PROGRESS TOWARDS RF CONDITIONING OF LOW-LOSS COUPLERS FOR A CONDUCTION-COOLED CRYOMODULE*

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Abstract

This work presents current progress on the conditioning of two new 25 kW couplers optimized for use in a compact, conduction-cooled SRF cryomodule. A connecting waveguide, previously used for conditioning the 805 MHz SNS couplers, was altered for use at 915 MHz. The necessary modifications were determined via RF modeling, while thermal analysis results identified additional cooling requirements during RF conditioning and provided insight about potential higher-power operation. Initial low-power conditioning will be performed with a 2.5 kW solid-state amplifier, with plans to use an industrial magnetron for RF conditioning at 25 kW in the near future.

INTRODUCTION

Studies by the U.S. DOE and national labs have found many critical applications which could be served by small-scale accelerators producing beams of a few MeV. These applications exist in a wide range of fields such as medicine, environmental sustainability, food processing, national security and more [1, 2]. Utilizing SRF cavities would offer more efficient handling of high-power beams, translating to increased throughput in many applications. However, the cooling requirements of SRF cavities have historically been cost prohibitive when considering MeV-scale machines.

Fortunately, recent improvements in both the RF performance of Nb_3Sn-coated cavities and the 4 K cooling capacities of multi-stage cryocoolers have made small-scale SRF accelerators feasible, with many new designs proposed for various industrial applications [3 - 5]. One of the designs currently pursued at Jefferson Lab also aims to take advantage of industrial magnetrons as a power source, greatly increasing the power efficiency of the system [6]. As part of this project, new fundamental power couplers (FPCs) were needed which could deliver high power to the SRF cavity while minimizing the heat load at the cold mass. The design and fabrication of these FPCs were completed by our collaborators at RadiaBeam [7]; the FPCs were then delivered to Jefferson Lab for RF conditioning.

COUPLER TEST STAND

A new coupler test stand is based on a setup previously used for the SNS 805 MHz couplers [8]. This design features a test cart with a removable connecting waveguide to which two couplers are mounted for RF conditioning. This section will discuss the primary modifications made for use with the new 915 MHz couplers.

Connecting Waveguide Modification

One of the connecting waveguides used for the conditioning of the SNS PPU 805 MHz couplers was sent to Jefferson Lab, which required modification for 915 MHz operation. The necessary length reduction would have caused machining interference with the various ports on the waveguide. To avoid this, the waveguide length was instead increased while its operational mode was changed from TE102 to TE103. In addition, small ports for IR windows were added to the bottom side of the waveguide, such that an IR camera could monitor the ceramic RF window temperatures during bakeout and RF conditioning. RF simulations of the coupler-waveguide system in traveling wave mode (performed in CST Microwave Studio) were used to optimize the parameters of these modifications; the model is shown in Figure 1. The optimized geometry resulted in an S11 of -40.14 dB at 915 MHz.

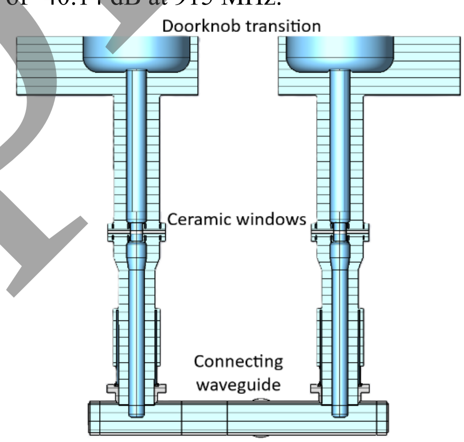

Figure 1: RF model of the couplers and connecting waveguide used in CST simulations.

Thermal Modelling of RF Conditioning

Thermal modelling was also performed in CST using coupled electromagnetic (EM) - thermal simulations. The EM portion used the same setup as the RF simulations described previously, while the thermal portion used a more detailed model to better represent the thermal response. Temperature-dependent thermal conductivities were applied for all materials, including a special material defined to model 316L stainless steel plated with 10 µm of copper. The coupled EM solver provided surface and volume loss densities as the primary heat loads in the system. A fixed temperature of 303 K was applied to represent water cooling where it was already included in the coupler design:

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warm inner conductor, ceramic RF window assembly, and WR975 to warm outer conductor flange.

First, simulations were performed for 25 kW forward power in traveling wave (TW) and four standing wave (SW) modes. These simulations were used to examine the expected temperatures of the couplers and connecting waveguide during RF conditioning, as well as to identify any additional cooling requirements. Next, simulations for up to 200 kW forward power in TW mode were performed to assess the possibility of conditioning the couplers at higher powers. Key takeaways from these simulations are summarized in Table 1, while an example result is shown in Figure 2.

