EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 171

Precise Wide Range Heatmeters for 1.5 K up to 80 K

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Abstract

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Presented at CEC-ICMC'97, Portland, July 29 - August 1st, 1997

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Geneva, 4 January 1998

PRECISE WIDE RANGE HEATMETERS FOR 1.5 K UP TO 80 K

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ABSTRACT

Two heatmeters were designed at CERN for applications below 20 K with the option to work also at temperatures up to 80 K. The new calibration principle and design permits the construction of wide range heatmeters with precision in the range of milliwatts. The calibration function takes into account the temperature dependence of the thermal conductivity of the heatmeter material. The heat flow measurement is, therefore, independent of the base temperature, i.e. it is also independent on the temperature drop across thermal contact between heatmeter and the cold source. The simple calibration function makes the heatmeter a user-friendly portable diagnostic device. It is possible to quantify parasitic heat flow without a previous calibration, or to calibrate the heatmeter during a measurement with a specimen.

INTRODUCTION

A heatmeter is a calibrated thermal resistance where the heat flow is measured as a function of its boundary temperatures. One of the main ideas is to use the heatmeter as a portable and interchangeable device. This implies that temperature sensors and heater for calibration are included in this device. This heatmeter principle was first developed and described by Kuchnir et al. at Fermilab 1985[1]. The heatmeters were designed for constant base temperatures (4.2 K and 77 K). Their calibration functions were, therefore, only valid for these base temperatures. A deviation from the base temperature would have required the application of correction factors.

Figure 1 shows two possible designs and the main features of heatmeters. In the original design at Fermilab, the thermal resistance of the heatmeters were determined by a stainless steel layer silver soldered between two copper blocks. This principle was adopted at CERN for a test bench to measure the heat load at different temperature levels of LHC prototype support posts [2]. The stainless steel was replaced by brass. Meanwhile, improvements have been made in both design and calibration principle, in order to adapt the idea of heatmeters in a better way to more general requirements, i. e. wide range applications for heat flow and temperatures[3,4]. The heatmeter of type 2 in Figure 1 shows the schematic design of the device that was developed at CERN. This time, the heatmeter is manufactured from a single piece of an aluminium alloy, i.e. a medium thermal conductor. The thermal resistance is determined by the ratio of section over length of the central part of the heatmeter. The tube-like design is to increase the aerial momentum of inertia for a given ratio. The bottom heater is an option for the control of the specimen temperature.

CALIBRATION

Theoretical calibration function

For wide range heatmeters the temperature dependence of the thermal conductivity needs to be taken into account. Equation 1 is a function that describes approximately the thermal conductivity of metal alloys in an appropriate small temerature interval:

$$k = \alpha \cdot T^n \tag{1}$$

α and n are considered constant within the temperature interval. This approximation function is practicable for regions where n (i.e. the slope of the graph k over T in a double logarithmic scale) varies only little with the temperature. In regions where n varies very fast, like for pure metals in the vicinity of 10 K where k has a maximum, such an approximation function is not practicable. Pure metals are therefore no good choice for wide range heatmeters with working temperatures around this maximum in k.

For normal electrical conductors at about liquid helium temperatures the heat is practically only carried by electrons. In this region the thermal conductivity is proportional to the temperature (n = 1), unless the material becomes superconductive [5].

