ACTIVELY COOLED RF POWER COUPLER: THEORETICAL AND EXPERIMENTAL STUDIES

R. Bonomi[a,b], V. Parma[a] - [a]CERN, Geneva, Switzerland - [b] ESS, Lund, Sweden

Abstract

In cryostats for Superconducting Radio-Frequency Cavities, the heat loads introduced by the high-power RF couplers represent an important fraction of the overall static thermal budget. Working at low temperature benefits from a reduced surface resistance (low dynamic losses) but is penalized by the high refrigeration cost. The external conductor of RF coaxial couplers provides a direct conduction path from ambient to cryogenic temperature plus is heated by resistive power deposition. Heat interception is therefore essential to contain heat in-leaks: a double-walled external conductor with a properly designed gas cooling effectively reduces heat loads to the cold bath by one order of magnitude. This paper presents the thermal design of the RF power coupler of the Superconducting Proton Linac (SPL) at CERN, featuring a helium vapour cooling between 4.5 K and ambient temperature. Numerical models, which can be used as design tools for other applications, have been developed to assess efficiency and thermal performance. A full-size mock-up cooled by liquid nitrogen has been built for experimental validation. Comparison between calculations and measurements is presented and discussed.

INTRODUCTION

For superconducting (SC) cryostats devices, heat load management is fundamental to maintain low temperatures in the most efficient way. The very low operating temperature required by a SC device results in a high electrical power consumption; for example, each watt of thermal power at 2 K costs about 1'000 W electrical*.

The SPL Fundamental Power Coupler (FPC)

The SPL cryomodule (cross section in Fig. 1) is composed of four elliptical niobium 5-cells cavities, each powered by one coaxial fundamental power coupler# (FPC) [1]. The contribution of each FPC to the thermal budget is considerable, accounting for 97% of the static thermal load per cryomodule at 2 K *if the FPC is not cooled* [2]. As a consequence, effective FPC cooling is essential in the thermal management of the cryomodule.

Helium gas cooling, between 4.5 and 300 K, is the choice for the SPL FPC, through a double-walled external conductor where the gas flows from the cold side. Among the others, this solution is supposedly the most thermodynamically efficient, especially for very tight heat load requirements [3].
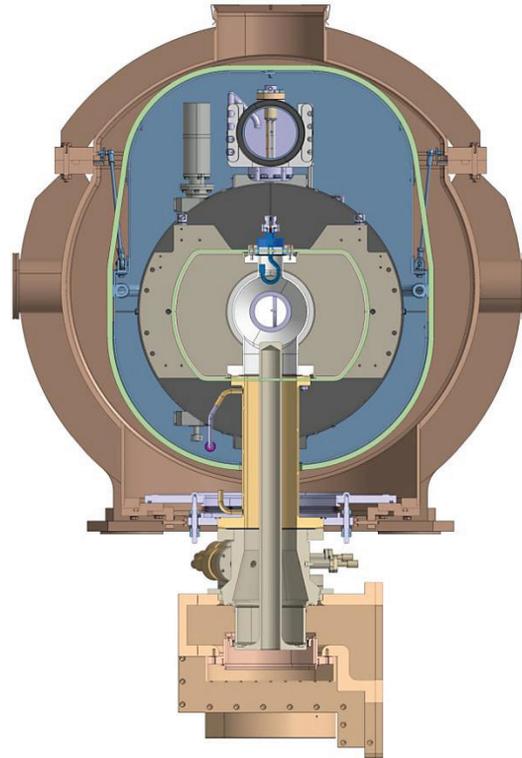
Figure 1: Cross section of the SPL cryomodule [1].

The total calculated refrigeration power required for a SPL-like FPC is reported in Table 1 for some common cooling methods. An optimised and adequately operated gas cooling (case 5) is highly effective, as it remains very close to the theoretical limit of the self-sustained cooling (case 2).

Table 1: Calculated refrigerator power for some SPL FPC cooling systems♦ (GHe: Gas Helium; boundary temperatures: 2-300 K)

Cooling Case	$P_{ref,tot}$ (kW$_{el}$)	Ratio
(1) No cooling	12.2	15.2
(2) Self-sustained GHe cooling (19 mg/s)	0.8	1
(3) 1 heat intercept at 80K	2.8	3.5
(4) 2 heat intercepts at 9-80K	1.3	1.6
(5) 4.5K non isothermal GHe cooling (40 mg/s)	1.0	1.2

♦ Efficiency at 50-80 K: 17 W/W (30% Carnot); efficiency at 4.5-9 K: 220 W/W (30% Carnot); efficiency at 2 K: 990 W/W (15% Carnot).
1 g/s helium at 4.5-300 K was considered equivalent to 100 W at 4.5 K [4].

