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PIP-II 650 MHz POWER COUPLER THERMAL STUDIES*

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Abstract

The Proton Improvement Plan - II (PIP-II) project is underway at Fermilab with an international collaboration involving CEA in the development and testing of 650 MHz cryomodules. One of the first main contributions of the CEA was the participation in the design efforts for the current 50 kW CW 650 MHz power couplers. This paper reports some of the results of thermal and parametric studies carried out by the CEA on these power couplers.

INTRODUCTION

The PIP-II/LBNF/DUNE project will be the first internationally conceived, constructed and operated mega-science project hosted by the Department of Energy of the United States [1]. The PIP-II project represents the upgrade plan of Fermilab accelerator complex [2]. It will lead to the construction of world's highest energy and the highest power CW proton Linac reaching 800 MeV. Five types of cryomodules will be built to achieve this performance. For the highest energy part of this Linac, the LB650 and HB650 cryomodules [3, 4], equipped with 650 MHz Superconducting (SC) cavities are used. The same Power Coupler (PC) design, presented in Fig. 1, was adapted for both cryomodules. In total, sixteen unit of these PCs will be needed for the Linac.

The work presented in this paper was carried out in the frame of the French participation to the PIP-II project. PCs dedicated to the HB650 cryomodules will experience the most constraining operation conditions in terms RF power level. For that reason, this paper will only focus on studies using the maximum RF power level corresponding to this case.

The aim of the following calculations is to estimate the maximum heat loads transferred by the 650 MHz PC to cryogenic system through the cavity, the 5 K and 50 K intercepts. This corresponds to an input CW RF power of 50 kW with 20% reflection. The reflection phase that we have chosen for the main part of this study maximizes the 2K heat load. The calculation is based on 2D axisymmetric model taking into account the geometry and the material properties of all the coaxial coupler parts from the cavity interface to the waveguide transition. The results of heat loads calculations presented in this paper englobes both of static and RF losses.

The anomalous heat effect on copper plating was estimated in preliminary design calculation and found to be not very significant. We made the choice to not consider it for this study.

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The Thermal Radiation Power (TRP) towards the SC parts is treated separately in the last part of this paper.

All the results presented here are obtained using the COMSOL Multiphysics software. Many of them were checked with HFSS-ANSYS software and good agreement between results was achieved.

POWER COUPLER DESIGN

Several design modification have been brought to the 650 MHz PCs during the last few years [5]. The current version (see Fig. 1) has a copper (Cu) plated stainless steel (SS) cold part instead of the electromagnetically shielded design [6]. The thickness of the outer conductor (OC) of the same part has been increased in order to enhance its mechanical strength. Moreover, a vacuum gauge port has been added. For some integration reasons, the corresponding cold cathode gauge will be used inside the cryomodule isolation vacuum witch is uncommon but already experimentally validated [7]. The window design has also been improved by modifying the vacuum RF volume geometry shape, increasing the ceramic thickness and replacing the aluminium sealing gaskets to CF. The warm coaxial part of the PC is now completely made of Cu plated SS. The 11.5"x 0.7" waveguide transition has been replaced by aluminium WR1150 waveguide type to overcome overheating issues encountered during RF power tests. Some improvements have also been carried out on the cooling air circulation inside the coupler for better efficiency and lower pressure drop. A simplified schematic representation of the cooling air circulation is shown in Fig. 2.

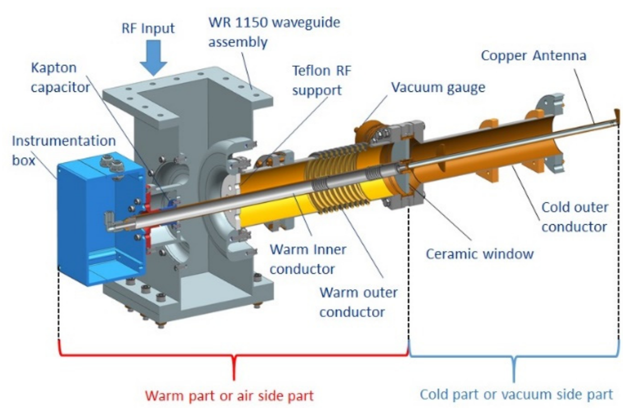

Figure 1: PIP-II 650 MHz Power Coupler.

