# RESULTS OF THE CRYOGENIC TESTING OF THE SNS PROTOTYPE CRYOMODULE[*]

I. E. Campisi[†], G. Ciovati, E. Daly, G. K. Davis, J. R. Delayen, M. Drury, P. Kneisel,
J. Mammosser, T. Powers, J. Preble, C. E. Reece, M. Stirbet, H. Wang, K. M. Wilson,
T. Whitlatch, M. Wiseman (TJNAF), M. Champion, S. Smee (SNS)

## *Abstract*

Jefferson Lab has developed a prototype of the medium beta SNS cryomodule. Tests were recently performed on the module, which includes three 805 MHz cavities of $\beta=0.61$, with coaxial power couplers and frequency tuners (mechanical and piezoelectric). The cavities exceeded accelerating gradients of 16 MV/m (design value 10.5 MV/m) with $Q_o$'s of about $10^{10}$ at the design field. One of the power couplers has been tested up to peak powers of over 700 kW. Results of the tests are reported in this paper.

## 1 INTRODUCTION

The Spallation Neutron Source is being built at Oak Ridge National Laboratory as a facility for materials studies [1]. The main part of the H- accelerating linac from 186 MeV to 1 GeV consists of 11 $\beta$ =.61 and 12 high $\beta$=.81 cryomodules containing 33 and 48 6-cell cavities, respectively.

In less than two years a complete $\beta$=.61 cryomodule was designed, its components manufactured, pre-tested and assembled [2][3][4][5]. The cryomodule itself was assembled during the spring of 2002 and a first series of test performed in June and July 2002. This test constitutes the first complete test ever of elliptical superconducting structures for $\beta < 1$ at high power in a horizontal cryostat.

## 2 COMPONENTS AND PERFORMANCE

### *2.1 Cavities*

The prototype cryomodule consists of three ß = 0.61 superconducting niobium cavities operated at a frequency of 805 MHz at a temperature of 2.1K. Eleven such modules are used in the machine to accelerate the H- beam from 186 MeV to 330 MeV.

Each ß = 0.61 cavity consists of six cells made from 4 mm thick high purity niobium sheets of RRR> 250 and features one higher order mode (HOM) coupler of the TESLA type on each beam pipe, ports for a high power input coupler (FPC) and a field monitoring probe. At the tapered beam pipe sections, which are made from reactor grade niobium, end dishes of 6 mm thick Nb55Ti for an integrated helium vessel are welded to the beam pipes close to the end cell irises. In Figure 1 the cavities' performance in the vertical cryostat are shown.

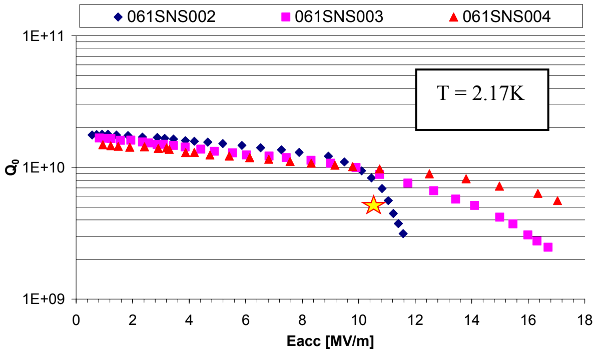

Figure 1. Results from vertical tests of the three prototype beta = 0.61 cavities

### *2.2 Fundamental power couplers*

Three coaxial fundamental power couplers [5] were installed together with the cooled outer conductors. The 50-Ohm couplers had been RF conditioned and tested previously in a test stand with powers up to 2 MW and 0.7 ms long pulses.

During the CM tests the couplers reached 700 kW in full reflection with 1 ms pulses, well above the specifications of 550 kW peak power. During limited duration tests, they exceed 120 kW average power with longer pulses, which is three times the design value.

### *2.3 Tuners*

Mechanical tuners of the TESLA-Saclay type were installed, modified in size and to incorporate a piezo actuator, which allows for fine-tuning and dynamic Lorentz force compensation.

The mechanical tuners provide a range of 480 kHz and a resolution better than 3 Hz with minimal backlash. The piezo tuners' range is approximately 3-4 kHz with a resolution of about 1 Hz.

### *2.4 HOM damping.*

Damping of the relevant longitudinal modes near bunch harmonics (which could extract significant power from the beam if not damped properly) was verified. The $TM_{021}$-$5\pi/6$, $TM_{021}$-$\pi$ and the beam pipe modes are centered at 2799, 2804 and 3217 MHz with external Q's of 3.7, 4.6 and 2.8 x $10^3$, respectively**.** The presence of some dipole modes with higher Q's ($10^5$-$10^6$) was noted: their effect on the beam is considered negligible.

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[†]campisi@jlab.org

Figure 2. SNS β=0.61 three-cavity string assembled in the clean room. Indium seals were used in this prototype while more efficient seals are being developed for production.

