SNS CRYOMODULE PERFORMANCE*

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Abstract

Thomas Jefferson National Accelerating Facility, Jefferson Lab, is producing 24 Superconducting Radio Frequency (SRF) cryomodules for the Spallation Neutron Source (SNS) cold linac. This includes one medium-β (0.61) prototype, 11 medium-β production, and 12 high beta (0.81) production cryomodules. After testing [1], the medium-β prototype cryomodule was shipped to Oak Ridge National Laboratory (ORNL) and acceptance check out has been completed. All production orders for cavities and cryomodule components are being received at this time and the medium-β cryomodule production run has started. Each of the medium-β cryomodules is scheduled to undergo complete operational performance testing at Jefferson Laboratory before shipment to ORNL. The performance results of cryomodules to date will be discussed.

INTRODUCTION

Jefferson Lab has started production of the 24 Superconducting Radio Frequency (SRF) cryomodules for the Spallation Neutron Source that is being built at ORNL. To date three cryomodules have been completed and two more are in various stages of completion. Production schedule includes completion and testing of one medium beta cryomodule approximately every three weeks. Testing plans for subassemblies and completed assemblies are in place to support this schedule. The testing program is intended to support design, acceptance, and operational characterization of the cryomodules. Critical cryomodule components are tested at sub-assembly levels prior to cryomodule integration. Testing of the completed cryomodules follows. Currently, three cryomodules have been completed. One of these has completed integrated testing in the Jefferson Lab Cryomodule Test Facility (CMTF), and the second is being tested.

SUB-ASSEMBLIES

The cost of, and time required for, disassembly and rework of a completed cryomodule is prohibitive and therefore critical sub-assemblies must be qualified prior to integration into higher-level assemblies. Additionally, lifetime testing is required for some components to ensure they will continue to be operational over the 40-year life required for SNS accelerator systems. Included in these two categories are the Fundamental Power Couplers (FPC), cavity frequency tuners for lifetime requirements, and the SRF cavities themselves.

Fundamental Power Couplers

SNS cavities use a coaxial coupler design for 48 kW average power and driven by a 550 kW klystron with 1.3 ms pulses at 60 Hz[2]. All FPC's are processed on one of two warm test stands [3]. Processing includes a 24-hour vacuum bake resulting in vacuum levels ~ 5 E-10 mbar followed by RF processing to 1 MW traveling wave and 2.4 MW standing wave power levels [4]. To date 21 FPC's have been processed to levels required for SNS operations with no difficulties

Cavity Frequency Tuners

The SNS tuner design has been adapted from a Saclay design for the TESLA cavities. For SNS application the requirements are listed in table 1. To achieve these requirements a piezo element has been incorporated into the "dead leg" and provides the required fine-tuning adjustment. The tuner assembly is shown in figure 1 with the drive train on the top left and the piezo element on the bottom right.

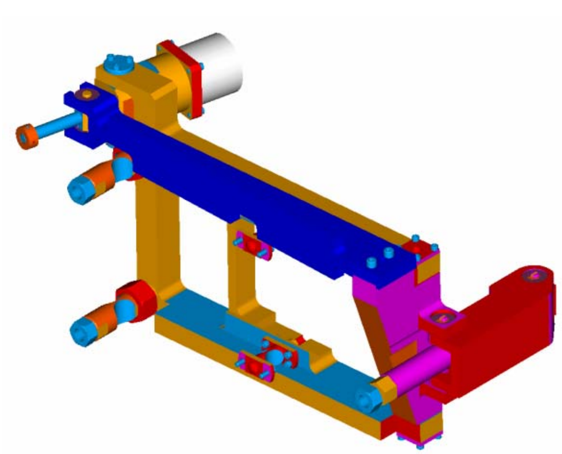

Figure 1. SNS Cavity Tuner Assembly

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Prototype tuners were fabricated and tested in the Vertical Test Area (VTA) where both prolonged test cycles and rapid turn around are possible. A complete tuner assembly was mounted to a mechanical spring representative of a cavity load at maximum tuning force. This assembly is place in an evacuated can to model the cryomodule insulating vacuum where the tuner operates. A linear position monitor was mounted on the tuner assembly and used to measure tuner travel during operation. Initial testing of the tuner included cycling over small ranges equivalent to 4 kHz and 16 kHz. Initially the tuner performed as expected but at the end of the first extended period of operation there was an increase in required torque from the motor to drive the tuner. This was thought to be a sign of wear on the lead screw. The tuner was then operated through its entire range of motion, equivalent to ~400 kHz, and the required motor torque returned to its initial value. Subsequent testing has included a full stroke cycle after each 6 months of equivalent life and the problem has not returned. A total of 30 years of equivalent life has been accumulated.

