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Industrial-Type Cryogenic Thermometer with Built-In Heat Interception

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INDUSTRIAL-TYPE CRYOGENIC THERMOMETER WITH BUILT-IN HEAT INTERCEPTION

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ABSTRACT

CERN is a major user of cryogenic machinery and its ancillary instrumentation. Many of these apparatus are assembled by subcontracting firms that do not have necessarily a very good knowledge of cryogenic techniques. This can result in cryogenic sensors malfunctioning with a loss of information that can be crucial during the commissioning or operation of cryogenic equipment. In particular cryogenic temperatures measured under vacuum conditions are often unreliable because of a poor thermal anchoring. In order to improve the performance of such temperature measurements a new thermometric block has been developed. It is fabricated by Prototype Circuit Boards (PCB) techniques and is thus well adapted to large-series production, it includes the thermalization of the leads and a cavity to insert a commercial temperature sensor. The main design goal was to manufacture a thermometer that can be installed by non-qualified personnel. For validating the design, prototype thermometers were mounted on an isothermal substrate as the temperature of the current and sensing leads was increased and they were exposed to thermal radiation. A temperature of 1.8 K was measured to within 50 mK when using copper leads of 2 mm diameter and about 100 mm long heated to 170 K on one end. This demonstrates the good performance of our thermometer blocks under extreme environmental conditions.

INTRODUCTION

Large-scale cryogenic machines require a huge number of cryogenic probes (temperature, level, pressure, etc.), a trouble-free operation requires these sensors to be reliable, maintain the specifications over the lifetime of the equipment and under its environmental conditions. One such machine is CERN's Large Hadron Collider (LHC) project[1] that will include a large number of superconducting magnets immersed in pressurised superfluid helium at 1.8 K. Temperature is an extremely important parameter for the LHC and furthermore its measurement is reputed for being difficult for a number of reasons like electrical leads thermalization, sensor long-term stability, signal recovery and in the case of a particle accelerator, ionising radiation hardness. The superconducting magnets for the LHC will be operated at a temperature between 1.8 K to 1.9 K, their absolute temperature should be known to within better than 0.02 K and with a 0.001 K resolution.

From a cryogenic point of view all thermal sensors should be placed inside the cryogen of which the temperature is being measured. On the other hand this complicates the cryostat design because vacuum-tight electrical connections are necessary when a cryogen-vacuum passage has to be realised. In the scope of the LHC project which will

Table 1. Parameters used for estimating the measured temperature

ρ_{Cu}, [W m^{-1} K^{-1}]	ρ_{isol} [W m^{-1} K^{-1}]	$\sigma_{stycast}$ [W m^{-1} K^{-1}]	e [µm]	λ [µm]	δ [µm]
7000	0.004	0.01	140	100	6

employ about ten thousand cryogenic thermometers, it will then be very interesting to make, as much as possible, the temperature measurements on the vacuum side of the coldmass. The main advantages are simpler cryostats and immunity from pressure waves produced when a superconducting magnet quenches. On the other hand thermal contact, thermal impedance across cryostat walls (usually stainless, a poor thermal conductor) through which heat losses are absorbed by the cooling cryogen and temperature sensor self-heating are of concern. For instance the 10 meter LHC prototype dipoles employ 50 mm thick stainless steel end plates, with the type of superinsulation employed[2] a degraded vacuum of 10^{-4} mbar yields a thermal flux of the order of 200 mW m^{-2} resulting in a 0.125 K temperature increase on the surface, very far from the accuracy requirements stated in the precedent paragraph. This means that temperature measurements on the vacuum side have to be performed on interconnecting tubes that have typically 2 mm thick walls. Before deciding to place the temperature probes on the vacuum side of the cold-mass, a cryogenic thermometer has to be designed, tested under realistic LHC operating conditions, it has to provide a good thermalization of the temperature sensor and be easy to mount by non-qualified personnel.

