DESIGN OF A 1.3 GHz HIGH-POWER RF COUPLER FOR CONDUCTION-COOLED SYSTEMS*

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Abstract

Cornell is designing a new standalone, compact SRF cryomodule which uses cryocoolers in place of liquid helium for cooling. One of the biggest challenges in implementing such a system is designing a high-power input coupler which is able to be cooled by the cryocoolers without any additional liquid cryogenics. Due to the limited heat load capacity of the cryocoolers at 4.2 K, this requires very careful thermal isolation of the 4.2 K portion of the coupler and thorough optimization of the RF behavior to minimize losses. This paper will present the various design considerations which enabled the creating of a conduction-cooled 1.3 GHz input coupler capable of delivering up to 100 kW CW RF power.

INTRODUCTION

While many particle physics experiments seek high-energy collisions up to the TeV range, there are also important applications for small-scale accelerators operating between 1 and 10 MeV. These applications cover various fields such as environmental sustainability, medicine, national security and industry [1,2]. Many of these operations would benefit from higher throughput and thus high average beam power (up to 1 MW), which superconducting radio-frequency (SRF) technology is well-suited for. However, established SRF accelerators require liquid helium to cool the cavities during operation. The use of helium requires additional complex and expensive infrastructure which becomes prohibitive for small-scale operations.

New research is examining the feasibility of using crycooolers in place of liquid helium for cooling Nb_3Sn-coated SRF cavities. Currently available commercial cryocoolers are capable of extracting up to 2.5 W of heat at 4.2 K [3], and improvements in Nb_3Sn cavity performance has resulted in cavities which only dissipate about 1 W of heat while operating continuously at 10 MV/m and 4.2 K [4–10]. Proof-of-principle studies have already been completed at laboratories such as Cornell [11,12], Fermilab [13] and Jefferson Lab [14], demonstrating the ability to operate conduction-cooled Nb_3Sn cavities at fields relevant to small-scale operations.

To further develop this technology, Cornell is designing a new, cryogen-free standalone cryomodule which only uses two cryocoolers as a cooling source [15]. The combined cooling capacity of the cryocoolers (PT-420RM and PT-425-RM) are 100 W at 45 K and 4.15 W at 4.2 K [3]. The primary operating parameters of this cryomodule are listed in Table 1. This paper will focus on the recently completed design of the RF input couplers which will be installed in the system. Due to the limited cooling capacity of the cryocoolers, careful attention must be paid to the coupler heat loads at 4.2 K. Here we will discuss how such challenges were addressed and examine the resulting RF and thermal behavior of the couplers.

Table 1: Cryomodule Operating Specifications

Property	Value	Units
Frequency	1.3	GHz
Energy Gain	1	MeV
Max Current	100	mA
Max Power	100	kW

DESIGN CHALLENGES

The design process for the couplers began using the injector couplers from Cornell's Energy Recovery Linac (ERL) as a baseline. The ERL injector couplers were designed to handle high average power (target 75 kW) with strong coupling to deliver power to a beam with a current up to 100 mA [16]. These properties match very closely to those desired for the new couplers, and thus the design provided an appealing starting point. However, many modifications were required for the couplers to be usable in the new conduction-cooled cryomodule. These can be summarized by the following challenges which were used to guide the design process:

1. Enable up to 100 kW operation (per coupler) while reducing 4.2 K heat load to ~1 W.
2. Remove all fluid cryogenic cooling and replace with conduction-cooling capabilities.
3. Reduce cost by simplifying overall design while maintaining necessary functionality.

