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Commissioning and operation of the horizontal test apparatus at SNS

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Abstract. The Spallation Neutron Source (SNS) at Oak Ridge National Lab (ORNL) has built, commissioned and operated a Horizontal Test Apparatus (HTA) vessel in the Radiofrequency Test Facility (RFTF) test cave. It can be operated at 4.5 K using the independent Cryogenic Test Facility (CTF). The HTA is designed to be a single cavity version of an SNS cryomodule with the ability to demount and replace the cavity. It provides the functionality for testing a single dressed SNS medium or high beta Superconducting Radiofrequency (SRF) cavity. The HTA is currently being used in support of R&D for in-situ plasma processing of the cavity's inner niobium surface. The design and commissioning of the HTA at 4.5 K will be presented as well as results from operating the HTA including cool-down, warm-up and steady state operations. Results from plasma processing a warm SCRF cavity in-between cold HTA tests will also be reported.

1. Background

The superconducting portion of the SNS linear accelerator (linac) is comprised of 11 medium-beta and 12 high-beta cryomodules. Each medium beta cryomodule contains three SRF cavities, while each high beta cryomodule contains four SRF cavities. The primary helium circuits of these cryomodules are cooled down to 2 K with helium supplied from the Central Helium Liquefier (CHL). While isolated cryomodules have been warmed to room temperature, the majority of the cavities in the linac have been cold since the SNS linac operation began in 2006 [1].

The SNS linac has achieved reliable operation with excellent beam availability on target. SNS is currently operating with a linac output energy of 940 MeV. The major limiting factor for higher accelerating gradients is field emission and/or multipacting in the SRF cavities that result in an end group quench. An end group quench is defined as a portion of the end group of the cavity becoming normally conductive. This does not result in an immediate trip of the cavity but negatively affects the cavity over multiple beam pulses. The cavity end groups were fabricated with reactor grade niobium which has a lower thermal conductivity than niobium with a higher residual resistivity ratio (RRR). Since end groups are cooled by indirect conduction to the helium circuits, the end groups become thermally unstable due to aforementioned electron activities [2].

To reach the SNS design output energy of 1 GeV, rework could be performed on the cavities in the SCL portion of the linac. However, the off-line rework of cryomodules to improve cavity performance

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is a time consuming and expensive task. The SNS began a research and development (R&D) effort to better understand limiting factors of the SNS cavities. Part of this effort is to address the possibility of in-situ processing of the inner surfaces of SRF cavities circumventing the need to disassemble or remove the cryomodule from the linac tunnel altogether [2]. SRF R&D activities in general require a flexible platform that has a similar environment to a real cryomodule. To conduct this study, there is a need to perform various tests on demountable fully dressed medium beta or high beta cavities. During these tests, the cavities would be operated with more cryogenic instrumentation but the same RF operating conditions as a cryomodule.

The need for testing cavities for both R&D as well as cryomodule production formed the basis for the HTA concept. Traditional vertical testing masks the thermal instability of the end groups because they are submerged in liquid helium. In the horizontal configuration, the end groups are only conductively cooled. This configuration provides the most relevant performance assessment of a cavity.

Two R&D initiatives currently utilize the HTA for testing. The first initiative to improve cavity performance is by using plasma inside the cavity vacuum volume. This is done at room-temperature and is accomplished by feeding and actively pumping a process gas and then using the RF modes of the cavity for ignition and tuning of the plasma to remove hydrocarbons from the inner surface [3,4]. Another initiative being studied to improve cavity performance is to increase the thermal conductivity of the end group by fabricating them out of high RRR Niobium. This is the proposed design change for cavities for Second Target Station (STS) Project at SNS [5].

2. HTA Design & Fabrication

HTA is designed to serve as a multi-purpose dressed cavity test vessel for either medium-beta or high-beta cavities. HTA vessel comprised the outer vacuum vessel, two accessing doors with one at each end of the vessel, two copper thermal shields cryogenically fed in series from a common cooling circuit, pressure and temperature cryogenic thermometry, overhead cavity support rail system and several access ports through the vacuum vessel.

