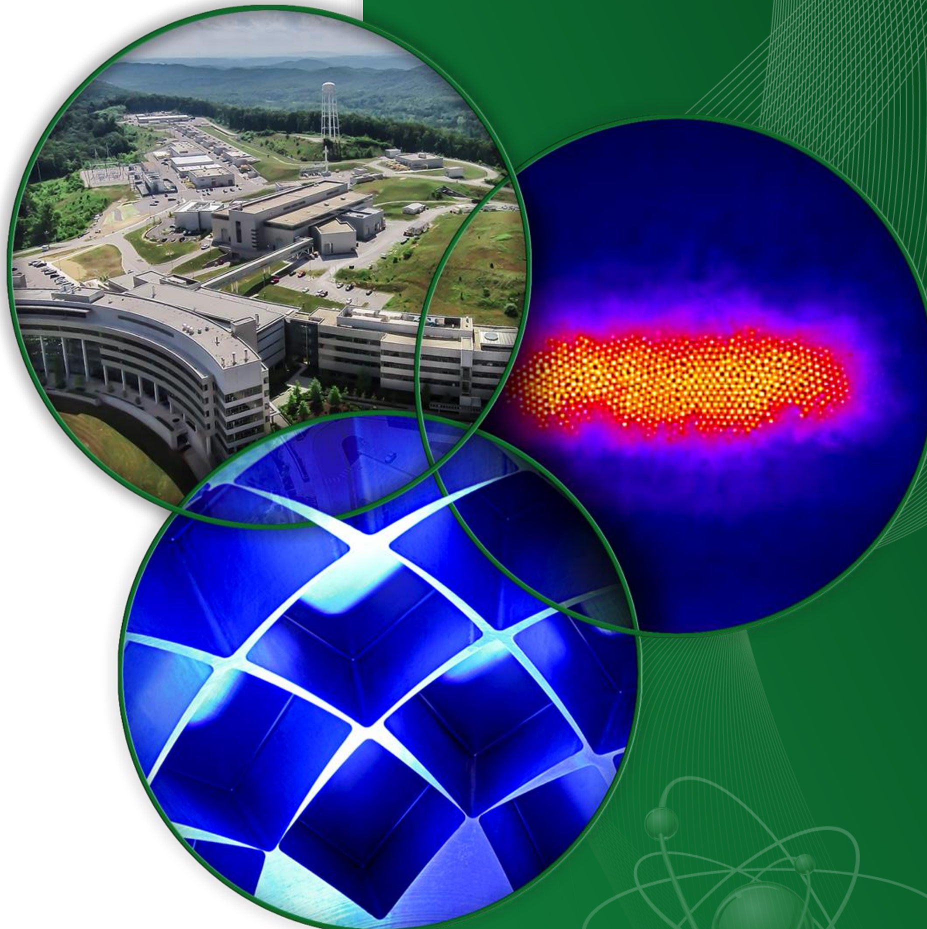
# Plasma Processing R&D



Presented at the

## Accelerator Advisory Committee Review

Marc Doleans
SCL Systems Group
Research Accelerator Division

March 24-26, 2015

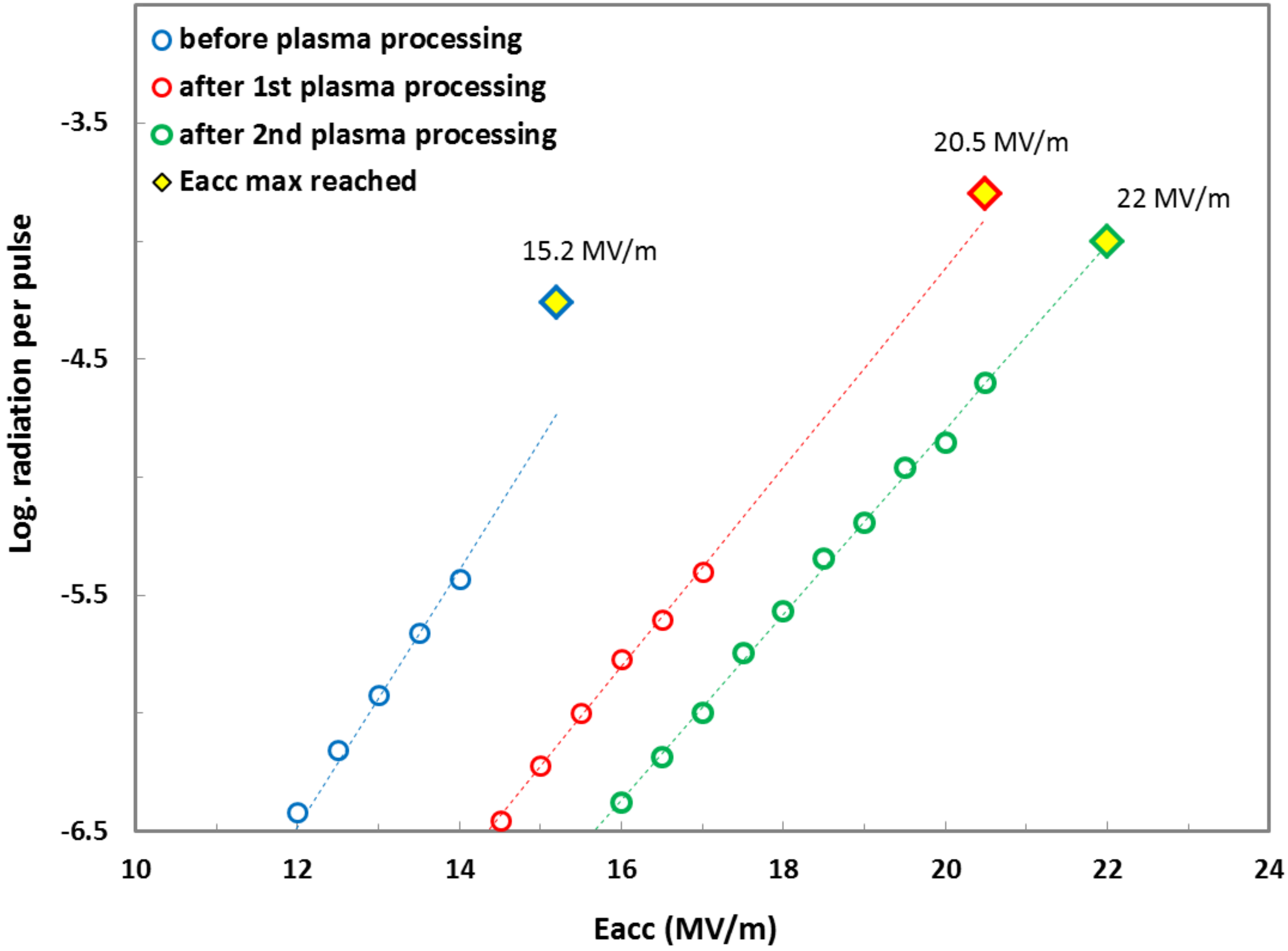


OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

# Since last review

- **Studies on Niobium samples to better understand interaction plasma and Nb surfaces**
- **Developed plasma processing procedure for HB 6-cell cavities**
  - Standard plasma tuning methodology
  - Standard gas mixture
  - Applied procedure to five offline cavities
- **In-situ plasma processing of a dressed cavity in HTA**
  - Cold-tests show cavity performance improvement

# Plasma processing R&D at SNS is going well !



# Overview

- Plasma processing for SNS SC linac: Context and objectives
- Standard plasma processing procedure for HB 6-cell cavities
- In-situ plasma processing and cold-test results of a cavity in HTA
- Future work and conclusion

