Plasma processing boosts the energy of the SNS superconducting linac

Marc Doleans for ORNL

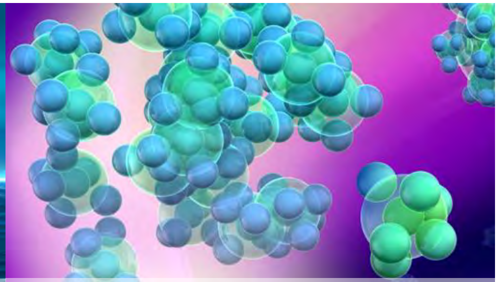
FRIB-APES Seminar

22 October 2021

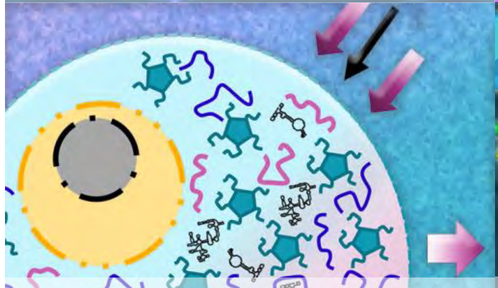
Overview

- Spallation Neutron Source at ORNL
  - Neutron scattering research for new discoveries in physics, biology, chemistry, materials science and engineering
  - 1.4 MW proton accelerator produces neutrons by spallation on a liquid mercury target

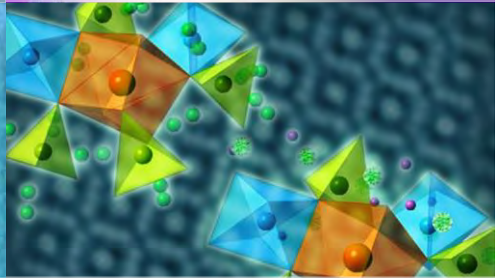
Nature **569**, 495-496 (2019)



ACS Cent. Sci. 2019, **5**, 1, 85–96



Molecular Cell **74**, 713–728 (2019)



Energy Environ. Sci.,2019, **12**, 945

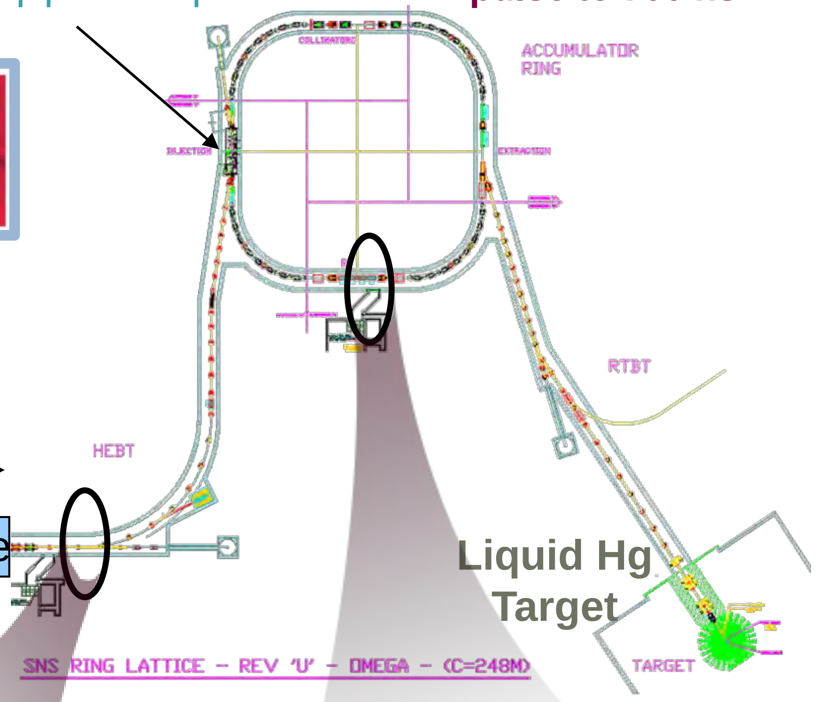
Aerial view of SNS at ORNL

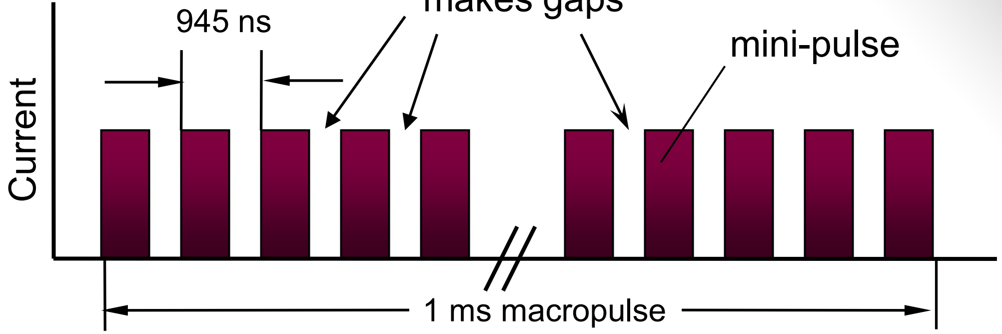
SNS Accelerator

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

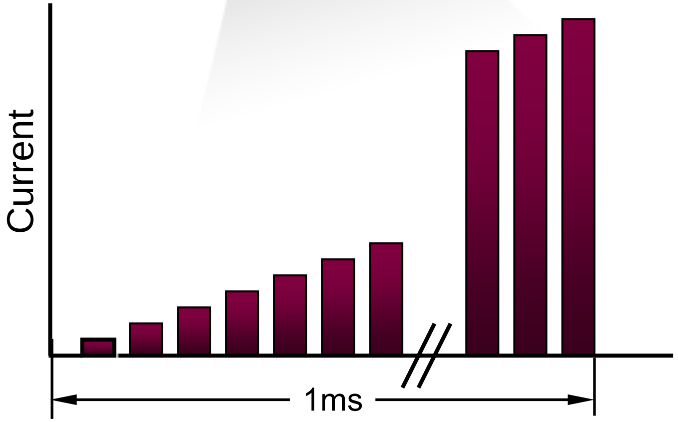
LINAC:
Accelerates beam to 1 GeV
SRF linac 23 cryomodules

Accumulator Ring:
Compress 1 msec long pulse to 700 ns





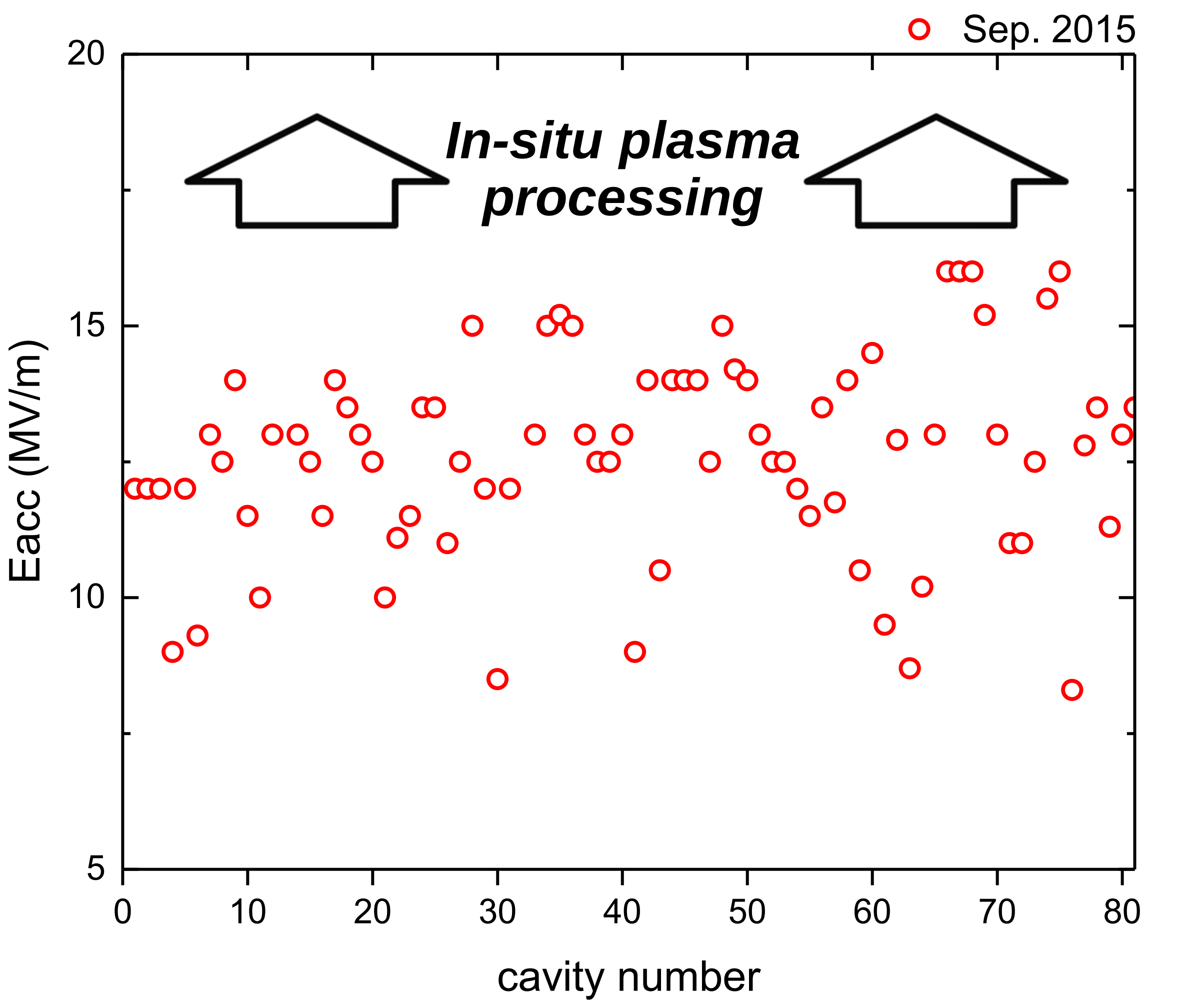
Average macropulse beam current: 26 mA



Nucl. Instrum. Methods Phys. Res. A **763 (2014) 610-673**

In-situ Plasma Processing to Reach 1 GeV Beam Energy

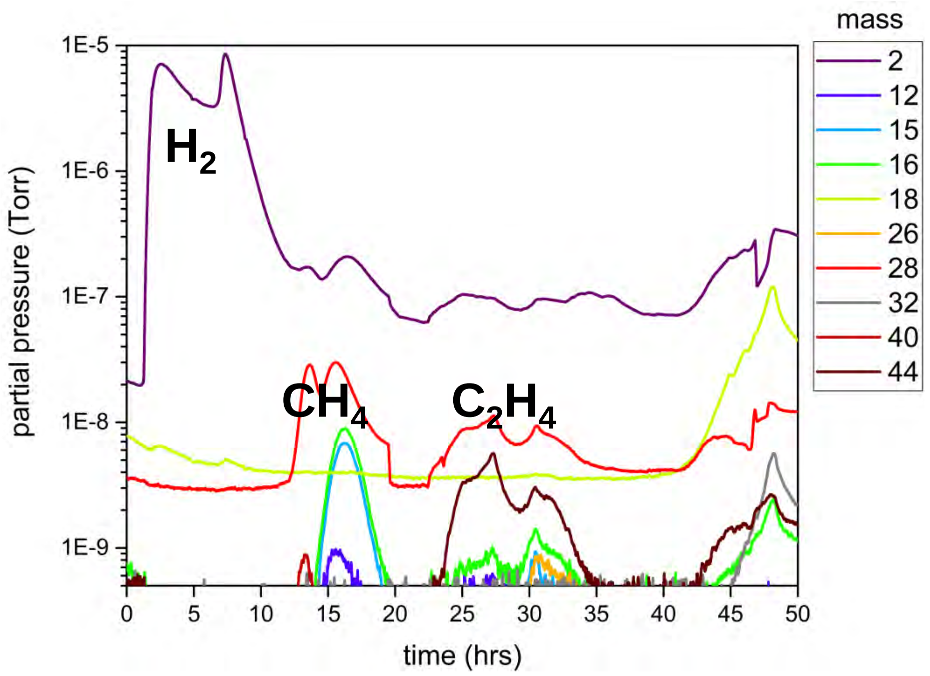
- Higher linac energy provides more margin for reliable operation at 1.4 MW
  - Goal was to improve from 940 to 1000 MeV beam energy at 60 Hz
- Most cavities at SNS are limited by field emission (FE) leading to thermal instability in end-groups
  - Average accelerating gradients are 12 and 13 MV/m for the two cavity geometries
- Developed in-situ plasma processing to reduce FE and increase accelerating gradients*

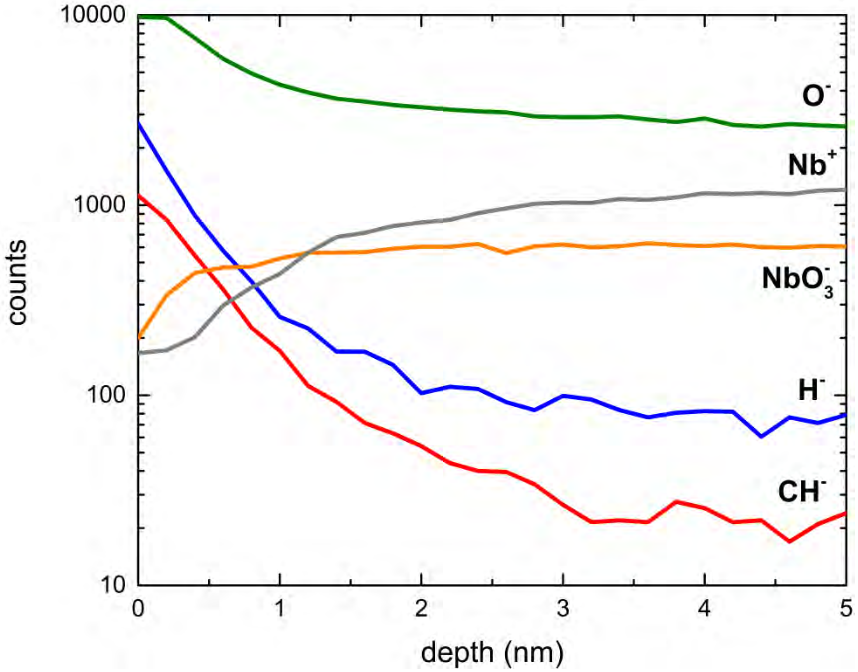


Nucl. Instrum. Methods Phys. Res. A **852** (2017) 20–32

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 on Nb small samples in secondary ion mass spectrometry (SIMS)
- Hydrocarbons tends to lower work function of Nb surface
  - Develop in-situ plasma processing to remove hydrocarbons from cavity RF surface





