PIP-II 650 MHz POWER COUPLER THERMAL STUDIES

H. Jenhani[#], S. Arsenyev, Université Paris-Saclay, CEA, DACM, 91191, Gif-sur-Yvette, France.
S. Kazakov, N. Solyak, Fermi National Accelerator Laboratory, Batavia, IL 6050, USA.

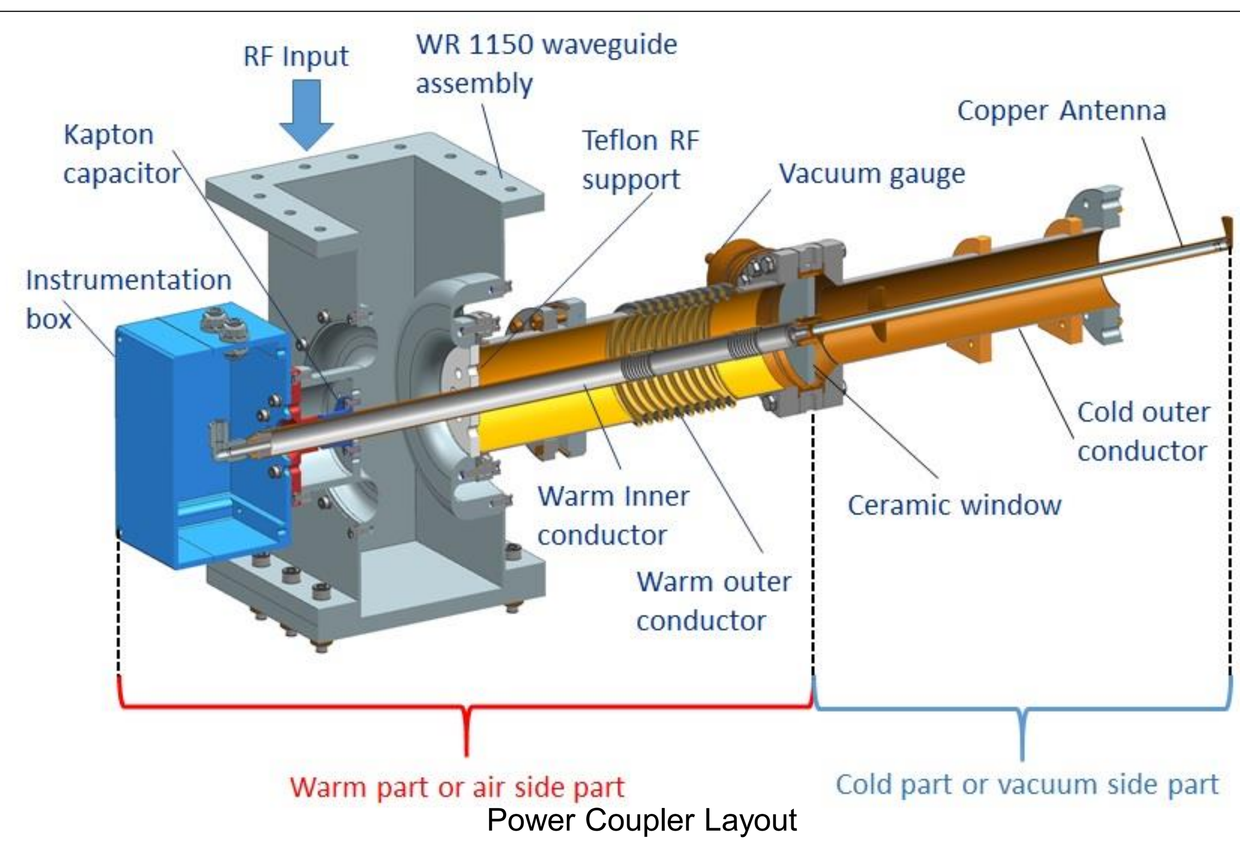
Abstract

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.

