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THE LCLS-II HE HIGH Q AND GRADIENT R&D PROGRAM*

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Abstract

The LCLS-II HE project is a high energy upgrade to the superconducting LCLS-II linac. It consists of adding twenty additional 1.3 GHz cryomodules to the linac, with cavities operating at a gradient of 20.8 MV/m with a Q_0 of $2.7{\times}10^{10}$. Performance of LCLS-II cryomodules has suggested that operations at this high of a gradient will not be achievable with the existing cavity recipe employed. Therefore a research program was developed between SLAC, Fermilab, Thomas Jefferson National Accelerator Facility, and Cornell University in order to improve the cavity processing method of the SRF cavities and reach the HE goals. This program explores the doping regime beyond what was done for LCLS-II and also has looked to further developed nitrogen-infusion. Here we will summarize the results from this R&D program, showing significant improvement on both single-cell and 9-cell cavities compared with the original LCLS-II cavity recipe.

INTRODUCTION

LCLS-II HE will add an additional 20 cryomodules to the superconducting LCLS-II linac. The SRF cavities in these cryomodules will operate at an average gradient of 20.8 MV/m. Together with increasing the LCLS-II average operating gradient from 16 to 18 MV/m, this will enable the combined LCLS-II and HE linac to provide electron energies up to 8 GeV. For qualificatin for string assembly, cavities must reach a Q_0 of $2.7{\times}10^{10}$ at 21 MV/m and a quench field of at least 23 MV/m in vertical test. LCLS-II nitrogen-doping results have suggested average gradients of ~23 MV/m, with significant spread [1]. While the average, LCLS-II cavity meets HE requirements, ~40% of the cavities do not. Therefore, an R&D program was developed to further push the boundaries of nitrogen-doping and improve cavity gradient reach while maintaining high Q_0.

NITROGEN-INFUSION

Nitrogen-infusion is similar to nitrogen-doping but involves treating a cavity at lower temperatures in a nitrgen atmosphere. Typically this is done at temperatures below 200°C. Unlike nitrogen-doping, infusion does not require a final electropolish to remove nitrides, as none are formed. Infusion has been shown to produce cavities with high Q_0 and very high gradients, upwards of 45 MV/m [2]. Cornell University pursued nitrogen-infusion to be potentially used by LCLS-II HE. Three cavities were treated. A summary of the treatments is shown in Table 1 and the Q_0 vs E_{acc} results for these three cavities are shown in Fig. 1.

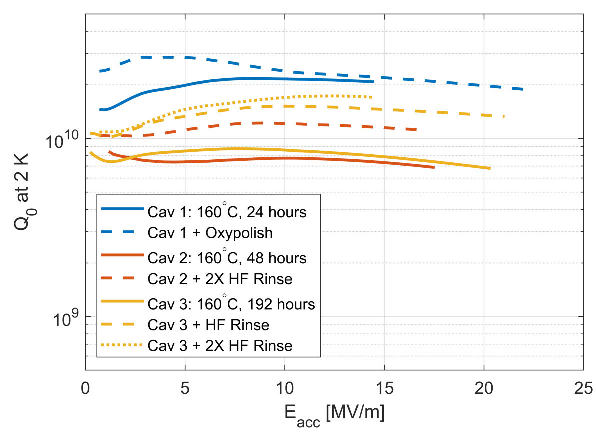

Figure 1: Q_0 vs E_{acc} performance for the three cavities prepared with nitrogen-infusion at Cornell. Contamination in the furnace led to high residual resistance which limited the Q_0.

Nitrogen-infusion is highly sensitive to contamination in the UHV furnace due to the lack of final EP after furnace treatment. Unfortunately, contamination in the Cornell furnace resulted in higher than expected residual resistance (R_{res}), as can be seen by the low Q_0 in Fig. 1. Due to this, additional treatments (HF rinse and Oxypolishing) were done on the cavities, in hopes of removing the contamination. Unfortunately, these subsequent treatments did not improve the cavity performance significantly.