In-situ plasma processing to reduce field emission

- 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

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

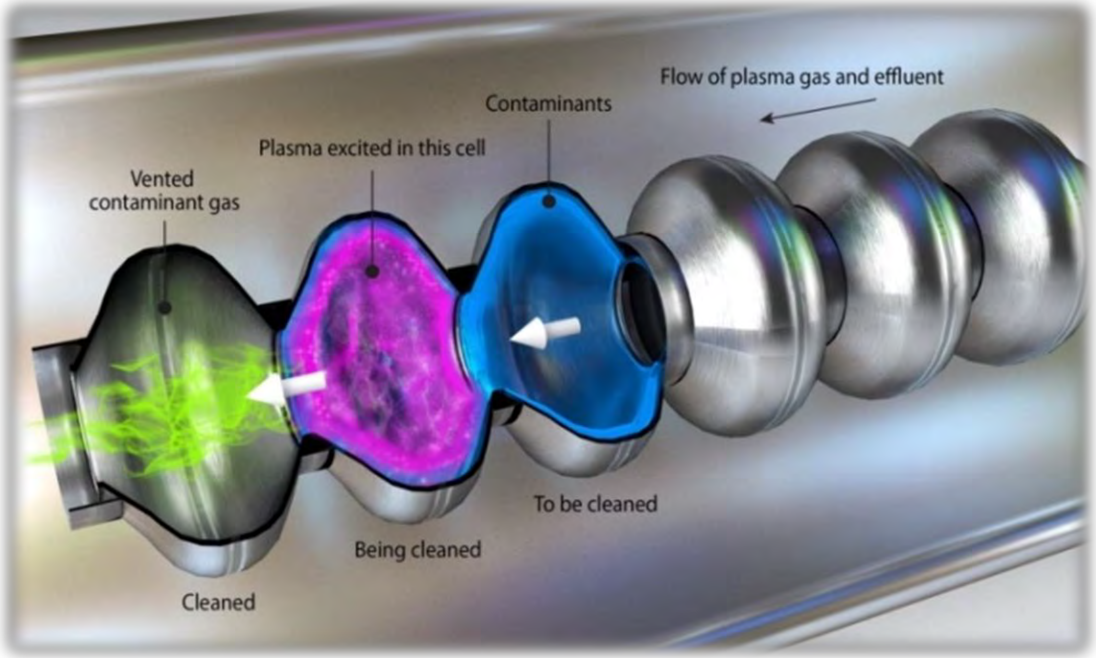
$$dJ = 0 \quad \Rightarrow \quad \frac{dE_{acc}}{E_{acc}} \approx \frac{3}{2}\frac{d\phi}{\phi}$$

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

Oxygen plasma for removing hydrocarbons

- 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

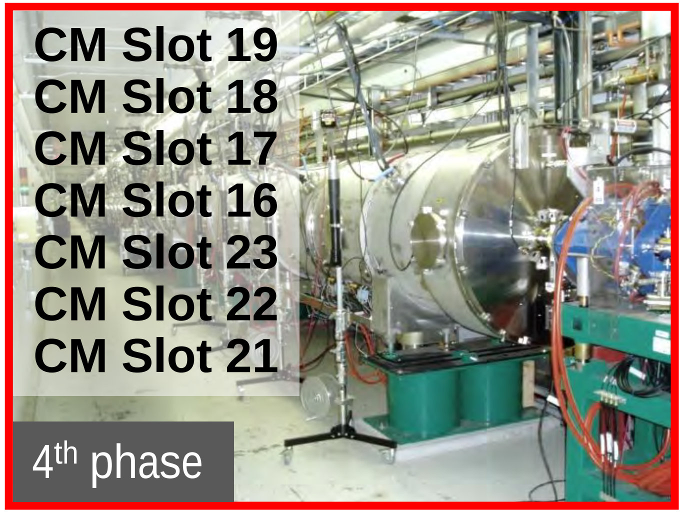


Nucl. Instrum. Methods Phys. Res. A **812**, 50–59 (2016)

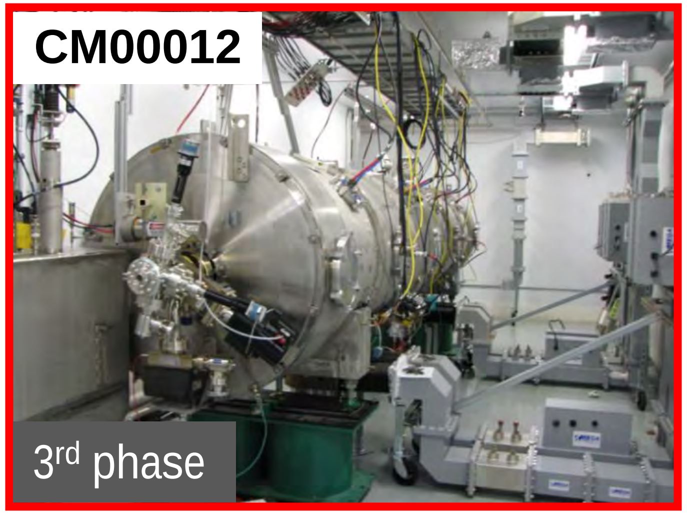
Plasma processing R&D strategy

R&D with Nb samples and offline cavities

Processing of 6-cell cavity in HTA*



In-situ processing in linac tunnel

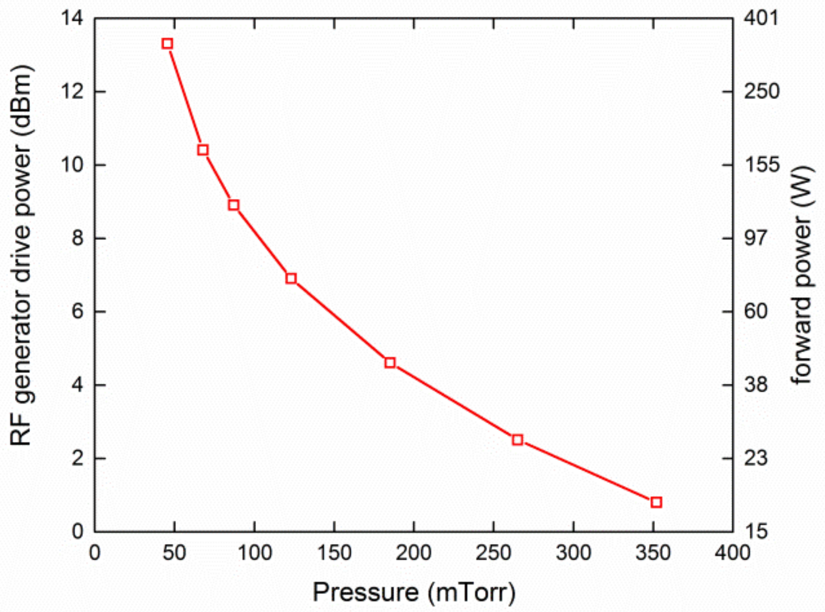


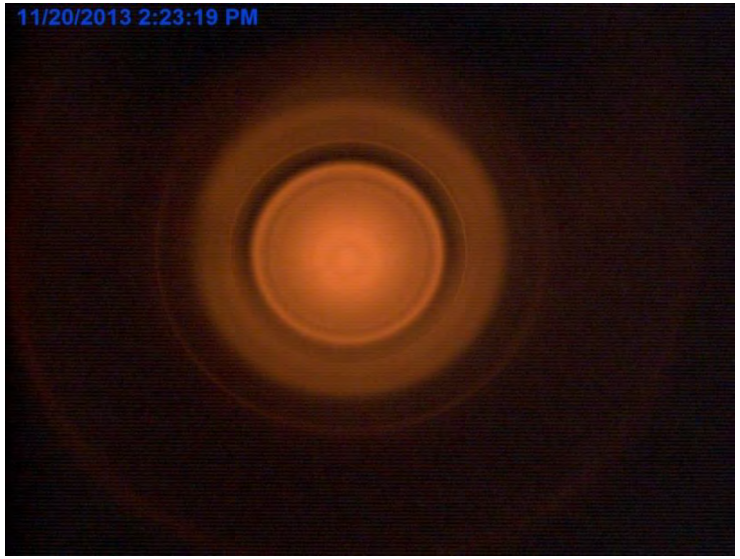
Processing of cryomodule in test cave

Proceedings of SRF2013, Paris, France, paper TUP057

Plasma ignition

- Dependence on gas mixture, pressure and RF mode
  - Determine best gas for plasma ignition/control - Neon at SNS
    - pumping, optical monitoring, stability
  - Determine working pressure – 150 mTorr at SNS
    - RF power, stability & sensitivity, margin cell/coupler
  - Map ignition conditions for each RF modes – 6 modes at SNS

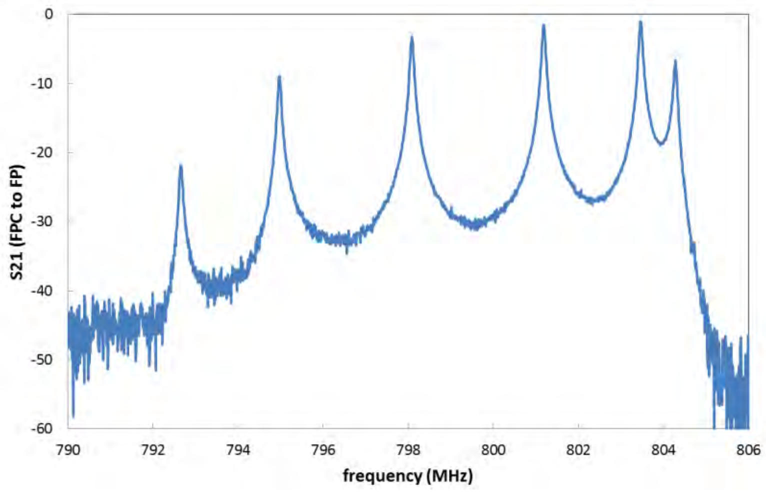


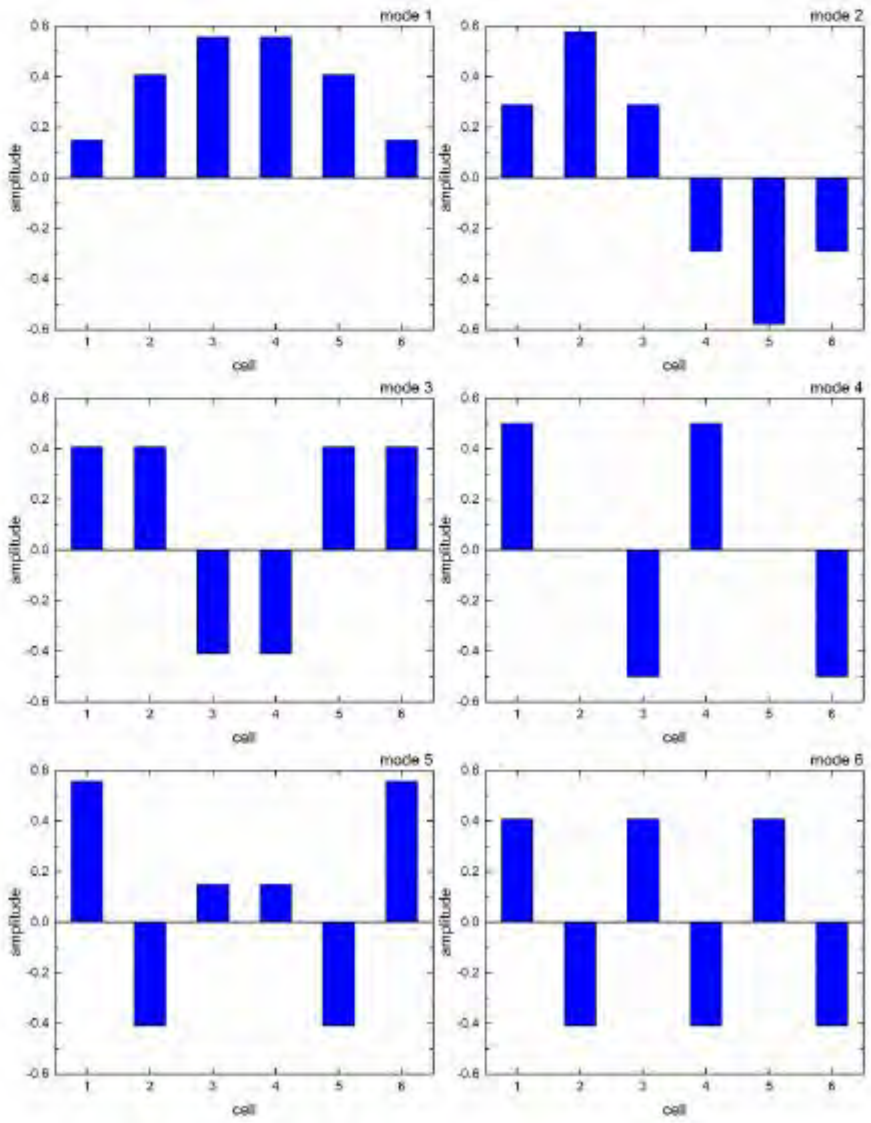


Fundamental passband modes

- 6-cell cavities provide six mode-patterns to be used for controlling the discharge in each cell of the resonators
- Mode 6 is the one used for beam acceleration
- Using modes on resonance can't break the left/right symmetry of the system

