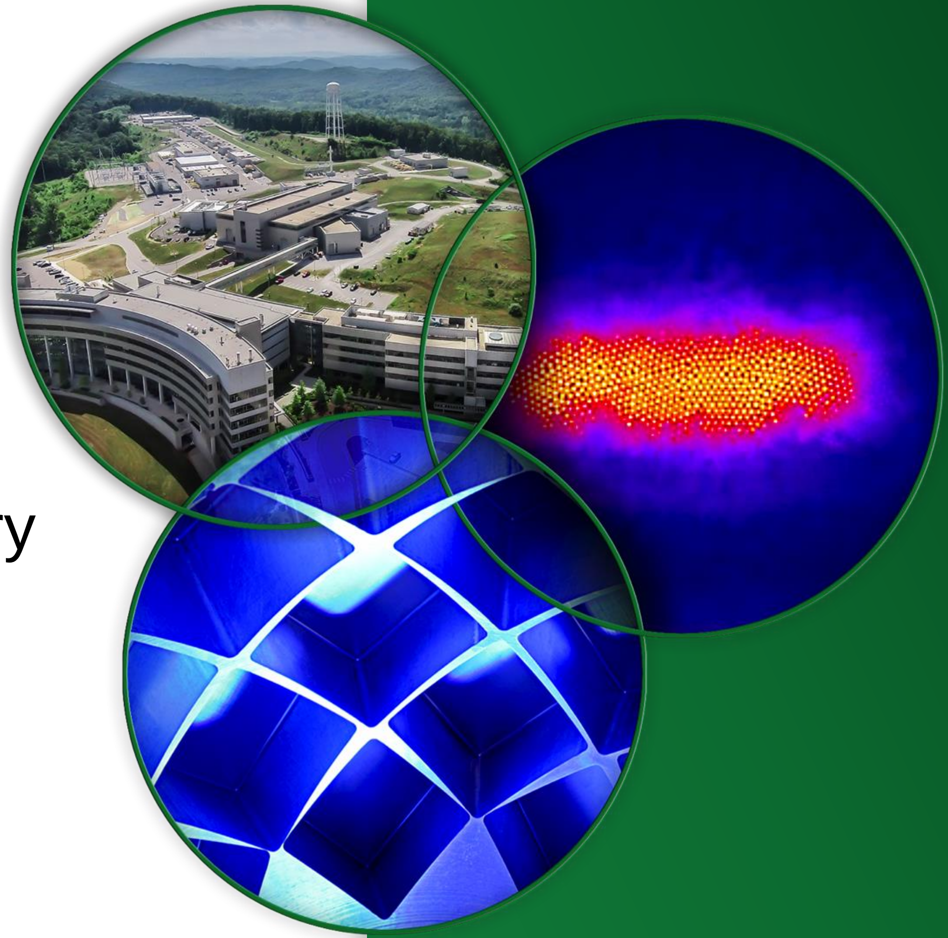
Plasma processing for SRF cavities



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SCL systems group

Oak Ridge National Laboratory

FNAL seminar

March 22, 2016

ORNL is managed by UT-Battelle
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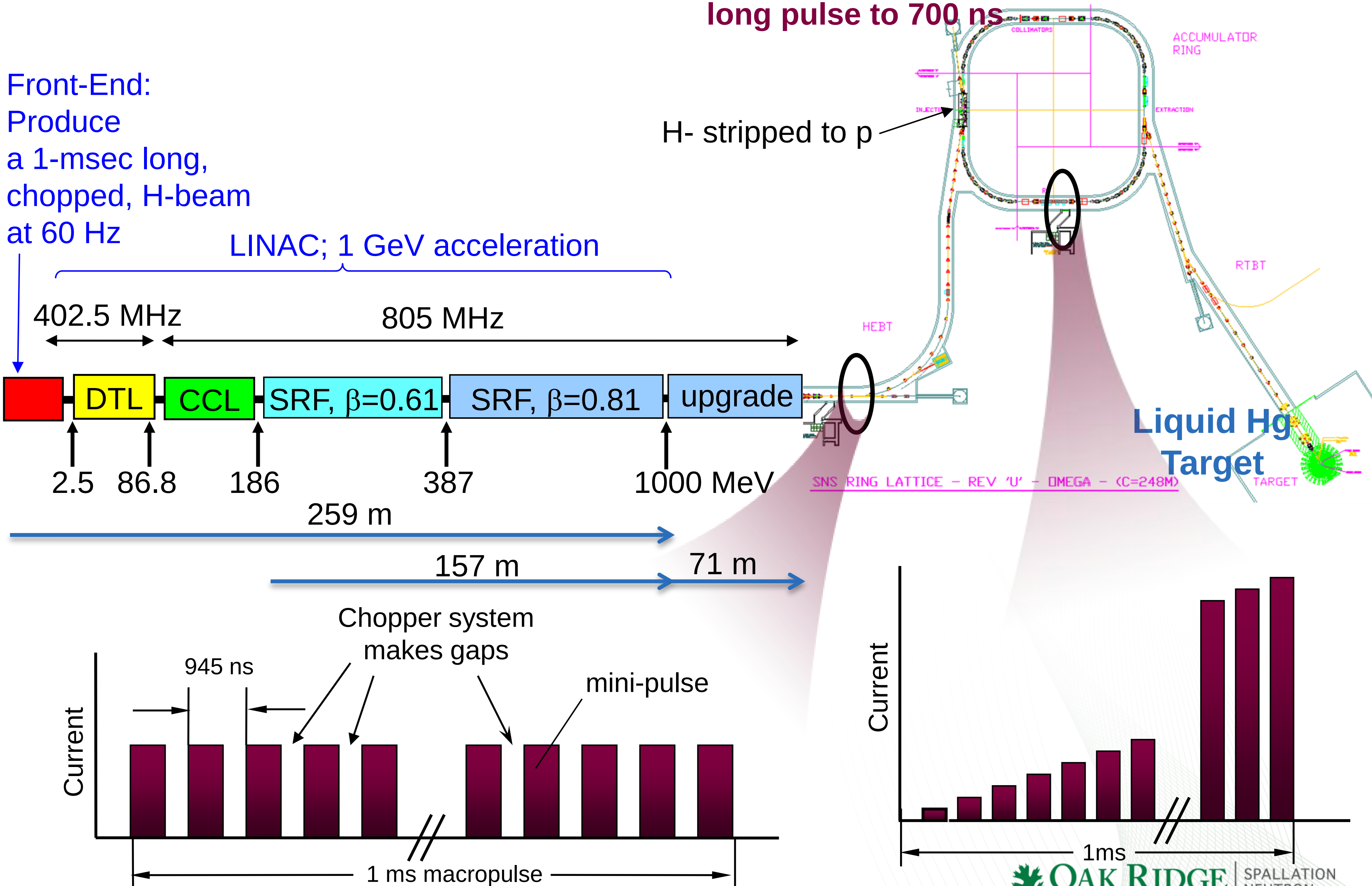
Overview

- **Motivation for in-situ plasma processing**
- **Plasma generation in SNS cavities**
- **Plasma surface interaction**
  - Improves work function
  - Reduce secondary emission yield
  - Helps removing adsorbed gases
- **Performance of plasma processed cavities**
  - Single cavities in horizontal test apparatus (HTA)
  - Offline cryomodule
  - Operating cryomodule

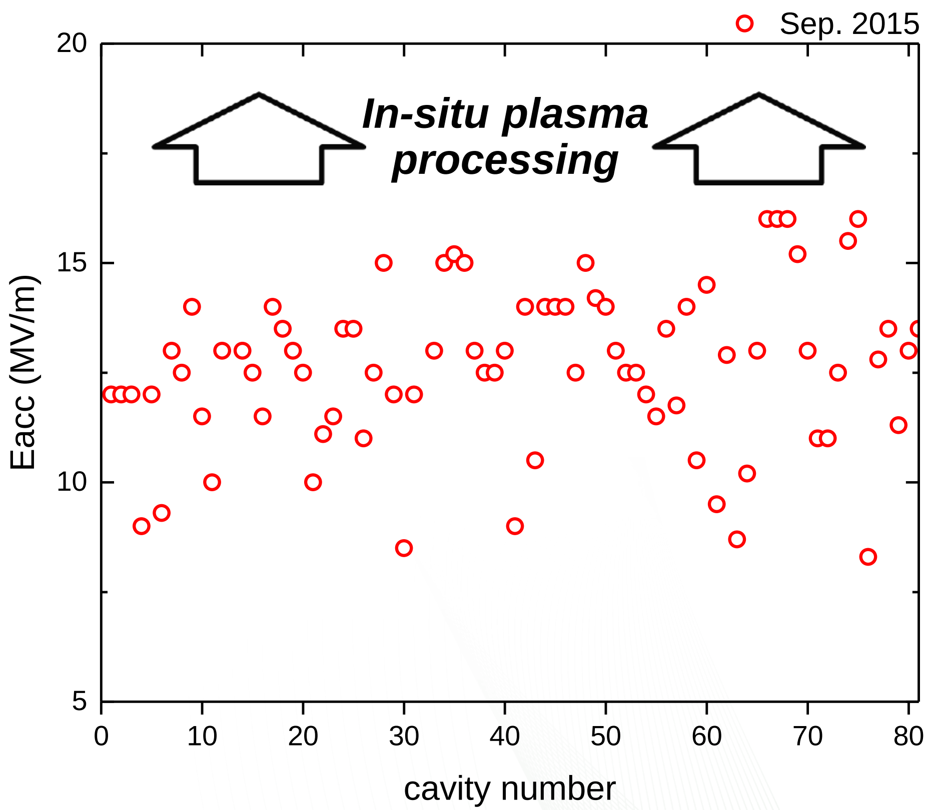
SNS Machine layout



Average macropulse beam current: 26 mA

In-situ plasma processing to increase linac energy

- **Higher linac energy provides more margin for reliable operation at 1.4 MW**
- **Most cavities at SNS are limited by field emission (FE) leading to thermal instability in end-groups**
  - Average accelerating gradients are 12 and 13 MV/m for the two cavity geometries
- **Developed in-situ plasma processing to reduce FE and increase accelerating gradients***



*M. Doleans, P. V. Tyagi et al. NIMA 812 (2016) pp50-59

In-situ plasma processing to reduce FE

- **Plasma processing aims at**
  - Reducing FE by increasing work function of cavity RF surface
  - Enabling operation at higher accelerating gradients
- **Scaling from Fowler-Nordheim equation**

$$J = a\frac{(\beta E)^2}{\phi} e^{-b\frac{\phi^{3/2}}{\beta E} + \frac{c}{\phi^{1/2}}}$$

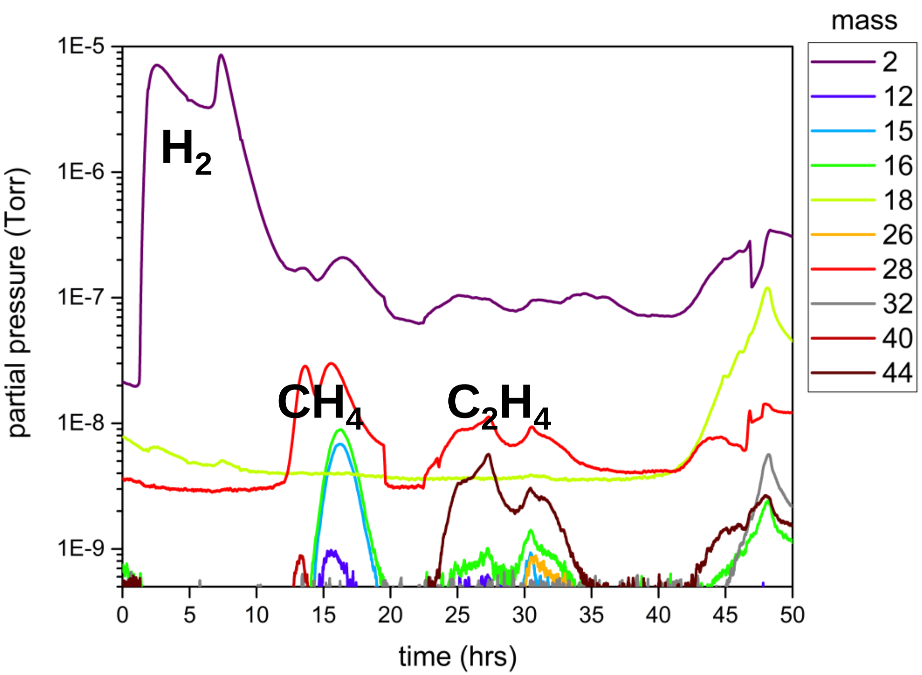
$$dJ = 0 \quad \Rightarrow \quad \frac{dE_{acc}}{E_{acc}} \approx \frac{3}{2}\frac{d\phi}{\phi}$$

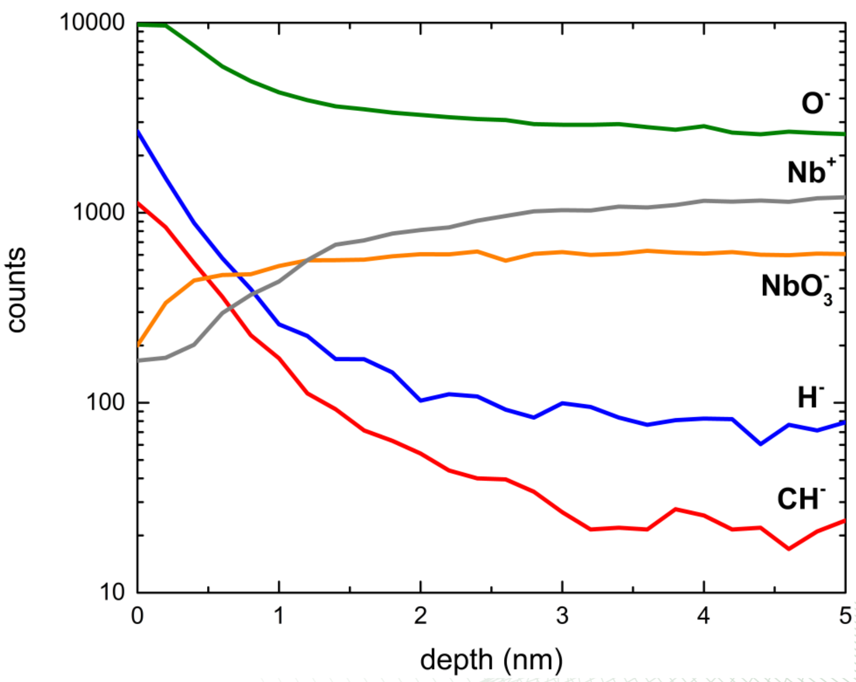
J : current density
E : surface electric field
β : field enhancement factor
ϕ : work function

  - 10-20% increase in ϕ leads to 20-30% increase in Eacc

Hydrocarbon contaminants on Nb surfaces

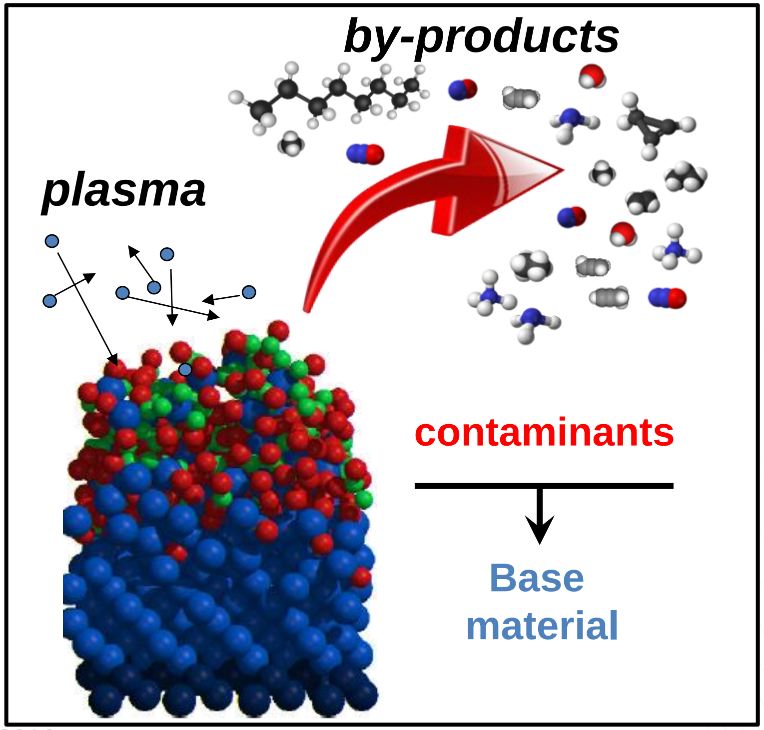
- **Hydrocarbon contaminants observed on all Nb surfaces**
  - Volatile hydrocarbons released from cryomodule surfaces during thermal cycle
  - Hydrocarbons on offline spare cavity surfaces
  - Hydrocarbons fragments seen in secondary ion mass spectrometry (SIMS)
    - Mechanically polished niobium samples
    - Chemically polished niobium samples (BCP)
- **Hydrocarbons tends to lower work function of Nb surface**
  - Develop in-situ plasma processing to remove hydrocarbons from cavity RF surface





Low e^- temperature and low-density reactive plasma for removing hydrocarbons in SNS cavities

- **Plasma is a rich and reactive environment**
  - Ions, e-, neutrals, excited neutrals, molecules, radicals, UV…
- **Plasma processing is a versatile technique used for various purposes**
  - Cleaning, activation, deposition, crosslinking, etching….
- **Chosen to develop a technique using reactive oxygen plasma at room-temperature**
  - Volatile by-products are formed through oxidation of hydrocarbons and pumped out



