PRODUCTION AND PERFORMANCE OF THE CEBAF UPGRADE CRYOMODULE INTERMEDIATE PROTOTYPES

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Abstract

We have installed two new cryomodules, one in the nuclear physics accelerator (CEBAF) and the other in the Free Electron Laser (FEL) of Jefferson Lab. The new cryomodules consist of 7-cell cavities with the original CEBAF cell shape and were designed to deliver gradients of 70 MV/module. Several significant design innovations were demonstrated in these cryomodules. 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 and FEL linac. Performances and limitations after installation in the accelerators are also discussed.

INTRODUCTION

In the framework of the 12GeV CEBAF Upgrade and while the final design for a 100MeV cryomodule is being developed [1], two cryomodules of an intermediate design have been constructed in 2002 and 2003. The first prototype was installed in the CEBAF accelerator tunnel in February 2003. The second cryomodule was installed in the FEL Linac in April 2004, as part of the 10kW FEL Upgrade.

Specifications [2]

This cryomodule design supplies an average energy gain of 70MeV at 2.04K. Many of its requirements 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 $6.5x10^9$ 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 and the nominal loaded-Q is $2.2x10^7$.

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.

The HOM couplers resemble the DESY welded type. Two are attached at one end of the cavity outside the tuner hub, oriented at 115º 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.

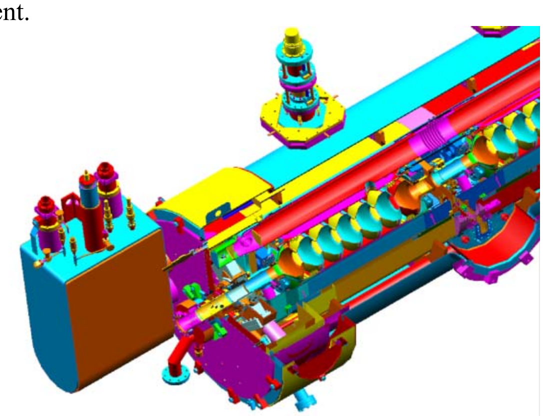

Figure 1: Cryomodule design.

Specifications for FEL Upgrade

Most of the specifications for a cryomodule for the 10kW FEL upgrade [4] are compatible with the specifications of the cryomodule for the CEBAF Upgrade, except for HOM damping requirements. The transverse modes should be damped to Q less than 10^6 in order for beam breakup threshold current to remain safely above the operating current. The beam current pursued for the FEL Upgrade is 10 mA. The RF power sources used in the FEL are 8kW klystrons.

CRYOMODULE FOR CEBAF

Cavities and cryomodule production

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. The performance of the cavities was tested in the Vertical Test Area (VTA) prior to the string assembly. 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 probe assembly, the cavities went through a final HPWR of two hours.

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.

Cavity performance in CMTF

After completion, the cryomodule was tested at 2K in the Cryomodule Test Facility (CMTF), operating with a local phase lock loop RF system.

The cavity performance was excellent in the CMTF. The average accelerating gradient achieved was 16.8MV/m with a total energy gain for the cryomodule of 83MeV. 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.

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 [5]. A threshold current predicted by MATBU code based on these data and the real beam optics is 10mA. All HOM data measured without beam indicate that the TE111 and TM110 mode damping is sufficient for the 12 GeV Upgrade machine (460 µA) but not for the FEL (>10 mA). No significant improvement for this design can be achieved without a major redesign of the end groups and tuner. The necessary modifications will be implemented in 100MeV Cryomodule.

Commissioning in CEBAF tunnel

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. 2).

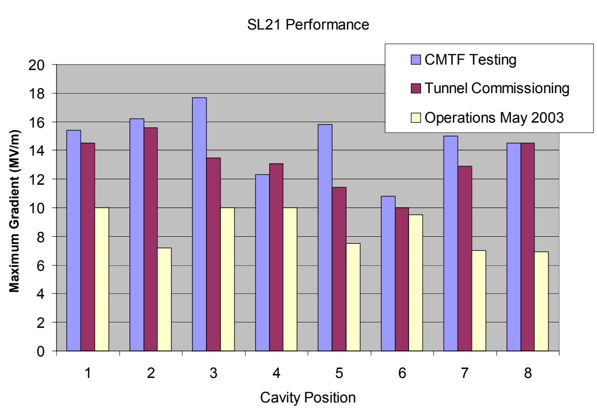

Figure 2: Comparison of cavities performance in CMTF and CEBAF tunnel

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 electronics solved this issue.

