FABRICATION AND TESTING OF THE SRF CAVITIES FOR THE CEBAF 12 GEV UPGRADE PROTOTYPE CRYOMODULE *RENASCENCE**

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Abstract

Twelve seven-cell niobium cavities for the CEBAF 12 GeV upgrade prototype cryomodule *Renascence* have been fabricated at JLab and tested individually. This set includes four of the "Low Loss" (LL) design and eight of the "High Gradient" (HG) design. The fabrication strategy was an efficient mix of batch job-shop component machining and in-house EBW, chemistry, and final-step machining to meet mechanical tolerances. Process highlights will be presented. The cavities have been tested at 2.07 K, the intended CEBAF operating temperature. Performance exceeded the tentative design requirement of 19.2 MV/m CW with less than 29 W dynamic heat dissipation. These results, as well as the HOM damping performance are presented.

HISTORY

The Thomas Jefferson National Accelerator Facility (Jefferson Lab) is preparing for an upgrade of the CEBAF accelerator to 12 GeV.[1] Over the past several years, a sequence of cryomodules have been designed and constructed toward the aim of maximizing the CW accelerating potential of each unit, compatible with the existing CEBAF infrastructure.[2,3] Improvements over the original cryomodule design include increased filling factor, more precise tuning control, higher power capable input couplers, and modified HOM damping schemes. [4] Two new cavity shapes have also been developed for potential use in the 12 GeV Upgrade.[5] Each has particular attractive features.

The final prototype cryomodule for the Upgrade, named *Renascence*, is in final assembly. The fabrication experience and qualification testing of the cavities for this cryomodule are reported here. At the time of the launch of the project neither a HG or LL design cavity had yet been built. To preserve options and learn, the decision was taken to include both cavity designs in *Renascence*.

FABRICATION

A batch of four LL and five HG 7-cell cavities for *Renascence* were fabricated at Jefferson Lab. From this batch eight were selected for inclusion in the cryomodule. An additional three HG cavities were fabricated as a follow-on effort for potential FEL application. All of these cavities were constructed in a "production style" manner from batched build-to-print components.

Material

The cavities were made from bulk niobium sheet with RRR ~430. Cells, HOM cans and coupling hooks, FPC waveguide bodies and beamtubes were all high RRR material. All flanges were $Nb_{55}Ti$, as were the transition rings welded between the cavity and titanium helium vessel.

Fabrication Strategy

The production strategy included a mixture of in-house (I) and local job-shop (O) fabrication steps.

- Press half-cells I
- Trim half-cells O
- EBW irises of two half-cells I
- EBW stiffening rings I
- RF measurement gauge for trimming I
- CNC dumbbell trimming to frequency I
- Grind dumbbell RF surfaces I
- Beamline flange machining O
- Beamtube forming I
- EBW beamtube seam I
- T-ring and transition ring machining O
- EBW flange to beamtubes I
- EDM HOM coupler hooks O
- Draw HOM cans (4/cavity) O
- EBW hooks in HOM cans I
- EBW coupling tubes and flanges I
- Trim HOM cans and flanges I
- EBW endgroup subassemblies I
- Mill FPC flange on endgroup I
- EBW equators I
- Tune check I
- 4 × 50 μm BCP etch I
- 600 C, 12 hour bake (hydrogen degas) I
- Tune cavity I
- EBW final beamtube for finished length I

All EBW steps were preceded by light BCP cleaning. Standardized programs were used for all welds. The only systematic difficulty encountered was fit-up consistency problem that was resolved by resequencing the stiffening ring weld prep to follow the dumbbell iris weld. The cryo-pumped JLab EBW chamber assured a pressure of < 10^{-5} torr prior to welding. On one cavity, the location of the reference field probe port tube inadvertently fell on the beamtube seam weld. Subsequent welding of the tube to the beampipe resulted in a thin spot which produced a leak only after the cavity received its bulk BCP etch. The leak was successfully repaired.

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Attaining and Tracking Cavity Tune

The tune sensitivities of various operations were established and then exploited to attain the desired frequency with minimal inelastic tuning. (Table 1) The variance in as-fabricated, untuned cavities was 50 kHz.

