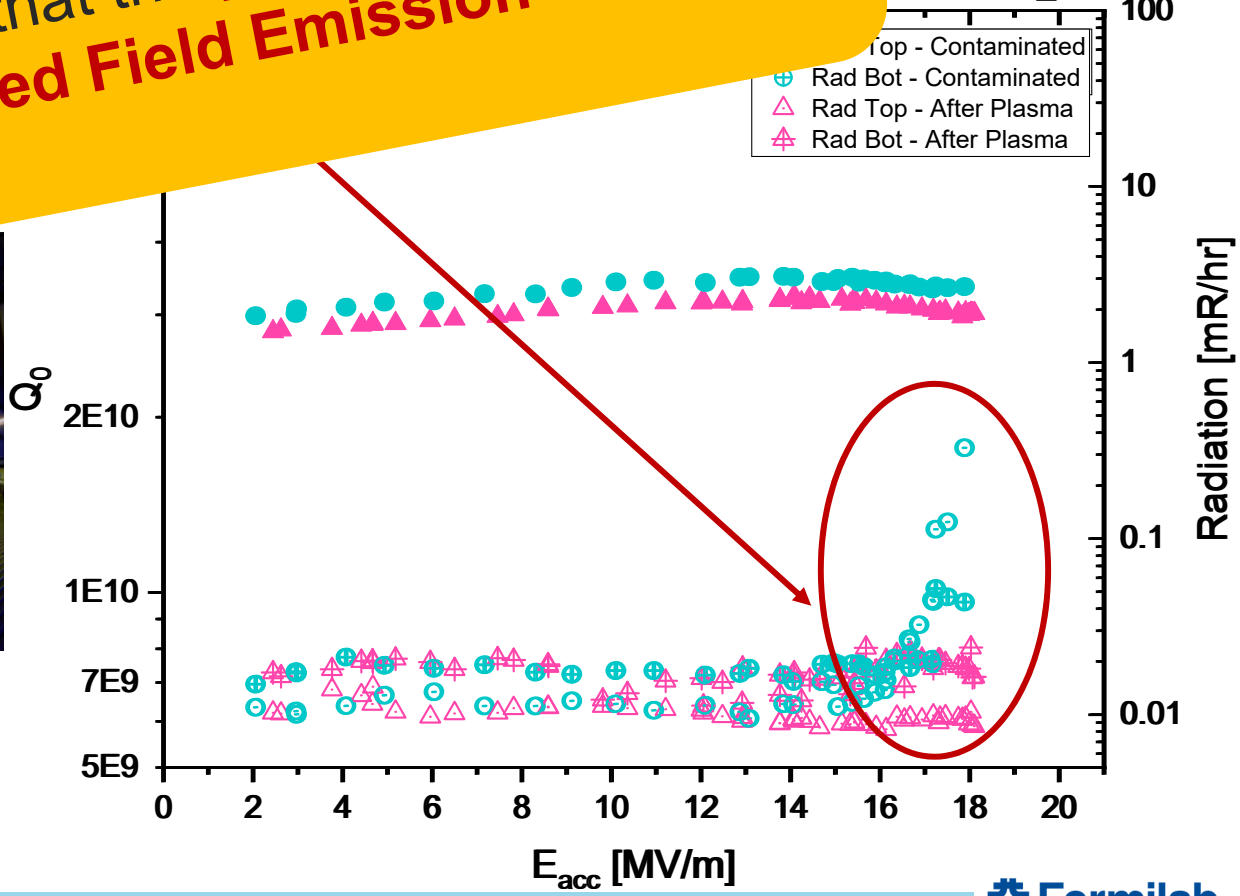
# Naturally Field Emitting cavity: RF results before and after plasma processing (1)