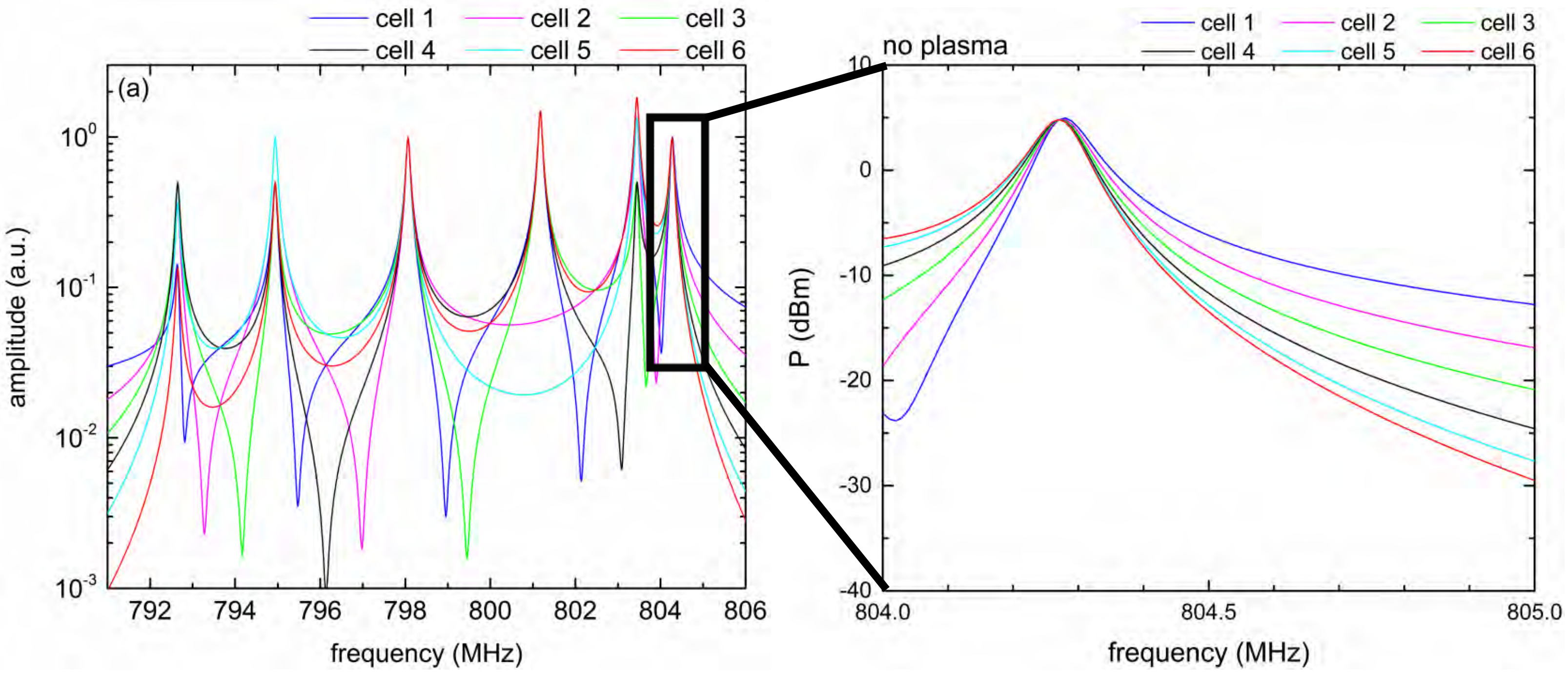
	freq	ign
	MHz	dBm
mode 1	792.664	10.9
mode 2	794.977	6.5
mode 3	798.089	5.9
mode 4	801.185	2.1
mode 5	803.462	1.3
mode 6	804.281	5.8





Plasma ignition in each cell of the SNS cavities

- Off-resonance mode excitation provides a way to break the symmetry and target each cell individually
- Off-resonance excitation is inefficient
- Dual-tone excitation
  - 1 mode on resonance +
  - 1 mode off resonance



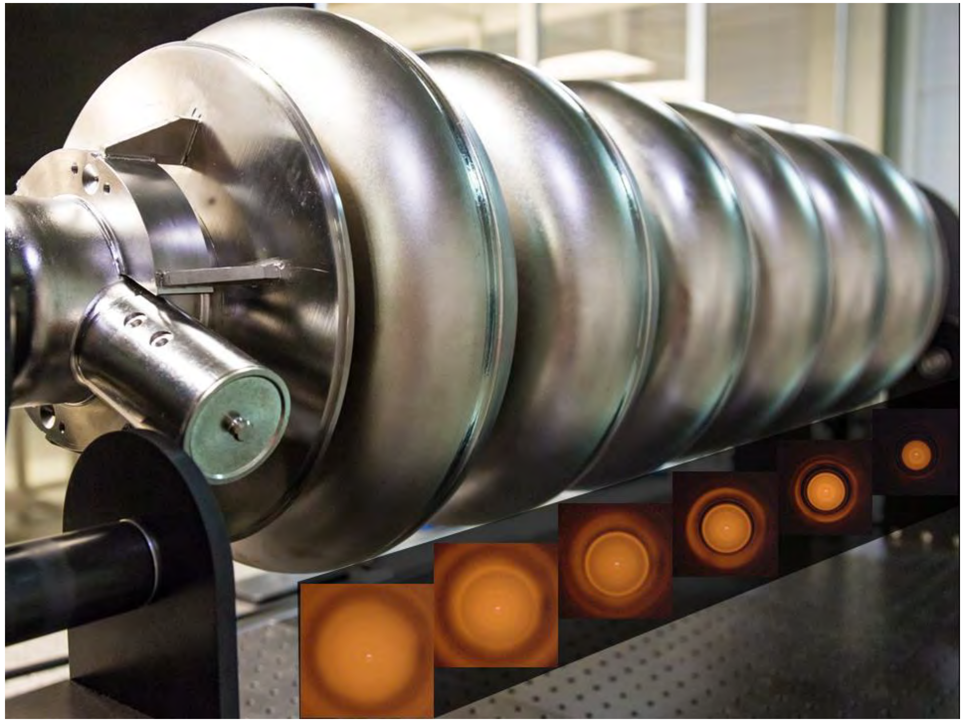
Dual-tone ignition parameters for *high-beta cavities*

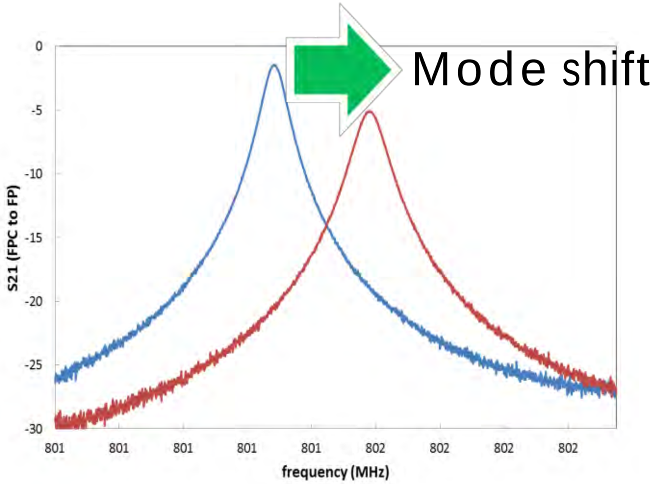
Cell ignition	RF gen. 1	δf_1 (hbw)	p_{RF1} (dB)	RF gen. 2	δf_2 (hbw)	p_{RF2} (dB)	Γ_1	Γ_2	Γ_3	Γ_4	Γ_5	Γ_6
1	mode 5	−1.0	−4.57	mode 6	+0.50	−3.46	1.00	0.72	0.41	0.37	0.62	0.90
2	mode 2	0.0	−2.02	mode 5	−2.50	0.87	0.74	1.00	0.24	0.18	0.88	0.69
3	mode 1	0.0	−1.80	mode 3	−1.50	4.15	0.88	0.80	1.00	0.91	0.89	0.78
4	mode 1	0.0	0.63	mode 4	−2.25	2.79	0.77	0.16	0.92	1.00	0.16	0.69
5	mode 2	0.0	−1.13	mode 6	−2.50	0.99	0.27	0.88	0.36	0.40	1.00	0.44
6	mode 5	0.0	−8.26	mode 6	−1.25	0.32	0.80	0.62	0.44	0.49	0.75	1.00

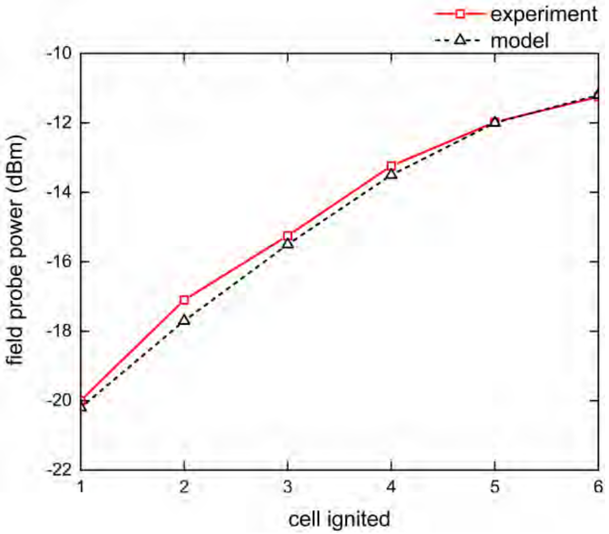
J. Appl. Phys., **120**, 243301 (2016)

Plasma monitoring

- The plasma discharge changes the dielectric constant and frequency of the cell
- This leads to an upward shift of the cell frequency and perturbation of the mode pattern (i.e. cell amplitudes)
- This perturbation can be used to locate the plasma inside the cavity without needing optical monitoring
  - Only using frequency shift of mode contains left/right ambiguity







J. Appl. Phys., **120**, 243301 (2016)

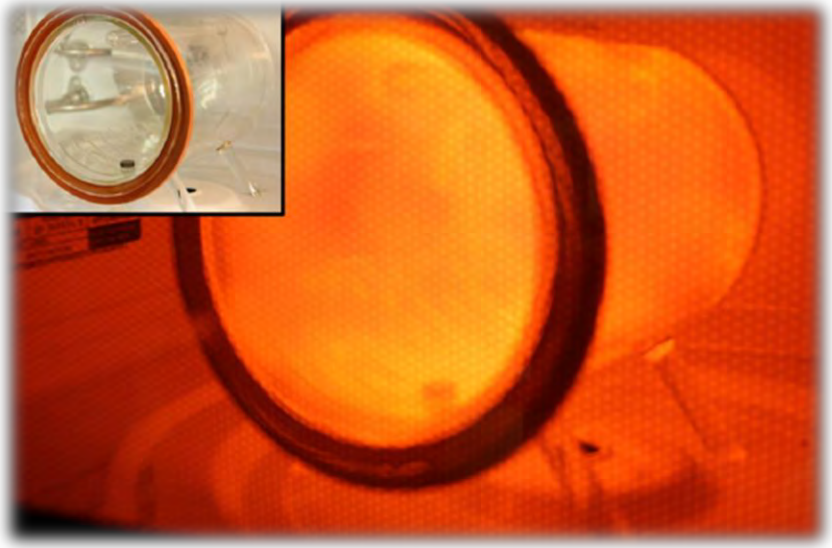
Plasma cleaning studies

- Plasma cleaning studies on small samples were conducted using a microwave barrel station

- Samples were introduced in the barrel and plasma cleaned using a neon oxygen mixture under various conditions

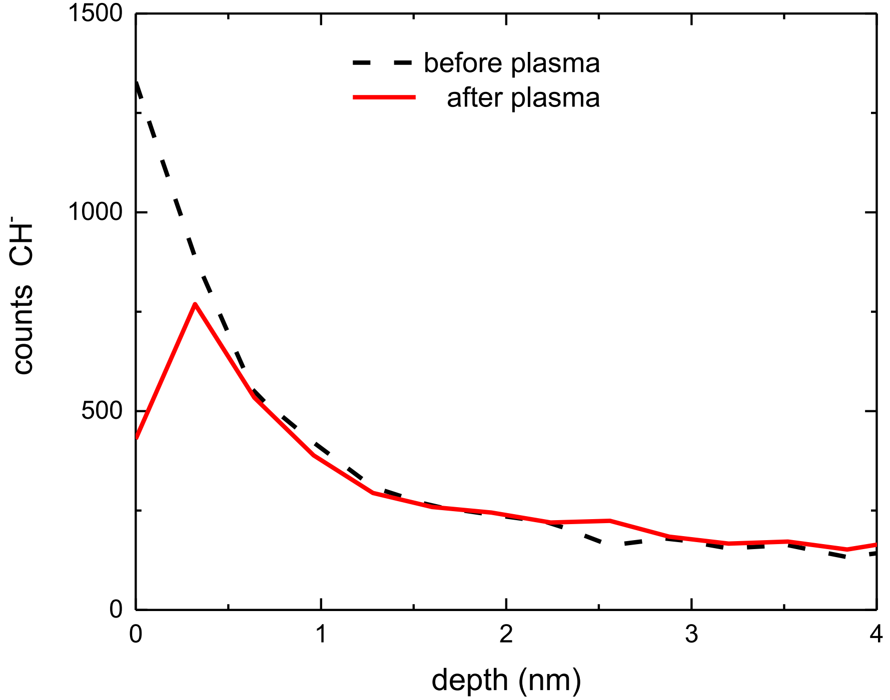
- Heating effects were mitigated by spacing out short plasma cycles and subsequently by using a cooled sample stage

