PERFORMANCE OVERVIEW OF THE PRODUCTION SUPERCONDUCTING RF CAVITIES FOR THE SPALLATION NEUTRON SOURCE LINAC*

J. Delayen, J. Mammosser, and J. P. Ozelis[#], Jefferson Lab, Newport News, VA 23606, USA

Abstract

As part of its efforts for the SNS construction project, Jefferson Lab has produced 23 cryomodules for the superconducting linac. These modules contained 81 industrially produced multicell Nb accelerating cavities. Each of these cavities was individually tested before assembly into a cryomodule to verify that they achieved the required performance. This ensemble of cavities represents the 3rd largest set of production superconducting cavities fabricated and tested to date. The timely qualification testing of such a collection of cavities offers both challenges and opportunities. Their performance can be characterized by achieved gradient at the required Qo, achieved peak surface field, onset of field emission, and observations of multipacting. Possible correlations between cavity performance and process parameters, only really meaningful in the framework of a large scale production effort, will also be presented. In light of the potential adoption of these cavities for projects such as the Rare Isotope Accelerator or Fermilab Proton Driver, such an analysis is crucial to their success.

SNS CAVITY PARAMETERS

The elliptical multicell niobium cavities for the SNS cryomodules are designed to accelerate hydrogen ions (protons) at the geometric velocity factors (β) 0.61 and 0.81, at an operating frequency of 805 MHz . The relevant performance and design parameters for the two cavity types are summarized in Table I.

Table I : Cavity Parameters

Parameter	Cavity Type β= 0.61	β=0.81
Operating Gradient (MV/m)	10.2	15.6
Q_o spec at Operating Gradient	$\geq 5 \times 10^9$	$\geq 5 \times 10^9$
E_{peak} (MV/m)	27.6	34.2
H_{peak} (mT)	58.0	73.2
E_{peak}/E_{acc}	2.71	2.19
B_{peak}/E_{acc} (mT/(MV/m))	5.72	4.72
Operating Temperature (K)	2.1	2.1

The SNS cavities were fabricated by Accel Instruments Gmbh, who also performed the initial tuning and bulk chemical processing using Buffered Chemical Polish (1:1:2). At Jefferson Lab the cavities were heat treated, tuned for field flatness, helium vessels attached, and again etched with BCP (1:1:2) and high pressure rinsed in preparation for testing.

CAVITY TEST PROGRAM

After chemical processing and high pressure rinsing with ultra pure water, the cavities are assembled with input couplers and field probes in the class 10 clean room. They are then evacuated to a vacuum of ~1×10^{-8} mbar and leak checked, once leak tight, they are then hermetically sealed, transferred from the clean room, and assembled onto a test stand. The test stand is inserted into a vertical dewar, which is then filled with liquid helium at 4K, and pumped to 2K for RF testing.

A typical RF test cycle consisted of measurements of cavity fundamental and bandpass frequencies, measurements of input coupling and cavity field decay time constant, and then Q_0 measurements as a function of cavity field. These tests were performed on all of the cavities that were utilized in the SNS cryomodules. Because Jefferson Lab's Vertical Test Area (VTA) was designed to accommodate production testing of CEBAF cavities, its multiple dewars and cryogenic systems are well suited to support a high throughput test program. A typical test turnaround was 24 hours from test stand insertion to subsequent removal. Initially, for both types of cavities, tests were performed on bare cavities as well as on cavities with helium vessels, until confidence was gained that the helium vessel welding procedure was well understood and yielded controlled results vis-à-vis cavity performance. From that time on, tests were only performed on cavities with helium vessels.

A set of 35 medium-β cavities were tested a total of 73 times as part of the cavity qualification effort. During the early stages of this program cavity performance was often limited by field emission, requiring a subsequent processing and test cycle. The cost and schedule implications of this were unacceptable, leading to a careful review of cavity processing and handling procedures, and suggested improvements. Subsequent cavity qualification performance increased markedly, as shown in Table II.

The high-β cavities were processed using the improved procedures utilized for the latter part of medium-β cavity processing and likewise tested in the VTA. A total of 48 cavities were tested 72 separate times. Several of these tests were used to evaluate cavity treatments and RF techniques in order to mitigate the effects of a multipacting barrier that was present at ~ 10 MV/m. Not including these tests, the high-β cavities required on

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[#] delayen,mammosser,ozelis@jlab.org

average 1.4 tests to qualify – a somewhat worse yield than that experienced for the latter part of medium-β cavity qualification effort. Measured performance characteristics for the high-β cavities are summarized in Table III, showing average performance of the entire cavity ensemble of tests, and average performance in the tests where the cavity met the operating requirements. A plot of gradient at Q_o spec for each of the high and medium-β cavities is shown in Figure 1.

