COMPACT 4 kW VARIABLE RF POWER COUPLER FOR FRIB QUARTER-WAVE CAVITIES *

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Abstract

A new compact 4 kW power coupler has been designed and prototyped at Argonne National Laboratory in collaboration with Michigan State University. The coupler is intended for use on the β=0.085 80.5 MHz superconducting quarter-wave cavities for the FRIB driver linac and also for the ReA6 cryomodule using the same quarter wave cavity design. The coupler has a cold RF window and a 3 cm variable bellows section. The short 16 cm length of the RF window plus bellows facilitates a simple and compact clean room installation onto the cavity coupling port. A prototype has been fabricated in collaboration with U.S. industry and cold tested at 3 kW forward power under realistic operating conditions at Argonne. Simulation and test results are presented.

INTRODUCTION

The front-end of the superconducting linac for the Facility for Rare Isotope Beams (FRIB) at Michigan State University includes two different types of 80.5 MHz quarter-wave resonators (QWR's) operating with β=0.041 and β=0.085. [1] The rf power coupler will be the primary means of locking the cavity rf phase to a master oscillator in the presence of microphonics and, at the same time, will provide the required beam power. The proposed full β=0.085 cavity rf bandwidth is 40 Hz, with a corresponding total rf power of 2.5 kW. In order to provide reasonable margin, coupler specifications call for reliable coupler operation at 4 kW CW power under all conditions of reflection angle.

DESIGN APPROACH

As always, a coupler should reliably deliver rf power to the beam at the nominal Qext and also be suitable for other modes of operation such as cavity rf (pulse) conditioning. The coupler should not adversely impact cleanliness of the high-gradient SC cavities either in assembly or long-term operation. Considerations for the previously tested ANL 4 kW, 72 MHz coupler are similar [2], and the early 4 kW design served as the starting point for the new coupler. RF parameters are given in Table 1.

The modular design has four separate components. These include a variable bellows, a 'cold' rf window, a 55-to-300 K transition and a room temperature rf window. Both window assemblies are built around a donut-shaped alumina disc with a hole for the center conductor. The discs have been fabricated from alumina ceramic and brazed between the copper inner and outer conductors at MPF Products Inc.. The ceramic material was chosen for its good combination reliable brazing characteristics and good rf performance.

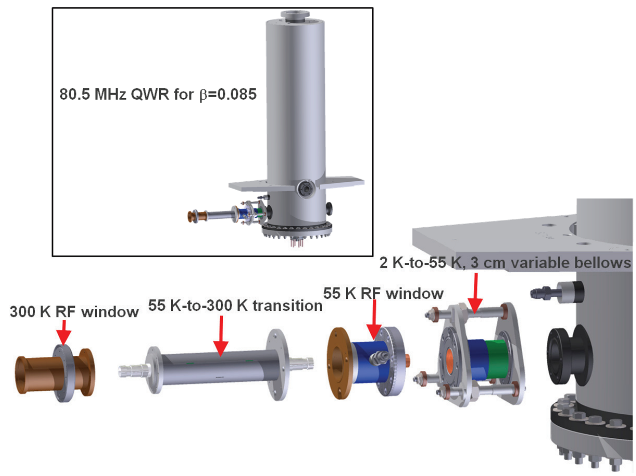

Figure 1: Prototype 4 kW coupler for FRIB quarter-wave cavity.

Adjustability of the center conductor by 3 cm into or out of the cavity coupling port is performed by compressing a cold bellows, formed from thin-walled stainless steel with 20 μm of copper deposited on the inner (rf) surface. The cold window is anchored to 55 K by circulating cold He

Table 1: Coupler Design Parameters

Parameter	Value
Nominal design power (kW)	4
Type	Coaxial capacitive
Outer diameter (cm)	4.1
Length (cm)	37
Impedance, nominal (Ω)	50
S11 @ 80.5 MHz (dB)	-31
Static load to 2K (W)	0.36
Static load to 55K (W)	4.1
Dynamic load to 2K (W)	0.15
Dynamic load to 55K (W)	8.4

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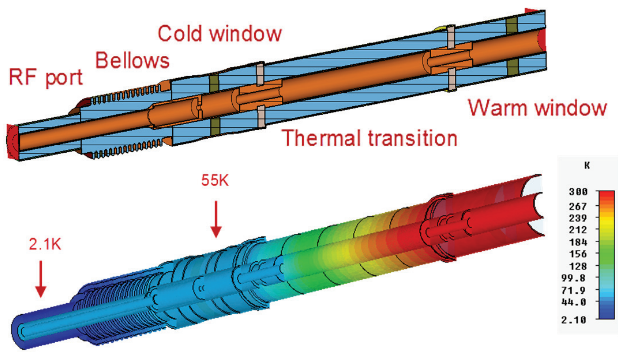

Figure 2: Coupler electromagnetic/thermal model in CST Studio for 4 kW forward power.

gas through the cold window assembly (see Figure 1). The ceramic window also separates cavity and cryomodule vacuum spaces. The center conductor is conductively cooled through the ceramic disc (λ~50 W/m-K at 55 K), so that the center conductor operates just above the intercept temperature of 55 K for all planned FRIB operating modes. The cold bellows and rf window are easily cleanable to the standards required for a clean SC cavity. The warm window, located near the wall of the cryomodule, separates the cryomodule vacuum from atmosphere.