PIP-II 650 MHZ POWER COUPLER

Power Coupler characteristics:

- Same Power Coupler for LB650 and HB650 cryomodules
- Frequency: 650 MHz
- Pulsed/CW
- Operation power < 43 kW
- Design target :
  - RF conditioning: 50 kW CW (TW and full reflection (all phases))
  - Cryomodule operation: 50 kW CW with 20% reflection (all phases)
- $Q_{ext} = 10^7 \pm 20\%$
- Air cooling
- HV bias



Power Coupler Layout

Main design modifications during the last few years :

- Cold part outer conductor (OC) with Cu plated stainless steel (SS) instead of the electromagnetically shielded design.
- The thickness of the cold part OC has been increased in order to enhance its mechanical strength.
- Bellows material changed from nickel alloy to SS
- A vacuum gauge port has been added (prototype version).
- TiN on ceramic window (prototype version)
- 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 The 11.5''x 0.7'' waveguide transition has been replaced by aluminium WR1150 waveguide type to overcome overheating issues encountered during RF power tests.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 improvement have also been carried out on the cooling air circulation inside the coupler for better efficiency and lower pressure drop.

CALCULATION MODEL AND ASSUMPTIONS

General considerations:

- For all the results presented here :
  - ✓ Air flow rate = 4 g/s.
  - ✓ RF power = 50 kW with 20% reflection with the reflection phase causing the highest impact on the 2K cryogenic load.
  - ✓ Cu plated RRR = 10 unless otherwise stated
- Results presented here are obtained using the COMSOL Multiphysics software. Comparison with HFSS-ANSYS software showed good agreement between the results.
- 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.
- The temperature data of the cooling air used for the convective heat exchange in the 2D model are previously calculated using the complete 3D model considering the worst heating condition.

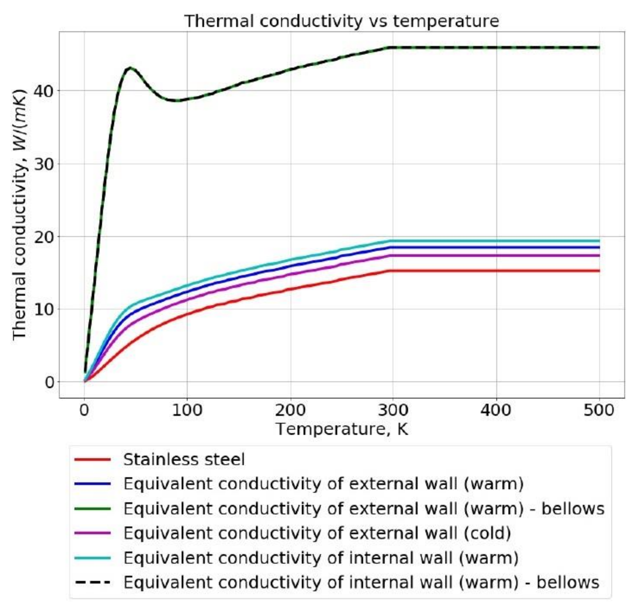
Material characteristics:

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

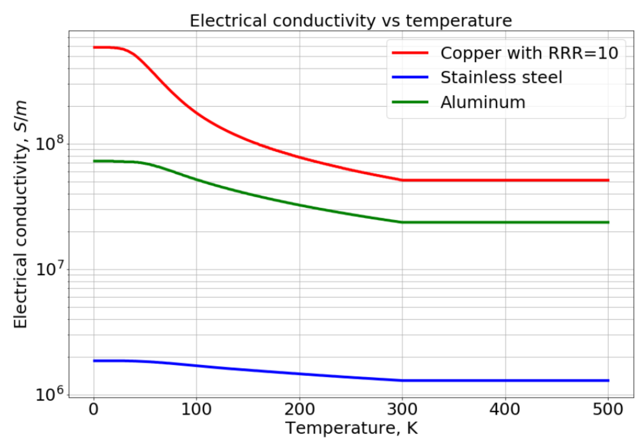
Dielectric material properties

	SS wall thickness [mm]	Cu plating thickness [µm]
Outer cond. air side	2.11	20
Outer cond. air side - bellows	0.2	20
Inner cond. air side	1.65	20
Inner cond. air side – bellows	0.2	20
Outer cond. vacuum side	1.65	10

