SPL RF COUPLER COOLING EFFICIENCY

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Abstract

Energy saving is an important challenge in accelerator design. In this framework, reduction of heat loads in a cryomodule is of fundamental importance due to the small thermodynamic efficiency of cooling at low temperatures. In particular, care must be taken during the design of its critical components (e.g. RF couplers, cold-warm transitions). In this framework, the main RF coupler of the Superconducting Proton Linac (SPL) cryomodule at CERN will not only be used for RF powering but also as the main mechanical support of the superconducting cavities. These two functions have to be accomplished while ensuring the lowest heat in-leak to the helium bath at 2 K. In the SPL design, the RF coupler outer conductor is composed of two walls and cooled by forced convection with helium gas at 4.5 K. Analytical, semi-analytical and numerical analyses are presented in order to defend the choice of gas cooling. Temperature profiles and thermal performance have been evaluated for different operating conditions; a sensitivity analysis of RF currents node position along the wall has also been performed. Finally, comparison with respect to other heat extraction methods is presented.

SPL CRYOMODULE: SUPPORTING SCHEME

In the framework of heat loads reduction, the number of potential heat sources in the SPL cryomodule has been kept as small as possible so that the required refrigerating power is minimised [1]. To achieve such reduction, the novel SPL cavity supporting scheme does not rely on tie-rods or space frame: cavities are only supported through the external conductors of the main RF power couplers and the inter-cavity supports between adjacent cavities (Fig. 1).

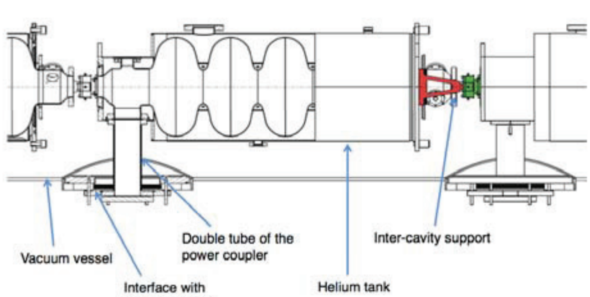

Figure 1: A sketch of the SPL cryomodule, with the RF power coupler and the intercavity support.

The outer conductor of each coupler is composed of a Double-Walled Tube (DWT) which allows for active helium gas cooling in order to reduce heat loads especially during RF operation. Given its multiple functions, determining the thermo-mechanical performance of the DWT is fundamental to keep the correct alignment while ensuring thermal performance.

DOUBLE-WALLED TUBETHERMAL ANALYSES

The SPL RF coupler (Fig. 2) features a fixed-coupling copper antenna (43 mm diameter) and an external conductor (100 mm diameter) which is composed of [2]:

- an inner stainless steel wall (1.5 mm thick) coated with a thin layer of sputtered copper (4 µm thick);
- an outer stainless steel wall (2.0 mm thick).

From the point of view of the conduction heat loads of this component, the variable to investigate is the temperature profile along the wall of the DWT. The heat leak to the helium bath, which has to be minimised, is in fact directly related to the temperature gradient along the DWT wall.

To model the thermal performances of the DWT in the SPL cryomodule a number of methods have been employed and compared; this has been done with the aim of developing efficient computation tools to assess the efficiency of the DWT active gas cooling of the SPL cryomodule as well as of other projects. In the following, such tools are described.

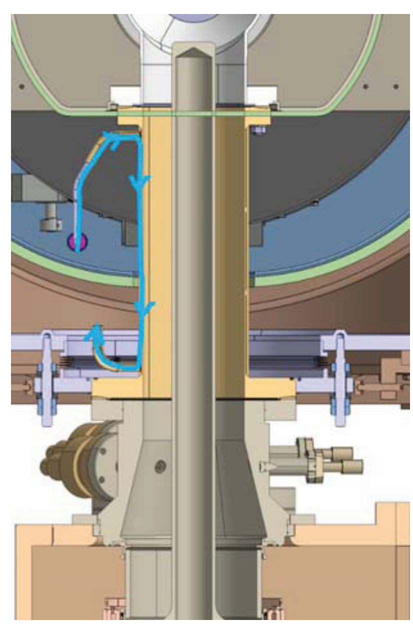

Figure 2: Cross section of the SPL power coupler with the helium channel for active gas cooling of the DWT.