A cryogenic thermometer has then been developed[3], the main design parameters of which are: (a) industrial robustness, (b) the thermal coupling of the sensor is done through its own wires, (c) the temperature measurement does not depend critically on the installation work and (d) it is compatible with large series fabrication techniques.

Frequently much care is given to produce a very good thermal contact between the sensor and the body under investigation. This contact is very difficult to obtain in view of

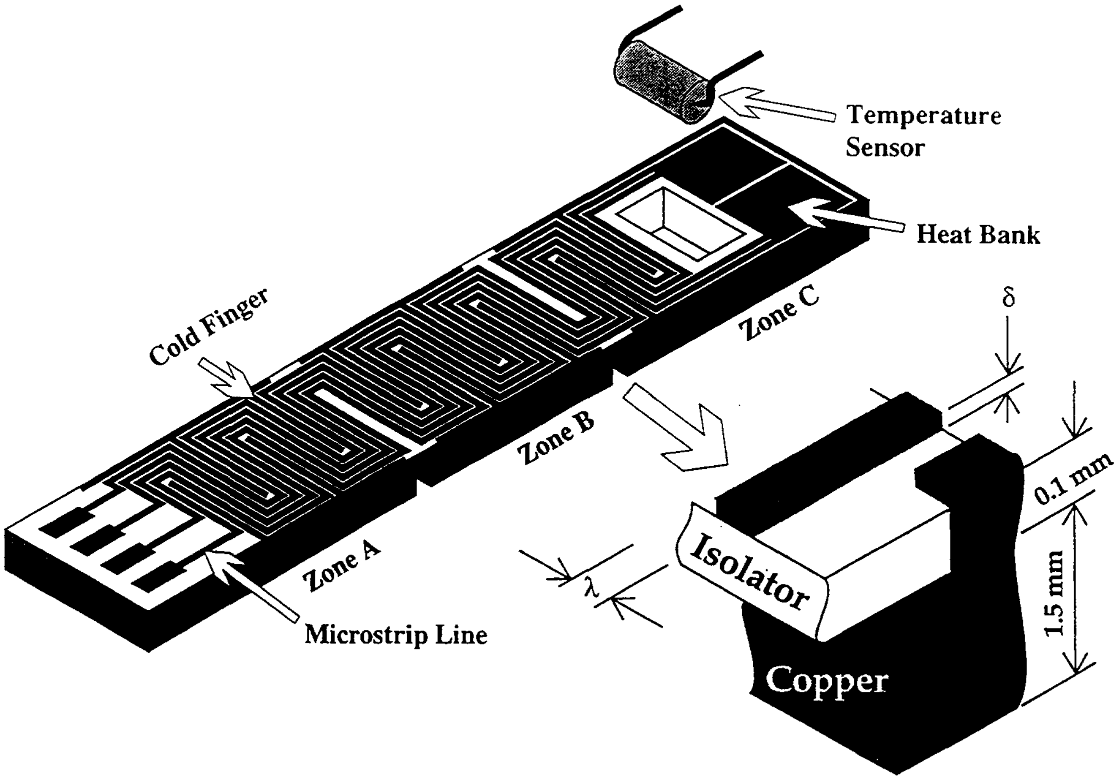

Figure 1. Thermometer layout showing the meandering microstrip lines of width λ and thickness δ, the solid copper plate thickness corresponds to that of a standard Allen Bradley carbon sensor. The thermometer size is 100 mm x 10 mm x about 2 mm.