## 3 TESTS

### 3.1 The Cryomodule Test Facility

The tests were performed in our recently renovated test facility. Improvements in magnetic shielding within the cave allowed for reaching the expected high $Q_0$'s. Improvements in the cryogenics capacity, in the test equipment, in the data acquisition and in controls were implemented for this test. For the fist time a 1.2 MW, 805 MHz pulse klystron was used in these tests at Jefferson Lab, together with two combined CW, 10 kW klystrons at the same frequency.

### 3.2 Cavity maximum fields and unloaded Q's

The cavity fields in pulsed mode are determined by measuring incident power, reverse detuned power, tuned transmitted power, and the emitted energy at the end of the pulse.

Unloaded Q's are measured calorimetrically. With 1 ms pulses and a 6% duty cycle, the calorimetric measurements are accurate only at the highest gradients. More accurate values of losses at lower gradients were obtained by increasing the external Q of the couplers up to $10^7$ with a stub tuner and by using the two 10 kW amplifiers in CW or with relatively long pulses (100 ms) and larger duty cycles (25-50 %).

All three cavities were limited by quenches, most likely initiated in the beam pipes on the fundamental power coupler side and triggered by field-emitted electrons. Two of the cavities had similar limitations at about 16 MV/m and the third cavity reached 21 MV/m. $Q_0$'s were clearly in the $10^{10}$ range up to at least 10-12 MV/m and dropped to the mid-low $10^9$ range at the maximum field.

### 3.3 Loaded and external Q's.

The external Q's of the fundamental power couplers (which approximately coincide with the loaded Q's of the cavities) were measured both by the bandwidth method at low power and by the decay method at all power levels. The values were slightly lower than the design value of 7.3 $10^5$: the lower Q's might be attributable in part to field imbalance (in two cavities) or deeper insertion of the center conductor because of the indium joint softness.

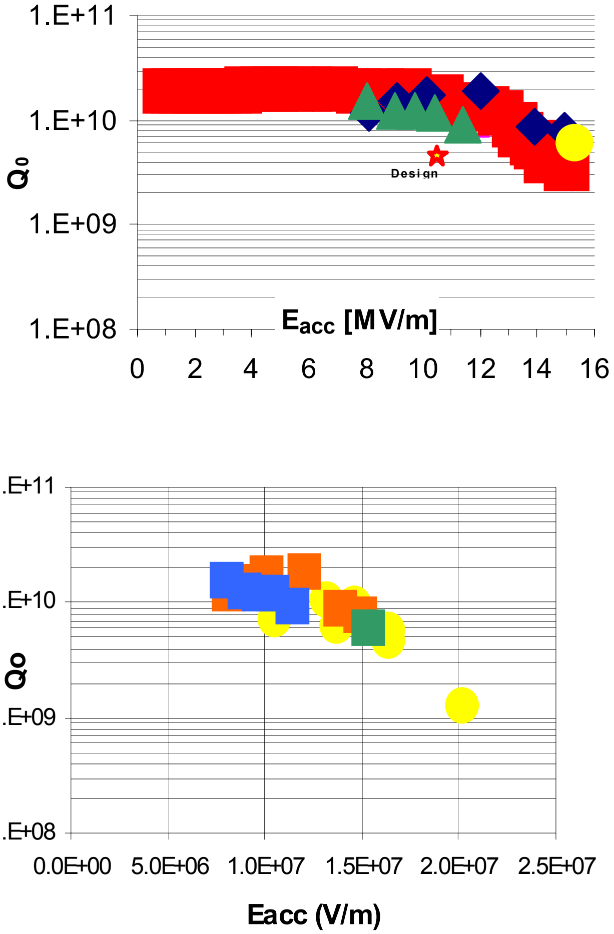

Figure 3. a) Comparison of result in cavity #2 obtained in the vertical test (red) and in the cryomodule with various pulse lengths (green blue, yellow). b) Cryomodule test results for cavity #3. Yellow are values with 1 ms pulse length, the other colors for longer pulses.

### 3.4 Interactions between the electromagnetic and mechanical modes.

In the SNS cryomodule excitation of the mechanical modes can take place through four mechanisms: ambient environmental vibrations, fluctuations of the helium pressure, operation of the mechanical and piezo tuners, and modulation of the RF field. All four were measured.

In the case of ambient vibration we measured the difference between the instantaneous frequency of the cavity and a stable frequency reference. This measurement was done every 2 ms for 100 sec and repeated eight times. After subtraction of a slow drift, a histogram was obtained that indicated a microphonics level of about 3 Hz rms, much less than the 15 Hz rms requirement. Frequency spectra of the microphonics were also measured over several frequency ranges.

Response of the cavity frequency under sinusoidal excitation by both the piezo tuner and modulation of the RF field amplitude was also measured. The cavity frequency responded quite differently from excitation from ambient vibration, piezo excitation, and RF field modulation. For example, the cavities underwent oscillatory ponderomotive instability at about 70 Hz at relatively low field (~2 MV/m) and showed the strongest response to RF field modulation at that frequency and around 100 Hz(Figure 4); the strongest response to piezo excitation and vibrations were around 170 Hz.