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Analytical and Numerical Analysis

The main coupler can be modeled in an extremely simplified manner as an equivalent "neck" placed between room and cryogenic bath temperature (Fig. 3).

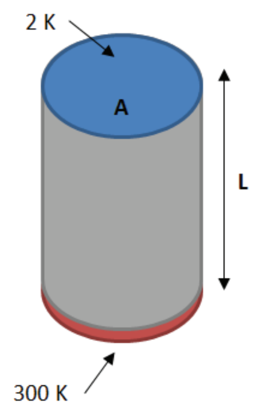

Figure 3: Simplified coupler geometry (neck): *A* is the cross section, *L* is the total length.

As a consequence, the thermal analysis is quite simple, as both analytical and numerical techniques can be applied; moreover, different types of cooling techniques, fluids and geometry ratios can be studied. As a result, one can obtain the feeling on what the *ideal* thermal performance of a steel neck would be.

Method. A numerical integration of the governing differential equations has been performed via a calculation software (Mathcad^{TM} [3]). The cases considered - calculated for different neck dimensions (length-over-cross section ratio, *L/A*)- are:

- No Cooling,
- Self-sustained Cooling[1],
- One/Two OptimisedHeat Intercepts[2] (at 8 and 80 K),
- Ideal Gas Cooling[3].

Results. In Fig. 3, the calculated heat leak to bath is plotted against *L/A*. The SPL DWT has a geometrical ratio of 260 m^{-1}.

From this plot, a number of areas can be distinguished, according to the operation point, i.e. the point obtained from the intersection of the neck geometry and the maximum acceptable heat load.

As a general design rule, when the operation point is above one of the straight lines, the cooling system defined by the line just below is ideally sufficient for sustaining that condition. For example, the region on the far-right, *above* the "No Cool" line, defines those longer/thinner necks that would not need any cooling. On the other hand, whenever the operation point falls in the region below the line of the double heat intercepts (straight solid line with filled circular markers in Fig. 4) it is recommended to use an active helium gas cooling (dotted lines without markers in Fig. 4).

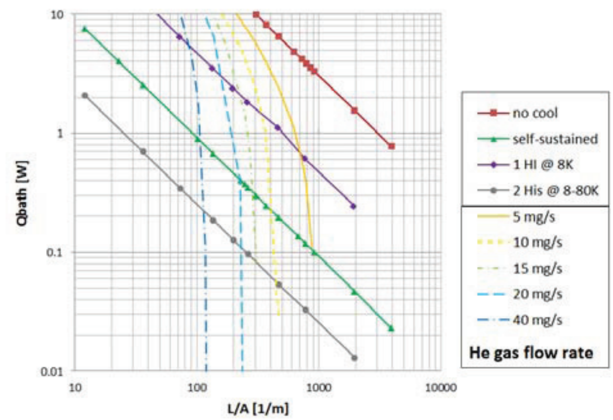

Figure 4: Heat transferred to a superfluid helium bath (300-2 K) as a function of geometry ratio *L/A*, and for different neck cooling techniques.

Semi-Analytical Analysis

To include RF power dissipation and radiation exchange with the antenna, and to properly investigate the benefits of active gas cooling, an improved study is necessary. A dedicated semi-analytical thermal model [4] has thus been implemented in Mathcad^{TM} (based on [5]).

Method. A one dimensional[4] steady-state thermal analysis has been set up by subdividing the fluid channel, the inner and the outer walls into several elements (defined by the nodes n_i) and by applying to each of them the analytical formulas describing conduction, convection, radiation, RF losses and gas enthalpy change.

The powers exchanged through the boundaries with the external ambient can be calculated with an energy balance on the boundary elements. In the simplified geometry of this analysis, the two flanges and the inlet-outlet pipes have not been modeled.

Figure5 represents the schematic of the heat exchange occurring among the elements: both walls exchange with the gas by convection (light blue arrows); RF losses (purple arrow) and radiation exchange with the antenna (green arrow) are relevant to the inner wall only.