The issues that manifested in the Cornell furnace highlight an intrinsic fallback of nitrogen-infusion. Since LCLS-II HE will use vendor furnaces to treat the cavities, the level of contamination in the furnaces is difficult to control. In principle, this risk could be mitigated by extensive oversight of the vendors' furnaces or having a designated furnace for infusion work. In practice however, this is not likely to be

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Table 1: Summary Of Nitrogen-infusion Treatments Carried Out By Cornell. Subsequent treatment refers to additional treatment that the cavity received after initial RF test.

Cavity	Infusion Temperature [°C]	Infusion Time [hrs]	Subsequent Treatment
Cavity 1	160	24	Oxypolish
Cavity 2	160	48	2x HF Rinse
Cavity 3	160	192	HF Rinse, 2nd HF Rinse

cost effective. Therefore, the R&D program abandoned the infusion work and focused on improving nitrogen-doping.

NITROGEN-DOPING IMPROVEMENT

Nitrogen-doping consists of heat treating a SRF cavity at high temperatures (typically 800°C) in a nitrogen atmosphere. LCLS-II cavities were prepared with the so-called 2/6 nitrogen-doping recipe, 2 minutes at 800°C in 25 mTorr of N_2 followed by 6 minutes in vacuum [3]. While nitrogen-doping consistently produces cavities with high Q_0, there is also, on average, a drop in quench field. This drop has been shown to be correlated with doping level, i.e. heavier dopings leading to lower quench fields [4]. Therefore, two parallel paths were explored in order to improve the gradient reach of nitrogen-doped cavities:

1. Light dopings, to produce cavities with higher mean free paths than LCLS-II cavities

2. Longer anneal times, to produce a very uniform doped layer

These two paths were pursued at FNAL and JLab on single-cell cavities.

Single-Cell Work

FNAL pursued a 2/0 doping, in which the cavity is doped for two minutes at 800°C and immediately cooled with no anneal. The choice of this recipe was based on expectations of increasing the mean free path of the doped layer leading to higher quench fields based on previous results [4]. Results from single-cell cavities prepared with the 2/0 recipe are shown in Fig. 2. As can be seen, all single-cell cavities exceeded the LCLS-II HE specifications. An average increase of ~2 MV/m compared with the average LCLS-II performance was noted.

Both FNAL and JLab pursued the 3/60 doping, in which the cavity is doped for three minutes at 800°C and then annealed in vacuum for 60 minutes. This recipe was motivated by the desire to create a very uniform and deep doped layer which could potentially reduce nanohydrides and remove the sensitivity of performance on the exact final EP amount [5]. Single-cell cavity Q_0 vs E_{acc} performance is given in Fig. 3. Performance of these cavities was excellent, with nearly all cavities exceeding gradients of 30 MV/m. Q_0 performance was also stellar, with one cavity reaching a Q_0 of more than 6×10^{10} at 21 MV/m and 2 K.

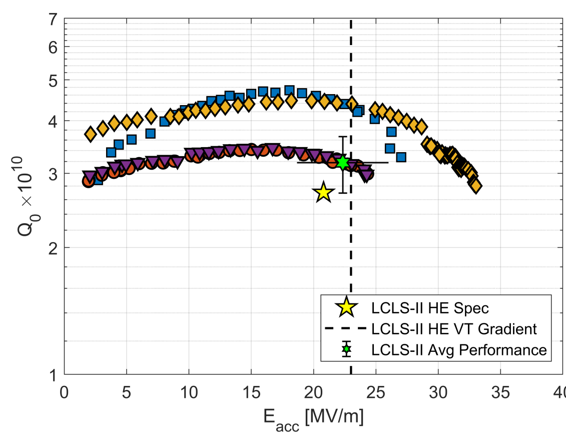

Figure 2: Q_0 vs E_{acc} results for single-cell cavities prepared with the 2/0 recipe. Also, shown is the average LCLS-II cavity performance. All single-cell cavities prepared exceed the LCLS-II HE specification.

