Plasma processing to improve SRF accelerating gradient

Presented at the

SRF2015 Conference
THBA01

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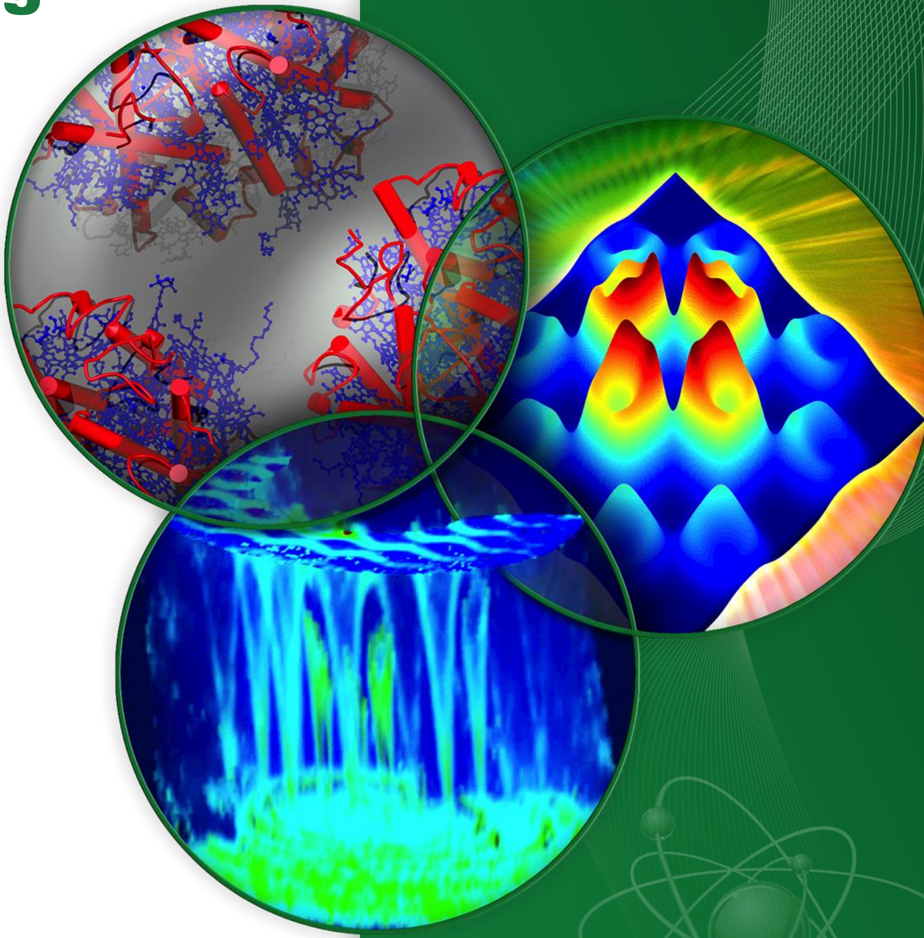
on behalf of SCL systems group

September 2015



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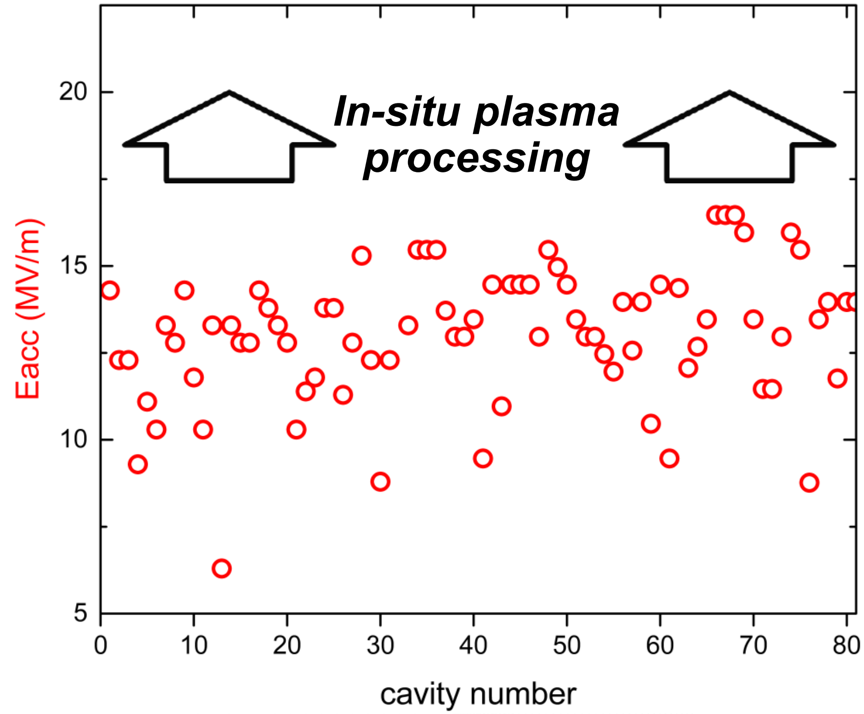
overview

- **Increase linac energy by in-situ plasma processing of superconducting linac cavities**
- **Plasma processing R&D**
  – Understanding of the plasma processing mechanism
  – Development of a reliable plasma processing technique
  – Performance improvement for single cavities in horizontal test apparatus (HTA)
- **On-going activity: Plasma processing of an offline cryomodule**

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
- **Developing in-situ plasma processing to reduce FE and increase accelerating gradients**



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**

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

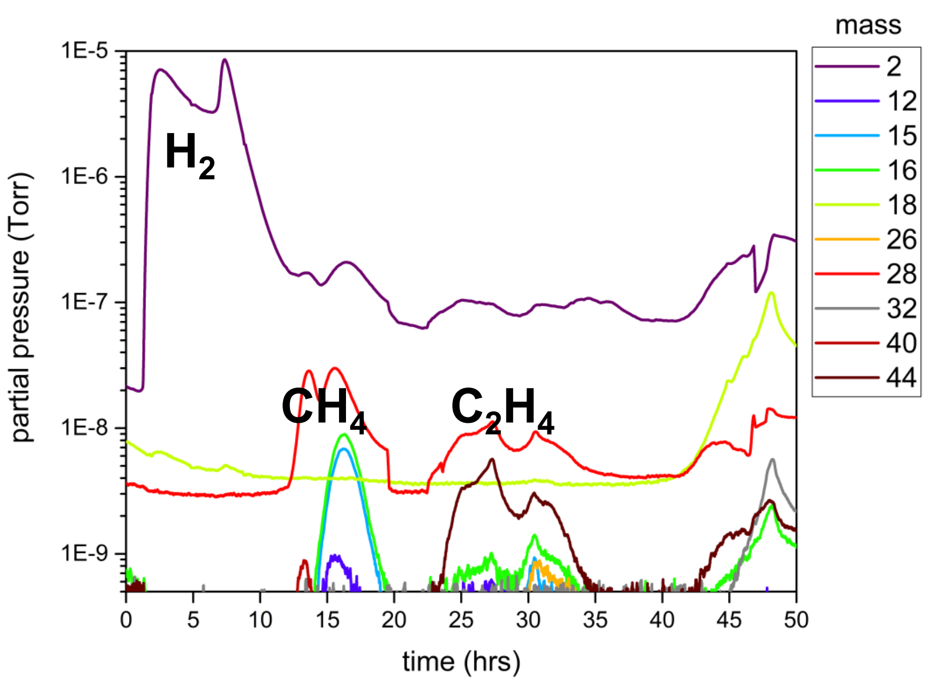
$$dJ = 0 \quad \Rightarrow \quad \frac{dE_{acc}}{E_{acc}} \approx \frac{3}{2}\frac{d\phi}{\phi}$$

