DEVELOPMENT AND TESTING OF PROTOTYPE FUNDAMENTAL POWER COUPLERS FOR FRIB HALF WAVE RESONATORS*

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Abstract

The driver linac for the Facility for Rare Isotope Beams (FRIB) requires superconducting Half Wave Resonators to accelerate ions to 200 MeV per nucleon. The Fundamental Power Coupler (FPC) is designed to deliver up to 14 kW of RF power at 322 MHz to the resonator and the beam in CW, and to increase the resonator's control bandwidth for stable operation. With the resonator over-coupled, the mismatch creates a standing wave in the FPC and transmission line downstream of the circulator. The FPC includes an alumina vacuum barrier to allow the resonator to be under ultra-high vacuum. The FPC also serves as a thermal break between the room-temperature transmission line and the resonator at 2 K, with thermal intercepts designed to minimize the heat load to the cryoplant. The FPC design allows for some variation in the coupling, in case a larger bandwidth is needed to mitigate microphonic disturbances. The RF and mechanical design of the coupler and conditioning stand is reviewed, and the results of high power RF conditioning and testing is presented.

DESIGN

Design History and Optimizations

The RF window design for the FRIB coupler takes advantage of existing technology, which has proven record of reliable operation. This design uses the RF windows developed for the Rare Isotope Accelerator (RIA), which had evolved from KEKB, and SNS. [1-3]. The FRIB design incorporates precisely the same methods used for fabrication of the inner conductor window assembly. For reliable operation at FRIB, additional design optimizations are necessary because some of the operating conditions are different.

The FRIB coupling is very high Q (~1e7). Because there is some uncertainty in the extent of the effect microphonics will have on the frequency stability of the cavity, the penetration of the probe into the cavity can be adjusted. This is provided for by the addition of a copper coated bellows on the outer conductor (Figure 1, (D)). A manual adjustment in coupling is done locally by a system of screws, which provides a method to mitigate large microphonic disturbances increasing the control bandwidth.

With a straight coaxial line, the ceramic disc had a direct line of sight to the high electric field region of the cavity, which is an increased potential for problems not realized in the design of the previous couplers. The addition of a tapered region on the inner and outer conductors mitigates this.

A multipurpose copper gasket (Figure 1A) is being developed to serve as the vacuum seal, 4.5 K conduction intercept, and the RF seal. This gasket allows for an excellent heat conduction path from the outer conductor walls, and is applied at the cavity flange.

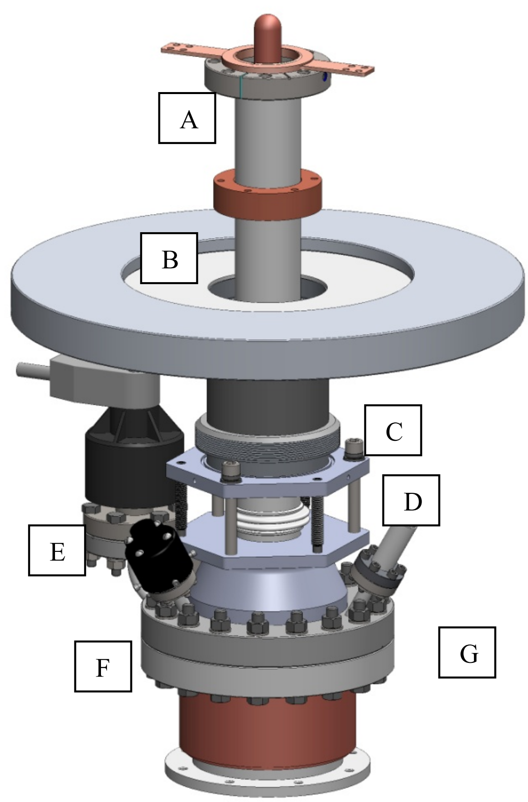

Figure 1: FRIB Prototype Fundamental Power Coupler. (A): 4K intercept, vacuum break ad RF seal, (B) 38 K intercept, (C) Bellows for thermal contraction (D) Bellows for coupling adjustment, (E) Cold Cathode Gauge, (F) Spark Detector, (G) E-probe.

