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17 January 1983CALIBRATION OF THE SCANNING THERMOMETER RESISTOR SYSTEM
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A calibration measurement for the temperature mapping system in use at CERN for superconducting accelerating cavities immersed in subcooled liquid helium is presented. It allows a study of cavity losses in a quantitative way by relating the temperature increase (ΔT) at the cavity outside wall to the power dissipated at the inside. The calibration set up simulates an isolated lossy region in a superconducting cavity. The influence of the bath temperature and the orientation of the heated surface have been investigated. ΔT is determined by the heat current density Q at the resistor location according to $\Delta T = \alpha Q^{3/4}$. The proportionality constant α depends on the particular experimental conditions. The experimental results are compared with heat transfer calculations in subcooled helium. As an application typical loss mechanisms in superconducting cavities are described.

Introduction

Every energy loss mechanism in a superconducting cavity is nearly totally converted into heat, which is transported through the cavity wall into the helium bath. Thus a temperature gradient is generated between the location of the heat source, and the cavity helium interface, which may be detected by appropriate thermometers.

A scanning thermometer resistor system was developed at CERN, which has proved to be a powerful device for detecting the heat loss distribution ("temperature maps") in superconducting cavities.¹ For a quantitative analysis of temperature maps, the temperature increase ΔT at the cavity helium interface, which is detected by the resistors, has to be correlated to the power dissipated at the interior cavity wall. For this reason a calibration measurement, in which a lossy spot in a superconducting cavity and its cooling mechanism are simulated, has been carried out.

Experimental set up and measurements

A heater plate of 2 mm (resp. 4 mm) thickness which can be rotated is vertically mounted and sealed to a stainless steel vacuum can pumped to a pressure below 10^{-5} mbar (fig. 1). A 10 mm diameter post at its inner side carries a resistance wire. Five (resp. nine) carbon thermometers constructed like those in use for the temperature mapping system were attached to the outside of the plate in a horizontal chain.

A germanium resistance thermometer is placed into a hole at the outside of the heater plate to measure the "true" temperature at the niobium near the niobium helium interface.

The following dependencies were measured:

- (a) The temperature increase of the thermometer resistors at constant heat current and different bath temperatures.

- (b) The temperature increase at constant bath temperatures and varying heat flux.
(c) For the 2 mm plate the temperature increase as a function of the plate orientation.
(d) The temperature distribution at the niobium helium bath interface for the 2 mm and 4 mm plate.

These measurements allow the determination of the heat current density at the subcooled to nucleate boiling transition, the determination of the peak nucleate boiling heat current for that particular plate in subcooled helium, and that of the heat transfer coefficient in subcooled helium.

During each cool down the carbon resistors were calibrated. The temperature increases were computed from the resistor voltages before and after the heat pulse was applied. The accuracy of these measurements was ± 10 mK. In a second step the temperature response ΔT of a resistor was measured for a constant heat input P at different bath temperatures T_B (fig. 2). From this measurement a correction formula was derived, which takes into account the influence of the bath temperature on the cooling conditions:

$$\Delta T T_B^{1.9 \pm 0.5} = \text{const}(P).$$

Finally, the temperature response of the resistors was investigated for different heat currents, while the bath temperature was held as constant as possible (the unavoidable heating of the subcooled bath was taken into account by the correction formula).

Results and discussion

The starting point of the data analysis is a plot of the temperature response $\Delta T(0)$ of the resistor at the center of the heater plate to a heat pulse of total power P (fig. 3) at constant $T_B = 2.5$ K. Many experimental runs for different cool downs are incorporated in this plot. We conclude that the reproducibility of results is better than $\pm 25\%$. In addition it is found that within this error interval the temperature response does not depend on the orientation of the heater plate.

A parametrization for the temperature increase $\Delta T(0)$ at the bath temperature $T_B = 2.5$ K as a function of the total power P released to the heater plate of 2 mm thickness (resp. 4 mm) is given by

$$\Delta T(0) = \alpha P^n \quad (1)$$

with $\alpha = 15 \pm 4$ (resp. 5 ± 1), $n = 0.80 \pm 0.05$

and $[T] = \text{mK}$, $[P] = \text{mW}$, $P < 200$ mW.

