STATUS OF THE LCLS-II ACCELERATING CAVITY PRODUCTION*

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Abstract

We present the status of the industrial fabrication of 1.3 GHz TESLA-type cavities for the LSLC-II project. After successful transfer of the cavity nitrogen-doping technology to industry in the first procurement phase, the cavity serial production began. The experience gathered during vendor qualification and production is reported.

INTRODUCTION

The European vendors RI Research Instruments, GmbH (RI) and Ettore Zanon, S.p.A. (EZ) have been awarded in May 2015 to each produce half of the superconducting RF accelerating cavities for the Linac Coherent Light Source (LCLS)-II project at the SLAC National Accelerator Laboratory [1]. The cavity procurement and all technical aspects are being managed by the Thomas Jefferson National Accelerator Facility (JLab) in collaboration with the partner laboratories Fermi National Accelerator Laboratory (FNAL) and SLAC. The procurement covers the following phases.

Phase I (6 months): Vendor Qualification (N-Doping)
Phase II (7 months): 1st Article Production (16 cavities)
Phase III (15 months): Full Production (250 cavities)
Phase IV (3 months): Option (up to 16 cavities).

The technical specifications and manufacturing procedures for the cavities are based on those established by DESY for the industrial 'built-to-print' mass fabrication successfully applied for the European X-ray FEL (EXFEL) [2]. We have reported in detail on the cavity qualification and production plan during the Phase I period [3]. Since then, Phase I and Phase II have been completed, while Phase III is ongoing. Phases II and III comprise the production of 266 1.3 GHz nine-cell TESLA-type cavities. This quantity is sufficient for the assembly of 33 cryomodules (CM) (16 at FNAL, 17 at JLab) adding to two prototype CMs. Two cavities have been procured by the project as replacement cavities owed to FNAL. Additional Nb and NbTi material has already been delivered to the vendors to acquire more cavities in an optional Phase IV depending on the needs for spares. Production cavities are integrated into the helium tanks at the vendor sites and shipped to the U.S. under vacuum, equipped with test hardware ready for vertical RF qualification conducted at FNAL or JLab.

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VENDOR QUALIFICATION PHASE I

Phase I focused on the transfer of the nitrogen-doping technology to industry aiming for high-Q_0 cavities. The introduction of the N-doping is the major difference to the cavity post-processing scheme applied to EXFEL cavities. Since the LCLS-II cavities operate in CW mode, high Q_0-values are crucial to reduce the dynamic heat load for the helium refrigeration system. The project objective is to achieve an unprecedented Q_0 of 2.7e10 at 2 Kelvin at an accelerating field of 16 MV/m for cavities installed in the CM. This also assumes that the cavity Nb material allows a moderate flux expulsion in an ambient field of nominally 5 mG in the CM with a moderate spatial temperature gradient along the cavity during cooldown. JLab worked closely with both vendors such that the N-doping can meet the technical requirements in compliance with the original LCLS-II process parameters and allowable margins (see Table 1).

Table 1: Original Furnace Process Parameters and Allowable Control Ranges as Part of the High Temperature Furnace Run for LCLS-II Cavity Nitrogen-Doping

Step	Temperature (°C)	Duration	N-Pressure (mTorr)
H degassing	800 ± 10	180 ± 5 min	0
N-Doping	800 ± 10	2 min ± 6 sec	26 ± 4
Annealing	800 ± 10	6 min ± 6 sec	0

The N-doping is succeeded by a final electropolishing (EP) removing a layer of 5-7 µm controlled by measuring the integrated current during the EP. A nomenclature describing the post-processing treatment according to 'N(min)A(min) EP(microns)' has been chosen. The recipe for vendors was thus dubbed N2A6 EP5. It presents a trade-off between the gain in the Q_0-value compared to conventionally treated, un-doped cavities and the concurrently observed reduction of the quench field limit.

Applying the recipe to prototype cavities fabricated by AES, Inc. in the past has shown that the specified Q_0 and accelerating field could be routinely exceeded in vertical tests allowing for some performance degradation after CM assembly.

According to the qualification plan, vendors upgraded their existing UHV furnaces with mass-flow-controlled high-purity nitrogen injection lines utilizing programmable logic controllers. To qualify for Phase II, each vendor had to first demonstrate technical compliance to the N2A6 EP5 recipe applied in sequence to two bare TESLA-type cavities, which passed vertical qualification tests prior to N-doping at JLab [3]. The cavities were then sent back to JLab to verify whether a Q_0-improvement has been achieved in agreement with past experience for prototype cavities. The findings are shown in Fig. 1.