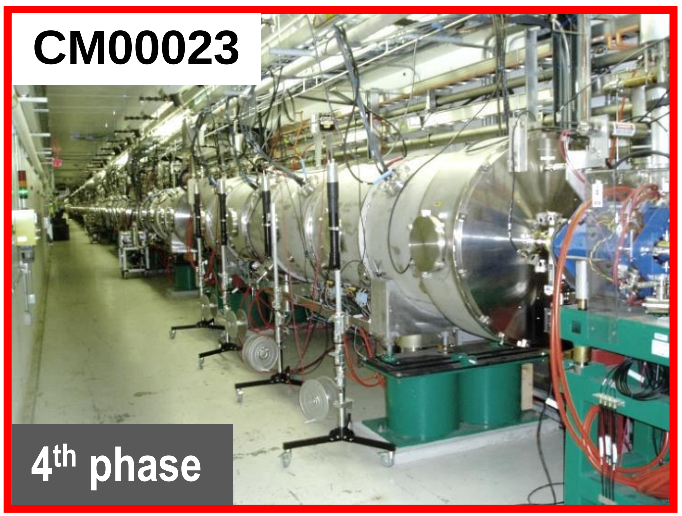
Plasma processing R&D strategy

✓

R&D with Nb samples and offline cavities

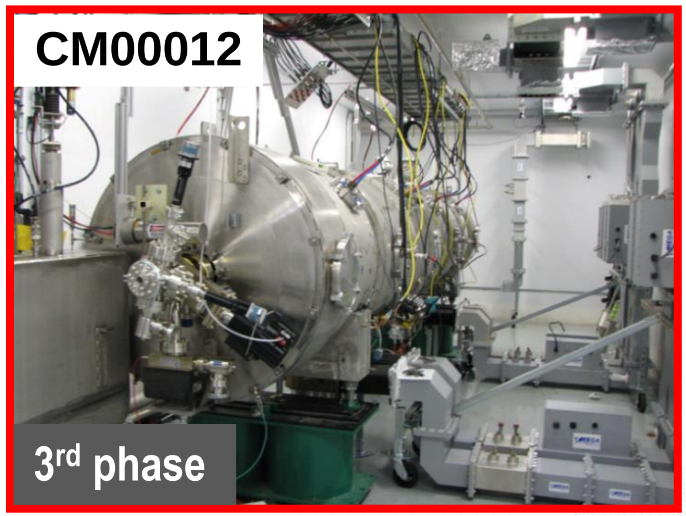
✓

Processing of 6-cell cavity in HTA*



In-situ processing in linac tunnel

On-going
FY16
FY17



✓

Processing of cryomodule in test cave

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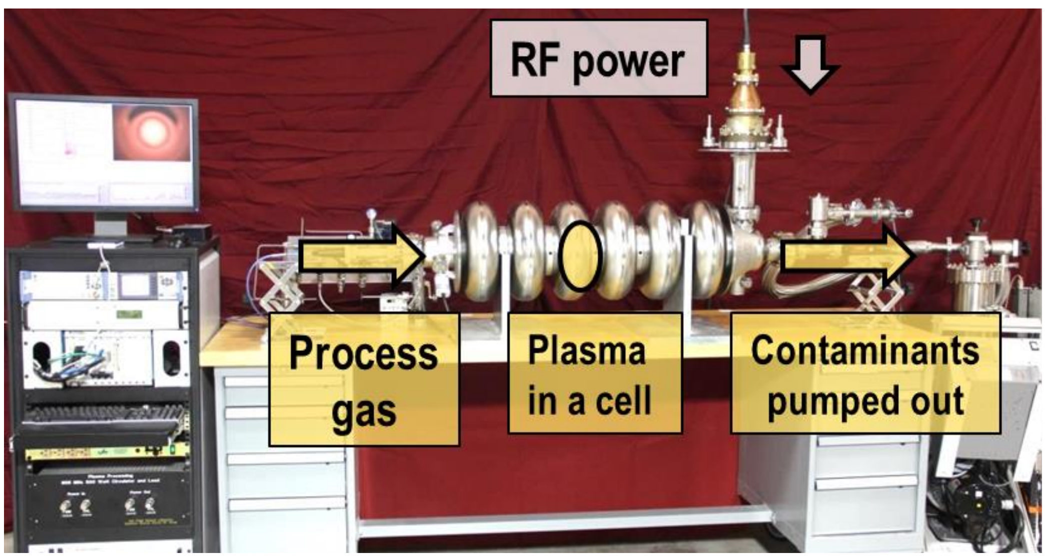
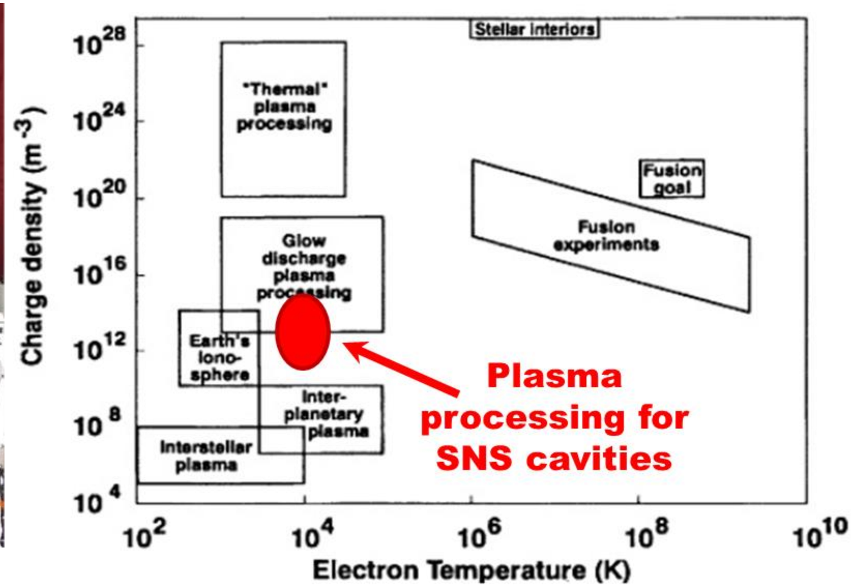
*HTA: Horizontal Test Apparatus

Basic plasma generation

- **Plasma generated inside cavity volume**
  - Gas manifold and RF station
    - Injection of gas in cavity (~1-500 mTorr)
    - Excitation of EM fields in cavity using solid state amplifier (10-1000 W)
  - Acceleration of seed electrons to reach ionization energy
  - Enough ionization to sustain plasma
  - Plasma ignites in discrete cell(s), tuning necessary





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Passband modes to create discharge

- **Mode frequencies and cell amplitudes**

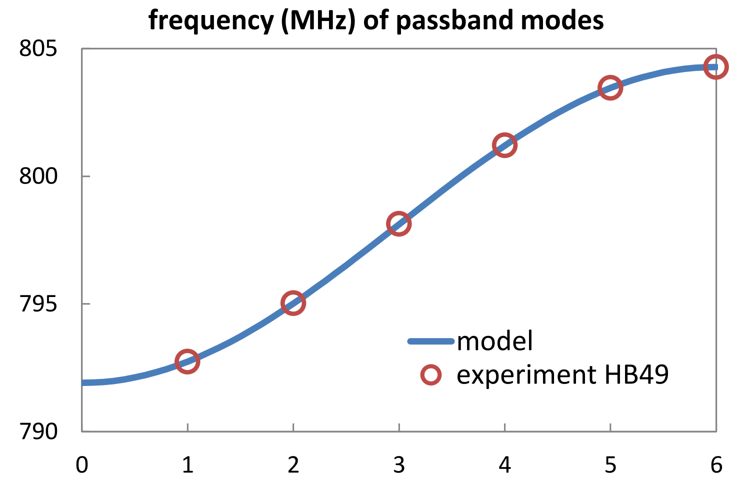
$$\Omega_m = \frac{\omega_m^2}{\omega_0^2} = 1 + k\left[1 - Cos\left(\frac{m\pi}{N}\right)\right]$$

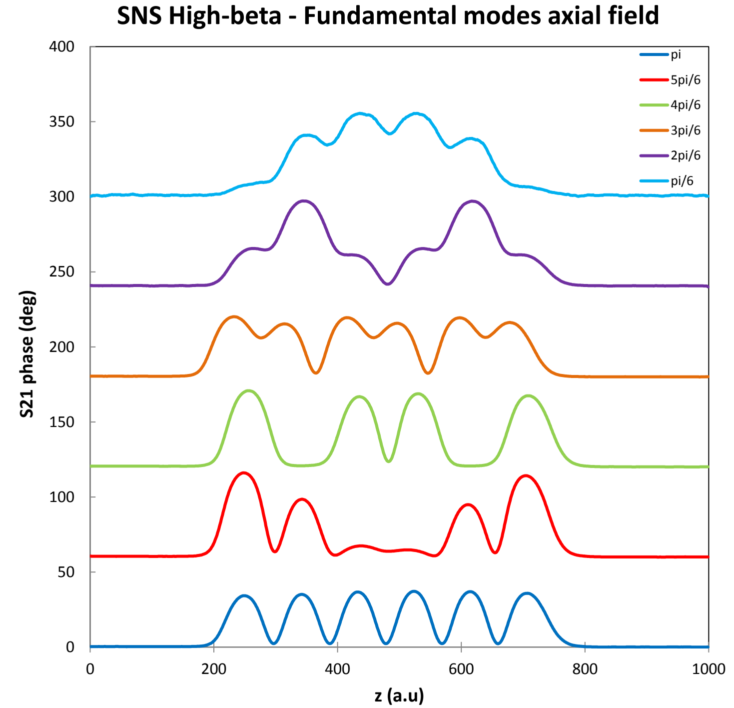
$$V_{mj} = \sqrt{\left(2-\delta_{mN}\right)/N}\ Sin\left(\left(j-1/2\right)\frac{m\pi}{N}\right)$$

NORMALIZED EIGEN VECTORS (ROWS=MODES, COLUMNS=CELLS)

$\frac{-1+\sqrt{3}}{2\sqrt{6}}$	$\frac{1}{\sqrt{6}}$	$\frac{1+\sqrt{3}}{2\sqrt{6}}$	$\frac{1+\sqrt{3}}{2\sqrt{6}}$	$\frac{1}{\sqrt{6}}$	$\frac{-1+\sqrt{3}}{2\sqrt{6}}$
$\frac{1}{2\sqrt{3}}$	$\frac{1}{\sqrt{3}}$	$\frac{1}{2\sqrt{3}}$	$-\frac{1}{2\sqrt{3}}$	$-\frac{1}{\sqrt{3}}$	$-\frac{1}{2\sqrt{3}}$
$\frac{1}{\sqrt{6}}$	$\frac{1}{\sqrt{6}}$	$-\frac{1}{\sqrt{6}}$	$-\frac{1}{\sqrt{6}}$	$\frac{1}{\sqrt{6}}$	$\frac{1}{\sqrt{6}}$
$\frac{1}{2}$	0	$-\frac{1}{2}$	$\frac{1}{2}$	0	$-\frac{1}{2}$
$\frac{1+\sqrt{3}}{2\sqrt{6}}$	$-\frac{1}{\sqrt{6}}$	$\frac{-1+\sqrt{3}}{2\sqrt{6}}$	$\frac{-1+\sqrt{3}}{2\sqrt{6}}$	$-\frac{1}{\sqrt{6}}$	$\frac{1+\sqrt{3}}{2\sqrt{6}}$
$\frac{1}{\sqrt{6}}$	$-\frac{1}{\sqrt{6}}$	$\frac{1}{\sqrt{6}}$	$-\frac{1}{\sqrt{6}}$	$\frac{1}{\sqrt{6}}$	$-\frac{1}{\sqrt{6}}$

- **6-cell cavity gives 6 modes**
- **Broad band solid state amplifier can excite any of these modes**
- **Dual tone rf generation**



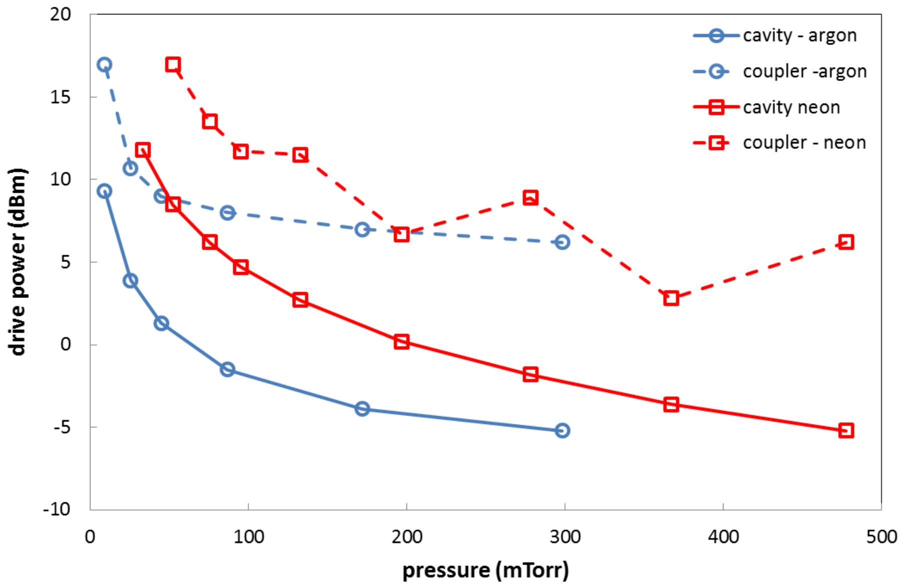


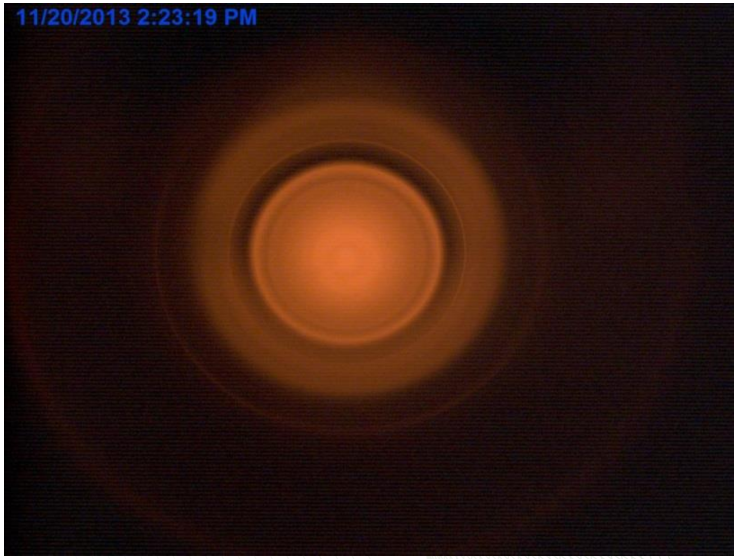
Basic field and ignition curve

- **Field required to initiate a rf discharge**
  - Accumulation of energy gain in rf field enabled by e- collisions with gas
- **Ignition depends on gas (ionization energy, pressure…), rf frequency, geometry**
  - Ignition curves in cavity and coupler to determine possible/optimum working pressure

$$E = \frac{2\omega}{\Lambda \nu_m}\left(\frac{2}{3} u u_i\right)^{1/2}$$

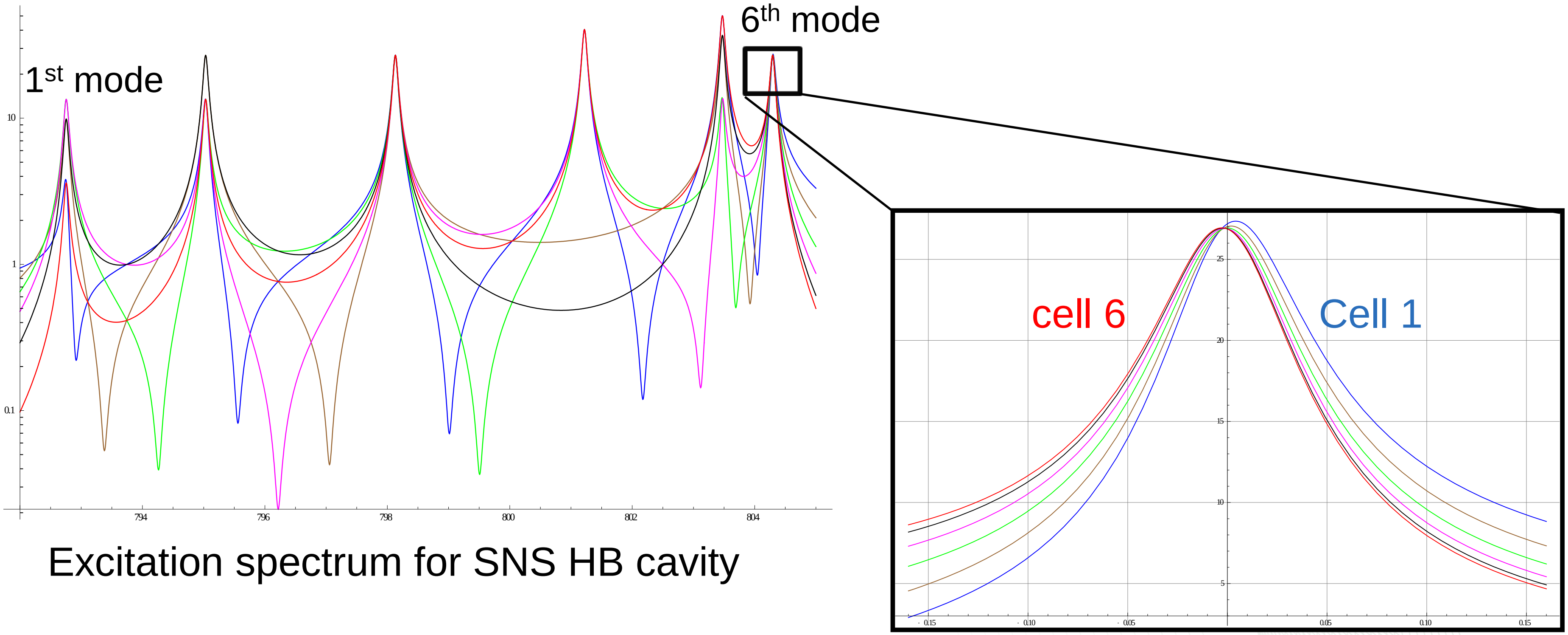
E~10 kV/m for SNS HB cavity and 150 mTorr of Neon





On/off resonance excitation

- **Perturbation theory applied to SNS cavities**
- **Useful to help igniting in specific cell, for example**
  - Use each side of pi-mode to excite each end-cell preferentially



Excitation spectrum for SNS HB cavity

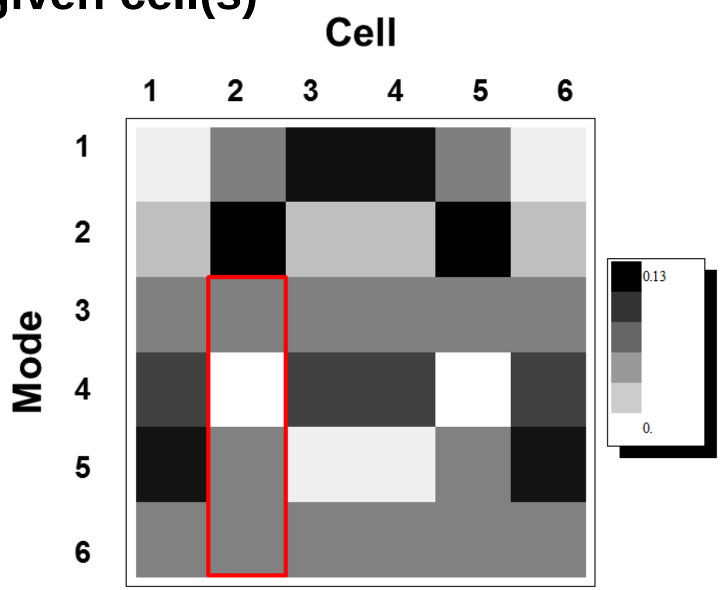
Plasma/rf cavity interaction*

- **The plasma acts as a dielectric medium loading the resonator volume**
- **The plasma shifts the resonance frequency upward**
- **Frequency shift is proportional to plasma density**
- **Mode properties perturbed by plasma in given cell(s)**

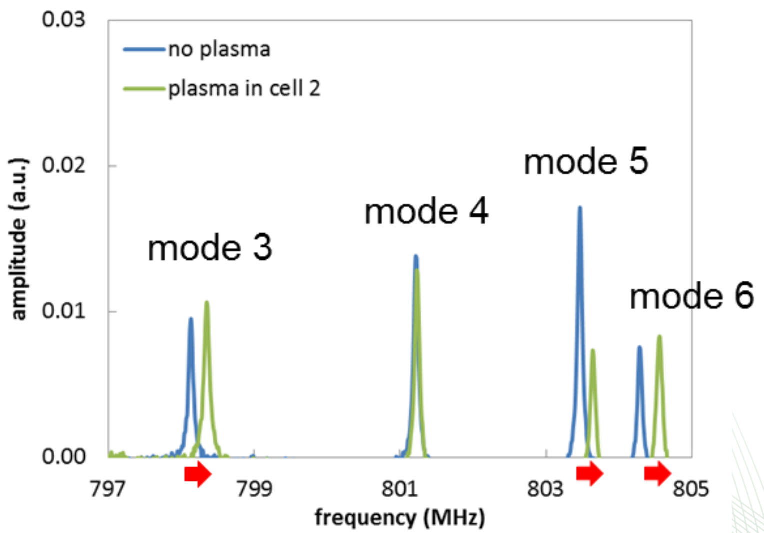
$$\frac{\delta\omega}{\omega} = \frac{1}{2\left(1+\beta^2\right)} \frac{\iiint_{plasma} \eta E^2 dV}{\iiint_{cavity} E^2 dV}$$

$$\eta = \frac{\omega_{plasma}^2}{\omega_{rf}^2} \alpha \, n_{plasma}$$

$$\varepsilon = 1 - \eta$$



Effect of plasma on mode freq.