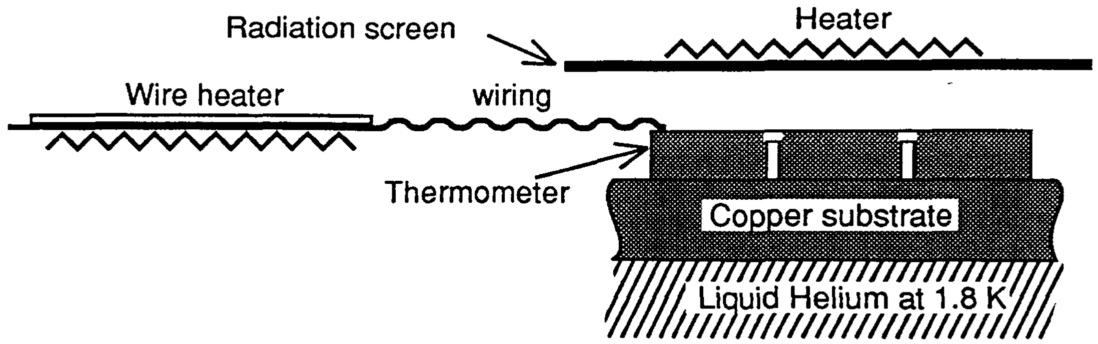

Figure 2. Schematical principle of the thermometer validation system. The thermometers are bolted to an isothermal substrate. The vacuum, the temperature of the electrical leads and the radiation screen can be regulated.

the size of many modern thin-film temperature sensors, their fragility and also because some sensors are inside a housing under vacuum conditions. In an industrial environment such a delicate and careful assembly of these sensors would be impossible to obtain at a reasonable cost.

THERMOMETER DESIGN

Cryogenic techniques require sensing leads thermalization for making proper temperature measurements. This dictates the use of long and thin wires of poor thermal conductance, with the last run in close thermal contact with the body under investigation. PCB techniques were chosen for fabricating the thermometer because it is very easy to obtain leads with small cross sections, typically the equivalent of a copper wire of a diameter of 44 μm or less, in the actual design it is the equivalent of a 670 mm long x 32 μm diameter copper wire. Furthermore PCB techniques permit large series production. Figure 1 shows schematically the thermometer design: the electrical microstrip lines follow a meandering pattern to maximise its length, this meander intercalates "cold fingers" anchored to the bottom plate, the temperature sensor is housed in a cavity and it is soldered to a "heat bank" that sinks sensor self heating thermal flow and photon radiation hitting the soldering pads. The lower part is made of solid copper of at least the same thickness as that of the sensor and it is divided in three parts in order to break longitudinal thermal conduction. In Figure 1 are not shown the screen that protects the sensor and microstrip wires from thermal radiation and the holes used for attaching the thermometers by using M4 size screws.

By neglecting transverse temperature gradients the following two-dimensional equation permits to calculate the measured temperature assuming that it depends only on the microstrip wires temperature:

$$\frac{\partial}{\partial x}\left[\rho_{cu}\frac{\partial T(x)}{\partial x}\right] = \rho_{isol}\frac{1}{e\,\delta}(T(x)\ -\ T') - \rho_{el}\left(\frac{i}{\lambda\,\delta}\right)^2 \qquad (1)$$

Table 2. Bottom copper plate temperature versus connecting wire terminal temperature. The measured temperature error in the absence of self-heating effects is also shown depending on the bottom plate design. The actual temperature that should be measured is 1.8 K.

T_{wire} [K]	$T_{zone\ A}$ [K]	$T_{zone\ B}$ [K]	$T_{zone\ C}$ [K]	Error [K]	$T_{monoblock}$ [K]	Error [K]
77	3.170	1.874	1.804	0.018	2.523	0.856
300	7.231	2.093	1.816	0.071	4.668	3.396

where ρ_{cu}, and ρ_{isol} are the thermal conductance of copper and the insulating substrate respectively, ρ_{el} the electrical resistivity, λ and δ are respectively the width and thickness of the copper microstrip wire, e is the insulating substrate thickness, T(x) is the microstrip temperature along the longitudinal position x, T' is the bottom copper plate temperature supposed constant and i is the electrical current flowing through the microstrip. In the actual design the Joule effect along the electrical microstrip lines can be neglected.

The exact solution of Eq. (1) has to be obtained numerically because the thermal and electrical conductances depend on the temperature, a worst case analytical solution was calculated by assuming the above variables constant, the values used for the calculation are listed in Table 1. Eq. (1) predicts that the microstrip temperature decreases exponentially along the longitudinal position towards T, the exponential factor being:

$$m = \sqrt{\frac{1}{e\,\delta}\frac{\rho_{isol}}{\rho_{cu}}} \tag{2}$$

Optimum temperature measurements require to maximise m. Its value depends strongly on the best resolution that can be obtained with PCB techniques for the microstrip and insulation thickness and also on the choice of materials through their thermal conduction.

