PERFORMANCE OF THE CEBAF PROTOTYPE CRYOMODULE *RENASCENCE* *

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Abstract

The prototype cryomodule *Renascence* was constructed as an energy building block for securing 6 GeV operation of CEBAF and to validate design elements for future CEBAF upgrade modules. These elements include the new “HG” and “LL” 7-cell cavity designs and a new tuner design.[1,2] Issues were identified during initial testing in 2005. The module has been reworked to address the issues with thermal stability, component breakage, and tuner motion. In addition, opportunity was taken to employ upgraded cleaning and assembly techniques for the cavity string. The HOM coupler heating issue was resolved, and seven of the eight cavities in the cryomodule have run stably at an average of 20 MV/m CW. The cryogenic, rf, and mechanical performance of the cryomodule are presented. Commissioning in CEBAF has just been completed in October 2007.

INTRODUCTION

Building on the experience from two previous intermediate upgrades [3,4], *Renascence* incorporated two new cavity designs, a new tuner design, and several other improvements (He riser size, radial wedge clamp on beamline between cavities, 1st CEBAF cryomodule with no use of In gaskets, serpentine Al gaskets on the rectangular waveguide flanges, heat shield refinements, maximized HOM damping…)

- Two optimization criteria were used for the LL & HG cavities.
  - The HG design minimized E_{pk}/E_{acc}.
  - The LL shape reduced cryogenic load.
  - The endgroups of the two cavity types were identical, two HOM couplers close in on each end of the cavity.

At the time of project initiation, in the midst of SNS CM production, it appeared that *Renascence* would also serve for a term in the JLab FEL, so efforts were made to maximize the HOM damping, beyond the particular requirements for CEBAF. The cavities for *Renascence* were developed, fabricated, and qualified in 2002-2004. During that time it was recognized that the amplitude of fundamental fields present in the HOM couplers dictated the use of a superconducting coupling probe. To fill this need, a custom high thermal conductivity probe feedthrough was developed. [5]

Cryomodule assembly took place in 2005. Initial testing encountered serious problems. Focus shifted to careful diagnosis of the problems and their remediation.

Renascence has subsequently been reassembled, tested and commissioned for beam operation in CEBAF.

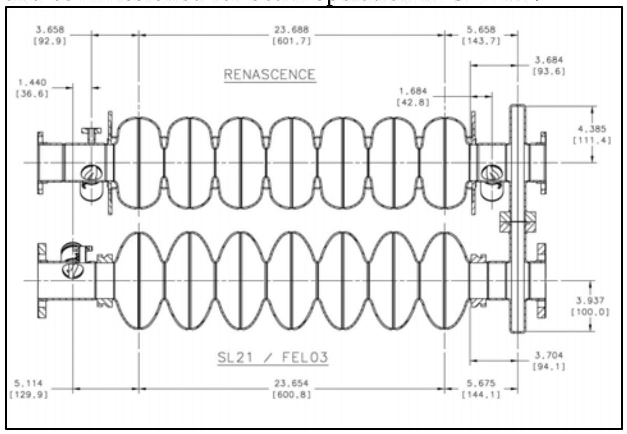

Figure 1. Comparison of the LL cavity geometry, including endgroups, used in Renascence, with the 7-cell OC geometry used in previous upgrade cryomodules.

PERFORMANCE AND PROBLEMS ON FIRST TEST

Feedthrough leaks sub 70 K

Instrumentation feedthroughs between insulating vacuum and liquid helium process line developed leaks during cooldown and below their acceptance leak check temperature of 77 K. The feedthroughs were removed *in situ* and the associated ports were blanked off.

The leaks were attributed to differential contraction stresses created by excessive potting of G-10 lead spacers with epoxy. That leaks only appeared at very low temperatures was quite unexpected. Subsequently used instrumentation feedthroughs returned to a previously qualified configuration.

End group quenching

Although all of the cavities had previously passed acceptance testing in individual vertical tests, quenching was encountered at low gradient during CW testing of all cavities.

A few of the HOM rf feedthrough temperatures were monitored and found to be excessive under static cryogenic conditions. (6.8 – 7.4 K). The heat conducted via the rf cable (subsequently found to be ~38 mW) and the relatively high thermal impedance between the feedthrough and the cavity beamtube yield these high static temperatures.

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Under all circumstances with rf in a cavity, when an HOM probe feedthrough temperature reached 8.2 – 8.5 K, the interior Nb probe went normal and the feedthrough temperature rose dramatically (60 – 90 K) prior to the cavity proper quenching.

Cavity response was much better in pulsed rf conditions 10% duty cycle. See Figure 2.

