

UPDATE ON NITROGEN-DOPED 9-CELL CAVITY PERFORMANCE IN THE CORNELL HORIZONTAL TEST CRYOMODULE*

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Abstract

The Linac Coherent Light Source-II (LCLS-II) is a new x-ray source that is planned to be constructed in the existing SLAC tunnel. To meet the quality factor specifications (2.7×10^{10} at 2.0 K and 16 MV/m), nitrogen-doping has been proposed as a preparation method for the SRF cavities. In order to demonstrate the feasibility of these goals, four 9-cell cavity tests have been completed in the Cornell Horizontal Test Cryomodule (HTC), which serves as a test bench for the full LCLS-II cryomodule. Here we report on the most recent two cavity tests in the HTC: one cavity nitrogen-doped at Cornell and tested with high Q input coupler and then again tested with high power LCLS-II input coupler. Transition to test in horizontal cryomodule resulted in no degradation in Q_0 from vertical test. Additionally, increased dissipated power due to the high power input coupler was small and in good agreement with simulations. These results represent a crucial step on the way to demonstrating technical readiness for LCLS-II.

INTRODUCTION

The Linac Coherent Light Source-II (LCLS-II) Project will construct a 4 GeV CW superconducting linac in the first kilometer of the existing SLAC tunnel [1]. In order to maximize cryogenic efficiency of the linac and ensure economic feasibility, the superconducting RF (SRF) cavities must reach an intrinsic quality factor (Q_0) of 2.7×10^{10} at 2.0 K and 16 MV/m. To meet this high Q_0 , nitrogen-doping [2] of the SRF cavities has been proposed. Cornell has recently recommissioned the Horizontal Test Cryomodule (HTC) [3] to hold a 9-cell ILC shaped cavity. As part of the LCLS-II R& D program, four 9-cell tests have been completed so far in the HTC. The first two (using ILC helium tanks) were discussed thoroughly in [4]. This paper will focus on the most recent cavity and compare its performance vertically and un-dressed, vertically and dressed (in LCLS-II helium tank), horizontally with high Q input coupler, and horizontally with high power input coupler.

EXPERIMENTAL METHOD

The Cornell HTC is a full cryomodule that can hold one 9-cell ILC shaped cavity, see Fig. 1. It was designed as

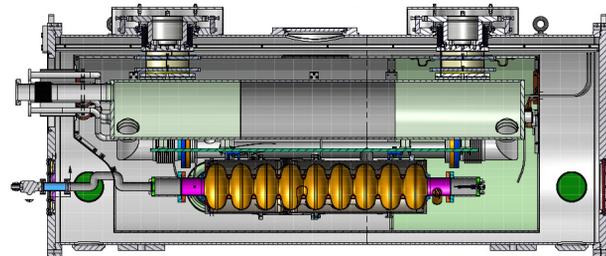


Figure 1: A schematic of a 9-cell cavity in the HTC.

a prototype to test SRF cavities under realistic cryomodule conditions. The cryomodule design is very similar to the LCLS-II cryomodule that will be used in the full machine. Ambient magnetic fields in the HTC are less than 5 mG. A 9-cell cavity (TB9AES018) was prepared with nitrogen-doping at Cornell. This consisted of a bulk vertical electropolish (VEP) of $120 \mu\text{m}$, heat treatment in vacuum at 800°C for three hours, heat treatment in 60 mTorr of nitrogen gas for 20 minutes at 800°C , an annealing stage in vacuum at 800°C for 30 minutes, and finally an additional $24 \mu\text{m}$ VEP. It was then welded into a prototype LCLS-II helium tank at FNAL. The dressed cavity was assembled into the HTC with a high Q input coupler ($Q_{ext} \approx 3 \times 10^{10}$). The cavity was also surrounded by a solenoid in order to induce a uniform external magnetic field parallel to the cavity axis for the purposes of studying cavity Q_0 sensitivity to ambient magnetic fields. A total of 13 cool downs were completed with various cool down rates, spatial temperature gradients, and applied external magnetic fields. After the first cool down, Q_0 vs E_{acc} was measured at different temperatures between 1.6 and 2.0 K in order to extract R_{BCS} vs. field (details of the method used to extract material properties are discussed in [5]). For each subsequent cool down, Q_0 vs E_{acc} was measured at 2.0 and 1.6 K. From this data, we were able to extract residual resistance and evaluate its dependence on cool down gradient and applied magnetic field. This test of TB9AES018 with high Q input coupler will be referred to as HTC9-3.

