VERTICAL TEST RESULTS FOR THE LCLS-II 1.3 GHz FIRST ARTICLE CAVITIES

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Abstract

The LCLS-II project requires 35 1.3 GHz cryomodules to be installed in the accelerator in order to deliver a 4 GeV electron beam to the undulators hall. These 35 cryomodules will consist of 8 1.3 GHz TESLA style SRF cavities, a design most recently used for the XFEL project in Hamburg, Germany. The cavity design has remained largely unchanged, but the cavity treatment has been modified to utilize the nitrogen doping process to allow for Quality factors in excess of $3x10^{10}$ at 16 MV/m, the designed operating gradient of the cavities in the CM at 2.0K. Two European vendors are producing most of the SRF cavities for these cryomodules; and the performance of the first article cavities, 16 from each vendor, will be reported on in this paper.

INTRODUCTION

The Linac Coherent Light Source II (LCLS-II) is a 4 GeV CW X-ray free electron laser (FEL) driven by a superconducting RF linac [1, 2]. It is being built to upgrade the capabilities of the current LCLS, a normal conducting FEL that has been in operation at SLAC since 2009. The original LCLS layout in the tunnel along with the LCLS-II accelerator is shown in Fig. 1. The LCLS-II upgrade will be complementary to LCLS as both accelerators will continue to provide x-rays to the existing near and far experimental halls, albeit not at the same time in the current operational plan. The upgrade to LCLS-II will expand the operational range of the FEL complex by providing X-ray pulses at up to 1 MHz repetition rate, an increase from the 120 Hz of LCLS, and covering the spectral range from 0.2-1.2 keV and 1-5 keV through two new undulator systems.

The LCLS-II project has a very tight schedule, 6 years from design through delivery of first beam. In order to accomplish everything that is required to design, build, install and commission a new accelerator in such a short period of time a collaboration between 6 Institutions in the United States has been established. Five Department of Energy (DOE) Laboratories, SLAC, LBNL, Argonne, FNAL and JLab, are each lending their expertise in their respective fields along with Cornell University providing their knowledge of superconducting RF as well as development of an alternative injector for LCLS-II. In the context of this paper the primary contributors are JLab, FNAL and SLAC providing the superconducting RF accelerator components necessary to drive LCLS-II.

THE ACCELERATOR

The superconducting RF (SRF) linac that will drive LCLS-II is made up of 35 – 1.3 GHz cryomodules and 2 - 3.9 GHz cryomodules. Each cryomodule contains 8 superconducting RF cavities. The 1.3 GHz cavities are based on the TESLA design, most recently used for XFEL, and have been modified for CW operation[3]. The preparation of the cavities has also been modified to incorporate the "High-Q_0 recipe" that utilizes nitrogen doping that can improve the Q_0 of the cavities by roughly a factor of 3 at the operating gradient of 16 MV/m. The downside of the nitrogen doping is that the cavities are more susceptible to trapping magnetic flux during cooldown, thus necessitating a much more strict ambient magnetic field requirement in both the vertical testing dewar and in the cryomodule[4-6].

The modifications for CW operation have included modifying the XFEL/TTF-III fundamental power coupler to handle the larger c.w. heat load, enlarging the exhaust chimney of the helium vessel to handle the larger dynamic heat load from the cavity, installing 2 cryogenic fill lines to improve the cooldown process and installing 2 layers of magnetic shielding to better achieve the stringent magnetic hygiene requirements that result from using the high Q_0 recipe.

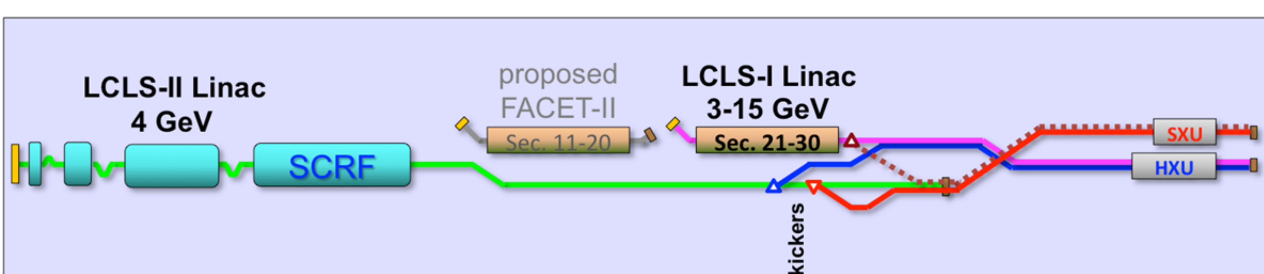

Figure 1: The LCLS-II Linac layout in the tunnel along with the existing LCLS accelerator.