THEORETICAL AND EXPERIMENTAL STUDIES

To assess the thermal performances of the SPL FPC, theoretical studies and experimental validation were carried out and are presented hereafter.

Theoretical Analyses

A Semi-Analytical Model [5] was initially developed in Mathcad™ to evaluate both temperature profile and exchanged power through the FPC. It is based on a system of steady state heat transfer equations for a simplified network of three sets of nodes along the FPC's wall, including solid conduction, gas convection, RF power dissipation and antenna radiation. Temperature-dependent material and gas properties were considered.

A Finite Elements Model, more complex and detailed, was subsequently developed with Ansys™ for confirmation of the results of the simplified model. The steady state thermal analysis was coupled with fluid-dynamics to include gas convection.

All theoretical studies considered, conservatively, that the gas flow remained in the laminar regime.

Experimental Studies

For an experimental validation of the SPL supporting scheme, a full-size mock-up was designed, built and tested at CERN (Fig. 2, top). The vacuum vessel housed the external conductors of two FPCs (Fig. 2, bottom), an inter-cavity support and a nitrogen reservoir, mimicking the presence of a SRF cavity, wrapped by 30 layers of MLI in order to reduce the radiative load.
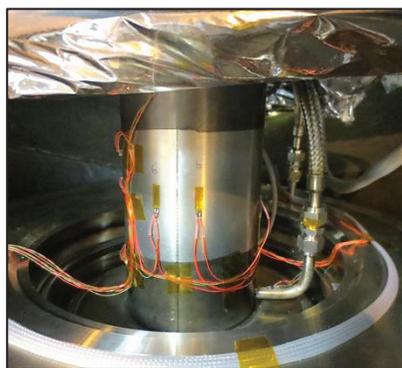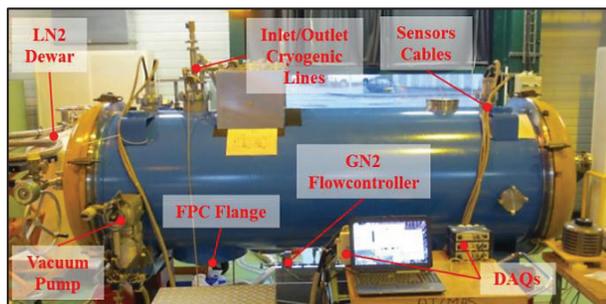
Figure 2: Experimental test stand in SMI2, CERN (top); FPC's external conductor equipped with sensors (bottom).

For easiness, nitrogen was used as cryogen: liquid N_2 for the cavity reservoir and gas N_2 for the FPC's external conductor. Cryogenic lines directly discharged in atmosphere. Appropriate safety valves for liquid-gas lines, cold masses and vessel were adopted. Insulation vacuum was kept at 10^{-6} mbar by means of turbo-molecular pump.

Thermal sensors, gas flow-controllers, level gauges and heaters (used to set the temperature of FPC's external flanges) were placed. A 1 Hz acquisition system was used for thermal measurements.

As the cryogenic circuits were independent, many cooling configurations could be tested, but we specifically focused on the dependency of the FPC's thermal performance on the gas mass flow rate.

RESULTS

Temperature Profile

The temperature profiles measured along the external side of the FPC's wall are compared to those estimated with the theoretical models. In Fig. 3, top plot, the uncooled wall temperature profile is illustrated.

For the cooled case, the results for GN_2 flow rates in the range 5-12 ln/min are collected in the last four plots of Fig. 3. To be noted, the inlet GN_2 temperature varies from case to case by up to 35% due to the relatively low specific heat of N_2 gas rendering its control difficult.

Heat Exchanged

The heat load to the 77 K bath shown in Table 2 was calculated from the heat balance on the boundary section of the FPC's wall, for both the theoretical models and measurements (as no direct heat load measurement has been implemented in the test set-up so far).

The estimated and implemented electrical power of the heater on the FPC's external flange is reported in Table 3.

Table 2: Estimated heat load to 77 K bath (W)

GN₂ Flow Rate (ln/min)	Semi-analytical	Finite elements	Test
0	10.5	13.2	9.6
5 at 84 K	2.4	2.5	1.6
7 at 114 K	6.1	6.0	4.9
10 at 90 K	2.7	3.3	3.7
12 at 84 K	1.7	2.9	1.6

Table 3: Heater power at FPC's external flange (W)

