SURFACE SCANNING THERMOMETERS FOR DIAGNOSTIC PURPOSE OF THE TESLA SRF CAVITIES

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ABSTRACT

150 specially developed superfluid helium cooled surface scanning thermometers have been constructed and successfully used as diagnostic probes of anomalous RF losses and Thermal Breakdown on TESLA SRF cavities. We report about these thermometers calibration (i.e Thermal response (ΔT) vs the Heater Power (Q)) in superfluid helium. Two different test-cells were used for this purpose : 1) the cell#1 which is equipped with a Joule-heated Niobium plate and designed to support a set of up to 16 thermometers simultanously, 2) the cell #2 consisting of a Joule-heated OFHC copper rod , equipped with 3 calibrated carbon resistors in the temperature range 1.5 K–20 K and placed in a vacuum can, which is used for precise calibration of one surface scanning thermometer in a large heat flux q range (i.e 10 mW/cm^2 $\leq$q $\leq$ 3 W/cm^2). The first test-cell allows us to get statistical information about the ΔT vs Q curves for different thermometers. Moreover, by comparison of the mean value of the surface scanning thermometers calibration curve (i.e ΔT vs Q) with the numerical simulation results or/and with a reference thermometer thermal response, an estimation of the thermometer measurement efficiency η is obtained for different mounting conditions (i.e with vs without the use of a thermal bonding agent between the thermometer tip and the test-specimen cold surface) of the temperature sensors on the test-specimen. Also are discussed the effect of the superfluid helium (He II) bath temperature T_{bath} on the thermometer measurement efficiency η. The calibration results obtained with the cell #2 show strong non-linearities in the ΔT vs q curves for the scanning thermometers when used without a thermal bonding agent : the thermometer measurement efficiency η increases strongly with q. The temperature maps obtained on TESLA cavities are successfully analysed using the present calibration data and numerical simulations results performed with different codes including a Finite Element Thermal Code.

INTRODUCTION

The development of He II surface thermometers for diagnosing and studying the thermal effects in supercoducting RF cavities has been a major activity of the Orsay Group during the recent past years. Several papers describe the different types of thermometers and the main experimental features : fixed thermometers for studies of the anomalous RF heating of samples mounted on special cavities [1], scanning thermometers for monocell cavities [2] and special vacuum thermometers for Kapitza conductance measurements [3].

In this paper we present the results of a new development in collaboration with the DESY laboratory, for constructing a diagnostic system for the 9-cell TESLA cavities. As compared to the older devices, a large number of thermometers (> 100) are mounted around the cavity which raises different mechanical and cabling problems. The complete description and the first results are given in an another paper [5]. In this paper we focuse on the calibration of the thermometers and the thermal analysis of some temperature mapping results obtained.

DESCRIPTION

The surface thermometer design [Fig. 1] is very close to the model developed earlier for the CERN group [2]. The sensitive part is an Allen-Bradley carbon resistor (100 Ohm, 1/8 W) housed in a silver block with a sensor tip of 1 mm diameter for the thermal contact to the external surface of the cavity. This housing is thermally insulated against the surrounding He II by an epoxy envelope (Stycast) moulded around the silver block and into a bronze piece which allows the sensor mounting on the rotating thermometric arm. The thermometers tip must present a good contact with the cavity wall when scanning : two springs located inside two holes in the body of the rotating arm are used for this purpose, the contact pressure control and adjustement is allowed by means of two screws. Each thermometer has two independent manganin wires thermally anchored to the silver block with ~ 15 cm free length for connecting to each cell board (14 thermometers). At the level of the boards the connectors ensure the cabling dispatching inside the cryostat allowing the motion of the rotating arm.

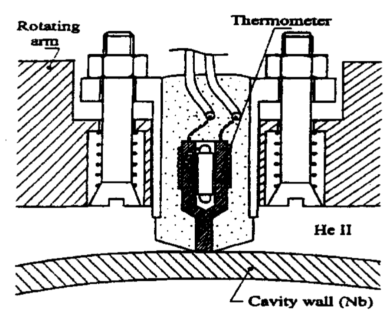

Fig. 1 : Cross section of a HeII surface thermometer

CALIBRATION RESULTS

Two different test-cells were used for the scanning surface thermometers calibration : a) the cell # 1 using a Joule-heated niobium plate as test-specimen, b) the cell # 2 were an OFHC Joule-heated copper rod is used as heater post.

