

STUDY OF THERMAL INTERACTION BETWEEN A 150 kW CW POWER COUPLER AND A SUPERCONDUCTING 704 MHz ELLIPTICAL CAVITY

M. Souli, M. Fouaidy, H. Sagnac, P. Szott, N. Gandolfo, S. Bousson, Institut de Physique Nucleaire d'Orsay, CNRS/IN2P3, Orsay, France

D. Braud, J.P. Charrier, D. Roudier, P. Sahuquet, B. Visentin, CEA Saclay, DSM/DAPNIA/SACM, Gif sur Yvette, France

Abstract

The power coupler needed for $\beta=0.65$ 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 THE 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 its RF performance. Experimental data are compared to numerical simulation results obtained with the Finite Element Method code COSMOS/M. These data allow us also to perform in-situ measurements of the thermal parameters needed in the thermal model of the coupler (thermal conductivity, thermal contact resistance). These data are 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 $\beta=0.65$ 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. Three cooling circuits are designed for this purpose: the first circuit consists of a helical copper heat exchanger brazed around the outer conductor with supercritical helium as a coolant (inlet temperature: 5K). The Inner conductor is cooled by a forced convection of water (inlet temperature: 288K) in a dedicated annular space. Finally a cooling jacket is used for the removal of heat due to dielectric losses in the RF window.

POWER COUPLER DESIGN SPECIFICATIONS

IPN Orsay and CEA Saclay institutes have set an R&D program to develop $\beta=0.65$ 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:

- 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 sizable 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 and the thermal contact conductance at the CF flange of the coupling port.

- Validate numerical simulation model based on the Finite Element Method 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

In order 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 a heat flux Q (heater H1, H2, or H3) is applied to the system, it will flow in three directions: Q_1 evacuated to LHe via the stainless steel tank, Q_2 transferred to LHe in the cavity iris region and Q_3 is effectively conducted to the cavity. The heat balance at the triple junction Cavity Iris (CI) - LHe Tank (LHeT) - Beam Tube (BT) is simply: $Q = Q_1 + Q_2 + Q_3$

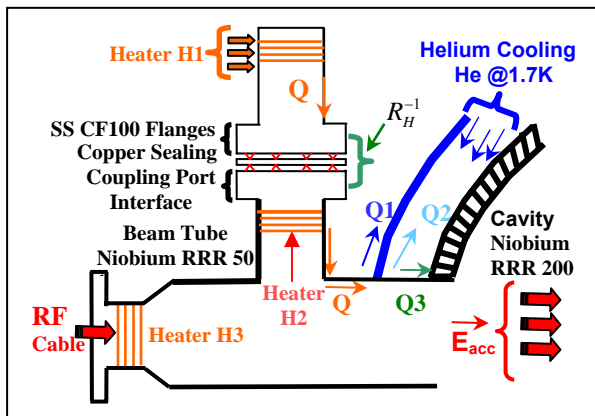


Figure 1: Description of the experiment.

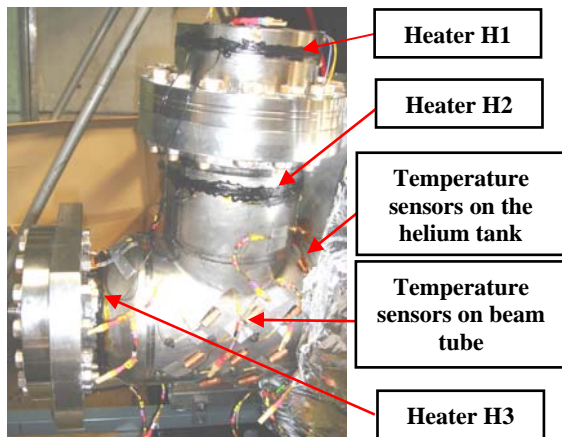


Figure 2: Photographic view of the temperature sensors and heaters (beam tube and coupling port).

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

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 allows us to evaluate the thermal balance at the triple junction.