Following the HTC9-3 test, the cavity was removed from the HTC and an LCLS-II high power input coupler was installed [6] before re-assembly in the HTC. This test will be referred to as HTC9-4. This coupler has an adjustable

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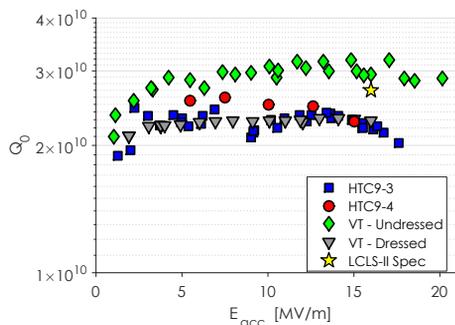


Figure 2: 2.0 K Q_0 vs E_{acc} for HTC9-3 and HTC9-4. No reduction in Q_0 was observed by using the high power coupler. Errors on Q_0 are dominated by systematic errors and are roughly 10%.

coupling which was set to $Q_{ext} \approx 3 \times 10^8$ for the initial measurements. The coupler was cooled directly using 5 K and 80 K helium gas. This cooling scheme is different from the one planned to be used in the LCLS-II cryomodule, in which the coupler will be cooled using thermal straps. Two cool downs were completed in HTC9-4, both very fast with vertical spatial temperature gradients greater than 60 K when the bottom of the cavity transitions to superconducting. The first cool down served to condition field emission. In the second cool down, Q_0 vs E_{acc} was measured at 2.0 and 1.6 K. Q_0 was measured cryogenically. Next, Q_0 as a function of forward power was measured by tuning the cavity off resonance slightly and increasing the forward power to maintain 10 MV/m. By adjusting the coupler Q_{ext} , the Q_0 was also measured as a function of Q_{ext} between 3×10^8 and 4×10^7 at 15 MV/m. Finally, coupler heating and pressure were measured during high power operation with the cavity de-tuned (full reflection) to study coupler heating and performance.

Q_0 VS E_{acc} RESULTS

Immediately after nitrogen-doping, the cavity was vertically tested and reached a Q_0 of 3×10^{10} at 2.0 K and 16 MV/m. After dressing in the prototype LCLS-II helium tank, the cavity Q_0 was reduced to 2.3×10^{10} in vertical test. Following dressing, the cavity was assembled in the HTC and tested with high Q input coupler, reaching a Q_0 of 2.3×10^{10} at 2.0 K and 16 MV/m. Finally, with high power input coupler in the HTC, the cavity again reached a Q_0 2.3×10^{10} at 2.0 K. The full set of 2.0 K Q_0 vs E_{acc} curves for these four steps are shown in Fig. 2.

The drop in Q_0 from 3×10^{10} to 2.3×10^{10} occurred during the cavity dressing step. A possible cause is an increase in residual resistance due to excess high pressure rinsing causing oxide growth on the surface. This has been seen in other cavities at FNAL that show similar reduction in Q_0 . More importantly though, the cavity Q_0 did not degrade any further with assembly in the HTC or with the high power coupler. This is a very important milestone, demonstrating that

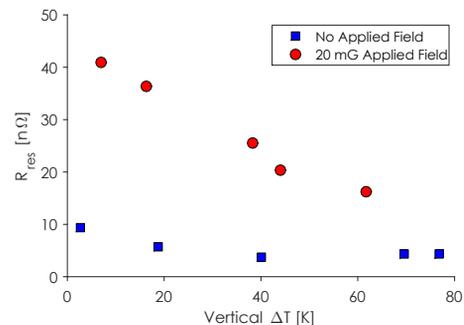


Figure 3: Residual resistance vs vertical spatial temperature gradients for HTC9-3. Larger vertical gradient gives smaller residual resistance.

