FIRST COLD TEST RESULTS OF MEDIUM-β 644 MHz SUPERCONDUCTING 5-CELL ELLIPTICAL CAVITY FOR THE FRIB ENERGY UPGRADE*

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Abstract

The CW superconducting linac for the Facility for Rare Isotope Beams (FRIB) will accelerate ions to 200 MeV per nucleon of uranium, with the possibility of a future energy upgrade to 400 MeV per nucleon via additional cavities. The design study [1] concluded that the 644 MHz 5-cell $\beta_{opt} = 0.65$ cavity is a superior option, maximizing accelerating gradient [E_{acc}] to meet the target energy upgrade while minimizing the additional cryogenic load, cryomoduls, and real estate. Two bare niobium [Nb] cavities, S65-001 and S65-002, have been fabricated. The first, S65-001, underwent 150 µm bulk electropolishing [EP], hydrogen degassing at 600°C for 10 hours, 20 µm light EP, and in-situ baking at 120°C for 48 hours following high-pressure water rinsing and clean assembly. In the first cold-test, S65-001 achieved a Q_0 of $2{\cdot}10^{10}$, equivalent to $R_s = 10\ n\Omega$, at its design E_{acc}, 17.5 MV/m ($V_{acc} = 12.4$ MV). The cavity was tested in a newly refurbished FRIB test dewar, equipped with a variable input coupler driven by a stepper motor. The second cavity, S65-002, has undergone a buffer chemical polish [BCP] and will be tested soon to compare against S65-001's performance. S65-002 was also used to investigate mechanical modes and passband/higher order modes at room temperature. This work is in preparation for S65-001 to undergo nitrogen doping/infusion at FNAL, to compare its nitrogen-doped performance against its EP performance detailed here.

INTRODUCTION

The upgraded linac will be able to deliver 400 MeV/u for the heaviest uranium ions and up to 1 GeV for protons, including a variety of light ions with energies higher than 400 MeV/u, which will increase the yield of rare isotopes from the targets. Further benefits of this upgrade include providing the same 400 kW of power on target but at a reduced dissipation power density at the beam-dump. The baseline design of the FRIB conventional facilities incorporated an 80-meter space reserved in the linac tunnel for energy upgrade cryomodules. In the past two years, several technical solutions have been studied to find the best option for the energy upgrade within this available real estate. Several types of superconducting [SC] cavities operating at different frequencies were investigated, and it was concluded that a 5-cell 644 MHz cavity with $\beta_{opt} = 0.65$ is optimal for the energy upgrade. The design parameters are described in [1]. Essentially, this design meets energy upgrade targets while minimizing heat load, number of additional cavities, and number of additional cryomodules.

RF SURFACE PROCESSING

The initial surface treatment of S65-001 was based on the standard ILC recipe for EP with a slightly modified hydrogen degassing step. The 150 µm bulk EP was carried out at Argonne National Laboratory [ANL], then baked FRIB's high-vacuum furnace for hydrogen degassing: first at 350°C for 12h, then at 600°C for 10 hours. The cavity was then moved to a bead-pull test stand at FRIB, and mechanically squeezed/stretched with tuning cuffs to achieve uniform cell-by-cell field distribution. After field-flatness tuning, the cavity was shipped to ANL for the final 20 µm EP, followed by high pressure water rinse and clean assembly. Final clean assembly of the variable coupler and vacuum fittings to the refurbished test-insert occurred at the FRIB clean-room facilities. After clean assembly, S65-001 was baked in-situ at 120°C for 48 hours, assembled to the dewar insert. This long, low-temperature bake was undertaken in order to ameliorate the potential for a high-field Q-slope, a practice common in 1.3 GHz TESLA cavities [2]. Cold test #1 (with high-power RF) was then conducted on S65-001. In preparation for cold test #2, S65-001 underwent another 20 µm EP at ANL, followed by HPR and clean assembly at FRIB facilities. A 60°C, 12 hour bake was then included to remove any remaining water from the cavity surface, and cold test #2 was conducted on S65-001.

