Plasma processing to improve SRF accelerating gradient

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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

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

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

- 10-20% increase in \( \phi \) leads to 20-30% increase in \( E_{\text{acc}} \)
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

1st phase: R&D with 3-cell and 6-cell cavities

2nd phase: In-situ processing in linac tunnel

3rd phase: Processing of cryomodule in test cave

4th phase: Processing of 6-cell cavity in HTA*

* 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
  - $\text{H}_2$, $\text{H}_2\text{O}$, CO and $\text{CO}_2$

- 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*

- 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

*MOPB115
Plasma processing increases work function

- Scanning Kelvin Probe instrument used to measure work function
  - Contact potential difference between reference probe and sample
  - Nb samples $\phi=4.7$ eV initially

- Plasma processing technique developed at SNS
  - Removes Hydrocarbons
  - Systematically improves the work function
  - 0.8 eV increase measured
    - $\sim$17% increase in $\phi$ can lead to
    - $\sim$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 successful: 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 cavity 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