R&D STATUS FOR IN-SITU PLASMA SURFACE CLEANING OF SRF CAVITIES AT SPALLATION NEUTRON SOURCE*

S-H. Kim[#], M. Crofford, M. Doleans, J. Saunders, ORNL, Oak Ridge, TN 37831, USA
J. Mammosser, JLab, Newport News, VA 23606, U.S.A.

Abstract

The SNS SCL is reliably operating at 0.93-GeV output energy with an energy reserve of 10 MeV. Field emission directly or indirectly (through heating of end groups) limits the gradients achievable in the high beta cavities in normal operation with the beam. One of the field emission sources would be surface contaminations during surface processing for which mild surface cleaning, if any, will help in reducing field emission. An R&D effort is in progress to develop in-situ surface processing for the cryomodules in the tunnel without disassembly. As the first attempt, in-situ plasma processing has been applied to the CM12 in the SNS SRF test facility after the repair work with a promising result. This paper will report the R&D status of plasma processing at the SNS.

INTRODUCTION

Since the initial commissioning of accelerator complex in 2006, the SNS has begun neutron production operation and beam power ramp-up has been in progress toward the design goal. Since the design beam power is almost an order of magnitude higher compared to existing neutron facilities, all subsystems of the SNS were designed and developed for substantial improvements compared to existing accelerators and some subsystems are first of a kind. Many performance and reliability aspects were unknown and unpredictable and it takes time to understand the systems as a whole and/or needs efforts for additional performance improvements. From the series of tests and operational experiences more understandings of systems and their limiting conditions in the pulsed mode are being obtained at high duty operation.

The final output beam energy mainly depends on the SRF cavity gradients. Presently, eighty cavities out of eight-one cavities are in service and the SCL is providing output energy of 930 MeV with about 10-MeV energy reserves. Actual operating gradients are set around 85-95 % of limiting gradients achieved at 60-Hz collective tests [1] for the stable operation since the machine availability is steeply increasing concern as a user facility. The SCL is providing beam acceleration for the neutron production as one of the most reliable systems at the present operating conditions.

In operation, the stable operating gradient of the high beta cavities is 12.8 MV/m in average mainly due to the heating of the end groups by electron loadings. Major contribution of electron loading is field emission which heats up the end groups and results in partial quench and gas burst. The average accelerating gradients achieved from the existing cavities are summarized in Figure 1. The high-beta cavities need about 2.5 MV/m performance improvements to achieve 1-GeV output energy, with 30- to 40-MeV energy reserve for fast recovery of operation from unexpected long-lead down time of not only cavities but also related systems.

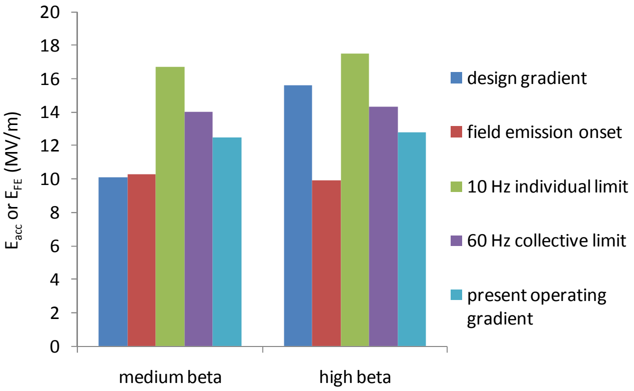

Figure 1: SNS cavity performance statistics.

At SNS, in-situ processing in the tunnel has been identified as an important area of research to improve the SRF cavity performances while minimizing the machine operational impact and saving cost for the improvements.

IN-SITU SURFACE PROCESSING

As cleaning methods have been improved for the niobium surfaces, field emission is not a fundamental limiting factor to reach a theoretical limit. But field emission is a one of the major limiting factors in the operational machines especially in the high duty machines and results in a large scattering of cavity performances. The sources of field emitters are known to be material defects and contaminants introduced during cavity assembling, water dry spots, residues after high pressure rinsing (HPR), electro-polishing (EP) and buffered chemical polishing (BCP). Condensed gases and chemicals could form surface layers and enhance field emissions. By nature the locations of field emitters are random and statistical. Characteristics of field emitters would change over time and processing seems to be harder after an initial cavity RF conditioning depending on types of field emitters.

While qualifying a cavity itself, combinations of post processing among HPR, EP or BCP could be applied to a less performing cavity. It is, however, very difficult to apply a conventional surface cleaning/processing after cavities are assembled in a cryomodule. Rebuilding a cryomodule for performance improvements is time-consuming and expensive. In-situ processing is one of the most promising solutions for improvement of the SNS

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[#] kimsh@ornl.gov

cryomodule performances and cryomodule recovery while in service.