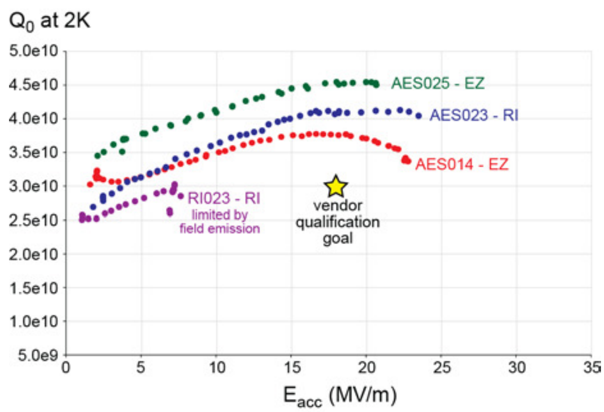

Figure 1: Vertical test results of four TESLA cavities after N-doping at RI and EZ, respectively. The cavity ID and vendor are denoted next to the data. Q_0-values are corrected for the cavity flange losses (stainless steel), which will not be present in a cryomodule.

Three cavities (AES014, AES023, and AES025) could be tested up to their quench field limit beyond 20 MV/m. These exceeded the vendor qualification goal (Q_0 = 3e10 at 18 MV/m), though this was not a strict qualification requirement. Cavity RI023 for instance showed an early onset of field emission, but its BCS-resistance was found to be reduced efficiently by N-doping to result in a maximum Q_0 of ~3e10 at 7 MV/m, albeit the test had to be aborted due to strong field emission below 10 MV/m. Mass spectra are recorded routinely before and after the heat treatment with a residual gas analyzer (RGA) located in the furnace. The data did not indicate any abnormal outgassing or contamination for RI023, e.g. in comparison with data for AES023 from the same vendor. The cause of the field emission was therefore regarded as independent from the N-doping. Hence, RI directly qualified together with EZ for Phase II. AES025 set a new record at the time by reaching a Q_0 of 4.5e10 at 2 K observed at 20 MV/m.

PRODUCTION PHASES II AND III

The LCLS-II project decided to purchase and to distribute to vendors all Nb and NbTi material required for the bare cavity production after quality control (100% inspection). The delivery was contingent on a duty-free, temporary import to Europe for cost-saving reasons. Material procurement, inspection and supply were managed by FNAL. The material suppliers comprise Tokyo Denkai (TD), OTIC Ningxia (NX), ATI Wah Chang (ATI) and the Heraeus Group. TD and NX shared the supply for the Nb half-cells sheets. In total, 5720 qualified sheets were delivered to vendors divided in equal quantity. The project faced several bureaucratic complications before customs authorities allowed the material to be exported from the U.S. to DESY, where shipments had to be inspected and cleared from customs within the EU for distribution to RI and EZ, respectively. Due the delay of the material supply, vendors were unable to begin Phase II seamlessly after completion of Phase I. The delay was aggravated by the fact that the Nb for cavity endgroup fabrication from one company had to be stopped intermittently since material specifications were not met, which had an impact on the continuity of cavity fabrication. After partial deliveries, the Nb and NbTi delivery was eventually completed in its entirety by Aug. 2016 with up to one year delay compared to need-by-dates, which would have theoretically guaranteed a seamless fabrication. Note that the production of first article cavities in Phase II was planned to provide sufficient time to fully characterize a subset of 16 N-doped cavities within a relatively long period of 7 months before commencing with the full production of 250 cavities to be delivered within 15 months. Due to the material supply delay, Phase II and Phase III have been tied together as best as practicable despite the contractual differentiation and associated milestone payments. In an attempt to recover the lost time, the project offered monetary incentives to the cavity manufacturers. Vendors were requested to provide additional labor to target the original completion date of Phase III by Sept. 2017. One vendor accepted the incentives and is continuing production according to the accelerated schedule.

No major issues were faced with other component supplies. The titanium for the helium tank, stainless steel tubes for the helium pipes as well as the bi-metallic (Ti-SS) transitions are acquired by vendors. All vertical test hardware is being procured and provided by JLab.

