STUDY OF THERMAL INTERACTION BETWEEN A 150 KW CW POWER COUPLER AND A SUPERCONDUCTING 704 MHZ ELLIPTICAL CAVITY

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Abstract

The power coupler needed for β=0.65 SRF elliptical cavities dedicated to the driver of XADS (eXperimental Accelerator Driven System) should transmit a CW RF power of 150 kW to a 10 mA proton beam. The estimated average values of the RF losses in the coupler are 130 W (respectively 46 W) for the inner (respectively outer) conductor in SW mode. Due to such high values of RF losses, it is necessary to very carefully design and optimize the cooling circuits of the coupler in order to efficiently remove the generated heat and to reduce the thermal load to the cavity operating at T=2 K.

An experiment simulating the thermal interaction between the power coupler and a 700 MHz SRF five cells cavity was performed in the CRYHOLAB test facility in order to determine the critical heat load that can be sustained by the cavity without degradation of RF performance. Experimental data are compared to numerical simulation results obtained with the Finite Element code COSMOS/M. These data allow us also to perform in-situ measurements of thermal parameters needed in the thermal model of the coupler (thermal conductivity, thermal contact resistance) and they were used to validate numerical simulations.

INTRODUCTION

EUROTRANS and EURISOL are two European programs based on a new generation of multi-megawatt protons linacs dedicated to a wide variety of scientific and industrial applications such as intense neutrons sources, radioactive beams, and nuclear waste transmutation. The driver of XADS [1] is a linac, which should deliver a 10mA CW protons beam at a final energy of 600 MeV-1GeV. SRF β=0.65 bulk niobium elliptical cavities operating at a fundamental frequency f=704 MHz and cooled by superfluid helium at T=2 K, are used as accelerating structures in the high-energy section of this linac. Furthermore, in XADS a high reliability (e.g. less than 5 shutdowns per year of more than one second duration each) and availability of the machine are needed [2]. The Power Coupler (PC) used for these cavities is a key component of the cryomodule. Therefore it should be carefully designed and optimized in order to achieve the needed performance and required reliability. More precisely, due to the high RF losses (Joule and dielectric losses), the thermal design of the cooling circuits of the PC is a critical issue for operating the cryomodule in reliable and stable operation and to reduce the thermal budget of the refrigerator at 2 K.

POWER COUPLER DESIGN SPECIFICATIONS

IPN Orsay and CEA Saclay institutes have set an R&D program to develop β=0.65 SRF cavities with their PC and cold tuning system for the XADS project. The design parameters and the main specifications of the coaxial PC are given in Table 1.

Table 1: Power Coupler main parameters.

Parameter (unit)	Specification
Frequency (MHz)	704
RF power (kW)	150 - CW
Impedance (Ω)	50
Outer Conductor (OC) material and diameter (mm)	Cu/SS 100
Inner Conductor (IC) material and diameter (mm)	Cu/OFHC 43.5

GOALS OF THE CRITICAL HEAT LOAD EXPERIMENT

The purpose of this experiment is to study the effect of a static heat load (beam tube or/and coupling port heating) on the thermal behavior and RF performance of the cavity. More precisely the main goals of this experiment are to:

- Determine the maximum residual heat load (critical heat load Q_c) from the cold extremity of the outer conductor that can be sustained by the cavity without degradation of its RF performance.
- Determine, by in situ measurements, some unknown thermal properties needed for thermal modeling of the PC namely the beam tube thermal conductivity k_{BT} and the thermal contact conductance RH^{-1} at the CF flange of the coupling port.
- Validate numerical simulation model based on the Finit Element Modeling COSMOS/M code by comparing experimental data to simulation results.
- Determine the thermal balance at the triple junction between the cavity, the beam tube and the stainless steel Liquid Helium (LHe) tank.