*M. Doleans et al. SRF2013

Perturbation RF modes by plasma

- **Plasma perturbs cell(s) frequency**
  - Affects mode frequency and amplitude
  - Similar conceptually as cavity tuning
  - Cell(s) detuned by plasma instead of mechanical deformation

- **Mode frequencies and amplitudes for j^{th} cell of N-cell cavity**

$$\Omega_m = \frac{\omega_m^2}{\omega_0^2} = 1 + k\left[1 - Cos\left(\frac{m\pi}{N}\right)\right]$$

$$\left|m\right\rangle_j = \sqrt{\left(2-\delta_{mN}\right)/N}\ Sin\left(\left(j-1/2\right)\frac{m\pi}{N}\right)$$

- **The mode properties due to the perturbation by the plasma are**

$$\Omega'_m = \Omega_m + \left\langle m\right|P\left|m\right\rangle$$

$$\left|m\right\rangle' = \left|m\right\rangle + \sum_{n\neq m}\frac{\left\langle n\right|P\left|m\right\rangle}{\Omega_m - \Omega_n}\left|n\right\rangle$$

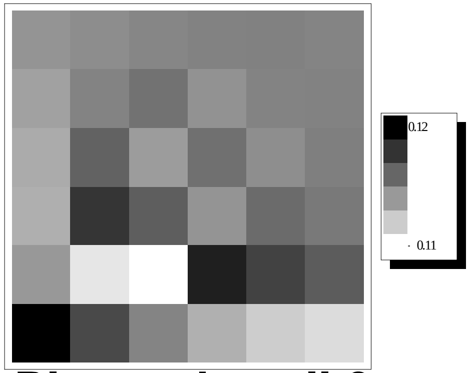
- **The perturbation matrix due to the plasma is**

$$P = \begin{pmatrix} \eta_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \eta_N \end{pmatrix}$$

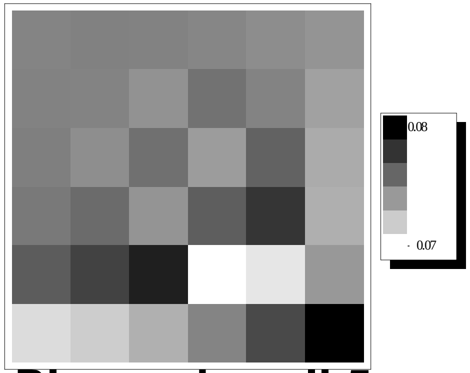
Effect on mode pattern in SNS HB cavity

- **Useful effect to tune and/or locate the plasma**
- **For examples**
  - For the pi-mode, the amplitude of an ignited cell always increases relatively to the other cells
  - For the pi/6 mode, if cell 3 ignited, amplitude cell 4 increases and vice-versa (useful to ignite in one and ignite the other)

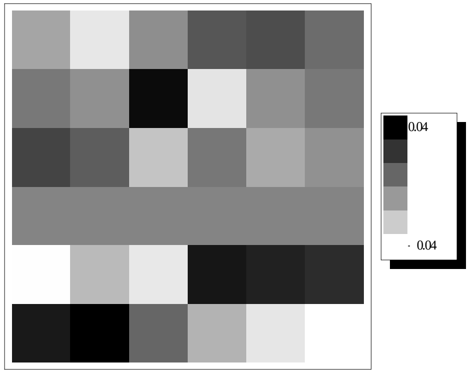
Plasma in cell 1



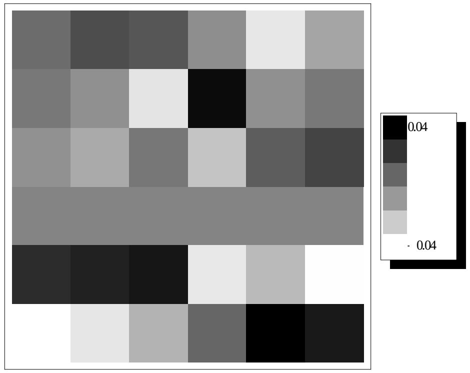
Plasma in cell 6



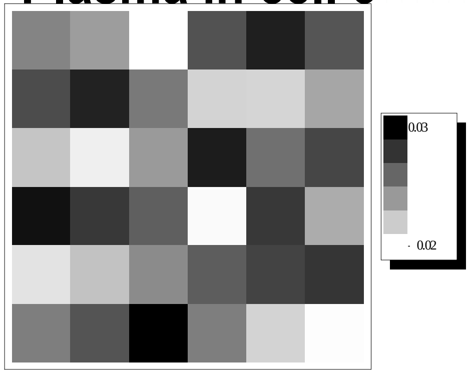
Plasma in cell 2



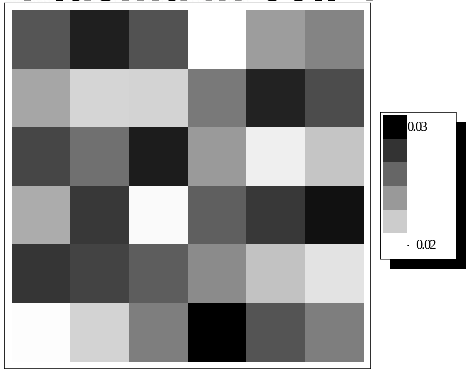
Plasma in cell 5



Plasma in cell 3

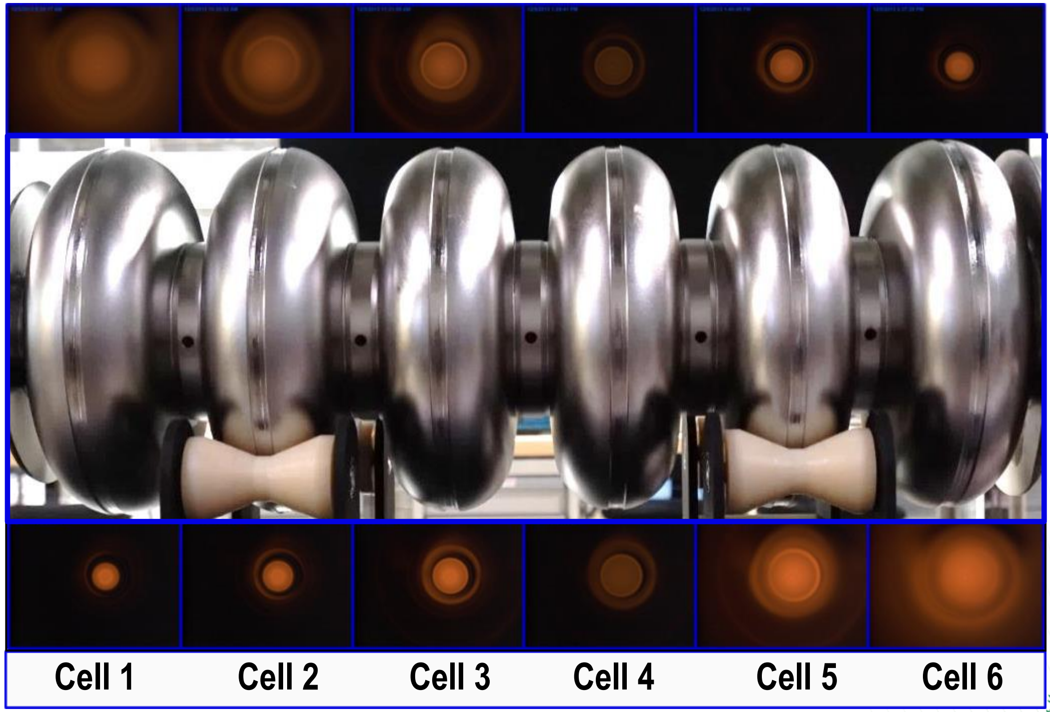


Plasma in cell 4



Reliable plasma generation in SNS HB cavities

- **Used successfully in 10+ cavities**
- **Cells ignited sequentially**
- **Filtered gas (3nm pore size filter)**
  - Neon (~150 mTorr) for plasma ignition and tuning
- **Oxygen added once plasma is ignited and stabilized in desired cell**
  - Oxygen cylinder is a non-flammable mixture with noble gas
  - Typically percent level of oxygen in plasma mixture



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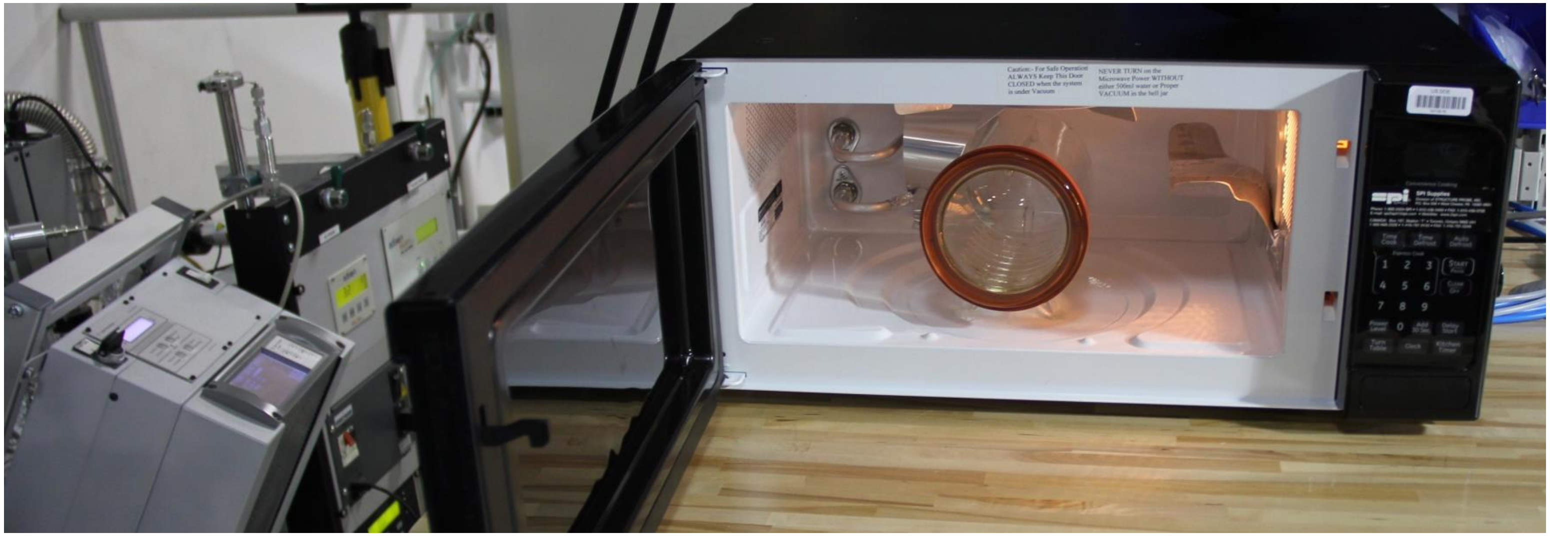
Study plasma/surface interaction



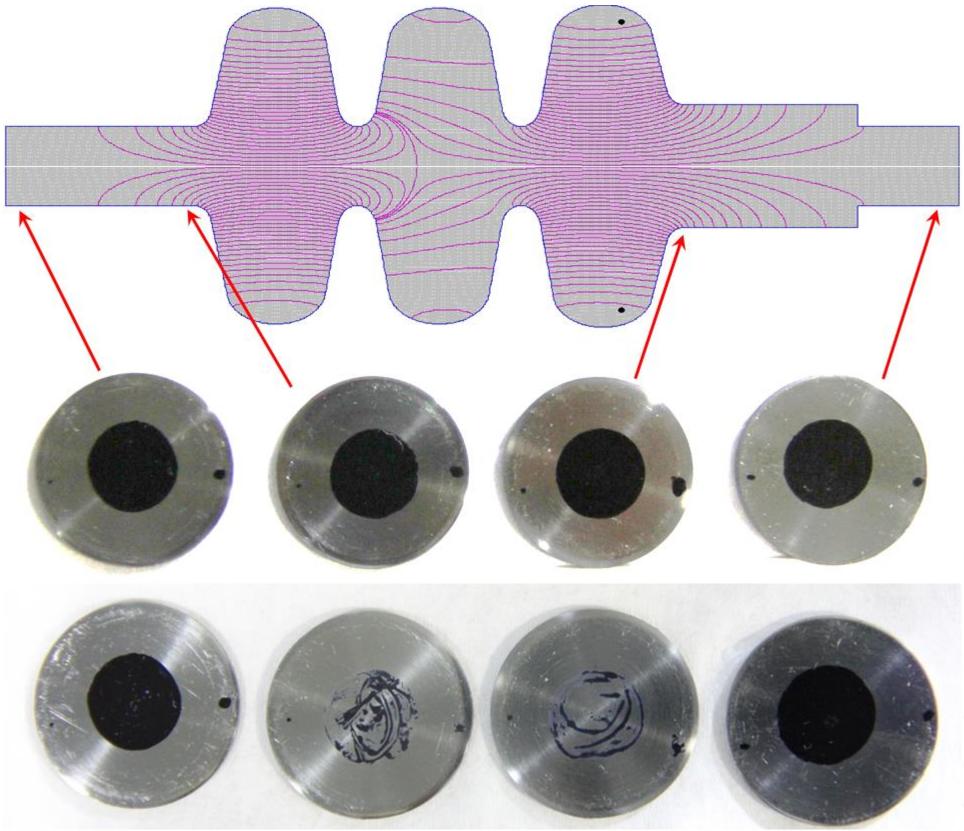
- **Plasma-barrel used to study plasma chemistry**
  - Niobium, cavity surface
  - Copper, inner and outer conductor of fundamental power coupler
  - Alumina, rf window of the fundamental power coupler
- **Neon plasma for main ignition and tuning in desired cell**
- **Oxygen plasma used to remove hydrocarbons**
- **Plasma can damage FPC (Sputter Cu on RF window, Cu oxidation)**

Oxygen in plasma cleans hydrocarbons

- **CxHy contamination added on surface of Nb sample**
  - Short cycles of plasma to avoid excessive heating
    - No heating in cavity as only ~watt transmitted to plasma
  - Cleaning of the sample (right, gif movie)
    - Frames are taken after every interval of plasma processing
  - Based on studies in barrel and SNS cavity
    - Neon-oxygen plasma with percent level of oxygen has been chosen

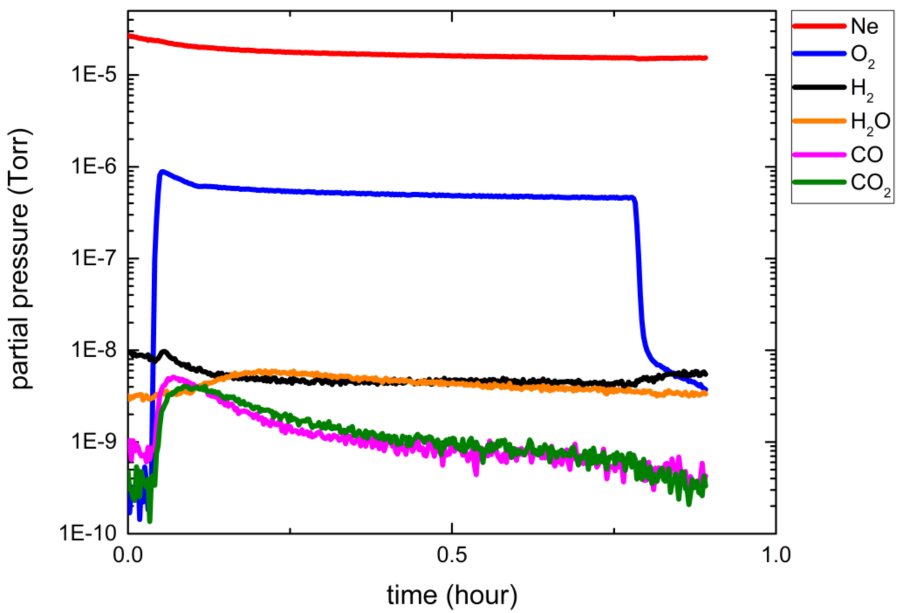
Example of hydrocarbon cleaning in a 3-cell cavity

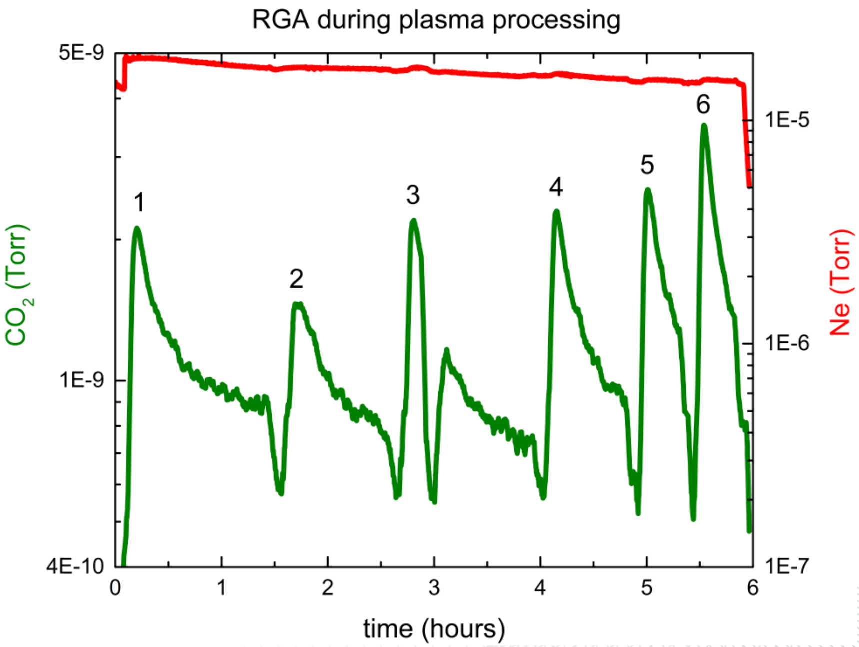
- **Contaminated samples added in cavity end-groups**
- **Plasma ignited in end-cells**
- **Didn't attempt to clean samples thoroughly**



Neon-oxygen cleaning applied to cavities

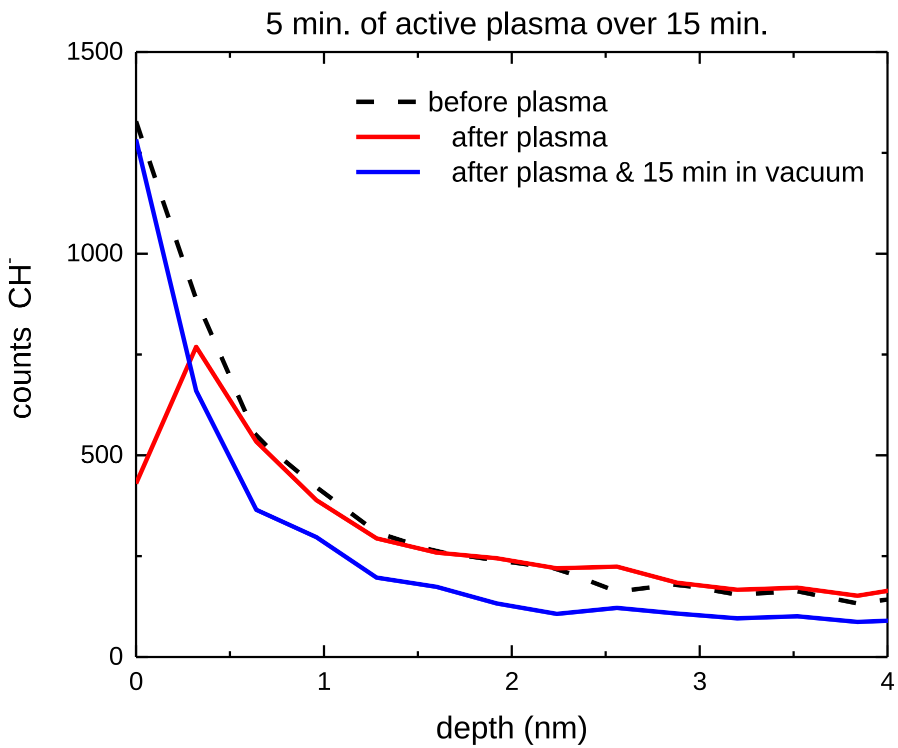
- **Hydrocarbons removed from top surface through oxidation and formation of volatile by-products such as**
  - H_2, H_2O, CO and CO_2
- **Residual gas analysis used to monitor plasma cleaning**
  - Depletion of surface hydrocarbons within 30-60 minutes per cell
  - Removes ~monolayers equivalent of hydrocarbons
  - Six cells of a cavity processed sequentially

