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MEASUREMENTS OF MULTI-LAYER INSULATION AT HIGH BOUNDARY TEMPERATURE, USING A SIMPLE NON-CALORIMETRIC METHOD

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We establish here the thermal performance of MLI between 300 K and 77 K or 4 K, without bringing calorimetric methods into play, through the accurate measurement of a temperature profile. A cylinder in thin copper, wrapped with MLI, is cooled at one extremity while suspended under vacuum inside a sheath at room temperature. For known thermal conductivity and thickness of the tube, the heat flux can be inferred from the temperature profile. In-situ measurement of the thermal conductivity is obtained by applying a know heat flow at the warm extremity of the cylinder. Results, cross-checked with a calibrated heatmeter, compare well with what previously obtained on a large-scale measuring facility.

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Measurements of Multi-Layer Insulation at high boundary temperature, using a simple non-calorimetric method

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INTRODUCTION

Albeit thermal performance of ideally installed Multi-Layer Insulation (MLI) should not require further experimental verification, still its influence on the overall performance of a cryostat may worry the cryogenic project engineer, and a particular implementation or a new supplier are subject to control and testing. It is true that actual insulation may double or triple with local packing density, thermal short circuits, discontinuities. Furthermore, qualification of MLI at warm boundary is difficult in that any mounting imprecision or fringe effect inherent to the test-bench topology brings to a sizeable reduction of apparent insulation.

We report here about an original method to measure MLI at warm boundary, based on a principle first presented in [1]. It relies on the measurement of a temperature profile along a MLI supporting cold cylinder, surrounded by a warm sheath. The measurement yields the heat flux (i.e. W/m^2), instead of a total heat flow (W). Results are verified with a calibrated heatmeter [2]. We first describe the set-up and its performance, then we present some results on layers' number, packing density, and thickness of the aluminium coating.

MEASURING PRINCIPLE

A hollow, closed cylinder in copper sheet, of radius r = 133 mm, wall thickness e = 0.5 mm and length L = 1520 mm is cooled from its upper extremity by cold gas or liquid, circulating in a tube brazed onto its flat surface. A heater is mounted on its lower extremity. The cylinder is suspended in an evacuated cylindrical vacuum vessel, whose internal surface is protected by a copper plate equipped with thermometers and heater. This copper plate provides a warm horizon at a controlled 300 K to the MLI, installed onto the cooled cylinder.