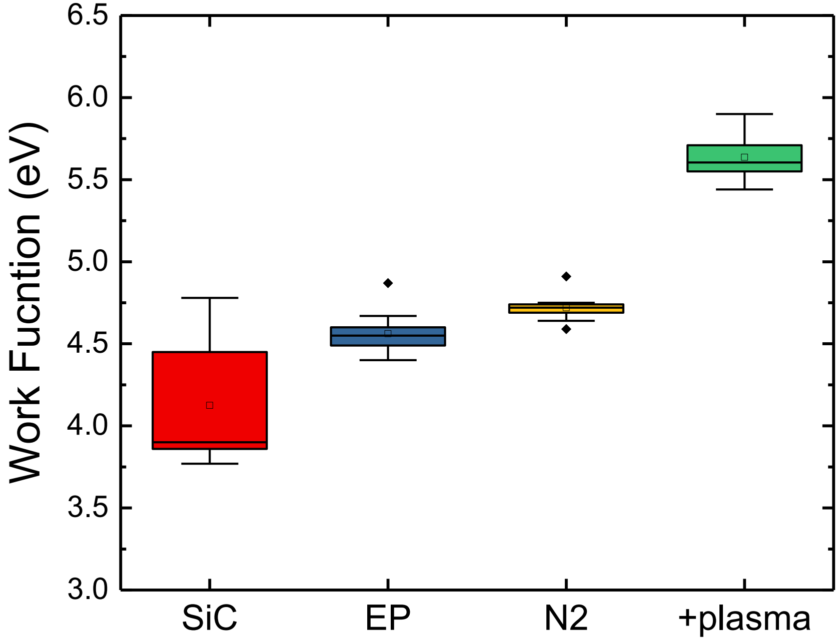
- Surface studies were conducted before and after plasma processing
  - Microscope, SIMS, Kelvin probe



Work function increase

- 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

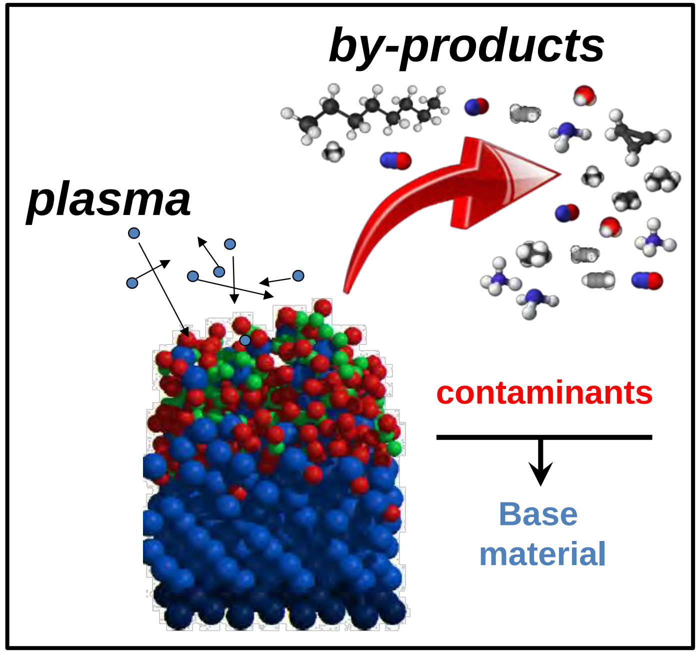


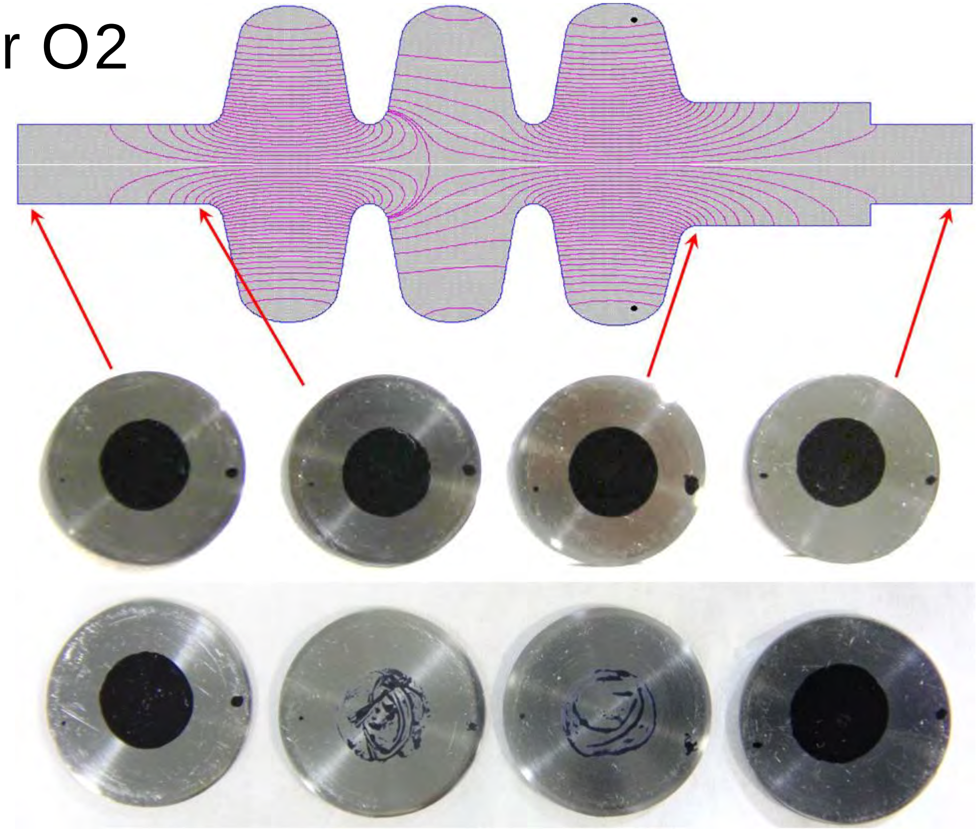


Applied Surface Science **369** (2016)

Plasma cleaning of contaminated samples in cavity

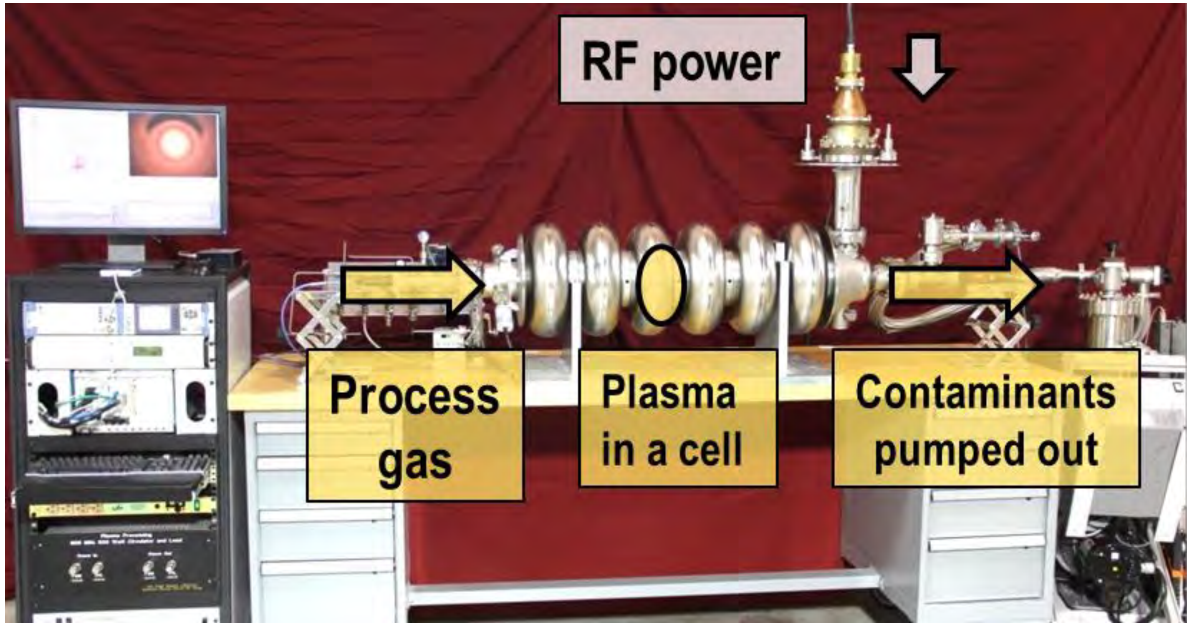
- Contaminated samples were introduced in a 3-cell cavity
- Plasma was generated in the end cells
  - Samples adjacent to end cells were being cleaned
  - Samples farther away weren't
  - Atomic O recombines into molecular O2

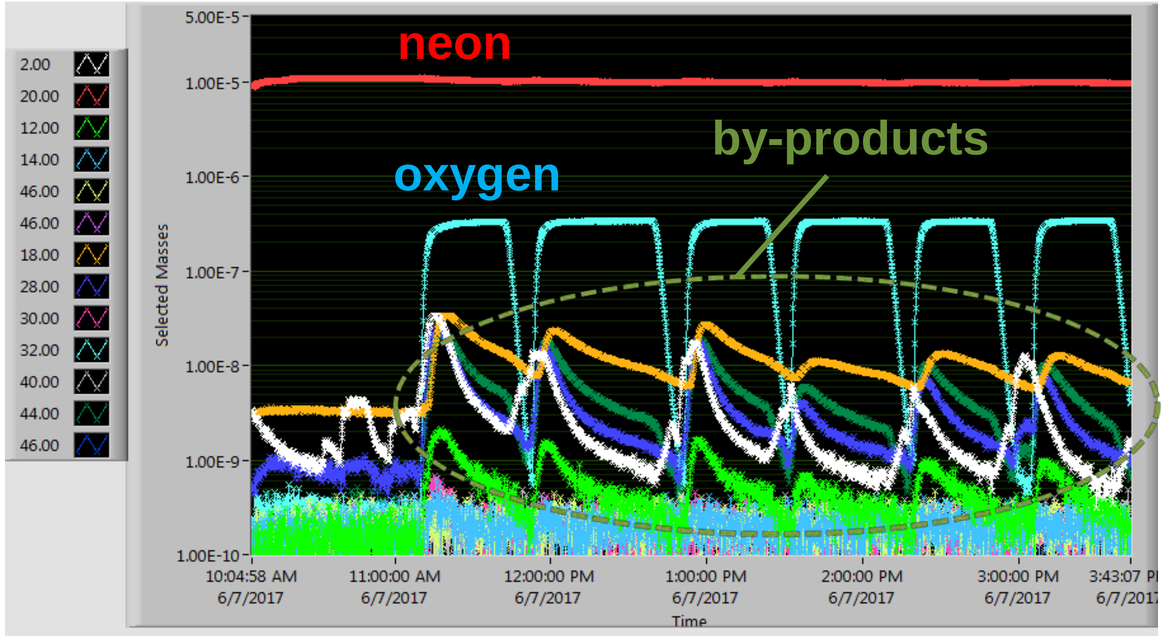




Monitoring of by-products during plasma processing

- Residual gas analysis during cleaning of the cavities
  - Volatile by-products of hydrocarbon oxidation are measured in real time
  - Decrease of their partial pressure indicate the top surface is being depleted of CxHy
  - Typical processing time per cell ~1hour per plasma cycle

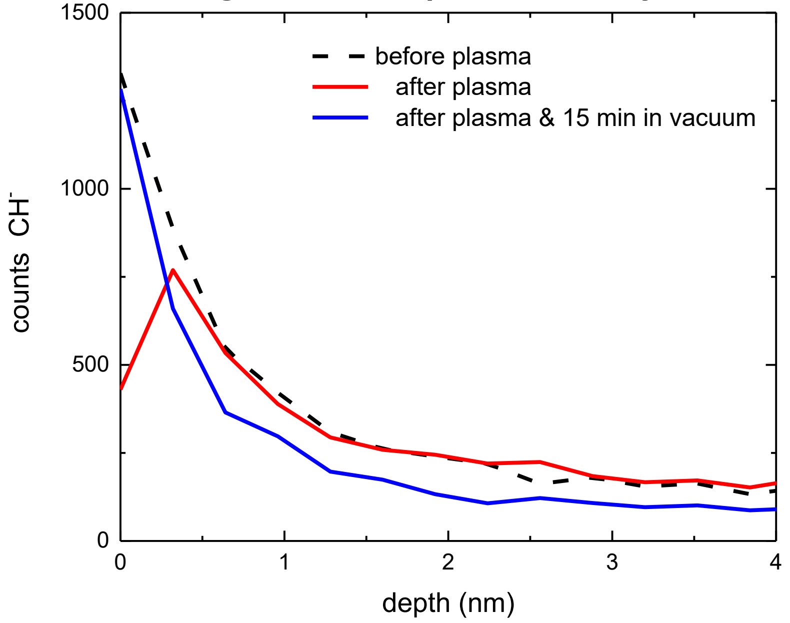




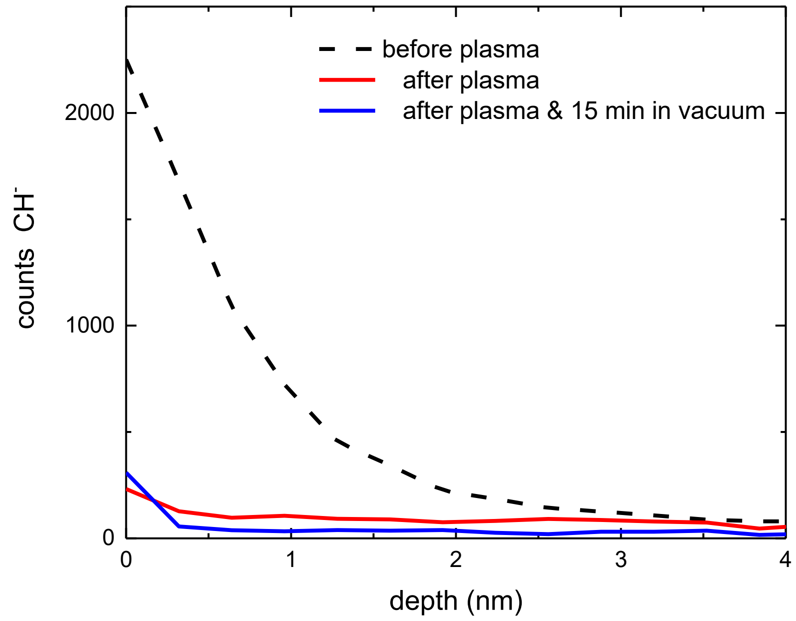
Mutiple plasma processing cycles

- Our plasma cleaning is a top surface process
- Over time at room temperature diffusion of of hydrocarbons from under layers to the top surface has been observed
  - For cavities, multiple cleaning cycles over a couple of weeks has shown to be an effective solution