Scope: study the effect of Plasma pr… tural field emission

- 9 c… Ne-$O_2$

RF test showed that the **plasma completely removed Field Emission**





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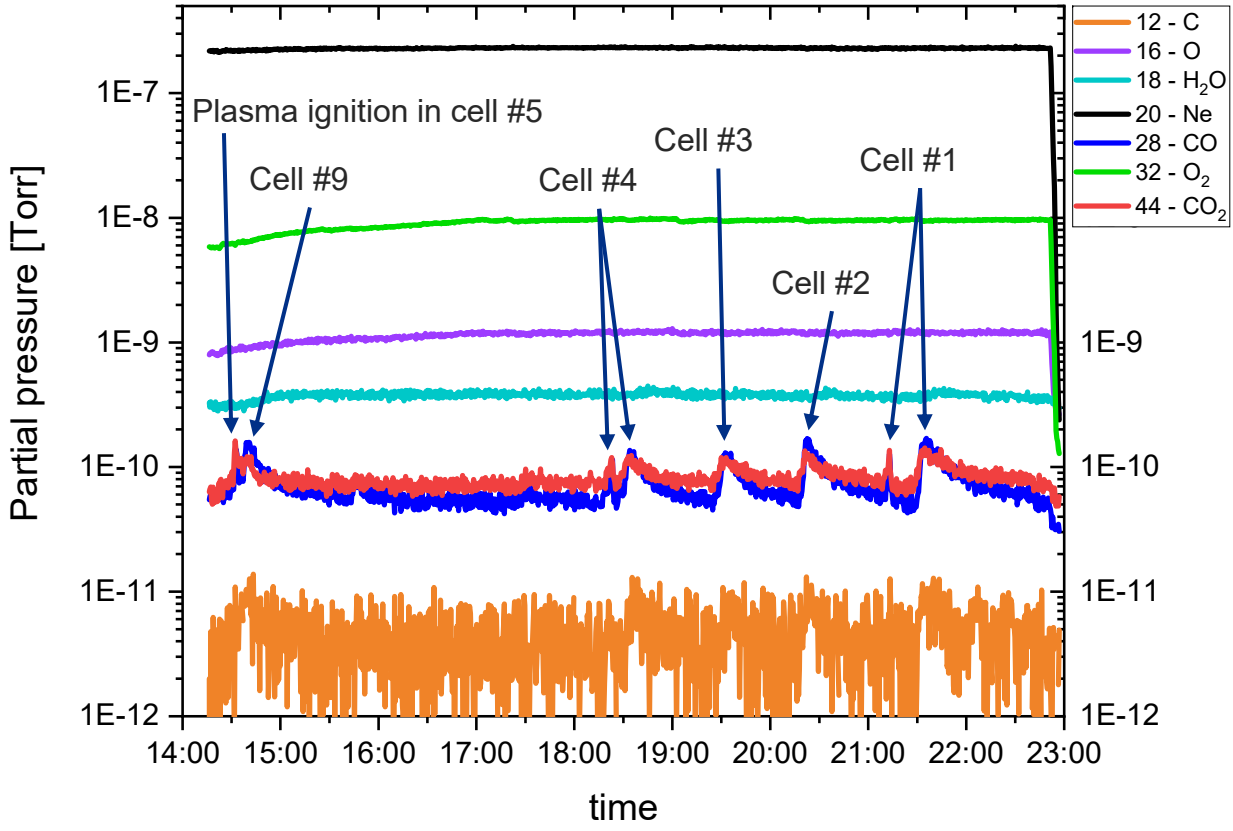
# Examples of Residual Gas Analyzer spectrum

- 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



- Introduction
- Plasma ignition in LCLS-II cavities
  - New method to control plasma ignition
  - RF measurements at different pressures with Neon and Argon
- Plasma cleaning test on 9 cell LCLS-II 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 method allows to **substantially reduce $P_{FWD}$** and enables the procedure on LCLS-II 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 ⟶ able to **remove hydrocarbon contamination** using Ne-$O_2$ at 75-80mTorr.
    - Developed a first recipe in terms of pressure, $O_2$ percentage, plasma density and duration. Systematic studies will follow.
- **Contaminated cavities** treated with plasma processing and RF tested before/after: **3 out of 4** showed **increase in performance!**

# Future work

- Systematic study to optimize processing parameters:
  - Pressure
  - Duration
  - $O_2$ concentration
  - Plasma density

- Plasma process and cold-test 9-cell LCLS-II cavities to acquire statistics on effectiveness in terms of field emission reduction


Thank you!