OVERVIEW OF SNS CRYOMODULE PERFORMANCE*

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Abstract

Thomas Jefferson National Accelerating Facility (Jefferson Lab) has completed production of 24 Superconducting Radio Frequency (SRF) cryomodules for the Spallation Neutron Source (SNS) superconducting linac. This includes one medium-β (0.61) prototype, eleven medium-β and twelve high-β (0.81) production cryomodules. Nine medium-β cryomodules as well as two high-β cryomodules have undergone complete operational performance testing in the Cryomodule Test Facility at Jefferson Lab. The set of tests includes measurements of maximum gradient, unloaded Q (Q_0), microphonics, and response to Lorentz forces. The Q_{ext}'s of the various couplers are measured and the behavior of the higher order mode couplers is examined. The mechanical and piezo tuners are also characterized. The results of these performance tests will be discussed in this paper.

INTRODUCTION

Jefferson Lab has recently completed construction of 24 SRF cryomodules for installation in the SNS superconducting linac. The medium-beta cryomodules were constructed around three medium velocity (β = 0.61) cavities. Of the twelve medium-β cryomodules (including prototype) that have been constructed, nine have been subjected to a series of acceptance tests in the Cryomodule Test Facility (CMTF) at Jefferson Lab. The high-β cryomodules are built around four high velocity (β = 0.81) cavities. Two of the high-β cryomodules were tested at Jefferson Lab.

The CMTF consists of a shielded test cave, connections to a 300 W helium refrigerator, and an adjacent control room. The test cave is a 21 m by 7 m area with concrete shielded walls, floor, and roof. Analysis indicates that the shielding should be adequate for 12 GeV (CEBAF) upgrade cavities operated at 28 MV/m [1]. The test cave is also magnetically shielded. This reduces ambient magnetic fields in the area around the cryomodule to 50mGauss or less [1].

Two high power RF sources were available to support SNS testing. The first is a 2.4 MW peak power, 60 kW average power klystron operating at 805 MHz. The second consists of two 8 kW, 805 MHz klystrons able to deliver up to 16 kW of CW power [1]. These two sources along with a 1 W low power source make it possible to complete the list of tests specified in Table 1.

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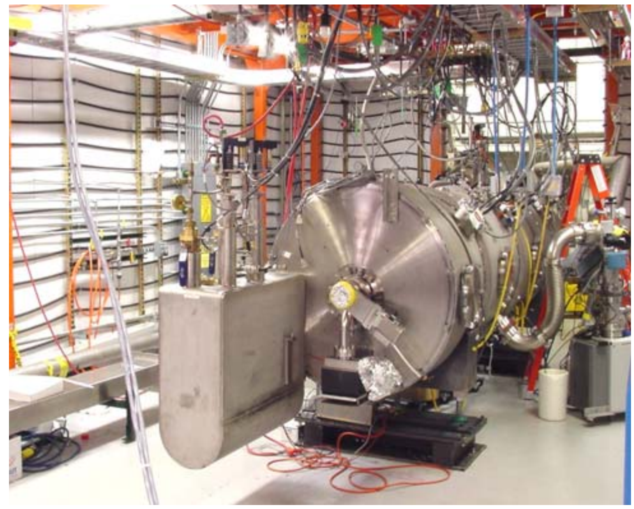

Figure 1: Medium-B cryomodule in test cave.

Some of the tests in Table 1 are marked with an asterisk. This is meant to denote a test or measurement performed on all cryomodules. As data was accumulated and confidence in the design increased, some tests such as microphonics and mechanical mode measurements and tuner resolution measurements were omitted from the list.

Table 1: Acceptance Tests

Test or Procedure	Purpose
*Warm and Cold Frequency Measurements	Understand changes in frequency from room temperature to 2K. Document passband frequencies.
*Tuner Range, Hysteresis and Resolution	Determine proper operation of piezo and mechanical tuners.
*High Power Processing and Extended Run	Condition coupler vacuum. Determine E_{max} and maximum stable gradient, E_{maxop}.
*Field Emission and Q_0	Measure Q_0 and field emission vs. gradient.
*Q_{ext}'s	Measure Q_{ext}'s of FPC, Field Probe and HOM Couplers.
Lorentz Force Pulse Response	Measure dynamic Lorentz force coefficient.
Microphonics and Mechanical Modes	Document mechanical resonances of cavities.