Three tests have been performed during this experiment. The first one was done at $T_{bath} = 4.2K$ without RF power in the cavity: this run was dedicated to the measurements of the thermal conductivity and thermal contact resistance. The second run, similar to the first one was done at $T_{bath} = 2K$. The third test was carried out at $T_{bath} = 1.7K$ with the cavity subjected to RF power and a static heater power in order to measure the critical heat load.

Preliminary FEM thermal analysis using COSMOS/M shows that a heater power of 10W is sufficient for observing sizable effect on RF performances of the cavity when operating at $T_{bath} = 1.7K$.

RF RESULTS

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

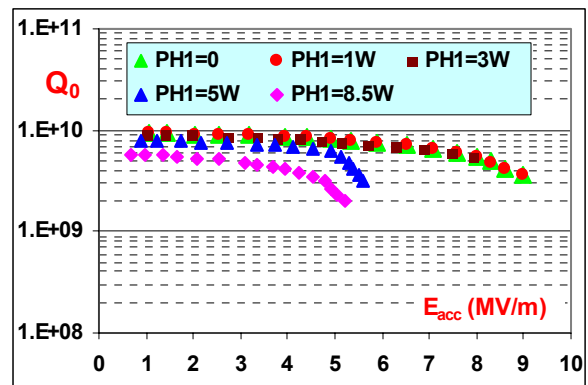


Figure 3: RF characteristics for different heater power PH1 at $T_{bath} = 1.7K$.

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. However, 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 significantly reduced (Table 2). Hence, the critical heat load Q_c is in the range from 3 W to 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)	$Q_0^{max} \times 10^9$ ($E_{acc} = 1 \text{ MV/m}$)
1-3	9.0	9.5
5	5.6	7.9
8.5	5.2	5.8

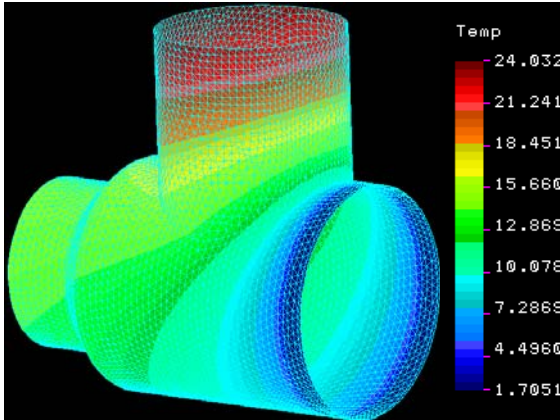
The strong degradation (i.e Q_0 slope) of cavity RF performance when subjected to a heater power $Q \geq Q_c$ could be attributed to an increase of surface resistance of the cavity active part region. The increase of the RF surface R_s has two possible explanations:

1 - Local temperature increase in an area where RF fields of the cavity are significant (BCS term contribution).

2 - The transition into normal state in the heated beam tube region (Fig.4).

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 computed $\Delta T = T_{wall} - T_{bath} < 1.5 \text{ K}$ for $Q=8.5 \text{ W}$) unless the Kapitza conductance HK is reduced by two orders of magnitude with reference to the standard values of this parameter (eg. $HK = 4000 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1} - 6000 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ at $T_{bath} = 1.7 \text{ K}$).

The computed 3D 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 $PH1=8.5 \text{ W}$

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 region P_{BT} :

$$P_{Total} = P_{Cav} + P_{BT} \quad (1)$$

As illustrated by the temperature distribution in fig. 4, the RF losses in the beam tube (P_{BT}) have two

contributions namely the superconducting part (P_{BTS}) and the normal resistive part (P_{BTN}) leading to the expression:

$$P_{BT} = P_{BTN} + P_{BTS} \quad (2)$$

P_{BTS} is calculated using the following expression:

$$P_{PTS} = \frac{1}{2} \iint_{A_s} R_{SS} H_s^2 dS \quad (3)$$

R_{SS} is composed two contributions the BCS resistance R_{BCS} [3] and the residual resistance R_{res} according to the well known relationship.

$$R_{SS} \approx R_{BCS}(T) + R_{res} \quad (4)$$

$$R_{BCS}(T) / n\Omega \approx 9 \cdot 10^{-5} \cdot \frac{f / \text{GHz}}{T} e^{-\frac{18}{T}} \quad (5)$$

For the actual test, the residual resistance measured at low field ($E_{acc} \leq 1 \text{ MV/m}$) is $R_{res} = 20 \text{ n}\Omega$; f is the resonance frequency of the cavity.