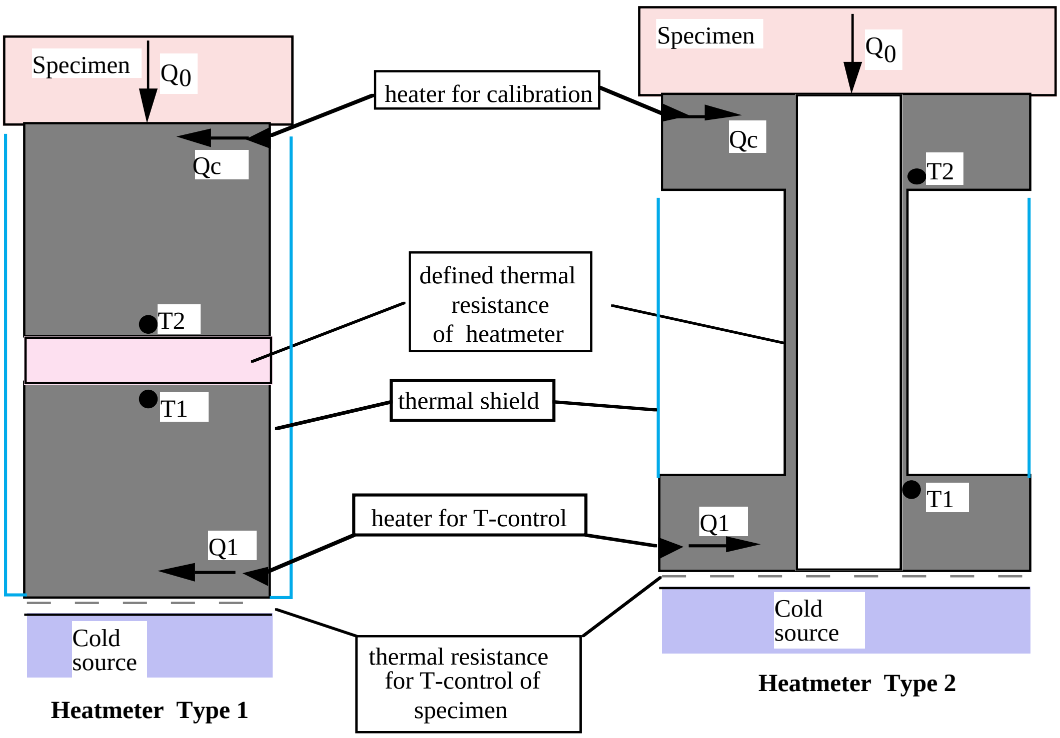

Figure 1. Two possible heatmeter designs

The heat flow through the heatmeter is then:

$$\dot{Q} = \frac{S}{L} \cdot \int_{T_1}^{T_2} k \cdot dT \tag{2}$$

$$\dot{Q} = \frac{S}{L} \cdot \frac{\alpha}{n+1} \cdot \left(T_2^{n+1} - T_1^{n+1}\right) \tag{3}$$

S and L are the section and length of the thermal resistance between the boundary temperatures T_1 and T_2. Such a calibration function is only valid in the temperature interval where it is defined. The width of this temperature interval depends on the material chosen and the maximal systematical error accepted. For wide range heatmeters a material has to be chosen that varies only little in n, in order to reduce the number of intervals. For a well known material, n can be estimated from the graph k as a function of T.

$$n = \frac{T}{k} \cdot \frac{\Delta k}{\Delta T} \tag{4}$$

When n is determined, α can be calculated from equation 1. In the real calibration function of a heatmeter the geometry and material parameters are unified in a single proportionality factor C.

$$C = \frac{S}{L} \cdot \frac{\alpha}{n+1} \tag{5}$$

Here, different calibration possibilities are proposed which may be applied to the same calibration data for cross-checking purposes.

- Calibration for n with unknown C.
- Calibration for C with known n (parasitic heat load physically eliminated)
- In situ calibration for C during a measurement with a specimen.

Calibration for exponent *n*

In principle, n can be chosen freely and an α be calculated from the calibration heating power $\dot{Q}_c$ and the corresponding boundary temperatures. The optimal fit, however, is the one that corresponds to the physical temperature dependence of the heatmeter material. From two calibration sets ($\dot{Q}_{c.1}$, $T_{2.1}$, $T_{1.1}$) and ($\dot{Q}_{c.2}$, $T_{2.2}$, $T_{1.2}$), the proportionality factor C of the calibration function can be eliminated and n can be calculated from the derivation of the calibration function, or, in other words, from the definition of the thermal conduction of a heatmeter.

$$\frac{\partial \dot{Q}}{\partial T} = \frac{S}{L} \cdot \alpha \cdot T^n \tag{6}$$

Interpreting $\partial \dot{Q}$ as the heat flow due to a temperature drop ∂T along the heatmeter at the temperature mean T, a mean n can be calculated from the two sets of calibration parameters:

$$n = \frac{\ln\left(\frac{\dot{Q}_{c.2}}{\dot{Q}_{c.1}} \cdot \frac{(T_{2.1} - T_{1.1})}{(T_{2.2} - T_{1.2})}\right)}{\ln\left(\frac{(T_{2.2} + T_{1.2})}{(T_{2.1} + T_{1.1})}\right)} \qquad (7)$$

This formula gives a good estimation for n in the temperature interval

$$T \in \left\{ \tfrac{1}{2}(T_{2.1} + T_{1.1}) \ldots \tfrac{1}{2}(T_{2.2} + T_{1.2}) \right\}$$

