

FCC-ee cavities RF power coupler: study on the optimal cooling strategy to boost the cryomodule energy efficiency

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Abstract. The RF fundamental power coupler (FPC) in SRF accelerating systems can have a major contribution to the cryogenic power consumption. In the framework of the FCC feasibility study, the focus on the energy saving is of primary importance given the size of the machine, with 264 cavities at 400 MHz and 488 cavities at 800 MHz for the collider, and 600 cavities at 800 MHz for the booster, at the ttbar working point. Additionally, this early stage of the design leaves freedom in exploring and comparing alternatives within a limited number of constraints. In this paper we present the comparison between active vapor cooling and fixed temperature heat interception for the FPC, with the aim of minimizing the heat loads to the helium bath - at 4.5K and 2K for the 400 MHz and 800 MHz cavities respectively - along with the overall cryogenic cost of the design solution. The choice for the FPC cooling method impacts the energy consumption, given the low efficiency of low-temperatures heat extraction, but it also affects the integration design of the coupler in the cryomodule, the cryogenic lines layout, and eventually the overall size of the cryomodule, with consequences on the tunnel space needs. In this paper, the results - concerning the temperature field on the FPC outer conductor, and the cryogenic cooling needs - are presented for the two cooling strategies and different coupler geometries. The data are derived with a semi-analytical model, describing the different heat transfer phenomena and the selected cooling strategy. The model is parametric with respect to the geometry and the RF inputs (RF power per cavity and electro-magnetic field across the outer conductor). In this way, it is possible to maintain flexibility towards the variations, in shape and heat loads, generated by integration choices, RF design constraints, and RF operating conditions across the four FCC working points. Additionally, the model serves as a tool to guide the design of the FPC, evaluating the direct impact of a choice on the final performances of the coupler in operation.

1. Introduction and scope of the study

Energy saving is an important challenge in accelerator design, and even more for the Future Circular Collider (FCC), with more than 1300 cavities – according to the current baseline - each equipped with a fundamental power coupler (FPC). The FPC outer conductor, is a direct thermal link between the cryostat helium bath and the ambient temperature, thus care must be taken to reduce the heat loads (HL) linked to this critical component, given the low efficiency of cooling at low temperatures. This study addresses the definition of a semi-analytical model to guide the



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design of the coupler outer conductor, in terms of geometry and cooling strategy, with the goal of minimizing the static and dynamic heat loads to the helium bath. This work is inspired by previous work done on a similar subject for the active cooling of the SPL FPC [1]. For FCC, it is possible to compare different cooling strategies – namely active cooling with vapour or supercritical helium and fixed temperature heat intercepts (HI) – and select the most promising, since the machine architecture, the cryogenic scheme, and temperature levels are still under definition. From the RF design point of view, the geometry of the FPC inner conductor (antenna), the RF power, the RF electromagnetic field and operating conditions are considered as input variables to the model. The semi-analytical model addresses the calculations on the temperature profile in the outer conductor, the heat loads to the different temperature levels and the equivalent cryogenic cost of the solution. Additionally, it is important to account for operational and reliability aspects of each solution; in this regard, the experiences from other machines using the same technologies are under study.

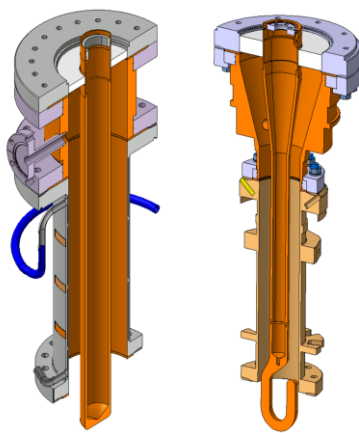


Figure 1. Left: “SPL coupler with active cooling”. Right: “Crab cavities coupler with two heat intercepts”.

Table 1. Cooling strategies: comparative overview.