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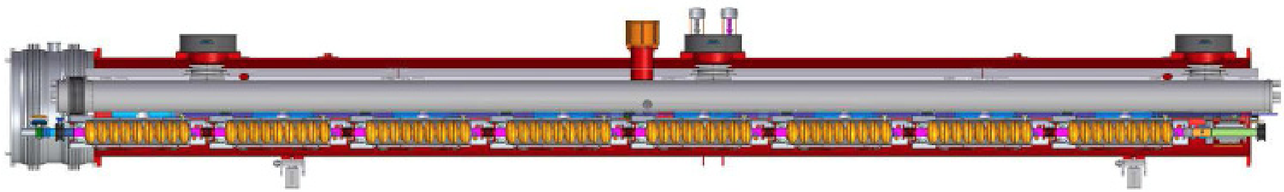

Figure 2: The LCLS-II 1.3 GHz Cryomodule.

THE 1.3 GHz CAVITIES

The 35 1.3 GHz cryomodules for LCLS-II are being assembled and tested at Jefferson Lab and Fermilab prior to delivery to SLAC for installation. Two prototype cryomodules were built using cavities from the ILC project while the balance of the 33 CMs are being built with cavities produced by Research Instruments (RI) and Ettore Zanon (EZ). As part of the vendor qualification each vendor was sent 2 previously tested cavities in order to demonstrate that they could properly carry out the nitrogen doping, a process that had never been done by a vendor before. These 4 cavities were doped at the vendors utilizing the standard 800°C “2/6” process and returned to the labs where they were tested[7]. The results from both vendors were positive and demonstrated that the modifications they had made to their heat treatment furnaces could produce nitrogen doped 1.3 GHz cavities. The fabrication of cavities was not part of the vendor qualification as both vendors had each produced 400 cavities for XFEL and the cavity geometry was largely unchanged.

In order to ensure the vendors entire fabrication processes had not adversely affected the performance of the cavities each vendor was asked to first produce 16 “First Article” cavities that would be used to qualify their overall process and performance. This was also used as a gating mechanism to release them for the balance of production of the 133 cavities each was responsible for delivering. RI began shipping cavities a few months before EZ due to material availability and schedule constraints.

The Q vs E plots for the first articles from EZ and RI can be seen in Figs. 3 and 4 respectively.

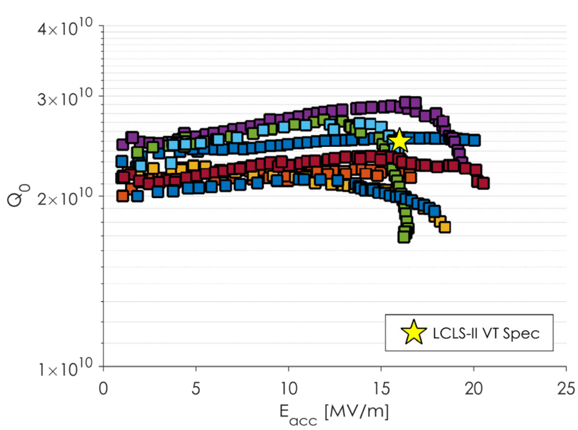

Figure 3: The Q vs. E curve for the first article cavities from EZ.

From these plots the first thing that is apparent is that only about 50% of the cavities meet the LCLS-II spec. This was immediate cause for alarm when testing began and multiple investigations into possible causes of this poor performance were launched since the prototype cavities had no problem meeting the specification. One of the items under investigation was the base material from which the cavities were formed and how the flux trapping of this material compared to the material from which the prototype cavities had been built.

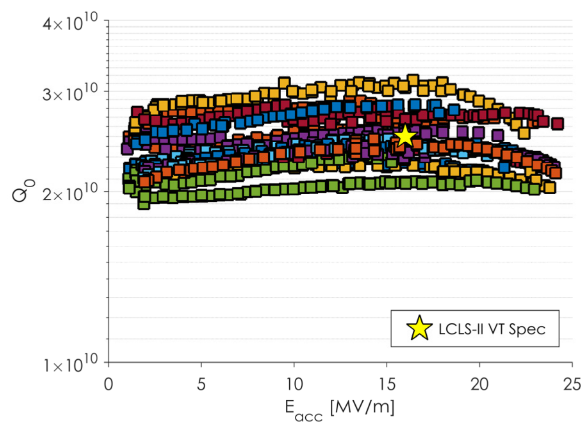

Figure 4: The Q vs. E curve for the 16 first article cavities from RI.

As the material in question was from 3 different vendors, 1 for the prototype and 2 for production, a significant effort was mounted to understand the data. The nitrogen doping process produces 1.3 GHz cavities that are capable of reaching Q_0 >3.0e10 at 16 MV/m, but come with the trade off that they are up more susceptible to trapping magnetic flux during cooldown through the lambda point. This susceptibility is up to 3.6 times higher than for an un-doped cavity[8]. The simple equation to explain the flux trapping contribution, and its effect on cavity performance is shown below as an extrapolation of the standard equation for cavity Q:

$$Q = \frac{G}{R_s}$$

$$where\ \ G\ is\ the\ cavity\ geometric\ factor\ and$$

$$R_S = R_{BCS} + R_0 + R_{TF}$$

$$where\ R_{TF} = S * \eta * B_{ambient}$$

$$s = sensitivity\ to\ magnetic\ field\ and$$

$$\eta = flux\ expulsion\ efficiency$$

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From the equation above one can see that two main factors can affect the cavity Q_0, the intrinsic resistance R_0, and the trapped flux R_{TF}. For the first article cavities the concern was initially focused on the trapped flux in the material causing the decrease in performance. However after performing several tests at various temperatures and remnant magnetic field levels the trapped flux contribution was determined and found that it alone could not account for all of the additional losses. It turns out the intrinsic residual resistance component was significantly higher for the production material than for the prototype (pCM) cavities with the standard chemical processing recipe. The difference in performance for the prototype vs. first article cavities is shown in table 1.

