VIBRATION RESPONSE TESTING OF THE CEBAF 12 GeV UPGRADE CRYOMODULES*

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Abstract

The CEBAF 12 GeV upgrade project includes 80 new 7-cell cavities to form 10 cryomodules. These cryomodules were tested during production to characterize their microphonic response *in situ*. For several early cryomodules, detailed (vibration) modal studies of the cryomodule string were performed during the assembly process to identify the structural contributors to the measured cryomodule microphonic response. Structural modifications were then modelled, implemented, and verified by subsequent modal testing and *in-situ* microphonic response testing. Interim and latest results from this multi-stage process will be reviewed.

VIBRATION TEST PROGRAM

A vibration test program was conducted during construction of the first C100 cryomodules, with the goal of improving the operational vibration response of the cryomodules. Beginning with C100-4, a simple modification was introduced that reduces the peak microphonic detuning to less than one-half of the original project design requirements.

The 12 GeV project "budgeted" for 25 Hz peak total detuning (4 Hz static plus 21 Hz dynamic) based on the available klystron power (13 kW), the design Q_{ext} (3.2×10^7) for the fundamental power couplers, and maximum beam load (465 µA) [1]. Tuner performance allowed the static detuning budget to be reduced, allowing the full 25 Hz for the peak dynamic detuning. Operational experience in CEBAF has established a 6× rule-of-thumb between standard deviation to peak detuning, giving us approximately 4.2 Hz rms detuning (one σ, assuming a Gaussian distribution).

Commissioning of the cryomodules in CEBAF includes measurement of the ambient microphonic response of each cavity in the cryomodule using established procedures and test equipment [2]. Microphonics testing of the first unit (C100-1) met design goals marginally, but results were higher than expected based on prototype testing. C100-1, as measured during operation in the CEBAF tunnel ranged as high as 21 Hz peak detuning over a 500 second time period. Early measurements taken in the cryomodule test facility were even higher, but were eventually attributed to anomalous local driving sources in that facility. The last full upgrade-style pre-production cryomodule ("Renascence") measured less than 15 Hz peak detuning for all cavities in the cryomodule test facility (historically, half this amplitude would be expected in the CEBAF tunnel due to the different vibration environment found there). The most relevant design changes between the two modules comprised removal of the stiffening rings from the cavity design and a completely different tuner design.

A typical spectrum from one of the noisier cavities in the first production cryomodule (C100-1) is shown in Figure 1. The spectrum is dominated by the peak at approximately 10.5 Hz. This peak shows up in the spectrum of all eight cavities, and is typically highest in amplitude in the middle of the string (cavities 4 and 5), becoming lower in amplitude as you move out to the ends of the string (cavities 1 and 8).

Vibration testing of the CEBAF 12 GeV upgrade cryomodules comprised FEA modelling, modal testing of cryomodule components, and operational RF testing of the completed, cold cryomodules. The end goal was to improve our understanding of the vibrational response of the cryomodule to the extent that it affects RF performance, and to improve that performance with minimal risk to the 12 GeV project.

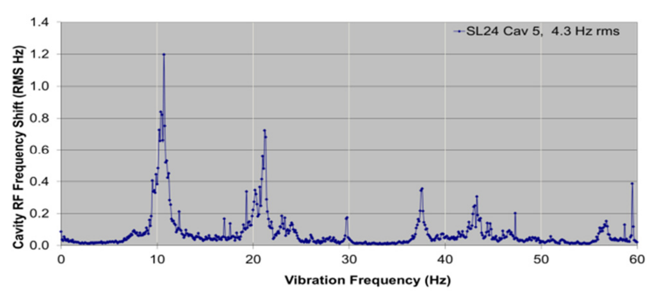

Figure 1: Spectra of Baseline (C100-1) Design

FEA Modelling

ANSYS™ finite element analysis software was used to create a 1-D simplified model of the string assembly. Once the model was validated against the modal test data, the model was used to vet various proposed design modifications including stiffening inside the cavity helium vessels, adding damping to the cavity string assembly, and changes to the cavity tuner. The conclusion of this analysis was that the tuner pivot plates were the least stiff component in the tuner assembly. Stiffening the pivot plate was judged to present low schedule, budget, and technical risk.

