CRYOMODULE TESTING OF NITROGEN-DOPED CAVITIES*

D. Gonnella†[1], B. Clasby[1], R. Eichhorn[1], B. Elmore[1], F. Furuta[1], M. Ge[1], A. Grassellino[2], C. Grimm[2], D. Hall[1], Y. He[1], G. Hoffstaetter[1], J. Holzbauer[2], J. Kaufman[1], P. Koufalis[1], M. Liepe[1], J.T. Maniscalco[1], O. Melnychuk[2], T. O'Connell[1], A. Palczewski[3], Y. Pischalnikov[2], C. Reece[3], P. Quigley[1], A. Romanenko[2], D. Sabol[1], W. Schappert[2], J. Sears[1], D. Sergatskov[2], E. Smith[1], and V. Veshcherevich[1]

[1]CLASSE, Cornell University, Ithaca, NY 14853, USA
[2]FNAL, Batavia, IL 60510, USA
[3]TJNAF, Newport News, VA 23606, USA

Abstract

The Linac Coherent Light Source-II (LCLS-II) is a new FEL x-ray source that is planned to be constructed in the existing SLAC tunnel. In order to meet the required high Q_0 specification of 2.7×10^{10} at 2 K and 16 MV/m, nitrogen-doping has been proposed as a preparation method for the SRF cavities in the linac. In order to test the feasibility of these goals, four nitrogen-doped cavities have been tested at Cornell in the Horizontal Test Cryomodule (HTC) in five separate tests. The first three tests consisted of cavities assembled in the HTC with high Q input coupler. The fourth test used the same cavity as the third but with the prototype high power LCLS-II coupler installed. Finally, the fifth test used a high power LCLS-II coupler, cavity tuner, and HOM antennas. Here we report on the results from these tests along with a systematic analysis of change in performance due to the various steps in preparing and assembling LCLS-II cavities for cryomodule operation. These results represent one of the final steps to demonstrate readiness for full prototype cryomodule assembly for LCLS-II.

INTRODUCTION

The Linac Coherent Light Source II (LCLS-II) is a new CW FEL that will be built in the existing SLAC tunnel. Due to requirements for high cryogenic efficiency, the SRF cavities in the machine will be prepared using nitrogen-doping [1]. A large collaborative effort has been undertaken between Fermilab, Jefferson Lab, and Cornell to research and develop the SRF technology for LCLS-II's main linac. The final step before building prototype cryomodules was a serious of single-cavity cryomodule tests at the three labs. This paper will discuss the results of five cryomodule tests in the Cornell Horizontal Test Cryomodule (HTC). The HTC is a full cryomodule capable of holding a single 9-cell cavity. Its design is very similar to the design for the full LCLS-II main linac cryomodule. For details on the HTC and it's adaption to use LCLS-II cavities, see [2].

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† dg433@cornell.edu

ORGANIZATION OF CRYOMODULE TESTS

A total of five cryomodule tests were completed at Cornell. These represent a systematic study of the SRF technology to be used in the LCLS-II main linac cryomodules. Of the five tests, four different cavities were used. Details on the cavities and the tests are shown in Table 1. These tests were organized in such a way to first test the feasibility of the high Q_0 specification (by installing with High Q input couplers), then to test the LCLS-II high power coupler (by measuring potential degradation as a result of the coupler installation on a previously tested cavity), and finally to test a fully dressed cavity with LCLS-II coupler and tuner. The results here are broken up by main topic rather than by each tests: changes from vertical to horizontal test, coupler studies, tuner studies, and cool down and flux trapping studies.

CHANGES FROM VERTICAL TO HORIZONTAL TEST

There is much concern in differences in how a cavity performs when tested vertically versus horizontally. Since assembly in cyomodule is much more difficult and involved that assembly on a vertical test stand, it has been widely accepted that some loss in cavity Q_0 will occur. Here we present a systematic look at how cryomodule assembly affects Q_0.

HTC9-1

The first HTC test consisted of a cavity dressed in an ILC helium vessel and assembled with high Q input coupler. The purpose of this test was to check the feasibility of meeting the LCLS-II Q_0 specifications after an assembly in cryomodule. The Q_0 vs E performance of the cavity at 2.0 K before dressing in vertical test and after assembly in the HTC is shown in Fig. 1. Before dressing, the cavity quenched at 15 MV/m at a Q of (3.5 ± 0.4)×10^{10}. After dressing and assembly in the HTC, the cavity quenched at 14 MV/m with a Q_0 of (3.2 ± 0.3)×10^{10}. This drop in Q_0 was attributed to a 1 ± 0.1 nΩ increase in residual resistance.