Single short plasma cycle

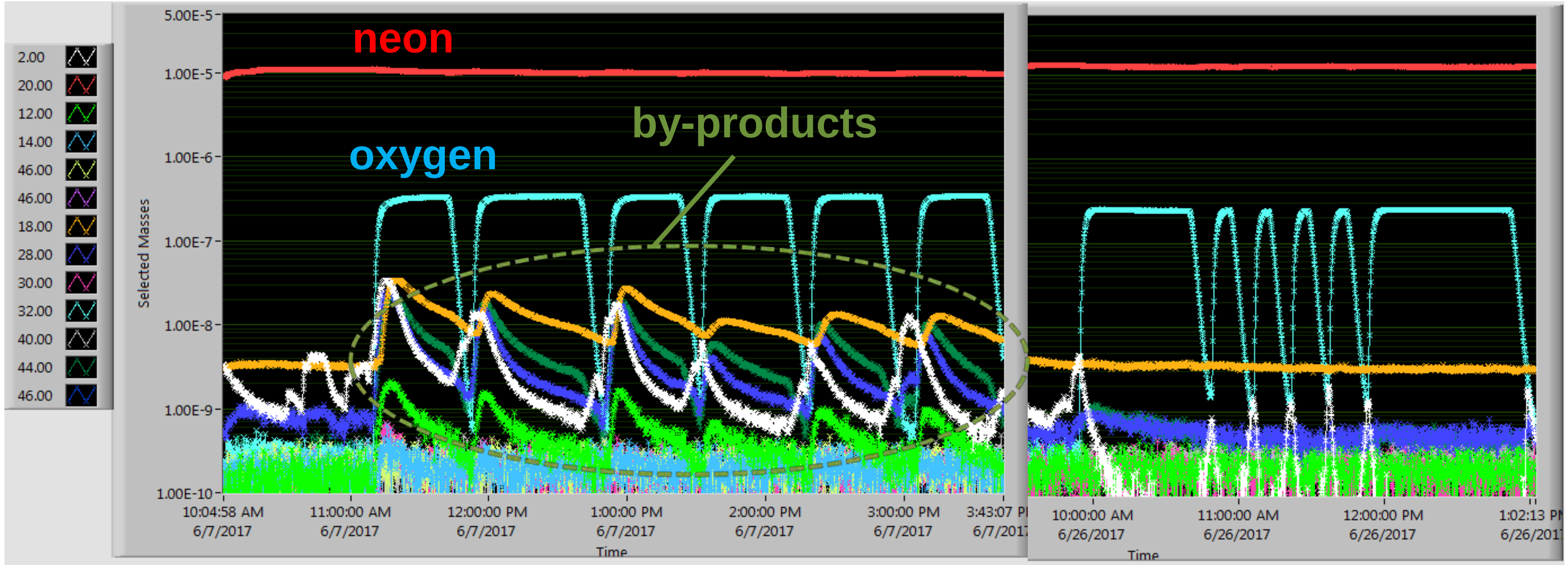


Multiple plasma cycles



Multiple cleaning cycles applied to cavities

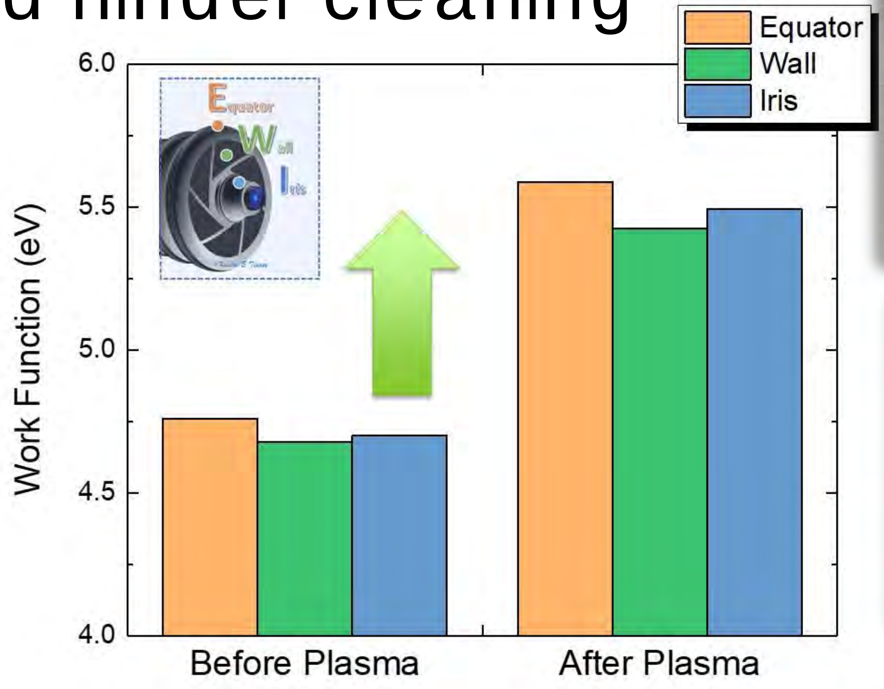
- 5 plasma cycles over 2 weeks is typical for plasma processing of cryomodules at the SNS
- Partial recovery of by-product between (early) cycles has been observed
- RF power to induce the discharge tends to increase as the surface gets cleaner, typically by about 1 dB

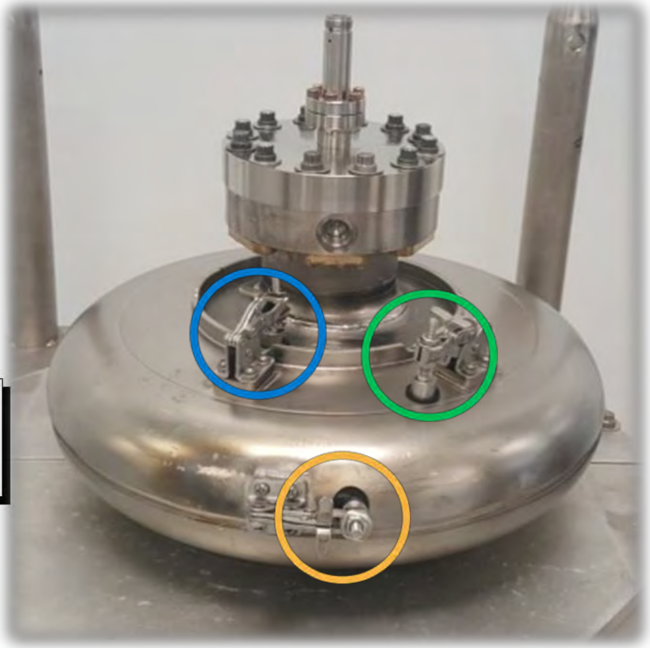


Cycle 1 Cycle 4

Plasma cleaning efficient from iris to equator

- Plasma cleaning studies were conducted in single cell cavity with small samples cut-outs
- Non uniformity of plasma density and recombination of atomic oxygen into molecular oxygen could hinder cleaning efficiency
- Samples inserted at various locations
  - Iris, wall and equator
- Work function shown to increase for all locations





Single-cell cavity with small sample cut-outs.

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

Proceedings of IPAC18, Vancouver, Canada, paper THPAL065

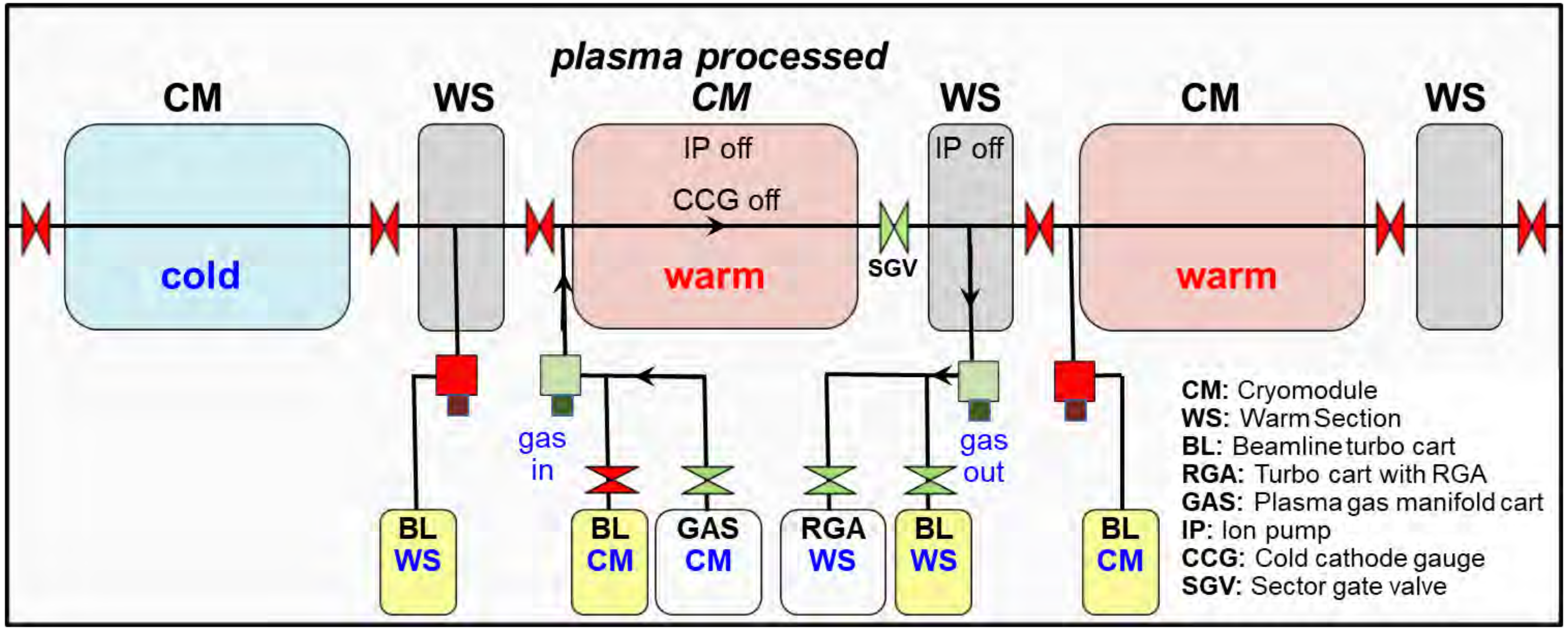
In-situ plasma processing at SNS

- Hardware comprises gas injection, RF and pumping systems
- Packaged in carts and rolled adjacent to the CM for plasma processing
- ~2 weeks to warm-up, plasma process and cool back down a CM

Gas injection system **RF systems** **Pumping system**

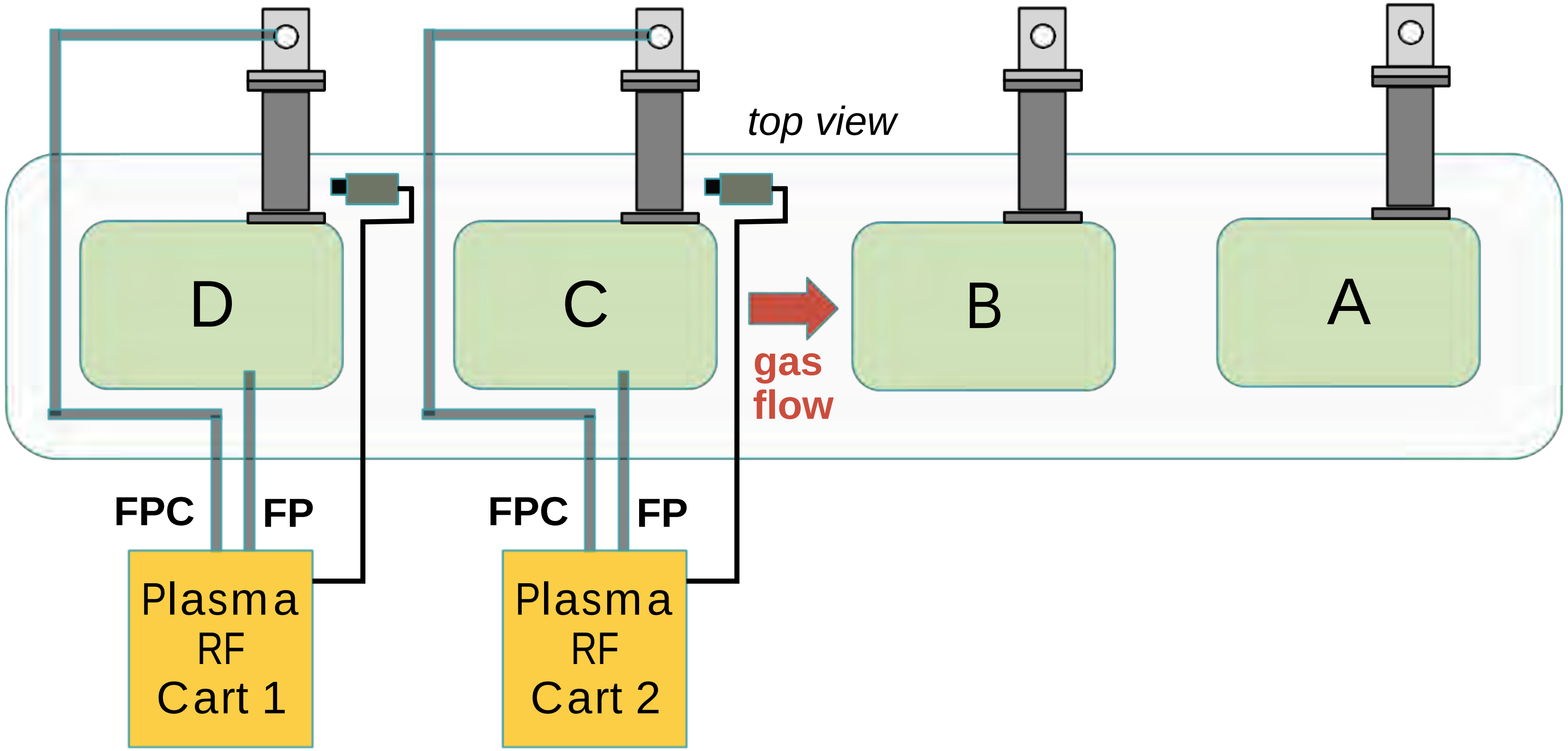
In-situ plasma processing in SNS linac - vacuum