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Modal Testing

The second production cryomodule (C100-2) was instrumented with triaxial accelerometers during the assembly process [Figure 2]. Hammer impact testing was performed at various stages during the assembly process, beginning with the completed string of eight cavities suspended in its space frame, and ending with the finished cryomodule prior to cool-down. Because a complete cryomodule is such a complex mechanical assembly with limited internal access, waiting until the module is completed before testing makes it difficult or impossible to determine how individual components and subassemblies influence the vibration response of the completed cryomodule. Because of the extreme temperatures inside an operating cryomodule, cool-down marked the last opportunity to collect data from accelerometers on the cold-mass.

A parallel set of modal tests was performed using a single C100 cavity mounted to its tuner in a stand-alone test stand (the tuner test stand) [Figure 3]. The goal for this set of modal tests was to understand how these components contributed to the overall vibration response of the cryomodule, and to test various engineering solutions intended to improve the vibration response.

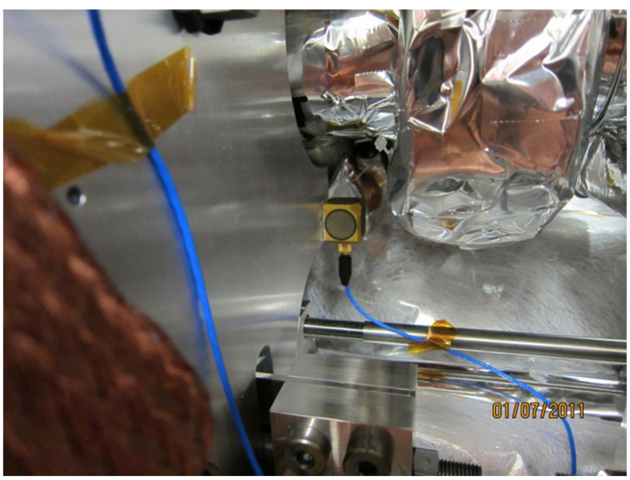

Figure 2: Accelerometer mounted to a tuner pivot plate during final assembly of the cryomodule.

TEST RESULTS

Results of String Modal Analysis

The following modes were identified as contributing to the operational microphonics:

1) First axial (10 Hz, beamline orientation) rigid body mode of the string: Center cavities have higher overall microphonics, most of which is accounted for by this mode. This effect is caused by the center axial nitronic rods, which impose a nearly fixed boundary at one end of cavity 4 and cavity 5. The warm tuner stacks actively participate in this mode, providing possible "hooks" to easily insert damping into the system.

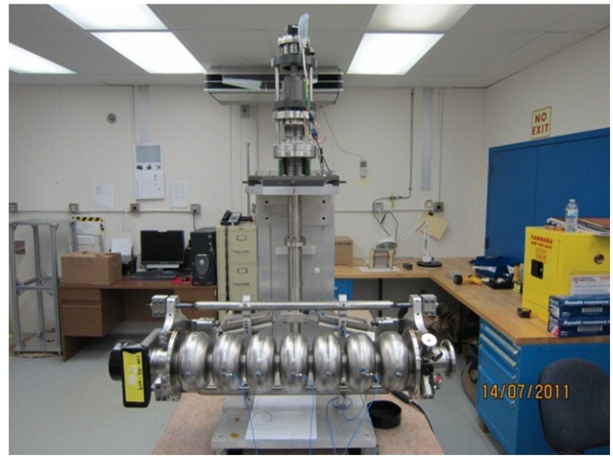

Figure 3: C100 Cavity in the Tuner Test Stand

2) Second axial modes of the string (20 to 25 Hz, varies with cryomodule): Each half-string (cav 1-4 or cav 5-8) has a mode where the four cavities move together, primarily in the axial (beamline) direction. The other half-string usually resonates at a slightly different frequency from cryomodule to cryomodule. The warm tuner stacks move very little in this vibration mode, any damping would involve changes to the cryomodule cold mass.
3) First bending mode of each individual cavity (40 to 45 Hz, varies cavity-to-cavity): The warm tuner stacks actively participate in this mode, providing possible damping "hooks" into the system.

Modified (stiffer) tuner plates were installed beginning with C100-4. The modal test of the cavity string was repeated during the assembly of C100-5. The results showed a decrease in the response at 10 Hz and between 40-45 Hz. The results also predicted a slight increase in response amplitude and frequency in the rage of 20-25 Hz.