CALCULATION MODEL AND ASSUMPTIONS

The use of the 2D axisymmetric model is motivated by the low contribution of the conductive heat transfer from waveguide transition to the cold part, through the warm coaxial part. This was corroborated by former calculation

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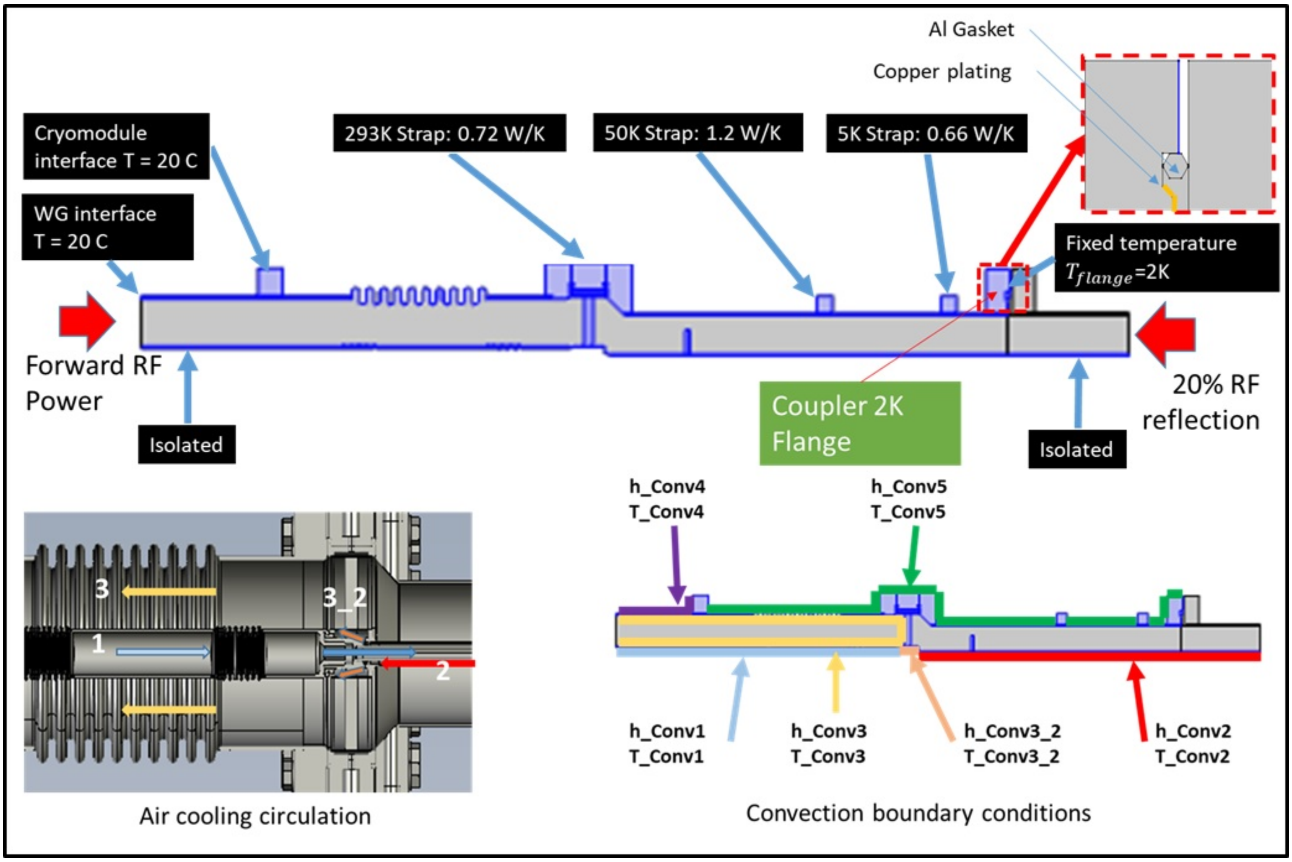

Figure 2: PC 2D axisymmetric model presentation and boundary conditions.

results. In fact, the heat exchange is dominated by the convective heat transfer through the circulating cooling air. This can be explained by the high thermal resistance of the thin warm part inner conductor (IC) and OC having each 0.2 mm thick bellows. As the waveguide can be removed, structure becomes coaxial and 2D axisymmetric calculation can be performed

The temperature data of the cooling air used for the convective heat exchange in the 2D model is calculated as follows:

- We use a complete 3D model (with waveguide) to calculate the maximum RF power losses for any phase of the reflected signal impacting each cooling circuit.
- The air temperature increase is then determined for a given flow rate (4g/s in our case).
- These values are used as inputs for the 2D model.

The 2D model will calculate the impact of the RF heating on surfaces for all the reflection phases. However, the temperature of the cooling air is always invariable for each circuit and corresponds to inputs from the 3D model. This may in some cases overestimate some results but remains coherent with our approach to estimate the highest heat loads obtainable in operation.

The RF heat dissipated in the aluminium gasket used for the coupler to cavity interface assembly is also considered in this calculation.