In the course of the data analysis the distribution $\Delta T(r)$ along the heater plate normalized to the maximum $\Delta T(0)$ at the center of the plate is - within experimental errors - found to be independent of the total heat input P up to 1 Watt. The full width half maximum of this distribution is 1.5 cm (resp. 2.8 cm). A suitable parametrization is given by

$$f(r) = \Delta T(r) / \Delta T(0) = \frac{(1 + 2.23 r[\text{cm}]^2)^{-1}}{(1 + 0.51 r[\text{cm}]^2)^{-1}}, \quad R < 2.0 \text{ cm} \quad (2)$$

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Finally from a reasonable hypothesis justified later the temperature response ΔT of each resistor follows the local heat current density Q like

$$\Delta T = \alpha Q^m. \quad (3)$$

Eqs. (1) to (3) lead from continuity arguments under stationary conditions to

$$P = 2\pi \int_0^R Q(r) r dr = 2\pi \alpha^{1/m} \alpha^{-1/m} P^{n/m} \int_0^R f(r)^{1/m} r dr$$

Thus we conclude

$$m = n$$

$$\alpha = \alpha (2\pi \int_0^R f(r)^{1/m} r dr)^m = 2.1^m \alpha \text{ (resp. } 10.7^m \alpha \text{)}$$

which yields according to the measurements

$$m = 0.80 \pm 0.05$$

$$\alpha = 39 \pm 12 \text{ (resp. } 41 \pm 10 \text{)}$$

for $[Q] = \text{mW/cm}^2$ and $[T] = \text{mK}$.

In a different analysis the data from the 4 mm plate are analyzed by χ^2 minimization which yielded

$$m = 0.67 \pm 0.05$$

$$\alpha = 32 \pm 4.$$

From two independent experimental runs we gain the final result

$$\Delta T[\text{mK}] = (33 \pm 3) Q \left[\frac{\text{mW}}{\text{cm}^2} \right]^{0.74 \pm 0.05}$$

On heat transfer in subcooled helium

In order to gain more insight into the mechanism of heat transfer, we apply the laws of convection heat transfer under the influence of buoyancy. The classical relation which describes this phenomenon is the Lorentz equation.²

$$Y = C (N_{Gr} N_{Pr})^n$$

Y, N_{Gr}, N_{Pr} = Nusselt, Grashof, Prandtl numbers

C, n = Dimensionless constants which depend on the nature of heat flow and on the geometry

The properties of the liquid helium³ are listed in table 1.

TABLE 1: Properties of liquid helium at different temperatures

Temperature	T	2.5	3.0	3.5	4.2	K
Specific heat	C	2.05	2.36	3.00	4.98	J/g/K
Viscosity	η	39.4	38.6	36.4	31.7	$\mu\text{P}^{(a)}$
Thermal conductivity	k	1.67×10^{-4}	1.82×10^{-4}	1.91×10^{-4}	1.96×10^{-4}	W/(cmK)
Density	ρ	0.147	0.143	0.138	0.125	g/cm ³
Volumetric expansion	β	0.0377	0.0608	0.0923	0.210	K ⁻¹
(a) $1 \mu\text{P} = 10^{-7} \text{ (N/m}^2\text{) s}$.						

For $T_B = 2.5 \text{ K}$, $N_{Pr,f} = 0.48$, and $N_{Gr,f} = 5.1 \times 10^4$ $L[\text{m}]^3 \Delta T [\text{K}]$, thus yielding $N_{Pr,f} \cdot N_{Gr,f} = 2.4 \times 10^4$ $L[\text{m}]^3 \Delta T [\text{K}]$ (L = height of the heated surface). The index f takes into account that the corresponding quantities have to be calculated for the "film" temperature².

From², eqs (7-4a) for vertical planes we conclude that for $L \sim 2 \text{ cm}$ the flow is turbulent and get

$$Y_f = 0.13 (N_{Gr,f} N_{Pr,f})^{1/3}$$

We get for the temperature increase

$$\Delta T[\text{mK}] = 141 Q[\text{mW/cm}^2]^{3/4} (\eta / 0.13^3 k^2 C_p \rho^2 g \beta)^{1/4} Q^{3/4}$$

The slight dependence on the film temperature

$T_f = (2T_B + \Delta T)/2$ was for simplicity not taken into account. It would result in a flattening of the curve with increasing heat flux, which we indeed observe.