It is very important to avoid longitudinal conduction along the bottom solid copper plate when a poor thermal contact between the thermometer and the body under investigation is present. In this case all the intercepted heat flows through a thermal resistance effectively increasing the value of T'. If the bottom plate is separated in three parts, the part that houses the sensor (zone C in Figure 1) is much cooler than the one were the connecting wires are soldered. For simulating this situation the poor thermal resistance is assumed to be that of a solid plate of 0.1 mm thick stycast whose thermal conductance is given in Table 1. Table 2 shows clearly that under poor thermal contact conditions a monoblock design for the copper plate gives very poor temperature measurements.

The effect of photon radiation can be estimated by using the Stefan-Boltzmann law[4]

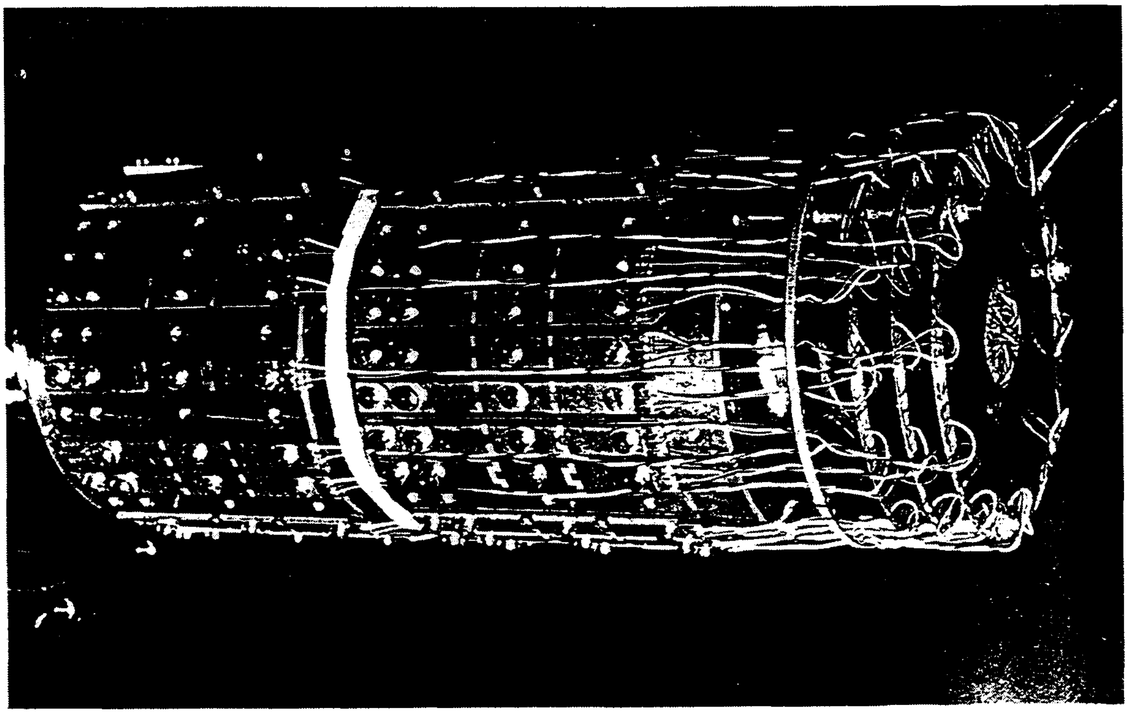

Figure 3. Photograph of the validation insert. The size of the thermometers is 100 mm x 10 mm x 2 mm and about a dozen thermometers can be seen bolted to the isothermal copper substrate. The wire terminal heaters are on the right-side. The heat radiation shield is removed. Liquid helium is present inside a cavity enclosed by the copper substrate

