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REWORK RECIPE DEVELOPMENT, ANALYSIS AND RESULTS OF SELECT 9-CELL CAVITIES FOR LCLS-II*

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Abstract

The SLAC National Accelerator Laboratory is currently constructing a major upgrade to its accelerator, the Linac Coherent Light Source II (LCLS-II). Several Department of Energy laboratories, including the Thomas Jefferson National Accelerator Facility (JLab) and Fermi National Accelerator Laboratory (FNAL), are collaborating in this project. The cryomodules for this project each consist of eight 1.3-GHz cavities produced by two vendors, Research Instruments GmbH in Germany (RI*) and Ettore Zanon S.p.a. in Italy (EZ*), using niobium cell material from Tokyo Denkai Co., Ltd. (TD) and Ningxia Orient Tantalum Industry Co., Ltd. (OTIC/NX)).

During the initial production run, cavity performance from one of the vendors (Vendor A) was far below expectation. All the cavities had low Q_0, later attributed to minimal EP as well as high-flux-trapping NX material, early quench behavior below 18 MV/m, with many having Q_0 roll-off at 12-16 MV/m. Production was stopped multiple times over the following 6 months, with test batches of cavities being made to ascertain the root cause of the problem. The final root cause of the problem was found to be inappropriate grinding of the RF surface prior to welding which left normal conducting inclusions in the surface. In addition, most cavities showed internal/external weld spatter which required post weld grinding and a very rough surface from operating the electropolishing machine in an etching rather than polishing regime.

All issues have been corrected on new cavities and rework is underway on the originally effected cavities.

TIMELINE FOR VENDOR A REWORK LCLS-II PRODUCTION

- **October 2016 –** First 8 cavities arrive with baseline 140 µm EP/800°C heat treatment recipe with lower than expected Q_0, quench field and strong Q-slopes on some cavities.
- **November 2016 –** Next 8 cavities unsorted NX 9-cells arrive with 900°C/200 µm recipe flux trapping was still an issue, and Q_0 varied widely between test setups [1-4]. These new cavities also had low quench field and strong Q-slopes on some cavities. Production was halted before all cavities available were tested. Analysis of the EP showed large variation in the total current, higher than expected temperature, and extreme surface roughness. Subsequent evaluation showed wrong cathode geometry and voltage, which caused etching rather than polishing during the chemical processing [5].
- **December 2016 –** JLab staff on site to verify production specified EP cathode and parameters. Four 9 cells without helium vessel sent thought production using the new EP parameters.
- **January 2017 –** All 4 test EP cavities were RF tested and showed good low field Q_0, but three still had a strong Q_0 slope between 12 and 18 MV/m, production shutdown again.
- **February to March 2017 –** Full review and onsite investigation into the root cause of the underperforming cavity results.
  - Shiny inclusions found on the sidewall of three cavities which received 275 µm EP, suggesting normal conducting inclusions.
  - Walkthrough of production work stations showed multiple steps where more inclusions were found from inadequate cleaning of tooling.
  - Global grinding with non-compliant tooling was found which could smear rather than remove metallic inclusions embedded in the niobium parts.
  - A cavity received 100 µm extra EP and still had Q-slope.
- **March to April 2017** – Four cavities went through the developed rework recipe with onsite direction from Jefferson laboratory staff.
- **July 2017** – All 4 cavities passed the operating specification and three of the four cavities pass the vertical test specification - rework was initiated on the 63 cavities and material affected by global grinding.
- **present**– As of April 12th 2018, 26 cavities have been tested with a pass rate of 76%

EFFECT ON QUENCH FIELD WITH EXTRA EP

When three of the four EP test cavities sent in January failed their RF test with the strong Q-slope before quench, the three failed cavities were tested again after an additional chemistry to understand what was causing the Q-slope. Two cavities received a 10 µm BCP, and one received 100 µm EP along with a re-dope at FNAL. One of the two BCP cavities went up in quench field while another didn't, suggesting if BCP was used more than 10 µm removal would be required in a rework recipe. The 100 µm EP cavity showed a minimal change in quench field with the Q-slope remaining, Fig. 1.

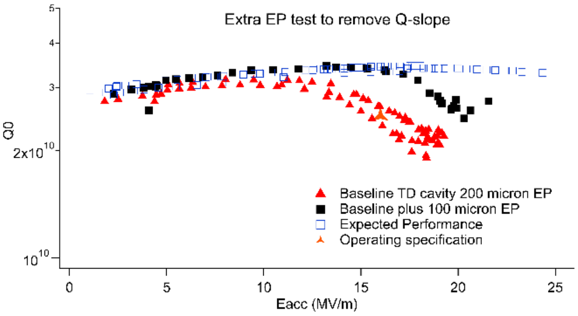

Figure 1: New TD cavity with correct 200µm electropolishing from the vendor showed strong Q-slope (red solid triangles), after receiving another 100 µm EP at FNAL the Q-slope remained (black solid squares). The expected performance of a newly manufactured cavity is shown for reference (open blue squares).