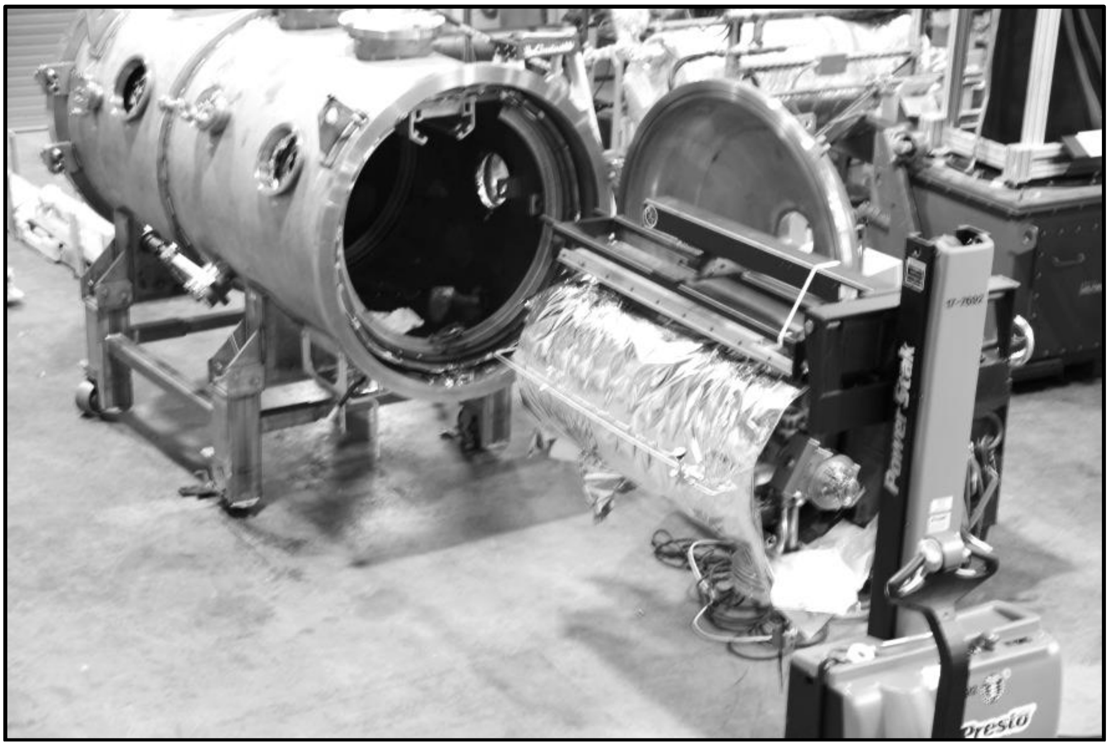

Figure 1. Cavity insertion into HTA using power lift.

The HTA overhead cavity rail system and support frame that attached to the cavity also includes a Presto Power Lift with a custom boom that allows the cavity dressed in magnetic shielding and multi-layer insulation (MLI) to be elevated to the level of the HTA supports and then slid into the HTA. The lift boom is equipped with a pair of teeth that mount into guide holes in the HTA to ensure proper alignment. Figure 1 shows a cavity on the lift just prior to insertion into the HTA.

The primary supercritical flow to the cavity is regulated by a Joule Thomson (JT) control valve in the supply u-tube which throttles the supercritical fluid to 4.3 K two phase flow at a pressure of 1.15 atm. The HTA is then equipped with a cool down circuit, allowing for efficient cooling through the cryogenic valve. The normal helium flow path out of the primary circuit is through a large return u-tube into the return transfer line and back to the CTF distribution box. Figure 2 shows the simplified HTA process and instrumentation diagram (P&ID).