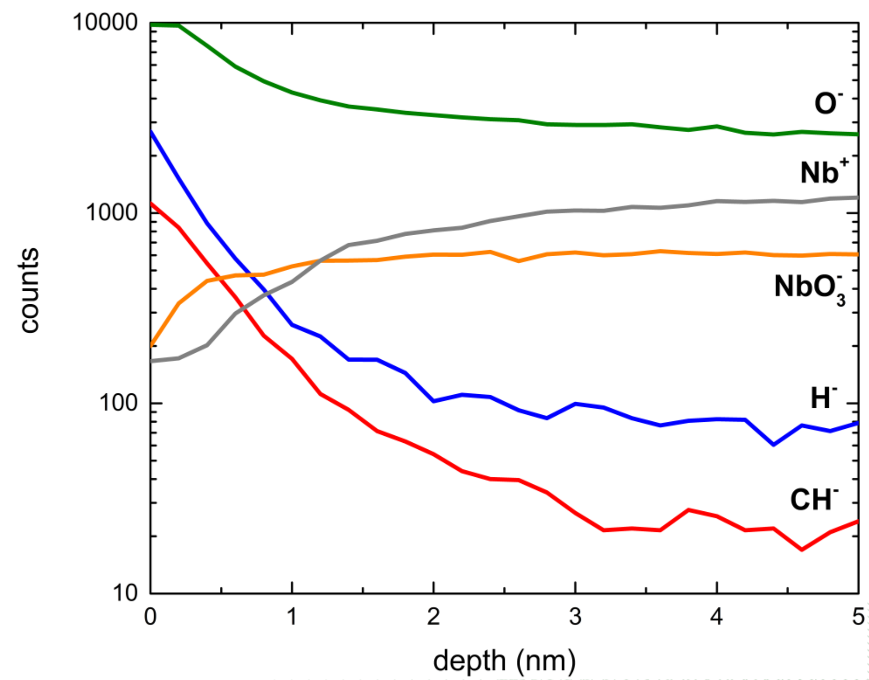
J : current density
E : surface electric field
β : field enhancement factor
ϕ : work function

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

Hydrocarbon contaminants on Nb surfaces

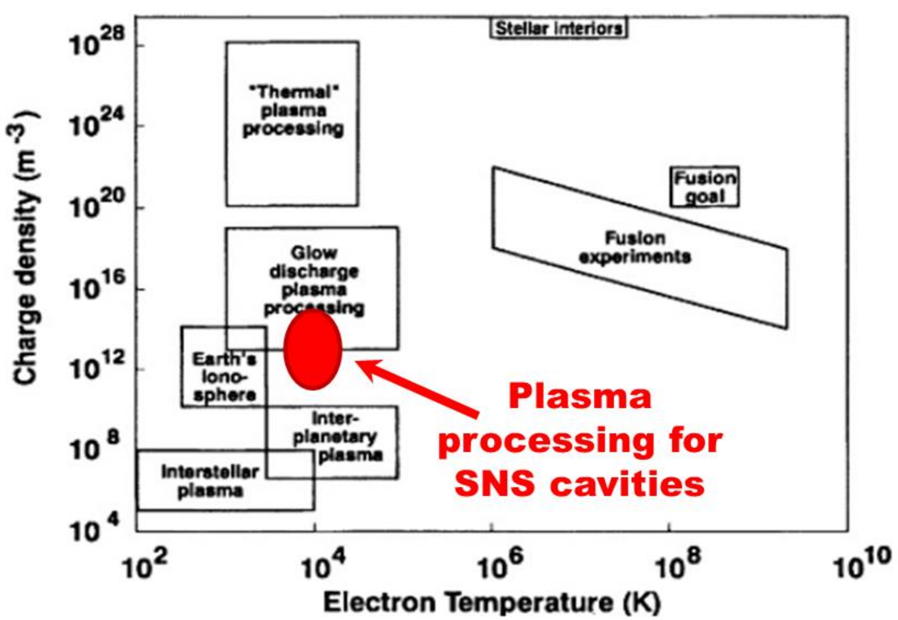
- **Hydrocarbon contaminants observed on all Nb surfaces**
  - Volatile hydrocarbons released from cryomodule surfaces during thermal cycle
  - Hydrocarbons on offline spare cavity surfaces
  - Hydrocarbons fragments seen in secondary ion mass spectrometry (SIMS)
    - Mechanically polished niobium samples
    - 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

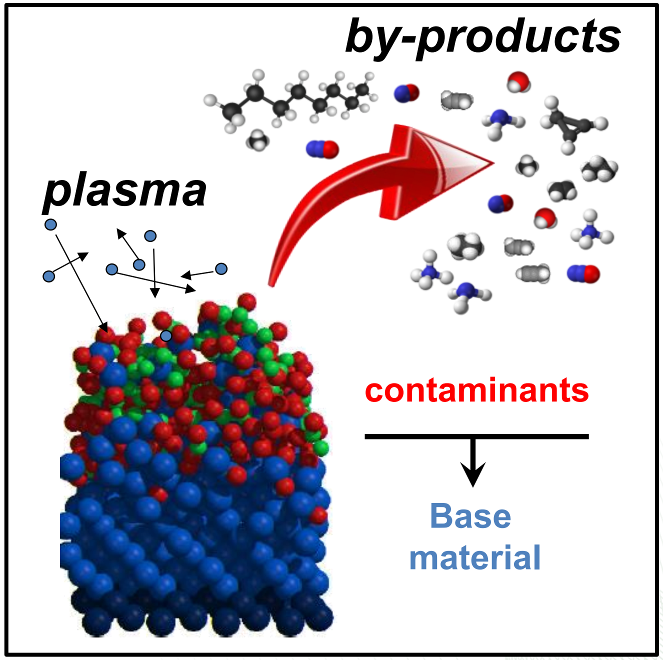




Low-temperature and low-density reactive plasma for removing hydrocarbons in SNS cavities

- **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 room-temperature reactive oxygen plasma**
  - Volatile by-products are formed through oxidation of hydrocarbons and pumped out