Table 1: The resistance contribution and expected Q_0 value to the pCM and first article cavities.

Parameter	pCM Material	First Articles
R_{BCS}	~4.5 nΩ	~4.5 nΩ
R_0	~2 nΩ	~5 nΩ
R_{TF}	1.4*(<0.2)*B	1.4*(<0.7)*B
Q_0 for B = 1 mG	$4x10^{10}$	$2.6\ x10^{10}$
Q_0 for B = 5 mG	$3.4x10^{10}$	$1.9\ x10^{10}$

Following these findings a program was launched to improve the performance of the production cavities. This resulted in 2 key process changes. First the bulk electropolishing removal was increased from 140 µm to 200 µm and the heat treatment temperature was raised from 800°C to 900°C. Time did not allow for a detailed decomposition of the relative effect of each of these changes, but in the end the cavity performance increased significantly and the magnetic field susceptibility decreased. Single cell test data suggests the intrinsic resistance was aided by the increase in electropolishing while the increase in heat treatment temperature helped reduce the susceptibility to trapped flux. Further research to better understand how the cavity performance is impacted by material properties when nitrogen doped will be carried out to better understand the phenomena seen here.

One of the other items that was investigated was the impact of niobium grain size and hardness of the sheet material that was used to cavity Q_0. As received only the material hardness of every sheet was recorded, the grain size was only measured on the hardest and softest sheet in each lot, so much of this data is not available. Figure 5 shows the average material hardness for each of the first article cavities produced by both RI and EZ. This material was provided from the 2 different material vendors, and all of the material met or exceeded the project specifications. Figure 6 shows the Q_0 measured at 16 MV/m for all of the first article cavities that were tested and a slight variation in Q_0 can be seen between the two vendors. From this data alone it is hard to draw any strong conclusions about the first article performance being directly attributed to material hardness, but further evaluation of cavities beyond the scope of this paper has shown that there is indeed a significant effect. It should also be noted that the first article cavities from EZ used the hardest sheet material that was procured for the project.

Following the first article production run and the changes to the processes cavity Q_0 did improve significantly and now routinely exceeds 3e10 at 16 MV/m.

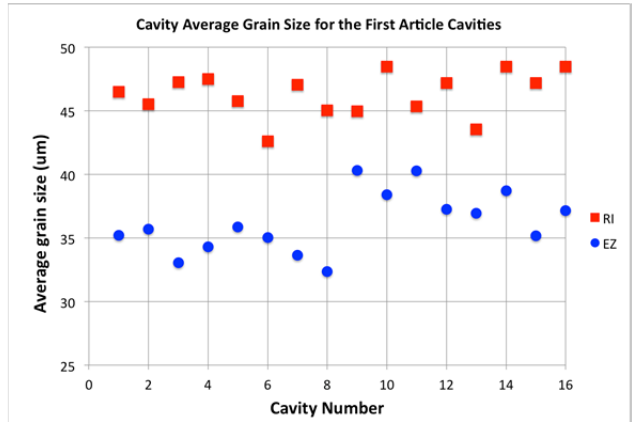

Figure 5: The material hardness of the first article cavities from RI and EZ.

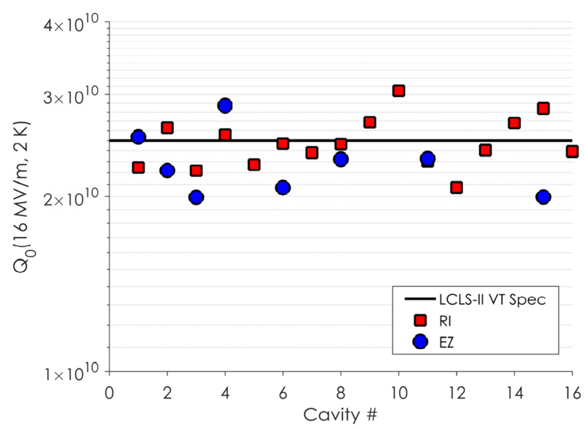

Figure 6: The Q_0 measured at 16 MV/m for each of the first article cavities that were tested from the 2 vendors.

CONCLUSION

The original LCLS-II recipe for nitrogen doping produced cavities that did not all meet the Q_0 requirement. Changes to the recipe following the first article production led to significant improvements in Q_0. It is suspected that the material grain size and hardness play a stronger role in the performance of nitrogen doped cavities compared to those treated with standard electropolishing. The gradient reach for these cavities all exceeded the specification.

ACKNOWLEDGMENT

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