FABRICATION AND TESTING STATUS OF CEBAF 12 GEV UPGRADE CAVITIES*

F. Marhauser[#], A. Burrill, K. Davis, D. Forehand, C. Grenoble, J. Hogan, R. Overton, A. Reilly, R.A. Rimmer, M. Stirbet, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, U.S.A.

Abstract

The 12 GeV upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Laboratory (JLab) is under way. All cavities have been built by industry and are presently undergoing post-processing and final low and high power qualification before cryomodule assembly. The status is reported including fabrication-related experiences, observations and issues throughout production, post-processing and qualification.

INTRODUCTION

By completion of CEBAFs presently ongoing upgrade activities it will have doubled the beam energy to 12 GeV, upgraded and expanded the beam transport systems, doubled the capacity of the central helium liquefier (CHL) and added a new experimental hall (D) and beamline for up to 5½ recirculating passes (figure 1).

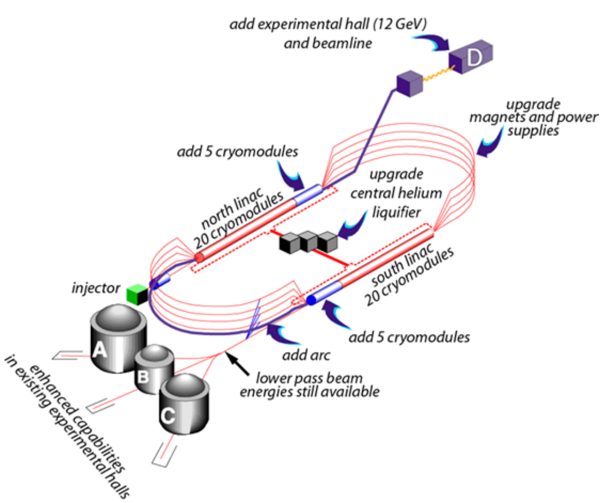

Figure 1: Layout of CEBAF indicating planned upgrades.

Ten new cryomodules (CM) will boost the energy gain per linac from 0.6 GeV to 1.1 GeV, i.e. with only a quarter of the existing quantity. This is facilitated by an increase of the cryomodule active RF length from 4m to 5.6m utilizing eight seven-cell Low Loss (LL) cavities (see Fig. 2). These will be operated nominally at an accelerating field of $E_{acc} = 19.2$ MV/m aiming for an unloaded quality factor of $Q_0 = 7.2e9$ at 2.07 K. Each cryomodule can then achieve 100 MV effective voltage ("*C100*"), de facto 108 MV leaving 10% contingency overhead. The cryomodule dynamic and static load at 2 K is budgeted to 300 Watts. Similarly, 400 Watts are taken into account at the inner 50 K radiation shield [1]. The additional cryogenic demands necessitate an upgrade of the existing CHL plant. Note that CEBAFs CW operation requires both DESY-type HOM coupler RF feedthroughs to be anchored to the He return pipe (see Fig. 3) for conduction cooling to avoid quenching of end groups [2].

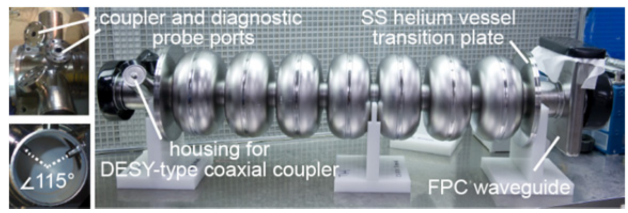

Figure 2: CEBAF 1.5 GHz upgrade type cavity (*C100*).

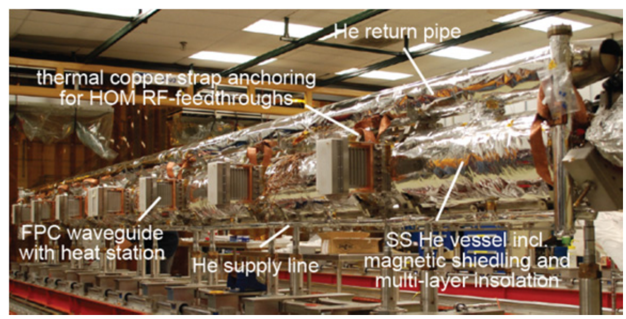

Figure 3: Cryomodule cold mass on the assembly rail.