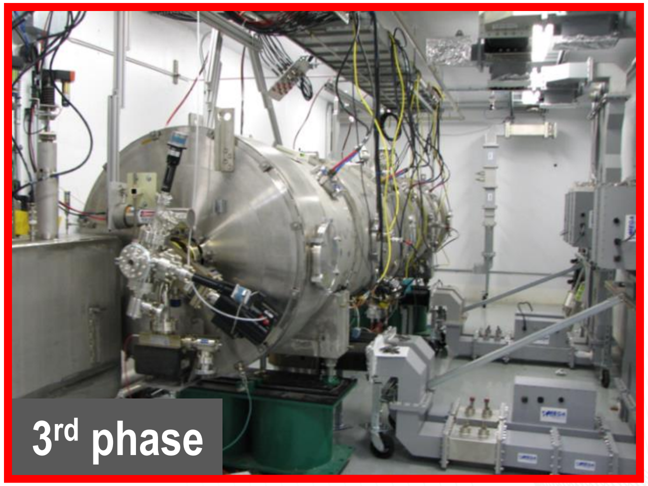
Plasma processing in four phases

R&D with 3-cell and 6-cell cavities

✓

Processing of 6-cell cavity in HTA*

✓



Processing of cryomodule in test cave

On-going

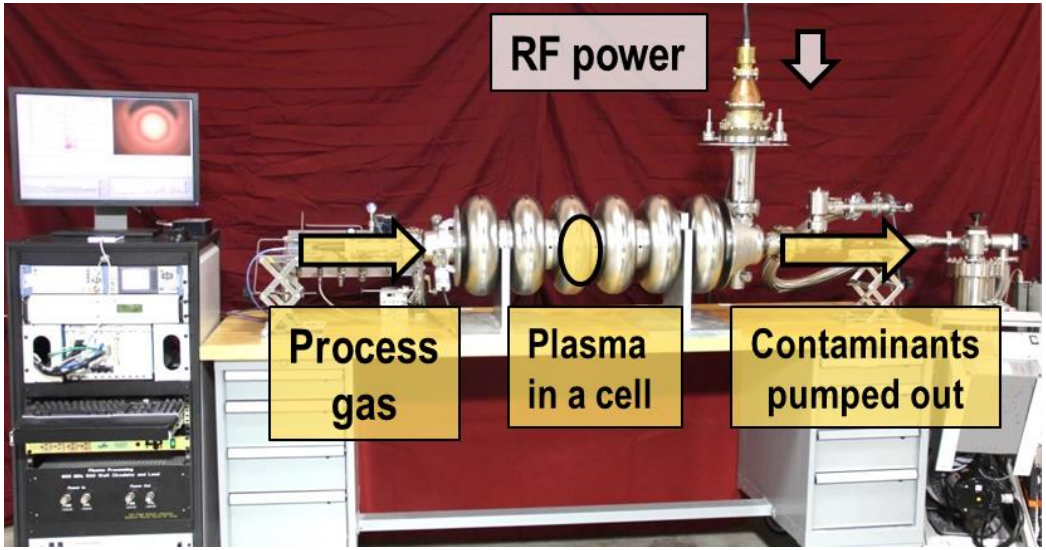
In-situ processing in linac tunnel

FY16
FY17

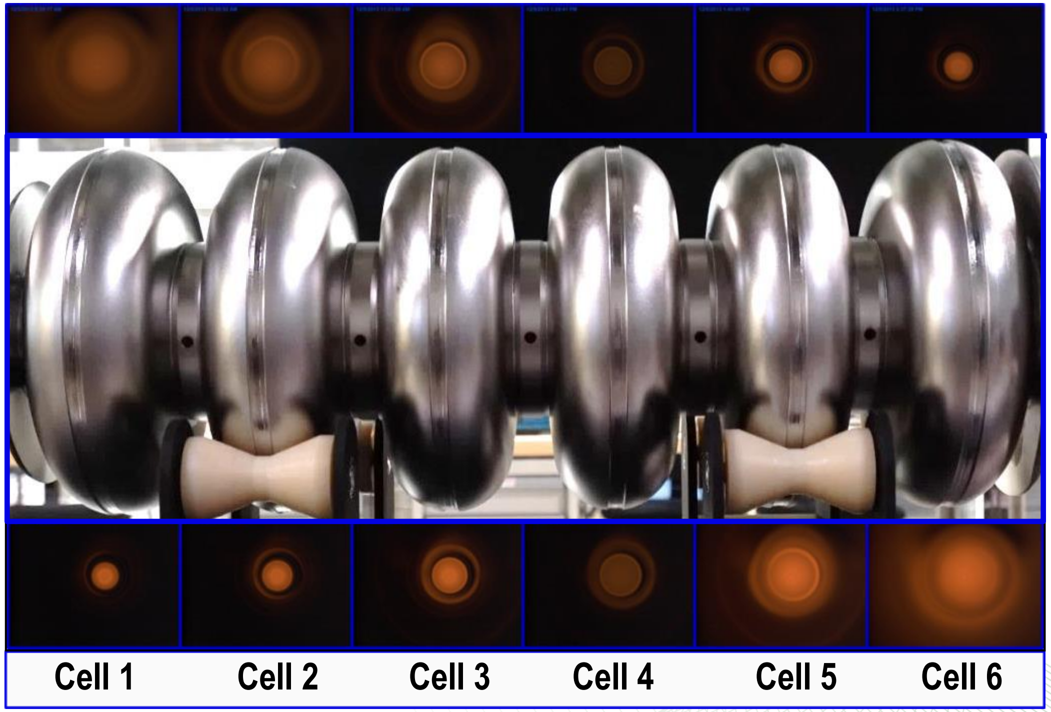
* Horizontal Test Apparatus

Reliable plasma generation in SNS HB cavities

- **Plasma generated inside cavity volume**
  - Gas manifold and RF station
  - Neon (~100 mTorr) for plasma ignition and tuning
  - RF power <1 kW