The stability of field flatness was of some interest with the reduced cell-to-cell coupling of these cavity designs, 1.49% LL and 1.72% HG. There was no difficulty obtaining field flatness of better than 3%, and the (random) walk of flatness with handling, baking, chemistry, testing, and helium vessel welding was measured to be less than 1%. We conclude that 1.5% cell-to-cell coupling presents no challenges to such 7-cell structures. Changes to the cavity inelastic tuner mechanism improved maintenance of alignment tolerances. This had been a significant problem with earlier cavities. Cavity beam centerline and flanges need to be concentric in the finished cryomodule. Reference rings machined into the cavity/helium vessel transition plates provide registration for alignment apparatus.

Table 1: Tuning sensitivities

	HG	LL
Dumbbell trimming	7.60 MHz/mm	5.24 MHz/mm
BCP	6.8 kHz/µm	3.5 kHz/µm
Δf 300 K air to 2 K, unconstrained	2.77 MHz	2.75 MHz

PROCESSING

As the preparation of these cavities was interleaved with the production of SNS cryomodules, very similar processing procedures were applied. The following list outlines the sequence of assembly, $HF:HNO_3:H_2PO_2$ (BCP) acid etch, and high pressure rinsing (HPR) with ultrapure water (UPW) that was used on these cavities.

- Degrease
- 20 µm BCP 1:1:2 @ 10°C
- 62 C UPW rinse to >17 MΩ-cm resistivity
- HPR 2x2 hours with fan spray nozzle
- Flange assembly (HOMs, FP, FPC tophat)
- HPR 2x2 hours with fan spray nozzle
- Overnight static drying in Class 10 environment
- Assembly
- Pumpout with clean vacuum system
- Leak check
- Sealed vacuum
- VTA test with coax/waveguide tophat $Q_1 \sim 7\times10^9$
- Option for 120°C bake, 48 hours and retest
- Final tuning
- Helium vessel welding

Final preparation for cryomodule cavity string:

- Degrease
- 20 µm BCP 1:1:2 @ 10°C
- 62 C UPW rinse to >17 MΩ-cm resistivity
- HPR 2x2 hours with fan spray nozzle
- Flange/feedthrough assembly (HOMs, FP)
- HPR 2x2 hours with fan spray nozzle
- Overnight static drying in Class 10 environment
- Assembly on string for cryomodule

TESTING

The cavities were tested in the JLab Vertical Test Area (VTA) and evaluated in several aspects:

- Verify fundamental frequency tune at 2 K
- Verify absence of multipacting limitations
- Verify setting of field probe coupling (Q_e=1×10^{12})
- Verify absence of quench-inducing defects
- Verify rf surface material quality – Q_0
- Assess the quality of preparation and assembly techniques and systems – field emission free?
- Qualify HOM coupler probe/feedthroughs
- Measure HOM frequencies and damping

Confident frequency control was demonstrated and, as predicted by simulation, no multipacting was observed in the HG or LL cavities. Some of the cavity tests were limited by field emission-induced effects, either Q_0 degradation or quench above 19 MV/m. When the processing systems were known to be in good working order and assembly techniques were smoothly followed, we attained excellent performance from all of the cavities. Figures 1 and 2 summarize the qualifying performance of each of the cavities tested. The 2 K heat quota allocated to each cavity in the 12 GeV upgrade project is 29 W CW. The $Q:E_{acc}$ contours that reflect this criterion are included in the figures. The project required average gradient specification is 19.2 MV/m, which was just met in these tests by the set of cavities selected for the *Renascence* cryomodule.

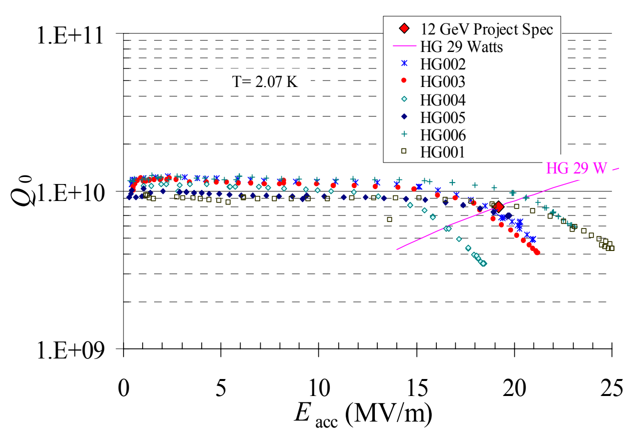

Figure 1. Qualification vertical tests of the High Gradient (HG) cavities.