Possible candidates of in-situ processing are examined for the SNS cryomodules mainly between helium processing and plasma processing.

The helium processing is a variation of RF processing, running at the operating temperature (2K or 4K), and vacuum pressure below discharge condition in the field emission regime. Helium processing of SRF cavities has been shown to be successful especially during the qualification of cavities in VTA [2]-[4], even though the mechanism is not fully understood [5],[6]. There are some reports on statistical improvements of cavity performances by the in-situ helium processing [7],[8]. Few statistics and experiences are, however, for the pure in-situ helium processing at a gradient higher than 10 MV/m and/or in pulsed mode with higher-order-mode couplers and coaxial type power couplers. In-situ helium processing was performed on one cavity in the SNS cryomodule with no success. During the processing there were aggressive multipacting at around HOM couplers and the processing could not be done at a gradient at higher than 8 MV//m.

Plasma surface cleaning is a well-known and widely-used technology in semiconductor industries and other areas [9-11] like vacuum devices, fusion devices and normal conducting cavities. There were some efforts for cleaning of lead plated SRF cavities using plasma in early days [12]. When radical molecules, ions, and electrons from the plasma discharge interacts with surfaces, there are reactions such as desorption of gases from the base material and grain boundaries, removal of organic materials, secondary reactions via activated species from desorbed/inner gases, ablation, and surface chemical restructuring. Some impurities and contaminants can be converted into vapour and can be pumped out. Plasma cleaning parameters (processing time, inert gas contents, vacuum, RF power, processing temperatures, etc.) need to be optimized for the specific purposes.

PLASMA SURFACE CLEANING

As a preliminary test a completely oxidized niobium sample was introduced in the air plasma at about 0.1-0.5 torr. The sample was processed for about 10 min. in the plasma chamber. The surfaces became shiny after the processing as shown in Fig. 2. The RGA traces during the processing indicate hydrogen and nitrogen desorption, carbon dioxide formation from carbon and oxygen and removal of oxide layer.

After the helium processing trial mentioned in the previous section, in-situ plasma processing has been applied to three cavities in the SNS high cryomodule at 4 K. Plasma cleaning is eventually planned to be at the room temperature. This cryomodule was the worst performing one and showed largest x-rays. Since this was the first attempt and processing parameters were not optimized at all, the plasma processing has been performed in a mild condition for a short time (<5 min.) with helium gases. After the plasma processing, the cryomodule was warmed up to pump out the helium gas and by-produced gases condensed on the surfaces (Fig. 3). Much larger amount of hydrogen gases than normal was pumped out and some unusual gases were monitored, which seem to be by-produced gases.

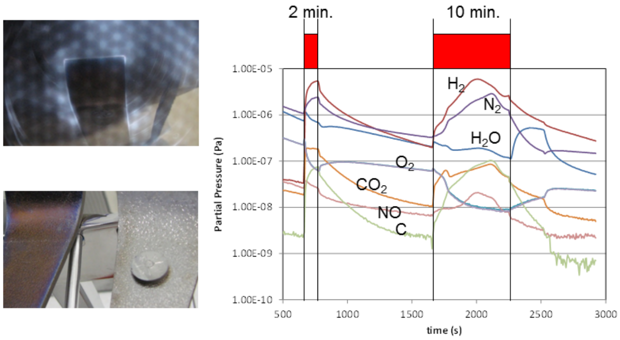

Figure 2: Plasma processing of a niobium sample in the microwave chamber.

Fig. 4 shows an example of by-produce gases. Partial pressures drop down at about same time, which indicates that elements with molecular mass 12, 16, 28, 30, 32, are fragments of the element with molecular mass 44.

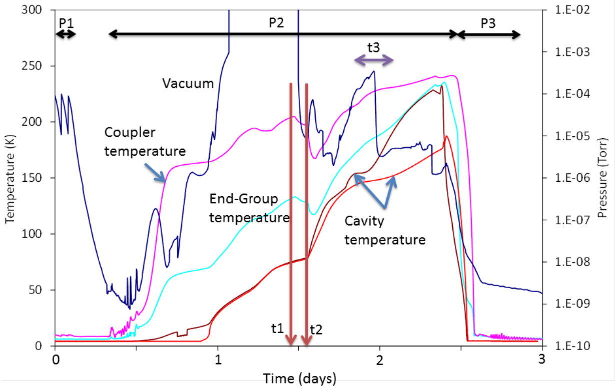

Figure 3: Vacuum and temperature evolutions while partial warming-up after plasma processing at cold temperature. (P1: plasma processing, P2: partial warm-up, P3, cool-down)

