PRODUCTION AND PERFORMANCE OF THE FIRST CEBAF UPGRADE CRYOMODULE INTERMEDIATE PROTOTYPE *

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Abstract

The first CEBAF Upgrade cryomodule intermediate prototype has been produced and installed in the CEBAF accelerator. It contains eight 7-cell cavities with the original CEBAF cell shape and was designed to deliver 70 MV. Several significant design modifications are demonstrated in this cryomodule. This paper describes the production procedures, the performance characteristics of these cavities in vertical tests, results of tests in the new cryomodule test facility (CMTF) as well as the commissioning in the CEBAF tunnel. The cryomodule showed gradient capabilities well beyond the design specifications in the CMTF. After its installation in the CEBAF accelerator, its performance suffers from some cryogenic limitations, which are discussed in this paper along with improvements proposed for future cryomodules.

CAVITIES AND CRYOMODULE PRODUCTION

In the framework of the the 12GeV CEBAF Upgrade and while the final design for a 100MV cryomodule is being developed [1], the first of two cryomodule of an intermediate design has been constructed in 2002. It was installed in the CEBAF accelerator tunnel in February 2003, replacing a 5-cell cavity CEBAF cryomodule.

Specifications [2]

This cryomodule supplies an average energy gain of 70MV at 2.04K. Many of its requirements (table 1) are very similar to the original CEBAF cryomodule [3]. An increased active length from 4 to 5.6 meters and an average operating accelerating gradient of 12.5MV/m provide the required energy gain. In order to operate at these gradients without exceeding the 2K refrigeration capacity, the quality factor Q_0 must be maintained at $6.5\text{x}10^9$ at 12.5MV/m. The cavity string is a single eight cavity hermetically sealed string. Each cavity has 7 cells using the CEBAF cell designs for interior and end cells.

The upgrade cryomodule is to be operated with 6.5kW RF power sources. The Fundamental Power Coupler (FPC) is a waveguide design to use a minimum of RF power for gradient and phase control. The nominal Q_{ext} is $2.2\text{x}10^7$.

The waveguide section providing the thermal transition between the cavity and vacuum vessel has a common vacuum with the cavity and is sealed with a warm ceramic window, eliminating the cold window that is problematic in the original CEBAF modules..

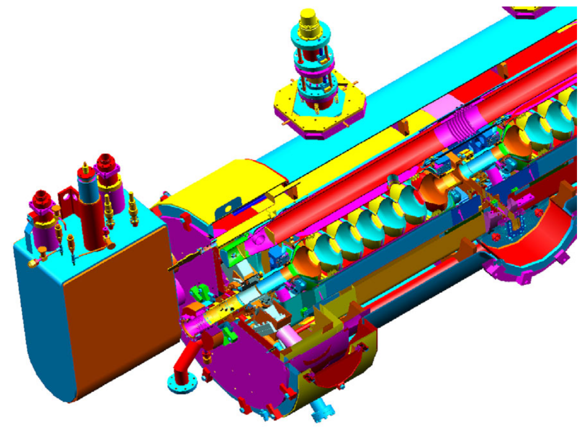

Figure 1: Cryomodule design.

Table 1: Specifications

Total voltage	70 MV
Cryounits (CU)	1
Cavities/CU	8
Structure	7-cells
Cavity length (7-cells)	70cm
E_{acc} average	12.5MV/m
Maximum power dissipation	17.5W
Q_0 at 12.5MV/m	$6.54\text{x}10^9$
Ep/Eacc	2.6
Hp/Eacc	47Oe/(MV/m)
Final frequency (MHz)	1497
RF windows/cavity	1
FPC coupling	λ/4 stub
Qext FPC (cavity coupling factor)	$2.2\text{x}10^7$
HOM coupling	Coaxial
Beam Line bellows	2
Vacuum valves	4
Frequency Tuner	Scissors type
2K RF Heat load	160 watts
50K RF Heat load	120 watts

The HOM couplers resemble the DESY welded type. Two are attached at one end of the cavity outside the tuner hub, oriented at 115° azimuth. The coupler center is at 80 mm from the 1st end cell edge. The first two passbands of TE111 and TM110 high order modes (HOM) have to be damped to avoid beam breakup problems at 460µA current.

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Cavities

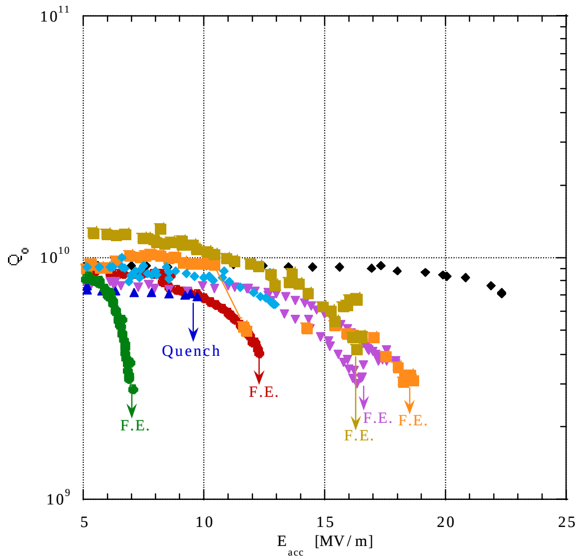

Figure 2: Cavities performance in Vertical Test Area.