and assuming that the sensor is sensitive mainly to radiation hitting the window defined by the solder pads and the area without copper film shield. The measured temperature error is then given by the following formula:

$$\Delta T = \frac{e}{\rho_{isol}} \frac{\Sigma}{S} \sigma \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1 \varepsilon_2} \left(T_{shield}^4 - T_{bank}^4 \right) \approx 2 \; 10^{-11} \left(T_{shield}^4 - T_{bank}^4 \right) \qquad (3)$$

where $\Sigma \approx 7$ mm^2 is the exposed window area, $S \approx 90$ mm^2 is the heat banks area, σ is the Stefan-Boltzmann constant (5.67 10^{-8} W m^{-2} K^{-4}), ε_1 and ε_2 are the emissivity factors of the exposed area and a radiation screen made of copper (assumed to be 1 and 0.2 respectively); and T_{bank} and T_{shield} are respectively the heat bank and shield surface temperatures (see Figure 1 and 2). The emissivity depends strongly on surface condition and may vary from sample to sample.

VALIDATION SYSTEM

An experimental set-up has been designed for measuring the performance of the fabricated thermometers, the measurement principle is schematically shown in Figure 2. A photograph of the actual cyogenic insert is shown in Figure 3. The thermometers are fixed by four M4 size screws to an isothermal substrate of known temperature, the temperature of the electrical leads and the radiation screen as well as the pressure of the residual vacuum can be regulated and measured. Up to 60 thermometers can be mounted in this apparatus that is used to simulate diverse environmental conditions. The isothermal substrate is a hollow cylinder machined in OFHC copper with the thermometers on the outer side and liquid helium on the inner side (Figure 3); its temperature is the same as that of the substrate. The wire heater is made of a planar heater bonded to a PCB with the sensing wires engraved on it, each copper microstrip wire is about 500 mm long, 200 µm wide and 23 µm thick and the sensing wires temperature is estimated by a platinum thermometer glued on the wires heater board. The radiation screen is made of 0.5 mm thick copper, the distance between this screen and the thermometer is of the order of 5 mm, its temperature is increased by using a planar heater and is monitored by two platinum