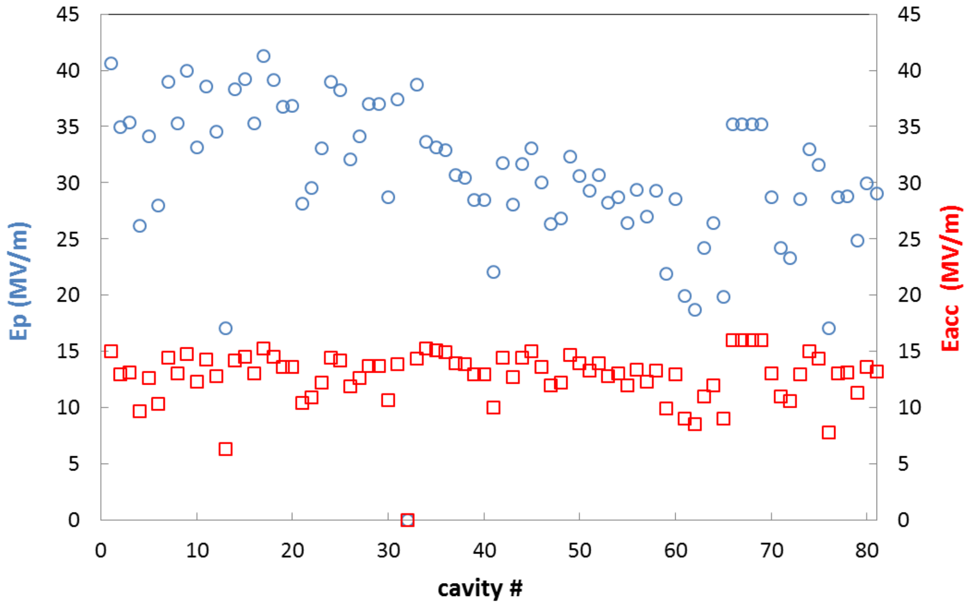
# Plasma processing R&D context and objectives

- **Beam energy increase to 1 GeV**
    - Provide contingency for1.4 MW operation
    - Developing in-situ plasma processing of HB cavities
        - HB cavities provides two-thirds of the beam energy gain in the SCL
        - **Objective**: Average increase of accelerating gradient (Eacc) by 2 MV/m

- **Second target Station (STS)**
    - In-situ plasma processing of MB cavities
        - Efficient use of existing RF power in MB section with higher beam loading
            - **Objective** : Average increase of Eacc by 1.6 MV/m

# In-situ plasma processing to reach 1 GeV

- **Most cavities at SNS are limited by field emission (FE) leading to thermal instability in end-groups**
- **In-situ plasma processing to reduce FE and increase Eacc in HB cavities**
  - HB cavities are operating below their design specification
  - Average peak surface field (Ep) is lower in HB cavities than in MB cavities
    - 28.5 MV/m (High Beta) vs. 34 MV/m (Medium Beta)
      - HB cavities more efficient at accelerating electrons from FE?
      - Larger residual contamination in HB cryomodules (e.g. surface hydrocarbons)?

