IMPROVED PROTOTYPE CRYOMODULE FOR THE CEBAF 12 GEV UPGRADE*

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Abstract

In order to provide a higher performance building block cryomodule for the CEBAF 12 GeV upgrade, modifications have been made to the design of the Upgrade Cryomodule. The prototype cryomodule will be completed in 2004 and be installed for operation in CEBAF. Design changes enable the use of higher gradient cavities to achieve greater than 100 MV per cryomodule while not exceeding the budgeted cryogenic load of 300 W during steady-state operation. They also include refinements based on experience gained during the construction of the first generation upgraded cryomodules as well as the prototype cryomodule for the Spallation Neutron Source. Two cavity designs will be used in the prototype, one optimized for E_{peak}/E_{acc} ratio, and the other optimized for minimum cryogenic load. The input waveguides, thermal shield and piping have been redesigned to accommodate the higher expected heat loads. The vacuum connections consist of niobium-titanium flanges, aluminum-magnesium seals and stainless steel clamps to provide reliable UHV sealing. The cavity tuner features one cold motor and two piezoelectric actuators to provide coarse and fine tuning respectively.

INTRODUCTION

A series of three cryomodules (CMs) is being constructed as part of JLab's efforts to increase the machine availability and reliability, provide additional acceleration for the Free Electron Laser (FEL) and produce prototypical CMs for the 12 GeV Upgrade of CEBAF. The first two CMs constructed are based on the initial "Upgrade CM" design [1,2]. The first of these has been completed, installed and commissioned in the SL-21 zone of the south linac of CEBAF, and the second, "FEL03," is planned for installation into the JLab FEL in late 2003. Both modules contain 7-cell cavities based on the original CEBAF cavity cell shape and are expected to exceed 70 MV of acceleration. The third module, dubbed "Renascence," incorporates several design changes in order to provide more than the 108 MV capability required by present plans for the 12 GeV upgrade of CEBAF [3]. It is planned for installation into CEBAF in late 2004, serving both as a reliability improvement for continuing 6 GeV operation, as well as a prototype for the 12 GeV upgrade.

To obtain the required level of HOM damping while revising the cavity cell shape to improve performance, it is necessary to move the coaxial HOM couplers closer to the cells. This displaced the tuner mount, requiring a new tuner design. Also, the input waveguide thermal engineering had to be revisited to avoid conducting too much heat to 2 K via the cavity input coupler flange. Anticipating continued progress in controlling field emission in niobium cavities, a development effort was started to design a heat-load optimized structure for CEBAF, referred to as the Low Loss (LL) cavity. This is being performed in parallel with the previously designed High Gradient (HG) cavity that minimizes the E_{peak}/E_{acc} ratio to reduce the risk of field emission performance limitations. The prototype CM *Renascence* will comprise a mixture of the LL and HG structures. Each cavity has four TTF-style HOM couplers. Specific details of the cavity designs can be found elsewhere [4].

Experience with construction of the first Upgrade CM also indicated a need to improve the flange seal designs, particularly those on the beam line. New solutions are included in plans for *Renascence.*

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CRYOMODULE REQUIREMENTS

The performance requirements for the improved prototype are identical in many ways to the initial prototypes in areas such as cavity tuning, alignment and overall dimensions. Only a few key requirements have been changed. A comparison between the first upgrade prototype and the improved prototype CM is given in Table 1. To attain 108 MV, each cavity must achieve a gradient of 19.2 MV/m. The concomitant requirements of high quality factor (Q) and high accelerating gradient are very challenging. In addition, cw operations and the narrow bandwidth of 75 Hz place high demands on the mechanical tuner design.

Table 1: Cryomodule Comparison

Parameter	70 MV CM [1,2]	12 GeV CM
Average cavity gradient (MV/m)	12.5	19.2
Q_{cavity}	6 E+09	8 E+09
$Q_{external}$	2 E+07	2 E+07
Klystron power, cw (kW)	8	13
2K RF heat load (W)	140	240
50K RF heat load (W)	120	104

The estimated and budgeted heat loads are listed in Table 2. These heat loads are significantly higher than what was planned for with the initial prototypes. Changes in the header piping are required to accommodate the higher heat loads.