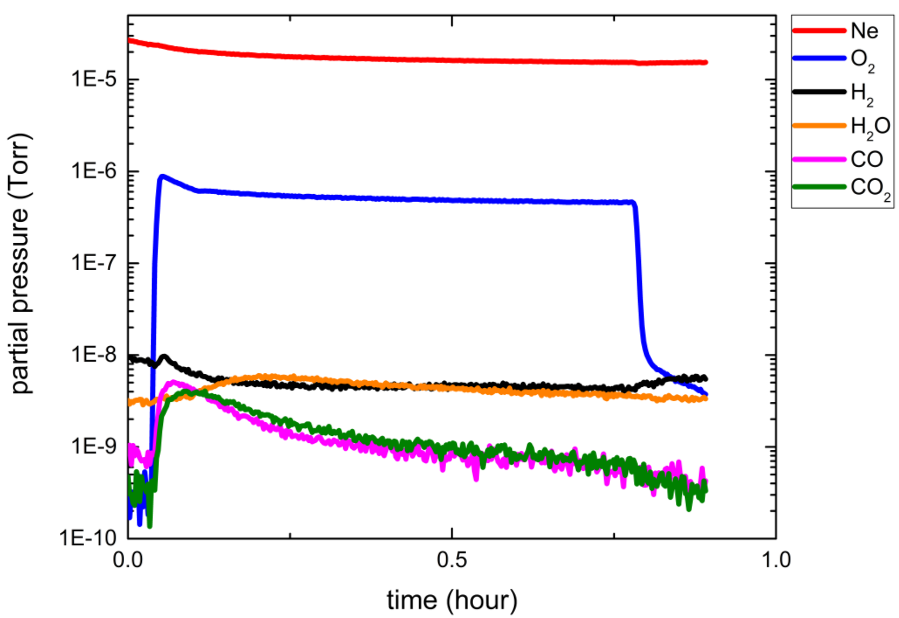


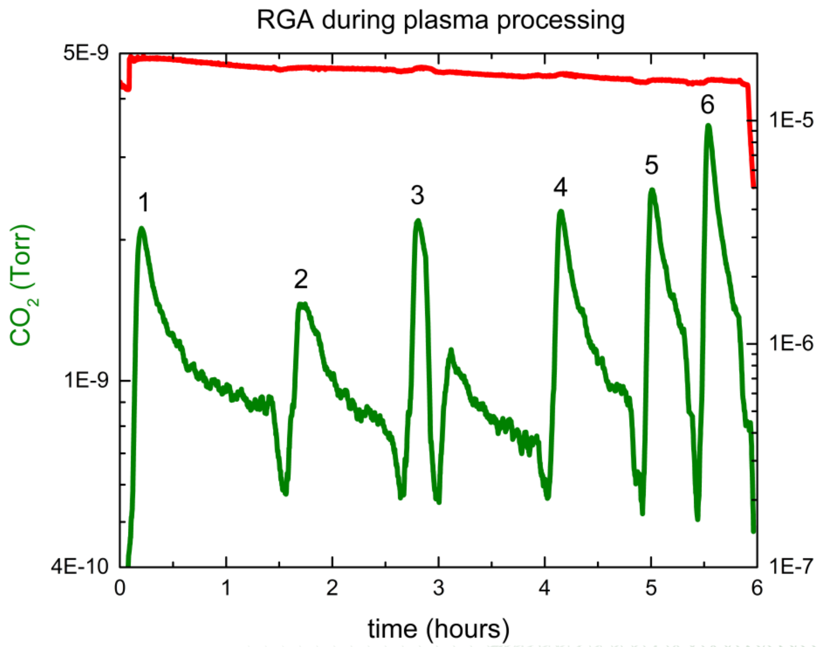
- **Plasma ignites in discrete cells, tuning necessary to process all cells**
  - Dual tone excitation (2 rf generators)
  - on and off-resonance excitation
  - Plasma loaded cavity theory



Removal of residual hydrocarbons by adding oxygen to the neon plasma

- **Hydrocarbons removed from top surface through oxidation and formation of volatile by-products**
  - H_2, H_2O, CO and CO_2
- **Residual gas analysis to monitor plasma cleaning**
  - Depletion of surface hydrocarbons within 30-45 minutes per cell
  - Removes 0.5-1.0 monolayer of hydrocarbon
  - Six cells of a cavity processed sequentially

