ELECTROMAGNETIC DESIGN OF 15 kW CW RF INPUT COUPLER*

S.V. Kutsaev, M.P. Kelly, P.N. Ostroumov,

Argonne National Laboratory, Argonne, IL, 60439, USA

Abstract

A new power coupler is under development at Argonne National Laboratory for a CW 40 MeV proton/deuteron linac for the SARAF project in Israel. This linac requires one 15 kW RF input power coupler per superconducting (SC) half-wave resonator (HWR) operating 176 MHz. A coaxial capacitive input coupler has been designed and analyzed for these purposes. This paper presents the results of 3D electromagnetic simulations of this coupler together with the cavities mentioned above. An analysis of multipacting discharge in the coupler is also presented.

INTRODUCTION

There are two types of RF input power couplers: capacitive and inductive. At the ANL ATLAS facility [1], we have gained long-term experience operating both types of RF couplers at low power, up to 500 Watts. For example, in the recently commissioned ATLAS Energy Upgrade cryomodule, six cavities are equipped with adjustable inductive couplers [2]. We have also developed an adjustable capacitive coupler which is installed on one of the cavities. This coupler was a simple modification of the inductive "loop" to antenna. In this application as a bottom mounted coupler on a quarter-wave (QWR) cavity, the cold tests have shown that the capacitive coupler is less susceptible to the RF heating in over-coupled operation than the loop coupler. Therefore, our development of an RF coupler for high power operation (>1kW) is based on a capacitive design.

MECHANICAL DESIGN

The considerations driving the mechanical design are to provide the following properties: variable coupling, stable operation at full power for any coupler position, minimization of total (static and dynamic) heat load, and compatibility with clean room assembly.

Primary components of the RF coupler are shown in Figure 1. The bellows assembly on the left provides an adjustment for the coupler central conductor into and out of the cavity coupling port and, at the same time, serves as a thermal isolation from the 4 K cavity flange to the 80 K thermal intercept. The compact 80 K RF window cools the central conductor through a brazed ceramic disc of alumina and also provides a means for clean sealing the cavity RF volume after high-pressure rinsing in a clean room. The 80 K–to–300 K transition is a separate component largely to reduce the heat load into the cryostat. Finally, the 300 K alumina window serves as the

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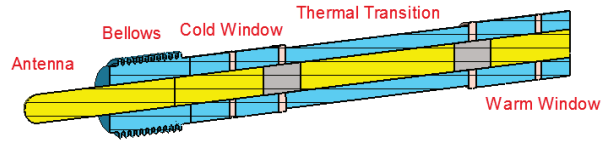vacuum break between the cryomodule vacuum and atmosphere

Figure 1: RF power coupler design.

RF windows are made of 96% purity Al_2O_3 ceramics. The cold window is mounted to the cavity in a clean room to minimize cavity contamination. The warm window is mounted outside the clean room prior the loading of the cavity string into the cryomodule. The vacuum between two windows is obtained independently.
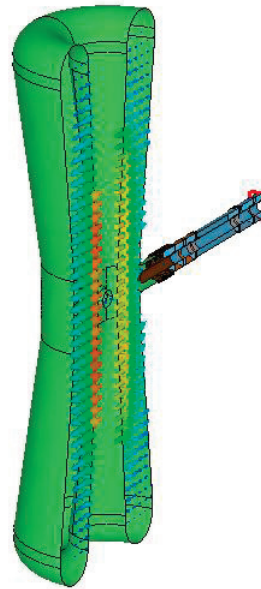

Figure 2: Power coupler connected to the HWR (electric field).

Cold components of the coupler experience both static and RF heat load. To reduce the heat load into the cryogenic environment of the cryostat and cavity, we have introduced a 70K (or 80K if liquid nitrogen available inside the cryostat) heat sink over the outer conductor. The inner conductor is cooled down through the ceramic cold window

MULTIPHYSICS SIMULATIONS

Extensive muliphysics simulations have been carried out to optimize the high-power coupler design. The most updated version of the CST Studio Suite [3] allows us to

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solve both RF and thermal problems during the RF coupler design process.