Design Requirements

Two HWR types will be used to accelerate heavy ions from 17 MeV to 200 MeV for uranium. The beam current is low enough that the coupling required for the beam loading may not be enough for to mitigate microphonic

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disturbances. Therefore, additional RF power is required to ensure stable operation [4]. The RF power requirements are summarized in Table 1. The "Baseline RF Power" denotes the maximum operating RF power of the amplifiers which will be installed per cavity. The "Maximum RF Power" denotes the RF power required in the case that the RF bandwidth must be doubled.

Table 1: RF Requirements for the 322 MHz HWRs

Parameter	Units	HWR29	HWR53
Number of Cavities	Each	78	144
Beta	(=v/c)	0.29	0.53
Beam Power	Watts	1069	2225
Control Bandwidth	Hz	54	32
Baseline RF Power	Watts	4,000	8,000
Maximum RF Power	Watts	5,000	11,000

A thermal analysis is being used to quantify the expected heat loads at the three cryogenic intercept locations prior to testing the prototypes. The results of the calculations are shown in Table 2. Based on this analysis, the intercept locations are optimized to provide the lowest heat load to the cryoplant during operation at full field. As the FRIB cryoplant procurement has begun based on these estimates, the calculations now provide a heat load budget that will be carefully checked with additional testing. If the heat load requirements are not met, additional cooling methods can be implemented easily without significant design changes, as a cooling port has been provided on the ceramic disc, and hollow inner conductor can be used for a separate coolant.

Table 2: Heat load budget from thermal calculations

Intercept Temperature	Maximum Static (Watts)	Maximum Total (Watts)
2 K	0.4	0.6
4.5 K	1.2	1.9
38-55K	3.7	5.5

As shown in Figure 1 (E,F,G), diagnostics are placed in the warm region of the FPC to provide feedback in the case that the coupler becomes unstable. A cold cathode gauge monitors the pressure in the beam line vacuum space, while a sapphire view port and an electron pick-up antenna are used for spark detection and coupler multipacting detection.

Advanced Modelling

The operating conditions of the FRIB power couplers are varied, depending on operating mode. The power coupler multipacting conditioning will be carried out in transmission mode. When installed into the cryomodules, the matching condition will range from full reflection (short circuit) to the beam loaded condition (beta=6). The multipacting and power handling characteristics of the coupler have been analyzed using advanced modelling capabilities at SLAC [5].

The RF fields in the FPC were obtained using S-Parameter simulation code S3P by driving the cavity through the coupler port. For each of the above cases, the input power was scanned up to 10kW with 100 W increments. At each power level, 50 RF cycles were simulated for obtaining resonant trajectories. Because of the symmetry of the FPC, the seed electrons were launched on a slice of the geometry along the coaxial axis to save simulation time. The results for the case of full reflection are shown in Figure 2. These results indicate that multipacting will exist in the coupler, but can be RF conditioned.

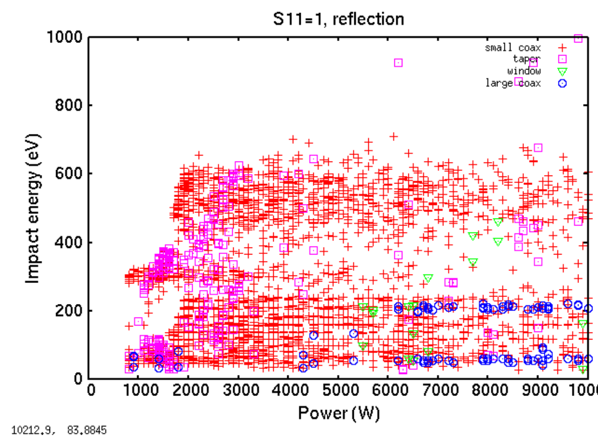

Figure 2: Calculated impact energy of multipacting bands of the FRIB FPC as a function of input power.

CONDITIONING AND TESTING

Four FRIB prototype power coupler assembles have been procured from two vendors along with some on site fabrication. These couplers are currently undergoing quality checks and testing. Low power coupling measurements have been performed to verify the proper coupling strength and range of coupling can be achieved. High power measurements are being performed to ensure adequate power handling capabilities and to develop a procedure for multipacting conditioning.