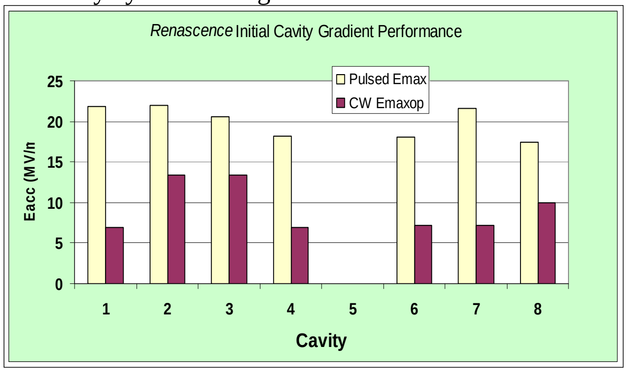

Figure 2. Initial *Renascence* cavity performance under CW and pulsed rf conditions.

To thoroughly characterize the problems, the cryomodule was warmed and a set of instrumentation and thermal clamping was added *in situ*. Heaters were added to several of the HOM feedthroughs and potential heat sources. The module was then recooled and tested. These tests and their analysis are described in another contribution to this workshop.[6]

Tuners

The mechanical tuner provides the capability of both coarse and fine tuning of the seven-cell cavities. The cavities are tuned in tension. The entire mechanism is attached to the helium vessel that surrounds the cells of the cavity. When coarse tuning, the motor (orange) spins, the drive screw (blue) actuates the primary lever (purple) which changes the cavity length thereby changing the cavity frequency. Moving the primary lever toward the motor will raise the frequency of the cavity. The mechanical advantage is ~30:1.

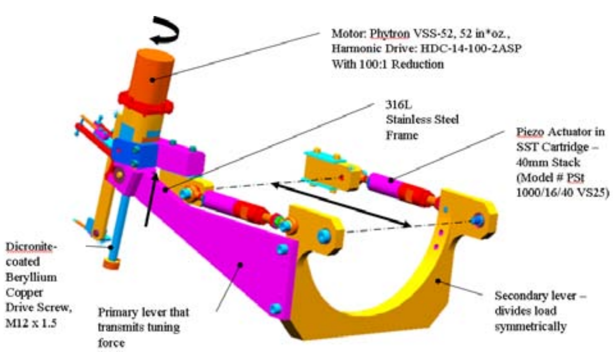

Figure 3. Tuner used in the *Renascence* cryomodule

- Two of the mechanical tuners bound up during the first test.
- The addition of a swivel in the tuner linkage during the rework reduced asymmetric loading on the mechanical linkage to eliminate the binding.

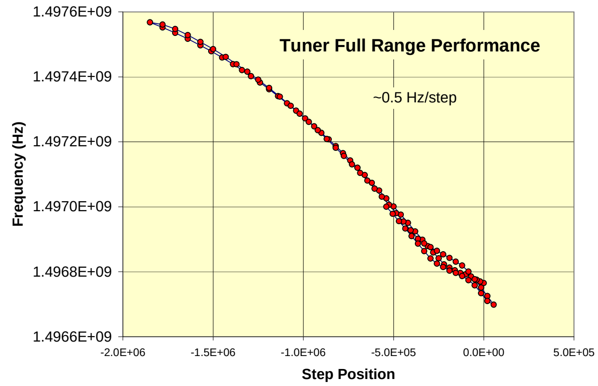

Figure 4. Mechanical tuner range

a. Piezo tuner response
   - 0.35 – 0.6 Hz/volt

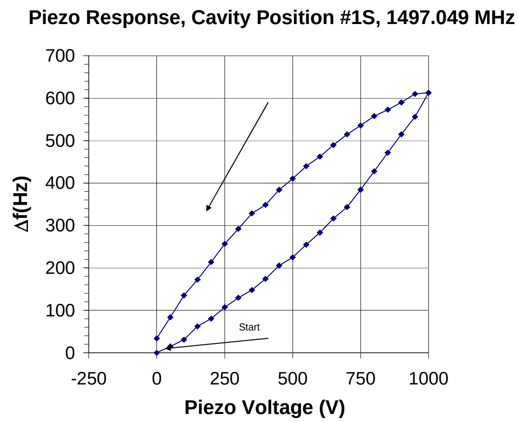

Figure 5. Piezoelectric turner range.

Leaking rf window

The warm ceramic window on cavity 5 was found to leak through the brazed interface between ceramic and Nb eyelet, so that cavity was inoperable for the initial round of testing.