TUNERS

Mechanical Tuner Tests

The mechanical tuners were tested to determine frequency range, hysteresis and resolution. Each tuner was cycled through its range from the clockwise limit switch to the counter-clockwise limit switch. Frequency as a function of tuner position was measured at increments of about 25 kHz. This also exposes possible wiring or other problems. In some cases, the tuner was then cycled through a smaller, 4 kHz loop using increments of about 200 Hz, to measure hysteresis. See Figure 2 for a typical plot of frequency vs. motor position.

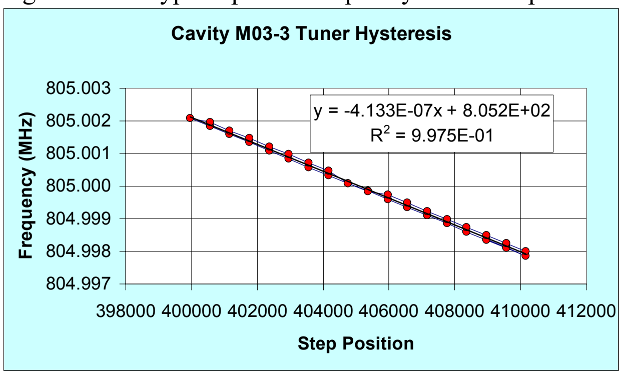

Figure 2: Mechanical tuner hysteresis.

The SNS requirement for the mechanical tuner range is 200 kHz (805 MHz ± 100 kHz). The measured range was 473.6 ± 47.5 kHz, roughly centered at 805 MHz. Twelve of the tuners were tested for hysteresis. The average value was determined to be 100 ± 50 Hz.

In order to determine the resolution of the mechanical tuner, the cavity is driven with a Voltage Controlled Oscillator / Phase Locked Loop (VCO/PLL) and a 1 W amplifier. The stepper motor is cycled back and forth by a set number of steps while looking at the field probe signal with a Cavity Resonance Monitor (CRM). The number of steps is reduced until the frequency shift is less than 60 Hz (SNS requirement) or until the frequency change can no longer be resolved [2]. Nine tuners on medium-β cryomodules were tested and met the SNS requirement. The measured resolution for these tuners was 9 ± 7 Hz.

Piezo Tuners

A similar set of measurements was performed on the piezo tuners. However, now instead of changing the stepper motor position, the voltage driving the piezo is varied. The measured frequency range for the piezo tuners was 3.2 ± 1.6 kHz. The average hysteresis was 809 ± 778 Hz.

The resolution of the piezo tuner was measured for nine of the tuners. The measured resolution was 13 ± 11 Hz. According to the SNS specification, the resolution must be less than 60 Hz.

OTHER LOW POWER MEASUREMENTS

Several other low power measurements were often conducted using the 1 Watt VCO/PLL and CRM setup. These included microphonics measurements and the use of the piezo tuner to stimulate the mechanical modes of vibration. The microphonics measurements give a measure of how external vibrations will affect cavity tuning. According to the SNS specification, the six sigma value of the cavity detuning probability distribution as measured should be less than 100 Hz. Eight medium-β and eight high-β cavities were tested and all performed better than required. The six sigma value for the measured cavities was 14.6 Hz ± 8 Hz.

HIGH POWER RF MEASUREMENTS

Most of the high power tests were performed using the pulsed klystron. A VCO/PLL locked to the cavity frequency was used to drive this source. The source was normally set up to deliver a 1.2–1.3 ms pulse with a 60 Hz repetition rate. On occasion, a much narrower pulse or slower repetition rate would be used to assist with coupler or cavity vacuum processing.