Operation with beam

While operating with the current CEBAF control system, significant issues arose. Higher Q_{ext} , therefore a narrower operating resonance induces greater sensitivity to Lorentz detuning, resulting in more demands on low level RF controls (originally designed for gradients of 5MV/m and Q_{ext} of $6.6x10^6$ [6]).

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 while 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 cavity gradients are reduced below 10MV/m. The He vessels for the next 70MeV cryomodule were modified by doubling the riser tube diameter to allow a larger heat removal capability. Modifications are implemented in the 100MeV 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 withdrawn to a flush position. This can be mitigated by carefully setting the stubs for minimum frequency pulling.

Stable operation was obtained below the thermal limit. Lower gradients (≤ 10MV/m) are applied to the cavities and the stub tuners are backed all the way out. This way, the waveguide temperatures are lower. In this mode of operation, the cryomodule still provides up to 55MeV.

A test at 2.04K was performed in order to test the cryomodule at its design temperature. For all cavities, except for two with known limitations, no cryogenic limit was obtained. And the total energy gain achieved was about 65MeV.

CRYOMODULE FOR FEL

Cavity performance in VTA and cryomodule production

The cavities were prepared before string assembly with the same procedure as for those for the CEBAF cryomodule. During the RF performance test in the VTA prior to the string assembly, one cavity was quench limited but most of the cavities performed well beyond specifications.

In order to mitigate the problem of thermal instabilities, the He vessel riser tubes were enlarged.

The cryomodule production went smoothly, taking advantage of the lessons learned during the assembly of the first 70MeV cryomodule. In order to avoid the pressure oscillations and elevated waveguide temperatures observed for the first 70MeV cryomodule installed in the CEBAF tunnel, a 2K heat station [7] has been added to lower the warm/cold waveguide transition heat load. Two waveguides have been instrumented with temperature diodes and 10W heaters.

Commissioning in FEL Linac

In order to comply with an aggressive schedule and a more thorough commissioning in "real condition", the new cryomodule was at first commissioned in parallel with the beamline in the FEL vault, in parallel with FEL operation.

The maximum gradients available (one cavity at a time, with a VCO), quality factors at different gradients, external quality factors (Q_{FPC}, Q_{probe}, Q_{HOM1}, Q_{HOM2}) and probe calibration factors were measured. All eight cavities performed above specifications with a total energy gain higher than 85MeV (Fig.3). The cavities were next operated in pairs with the production LLRF system for 8 hours in order to determine the maximum sustained gradients for the individual cavities. The sum of the accelerator gradients for this test was 83.5MeV. When operated as a cryomodule, the total energy gain achieved was 82MeV. This test was terminated after 2 hours so the FEL operations staff could operate the machine at lower gradients. The system was operated at 60MeV for several weeks with no trips.

Figure 3: comparison of cavity performance in VTA and FEL Linac.

During the commissioning, before the waveguides were installed, the cryomodule HOM parameters, frequencies and loaded quality factors of the TM010 fundamental passband and TE111 and TM110 dipole mode passbands were measured [8]. Some couplers and RF diodes have been installed on the HOM terminations for HOM power observations during beam breakup thresholds studies. This will help the ongoing development of methods to suppress the onset of beam breakup. In the meantime, the cryomodule carries enough current for operation in the FEL.

The addition of this cryomodule to the FEL brings the total energy available up to 150MEV. An output power of 10kW was obtained recently during pulsed operation at 60Hz with 1ms pulses, 5mA of drive current at 145MeV. The next step, 10kW CW power, should be achieved anytime soon.

SUMMARY

The cryomodule installed in the CEBAF tunnel showed very good performance in the Cryomodule Test Facility and during commissioning in CEBAF tunnel. The potential total accelerating voltage is more than 80MeV, well beyond the design value. Due to the present operating temperature (2.09K) and some cryogenic design limitations, the cryomodule has to be operated at lower gradients (~ 10MV/m), producing only about 55MeV. However a test at 2K has demonstrated that this cryomodule can produce at least 65MeV. It is still by far the highest performing cryomodule in the CEBAF machine and has been under stable operations for almost a year now.

Modifications in the design were implemented in the cryomodule installed in the FEL Linac. This cryomodule has also shown excellent performances during its commissioning in the FEL vault. It has demonstrated gradient in excess of 80MV. Methods to mitigate the onset of beam breakup are under development. Nevertheless, this cryomodule produces enough current to operate in the FEL Linac.

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