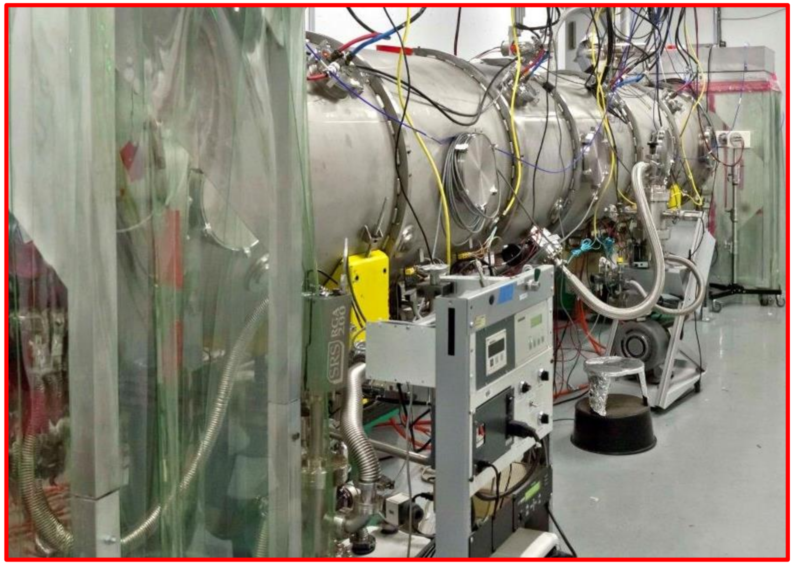


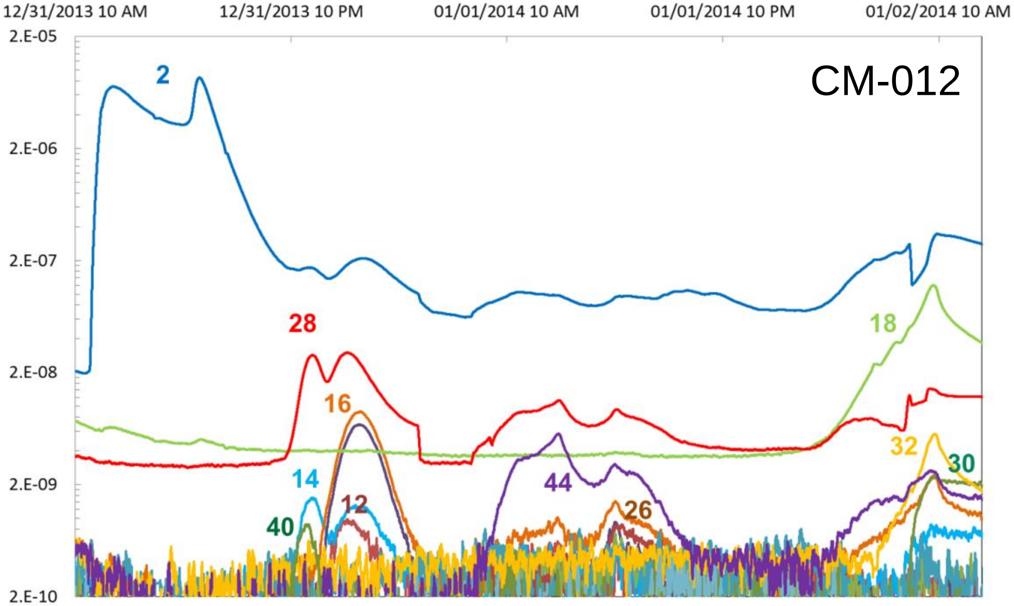



OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

# Hydrocarbon contaminants in HB cryomodules

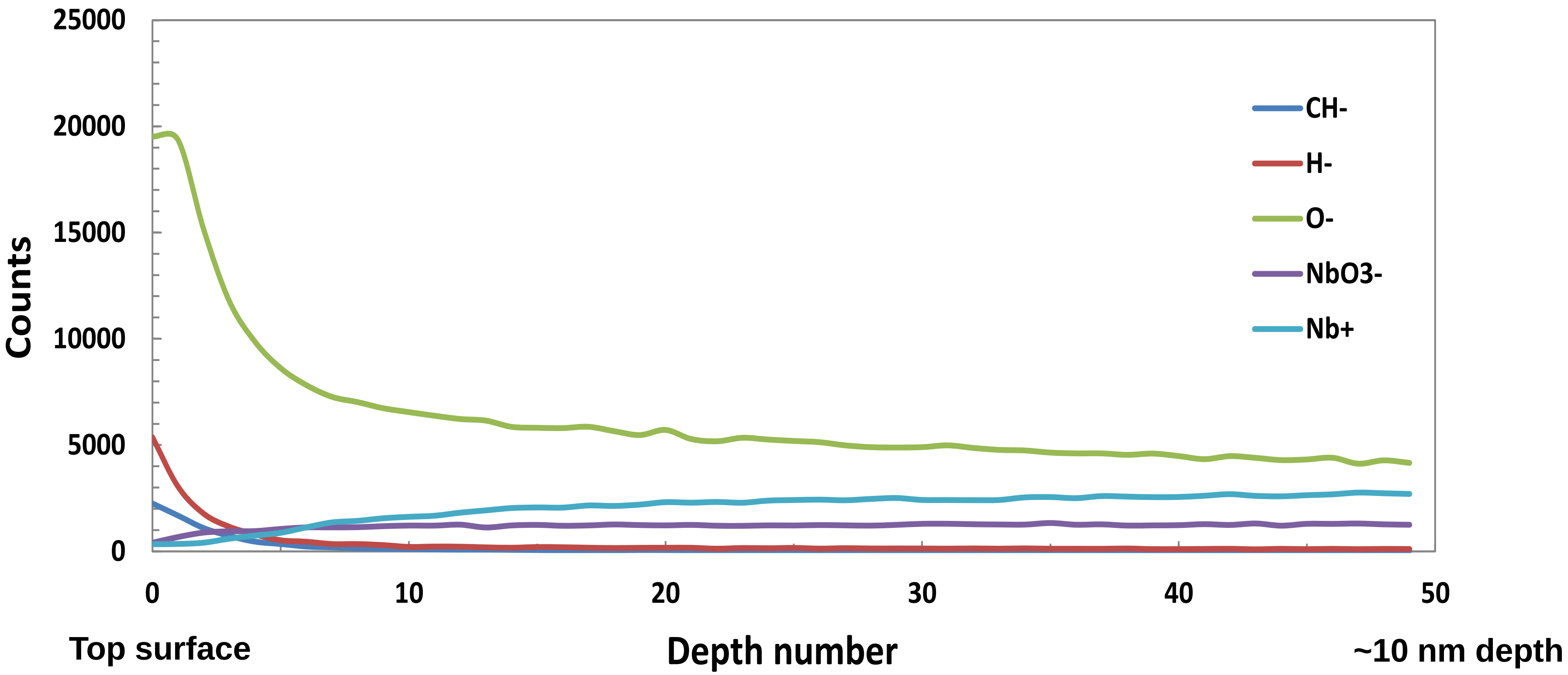
- **Warm-up sequence of CM-012 from 2K to room-temperature shown below**
- **Volatile species released from cryomodule surfaces and measured in RGA**
  - $H_2$, $N_2$, Ar, CO, $CH_4$, $C_2H_4$, $CO_2$, $H_2O$…
- **Evidence of residual Hydrocarbons $C_xH_y$ released from inner surfaces**
  - Surface Hydrocarbons can be aggravating factor to field emission process that limits accelerating gradients in the SNS SCL
  - Suspect that a significant fraction of non-volatile Hydrocarbons remain on inner surfaces
- **Plasma processing R&D aims first at developing an in-situ processing technique to remove residual Hydrocarbons to increase accelerating gradients**





# Hydrocarbons also measured on Niobium samples

- **Secondary Ion Mass Spectrometry (SIMS) done on various Nb samples**
  – Signal near top surface related mainly to H, C, and O elements for mechanically polished samples
    - Similar results with addition of fluorine element for Buffered chemically polished samples
  – Subsequent layers related mostly to Niobium and Niobium oxides



# Removing hydrocarbons to increases work function and reduce field emission

- **Most SNS cavities are limited by FE leading to thermal instability**
  - Field emitted electron current density from the surface follows Fowler-Nordheim equation
  - Electrons probability to tunnel out increases
    - The higher the electric field ($\beta$E)
    - The lower the work function $\phi$

$$J \propto \frac{(\beta E)^2}{\phi} e^{-b\frac{\phi^{1.5}}{\beta E}}$$

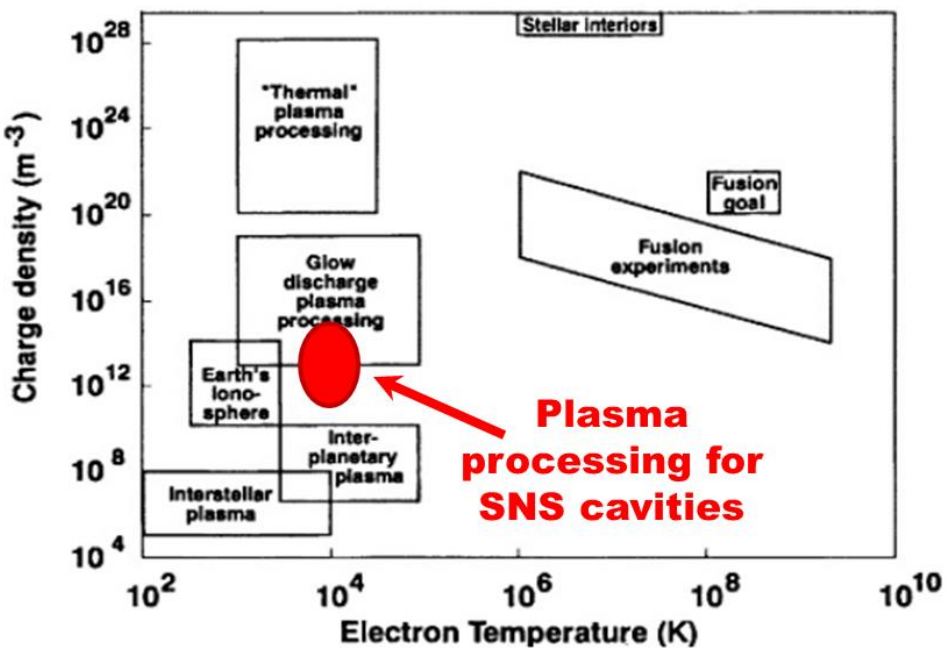
J current density
E surface electric field
$\beta$ field enhancement factor
$\phi$ work function

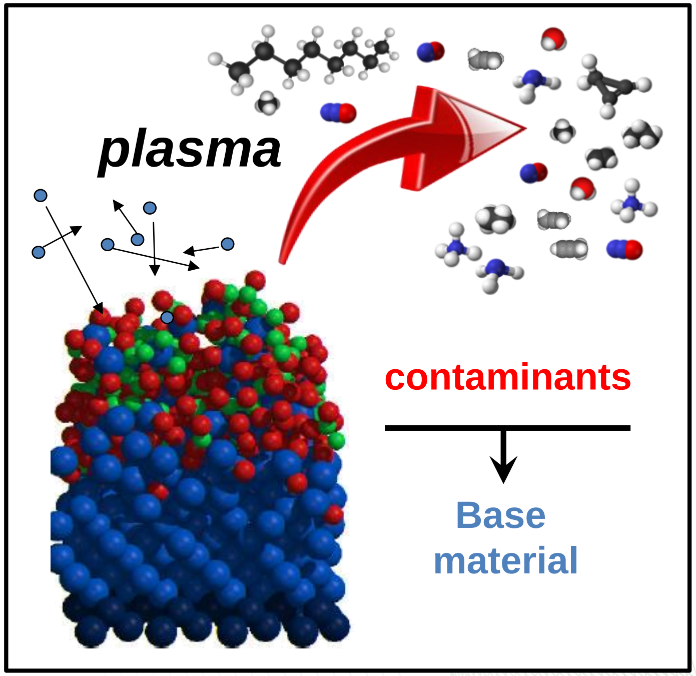
- **Plasma processes can help reducing FE**
  - Plasma processing to increase the work function $\phi$
    - E.g. by cleaning residual hydrocarbons (**current SNS R&D**)
  - Plasma processing to reduce field enhancement factor $\beta$
    - E.g. plasma etching
  - Plasma processing of particulate contaminants could improve both $\phi$ and $\beta$

- **As a rough scaling, it is estimated that accelerating gradient of SNS HB cavities could be increased by 2 MV/m if their surface work function is improved by 0.4 eV**
- **Studies for plasma processed Nb samples were performed to investigate their change in work function after plasma processing**

# 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 in many industries for various purposes**
  - Cleaning, activation, deposition, crosslinking, etching**….**
- **Chosen to develop room-temperature reactive oxygen plasma**
  - Volatile Hydrocarbon are formed through oxidation and pumped out