HOM coupler MP one cavity

During pulsed rf testing, evidence of multipacting interior to one HOM coupler was observed on cavity 3. At 17.9 MV/m the fundamental power emitted from one coupler departed from linearity with respect to the normal stored energy response maintained by the power emitted from the field probe and the other HOM couplers. In addition, anomalous heating was observed on the exterior of this HOM can body, while not on the top of the can or its coupling probe. This data is interpreted as multipacting occurring on the coupler interior hook.

After subsequent high pressure rinsing following disassembly of the cryomodule, this anomalous behavior was no longer present.

HOM damping

Even though operation in the fundamental mode was precluded by the thermal limitations, a full characterization of the HOM damping provided by the four couplers per cavity was accomplished. In addition, the HOM damping produced by the couplers on the field probe end of each cavity was measured. When the cavity design was commissioned there was concern that with reduced cell-to-cell coupling there would be increased risk of trapped or “tilted” modes that would be inadequately damped by couplers only on one end of the cavity. Figure 6 shows the dipole mode shunt impedances derived from the 4 and 2 coupler measurements. These measurements demonstrated that sufficient damping was provided by the two couplers on one end of the cavity.

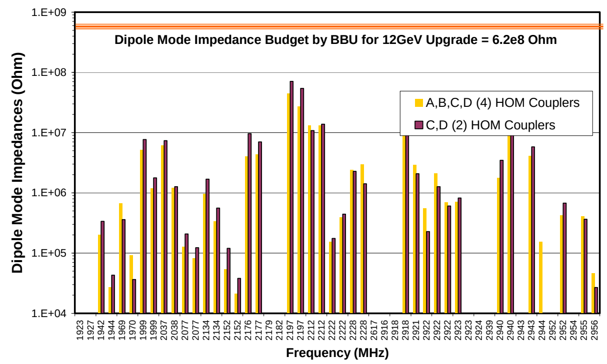

Figure 6. *Renascence* LL cavity dipole HOM impedance with two and four HOM couplers.

Microphonics

The Cavity Resonance Monitor was used to measure the cold (2K) cavity RF resonant frequency shift in the CMTF test cave. A 1 watt amplifier was used to drive the cavity CW via a VCO/PLL. A 50000 point histogram at 1 ms per sample was performed. Typical results are shown in Figure 7. Experience indicates that the CMTF is a noisier environment than the CEBAF tunnel by a factor of approximately two.

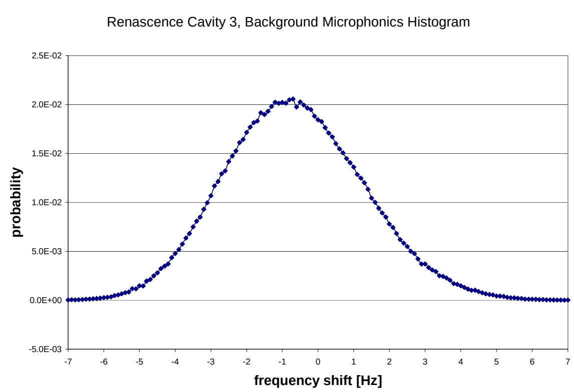

Figure 7. *Renascence* LL cavity detuning histogram

As part of ongoing research into cavity mechanical vibration response, modal testing of one cavity was performed and repeated at various stages of the cryomodule assembly. During the fabrication process, one cavity was instrumented with four accelerometers rated for cryogenic (LN2) temperatures. The four accelerometers were attached to four adjacent cavity stiffening rings (located at the iris of each cell). An initial modal response test was performed before welding on the He vessel. This modal response test was repeated at subsequent milestones of assembly: string assembled into the space frame, space frame loaded into the cryostat, and cryomodule cooled down to 4K. One accelerometer failed during He vessel welding and the remaining three sensors failed when cooled to 4K. A comparison of the vibrational modes predicted by modeling with those measured during warm testing is summarized in Table 1. Failure of the accelerometers during cooldown prevented the culmination of the test series: correlating measured cavity vibration with measured cavity detuning (microphonics) at operating temperature.

The cavity RF detuning response to swept sinusoidal excitation from the piezo tuner was measured and is shown in Figure 8. The spectrum is very crowded and exact correlation with measured cavity mechanical resonances is impossible without the cold modal test that was planned. The hypothesis is that some peaks correlate with cavity mechanical resonances, while other are caused by ancillary structures such as nitronic rods, tuner arms, and even the vacuum vessel modes.

Table 1. Predicted and measured lowest vibrational modes of *Renascence* LL cavity.