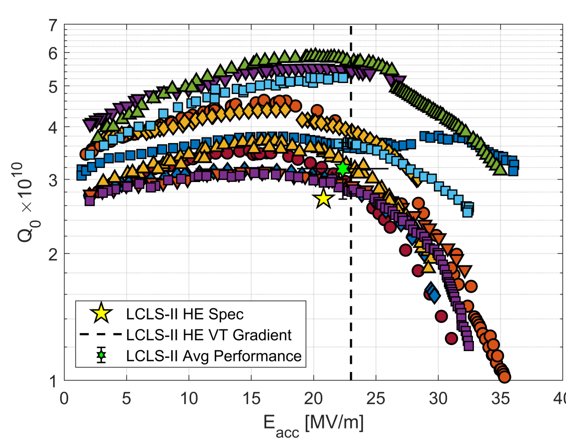

Figure 3: Q_0 vs E_{acc} performance for single-cell cavities treated with the 3/60 recipe. Excellent performance was achieved, with some Q_0 as high as 6×10^{10} at 2 K.

9-Cell Work

In light of the excellent single-cell performance outlined in the previous section and in Figs. 2 and 3, the two candidate recipes were applied to a variety of 9-cell cavities. Three 9-cell cavities were provided by FNAL and an additional 16 9-cell cavities from the end of LCLS-II production were used. The four prepared at FNAL were treated with the 2/0 recipe, while the 16 were divided in the following way:

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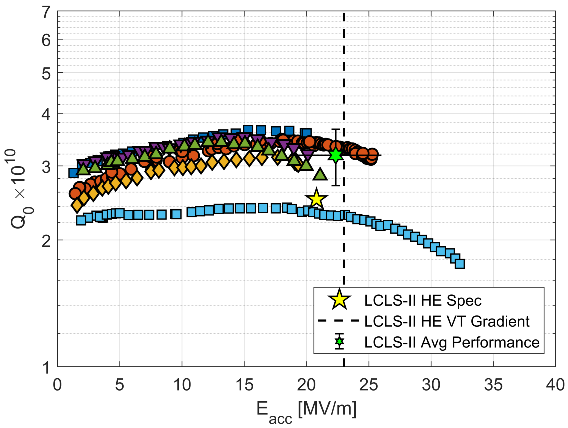

Figure 4: Q_0 vs E_{acc} performance of the 9-cell cavities treated with the 2/0 recipe.

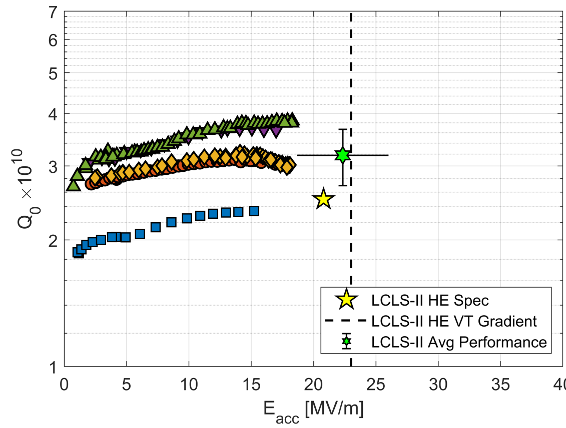

Figure 5: Q_0 vs E_{acc} performance of the 9-cell cavities treated with the 3/60 recipe.

- 4 cavities prepared with the standard LCLS-II recipe (2/6)
- 4 cavities prepared with the 2/0 recipe and the standard LCLS-II 5-7 μm nominal light EP
- 8 cavities prepared with the 3/60 recipe and a light EP of 7-9μm

Unfortunately, the performance of the 9-cell cavities was not as excellent as the single-cell cavity performance. The full results of the 20 cavities prepared are shown in Table 2. The Q_0 vs E_{acc} performance for the 2/0 cavities and 3/60 cavities is shown in Figs. 4 and 5, respectively.