The cavities have undergone an average total material removal of 400µm and a heat treatment under vacuum at 650ºC for 6 hours. The He vessels were welded after the cavity tuning. Figure 2 shows the performance of the cavities tested in the Vertical Test Area (VTA) prior to the string assembly (n.b.: the low-performing cavity shown was reprocessed and subsequently passed specification) One cavity was quench limited but the overall average gradient still met the design specification.

The final cavity surface preparation was 20µm of BCP 1:1:2 followed by a High Pressure Water Rinse (HPWR) of two hours. After the probes assembly, the cavities went through a final HPWR of two hours.

Cryomodule

In order to maximize the active length, the bellows and the vacuum valves between cavities have been removed from the upgrade design. The absence of beam-line bellows induced cavity tuning interactions and some assembly and alignment complications.

CRYOMODULE TEST IN CMTF

After completion, the cryomodule was tested in the Cryomodule Test Facility (CMTF), operating with a local phase lock loop RF system. Figure 3 shows some views of the cryomodule assembly.

Cavity Performance

The cavity performance was excellent in the CMTF (Fig. 4). The average accelerating gradient achieved was 16.8MV/m with a total energy gain for the cryomodule of 83MV. The cavities were limited by quench except for three cavities that were arc limited. Due to a weld defect, one cavity quenched at low gradient.

Figure 3: Different views of the cavity string, the cryomodule assembly and CMTF.

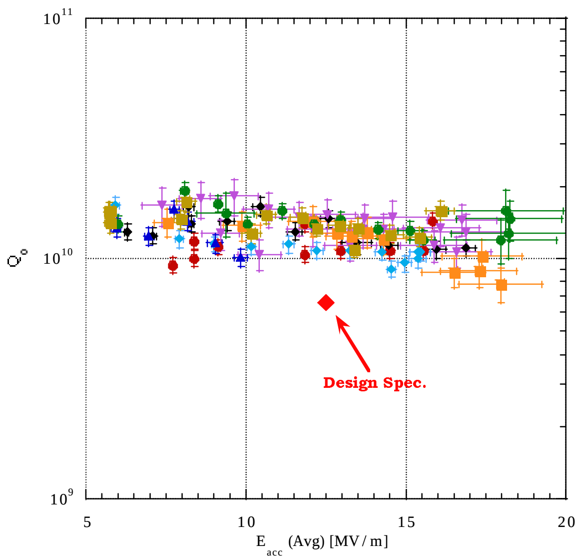

Figure 4: Cavities performance in CMTF.

HOM Damping

External Q values of the HOM couplers and waveguide were measured on a copper model, on cold niobium cavities in vertical tests and finally in the cryomodule without beam [4]. A threshold current predicted by MATBU code based on these data and the real beam optics is 10mA.

Five of eight cavities were tested in the VTA with both HOM couplers and Field probe installed and with their cable connections up to the warm interface. The waveguide was shorted with a niobium blank and the whole assembly was cooled to 2K. The power coupling port was mounted on the bottom beamline flange with a Q external of the TM010 π mode ~ 10^9. The damping by the HOM couplers was measured. A separate cavity test was carried out with the waveguide connected to a warm load through a warm window. The result indicates that the waveguide has a limited HOM damping.

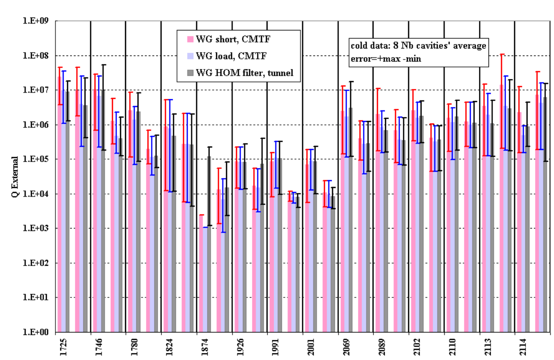

Figure 5: HOM damping data obtained in VTA and CMTF.

After the cryomodule was cooled down to 2K and before the waveguides were connected to the high power source in the CMTF, the loaded Q of the HOMs was measured by the transmission for HOM_1 to HOM_2 with the waveguide short and loaded configurations. These measurements were similar to the VTA data and showed only weak coupling to the FPC for the high Q modes. Figure 5 summarizes the data obtained in the VTA and the CMTF.

All HOM data measured without beam indicate that the TE111 and TM110 mode damping is sufficient for the 12 GeV Upgrade machine (460 µA). No significant improvement can be achieved without a major redesign of the end groups and tuner.

Lorentz Force Detuning and Microphonics

Lorentz force detuning was measured and the mean coefficient was about 1.4 Hz/(MV/m)^2.