The first challenge presented the most significant obstacle to overcome. This restriction indicates that the heat load at 4.2 K must be a factor of about 10^5 smaller than the targeted forward power. Achieving this required significant optimization of the coupler's RF design in order to minimize reflections and improve heat load distribution. One implemented solution was the addition of a quarter-wave transformer to each side of the inner bellows. The geometry of this transformer was optimized in order to minimize

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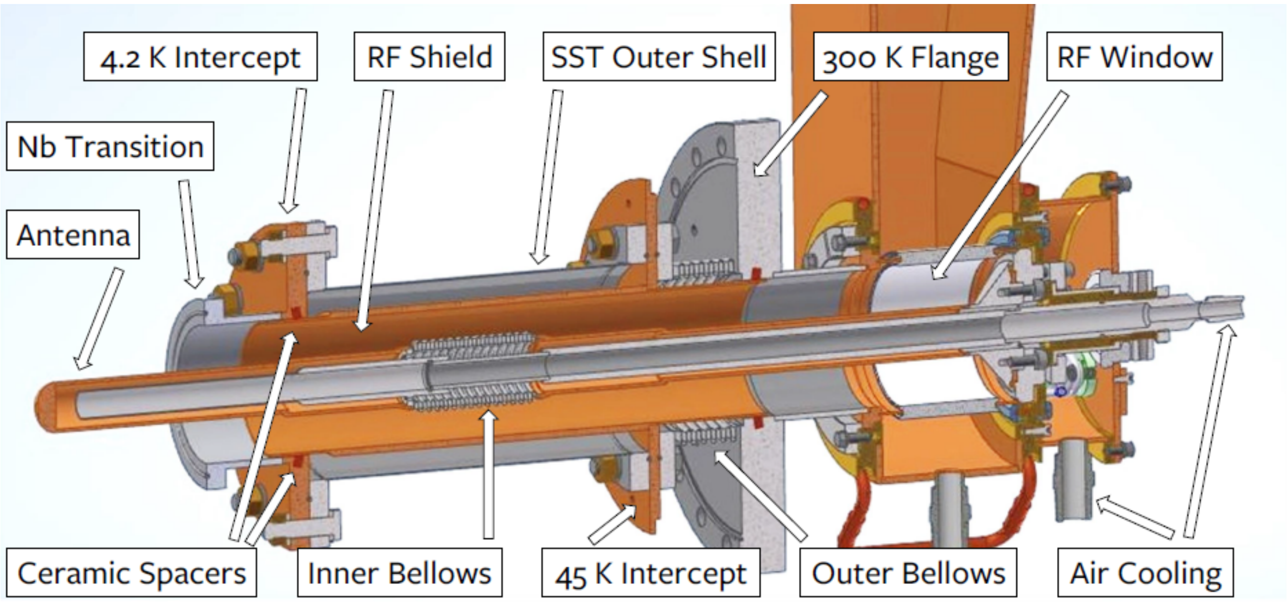

Figure 1: Final design of the high-power couplers for Cornell's new conduction-cooled cryomodule.

reflections for the full ±8 mm stroke of the inner bellows. A second key addition was the use of an "RF shield" to act as the outer conductor of the coaxial line. This shield was inspired by a design developed at Fermilab [17], which was then further modified for use in our coupler. The purpose of this RF shield is to reduce the heat load at 4.2 K by "redirecting" the RF losses to the 45 K heat load. This is done by ensuring that the shield is only thermally anchored to the 45 K intercept, which is accomplished using small ceramic spacers at both ends to prevent thermal contact to colder or warmer components.

The second challenge relates to how the heat loads can be extracted from the new coupler. In Cornell's ERL injector modules, for example, heat pipes bring fluid cryogenics directly to the heat intercepts placed at different stages of the coupler. In a cryocooler-based cryomodule, however, the cold heads of the cryocoolers are separated from the coupler and must be connected via a conductive path. As such, it must be ensured that the heat intercepts offer strong thermal contact to both the coupler components as well as the thermal path which will be used to extract the resulting heat. This motivated the use of large copper disks for the intercepts, which would provide a reliable connection between the coupler's RF surfaces and the rest of the thermal path to the cold heads.

The third challenge is motivated by reducing the complexity and cost of the system to make it more accessible and reliable. Simplifying the coupler design results in fewer possible points of failure and a simpler assembly and installment process. Two major steps taken to achieve this were removal of the cold RF window and only using one set of outer bellows. Taking out the cold window significantly simplifies the "cold" portion of the new coupler and also eliminates any concern of particles being ejected out of the cavity and striking the ceramic. While the ERL injector couplers had multiple sets of bellows to accommodate significant transverse deflection of the coupler, the new design is reduced to a single set of bellows which is only required to allow for thermal contraction.