The natural turbulent convection heat transfer curve is plotted in fig. 3 together with the nucleate boiling heat transfer curve. The natural convection heat transfer curve ends at 4.2 K, the boiling point of the liquid, which in the scale of fig. 3 corresponds to $\Delta T = 1700 \text{ mK}$ and $Q = 25 \text{ mW/cm}^2$.

We can divide the plot into three regions: turbulent free convection, transition from turbulent free convection to nucleate boiling, and nucleate boiling.

For the turbulent free convection region our conclusion is twofold: (a) the measured slope corresponds to the calculated slope, and (b) the measured ΔT can be as low as 25% (up to $P = 100 \text{ mW}$) as the calculated curve. But this fact is not at all astonishing for we must not assume that the thermometer resistor measures exactly the temperature of the wall. We know instead, that it is very difficult to transfer heat via a metallic contact, unless some special precautions are made. Thus we conclude that the thermometer resistors measure to a large extent the temperature of the surrounding liquid. This is confirmed by an experiment, where we covered the side of the thermometers facing the helium bath with silicon rubber. The temperature response increased by a factor 3 with respect to that of the "naked" thermometers.

The flat part of the experimental curve can be understood as follows. A small region of the heater plate surface has started nucleate boiling, by which the heat is removed more effectively. In this state bubbles form which enhance the heat conductivity. The heat input can therefore be increased without a temperature rise being observed, until the power flux density reaches that value on the nucleate boiling curve which corresponds to $\Delta T = 1.7 \text{ K}$. If the heat input is increased further, the temperature increases according to nucleate boiling, and the measured

temperature increase ΔT approaches the real wall temperature increase $\Delta T'$ more and more because the volume of homogenous temperature around the thermometer resistor increases.

For the third region of fig. 3, the nucleate boiling region, the experimental ΔT should lie on the nucleate boiling curve, which is really observed.

In another experiment we tried to find out whether the "real" $\Delta T'$ is indeed described by the theory of natural free convection. For this reason we introduced a germanium thermometer into a small hole at the outside heater plate center. For the transition point from free convection to nucleate boiling we found $Q = 24 \text{ mW/cm}^2$ and $\Delta T' = 1.7 \text{ K}$,

which is identical with the calculated transition point.

Applications

For illustrating the potentialities provided by the calibration of the resistor thermometers we present three examples. They cover typical loss mechanisms in superconducting cavities. These are overall losses, which are distributed homogeneously over large surface areas, pointlike losses ("weak spots"), which may lead to a breakdown of the energy stored in a cavity, and linelike losses due to electron impact, which may limit the Q-factor of the cavity and prevent to increase the accelerating field.

From the measurement of the heat current density Q originating from homogeneously distributed overall losses its physical nature can often be clarified. In addition, the corresponding surface resistance R_s can be determined via the relation $Q = R_s H^2/2$ provided the local magnetic field H is known. In fig. 4 the surface resistance at 7 MV/m in the high magnetic field region of a 500 MHz horizontally mounted single cell cavity is shown as a function of the azimuth ϕ rotating around the cavity symmetry axis. If R_s is due to frozen in magnetic flux, which is directed perpendicular to the symmetry axis of the cavity then it should satisfy a relation $R_s(\phi) = R_s |\cos \phi|$ which is indeed observed (cf. solid line). It is remarkable, that these losses are dominant although the ambient field was shielded to 130 mOe.

