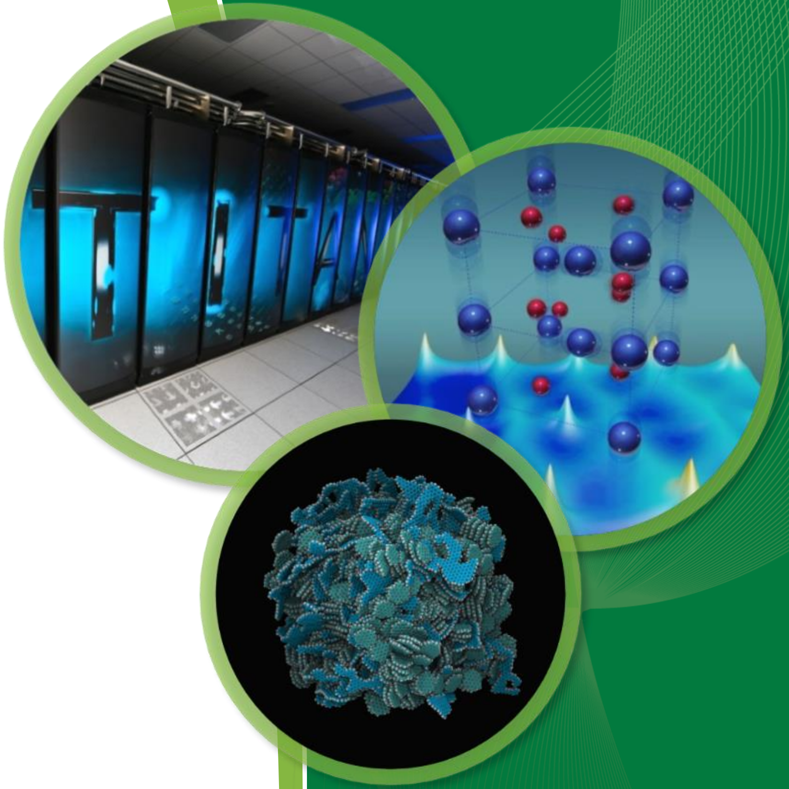
Plasma Processing at ORNL

Marc Doleans

ORNL/SNS

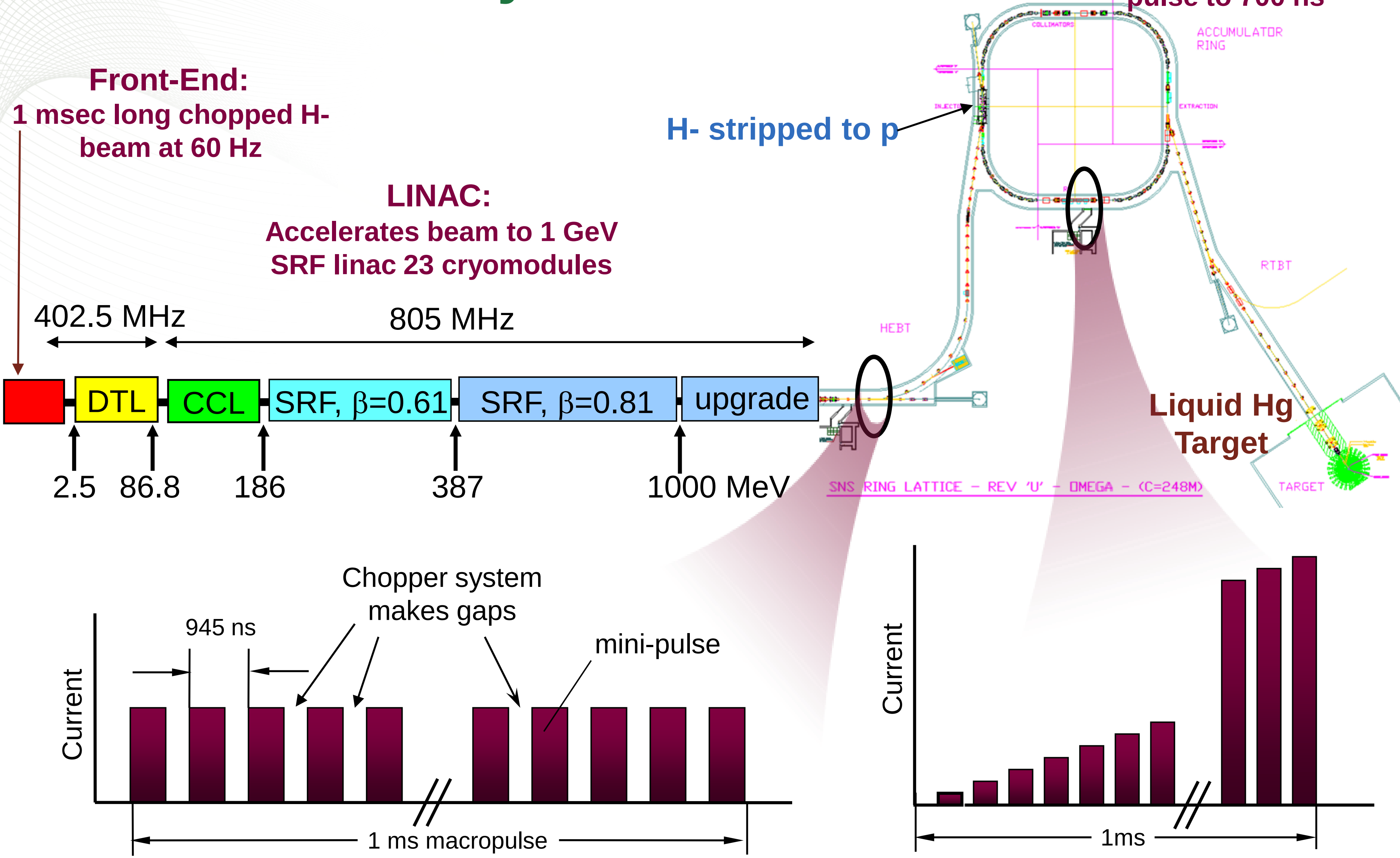


Overview

- In-situ plasma processing at SNS
  - Deployment to high-beta cryomodules led to 1 GeV beam energy!
  - Future deployment to medium beta CM for Proton Power Upgrade (PPU)

- Plasma processing R&D for LCLS-II cryomodules
  - R&D collaboration between SLAC, FNAL and ORNL

