Plasma Processing to Improve the Performance of the SNS Superconducting Linac

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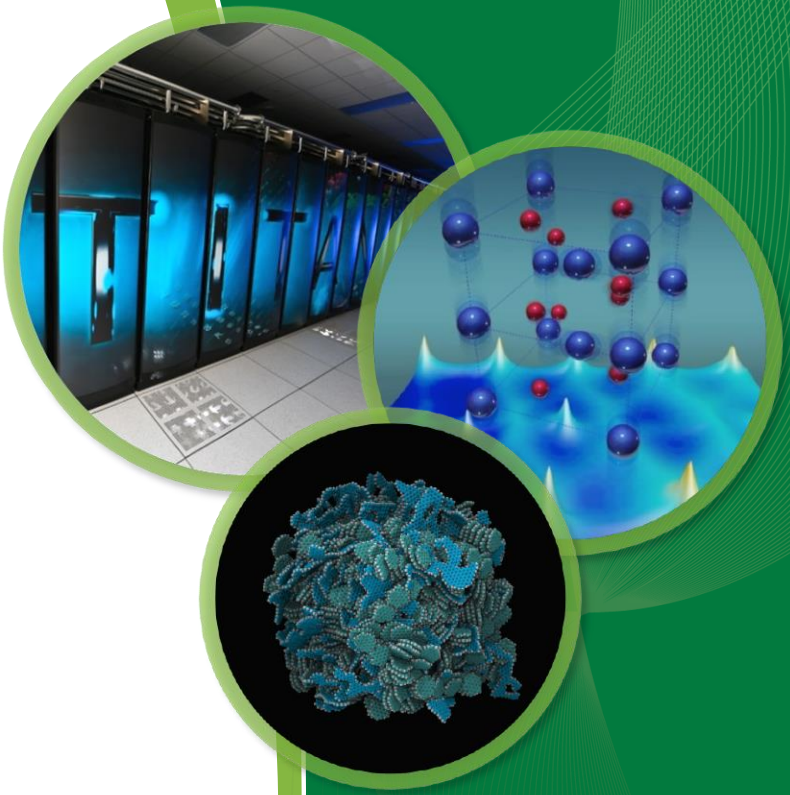
on behalf of SCL systems group

ORNL/SNS



ORNL is managed by UT-Battelle
for the US Department of Energy

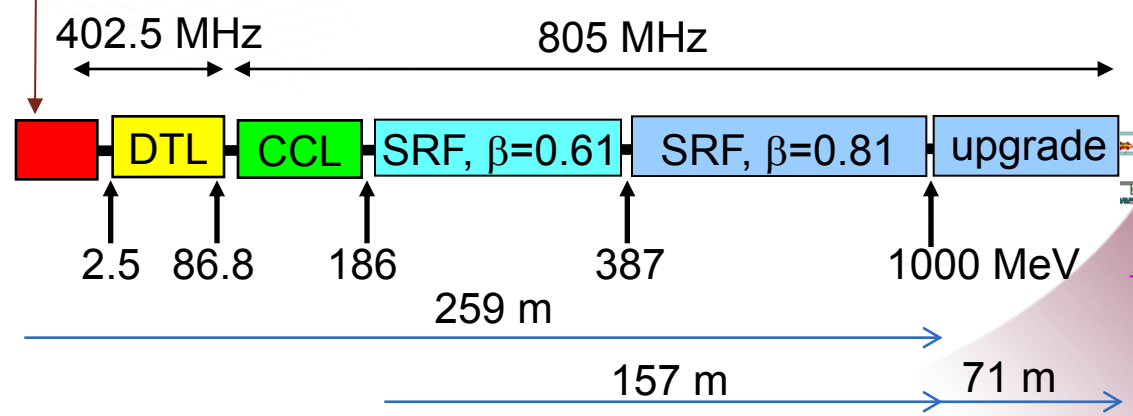
SNS Machine Layout

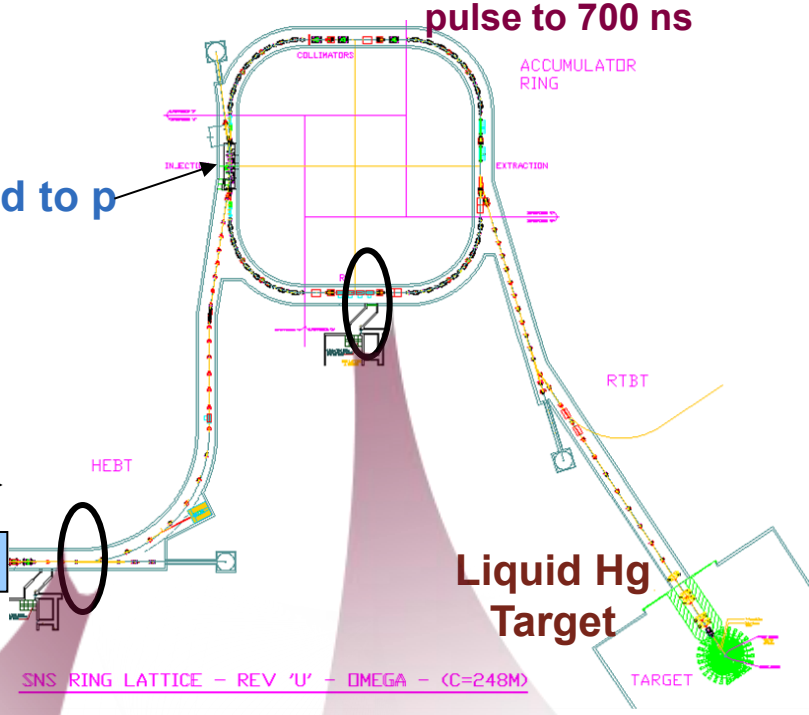
Front-End:
1 msec long chopped H- beam at 60 Hz

LINAC:
Accelerates beam to 1 GeV
SRF linac 23 cryomodules

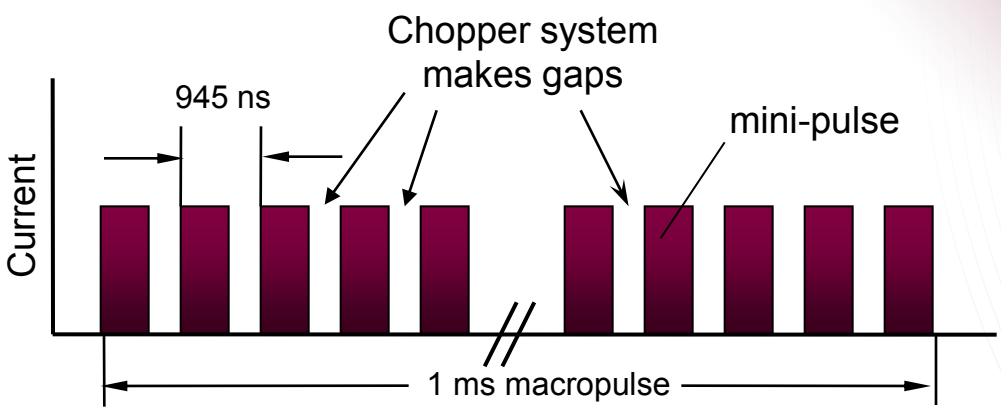
Accumulator Ring:
Compress 1 msec long pulse to 700 ns