	Active cooling	Heat interception
OPEX (thermodynamic efficiency)	Exploitation of the sensible heat of helium from T_{cold} to T_{amb}	Heat loads released at higher T levels instead of the helium bath
CAPEX	Liquefaction capacity required	Additional cryogenic lines and valves
Operational complexity and flexibility	High. Possibility to adapt the cooling capacity by changing the helium flowrate	None
Reliability	To be assessed	High
Machines	LHC, ESS, SPL	LHC Crab, PIP-II, XFEL

2. Numerical model set up

The outer conductor is discretized along the longitudinal dimension, each node of the mesh exchanges heat with the adjacent ones (conduction/convection), additionally the RF dissipation and radiative heat load from the antenna are considered. The analysed domain is limited – on one side - by the warm flange at ambient temperature, and – on the at the other end -by the cold flange at the helium bath temperature. The longitudinal temperature profile is derived by solving the system of the energy balance equations for every node. The complexity of the solution arises from the dependency of properties and heat transfer coefficient to the unknown local temperature, both for the outer conductor in stainless steel with copper sputtering (25 um RRR100) and for the helium flow.

2.1 Active cooling with helium (supercritical or vapor at 4.5K)

The double wall outer conductor (DWT) consists of two concentric cylinders separated by an intermediate gap – about 1-2 mm wide – in which the helium flow is guided along a heat exchange path (for example a spiral one). The discretized model consists of 3 layers (Figure 2.). To derive the energy balance equations it is considered that: (I) Each element of the inner wall (Wall I) is heated up by conduction, RF dissipation and radiation from the FPC antenna, while it gets cooled by convection with the correspondent helium flow element; (II) Each element of the external wall

(Wall E) exchanges by convection with the correspondent gas element; (III) Each element in the helium channel exchanges heat by convection with the two walls with a consequent increase in its enthalpy/temperature.

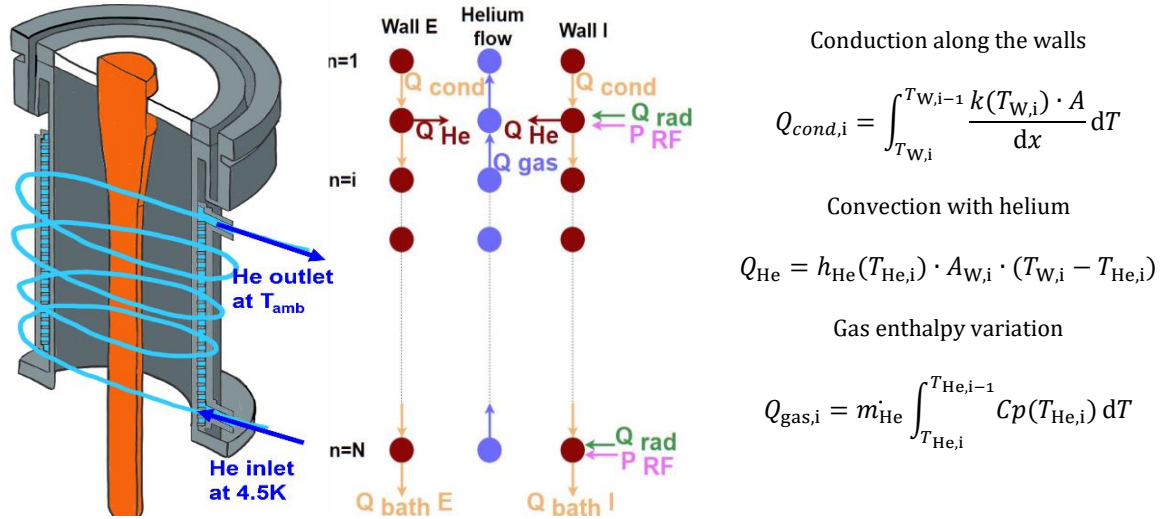


Figure 2. Left: “Double wall outer conductor sketch”. Centre: “Domain discretization for the double wall outer conductor and heat transfer phenomena”. Right: “Reference nodal equations”.

The energy balance for a generic “i” node is given by the following set of equations:

$$Q_{cond}(T_{W_{I,i-1}}, T_{W_{I,i}}) + P_{RF}(T_{W_{I,i}}) + Q_{rad}(T_{W_{I,i}}) = Q_{cond}(T_{W_{I,i}}, T_{W_{I,i+1}}) + Q_{He,I}(T_{W_{I,i}}, T_{He,i})$$

$$Q_{cond}(T_{W_{E,i-1}}, T_{W_{E,i}}) = Q_{cond}(T_{W_{E,i}}, T_{W_{E,i+1}}) + Q_{He,E}(T_{W_{E,i}}, T_{He,i})$$

$$Q_{He,I}(T_{W_{I,i}}, T_{He,i}) + Q_{He,E}(T_{W_{E,i}}, T_{He,i}) = Q_{gas}(T_{He,i}, T_{He,i-1})$$

The system is solved imposing as boundary conditions:

- For the inner and outer walls $T_{wall,1} = 300 K$ and $T_{wall,N} = 4.5 K/2 K$, temperatures of the warm and cold flanges respectively.
- For the helium flow $T_{He,N-1} = T_{He,N} = 4.5 K$, the temperature at the warm flange is part of the solution since it depends on the efficiency of the convective heat transfer along the helium channel.