Q_0 's reached vertically can be maintained both horizontally and with high power couplers.

MAGNETIC FIELD STUDIES IN HTC9-3

The impact of cool down rate on magnetic flux trapping has been studied at Cornell and FNAL [4, 7, 8]. It has been shown that larger transverse spatial temperature gradients will cause larger flux expulsion. By analyzing the extensive Q_0 vs E_{acc} data from HTC9-3, one can extract the sensitivity to ambient magnetic field for the cavity. Specifically, slow cool down which results in significant flux trapping, gave an additional 1.8 nΩ/mG of residual resistance. Fast cool down resulted in an additional ~ 0.7 nΩ/mG of residual resistance. Comparitively, previous tests at Cornell have demonstrated an increase of 0.5 nΩ/mG in fast cool down in the HTC [4]. In addition, we studied the effect of vertical spatial temperature gradient on the residual resistance. Figure 3 shows the residual resistance versus the vertical temperature gradient. From this we can see two things: first, for the points with applied magnetic field, larger gradients result in less residual resistance (consistent with previous measurements) and second, for the points with no applied magnetic field, there is not a significant improvement in R_{res} above gradients of ~ 20 K. This tells us that the gradients achieved in HTC9-4 were more than sufficient to maximize flux expulsion in ambient magnetic fields less than 5 mG (LCLS-II cryomodule specification). Figure 4 shows the residual resistance for each cool down as a function of the maximum helium gas flow during the cool down. In cool downs without applied magnetic field, flow rates greater than ~ 1 g/sec were sufficient to minimize residual resistance. These measurements are consistent with our findings that the lower Q_0 in the HTC is a direct result of cavity dressing, not from trapped magnetic flux during cool down.

COUPLER STUDIES IN HTC9-4

In order to study the effect of operating at high RF drive power on Q_0 , the cavity was tuned off resonance and then forward power was increased to maintain 10 MV/m. Q_0 was then measured. This was repeated up to 4.7 kW. The results are shown in Fig. 5. We can see that the Q_0 is stable up to

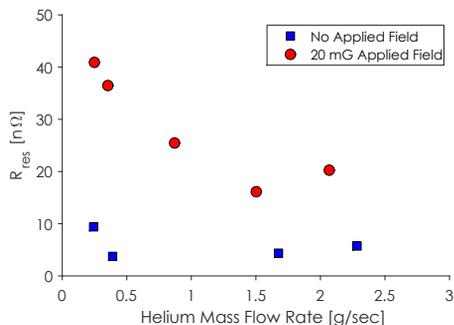


Figure 4: Residual resistance vs maximum helium gas flow rate during cool down. Larger flow rate gives smaller residual resistance up to ~ 1 g/sec.

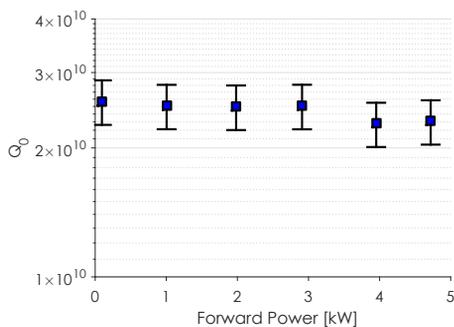


Figure 5: Q_0 vs forward power at 10 MV/m and 2.0 K for HTC9-4.

about 3 kW and then drops slightly. This drop corresponds to ~ 0.3 W increase in dissipated power which would be about a 10% decrease in Q_0 at 16 MV/m. This increase in 2.0 K P_{diss} is consistent with simulations completed at SLAC and FNAL that predicted an increase of 0.2 W of P_{diss} at high power [6].

