STATUS OF THE SNS SUPERCONDUCTING CAVITY TESTING AND CRYOMODULE PRODUCTION*

J. Mammosser [1], TJNAF, Newport News, VA. 23606, USA

Abstract

Thomas Jefferson Nation Accelerator Facility (Jefferson Lab) in Newport News Virginia, USA, is fabricating superconducting accelerator modules for the Spallation Neutron Source (SNS) project, currently under construction in Oak Ridge, Tennessee. This paper outlines the production requirements and gives an update on the current status of the production of these modules. The paper also discusses the problems encountered in production to-date, vertical and horizontal RF test results on cavities and the status of the electropolish program at Jefferson Lab.

INTERNATIONAL COLLABORATION

The SNS module project started with a cavity prototyping effort led by Peter Kneisel at Jefferson Lab and was an international collaboration from the start with many SRF Laboratories around the world [2]. Several of the SRF Laboratories provided major contributions to the two cavity designs as well as scaling some of the sub-components of existing designs to meet SNS accelerator requirements. With production well underway this collaboration is still continuing and growing and now the collaboration is focused more on production methodology procedures and performance.

PRODUTION REQUIREMENTS

Jefferson Lab is responsible for producing, testing and shipping 23 superconducting (SC) modules to the SNS project site. Eleven of these modules consist of 3 medium beta (0.61) cavities and twelve modules of 4 high beta (0.81) cavities. The cavities, module components and associated auxiliary parts are fabricated in industry and shipped to Jefferson Lab. Jefferson Lab is then responsible for inspecting, processing and testing components prior to assembling the various subcomponents into a SC cryomodule. The module then is tested at Jefferson Lab and then shipped to Oak Ridge, Tennessee where it is installed into the linac and commissioned. Below are a few details of the design and the test requirements for the medium (MB) and high beta (HB) cavities.

Medium Beta Cryomodule Requirements:

- Produce 11 strings of 3 cavities each
- Assemble and test RF couplers for each cavity
  - 50 OHM design
  - 50 KW average power
  - Peak power 550 KW @ 1.3 ms 60Hz
- Qualify cavities and assemble into strings
  - Beta = 0.61, 805 MHz
  - Epk/Eacc = 2.71, Bpk/Eacc = 5.72 mT/(MV/m)
  - R/Q = 279 ohms
  - VTA qualifying gradient Eacc > 10 MV/m @ Q of 5E9, 2.1K
- Assemble strings into cryomodules
- RF test Modules and ship to SNS

High Beta Cryomodule Requirements:

- Produce 12 strings of 4 cavities each
- Assemble and test RF couplers for each cavity
- Qualify cavities and assemble into strings
  - Beta = 0.81, 805 MHz
  - Epk/Eacc = 2.19, Bpk/Eacc = 4.72 mT/(MV/m)
  - R/Q = 483 ohms
  - VTA Qualifying Gradient Eacc > 16 MV/m @ Q of 5e9, 2.1K
- Assembly strings into cryomodules
- RF test some modules and ship to SNS

PRODUCTION STATUS

Couplers

The coupler effort at Jefferson Lab consists of receiving, mechanically and electrically inspecting sub-components, cleaning and assembly of sub-components for RF testing as pairs, and RF qualifying couplers for cavity string assembly. Couplers are RF tested with a 1MW RF test-stand provided by LANL and installed at Jefferson Lab. Currently twenty-three couplers have been qualified for MB strings with no major problems.

Strings

Before strings can be assembled, received cavities must be processed, assembled and qualify in a vertical test. So far, twenty one cavities have been RF qualified in vertical tests and assembled into strings and turned over for completion into cryomodules M1-M7. A typical MB string assembly in the production cleanroom is shown in Figure 1.

Cryomodules

Three of the seven strings were completed into cryomodules and RF qualified, M1-M3. M1 and M2 have been shipped to the SNS project site. M4 through M6 are in various stages of construction and M7 has been received as a string. A cryomodule after RF qualification

*Work supported by the U.S. DOE Contract# DE-AC05-84ER40150

in the Jefferson Lab module test cave is shown in Figure 2.

Figure 1: Typical assembly of a MB string.