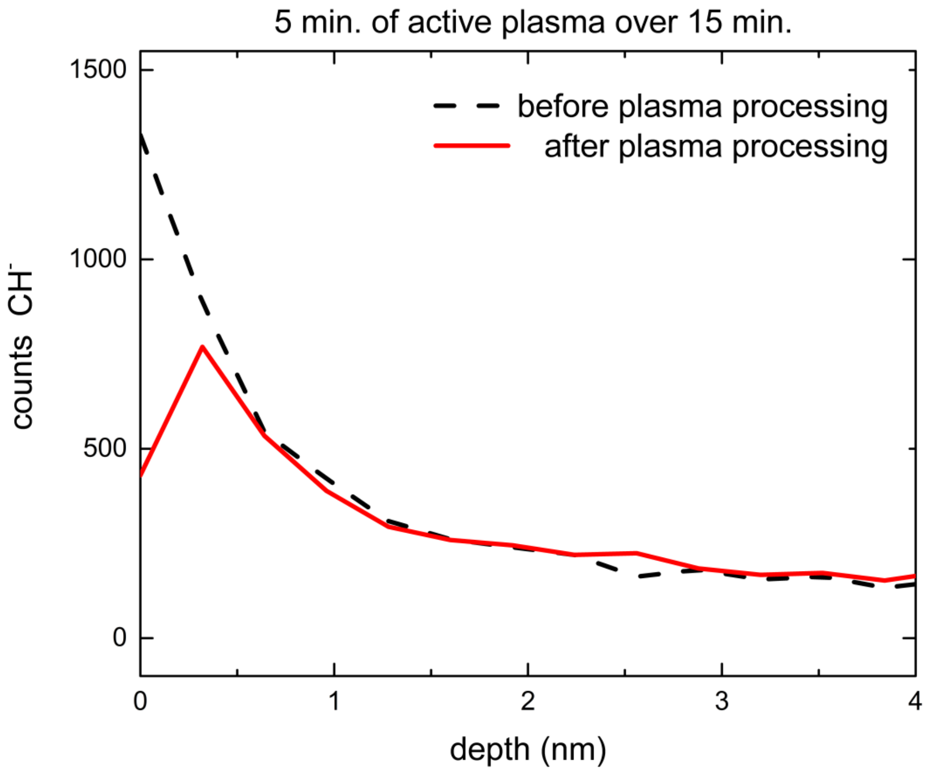


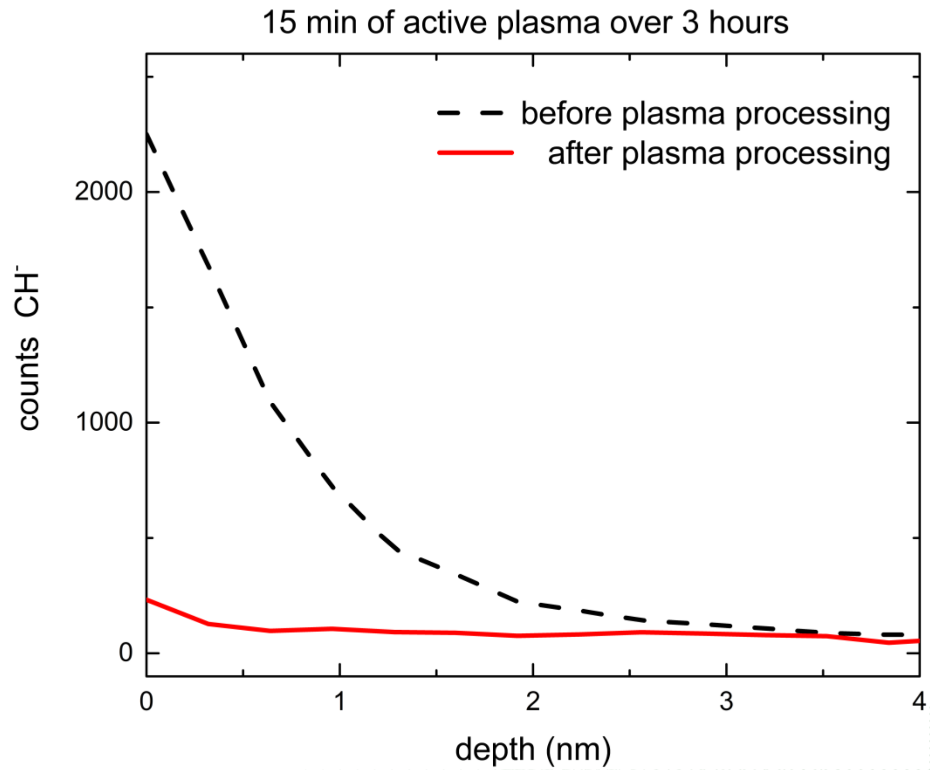


Hydrocarbons removal studies using Nb samples*

*MOPB115

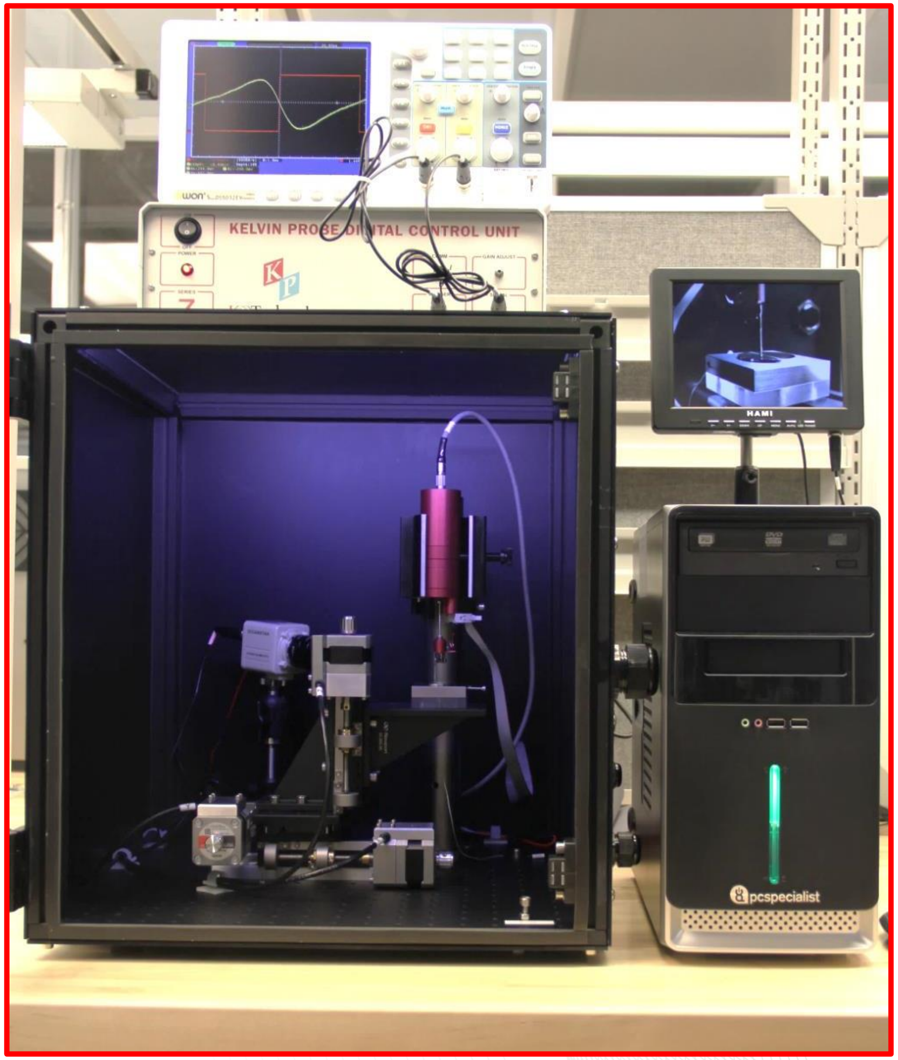
- **Hydrocarbons concentrated near the top surface of Nb samples before plasma processing (black dashed curves)**
- **After short plasma processing time (left figure)**
  - Top surface layer is depleted of hydrocarbons
- **After longer plasma processing time (right figure)**
  - Top surface layer and deeper layers depleted of hydrocarbons





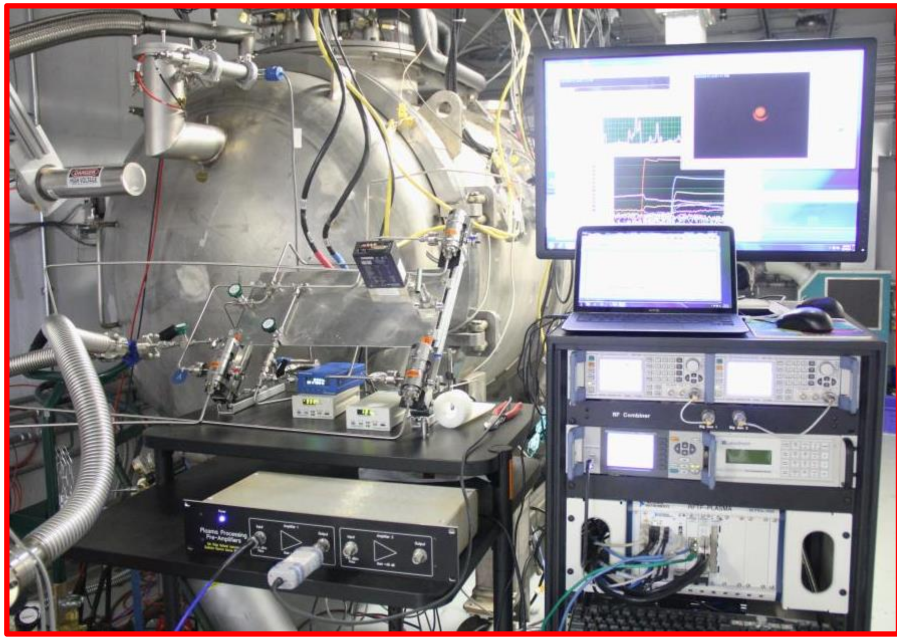
Plasma processing increases work function

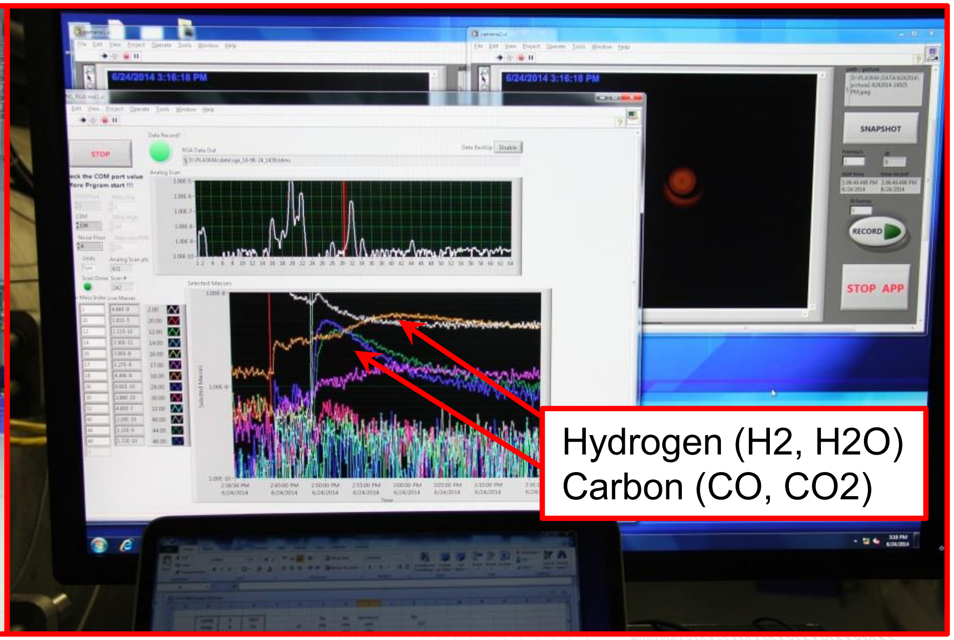
- **Scanning Kelvin Probe instrument used to measure work function**
  - Contact potential difference between reference probe and sample
  - Nb samples ϕ=4.7 eV initially
- **Plasma processing technique developed at SNS**
  - Removes Hydrocarbons
  - Systematically improves the work function
  - 0.8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



