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QUENCH STUDIES OF SIX HIGH TEMPERATURE NITROGEN DOPED 9 CELL CAVITIES FOR USE IN THE LCLS-II BASELINE PROTOTYPE CRYO-MODULE AT JEFFERSON LABORATORY

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Abstract

Jefferson Lab (JLab) processed six nine-cell cavities as part of a small-scale production for LCLS-II cavity processing development utilizing the promising nitrogen-doping process. [1] Various nitrogen-doping recipes have been scrutinized to optimize process parameters with the aim to guarantee an unloaded quality factor (Q_0) of 2.7e10 at an accelerating field (Eacc) of 16 MV/m at 2.0 K in the cryomodule. During the R&D phase the characteristic Q0 vs. Eacc performance curve of the cavities has been measured in JLab's vertical test area at 2 K. The findings showed the characteristic rise of the Q0 with Eacc as expected from nitrogen-doping. Initially, five cavities achieved an average Q0 of 3.3e10 at the limiting Eacc averaging to 16.8 MV/m, while one cavity experienced an early quench accompanied by an unusual Q_0 vs. Eacc curve. The project accounts for a cavity performance loss from the vertical dewar test (with or without the helium vessel) to the horizontal performance in a cryomodule, such that these results leave no save margin to the cryomodule specification. Consequently, a refinement of the nitrogen-doping has been initiated to guarantee an average quench field above 20 MV/m without impeding the Q_0. This paper covers the refinement work performed for each cavity, which depends on the initial results, as well as a quench analysis carried out before and after the rework during the vertical RF tests as far as applicable.

INTRODUCTION

JLab is collaborating with FNAL and Cornell to expedite the development and exploitation of methods to produce dramatically lower-loss SRF cavities using the nitrogen-doping (N-doping) technique discovered by FNAL. [1] The LCLS-II project is eager to take advantage of these developments to minimize cryogenic capital and operating costs. JLab's contribution to this effort centered on systematic processing and tests of a set of single-cell 1.3 GHz cavities, followed by a "'production-style"' run treating six existing TESLA-style nine-cell cavities (AES031-036) to assess the performance in dependence

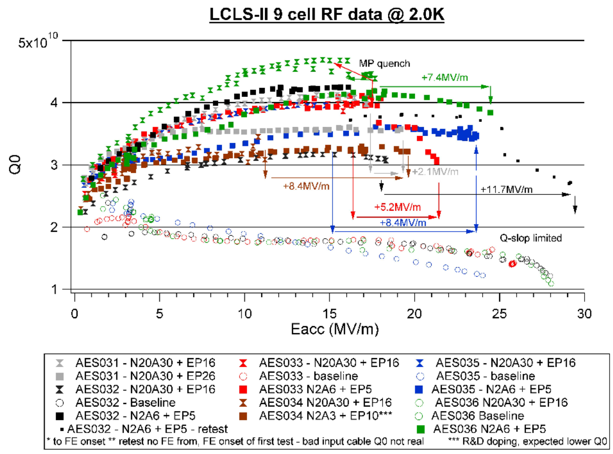

Figure 1: All RF test results for the 6 - 9 cell cavities.

on various nitrogen-doping recipes. Based on the single cell tests, a recipe for the nine-cell cavities has been determined which meets the desired project specifications. The initial nine-cell surface processing consisted of a UHV furnace heat treatment at 800 deg. C for 3 hours followed by controlled nitrogen injection for 20 minute at an average N2-pressure of 26 mTorr with an additional 30 minute annealing time under vacuum before letting the furnace cool down unconstrained with active pumping. After the N-doping each cavity received a 16 μm interior surface removal by Electropolishing (EP) to remove the topical highly nitrogen-enriched surface layer. [3] The nomenclature used in the following refers to the nitrogen injection time (N), annealing time (A) and EP surface removal, e.g. here **N20A30_EP16**. Three of the first nine-cell tests were published already. [4]

At this time is became clear that although a sufficiently high *Q_0* could be guaranteed at 16 MV/m, but the average quench field (Q_o >16=MV/m) was too close to the LCLS-II operating specification. In addition one has to consider that all N-doped cavities quenched at a much lower field than routinely achievable with conventional post-processing methods. [5] Consequently, an alternate recipe is scrutinized to obtain an average quench field beyond 20 MV/m without reducing the high Q0 already achieved. An N-doping refinement program resulted in a N2A6 EP5 recipe, which in fact resulted into quench fields 20 MV/m. [6] As a consequence, four of the six cavities at JLab were 'reset' by removing 50 μm from the

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[1] Qo for cavities has an additional 1.4nohms residual removed for all data because of stainless steel flanged present on cavity. [2]

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Table 1: Full Cavity History for Each of the 6 Nine Cells, Time Is Going from Left to Right.