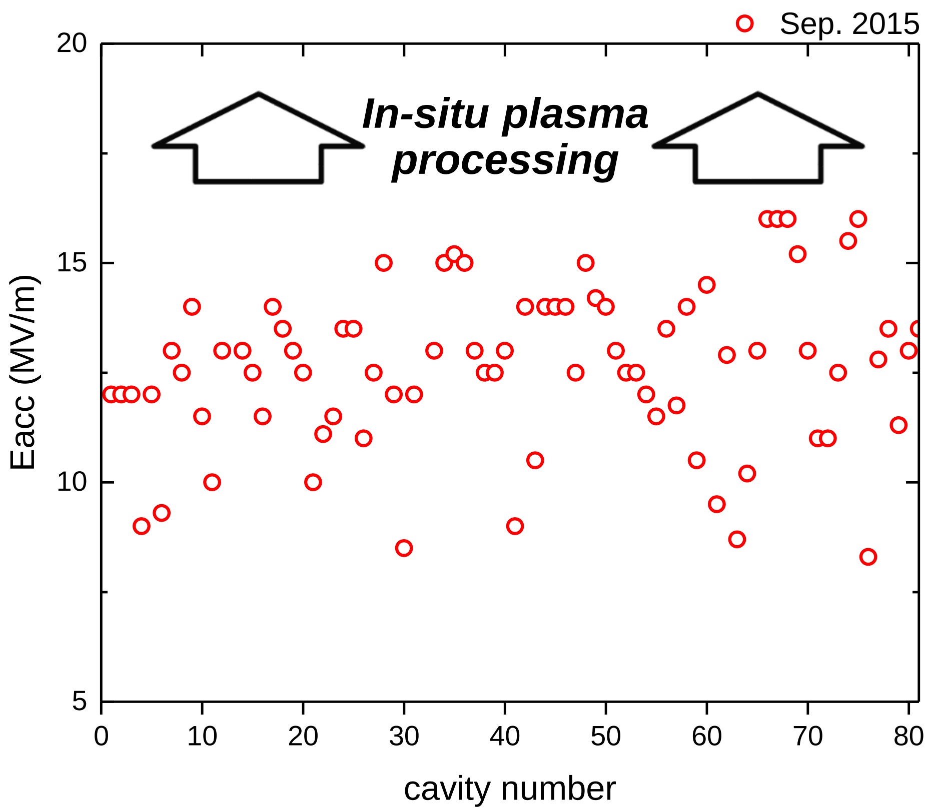
SNS Machine Layout



Average macropulse beam current: 26 mA

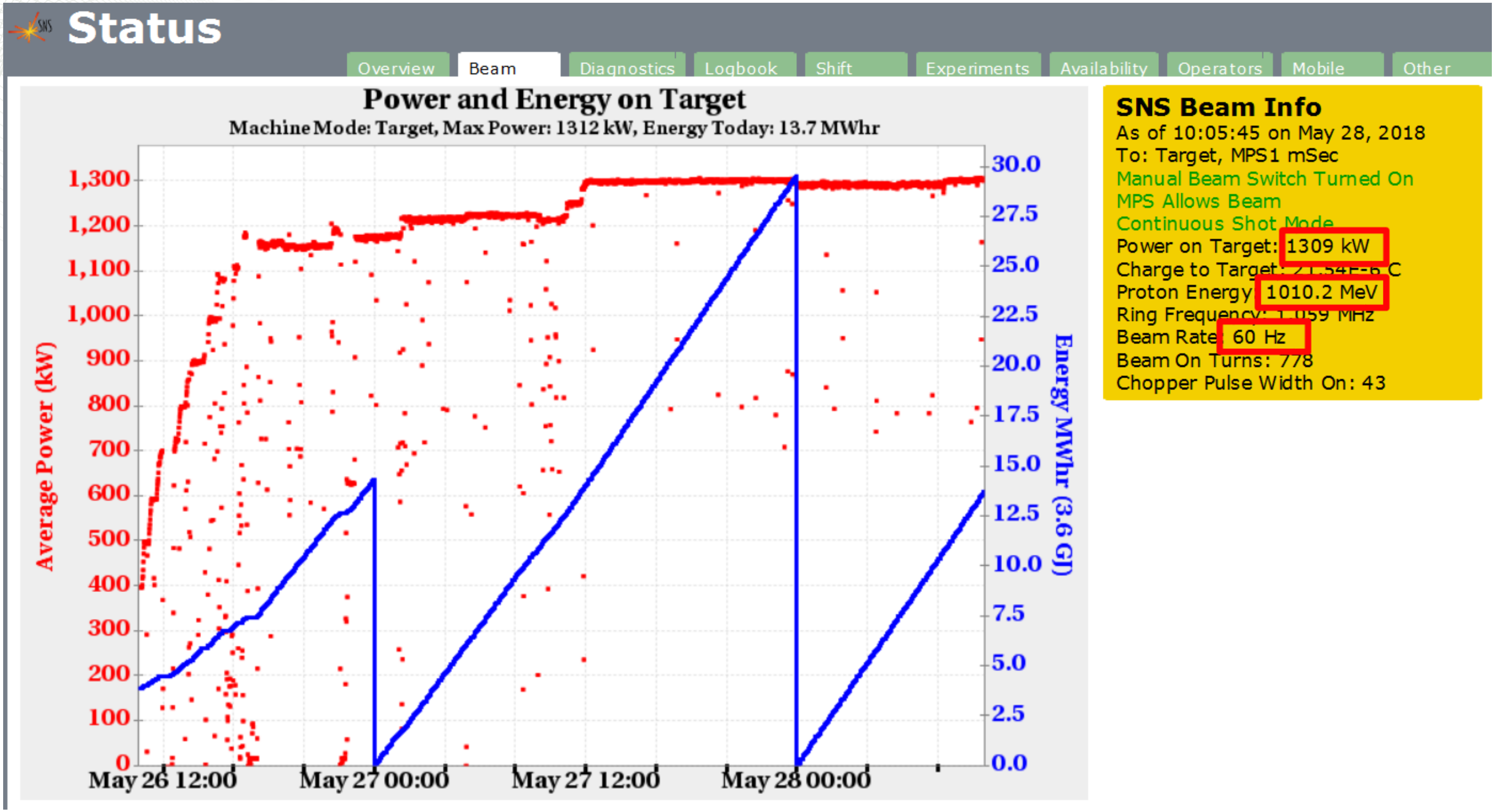
In-situ plasma processing to increase SNS linac energy

- **Higher linac energy provides more margin for reliable operation at 1.4 MW**
  - Aim 1 GeV 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***



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

SNS operating at 1 GeV !



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

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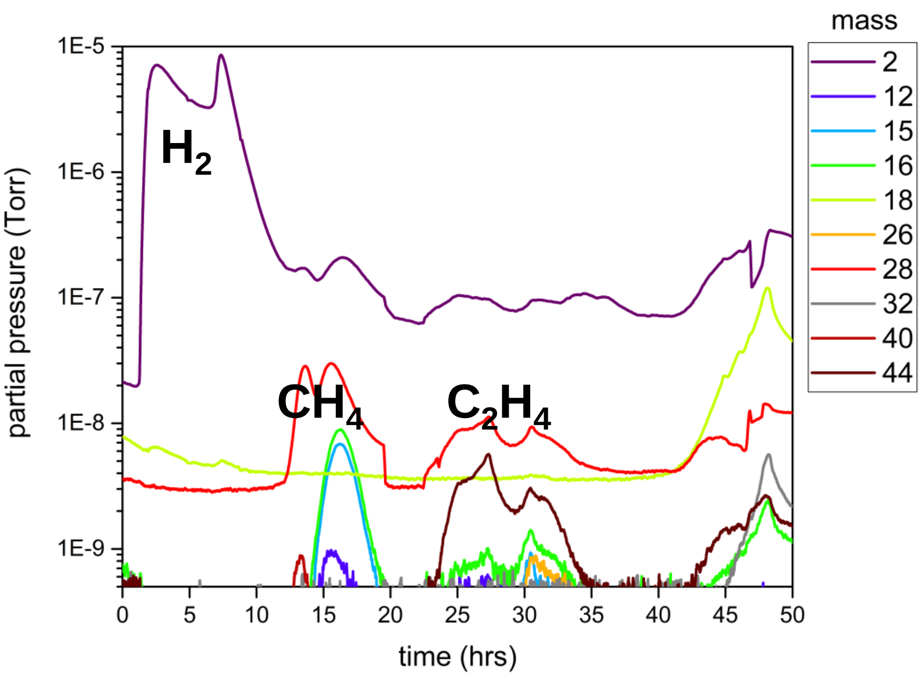
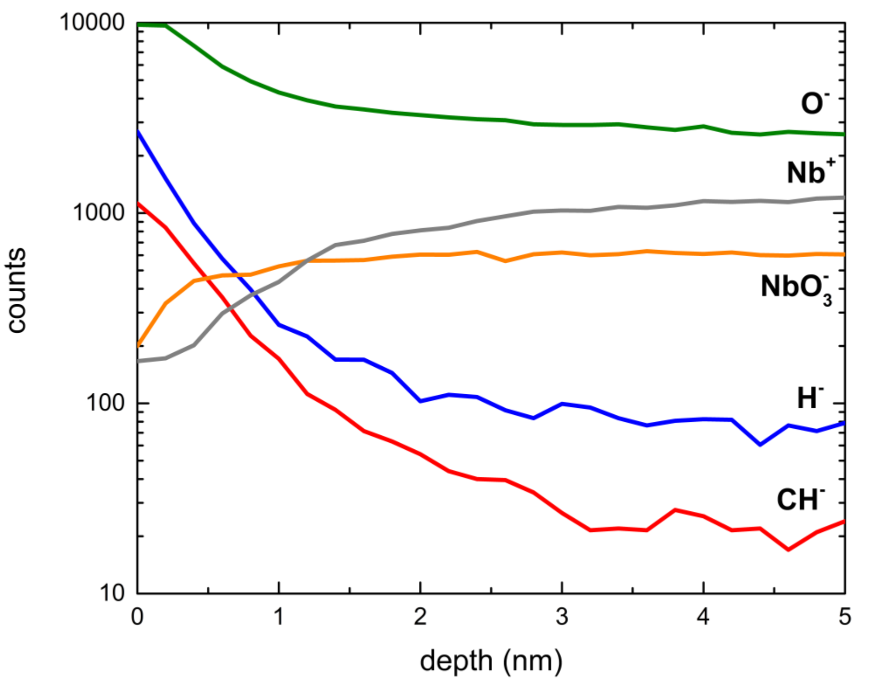
Hydrocarbon contaminants on Nb surfaces