A - Results with the test-cell # 1

Superfluid helium

A representative batch (32) of the 150 thermometers fabricated for this device were tested using a special calibration chamber [1] allowing the mounting of 16 thermometers at every test. In principle all thermomters are located in a region subjected to the same heat flux density. In this experiment the thermometers tip were glued to the Nb heated plate by means of a good thermal bonding agent (Apiezon N Grease) in order to verify the fabrication process. The two thermometers batches (2 x 16) give a mean thermal response $<\Delta T>_1 = 8.0$ mK and $<\Delta T>_2 = 8.8$ mK respectively for a total heater power of 195 mW at $T_{bath} = 1.8$ K. Numerical simulation of the plate heater assembly for the same experimental conditions gives $\Delta T = 56$ mK. This calculation was performed in order to evaluate the thermometer efficiency η defined as the ratio of the experimental thermal response ΔT_{exp} to the simulated temperature jump ΔT_{sim} at the Nb - He II interface. In this case we obtained $\eta = 0.14$.

A complementary test was performed by mounting the thermometers in the real operating conditions of the scanning device, (e.g. without any bonding agent between the thermometer tip and the Nb wall). The results for a batch of 13 thermometers is presented in Fig. 2 at two different heater powers of 1.86 W and 2.8 W. A first group of thermometers was mounted with a contact pressure of ~ 10 bars (spring load of 80 gr) giving $<\Delta T>_{1.86} = 2.1$ mK, a second group was monted with a pressure of ~ 62 bars (spring load of 500 gr) giving $<\Delta T>_{1.86} = 6.4$ mK. A third group of fixed thermometers (e.g. glued with grease, not displayed) gives $<\Delta T>_{1.86} = 92$ mK. At a higher power (2.8 W) the measurements were $<\Delta T>_{2.8} = 6.3$ mK (at a pressure of 10 bars) and $<\Delta T>_{2.8} = 16$ mK (at a pressure of 62 bars). All these results clearly show an important decrease of the measurement efficiency when no bonding agent is used : η is now close to 0.01. Notice that in this case, the efficiency is heater power dependant.

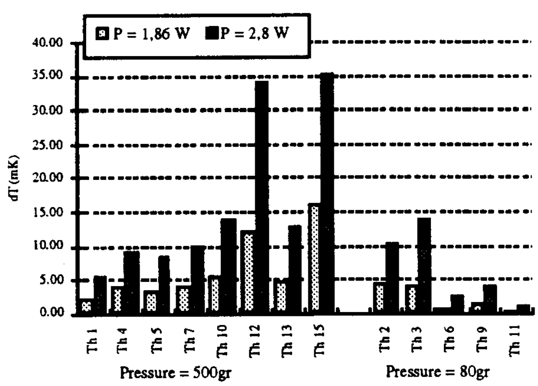

Fig. 2 : Thermal response at $T_{bath} = 1.8$ K
(without contact grease)

Subcooled helium I

The subcooled helium bath obtained for temperature over the λ point (T>2.176K) and a pressure of 1 bar gives the possibility to study heat losses in the cavity wall in a far less constrained mode than in HeII. In this case the heat transfer mechanism is dominated by free convection cooling (laminar or turbulent) which induces the formation of a thick superheated helium boundary layer, the temperature is now quite easy to measure without taking many precautions in the mounting conditions of the thermometers. The calibration was made with the same thermometer batch and the same chamber. The results are displayed in Fig. 3. The same three groups of thermometers were tested giving respectively $<\Delta T>_{80g} = 572$ mK, $<\Delta T>_{500g} = 651$ mK and $<\Delta T>_{fixed} = 537$ mK for a total power of 146 mW at 2.5 K. These values show clearly a rather insensitivity to the mounting conditions and a much reduced dispersion in each group as compared to superfluid helium results. The agreement with a previous published equivalent thermal resistance [4] in subcooled helium at 2.5 K is quite good : the mean measured value is $R_{th} \sim 30$ K/W/cm^2 which is consistent with the calculated value of 65 K/W/cm^2 for the same heater power [4]. This agreement seems to be quite good considering all the hypothesis and simplifications adopted to calculate this thermal resistance in a free convection bath with turbulent flow using dimensional analysis. Anyway and as expected, the comparison with superfluid helium results in terms of thermal boundary resistance (e.g. $R_{th} \sim 2$K/W/cm^2, Kapitza resistance at 1.8K) shows up the benefit of operating in subcooled normal helium. However, the price to be paid is a reduced spatial resolution and a reduced operating accelerating field due to the global cavity heating.