Cavity ID	Bulk chemistry	Doping round 1	Post doping EP	Reset chemistry for baseline	Doping round 2	Post doping EP
AES031	128μm EP	N20@26mtorrA30	16μm EP	NA	not re-doped	10μm EP
AES032	10μm BCP + 123μm EP	N20@26mtorrA30	16μm EP	50μm EP	N2@26mtorrA6	5μm EP
AES033	10μm BCP + 123μm EP	N20@26mtorrA30	16μm EP	50μm EP	N2@26mtorrA6	5μm EP
AES034	123μm EP	N20@26mtorrA30	16μm EP	44μm CBP + 50μm EP	N2@26mtorrA30	10μm EP
AES035	10μm BCP + 123μm EP	N20@26mtorrA30	16μm EP	45μm EP	N2@26mtorrA6	5μm EP
AES036	10μm BCP + 123μm EP	N20@26mtorrA30	16μm EP	50μm EP	N2@26mtorrA6	5μm EP

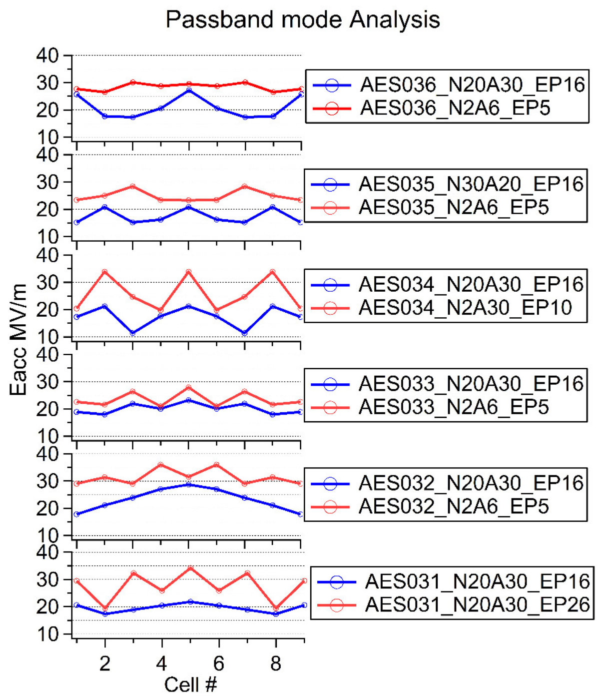

Figure 2: Passband mode analysis for all quench limited tests, separated by cavity for comparison.

interior surface by EP (AES032, 33, 35 and 36), which is expected to restores the nitrogen concentration to its original level in the as-built cavity. [7] In this manner a baseline performance of the cavities can be re-establish. The baseline performance of the remaining two cavities however was omitted, i.e. one cavity received only a light EP (AES031) and another (AES034) was sent to centrifugal barrel polishing (CBP) before subsequent doping.

CAVITY RESULTS

The full cavity treatment history and 2.0 K RF performance results for all six cavities are summarized in Table 1 and Figure 1, respectively. One can see that after the reset treatment, the baseline performance for cavities AES032,033,035,036 was merely Q-slope limited without quench.[2] This result implies the important fact that the quench field experienced initially were due to N-doping and not cavity manufacturing. After applying the **N2A6_EP5** recipe the quench fields on all the baseline cavities went up. The cavity AES031 only had marginal improvements to its π-mode quench field from its additional EP, and AES034 gradient almost doubled, but at a lower field than was expected from its lighter doping. Single cell results suggest quench field from **N2A30_EP10** recipe should produce quench fields in the mid 20MV/m's [8].

In addition to finding the quench field in accelerating π-mode, RF tests were carried out by powering all other eight fundamental passband modes to investigate the quench field limits. These passband mode measurements help to determine whether an individual cell is responsible for quenching the cavity as has been the case for some early nine-cell cavities processed with un-doped ILC-style recipes, or from multiple cell all close to the same fields. From the raw data, we then determined the averaged quench fields in all passband modes as plotted in Figure2. A summary of all tests is listed in Table2. When the π-mode quench field is close to the average quench field and the standard deviation of the quench is relatively small, we assume that all quenches experienced in a cavity are created in a similar same way, i.e. due to the nitrogen doping. At this time the passband measurement data are not sufficient to provide a clear explanation of the quench fields experienced. As a side note, except for AES034 (see section quench localization) no cavities showed any sign of quench location from a pit-like defect verified by using JLab's high resolution long range microscope inspection system. For the given defect size in AES034 (300 nm), previous experience from ILC cavities implies the quench field at 11.2MV/m is lower than expected from its size and location. [5, 9]

In order to better understand the quench differences between the two doping round, as we can't explain variation from the mode analysis alone, we attempt a simple statistical analysis treating each mode for each cavity as individual cavities. To do this we took the average of the mode averages in Table 2 for each doping and compared these averages to their standard deviations. From this very simple model it appears that changing the doping from a heavier **N20A30_EP16** to a light **N2A6_EP5** does not change the distribution in the cavities on average, but increases the quench fields (standard deviation percentage in yellow).

QUENCH LOCALIZATION

The two outlier cavities AES031 and AES034 were treated differently than the other cavities. For these two the

[2] no 120C bake on any cavity at any time

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Table 2: π-mode and Average Passband Quench Field for Each Cavity Test.