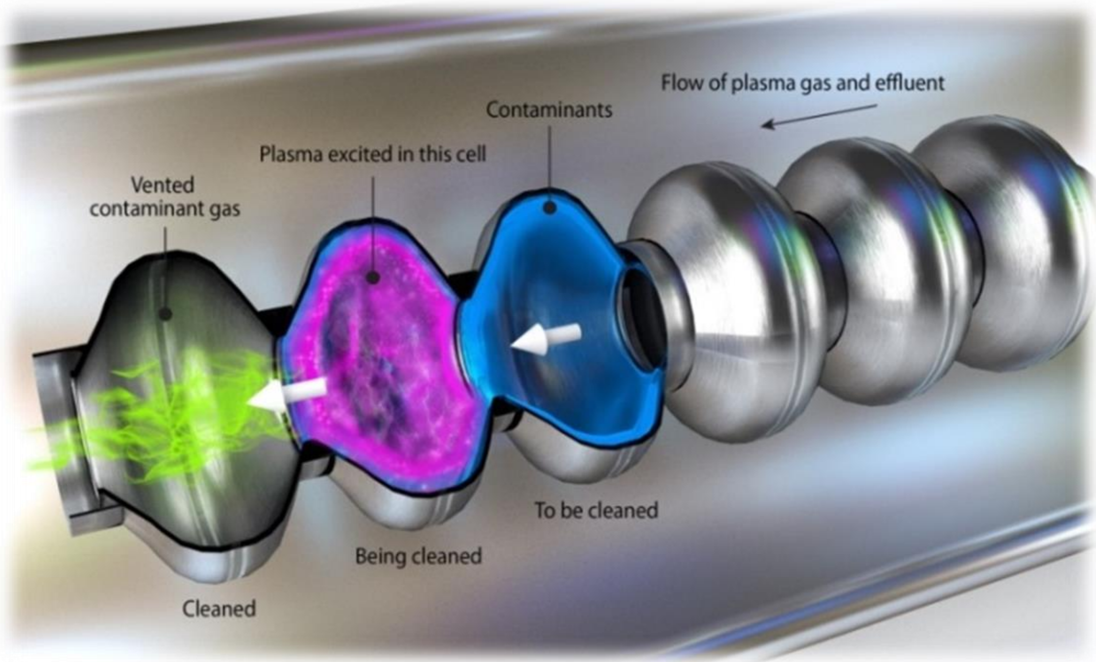
- **Hydrocarbon contaminants observed on all Nb surfaces**
  - Volatile hydrocarbons released from cryomodule surfaces during thermal cycle
  - Hydrocarbons on offline spare cavity surfaces
  - Hydrocarbons fragments seen in secondary ion mass spectrometry (SIMS)
    - Mechanically polished niobium samples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





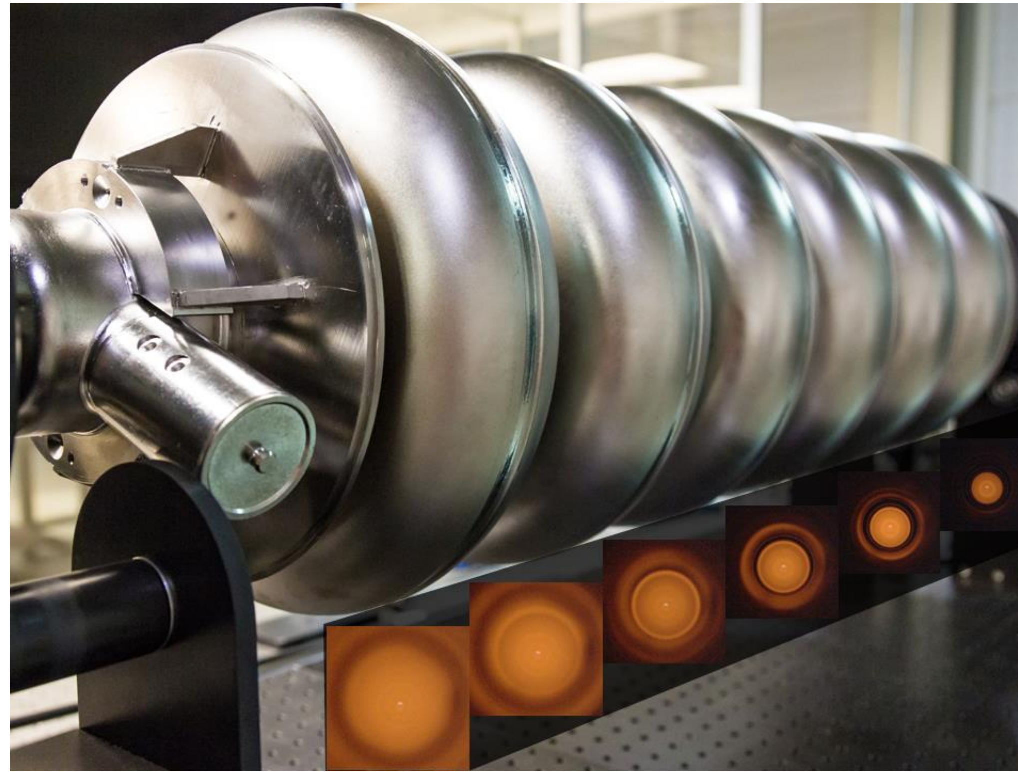
Oxygen plasma for removing hydrocarbons at SNS

- **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 control

- **Plasma excited in each of the six cells sequentially**
- **Fundamental passband modes excited through the power coupler**
  - Dual-tone ignition technique to ignite each cell*
- **Position of plasma in cryomodule determined using field probe***