Table 1: Thermal Simulation Key Takeaways

Simulation Description	Key Result
25 kW, TW	Additional cooling required on connecting waveguide*
25 kW, SW	All temperatures < 360 K; no concerning thermal gradients
100 kW, TW	T_{max} = 404 K; RF window ΔT = 20 K; ~200 W required cooling is achievable
200 kW, TW	T_{max} = 532 K; RF window ΔT = 40 K; 400+ W required cooling is unrealistic

* Used in all subsequent simulations.

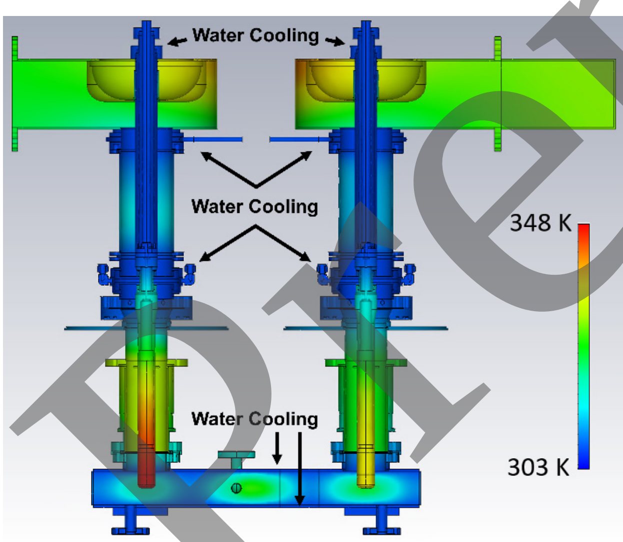

Figure 2: Example of a thermal modelling result, featuring a standing wave mode for 25 kW forward power.

Low-Power Conditioning Layout

Figure 3 shows the test stand layout which will be used for the initial low-power conditioning of the couplers. A 2.5 kW solid-state RF generator (model PTL-2.5CI-PREHD-0, Crescend Technologies) will provide power to the system. A 75 kW circulator is used to protect the generator from any unexpected reflections during conditioning, redirecting them to a dry load. The (forward) RF power then reaches the couplers and connecting waveguide. The downstream coupler will be connected to either a 75 kW water load for the TW mode or one of four shorted WR975 segments for SW modes. Two directional couplers are included to monitor power flow at both couplers.

The RF generator includes an emergency stop interlock input which cuts power output within 5 µs when triggered. This input will be connected to several system interlocks for fast RF shutoff: arc detection, reflected power, coupler vacuum, RF connections (e.g. gas barrier) and cooling water flow. Slower interlocks such as temperature limits will be processed in LabView, which will also provide the primary controls for the conditioning.

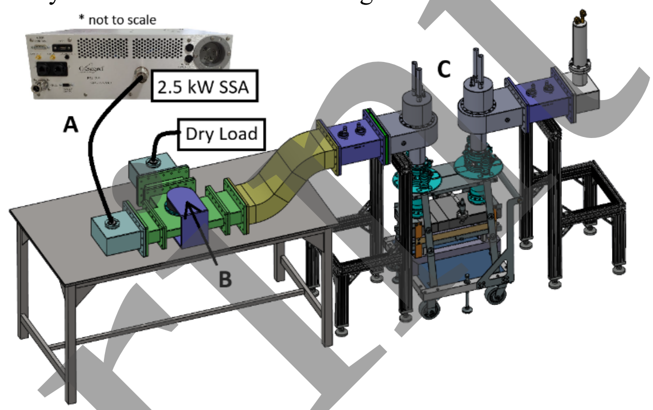

Figure 3: CAD model of the low-power conditioning setup: (A) 2.5 kW solid-state RF generator, (B) circulator with reflected power dump, (C) test cart with couplers and connecting waveguide.

COUPLER BAKEOUT

Upon receiving the new couplers, the various subassemblies were inspected for any machining defects or shipping damage. The vacuum components (along with the connecting waveguide) were then ultrasonically rinsed for 15 minutes in a 1% Citranox solution heated to 50 °C. This was followed by thorough flushing, first with DI water and then isopropyl. Finally, the components were blown off with ionized N_2 to dry and inspected for any signs of oxidation. All parts were then transferred to an ISO 4 cleanroom for assembly onto the test cart, as shown in Figure 4. Once assembled, the system was pumped down and leak checked before moving to a newly developed bakeout station.

Baking System Setup

An existing bakeout cart was re-used for the new baking system. The cart includes twelve relay-controlled outlets which were used to power heating straps wrapped around the assembly. The relays were connected to a PLC which provided simple “on-off” signals depending on whether the temperature around each heat strap, measured by a corresponding type-K thermocouple, was above or below a defined setpoint. LabView was used for monitoring and logging the assembly temperatures as well as automating the PLC setpoint control.