PRINCIPLE AND DESCRIPTION OF THE EXPERIMENT

To simulate the thermal interaction between the PC and the cavity, a static heater (H1) consisting of manganin wire is attached to the stainless steel flange (Fig.1-Fig.2) of the coupling port. A similar second heater (H2) is located below the same flange. A third heater (H3) attached to the extremity of the beam tube is used for measuring the beam tube thermal conductivity. When the system is subjected to a heat flux Q (heater H1,H2, or H3), it will be divided into three parts: Q1 evacuated to LHe via the stainless steel tank, Q2 transferred to LHe in the cavity iris region and Q3 is effectively conducted to the cavity. The heat balance at the triple junction Cavity Iris (CI) - LHe Tank (LHeT) - Beam Tube (BT) is simply:
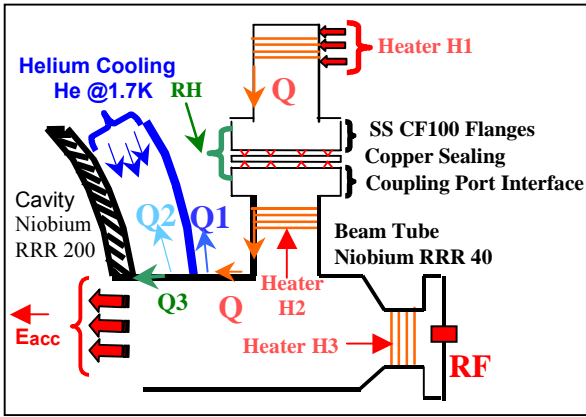
Q= Q1+ Q2+ Q3

Figure 1: Description of the experiment « Critical Heat Load on 704 MHz SRF cavity »

Seventeen temperature sensors were used for this experiment (Fig. 2): 15 Allen Bradley resistors calibrated in the temperature range 1.5K - 77K and four Pt100. They are placed along the isotherms of the beam tube according to a preliminary FEM thermal calculation (Fig. 4).
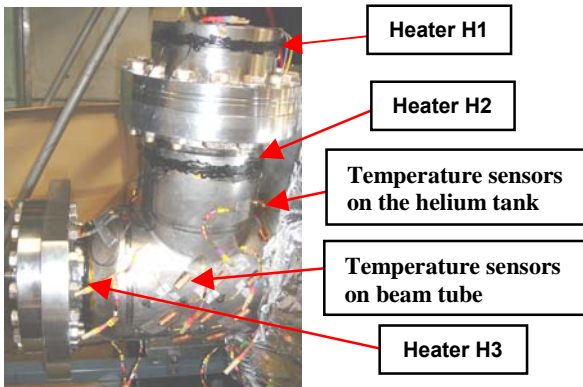

Figure 2: Photographic view of the temperature sensors and heaters (beam tube and coupling port).

Three temperature sensors are located on the helium tank (vacuum side) close to the triple junction. They were used to measure the temperature profile along the cold wall: with the help of numerical simulation this profile will be used to evaluate the thermal balance at the triple junction.

Preliminary FEM thermal analysis using COSMOS/M shows that a maximum heater power of 10W power heater is sufficient for observing sizable effect on RF performance cavity when operating at 1.7K

RF RESULTS

Several experimental tests were performed with different powers on the heater H1 (1W $\leq$ PH1< 8.5W) at T_{bath} =1.7K leading to the network of curves presented in Fig. 3.

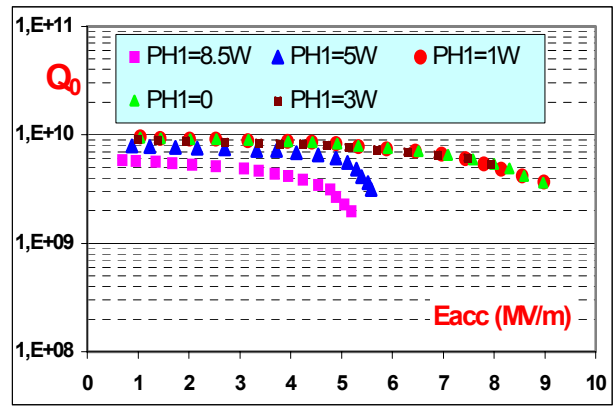
Figure 3: RF characteristics for different heater power PH_1 at T_{bath} =1.7K.

Compared to the reference curve (i.e. Q_0=f(E_{acc}) with zero heater power), no degradation of the cavity RF performance is observed for heater power up to 3 W. Moreover, for a heater power PH1$\geq$5W a strong degradation of the RF performance is clearly measured. More precisely, the maximum accelerating field (E_{acc}^{max}) achieved and the quality factor are much reduced (Table 2). Hence, the critical heat load Qc is in the range 3 W and 5 W.

Table 2: Effect of the heater power on the maximum achievable accelerating gradient and unloaded quality factor.

Heater Power (W)	$E_{acc}^{max}(MV/m)$	$Q_0^{max} \times 10^9$ ($E_{acc} = 1MV/m$)
1-3	9.0	9.5
5	5.6	7.9
8.5	5.2	5.8

The strong degradation (i.e Q_0 slope) of cavity RF performance when subjected to a heater power Q $\geq$ Qc could be attributed to an increase of surface resistance of the cavity (BCS term). The R_S increase has two possible explanations:

1 - Local temperature increase in an area where RF fields of the cavity are significant.