BEAD PULL MEASURMENTS

Figure 1 shows a schematic of the FRIB bead-pull test stand. An 8mm brass bead is threaded onto nylon monofilament, and mounted on pulleys above and below the cavity. The bottom end is attached to the stepper motor, and the top is weighted over a third pulley. Jigs attached to the beam ports ensure that the bead is drawn precisely along the center of the beam axis. As the bead traverses the cavity, it perturbs the cavity's resonant frequency. This perturbation is treated formally with the Slater perturbation theorem [3]. The resonant frequency shift is related to the phase shift, $\frac{\tan\phi}{2Q_L} = \frac{\Delta\omega}{\omega_0}$, where $\Delta\omega$ is the difference between the unperturbed (ω_0) and perturbed resonant frequencies, and ϕ is the measured phase change from resonance [4]. A vector network analyser provided 10 dBm to the input coupler, and measured the change in the phase at the pickup port at the unperturbed π-mode frequency. A Labview program was created [5] to step the bead through

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the axis in small increments, and record the phase-shift data from the VNA. A MATLAB script then processed the data, calculating the relative field flatness and cell-by-cell tuning in kHz needed bring the five cell fields to 100% similarity in the π-mode. The cell tuning apparatus consists of two stainless steel cuffs with two turnbuckles affixed 180 degrees apart (Fig. 1). Results of the field-flatness tuning of S65-001 are shown in Fig. 2, in which we achieved a final field-flatness of 97% starting from a value of 72%. S65-002 was tuned similarly and also achieved a final field-flatness of 97%, calculated from the cell fields, 1 - $(E_{max} - E_{min})/E_{average}$. Figure 2 further demonstrates that the vertical orientation of the cavity does not affect the final field flatness in the hanging orientation used in the test dewar. The change in resonant frequency as a function of deflection (squeezing) was measured with a dial indicator and found to be -238 ± 16 KHz/mm, and the cavity could withstand up to 100 KHz of deflection without permanent deformation. The pass-band modes of S65-002 were also measured (Fig. 3).

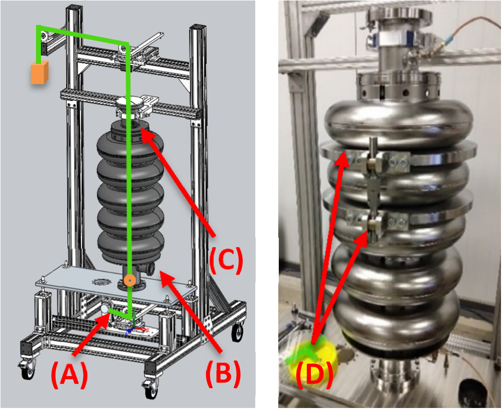

Figure 1: Bead-pull test stand used for the FRIB energy upgrade 644 MHz β=0.65 elliptical cavities. The green line represents the nylon monofilament and the orange sphere is the bead. (A) Stepper motor. (B) Input coupler. (C) Pickup coupler. (D) Cell tuning cuffs (SS304) and turnbuckle.

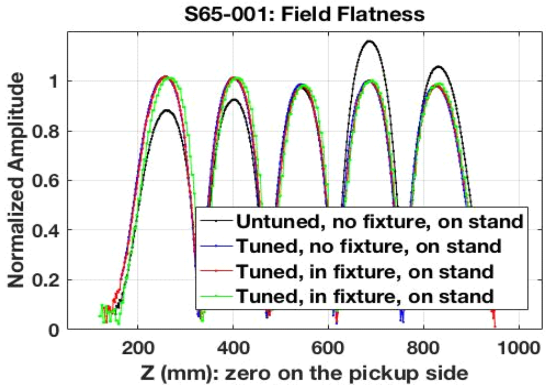

Figure 2: Comparison of untuned S65-001 without fixture (black) to the final tuning of S65-001 without fixture (blue), with fixture (red) and hanging (green) demonstrating that the vertical seating of the cavity on the bead-pull test stand does not affect the field flatness in the dunk-test (hanging) orientation.

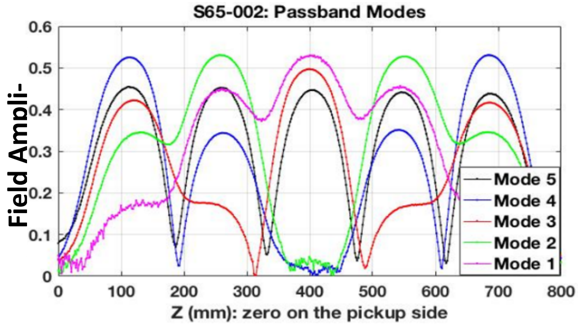

Figure 3: S65-002 passaband modes measured at the same stored energy.

