PLASMA PROCESSING TO IMPROVE THE PERFORMANCE OF THE SNS SUPERCONDUCTING LINAC

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Abstract

An in-situ plasma processing technique has been developed at the Spallation Neutron Source (SNS) to improve the performance of the superconducting radio-frequency (SRF) cavities in operation. The technique uses a low-density reactive neon-oxygen plasma at room-temperature to improve the surface work function, to help removing adsorbed gases on the RF surface and to reduce its secondary emission yield. Recently, the plasma processing technique has been applied to one offline cryomodule and to two cryomodules in the linac tunnel. Improvement of the accelerating gradient has been observed in all three cryomodules.

INTRODUCTION

The SRF cavities at the SNS are operated at 805 MHz in pulsed mode with 60 Hz repetition rate [1]. The cavities are packaged in cryomodules hosting 3 or 4 cavities cooled down to 2 K during neutron production. The average accelerating gradient of the 81 cavities installed in the linac tunnel is 12.5 MV/m. Thermal instabilities at the extremities of the cavities induced primarily by field emitted electrons prevent from operating cavities at higher accelerating gradients [2]. Field emission process in SRF cavities has been linked to surface defects and to particulate contamination at the high electric field regions on the RF surface. Surface studies on small samples and residual gas analysis during warm-up of operated cryomodules at the SNS indicate that hydrocarbon contamination can also be present at the niobium surface and measurements using the Kelvin probe method show that such contamination tends to lower the work function of the surface and be an aggravating factor for field emission [3, 4].

The new in-situ plasma processing technique developed at the SNS removes the hydrocarbon contaminants from the niobium surface using a reactive neon-oxygen plasma. The volatile by-products of oxidation are continuously removed from the cavity volume by vacuum pumping. Cold-test of dressed cavities in the horizontal test apparatus at the SNS showed that plasma processing can help increasing their accelerating gradient [3]. The new cleaning technique has since been applied to three SNS cryomodules, one offline cryomodule and two cryomodules in the linac tunnel.

PLASMA PROCESSING OF CRYOMODULES AT THE SNS

The plasma processing technique was developed and tested using individual cavities but was designed to be directly applicable to SNS cryomodules. For example, the plasma processing gas manifolds and RF stations are packaged in carts that can easily be rolled into place to plasma process a cryomodule in the SNS linac tunnel as shown in Figure 1.

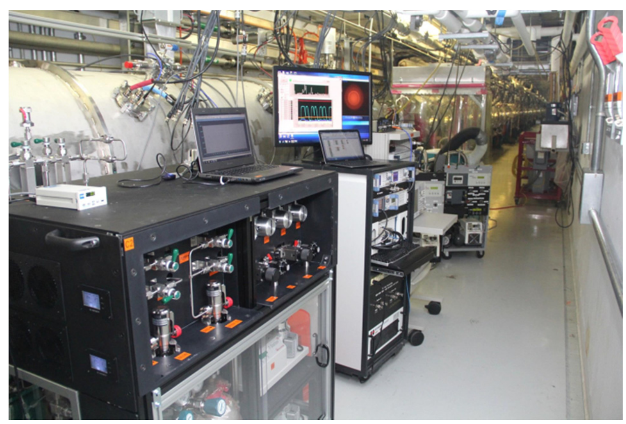

Figure 1: Plasma processing of a cryomodule in the SNS linac tunnel.

The SNS superconducting linac is segmented with a warm section after each cryomodule. The warm sections have quadrupole doublets for transverse focusing of the H^- beam and concomitant beam diagnostics. Sector gate valves are located at the extremities of each cryomodule which allows the vacuum space of a module to be isolated from the rest of the linac, for example when thermal cycling is performed. An ion pump is installed on each cryomodule and on each warm section and a pumping port with a manual valve is available at each pump. The valves are in closed position and capped during normal operation. The sector gate valves and the manual valves are being used to plasma process cryomodules individually without affecting near-by cryomodules and without requiring venting of the beamline.