The cavities prepared with the 2/0 recipe at FNAL showed moderate performance. Two of the cavities (CAV0017 first test and CAV0018) were limited by low field quench in only cell 1. All other cells quenched above 25 MV/m [6]. Incidently cell 1 was the cell closest to the nitrogen inlet in the furnace. Flipping CAV0017 so that cell 1 was further from the inlet resulted in the cavity quenching above 25 MV/m but still limited in the cell closest to the inlet (cell 9 in this case). Investigations into this phenomenon are currently underway.

The last 32 cavities from the end of LCLS-II production which were used for 9-cell studies were fabricated by Zanon (EZ), bulk EP'd by EZ, heat treated and doped by RI, and final EP'd by EZ. This was different from the rest of LCLS-II production in which each cavity vendor treated their own cavities in their own furnace. Furnace contamination at EZ, which manifested near the end of LCLS-II cavity production, resulted in them using RI as a subcontractor for the heat treatment and doping cycles. Of these 32 cavities, 16 were the ones used for the HE R&D studies. These 16 cavities all performed worse than expected based on the single-cell results.

LCLS-II cavities, prepared with the 2/6 recipe, had an average quench field of ~23 MV/m and it was expected that this performance would be the baseline performance for the last 16 cavities. However, as is shown in Fig. 6, there is a clear downward shift in the quench fields of the last cavities

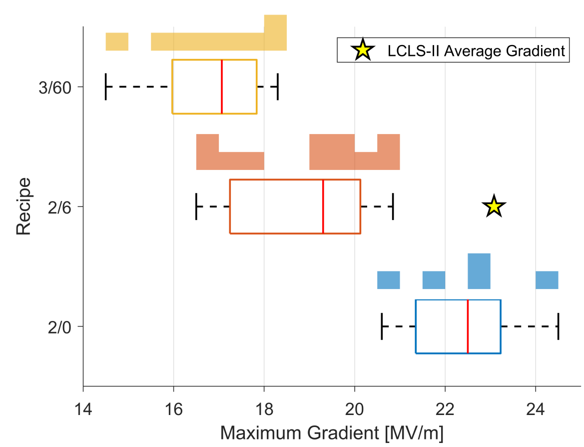

Figure 6: A comparison of the quench fields for 9-cell cavities prepared with the three different recipes at the cavity vendors. 2/6 Baseline performance was significantly worse than the average LCLS-II performance. The 2/0 recipe demonstrated an average increase of 3 MV/m with respect to the 2/6 recipe. The colored bars show histograms of the results, overlaid with the boxplot. The scale for each of the histograms are the same.

regardless of recipe. The 3/60 was affected the worst, and the 2/0 the least, but even the 2/6 baseline cavities performed 3-4 MV/m lower than the average LCLS-II performance. This suggests that there was a fundamental issue with the cavity fabrication, heat treatment, EP, or some combination of those factors. Additionally, the cavities were treated at different temperatures prior to the doping stage to account for differences in flux expulsion. As described in [1], quench fields have been shown to be degraded when cavities are treated at 975°C in RI's furnace. This further confounds the data.

Optical inspection of the inside of four of the cavities showed clear weld issues and defects, likely due to improper weld stackup procedures, see Fig. 7. EZ had previously suffered from similar issues at the beginning of LCLS-II

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Table 2: Preparation And Results Of The 9-Cell Cavities Treated As Part Of The HE R&D Program