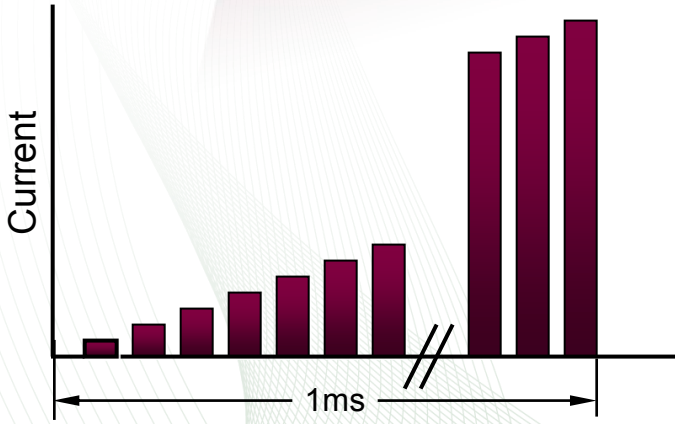
H- stripped to p





Liquid Hg Target

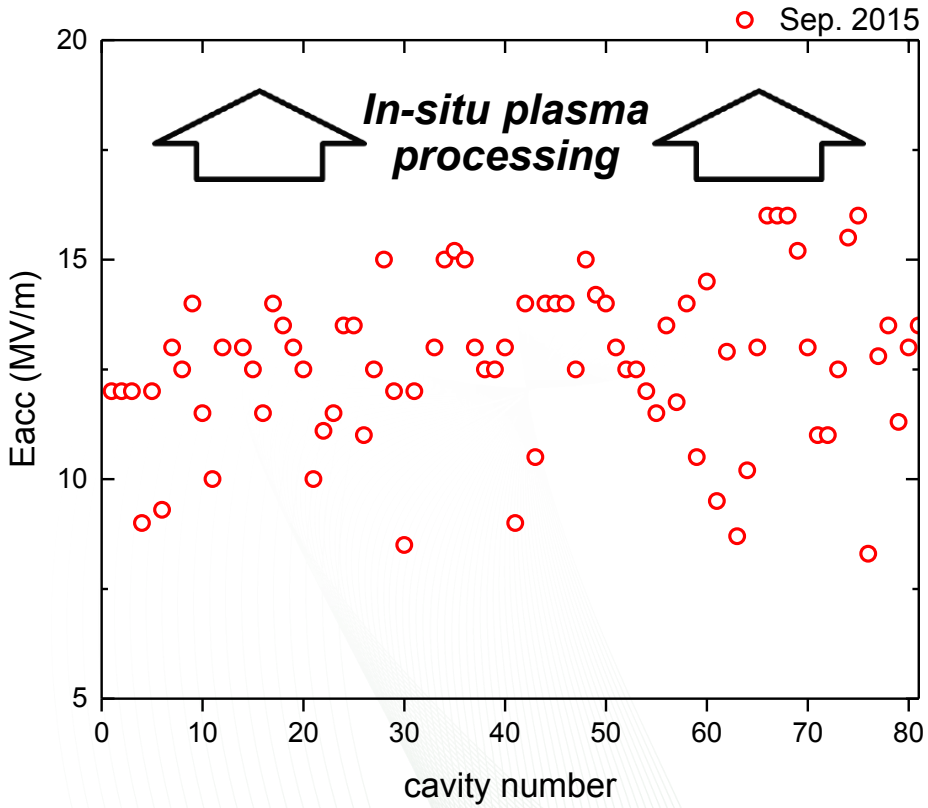




Average macropulse beam current: 26 mA

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 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**

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

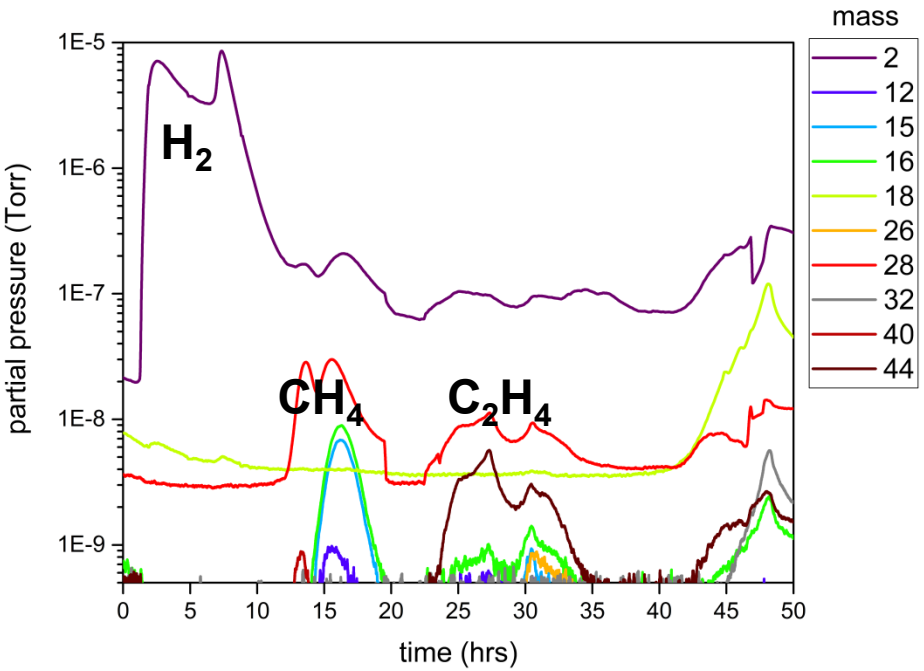
$$dJ = 0 \quad \Rightarrow \quad \frac{dE_{acc}}{E_{acc}} \approx \frac{3}{2}\frac{d\phi}{\phi}$$

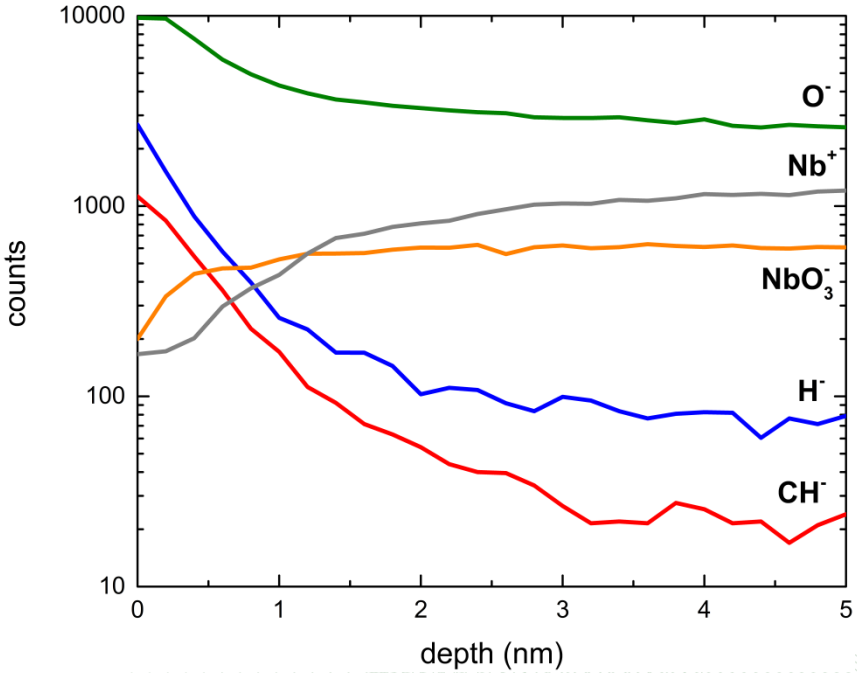
J : current density
E : surface electric field
β : field enhancement factor
ϕ : work function

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

Hydrocarbon contaminants on Nb surfaces

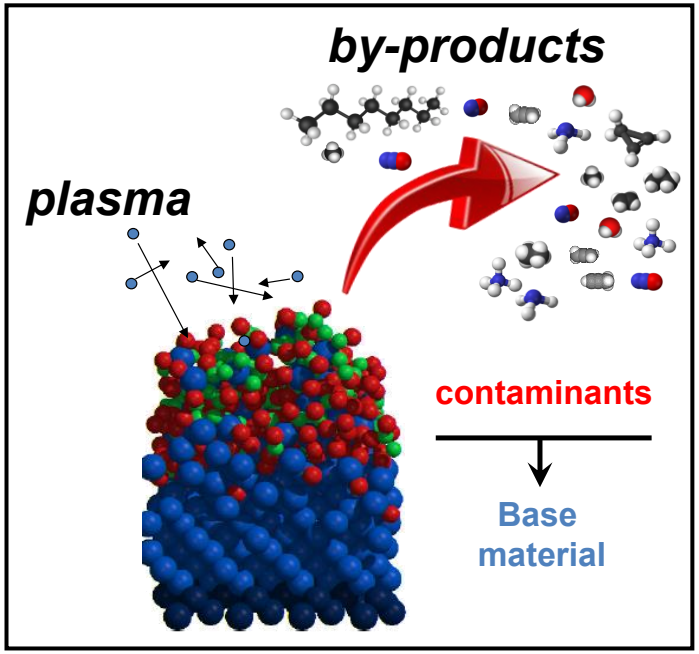
- **Hydrocarbon contaminants observed on all Nb surfaces**
  - Volatile hydrocarbons released from cryomodule surfaces during thermal cycle
  - Hydrocarbons on offline spare cavity surfaces
  - Hydrocarbons fragments seen in secondary ion mass spectrometry (SIMS)
    - Mechanically polished niobium samples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

