SUPERCONDUCTING RF ACTIVITIES AT NSCL*

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Abstract

The NSCL has initiated an SRF research and development program. A β=0.47 805 MHz six-cell cavity for RIA is being designed and prototyped in collaboration with JLAB and Milano. Single-cell tests have demonstrated E_{acc} up to 18.4 MV/m, and $Q>10^{10}$ at the design gradient of 8 MV/m without multipacting. An existing β=0.055 80 MHz quarter-wave resonator has been tested and a superferric quadrupole for SRF linacs has been built in collaboration with Legnaro. Additional microphonics, piezoelectric, and x-ray imaging research is presented.

1 INTRODUCTION

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) has initiated a superconducting radio frequency (SRF) cavity research and development program. Of interest are linear accelerators such as the Rare Isotope Accelerator (RIA) as well as basic research in SRF.

NSCL is a major nuclear physics research facility funded by the National Science Foundation and Michigan State University [1]. Recently upgraded, the facility consists of two coupled, high-energy, superconducting cyclotrons producing stable ions from hydrogen to uranium with energies of 100-200 MeV per nucleon and beam powers of up to several kW. Radioactive beams are produced via particle fragmentation, isotopically selected with a large acceptance fragment separator, and transported to one of several experimental vaults.

In 2000, the U.S. Nuclear Science Advisory Committee recommended that RIA be the next major project in heavy-ion nuclear physics research. The NSCL is pursuing a full range of RIA-related research, including the development of SRF accelerating structures. The SRF research on high energy axisymmetic structures is a collaboration with Thomas Jefferson National Accelerator Facility (JLAB) and INFN Milano. The research on low-velocity structures such as quarter wave resonators (QWR) and the use of superferric quadrupoles in SRF linacs is a collaboration with INFN Legnaro.

2 SRF INFRASTRUCTURE

Construction of the SRF facility began in mid-2000 with funding provided by MSU, and is now basically complete. Figure 1 shows the facility layout in the NSCL high-bay. A 40 ton crane passes over this area and is used to lift components such as cavities and Dewar inserts.