Cavity	Heat Treatment Temperature [°C]	Doping Recipe	EP Post Doping [μm]	Prepared at	Quench [MV/m]	Q_0 at 16 MV/m (21 MV/m)
CAV357	925	2/6	7	EZ/RI	17.2	3×10^{10}
CAV358[1]	925	2/6	7	EZ/RI	20.8	2.7×10^{10}
CAV360[1]	925	2/6	7	EZ/RI	20.2	3×10^{10}
CAV361	925	2/6	7	EZ/RI	19.1	2.8×10^{10}
CAV349	975	2/0	7	EZ/RI	15	2.4×10^{10}
CAV350	975	2/0	7	EZ/RI	20.6	3.5×10^{10}
CAV363	925	2/0	7	EZ/RI	21.6	3.5×10^{10} (2.9)
CAV364	925	2/0	7	EZ/RI	22.5	2.4×10^{10}
CAV363	925	2/0	10	EZ/RI	24.5	3×10^{10} (2.9)
CAV350	975	2/0	10	EZ/RI	22.8	3×10^{10} (2.9)
CAV355	925	3/60	11	EZ/RI	18.1	3.1×10^{10}
CAV356	925	3/60	11	EZ/RI		
CAV359	925	3/60	11	EZ/RI	17.2	3.8×10^{10}
CAV362	925	3/60	11	EZ/RI	18.3	3.8×10^{10}
CAV351	975	3/60	11	EZ/RI		
CAV352	975	3/60	11	EZ/RI	15.5	2.3×10^{10}
CAV353	975	3/60	11	EZ/RI	16.9	3.1×10^{10}
CAV354	975	3/60	11	EZ/RI		
CAV353[1]	975	3/60	15	EZ/RI	17	3.5×10^{10}
CAV0017	900	2/0	7	FNAL	20	3×10^{10}
CAV0017	900	2/0	7	FNAL	25.5	3×10^{10}
CAV0018	900	2/0	7	FNAL	20	3×10^{10}
TB9RI022	800	2/0	7	FNAL	32	2.5×10^{10}

[1] Field emission present

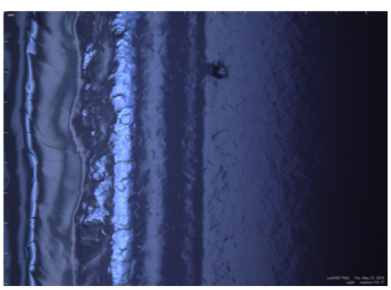

Figure 7: An example optical inspection issue from one of the 16 cavities produced by EZ. The weld appears wavy and a defect is present, suggesting an improper weld stackup prior to electron-beam welding.

production, which was since fixed [1]. However, if this was the case, one would expect that a full cavity reset would not improve the quench field. Figure 8 shows that in fact the opposite is true - a cavity that was reset with 60 μm EP reached fields above 25 MV/m (power limited not quench). However, this cavity was not optically inspected so it is unknown if it suffers from similar weld issues as the four that were inspected. Further studies are required to understand this difference.

While the 9-cell results from the vendor produced cavities are discouraging, it is clear that an issue within the production limited performance. As described above and in detail in

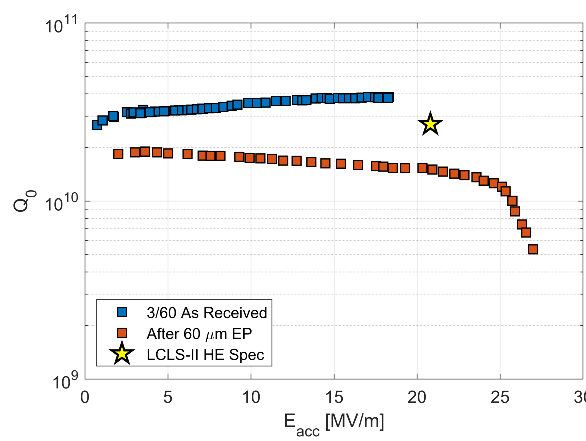

Figure 8: Q_0 vs E_{acc} performance of a cavity treated with 3/60 at the vendor and then reset with 60 μm EP at FNAL. After reset, the cavity performs similar to standard prepared cavities, suggesting that manufacturing issues were not present.