These solutions, along with other key components, can be seen in the final coupler design shown in Fig. 1. The remaining sections will discuss the results of RF and thermal simulations using this coupler design, as well as structural considerations which were studied. It should be noted that the RF and thermal simulations were part of an iterative process which led to the design solutions discussed above, and it will only be the final results which are shown below.

RF & THERMAL SIMULATION

RF design of the coupler was performed in CST Microwave Studios where key components (e.g inner bellows, RF shield) were analyzed individually before being combined into a full model. Figure 2 shows the final model as constructed in CST. The waveguide portion of the model (seen on the right end) was directly modeled after the ERL injector couplers, while the remaining components were newly designed. Of particular interest are the RF shield and inner bellows with quarter-wave transformers as discussed previously. Frequency domain simulations were used to optimize S_{11} at the operational frequency of 1.3 GHz. As seen in Fig. 3, this optimization achieved an S_{11} value of less than −80 dB. In addition, the antenna tip was modified to obtain a Q_{ext} of 2 E5 at full extension for optimal beam coupling. The maximum Q_{ext} is 1.77 E6, offering nearly a full order of magnitude variation.

The RF model in Fig. 2 also shows the resulting material losses calculated in CST for the various components of the coupler. These losses were then applied as heat loads to a separate mechanical model in Ansys to simulate the thermal

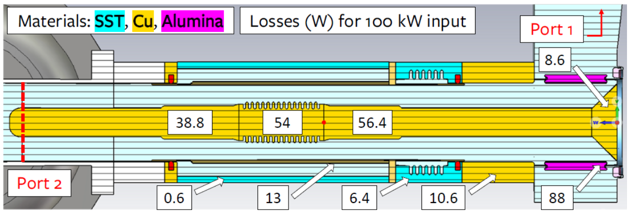

Figure 2: RF model of the newly designed coupler. Material assignments are indicated via the highlighted text. Port locations are shown in red while the boxed numbers list the resulting RF losses for 100 kW forward power.

response to different levels of forward power, namely 0, 50, and 100 kW. These represent static conditions, the original operating spec, and the updated target power. Additional boundary conditions applied in the model include: thermal radiation on all inner surfaces of the coupler; air cooling of the RF window and inner conductor; RF shield intercept held at 45 K; transition piece intercept held at 4.2 K.

Results of the thermal simulation corresponding to 100 kW forward power are shown in Fig. 4. The entire RF shield remains near 45 K, indicating good thermal isolation thanks to the ceramic spacers. In addition to protecting the 4.2 K components, the RF shield also prevents overheating on the outer bellows. As shown, the maximum temperature on the bellows is just under 310 K, even without the use of copper plating (see Fig. 2). The maximum temperature on the inner conductor is just over 350 K, which occurs on both the inner bellows and the end of the antenna. The RF window only warms up to about 325 K due to the direct air cooling provided.

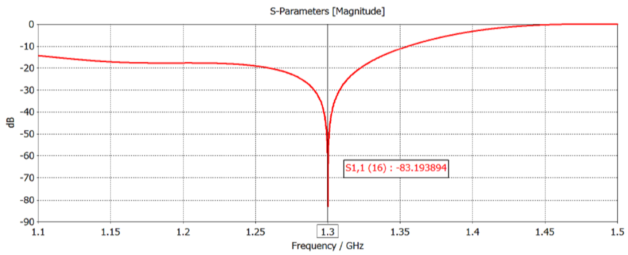

Figure 3: Optimized S_{11} parameter, shown between 1.1 and 1.3 GHz. Minimum $S_{1}1$ achieved is less than −80 dB.

For forward power of 0/50/100 kW the resulting heat loads at 45 and 4.2 K are 21.1/29.5/37.9 W and 0.46/0.80/1.11 W, respectively. This confirms that our primary design challenge has successfully been addressed. With two couplers operating at maximum power, 2.22 W of the 4.15 W cooling capacity at 4.2 K is used.