During the coupler cold operation, the coupler "2K flange" (Fig. 2) temperature would be higher than the cavity temperature. Nevertheless, for this study we made the choice to impose the lowest temperature (2 K) on that flange to simulate the worst condition in terms of 2 K heat losses. Additional parametric calculation results presented in this paper estimates the impact of this choice on the result by varying that temperature from 2 K to 10 K.

General Boundary Conditions

The boundary conditions are detailed in Fig. 2. The convection data are detailed later in this paper.

Materials

IC and OC of the warm coaxial part are made of Cu plated 316L SS. For the cold part, the IC is made of bulk copper and the OC is made of Cu plated 316L SS. Cu plating nominal thickness is 20 µm everywhere except for the cold part OC where only 10 µm are required to reduce the conductive heat transfer to the cryogenic circuits.

Table 1: Dielectric Material Properties

	ε_r	Tan(δ)	k [W/(m.K)]
Alumina	9.8	1.0E-04	27
Teflon	2.1	1.0E-04	0.25

The nominal RRR is 10, but, values up to 100 can be accepted. The ceramic is made of AD-998 alumina. Dielectric materials properties are given in Table 1. The capacitor thermal heating contribution is neglected.

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The Cu and SS material properties considered for this study are obtained from CryoComp V 5.2 Software. The electrical and thermal properties of the materials are managed by COMSOL Multiphysics according to the temperatures obtained by coupled RF/thermal calculation. The thermal conductivity of cu-coated SS walls, used for calculation, is an equivalent conductivity based on materials respective thicknesses and conductivities (see Fig. 3).

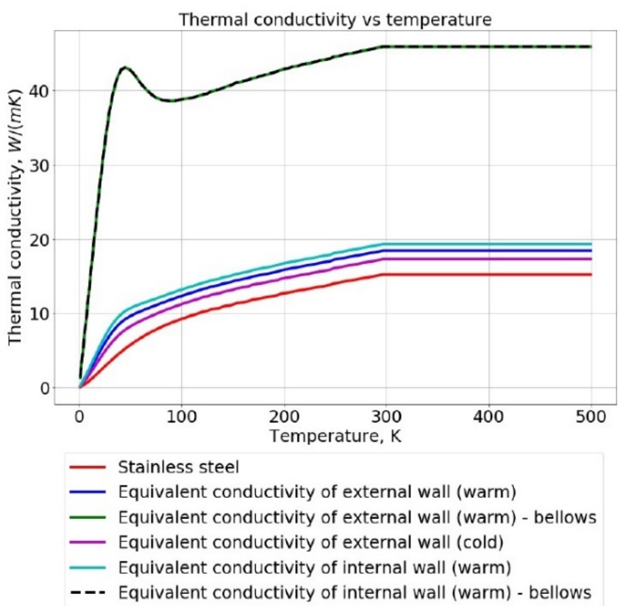

Figure 3: Equivalent thermal conductivities.

Convection Conditions

The nominal cooling air flow rate used for the coupler cooling is 4 g/s. The heat transfer coefficient "h" values are given by Fermilab former calculations (see Table 2). As explained previously, the temperature of the air in each part of the coupler was obtained using the RF losses results calculated on a complete 3D model taking in account the waveguide transition. These calculations are not detailed here. The total power transferred to the air is estimated to about 128 W. The maximum increase of the air temperature from the inlet to the outlet is estimated to 32 °C.

The convective heat exchange parameters used for the 2D model are given in the following table.

Table 2: Convective Heat Transfer: Boundary Conditions

Boundaries	**h [W/(m².K)]**	**T [K]**
Conv1	46	299
Conv2	414	312
Conv3_2	80	320
Conv3	3	323
Conv4	5	293
Conv5	- (vacuum)	- (vacuum)

THERMAL CALCULATION RESULTS

"2K Flange" Temperature

Although the boundary temperature set at 2 K on one side of this flange (see Fig. 2), it was found that surfaces exposed to RF could reach more than 9 K for the phase generating the highest PC heat load towards the cavity (Fig. 4). This temperature could reach 13 K if the set temperature is increased from 2 K to 10 K. The temperature limitation to 13K could be explained by the contribution of the 5 K intercept.