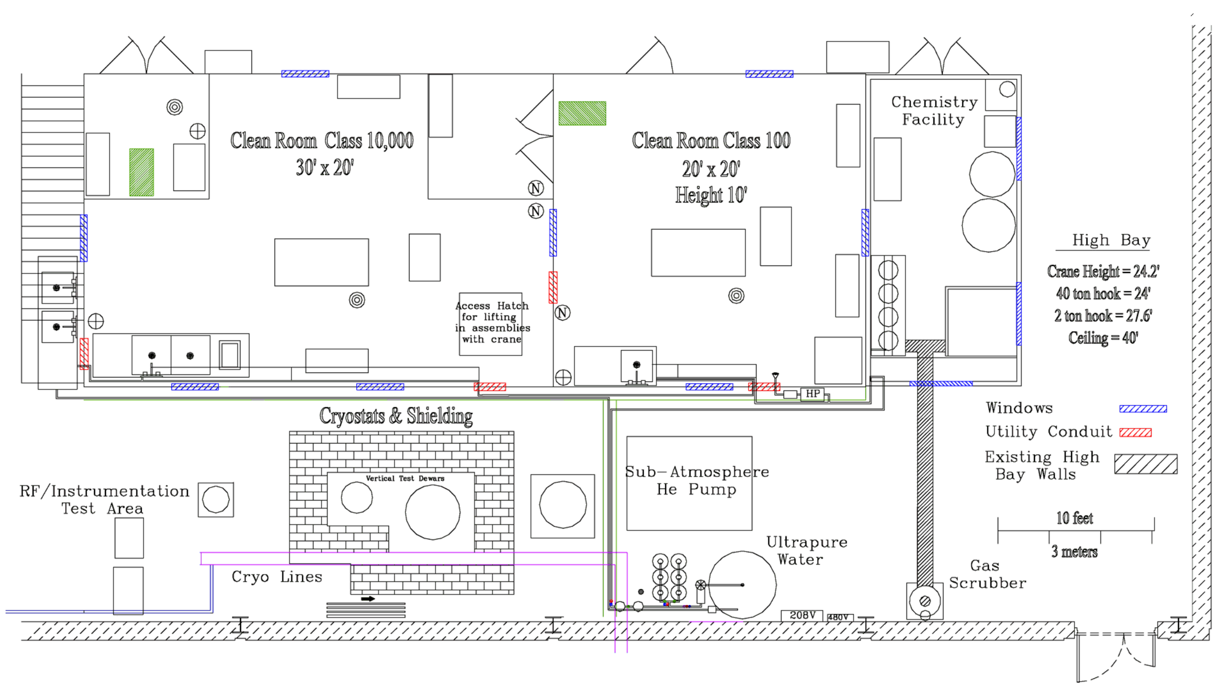

Figure 1. Layout of the NSCL's Superconducting RF Research and Development Facility.

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The cleanroom has two segments [2]. A class 100 cleanroom of 400 square feet (37.2 m^2) is used for high-pressure water rinsing and for final assembly of cavity components. The adjacent 600 square feet (55.7 m^2) is designated Class 10,000 and is used for initial cleaning of parts, gowning of personnel, and assembly of the vertical cryostat insert that can be lowered through a hole in the ceiling. Routinely monitored particulate levels are around Class 10 in the Class 100 room and around Class 100 in the Class 10,000 room due to stringent procedures and full gowning of personnel in both rooms.

The ultra-pure water system is a continuously flowing loop of about 5 gallons per minute (18.9 liters/min) at ~18 MΩ·cm. The system is shown in Figure 2 with nearly all components including the 500 gallon (2000 liter) storage tank made of polypropylene. The water passes through multiple deionizing beds, a sub-micron filter, and an ultraviolet light for control of bacteria. A dry nitrogen cover gas is maintained above the storage tank to further limit bacterial growth. Makeup water comes from the laboratory's 4 MΩ·cm cooling water and water stills.

The high-pressure water rinse system in the Class 100 cleanroom supplies up to 1.5 gpm (6 liters/min) at 1400 psi (95 bars) to sapphire or stainless steel nozzles. The cavity is rotated and translated to wash the entire rf surface with a mechanical system based on that used at JLAB to process the original 1.5 GHz cavities.

The full chemistry facility is adjacent to the cleanroom and consists of a 200 square foot (18.6 m^2) PVC room that is maintained at negative pressure and a 500 cubic feet per minute (14.2 m^3/min) wet scrubber for removal of NO_2 and acid vapor. This facility is under construction and should be operational by the end of 2001.

A prototype chemistry room was set up earlier to etch niobium samples, measure NO_2 emission rates and verify procedures for handling the buffered chemical polish (BCP). A 1:1:2 BCP mixture was used and consists of fully concentrated acids; 1 part hydrofluoric, 1 part nitric and 2 parts phosphoric acid. Acid at this concentration removes about 2 μm per minute at 15 C. This prototype chemistry facility demonstrated the ability to work with quantities, ~10 gallons (~40 liters), of BCP and was used to etch the 80 MHz QWR.

The NSCL's coupled cyclotron upgrade included a 1.7 kW, 4.2 K cryogenic system. This new cryoplant has excess capacity which is available for SRF research. For cavity tests at 4.2 K, the boil-off is returned to the cryoplant and re-liquefied. Testing below 4.2 K will be done with a sub-atmospheric pumping system consisting of a heater, butterfly control valve with capacitive manometers, and roots blower backed by a roughing pump. The roots blower has a pumping capacity of 3110 m^3/hr (1830 cfm) allowing up to 60 W to be continuously dissipated in the liquid helium at 2 K. Helium from the roots blower is exhausted to the atmosphere. In the future, a filter may be purchased to purify the gas for return to the cryoplant.

Figure 2. Ultra-pure Water System.