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Table 1: Summary of HTC Tests

Test	HTC9-1	HTC9-2	HTC9-3	HTC9-4	HTC9-5
Cavity	ACC012	AES011	AES018	AES018	AES031
Prepared by	FNAL	FNAL	Cornell	Cornell	JLab
Q_0**(2 K, 16 MV/m)**$\times 10^{10}$	3.2 ± 0.3[1]	2.7 ± 0.3	2.3 ± 0.2	2.3 ± 0.2	2.4 ± 0.2[2]
Quench Field [MV/m]	14	18	18	18	Limited by HOM multipacting
Coupler	High Q	High Q	High Q	LCLS-II	LCLS-II
Helium Vessel	ILC	ILC	LCLS-II	LCLS-II	LCLS-II
Other					Tuner, HOM antennas installed

[1] Q_0 given at 14 MV/m due to quench.
[2] Q_0 given at 5 MV/m due to large Q slope from multipacting in HOM can.

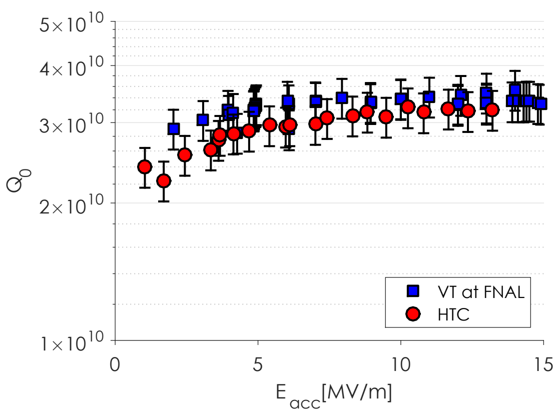

Figure 1: Q_0 vs E perfomance at 2.0 K before and after assembly in the HTC for HTC9-1 (ACC012).

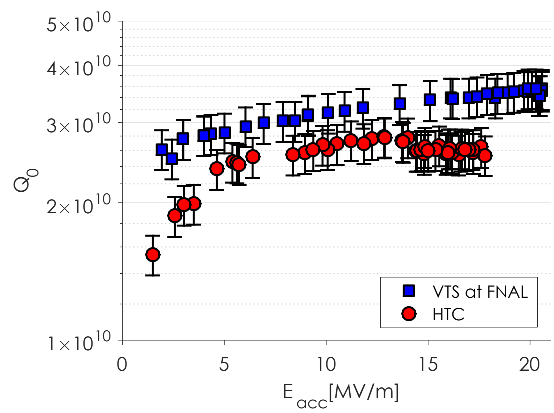

Figure 2: Q_0 vs E perfomance at 2.0 K before and after assembly in the HTC for HTC9-2 (AES011).

HTC9-2

In the second test in the HTC, a cavity was again assembled in an ILC helium vessel with high Q input coupler. The Q_0 vs E performance at 2.0 K before dressing in vertical test and after assembly in the HTC is shown in Fig. 2. Before dressing, the cavity quenched at about 20 MV/m, with a Q_0 of $(3.4 \pm 0.3)\times10^{10}$ at 16 MV/m. After dressing and HTC assembly, the cavity quenched at 18 MV/m with a Q_0 of $(2.7 \pm 0.3)\times10^{10}$ at 16 MV/m. This drop in Q_0 was attributed to an additional residual resistance of 2 ± 0.2 nΩ.

HTC9-3 and HTC9-4

The third and fourth HTC tests used the same cavity, dresed in an LCLS-II helium vessel first with high Q input coupler and second with high power LCLS-II input coupler. For this cavity, a systematic study was conducted in which the cavity was vertically tested both before and after dressing and then in the HTC with and without high power input coupler. The Q_0 vs E results for these tests are shown in Fig. 3. Before dressing, the cavity reached a Q_0 of $(3.0\pm0.3)\times10^{10}$ at 16 MV/m and a quench field of 20 MV/m. After dressing, in vertical test, the cavity Q_0 dropped to $(2.2 \pm 0.2)\times10^{10}$ at 16 MV/m, an increase in residual resistance of 3 nΩ. After assembly in the HTC, the cavity performance remained unchanged both with and without high power input coupler. The change in residual resistance in the first four tests