GN₂ Flow Rate (ln/min)	Semi-analytical	Finite elements	Test
0	10	10	10
5 at 84 K	26	26	27
7 at 114 K	30	29	17
10 at 90 K	44	43	41
12 at 84 K	48	37	41
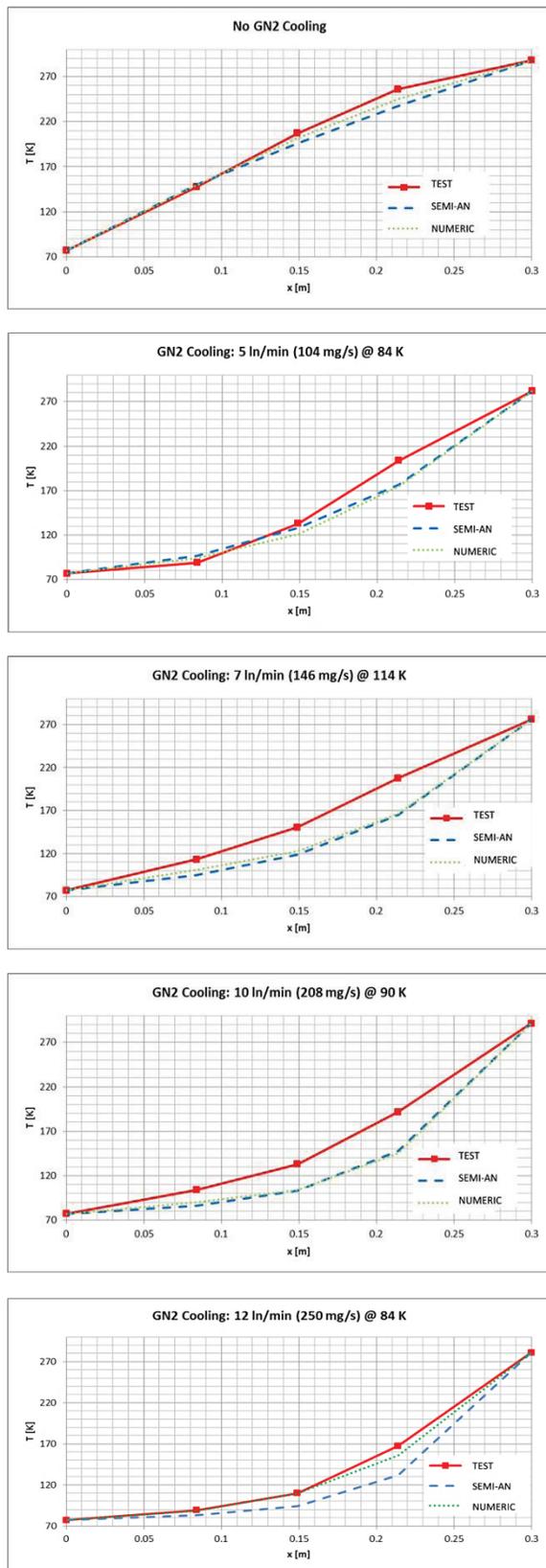
Figure 3: FPC temperature profiles for 0-250 mg/s (different inlet GN$_2$ temperatures).

DISCUSSION

Temperature Profile

Good agreement between predicted and measured temperatures was found especially at cold and for fully stable steady state conditions (0, 5 and 12 l/min). Larger differences (7 and 10 l/min) were most probably due to the residual transients. Despite the simplifications, the semi-analytical model was proven to be as precise as the finite elements analysis.

Heat Exchanged

A strong reduction in power released to the bath was observed between the uncooled and cooled case (10 W down to 2 W). The variation of this quantity can be as high as 40% between theory and test due to the unfinished thermal transients; still, the order of magnitude between theoretical and inferred results remains comparable.

The unsteady thermal conditions at the FPC's flange might also explain the variation in heating power for the 7 l/min case.

CONCLUSION

Thermal performance of a SPL-like power coupler was demonstrated both theoretically and experimentally. In general, good agreement with predicted values was found with the test. The advantage of gas cooling over the uncooled case is confirmed by the flattening of the thermal gradient along the FPC's wall, which gives a proportionally lower heat exchanged at cold.

For an increased precision, direct measurements of heat load should be implemented in a future test.

ACKNOWLEDGMENTS

REFERENCES

[1] V. Parma et al., "Status of the Superconducting Proton Linac (SPL) Cryo-module", Proceedings of SRF2013, Paris, France (2013).

[2] R. Bonomi, "Heat loads for the SPL SCM", Calculation Note, (2013), unpublished.

[3] R. Bonomi et al., "SPL RF Coupler Cooling Efficiency", SRF2013, Paris (2013).

[4] U. Wagner, "Refrigeration", CERN, Geneva, Switzerland.

[5] R. Bonomi et al., "A simulation Tool for Steady State Thermal Performance Applied to the SPL Double-Walled Tube RF Power Coupler", CERN-ACC-NOTE-2014-0020 (2013).