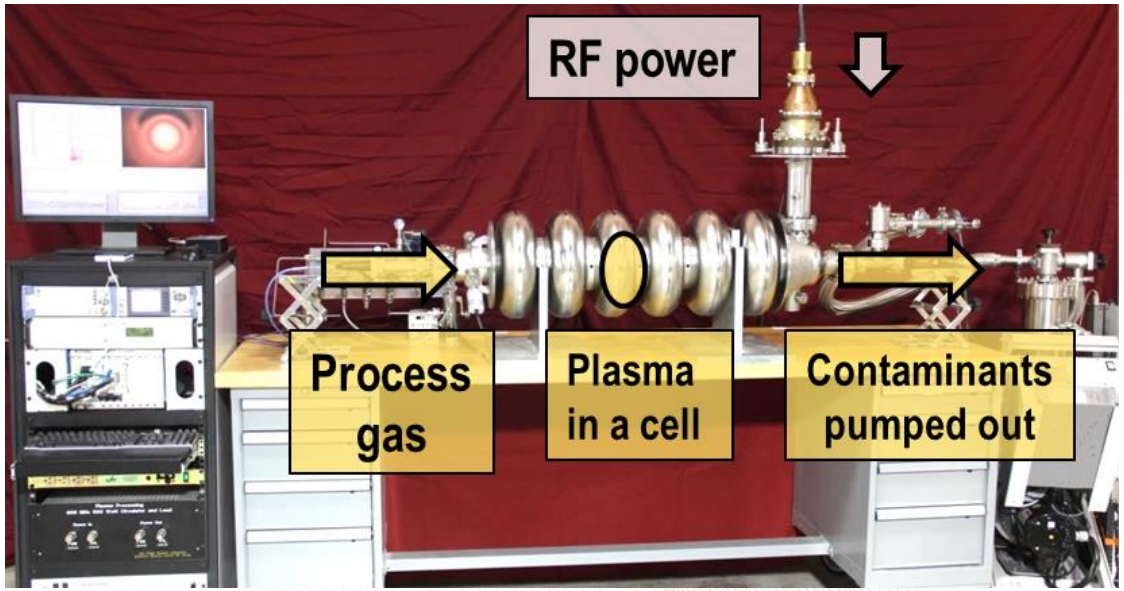




Low e⁻ temperature and low-density reactive plasma for removing hydrocarbons in SNS cavities

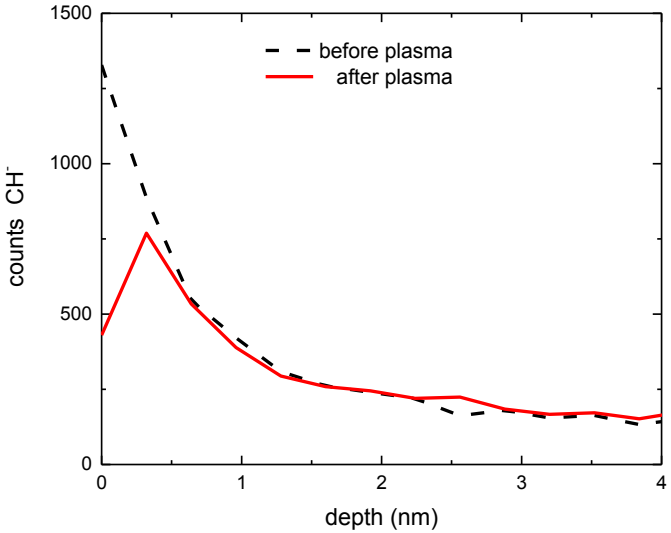
- **Plasma is a rich and reactive environment**
  - Ions, e-, neutrals, excited neutrals, molecules, radicals, UV…
- **Plasma processing is a versatile technique used for various purposes**
  - Cleaning, activation, deposition, crosslinking, etching….
- **Chosen to develop a technique using reactive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

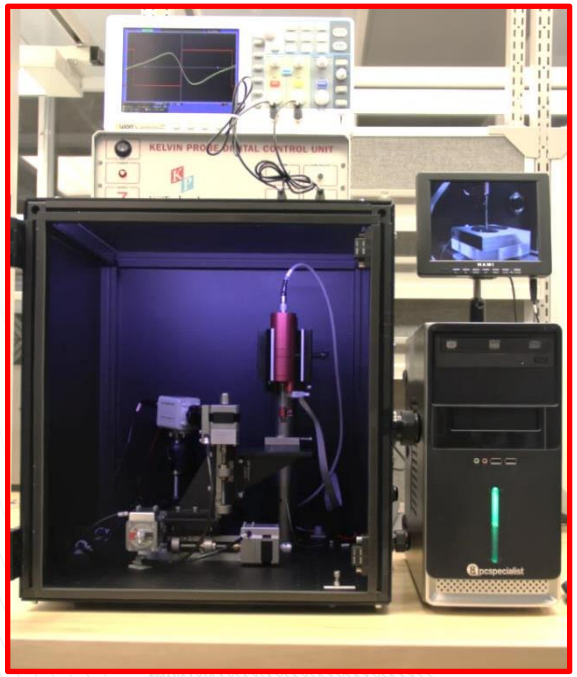




Plasma processing increases the work function of the Nb surface *

- **SIMS measurement shows that the hydrocarbons are removed from the Nb top surface**
- **Scanning Kelvin Probe shows that the work function increases**
  - Nb samples ϕ=4.7 eV initially
  - Neon-oxygen plasma processing systematically improves the work function
  - ~0.8 eV increase measured
  - Work function tends to degrade after venting to air

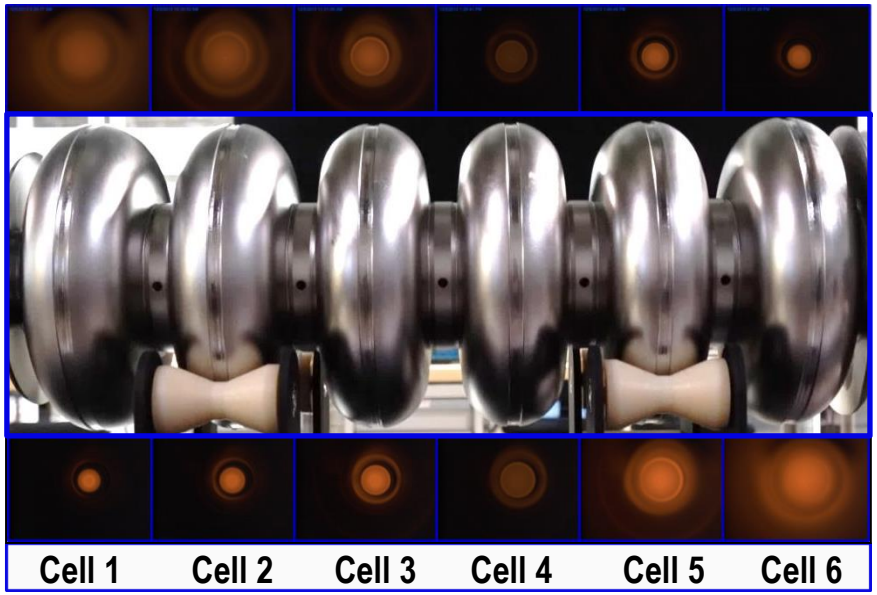


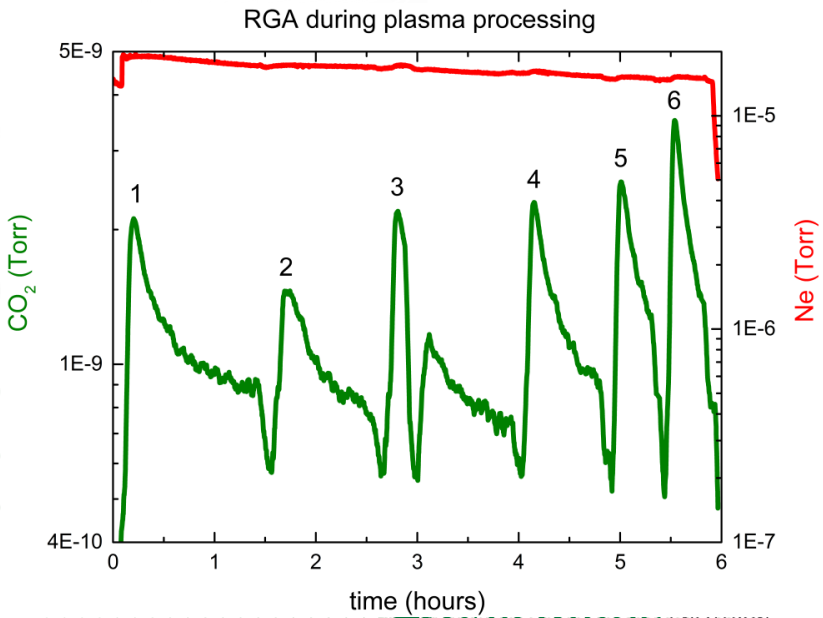


*Applied Surface Science **369** (2016) 29–35

Neon-oxygen cleaning applied to SNS HB 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