Table II : Medium β Cavity Average Performance

Parameter	Processing Procedures	
	Original	Improved
Gradient at Q_o spec (MV/m)	11.0	15.5
Maximum Gradient (MV/m)	12.0	16.4
Q_o at Operating Gradient	6 x 10^9	1.2 x 10^{10}
Field Emission Onset (MV/m)	8.3	10.7
Number of Tests to Qualify	1.9	1.1

Table III : High β Cavity Average Performance

Parameter	All Tests	Passed Tests
Gradient at Q_o spec (MV/m)	15.8	17.7
Maximum Gradient (MV/m)	15.9	18.7
Q_o at Operating Gradient	6.7 x 10^9	9.9 x 10^9
Field Emission Onset	5.9	6.2

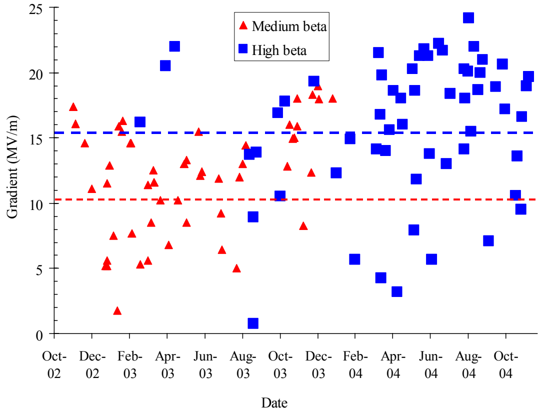

Figure 1. Gradient at $Q_o = 5 \times 10^9$. The gradient spec for the medium (high)–β cavities is indicated with the dashed red (blue) line.

A predominant limitation of both the medium and high-β cavities was unpredictable field emission (FE) loading, as can be seen by the scatter in the gradients in Figure 1. This is also observed in Figures 2 and 3, which show, respectively, a set of Q_o vs E curves for the medium and high-β cavities. The spread in these curves is indicative of the variation in FE loading. While improved processes and procedures helped to postpone the onset of FE to higher gradients, particularly with the medium-β cavities, FE was rarely completely eliminated. Attempts to correlate FE onset with high pressure rinse water quality, were inconclusive [1]. Additional efforts are needed to identify the appropriate process environmental parameters or production controls that correlate more positively with observed performance.

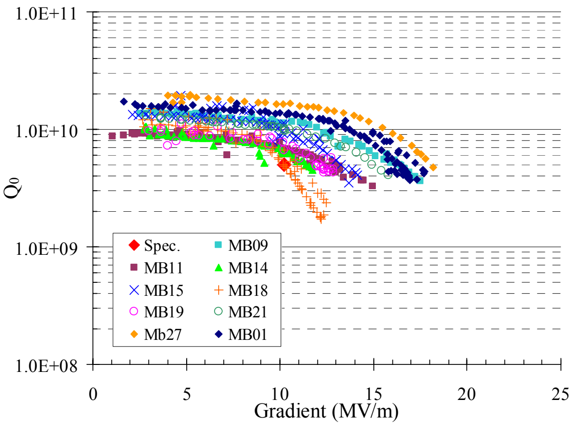

Figure 2. A set of Q_o vs E curves for the medium-β cavities, showing a typical spread in performance resulting from FE loading.

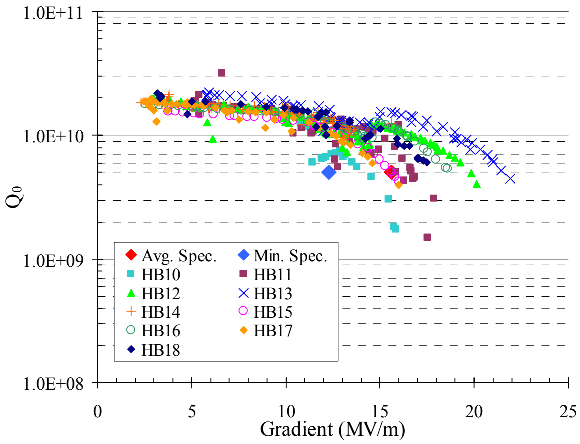

Figure 3. A set of Q_o vs E curves for the high-β cavities, showing a typical spread in performance resulting from FE loading.

COMPARISON WITH CRYOMODULE PERFORMANCE

As part of the SNS SC Linac effort, 8 medium-β and 2 high-β cryomodules were tested in the JLab Cryomodule Test Facility (CMTF) [2]. This testing included measuring Q_0 vs E curves and onset of field emission, and provides an opportunity to compare cryomodule performance with cavity performance as measured in the VTA. The gradient reached at the Q_o spec is plotted in Figure 4 for both the

VTA and CMTF data. The data in triangles (squares) represent the medium (high)-β cavity measured gradients, while the red (blue) lines represent the specification for the medium (high)-β cavities. Typically, cavity gradients in the CMTF were found to be higher than those measured in the VTA. This increase is perhaps due to the much lower RF duty factor (6-7%) employed during module testing. The lack of correlation in onset of field emission is a result of the additional processing after the VTA testing, yielding two different cavity surfaces.