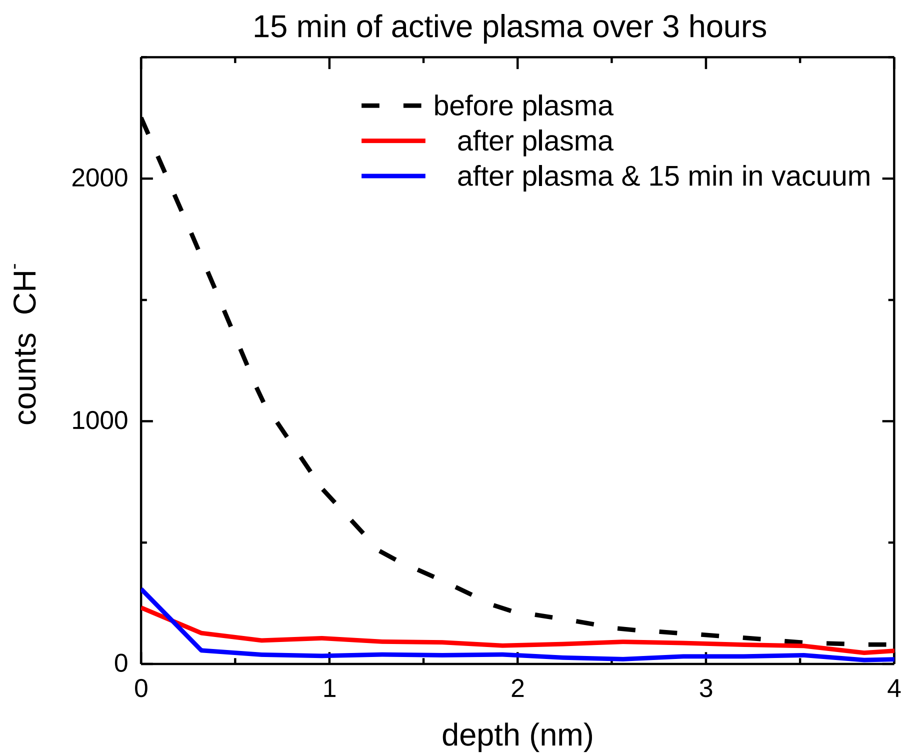




Evolution of Nb surface after plasma cleaning

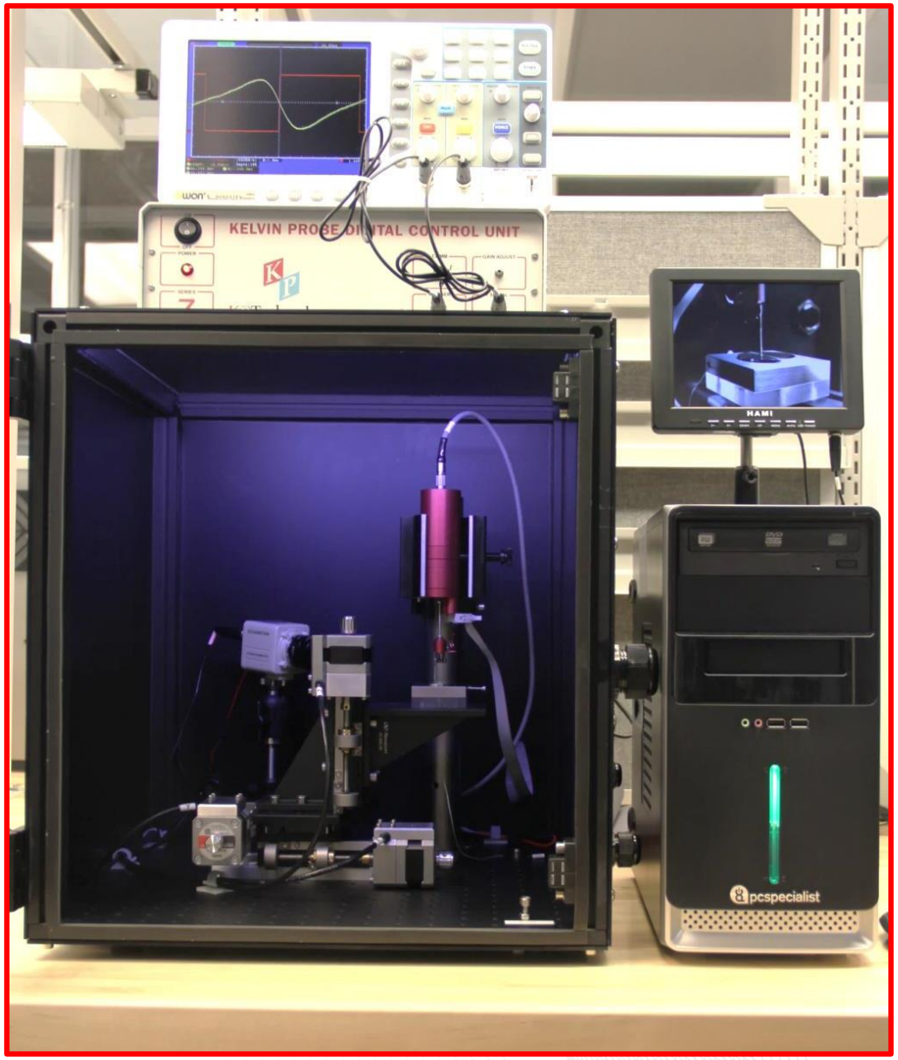
- **Hydrocarbons concentrated near the top surface of Nb samples initially**
- **After short plasma processing time (left figure)**
  - Top surface layer is depleted of hydrocarbons
  - Near surface hydrocarbons migrate to the top surface over time
- **After longer plasma processing time (right figure)**
  - Top surface and near surface depleted of hydrocarbons
  - Multiple plasma cycles efficient to remove hydrocarbons at top and near surface





Plasma processing increases work function*

- **Scanning Kelvin Probe instrument used to measure work function**
  - Contact potential difference between reference probe and sample
  - Nb samples ϕ=4.7 eV initially
- **Plasma processing technique developed at SNS**
  - Removes Hydrocarbons
  - Systematically improves the work function
  - 0.8 eV increase measured
    - ~17% increase in ϕ can lead to
    - ~25% increase in Eacc



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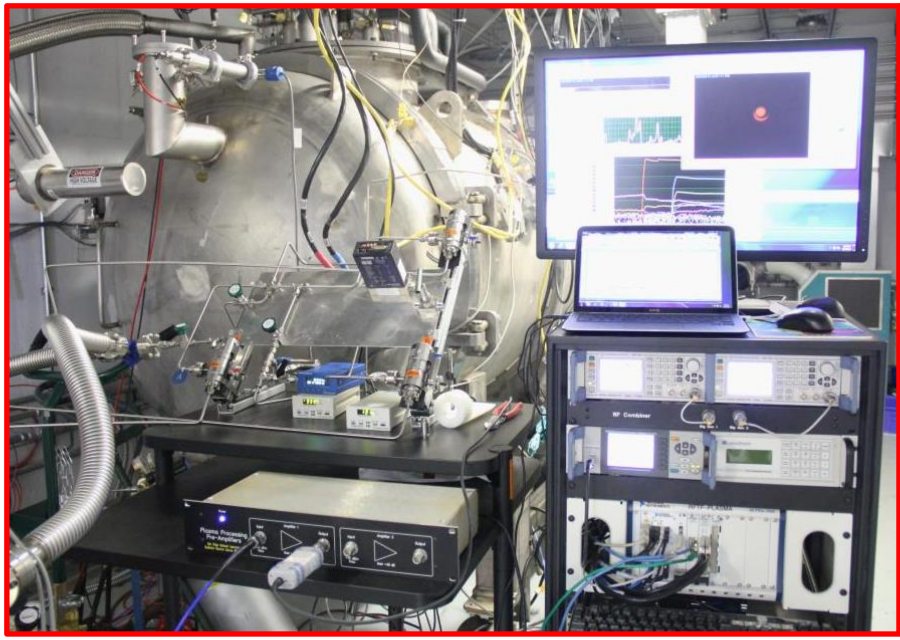
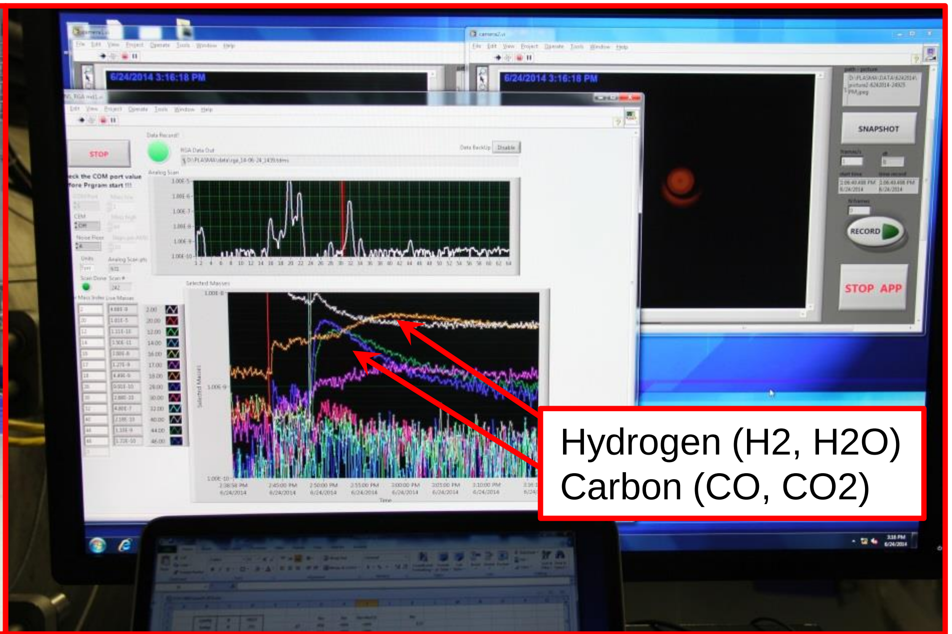
*P. V. Tyagi, M. Doleans et al. Applied Surface Science 369 (2016) 29–35

PLASMA PROCESSING OF TWO CAVITIES IN HTA

In-situ plasma processing of cavity in HTA leads to performance improvement

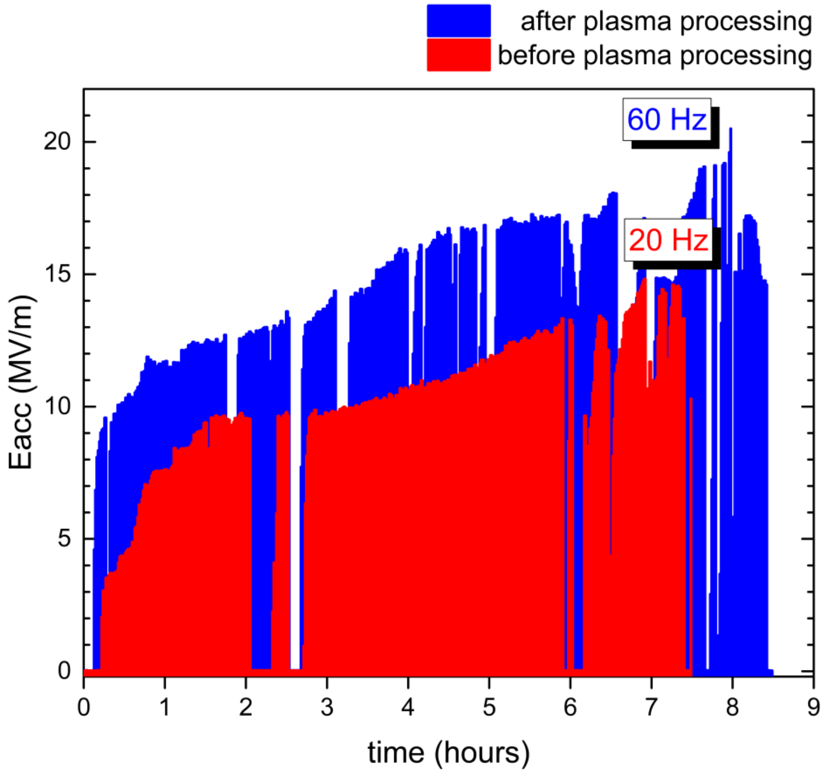
- **Two spare cavities were dressed with helium vessel and prepared in cleanroom (HB59 and HB52 cavities)**
- **HB59 and HB52 cavities were tested in HTA before and after plasma processing**
- **In-situ plasma processing for each cavity was done in HTA at room-temperature between cold-tests**

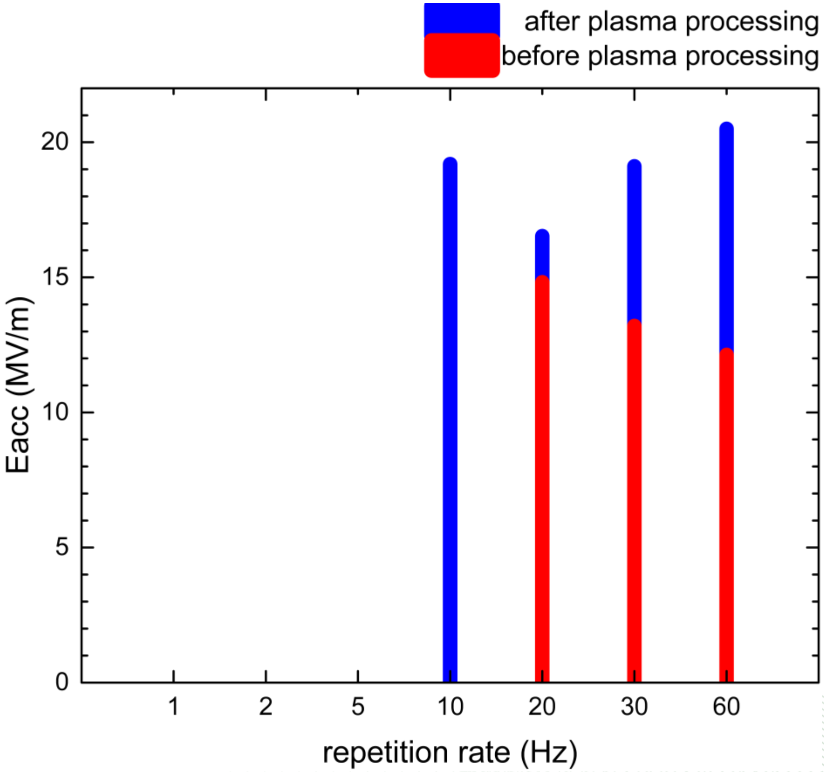




Plasma processing improves HB59 performance

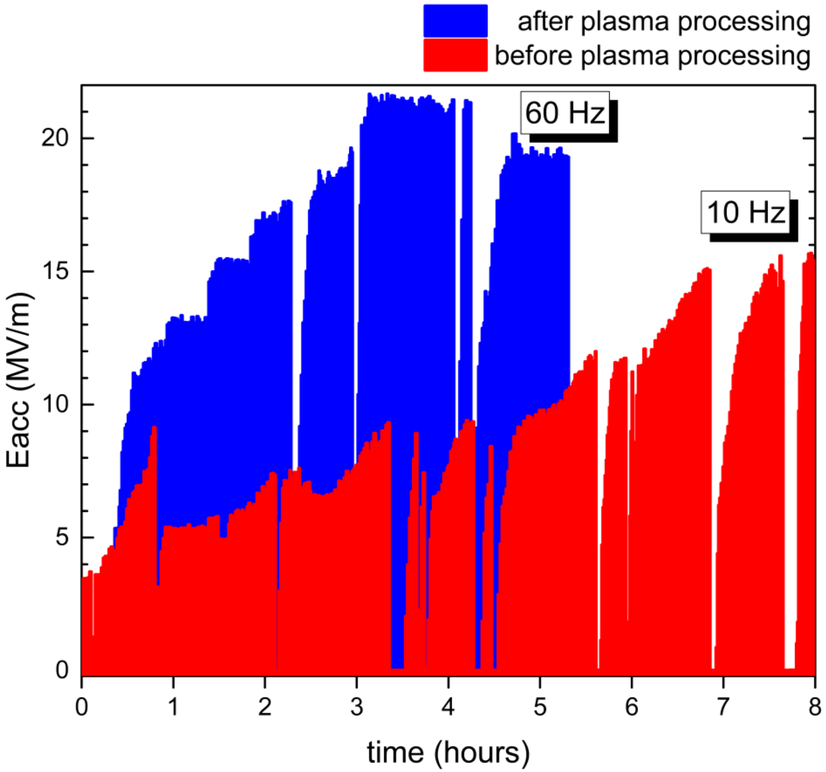
- **Before plasma processing**
  - Frequent trips associated with vacuum activity and temperature increase during RF conditioning
  - Reached 15.2 MV/m at 20 Hz repetition rate
- **After plasma processing**
  - Easier RF conditioning
  - Reached 20.5 MV/m at 60 Hz repetition rate

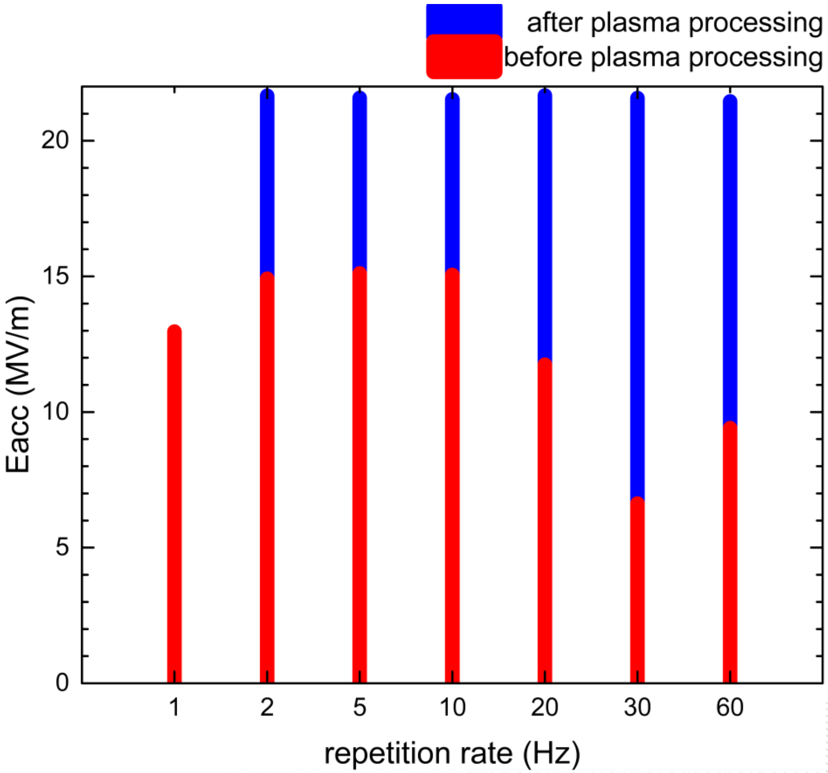




Plasma processing improves HB52 performance

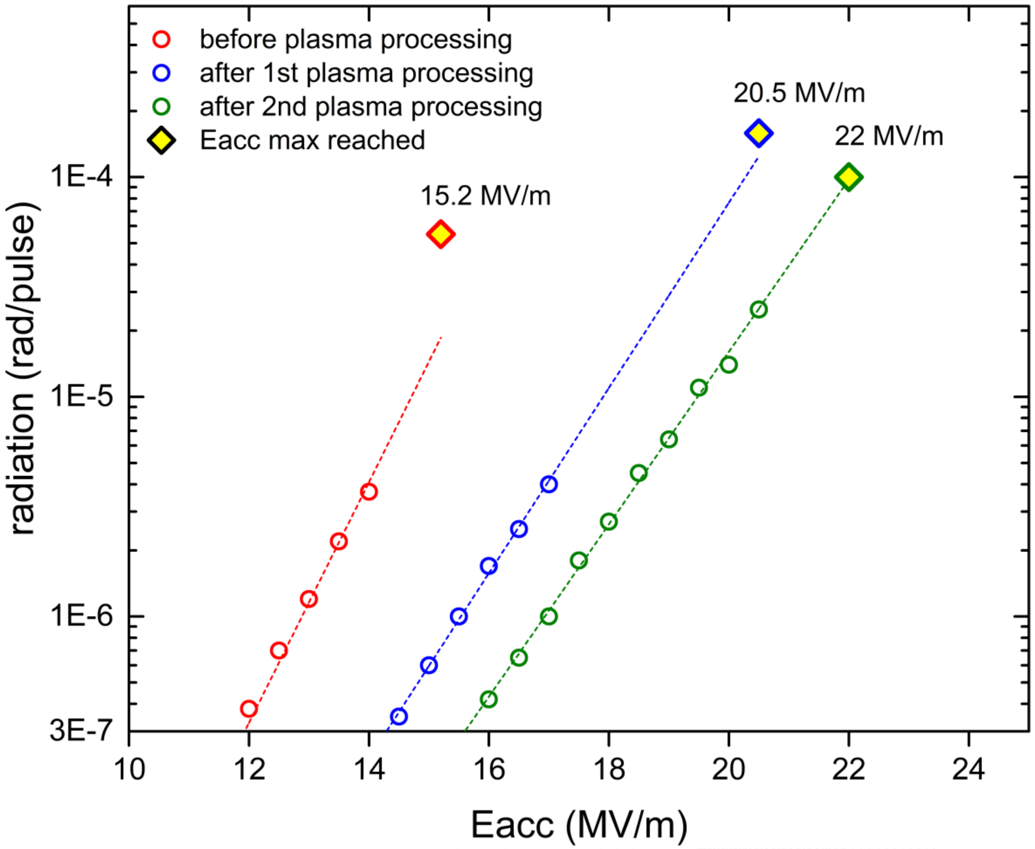
- **Before plasma processing**
  - Frequent trips associated with vacuum activity and temperature increase during RF conditioning
  - Reached 15 MV/m at 10 Hz repetition rate
- **After plasma processing**
  - Easier RF conditioning
  - Reached 21.5 MV/m at 60 Hz repetition rate