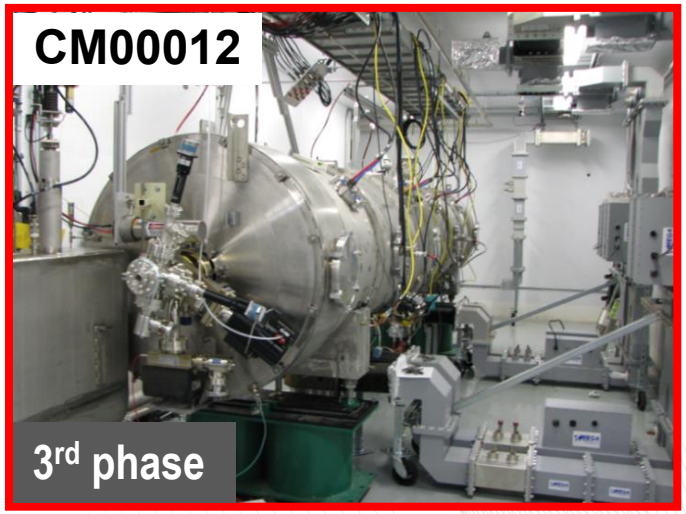




Plasma processing progress at SNS

R&D with Nb samples and offline cavities

Processing of 6-cell cavity in HTA*



Processing of cryomodule in test cave

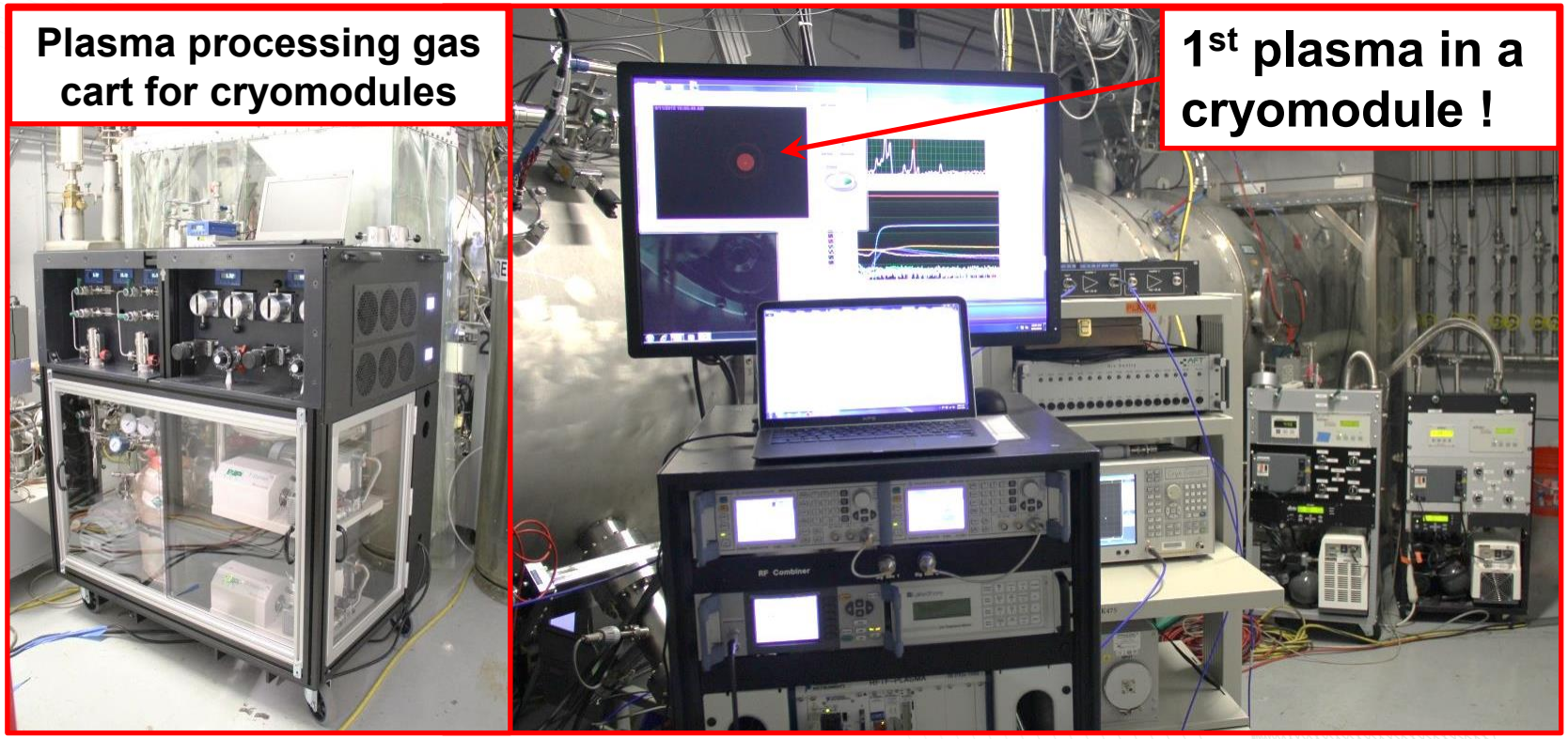
On-going
FY16
FY17

In-situ processing in linac tunnel

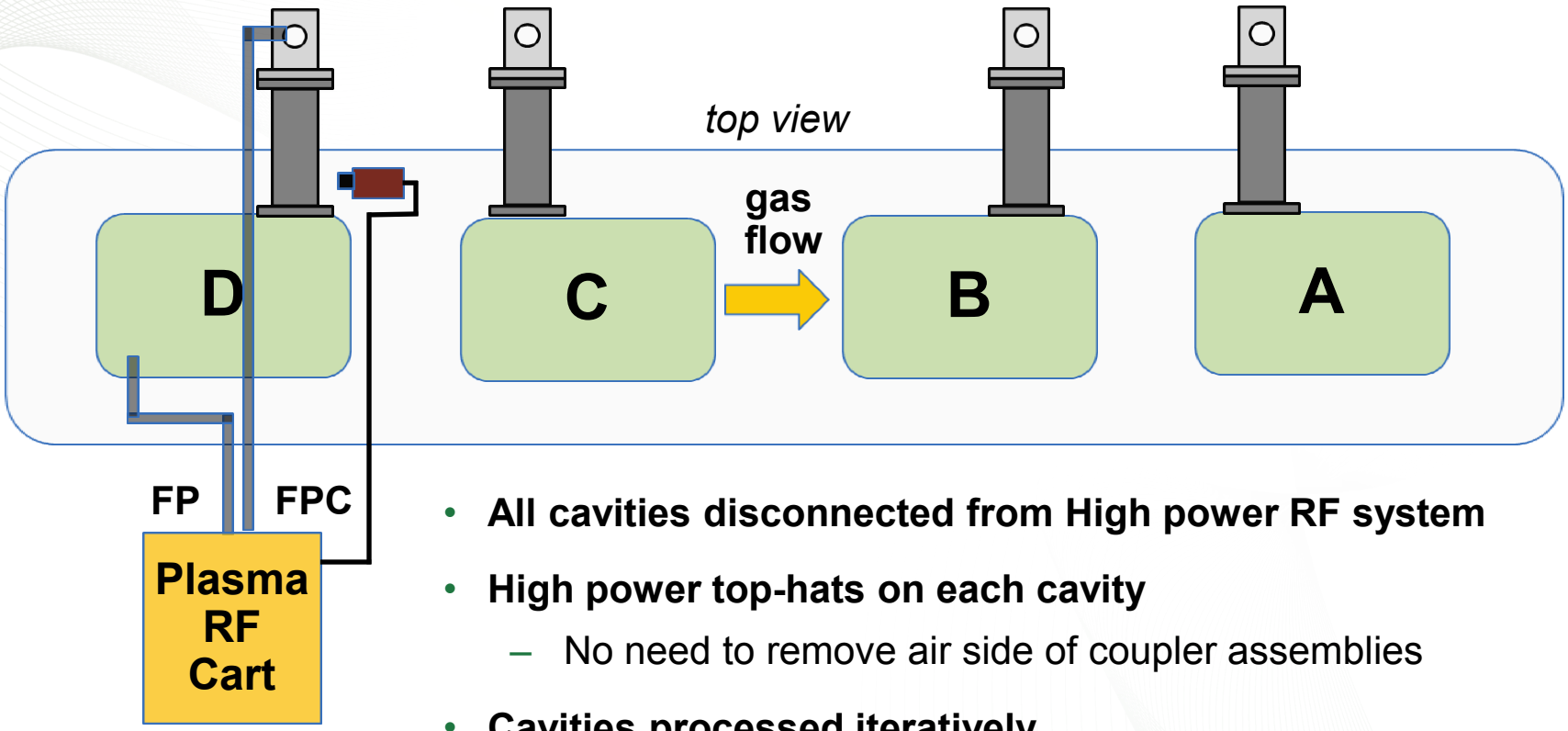
*HTA: Horizontal Test Apparatus

1st Plasma processing of a cryomodule

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



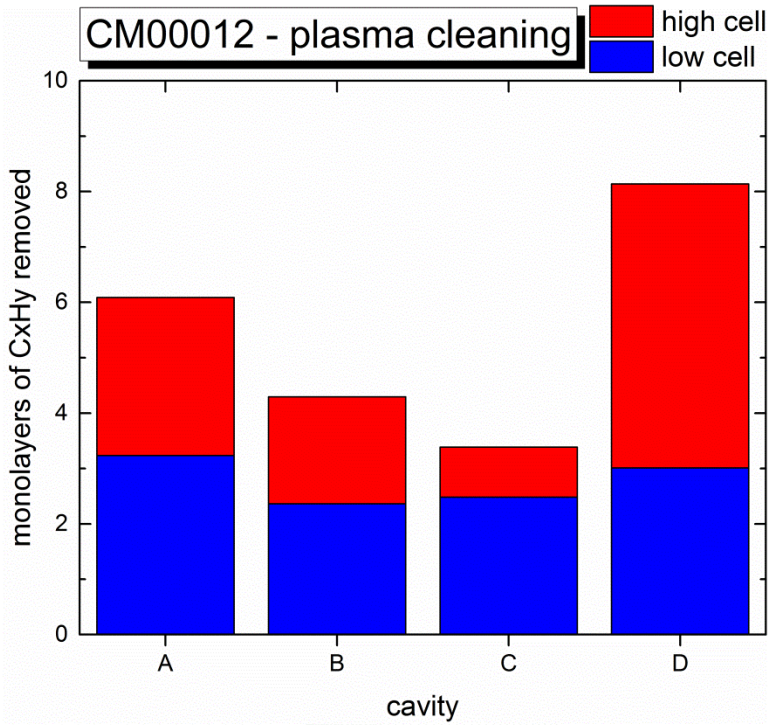
RF configuration during plasma processing



- **All cavities disconnected from High power RF system**
- **High power top-hats on each cavity**
  - No need to remove air side of coupler assemblies
- **Cavities processed iteratively**