The three tests combined suggest the remaining Q-slope is not related to a single physical defect, or "bad EP", but possible due to a normal conducting inclusion.

During the initial test (Fig. 1 red triangles) there was rather strange quench processing behaviour, without any radiation or sign of multipacting, with the quench field actually going up by 1 MV/m. Although the change was small, this is similar to quench processing of a normal conducting inclusion field emitter [6]. Again suggesting a normal conducting inclusion in the high peak magnetic field region which can't be dissolved with electropolishing - aluminium and possible stainless steel are prime candidates.

EMBEDDED METALLIC DEFECTS AND GLOBAL GRINDING FOUND

From January to March 2017 a full investigation of the manufacturing facilities at the Vendor was performed. All workstations were fully loaded with parts as production was halted after it was fully ramped up with over 25 cavities already welded into their tanks and almost all niobium half-cell already stamped. This allowed for an audit of all work stations in the production cycle that touched the sheet niobium up through the cleanroom.

There were two main findings. One, multiple workcenters showed a high risk of embedding material with each progressive center showing more and more defects. The amount of defects found and some of the techniques being used were outside the generally accepted practices in the field, see example of aluminium defect found in dumbbell before grinding in Fig. 2, top. Two, right before final weld prep chemistry, a final grinding step is done to remove any accidentally embedded material or handling defects. The industry standard and contractually enforced protocol is to perform local grinding on the defect area only with encapsulated abrasives. This ensures minimal material removal as well as reducing the chance of smearing the soft niobium over the embedded defects. The Vendor was instead performing a global polish with a non-conforming abrasive. The tooling made the surface look better from a visual inspection point of view, but could smear the niobium over itself and cover the embedded foreign defect without removing them.

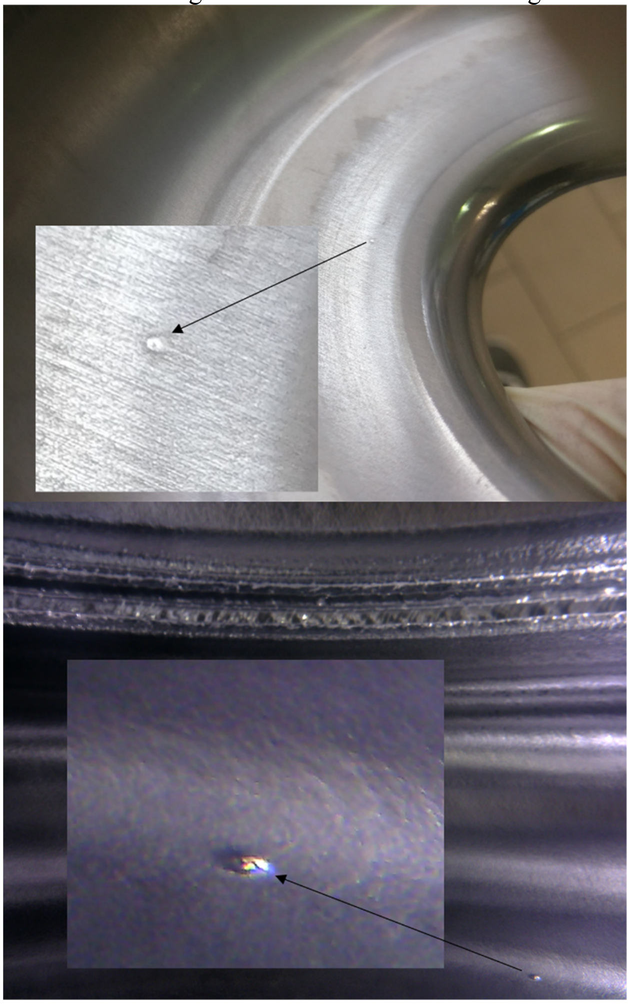

Figure 2: Top, large embedded aluminium defect found in dumbbell right before grinding. Bottom, embedded metallic looking defect in the sidewall of a finished cavity after 275µm EP.

At the same time 4 cavities which received 200 µm of non-conforming EP (EP done in the etching regime) plus an additional 75 µm of the correct EP (done in the polishing regime) went through internal inspection. In three of the four cavities metallic looking embedded defects were found on the internal side wall, see example in Fig. 2 lower image. This suggested the foreign material does not react to the electrochemistry and must have been embedded at the vendor after eddy-current scanning at DESY which detect foreign material ~500 µm into the surface[7].

9 CELL REWORK PROTOTYPE RECIPE AND RF TESTS

Based on the finding of the embedded material both at the part level as well as on the sidewall of the cavity a rework recipe needed to be devised to remove the foreign material and then prepare the surface for doping. The list below reviews the requirements that went into the discussion making for the recipe.