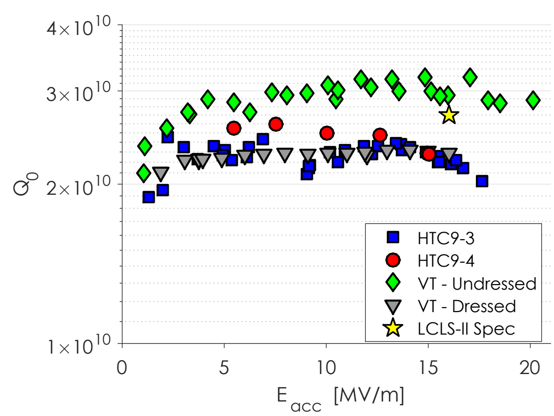

Figure 3: Q_0 vs E perfomance at 2.0 K before and after assembly in the HTC for HTC9-3 and HTC9-4 (AES018).

has been attributed to excessive HPR on the three cavities leading to lossy oxide growth. It is important to note that the cryomodule assembly itself and use of the high power coupler resulted in no additional degradation to cavity Q_0.

HTC9-5

The fifth and final HTC test was completed with a cavity assembled in an LCLS-II helium vessel, a high power LCLS-II input coupler, tuner, and HOM antennas. This test

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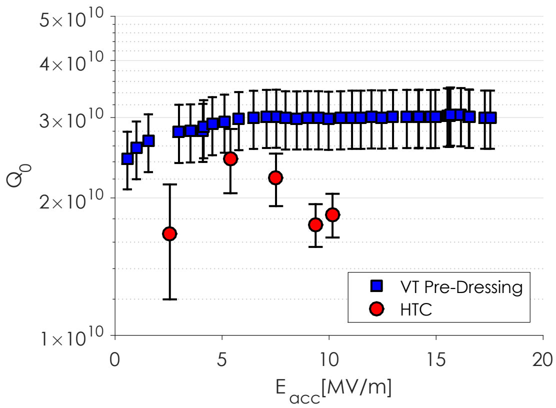

Figure 4: Q_0 vs E perfomance at 2.0 K before and after assembly in the HTC for HTC9-5 (ACC031).

represented a fully dressed cavity as it would be in a true accelerator. The Q_0 vs E results for this test and of the cavity before dressing are shown in Fig. 4. Before dressing, the cavity reached a Q_0 of $(3.0 \pm 0.3)\times10^{10}$ at 16 MV/m and 2.0 K. After assembly in the HTC the cavity was limited by strong heating in one of the HOM cans most likely due to multipacting. There was also a short in this HOM antenna between the F-part of the antenna and the output pickup. This should normally be capacitive coupling. This resulted in a large Q slope and ultimately limited the field in the cavity to 10 MV/m with a Q_0 of $(1.8 \pm 0.2)\times10^{10}$.

COUPLER STUDIES

Fundamental studies on the LCLS-II high power coupler were conducted during HTC9-4 and HTC9-5. In both cases the coupler was cooled by 5 K and 80 K helium gas. HTC9-4 measurements focused on the effect of the coupler on the cavity Q_0. Figure 5 shows a measurement of Q_0 vs forward power at 10 MV/m. The cavity was detuned slightly off resonance and the forward power increased to maintain a constant accelerating field in the cavity. Q_0 was constant at $(2.7\pm0.3)\times10^{10}$ up to 3 kW. Above 3 kW, the Q_0 dropped to $(2.3\pm0.2)\times10^{10}$. For more details on this study see [3].This drop corresponds to âĹij 0.3 W increase in dissipated power which would be about a 10% decrease in Q_0 at 16 MV/m.

During HTC9-5 coupler heating was measured at 4.4 kW in full reflection. Coupler heating on the 80 K and 5 K system is shown in Fig. 6. Heat loads on the 5 K and 80 K system were also measured. This was done by first calibrating to a heater that was placed on the inlet gas to the coupler for both cooling gas systems. It was found that the 5 K system experienced a 0.6 W dynamic heat load and the 80 K system a 7.2 W dynamic heat load at 4.4 kW in full reflection. These results suggest significantly lower dynamic heat loads than have been observed in similar tests at FNAL and in coupler simulations [4].