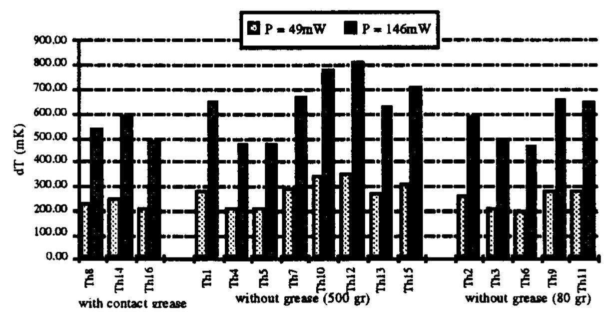

Fig. 3 : Subcooled normal helium test 2.5 K < T_{bath} < 3 K

B - Results with the test cell # 2

Calibration cell #2 description

This new calibration chamber was specially designed in order to carefully calibrate one surface scanning thermometer in a large heat flux range (10 mW/cm$^2 \leq q \leq 3$ W/cm^2) and to check on the consistency of calibration results with the relatively high temperature difference ΔT with respect to T_{bath}) observed on some T-map hot spots (i.e. $\Delta T \cong 3.5$ K).

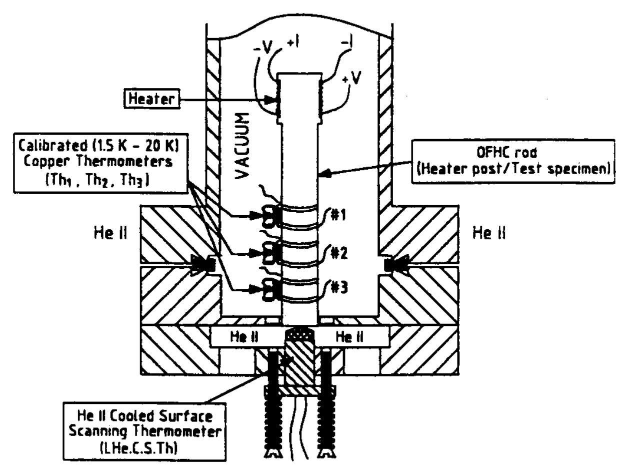

Fig. 4 : High heat flux calibration cell for HeII cooled surface scanning thermometers

This test cell # 2 (Fig. 4) consists mainly of a Joule-heated OFHC copper rod (test specimen), equipped with three carbon resistors Th1, Th2 and Th3 calibrated (temperature range : 1.5 K - 20 K) prior to this experiment in a dedicated chamber, placed in a vacuum can and brazed to a 2 mm thickness stainless steel plate.

The thermometers Th_1, Th_2 and Th_3 (copper thermometers) are used for in-situ measurement of the copper thermal conductivity k and hence to deduce easily the "true" wall temperature T_s of the HeII-cooled surface. The scanning thermometer to be calibrated is naturally placed on this cold surface with a mounting scheme close to that used on the rotating mapping system of TESLA cavities [5].

Calibration results with the cell # 2

The thermal response (Fig. 5) of the scanning thermometer (Th_4) is strongly non-linear when it is used without a thermal bonding agent (Apiezon N-Grease). More precisely the measurement efficiency $\eta = \frac{\Delta T}{T_s - T_{bath}}$ in the case of no bonding agent increases with the heat flux q from η = 5 % for q ≅ 50 mW/cm² to η ≅ 30 % for q = 2 W/cm².