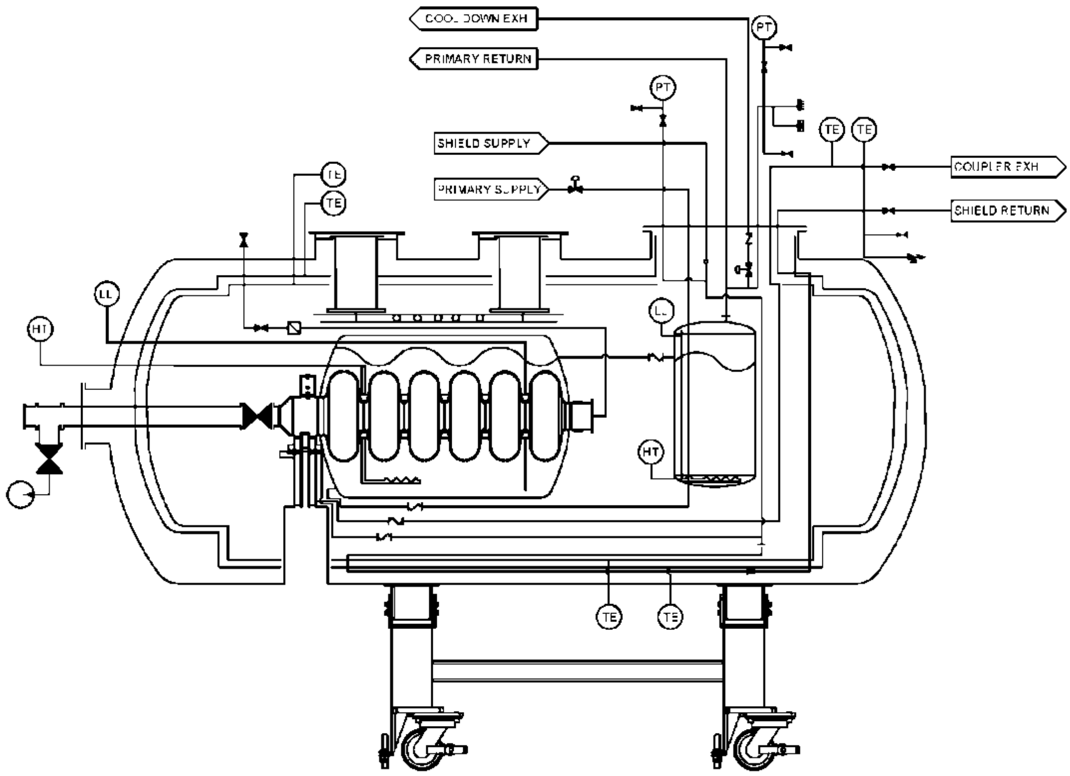

Figure 2. HTA Simplified P&ID

The primary circuit of the HTA is protected by an operational relief at 1.68 atm and a burst disc at 2 atm. Both the operational relief and the burst disc will need to be replaced if sub-atmospheric operation of the HTA is desired with the CTF's new Kinney vacuum pump.

The primary circuit of the HTA has two liquid repositories: the cavity helium vessel and the fixed dewar. Both the cavity and dewar are installed with separate and redundant liquid level probes and heater elements. During initial HTA testing both heaters were able to supply a combined 260 W into the Helium bath while maintaining stable liquid level. One novel design added to the HTA is the variable position primary bayonet. With the primary bayonet supplying directly into the top of the dewar, the variable position bayonet was added to the design to allow the stinger tip to fit over a nozzle at the bottom of the dewar and thus supply directly to the cavity. In theory, once the cavity was full, the stinger could be retracted to fill the dewar. In practice, this functionality did not prove necessary as a retracted stinger still provided sufficient cooling directly to the cavity.

One significant advantage of the HTA is the possibility to test a dressed cavity in a cryomodule like environment while having a lot of flexibility to add instrumentation whenever necessary. For example, additional thermometry was installed to better assess the temperature profile of cavity end groups during RF operation inside the HTA. Figure 3 shows the placement of 16 diodes on the outside of the cavity helium vessel, beam tube, coupler and coupler cooling flow circuits. These thermal sensors provide important information on the location of some unexpected thermal loads for example from electron activity inside the cavity volume.