FABRICATION AND POST-PROCESSING

Though JLab incorporates the infrastructure for SRF cavity production, it was decided to outsource the *C100* cavity fabrication to industry to free up sufficient resources for cavity and cryomodule qualification, assembly, acceptance testing and commissioning. A statement of work for the cavity assemblies was outlined in June 2008 covering the baseline material procurement and cavity production requirements per JLab specifications, which was followed by a call for tender and evaluation of bids received from industrial vendors. The contract was awarded to Research Instruments (RI), Germany [3], who officially commenced with the fabrication of 80 *C100* cavities plus six spares in July 2009. By January 2010, the statement of work was amended to add a post-production chemical cleaning of cavities by bulk Buffered Chemical Polishing (BCP) with subsequent final tuning. This aimed to guarantee the delivery of pre-tuned cavities built to a reasonable set of RF relevant requirements and to geometrically tolerable dimensions. Yet, the vendor was freed from responsibilities to comply with high power performance

*Work authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
[#] now at Muons, Inc., e-mail: frank@muonsinc.com

specifications. All 86 cavities were delivered successively within July 2010 to March 2011. Per specification, the cavities were tuned to a warm target frequency (1494 MHz ± 100 kHz) with a fundamental mode field flatness complying to maximally ± 5% peak amplitude deviation from the averaged peak field amplitude.

Upon delivery, cavities undergo thorough inspection, post-processing and detailed RF qualification procedures. This comprises individual testing of cavities in the Vertical Test Area (VTA) and - once succeeded - horizontal acceptance testing of cavities after cryomodule string assembly in the Cryomodule Test Facility (CMTF) before installation and commissioning in CEBAF.

Cavity pre-qualification includes visual inspection of sealing surfaces, the geometrical inspection of cavity dimensions and interface locations, a check of the cavity straightness as well as field profile and frequency measurements (in air) at reception and after various post-processing steps. A final fundamental mode field flattening is done in loop with mechanical corrections in case geometrical dimensions are unacceptably out of tolerance. For field profile measurements, a standard bead-pull technique is employed obeying "no-touch" principles. After final tuning, field profiles of prominent Higher Order Modes (HOMs) are measured. This quality control was implemented to reveal potentially tilted dipole HOMs. In fact, a large volatility in HOM-damping efficiency was experienced in the past [4]. The qualification also includes HOM dipole passband surveys in the VTA prior to cryomodule installation.

For chemical post-processing, an alteration to previous baseline procedures was adapted. Hereby a final light Electropolishing (EP) instead of BCP has been proven to provide excellent results in pushing E_{acc} beyond project requirements by mitigating the medium field Q_0-slope [5]. Its success has been consolidated among a series of in-house produced upgrade type cavities ([4], [6]), such to become an established measure for *C100* cavities. The now routine post-processing steps include ultrasonic degreasing of the surface in water-soap detergent (micro-90), a vacuum furnace heat treatment for hydrogen degassing (600ºC for 10 hrs.), the light chemistry by EP (~30 µm surface removal), ultrapure high pressure water rinsing (HPR, 1250-1300 psig), class 10 clean room assembly and a final in-situ bake-out (120ºC for 24 hrs.).

EXPERIENCES AND ISSUES

In the following, experiences and main issues throughout cavity production, qualification and post-processing are detailed.

All cavities were fabricated from RRR > 250 fine grain niobium sheets using standard deep drawing and electron beam welding techniques. The procurement of stainless steel required for the tee brazing of the helium vessel transition end plates (cf. Fig. 1), NbTi alloy for cavity flanges and Nb material for coupler housings ordered from Heraeus [7] proceeded without issues. However, a delay concerning the cell material procurement was encountered, which has been sub-contracted by RI in equal shares to the niobium suppliers Tokyo Denkai and ATI Wah Chang [8]. The latter failed to deliver Nb sheets according to RRR > 250 specification due to technical problems, which kept unresolved after several months. To prevent further delays, the contract was terminated by March 2010, and the remaining cell material was re-ordered from Tokyo Denkai.