Table 2: Lorentz force coefficients

Mean	**[Hz/(MV/m)^2]**
1	1.51
2	1.34
3	1.33
4	1.39
5	1.21
6	1.60
7	1.37
8	1.46
Avg	**1.40**

Low-power microphonics were measured at 4.5-10 Hz (Fig. 6) depending on cavity and conditions and the spectra show some mechanical modes of the cavity and some peaks suspected to be from environmental sources such as the CTF.

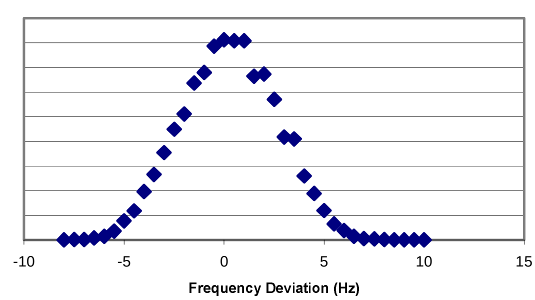

Figure 6: Microphonics measured for one cavity.

The static heat load was measured to be about 20W and the shield heat load was 240W, 60W higher than expected. The tuner resolution was 2.2Hz/µsteps.

COMMISIONING IN CEBAF TUNNEL

Cavity Performance

Single-cavity operations with a portable voltage controlled oscillator (VCO) control system in the tunnel were very good. The VCOs tolerated frequency shifts due to pressure transients. All but two cavities were power limited at an average gradient of 14.9MV/m (Fig. 7).

The first operation of the cryomodule with the present CEBAF epics control and low level RF (LLRF) system caused some oscillations due to the excitation of the nearest passband mode (~2.6MHz). The control loop was designed with an LC notch filter tuned to reject the next 5-cell cavity mode, which falls within the klystron bandwidth. In the 7-cells cavity, this mode is closer to the accelerating mode and was driven by the RF causing instabilities in the control loop. Some modifications and optimization of the parameters of the RF control loop solved this issue. But the LLRF stability still limits the cavity operation at gradients higher than 11MV/m.

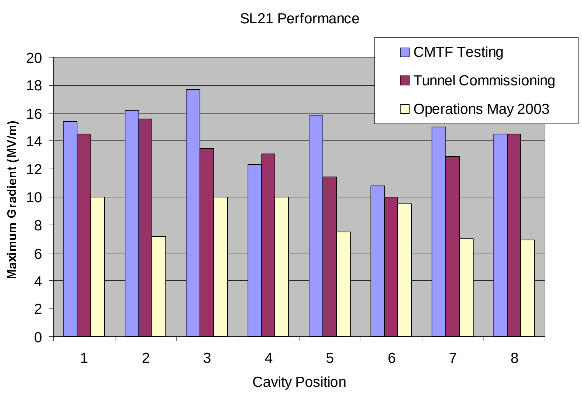

Figure 7: Comparison of cavities performance in VTA, CMTF and CEBAF tunnel.

Operation With Beam

While operating with the current CEBAF control system, significant issues arose.The cryomodule higher power dissipation induces a higher sensitivity to operating He pressure. Higher Q_{ext} induces greater Lorentz detuning and a narrower operating resonance, resulting in more demands on low level RF controls (originally designed for gradients of 5MV/m and Q_{ext} of $6.6x10^6$ [5]) and in more coupler heating. The reduced liquid He volume requires the end groups to be conduction cooled.

Thermal instabilities appeared due to the small diameter of the riser tube from the He vessel. Its thermal capacity is very sensitive to the operating temperature. It was designed to operate at 2.04K where the present CEBAF operating temperature is 2.09K. The total allowable heat measured at 1.99K is 180W versus 95W at 2.095K. At this heat level, the cavities gradient is reduced below 10M/m. The He vessels for the next 70MV cryomodule have been modified to allow a larger heat removal capability. Modifications are implemented in the 100MV cryomodule design to avoid these limitations.

The use of stub tuners to lower Q_{ext}, not included in the design, induced excessive heating of the FPC waveguide flanges. Some measurements showed that the waveguide heating was reduced by half with operation with the stub tuners wound out.

Stable operation is obtained below the thermal limit. Low gradients ($\leq$ 10MV/m) are applied to the cavities and the stub tuners are backed all the way out. This way, the waveguide temperatures are lower and the directional couplers are reading consistently. In this mode of operation, the cryomodule still provides up to 55MV.

Due to the limitations from the current controls system, cryogenics, Low-Level RF, the real performance of the cryomodule in the CEBAF tunnel has not yet been established.

CONCLUSIONS

The first “70MV” CEBAF Upgrade Cryomodule showed very good performance in the Cryomodule Test Facility. The potential total accelerating voltage is more than 80MV, well beyond the design value.

During commissioning in CEBAF tunnel, the individual cavity tests with VCOs were very good.

Due to the present operating temperature (2.09K), the existing LLRF system and some design limitations, the cryomodule has to be operated at lower gradients (~ 10MV/m), producing only about 55MV. It is still by far the highest performing cryomodule in the CEBAF machine and it is now under stable operation. With some further controls refinements, additional voltage capacity is expected.

Modifications are implemented in the final cryomodule design to avoid the cryogenic heat generation issue in the 12 GeV Upgrade.

AKNOWLEDGEMENTS

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