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

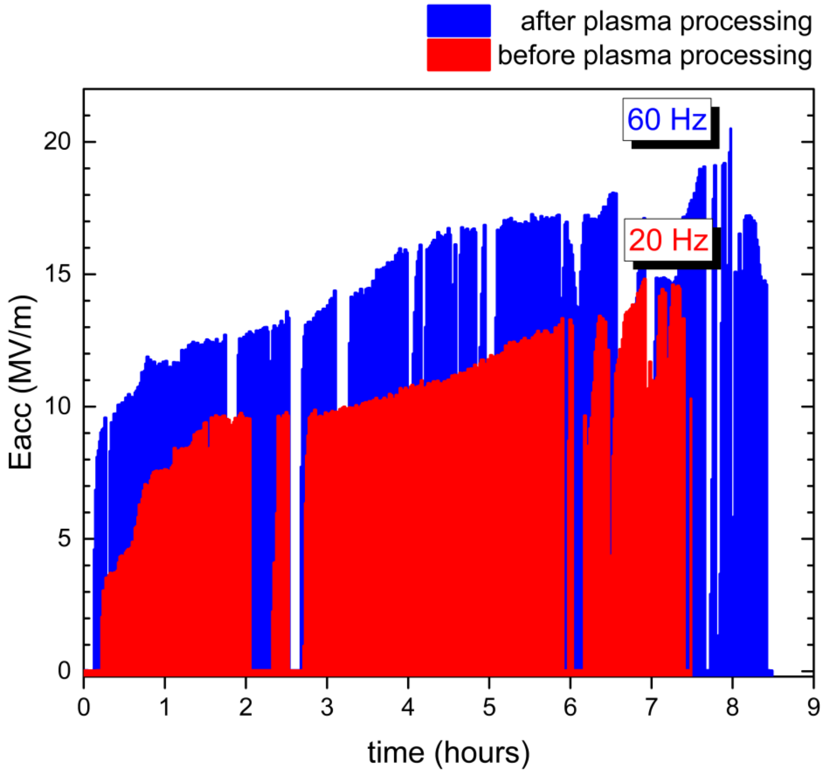
- Two spare cavities were dressed with helium vessel and prepared in cleanroom (HB59 and HB52 cavities)
- HB59 and HB52 cavities were tested in HTA at 4.5 K before and after plasma processing
- In-situ plasma processing for each cavity was done in HTA at room-temperature between cold-tests

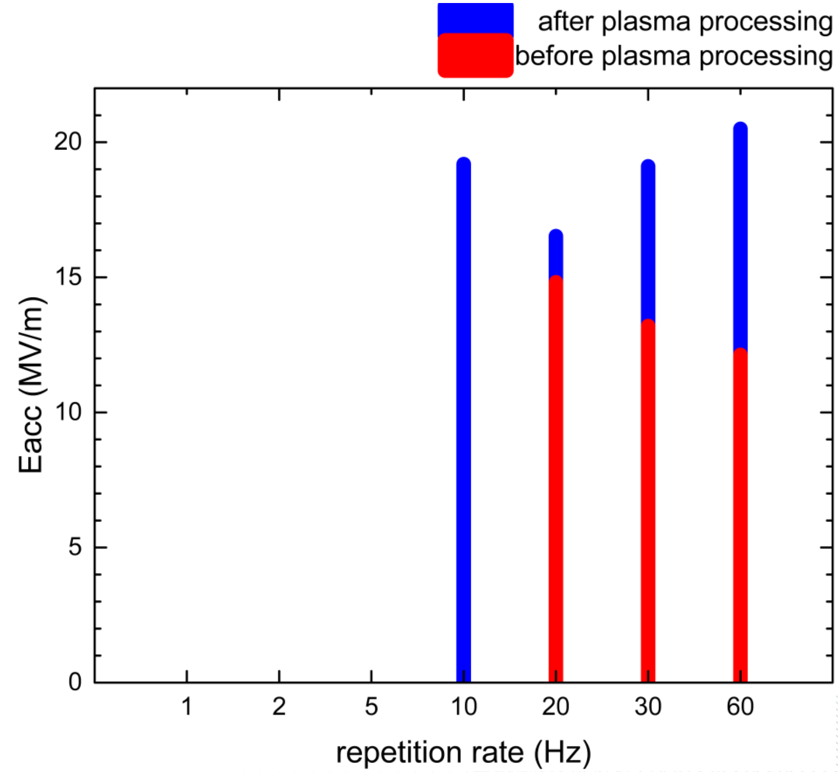




Plasma processing improves HB59 performance

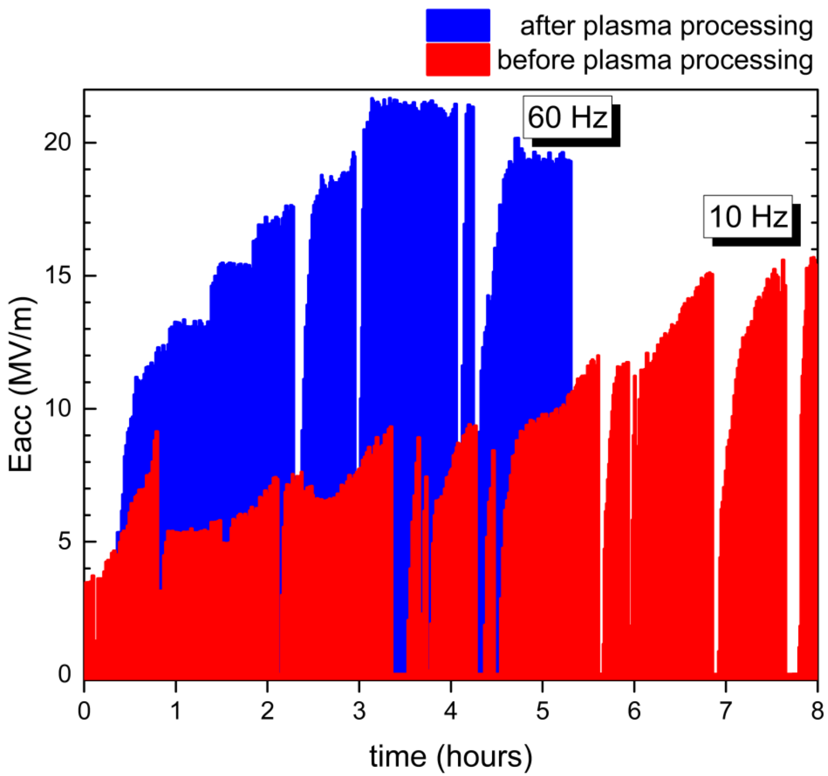
- **Before plasma processing**
  - Frequent trips associated with vacuum activity and temperature increase during RF conditioning
  - Reached 15.2 MV/m at 20 Hz repetition rate
- **After plasma processing**
  - Easier RF conditioning
  - Reached 20.5 MV/m at 60 Hz repetition rate

