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THE JOINT HIGH Q_0 R&D PROGRAM FOR LCLS-II*

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Abstract

The superconducting RF linac for LCLS-II calls for 1.3 GHz 9-cell cavities with an average intrinsic quality factor Q_0 of 2.7×10^{10} at 2K and 16 MV/m accelerating gradient. A collaborative effort between Cornell University, FNAL, and JLab has been set up with the goal of developing and demonstrating a cavity treatment protocol for the LCLS-II cavities meeting these specifications. The high Q_0 treatment protocol is based on nitrogen doping of the RF surface layer during a high temperature heat treatment. This novel SRF cavity preparation was recently developed at FNAL and shown to result in SRF cavities of very high Q_0 at 2K with an increase in Q_0 from low to medium fields. N-doped single cell cavities at Cornell, FNAL, and JLab routinely exceed LCLS-II specification. 9-cell N-doped cavities at FNAL achieve an average Q_0(T=2K, 16 MV/m) of $\sim 3.4\times10^{10}$ with an average quench field of $\sim$ 19 MV/m, meeting therefore overall with good margin the LCLS-II specification.

INTRODUCTION

The "Linac Coherent Light Source-II" Project will construct a 4 GeV CW superconducting linac in the first kilometer of the existing SLAC linac tunnel [1]. The new superconducting radio-frequency (SRF) linac will provide the electron beam for two new undulators, one optimized as a soft x-ray (200-1,300 eV) source, and the second providing 1-5 keV photons. First light from the new facility is expected in September 2019.

The LCLS-II baseline design calls for 1.3 GHz 9-cell cavities with an average intrinsic quality factor Q_0 of 2.7×10^{10} at 2K and 16 MV/m accelerating gradient. High intrinsic quality factors are essential in keeping cryogenic infrastructure and operating cost within reasonable limits.

JOINT HIGH Q_0 R&D PROGRAM

The joint LCLS-II High Q_0 R&D effort aims to (a) establish a processing protocol suitable for production use which results in increased Q_0 values for 1.3 GHz superconducting cavities, operated at 2.0 K and (b) will establish a value of Q_0 that can be reliably demonstrated in a production acceptance testing setting. This R&D effort will also characterize the magnetic field environment required to preserve this performance in operational cryomodules and establish cavity optimal cool-down parameters. Success in the LCLS-II High Q_0 R&D program will lower the technical risk on the capacity of the cryoplant for the Project.

The recently-developed high Q_0 cavity surface processing recipe involving nitrogen-doping [2, 3] is an adaptation on internationally-recognized standard baseline recipes for producing high performance SRF cavities developed over the past decade. The LCLS-II High Q_0 R&D program will determine the small modifications that result in a realistic, industrial, cavity production process yielding high Q_0 that may then be applied to the fabrication and processing of LCLS-II cavities. The basic process adds $\sim$ 20 mTorr nitrogen gas exposure at 800°C following the typical 800°C vacuum bake. After a light electropolish to remove surface nitrides that form, one is left with a surface that appears to be lightly doped with interstitial nitrogen and exhibits significantly reduced RF surface resistance compare with prior methods.

In CY2014, LCLS-II began funding work in the partner labs (Cornell, FNAL, and JLab) in order to expedite the migration of this "High Q_0" technique from the lab to an element within a robust production process to be specified for use in LCLS-II construction.

Obtaining the highest Qs requires minimization of parasitic losses induced by the magnetic field environment present during cool-down of the cavities. This implies a new level of scrutiny of the materials used in nearby test hardware and also the cool-down thermal dynamics that either generate and/or exclude magnetic flux from the cavity. Such flux generates residual losses and thus limits the realized Q_0.

The work has three elements: (1) rapid single-cell work to explore the parameter space and to qualify basic procedures, (2) treatment and testing of 9-cell cavities in isolation, typically in vertical test dewars, to demonstrate that the basic process may be extended to accelerator cavities, and (3) testing of 9-cell cavities in horizontal test cryostats that include ancillary coupler, tuning, and shielding hardware to evaluate the challenges of preserving the high Q_0 performance in realistic cryomodule configurations. The goals of this effort are to quickly establish the technical credibility and viability of exploiting this new high Q_0 protocol as a central design element for LCLS-II. A well-defined, commercially imple-

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mentable protocol will be specified, and the performance obtained by using that protocol will be demonstrated.

CURRENT STATUS

Single Cell R&D

Single-cell work is currently ongoing at all three partner labs to optimize process parameters and qualify basic procedures and facilities.

Cornell: Three single-cell cavities fabricated at Cornell were given a nitrogen doping and different amounts of material removal. All three cavities showed excellent performance, exceeding LCLS-II specifications, with 2 K quality factors of 3.5×10^{10} to 4.5×10^{10} and quench fields up to 32 MV/m [4]; see Fig. 1. Material parameters extracted from surface impedance measurements show that the N-doping leads to RF surface layers with very small mean free paths ($\ell \sim 10$ nm), i.e. to a superconductor in the dirty limit.