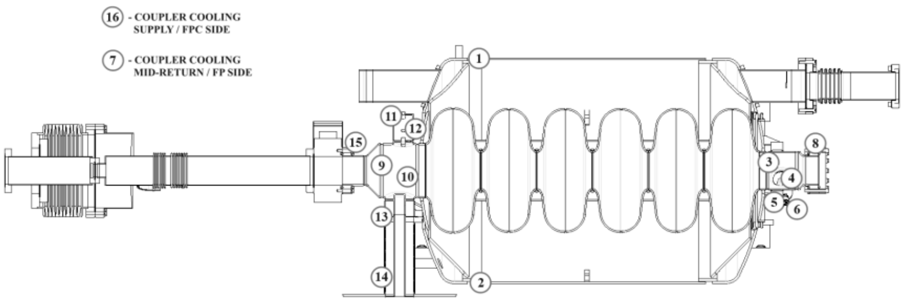

Figure 3. HTA cavity and beam tube diode map.

Two additional unique features of the HTA are the design of the beam tube connections at both the field probe and coupler sides of the cavity. As will be discussed later, an optical line of sight was required to observe the plasma ignition inside the cavity. For this reason, the coupler beam tube extension was required to be straight and not contract to obscure a clear optical line of sight. This straight beam tube extension is shown in figure 4. The gas feed line into the cavity beam tube is connected at the field probe end of the cavity.

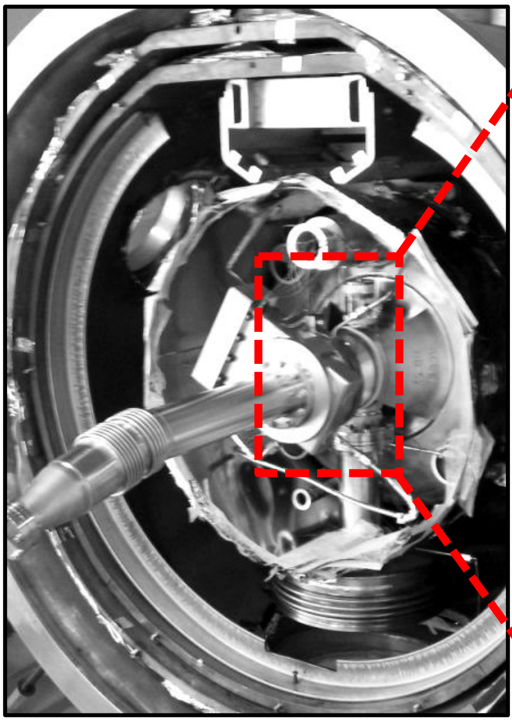

Figure 4. HTA cold vacuum beam line valve and beam tube extension

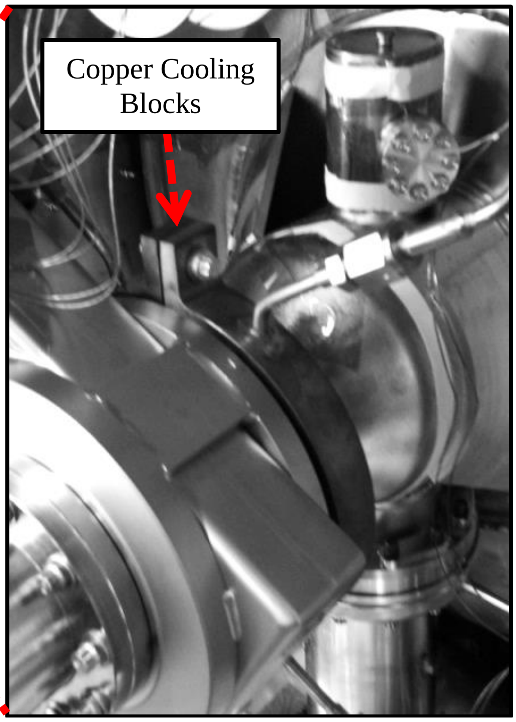

Figure 5. HTA beam line copper cooling block.