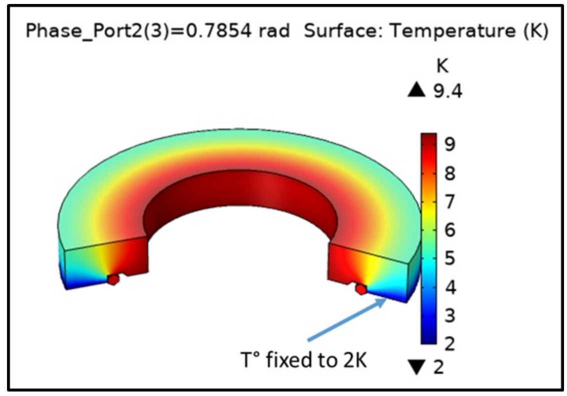

Figure 4: "2K flange" temperature profile.

Heat Loads (Without Thermal Radiation)

The heat loads results are summarized in Table 3. The thermal radiation heat exchanges are not considered.

Table 3: Calculated Heat Loads. *The RF reflection phase chosen to maximize the 2 K heat load.

	2K Heat Load [W]	**5K Heat Load [W]**	**50K Heat Load [W]**
Worst Heat load configuration*	0.89	1.67	8.72
Heat load variation range (all phase)	0.18 to 0.89	1.47 to 1.87	8.71 to 9.06

Next results are calculated for the RF reflection phase corresponding to the "worst heat load configuration", unless otherwise noted.

PARAMETRICAL STUDY

Heat Loads vs the "2K Flange" Temperature

The variation of the boundary temperature of the "2K flange" from 2 K to 10 K induces less than 10% variation on the 2 K and 5 K heat loads. It has almost no effect on the 50 K and 293 K heat loads (see Fig. 5). This confirms that the choice we made to set that boundary at 2 K for our calculation do not induce a high overestimation of the heat loads calculation.

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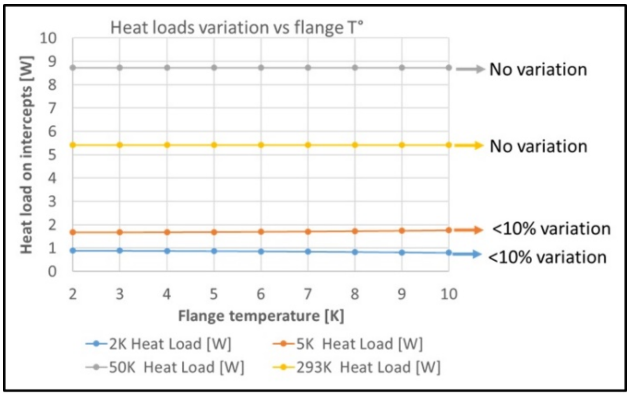

Figure 5: Heat loads vs the "2K flange" temperature.

Cu Plating Thickness Variation

During the manufacturing of the PCs, some Cu plating thickness deviations can occur. We studied the impact of this thickness variation for the cold (OC) on 2 K, 5 K and 50 K heat load.

Figure 6 shows the change in heat loads as a function of Cu plating thickness variation form 5µm to 30 µm (10 µm is the nominal thickness). This calculation highlights the fact that there is no significant 2K heat load variation. Nevertheless, the 5 K heat load is the most impacted by this deviation: up to +56% for 30 µm thickness.

Impact of High RRR

A relatively high Cu RRR could be encountered during the production of the PCs. We studied the impact of an RRR=100 (nominal RRR=10) on 2 K, 5 K and 50 K heat loads. Results (Fig. 6) show that for the nominal Cu plating thickness, an RRR equal to 100 has no impact on the 2 K heat load but is very impacting for the 5 K. The graph presented here can give quantitative estimation of the impact of a Cu plated thickness deviation conjugated with high RRR values.

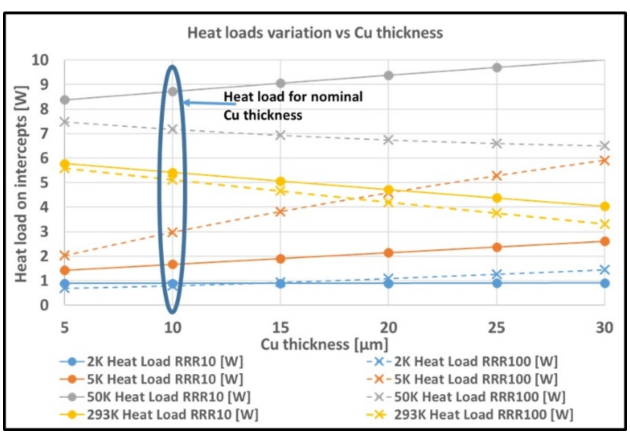

Figure 6: Impact of the Cu plating thickness variation and high RRR on conductive heat loads.

THERMAL RADIATION CALCULATION

The objective of this work is to estimate the impact of the TRP generated by the 650 MHz PC on the SC part. For this calculation we used the COMSOL Surface to Surface Radiation module. This allows to estimate more accurately the radiative heat exchange as it considers the view factors between all the radiating surfaces of the model.