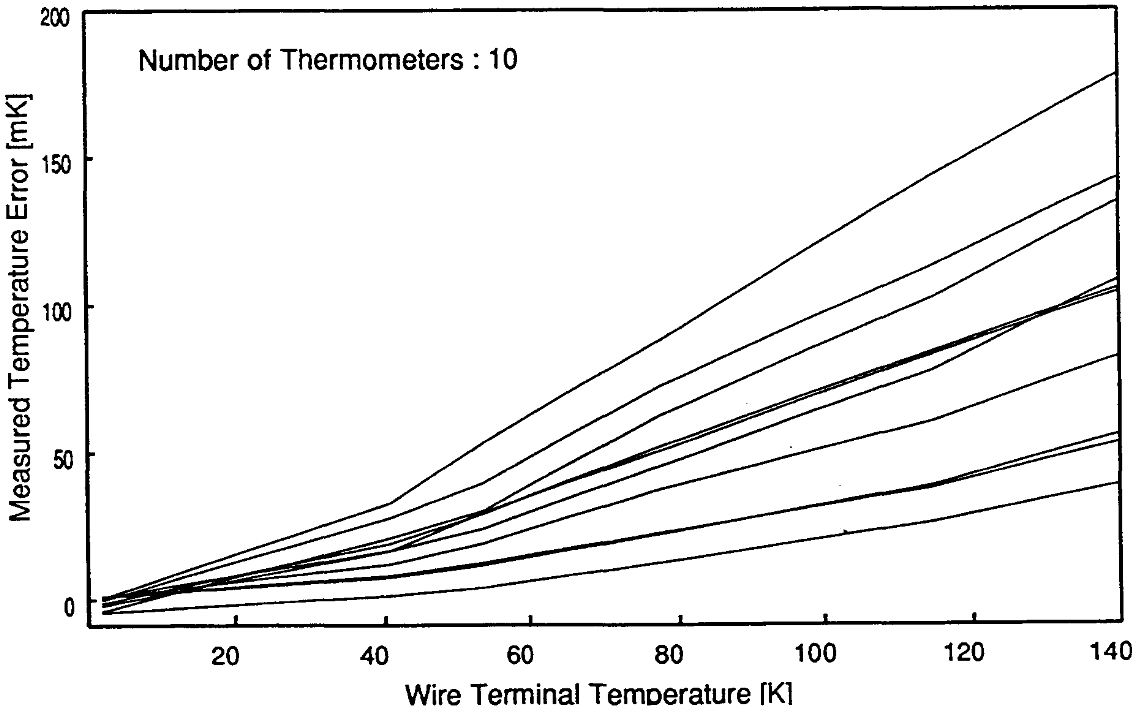

Figure 4. Measured temperature error versus wire terminal temperature. Residual vacuum is better than 3.5 10^{-5} mbar. The sensing leads are copper wires 120 mm long x 0.25 mm diameter.

thermometers. The thermometer chamber can be operated with or without liquid helium and when working in vacuum conditions the chamber is pumped by using a turbomolecular pump. The best residual vacuum obtained is of the order of 2 10^{-5} mbar, this relatively high value is the consequence of a long pumping line (1.5 meter x 25 mm diameter) crowded by wires and of outgassing from the many threaded holes and large area bonded heaters.

The thermometers are cabled in a true four wire configuration and the temperature sensors resistance can be measured at various excitation currents to within better than 0.05%. The thermometers resistance is measured sequentially by using a 40 x 4-wire channel scanner, a programmable d.c. current source and a digital voltmeter. During the measuring cycle the liquid helium bath temperature can be maintained to within better than 1 mK when operating in superfluid helium at about 1.8 K.

The temperature reference[5] is given by the pressure against the liquid helium bath and can be cross checked by commercially calibrated sensors as well as by using some sensors calibrated in house. When working in superfluid helium a maximum dispersion of 5 mK between the pressure and the resistive thermometric references is observed. For temperatures above the lambda point the helium gas pressure reference is awkward to use because of the relatively long stabilisation time for the liquid helium bath temperature that is in the order of half an hour, this might be due to the relatively large liquid reservoir capacity that ranges from 40 to 100 litres of liquid helium.

RESULTS

The thermometer block has been operated under various environmental conditions, and no contact grease is used to improve the thermal contact of the thermometers with the isothermal substrate. The residual vacuum is better than 3.5 10^{-5} mbar and the electrical connections between the wire heater and the thermometer (see Figure 2 and 3) is done with copper wire of 0.25 mm diameter x 120 mm length. Ten thermometers have been investigated and their measurement errors are shown in Figure 4, the error data show some dispersion that is probably due to a spread in the fabrication parameters. The microstrip wire thickness and width are near to the lowest values that can be obtained at a reasonable