Further complicating this design was the requirement for this beam tube line to pass through the same vacuum vessel door from which the cavity is installed and retracted. To accomplish these requirements, a two piece beam tube was fabricated, modeled after the same design used in the SNS cryomodules. This design features two formed bellows with a space in-between to connect to the thermal shield through a copper clamp and copper straps.

The shield circuit is designed to be regulated to an exhaust temperature from the HTA of 30 K to 50 K. The shield circuit is split from the primary feed circuit inside the CTF distribution box. As a result the shield is supplied with 6 K supercritical helium, which is only slightly higher temperature than the primary supply temperature as this shield circuit also cools the thermal shielding in the supply transfer line. A supply valve in the CTF distribution box regulates the supply flow rate to the shield and an exhaust cryogenic control valve regulates the shield pressure to maintain the circuit above 2.4 atm.

The flow to cool the HTA coupler is split from the shield supply flow inside the HTA. In order to improve the cool down time and thermal stability of the cavity end groups, two copper cooling blocks were added to the cavity beam tube flanges with integrated ¼” flow channels. The copper cooling block on the coupler end of the cavity is shown in figure 5. The entire coupler cooling circuit is attached with VCR fittings. Example of cool down sequences without and with these cooling blocks will be shown in the next section. The flow path through this circuit is first through the RF coupler flange on the cavity, then through the two copper blocks, and finally through the coupler tube spiral cooling channel before being exhausted to the RFTF test cave cooldown header.

HTA also includes a warm vacuum cross for instrumentation and optical camera port, as shown in figure 6. Installed on this cross are connections to the turbo-cart vacuum pump, a retractable phosphorus screen and a retractable faraday cup. All three are necessary to gage the cavity performance during cold testing.

Figure 6. HTA beam tube cross and out warm to cold transition piece

3. HTA Commissioning & Cold Operation

Starting in May of 2014, the HTA was installed with cavity number HB-59 and cooled to 4.3 K [6]. This initial cooldown was for commissioning the cryogenic components of the HTA. The HTA was supplied with supercritical 5 K helium from the CTF standalone system. This represents a departure from previous cryogenic testing in the RFTF test cave when supercritical helium was supplied from the main SNS CHL [7,8].

Figure 7 shows the first cool down of the HTA using the full capacity of the CTF cryogenic plant to all three parallel circuits. During this test, the HTA took 36 hours to become thermally stable at about 12 K. The end groups of the cavity, which are only indirectly cooled from both the cavity helium bath and the coupler cooling copper blocks on the beam tube flanges, required an additional day before temperatures in the end groups achieved 5.5 K and permitted RF testing. Figure 8 shows the cool down performance improvement after the installation of the copper cooling blocks. During the second HTA test, the end groups achieved the same initial temperature as the first test after only 24 hours and were thermally stable after 33 hours at 5.5 K for RF testing.

The HTA also demonstrated the ability to return to room temperature in about 48 hours after cold testing is completed. This was accomplished through a combination of room temperature helium flow and spoiled insulating vacuum.

The static heat load to the cavity liquid helium bath was calculated by observing the liquid level drop with the primary JT valve closed. This heat was then calculated to be 9.6 W. It is difficult to determine the static heat load of the shield circuit as no flow meter is present on either the supply or exhaust. The coupler cooling flow was measured with the outlet valve fully open to be 0.75 g/s in the range of 6 K to 10 K.