  - Multiple RF carts can allow simultaneous processing of cavities
- **Cavities being plasma processed**
  - FPC and field probe connected to RF cart
  - Camera monitors any discharge in FPC

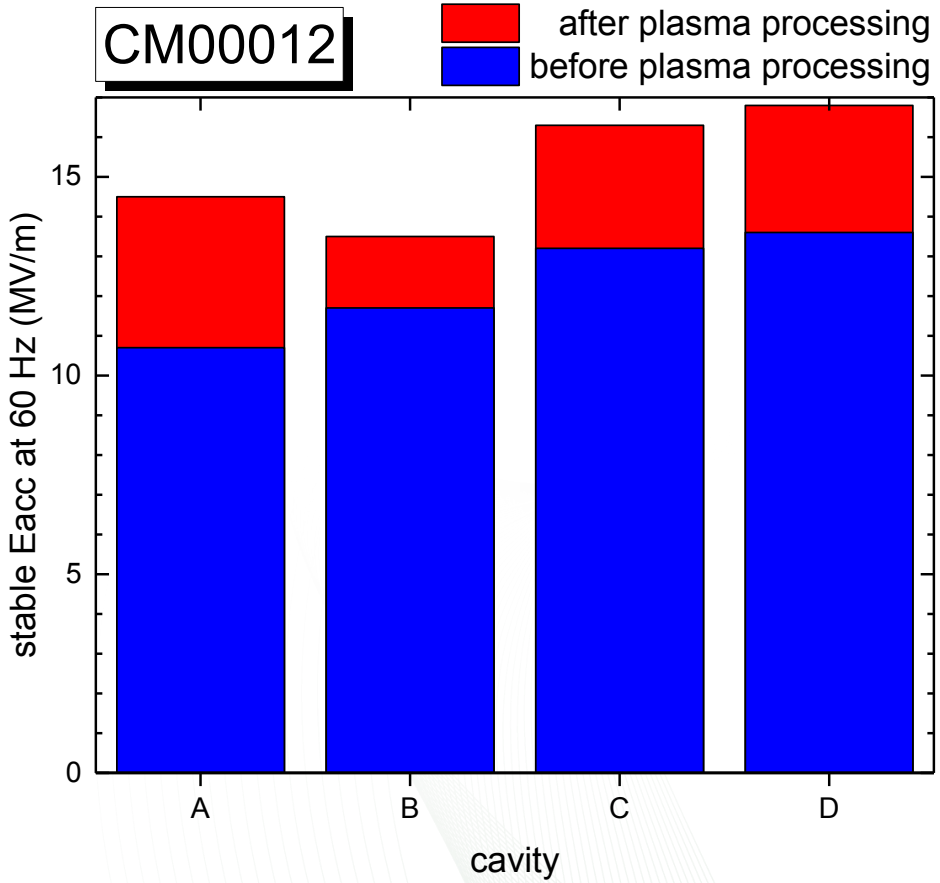
Hydrocarbons removed from CM00012

- **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 weeks**
- **Not same amount of contamination in all cells**
- **Beneficial to spend more time plasma processing cells with largest contamination**
  - Lesson learned applied during cleaning of cryomodules 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

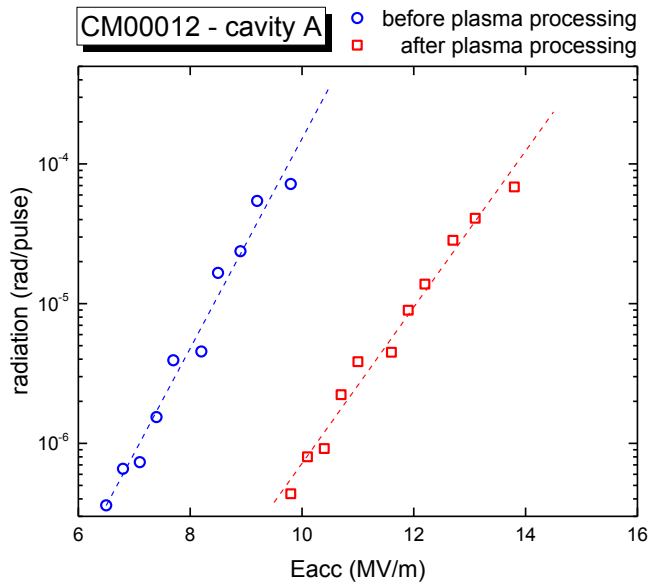


Ready to deploy plasma processing in linac tunnel

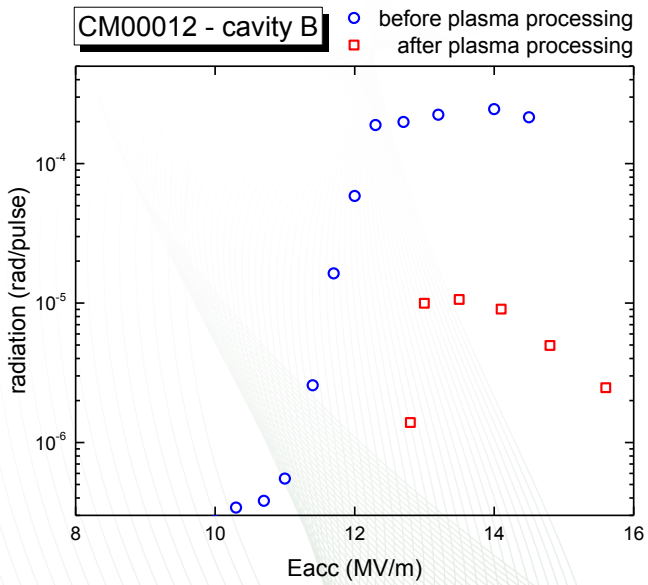
Radiation level reduced after plasma processing

