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SERVICE TECHNIQUE DE CRYOGÉNIE ET DE MAGNÉTISME

DAPNIA/STCM 96-01 Juin 1996

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Thermal Behaviour of Electrical Multilayer Insulation Permeable to Superfluid Helium

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Electrical multilayer insulations made of Kapton® tapes and prepreg or adhesive Kapton® tapes, used in dipole magnets, may offer a complicated arrangement of thin helium channels which cannot be easily predicted and modelled. Several insulation systems have been tested in order to characterize their helium channels pattern. Heat transfer data analysis shows clearly the contribution of superfluid channels inside the insulation. Appearance of the vortex-free regime for very small temperature differences (10^{-5} to 10^{-3} K) and of the Gorter-Mellink regime for higher temperature differences allows to establish the mean value of the channels diameter. We present in this paper the thermal behaviour of several combinations of insulating materials with different geometrical arrangements and porosities.

INTRODUCTION

The research and development program for the Large Hadron Collider dipoles developed at CERN includes stability studies which are carried out in collaboration between CERN and CEA/Saclay. For NbTi magnets cooled by superfluid helium the most severe heat barrier comes from the electrical insulation of the cables. This paper reports a work which is part of the thermal study program. It deals with the intrinsic qualification of different insulation systems. Their global thermal performance in the surroundings of the winding is studied with a different experimental model [1].

Classically, an insulation is a composite made up of a first wrap, a tape wound around the cable for electrical insulation, and a second outer wrap protecting mechanically the inner wrap, creating helium channels and gluing to the next conductor to keep the coil in shape. In the tests described, wraps are reproduced as plane layers. One (samples B22 and B23) or two (sample B25) sublayers of 11 mm wide Kapton® tapes with an overlap of 50 % are used for the first layer. For the second layer, adhesive Kapton® tapes, 12 mm wide with a spacing of 2 mm (B23 and B25) or 4 mm (B22), are employed.

THERMAL QUALIFICATION OF INSULATION

Two 50.3 cm^2 wide insulation samples are clamped between two isothermal baths of He II, each of them being able to reach different temperature. A detailed description of the experimental set-up is given in [2] and summarized in figure 1. Temperature measurement is made after attaining a stationary temperature for both baths, the outer one being regulated and held constant for the whole test over the range of power dissipation values in the inner bath. The difference in temperature between the two baths is plotted as a function of the generated power. This curve, of which an example is given in figure 2a, characterizes the overall thermal resistance between the heated bath and the cold bath. The measured resistance includes the Kapitza resistance, the resistance of the insulating material and the resistance of the helium paths through the insulation samples.

Tests have been performed at Saclay in a pressurized He II cryostat. Preliminary results reported in [2] have shown that heat transfer is influenced by He II heat transfer even for small volume of helium inside insulation. At low heat flux, heat transfer is purely governed by He II. Fits in this range of heat flux have allowed to determine an equivalent geometrical factor $A/L^{1/3}$ which characterizes a permeability of the medium related to He II heat transfer in a net of narrow channels (equivalent cross-sectional area A,

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length L) opening on either side the insulation. For higher heat flux, a model which considers insulation material and He II thermal paths in parallel agrees with measurement within 10 %.