STRUCTURAL STABILITY

Once the RF and thermal behavior of the coupler was understood, a couple areas of concern had to be examined for structural stability before fully finalizing the design. The inner conductor assembly became a concern due to the removal of the cold RF window from the coupler. Eliminating this intermediate support results in a long lever arm acting on the connecting joint which mounts the inner conductor to the rest of the coupler body (see the right side of Fig. 1). In addition, the flexibility of the inner bellows puts more stress on the tuning rod assembly inside the inner conductor, as the end of the inner conductor would otherwise be unsupported.

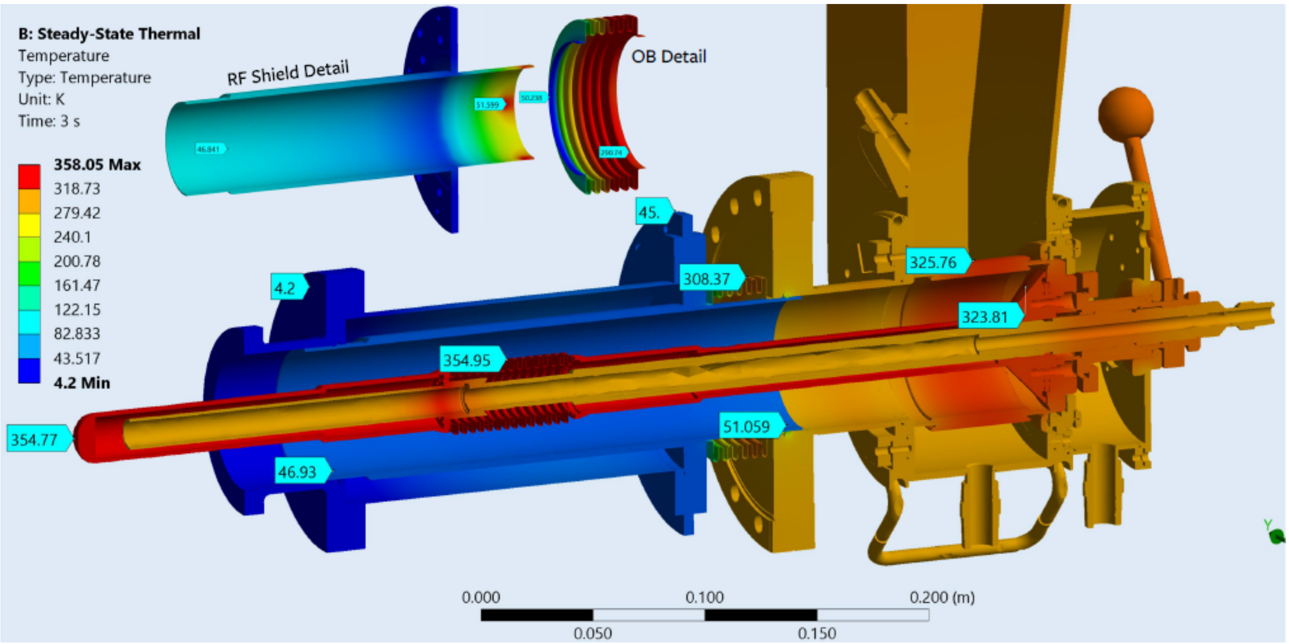

Figure 4: Results of a thermal simulation for 100 kW forward power in the coupler. The temperature scales for the two inserts are different from that of the main model, and are included to show more detailed temperature profiles of the RF shield and outer bellows.

The wall thickness of the first segment of the tuning rod was increased to help address this concern.

Figure 5 shows deformation and stress results of a structural analysis performed in Ansys. A maximum deformation of 0.2 mm is seen at the end of the inner conductor, while a maximum stress of about 30 MPa is seen where the tuning rod connects to the inner conductor at the far end of the bellows. The tuning rod is made of 316 stainless steel, which has a yield strength between 200-300 MPa. This confirms that the assembly stresses are well within a safe operating range. A modal analysis was also performed on the structure, which showed a fundamental mechanical mode at 44 Hz. While there was an original goal to adjust the design to increase the fundamental mode above 60 Hz, it was found that the necessary increase in rigidity was impractical, such as further increasing the tuning rod wall thickness so much that the air cooling capabilities would be significantly hindered. Therefore, it was decided to keep the original design with a fundamental mode at 44 Hz.