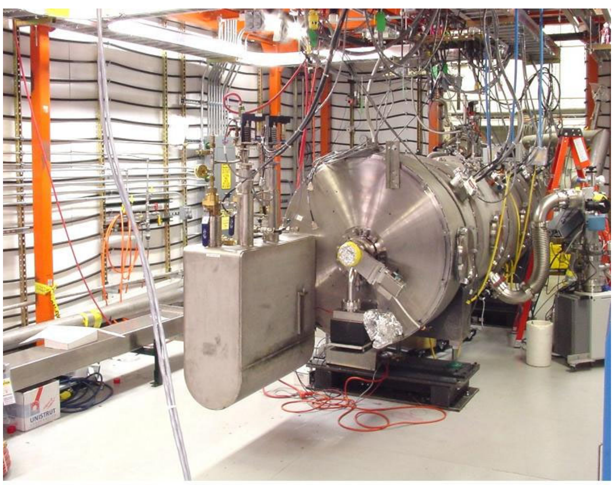

Figure 2: Cryomodule testing in test cave.

MB CAVITY PERFORMANCE

MB Assembly Sequence

Medium Beta cavities all went through the following sequence as part of their vertical test qualification and preparation for string assembly:

Initial inspection, mechanical inspection, RF tuning, degreasing, furnace treatment to 600°C, RF inspection, helium vessel welding, degreasing, chemistry (BCP) removal of 50µm, high pressure rinsing for 2 hours, assembly of mating flanges except bottom beam-line, high pressure rinsing for 2 hours, assembly of the final bottom flange, evacuation and leak-test, vertical RF test at 2.1K and RF inspection and degreasing.

Coupler Performance

Couplers were assembled as pairs on a waveguide test stand, evacuated and leak-tested. These assembled couplers were then preconditioned by baking at 200 °C for 24 hours. Typically these assemblies would reach pressures of 5E-10 mbar after baking. Next the couplers were RF conditioned and then tested in traveling and standing wave configurations. The traveling wave of 1 MW and the standing wave of 2.4 MW pulsed was the limiting test RF power. Twenty three of twenty four tests resulted in qualified couplers for strings. One of the couplers was rejected due to discoloration on the window ceramic. Couplers were processed to 1 MW in typically 6-15 hours and four of the test assemblies took longer time to reach adequate vacuum pressures.

Cavity Vertical RF Test Performance

Fifty-one vertical RF tests were performed so far and qualified only twenty-one cavities. Statistics for these vertical tests shows that the mean peak surface field reached at the Q-specification of 5e9, for the fifty-one tests, was 27.7 MV/m with a standard deviation of 11.1. The twenty-one cavities chosen for strings had a mean of 36.5 MV/m with a standard deviation of 5.64. The peak field specification required is 27.6 MV/m, which is just about at the mean of the distribution. Due to the high failure rate of cavities in vertical test a review of the current procedures and process parameters is now underway.

Technical Issues Encountered While Qualifying Cavities

Two major technical problems have been encountered while qualifying cavities for string assembly. One of the problems was with seal-leaks at cavity flange joints on assemblies for vertical test as well as string assemblies. The cavity flanges are made from niobium/titanium material and are sealed using an aluminum/magnesium gasket that crushes under high line-loads with standard bolt/nut hardware. This sealing method was developed for SC cavities at DESY [3]. An extensive seal testing program is underway at Jefferson Lab. The following are reasons for the production seal leaks:

- Low seal line loading
- Improper tolerance or mating components
- Poor seal surface preparation (scratches)

These issues were resolved by providing better alignment of components during assembly, removal of scratches by mechanical polishing and providing a higher and more consistent line loading of the seals. All seals are now at a torque of 40 ft lbs and use high strength bolt (A286) hardware. The following Figure 4 shows data from seal loading tests made with a special apparatus. The test system consisted of a press with a load cell that would provide loading two ideal mock flanges. A seal was placed between the two flanges and a load was applied and the flange spacing was measured optically to determine the displacement or seal crush for the load applied. This work was performed by Larry Phillips and Tim Rothgeb.