A nitrogen-doped cavity and 120°C baked cavity were cooled in uniform ambient magnetic field and their residual resistances were measured for a variety of different ambient fields and cool-down rates. It was found that the nitrogen-doped cavity was ~ 3.6 times more susceptible to residual losses from trapped flux than the 120°C baked cavity [5].

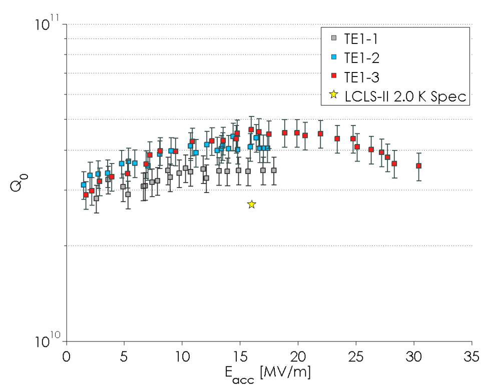

Figure 1: 2.0 K Q_0 vs Eacc performance for the three Cornell single-cell N-doped cavities.

FNAL: FNAL has up to today more than 40 tests of single-cell 1.3GHz cavities prepared via nitrogen doping under different partial pressure, duration and temperature regimes. A subset of the Q vs E performance obtained for these cavities is shown in Fig. 2, showing the systematic improvement of quality factors compared to standard surface treatments. Recently, FNAL nitrogen bake has evolved from a one step diffusion process, where the nitrogen supply and the high temperature were simultaneously shut off, to a two step diffusion process [6] to allow to flatten the ideal nitrogen concentration, which produces the higher quality factors, over a larger depth from the cavity surface. This is an important step towards the implementation of this technology on a large scale production, allowing to reduce the risk of spread in Q_0 values due to tolerances in material removal post gas bake. Another important achievement that came with the two steps diffusion implementation was the improvement of quench fields of nitrogen doped single cell cavities, which from a systematic barrier at 20.5 MV/m, moved to gradients in the range 25-30.5 MV/m.

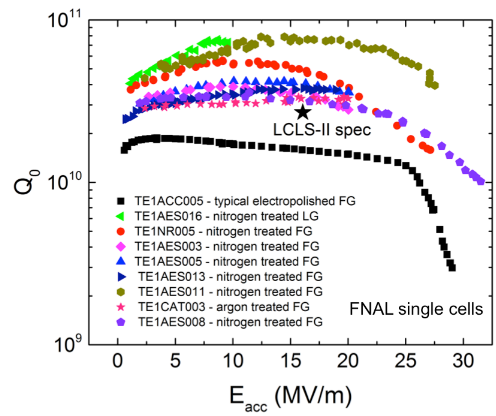

Figure 2: 2.0 K Q_0 vs Eacc performance for sample of FNAL single-cell N-doped cavities.

JLab: JLab is implementing a structured study using a set of nine single-cell cavities in a two-dimensional parameter space assessment. Working from successful protocols identified by FNAL, JLab varies the N-dose time and EP removal amount in a matrixed manner using sets of three cavities in each operation. This will minimize systematic errors, exercise the JLab facilities in the same way intended for use with 9-cell cavities, and demonstrate useful windows for process parameter ranges. JLab built six new cavities for this program and has contributed three NP-funded cavities to attain the required complement. JLab also upgraded its cavity heat treatment furnace to enable the controlled gas introduction at temperature required to apply the nitrogen diffusion process. In order to clearly distinguish improvements in cavity intrinsic rf losses from other parasitic effects, JLab has reworked cavity test hardware with carefully minimized permeability materials and magnetic field monitoring specifically for this project. The first pass through the matrix of nine single-cell tests has been completed. This found reliable high Q_0 performance with 2 minute nitrogen gas exposure and 10 μm EP, with little sensitivity to post-gas exposure dwell time duration in the range of 10-30 minutes. The second pass has just begun. It will examine a second matrix of parameters starting from a 20 minute nitrogen gas exposure.

9-cell Cavity Vertical Tests

FNAL has now doped several 1.3 GHz 9-cell cavities with the scope of transferring the single cell processing technique to a nine cell structure and studying the ideal process parameters to meet LCLS-II specs for both Q and gradients. Table 1 summarizes the results obtained so far in terms of Q_0 and

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Table 1: Performance of FNAL N-doped 9-Cell Cavities