Two vertical liquid helium Dewars with liquid nitrogen shields have been installed with inserts including aluminum thermal baffles. A two layer magnetic shield of μ-metal around the Dewars reduces the stray field to about 10 mGauss (1 μT). The Dewars with cryolines, inserts and radiation shielding are shown in Figure 3. The smaller Dewar has a 15 inch (0.38 m) diameter and a maximum helium level of 48 inches (1.2 m). The larger Dewar has a 30 inch (0.76 m) inner diameter and a maximum helium level of 60 inches (1.5 m). Both Dewars are surrounded by a 2.5 foot (0.76 m) thick concrete x-ray shield.

Figure 3. Vertical Dewars.

3 SRF RESEARCH & DEVELOPMENT

Through August 2001, three different cavities have been tested at NSCL. The first was a 1.5 GHz single-cell cavity lent by JLAB, which was used for initial tests. The second was an 80 MHz QWR on loan from Legnaro. The third was an 805 MHz single-cell cavity that was built by the NSCL/JLAB/Milano collaboration.

3.1 805 MHz β=0.47Axisymmetric Cavity

The RIA linac will accelerate heavy ions over the same velocity range as the proton linac for the Spallation Neutron Source (SNS). It was decided to use the 6-cell axisymmetric 805 MHz cavities and cryostats of SNS for the downstream portion of the RIA linac, thereby saving non-recurring development and engineering costs. For additional cost savings, it was decided to extend the SNS multi-cell design to lower velocity, $\beta=v/c=0.40$, using the same cryostats and RF systems. Axisymmetric cavities will thus constitute about three-quarters of RIA's total accelerating voltage, and most of that voltage will be provided by cavities already developed for SNS. The axisymmetric cavities will accelerate the RIA beam from $\beta=0.40$ to $\beta=0.72$. This velocity range can be covered with two different types of 6-cell cavities, one with a geometric β, β_g, of 0.47 and the other with a β_g of 0.61. The $\beta_g=0.61$ cavity will be of the existing SNS design.

The 6-cell $\beta_g=0.47$ cavity design and the first single-cell experimental results are presented in [3]. Additional multipacting simulations are presented at this workshop [4]. Two $\beta_g=0.47$ single-cell prototypes were fabricated to confirm design performance, including frequency, field level and Q, and to check for ancillary problems such as multipacting. The structures were fabricated from 4 mm sheet Nb with RRR>250. The aluminum alloy dies were fabricated at NSCL and the stamping was done at JLAB with a 450 ton press as shown in Figure 4. The half-cells, beam tubes, and flanges were joined by electron beam welding and the completed single-cell cavities were etched using BCP to remove about 100 μm from the surface at JLAB. In the future, deep drawing could be done at a vendor's 850 ton press near the NSCL and electron beam welding at Sciaky, Inc. in Chicago where NSCL has already done sample niobium welds.

Figure 4. Dies for deep drawing of RIA half-cell.

Figure 5. High pressure rinsing of RIA cavity.

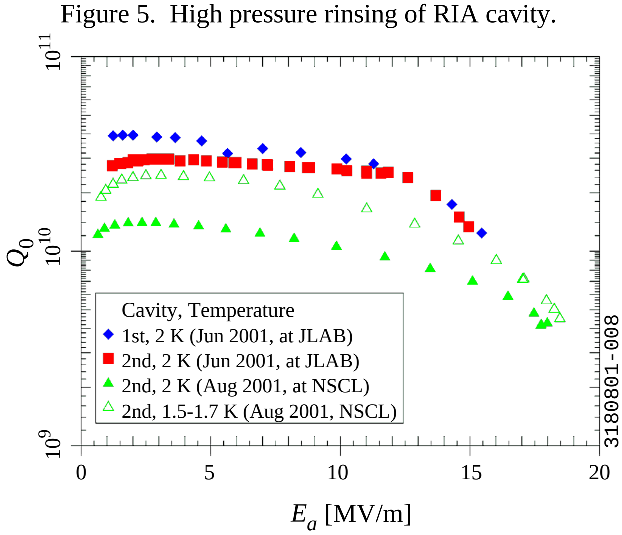

Figure 6. Measured dependence of Q on accelerating gradient for the RIA cavity.