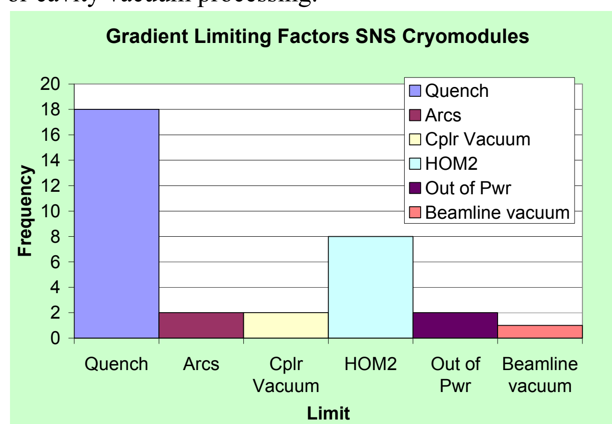

Figure 3: Limits to gradient.

Processing the coupler vacuum was the first task to be completed when high power was turned on. The process generally lasted for a number of hours but in a few cases, lasted several days. Once the coupler vacuum was removed as a gradient limit, the search for other limiting factors would commence. Most cavities were eventually limited by quenches or high power levels at the HOM2 coupler.

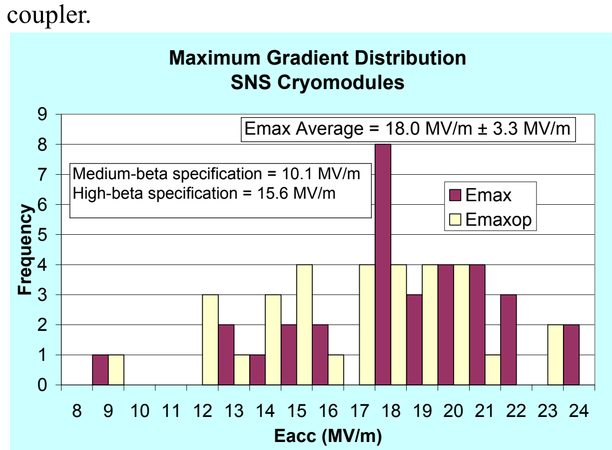

Figure 4: Distribution of maximum gradients.

Figure 3 shows the different factors that limited higher gradient. This is followed by Figure 4 which shows the distribution of E_{max}, the maximum attainable gradient and E_{maxop}, the maximum stable gradient. E_{maxop} is the maximum gradient at which a cavity would run for at

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least an hour without problem. It should be noted that only one cavity could be excited at a time. Limitations arising from module cooling issues when all cavities are operated together might impose lower limits

Once the coupler vacuum was processed and the maximum gradient was understood, field emission and Q_0 were measured. Figure 5 shows the distribution of gradients at which field emission starts.

The last of the high power measurements is the measurement of Q_0 as a function of gradient. Q_0 was measured calorimetrically. The RF heat load was determined as a function of the rate of rise in helium pressure in a cryogenically isolated cryomodule

Figure 6 shows the aggregate of all the Q_0 curves measured for all of the SNS cryomodules, while Figure 7 show the distribution of Q_0 values measured at the specified operating gradients.

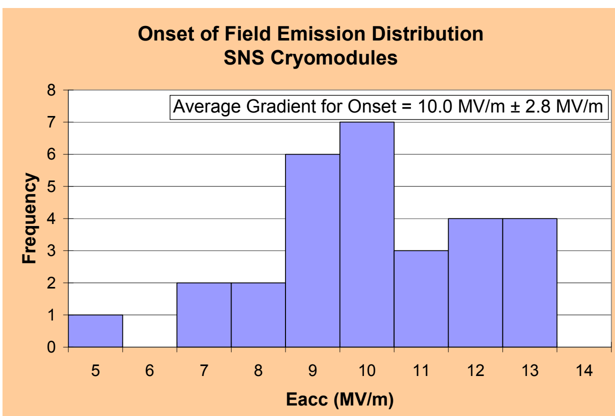

Figure 5: Field emission onset.