Results of Tuner Test Stand Modal Analysis

In support of the investigation into microphonics on C100 cryomodules, a series of bench measurements were collected utilizing the tuner test stand [Figure 3]. The bench setup consisted of a bench-mounted C100 tuner, cavity, and in some test configurations, a helium vessel as well. The intent was to: perform a head-to-head comparison of several potential design modifications, experimentally define the vibrational modes of the system, and determine at what level measurements acquired on this fixture translated into actual performance of the tuner/cavity system in a fully assembled cryomodule. Because the boundary conditions on the bench are different than in the cryomodule, it was fully expected that the vibrational response would be different. But it was expected that at least portions of the system response would be similar enough that the results would prove useful to the overall study. The modifications that were studied include 1) a retrofit cell support device between the helium vessel and the cavity (both with and

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without a cryogenic damping mesh material installed), and 2) stiffened tuner pivot plates.

The vibrational response of the cavity with and without the support devices was substantially the same with only modest reduction in amplitude with the support device. The results of the testing with and without the stiffened tuner pivot plates showed more promise. The overall modal response between the two configurations was similar as far as mode shapes and resonant frequencies. The configuration with the stiffened arms resulted in reduced vibrational amplitudes for several modes and a significant reduction in amplitude for a lateral bending mode of the cavity.

Operational Testing of the C100 Cryomodules

As of July, 2012, four C100 cryomodules have been installed and commissioned in CEBAF. Two of these cryomodules (C100-1 and-2, baseline tuner design) have been used to deliver beam to physics experiments during the final 6 GeV run. C100-2 demonstrated the ability to meet the 12 GeV design goals of 108 MeV per cryomodule with 465 μA of beam loading. Two more cryomodules (C100-4 and -5, modified tuner design) were installed at the beginning of the 12 GeV Long Shutdown. They have not been used to accelerate beam [3].

Since all of the cryomodules have not completed their construction, it was especially valuable to perform a validation test of the design modification: to compare the vibration response of a baseline cryomodule and a modified cryomodule. Because microphonic response is somewhat variable as a function of time and position in the linac, direct comparison of existing microphonics data (measured weeks or months apart) was not ideal. A baseline cryomodule and a modified cryomodule were operated in adjacent zones in the CEBAF tunnel with all sixteen cavities simultaneously at 10 MV/m, using the normal accelerating operating mode (constant frequency, fixed gradient regulation). The results are summarized in Table 1. Comparing the spectra of this data for C100-1 vs. C100-5, the dominant frequencies are similar; the relative contribution of the 10 Hz and 40-45 Hz components has been substantially reduced, at the expense of a moderate increase in the 20-25 Hz components. The overall ambient microphonic response of the cavities improved (decreased) by an average of 42%. This data is consistent with commissioning microphonics data measured independently on C100-1 through 5.

Table 1: Operational Microphonics in the CEBAF Tunnel, Baseline vs. Modified Design (peak detuning, Hz)

Cryomodule	C100-1 (baseline)	C100-5 (modified)	% Improved
Cavity 1	11.8	5.1	57%
Cavity 2	12.8	6.7	48%
Cavity 3	13.7	5.6	59%
Cavity 4	13.5	7.4	46%
Cavity 5	18.0	9.6	46%
Cavity 6	9.1	8.5	8%
Cavity 7	9.7	5.6	42%
Cavity 8	8.9	5.8	35%

Other Operational Issues

CEBAF accelerator operations group have had six months experience with first two C100 cryomodules. During this time, operations worked closely with the Low-Level RF group to define and improve the control system parameters and user interface [4]. One remaining issue that may be related to vibration response and/or controls: when operating at or near the limits of klystron power (high gradient and high beam loading), a single cavity trip can lead to a cascade that trips some, or all, of the other cavities in the zone. When a cavity trips, the associated loss of Lorentz force causes a step detuning of that cavity. Such trips contain substantial high frequency mechanical energy that travels through the string detuning other cavities (all eight cavities are rigidly coupled to each other). In some cases, all eight cavities trip within a few seconds. The root cause of these trips and how to control them are operational issues that are still being studied. Thus far, this has not proven to be a significant factor reducing beam availability. We are studying control system changes to reduce these trips, and to improve the associated recovery time once a trip happens.

SUMMARY

The first four C100 cryomodules have been commissioned; the first two were used to deliver beam to the CEBAF physics program over a six-month period. The microphonic response of the first two modules was within design requirements, but higher than expected. A vibration test program was performed. Various proposed changes were analysed, resulting in production changes to the cavity tuner. The first two cryomodules incorporating these modifications have been commissioned and tests show, on average, a 42% improvement in operational microphonic response (less than half of the original 12 GeV design envelope). This tuner modification will be included in the last seven C100 cryomodules, scheduled to be complete by the end of 2012.

REFERENCES

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