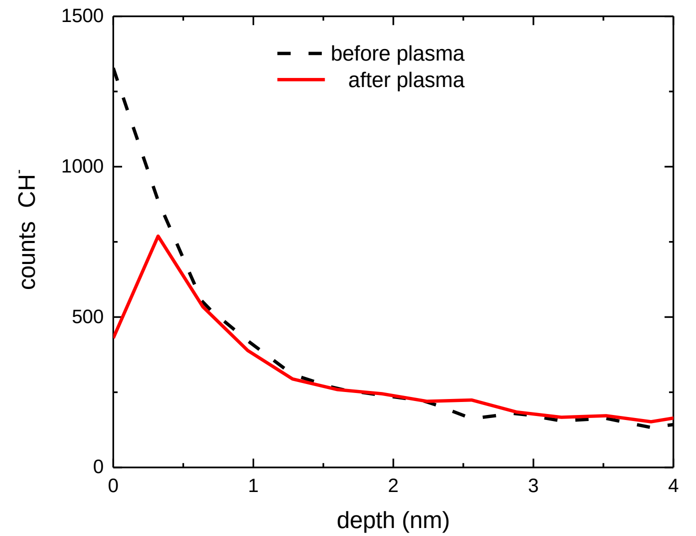


Dual-tone ignition parameters for *high-beta cavities*

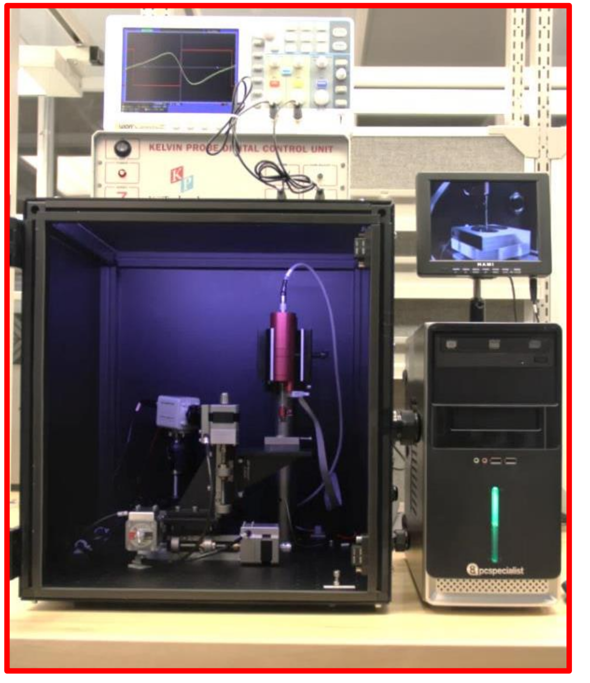
Cell ignition	RF gen. 1	δf_1 (hbw)	p_{RF1} (dB)	RF gen. 2	δf_2 (hbw)	p_{RF2} (dB)	Γ_1	Γ_2	Γ_3	Γ_4	Γ_5	Γ_6
1	mode 5	−1.0	−4.57	mode 6	+0.50	−3.46	1.00	0.72	0.41	0.37	0.62	0.90
2	mode 2	0.0	−2.02	mode 5	−2.50	0.87	0.74	1.00	0.24	0.18	0.88	0.69
3	mode 1	0.0	−1.80	mode 3	−1.50	4.15	0.88	0.80	1.00	0.91	0.89	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

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

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

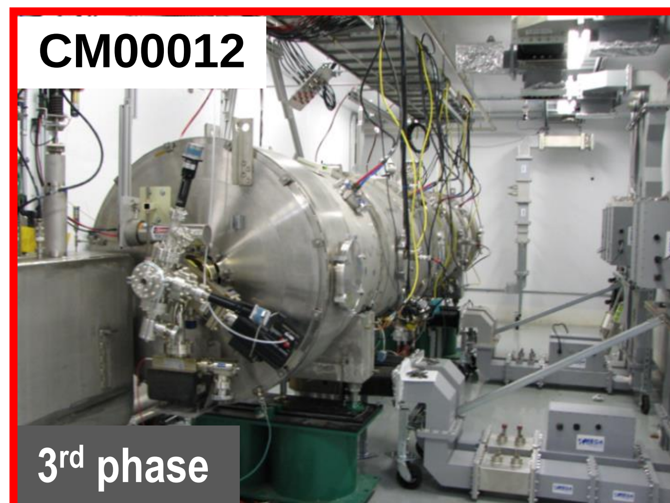


*P.V. Tyagi et al., Applied Surface Science **369** (2016) 29–35

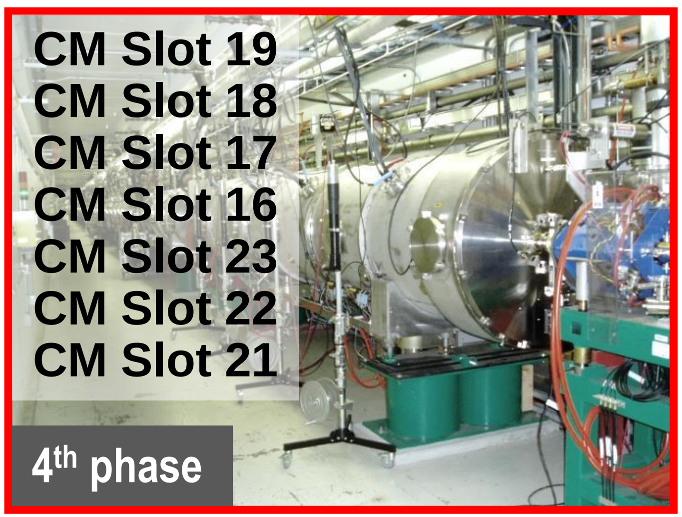
Plasma processing at SNS to reach 1 GeV

R&D with Nb samples and offline cavities

Processing of 6-cell cavity in HTA*



Processing of cryomodule in test cave



In-situ processing in linac tunnel

*HTA: Horizontal Test Apparatus

Plasma processing of an offline cryomodule

- **Plasma processing hardware**
  - Process gas cart
  - RF carts
  - Pumping carts
- **2 RF carts are used to process 2 cavities simultaneously**

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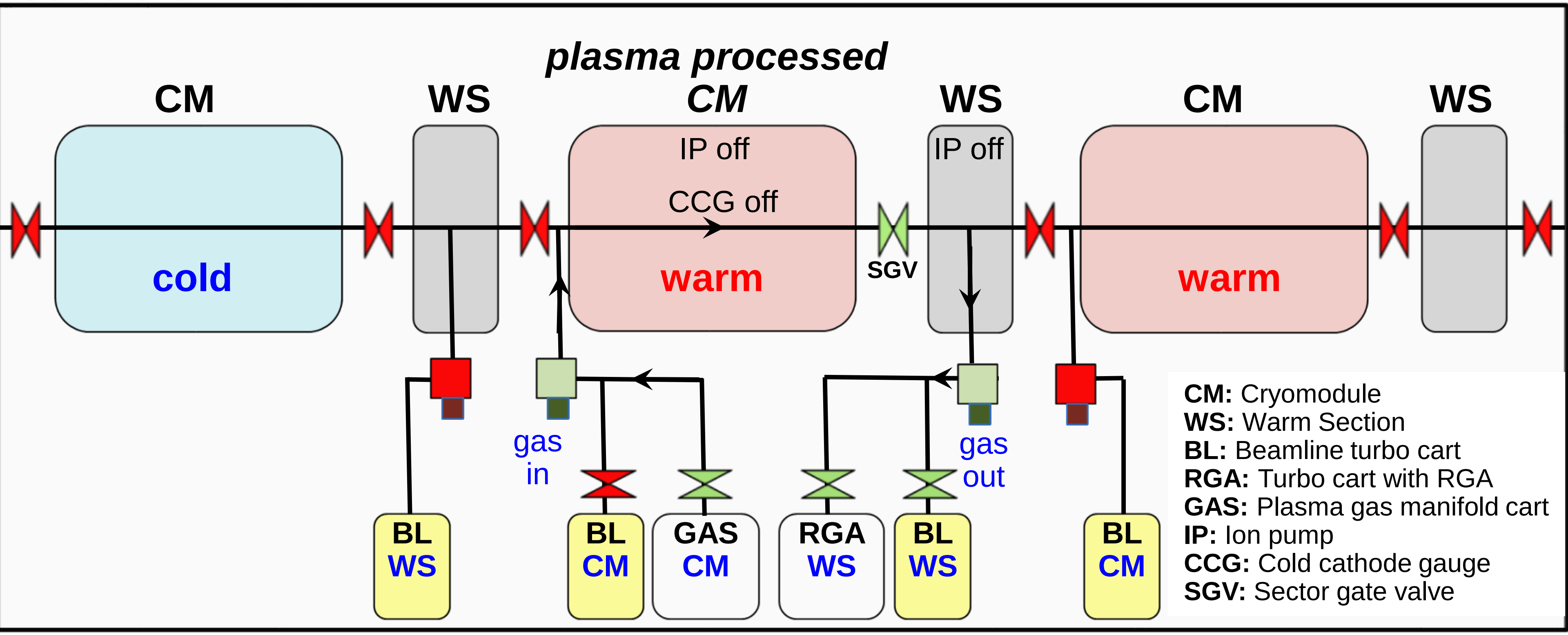
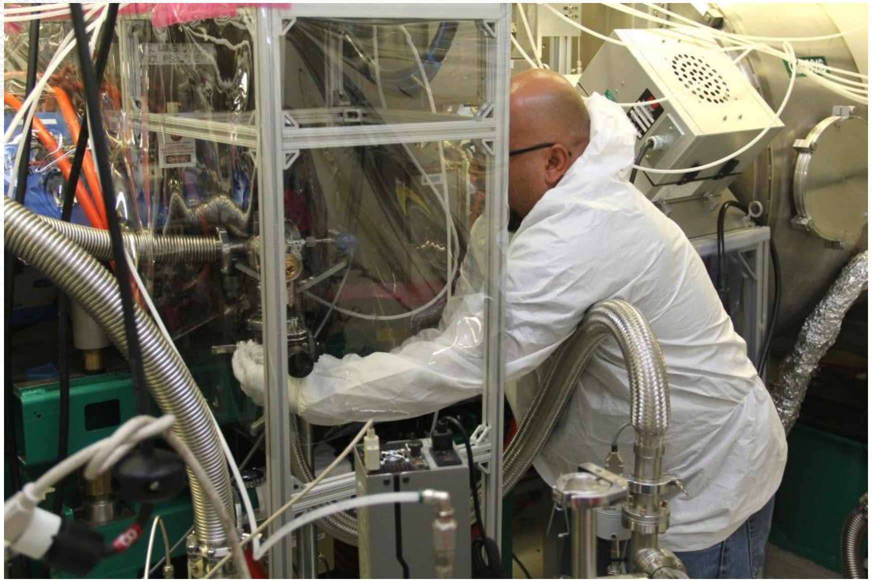
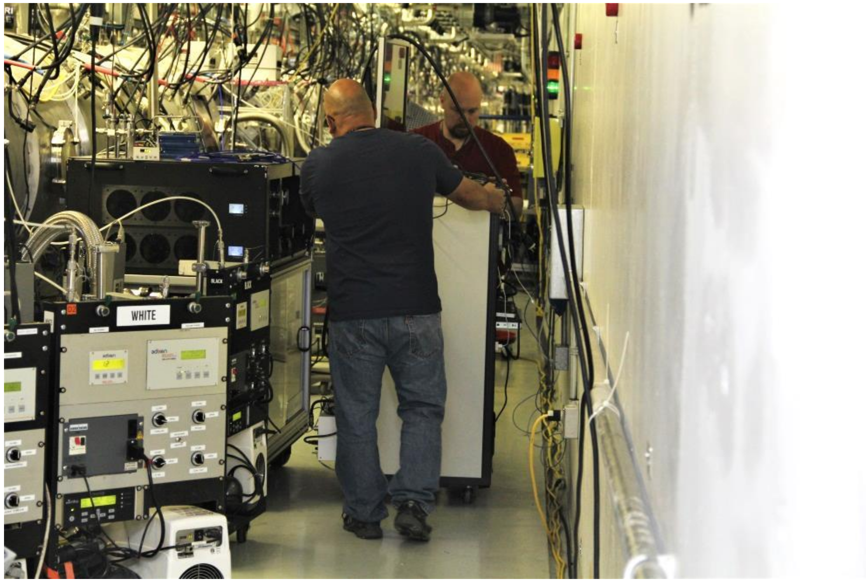
Plasma processing of a CM in SNS linac