Meanwhile, electron beam welding procedures and deep drawing tools were approved granting the fabrication for the first half of cavities. During fabrication, parts are immersed in BCP solution for cleaning prior to electron beam welding, which typically removes about 50 µm from the interior. A vertical bulk BCP of the completed cavity - circulating the acid - aims to remove oxides and residues from the welding process within a surface damage layer of ~100 µm. This post-production etching has been qualified in May 2010 with two LL cavities built at JLab shipped to RI. The bulk BCP turned out to deliver a consistent and relatively uniform removal along cells as desired thanks to the use of an acid stirrer system. Since the frequency shift by bulk BCP is significant (~ 1.2 MHz), it was fed back to tuning rationales at the end group/dumbbell trimming stage.

At project start, JLab provided a set of drawings that was translated by RI for internal use during fabrication. Two translation errors slowed down the initial cavity production for several weeks. Firstly, the HOM coupler coaxial ports and housings - already completed in full - have been inadvertently built to TESLA cavity coupler dimensions (1.3 GHz). Fortunately, the geometrical deviations to JLab's 1.5 GHz scaled versions present a negligible loss in the broadband HOM damping efficiency. This was verified by RF calculations and VTA HOM surveys using the first two cavities produced. A major fabrication delay could thus be averted. Secondly, an undersized helium vessel (HV) transition end plate diameter was inadvertently introduced, which affected the first seven cavities produced until discovery. This postpones their assembly in cryomodules since the HV welding with proper alignment could not be guaranteed in time. To transition from the undersized diameter to JLab's HV design, RI provided custom made stainless steel heads by December 2010 at no additional cost.

Another issue was related to the HV head fabrication conducted at Spuncast [9]. Unfortunately, JLab has specified the material to SS316L grade without denoting the ferrite content or permeability requirements. In fact, the vendor added 14% ferrite to ease casting. This has left a significant residual magnetic field. A VTA mock-up with one existing LL cavity revealed that it would have resulted in unacceptably low Q_0-values for *C100* cavities. The problem has been discovered early enough to modify the contract at the expense of rejecting the first batch of 18 delivered heads.

Two further concerns were expressed in connection with airborne and ground transportation of completed cavities. Firstly, several cavities were shipped with inadequate FPC flange protection. Two cavities experienced severe scratches and nicks during transportation and were sent back for repair (C100-RI-26, C100-RI-39). Note that the UHV sealing of this rather large rectangular flange - utilizing an AlMg serpentine gasket – is delicate and requires a pristine sealing surface finish ($R_a \leq 0.4\mu m$). A failure rate of ~20% to provide superfluid He leak tightness has been experienced through initial VTA-testing at the cost of major time delays. To overcome this issue, elaborate lapping of sealing surfaces is required.

Secondly, a mishandling during shipment of cavity pellets by the engaged carriers was evidenced by activated tilt and shock indicators. The involved transportation agencies were reluctant to provide further assistance to secure quality control. RI and JLab decided to equip the last cavity shipment with a GPS-module and data logger. This revealed that (un-)loading of pellets into trucks at airports triggered severe responses that were analysed as "free-fall" events (!). Though cavities were cushioned appropriately within containers, potential cavity deformations - not visible upon reception - may materialize upon subsequent cavity qualification. E.g. field profiles for some cavities - yet within tolerance at the manufacturer's site - were found to be out of tolerance, though remedied by further post-production tuning. A series of cavities also showed tilted HOM fields for crucial TM_{111} mode pairs. Corresponding impedances for one cavity exceeded the allowable impedance threshold for beam breakup instabilities and was rejected from further usage.