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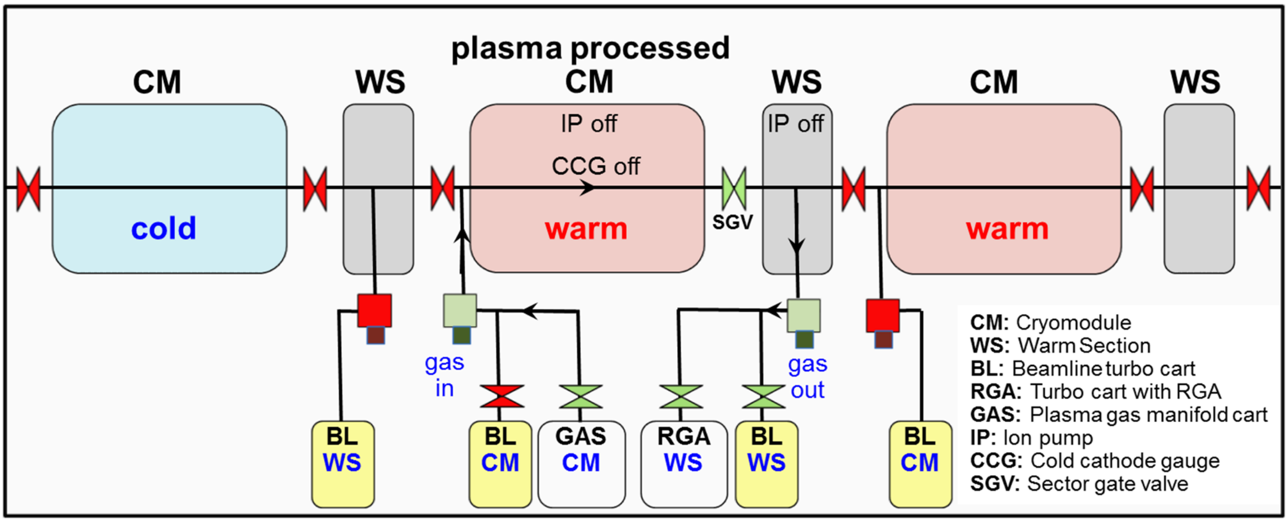

Figure 2: Schematic of the vacuum connections during the plasma processing of a cryomodule at the SNS .

As shown in Figure 2, the process gas is injected at one end of a cryomodule and pumped through the warm-section at the other end. During the plasma processing, a continuous process gas flow in the order of 25 sccm is established with a pressure of 150 mTorr in the cryomodule. Pirani-type vacuum gauges are used to measure the pressure at the inlet and outlet of the cryomodule. Residual gas analysis is used to monitor the neon-oxygen gas mixture as well as to monitor the volatile by-products formed by the interaction of the plasma with the surface. As shown in Figure 2, multiple sector gate valves on each side of the processed volume are maintained in a closed position during the plasma processing period. For protection against small gas leaks through sector gate valves, turbomolecular pump carts are installed on the warm section and on the cryomodule immediately adjacent to the volume filled with process gas. This cryomodule is also warmed-up to avoid any cryopumping of the process gas on the cold surfaces in the event of a small leak through the sector gate valve. No leak has been observed during the plasma processing of the first two cryomodules in the SNS linac tunnel. Since the process gas pressure is in the medium vacuum range, ion pumps and cold-cathode gauges are turned off during plasma processing.

The RF stations used for igniting the plasma inside the cavities of SNS cryomodules have 500 W to 1 kW solid state amplifiers at 805 MHz with enough bandwidth to excite any of the TM_{010} passband modes of the six-cell elliptical cavities. The RF stations have circulators and loads so that full reflection of the RF power is permitted. This is important since the SNS cavities are strongly under-coupled at room temperature (i.e. $Q_{ex}>>Q_0$). The superconducting cavities in operation at the SNS are individually powered by high-power klystrons. A small flexible section of waveguide is installed near each cavity. It can be easily removed to disconnect a cavity from the high-power RF system and a waveguide termination with a small coaxial antenna can be installed in lieu for local low-power measurement of the cavity RF parameters. Similar waveguide termination is used to connect a plasma processing RF station to a cavity via a heliax cable. The field probe of a plasma processed cavity is also connected to the RF station and power meters are used to monitor the forward, reflected and transmitted powers. The coaxial-type fundamental power coupler of each cavity is equipped with a view port and a camera is used to optically verify that no plasma discharge occurs in the coaxial line. The schematic of the connection of an RF station to a cavity in a cryomodule is shown in Figure 3. After a cavity is plasma processed, the RF station is moved to the next cavity. Multiple cycles of plasma processing can be done for optimum cleaning. Multiple RF stations can also be used to plasma process cavities simultaneously.