2 - The transition into normal state in the heated beam tube region (Fig. 7).

A simple analytical thermal model was used to check the assumption of the cavity active part temperature increase. The results show that such an assumption is not correct (i.e maximum observed $\Delta T =T_{wall}-T_{bath} <1.5K$ For Q=8.5W) unless the Kapitza conductance HK is reduced by two orders of magnitude with reference to the standard values of this parameter (eg. HK= 4000W.m^{-2}.K^{-1} - 6000 W.m^{-2}.K^{-1} at T=1.7K).

The computed temperature distribution (Fig. 4) for a heater power of 8.5W show that the major part of the beam tube is in the normal conducting state leading to an increase of the RF surface resistance by more than 4 orders of magnitude.
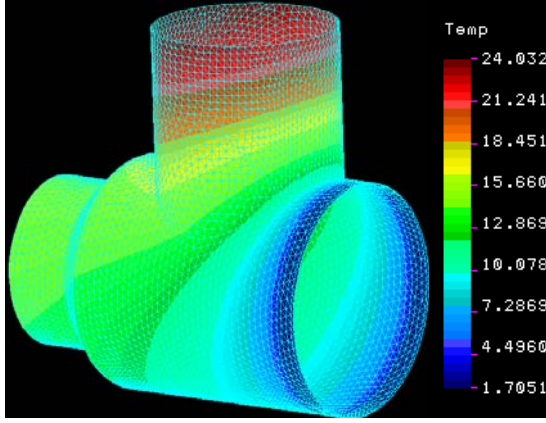

Figure 4: Computed isotherms in the beam tube and coupling port region for PH1=8.5W

The total RF power P_{total} dissipated in the cavity, including the beam tube, is simply the sum of the RF losses in the cavity active part (P_{cav}) and the heated beam tube P_{BT}:

$$P_{total} = P_{cav} + P_{BT}$$

The RF losses in beam tube can be written as:

$$P_{BT} = \frac{1}{2} \iint_s R_s H_s^2 \, dS \approx \frac{1}{2} \overline{R_s}(T) \iint_s H_s^2 \, dS \quad (1)$$

$$\overline{R_s}(T) = \frac{1}{(T_{max} - T_{min})} \int_{T\min}^{T\max} R_s(T) \, dT$$

where Rs(T) is the RF surface resistance and is the mean value of Rs(T) between T_{min} and $T_{max.}$

For the niobium in normal state of the surface resistance is:

$$R_s = \sqrt{\frac{\mu\omega\rho(T)}{2}} \quad (2)$$

Where the electrical resistivity $\rho(T)$ is the sum of phonon contribution $\rho_{Ph}(T)$ and the residual part ρ_r caused by impurities, dislocations and defects.

$$\rho(T) \cong \rho_{Ph}(T) + \rho_r \quad (3)$$

$$\rho_{Ph}(T) = 6.5\,10^{-14}\,T^3 \quad \Omega.m \quad for\ T \leq 25\ K \quad (4)$$

At low temperature (T<25K) ρ_r is the dominant term. Using these formula and the beam tube (BT) RRR $\approx$50, we have computed the power dissipated as function of the accelerating gradient Eacc (Fig. 5). The computed values are in very good agreement with experimental data (deduced from Q_0 vs Eacc) up to Eacc $\approx$ 4.5MV/m. For Eacc> 4.5MV/m, there is a large discrepancy: this is due to anomalous RF losses presently under study.
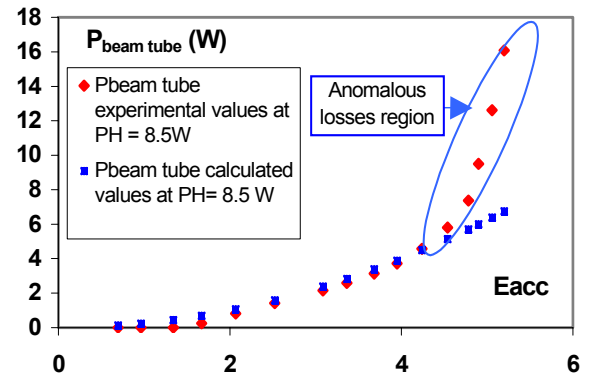

Figure 5: Comparison of computed beam tube RF losses with experimental data for PH1=8.5W.