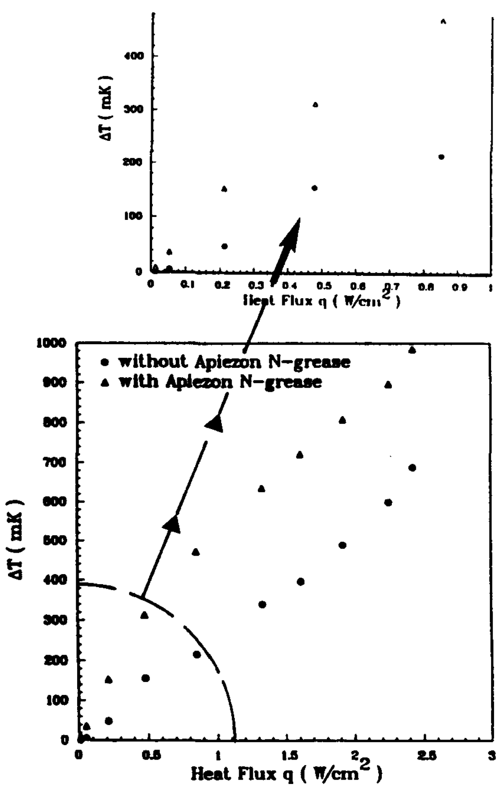

Fig.5 : High heat flux thermal response of HeII-cooled surface scanning thermometers (effect of the Apiezon N Grease on ΔT vs q)

Moreover, for heat flux q larger than 150 mW/cm², the efficiency is only reduced by a factor ≈ 1.5 - 2 as compared to the case with the Apiezon N-Grease. Notice that q = 150 mW/cm² corresponds to RF Joule heating of a 500 nΩ defect surface resistance, located at the equator of a 9-cell TESLA cavity operating at E_{acc} = 25 MV/m. Finally, the heat transfer charasteristic curves in saturated superfluid helium (Fig. 6) clearly show that the surface scanning thermometer, even when mounted in real operating conditions (i.e. without Apiezon N-Grease), is able to detect and to investigate reliably phase change phenomena (i.e. film boiling transition and vapor layor resorption) at the copper-HeII interface and very precisely. This last remark is very important for high anomalous RF losses diagnostic analysis : the heat flux to dissipated in very hot spots could reach values close to the actually measured critical heat flux (2 W/cm²) and eventually induces the cavity quench due to the local HeII vaporization and the resulting low heat transfer coefficient (≅ 0.04 W/cm².K) in the film boiling regime [6].

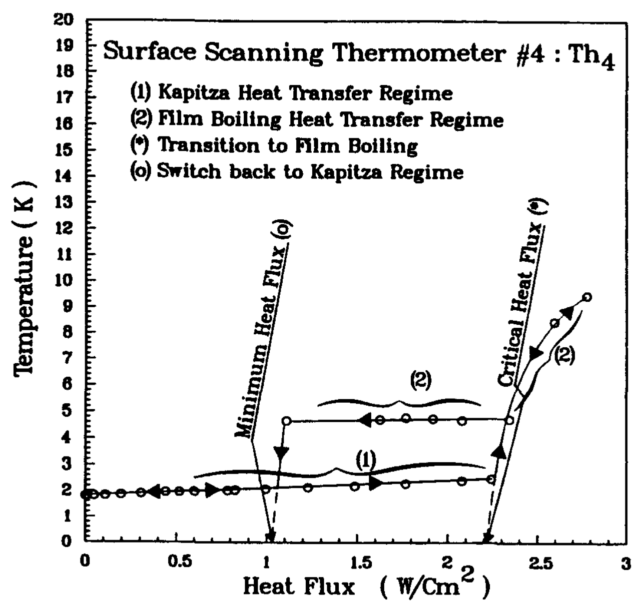

Fig. 6 : Heat transfer characteristics in saturated superfluid helium bath - heated copper surface facing downward (T_{bath} ≅ 1.8 K, HeII-Cu interface immersion depth = 11 cm)

EXPERIMENTAL RESULTS

The first experimental results using a completely equipped rotating arm (116 thermometers) have been obtained with a prototype TESLA cavity (1.3 GHz, 9 cells) [5]. This cavity, after a heat treatment at 1400 °C in a vacuum furnace, was tested in a vertical cryostat at the DESY TTF facility. During the experiment, high power processing (HPP) was performed which leads to an important improvement of the cavity performances : E_{acc} = 20 MV/m at $Q_0 = 2 \times 10^9$ (Q_0 at low field ≅ 10^{10}). Several T-maps were recorded during the test in superfluid helium bath (before and after HPP) and in a subcooled helium bath (after HPP).