Stainless steel and Cu thicknesses



Thermal conductivity vs temperature



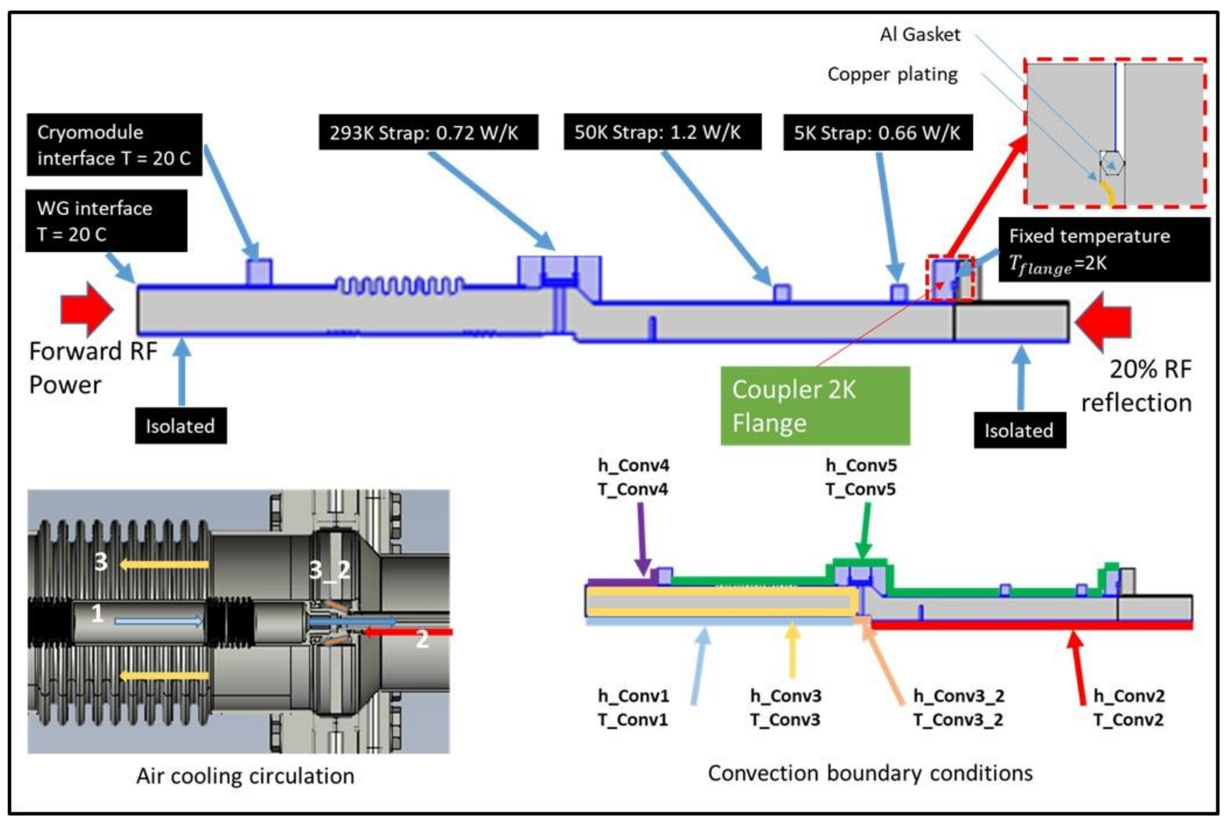
Electrical conductivity vs temperature

Convection 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)

Convective heat transfer assumptions

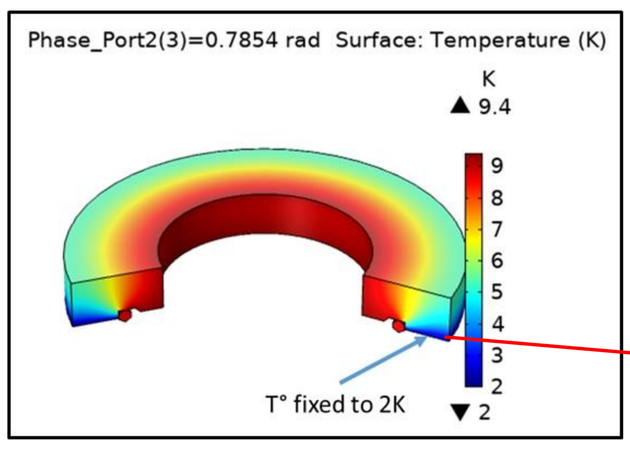
- The total power transferred to the air : ~128 W.
- The maximum increase of the air temperature from the inlet to the outlet : 32 °C.