- Cavity production tools for recovery must be available at the vendor.
- Must be able to dissolve aluminum and/or steel (regular or stainless) EP itself is not good enough.
- For most cases keep the cavity within the proper length tolerance, ~ 3 mm extra length would be ok or 100 µm total chemical removal.
- Final chemistry before the furnace must be electropolishing 30-35 µm to smooth the surface roughness from BCP.
- Visual inspection and local grinding can be done to enhance acceptance rate, but should not be required to achieve 75% passing rate.
- Assumes the welding of the cavities is good.
- Rework could only be performed after bulk EP to expose the underlying embedded and possible covered foreign inclusions

<u>Final rework recipe:</u>

30 µm BCP, flip the cavity + 30 µm BCP + 35 µm EP then standard doping and finish manufacturing.

Based on the recipe above, four cavities went through the vendor's production line with Jefferson Laboratory experts on site to supervise the changes. This was done in parallel to new cavities being produced with new procedures. The results from the four cavities are shown in Fig. 3.

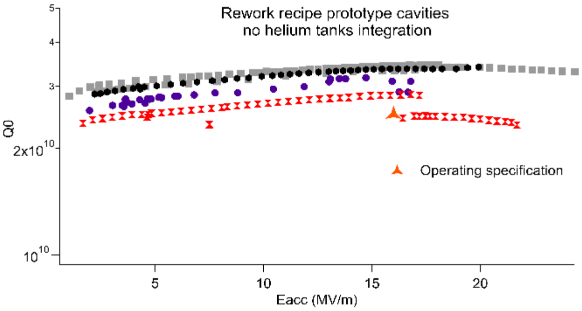

Figure 3: Rework recipe prototype cavities, all cavities passed the operating gradient specification of 16MV/m with three passing the vertical test specification of 19MV/m. One cavity shows a Q-drop from quench processing which is normal.

CURRENT REWORK STATISTICS

As of April 12th 2018, 26 cavities have been tested with a pass rate of 76%. The results are rather different based on when they were welded. The first set of rework cavities were made from cavities welded after the production shutdown and the second set is before the production shutdown. Almost all of the old weld cavities showed some internal or external welding spatter, while none of the new welds had any sign of internal or external weld spatter. The results and statistics from each lot are shown in Fig. 4:

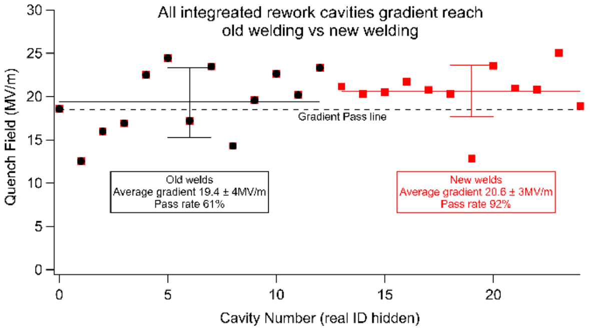

Figure 4: Quench field gradient and pass rate statistics for two subsets of cavities that received the rework recipe; one welded with old preparation procedure and ones welded after the production shutdown with new procedures.

There is a clear statistical difference between the vendor's old welding preparation technique and the new one used after the production shutdown.

SUMMARY

The rework of Vendor A's mismanufactured cavities is underway. About 60% of the cavities have been delivered and 40% tested. The current pass rate overall is 76% with 92% pass rate of the newly welded cavities and 61% on originally-welded cavities. Overall, the rework is going well, and this rework combination of BCP + EP should be considered in the future with doped cavities that require significant performance recovery effort. All issues related to the rework cavities have been corrected on new cavities with performance within expectations except for a few examples which will be published later.

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REFERENCES

[1] A. D. Palczewski, F. Marhauser, A. Grassellino and S. Posen, "Material Qualification of LCLS-II Production Niobium Material Including RF and Flux Expulsion Measurements on Single Cell Cavities," in *Proc. LINAC'16*, East Lancing, MI, USA, Sept. 2016, paper MOPLR026.

[2] A. Burrill *et al.*, "Vertical Test Results for the LCLS-II 1.3 GHz First Article Cavities," in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1152-1155.

[3] F. Marhauser *et al.*, "Status of the LCLS-II accelerating cavity production," in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1164-1166

[4] D. Gonnella *et al.*, "RF Performance of Nitrogen-Doped Production SRF Cavities for LCLS-II," in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1156-1159

[5] C. Reece, F. Marhauser and A. Palczewski, "The transfer of improved cavity processing protocols to industry for LCLS-II: N-doping and electropolishing," in *Proc. SRF'15*, Whistler BC, Cananda, Sept. 2015, pp. 418-422.

[6] J. H. Graber, "High power RF processing studies of 3 GHz Niobium superconducting accelerator cavities," Disseration, Cornell University, 1993.

[7] A. Brinkmann, M. Lengkeit, X. Singer and W. Singer, "Testing of Niobium Material for the European XFEL Preseries Production," in *Proc. LINAC'10*, Tsukuba, Japan, 2010, p. 788.