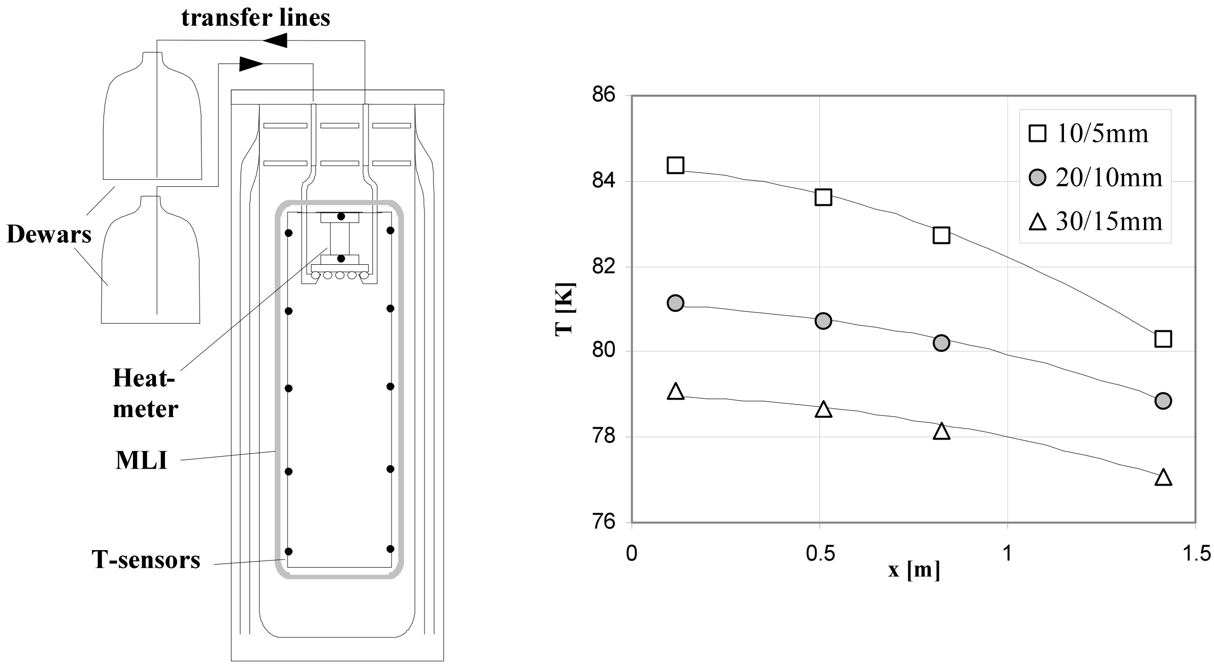

Figure 1 Left: Scheme of the test-bench. Right: Temperature profile obtained with type A MLI, for $20 cm^{-1}$ packing density, and variable total number of layers (10, 20 and 30). Lines are parabolic fits with *q/k* as a free parameter.

The temperature profile along the cold cylinder is obtained from the one-dimensional heat equation:

$$\frac{d^2T}{dx^2} = -\frac{q}{ke} \tag{1}$$

over an infinitesimal volume of cylinder, of constant thermal conductivity *k* and thickness *e*, irradiated by a heat flux *q*. In an evacuated space, *q* is generated by radiation only: for a sufficiently low total ΔT along the cylinder, it can be considered as constant with *T*. With boundary conditions:

$$T(x = l) = T_o \tag{2a}$$

$$ke\frac{dT}{dx}\bigg]_{x=0} = -\frac{Q_1}{2\pi r} \tag{2b}$$

where T_o is the cold extremity temperature and Q_1 the heat flow onto the bottom plate of the cylinder, we obtain the temperature profile:

$$T(x) - T_0 = \frac{q}{k}\cdot\frac{1}{2e}(l^2 - x^2) + \frac{Q_1}{k\cdot S}(l - x) \tag{3}$$

with $S=2\pi re$ conducting cross section. If Q_1 is produced only by radiation on the bottom plate $A=\pi r^2$, we have $Q_1=qA$, and the temperature profile becomes

$$T(x) - T_0 = (\frac{q}{k})\cdot\frac{1}{2e}(l^2 - x^2) + (\frac{q}{k})\cdot\frac{A}{S}(l - x) \tag{4}$$

featuring the unknown parameter *q/k*. With an additional heating Q_h from the electrical heater, we obtain:

$$T(x) - T_0 = (\frac{q}{k})\cdot\frac{1}{2e}(l^2 - x^2) + (\frac{q}{k})\cdot\frac{A}{S}(l - x) + Q_h\frac{1}{kS}(l - x) \tag{5}$$

We can therefore infer q/k from a first measurement of the temperature differences $T(x_2)-T(x_1)$, then k alone by applying an additional heating power Q_h to the coldest extremity.

The value of $k(T)$ inferred from the temperature profile was compared with what obtained from residual resistivity ratio *RRR* measurements, according to the NIST parametrization for $k(T)$ of copper with *RRR* [3]. A good agreement is obtained: for example, $RRR=230$ is measured electrically, where $RRR=267$ is obtained from the measured k value. For data evaluation, the NIST parametrization is subsequently applied. Two sheets of different *RRR* value, $RRR=89$ and *230*, were tested successfully.

In order to validate the method, we installed a calibrated thermal impedance, or heatmeter [2], between the cold upper plate and the cooling circuit. The heatmeter measures the total heat flow [W], whereas from the temperature profile we obtain a net heat flux [W/m^2]. Results obtained with the heatmeter or by linear interpolation of the T-profile essentially coincide. Error for the T-profile measurements is estimated at about 10%, determined by the uncertainty on the thermal conductivity value of copper, and at about the same value for the heatmeter, determined by residual heat loads. MLI installation is also critical for the reproducibility of the measured heat flux.

Temperature is measured respectively with platinum and carbon resistor sensors at liquid nitrogen and liquid helium temperature. The cryogen is transferred from one Dewar to a second via the test-bench; consumption is then essentially determined by the two transfer lines, attaining ~10 W. Long stabilization times are respected, since at least 36 h are necessary for the system to reach equilibrium at 77 K.