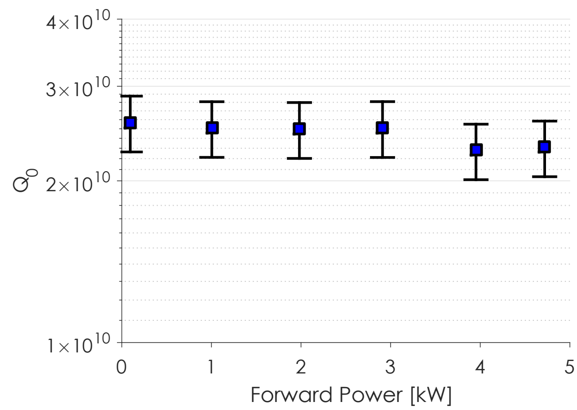

Figure 5: Q_0 at 10 MV/m vs forward power during HTC9-4. Q_0 was unaffected up to 3 kW after which it slightly dropped.

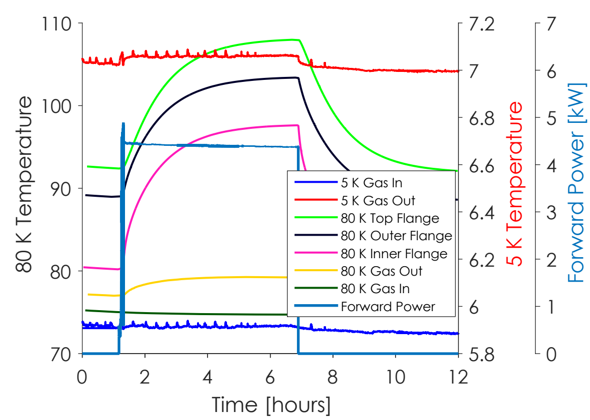

Figure 6: Plot of coupler heating on the 5 K and 80 K system. Note that the coupler in the HTC was cooled with 5 and 80 K gas whereas LCLS-II will use thermal straps to cool the couples.

TUNER STUDIES

The installed tuner includes piezoelectric stacks in series with the slow tuning mechanism to provide fast tuning. Piezo transfer functions and amplitude transfer functions were measured. While the cavity resonance was tracked by phase lock loop, the drive amplitude was modulated by 5% at a modulation frequencies from 1 to 1000 Hz. For full description of tuner results see [5].

HOM COUPLER MEASUREMENTS

HTC9-5 was limited in field and Q_0 due to a short and multipacting in one of the HOM cans. Above 8 MV/m, the Q_0 dropped significantly and the coupler side HOM can showed large heating. This heating reached higher than 40 K at 12 MV/m and resulted in the beam tube warming close to T_c. Heating on the HOM can as a function of E_{acc}^2 is shown in Fig. 7. Fields higher than 12 MV/m could not be reached: as the power was increased, the field stayed the same, a clear symptom of multipacting.

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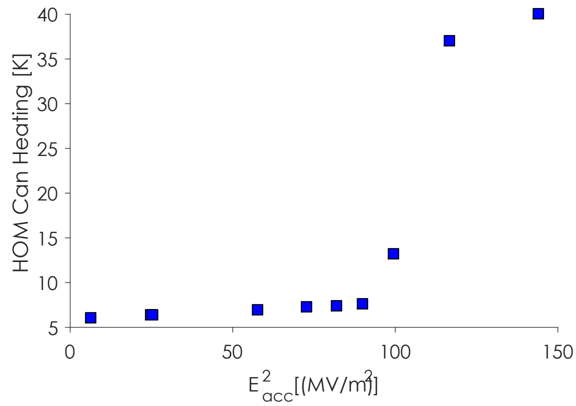

Figure 7: Heating on the HOM can during HTC9-5. This is a clear symptom of multipacting. The highest point was not in steady state since temperatures got too high and the power was administratively turned off.

COOL DOWN AND FLUX TRAPPING STUDIES

Fast cool down has been shown to be necessary for good performance in nitrogen-doped cavities [2, 6], but the details of the cool down are critical, especially for cavities assembled horizontally. The differences in how a cavity in the two helium vessels (ILC and LCLS-II) cool down was systematically studied. The ILC vessel has one helium input port below cell 3 and a chimney above cell 2. The LCLS-II helium vessel has two helium inlet ports symetrically placed below cells 3 and 7 and a chimney in the center. Table 2 summarizes the way in which the two helium vessels cool down. Figure 8 shows a typical cool down for the LCLS-II vessel. It was found that the ILC vessel cooled one side very quickly, resulting in large longitudinal spatial temperature gradients which in turn led to additional magnetic fields from thermal currents. The LCLS-II vessel on the other hand cooled both sides very uniformly leading to large transverse spatial temperature gradients and significantly smaller longitudinal gradients relative to the vertical temperature gradients. This means that even the LCLS-II vessel can reach larger transverse temperature gradients without significant increase in the longitudinal gradients. It has been shown that large transverse spatial temperature gradients are necessary for sufficient flux expulsion in nitrogen-doped cavities [2]. Large transverse temperature gradients can be achieved by increasing the helium mass flow during cool down. This effect can be seen clearly in Fig. 9 in which an uniform external magnetic field was applied to HTC9-3 and residual resistance measured for different applied magnetic fields. It was found that larger helium gas flow led to less residual resistance. With no applied field, helium mass flow above ~1 g/sec was sufficient to reach high Q_0.