During the first run, the cavity reach a maximum accelerating field (E_{acc}) of 11.2 MV/m limited by a very heavy field emission. The Q_0 decreased from ~10^{10} at low field to 8×10^8 at the maximum field. A first T-map was

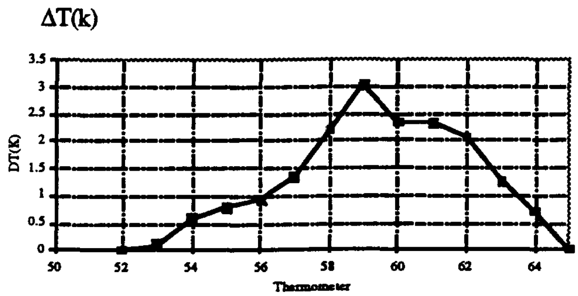

Fig. 7 : ΔT (5th cell) at 130° azimuthal angle

recorded at this value exhibiting very high ΔT in the 5th cell. The heated region was very extended : it concerns 12 thermometers of the 5th cell (Fig. 7) and presents several maximums at different angles between 100° and 200° (Fig. 8). Very high ΔT were measured (1K - 3.3 K) in this cell. The first question raised by these results is if we may trust the measurements. In order to explain this, a very high measurement efficiency of the thermometers must be considered and it is effectively the case (see the previous section).

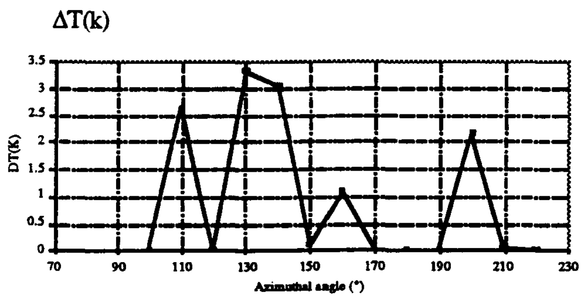

Fig.8 : ΔT (thermometer #59) vs. azimuthal angle

Moreover, evidence of high ΔT measured in monocell cavities with scanning thermometers has been observed many times. Values of ΔT in the range of 100 mK to 200 mK have been measured in Nb/copper cavities at CERN [2] with largely lower RF power levels (~ 2 to 10 W). If we admit a very good efficiency at the high heat flux density encountered in this cavity, another questionable point remains : are such high heat flux densities levels compatible with the critical heat flux in He II ? Some papers on this subject confirms that metallic heated plates in He II exhibit very high ΔT (5 to 6 K) in the Kapitza regime before reaching the critical flux inducing the transition to film boiling [7].

Extensive calculations of primary FE electrons trajectories at 11.2 MV/m shows that emission sites located in the proximity of the iris of the 5th cell could explain such impacts in the equator region of this cell. The azimuthal spreading of the heated area is more difficult to understand. Numerical simulation using a Finite Element Method based commercial code (Systus) was performed in order to analyse the hot spot induced by FE electrons impacting on the RF surface. The steady-state 2D model used considers a RRR = 379 Nb plate (length in the azimuthal direction : lx = 10 cm, lenght along the cavity profile : lz = 20 cm, thickness : e = 2.5 mm) uniformly heated by the electron beam bombardment (impacting area : 2 mm x 200 mm) on the RF surface and cooled by superfluid helium (T_{bath} = 2.1 K) on the other side. The resulting temperature profiles for a total power deposited by the electron beam Pel = 5 W are presented in Fig. 9a for the RF surface and in Fig. 9b for the HeII-cooled surface.