2.2 Fixed temperature heat interception

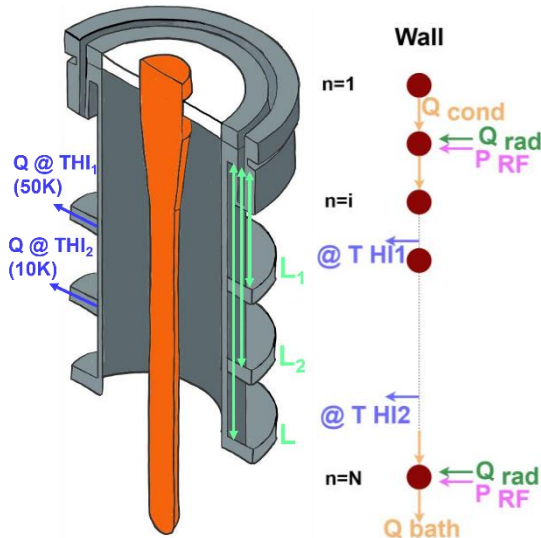
The outer conductor is constituted by a simple cylinder in case of cooling with HI, the heat is extracted in specific locations along the longitudinal extension by thermalizing the outer conductor to a cryogenic line inside the cryomodule (**Figure 3.**) The temperature of the cryolines (THI_1, THI_2) is inserted as input in the model, and the location of thermalization points is calculated by minimizing the total cryogenic cost related to conduction.

To derive the energy balance equations it is considered that each element along the outer conductor wall is heated up by conduction, RF dissipation and radiation from the FPC antenna. In correspondence of the HI, the conduction HL from the upstream sector is discharged to that temperature level, instead of being transmitted. The energy balance for a generic “i” node is given by Equation (1), in case the node “i” is below a thermalization point by Equation (2), or above a thermalization point by Equation (3):

$$Q_{cond}(T_{W,i-1}, T_{W,i}) + P_{RF}(T_{W,i}) + Q_{rad}(T_{W,i}) = Q_{cond}(T_{W,i}, T_{W,i+1}) \quad (1)$$

$$Q_{cond}(T_{THI,1}, T_{W,i}) + P_{RF}(T_{W,i}) + Q_{rad}(T_{W,i}) = Q_{cond}(T_{W,i}, T_{W,i+1}) \quad (2)$$

$$Q_{cond}(T_{W,i-1}, T_{W,i}) + P_{RF}(T_{W,i}) + Q_{rad}(T_{W,i}) = Q_{cond}(T_{W,i}, T_{THI,2}) \quad (3)$$



Cryogenic cost of the conduction HL

$$\begin{aligned} \min\{f(L1, L2)\} = & C_1 \frac{A}{L_1} \int_{T_{THI_1}}^{T_{amb}} k(T) dT \\ & + C_2 \frac{A}{L_2 - L_1} \int_{T_{THI_2}}^{T_{THI_1}} k(T) dT \\ & + C_3 \frac{A}{L - L_2} \int_{T_{bath}}^{T_{THI_2}} k(T) dT \end{aligned}$$

with $C_1, C_2,$ and $C_3,$ efficiency factors (% of Carnot COP) according to the T level at which the HL is discharged

Conduction along the walls

$$Q_{cond,i} = \int_{T_{W,i}}^{T_{W,i-1}} \frac{k(T_{W,i}) \cdot A}{dx} dT$$

Figure 3. Left: "Outer conductor with heat intercepts sketch". Centre: "Domain discretization for the outer conductor wall and heat transfer phenomena". Right: "Reference nodal equations".

The system is solved imposing the same boundary conditions described in Subsection 2.1.