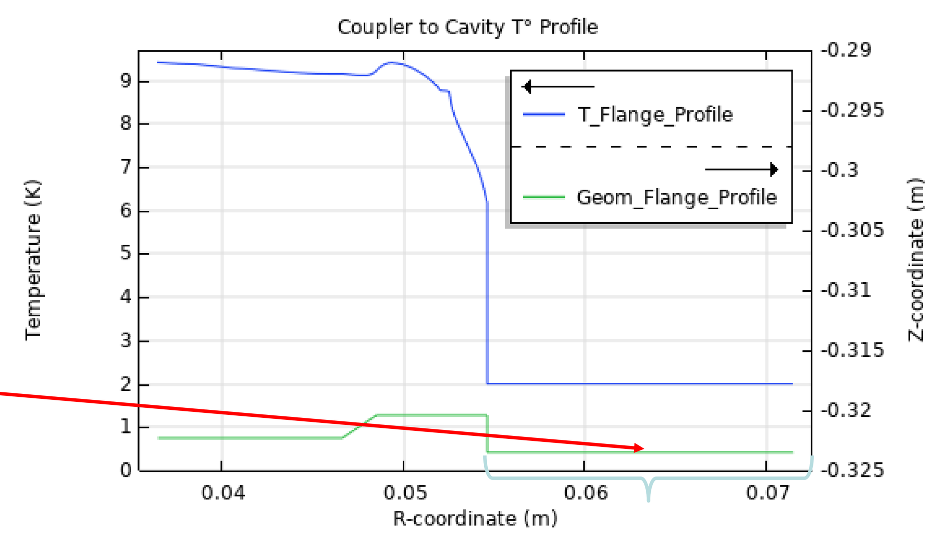
Power Coupler 2D axisymmetric model and boundary conditions

THERMAL CALCULATION RESULTS

"2K flange" temperature



"2K flange" temperature profile



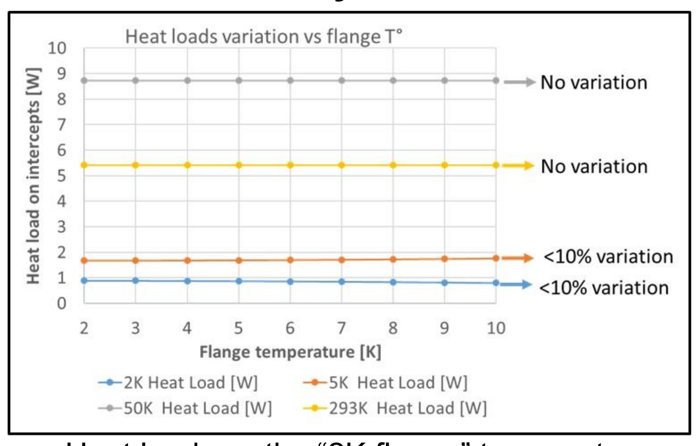
Although the boundary temperature set at 2K on one side of this flange, it was found that surfaces exposed to RF could reach more than 9 K for the phase generating the highest PC heat load towards the cavity. This temperature could reach 13 K if the set temperature is increased from 2K to 10 K. The temperature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

Heat loads (without thermal radiation)

	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

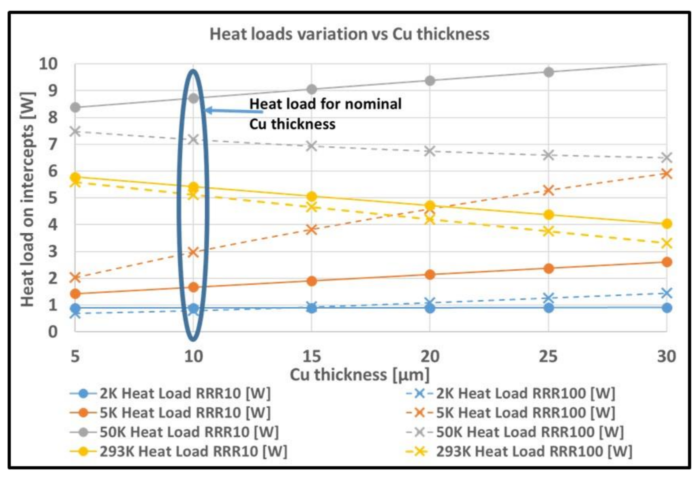
Calculated heat loads. *The RF reflection phase chosen to maximize the 2K heat load.