THERMAL RESULTS

Two very important parameters used in the PC-cavity thermal model are unknown: the beam tube thermal conductivity k_{BT} and the thermal contact resistance RH^{-1} at the CF flange interface of the coupling port.

Beam tube thermal conductivity:
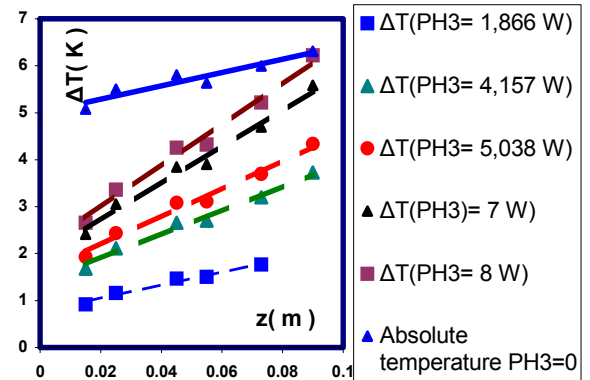
The heating profiles are linear (Fig. 6).

Figure 6: Thermal conductivity measurement values

The slopes of these curves are simply given by:

$$\nabla T = \frac{PH_3}{S_{BT}.k_{BT}} \quad (5)$$

Where S_{BT} is the cross section of the beam tube, PH3 is the heater power.

The thermal conductivity values as deduced from our measurement using equation (5) are presented in Fig. 7. These data are compared to previous results [3] and a good agreement is found.
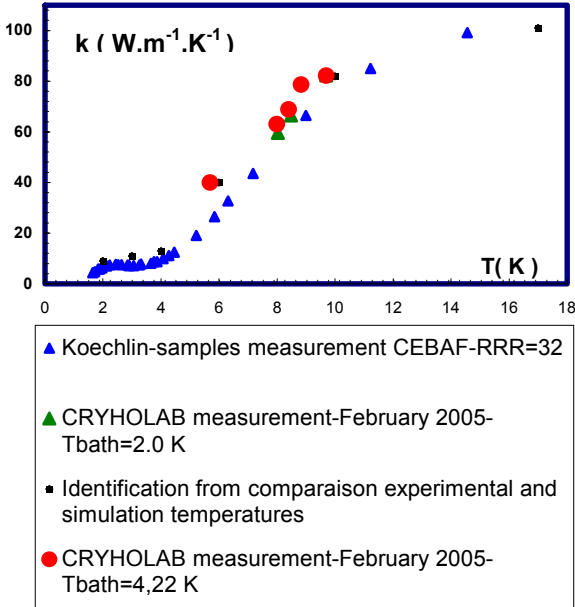

- ▲ Koechlin-samples measurement CEBAF-RRR=32

- ▲ CRYHOLAB measurement-February 2005-Tbath=2.0 K

- ■ Identification from comparaison experimental and simulation temperatures

- ● CRYHOLAB measurement-February 2005-Tbath=4,22 K

Figure 7: Thermal conductivity measurement values

Thermal contact conductance measurement:

Using the temperature measured by the thermometers located on the two sides of the coupling port interface, we have deduced the experimental value of RH^{-1} vs T:

$$R_H^{-1} = \frac{PH_1}{(\Delta T . A_C)} \qquad (6)$$

Where ΔT is the temperature gap at the BT-CP interface and Ac the contact surface area.
The corresponding data are illustrated in Fig. 8
Due to the lack of data for Cu/SS interface conductance in the literature we have compared our results with the previous values of conductances for Cu/Cu and SS/SS. Actual data are consistent with results previously reported [4].
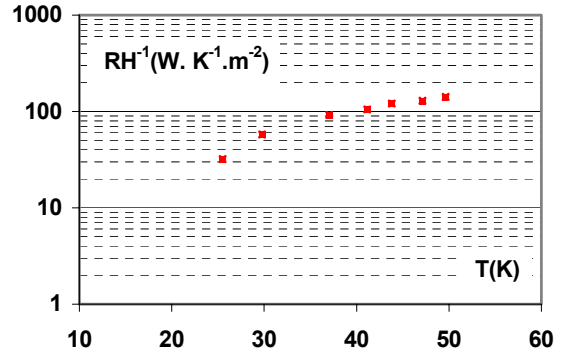

Figure 8: Thermal contact conductance measurement vs. temperature

Validation of the finite element thermal model:

Our thermal simulation results are compared to experimental data (Fig. 9). The relative deviation between computed and measured temperature distribution is less than 15% (Table 3).