The first cavity tests were done at JLAB. One of the cavities was shipped to NSCL and retested. Figure 5 shows the cavity being high pressure rinsed in the NSCL's Class 100 cleanroom. The cavity was then retested at NSCL over the temperature range of 1.5-2.2 K. Figure 6 shows the measured dependence of Q on the accelerating gradient for tests at JLAB and the NSCL. The tests demonstrate E_{acc} up to 18.4 MV/m, and $Q>10^{10}$ at the RIA design gradient of 8 MV/m. The test was stopped at 18.4 MV/m when the maximum 32 W power level of the amplifier was reached. These results provide a proof-of-principle for the RF performance of the $\beta_g=0.47$ cavity and demonstrate that multipacting is not a problem for this cell shape. The single-cell results support fabrication of the 6-cell structure.

For the R&D prototyping phase, the 6-cell design was modified to use the same diameter beam pipes at both ends. This will simplify prototype fabrication since only two types of dies are needed. A 6-cell copper prototype is being built to verify the frequency and tuning characteristics. Three niobium 6-cell structures will then be fabricated with vertical testing by the end of 2001. Systems tests of a 6-cell horizontal system will proceed in 2002-2003.

Microphonics measurements on the single-cell cavity are shown in Figure 7. Using a spectrum analyzer, the phase-locked center frequency of the cavity was found to oscillate with a total width of 75 Hz. To determine the source of the detuning, an FFT of the phase-lock loop's error signal was taken, as shown in Figure 7A. Also, an accelerometer (KISTLER Instrument Corp.) was placed on top of the Dewar and mechanical vibrations were measured, as shown in Figure 7B. The helium roughing pumps generated 57.9 Hz, 120 Hz and 125.4 Hz vibrations and the turbo pump was seen at 420 Hz. The peaks were identified by shutting off the sources. No significant frequency detuning was present above 500 Hz and the largest vibrations were due to the sub-atmospheric helium mechanical pumps.

Microphonics simulations were carried out using COSMOSM V2.6. Two sets of boundary conditions were used. In the first model, the end flanges were fixed in all degrees of freedom. The two lowest natural frequencies were 390 and 441.8 Hz. In the second model, one flange was free. This model gave a natural frequency of 91.5 Hz for the pendulum mode. The second mode was axial compression with a frequency of 209 Hz. The actual boundary conditions are between these two idealized models so the lowest natural frequency should be between

91.5 Hz and 390 Hz. The peak around 195 Hz may thus be a mechanical resonance.

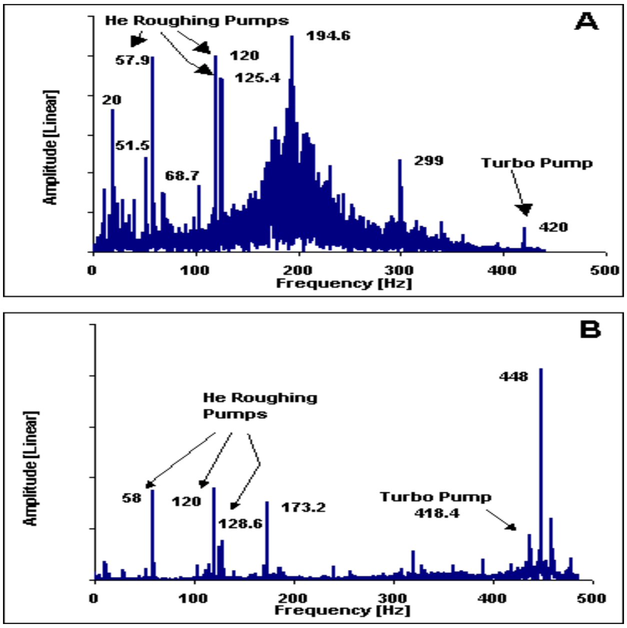

Figure 7. Microphonics spectrum from FFT of (A) cavity's phase lock loop/error signal, and (B) accelerometer on top of Dewar.