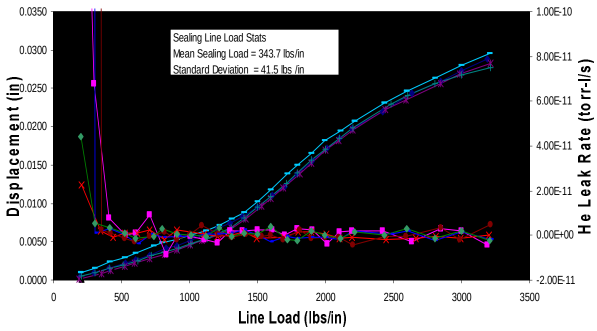

Figure 4: Seal Loading Data.

Figure 4 shows that the seals are leak tight under ideal conditions with line loading of less then 500 lbs/in. and seal crushes of only a few thousands of an inch. The reason the cavity seals were leaking in production, was that for the calculated line load the actual loads were much lower on the real hardware because much of the force was going into friction (galling) due to clean hardware with no lubrication for sliding. Along with this standard vacuum bolt hardware was used which only marginally allowed for the needed load. In other words the bolts were at their limits for yielding under load values chosen to work at non-ideal flange surface-conditions or seal crushes of fifteen thousands of an inch.

The second Problem encountered was early field emission onset during vertical qualifying tests. Field emission is typically caused by particulate contamination on cavity interior surfaces. These particulates are heated by RF fields and produce field-emitted electrons [4] that are accelerated by the RF fields and then strike adjacent cavity surfaces. This process increases current density as a function of field strength and therefore limits the gradient one can achieve due to increased cavity surface losses, therefore lowering the Q-value as a function of field. The definition of field emission onset at Jefferson Lab is the gradient at which the radiation detector signal rises above the background signal. The detector is in a fixed location just outside the dewar insert top-plate. This early field emission during vertical tests also led to RF cable breakdowns during many tests at connectors and bends in cables. When cavity surfaces produce field emission the Q-value lowers and more incident power is reflected, RF joints and cable imperfections heat due to impedance mismatches and liquid helium at connection joints is boiled-off to produce gas at pressures required for glow discharge to occur [5]. Field emission also caused longer testing (processing) time, which led to the discovery of another problem of heating of HOM RF probe feed-through. This problem was discovered when a copper RF probe tip for the HOM coupler probe was melted during the vertical RF testing. It was determined that the RF ceramic feed-through had a poor thermal design which could significantly heat up during a 30 minute continuous wave RF test under the right conditions. An effort has started at Jefferson Lab to mitigate this problem by providing a better thermal path for the RF heat on the probe.

Vertical Test Field Emission Limits

It is clear to see that data taken during vertical RF test was field emission limited in most tests. A comparison of test statistics of cavities chosen for string assembly to all MB cavity test shows that 50% of tests did not qualify cavities due to early field emission. Figure 5 shows statistics from all fifty-one cavity tests where the mean of the distribution was 20.9 MV/m peak field with a standard deviation of 10.5. Figure 6 shows the cavities chosen for string assembly with a mean of 26.94 MV/m and a standard deviation of 8.74. The cavities that did qualify had field emission starting just at their design specification.

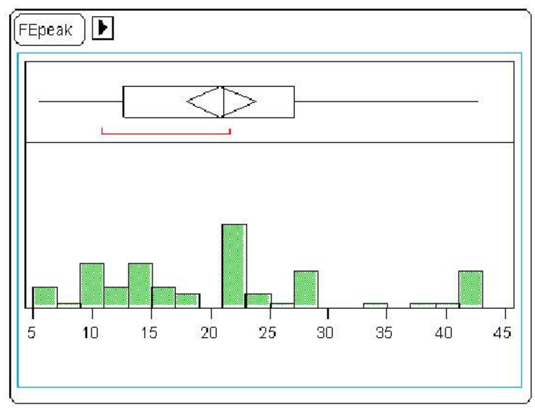

Figure 5: Peak surface field at which field emission starts for all MB vertical tests, 51 tests, mean-20.9MV/m, and standard deviation of 10.5.