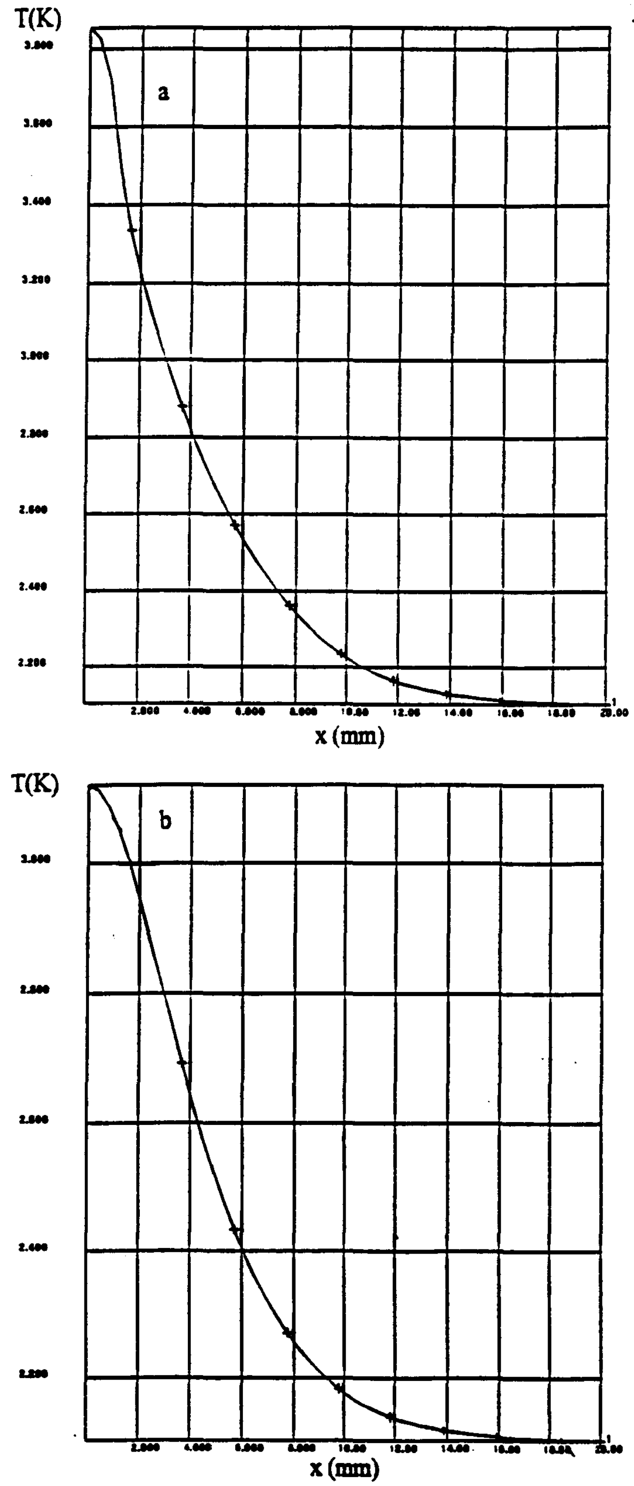

Fig. 9 : Temperature profile along the x-coordinate on the RF surface (a) and on the HeII-cooled surface (b) **(total power deposited by the FE electron beam : Pel = 5W, T_{bath} = 2.1 K)**

At this power level, the maximum temperatures reached are $T_{\max}^{hot} = 3.855K$ and $T_{\max}^{cold} = 3.118K$ for the HeII cooled surfaces respectively. The HWHM are respectively 3.2 mm (RF surface) and 4.5 mm (cold surface). Moreover, the temperature distribution within the Nb plate were computed as function of Pel up to 5W : the resulting $T_{\max}^{cold}$ vs Pel dependence is strongly non-linear. More precisely, $T_{\max}^{cold}$ is proportional to Pel up to ≈ 600 mW, then a departure from the linear behaviour is observed with a reduced slope up to Pel ≅ 5W were $T_{\max}^{cold}$ reach an asymptotic value of ≅ 3.9 K.

To explain the ΔT shapes observed, a first hypothesis of separated sites located in the same cell at different angles along the iris must be admitted. From the point of view of the total power involved in this experiment we have performed the integration of the heat power density over the heated region :

$$Q = \int_s q ds \approx S_{th} \sum_n h_k \Delta T_n$$

where S_{th} is an estimation of the equivalent heated surface measured by one thermometer which has been arbitrarily taken equal to the product of the distance between two thermometers and length corresponding to a scanning angle of 10°. h_K is the Kapitza conductance at the measured point

$$h_k = H_K.f(\Delta T) = h_o\, T_{bath}^n \,.\, f(\Delta T/T_{bath})$$

$$H_k = 0.017\, T^{3.62}\ W/cm^2K\quad [8].$$

This integration gives Q ~ 100 W which seems to agree quite well with the RF power measurements. The power attributed to the electrons is easily deducted from the ΔQ_O at E_{acc} = 11.2 MV/m ($\Delta Q_O = 10^{10} - 8 \times 10^8$). A simple calculation gives $P_{electron}$ ~ 170 W. So, we obtain values which are of the same order of magnitude : the discrepancy could be attributed to H_K variations from a Nb sample to another one and to η which is ≈ 30 %. This good agreement could add some confidence to the recorded ΔT.This strong field emission was efficiently treated by HPP technique in the same experiment and a very good Eacc value was reached (20 MV/m). A T-map taken at 17.7 MV/m shows that the heating observed in the 5th cell has disappeared and that some lower heating is now measured in the cells #5 and #7 reaching some peaks of ΔT ~50mK at angles of 100° and 280°.

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