- **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



Installation of plasma processing hardware





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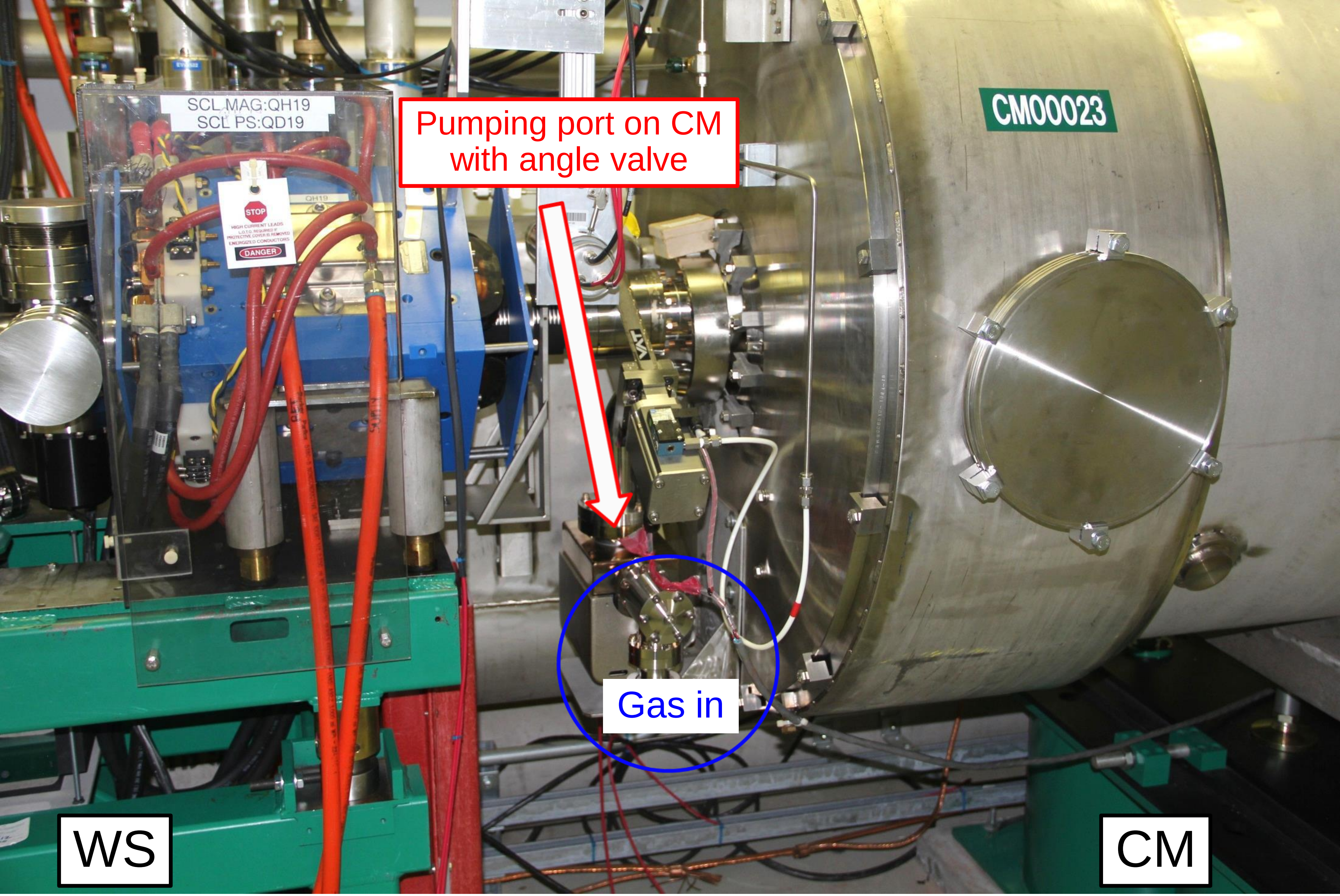
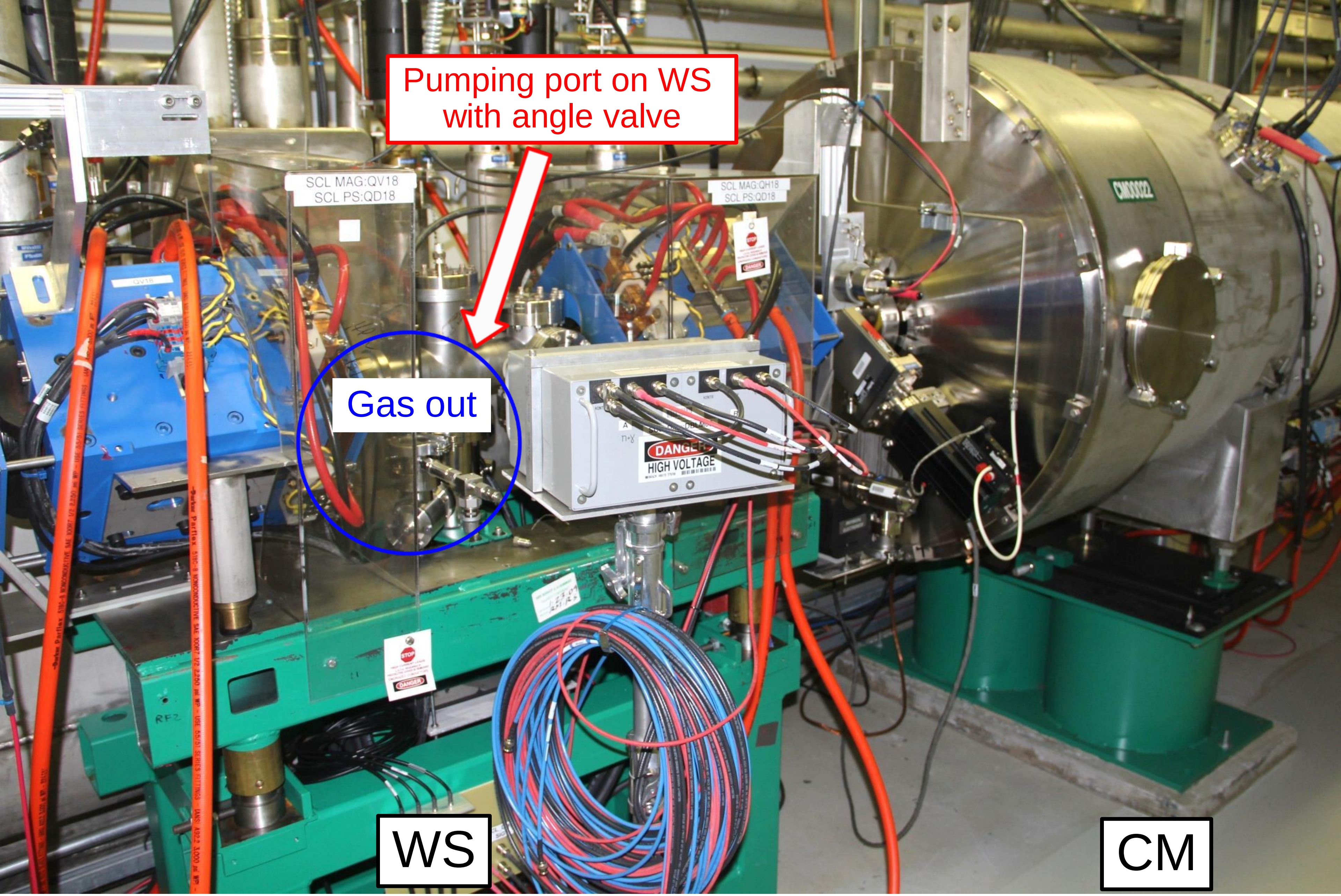