	Mechanical	Piezo
Travel (mm)	1.8	10^{-2}
Freq. Range (kHz)	200	2
Freq. Resolution (Hz)	60	NA
Load (N)	8900	15000

Table 1. SNS Tuner Requirements

Cavities

All cavities undergo a final assembly and testing at Jefferson Lab that includes warm tuning, installation into helium vessels, and qualification in the VTA prior to being assembled into a cavity string and then into a cryomodule. Warm tuning is performed at several stages of the assembly with a final check of the field flatness after the helium vessel installation process. The SNS requirement for cavity field flatness is <8%. A typical measurement is shown in figure 2 and the measurements to date are shown in figure 3.

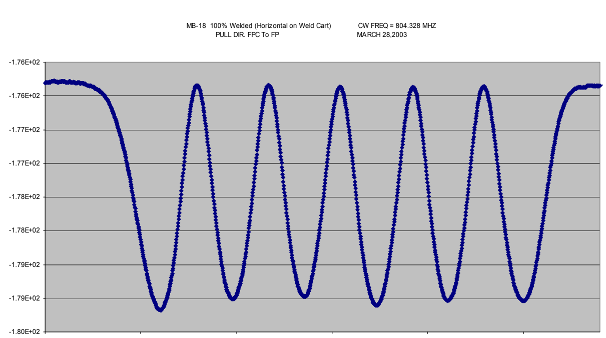

Figure 2. Typical Field Flatness Measurement

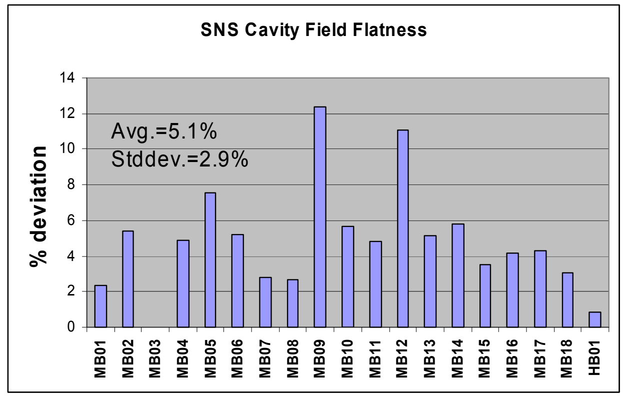

Figure 3. Field Flatness Measurements to Date

During VTA cold testing the cavities are qualified at 2 K. To date 16 cavities have been qualified which includes the measurement of cavity Q_0, figure 4, onset of field emission (FE) and the maximum E_{acc} and is interpreted as ???. Eacc limitations include cavity quench, field emission, and RF power limitations.

Eacc Limit	Q0 at 10 MV/m	FE Onset
15 MV/m	1.2 10^{10}	9 MV/m

Table 2. Average Values from VTA Testing

For cavities that have passed qualification testing, average values for limiting E_{acc}, Q_0 at nominal operating gradient, and onset of field emission, as evidenced by the start of measurable radiation, are listed in table 2. VTA testing is also monitored for trends as a feedback into the production process and process charts are maintained. Process charts are shown in figure 5 and 6.

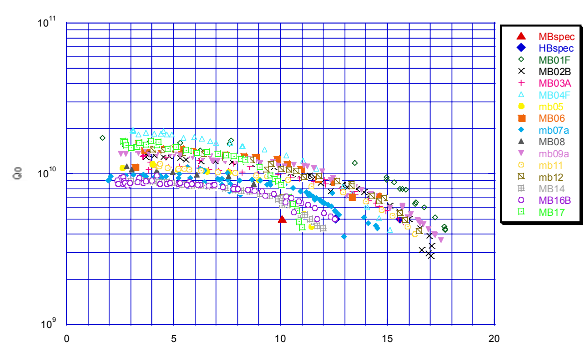

Figure 4. Q_0 vs E_{acc} for SNS Medium Beta Cavities

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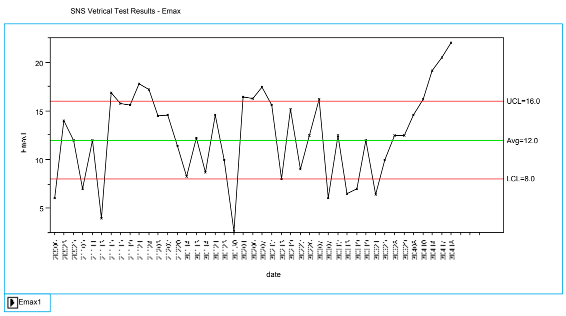