Since the intended operating condition for the 12 GeV upgrade is 2.07 K, the tests were performed at that temperature, and the Q_0 of the cavities was largely BCS limited. The source of the droop of Q_0 above ~18 MV/m has not been established. It was not associated with field emission loading. The droop also remained unchanged after a few of the cavities received a 48 hour bake at 120°C, even though the low-field Q_0 increased in the expected manner. (See the cavities LL002 and LL004 in Figure 2.)

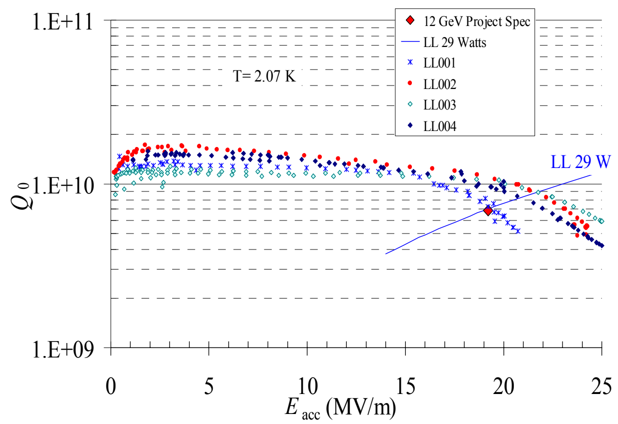

Figure 2. Qualification vertical tests of the Low Loss (LL) cavities.

HOM Damping

The 460 µA CW operation of 12 GeV CEBAF leads to modest requirements for damping of higher-order modes (HOMs) in the accelerating cavities. Simulation studies have yielded a frequency-independent specification for the shunt impedance of dipole modes in each cavity of $< 6.2\times10^8\ \Omega$ to avoid beam breakup (BBU) instability thresholds.[6] To provide confident damping even with the potential for as yet uncharacterized "field tilt" of HOMs, the decision was made to include two HOM couplers on each end of each cavity. The couplers are an adaptation of the loop coupling DESY/Saclay design for TTF that incorporates a notch filter rejection of the fundamental.

3-D modeling analysis of the fields in the coupler indicate that amplitude of surface magnetic fields on the out-coupling probe are ~10% of the peak fields in the accelerating cells.[7] To sustain these fields without dominating losses dictates that the probe must be superconducting. A development program was required to produce an rf feedthrough that provided adequate thermal conduction through the sealing dielectric to stabilize the Nb superconducting probe. Two designs of such a feedthrough were realized and tested.[8]

One each of the HG and LL cavities were tested in the VTA with all HOM couplers installed and tuned. The loaded-*Q* of each HOM up to 3 GHz was measured. The damping of the dipole modes was found to be better than that required by more than a factor of ten for all modes. Figure 3 shows the resulting dipole mode impedances for a LL cavity. More detailed analyses of the HOM damping are planned during testing of the *Renascence* cryomodule. The adequacy of using only two couplers per cavity in future modules will be evaluated.

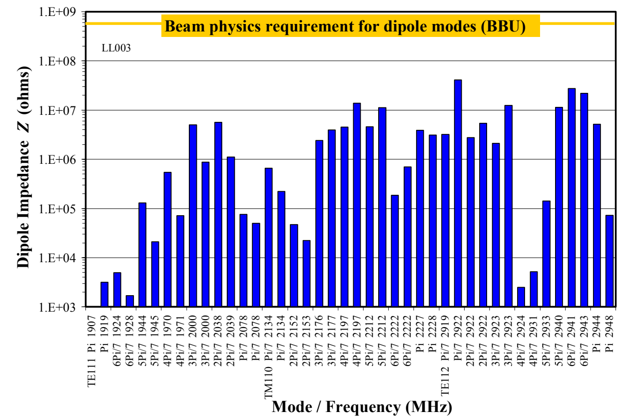

Figure 3. Impedance of dipole modes of 7-cell LL cavity LL003 with four HOM couplers in the JLab VTA. ($Z = (R/Q)_T \times Q_l$).

SUMMARY AND PLANS

The seven-cell HG and LL cavities for *Renascence* have been successfully constructed and tested. Performance, particularly of the LL cavities has well exceeded the minimum requirements for the CEBAF 12 GeV project. Production procedures are in hand.

The *Renascence* cavity string was assembled in February 2005, and the cryomodule assembly completion is expected in June 2005. Testing of the cavities in the cryomodule will follow, and accelerator installation is planned for September.

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