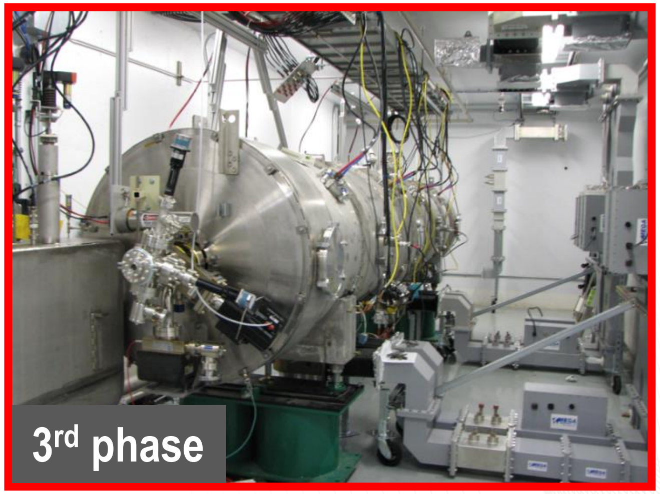


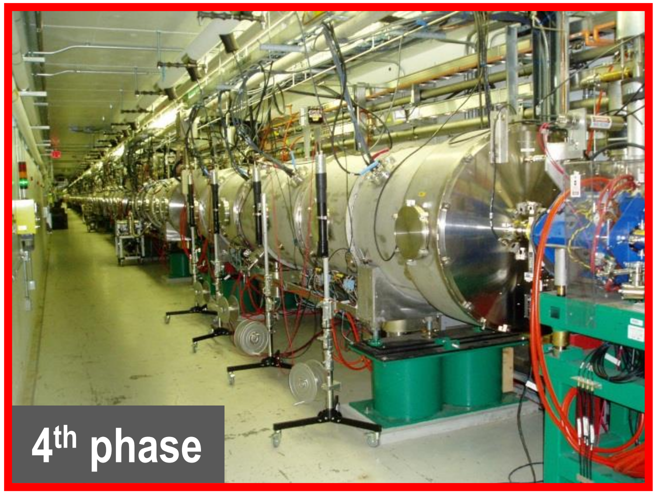
# Plasma processing R&D in four phases


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


Processing of 6-cell cavity in HTA




Processing of cryomodule in test cave

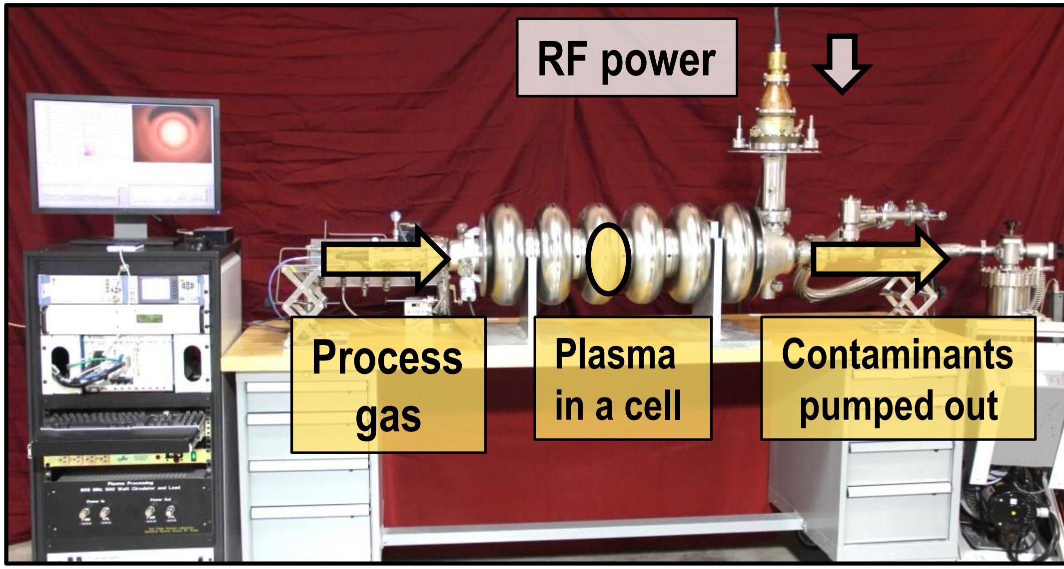



In-situ processing in linac tunnel

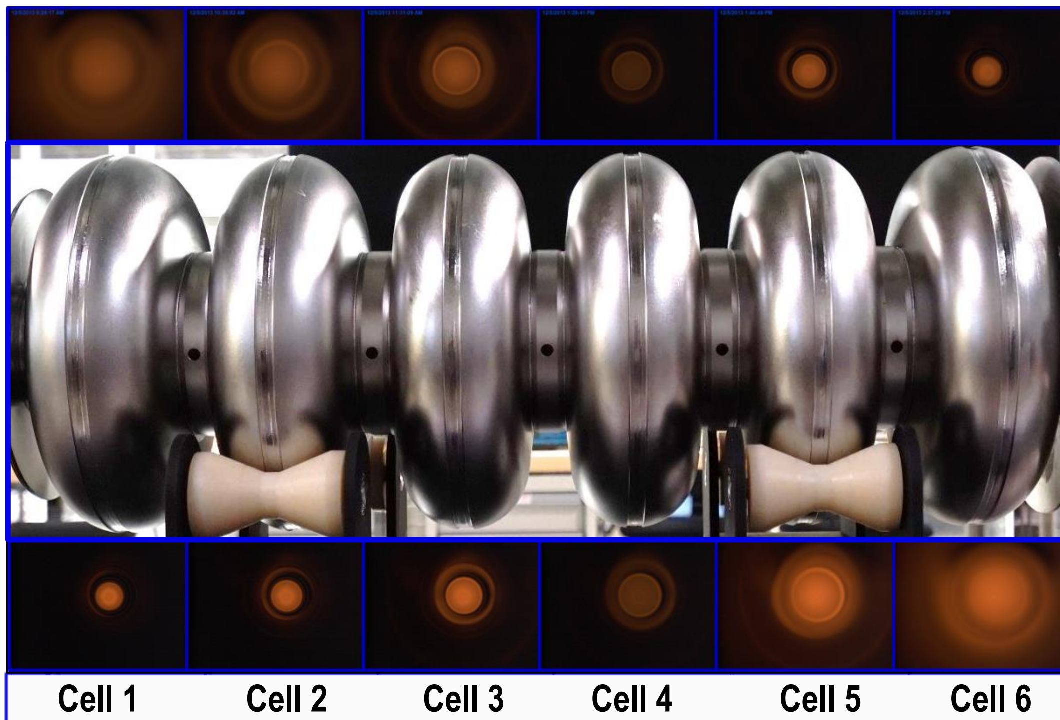
# Status of plasma processing R&D

- ✓ **Phase 1 - main objective achieved**
  - Defined plasma processing procedure for HB cavities
- ✓ **Phase 2 - main objective achieved**
  - In-situ plasma processing of a cavity in HTA
  - Demonstration of performance improvement through cold test
  - In-situ processing of a second cavity is planned
- **Phase 3 - in progress**
  - Hardware development for plasma processing of an offline cryomodule
  - Processing and cold-test of HB offline cryomodule is planned in FY15
- **Phase 4**
  - Plasma processing for HB cryomodules in SNS linac is planned in FY16 and FY17
- **Development work coordinating with plasma processing R&D**
  - Existing and new SRF facilities (CTF, VTA, HTA etc…)