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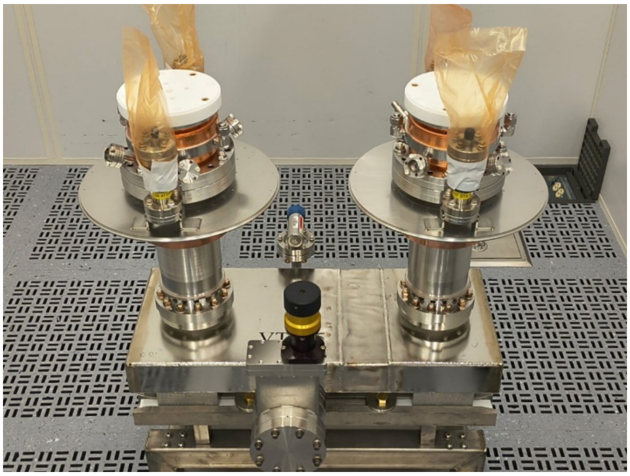

Figure 4: Vacuum-side coupler assemblies mounted to the modified connecting waveguide in the cleanroom.

Figure 5 shows an image of the fully prepared baking setup. Thick fiberglass insulation was added in the space around the couplers to create a "pseudo-oven" effect for more even heating. Nitrogen purge lines were added to the setup to prevent the air-side copper RF surfaces of the ceramic window assemblies from oxidizing during the bakeout.

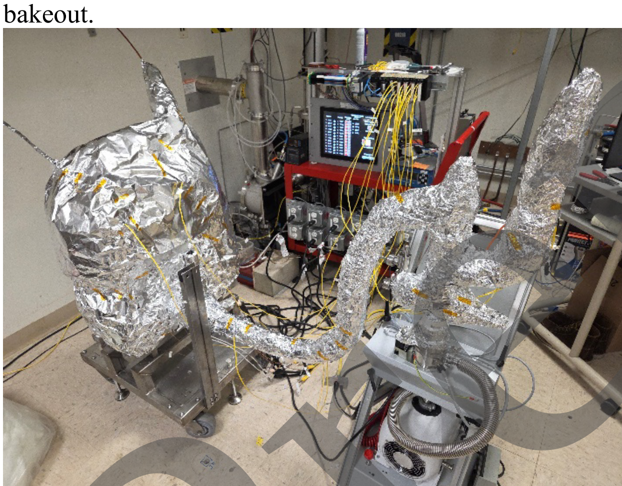

Figure 5: Image of the completed bakeout station showing the test cart with enveloped couplers and connecting waveguide (left), pump cart (right) and bakeout cart (background).

Bakeout Process

To test the new bakeout system, an initial bake of the pump cart and hose was performed, during which the gate valve to the connecting waveguide was closed. After a successful demonstration of the controls, final preparations were made for the full coupler bakeout. The setup was baked at 200 °C for 66 hours, with a 12-hour ramp up and an 18-hour ramp down. The temperature profiles of the couplers and connecting waveguide are shown in Figure 6. The residual gases with the highest partial pressures after baking were H_2O (6.5×10^{-10} Torr) and H_2 (8×10^{-9} Torr). The final coupler pressures were between $1.0 - 1.3\times10^{-8}$ Torr, which is low enough to proceed to RF conditioning.

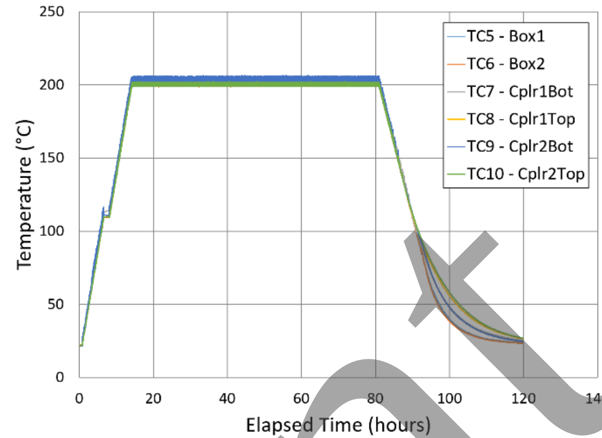

Figure 6: Temperature profiles during the bakeout. A system restart to set up the IR camera caused the break in the ramp-up.

CONCLUSION

Two new FPCs, designed and fabricated by RadiaBeam for operation in conduction-cooled cryomodules, have been received at Jefferson Lab for commissioning. In preparation, a repurposed connecting waveguide was modified for use with the new FPCs. Simulations of the coupler-waveguide system indicate that RF conditioning in TW mode should be feasible up to 100 kW, well above the original specification. The couplers' components have been successfully cleaned, assembled in the cleanroom to be leak-tight and the assembly has been successfully baked using a newly developed bakeout system.

The couplers are ready for initial low-power conditioning using a 2.5 kW RF generator. Once this is completed, the current goal is to perform the remaining conditioning (to at least 25 kW) with an industrial magnetron as the power source. However, the feasibility of this process still requires demonstration. In particular, the speed at which the magnetron's RF output can be cut off in an interlock event must be characterized.

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