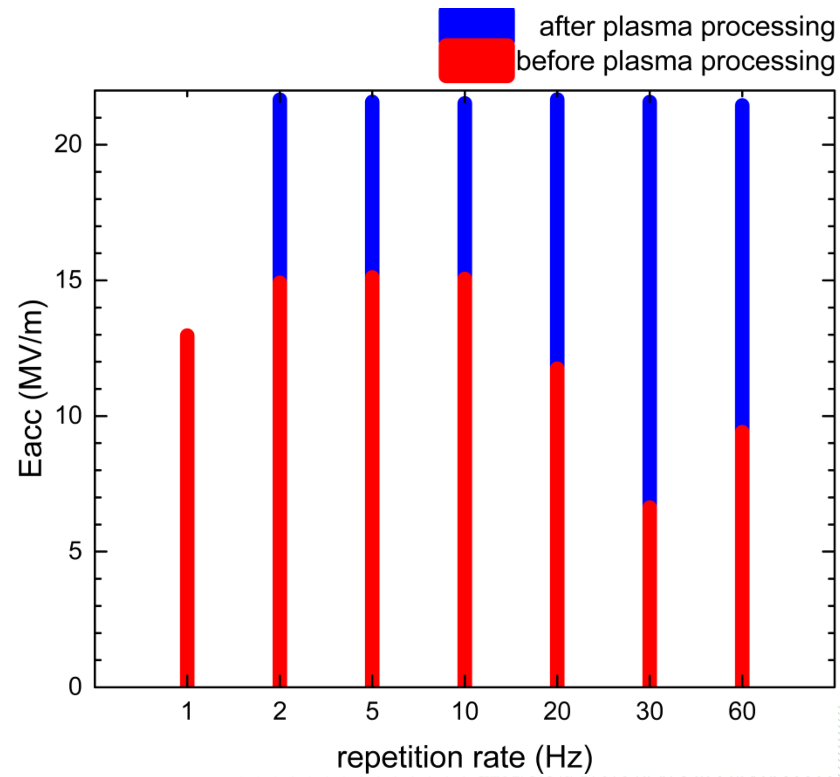




Plasma processing improves HB52 performance

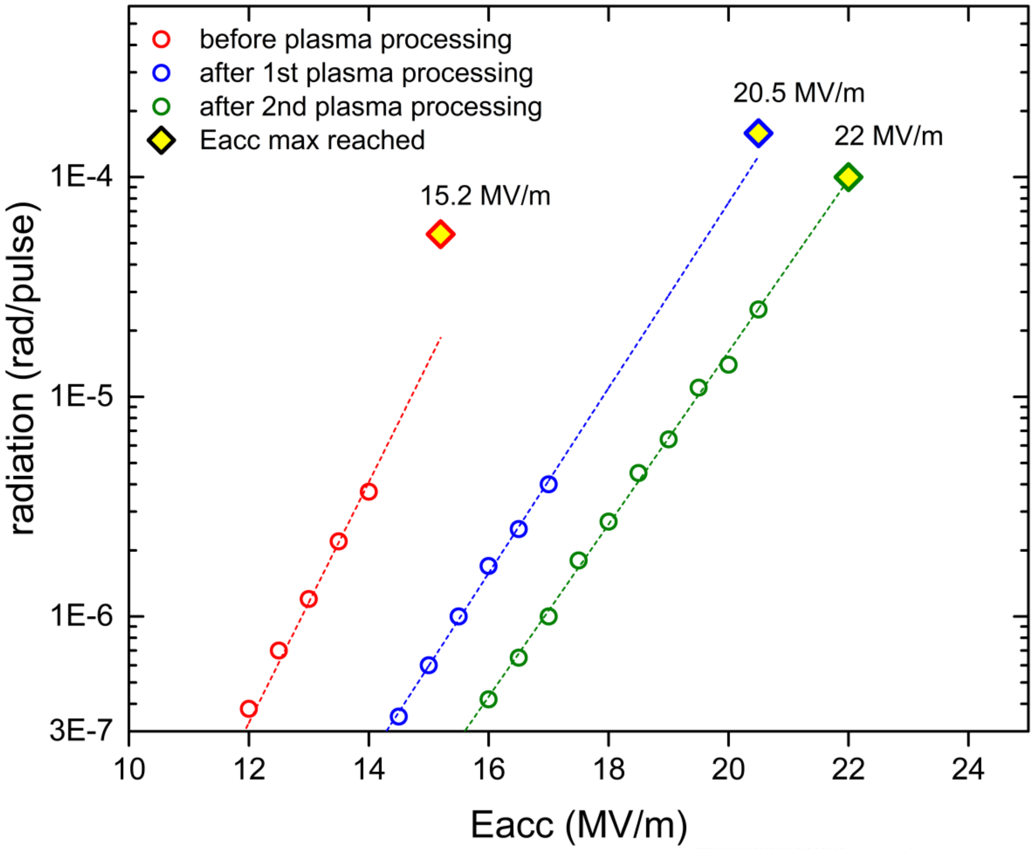
- **Before plasma processing**
  - Frequent trips associated with vacuum activity and temperature increase during RF conditioning
  - Reached 15 MV/m at 10 Hz repetition rate
- **After plasma processing**
  - Easier RF conditioning
  - Reached 21.5 MV/m at 60 Hz repetition rate