P_{BTN} is calculated with the following expression:

$$P_{PBN} = \frac{1}{2} \iint_{A_N} R_{NS} H_s^2 dS \approx \frac{1}{2} \overline{R_{NS}}(T) \iint_{A_N} H_s^2 dS \quad (6)$$

$$\text{With } \overline{R_{NS}}(T) = \frac{1}{(T_{max} - T_{min})} \int_{T_{min}}^{T_{max}} R_s(T) dT \quad (7)$$

$R_{NS}(T)$ is the RF surface resistance of niobium in normal state, $\overline{R_{NS}}$ is its mean value between $T_{min}=9.26$ and the maximum temperature in the beam tube T_{max} (Fig. 4)

For the niobium in normal state the surface resistance is:

$$R_{NS} = \sqrt{\frac{\mu\omega\rho(T)}{2}} \quad (8)$$

The electrical resistivity $\rho(T)$ is the sum of the phonon contribution $\rho_{ph}(T)$ and the residual part ρ_r caused by impurities, dislocations and lattice defects:

$$\rho(T) \cong \rho_{ph}(T) + \rho_r \quad (9)$$

$$\rho_{ph}(T) = 6.5 \cdot 10^{-14} T^3 \Omega \cdot \text{m} \quad \text{for } T \leq 25 \text{ K} \quad (10)$$

At low temperature ($T < 25 \text{ K}$) ρ_r is the dominant term. Using the previous formulas, the magnetic field distribution in the beam tube region [4] and RF parameters of this [4], we have computed the power dissipated in the beam tube as function of the accelerating gradient E_{acc} . For a given E_{acc} the contribution of the superconducting part P_{BTS} is lower than the normal resistive part P_{BTN} by four orders of magnitude. As a consequence the corresponding term so P_{BTS} could be neglected in the relationship (2).

The computed values (Fig. 5), according to the model, are in very good agreement with experimental data (deduced from Q_0 vs E_{acc}) up to $E_{acc} \approx 4.5 \text{ MV/m}$. In this region (i.e $E_{acc} \leq 4.5 \text{ MV/m}$) the observed difference between the two curves $Q_0 = f(E_{acc})$ for $PH1=0 \text{ W}$ and $PH1= 8.5 \text{ W}$ (Fig. 3) is mainly due to RF power dissipation in the beam tube. For $E_{acc} \geq 4.5 \text{ MV/m}$ and

PH1 ≥ 5 W, anomalous RF losses (e.g. non quadratic RF losses) are clearly observed in the characteristic Q_0 vs Eacc. The actual thermal model did not take into account such phenomena and a large discrepancy between numerical simulation results and experimental data is observed for Eacc ≥ 4.5 MV/m. a thorough study is undertaken in order to investigate this problem.

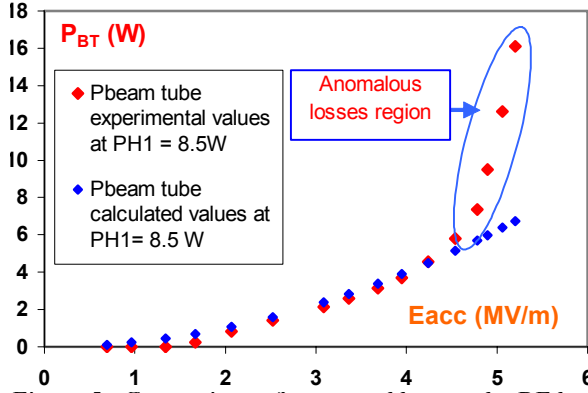


Figure 5: Comparison of computed beam tube RF losses with experimental data for PH1=8.5W.

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 conductance R_H^{-1} at the CF flange interface of the coupling port.

Beam tube thermal conductivity:

The measured heating profiles are linear (Fig. 6).