SCL MAG:QH19
SCL PS:QD19
CM00023
Pumping port on CM
with angle valve
Gas in
WS
CM

Beam



Beam

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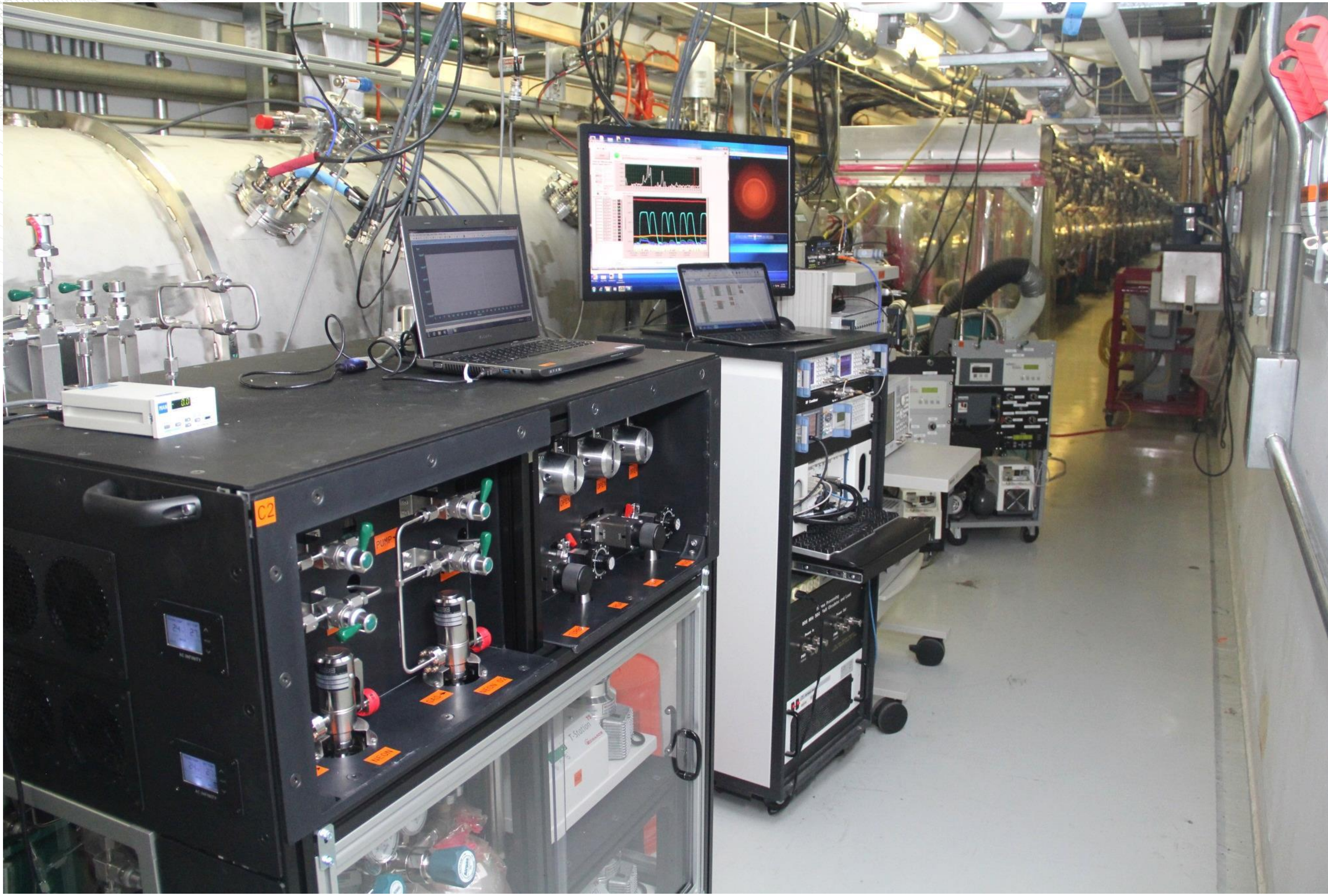
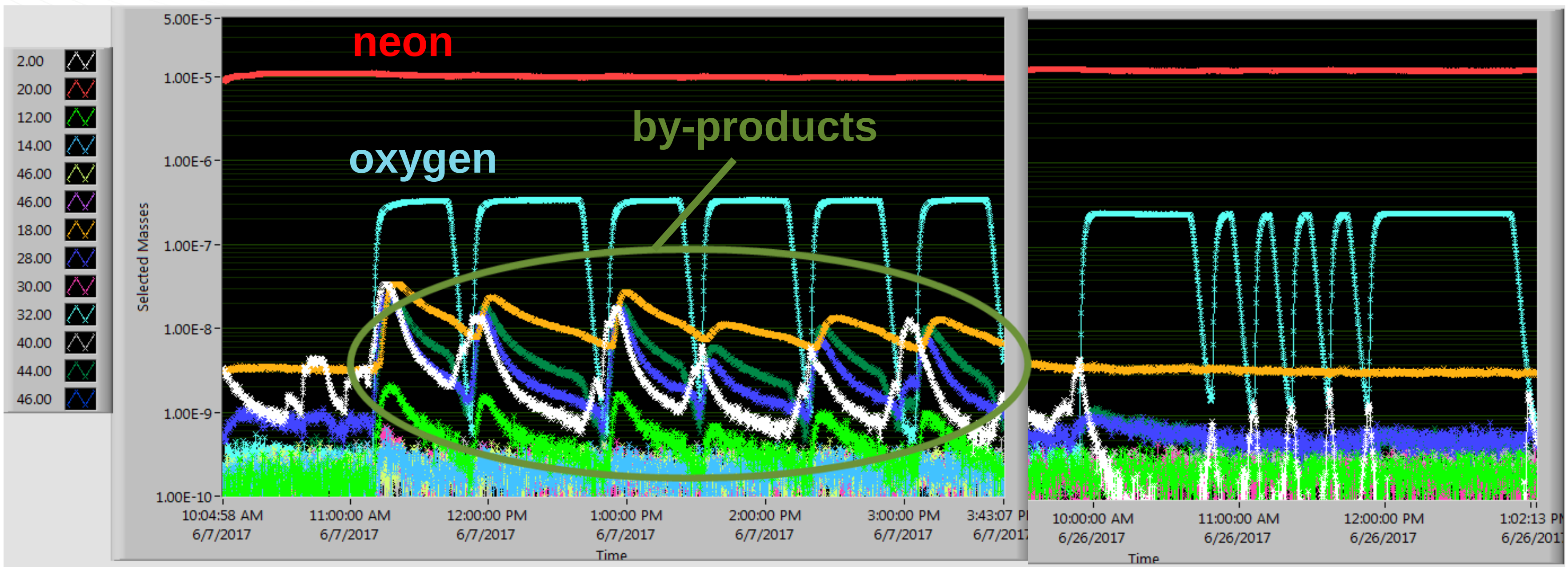
Plasma processing hardware in SNS tunnel