MECHANICAL MODE STUDIES

In operational contexts, cavities are subjected to many 0 Hz to 200 Hz mechanical vibrations, propagating principally through the cryogenics systems. The 5-cell elliptical cavity is particularly susceptible to the cavity bellows/accordion mode [1]. To investigate, S65-002 was mounted on the bead-pull stand and driven by 10 dBm at its π-mode frequency. A speaker was mounted to the base and swept through 200 Hz with a function generator. The resultant spectrogram (Fig. 4) revealed a mechanical mode at 95 Hz. Accelerometer data confirmed this was the bellows/accordion mode, in which the phase of each cell slightly leads that of the previous cell. At room temperature, the decay rate was determined to be 14 ± 2 dBm/sec, corresponding to a reasonably low Q-factor of 185.

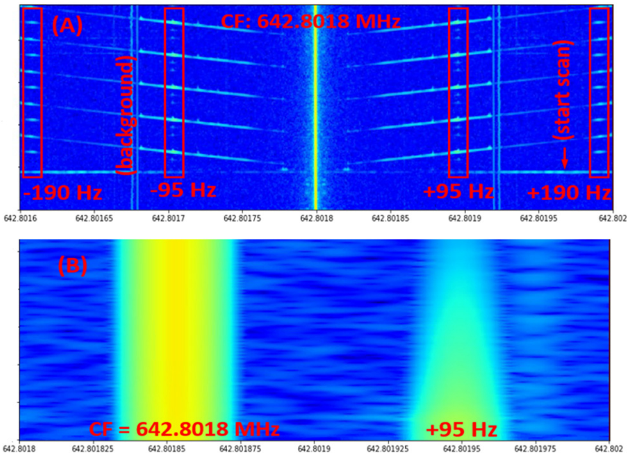

Figure 4: (A) Spectrograph of the S65-002 30sec mechanical mode scans. The 95 Hz accordion mode and its first harmonic at 190 Hz are apparent, marked in red. (B) decay time measurement.

TEST CRYOSTAT MODIFICATIONS

The FRIB production facilities were modified for the dunk testing of these bare Nb, elliptical 5-cell 644 MHz cavities. The cavity insert is shown in Figure 5, with key features labelled. A new variable coupler was developed, driven by a stepper motor plunged into the liquid helium with the rest of the assembly. A magnetic survey of the dewar verified all background and coupler assembly magnetic fields are 2-3 mG and always less than 5 mG.

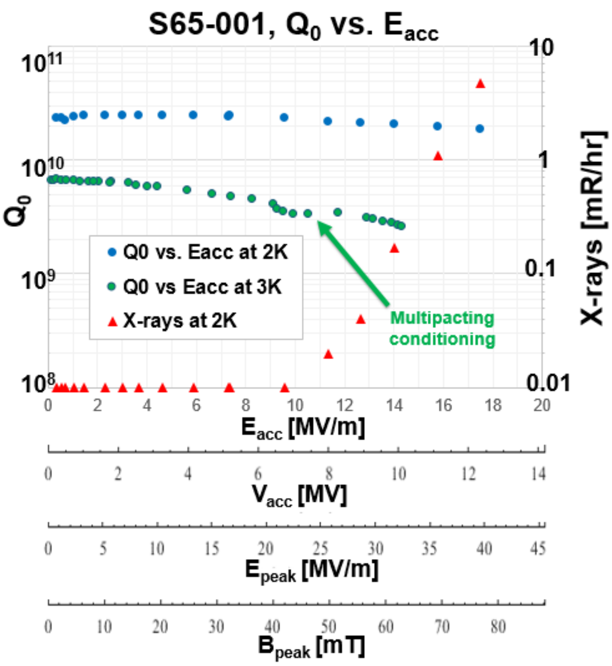

Figure 5: Q-curve of S65-001, cold test #1, with concurrent X-ray emission on the right-hand axis.