Parametrical study



Heat loads vs the "2K flange" temperature

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



Heat loads vs Cu plating thickness and RRR

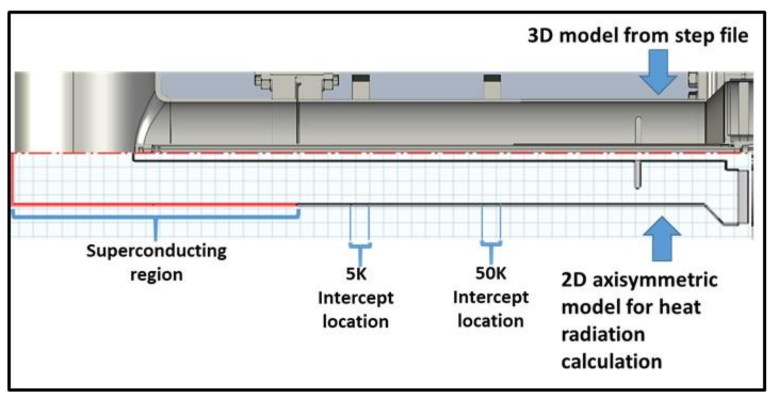
Impact of Cu plating thickness variation:
This calculation highlights the fact that there is no significant 2K heat load variation when thickness changes. Nevertheless, the 5K heat load is the most impacted by this variation: up to +56% for 30 µm thickness.

Impact of high RRR:
For the nominal Cu plating thickness, an RRR equal to 100 has no impact on the 2K heat load but is very impacting for the 5K. The graph presented here gives quantitative estimation of the impact of a Cu plated thickness deviation conjugated with high RRR values.

THERMAL RADIATION POWER (TPR) CALCULATION

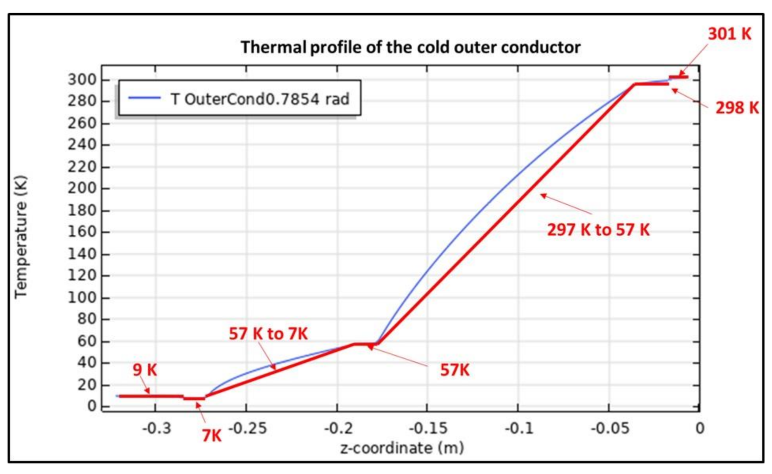
Model and assumptions

- 2D axisymmetric model
- The geometry of the superconducting region is simplified.



Thermal radiation calculation model

- 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
- The emissivity of the ceramic, the Cu and the superconducting part are respectively ε_{Al2O3}, ε_{Cu}, and ε_{SC}.
- Temperatures of the coupler surfaces are obtained from the heat loads calculations presented previously. The applied temperatures on the ceramic and the inner conductor (IC) surfaces are average values and are respectively equal to 304 K and 320 K. For the OC we applied the approximate temperature profile given in the opposite figure.



Outer Conductor thermal profile: in blue the calculated profile, in red the applied approximate profile

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

TRP results

- Increasing of the ceramic emissivity by 40% do not impact the result: Small view factor between the ceramic and the SC part.
- The most pessimistic case (#1) : TRP toward the SC parts = 0.52 W.
- **The most realistic case (#4) : TRP toward the SC parts = 0.39 W.** Adding this value to the 2K heat load calculated with RF/thermal model, **we obtain a maximum value of 1.28 W.**

Conclusion:

This poster 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 2K, 5K and 50K 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 2K 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.

hassen.jenhani@cea.fr