FABRICATION

A pair of prototype couplers have been built and then tested at ANL on a 72.5 MHz QWR cavity. The cavity will be installed as part of an upgrade of ATLAS and is sufficiently close in terms of frequency to the FRIB QWR that rf performance should differ little. Fabrication for the MSU coupler also borrows heavily from techniques used for the ANL 72 MHz 4 kW coupler reported on previously [2].

Both warm and cold window assemblies are built around a 4 cm diameter, 6.4 mm thick alumina disc with a hole for the center conductor. The discs were in turn fabricated from 97.6% pure WESGO Al 300 alumina and brazed using a copper-gold alloy between the copper inner and outer conductors by MPF Products Inc. The ceramic material was chosen for its combination reliable brazing characteristics and good rf performance. For the cold window, a vacuum tight stainless vessel surrounds the outer conductor and is used to directly cool the outer conductor and the ceramic using circulating helium or liquid nitrogen.

The cold bellows assembly is made by TIG welding a thin- wall (150 µm thick) formed 321 stainless steel bellows directly into a pair of CF flanges (see Figure 1). A three post and bushing guide mechanism, both from 304 stainless steel, is located just outside the bellows/flange assembly. The posts and bushings are Dicronite coated to maintain clean, low friction sliding under vacuum and at cryogenic temperatures. Critically, the 20 µm of copper plating is deposited as the last fabrication step by Saporito

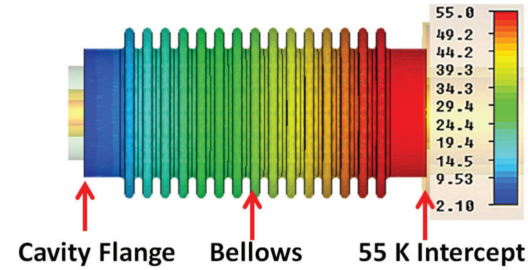

Figure 3: Temperature map for a copper-plated stainless steel bellows for P_{for}=4 kW in full reflection

Finishing. The necessity of the copper plating is discussed below.

ELECTROMAGNETIC AND THERMAL MODELS

To provide a large operating margin at the highest power levels of 4 kW, the electromagnetic and thermal analyses have been performed in CST studio. The intent is to design so that no part of the coupler approaches a condition where thermal runaway might occur. CST simulations have been checked analytically, where reasonable, to establish confidence in the results. Multipacting is not predicted to be a problem at 80.5 MHz in the range 0-4 kW. Even so, it can be suppressed by the straightforward application of a bias voltage to the center conductor [3].

Temperature dependent physical properties of the materials (copper, stainless steel, ceramic), including thermal conductivities, resistivities, and heat capacities have been modelled by breaking the CST 2011 model into discrete pieces. Results in Figure 2 and 3 (note that temperature scales are different) show no localized heating for the case of 4 kW forward power in full reflection and overcoupled. Generally, the coupler is far from overheating.

The low-conductivity thin-wall thermal transitions are the most susceptible to overheating since the thin wall 'thermal break' also reduces the capabilty to dissipate rf losses. Figure 3 shows a detailed view of the CST model for the cold bellows, which includes an accurate model for the 20 µm copper plating onto 150 µm of stainless steel. The copper cryogenic properties were taken to be those for OFHC copper. Higher accuracy could be gained with detailed knowledge of the composition of the copper plating. OFHC represents a middle ground in terms of thermal and electrical conductivity in the range of 2 K to 55 K.

For the case of 4 kW forward power in the overcoupled condition, the total calculated rf loss in the bellows was 260 mW, concentrated near the 55 K intercept due to the higher electrical resistivity at that temperature. Even so, the temperature gradient is smooth and monotonically changing and no significant heating is predicted. Since rf losses increase as the square root of the electrical resistance, an unplated stainless bellows would have losses roughly 15 times higher losses or about 4 W at 4

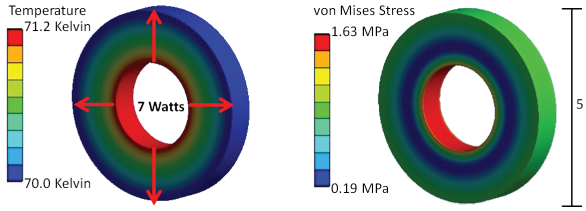

Figure 4: Internal stress in a ceramic window due to a temperature gradient.

kW forward power. More than half of the losses would go into 2 K helium and for this reason alone an unplated bellows at this diameter was not considered.