In no case however can the connection to mishandling been proven unambiguously. Apart from cell fabrication tolerances, this is hindered by the fact that *C100* cavities are known to distort easily during handling scenarios such as moving, lifting and rotating for bench tuning, chemical treatment, high pressure water rinsing, bake-out and (dis)assembly (from)/in a vertical test cave and HV welding. All scenarios have shown to impair the frequency and field flatness ([10], [11]) and enforced improved quality assurance throughout post-processing.

The mechanical weakness of *C100* cavities is a consequence of omitting cell stiffening rings - yet in use for prototypes - as a trade-off to facilitate mechanical tuning by lower torque, low-cost warm motors. The weakness also elevates microphonics in cryomodules to a level of concern as experienced recently.

VTA RF QUALIFICATION

Fig. 4 comprises the VTA RF high power qualification results of so far tested 33 cavities inside helium vessels. The colors indicate different field emission (FE) radiation regimes as measured at the dewar. It should be mentioned that FE induced trips are the main operational constraints in CEBAF. The onset of FE, yet distinguishable from the background, has been categorized at FE >0.0001 mSv/hr. Test were typically aborted, when radiation levels exceeded 1 mSv/hr to prevent from potential field emitter explosions and associated non-recoverable surface damages. Note that an operational limit to cease testing at E_{acc} = 27 MV/m was obeyed in most cases to accelerate qualification throughput and mitigate risks, even in absence of FE without encountering a quench. All cavities exceeded the specification. This is also true for the achieved Q_0-values (not shown), which typically ranged around 1e10 at 20 MV/m. So far, two cavities did not qualify to proceed for HV welding, namely C100-RI-08 (damaged by nozzle of misaligned HPR wand) and C100-RI-16 (exhibiting strongly tilted HOMs).

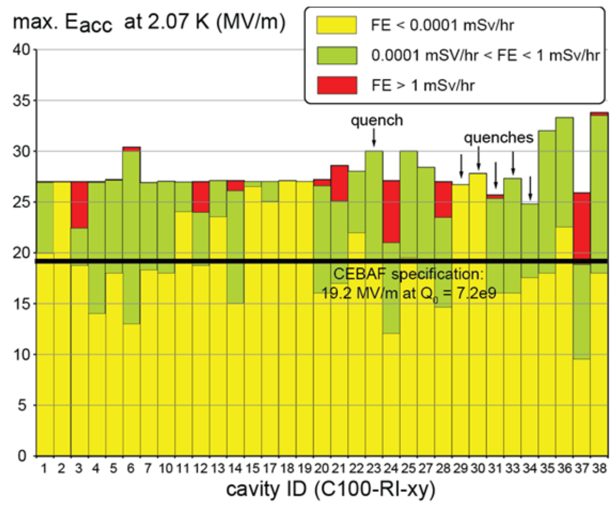

Figure 4: VTA performance of *C100* cavities.

DISCUSSION

A fabrication and testing status of cavities for the 12 GeV upgrade program currently conducted at JLab has been presented. All 86 cavities have been produced by Research Instruments (Germany) and delivered to JLab by March 2011. So far, 33 cavities were successfully qualified with helium vessels, 16 of which have been assembled already in the first two cryomodule strings (C100-1, C100-2) awaiting final acceptance testing. Present concerns are concentrated on elevated microphonics and tilted HOM field profiles.

As part of fabrication protocols, several issues have been disclosed, which might be useful information for the accelerator community. Their mitigation was addressed by quality assurance programs conducted as best as practicable with shared responsibilies between Research Instruments and JLab.

REFERENCES

[1] E. Daly et al., Proc. PAC03, TPAB077.
[2] C.E. Reece et al., Proc. SRF07, WEP32.
[3] http://www.research-instruments.de/.
[4] F. Marhauser et al., Proc. LINAC10, THP009.
[5] C. Reece et al., Proc. LINAC10, THP010.
[6] F. Marhauser et al., these proceedings, MOPC113.
[7] www.heraeus.com.
[8] www.wahchang.com.
[9] www.spuncast.com.
[10] F. Marhauser, technical note JLAB-TN-10-021.
[11] F. Marhauser, these proceedings, MOPC115.