The static Lorentz detuning coefficient was measured for all three cavities and ranged from 3.9 to 10 Hz at 1 MV/m.

Of primary importance for pulsed operation is the dynamic frequency excursion during the RF pulse since it will need to be compensated by the RF control system and will impose a requirement on the amount of RF power needed for operation. Figure 5 shows the cavity frequency at 10 MV/m during an RF pulse similar to that during actual SNS operation. Typical maximum frequency excursion during an RF pulse is on the order of 400 Hz. Also shown in Figure 5 is the cavity frequency during simultaneous pulsed operation of the RF and the piezo tuner. Without any attempt at optimization, a reduction of the frequency excursion by a factor of 2 was easily obtained.

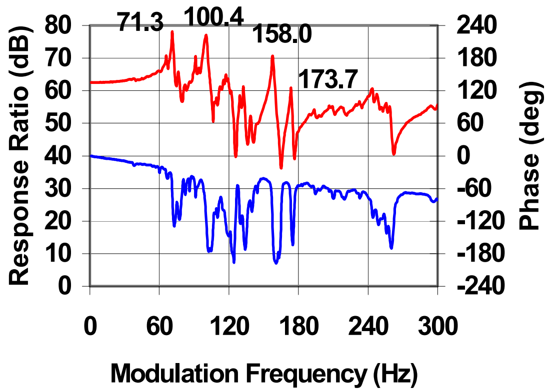

Figure 4. Pulse modulation response of one of the cryomodule cavities. The main resonances are indicated in the figure (red=amplitude, blue=phase).

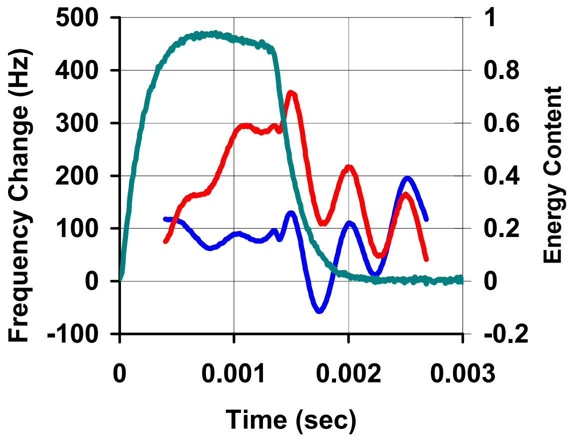

Figure 5. Dynamic Lorentz detuning response at 10 MV/m of one of the cavities without (red) and with (blue) a simple piezo compensation pulse. The maximum allowed modulation is 470 Hz, well above the observed values. The green trace is the energy content in the cavity during the RF pulse.

Table 1. Summary of the results of the test performed on the SNS Prototype Cryomodule.

| Cavity | 1 | 2 | 3 |
|---|---|---|---|
| Parameter | | | |
| Upper tuner freq. (805.xxx MHz) | 0.097 | 0.058 | 0.065 |
| Coupler peak power kW | 300 | 300 | 700 |
| Coupler average power kW | in progr. | 120 | 120 |
| Coupler Qext | 4.8E+05 | 5.4E+05 | 3.8E+05 |
| Field Probe Qext | 2.1E+11 | 7.4E+10 | 1.3E+11 |
| Eacc max pulse MV/m | 16 | 16 | 21 |
| Qext modified max | 1.0E+07 | 2.5E+08 | 1.0E+07 |
| Qo at 10.5 MV/m | 1.0E+10 | 1.0E+10 | 1.0E+10 |
| Qo at Eacc max | noisy | 6.0E+09 | 2.0E+09 |
| Tuner range (min) | 480 kHz | 480 kHz | 480 kHz |
| Tuner backlash | <30 Hz | <30 Hz | <30 Hz |
| Tuner resolution | <3 Hz | <3 Hz | <3 Hz |
| Piezo range kHz | 4 | 3 | 4 |
| Piezo frequency response kHz | 2 | 2 | 2 |
| Piezo sensitivity Hz | 1 | 1 | 1 |
| Largest microphonics peak freq. Hz | 158 | 170 | 163 |
| Static Lorentz coeff. Hz/(MV/m)$^2$ | -10.1 | -3.9 | -5.8 |
| Dynamic Lorentz coeff. Hz/(MV/m)$^2$ | -6.5 | -3.8 | -4.0 |
| HOM damping | 1.0E+04 | 1.0E+04 | 1.0E+04 |
| HOM 1 Qext FPC side | 1.3E+11 | 1.2E+11 | 5.6E+10 |
| HOM 2 Qext Probe side | 9.7E+11 | 9.4E+11 | 1.7E+12 |
| Static Heat load of primary circuit | 17W | | |

## 4 CONCLUSIONS

Tests of the Prototype SNS Cryomodule, the first test ever of low β elliptical cavities at high power in a horizontal cryostat, have exceeded the specifications and that no element of the cryomodule limits its performance.

## 5 ACKNOWLEDGEMENTS

We acknowledge the contributions of many colleagues from the SNS Partner Laboratories.

## 6 REFERENCES

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