- **Examples of radiation signals from two cavities**
- **Plasma processing has been observed to reduce radiation related to both field emission and multipacting**
- **Reduction varies between cavities**

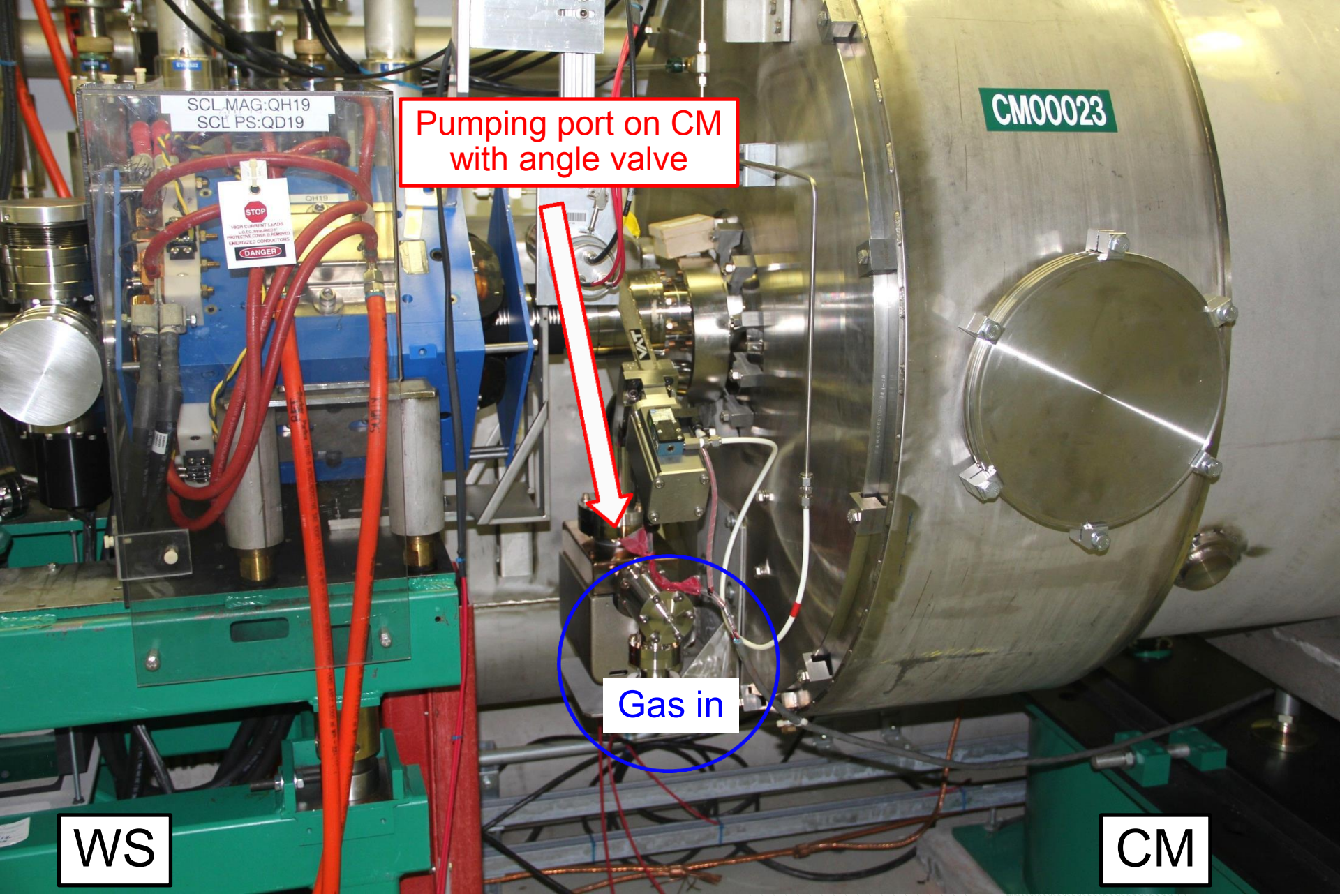
Field emission regime



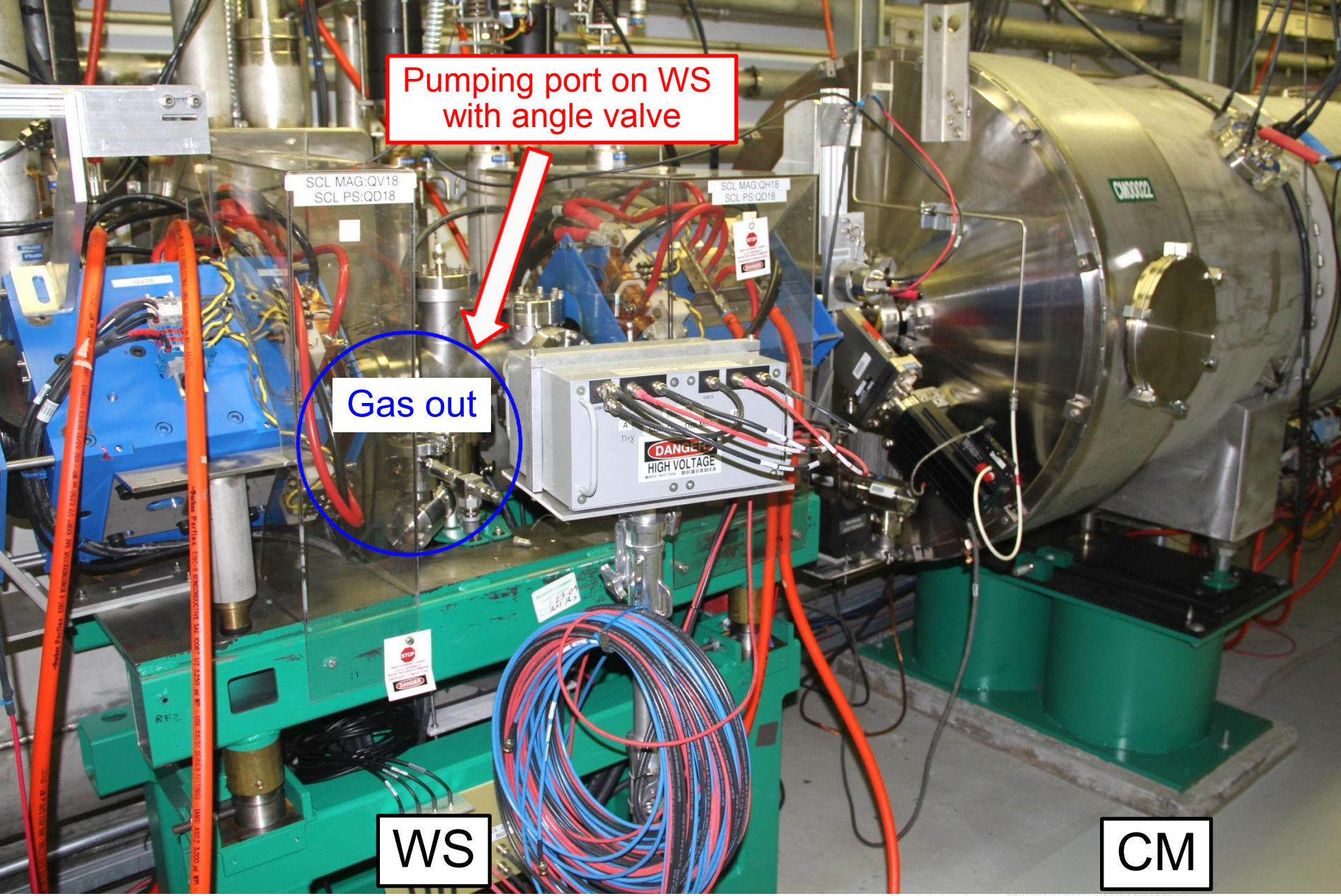
Multipacting regime



PLASMA PROCESSING OF CRYOMODULE IN SNS LINAC TUNNEL