"Weak spots" often consist of small regions ($\phi < .1$ mm) of normal conducting material which above a certain field level may drive the surrounding cavity surface normal conducting and thus to a breakdown. In fig. 5 lines of equal heat current density are shown for such a weak spot in a four-cell 500 MHz cavity at 2 MV/m, not far below the quench threshold at 2.6 MV/m (4.2 K)^(*). The deviation from circular symmetry is attributed to warm helium liquid flowing upwards and rising the temperature response of the resistors above the weak spot. The full width half maximum in ΔT of this spot is 1.4 cm, the total dissipated power is found by integrating the heat current density over the surface to be 280 mW. The peak temperature increase was 1156 mK at $T_B = 2.44$ K. These figures confirm the calibration measurement for 2 mm wall thickness, where this temperature increase would correspond to a total dissipated power of $310 \pm 15\%$ mW. This is by far lower than the measured peak total heat current which could flow into the 2 mm thick heater plate in subcooled helium before film boiling started (> 12 W). By this we conclude that in subcooled helium this particular field breakdown was not induced by film boiling at the niobium-helium interface. As the breakdown field at 4.2 K was nearly the same as in the subcooled state we infer that this assertion is also true for boiling helium at 4.2 K. For a generalization of this result we make use of the relation that defects of the same surface resistance, inducing the quench at higher fields E_{max} , have a smaller radius r according to $E_{max} \sim r^{-1/2}$. On the other hand the maximum tolerable total power P_{max} is proportional to the radius², from which we conclude that the maximum total dissipated power decreases as $P_{max} \sim E_{max}^{-4}$. For this reason we generalize that at fields above 2.6 MV/m for 2 mm thick niobium sheet material (thermal conductivity at 4.2 K ~ 10 W/m/K) the quench is not induced by a nucleate boiling to film-boiling transition at the niobium helium interface.

If a region of a cavity is hit by electrons, the power released is determined by the product of the total charge/second deposited there and the impact energy, which can be computed by means of electron tracking programs simulating the movement of electrons in the electromagnetic field of a cavity.¹ As this power is measured and the impact energy is known, the total charge/second of the electrons impinging can be determined. As each small surface area along the line of electron impact corresponds to a certain phase of the r.f. field at the instant of electron emission, the emitted current can be determined as a function of the r.f. phase (fig. 6).⁵ For Fowler-Nordheim field emission the field enhancement factor and the emitting area for this particular example are 830 and 5×10^{-15} m² resp.

Conclusion

- The calibration of the temperature rise ΔT to the heat flux density Q can be represented by the relation

$$\Delta T[\text{mK}] = (33 \pm 3) Q [\text{mW/cm}^2]^{0.74 \pm 0.05}$$
 for $\Delta T < 1.25$ K and $T_B = 2.5$ K.
- There is a dependence of the temperature rise ΔT on the bath temperature T_B according to

$$\Delta T(T_B) \cdot T_B^{1.9 \pm 0.5} = \text{const.}$$
- The total heat P dissipated in a "weak spot" (full width half maximum of the temperature at the outer surface 15 mm, resp. 28 mm) gives rise to a maximum temperature response

$$\Delta T [\text{mK}] = (15 \pm 4) P [\text{mW}]^{0.74 \pm 0.05}$$
 (resp. $(5 \pm 1) P [\text{mW}]^{0.74 \pm 0.05}$).
- For 500 MHz cavities measured at CERN¹ the quench is not induced by a nucleate boiling - film boiling transition.
- The resistor thermometer response on a heat source at the cavity interior surface can be described by turbulent convection heat flow.

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(*) 2.8 MV/m at 2.2 K

Fig. 1. Vacuum vessel and niobium heater plate with 9 thermometer resistors.

Fig. 2. Bath temperature dependence of thermometer response at heater plate center for different total heat input (2 mm thickness of plate).

Fig. 3. Temperature increase ΔT at heater plate center resistor as a function of the total heat input (2 mm thickness of plate). The scale for the heat flux density follows from the data analysis and is independent of the plate thickness.

Fig. 4. Azimuthal dependence of the surface resistance in the high magnetic field region at 7 MV/m and 2.9 K. The losses are dominated by frozen in magnetic flux.

Fig. 5. Lines of equal heat flux density at the quench region of a 500 MHz 4-cell cavity. The quench occurred at 2.6 MV/m accelerating field. The maximum heat flux density is 120 mW/cm², the integral heat flux 280 mW.

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Fig. 6. The calorimetrically measured instantaneous current of an electron emitter as a function of the r.f. phase at emission (500 MHz, $E_{acc} = 4$ MV/m). The solid line gives the best Fowler-Nordheim fit. The maximum current is 130 μ A.