Figure 5. Cavity E_{acc} Limit Process Chart

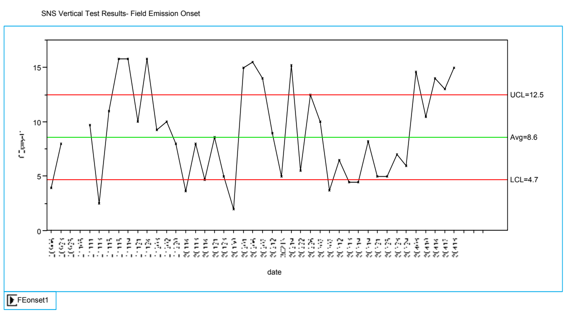

Figure 6. Cavity FE Onset Process Chart

INTEGRATED CRYOMODULE PERFORMANCE

During integrated cryomodule testing systems are in their final configuration and operated at 2 K using low power RF, a 20 kW CW RF source and 1 MW pulsed RF source. Testing of the first three or four cryomodules will include a larger set of tests to include design and operational characterization that will be eliminated on subsequent tests where acceptance testing is the goal. Additional tests will be required as issues of interest are identified throughout production.

Cryogenics

The SNS cryomodule incorporates a final counter-flow heat exchanger into the cryostat utilizing the sub-atmospheric return helium gas to cool the primary supply process stream before the J-T valve [5] and uses a bypass to circumvent this during cooldown. A typical cooldown is shown in figure 7. The cavities are cooled at a rate of ~200 K/Hr with the entire process taking ~8 hours from opening the J-T valve to the start of liquid collection. Heat loads for the primary and shield circuits, 12 ± 3 and 130 ± 10 watts respectively, are measured several days after cooldown to ensure all components are in thermal equilibrium.

Fundamental Power Coupler

After cooldown of the cryomodule the FPC's for all cavities require RF conditioning. Conditioning is

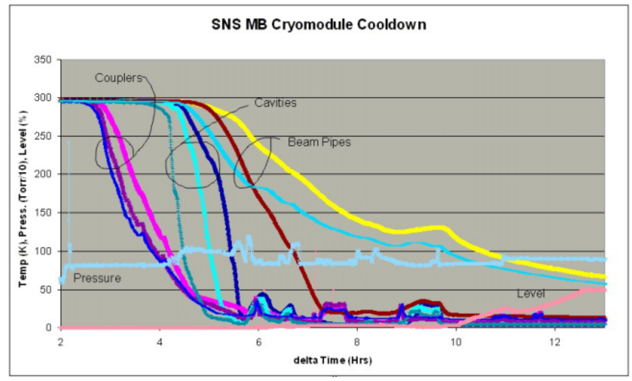

Figure 7. Cryomodule Cooldown

accomplished with the 1 MW RF source using 1.3 ms pulses at 60 Hz while maintain the coupler vacuum below 10^{-7} mbar. RF power is increased to 180-250 kW on all cavities with a typical process shown if figure 8. After initial conditioning the FPC's demonstrate a memory of the conditioning and do not require reconditioning during turn on after days of non-operation although some minor exceptions have been observed.

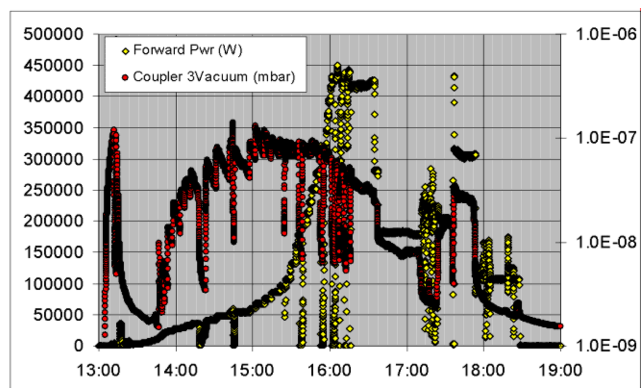

Figure 8. FPC Processing with Time in Hours

Cavity Frequency Tuner

Eight tuners have been tested after integration into cryomodule including three in the medium-β prototype and five in the first production cryomodule. During the testing of the prototype cryomodule the tuners performed as expected with the mechanical and piezo tuners providing in excess of 400 kHz and 3 kHz tuning range respectively. The mechanical tuner performance over an abbreviated range and the piezo tuner resolution measurement are shown in Figures 9 and 10. The piezo tuner was not part of the initial design and was included to allow for compensation for Lorentz force detuning during pulsed operations.