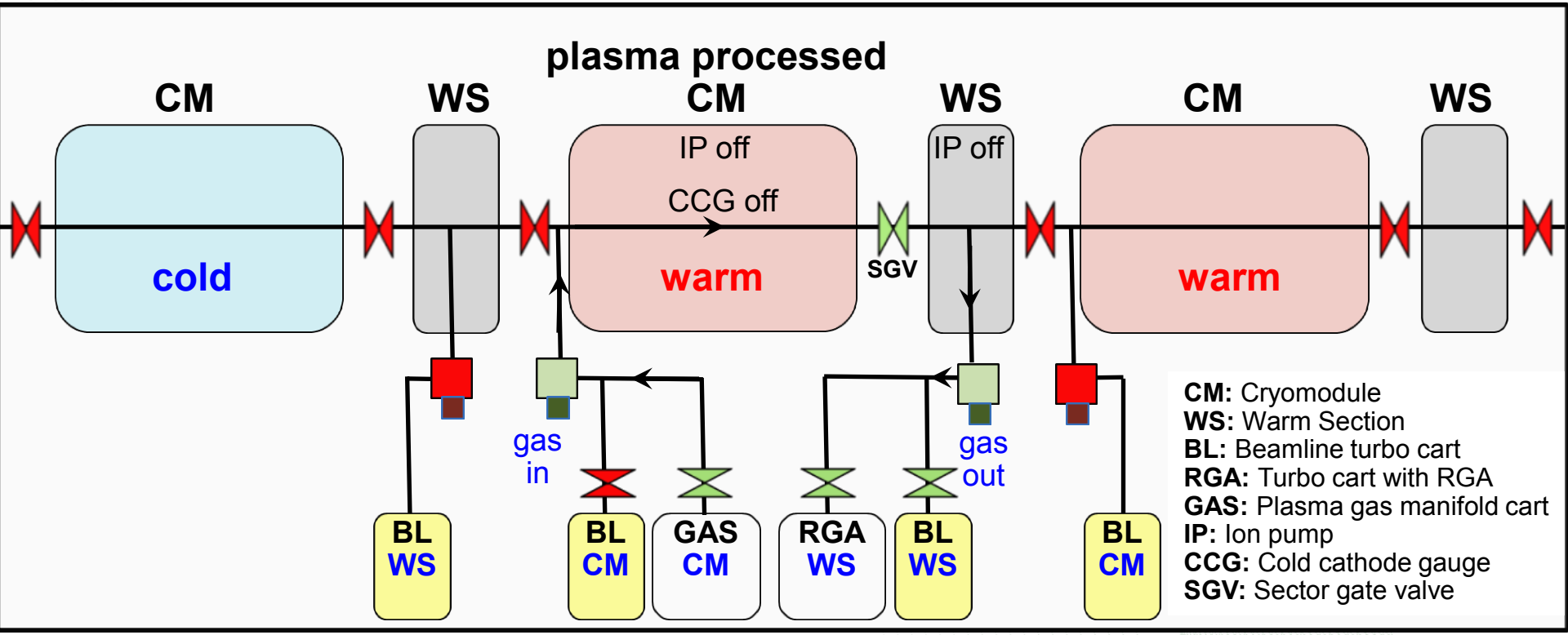
Beam



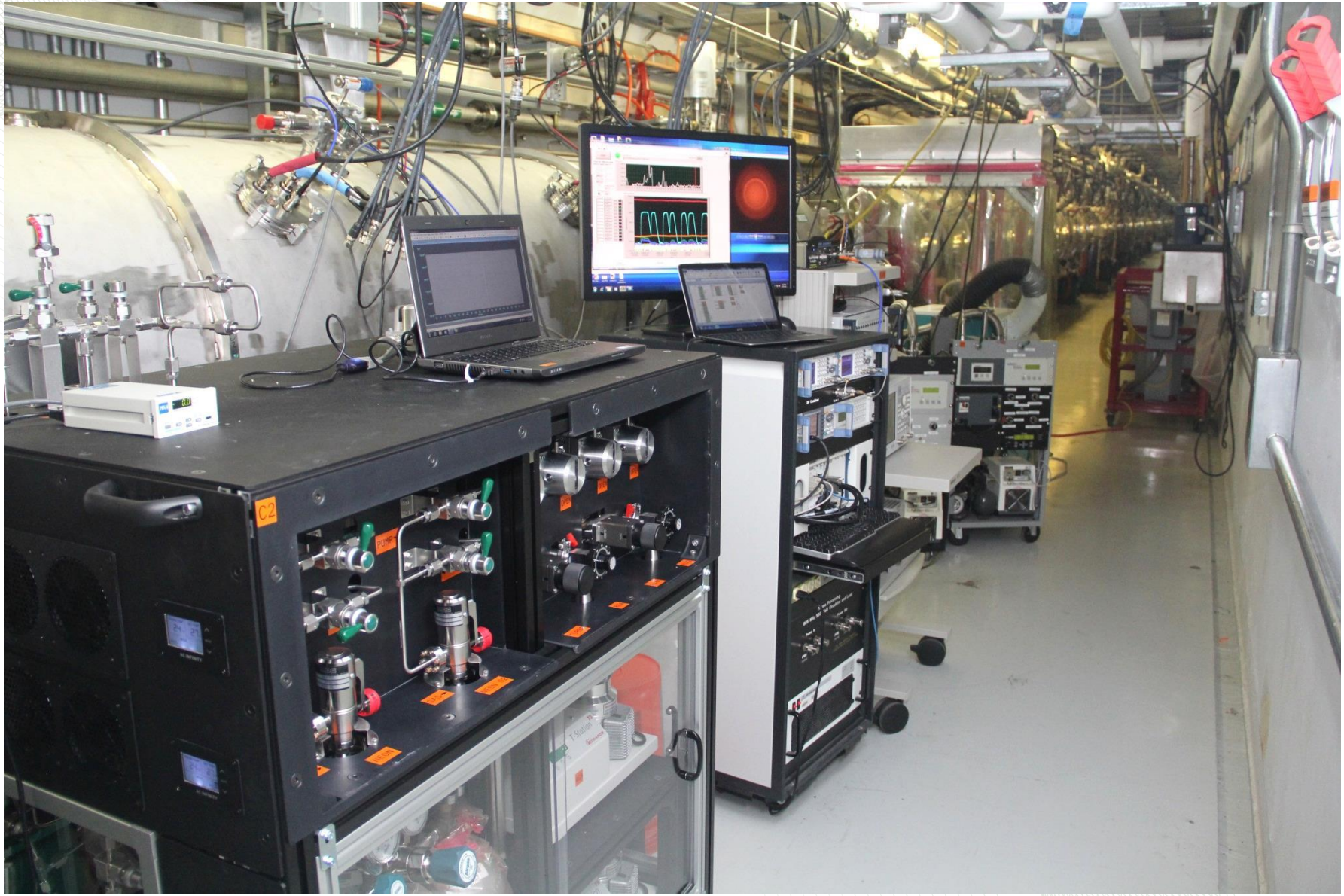
Beam

Plasma processing in SNS linac tunnel

- **Warm-up 2 cryomodules**
- **Sections seeing process gas during processing**
  - Ion pumps and CCGs off
- **Adjacent sections not seeing process gas**
  - Close sector gate valves to protect nearest cold cryomodules