2.3 RF power dissipation, radiation from the FPC antenna and cryogenic cost

To calculate the heat generated by RF power dissipation, the model takes as input the 1D map of the magnetic field [A/m] along the longitudinal coordinate of the outer conductor, coming from RF simulations in the frequency domain. The power dissipation in each segment (dx) is given by:

$$P_{RF,i} = \left(\frac{1}{2} \cdot duty \cdot R_{WI}(T_i) \cdot \pi D \int_{x_i-dx/2}^{x_i+dx/2} |F_{op} \cdot H(x)|^2 dx \right)$$

with $R_{WI}(T_i)$ local electrical resistance of the copper layer. The coefficient F_{op} , multiplying the amplitude of the magnetic field, depends on the machine operating condition, in particular, according to the expected amount of reflected power that sums up to the forward power, increasing the total heat dissipated in the FPC. Three different scenarios should be considered: (I) Nominal operation $F_{op} = 1$, (II) Off - nominal operation/beam transients $1 < F_{op} < 2$, (III) Full reflection scenarios which may be necessary to achieve during coupler conditioning $F_{op} = 2$, with increment of a factor 4 on the RF power dissipated.

The heat load of the antenna can be modelled as radiation between two concentric cylinders (view factor equal to 1):

$$Q_{rad,i} = \frac{\sigma A_{W,i} (T_{ant}^4 - T_{W,i}^4)}{\frac{1}{\varepsilon_{W,i}} + \frac{A_{W,i}}{A_{ant,i}} \cdot \left(\frac{1}{\varepsilon_{ant}} - 1 \right)}$$

The equation is considered in a discrete form, which results in an underestimation of the total radiative contribute: for every segment dx , it is considered only the predominant contribute from the correspondent antenna segment directly facing dx , discarding the partial contributes from the adjacent sections. This has a negligible effect on the temperature profile, since the magnitude of

the radiative load on the outer conductor is approximately 10% of the RF dissipation load. The radiation load to the helium bath coming from the ceramic window and the tip of the antenna protruding after the cold flange are not considered in this model. Their contribution is not negligible in absolute terms but it is independent from the cooling strategy, thus not considered in the comparison. The antenna, made of copper, is considered at a uniform temperature of 40°C when transmitting RF power at constant emissivity ($\epsilon_{ant} = 0.1$), while for the outer conductor copper layer, the local emissivity is a function of the nodal temperature.

The cryogenic cost (W_{el}) is calculated considering the heat released to the helium bath (assuming 30% and 15% of Carnot efficiency for the HLs released at 4.5 K and 2 K respectively) plus additional contributions depending on the cooling strategy. For the active cooling, the helium vapor is recollected at the warm flange at T_{amb} , thus the cost for the cryopant is estimated as the equivalent refrigeration load required to bring the helium vapor at T_{amb} to liquid helium at 4.5 K (approximately 1 g/s is equivalent to 100 W at 4.5 K). For the cooling with HI, the cost of the HLs released at the two temperature levels is calculated with the correspondent efficiency factors.

3. Results

The results reported refers to the current RF parameters for the FCC power coupler of the 2-cells 400 MHz cavities, operating at 4.5 K. The RF power transmitted is 378 kW in continuous wave (CW) mode, at the H and W working points. The geometry of the FPC is still under definition, so the parameters in **Table 2.** are preliminary values for the outer conductor (similar to the ESS FPC for HB cavities, used for benchmarking the model results).

Table 2. FPC geometry input parameters

Length	Cylinder inner diameter	Double wall cylinder parameters (active cooling)	Wall thickness (HI)	Helium spiral channel cross section	Helium inlet temperature	Temperature heat intercepts
Different options evaluated: 350, 450 mm	100 mm	1.5 mm (inner wall) 1 mm (helium channel) 2 mm (outer wall)	3.5 mm	Triple helix 2.5 x 1.5 mm ²	4.5 K	50 K (THI ₁), 10 K (THI ₂)

3.1 Active vapor cooling

Table 3. reports the results for different values of He flowrate and length of the outer conductor. For nominal operations, with 40 mg/s of He flowrate, the heat released to the bath is 1.38 W, with an equivalent cryogenic cost of 1.7 kW. Doubling the He flowrate, the heat released to the bath is below 1 W, but the overall load to the cryogenic plant is higher, 1.9 kW, given the higher mass flow to liquefy to 4.5 K. A different outcome may be obtained if the same analysis is performed with cavities operating at 2 K since the cryogenic cost of the HL released at 2 K is higher (efficiency for cooling to 2 K drops to 15%). Keeping the mass flow to 80 mg/s, with almost the same equivalent electric cost for the cryogenic plant, 2 kW, it is possible to reduce the overall length of the coupler, by 100 mm (22%), which would permit a reduction of the cryomodule total envelope and space occupation in the machine tunnel.