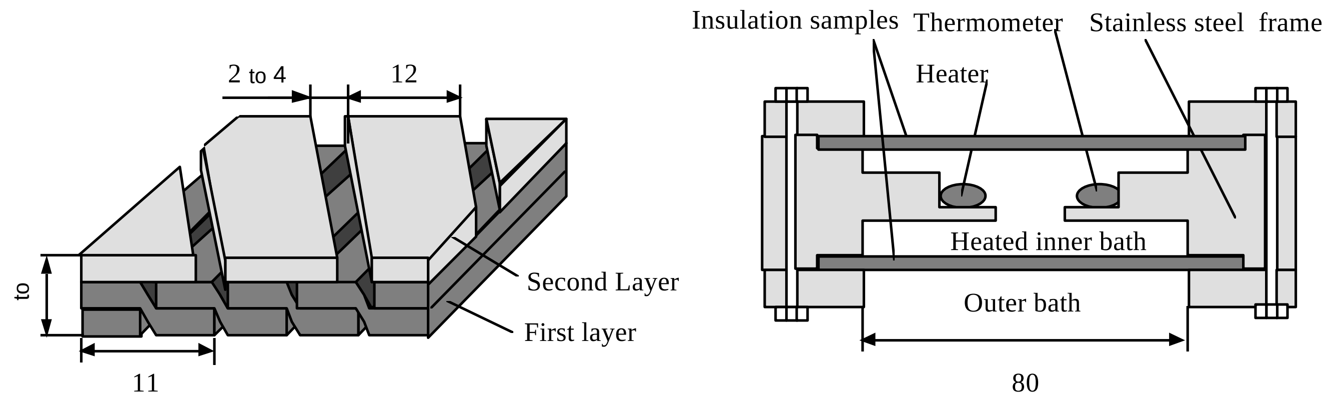

Figure 1 Schematic diagram of insulation and experimental setting. Dimensions are in mm

EXTENSION OF MEASUREMENTS TO VERY LOW TEMPERATURE DIFFERENCES

In another test facility at LIMSI, with a very precise temperature controlled saturated He II bath, using a resistance a.c. bridge equipped with a lock-in null detector, it has been possible to measure temperature difference as small as 10 µK across the same insulation samples.

Figure 2b shows an typical example of the inner bath temperature rise ΔT, for different temperatures of the outer cold bath T_b.

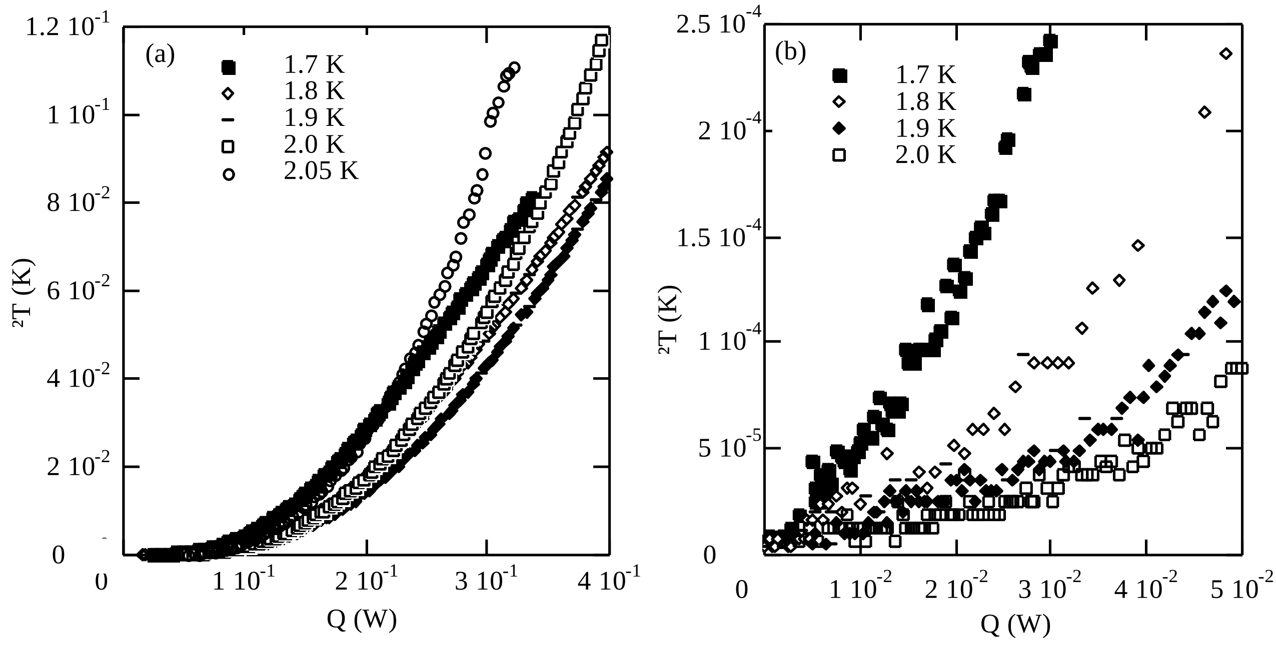

Figure 2 Temperature difference between the two He II baths as a function of the power dissipated in the inner bath for various outer bath temperatures. Sample B22. (a) : range [1 mK, $\Delta T_\lambda = T_\lambda - T_b$]. (b) : small ΔT

MEASUREMENT ANALYSIS

Heat is transported in He II according to the movement of the normal fluid from the hot source towards the cold source. The motion of this viscous fluid undergoes a resistance whose magnitude varies according to the associated Reynolds number and the possible presence of vortices in the superfluid component.