Mode	Predicted Natural Frequency (Hz)			Measured Natural Frequency
	Shape	Cryo	Room Temp	Room Temp
1	bending	101	92	78
2	bending	275	251	239
3	axial	355	324	374
4	bending	503	459	410
5	axial	704	642	692
6	bending	744	679	782

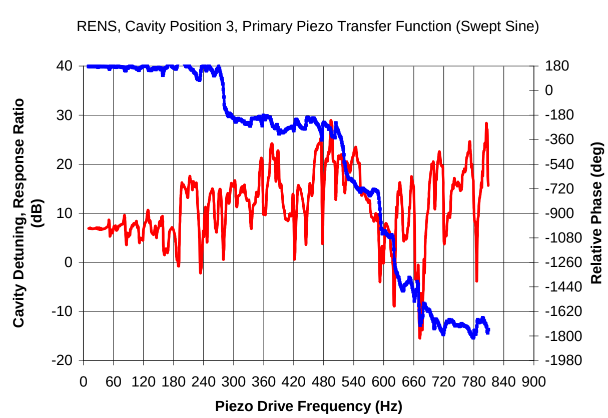

Figure 8. *Renascence* swept sine vibration response

Thermal performance of input waveguide

This cryomodule is designed for operation of each cavity near 20 MV/m with ~8 kW CW from dedicated 13 kW klystrons. This power is coupled to each cavity via a transition waveguide between room temperature and 2 K. These transition units consist of copper-plated stainless steel, with two bellows and an intermediate 50 K heat station.

The thermal profile and heat loads predicted by a one dimensional finite difference model for 8 kW of RF are shown in Figure 9 below together with measured temperatures from one instrumented unit. The waveguides performed as expected.

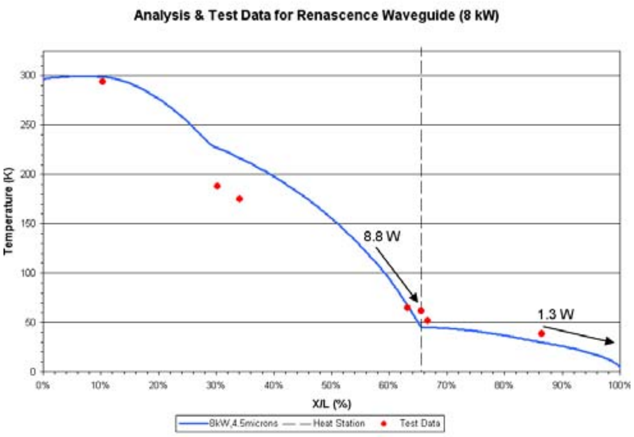

Figure 9. Thermal profile of Renascence input waveguide under 8 kW standing wave conditions.

REWORK

The *in situ* instrumentation modifications successfully revealed the source of the performance issues and indicated the route to correction. Since the HOM damping measurements demonstrated the adequacy of using only two HOM couplers, the decision was taken to remove the two unnecessary coupling probes which were also placed in the most vulnerable thermal location.

In principle, this probe removal could have been accomplished without full disassembly of the cavity string. To minimize the risk of particulate contamination, however, the decision was taken to fully disassemble the string and High Pressure Rinse (HPR) each cavity again following probe removals.

Process for rework

The cryomodule was returned to the assembly room and disassembled down to cavity string and helium circuit. The helium piping attached to each cavity helium vessel was stabilized and then parted. The string was then passed back into the cleanroom, where it was backfilled with dry nitrogen and the two HOM probes were removed from each cavity.

Two cavities include cavity #3 which had exhibited the multipacting in an HOM coupler, were HPR'ed and tested with helium vessel attached in the VTA to qualify the handling process. No acid etch was applied during the rework.

The waveguide/window assemblies were dismounted and cleaned and the leaking rf window was replaced. The cavity string was reassembled and passed back to the cryomodule assembly area.

Design changes implemented

In order to provide confident thermal anchoring of the remaining HOM feedthroughs a few design changes were implemented in the rebuild of *Renascence*. Copper straps were used to anchor the individual feedthroughs to 2 K supply piping and thermal intercepts for the HOM rf cables were developed and implemented. These consisted of rf stripline units using high-purity alumina substrates to establish a thermal anchor for the inner conductor.