Fig. 6, even the 2/6 cavities performed worse than expected. In fact, the performance of the 2/0 cavities was ~3 MV/m higher than the 2/6 cavities. This suggests that if the issues with cavity production were improved, the 2/0 recipe would have produced cavities that consistently exceeded the LCLS-II specification. Moreover, after additional EP, two of the vendor produced 2/0 cavities met the HE gradient specifi-

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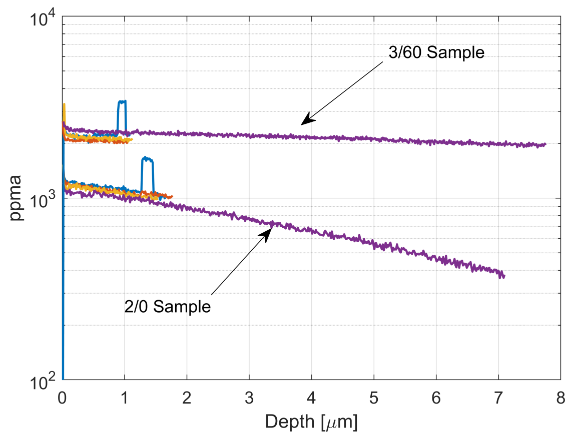

Figure 9: SIMS data showing the depth profile of 3/60 and 2/0 samples treated in RI's furnace with the 9-cell cavities. 0 μm of depth on this plot is after a 5 μm EP. Colors represent different locations on the sample measured.

cation. Combined with the cavities prepared at FNAL, four 9-cell cavities were demonstrated to have performance in excess of the LCLS-II HE requirements.

Sample Analysis

In addition to RF measurements on cavities, samples treated with various cavities have been analyzed using Secondary Ion Mass Spectroscopy (SIMS). Samples treated with the 2/0 and 3/60 cavities at RI were measured at Virginia Tech and the results are shown in Fig. 9 [7]. As you can see, the nitrogen concentration in the 3/60 samples is fairly constant to ~12 μm into the bulk. For the 2/0 sample, the nitrogen concentration starts about 2-3 times lower than the 3/60 (as expected) and drops quickly as one goes deeper into the bulk.

SIMS measurements were also carried out on samples treated with a 2/0 cavity in the FNAL furnace. These results are shown in Fig. 10. Interestingly the nitrogen concentration in the two samples is very similar, even when additional EP was done. This may suggest that there were additional errors in the EP measurement.

CONCLUSIONS

The LCLS-II HE R&D program has explored three paths to a new cavity recipe which can produce SRF cavities that can consistently reach 23 MV/m with high Q_0: nitrogen-infusion, 2/0 nitrogen-doping, and 3/60 nitrogen-doping. Infusion proved to be too sensitive to furnace contamination to reliably produce good cavities for a large accelerator production. Both the 2/0 and 3/60 recipes produced excellent single-cell cavities which far exceeded the LCLS-II HE requirements. However, 9-cell performance was less than stellar. 9-cell cavities prepared at FNAL had good results, with 50% of the cavities exceeding HE requirements, however more studies need to be completed to understand why one cell of the cavities that failed were limited compared

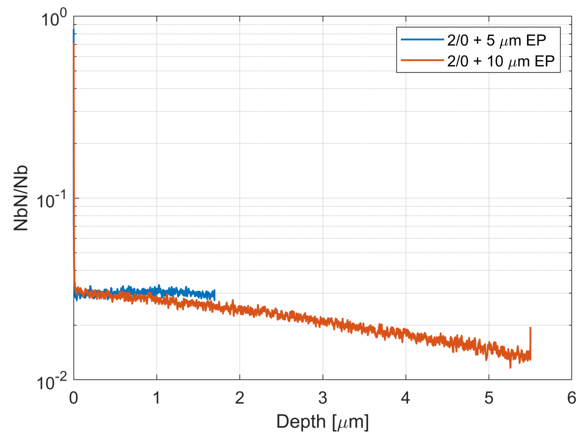

Figure 10: SIMS data taken at FNAL on a sample doped in the FNAL furnace with the 2/0 doping.

with the rest of the cavity. Vendor produced 9-cell cavities showed significantly worse performance than expected, however there are indications that there were issues with cavity fabrication. Studies are ongoing to understand this difference.

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