When present, the RF power deposited on the inner wall of the DWT dissipates as heat, thus increasing the heat leak to the bath. For this so-called dynamic case, the RF current distribution on the inner wall is an input to the calculation, which can range between a travelling (where the envelope defines a constant current) or a standing wave (where the current wave envelope is sinusoidal) can be assumed. The standing wave case branches into two extreme sub-cases, depending on whether the DWT cold end acts as an "open-circuit" (zero RF current) or as a "short-circuit" (maximum RF current). Furthermore, the

[1]Self-sustained cooling occurs when all the thermal power reaching the bath is used to create the cryogen vapour flow.
[2] Heat intercepts are ideal and optimised with respect to the position along the neck which gives the lowest total refrigerating power.
[3] Active gas cooling with the assumption that gas and neck have the same temperature at each point.
[4] Heat transfer in radial direction has not been considered.
[5] A heater is foreseen to be placed on the external flange of the DWT to ensure that its temperature does not go below the dew point.

wave position along the wall also changes in relation to the RF functioning.

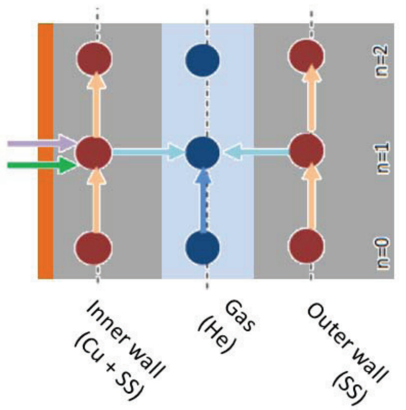

Figure 5: Heat exchange among elements of the mesh.

The boundary temperatures of the walls are fixed at 2 and 300 K[5]; for the helium gas, the inlet temperature is 4.5 K (1.3 bar helium vapour) and the helium flow rate chosen for the SPL DWT is 40 mg/s.

Material and fluid properties are considered to be temperature-dependent and have been estimated with [6] and [7], respectively.

Results- Static Case. The three temperature profiles of inner, outer wall and gas are plotted in Fig. 6 for the static case (RF power is null, radiation exchange from the 300 K antenna is considered), with or without cooling. As a result, the gas cooling is proven to be efficient as it allows for a strong reduction of the heat load to bath from 13 W to 0.1 W.

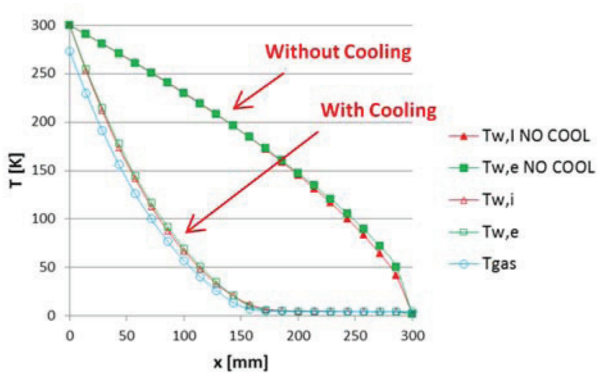

Figure 6: Static case, with and without cooling - Temperature profiles of internal (i) and external (e) walls, and helium gas along the DWT for non-cooled (filled markers) and cooled DWT (empty markers).

Results –Dynamic Case. The RF boundary conditions considered for the SPL coupler are: 704 MHz, 1 MW peak power, 10% duty cycle (200 A peak pulse current). Such values stem from the RF design and correspond to 100 kW average transmitted power.

For the *reference dynamic case*[6], out of the overall thermal balance around 10 W are due to RF power dissipation, whereas only 1-2 W are related to the antenna's radiation. For this case, heat leak at 2 K is again expected to be around 0.1 W.