- Warm-up 2 cryomodules
- Sections seeing process gas
  - Ion pumps and CCGs off
- At least 2 sector gate valves between process gas and cold surface
  - Mitigates risk of gas condensation on cold surfaces
  - Active pumping in the buffer sections aadjacent to plasma processed CM

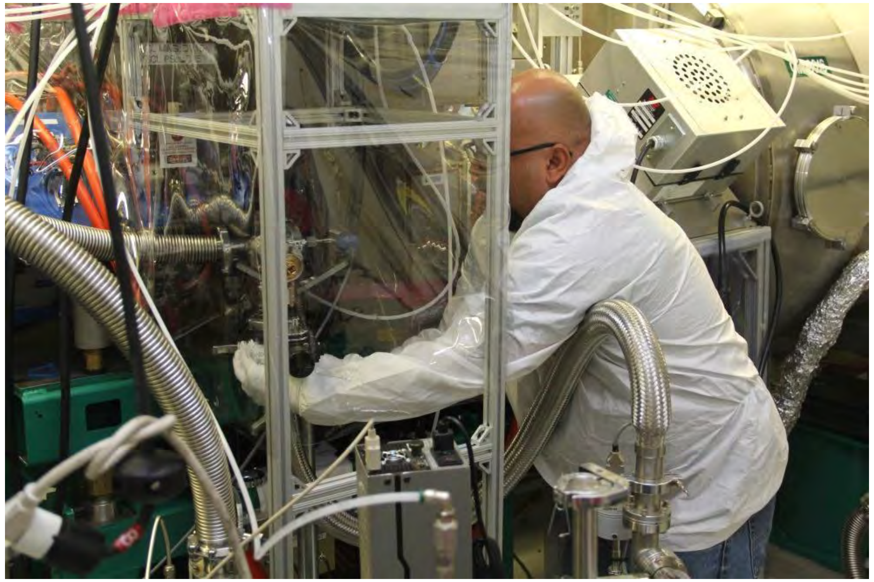


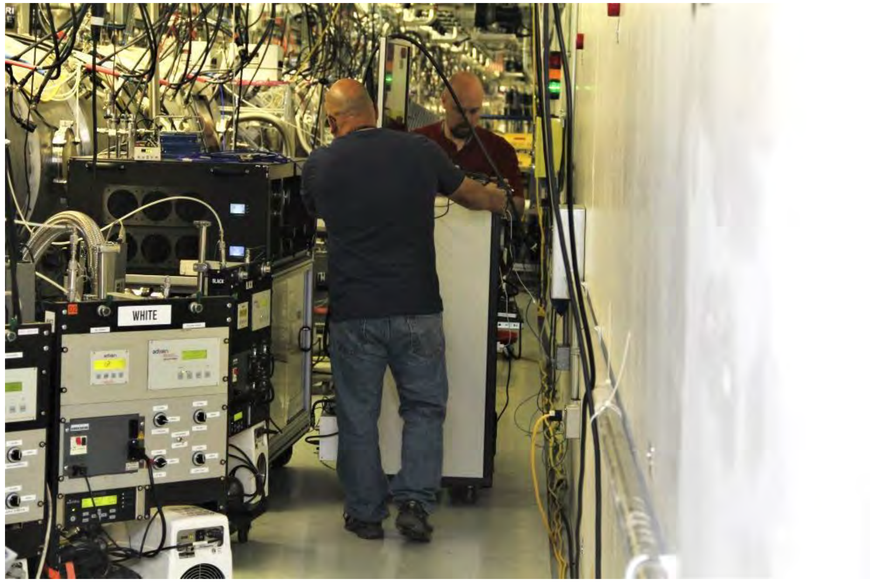
In-situ plasma processing in SNS linac - RF

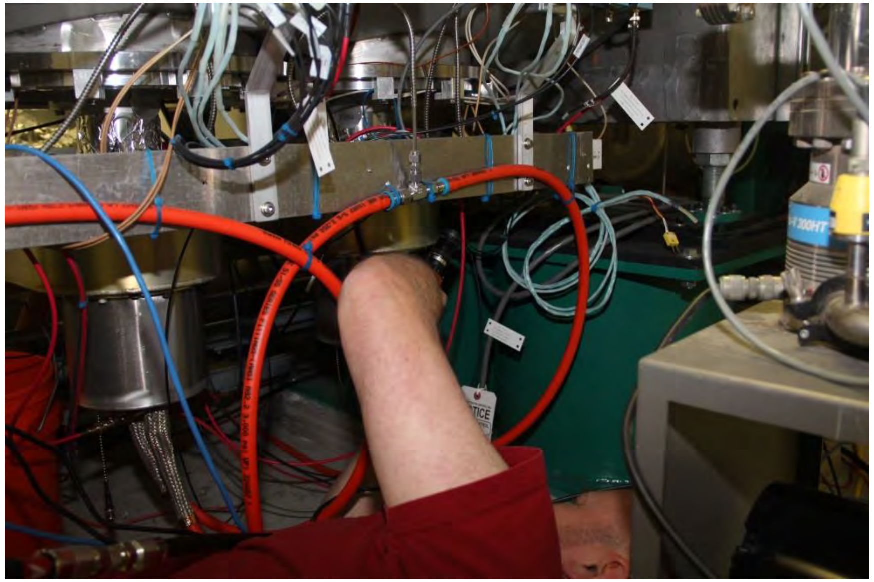
- All cavities disconnected from High power RF system
- High power top-hats on each cavity (2kW rated)
  - No need to remove air side of coupler assemblies
- Cavities processed iteratively
  - Multiple RF carts for simultaneous plasma processing of cavities
- Cavities being plasma processed
  - FPC and field probe connected to RF cart
  - Camera monitors any discharge in FPC