Cavity ID	Doping round 1 quench field	Doping round 1 average passband quench field	Doping round 1 standard deviation from passbands	Rest quench field	Doping round 2 quench field	Doping round 2 average passband quench field	Doping round 2 standard deviation from passbands
AES031	17.4MV/m	19.7MV/m	1.5MV/m	NA	19.4MV/m	27.8MV/m	5.2MV/m
AES032	18.4MV/m	22.6MV/m	4.1MV/m	Q-slope	29MV/m	31MV/m	2.8MV/m
AES033	16.4MV/m	20.0MV/m	1.8MV/m	Q-slope	21.6MV/m	23.5MV/m	2.6MV/m
AES034	11.2MV/m	17.4MV/m	3.6MV/m	NA	19.6MV/m	25.2MV/m	6.3MV/m
AES035	15.3MV/m	17.0MV/m	2.6MV/m	Q-slope	23.4MV/m	24.8MV/m	2.0MV/m
AES036	17.2MV/m	21MV/m	4.0MV/m	Q-slope	24.5MV/m	28.3MV/m	1.3MV/m

Table 3: Comparison between the Average π-mode Quench Field and Average Quench Field for All Passband Modes between the Two Doping Rounds; as well a comparison between the **N20A30_EP16** and **N2A6_EP5** dopings.

Tests	Average π-Mode Quench Field	Standard deviation π-Mode	% Standard deviation π-Mode	Average quench field pass-bands	Standard deviation pass-bands	% Standard deviation pass-bands
Doping round 1	15.9MV/m	2.4MV/m	14.9%	19.6MV/m	2.1MV/m	10.6%
Doping round 1 without AES034	16.8MV/m	1.0MV/m	6%	20.0MV/m	2.0MV/m	10.1%
Doping round 2	23.2MV/m	3.8MV/m	16.2%	26.8MV/m	2.8MV/m	10%
N2A6 + EP5 only	25.0MV/m	1.6MV/m	6.5%	27MV/m	3.3MV/m	12%

Table 4: Quench Cell Location Found by OST.

Quenching cell	AES031 N20A30_E16	AES031 N20A30_E26	AES034 N2A30_E10
Cell 1	$7\pi/9$,$6\pi/9$	$7\pi/9$, $6\pi/9$	$8\pi/9$,$7\pi/9$,$5\pi/9$
Cell 2			$3\pi/9$
Cell 3			$2\pi/9$
Cell 4			
Cell 5			
Cell 6		$1\pi/9$	π,$6\pi/9$,$4\pi/9$, $1\pi/9$
Cell 7	$5\pi/9$,$2\pi/9$	$5\pi/9$,$2\pi/9$	
Cell 8	π,$8\pi/9$,$4\pi/9$, $3\pi/9$	π,$8\pi/9$ $4\pi/9$, $3\pi/9$	
Cell 9			

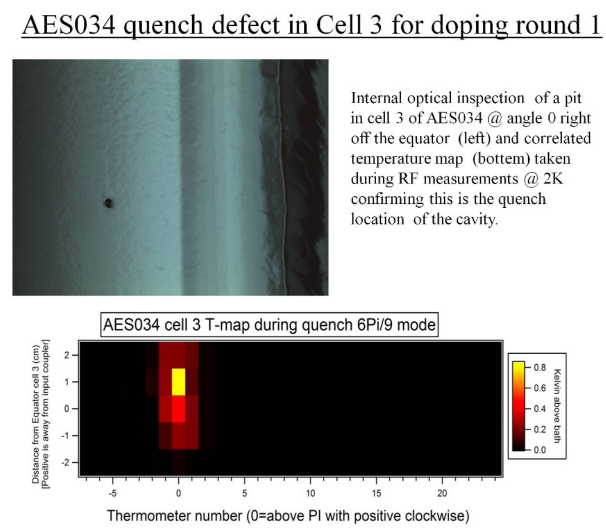

Figure 3: Quenching defect from AES034 doping round 1.

exact quench location before and after rework needed to be known. For AES031 we wanted to understand if given an additional light EP, would the quench location change or be randomized. In this case both tests of AES031 were carried out with OST sensors to track the exact quench in all modes, and for the second test of AES034 OST were used to track the quenching defect in Cell 3 found by temperature mapping(see Figure 3). The exact quenching cell for the three test are shown in Table 4. For AES031, three of the four quenching cell did not change (exact location confirmed but picture not shown), this includes the limiting π mode cell 8. As for AES034 the quench in cell 3 in π-mode clearly changed after CBP and re-doping, and the quench in cell 3 also changed location (exact locations confirmed but picture not shown).

COMMENTS

- **N2A6_EP5** doping clearly produced an higher average quench field than **N20A30_EP16**.
- Using a very simple theoretical model, the percent gradient spread between **N2A6_EP5** and **N20A30_EP16** is statistically the same.
- An addition light doping of AES031 did not increase the quench field dramatically nor change the quench location, but did increase the spread, suggesting AES031 quench might be defect driven.
- Nitrogen doping recipes used so far yield lower quench fields than achieved in baseline tests (no N-doping) of a given cavity.
- There is still a lack of understanding why a given cavity quenches at a given location after N-doping, except for the special case of AES034(with identified defect site).

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