Model and Assumptions

The 2D axisymmetric model of the PC cold part used for this calculations is presented in Fig. 7. The geometry of the superconducting region is simplified. Conductive heat transfer is not permitted between the surfaces. Only heat radiation is allowed. We assume that the TRP has no significant impact on the PC thermal profile.

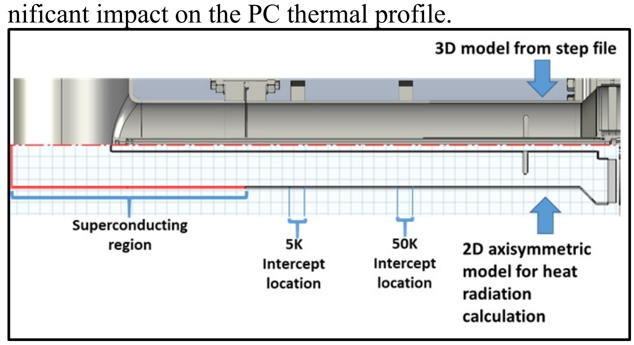

Figure 7: Thermal radiation calculation model.

All the temperatures of the coupler surfaces used here are obtained from the heat loads calculations presented previously. The applied temperatures on the ceramic and the IC surfaces are average values and are respectively equal to 304 K and 320 K. For the OC we applied the approximate temperature profile represented in Fig. 8.

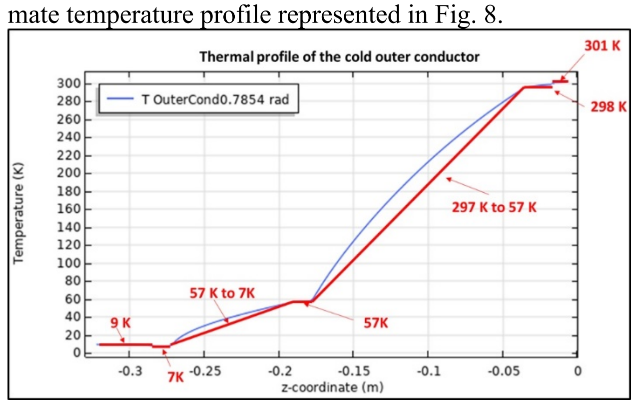

Figure 8: OC thermal profile: in blue the calculated profile, in red the applied approximate profile.

The emissivity of the ceramic, the Cu and the superconducting part are respectively ƐAL2O3, ƐCu, and ƐSC. For ceramic and Cu we used two emissivity values: one pessimistic and the other realistic. For the SC part the niobium emissivity could be estimated to 0.05 [8]. Nevertheless, the simplified geometry used in our model is not representative of the complex geometry of the cavity and beam tube. As a result, the major part of the TRP flowing from the PC to the SC part will not be reflected back due to the multi reflections. For that reason an emissivity equal to one is probably the most realistic.

TRP Results

The TRP calculation results are presented in Table 4. We can see that increasing of the ceramic emissivity by 40%

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do not impact the result. This is due to the RF matching disc existing on the cold part IC (Fig. 1) which reduces dramatically the view factor between the ceramic and the SC part.

The most pessimistic case (#1) gives a maximum TRP of 0.52 W toward the SC parts. Nevertheless, we consider that emissivity values assumed in case (#4) are the most realistic. This gives a TRP of 0.39 W. Adding this value to the 2 K heat load calculated with RF/thermal model (Table 3) we obtain a maximum value of 1.28 W.

Table 4: TRP Results

Cases	ε_{AL2O3}	ε_{Cu}	ε_{SC}	TRP to the SC Part [W]
Case1	0.7	0.1	1	0.52
Case2	0.5	0.1	1	0.52
Case3	0.5	0.1	0.05	0.25
Case4	0.7	0.05	1	0.39
Case5	0.5	0.05	1	0.39
Case6	0.5	0.05	0.05	0.22

CONCLUSION

This paper presents some of the multiple studies performed by CEA on the Fermilab 650 MHz PC design. The model simplification assumptions were motivated by initial calculation using more complex model to check the reliability of the choices. The accuracy of the calculation was verified by comparing results obtained by two different software COMSOL Multiphysics and HFSS-ANSYS. The 2 K, 5 K and 50 K heat load induced by the PC in the HB650 cryomodule are first determined without considering the thermal radiation transfer. Then, the impact of the radiated power on the 2 K heat load was calculated separately using a simplified model. The use of 2D axisymmetric model allowed relatively fast computation, which gave the possibility to perform some parametric studies.

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