Flux Expulsions Issue – Recipe Changes

The cavity R&D phase conducted throughout 2014 by three laboratories (Cornell University, FNAL and JLab) led to the N2A6 EP5 recipe based on the encouraging results with AES cavities made from ATI half-cell sheet material. By 2016 it became clear that the material properties of the sheet material used for cavity production significantly affects the flux expulsion efficiency during cooldown and consequently impacts the residual resistance [4]. The Nb bulk properties, specifically related to the grain size, can drastically influence the flux expulsion efficiency from almost none (all flux trapped) to nearly ideal behaviour (all flux expelled). RF tests with single-cell cavities built at JLab during Phase II – made from TD and NX production material - confirmed that the magnetic flux expulsion is considerably less efficient than that obtained with ATI material [5]. The resulting Q_0-degradation - from values typically in the 3e10 regime

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into the mid to lower 2e10 range at 2 K - has therefore been anticipated and verified for the first article LCLS-II cavities made from TD material. R&D results showed that one can regain the higher Q_0-values by a higher annealing temperature of the cavity in the UHV furnace. Therefore the original recipe in Table 1 has been revised at vendors by heating the cavities at 900 °C for 3 hours prior N-doping in lieu of 800 °C. In addition to the higher temperature treatment, the project mandated to increase the removal by bulk EP from 140 um to 200 um (controlled by the integrated current method ~ removal by weight) in the hope to further reduce the residual resistance. The claim was that a larger than usual Nb damage layer removal must be removed, though it has not been systematically studied independent from the 900 °C heat treatment, not with substantial statistics and not with nine-cell cavities at the time. Both recipe changes were implemented into the serial fabrication in the early stage of Phase III by Aug. 2016. The new recipe has shown to work successfully on TD cavities delivered from one vendor that reached Q_0-values within 3e10-4e10 at 16 MV/m at 2 K at ambient fields from 5-10 mG. Further details of vertical test results are presented in ref. [6]. Note that - in order to more swiftly verify the impact of the new recipe during production - two bare cavities were sent to FNAL by one vendor.

Yet, previous R&D on single-cells has also revealed that NX material showed inferior flux expulsion efficiency than TD material. For this reason vendors were asked by mid of Aug. 2016 to preferably consume TD material for cavities as best as practicable to allocate more time to understand the response of NX material to various heat treatments. In fact, results for the first LCLS-II cavities made from NX material were less encouraging after the recipe change since Q_0-values did not exceed 3e10. Present R&D is focusing on the correlation of the Q_0-values in dependence on the ASTM grain size for the NX base material, which may vary from ASTM 5-8 and which can be traced back to the heat lot of the ingot. As a consequence, the NX sheet material has been categorized into lots of large (*A*), medium (*B*), and fine (*C*) grain size with lot *A* being favourable for flux expulsion. For that reason, the cavity composition by lots has become important. A recipe change for cavities made from lot *B* material is being explored by annealing the cavities at 950 °C prior N-doping, while lot *C* material is avoided for further use. Instead, the project has ordered additional 320 TD sheets to feed into production. One of the concerns with the higher cavity annealing temperature has been the softening of the cavity material. This for instance concerns potential cavity cell deformations during transit. With cavity crates being exposed to peak forces typically not exceeding 3g, the dressed cavities have so far not been damaged as implied by RF inspections showing that the accelerating π-mode frequency is well within the specified tolerance (+/- 100 kHz) and that the field flatness is maintained.

Quality Control

For quality control, the three following hold points (HPs) were introduced in the fabrication plan [3]:

HP 1 - After the mechanical fabrication of bare cavity
HP 2 - After Bulk EP and N-doping
HP 3 - After completion of the fully dressed cavity

Cavity fabrication may only proceed after successful clearance of HP data. The HPs comprise all major fabrication and process data. The initially laid-out fabrication process flow chart detailed in ref. [5] has not been altered except for the discussed recipe changes and implementing non-time invasive Ethanol rinsing after the bulk and final EP to counteract potential sulphur contamination. Cavity status is shown in Table 2.

Table 2: Status for Cavities that passed respective HPs and Cavities delivered (by 30th April 2017)

Step	HP 1	HP 2	HP 3	Delivered
Vendor A	63	50	37	37 (18 TD, 19 NX)
Vendor B	110	91	85	85 (61 TD, 24 NX)

CONCLUSION AND OUTLOOK

Since last reported, the N-doping process has been transferred successfully to industry by JLab. Close to half of the baseline cavities have been produced and delivered as of writing. The start of the production was significantly delayed due to late deliveries of project-supplied Nb and NbTi material to vendors. The project has regained lost time with one vendor through an incentivized schedule. Encountered delays at both vendor sites during the current production phase are mainly due to persisting and initially unforeseen R&D efforts to guarantee high-Q_0 cavities for LCLS-II. These efforts target the improvement of the flux expulsion efficiency of the production material by annealing cavities at elevated temperatures prior to the N-doping. One recipe change - baking cavities at 900 °C instead of 800 °C for three hours - has been implemented at the early stage of Phase III. This has provided the desired improvements for cavities made from TD material, while a further elevated temperature is currently contemplated for cavities made from NX material. As a consequence, several bare rather than fully dressed cavities have been requested from vendors intermittently during Phase III to expedite the R&D effort in trade-off with the original production schedule.

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