A sensitivity analysis on RF current wave position has been performed, as this information can be useful to estimate the loads for different operating conditions (conditioning of the cavities, normal operation). In Fig.7, RF power dissipated and heat load to bath are represented for the two cases previously mentioned (short-circuit and open-circuit end) against position of the current wave boundary along the cooled wall of the DWT. By "shifting" the current wave further from the cold extremity towards the RF cavity, the resulting load to the bath may change by a factor of 5, the RF dissipated by a factor of almost 2 (for the non-cooled case, those factors would both be around 1-1.2).

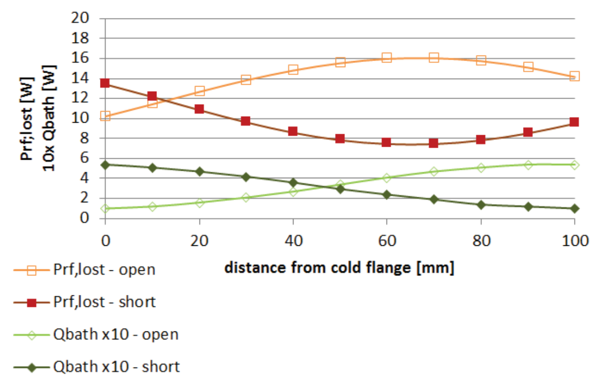

Figure 7: Dynamic case, with cooling - RF losses and thermal load to bath (x10, for better visualization) for different RF current configurations.

Finite Element Analyses

The thermal results predicted by the semi-analytical model above can be refined by means of a FE analysis. For this purpose, two sub-models have been set up in Ansys Workbench [8], to study separately static and dynamic case. The same boundary conditions, material-fluid properties and RF conditions previously discussed have been used and the results have been compared to those of the semi-analytical approach.

Method - Static Case. For the static case, a coupled steady-state thermal and fluid dynamics analysis has been implemented in ANSYS Workbench; the CFX solver has been used in order to better investigate the heat exchanged between helium and walls.

As confirmed by previous calculations [4], a laminar fluid regime is the adequate choice for this problem as the Reynolds Number never exceeds the critical value even for very low gas temperature (Fig. 8).

[6]Cooling with 40 mg/s of helium at 4.5 K, standing wave current distribution for the open end case, radiation from the antenna at 330 K.

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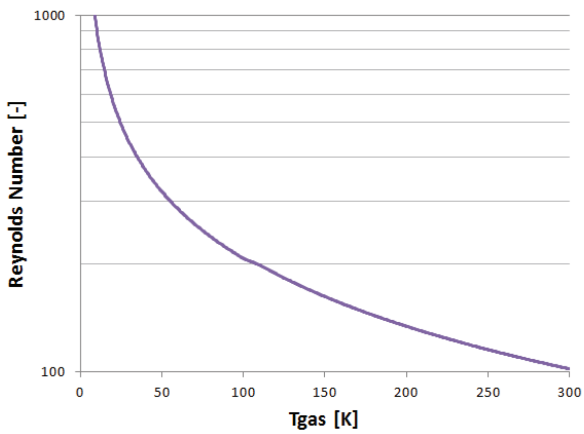

Figure 8: Reynolds Number versus gas temperature (for an equivalent channel hydraulic diameter of 2 mm; helium properties are calculated at 1.5 bar [7]).

Results - Static Case. As visible in the upper plot of Fig. 9, the wall temperature profile (average) obtained with this analysis is very similar to that obtained with the semi-analytical model. Whilst predictions are similar at the channel entrance, a bigger difference appears when looking at the foreseen gas temperature at the exit of the channel (left-hand side of the lower plot in Fig. 9): this is due to the simplifications applied in the Mathcad model, such as the absence of the flanges and the constant heat transfer coefficient.