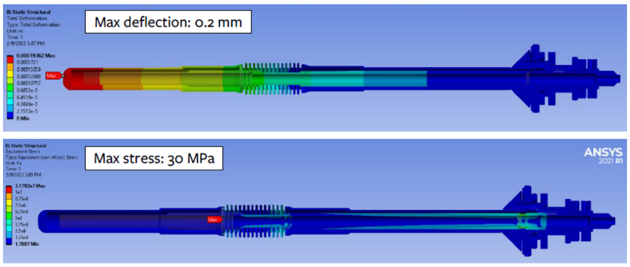

Figure 5: Top: Total deformation of the inner conductor assembly, showing a maximum deformation of 0.2 mm at the antenna tip. Bottom: Total stress (von-Mises) in the inner conductor assembly, showing a maximum of about 30 MPa.

A second area of concern was the outer steel shell between the 45 K and 4.2 K intercepts. This component is used as a heat block to minimize heat flow between the two intercepts. As such, it has a wall thickness of only 0.5 mm. During the eventual assembly of the full cryomodule, the coupler will be pumped under vacuum before the surrounding cyomodule volume. As such, a structural analysis was completed for this component to check for stability against buckling. Results of this analysis are shown in Fig. 6, both for an unaltered model as well as one in which a perturbation was introduced to the cylindrical shell. This was done to check how much of an effect an imperfection in the cylindrical structure would have. The unaltered model had a maximum stress of about 10 MPa, while the perturbation increased the maximum stress to about 30 MPa. Both of these values are well within the yield strength of 316 stainless steel, confirming that this component will withstand the expected pressure difference without modifications.

CONCLUSION

The design of a new high-power 1.3 GHz coupler for a conduction-cooled cryomodule has been completed. The RF design has been optimized such that the 4.2 K heat load is only 1.11 W for 100 kW forward power. This is possible in part due to the use of an RF shield which sinks most of the RF losses at 45 K, preventing the colder components from seeing high fields. Further RF optimizations, such as the use of quarter-wave transformers at the inner bellows, produced an $S_1 1$ less than −80 dB at the operating frequency. Thermal modeling shows reasonable temperatures across all components, with the antenna tip at just over 350 K and the RF window at 325 K as a result of the included air cooling. Certain components were checked for structural stability, which were confirmed to be well within their respective stress limits. With the coupler design completed, the fabrication process will now move forward.

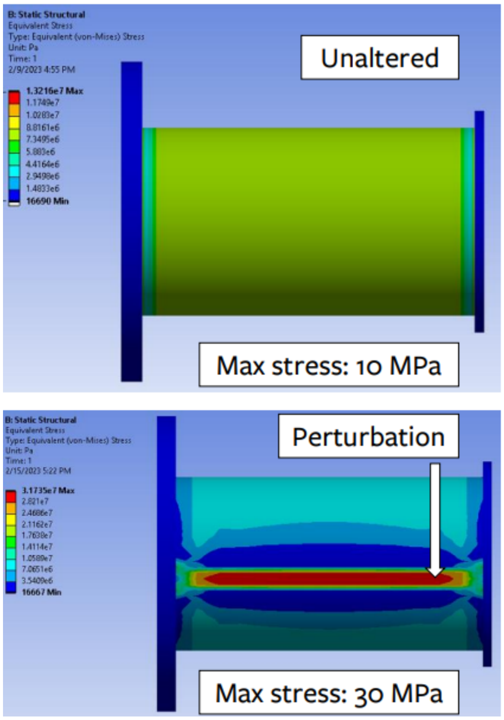

Figure 6: Top: stress results for the unaltered steel shell, showing a maximum stress of about 10 MPa. Bottom: stress results for the steel shell with a perturbation added, showing a maximum stress of about 30 MPa.

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