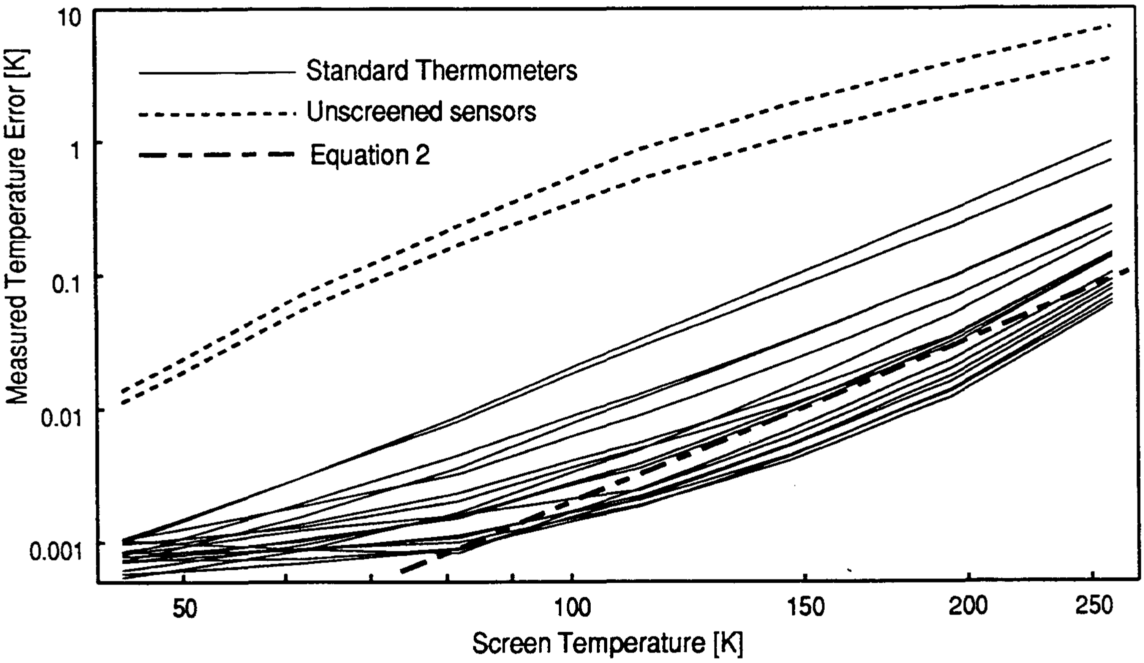

Figure 5. Measured temperature deviation when exposing the thermometers to photon radiation. The total number of thermometers investigated is 22. Two unprotected sensors are also shown and as expected they are much more sensitive to thermal radiation.

Table 3. Expected measurement error when varying the insulating substrate and microstrip wire thickness. The wire terminal temperature is 140K.

T_{wire} [K]	e [μm]	δ [μm]	Error [K]
140	140	6	0.012
140	140	8	0.041
140	140	10	0.096
140	140	12	0.181
140	110	6	0.003
140	170	6	0.028

cost when using PCB techniques and they are thus the most likely parameters that will have a large spread in their actual values. These dimensions are impossible to measure directly because of the radiation shield that is bonded by using multi-layer PCB techniques, according to resistance data the microstrip wire thickness varies between 6 μm and 10 μm. Also the insulating substrate thickness can be expected to vary by a factor of ±20 %. Table 3 shows the calculated measurement error depending on the most critical fabrication parameters with a wire terminal temperature of 140 K. Table 3 explains partially the dispersion of the data observed in Figure 4.

The effect of radiation heat transfer to the thermometric blocks is shown in Figure 5, the measurement error saturates below about 1 mK because of sensor stability problems and measurement accuracy. Two thermometers with unscreened temperature sensors are also shown for reference, as expected they result in much more important errors when comparing with our standard thermometers. Many of the measured errors are greater than what is expected from Eq. (2), this can be due to an increase of the PCB upper shield temperature that is relatively thin (about 30 μm) to evacuate efficiently the radiative heat to the bottom plate or to a bad choice of emissivity factors. Nevertheless temperature measurements to within 10 mK can be performed in presence of radiation shields at liquid nitrogen temperature level.

CONCLUSION

A cryogenic thermometer has been designed with the main goal being to perform reliable temperature measurements on the vacuum side of a cryostat. The thermometer has been tested and under adverse environmental conditions adequate temperature measurements can be performed.

More experimental data is necessary for assessing the effect of insulating vacuum, of mounting procedures and thermal impedance through walls separating the vacuum and the cryogen of which the temperature is being measured. Also the use of a different material for fabricating the microstrip wires of the thermometric block should be investigated, the goal being to choose a material with a lower thermal conduction than copper. Copper was chosen because it is the most common material used by PCB manufacturers and then they are very familiar with the techniques necessary to obtain very small dimensions with an acceptable yield.

The type of thermometer described in this paper is being installed in different equipment at CERN and in many cases comparison thermometers are located inside the cryogen. The results obtained on the field will permit us to asses under which conditions we can use the thermometers for future installation on the LHC ring.

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