Table 2: Estimated & Budgeted Heat Loads

	2K Heat Load (W)	50 K Heat Load (W)
Static	< 25	180 - Shield 56 - Coupler
Dynamic (8 cavities)	240	108
Total	275	340
Budget	300	400

DESIGN IMPROVEMENTS

The initial design effort for the upgrade CM was significant and resulted in an integrated solution that considered these key areas: the cavity structure, beam line interfaces, RF power coupling, cavity tuning, and cavity suspension and alignment. Based on experience with the first prototype as well as added experience with the SNS CM design, most of these key areas were studied again in an effort to improve upon the existing design where possible. In addition, the thermal shield and header piping was re-designed to improve clearances for thermal performance, reduce the manufacturing cost and simplify the assembly sequence. In all cases, design improvements that minimally impacted the CM cost were carefully considered. Each of the improvements is discussed in detail.

Cavity Flanges

In order to package 108 MV of acceleration into 5.6 meters of active length within the existing CEBAF slot length, there are no beam line bellows in the cavity string assembly. There is very little axial beam line space available for installing and tightening fasteners. The cavity beam line flanges are sealed with crushable aluminum-magnesium seals like those developed for the TESLA cavities and adopted for the SNS cavities.

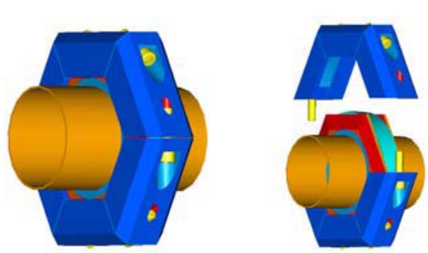

Figure 1: Radial Wedge Flange Clamp – Assembled (left) and Partially Disassembled (right)

To provide the high sealing forces required in limited axial space, a new flange clamping mechanism is used for the cavity beam line flanges. The design (Fig. 1) is called a radial wedge flange clamp [5] and is based on using multiple flat wedges within a set of self-centering clamps to transmit high clamping forces needed for metal-to-metal seals. The clamp and seal assembly has been successfully leak tested while at 2K in separate tests with a Conflat® copper gasket as well as an aluminum-magnesium metal gasket.

Sealing the rectangular waveguide flange with anything other than indium has proven difficult. Efforts to develop an alternative using an aluminum-magnesium seal or other materials are proceeding. If no alternative is found, these flanges will be sealed with an indium gasket.

13 kW Fundamental Power Coupler Waveguide

The original upgrade waveguide design was capable of transmitting 6 kW of RF power to the cavity [6]. The waveguide for *Renascence* is capable of transmitting up to 13 kW of RF power to the cavity [7]. For the prototype, an additional heat station (Fig. 2, shown in red) from the waveguide to the thermal shield is required to transmit the required power while managing the thermal load to the primary helium circuit. The heat load conducted to the cavity end group is large, nearly 4 W (Fig. 2). An additional 60K heat station (Fig. 2, blue curve) was chosen for this prototype for cost reasons. The waveguide design for the production CMs will have an intermediate 300 K heat station (Fig. 2, red curve) since it is a more efficient design solution. The FPC end group on the cavity is fabricated from niobium with RRR > 250 in order to avoid overheating during RF operations.