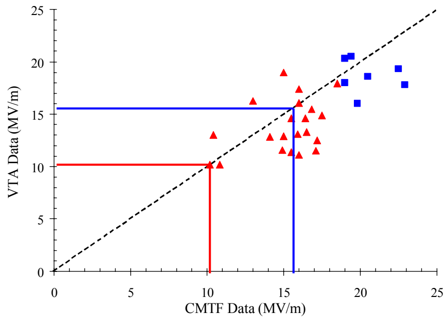

Figure 4. Gradient at $Q_0 = 5 \times 10^9$, as measured in the VTA and CMTF, for the medium-β (triangles) and high-β (squares) cavities.

PREDICTION OF CAVITY VERTICAL QUALIFICATION TEST YIELD

A large ensemble of cavities, such as those tested for the SNS, provides an opportunity to perform a statistical analysis on a non-negligible population size. As there is interest in utilizing similar cavity structures for other SRF accelerator projects, such as the Proton Driver, and Rare Isotope Accelerator, an analysis of the cavity qualification rate as a function of achieved gradient and Q_0 specifications was performed. In this manner, one might be able to predict the cavity yield for similar cavities, processed in an identical fashion, but for a range of desired gradient and Q_0 performance.

In Figures 5 and 6, the normalized production yield for the SNS medium-β cavities is shown. Similarly, in Figures 7 and 8, the high-β yield is plotted. From inspection of these curves, it is clear that cavity qualification yield declines sharply as the cavity performance parameters are made increasingly more stringent. To achieve a reasonable cavity qualification yield for performance specifications significantly more demanding than those of the SNS will require an improved level of contamination control and more robust processing methodologies and infrastructure.

REFERENCES

[1] J. Delayen, J. Mammosser, J. Ozelis, “Analysis of the Qualification Tests Performance of the Superconducting Cavities for the SNS Linac”, Proc. LINAC 2004, Lübeck, Germany, August 2004.

[2] M. Drury, et al. “Overview of SNS Cryomodule Performance”, paper RPPE060, these proceedings.

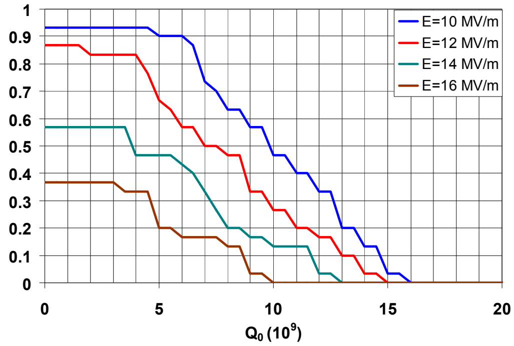

Figure 5. Fraction of 30 VTA tests of β=0.61 cavities exceeding a Q_0 at various operating gradients.

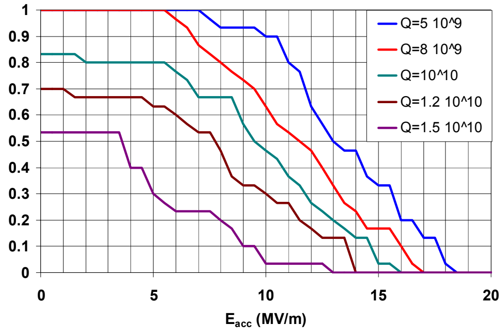

Figure 6. Fraction of 30 VTA tests of β=0.61 cavities exceeding a gradient at various Q_0.

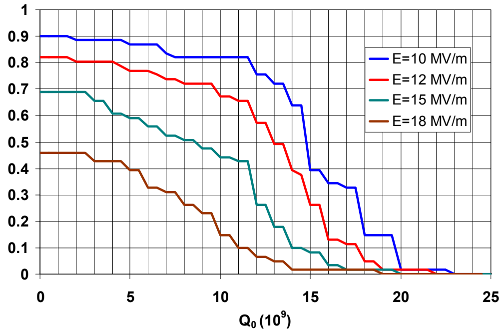

Figure 7. Fraction of 61 VTA tests of β=0.81 cavities exceeding a Q_0 at various operating gradients.

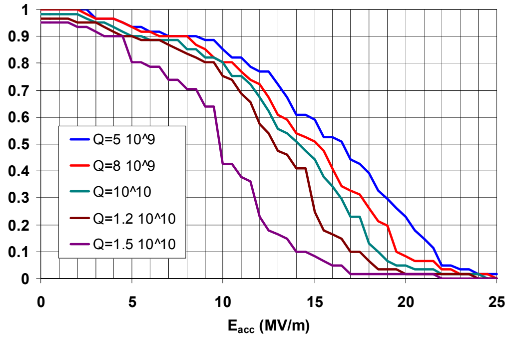

Figure 8. Fraction of 61 VTA tests of β=0.81 cavities exceeding a gradient at various Q_0.