Technical Issues Encountered While Qualifying Cryomodules

Two different component failures were encountered during the fabrication and testing of cryomodules. Tuner motors installed on cryomodules started to intermittently fail on the first production cryomodule tests. After the first cool-down two of the three motors failed. The module was warmed up and motors were replaced and two failures occurred after the second cool-down. Also vacuum leaks were encountered on coupler bellows and in end cans as well. All these failures were attributed to vendor production changes and inadequate QA procedures used by vendors after first articles were received and tested at Jefferson Lab. In the case of the tuner motor the vendor had replaced a series of wavy washers with a single washer on the shaft. These washers are used for providing preloading and allowing for compliance during cool-down and at operation. These problems were mitigated by providing feedback to the vendors and by jointly addressing the issues.

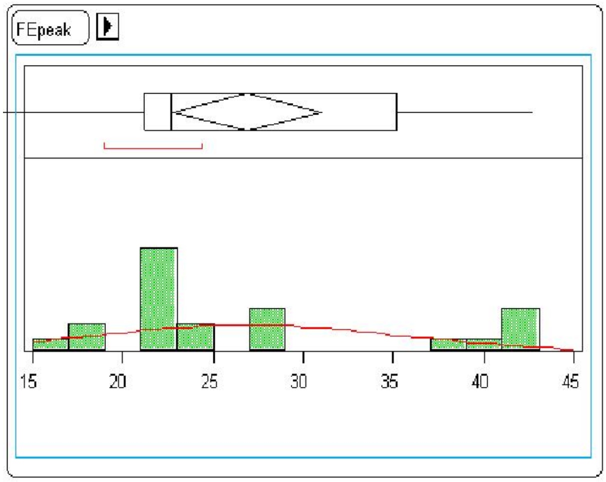

Figure 6: Peak surface field at which field emission starts for all qualified MB vertical tests, 21 tests, mean-26.9MV/m, and standard deviation of 8.74.

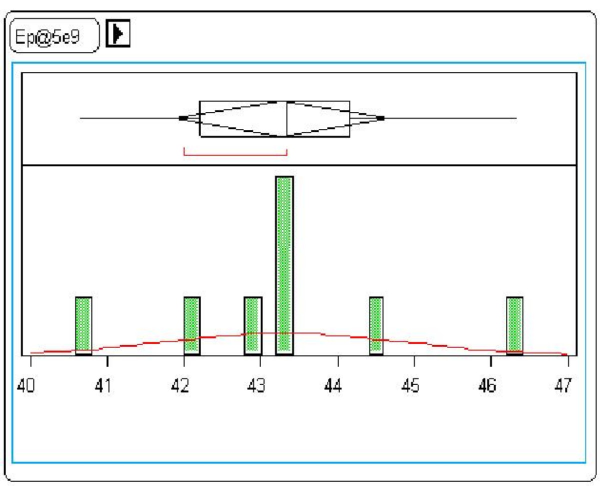

Figure 7: M1-M3 Horizontal RF tests results, Peak fields at Q specification of 5e 9, pulsed, data from 8 cavity tests.

Cryomodule Test Results

To-date three MB cryomodules have been fully RF qualified and have shown excellent RF performance. Figure 7 shows the distribution of peak surface fields achieved during module commissioning tests at Jefferson Lab. The graph shows that the cavity performances are well above the specification of 27.6 MV/m and very closely grouped. These cavities did however encounter field emission from surface fields as low as 20 MV/m, during the tests as seen in figure 8.

Comparing the field emission onset data from module testing to that of the cavities tested during vertical tests shows that field emission starts at about the same gradients even though the cavities had subsequent chemistry and are assembled with a slightly different procedure. The improvement in the usable gradient performance of the cavities assembled in cryomodules must be due to the different RF testing conditions. The cavities are tested with short 1.1 ms pulses as apposed to CW in vertical tests.

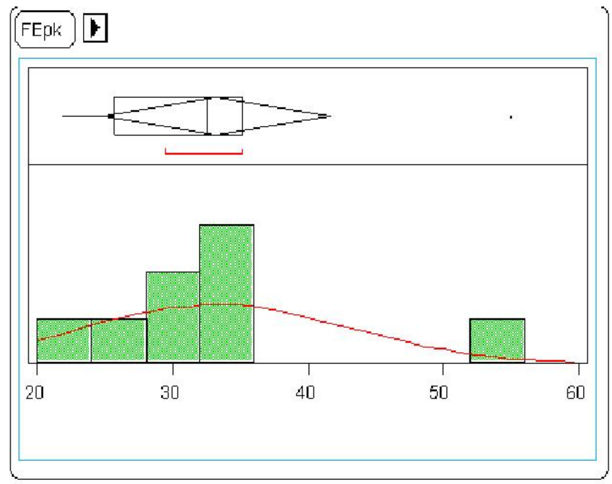

Figure 8: The distribution of field emission onset during the eight cavity tests of the M1-M3.