Table 2: Cooling of ILC vs LCLS-II Helium Tanks. The order of cavity cell cooling is shown. Lower numbers, implies faster cooling. Also shown in the maximum spatial temperature gradients when the first part of the cavity goes through T_c.

Tank Type	ILC	LCLS-II
Cell 1 Bottom	2	2
Cell 1 Top	4	6
Cell 5 Bottom	1	1
Cell 5 Top	3	4
Cell 9 Bottom	N/A	3
Cell 9 Top	5	5
Typical ΔT_{long} [K]	~ 9	~ 7
Typical ΔT_{trans} [K]	~ 16	~ 31

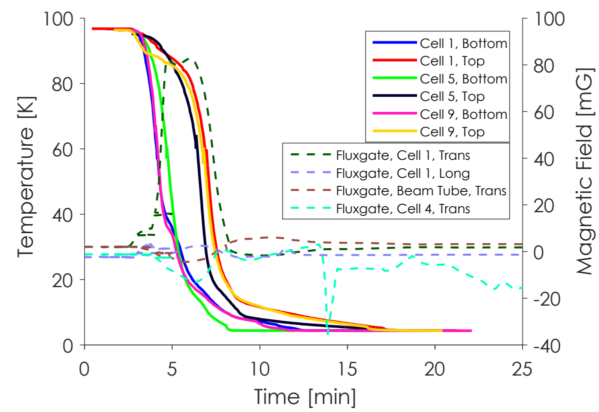

Figure 8: A typical cool down for the LCLS-II helium vessel.

CONCLUSIONS

Four cavities were tested in five separate tests at Cornell in the HTC. From these tests we learned many important lessons. Firstly, assembly in a cryomodule does not inherently lead to an increase in residual resistance. The first three cavities did show an increase in residual resistance but this

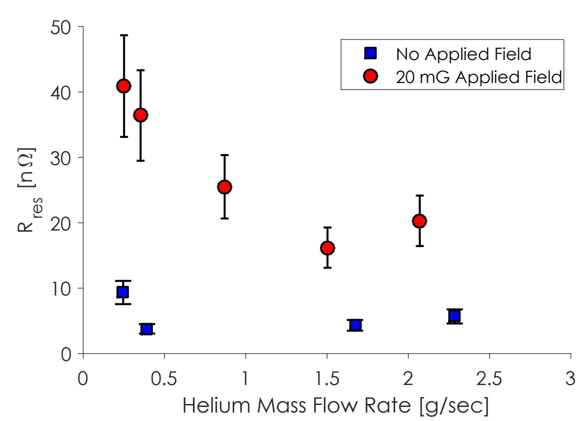

Figure 9: Residual resistance vs helium mass flow rate in an applied external magnetic field of 20 mG and no external magnetic field. Larger mass flow rate resulted in less residual resistance due to more efficient flux expulsion.

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was due to excessive HPR resulting in lossy oxides on the surface, not related to assembly in the HTC. Secondly, the high power input coupler does not have a negative impact on the Q_0 of the cavity. Thirdly, large transverse spatial temperature gradients are necessary for efficient flux expulsion and high Q_0 in nitrogen-doped cavities. Ultimately, helium mass flow rates above 1 g/sec were sufficient to reach the highest possible Q_0. Finally, the LCLS-II helium vessel cools cavities in such a way to maximize transverse temperature gradients (good for flux expulsion) while minimizing longitudinal temperature gradients (good for minimizing additional magnetic fields from thermal gradients).

These results are very promising for the feasibility of SRF technology for LCLS-II. The lessons learned here are sufficient for understanding mechanisms behind high Q_0 performance in nitrogen-doped cavities in cryomodule and represent a crucial step on the way to building a full prototype cryomodule for LCLS-II.

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