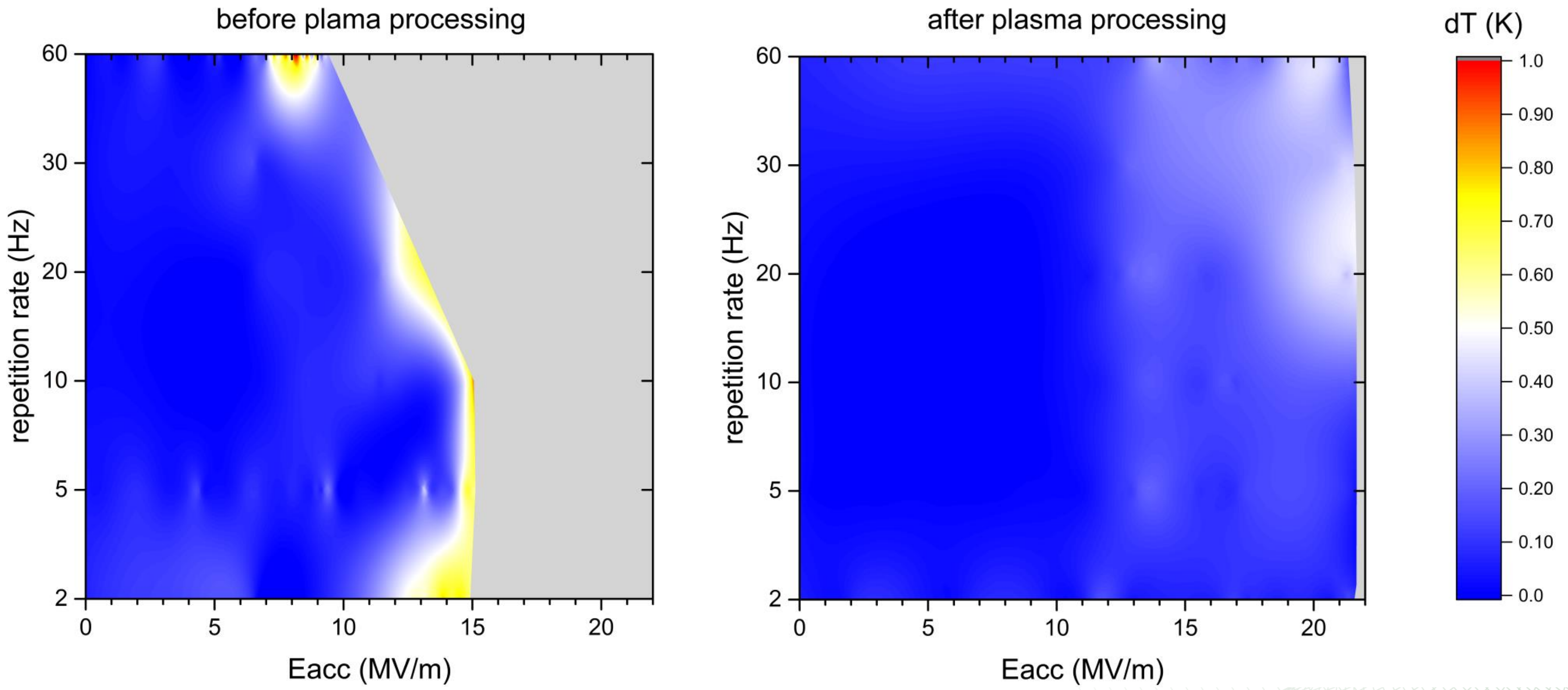
Plasma processing reduces field emission

- **HB59 cavity plasma processed twice in HTA**
- **Radiation associated to FE measured during cold-tests**
- **Field emission onset increased**
  - ~20% increase after first plasma processing
  - ~30% increase after second plasma processing
  - Reasonable agreement with expectation from surface studies
- **Further improvement after second plasma processing may be linked to further depletion of hydrocarbon levels below top surface**



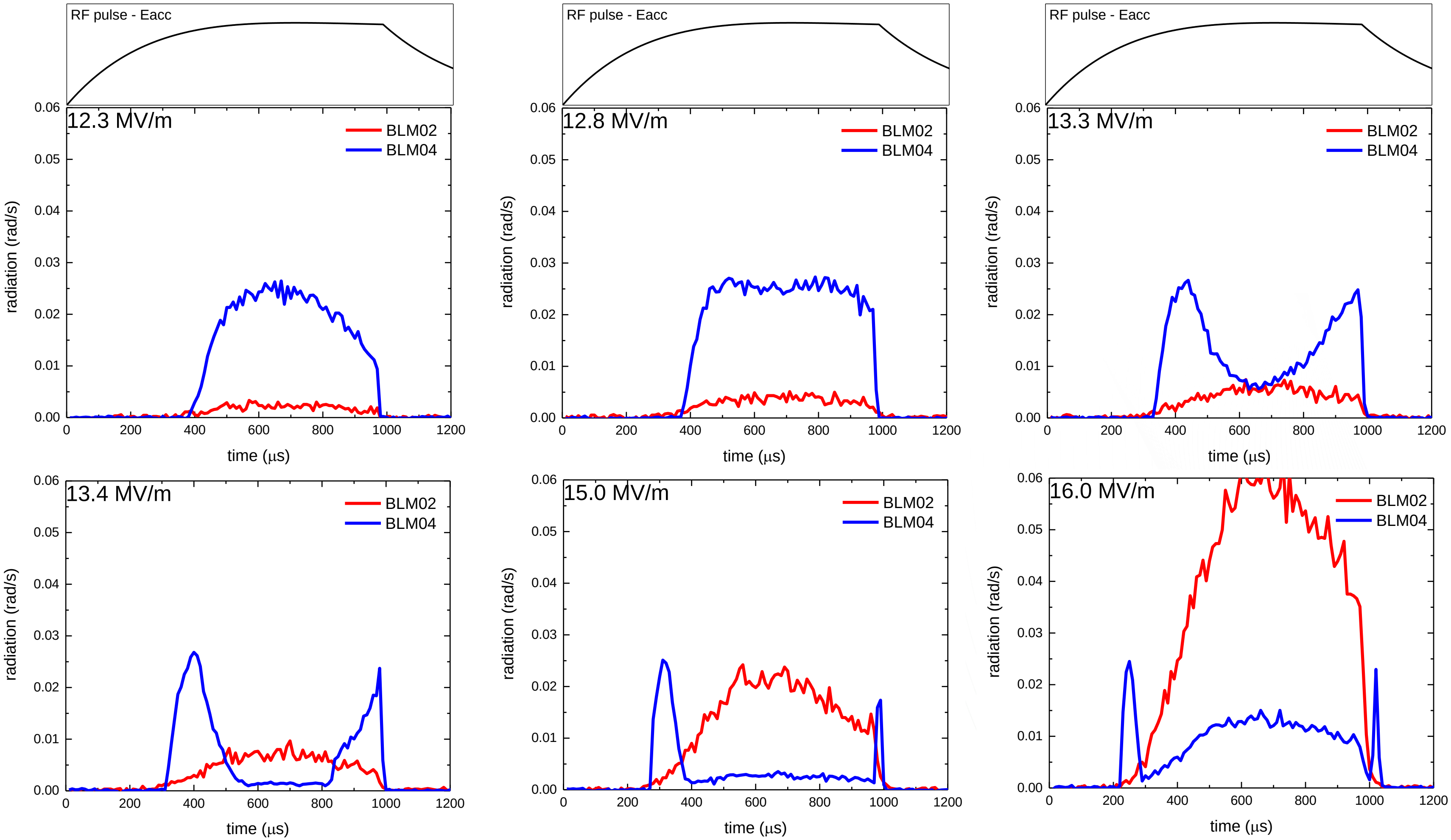
Plasma processing might also reduce SEY

- **SNS HB cavities show multipacting activity between 9 and 14 MV/m**
  – Normally reduces after RF conditioning and cavity performance then limited by FE
  – Some cavities have severe multipacting which limit their performance
- **Cavity HB52 performance initially limited by multipacting**
  – Severity of multipacting significantly reduced after plasma processing
    - Reduction of SEY possibly from reduction of escape probability and/or removal of hydrocarbons with large intrinsic SEY



Multipacting and FE radiation

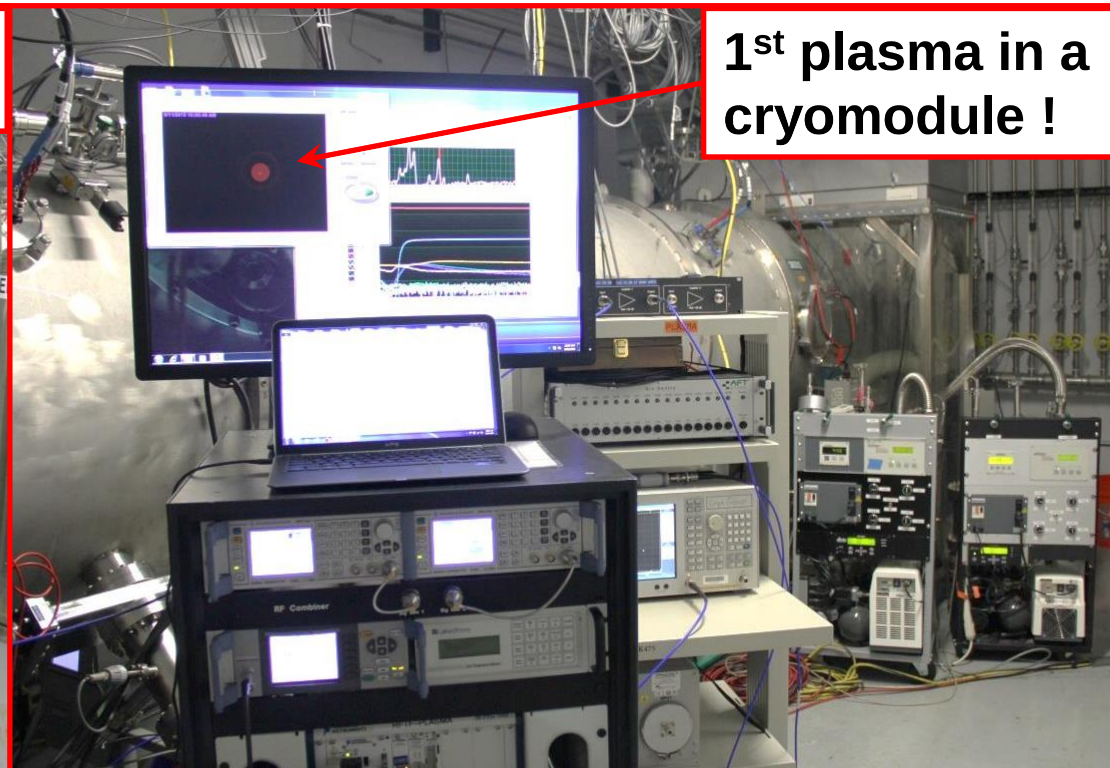
- **Radiation monitors useful diagnostics to assess cavity performance**
  - Waveform during RF pulse informs about type of electron activity
  - Integrated value per pulse simple value of merit for electron activity
  - Radiation associated to multipacting tend to saturate after multipacting band is passed
  - Radiation associated to FE follow the electric field waveform and keep increasing



PLASMA PROCESSING OF AN OFFLINE CRYOMODULE

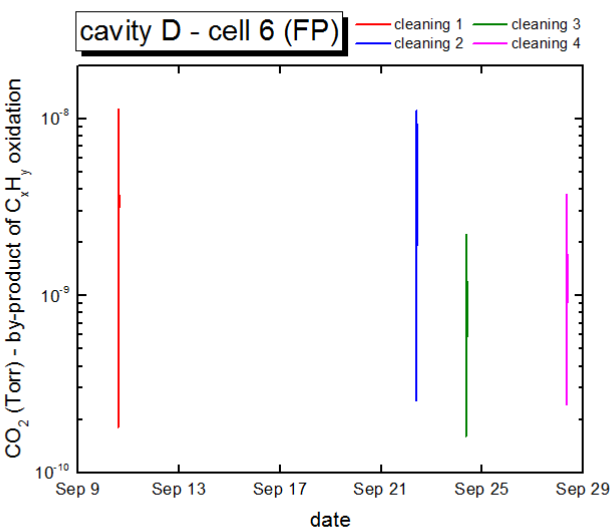
1st Plasma processing of a cryomodule

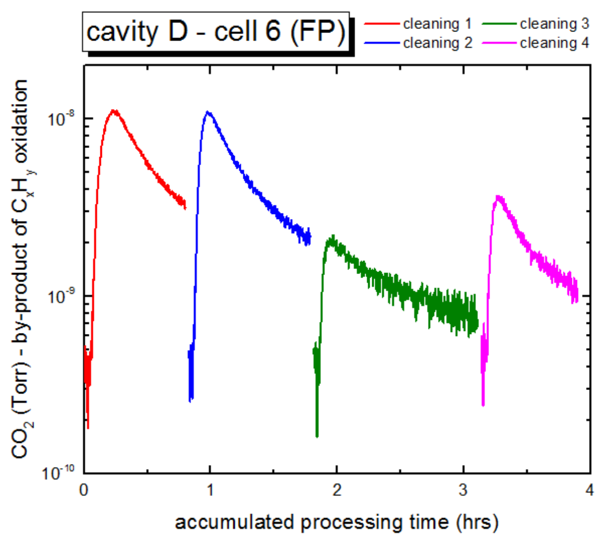
- **Offline high-beta cryomodule in RFTF test Cave (CM00012)**
- **Main plasma processing hardware for cryomodule**
  - Plasma process gas cart
  - Plasma RF cart
- **Plasma processing technique successfully applied to 4 cavities of cryomodule**

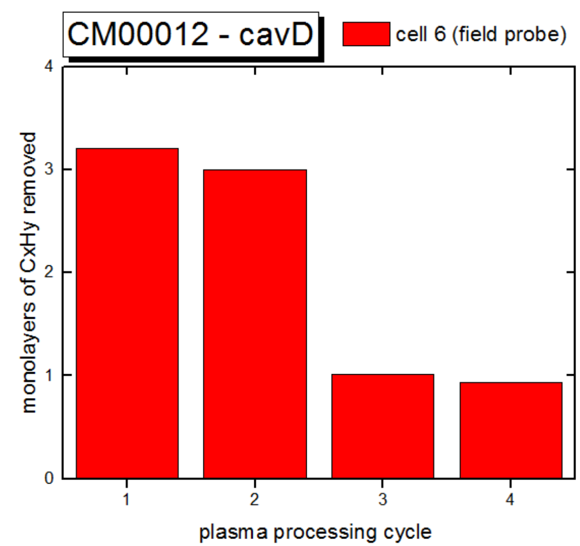


Hydrocarbons in CM00012 cryomodule

- **Estimated amount of hydrocarbons removed**
  - Done by Integration of RGA signal from oxidation by-products such as CO_2
  - Few monolayers equivalent
- **Multiple cleaning cycles done over 2-3 weeks**
  - Used lessons learned from plasma processing of cavities in HTA
    - Possible resurgence of hydrocarbons at top surface after cleaning over time
    - Best cleaning obtained using multiple cycles

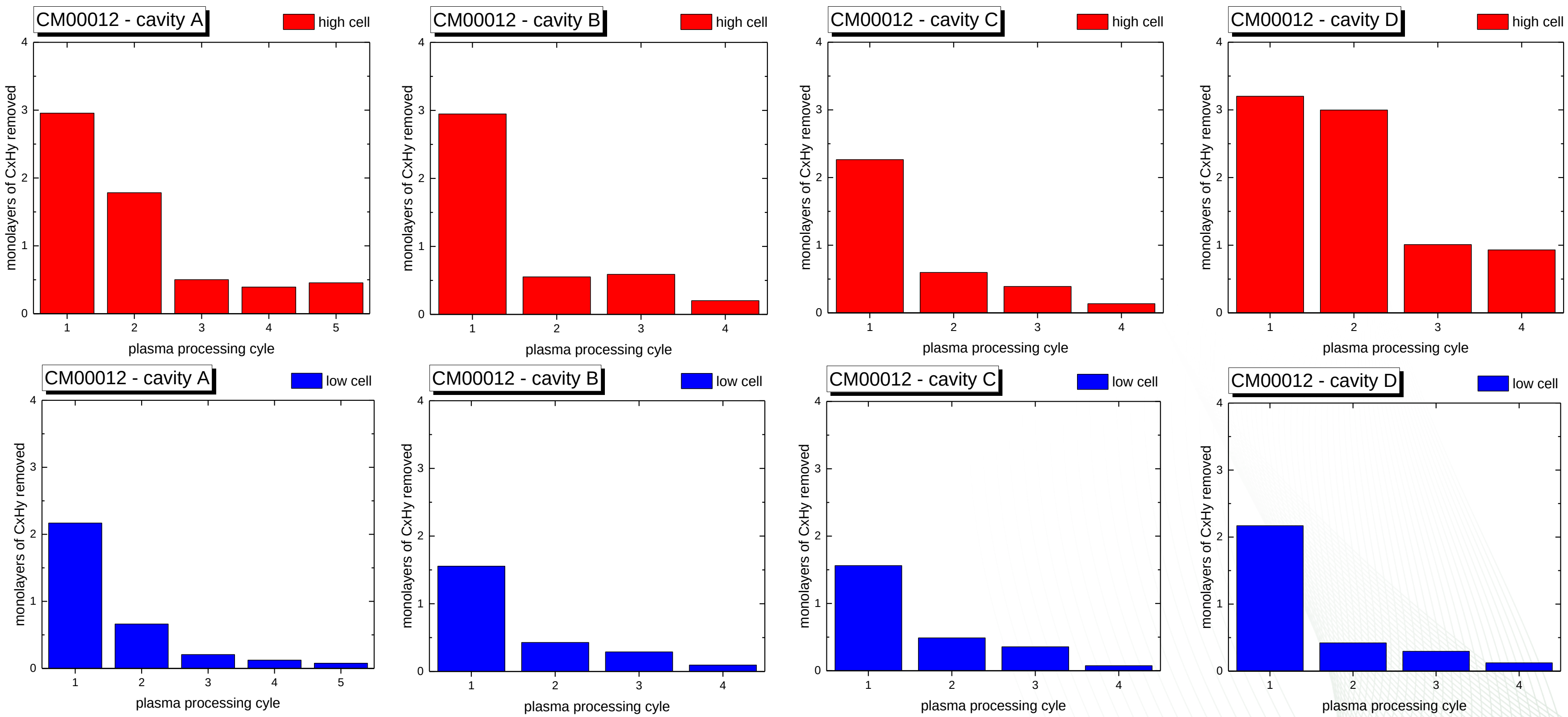






Plasma processing of CM00012 cryomodule

- **Removal of hydrocarbons from all 4 cavities (A, B, C, D)**
  - Systematic estimation of removed amount
- **Several monolayers equivalent removed from each cavity**
  - ~2/3 of cells cleaned adequately
  - ~1/3 cells could benefit from additional plasma cleaning