MLI PERFORMANCE WITH LAYER THICKNESS, PACKING DENSITY, LAYER NUMBER

Two types of MLI blankets, differing in the thickness of the Al layer (type A featuring a 400 Å and type B a 150 Å coating) were tested. The thickness had been determined independently by room temperature electric measurement. Further, we measured one of the blankets (type A) with variable layer number (10, 20 and 30), keeping the packing density constant at 20 cm^{-1}. The other blanket (type B) was tested with 3 different packing densities (30/6 mm^{-1}, 30/8.5 mm^{-1} and 30/15 mm^{-1}), according to two possible installation scenarios for the insulation of the thermal screen of the ATLAS barrel toroid [4], as well as in the nominal packing density for the LHC cryomagnet's cryostat, 20 cm^{-1}. For most tests, the blankets were installed layer-by-layer and closed with aluminized adhesive tape. For the three ATLAS-type installations, we mounted two blankets of 15 layers each, closed with aluminized adhesive tape with an overlap of 100 mm, the two overlapping sections displaced azimuthally by 200 mm, in agreement with the specification. Also, in these tests the external layer of the blanket is covered with a glass-fiber net.

Table 1 gives the heat flux for variable number of layers at a constant packing density of 20 cm^{-1}, at two different cold boundary temperatures. For comparison with literature, we refer to the review of MLI by N.T.Nast [5], quoting values for ideally installed MLI at 15 cm^{-1}, virtually independent on cold boundary temperature. The very small apparent dependence of our data on cold temperature is below experimental precision.

Table 1 Heat flux versus layer's number for type A MLI at two low boundary temperatures T_c.

Layer's number	T_c=80 K [W/m^2]	T_c= 5 K [W/m^2]	From [5], 15 cm^{-1} [W/m^2]
10	0.95	0.97	0.9
20	0.49	0.51	0.47
30	0.43	0.44	0.31

In Table 2, we present the heat flux measured for type B MLI at variable packing density, for two cold boundary temperatures. Again, we can compare these values with [5], where figures are given for 37 layers at variable packing density. The agreement is excellent, in spite of voluntary installation imperfections (overlap of blankets), which were introduced to respect the ATLAS specification, and in spite of a glass-fiber net which covers the external layer of type B blanket.

Finally, we have seen that the thickness of the Al-coating does not influence the thermal performance of the blanket (table 3). To ensure identical conditions, the glass-fiber net protecting the external layer of the blanket was removed. Literature on the subject is spare, however, emittance is foreseen to increase by 30% from 400 Å to 150 Å coating thickness [6], and this change should reflect in a sizeable (20%) change in heat flux [5]. Further effort to increase the precision and the reproducibility of the measurement is under way.

Table 2 Heat flux versus packing density for type B MLI at two low boundary temperatures T_c.

Packing density	T_c= 80 K [W/m^2]	T_c= 5 K [W/m^2]	From [5], 37 layers [W/m^2]
30/6 mm^{-1}	2.52	-	2.5
30/8.5 mm^{-1}	1.48	1.44	1.3
30/15 mm^{-1}	0.40	0.51	0.41

Table 3 Heat flux versus Al-coating thickness for 30/15mm at two low boundary temperatures T_c.

	T_c= 80 K [W/m^2]	T_c= 5 K [W/m^2]
400 Å (type A)	0.43	0.44
150 Å (type B)	0.32	0.43

In Table 4, we compare data from this paper with the results obtained on a facility built to verify the performance of thermal insulation for the LHC dipole cryostats [7] . We observe that the laboratory installation yields values closer to the "ideal" performance predicted by [5] than the real-scale field installation in a 15m long cryostat. However, the deviation from ideal behaviour is small, confirming that installation procedure and technique of MLI for the LHC magnet's cryostats is well optimized.

Table 4 Comparison between this paper, 30 layers type A MLI, and [7] in real-scale installation.

This paper [W/m^2]	Real-scale installation [7] [W/m^2]
0.43	0.47

CONCLUSIONS

A new, rapid method for precise measurement of thermal insulation at warm boundary temperature is operative and has been applied to evaluate implementation of the MLI for the thermal shield of the ATLAS barrel toroid. As a result of high packing density, large heat flux is obtained with respect to ideal, ~15 cm^{-1} density installation. In spite of only 150 Å thickness of the Al coating, the thermal performance for ideal packing density is identical to blankets of 400 Å coating thickness.

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