Table 3: Comparison between the experimental value of temperature and the simulated one for $PH_1=2W$

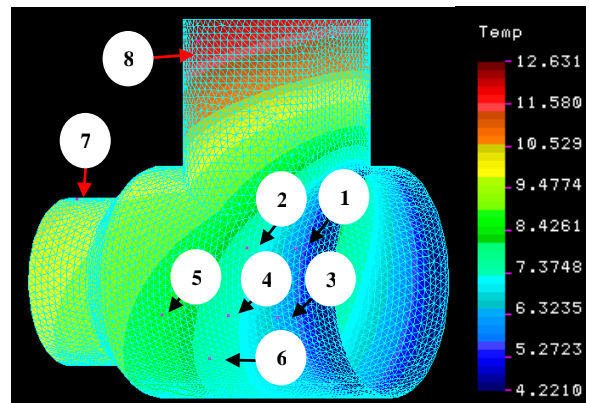| Sensors reference	Experimental temperature (K)	Simulated temperature (K)	Relative deviation (%)
1	5.6	5.5	9.4
2	6.7	6.5	2.9
3	6.4	5.6	12.4
4	7.0	6.6	5.5
5	7.6	7.3	3.8
6	7.2	6.8	4.7
7	9.5	8.3	12.5
8	11.4	11.0	3

Figure 9: Computed isotherms for PH1=2W

Thermal balance at the junction cavity iris, beam tube, Helium tank:

In order to calculate the values of heat fluxes Q1, Q2 and Q3, we have developed a 2D axisymetrical thermal

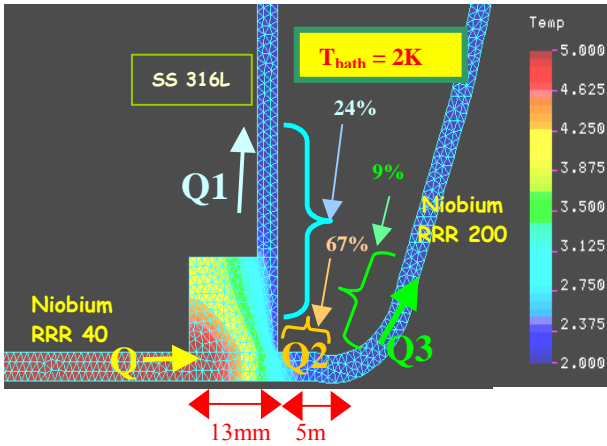model (Fig. 10). The Kapitza conductance used in this model is HK= 6000 $W.m^{-2}.K^{-1}$.

Figure 10: 2D axisymetrical model and thermal heat balance at the triple junction

Using the following equation:

$$Q_{i[i=1,2,3]} = \iint_S HK.\Delta T.dS \quad (5)$$

Where ΔT (K) = $T-T_{bath}$ is the temperature difference between the solid wall and the Helium bath and S is the heat transfer area.

The results show that the large part (91%) of the applied heat flux is transferred to the LHe bath upstream the cavity iris.

CONCLUSION AND OUTLOOK

A dedicated experiment on a five cell 700MHz elliptical cavity was successfully performed to measure the critical heat load Qc (3W<Qc<5W). This value of Qc will be used as an upper limit of the residual heat load at the cold extremity of the outer conductor. All the thermal aspects of the interaction between the power coupler and the cavity were analyzed. An extensive analysis of the Q_0 slopes will be performed soon using 3D electromagnetic simulations. The unknown parameters of our thermal model (k_{BT}, RH^{-1}) were in situ measured in the CRYHOLAB test facility. This model was validated by comparison with experimental data. A large part (91%) of the beam tube heat load is evacuated to the bath upstream cavity iris. A new experiment will be performed soon to test the efficiency of the heat exchanger of the outer conductor.

REFERENCE

[1] Alex C. Mueller, "Nuclear waste incineration and accelerator aspects from the Eurepean PDS-XADS study", Nuclear Physics A, Volume 751, 18 April 2005, Pages 453-468.

[2] J-L. Biarrotte, "High Power CW Superconducting LINACS For EURISOL and XADS", LINAC'04, Lübeck, Germany.

[3] F. Koechlin and P.Dolegieviez, Proc.5fi Workshop on RF Superc. (Hamburg, 1991, Aug. 19-23) Vol.1, 463 [report M92-01. DESY Lab. Hamburg. Germany].

[4] E. Gmelin & al, "Thermal Boundary Resistance of Mechanical Contacts between Solids at Sub-Ambient Temperatures", J. Phys. D: App. Phys.32 (1999)