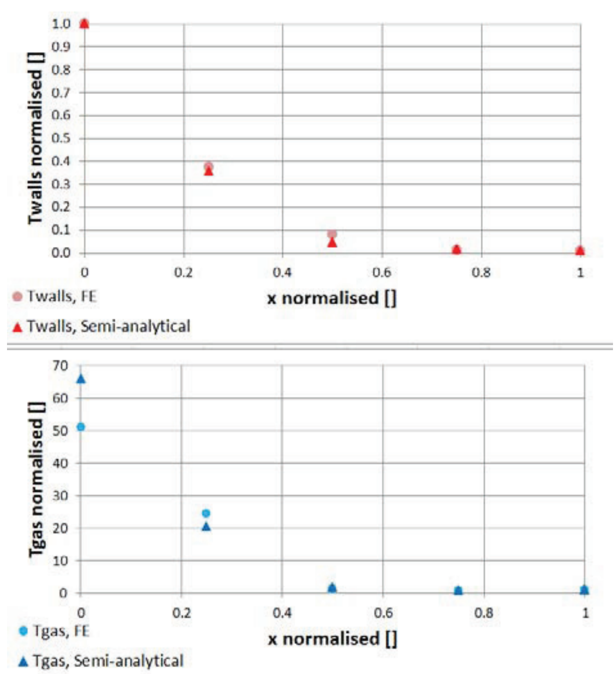

Figure 9: Static case, with cooling - Normalised temperature profiles comparison between finite elements and semi-analytical studies.

Method - Dynamic Case. With a ANSYS-HFSS [9] coupled analysis one can evaluate the RF fields inside the coupler and how much they dissipate on the external conductor, in case of no cooling. The resulting power dissipation on the wall obtained from the RF fields calculated in HFSS has been imported into a steady-state thermal analysis where temperatures and powers can be calculated.

Results - Dynamic Case. For a first analysis, the geometry in ANSYS has been kept as similar as possible to the one used for the semi-analytical study (i.e. inner and outer walls are insulated and flanges are omitted).

For what concerns the temperature profile, good agreement with the semi-analytical model has been found (see Fig.10). The heat transferred to the wall boundaries is also consistent between models.

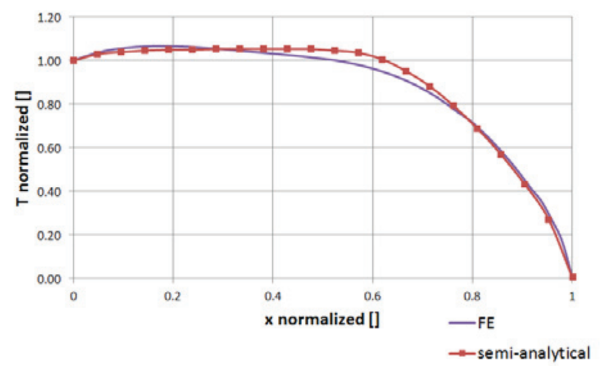

Figure 10: Dynamic case, without cooling - Normalised temperature profile comparison between finite elements and semi-analytical studies.

A second analysis has been done to investigate the influence of the two flanges on the coupler performances. As a preliminary result, a lower value of maximum temperature has been obtained, which is possibly due to the bigger conductive section in presence of the flanges.

CONCLUSIONS

Different analyses carried out to assess the thermal performance of the DWT of the SPL power coupler.

It has been shown that simple analytical and numerical analyses can be used during the early design process of the DWT and for choosing the adequate cooling system.

The semi-analytical approach is very powerful and versatile as it allows for a quick calculation of conduction, convection, radiation and RF dissipation inside the DWT. Moreover, input parameters (geometry, boundary conditions, materials, fluids, RF conditions, …) can be easily modified to optimize the mechanical, thermal and RF design.

Regarding temperature profiles and heat exchange results, good agreement has been found between the semi-analytical and the finite elements results. Nonetheless, further studies are on-going in order to finalise a more comprehensive FE model where electromagnetics and fluid dynamics are coupled.

Summarizing, the performed calculations clearly prove that the external conductor of the RF main coupler must be actively cooled if one wants to drastically reduce the heat leaks in the SPL cryomodule. When the DWT is cooled by gaseous helium at 4.5 K, the heat load at 2 K can be estimated as lower than 0.5 W; this load is slightly bigger than the one estimated via the simplified semi-analytical model, which also yields to13-25 W for the un-cooled DWT (power or not powered respectively).

An experimental set-up is also in preparation at CERN for validating the DWT design of the SPL, as well as its operating parameters, and to further investigate the validity of the thermal performance estimates.

ACKNOWLEDGMENTS

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