Very often the heat flux densities $q = Q/A$ are such that the double convection velocities $v = v_n - v_s$ exceed the thresholds for the formation of vortices. The mutual friction generated becomes thus dominant and leads to a transport law known as the Gorter-Mellink regime [3,4], $|q|^2\vec{q} = -f(T)\vec{\nabla}T$, where $f(T) = \left(\rho_s^3 s^4 T^3\right)/\left(A(T)\rho_n\right)$ with the notations used by the authors stated, that leads to :

$$Q^3 = \left(\frac{A}{L}\right)^3 \int_{T_b}^{T_b+\Delta T} f(T)dT \qquad (1)$$

In media of small dimensions, the critical velocities for the formation of vortices become sufficiently high such that the corresponding critical flux densities are non-negligible [5]. This gives a small range in which heat is transferred by a normal fluid without any interaction with the superfluid component. The Landau two-fluid model without interaction [6], leads to the transfer law $\vec{\nabla}p = \rho s\vec{\nabla}T$, with $\vec{\nabla}p = -\left(12\mu_n/d^2\right)\vec{v}_n$ for narrow slits of thickness d in the Poiseuille regime, that is :

$$Q = \left(\frac{A}{L}d^2\right)\frac{(\rho s)^2 T}{12\mu_n}\Delta T \qquad (2)$$

The analysis of the experimental results, of which an example is reproduced in figure 3, indicates :

- the importance of the He II contribution to heat transfer by an estimation of the purely conductive part through the solid structure, Q_{sol}, from measurements of the conductivity and of the Kapitza resistance, which were done in the same experiment cell on samples of plain Kapton® foil
- the possible existence of a laminar Landau regime
- in the affirmative case, the determination from equation (2) of the geometric factor $Ad^2/L = \sum_1^n A_i d_i^2/L_i$ equivalent to the totality of n micro-channels
- the verification of the hypothesis by the temperature independence of this geometric factor
- an estimated value of the critical heat flow Q_c and the corresponding superfluid velocity v_{sc}
- the Gorter-Mellink regime by a research of a zone (in which Q_{sol} is ever lower than 0.1 Q) having a Q^3 dependency and, within the precision of f(T), a value of the geometric factor $A/L^{1/3} = \sum_1^n A_i/L_i^{1/3}$, after equation (1), and finally, the verification of its non-dependence with temperature.