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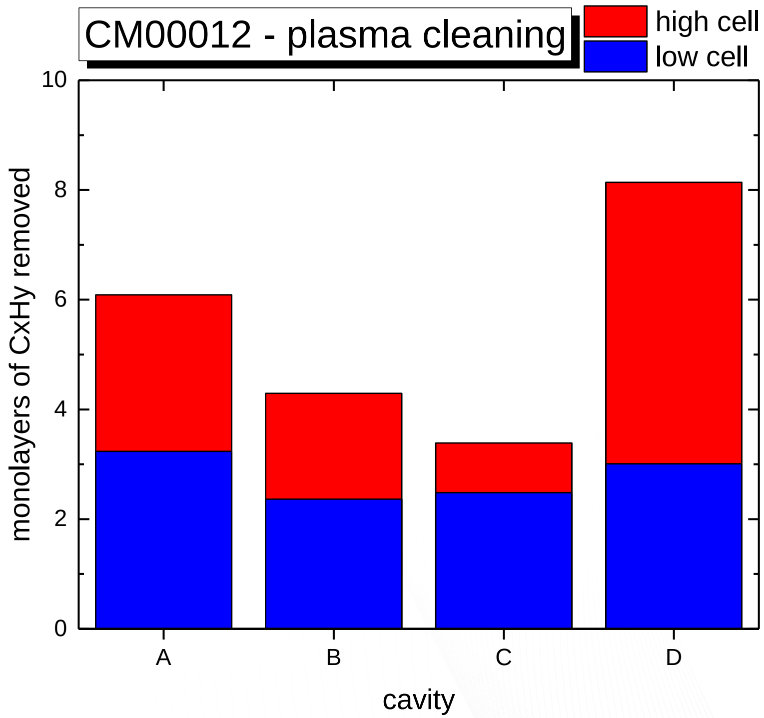
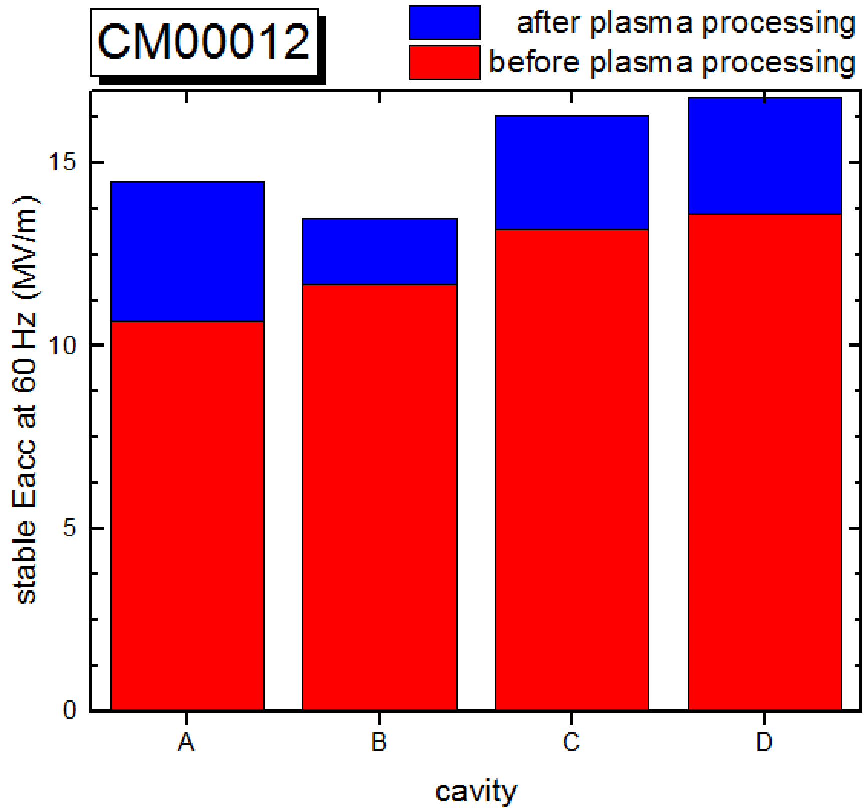
Total hydrocarbon removed from CM00012

- **End cells of cavities are found to be more contaminated**
- **Worse cells are at extremities of cryomodule**
- **Beneficial to spend more time plasma processing cells with largest contamination**
  – Lesson learned applied during cleaning of CM00023 in tunnel



Performance of CM00012 cryomodule improved after plasma processing

- **Stable accelerating gradient at 60 Hz improved for all 4 cavities**
- **Gradients improved by ~25%**
  - Avg. gradient 12.3 MV/m before plasma processing
  - Avg. gradient 15.3 MV/m after plasma processing
  - Cavity A improved by 35%
  - Cavity B improved by 15%
    - Initially limited by combination of multipacting and hot spot in end group
    - Plasma processing reduced severity of multipacting which helped improving performance



Ready to deploy plasma processing in linac tunnel

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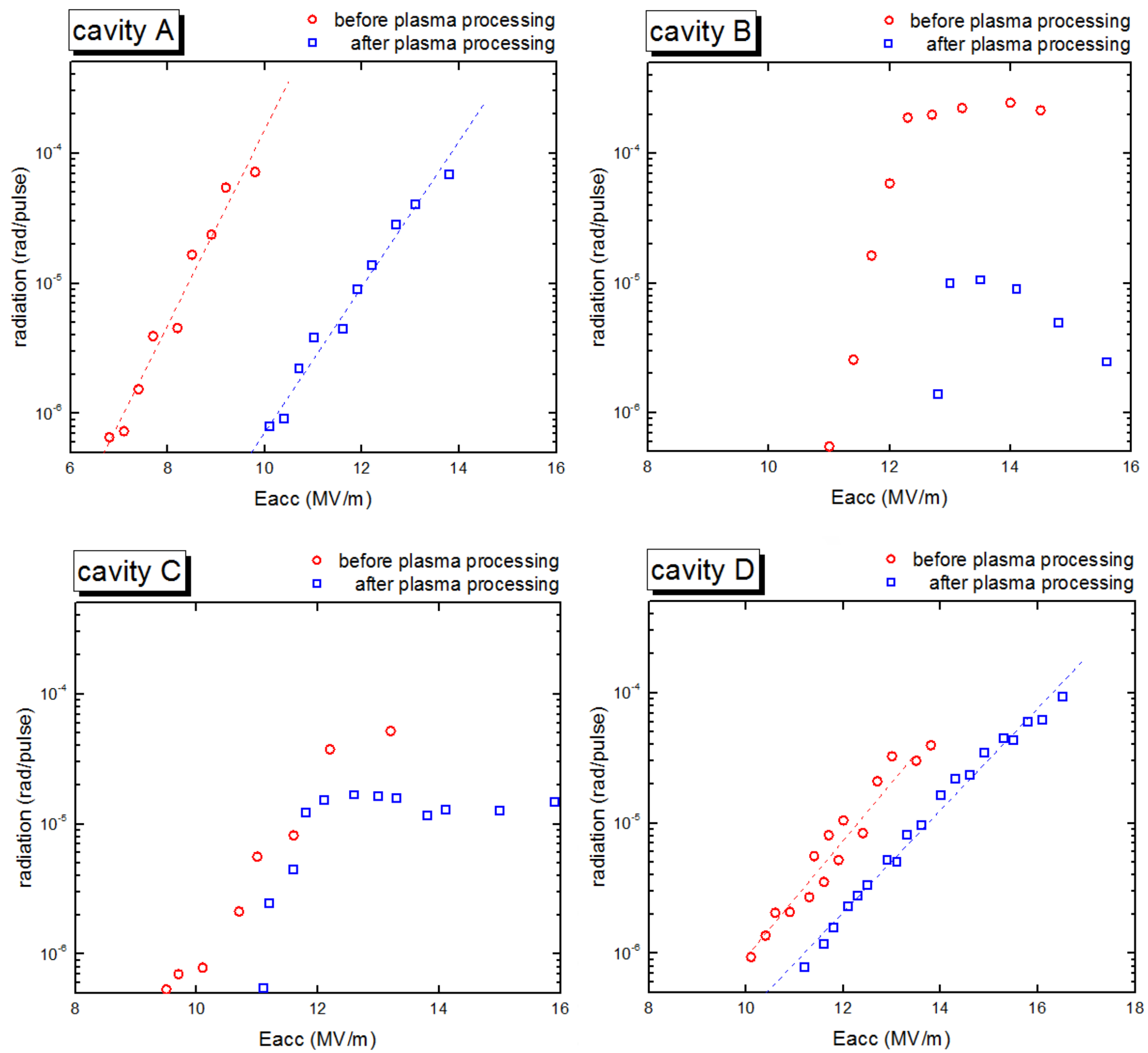
Radiation level reduced after plasma processing

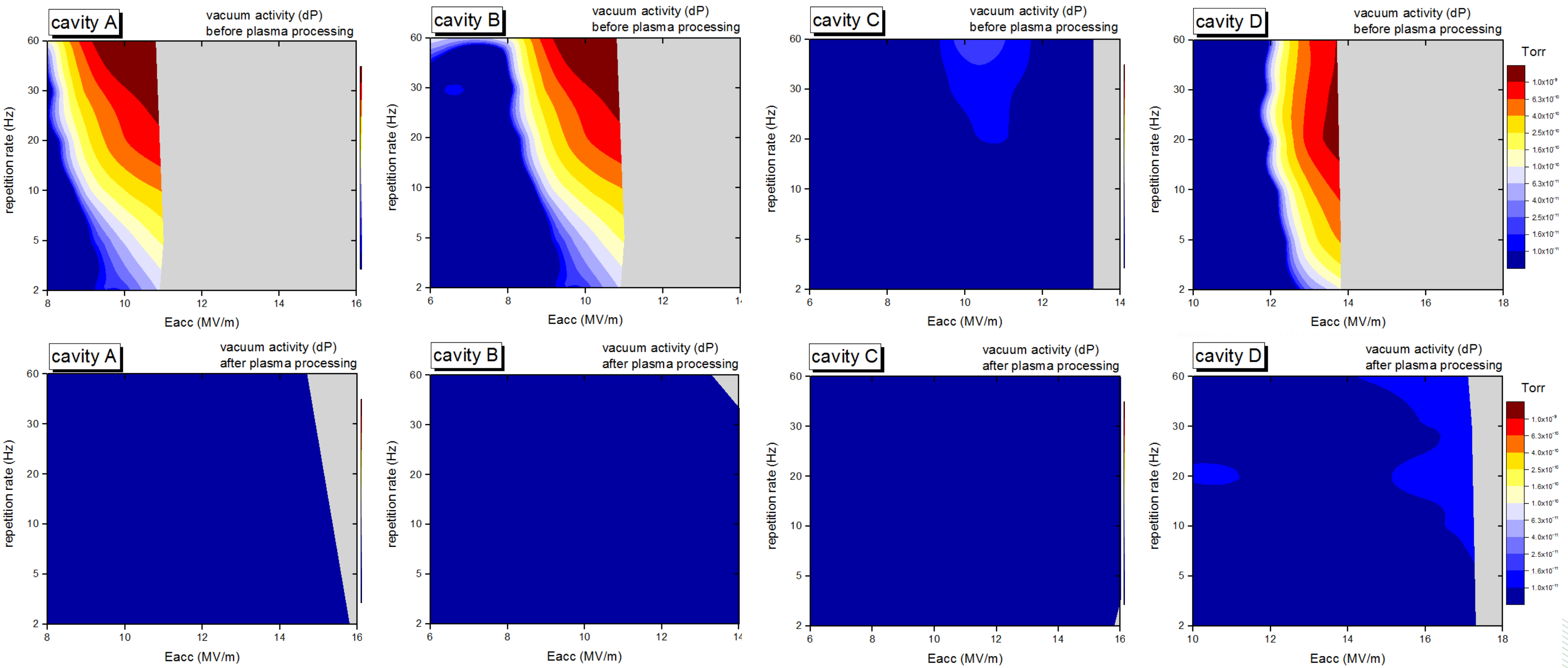
- **Cav A and D radiation dominated by field emission**
- **Cav B and C radiation dominated by multipacting**
- **Plasma processing reduced radiation level at given gradient in all cavities**



Vacuum improved after plasma processing

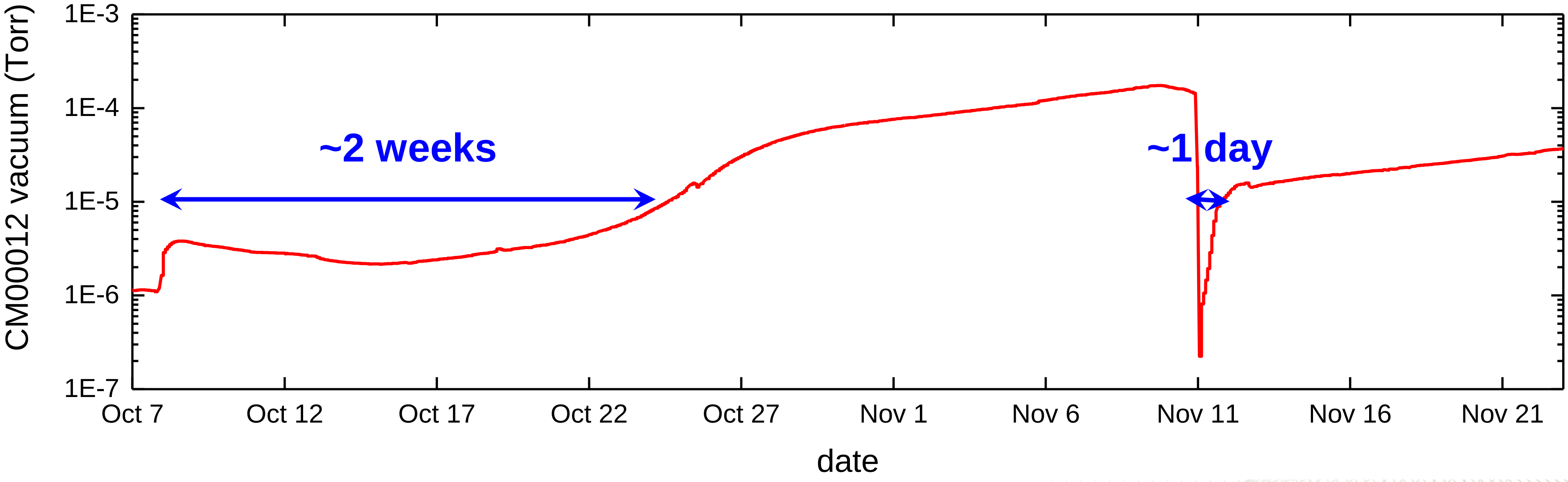
- **Plasma processing helps removing adsorbed gases at surface and deplete near surface of hydrogen**
- **Reduced vacuum activity during RF conditioning**
  - Eases conditioning (e.g. enables conditioning at higher rep. rate)
  - Minimize risk during conditioning (e.g. less risk of arcing)

Vacuum activity for cavities during rf conditioning
Before (top row) and after (bottom row) plasma processing



Evolution of cryomodule vacuum after plasma proc.

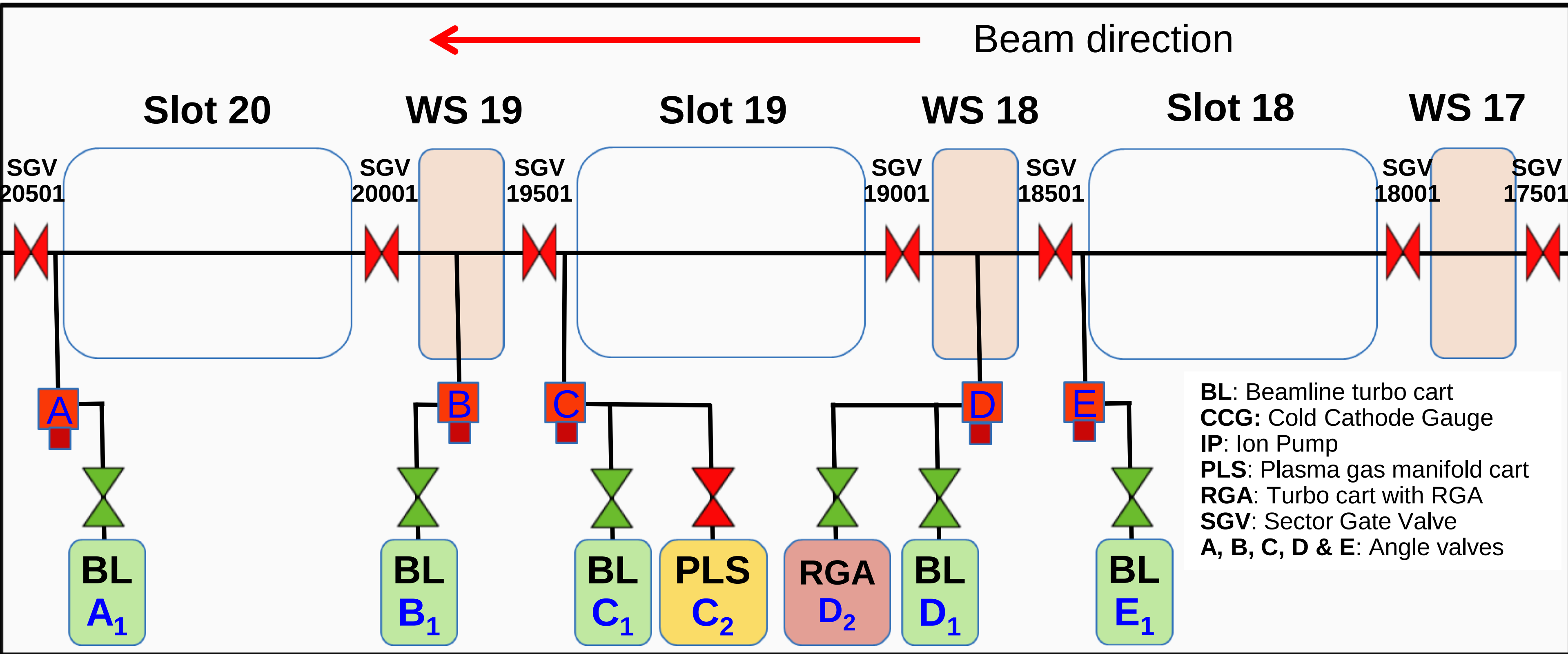
- **Cryomodule at room temp isolated from active pumping**
  – Beamline vacuum monitored using CCGs
  – Change in vacuum level related to H_2 outgassing
- **Took ~2 weeks to reach 10^{-5} Torr**
  – Plasma processing depleted top and near surface of hydrogen
    - Migration of hydrogen to the top surface took ~2 weeks at room temperature
  – Beamline pumped back down on Nov. 11 and isolated from pumping again
- **Took ~1 day to reach 10^{-5} Torr**
  – Much faster rise in pressure because hydrogen already migrated back to top and near surface