# Successful plasma tuning methodology for HB cavities



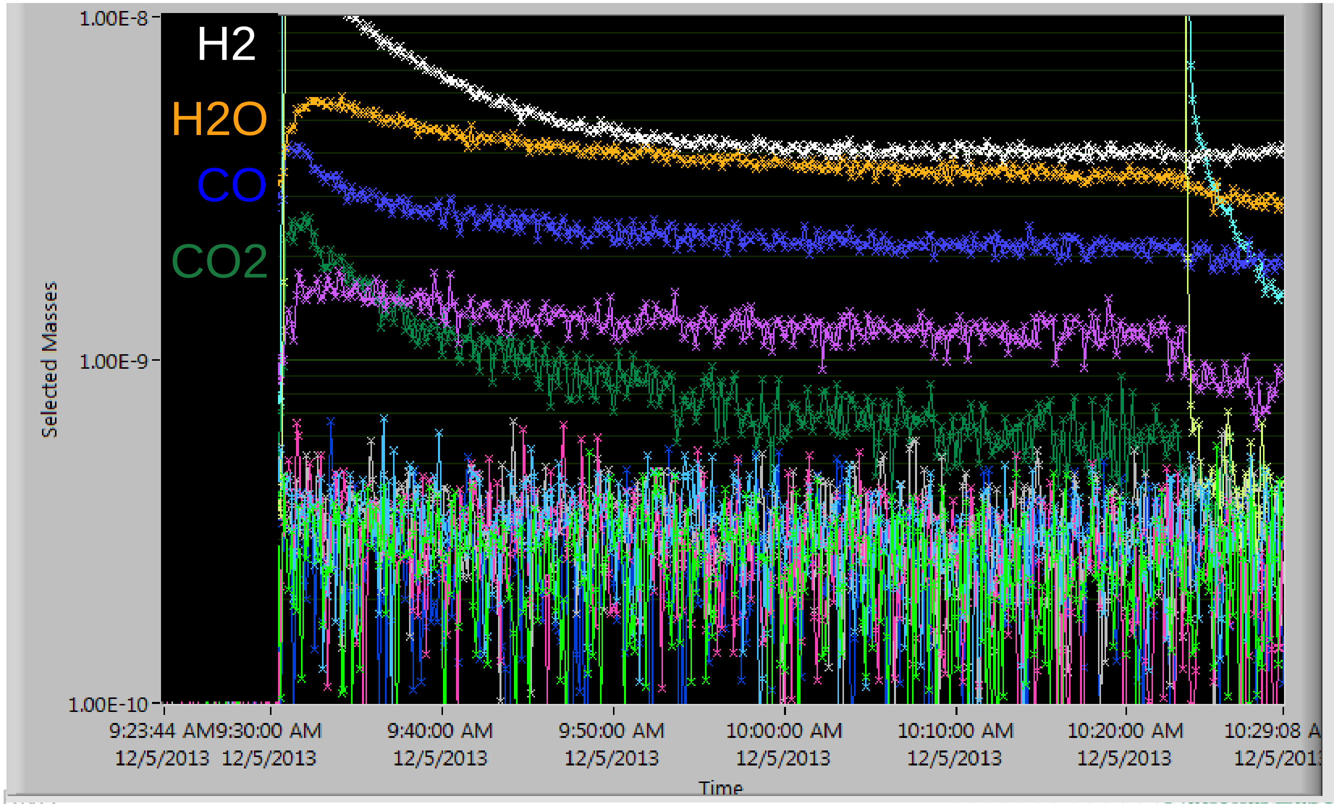

- **Plasma ignites in discrete cells, tuning necessary to process all cells**
  - Dual tone excitation (2 rf generators), on and off-resonance excitation, and plasma loaded cavity theory were used to define an ignition procedure for SNS HB cavity
  - Neon plasma for tuning
  - RF power < 1 kW




- **Camera pictures showing a Neon plasma ignited in cell 1 to 6 sequentially in SNS HB cavity**
  - **Top row**: view from left camera
  - **Bottom row**: view from right camera

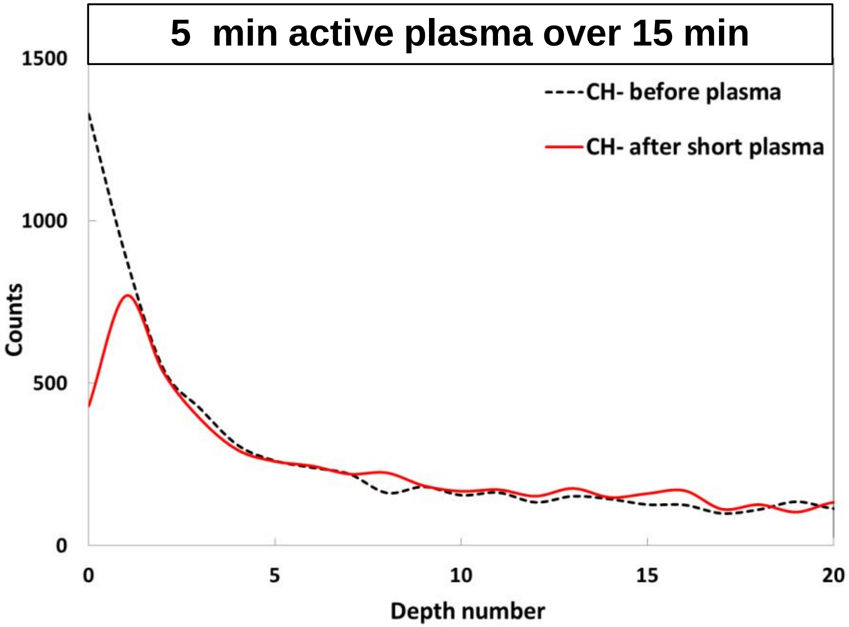
# Removal of residual hydrocarbons from HB cavity surfaces by introducing oxygen in plasma

- **Hydrocarbons on Nb surfaces observed  repeatedly during R&D**
  - On cavities used in operation, offline cavities, Nb samples…
- **Hydrocarbons removed from top surface through oxidation and formation of volatile compounds (H2, H2O, CO and CO2)**
  - Typical example of gas analysis during plasma processing of a HB cell shown below

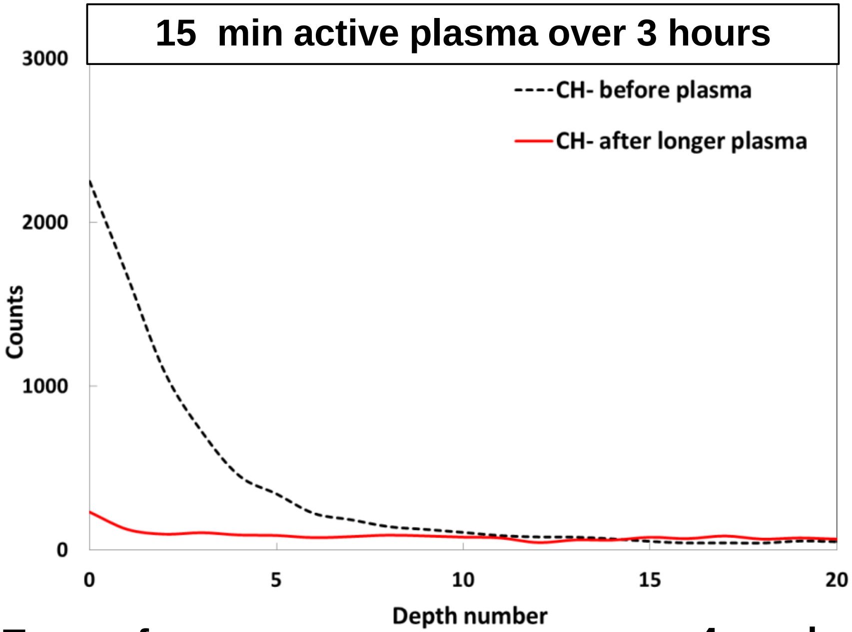


# Hydrocarbons removal studies using Nb samples

- **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 but deeper layers aren't
- **After longer plasma processing time (right figure)**
  - Top surface layer and deeper layers depleted of hydrocarbons