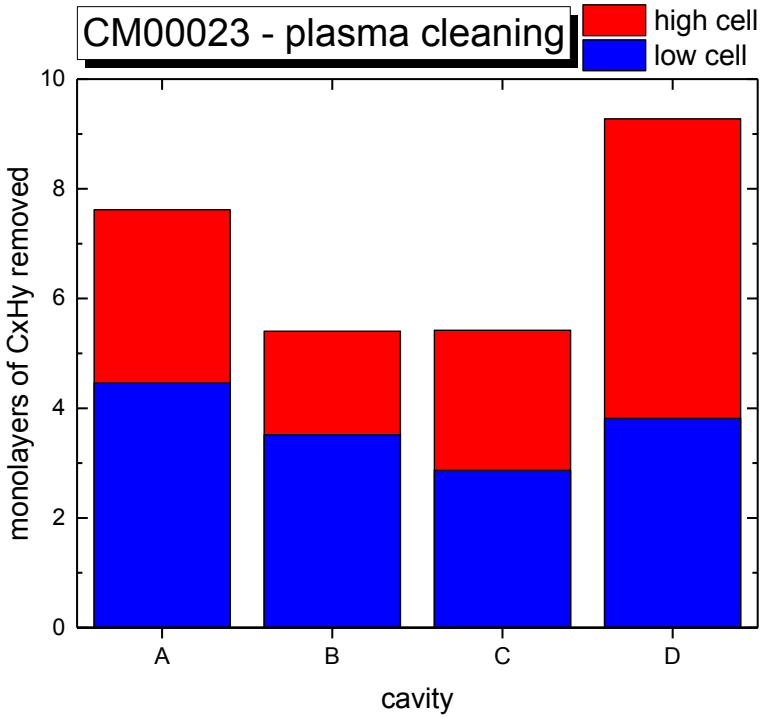
Plasma processing hardware adjacent to CM00023

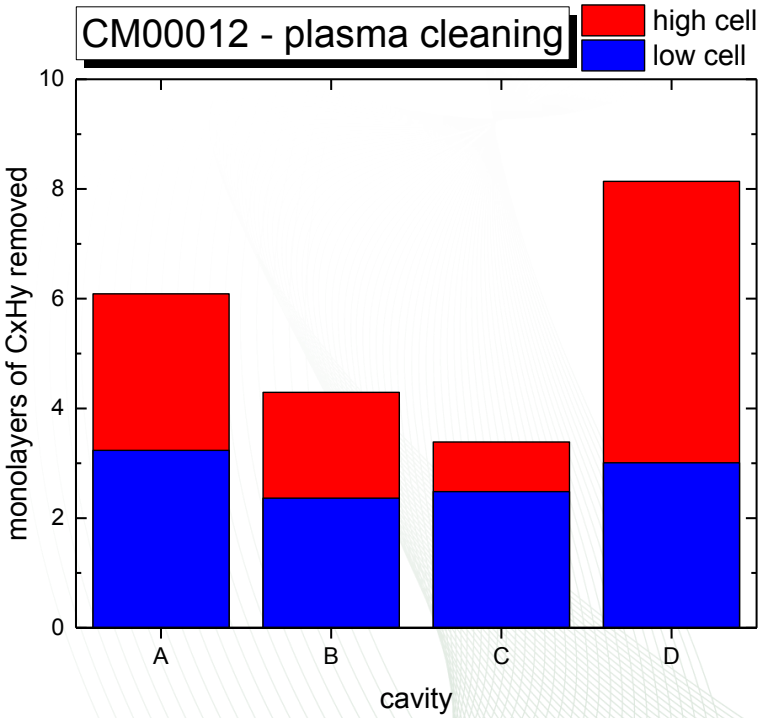


Applied ALARA: Radiation survey indicated best location for minimum radiation exposure during work (<1 mrem/hr)

First in-situ plasma cleaning of hydrocarbons in linac tunnel successfull

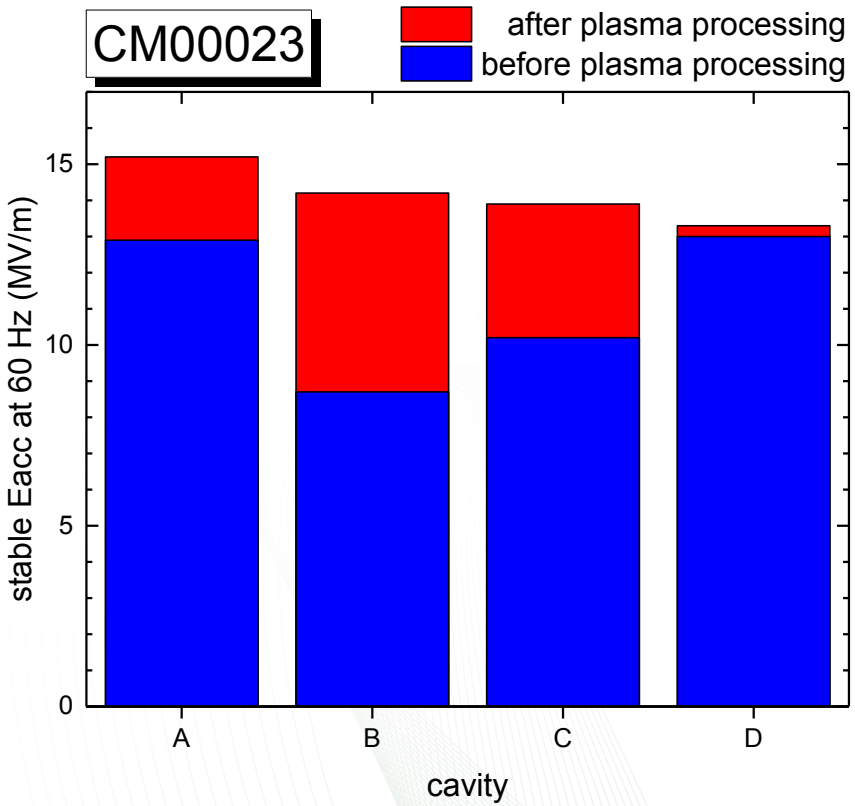
- **Removal of hydrocarbons from all 4 cavities (A, B, C, D)**
  - Blind tunning, RF probe signal useful to confirm location of plasma
- **Several monolayers equivalent removed from each cavity**
  - Contamination pattern similar to offline cryomodule
  - Used lesson learned and plasma processed cavity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





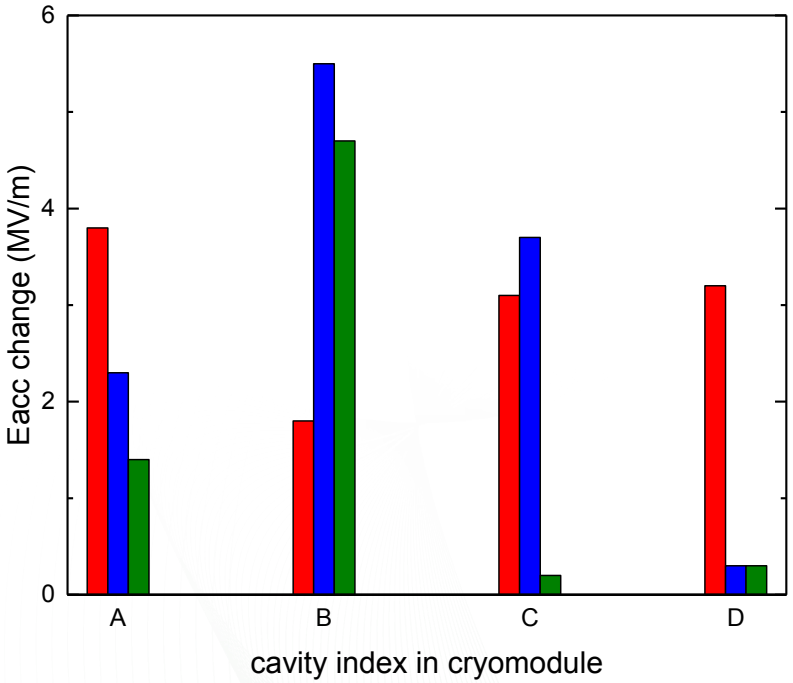
Performance of CM00023 cryomodule improved after plasma processing

- **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



3 cryomodules successfully plasma processed so far

- **1 offline cryomodule**
- **2 cryomodule in tunnel**
- **Improvement of Eacc**
  - Range from 0.2 MV/m to 5.5 MV/m
  - 2.5 MV/m increase on average (21%)
  - No cavity performance degradation from plasma processing observed so far
- **Cryomodules operating stably**
  - No change of performance after months of operation
- **SNS linac**
  - Currently operating at 972 MeV
  - Highest energy on production target at 60 Hz to date



CONCLUSION

- **In-situ plasma processing developed at SNS to increase accelerating gradient of cryomodules 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**
  - 2 cavities in HTA
  - 1 offline cryomodule
  - 2 cryomodules in linac tunnel
- **Further deployment of plasma processing in SNS linac tunnel to high-beta cryomodules planned for FY17**
- **Near term goal is to reach 1 GeV linac beam energy at 60 Hz**
- **Applicability of the new technique to other SRF cavities is being explored**