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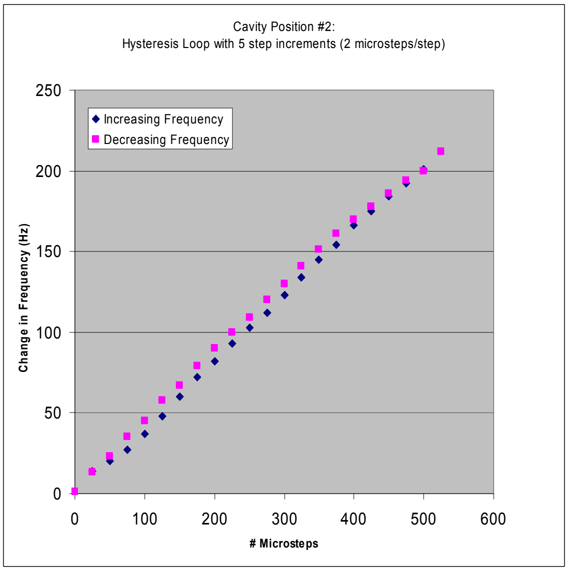

Figure 9. Mechanical Tuner

After initial fabrication and test of the prototype tuners a production run for the medium and high beta cryomodules followed. Identical components were procured and integrated into the production cryomodules without subassembly testing. During the testing of M01, the first medium-β production cryomodule, all tuners worked after cooldown but two mechanical tuners, position #1 and #2, started to operate

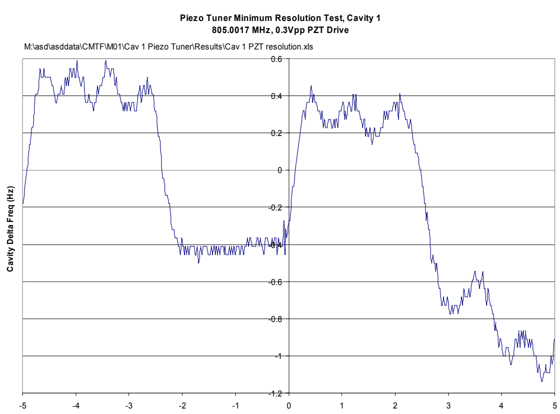

Figure 10. Piezo Tuner Resolution, ~ 1Hz

intermittently after a period of several days with no operation. The third tuner, position #3, continued to perform as expected. The two problematic tuner drive assemblies were removed and replaced with assemblies that had been qualified in the VTA using the life cycle test fixture. Qualification included operations over the full range of motion as well as periods of cold soaking to approximate conditions observed in the M01 cryomodule. After a second cool down and test cycle two tuners, position #2 and #3 operated intermittently. Cavity position #1 has operated continuously since replacement.

Investigation into the source of the tuner problems is underway. The suspect components are in the drive assembly and include the cold stepper motor, harmonic drive, lead screw, and lead screw nut. We are presently working with the designers and vendors to identify failure modes and solutions.

Cavity Performance

During testing in the CMTF cavity performance is characterized including Q_0 and FE as a function of E_{acc}, maximum E_{acc}, Q_{ext} of FPC's, HOM damping, HOM probe rejection of fundamental power, and identification of cavity mechanical modes using Lorentz force and the piezo tuner as drivers. The cavities have all performed above specification for Q_0, Figure 11, and maximum E_{acc}. Maximum gradient for all cavities has been in the range of 15-20 MV/m with the onset of FE above 10 MV/m for ½ of the cavities and no measurable radiation for the other ½ of the cavities at maximum gradient.