**Top surface** **~4 nm depth**




**Top surface** **~4 nm depth**

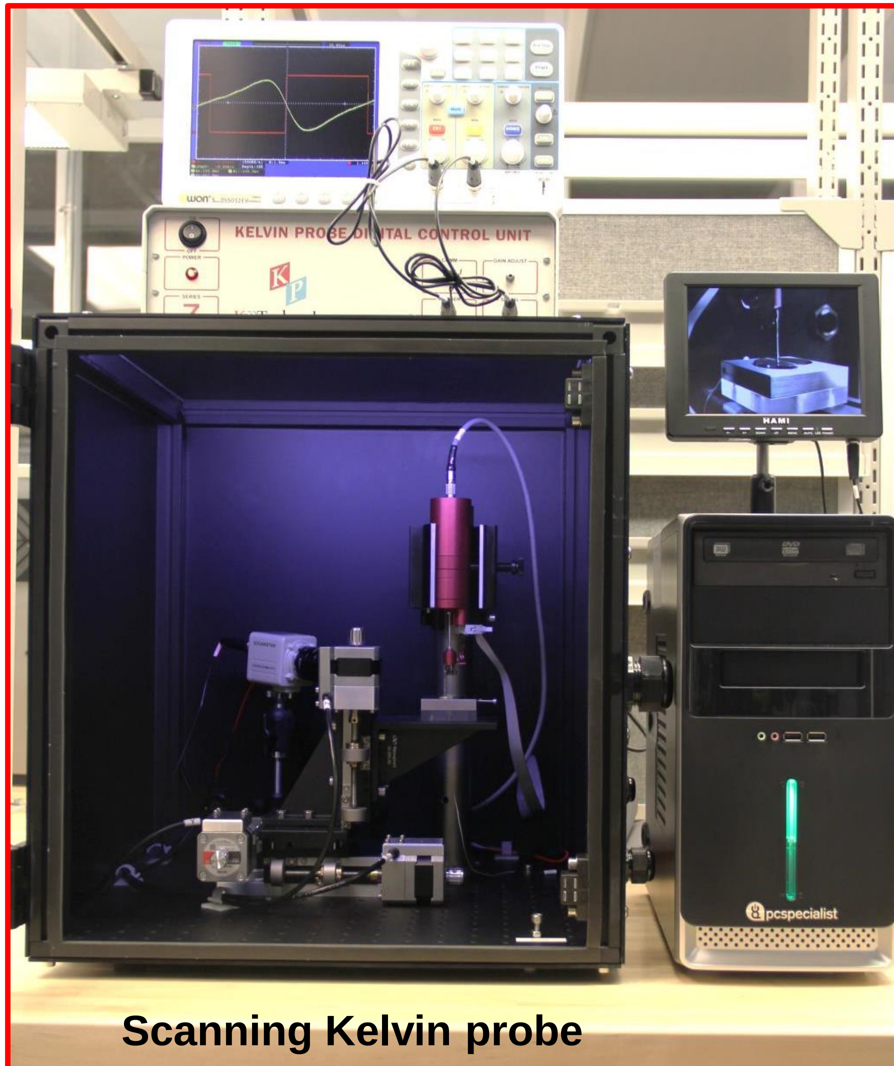
OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

# Plasma processing procedure for HB cavities

- **A procedure to clean each cell of a SNS HB cavity sequentially has been developed**
  - A chemically inert Neon plasma is ignited and tuned into the desired cell of cavity
  - Cleaning agent (e.g. Oxygen) is then introduced into the mixture
  - Once cleaning is done, the cleaning agent is removed from the mixture
  - Plasma is then turned off and the procedure repeats for the next cell
- **The procedure is robust**
  - Successfully applied to five different cavities so far
- **The procedure is safe**
  - Chemically active components are only introduced when the plasma is stable and positioned into the desired cell
  - Uncontrolled ignition (e.g. in the power coupler) is monitored and any risk mitigated since only traces amount of chemically active gases are present during tuning of the plasma
- **The procedure can be repeated as necessary**
  - For example to further depletion of hydrocarbon levels below top-surface

# Plasma processing increases work function

- **Scanning Kelvin Probe instrument used to measure work function**
  - Contact potential difference between reference probe and sample
- **Plasma processing technique developed at SNS**
  - **Removes Hydrocarbons**
  - **Systematically improves the work function**
    - For mechanically polished samples
    - For buffered chemical polished samples
    - ~0.5 to 1 eV increase  of work function has been observed
- **Increase of work function can reduce FE in cavities**



**Scanning Kelvin probe**

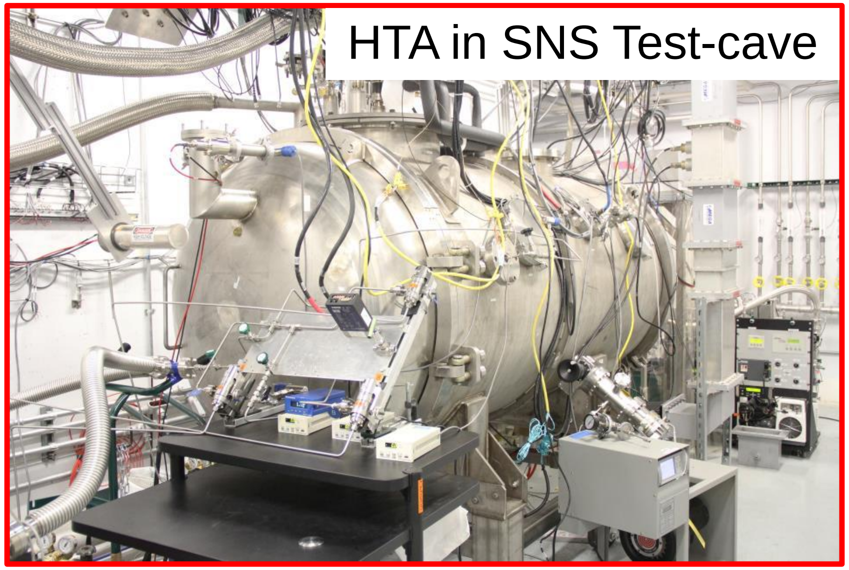
# In-situ plasma processing of cavity in HTA leads to performance improvement

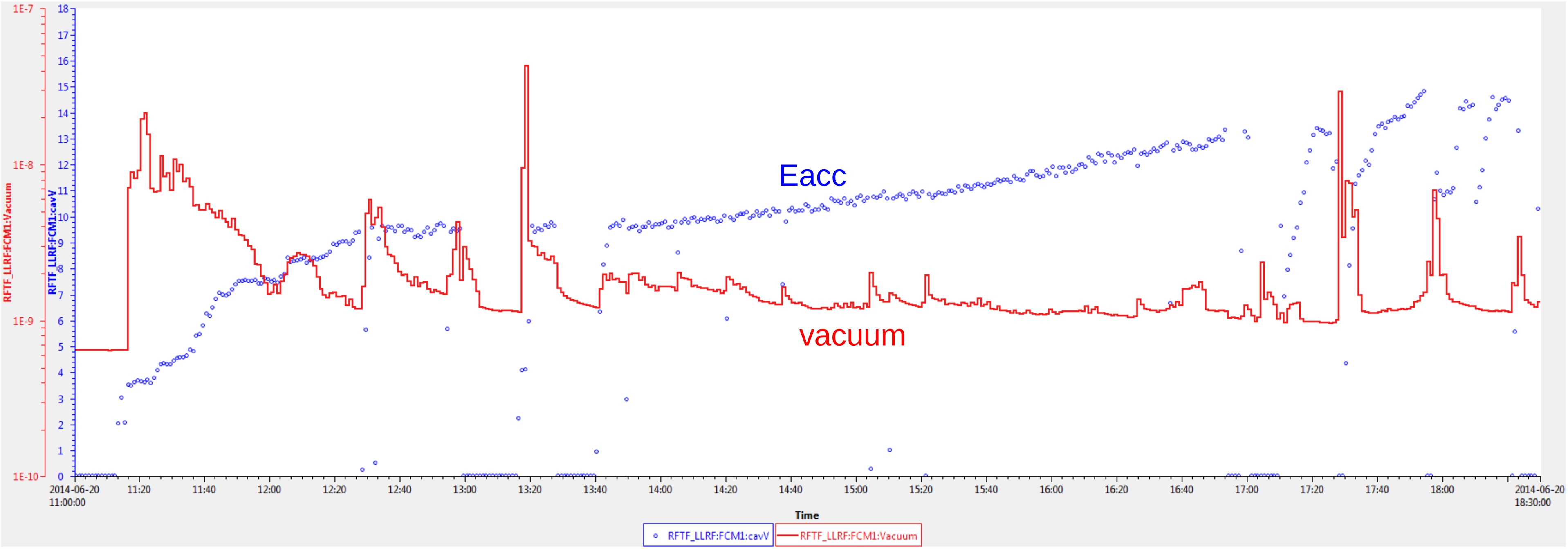
- **Work in support of the plasma processing R&D**
  - Horizontal test apparatus was integrated into the SNS SRF test facility in June 2014
  - Spare cavity (HB59) was dressed and prepared in cleanroom