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

Example of gas analysis during plasma processing of a CM at SNS

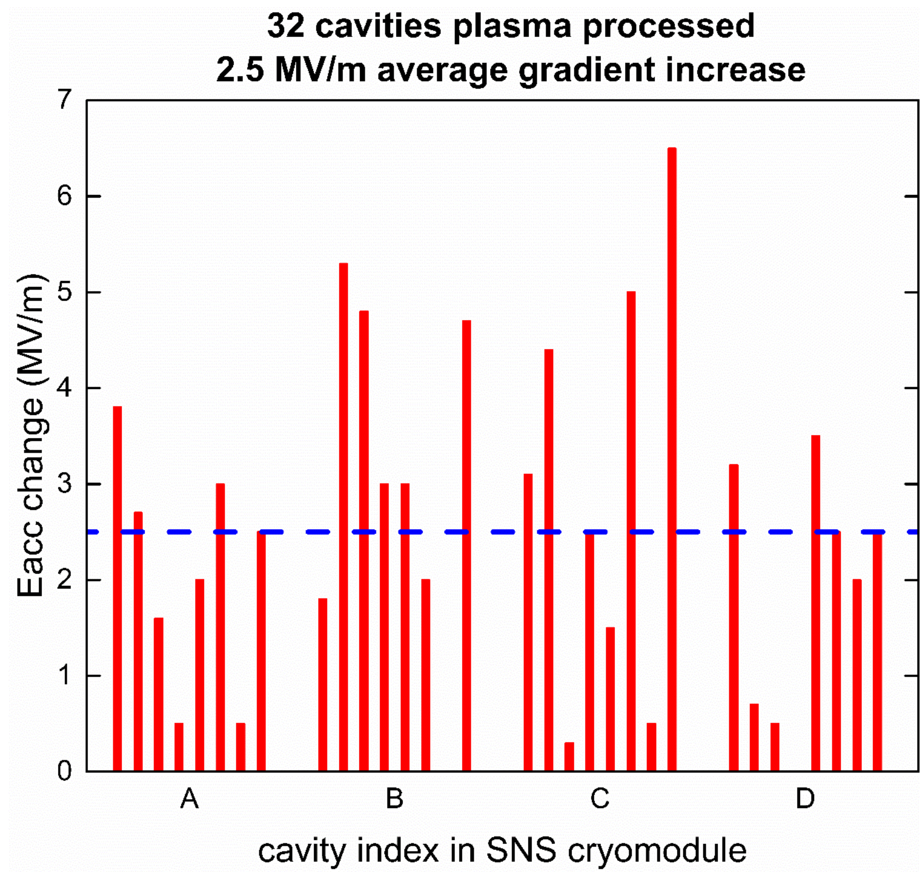
- **Residual gas analysis during cleaning of the cavities**
  - Reduction of by-products as the surface is depleted of hydrocarbons through multiple cleaning cycles



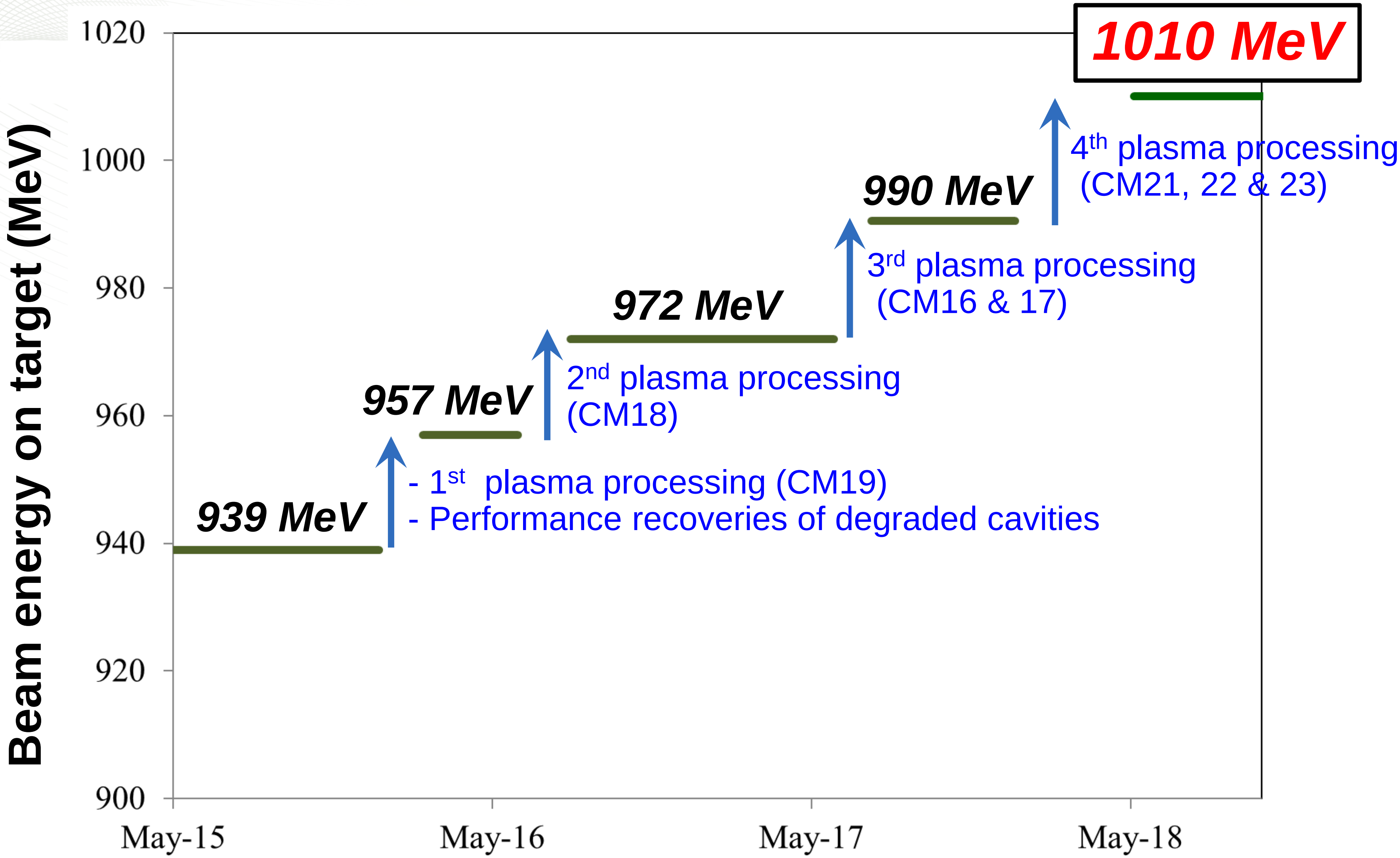
Cycle 1 **Cycle 4**

Plasma processing deployment at SNS

- 8 high beta cryomodules have been successfully plasma processed
  - 7 cryomodules in the tunnel
  - 1 cryomodule offline
  - Accelerating gradient increased by 20% on average
    - Improvement of E_{acc} ranges from 0.2 to 6.5 MV/m
    - 10 MV/m gain per cryomodule on average
    - No performance degradation from plasma processing observed so far