Calibration for the proportionality factor *C*

If the exponent n is known for a given temperature interval, either from literature or from a calibration like described above, it is quite easy to get the proportionality factor C from one calibration set ($\dot{Q}_{c.i}, T_{2.i}, T_{1.i}$):

$$C_i = \frac{\dot{Q}_{c.i}}{T_{2.i}^{n+1} - T_{1.i}^{n+1}} \qquad (8)$$

In the defined temperature interval, where n was supposed to be constant, C_{i} should be the same for each calibration set. The constancy of C_{i} for different calibration sets is, therefore, a quality criteria of the calibration. During this calibration, parasitic heat load to the heatmeter needs to be physically eliminated. There is, however, a possibility to calibrate the heatmeter at the presence of parasitic heat flow or during a measurement with a specimen.

Calibration at the presence of parasitic heat flow

Supposing this parasitic heat flow Q_0 to be constant during the calibration, equation (8) becomes:

$$C_i = \frac{\dot{Q}_0 + \dot{Q}_{c.i}}{T_{2.i}^{n+1} - T_{1.i}^{n+1}} \qquad (9)$$

From two calibration sets (i = 1, 2), $\dot{Q}_0$ can be eliminated.
With $C_1 = C_2 = C$ and $\Delta_i = T_{2.i}^{n+1} - T_{1.i}^{n+1}$, C can be determined with equation (10):

$$C = \frac{\dot{Q}_{c.2} - \dot{Q}_{c.1}}{\Delta_2 - \Delta_1} \qquad (10)$$

Precision of a heatmeter

In the proposed design, the heat flow measurement is reduced to two absolute temperature measurements. Thus, the precision of the heat flow measurement is directly dependent on the precision of the temperature measurement. However, the thermal conduction of the heatmeter can be chosen in a way, that for the minimal expected heat flow at a given temperature, the temperature drop along the heatmeter is just big enough to be quantified with certainty. In the design of wide range heatmeters, one should also take into account the temperature dependence of the sensitivity of the temperature sensors. Equation

(11) is a good estimation for the precision of a heatmeter at a given temperature level and for the case that the sensors are not calibrated together.

$$\Delta \dot{Q} = 2(n+1)CT^{n} \cdot \Delta T \qquad (11)$$

Where n and C are the exponent and proportionality factor of the previous equations, T is the temperature level and ΔT is here the uncertainty of the temperature measurement at this temperature level.

Using temperature sensors that were calibrated together, the precision of the heat flow measurement can be improved considerably, because systematical calibration errors of the sensors are partly eliminated.

EXAMPLE

Two different heatmeters of type 2 were developed at CERN, both designed for operation below 20 K with the option to work up to 80 K. The measurements presented in this paper were made on a heatmeter that was initially designed to measure the heat load due to resistive radio frequency losses in coaxial cables. The required precision was 5 % of the measured value over a range of 20 mW to 600 mW at about 10 K [4].

Heatmeter material:
Aluminium alloy Al Mg Si 1 (Anticorodal 100)

Geometry:
Ratio Section over Length $\frac{S}{L} = 0.006\,[m]$

Temperature sensors:
Carbon-Ceramic sensors TVO from JINR, Dubna, Russia
Calibrated together from 1.5 K and 300 K.
Absolute precision: ≈ 0.1 % of the measured value

Calibration below 20 K

For the calibration below 20 K, the heatmeter was mounted on a copper plate that was cooled by liquid helium at 4.2 K. The assembly was surrounded by an insulation vacuum of 10^{-6} mbar and shielded by a thermal screen at about 10 K.

In Figure 2 the proportionality factor C is calculated for each set of calibration heat flow Q_c and the corresponding boundary temperatures using equation (8). C^* is the proportionality factor calculated with equation (10) from two adjacent calibration sets.

The precision of the heatmeter turned out to be about ± 1 mW up to a heat flow of 500 mW. At a heat flow of 1200 mW, the precision was still better than ± 6 mW. The heatmeter was removed several times from its mounting place and remounted again under slightly different conditions. The recalibrations showed no measurable changes in the calibration parameters. From the calibration data, n could also be determined to be 1 ± 0.01. For $Q_c = 0$, C becomes zero, because of a residual ΔT of 16 mK. This ΔT may be caused by parasitic heat flow of below 1 mW and an uncertainty in the temperature measurement. In C^* the parasitic heat flow is eliminated using equation (10).