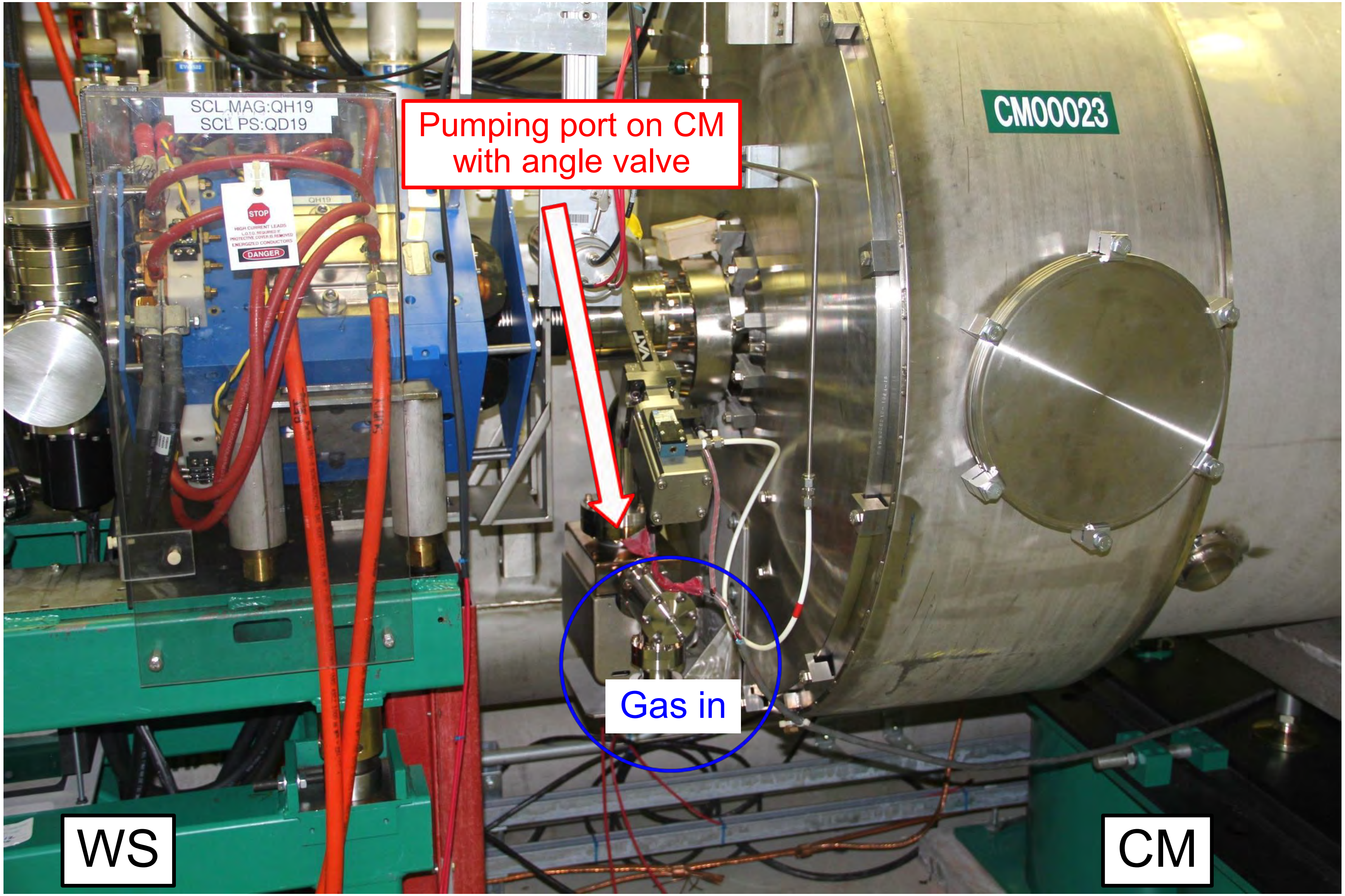


Installation of plasma processing hardware





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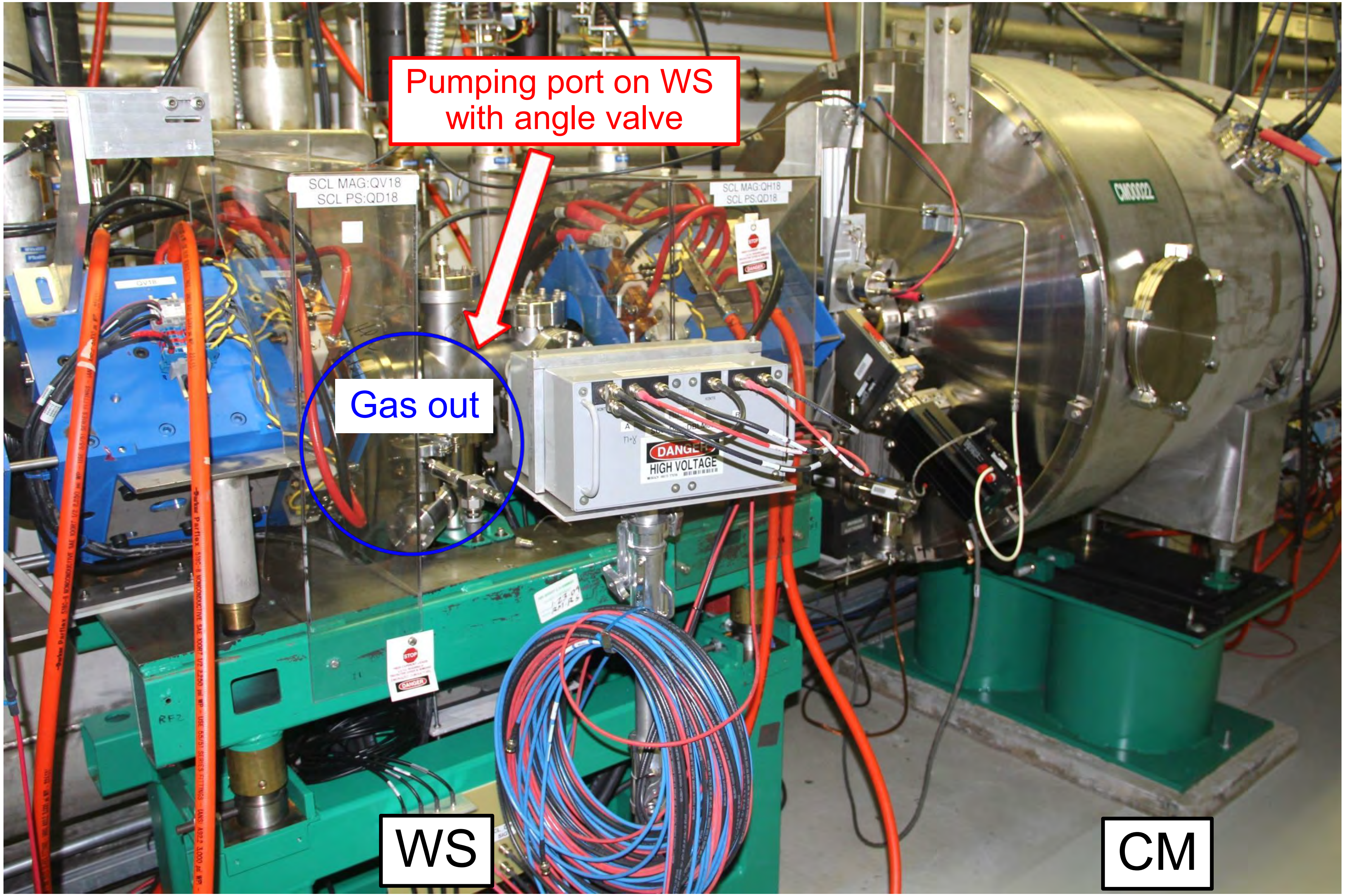
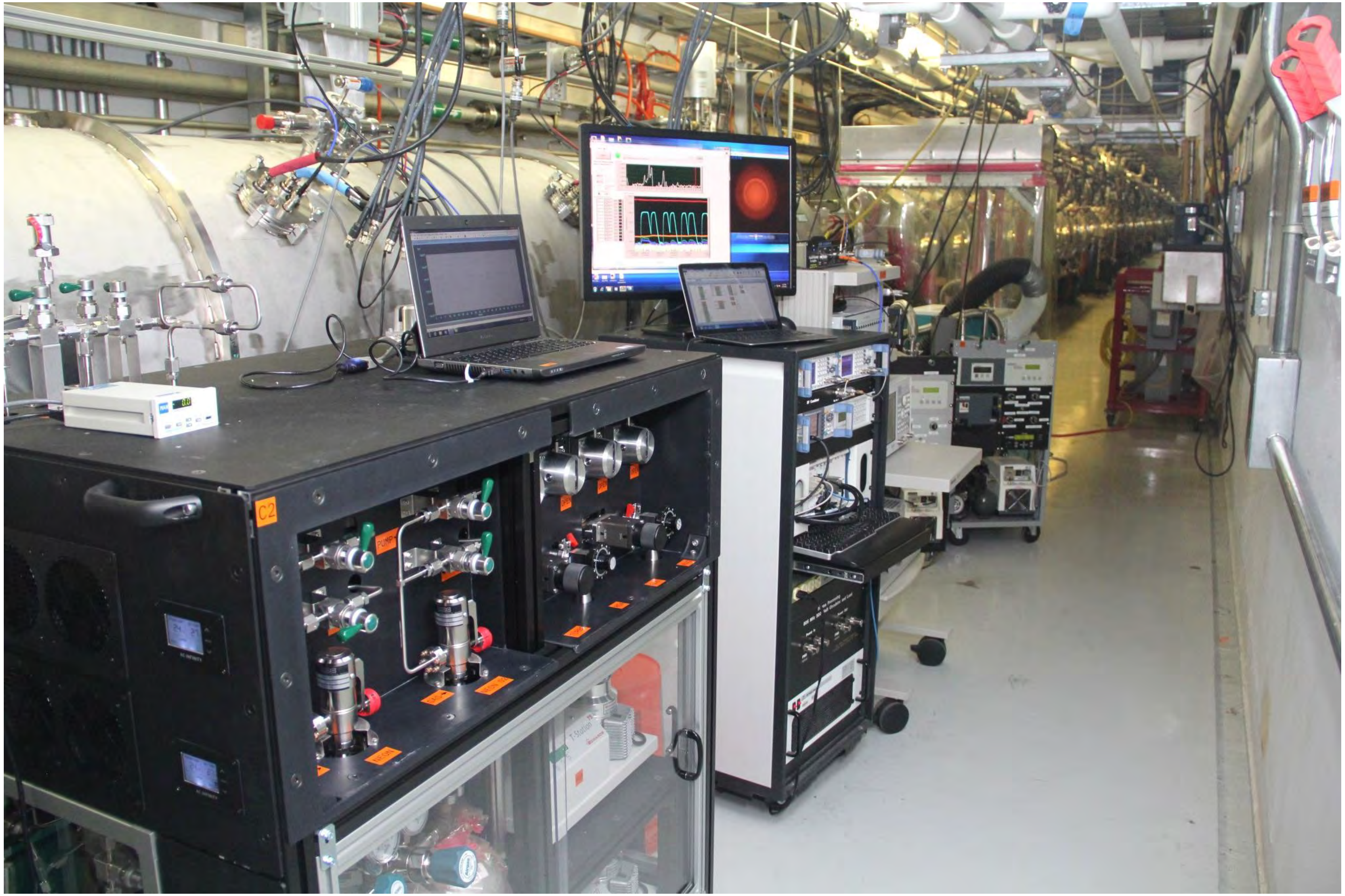
STOP
DANGER
CM00023
Pumping port on CM with angle valve
Gas in
WS
CM

Beam


Pumping port on WS
with angle valve
SCL MAG:QV18
SCL PS:QD18
SCL MAG:QH18
SCL PS:QD18
Gas out
DANGER
HIGH VOLTAGE
WS
CM

Beam

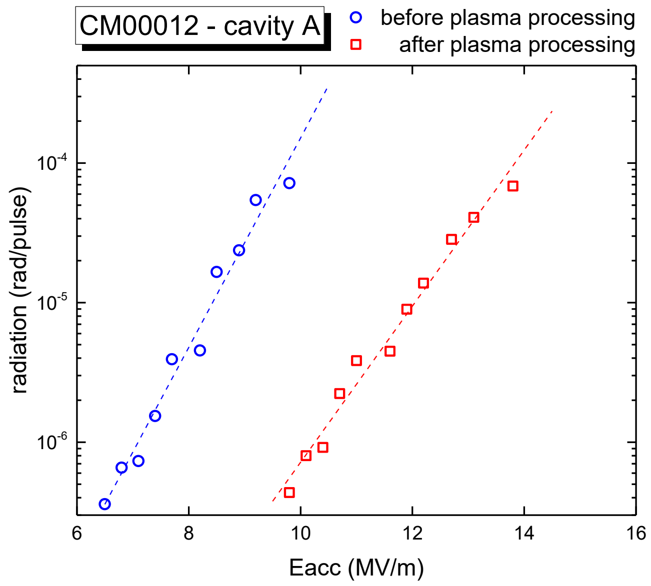


Applied ALARA: Radiation survey indicated best location for minimum radiation exposure during work (<1 mrem/hr)

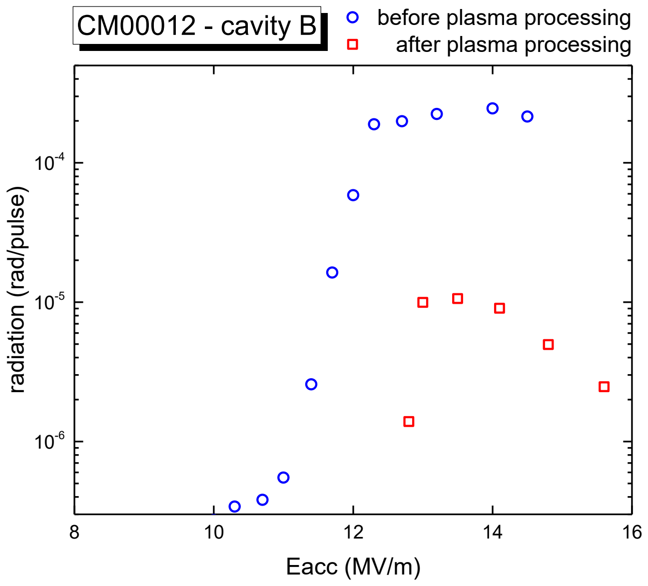
Radiation level reduced after plasma processing

- 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

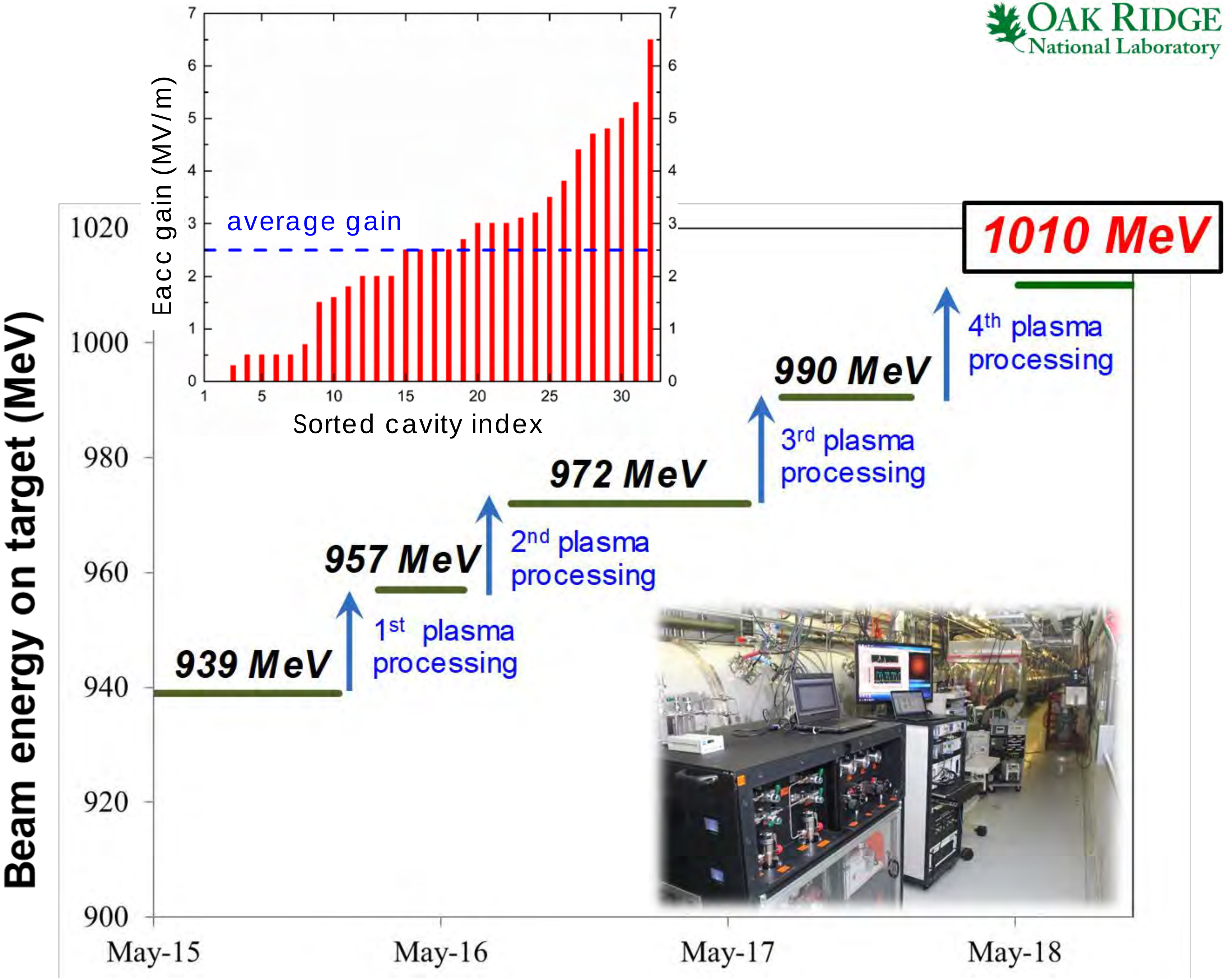


Multipacting regime



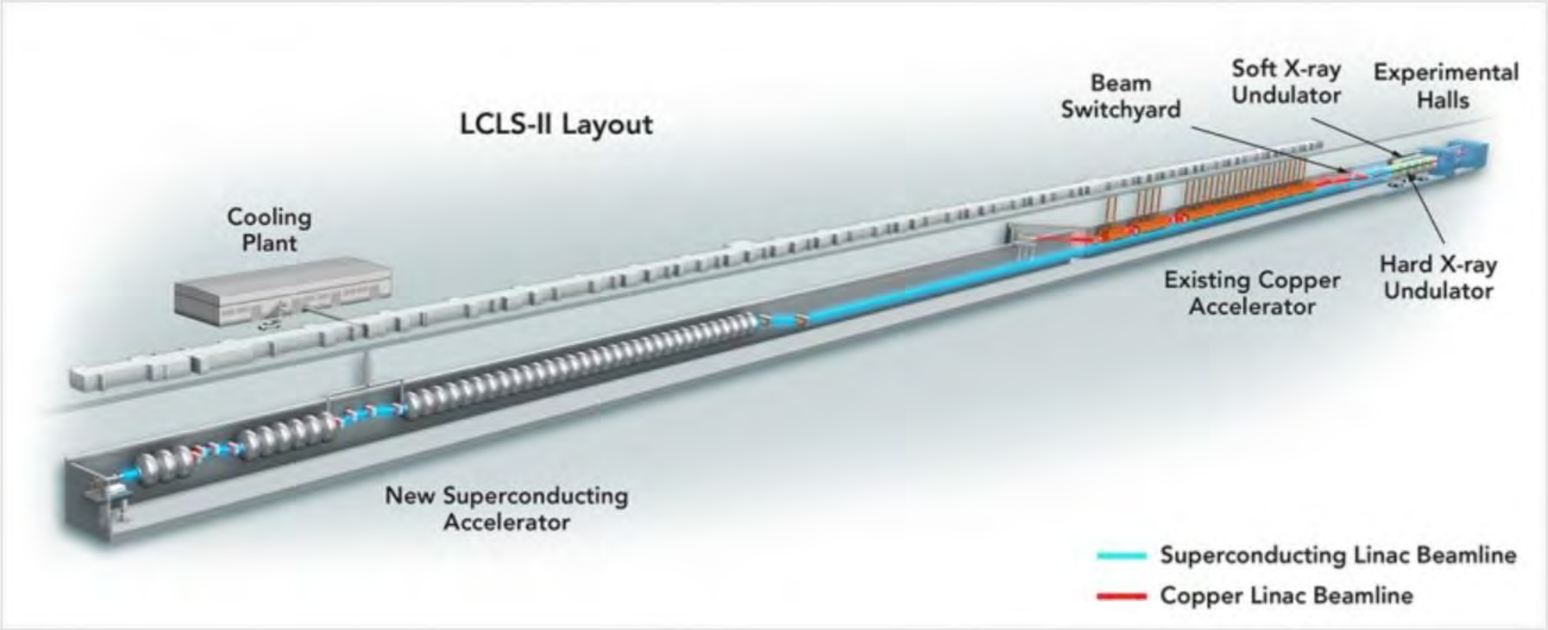
Boost to 1 GeV

- In-situ plasma processing in linac tunnel done during SNS planned down periods on HB CMs
- 32 cavities plasma processed at SNS with an average Eacc increase of 2.5 MV/m
- Beam energy at SNS has been sustained at 1 GeV since summer 2018