As discussed, both the warm and cold windows are fabricated from the 97.6% WESGO Al 300 alumina. To verify that the ceramic will operate far away from its physical and mechanical limits, ANSYS model simulations were performed to estimate the induced stresses in the ceramic due to (cyclic) temperature gradients. ANSYS permits the direct incorporation of temperature dependent thermal conductivity, Young's modulus and Poisson's ratio. Here, values were taken from the Ref [4]. The model in Figure 4. is a slightly more demanding case than anticipated for the FRIB coupler, with a 5 cm diameter ceramic and a higher radial heat flow (7 W versus 2 Watts). For this case the temperature gradient is 1.2 K and the maximum von Mises stress of 1.6 MPa is located at the inner diameter of the ceramic. This value is about 100 times lower that the values (120-220 MPa) where cyclic fatigue loading has been shown to be important. It does indicate that cooling the ceramic very rapidly, by immersing in liquid nitrogen, should be avoided.

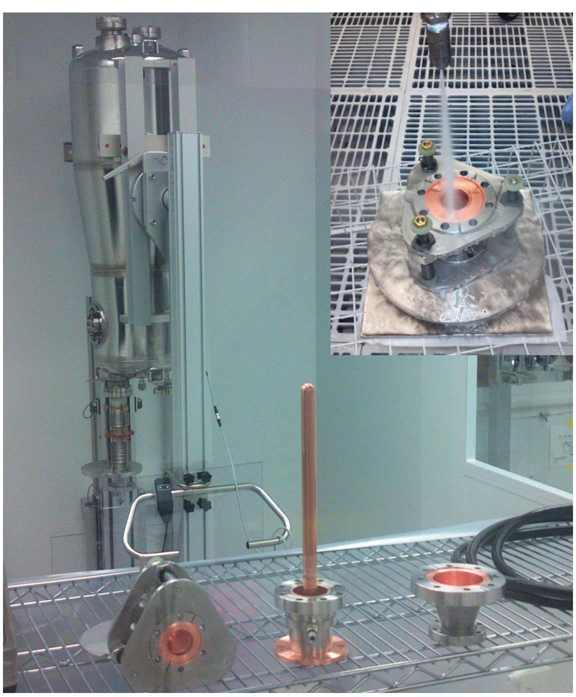

Figure 5: Prototype bellows assembly (inset) and cold window in the clean room

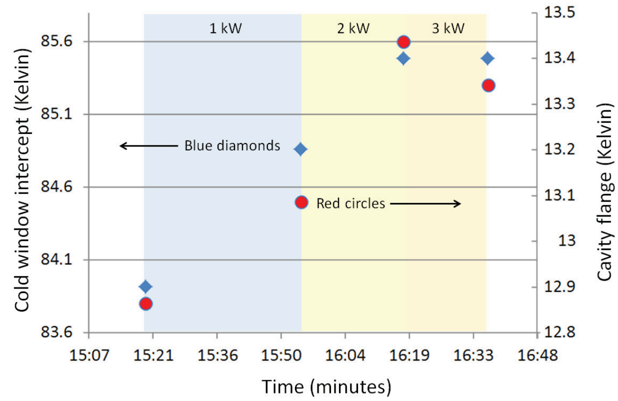

Figure 6: Thermometry for cold rf testing.

CLEAN ASSEMBLY AND TESTING

The copper plated bellows assembly and the cold window were manually high-pressure rinsed and assembled in the clean room as shown in Figure 5. Particulate measurements performed using a Climet model 750i particle counter placed below the parts with air flow from above indicate components are cleanable consistent with ISO class 5 standards.

The coupler assembly was tested cold with forward power levels of 1-3 kW. For these tests the cavity temperature was 4 K and the intercept was at 80 K. Results of temperature measurements are shown in Figure 6. The temperature rise at the 80 K intercept of 2 degrees corresponds to a heat load of 2.5 W, as determined using a reference heater. Similarly, at the cavity coupler flange the heat load was 120 mW. Both values are about 30% lower than the CST predictions, a difference not unexpected due to uncertainty in the copper cryogenic properties which are very sensitive to purity.

CONCLUSION

A pair of prototype power couplers intended for the MSU/FRIB β=0.085 QWR's have been designed, simulated, built and tested at ANL. RF performance on a cavity with up to 3 kW forward power is in good agreement with simulations. The coupler should provide ample performance margin for planned operating conditions at FRIB.

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