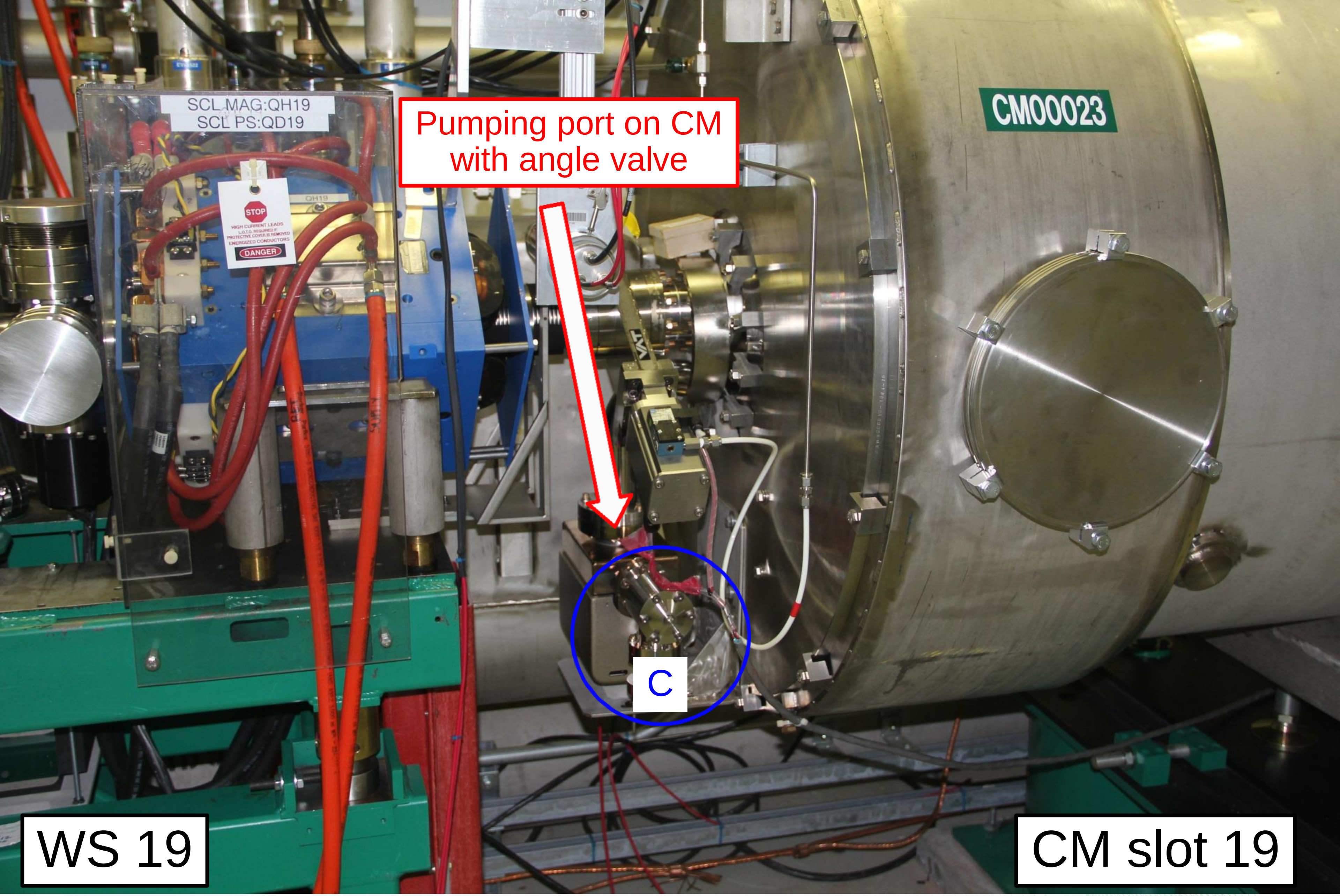


FIRST PLASMA PROCESSING OF CRYOMODULE IN SNS LINAC TUNNEL

Vacuum connections for plasma processing

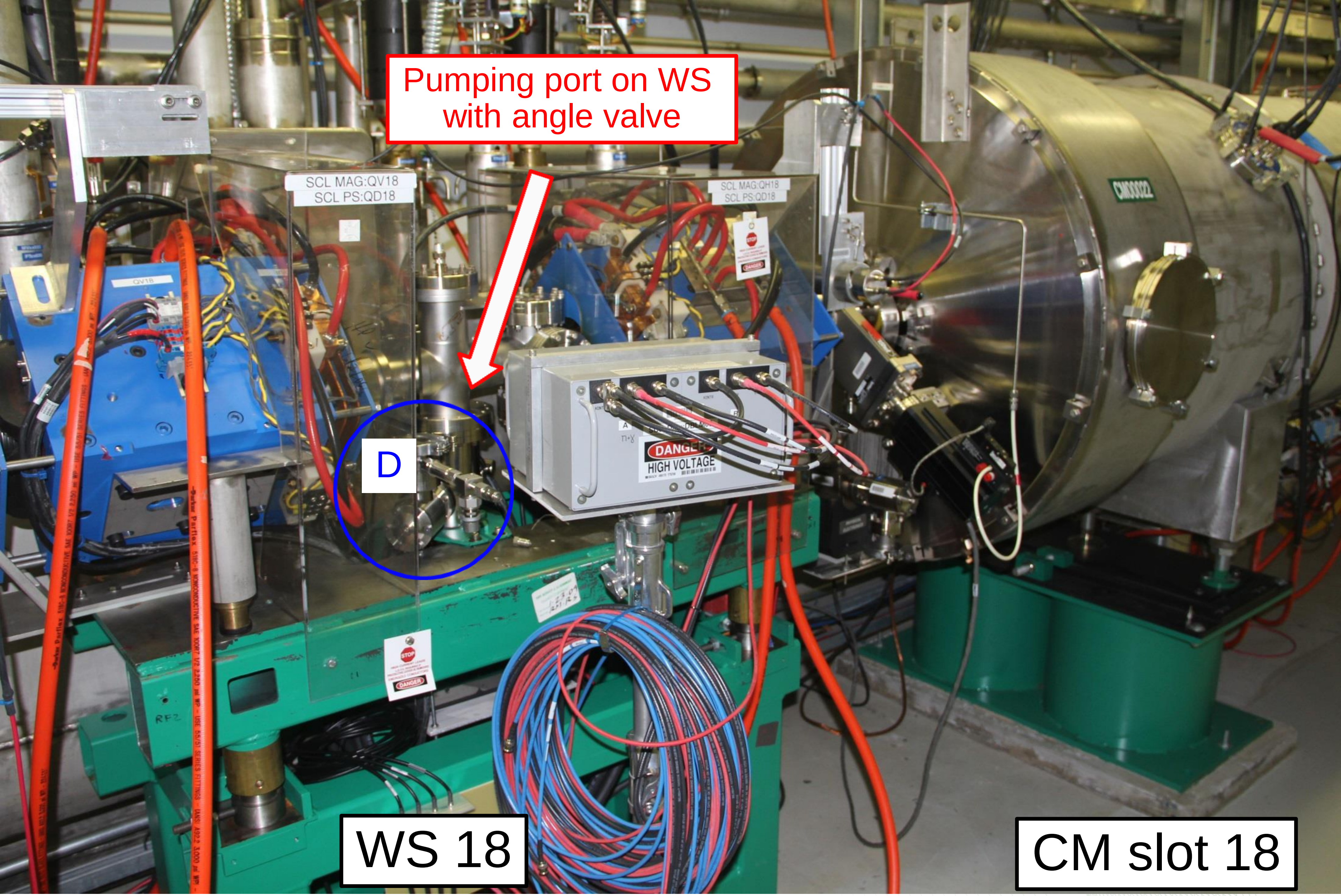
- **Warm up three cryomodules**
  - Slot 18, 19 and 20
- **Beamline turbo carts (turbo) on each cryomodule and warm sections**
- **Plasma gas manifold cart to inject gas cavity D side**
  - Connections at cryomodules using standard cleanroom and 3nm pore size particulate filter
  - Non-flammable gas cylinders and 16psig relief valve (< cryomodule relief pressure)
- **Pumping /monitoring of process gases**
  - Pirani gauges at connections inlet and outlet of cryomodule and RGA analysis





(serial number CM00023)

Downstream



Downstream

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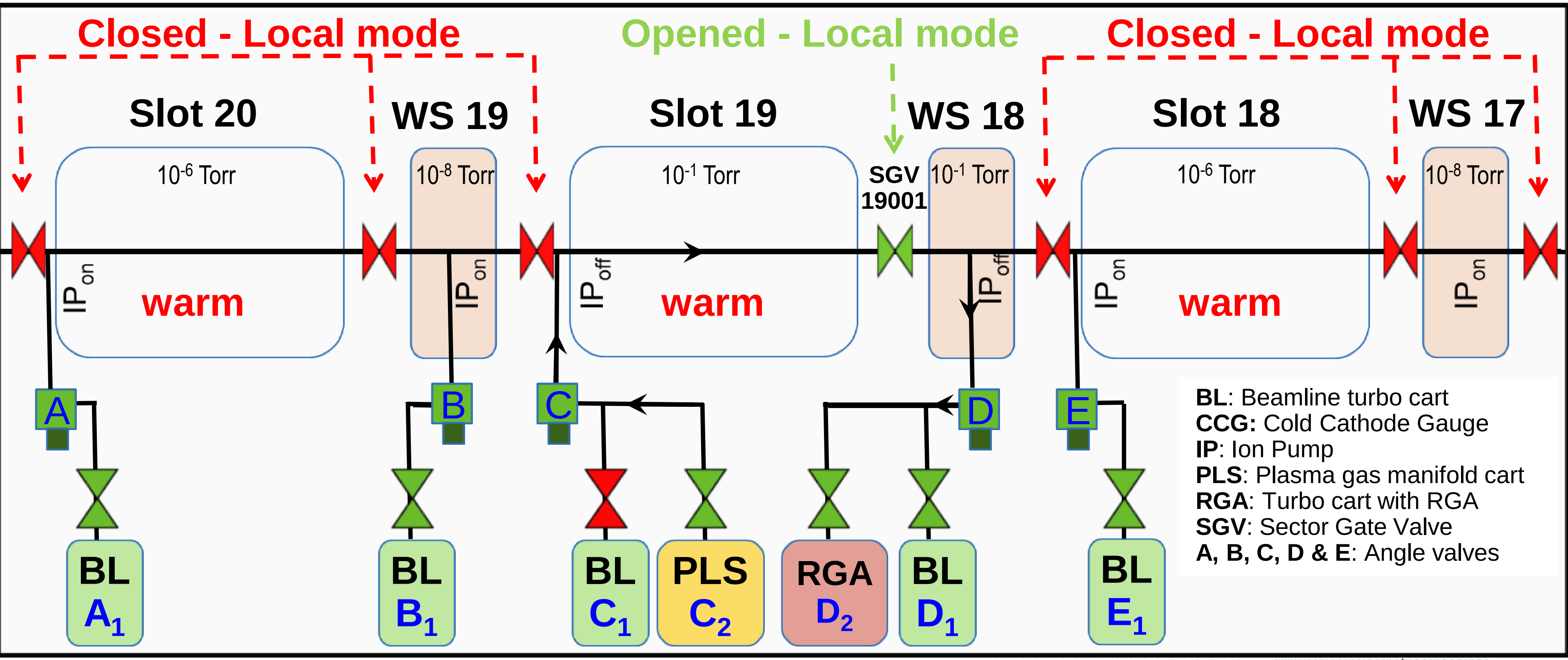
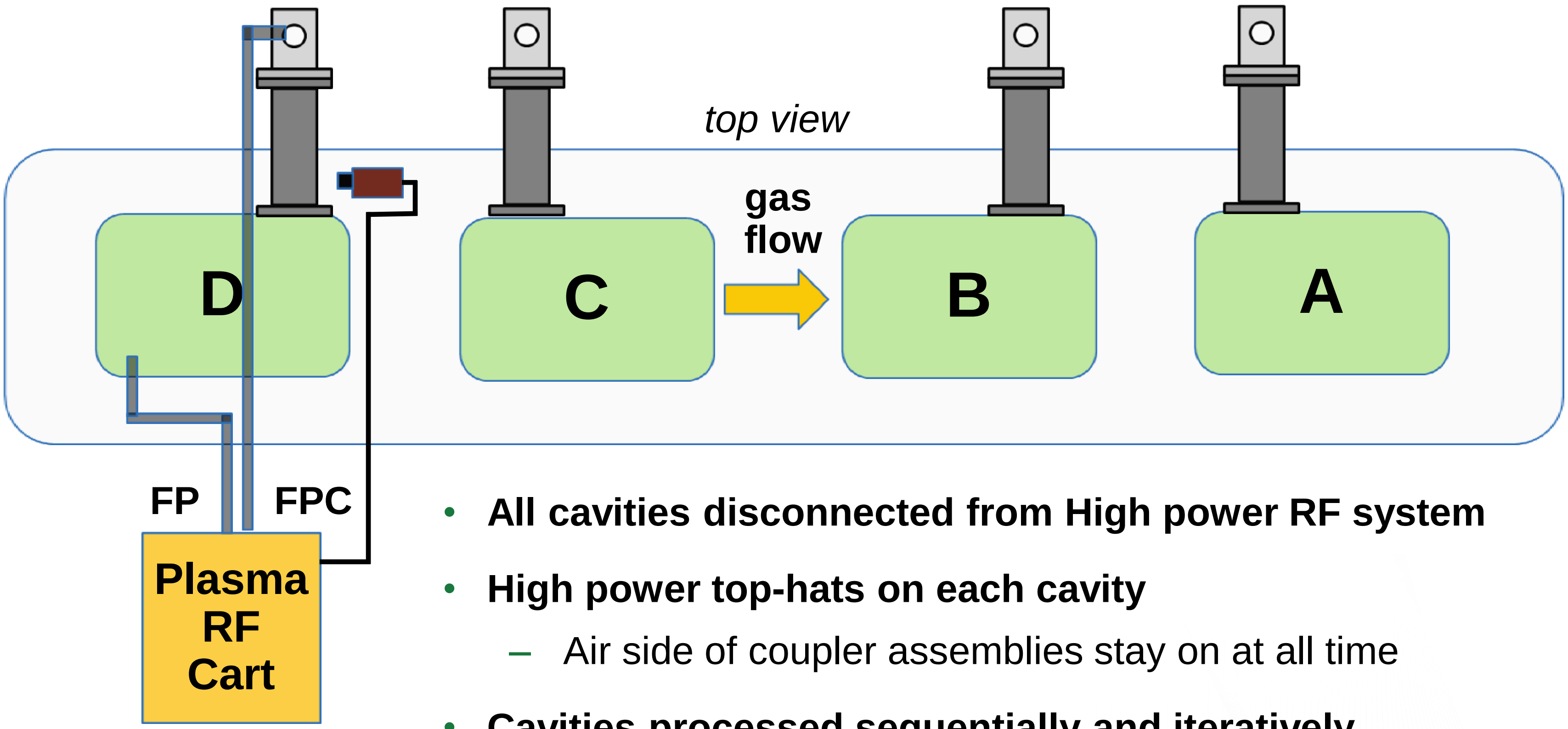
Vacuum configuration during plasma processing

- **Sections seeing process gas during processing: CM slot 19 and WS 18**
  - Ion pumps and CCGs off
- **Adjacent sections not seeing process gas**
  - 3 gate valves closed on each side to protect nearest cold cryomodules (slots 17 & 21)
    - Local mode only to avoid any accidental opening
  - IP on and extra pumping using beamline turbo carts (WS19 and CM slots 18 and 20)

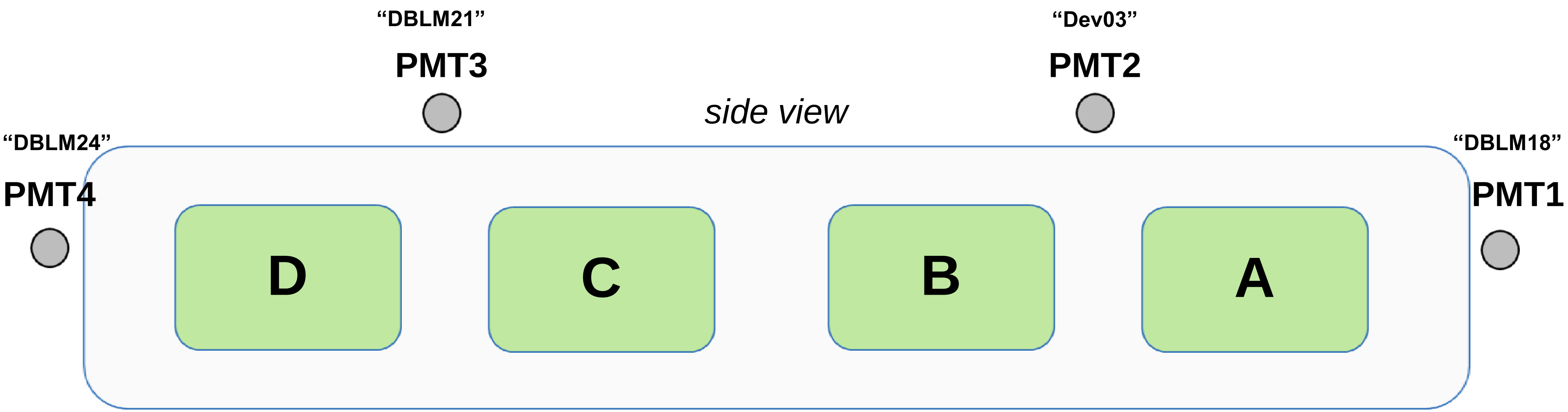


RF configuration during plasma processing



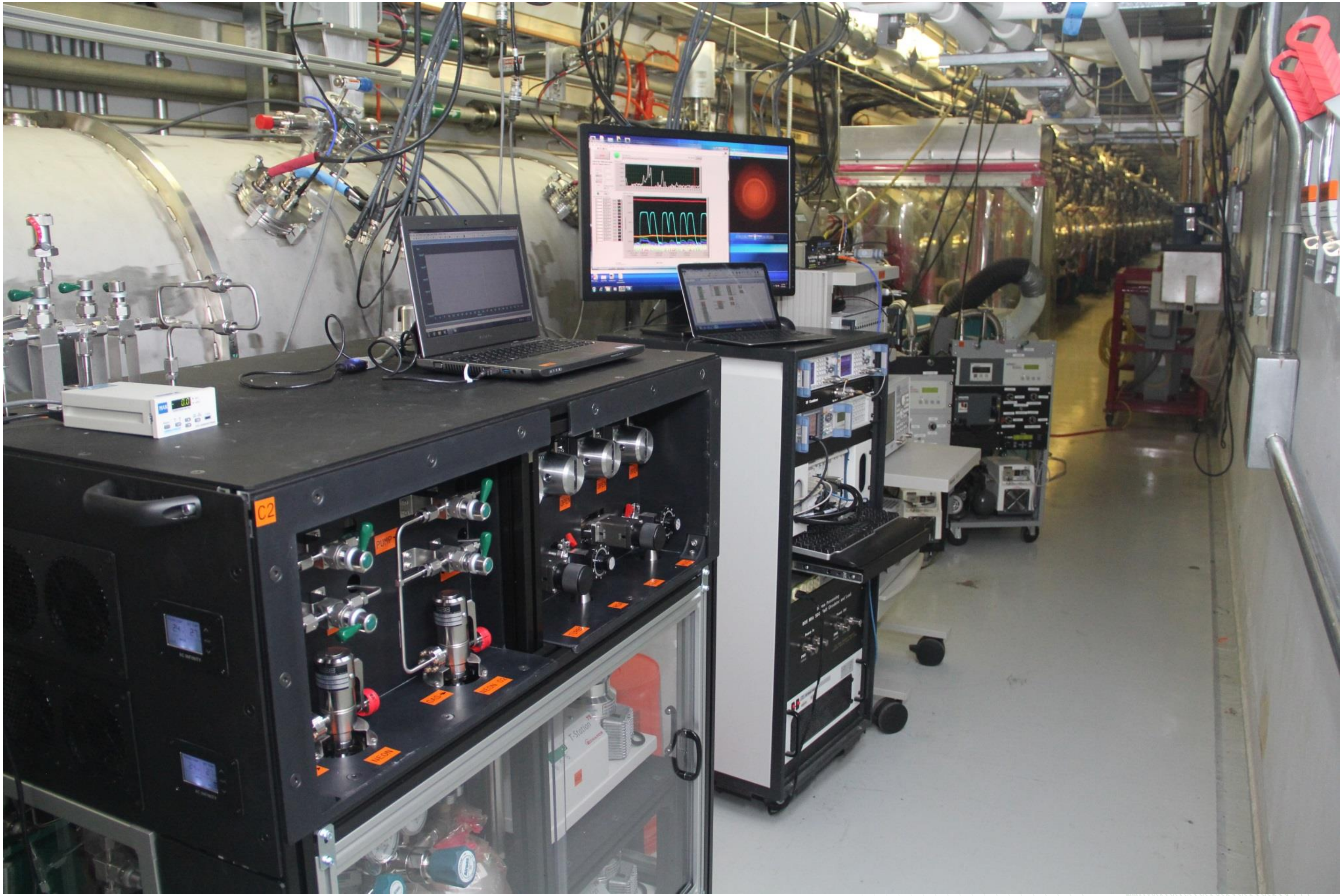
- **All cavities disconnected from High power RF system**
- **High power top-hats on each cavity**
  - Air side of coupler assemblies stay on at all time
- **Cavities processed sequentially and iteratively**
  - Following gas flow from cavity D to A
- **Cavity being plasma processed**
  - FPC and field probe connected to RF cart
  - Camera monitors any discharge in FPC