CAVITY ELECTROPOLISH STATUS

A production electropolish system has been designed, purchased, installed and commissioned at Jefferson Lab. This system was designed after the KEK horizontal continuous current method [6] and major system component were fabricated in industry. The design consisted of a self contained process cabinet fabricated by Ployflow Engineering Inc. (USA), electropolish components (rotary sleeves, cathode and cavity frames) designed and fabricated at Nomura plating Co., Ltd (Japan) and assembly and rotation table designed and fabricated at Jefferson Lab. This system has been commissioned and work has started to develop the procedures to electropolish HB cavities for production runs. To date, four production HB cavities have been electropolished with this equipment and the vertical test results are limited as with the MB tests by heavy field emission. Work continues to develop process procedures to eliminate field emission, develop uniform electropolished surfaces and fully utilize performance from the electropolishing process for HB production.

SUMMARY

Jefferson Lab will produce all the MB and HB superconducting accelerating cryomodules for the SNS project. Many of the subcomponents have been received and inspected at Jefferson Lab and production of the MB cryomodules is well underway with the first two modules shipped to the SNS project site.

During this production startup many technical problems were encountered and resolved. Coupler bellows and end-can vacuum leaks were encountered and resolved by better vendor procedures. Tuner motor failures were resolved by careful inspection, comparison with prototype motor designs and cryogenic testing. Cavity flange seal leaks were resolved by developing a better understanding of the sealing mechanism through careful testing of flange components under various mechanical and thermal conditions.

Currently the main production technical issue is with early field emission onset during vertical qualification tests. Field emission on the MB cavity tests has typically started around 8 MV/m and has significantly reduced the number of cavities qualified. Cavities on average must be tested at least twice before they reach qualifying gradients at Q-values of 5E9. This is worrisome because it increases the labor for qualifying cavities and HB cavities must reach higher gradients. Currently plans are to review production processes and procedures to identify areas that can be improved and additional studies of the current process is underway. Although a difficulty in qualifying cavities has slowed the production process, the cavities that were qualified and assembled into modules have performed well above the MB specifications.

Electropolishing at Jefferson has begun with the commissioning of a new process cabinet designed to process HB cavities. This effort is in the early stages of development but is aimed at increasing HB cavity performances with the KEK developed electropolishing method. All ready this system has been used to process four production HB cavities, but they were field emission limited during the RF tests. It is clear that in order to develop the electropolish process for production the field emission problem must be solved first.

ACKNOWLEDGEMENTS

The work presented within this paper was performed by many of the Jefferson Lab SRF and Engineering department scientists, engineers, designers, technicians and support staff. Along with this Jefferson Lab staff many SNS scientists, engineers and technicians are directly involved with the production cryomodule effort. This author would like to thank the staff mentioned above as well as Kenji Saito and Axel Matheisen for their continuing support of this work and further development of better RF cavity performance at Jefferson Lab.

REFERENCES

[1] http://www.mammosse@jlab.org.

[2] P. Kneisel, "Mini ASAC Meeting" June 19th, 2000 Internal Report.

[3] A. Matheisen, "Status of The RF Superconductivity Activities at DESY", The 10th Workshop on RF Superconductivity 2001, (2001), Tsukuba, Japan, p.24-28.

[4] R. Woo, "Final Report on RF Voltage Breakdown in Coaxial Lines", Technical report 32-1500, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA., October 1, (1970), p. 9.

[5] Good, R. H., and Muller, W. E., "Field Emission,", "Handbuch der Physik", (Encyclopedia of Physics), second addition, Vol. XXI, Berlin, Springer, (1956), p.176-23.

[6] K. Saito, "R&D of Superconducting Cavities at KEK", Proceedings of the 4th Workshop On RF Superconductivity, (1989), Tsukuba, Japan, p. 651.