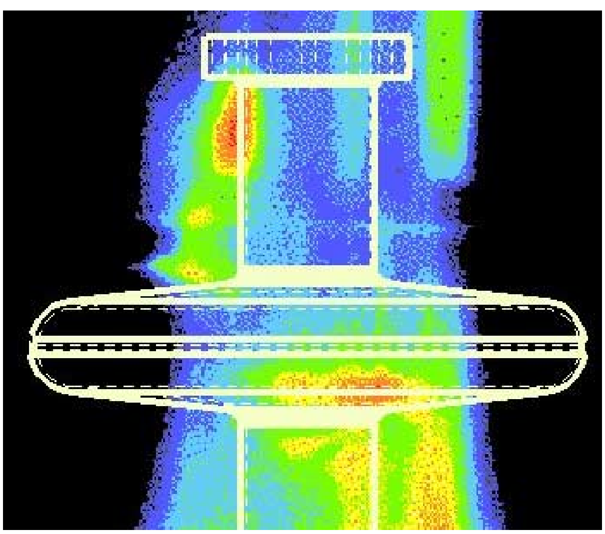

Figure 8. X-ray image of cavity using lead "pin-hole camera".

X-ray images of the single-cell cavity were taken through the Dewar and magnetic shield using a lead "pin-hole camera" and high sensitivity re-useable x-ray film (Fuji BAS-2500). This technique has been used to image room temperature linac structures [5]. Figure 8 shows an image with the cavity superimposed to show emission sites around the iris and in the beam pipe. This demonstration image used a relatively large 0.25 inch aperture in the lead. The lead shield had some thin gaps that caused some of the streaking away from the cavity. The image was taken with the cavity at a high E_{acc} of about 15 MV/m.

3.2 80 MHz β=0.055 Quarter-wave Cavity and Superconducting Quadrupole Development

INFN Legnaro and NSCL are collaborating on the development of low β cavities and iron-dominated superconducting quadrupoles for use in SRF linacs. In early 2001, a spare Legnaro 80 MHz β=0.055 QWR (model Z5) with a suspected welding defect was sent to the NSCL for possible repair[6].

The first test of this cavity at Legnaro showed a *Q* that quickly dropped below 10^8 and quenched at $E_{acc} < 4$ MV/m. The cavity was etched a second time at CERN and showed a significant improvement, but it was still not as good as the other Legnaro cavities. If the defect was sufficiently small, then a third etch at the NSCL could further improve the performance.

The cavity was tested at NSCL using a phase-locked loop and a self-excited loop before etching, obtaining basically the same results as at Legnaro. The cavity was then etched to remove about 50 µm of material, high pressure rinsed, and retested. Figure 9 shows the quarter-wave resonator installed on the Dewar insert in the cleanroom. Similar results were obtained, as shown in Figure 10, which compares the results of tests at Legnaro and NSCL after the final etch. The *Q* degrades from 10^9 to 3×10^8 while still reaching 5 MV/m accelerating gradient. The limit of 5 MV/m at NSCL was due to the x-ray personnel dose limit, since the radiation shield had not yet been built. At 4.4 MV/m the x-ray energy spectrum was measured using a germanium detector with a peak energy of 300 keV.

Etching did not remove the defect, which implies that it is >50 µm, so the cavity was visually inspected using optical scopes and borescopes. Several suspect points were noted, but nothing conclusive was identified. The next step will be to hook up a temperature system (resistive or second sound) to pinpoint the problem and develop a corrective plan.

Figure 9. QWR installed on insert.