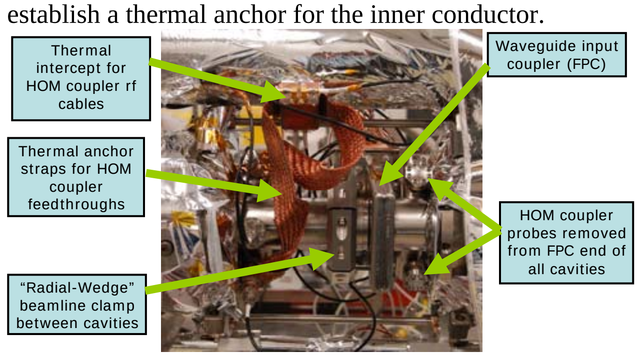

Figure 10. Final configuration of HOM probes and thermal anchoring in *Renascence*.

FINAL PERFORMANCE

Acceptance testing

Renascence was completed and tested in summer 2007. Seven of the eight cavities performed very well. The remaining HOM feedthroughs were monitored and their temperatures typically increase by 0.2 K between rf off and maximum gradient conditions. Cavity number 7 showed dramatic degradation in quality factor, to the point of being unusable. Attribution of the degradation is uncertain; investigation centers on the high pressure rinse operation applied to that cavity.

The maximum quench gradients obtained are depicted in Figure 11, together with stable 1 hour run conditions from the CMTF test.

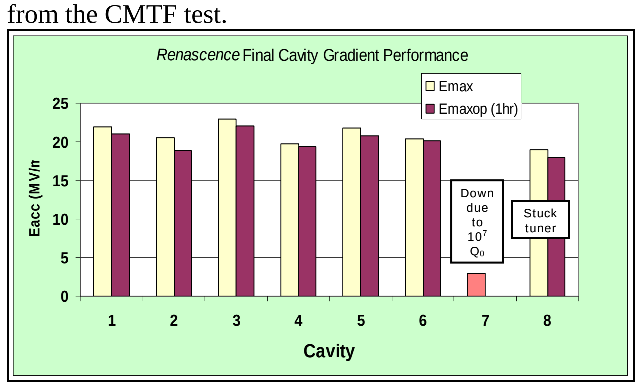

Figure 11. Final cavity performance during acceptance testing

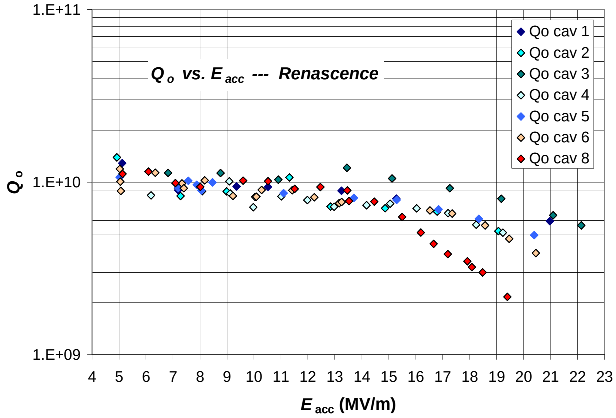

Figure 12. Cavity Q_0 measurements from Renascence acceptance testing.

The Q values verses accelerating gradient are presented in Figure 12. These Q_0 measurements are lower bounds for actual operating conditions due to the particular technique used. The helium pressure during measurements ranges 32 – 38 torr (temperature varies during measurement 2.11 – 2.17 K). The design operating pressure is 29 torr (2.07 K). At 2.15 K one expects the BCS-limited Q_0 to be 7-8 $\times 10^9$.

Other performance features

- HOM coupler Q_{ext} were stable and $> 10^{12}$
- Static heat load to 2K: 27.5 W
- Pressure sensitivity (cavities have stiffening rings)
  - HG – 50 Hz/torr
  - LL – 52 Hz/torr
- Static Lorentz detuning for both LL and HG cavities: -1.0 Hz/(MV/m)^2
- Cavity 8 tuner failed to reach 1497 MHz, so is not operable in CEBAF.

Commissioning and operation in CEBAF

Renascence was installed in CEBAF in August 2007 and has been commissioned for operation. The operational voltage range is constrained by available rf power. The cryomodule was installed into an existing slot in the CEBAF north linac (NL04) with klystrons capable of up to 6.5 kW. The existing low level rf controls have been adapted to control these cavities. For the ~400μa linac currents planned in CEBAF, the six operable cavities can be sustained at 14 MV/m, providing 59 MV.

CONCLUSIONS

After serving as a learning vehicle for several new system designs, *Renascence* is now installed and operating in CEBAF. The thermal performance issues were successfully identified and remedied. The cavity performance levels set a new standard for CW SRF accelerators.

Tuner issues remain after the rebuild, and the decision has been taken to use the previously qualified tuner design in forthcoming cryomodules for the CEBAF 12 GeV upgrade. Building on the experience from Renascence, an optimized cavity configuration has been developed for use in the 12 GeV project. [7]

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