Since the coupler is adjustable, it is of interest to measure how Q_0 is affected by Q_{ext} while holding 15 MV/m. The coupler was adjusted between $Q_{ext} = 4 \times 10^7$ (1.8 kW for 15 MV/m) and 3×10^8 (230 W for 15 MV/m) and Q_0 was measured. These results are shown in Fig. 6. We can clearly see that there was no significant impact of Q_{ext} on Q_0 .

The final measurement conducted on HTC9-4 was a measurement of coupler heating and pressure while operating at high power for many hours. The cavity was tuned off

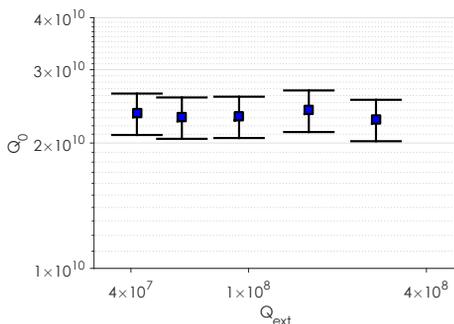


Figure 6: Q_0 vs Q_{ext} at 15 MV/m and 2.0 K for HTC9-4.

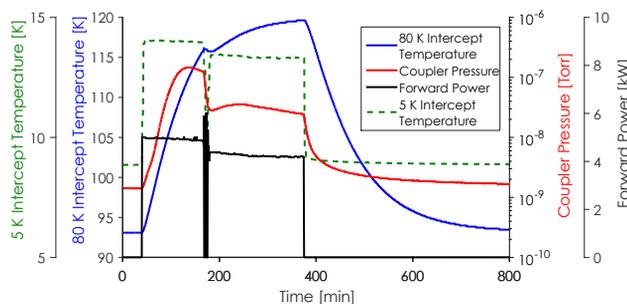


Figure 7: HPC pressure and temperatures of the 5 and 80 K intercepts for many hours of high power operation under full reflection. Also shown is the forward power.

resonance so that the coupler was under full reflection. We began by operating at 5 kW, however approximately 3 hours into the measurement, an RF trip occurred that was unrelated to the coupler. After this trip, forward power was 4 kW. Figure 7 shows the results of these measurements. The 5 K intercept reached a steady state value of 14 K within ten minutes. The 80 K intercept reached a steady state value of 120 K after approximately 6 hours. The coupler vacuum reached a maximum pressure of 1×10^{-7} Torr after 3 hours of operation and then began to decrease. No multipacting or vacuum events were observed in the coupler during these measurements.

CONCLUSIONS

A nitrogen-doped 9-cell cavity was tested in the Cornell HTC in order to demonstrate the feasibility of high Q_0 cavities for LCLS-II. It was found that a helium gas mass flow rate greater than 1 g/sec was sufficient to minimize residual resistance from trapped ambient fields. In HTC9-4, it was shown that the high power coupler had no negative impact on the Q_0 of the cavity. Cavity Q_0 was unaffected up to 3 kW and then had a slight decrease at higher forward powers, corresponding to about a 10% decrease in Q_0 at 16 MV/m and 2.0 K, consistent with coupler simulations. Q_{ext} also had no significant impact on Q_0 . Heating and pressure in the coupler was within specifications and no multipacting was observed during high power operation. These results show that the LCLS-II coupler is adequate for LCLS-II and does not inherently cause significant decreases in Q_0 with the Cornell cooling scheme.

Cornell plans to test one more fully assembled 9-cell nitrogen-doped cavity in the HTC for LCLS-II. For this fifth test, a cavity with significantly higher Q_0 in vertical test after dressing will be used which will provide an even clearer picture of the effect of the high power coupler on the LCLS-II cavity performance. Once this is completed, we will have a good picture of what performance to expect from the LCLS-II cavities. These measurements are another crucial step on the path to demonstrating readiness for LCLS-II.

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