Name	quench field [MV/m]	Q_0 (2K, 16 MV/m)
TB9AES011	22	3.4×10^{10}
TB9ACC015	17	4.5×10^{10}
TB9ACC015	23	4.2×10^{10}
TB9ACC012	12	4.2×10^{10}
TB9ACC012	17	3.0×10^{10}
TB9ACC012	16	3.5×10^{10}
TB9AES020	14	2.6×10^{10}
TB9AES003	21	2.6×10^{10}
TB9AES003	23	2.6×10^{10}
TB9AES026	22	2.8×10^{10}

quench fields reached by the 9-cell cavities treated with different nitrogen treatments (duration) or same gas treatment but for sequential amount of material removal. Results so far show an average Q_0(T=2K, 16 MV/m) ~ 3.4×10^{10} and average quench field of ~ 19 MV/m, meeting therefore overall with good margin the LCLS-II specifications. Detailed analysis [7] shows that all the cavities are identical in terms of BCS surface resistance, showing R_{BCS}(2K, 16 MV/m) ~ 4 nΩ, which is less than half of what is typically obtained with the 120°C bake surface processing. It is important to notice that several additional tests have been performed to study the origin of the spread in residual resistance and two important things have been found: 1) the effect of using stainless steel flanges versus NbTi flanges adds ~ 1.5 nΩ residual resistance; 2) the difference in residual resistance from cavity to cavity is always localized in the end cells. In all cavities the central seven cells show an average residual resistance of ~1 nΩ, while the end cells residual varies from 1 up to 10 nΩ, potentially due to higher remnant fields near the end cells. Another important milestone achieved at FNAL is the vertical test of a dressed high Q_0 cavity. Results shown in Fig. 3 show that post LHe tank welding the quality factor remained unchanged at ~ 3.4×10^{10} at 2K and 16 MV/m with fast cooling from 300K and 15K. A significant degradation in quality factor is observed in the dressed cavity if cooling is performed slowly through the normal conducting to superconducting transition, consistent with previous findings [8], indicating that particular attention will have to be paid to this phenomenon in the cooling procedure of LCLS-II cryomodules. Results are described more in detail in [9].

At JLab, a set of six 9-cell cavities has been received from FNAL and preparations for their initial processing has begun. JLab will process and test this set of 9-cell cavities using a candidate production-style process that folds the new N-doping elements into a standard baseline recipe.

Cornell has started processing three 9-cell cavities. In a first vertical test, a Cornell N-doped 9-cell cavity reached fields above 20 MV/m, with a BCS surface resistance of ~ 4 nΩ, consistent with FNAL results.

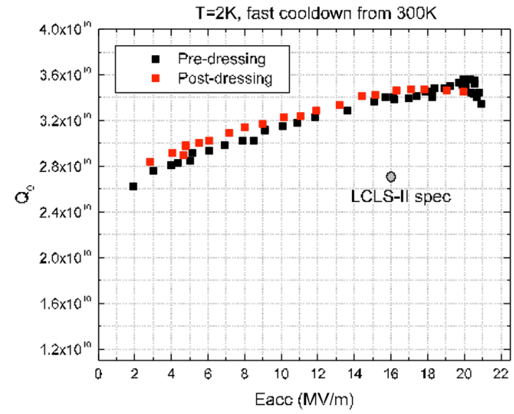

Figure 3: 2K vertical test performance of FNAL first high Q_0 doped cavity before and after LHe tank welding.

9-cell Horizontal Cryomodule Tests

Performance testing of 9-cell cavities in horizontal configuration with operationally realistic cryogenic, vacuum, RF, and mechanical interfaces is most representative of conditions intended within the finished LCLS-II cryomodules. CW RF testing on this platform is required to demonstrate control of all the factors which can affect the operational Q_0 of the SRF cavities once installed in a cryomodule, and also some of the other potential contributors to dynamic cryogenic load.

Fermilab's Horizontal Test Stand (HTS) is currently upgraded to reduce the ambient magnetic field at the cavity location, and will be used to evaluate the performance of three dressed LCLS-II cavities during the second half of 2014.

Cornell's unique one-cavity cryomodule (Horizontal-Test-Cryomodule, HTC [10]) has been modified to host LCLS-II 9-cell cavities. The cross-section of the HTC very closely resembles that of the planned LCLS-II cryomodules, and therefore allows performance testing of the LCLS-II cavities under the most representative of conditions. Three LCLS-II HTC tests are planned for the second half of 2014.

CONCLUSIONS AND OUTLOOK

The LCLS-II High Q_0 R&D effort at Cornell, FNAL, and JLab is well on its way towards establishing the technical credibility and viability of exploiting the new high Q_0 N-doping protocol as a central design element for LCLS-II. N-doped single cell cavities at all three partner labs routinely exceed LCLS-II specification. 9-cell N-doped cavities at FNAL achieve an average Q_0(T=2K, 16 MV/m) of ~ 3.4×10^{10} with an average quench field of ~ 19 MV/m, meeting therefore overall with good margin the LCLS-II specification. Future work will focus on defining the "frozen LCLS-II" high Q_0 protocol, determining critical parameters, finishing the transfer of the process to 9-cell cavities, and conducting performance verification in horizontal tests to understand Q_0 preservation, obtain Q_0 data under cryomodule conditions, and develop optimized cool-down procedures.

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