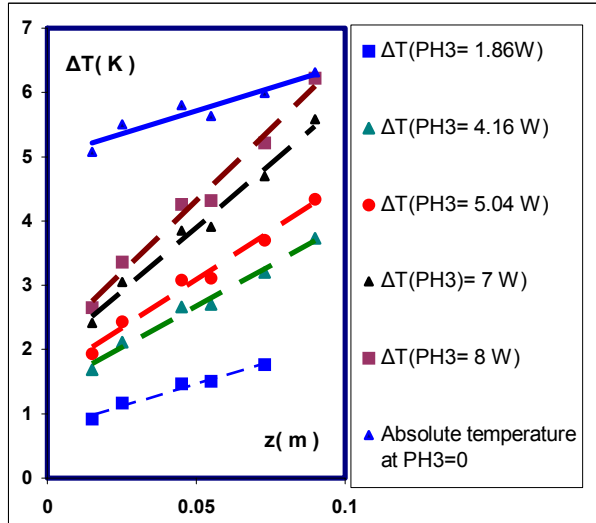


Figure 6: Beam tube thermal profile for $T_{bath}=4.2$ K

The slopes of these curves are simply given by:

$$\nabla T = \frac{PH3}{S_{BT} \cdot k_{BT}} \quad (11)$$

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

The thermal conductivity values k_{BT} as deduced from our measurement using equation (11) are shown in Fig. 7. These data are compared to previous results [5] and a good agreement is found.

It should be stressed that due to parasitic conduction heat flux via the RF cable the minimum temperature measured of the beam tube is higher than 5K for zero heater power (Fig. 6).

Note that due to cryogenic problems at $T_{bath}=2$ K we did not perform enough thermal conductivity measurements for $T \leq 5$ K.

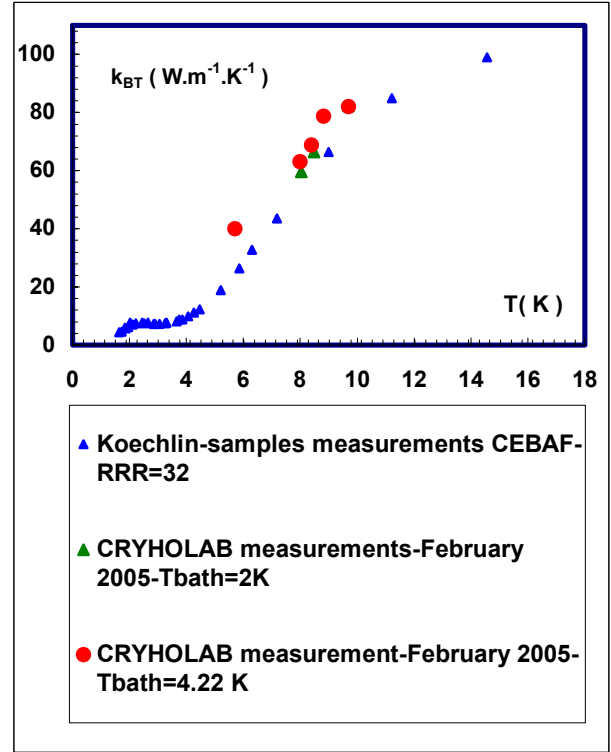


Figure 7: Thermal conductivity measurement values

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 R_H^{-1} vs T:

$$R_H^{-1} = \frac{PH1}{(\Delta T \cdot A_C)} \quad (12)$$

Where $\Delta T = T_2 - T_1$ is the temperature jump at the BT-CP interface, T_2 and T_1 are the temperature on the both sides of the interface and A_C is the contact surface area.

The corresponding data are illustrated in Fig. 8. The interfacial temperature T is defined as:

$$T = \frac{T1 + T2}{2} \quad (13)$$

As R_H^{-1} is low and $\Delta T \geq 32$ for PH1 ≥ 1 W the interfacial temperature values are higher than 25K.