3.2 Heat intercepts

Table 4. shows the results for several longitudinal position of the thermalization points, within an interval of $\pm 10\%$ of the initial calculated value (minimizing the cost of conduction only). Each couple of longitudinal coordinates gives a specific temperature profile, the best solution

minimizes the cryogenic cost, but also presents a uniformly decreasing temperature gradient along the longitudinal coordinate, fundamental to avoid electrons emission and multipacting during coupler conditioning.

Table 3. Heat released to the bath and cryogenic cost linked to a single FPC, when cooled with helium flowrate.

	A1) L = 0.45m RF off	B1) L = 0.45m RF on, F _{op} = 1	C1) L = 0.35m RF on, F _{op} = 1	D1) L = 0.45m RF on, F _{op} = 2
Heat to helium bath	0.5W	1.38W	1.17W	4.55W
Liquefaction capacity	40mg/s	40mg/s	80mg/s	80mg/s
Refrigeration load at 4.5K	875W	875W	1.7 kW	1.7kW
(W _{el})	0.96kW	1.7kW	2 kW	2.7kW
RF power dissipation	-	17W	13W	66W

Table 4. Heat released to the bath and cryogenic cost linked to a single FPC, when cooled with heat intercepts.

	A2) L = 0.45m RF off	B2) L = 0.45m RF on, F _{op} = 1	C2) L = 0.35m RF on, F _{op} = 1	D2) L = 0.45m RF on, F _{op} = 2
Heat to helium bath	0.3W	2.21W	2.29W	5W
Heat at 10K	4.4W	5.1W	7.33W	17W
Heat at 50K	46W	50.7W	63W	53W
(W _{el})	1.2kW	2kW	2.2kW	3.7kW
RF power dissipation	-	22.7W	19.6W	88W

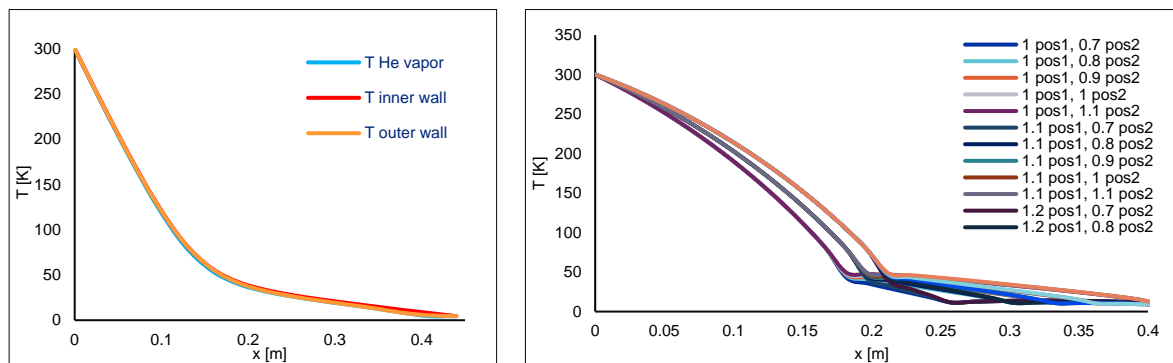


Figure 4. Example of temperature profile plots. Left: “Scenario B1”. Right: “Scenario B2”.

4. Conclusions

This semi-analytical model offers the possibility to compare different cooling strategies for the FPC, in terms of cryogenic efficiency, it also serves as guideline in the design of the FPC geometry. From the preliminary results on equivalent scenarios (B1 and B2), active cooling allows for a 15% reduction of the cryogenic cost. Additionally, the active cooling offers, in principle, high adaptability in the cooling capacity to face the different RF operating conditions. These benefits must be compared with the high reliability and of the solution with heat intercepts. The future studies will focus on the fluid dynamic design of the double wall heat exchanger, to ensure efficient convective heat transfer, for several values of helium flowrate.

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