In-situ plasma processing boosts SNS to 1 GeV



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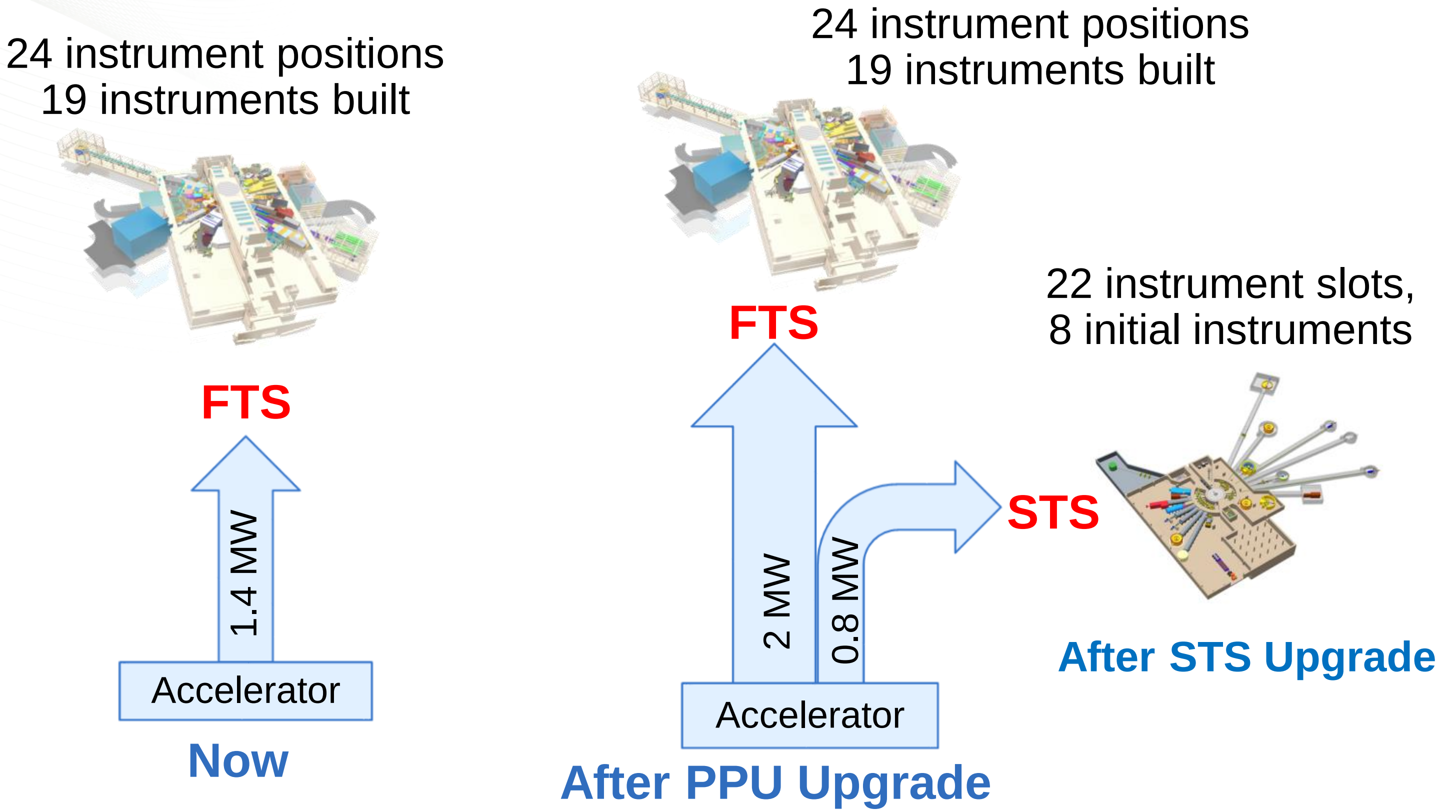
Beyond 1 GeV and 1.4 MW at SNS

(courtesy J. Galambos)



- Upgrade to 1.3 GeV and 38 mA beam loading (2.8 MW) – **PPU**
- Second Target Station - **STS**

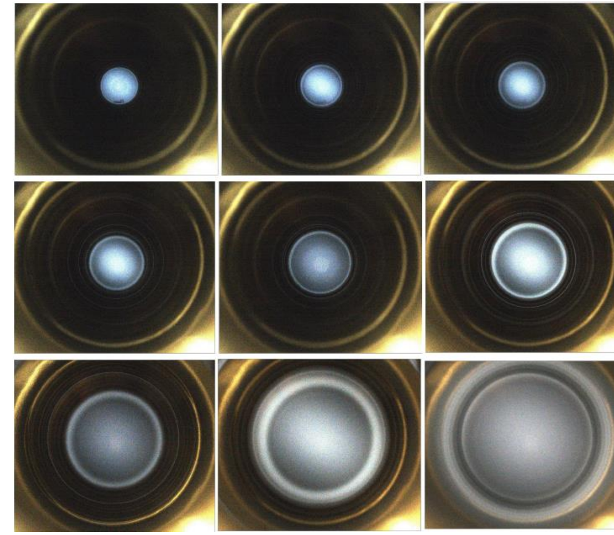
PPU SCL Scope

- **Road to 1.3 GeV**
  - **7 additional cryomodules will be installed in empty slots**
    - Design E_{acc} for new PPU cavities is 16 MV/m
  - **Improvement of existing cryomodules**
    - Use future spare medium beta CM to replace low performing cryomodule
    - Plasma processing for medium beta cryomodules
      - Leverage available RF power in medium beta cryomodules
      - Increase medium-beta cavities Eacc by 1.7 MV/m on average
      - Will modify plasma processing recipe developed for high-beta cavities
        - Existing hardware will be used (same frequency 805 MHz)
        - Develop dual tone ignition parameters

Plasma processing for LCLS-II

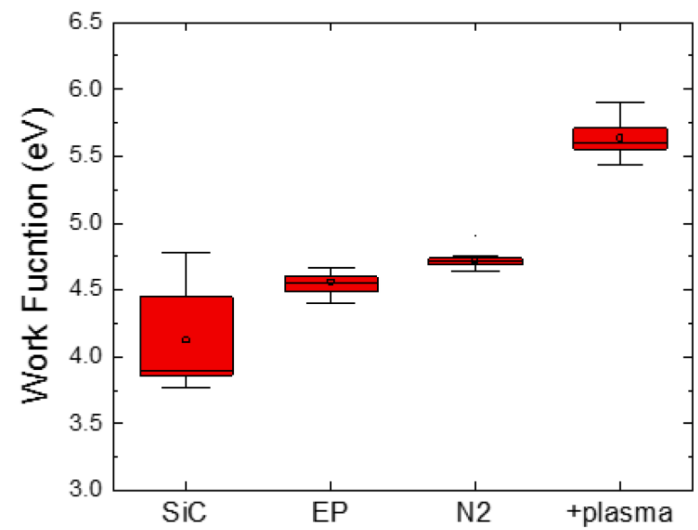
- On-going collaboration between three Laboratories funded by BES

Fermilab SLAC NATIONAL ACCELERATOR LABORATORY OAK RIDGE National Laboratory



(courtesy P. Berrutti, FNAL)

- Plasma processing for 9-cell 1.3 GHz LCLS-II cavities
  - Plasma ignition methodology modified to use HOM couplers *
  - Plasma processing increases work function for LCLS-II niobium surface **



* P. Berrutti et al., “Update on plasma processing R&D for LCLS-II”, IPAC18
** K. Tippey et al., "Improving the work function of nitrogen doped surfaces…“, IPAC18

CONCLUSION

- **In-situ plasma processing deployed successfully at SNS**
  - 1 GeV beam energy reached!
- **Plasma processing for PPU Project**
  - Plasma processing for medium beta cryomodules
- **Plasma processing for LCLS-II**
  - SLAC, FNAL and ORNL collaboration
  - Progressing very well
    - Plasma processing of an LCLS-II cavity in the near future at FNAL!