Radiation monitors for evaluating performance before/after plasma processing



- **Radiation waveforms during cavity operation at cold**
  - Helpful for rf conditioning
  - Relevant diagnostic to quantify and understand cavity performance
- **PMTs have better sensitivity for detection of X-rays from cavity operation**
  - 4 PMTs temporarily installed in the tunnel at slot 19
  - Used to evaluate radiation level for each cavity before and after plasma processing

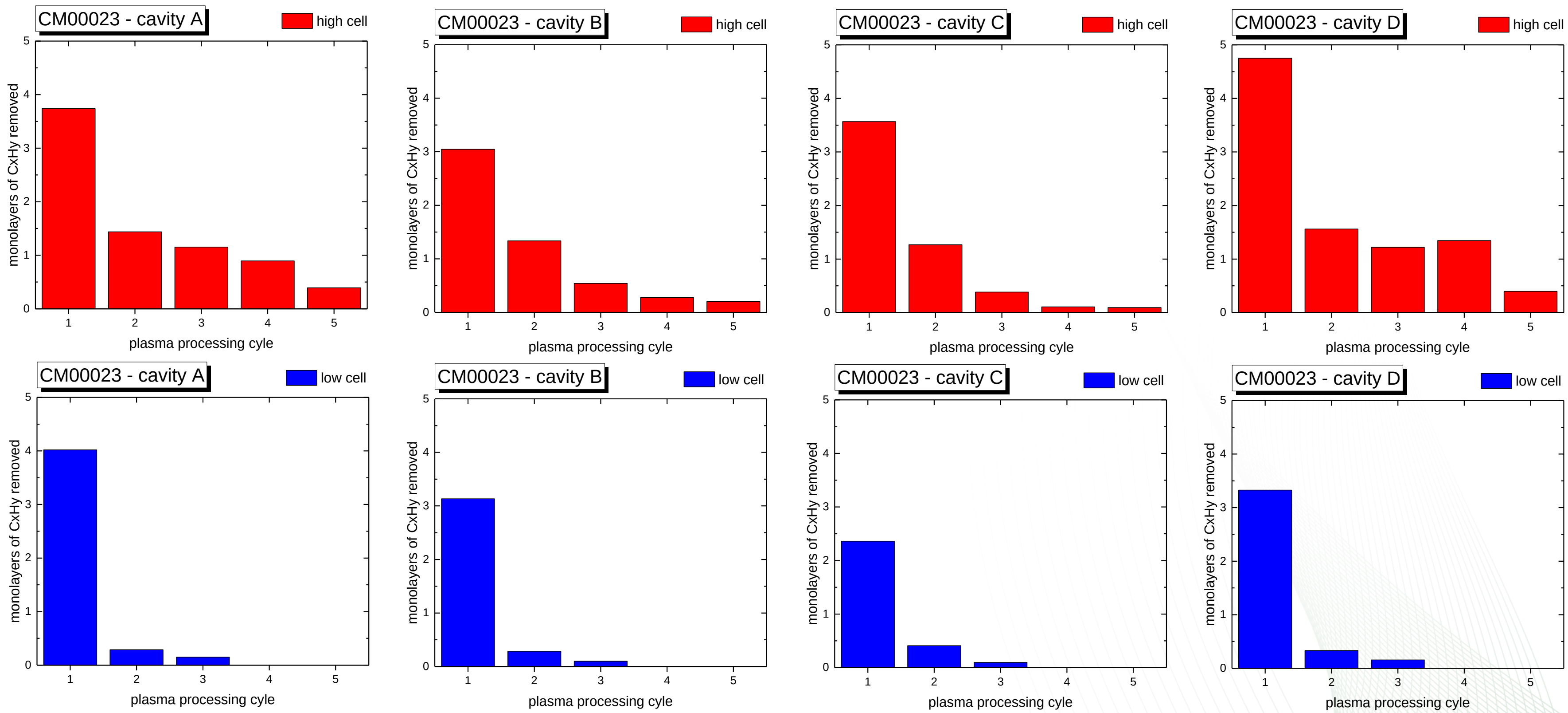
Plasma processing hardware adjacent to CM slot 19



Applied ALARA: Radiation survey indicated best location for minimum radiation exposure during work (<1 mrem/hr)

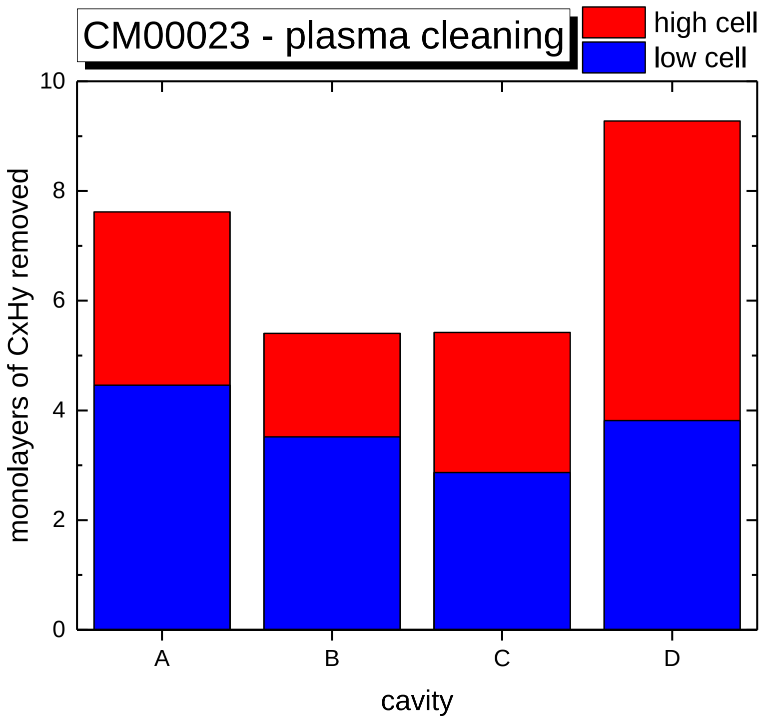
Plasma processing of CM00023 cryomodule

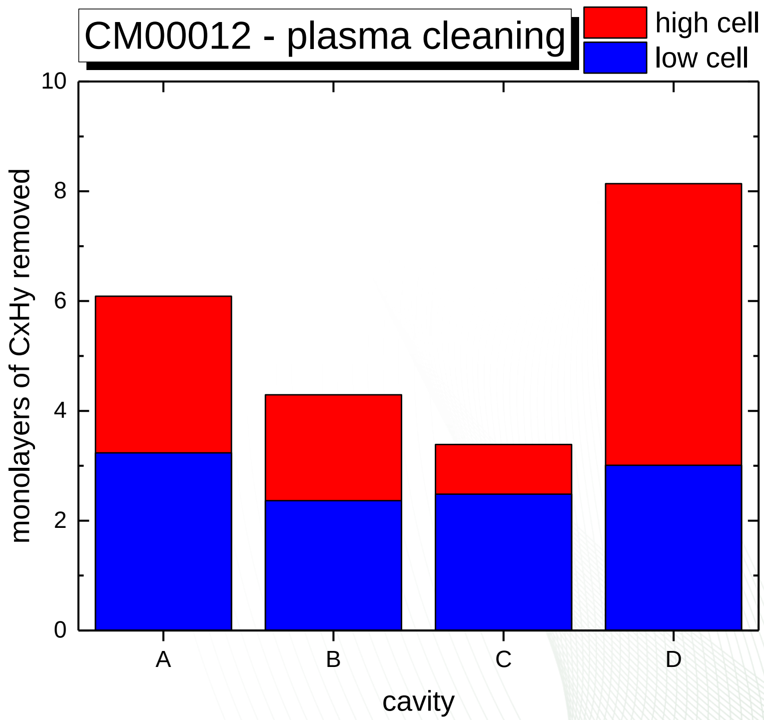
- **Removal of hydrocarbons from all 4 cavities (A, B, C, D)**
  - Blind tunning, RF probe signal useful to confirm location of plasma
- **Several monolayers equivalent removed from each cavity**
  - Contamination pattern similar to offline cryomodule
  - Used lesson learned and plasma processed cavity extremities more



First in-situ plasma cleaning of hydrocarbons in linac tunnel achieved!

- **Similar contamination pattern as offline cryomodule**
- **Multiple RF carts would allow to plasma process cavities simultaneously**
  - Reduce amount of time needed for plasma processing
    - Further improve on ALARA (less time in the tunnel)
    - Facilitate coordination with other work in tunnel during maintenance period





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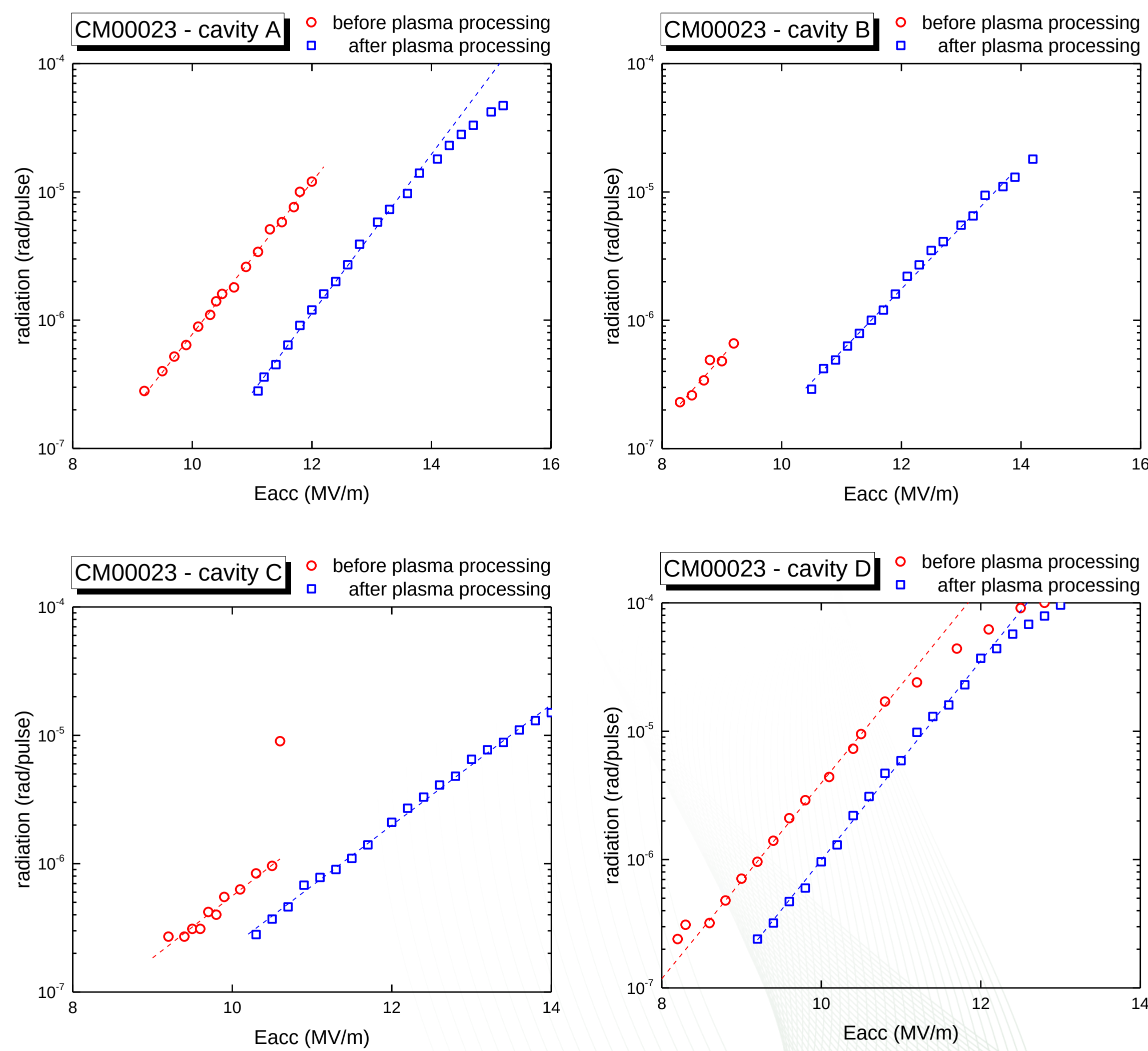
Radiation level reduced after plasma processing

- **Plasma processing reduced radiation level at given gradient in all cavities**
- **Cavities more stable even at higher radiation level after plasma processing**



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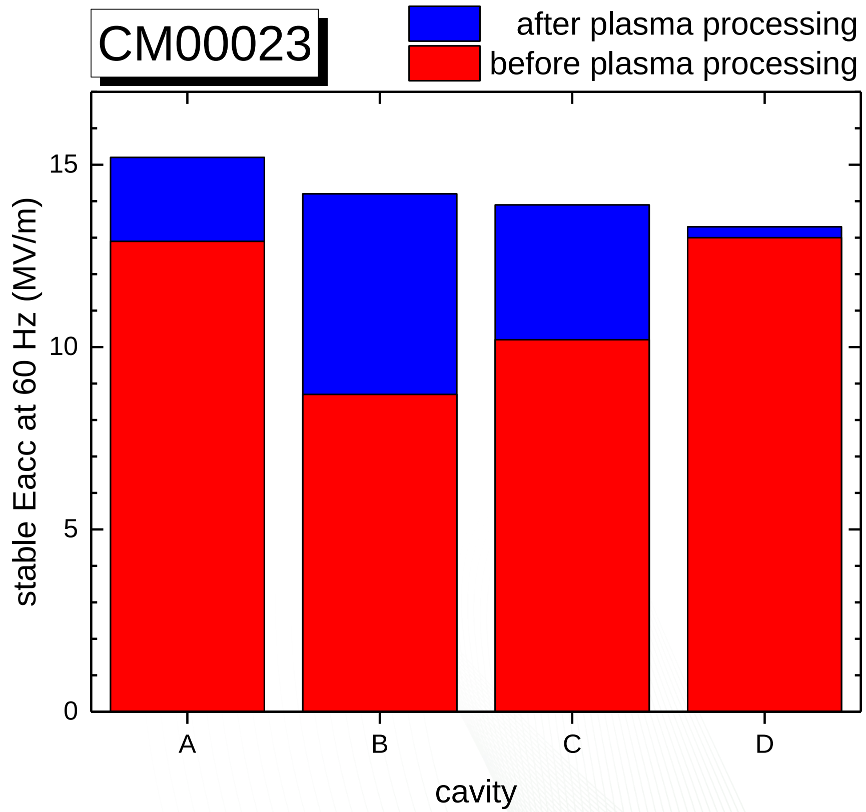
Performance of CM00023 cryomodule improved after plasma processing

- **Stable accelerating gradient at 60 Hz improved for all 4 cavities**
- **Gradients improved by ~25%**
  - Avg. gradient 11.2 MV/m before plasma processing
  - Avg. gradient 14.2 MV/m after plasma processing
  - Cavity B improved by 60%
  - Cavity D barely improved
    - Unclear why (Ion pump burst at restart?)
    - Strong emitter affects all cavities



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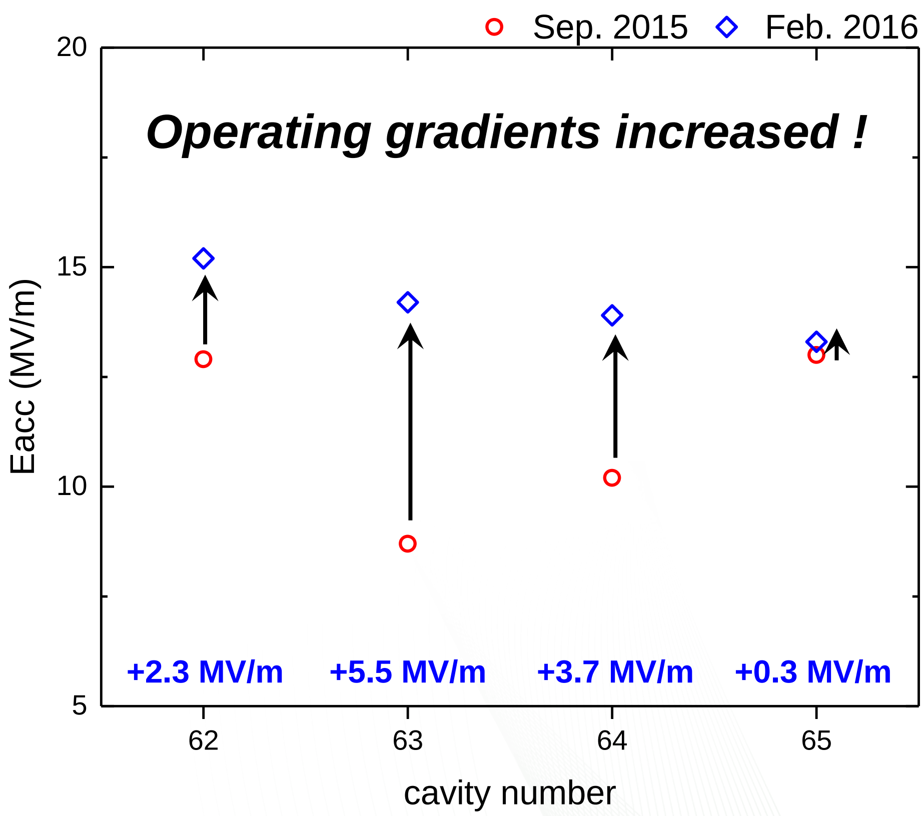
First plasma processing of a cryomodule in the SNS linac tunnel is a success !

- **Plasma processed cryomodule slot 19 (CM00023)**
- **Average accelerating gradient**
  - 11.2 MV/m before plasma processing
  - 14.2 MV/m after plasma processing
- **Beam energy increase from plasma processing of slot 19**
  - ~11 MeV



CONCLUSION

- **In-situ plasma processing developed at SNS to increase accelerating gradient of cryomodule in operation**
- **Plasma cleans surface hydrocarbons and increase work function to reduce field emission**
  - Also helps removing adsorbed gases and reduce SEY
- **So far, plasma processing was successfully applied to**
  - Two cavities in HTA
  - Offline cryomodule
  - One cryomodule in operation
    - ***11 MeV beam energy gain leading to highest energy on production target at 60 Hz (957 MeV)***
- **Further deployment of plasma processing in SNS linac tunnel to high-beta cryomodules planned for FY16 and FY17**
- **Plasma processing of medium-beta cryomodules will follow**
- **Applicability of the new technique to other SRF cavities is being explored**