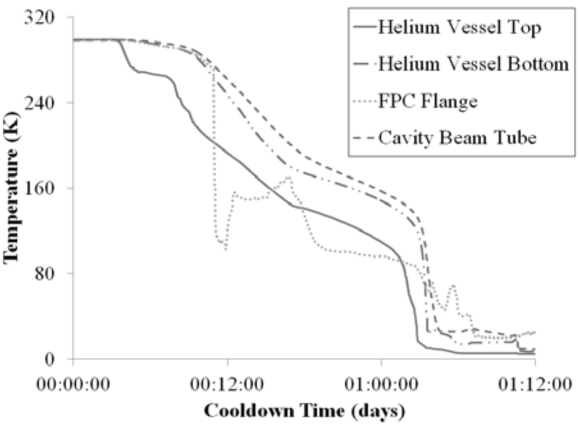

Figure 7. HTA cool down plot

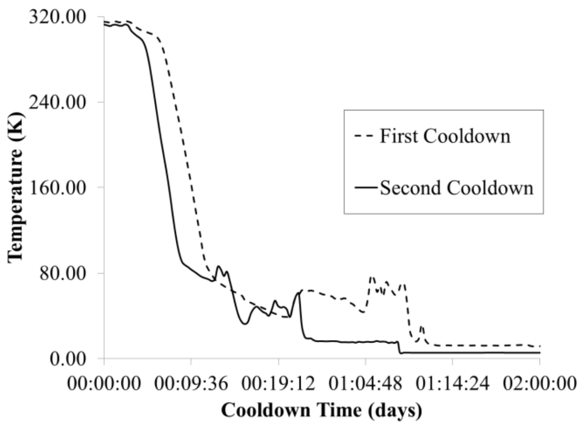

Figure 8. Cavity end group temperature during cool down sequences.

4. Current utilization of HTA for R&D

HTA is the ideal platform for SRF developments such as plasma processing since it provides a similar environment as in a cryomodule while offering great flexibility for instrumentation. The testing methodology employed in the HTA for plasma processing R&D is to first conduct a cold test with the cavity at 4.3 K in order to establish a baseline performance. The HTA is then warmed up and plasma processing is then performed once the cavity is thermally stable at room temperature. In order to assess the performance improvement or degradation due to plasma processing, a second cold test at 4.3 K is performed thereafter.

The plasma processing hardware adjacent to the HTA vessel is shown in figure 9. The manifold to the left of the plasma processing setup is for carefully controlling the gas mixture and gas flow into the cavity. The plasma processing station is to ignite and tune the plasma as well as monitoring the residual gas analyzer (RGA) traces and image of the plasma inside the cavity. Similar hardware will be used in both the RFTF and SNS linac tunnel for in-situ processing of cavities in cryomodules.