CAVITY TEST RESULTS

The first cold, high-power RF test of S65-001 was conducted in the MSU/FRIB test dewar. Cavity frequency lock was accomplished by a phase-locked-loop [PLL] built for the purpose, including a variable phase-shifter. At temperature, the cavity loaded Q, Q_L, is calculated from a decay time measurement ($\Delta a/\Delta t$), and $Q_0 = Q_L\left(1+\beta+\frac{P_t}{P_d}\right)$. P_t is the power transmitted through the cavity, and P_d is the power dissipated in the cavity. The variable coupler and phase is adjusted by hand to the critically coupled condition by finding the position that minimises the measured reflected power, P_r. β is thus taken to be 1. This value of Q_0 is then used to calculate the pickup external Q, Q_{e2}. This is then taken as a constant, and used to calculate the cavity Q_0 as a function of E_{acc} with a G-factor of 188Ω and an R/Q value of 368Ω [1] [3]. The Q-curve from this first cold test of S65-001 appears in Figure 5. The cavity achieved 17.5 MV/m of accelerating gradient with a quality factor of $Q_0 = 2\cdot10^{10}$, corresponding to 10 nΩ of surface resistance. In cold test #1, after a period of CW multipacting [MP] conditioning, field emission [FE] was discovered in the 10 MV/m region. This FE ultimately limited the cavity gradient before the quench limit could be determined. In cold test #2 of S65-001, MP was observed to be compounded with the FE, but it was shown that the high Q is reproducible. Passband modes (Fig. 3) were excited, however all modes encountered FE at approximately the same cavity field level, indicating a distribution of field emitters in the cavity. Some coupler MP was observed in the second cold test, and was supressed by the application of 100 V bias to the coupler.

Further, since surface resistance, R_S, is exponentially related to the ratio of the critical temperature, T_c=9.2K, over cavity temperature [3], the functional band gap for the superconducting Nb in this cavity, $\Delta(0)$, can be found. In Fig. 6, $\Delta(0)$ is measured at 1.1 meV for all values of E_{acc}. For this measurement, cavity temperature did not dip into the range in which the residual resistance, R_0, could be easily extracted. Figure 6 hints that the origin of the medium-field Q-slope in this EP-ed, 120°C-baked cavity is the BCS resistance, however measurements below the lambda point of He (2.1K) would be needed to confirm. Decay time measurements were also made of the passband modes of S65-001, and the input and pickup external Q_{e1} and Q_{e2} calculated in the manner described above. These appear in Table 1. The Lorentz force detuning coefficient was determined in this test to be -6.1 Hz/(MV/m)^2.

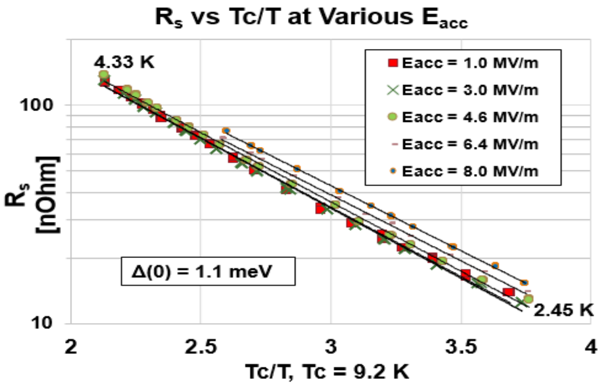

Figure 6: Sample of Surface resistance (Rs) plotted against Tc/T, at various accelerating gradients. The superconducting bandgap for the Nb in this cavity is 1.1 meV, independent of E_{acc}.

Table 1: Input and Pickup Coupling in the Passband Modes

Mode	Freq. (MHz)	Q_{e1}	Q_{e2}
#1 (π/5)	638.720	9.83e9	1.22e14
#2 (2π/5)	640.858	3.00e9	4.14e13
#3 (3π/5)	642.142	1.52e9	2.38e13
#4 (4π/5)	643.316	1.17e9	1.76e13
#5 (π)	643.789	1.61e9	4.36e13

CONCLUSION

The first high-power RF cold test results for the 644 MHz FRIB energy upgrade cavity validates its novel geometric design for application to the development of CW, medium-β accelerating structures. S65-001 underwent a standard ILC EP treatment procedure plus a 120°C in-situ bake for 48 hours and met its design gradient target of 17.5 MV/m. The next steps in its development shall be the exploration of nitrogen doping techniques pioneered at FNAL [6], to push both gradient and Q frontiers in the medium-β regime, seeking more efficient, less costly accelerating structures for applications at FRIB, and beyond.

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