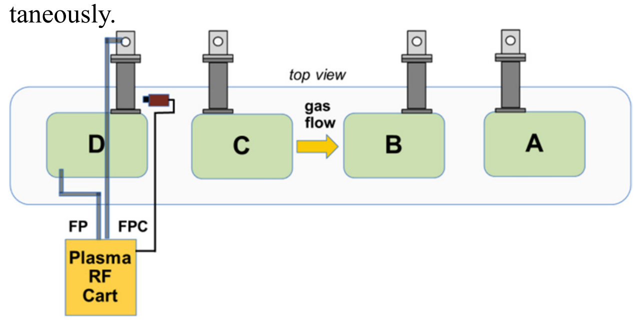

Figure 3: Connection of the plasma processing RF station to a cavity in a high-beta cryomodule. The cavities are indexed with letters A to D.

As detailed in [3], results from the residual gas analysis done during plasma processing can be used to estimate the amount of hydrocarbons removed from the RF surface of the cavities. For the cryomodule plasma processed offline, CM00012, and for one of the cryomodule plasma processed in the linac tunnel, CM00023, the cavities were processed individually. Figures 4 and 5 show the amount of hydrocarbon contaminants removed for each cavity of these two cryomodules. Only, the cells with the lowest and highest amount of contaminants are shown.

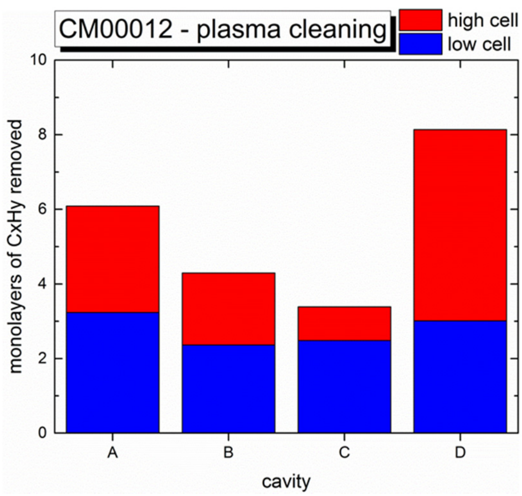

Figure 4: Amount of hydrocarbon removed by plasma processing of the offline high-beta cryomodule at the SNS.

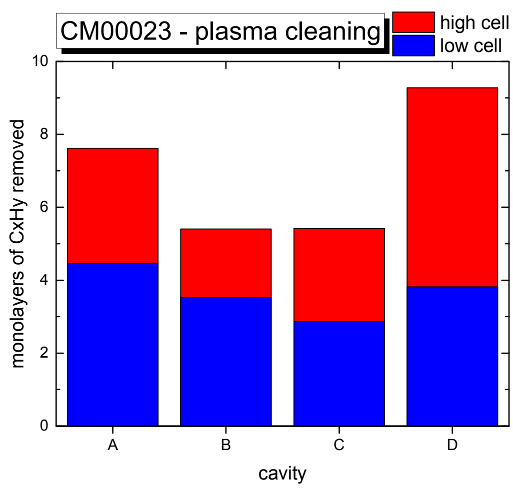

Figure 5: Amount of hydrocarbon removed by plasma processing of the CM00023 cryomodule in the SNS linac tunnel.

As illustrated, the equivalent of multiple monolayers of hydrocarbon contamination was removed by the plasma processing technique in both cryomodules. The end cells of cavities and in particular the cells at the extremities of the cryomodules were found to be the most contaminated. Another cryomodule, CM00022, was subsequently processed in the linac tunnel. For this cryomodule, two RF stations were used to plasma process cavities simultaneously. As the result, contamination data is not available for each individual cavity in this cryomodule.

CRYOMODULE PERFORMANCE IMPROVEMENT AFTER PLASMA PROCESSING

After plasma processing, the cryomodules were cooled back to cryogenic temperature and their cavities tested. The change of the accelerating gradients at 60 Hz repetition rate for the cavities of the three plasma processed SNS cryomodules is shown in Figure 6. Performance improvement for the cavities ranges from 0.2 MV/m to 5.5 MV/m for an average improvement of 2.5 MV/m (21%). No degradation of performance has been observed so far after plasma processing.

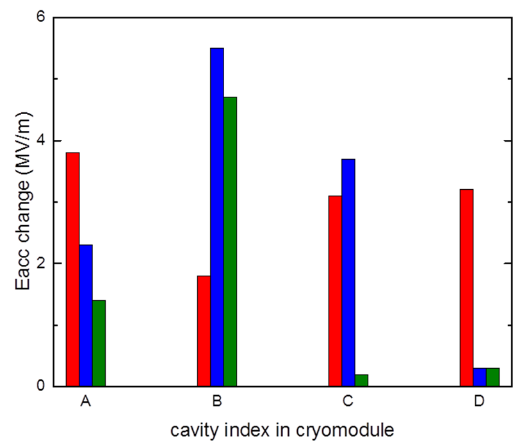

Figure 6: Improvement of the accelerating gradients for the cavities of the first three plasma processed SNS cryomodules.