- **First cold-test of an in-situ plasma processed cavity in HTA**
  - HPRF (High-power RF) baseline test of HB59 at 4K
    - To establish cavity performance before plasma processing is applied
  - In-situ plasma processing of HB59 at room-temperature
  - HPRF test of HB59 at 4K after plasma processing
    - Clear improvement of cavity performance observed

# HB59 test prior to plasma processing

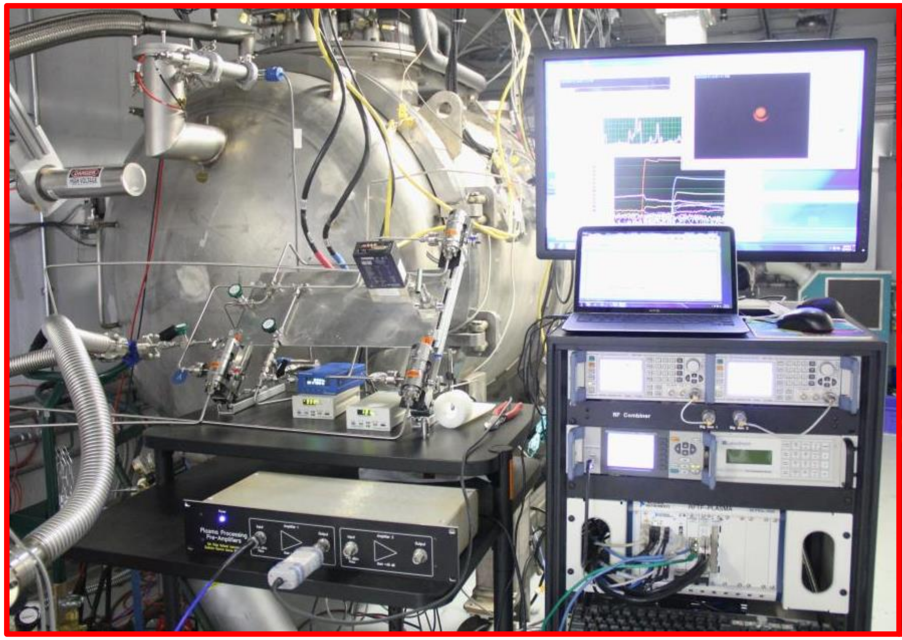
- **HB59 reaches 15.2 MV/m**
  - Progressive RF conditioning over ~8hrs
  - Lots of vacuum activity throughout conditioning
  - Eacc stable at 14 MV/m at 20 Hz rep. rate
    - Not stable at 60 Hz
  - Repetitive quenches at ~15 MV/m



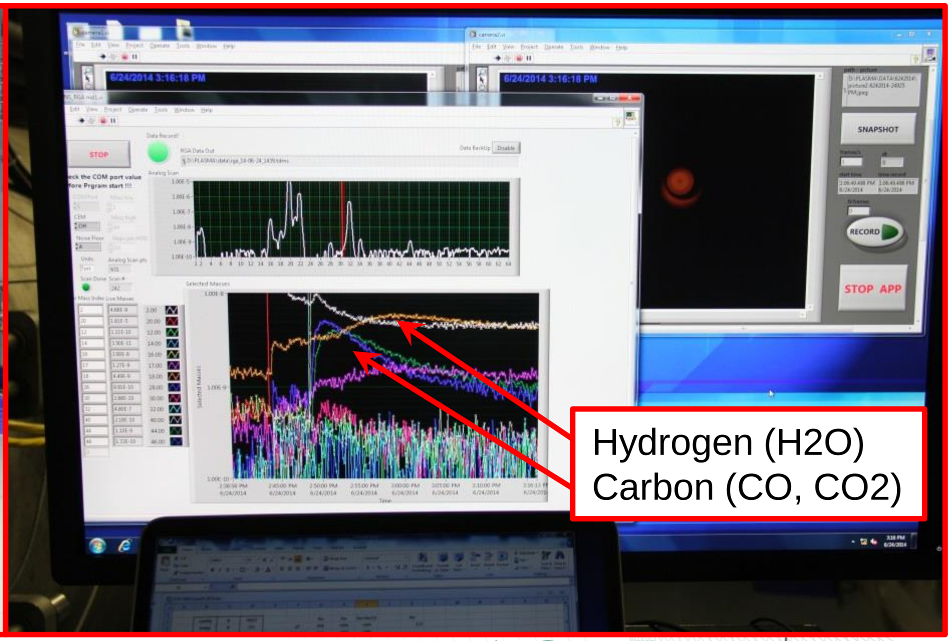



# In-situ plasma processing of HB59 in HTA

- **First in-situ plasma processing achieved in HTA**
  - HTA warmed back-up to room-temperature
  - Plasma processing procedure developed at the SNS applied to HB59
    - All 6 cells successfully ignited and processed
    - ~45 minutes processing per cell
    - Evidence of hydrocarbon removal from all cell surfaces
- **HTA cooled back down after plasma processing**