Collaboration - Plasma proc. for 1.3 GHz cavities

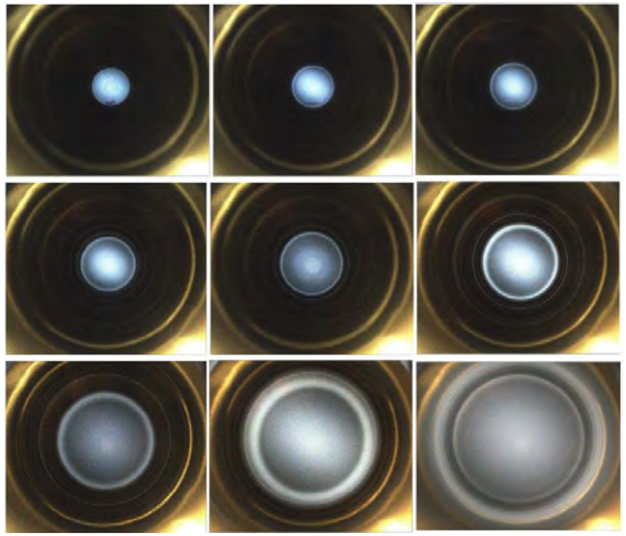
- LCLS-II will use 35 accelerating modules with 9-cell 1.3 GHz cavities to produce a 4 GeV electron beam and extremely bright X-ray laser light
  - Cryomodules fabricated at FNAL and JLab
- Plasma processing is being developed to help sustain beam energy and accelerator performance over time
  - Plasma processing test on LCLS-II HE vCM planned in 2021

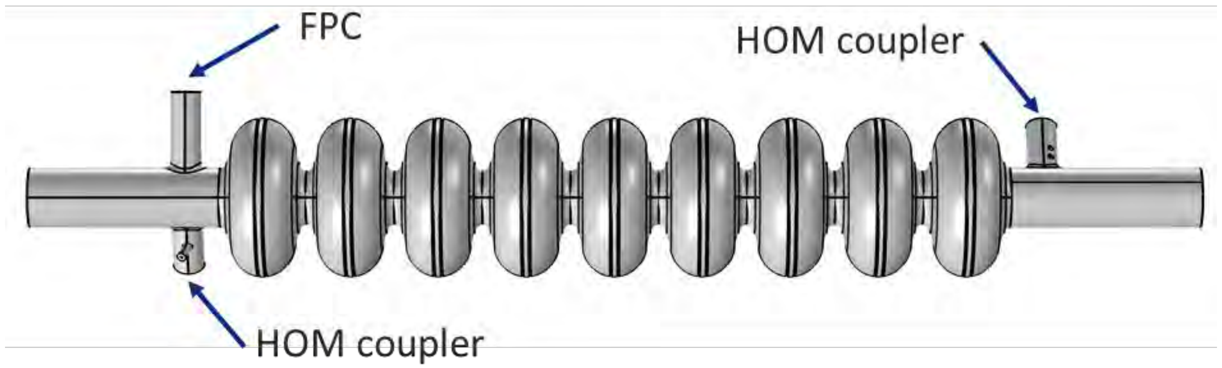


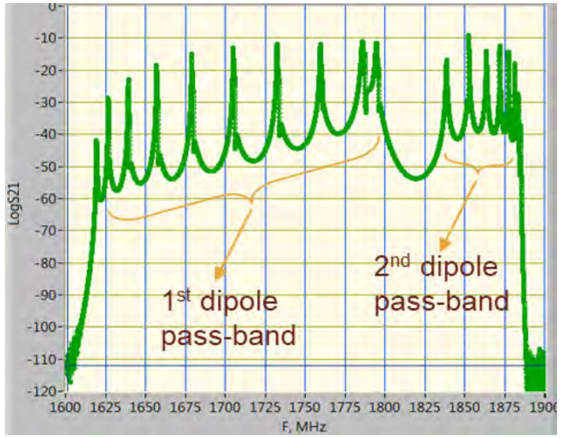
More information about LCLS-II : Y. Ding,"Status of the LCLS-II CW X-ray FEL", **Invited talk at LINAC20**

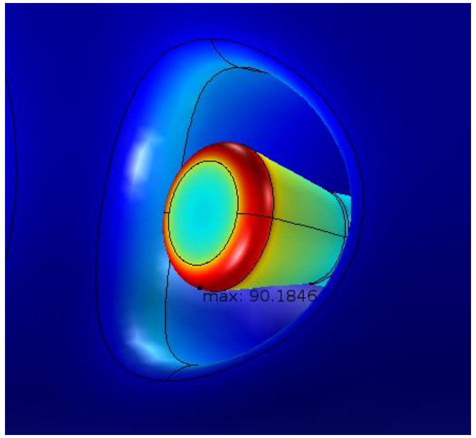
Plasma processing using HOM couplers

- Large mismatch between Q_{ex} and Q_0 at warm for LCLS-II cavities makes it difficult to use FPC for plasma ignition
- P. Berrutti at FNAL developed a solution using HOM couplers
  - Strong coupling to dipole pass-band modes
  - Only a few watts needed to ignite a plasma
  - Dual-tone method used to move the plasma in desired cell





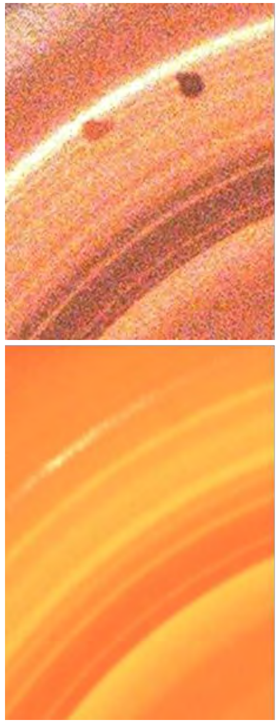


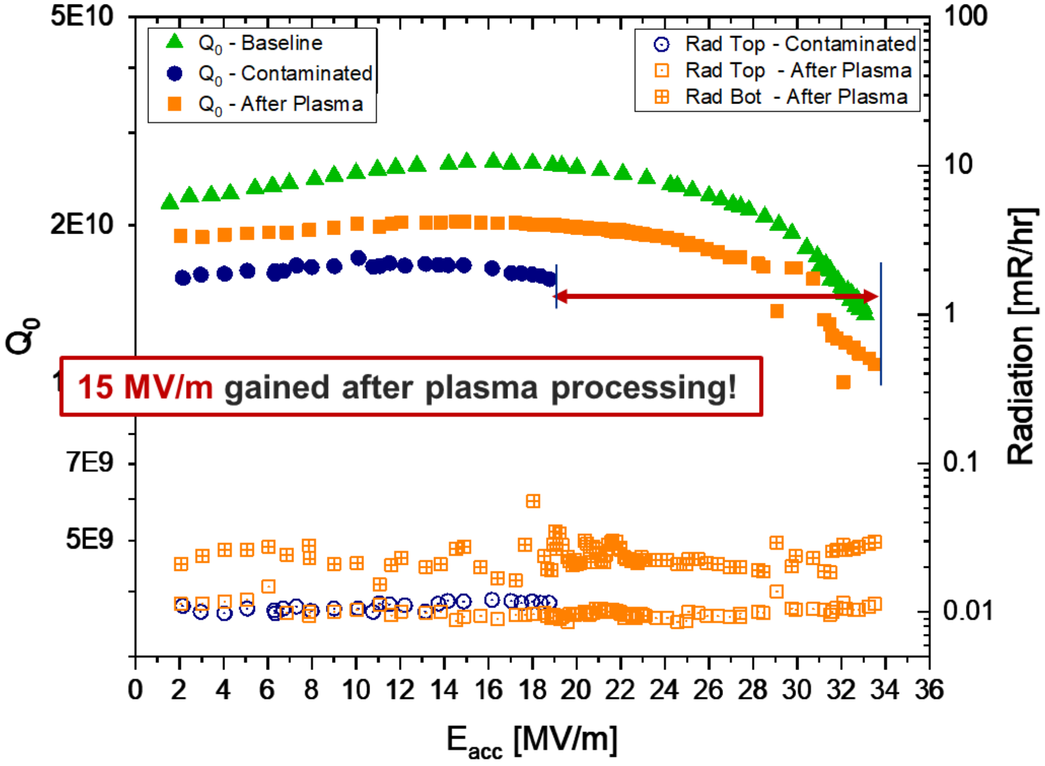


J. Appl. Phys. **126**, 023302 (2019)

Performance recovery using plasma processing

- 1.3 GHz single cell cavity contaminated with carbon
  - Eacc and Q_0 degraded
  - Eacc fully recovered after 17h with Ne-O2 plasma



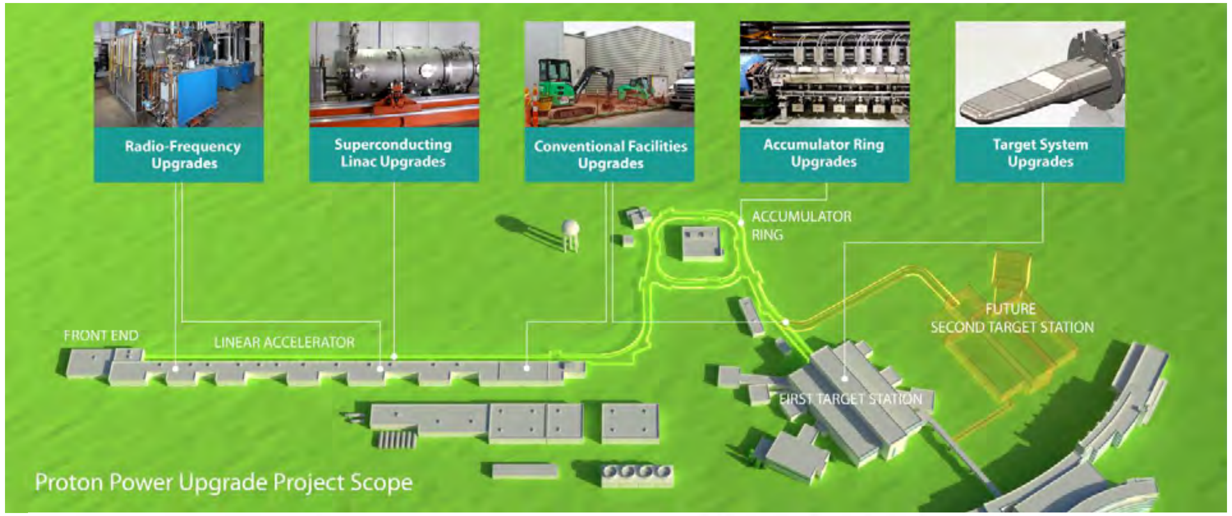


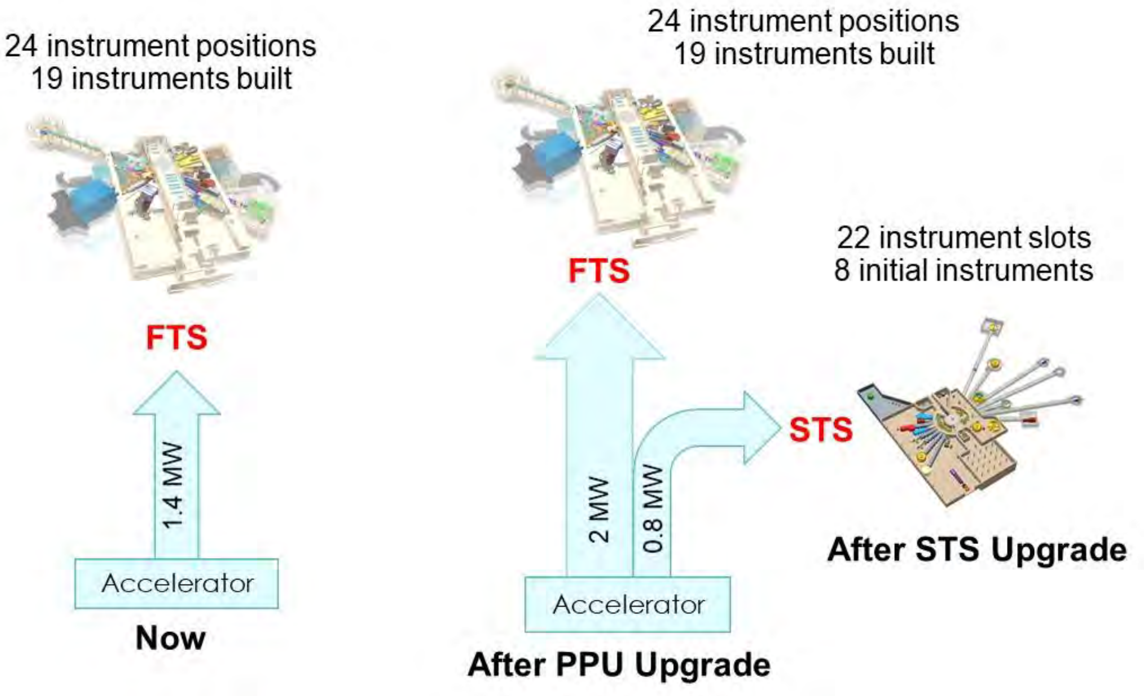
Phys. Rev. Accel. Beams **24**, 022002 (2021)

Beyond 1 GeV and 1.4 MW at SNS

- Proton Power Upgrade Project - PPU
  - Under construction
  - 1.3 GeV and 2.8 MW beam
  - Early project completion is planned for 2025
  - https://neutrons.ornl.gov/ppu

- Second Target Station Project - STS
  - CD-1 approval given in Nov. 2020
  - https://neutrons.ornl.gov/sts





Conclusion

- In-situ plasma processing for superconducting RF resonators was developed at ORNL and successfully applied to increase the beam energy at the SNS
- Active developments and collaborations with other Laboratories for adapting plasma processing to other facilities