Electromagnetic Simulations

Electromagnetic simulations of the coupler were performed using the frequency domain solver (F-solver) of the CST Microwave Studio software package. This solver is preferable to the Time Domain solver due to faster and more accurate results. Also, a significant advantage of the F-solver is the possibility to use a tetrahedral second order curved element mesh which can provide accurate representation of curved surfaces.

The simulations of the initial design (Fig .1) revealed that power reflections were too high at the level of -15dB at an operating frequency of 176 MHz. Therefore, several design changes have reduced reflections. Three parameters of the coupler were adjusted:

- Dimensions of the thermal transition: its length and diameter;
- Dimensions of the bellows, particularly the shape of the neck and diameter;
- The antenna diameter.

Significant changes of the thermal transition dimensions were necessary to reduce the reflected power by several dB. The S11 parameter is a weak function both of the bellows neck shape and bellows inner diameter Finally, by varying the antenna diameter, the S11 parameter was reduced to below -30 dB. The simulations in a wide frequency range show that a sharp -60 dB minimum of S11 is located above our target frequency. This minimum can be shifted to the desired frequency by changing the cavity port diameter. However, a two-inch port diameter is a standard feature of ANL-built cavities and changing the port diameter is not desirable.

The external Q-factor of the coupled cavity can be changed by 2 orders of magnitude by adjusting penetration length by one inch only as is shown on Figure 2.

Thermal Simulations

Thermal analysis of the RF coupler was performed with CST MPhysics Studio 2012. Prior to the detailed thermal simulations, the CST results were verified by analytical estimates for simplified cases. Excellent agreement was achieved which established good confidence in detailed simulations of complex geometries and heat distribution.

The effect of RF heating is an inherently nonlinear problem due to the physical properties (thermal and electrical conductivities, heat capacities) of the materials. As CST does not have the capability to simulate non-linear properties of materials as a function of temperature, an iterative approach was used to include this dependence.
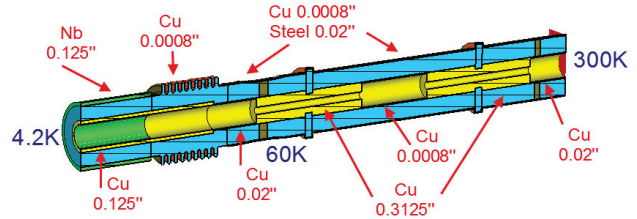

Figure 3: RF power coupler CST thermal model.

Figure 3 shows an example of the MWS model with realistic material thicknesses for the thermal simulations of coupler. To reduce the RF surface resistance copper plating is applied to the stainless steel bellows. In simulations we include both thin layers of copper and stainless steel. Due to the very thin materials, the hexahedral mesh is not suitable. Therefore, the model has been meshed using tetrahedral elements. The latter provides a good physical model even for the relatively thin 20 μm copper plating on both the bellows and the 80-K-to-room temperature transition. The results of coupled RF and thermal simulations are shown in Figure 4 and Table 1.
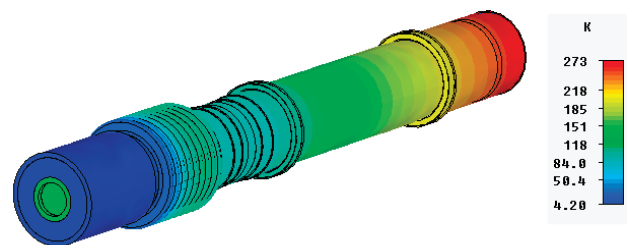

Figure 4: RF power coupler temperature map.

To reduce the heat load to the SC zone, a 5K thermal intercept at the centre of the bellows was introduced and investigated (see Fig. 5). For this case, there is no temperature raise. Nevertheless, the heat flow to the helium is increased to 2.5W (0.17W of which are to 2K helium zone). Though this design cannot be used in SARAF, it is suitable for the other project with cavities at 2K.
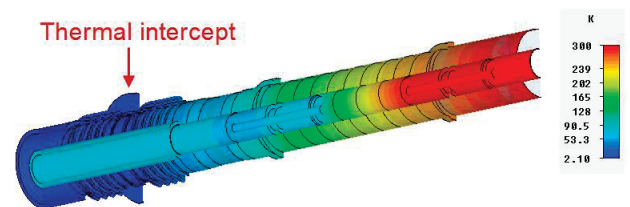

Figure 5: Temperature map RF power coupler with thermal interceptor.