The radiation during the RF operation of cavities before and after plasma processing was also measured. The integrated amount of radiation measured with photomultiplier tubes over an RF pulse is summarized in Figure 7 for the CM00012 cryomodule and in Figure 8 for the CM00023 cryomodule. As mentioned, the majority of the cavities are in the field emission regime. At a given accelerating gradient, the amount of radiation has decreased after plasma processing. As explained in [3,4], the increase of the work function for the RF surface can lead to a reduction of the amount of field emitted electrons. Some cavities, e.g. cavities B and C in the offline cryomodule CM00012, are limited by multipacting. For these cavities, the severity of the multipacting was reduced after plasma processing which also led to an increase of their accelerating gradient.

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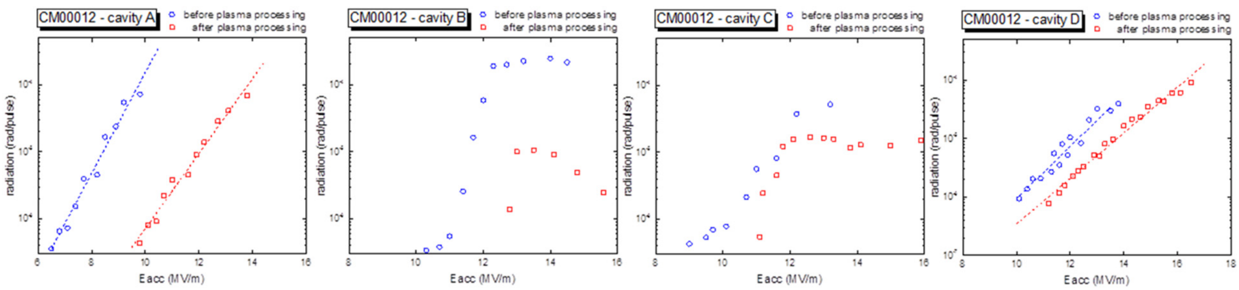

Figure 7: Radiation per pulse before and after plasma processing for the offline cryomodule.

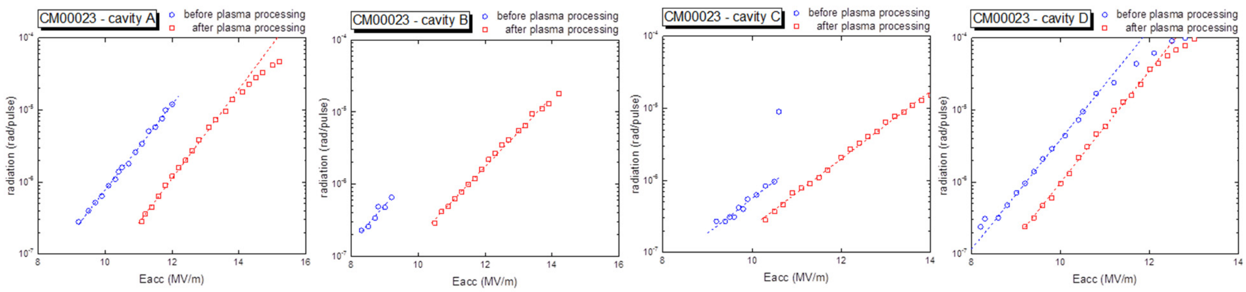

Figure 8: Radiation per pulse before and after plasma processing for the CM00023 cryomodule in the linac tunnel.

All the cavities plasma processed with the neon-oxygen mixture have shown performance improvement. The improvement has been large for some cavities where the hydrocarbon contaminants were a significant limiting factor. Some other cavities have improved modestly indicating that the performance of those cavities was mainly limited by something other than the hydrocarbon contaminants. Other types of contaminant (e.g. metallic particulate), surface defect or hot spots are examples of other possible limiting factors in SRF cavities [5].

SUMMARY

The plasma processing technique developed at the SNS has been applied to three cryomodules. Removal of surface hydrocarbons was observed in all plasma processed cavities. The accelerating gradient of the plasma processed cavities increased between 0.2 MV/m and 5.5 MV/m for an average improvement of 2.5 MV/m. As the result, the linac beam output energy at 60 Hz repetition rate is the highest to date at 972 MeV. Additional cryomodules will be plasma processed with the aim to reach 1 GeV beam output energy in the near future.

ACKNOWLEDGMENT

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