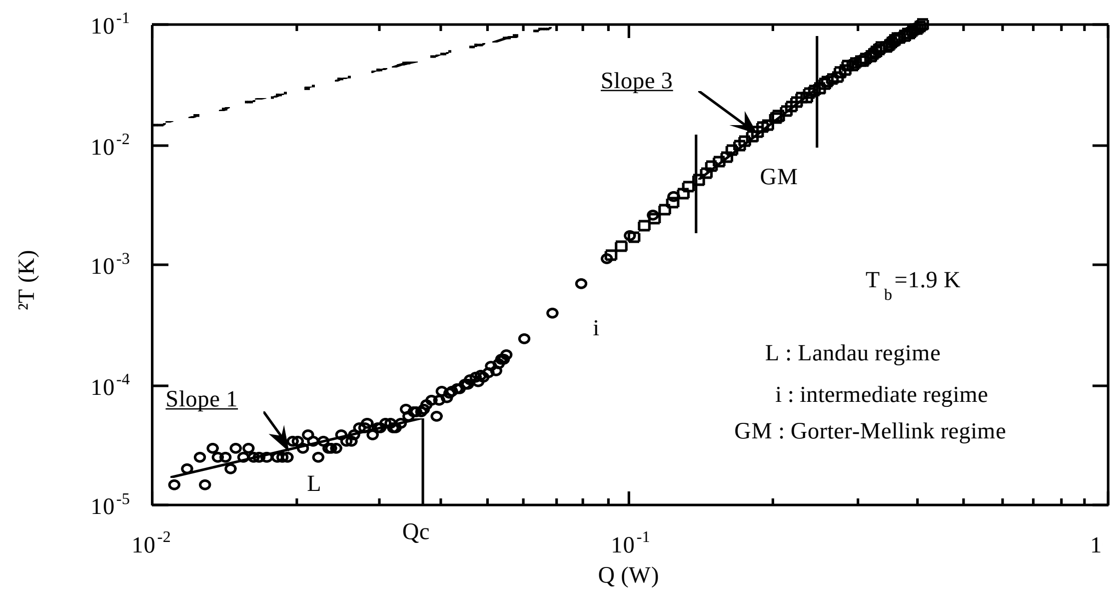

Figure 3 Different heat transfer regimes. Sample B22. The solid curves are the best fits (including measurement errors) to the data using equations (1) and (2). The dashed line is the estimated purely conductive part

Those different results, extracted from the ΔT(Q) curve of sample B22, are reported in table 1. We note that the geometrical coefficients corresponding to the two regimes stated above are almost constant in a large temperature range. It is possible to deduce values of A and d, that is A = 5.74 mm^2 and d = 22 µm, by making the hypothesis that the He II slits are of length 5.5 mm corresponding to the overlapping of the tape of first insulation layer, and by supposing identical dimensions for all the parallel slits. The critical flux densities Q_c/A vary from 0.32 W/cm^2 to 0.68 W/cm^2 when the temperature of the bath varies from 1.7 K to 2.0 K. The critical velocities (superfluid values) vary from 1.0 cm/s to 3.1 cm/s and the associated Reynolds numbers from 156 to 100. We thus verify that the normal fluid flow is laminar in the Landau regime.

Table 1 Equivalent geometric factors of the insulation sample B22

Temperature		1.7 K	1.8 K	1.9 K	2.0 K	2.05 K
Ad^2/L	10^{-14} m^3	53 ± 5[1]	53 ± 7	49 ± 6	41 ± 9	
$A/L^{1/3}$	10^{-5} m$^{5/3}$	3.29	3.29	3.25	3.17	3.25

[1] The precision includes the precision in the measurements and the precision in the fits of Landau and Gorter-Mellink zones.

The preceding results obtained for different insulations are summarized in table 2. For sample B25, the slits are very narrow ; the wall friction of the normal fluid induces a non-negligible temperature gradient which does not allow a good identification of the Gorter-Mellink regime. We observe that the results of B22 and B23, for which L is a priori identical, brings to front a factor 2.6 on A which is coherent with the ratio 2 on the spacing of the second layer tape and the fact that the thickness d of the slits also decreases when the spacing decreases. The doubling of the first layer (B25) can be understood by a strong reduction of the effective permeability, which we must attribute not only to the increase of the channel lengths but equally to a decrease of d.

Table 2 Characteristic geometric parameters of the He II slits of different insulation systems

Sample number	first layer Kapton® tape (50 % overlap)	spacing of the second layer tape[2]	Ad^2/L 10^{-14} m^3	$A/L^{1/3}$ 10^{-5} m$^{5/3}$	$(A/L^{1/3})/A_{tot}$ 10^{-3} m$^{-1/3}$
B22	150 HN (38 µm)	4 mm	49	3.25	3.23
B23	150 HN (38 µm)	2 mm	7.1	1.19	1.17
B25	2 × 100 HN (25 µm)	2 mm	0.18		

[2] Kapton® 270 LCI tape (adhesive, 68 µm)

CONCLUSION

The results and the method of analysis presented allow a detailed qualification of insulations by determining characteristic geometrical magnitudes of thermal properties and, in particular, that of parameter d, the thickness of slits which can only be attained experimentally.

ACKNOWLEDGEMENTS

The authors are grateful to Dr D. Leroy and Dr B. Szeless from CERN for helpful discussions. Special thanks to Mrs A.M. Puech and Mr Gaubert for the sample preparation and measurements.

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