As expected from simple analytical calculations, the temperature increase of the thick-walled copper central conductor is small (about 10 K) due to a good mechanical integrity and small ΔT across the ceramic braze connection. In terms of RF heating, the thin-walled outer

conductor bellows are the most concerning. However, for the proposed design with 20 µm copper plating, the heating is only 30K above the temperature of the thermal intercept which is entirely tolerable.

Table 1: Thermal Power Flows in the Coupler

Parameter	Value	
Thermal Itnerceptor	no	yes
Input RF Power, kW	15.0	
Heat Flow to SC zone (static), W	0.67	0.057
Heat Flow to SC zone (total), W	1.59	0.165
Heat Flow to Interceptor, W	-	2.49

A 20 µm copper plating at the bellows section is an optimal value. Thicker plating increases thermal conductivity leading to excessive static flow to the SC zone. On the other hand, a very thin plating causes overheating at the bellows due to the dynamic load.

Multipacting Simulations

The multipacting phenomenon, a secondary electronic discharge, is considered a predecessor for voltage breakdowns in RF cavities and couplers. Therefore the coupler design should avoid conditions that can lead to multipacting.

The multipacting simulations were done in CST Particle Studio. We used PIC solver with imported electromagnetic fields at 176MHz from previous MWS simulations. The simulations show that the exponential growth of secondary electrons number for all power levels in full a reflection regime. Traveling wave regime simulations predict the particles number growth at 500 – 5500 W incident power levels. The area of discharge is located on the outer conductor of the warm window at lower power levels and shifts towards the antenna region at higher power (Fig.6).
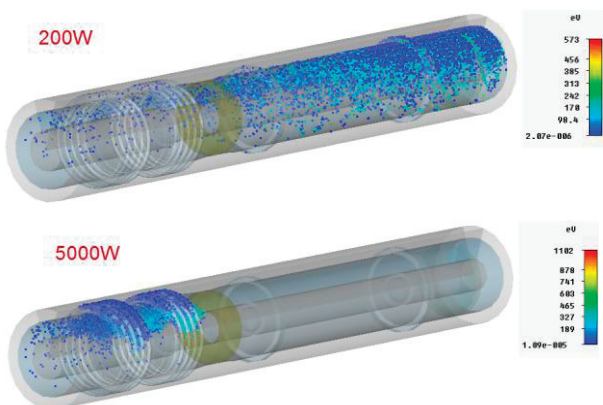

Figure 6: Locations of multipacting regions.

The simulations were repeated with the independent MultP-M code [4]. According to these results, the particle number growth begins at a power level of 50 W, reaches maximum at 500 W and completely stops at 2.5 kW for the full reflection mode. When the coupler is matched, the numbers are the same except the maximum shifts to 1000W.

To benchmark the simulation code, we have performed a simulation of the 72.75 MHz RF coupler that is currently used at ANL for testing SC cavities. The simulations in MultP-M show no evidence of multipacting discharge in this coupler for a power range from 0 to 4 kW. Similarly, no multipacting has been observed in this power range in experiments.

The most practical method to suppress the multipacting discharge is to apply a DC bias to the inner conductor. The simulations in PS show that the voltage of 300V is enough to stop the exponential growth of particles. In order to apply the bias, a gap in the inner conductor must be created to isolate the RF power. Simulations show that a 0.02'' gap with an inserted sapphire disk is enough to get less than -20 dB reflection coefficient.

CONCLUSIONS

A new power coupler for application with SC cavities has been designed and is being prototyped. The coupler provides up to 30 mm axial stroke and adjustment of the external quality factor by 2 orders of magnitude. The coupler design was optimized to achieve the level of power reflections less that -20dB in the presence of biasing voltage applied to the inner conductor

Thermal simulations were performed using CST Studio and predict very low heating in the bellows section. Multipacting discharge simulations show a little concern especially for power levels less than 4kW. This can be avoided by using a bias voltage if necessary A final decision on the bias voltage will be made after testing of the prototype coupler.

ACKNOWLEDGMENTS

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