Plasma Processing to Improve the Performance of the SNS Superconducting Linac

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SNS Machine Layout

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

LINAC:
Accelerates beam to 1 GeV
SRF linac 23 cryomodules

402.5 MHz 805 MHz

DTL CCL SRF, $\beta=0.61$ SRF, $\beta=0.81$ upgrade

2.5 86.8 186 387 1000 MeV

259 m 157 m 71 m

Accumulator Ring:
Compress 1 msec long pulse to 700 ns

Liquid Hg Target

Chopper system makes gaps

Current

945 ns mini-pulse

1 ms macropulse

Average macropulse beam current: 26 mA

Current

1 ms
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

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

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

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

J : current density
E : surface electric field
\( \beta \) : field enhancement factor
\( \phi \) : work function
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 $\phi=4.7$ eV initially
  - Neon-oxygen plasma processing systematically improves the work function
  - $\sim0.8$ eV increase measured
  - Work function tends to degrade after venting to air

Neon-oxygen cleaning applied to SNS HB cavities

- Hydrocarbons removed from top surface through oxidation and formation of volatile by-products such as:
  - \( \text{H}_2, \text{H}_2\text{O}, \text{CO} \) and \( \text{CO}_2 \)

- Residual gas analysis used to monitor plasma cleaning:
  - Depletion of surface hydrocarbons within 30-60 minutes per cell
  - Removes \( \sim \) monolayers equivalent of hydrocarbons
  - Six cells of a cavity processed sequentially
Plasma processing progress at SNS

1st phase
R&D with Nb samples and offline cavities

2nd phase
Processing of 6-cell cavity in HTA*

3rd phase
Processing of cryomodule in test cave

4th phase
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
PLASMA PROCESSING OF CRYOMODULE IN SNS LINAC TUNNEL
Pumping port on CM with angle valve

Gas in

Beam

WS

CM
Pumping port on WS with angle valve

Gas out

WS

CM

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 tuning, 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