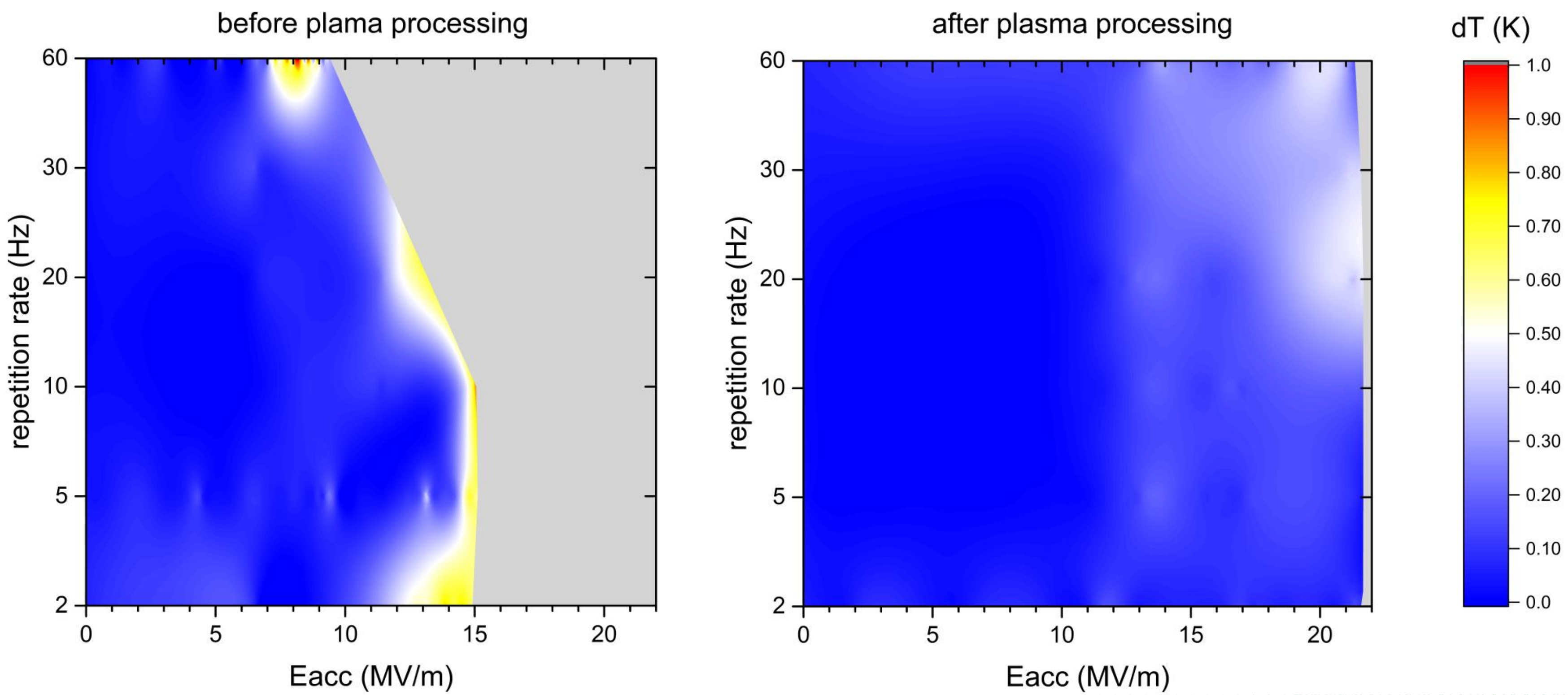
Plasma processing reduces field emission

- **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**



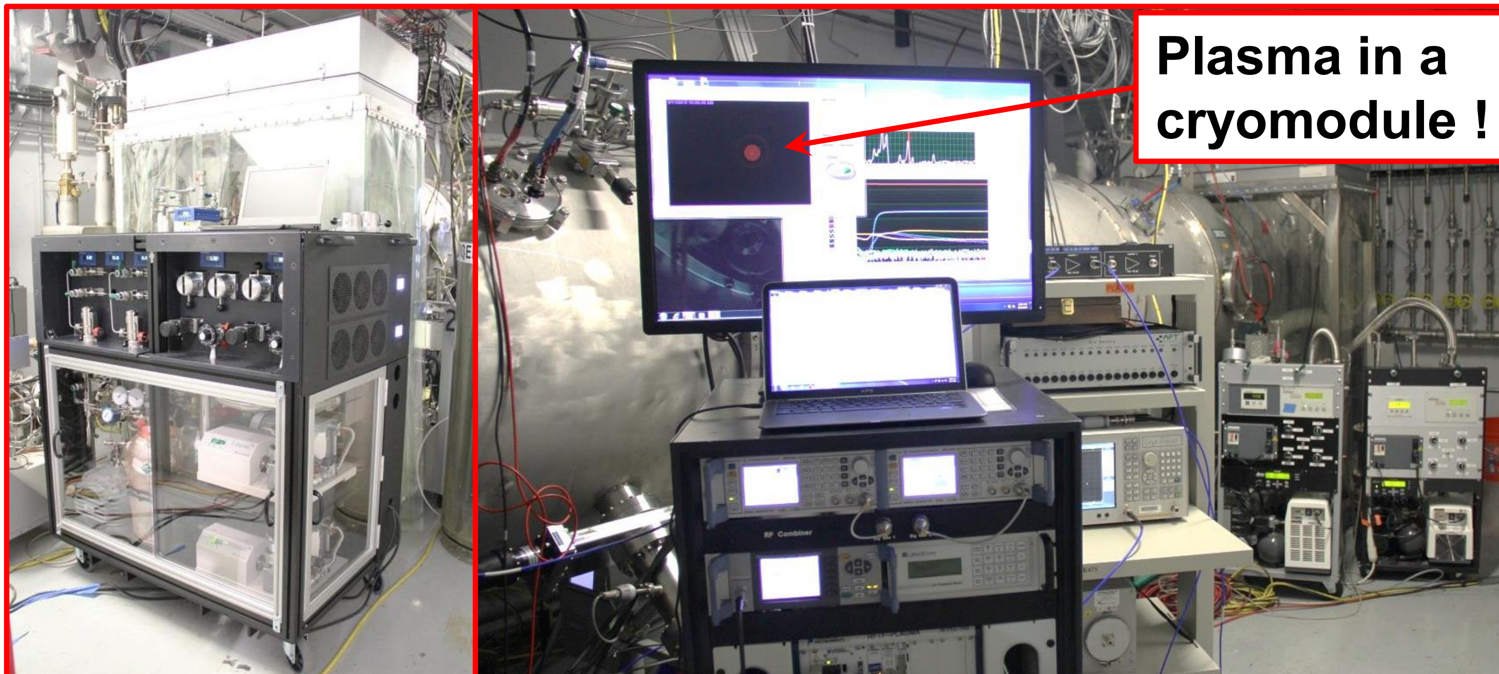
Plasma processing might also reduce SEY

- **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



Plasma processing of an offline cryomodule

- **Cryomodule baseline test completed**
  - Repairs succcessful: HOM antennas removed and FP replaced (MOPB112)
  - Cryomodule performance similar as in operation
- **Plasma processing of cryomodule on-going**
  - Plasma ignition/tuning successful for all 4 cavities of the cryomodule
  - By-products of hydrocarbon oxidation observed in RGA
  - Cryomodule will be re-tested after plasma processing



CONCLUSION

- **Plasma processing effort is going well**
  - Standard plasma processing procedure defined
  - Achieved in-situ plasma processing of a cavities in HTA
- **Demonstrated cavity performance improvement after plasma processing**
- **Plasma processing of an offline HB cryomodule is on-going**
- **Deployment of plasma processing in HB cryomodules of SNS linac planned in FY16 and FY17 to reach 1 GeV beam energy**
- **Plasma processing of MB cavities for STS* is also planned**