Due to the lack of data for Copper Stainless Steel (Cu/SS) interface conductance in the literature we have compared

our results with the previous values of conductances for Cu/Cu ($R_H^{-1} = 15-775 \text{ W.K}^{-1}.\text{m}^{-2}$) and for SS/SS ($R_H^{-1} = 12-110 \text{ W.K}^{-1}.\text{m}^{-2}$) [6]. Our data are consistent with results previously reported [6].

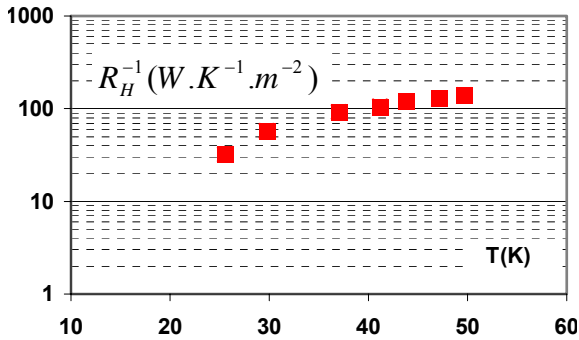


Figure 8: Thermal contact conductance measurement vs. temperature

Validation of the finite element thermal model:

Our thermal simulation results are compared to experimental data (Fig. 9). The relative difference between computed and measured temperature distribution is less than 12.5% (Table 3).

Table 3: Comparison between experimental and computed temperature for PH1=2W

Sensors reference	Experimental temperature (K)	Simulated temperature (K)	Relative difference (%)
1	5.6	5.5	1.8
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

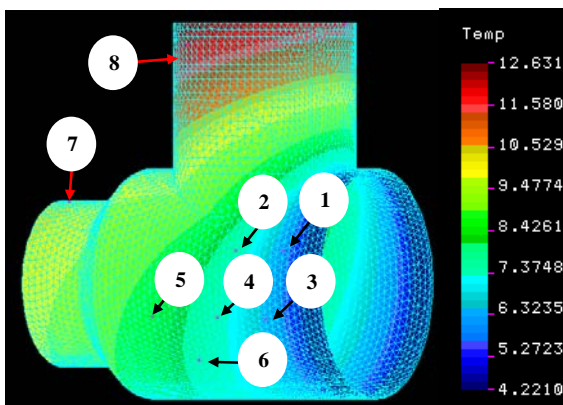


Figure 9: Computed isotherms for PH1=2W

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 $HK = 6000 \text{ W.m}^{-2}.\text{K}^{-1}$.

Using the following equation:

$$Q_{i[i=1,2,3]} = \iint_S HK \cdot \Delta T \cdot dS \quad (14)$$

Where $\Delta T(\text{K}) = T - T_{\text{bath}}$ 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.

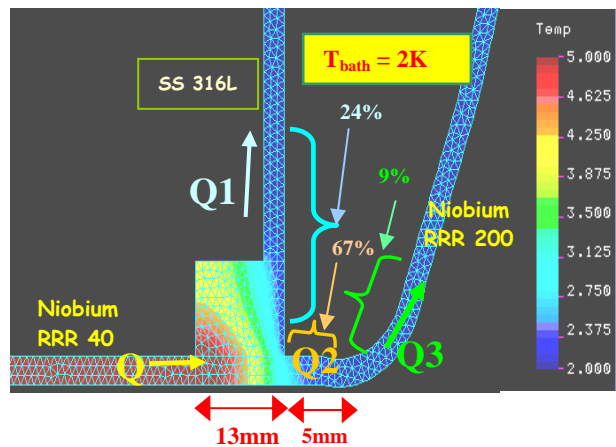


Figure 10: 2D axisymetrical model and thermal heat balance at the triple junction

CONCLUSION AND OUTLOOKS

A dedicated experiment on a five cell 700MHz elliptical cavity was successfully performed to measure the critical heat load Q_c ($3\text{W} < Q_c < 5\text{W}$). This value of Q_c 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} ,) were in situ measured in the CRYHOLAB test facility. This model was validated by comparison with experimental data. R_H^{-1} A large part (91%) of the beam tube heat load is evacuated to the bath upstream cavity iris. A new experiment will be performed in the near future to test the efficiency of the heat exchanger of the outer conductor.

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