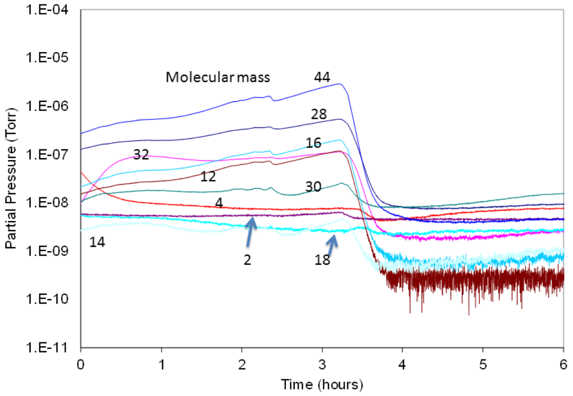

Figure 4: RGA readings during the time, t3 in the Fig. 4.

Radiations are compared before and after the plasma processing. To measure radiations precisely additional diagnostic tools are equipped in the SNS test cave (Fig. 5). Results from this effort have shown that the plasma processing can significantly reduce field emission and surface contaminations on a fully assembled cryomodule (Fig. 6). The cryomodule was then installed into the tunnel where it resided today operating at about the average performance for high beta cryomodules.

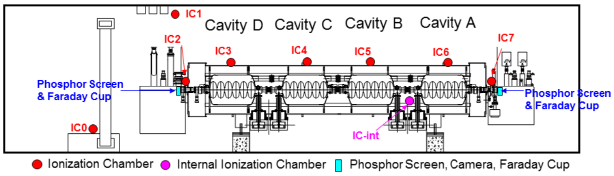

Figure 5: Diagnostic equipment in the SNS test cave.

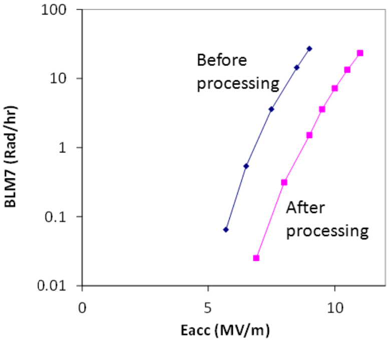

Figure 6: peak radiation readings vs. Eacc before and after the plasma processing

As reductions of x-rays from field emission after this very preliminary and light plasma processing at the cold temperature have been established, the plasma processing has been identified as an important area of R&D for the SNS cryomodules, and hardware setups for the systematic studies are in progress including a 3-cell cavity, a fast turn-around plasma chamber for small samples and a test cavity. The R&D will focus on the removal of surface contaminants and trapped gases, altering oxidation-state surface condition and eventually developing a procedure that is statistically optimal with possible contaminants. One of the main tools for the study is a TM020 test cavity (Fig. 7) that has been designed and fabricated. The test cavity is specially designed to have low Bp/Ep (=1.16 mT/(MV/m). The bottom plate of the test cavity is demountable and can be utilized in the plasma chamber and assembled to the power coupler port of the SNS cavities for the witness during the processing.

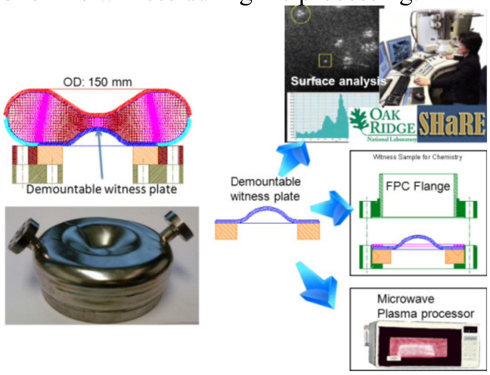

Figure 7: R&D plans using the test TM202 cavity.

The R&D effort for the plasma cleaning at the SNS is just a starting phase, and optimizations for the statistical improvements of the SNS cavity performances will need a systematic plan for the final in-situ cleaning procedure. Since there are components made of copper such as HOM coupler feedthroughs and inner conductors of the fundamental power coupler, and there can be solid-state by-products while cleaning via chemical reactions, inert gases and processing parameters should be chosen in a conservative way. Followings are expected from the mild plasma cleaning based on the initial tests at SNS and experiences in other areas.

- Mild ablation effect can be introduced, which will remove or smoothen the small material defects or contaminants (< 1μm).
- The absorbed in the surface and the trapped gases in the grain boundaries can be removed efficiently with an optimized cleaning process. Oxide surfaces can be also removed. These features can have a similar effect of low temperature baking and a plasma processing can be a post processing step while commissioning cryomodules.
- Helium can exchange other absorbed gases on the surfaces during the plasma cleaning. This can be removed easily after processing by its nature.

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