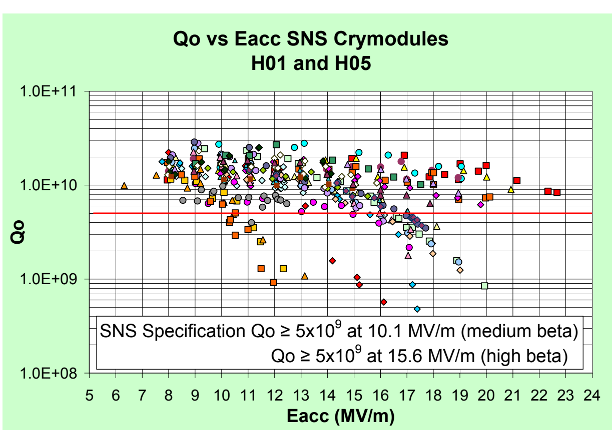

Figure 6: Q_0 vs. Eacc.

A number of other measurements were conducted during high power operations. These along with results are detailed in Table 2. Note: the dynamic Lorentz measurement was performed on 17 cavities only. It is a measure of the amount of detuning caused by a single RF pulse at the specified operating gradient.

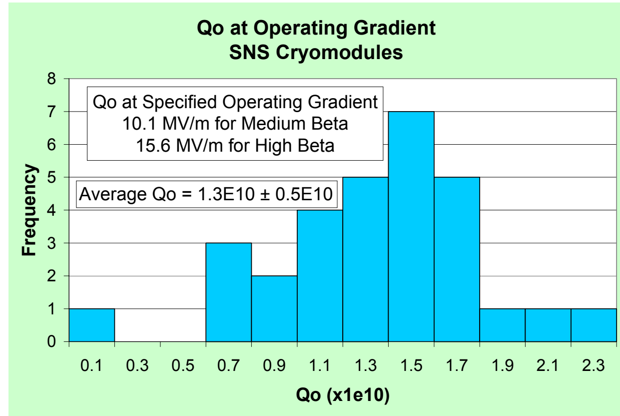

Figure 7: Q_0 distribution.

Table 2: Other Results

Quantity	Specification	Average
Q_{ext} FPC (med - β)	$7.3\times10^5 \pm 20\%$	$6.8 \pm 1.3\times10^5$
Q_{ext} FPC (hi - β)	$7.0\times10^5 \pm 20\%$	$7.2 \pm 1.0\times10^5$
Q_{ext} Field Probe (med - β)	1.052×10^{12} - 2.642×10^{12}	$2.0 \pm 1.2\times10^{12}$
Q_{ext} Field Probe (hi - β)	1.052×10^{12} - 2.683×10^{12}	$1.8 \pm 0.9\times10^{12}$
Q_{ext} HOM1 (med - β)	$> 3\times10^{10}$	1.2×10^{14}
Q_{ext} HOM1 (hi - β)	$> 5\times 10^{10}$	5.0×10^{12}
Q_{ext} HOM2 (med - β)	$> 3\times10^{10}$	2.3×10^{13}
Q_{ext} HOM2 (hi - β)	$> 5\times 10^{10}$	1.0×10^{13}
Dynamic Lorentz detuning (Hz)	< 470 Hz	241± 97 Hz

CONCLUSION

Testing of the SNS cryomodules has been completed. All met or exceeded the requirements for gradient and Qo.

REFERENCES

[1] Powers, T. Allison, G. K. Davis, M. Drury, C. Grenoble, L. King, T. Plawski, and J. Preble, "Upgrade To Cryomodule Test Facility at Jefferson Lab", SRF Workshop 2003.

[2] M. Drury, I. E. Campisi, E. Daly, G. K. Davis, J. R. Delayen, C. Grenoble, J. Hogan, L. King, T. Powers, J. Preble, M. Stirbet, H. Wang, M. Wiseman, "SNS Medium-Beta Cryomodule Performance", SRF Workshop 2003.