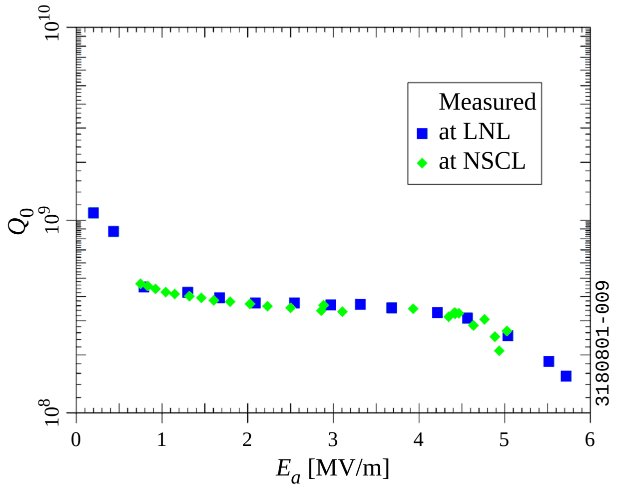

Figure 10. Measured dependence of Q on accelerating gradient for 80 MHz cavity, before and after etching at NSCL.

A superferric (iron-dominated, superconducting coil) quadrupole has been designed and built for use in SRF linacs [7]. The design field values are for a low β SRF linac. The quadrupole length is 50 mm with a 40 mm diameter bore and an operating field gradient of 31 T/m. Field clamps have been designed to reduce the stray field to <10 mG (1 μT) at 0.1 m from the magnet. Figure 11 shows the quadrupole during magnetic field mapping at room temperature. Cryogenic tests are being planned to measure the stray field.

Figure 11. Superconducting quadrupole during magnetic field mapping at room temperature.

3.3 Piezoelectric tuner

Piezoelectric tuners for fast tuning and active mechanical damping are being pursued. Low voltage PZT actuators (Piezosystem Jena, Inc.) have been tested at room temperature and in liquid nitrogen. The actuator's motion of 40 μm at room temperature decreases to 12 μm in liquid nitrogen. Future tests at 2-4 K, which should give similar results to those at 77 K, will be performed for static and dynamic conditions.

3.4 Nb Mechanical Property Measurements

In collaboration with the Materials Science and Mechanics department at MSU, material properties of high RRR niobium (RRR >250) were studied and compared to reactor grade niobium (RRR ~30) [8]. Figure 12 shows a stress-strain plot that was calculated from tensile tests and showed agreement with previous published results. Optical work provided microstructures of high RRR material as shown in Figure 13, and show a recrystallized structure with grain sizes consistent with requirements for mechanical forming, <50 μm.

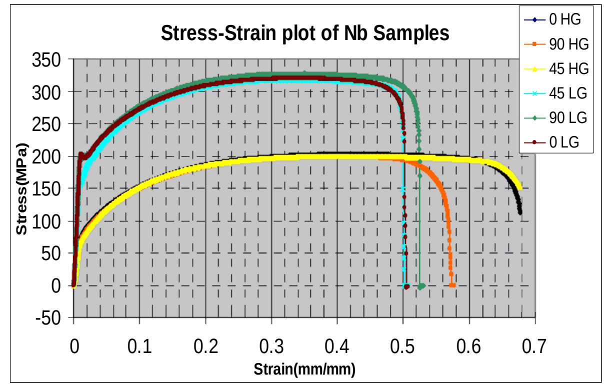

Figure 12. Stress-strain plot of Nb.

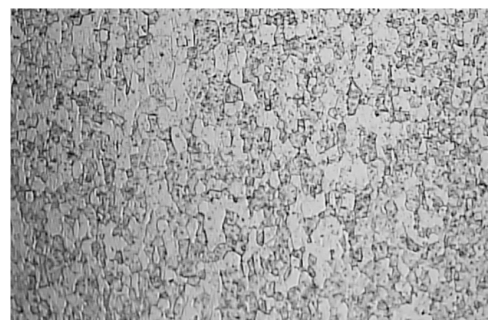

Figure 13. Grain structure of RRR Nb.

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