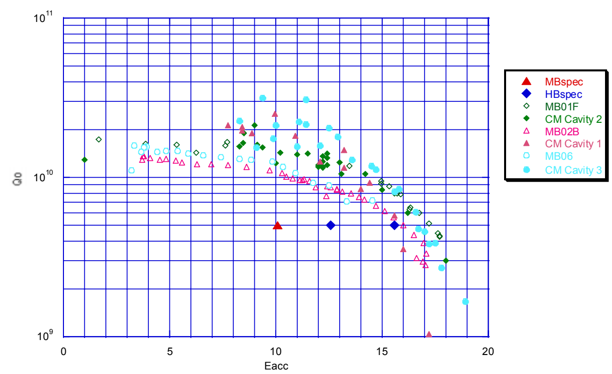

Figure 11. Cavity Q_0 in Final Assembly

Considerable attention has been focused on the mechanical modes of the cavities and the dynamic Lorentz force detuning of the cavities as there is a concern regarding control of the RF during pulsed operations [6]. Dynamic Lorentz force detuning is measured by the cavity frequency shift during a RF pulse while operating at the SNS design of a 6% duty factor at 60 Hz and operating gradient of 10.1 MV/m. The measured frequency shift of ~300 Hz is below the requirement of 470 Hz. The frequency shift resulting from background microphonics noise is also measured. Measurements of the first mode and amplitude for M01 are included in Table 3. These levels are well within requirements for SNS.

RMS Background, Hz	1.1	2.9	1.3
1st Mechanical Mode	69	60	69

Table 3. M01 Microphonics Amplitude and 1st modes

Measurements of the mechanical modes are done both by sweeping the modulation frequency of an amplitude modulated cavity gradient and piezo excitation voltage.

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The transfer functions for these are shown in Figures 12 and 13 where the x-axis shows the frequency of the driving term and the y-axis is the cavity response amplitude.

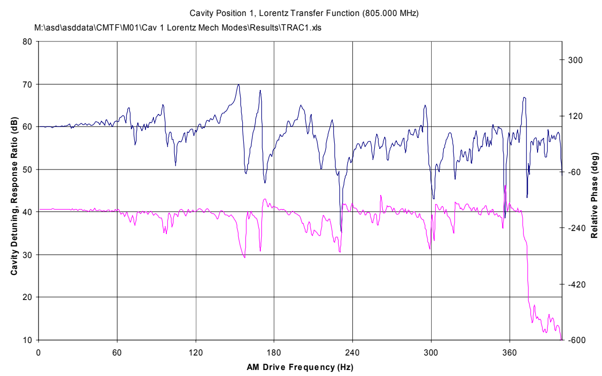

Figure 12. Gradient Modulated Mechanical Mode Mapping

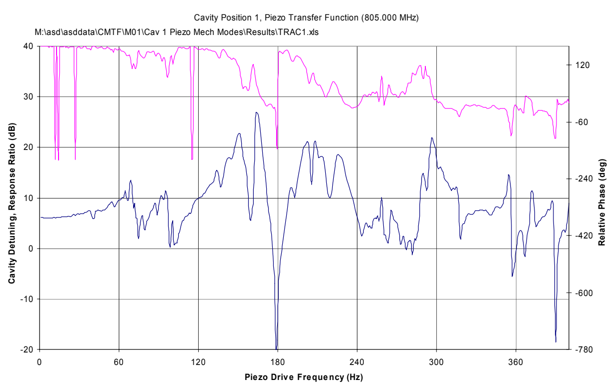

Figure 13. Piezo Modulated Mechanical Mode Mapping

HOM damping is measured for all significant modes as well as the rejection of the fundamental frequency by the pickup probe. HOM mode filters achieve Q's below 10^4 for all critical modes, meeting the SNS requirements. Initial Q specification for the HOM filter fundamental notch filter was 10^{12} but has been reduced to $3x10^{10}$ and measured values range from $\sim 5x10^{10}$ to $\sim 5x10^{14}$.

SUMMARY

The performance characterization of the SNS cryomodules has included testing of sub-assemblies for more than 4 cryomodules and 2 final assemblies, the prototype and first production medium-β cryomodule. Cavity performance has exceeded E_{acc} and Q_0 requirements for all qualified components and completed assemblies with no significant change in performance between VTA and cryomodule configurations. A focused testing program continues to characterize cryomodule performance for SNS operations. These tests will continue as required to support operations at SNS.

There are problems with the mechanical tuners resulting in intermittent operation. The suspect components are in the drive train that can be replaced with little effort. Replacement of the tuner drive assemblies is planned after rework and qualification of assemblies has been completed.

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