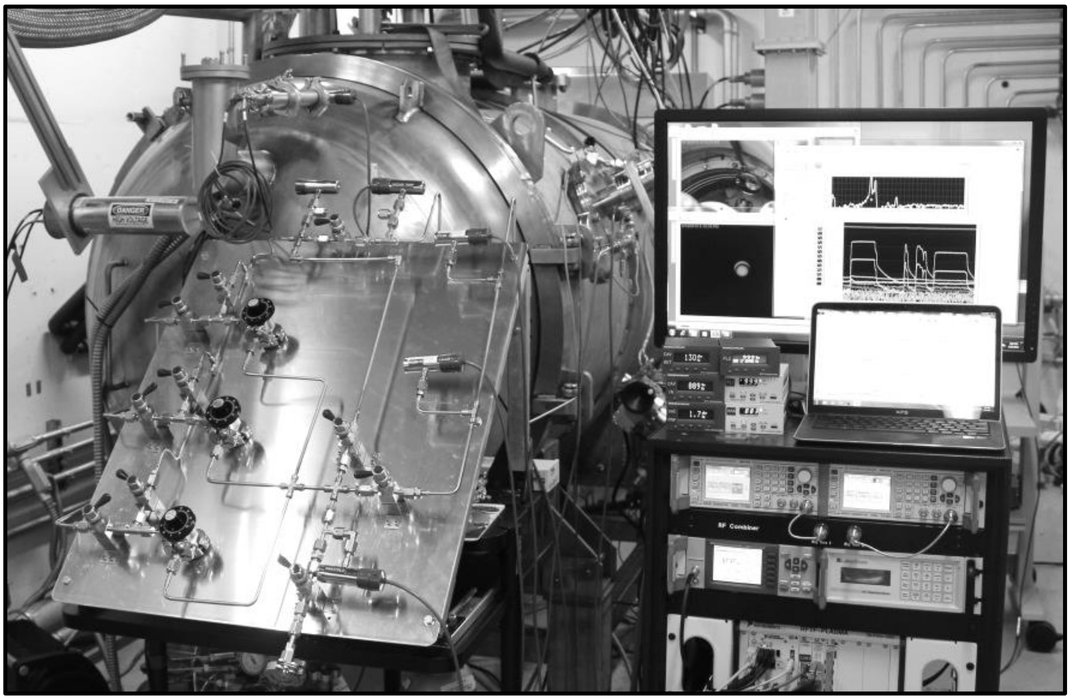

Figure 9. Plasma processing hardware adjacent to the HTA vessel in RFTF test cave

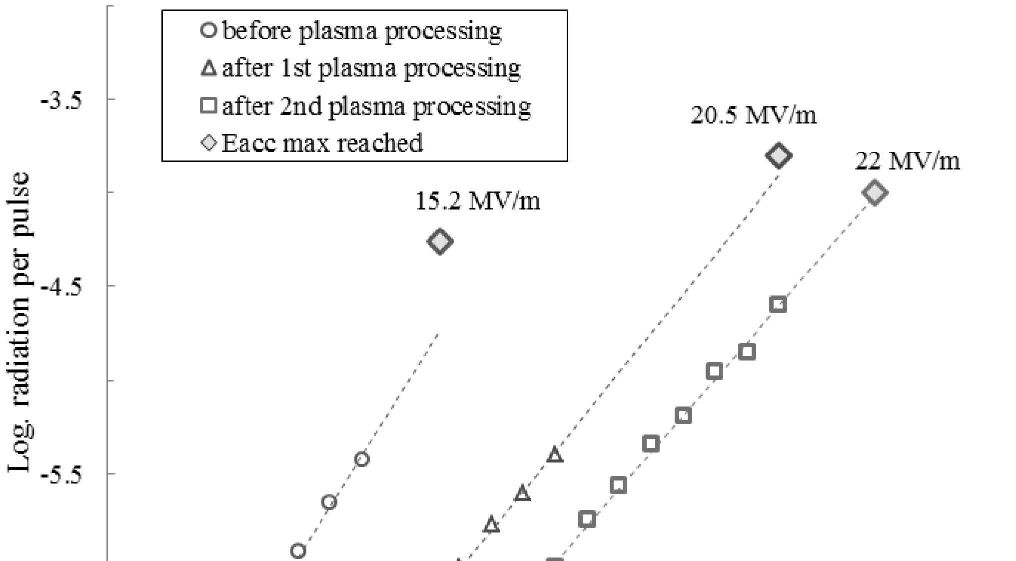

Figure 10. HTA plasma processing result.

Figure 10 shows an example of cavity performance before and after plasma processing using the HTA. This figure shows that the measured radiation onset increased from 12 MV/m to 14.5 MV/m after a first plasma processing and to 15.5 MV/m after a second plasma processing. The peak gradient also increased from 15.2 MV/m to 20.5 MV/m after the first processing and to 22 M/m after the second processing [9].

5. Summary

The HTA performed as desired over five cryogenic tests at 4.3 K during the past two years and this new infrastructure was critical for the plasma processing R&D. Cavities plasma processed inside the HTA vessel showed significant performance improvement and demonstrated that the HTA is an ideal platform for testing cavities in a cryomodule like environment while providing great flexibility to add instrumentation tailored to the specific needs of the R&D being conducted. Test of cavities in the HTA at 2 K using a Kinney pump system, cold test of cavity with high RRR end groups, test of 700 kW fundamental power coupler with a cavity and development of a medium-beta dressed are being planned. Use of the HTA to develop plasma processing at cryogenic temperature, for example to speed-up the conditioning process of a cavity is also being considered.

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