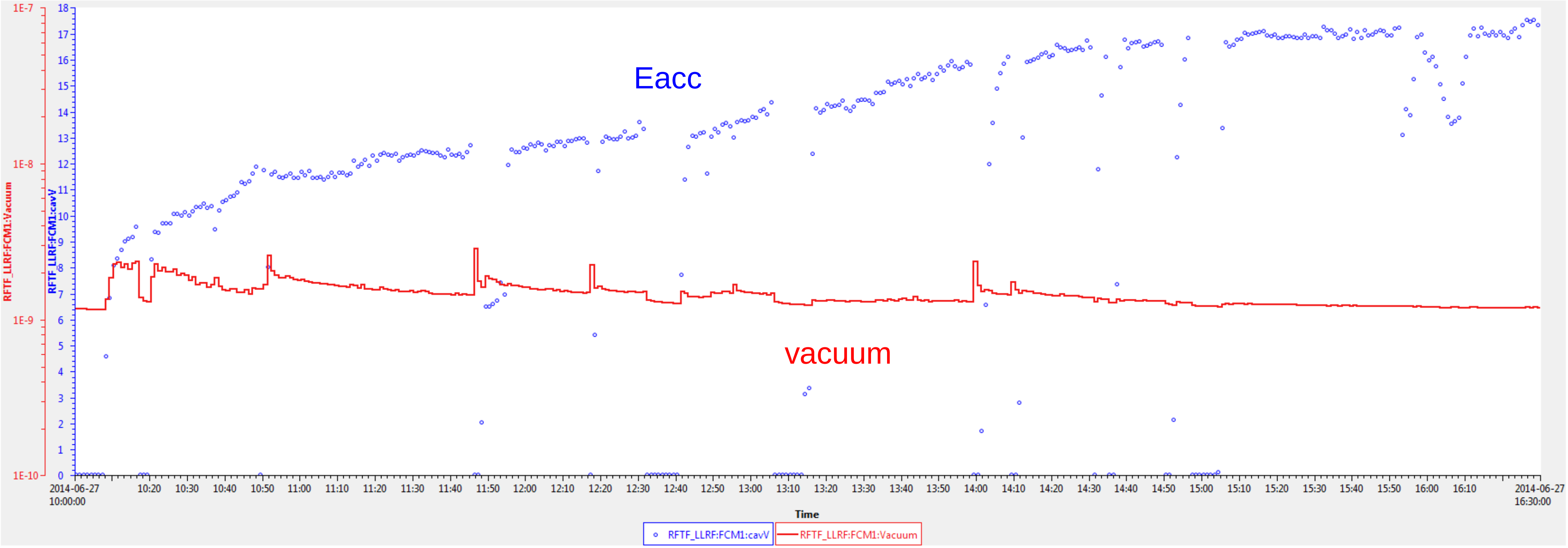
Plasma processing of HB59 in HTA




Hydrocarbon oxidation by-products from HB59 cavity

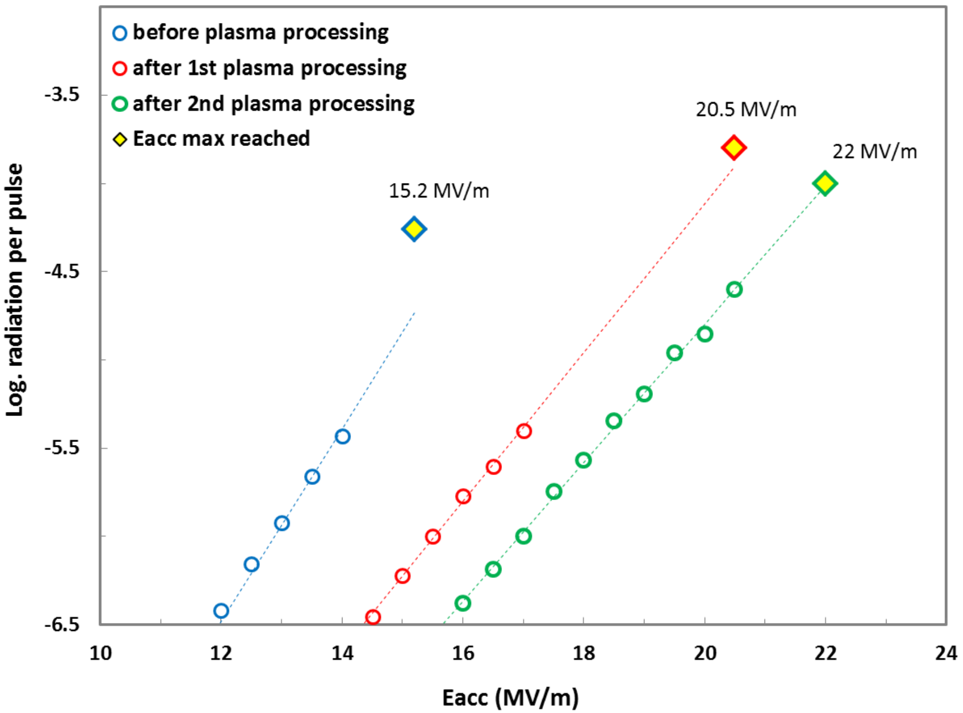
# HB59 performance improved after plasma processing

- **HB59 tested at cold in HTA after plasma processing**
- **HB59 reaches 20.5 MV/m**
  - Reduced vacuum activity during conditioning
  - Reduced radiation levels
  - Eacc stable at 18.5 MV/m at 60 Hz



# Summary of performance improvement from in-situ plasma processing of HB59

- **HB59 performance was improved by in-situ plasma processing**
  - Measurable field emission onset increased
  - Stable accelerating gradient increased
  - Improvement of performance furthered after second plasma processing
    - Could be linked to further depletion of hydrocarbon levels below top surface
  - Overall improvement exceeds average improvement pursued
- **In-situ plasma processing of a second dressed cavity is planned**

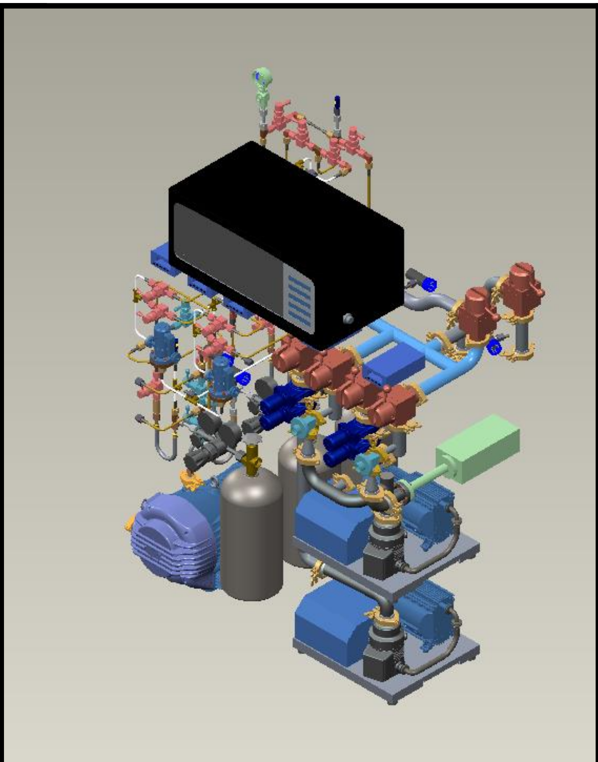
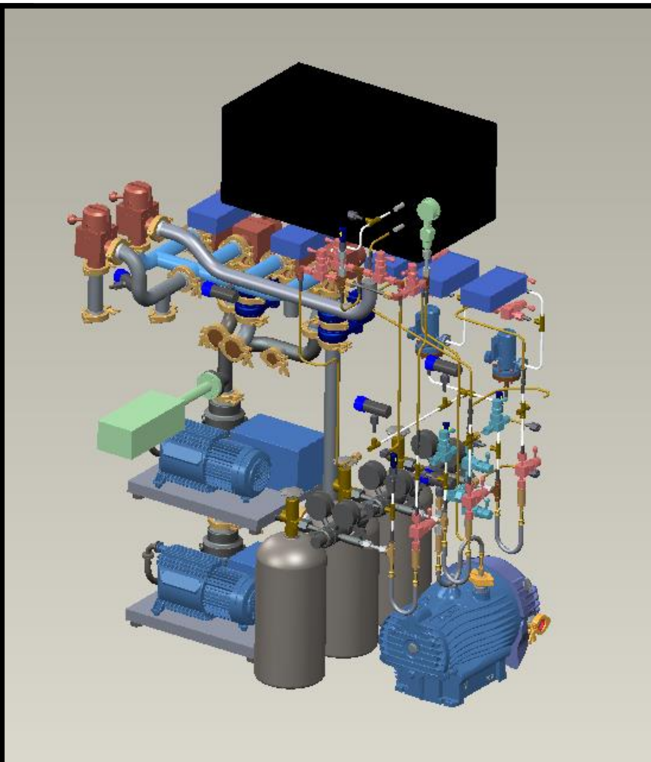





OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

# Hardware development for plasma processing of a cryomodule (third R&D phase)

- **Plasma processing of an offline HB cryomodule is planned in FY15**
  - A new manifold is required for the plasma processing of a full cryomodule
    - Main 3D engineering model for a plasma cart has been completed
      - Cart can be configured for single cavity /microwave processing (as shown in pictures below) or for cavity/cryomodule processing
      - Procurement of the cart components has started
      - Parts cleaning and assembly of the cart in the SRF cleanroom are being planned

# Conclusion

- **Plasma processing R&D is going well**
- **Standard plasma processing procedure defined**
- **Achieved in-situ plasma processing of a cavity in HTA**
- **Demonstrated cavity performance improvement after plasma processing**
- **In-situ plasma processing and cold-test of a second cavity in HTA is in preparation**
- **If successful, plasma processing of an offline HB cryomodule is planned for FY15**
- **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**