Coupling Measurements

Four window assemblies and four outer conductor assemblies have been procured. Low field coupling measurements have been performed on the first five prototype cavities, revealing up to 50% variation in the input coupling, depending on the cavity-coupler combination used. This coupling variation corresponds to a variation of input penetration by nearly 2mm which is addressed by adjusting the thickness of multipurpose gasket in Figure 1A. The next design iteration will incorporate additional travel on the outer conductor bellows, which will provide additional mitigation of the coupling variation.

Test Stand Design

A test stand has been developed to test and condition the RF couplers at high power. An amplifier, designed to deliver more than 14 kW of forward power in the fully reflective mode of operation, has been procured, although initial systems tests have identified some problems in achieving the full power capabilities.

A connecting resonator has been fabricated to reduce power coupler conditioning efforts with the ability to condition two couplers simultaneously. This resonator is a shallow, shorted, rectangular waveguide which is shown in Figure 3. The resonator has a fundamental mode at 322 MHz. The power is transmitted from the amplifier via EIA standard 3-1/8" coaxial 50 ohm transmission line. The power couples to the rectangular resonator through the first power coupler, and then is transmitted from the resonator to the second coupler and into2a matched high power load.

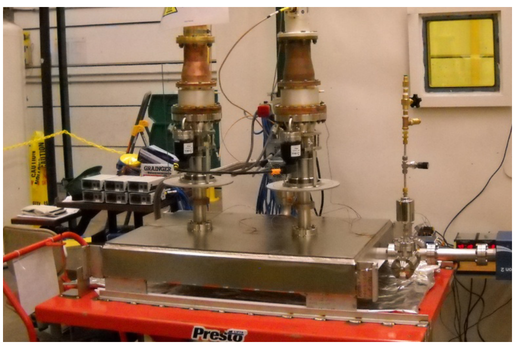

Figure 3: Power coupler test stand.

The vacuum assembly, which is rated for ultra high vacuum, consists of two FPC assemblies and the connecting resonator. In addition to the diagnostics installed on each FPC, the connecting resonator has a turbo pump, bleed in valve for filtered dry nitrogen, and residual gas analyzer.

For the prototype test, all vacuum components were degreased, ultrasonically cleaned, dried, and then assembled in a class 10,000 cleanroom. After leak checking, the assembly was baked initially at 140 C for 48 hours, then 200 C for 15 hours. RF conditioning started with an attempt to condition both power couplers in transmission mode. However, the coupling to the connecting resonator was too weak to achieve a good transmission, so the majority of the RF conditioning was conducted in full reflection. Multipacting barriers were initially observed between 1.5 and 2 kW, which is consistent with multipacting calculations. These barriers were easily conditioned with short RF pulses up to 6 kW. More difficult barriers were encountered above 6 kW peak power. High temperatures were observed on the outer conductor at the bellows region. The high temperatures at the bellows are likely due to the multipacting in the taper region, as predicted in the model (and shown in Figure 2). The multipacting barriers above 6kW are slow to condition for several reasons, including limitations on the RF amplifier, overheating of the copper plating, and out gassing exceeding the capacity of the vacuum pump.

ADDITIONAL PROTOTYPE TESTING

Cryomodule Test

A technology demonstration cryomodule (TDCM) is being built to test the FRIB HWR cryomodule. A complete set of systems tests will be performed, including a long term test of the cavities and couplers at full field. Diagnostics are being installed such that the heat loads to all the cryogenic intercepts on the couplers can be quantified. Additionally, temperature measurements on the inner conductors will be performed to determine if additional cooling will be necessary.

FUTURE OUTLOOK

Next generation prototype coupler assemblies will be procured for the next round of preproduction cryomodule testing, which is scheduled for 2012. These FPCs will have a few design changes based on the experiences with the first prototypes. More range in coupling will be achieved by adding longer outer conductor bellows. Changing the characteristic impedance of the narrow region of the inner conductor should reduce the time required for multipacting conditioning. The length of the outer conductor has already been reduced by extending the coupler ports on the cavity. This allows for better transmission to the connecting resonator, which enables the conditioning both couplers simultaneously.

In addition to design changes, power coupler conditioning procedures will be optimized. An oven will be built to conduct a thorough bake out of the vacuum surfaces to help decrease RF conditioning time.

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