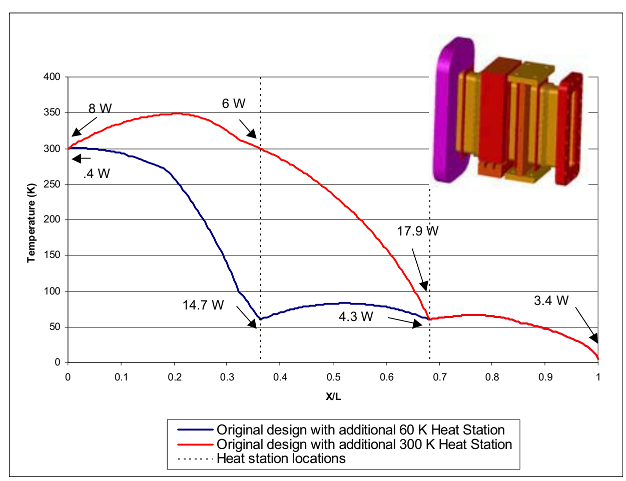

Figure 2: 13 kW Waveguide Thermal Profile

The plating thickness for the waveguides has been increased. The upgrade specification had been 1.6 µm nominal thickness with a range of -20% to +30%. The range was based on achievable limits quoted by the vendor. The specification was changed to 4.5 ± 1.5 µm to avoid inadequate copper plating coverage.

Thermal Shield

The thermal shield intercepts the radiative heat loads and conductive heat loads from both heat stations on the FPC waveguide. More thermal straps have been included on the thermal shield to transport the additional heat deposited in the FPC waveguide during high power operations. There are six straps on the inner heat station and ten straps on the outer heat station

In order to simplify the piping design, only a single pass from the supply to the return is included. The thermal straps are attached to the shield near the cooling line. A helium mass flow of 8 gram/sec is required to remove the budgeted heat load of 400 W with a temperature rise from 35 to 45 K.

Helium Vessel and Headers

The titanium helium vessel consists of two heads, two bellows and a cylindrical shell. The heads are welded to a niobium-titanium transition ring, which is part of the cavity end group. The bellows are located near the helium vessel head opposite the FPC and enable cavity tuning. The helium vessel heads are added to the cavity after any high temperature baking in order to avoid embrittlement of the titanium.

The dynamic heat load per cavity is estimated at 30 W. In superfluid helium the maximum critical heat flux is conservatively 1 W/cm^2 [8], requiring a 30 cm^2 cross-section to support the heat flow into the return header. The vertical piping connections between the helium vessel and the return header have been increased from 1-½” IPS to 2” IPS to avoid exceeding the critical heat flux.

Cold Tuner

The tuner system consists of a coarse mechanical tuner and a fine piezoelectric tuner and satisfies the same design requirements as the first prototype tuner (Table 3). This tuner mechanism differs significantly from the first prototype because all of the components are cold, including the motor, harmonic drive and piezoelectric actuators. This design approach, adopted from the TESLA design and applied to the SNS design, relies on the component evaluation tests that were conducted to prove out the SNS tuner system. The range and resolution goals are derived from these tests.

Table 3: Tuner Requirements and Design Goals

Parameter	Requirement	Design Goal
Coarse Range (kHz)	> 400	> 600
Coarse Resolution (Hz)	< 100	< 3
Coarse Backlash (Hz)	< 25	< 10
Fine Range (Hz)	1000	> 2000
Fine Resolution (Hz)	< 1	< 1

Alignment

The overall alignment requirements are identical to not only the first prototype but also the original CEBAF CMs; the cavities are aligned to the ideal beam line reference within 2 mrad RMS. A pair of fiducial rings, which are machined into the end plates prior to cavity assembly, defines the cavity mechanical centerline. The eight-cavity string is positioned relative to the nominal beam centerline via Nitronic stainless steel rods within the spaceframe. The cavity flanges have compliance that, when combined with the relatively flexible FPC end group, enables lateral adjustment of the cavity ends without the need of inter-cavity bellows [9]. The alignment scheme uses the same techniques employed to acceptably align the cavity string for the first prototype CMs.

SUMMARY

The design of the improved prototype CM is underway. The design effort is proceeding more rapidly than for the first prototypes because the majority of the interfaces between components have been defined.

Prototype cavities have been constructed. The new tuner design is complete and in fabrication. Detailed designs for other components such as the thermal shield and helium vessel are in progress.

Cavity, helium vessel and tuner testing is planned for this coming summer. The cavity string assembly is planned for the end of 2003. The completed CM, with a mixture of high gradient and low loss cavities, is scheduled for mid-spring 2004 with testing completed by fall 2004.

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