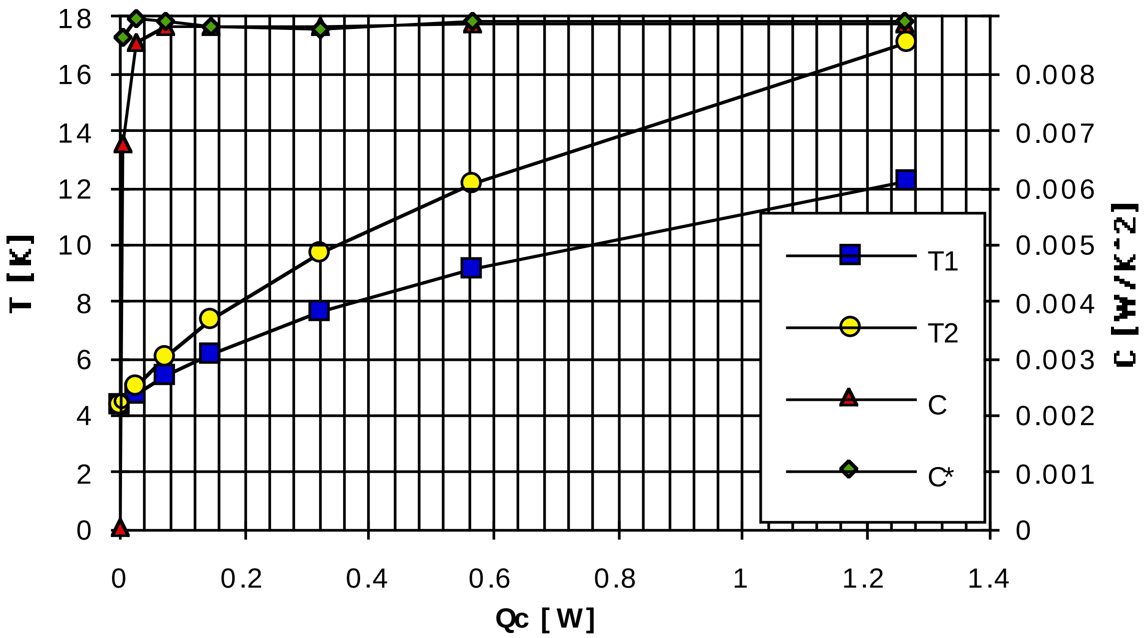

Figure 2. Calculated proportional factors C and $C*$ for sets of Qc, $T1$ and $T2$.

Calibration from 10 K to 80 K

For the calibration in the temperature range from 10 K to 80 K, the copper plate was cooled with cold gaseous helium.

The calibration heater was adjusted to a fixed value ($\dot{Q}_c$ = 899 mW) and the temperature drop along the heatmeter was measured as a function of the temperature level. The temperature of the copper plate was adjusted by varying the GHe mass flow.
For a constant calibration heat flow equation (7) becomes

$$n = \frac{\ln\left(\frac{(T_{2.1} - T_{1.1})}{(T_{2.2} - T_{1.2})}\right)}{\ln\left(\frac{(T_{2.2} + T_{1.2})}{(T_{2.1} + T_{1.1})}\right)} \tag{12}$$

$$n = \frac{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}{\ln\left(\frac{\overline{T_2}}{\overline{T_1}}\right)} \tag{13}$$

Table 1 shows the measured exponents n at different temperature levels

Table 1. Mean exponents n of the heatmeter material

T- interval	exponent n
1.5 K - 20 K	1.00 ± 0.01
20 K - 40 K	0.97 ± 0.03
40 K - 50 K	0.55 ± 0.05
50 K - 75 K	0.25 ± 0.05

Table 2. Parameters n and C of the calibration functions of the heatmeter

	valid in T-interval	n	C [W/(m·K^{n+1})]
Function 1	1.5 K - 40 K	1	0.0085
Function 2	40 K - 80 K	0.4	0.11

From the calibration data, the calibration parameters were defined, covering two temperature intervals.

The calibration function is: $\dot{Q} = C \cdot \left(T_2^{n+1} - T_1^{n+1}\right)$, where the parameters C and n used for the corresponding temperature interval are given in Table 2.

In Figure 3 the calculated heat flow is compared to the constant reference heat flow. Function 1 covers well the interval from 1.5 K - 40 K and starts deriving above. Function 2 covers relatively well the interval between 40 K and 80 K. The measured accuracy in this temperature interval is better than 0.1 W. If a higher accuracy is required, the temperature range could be divided into three temperature intervals instead of two.

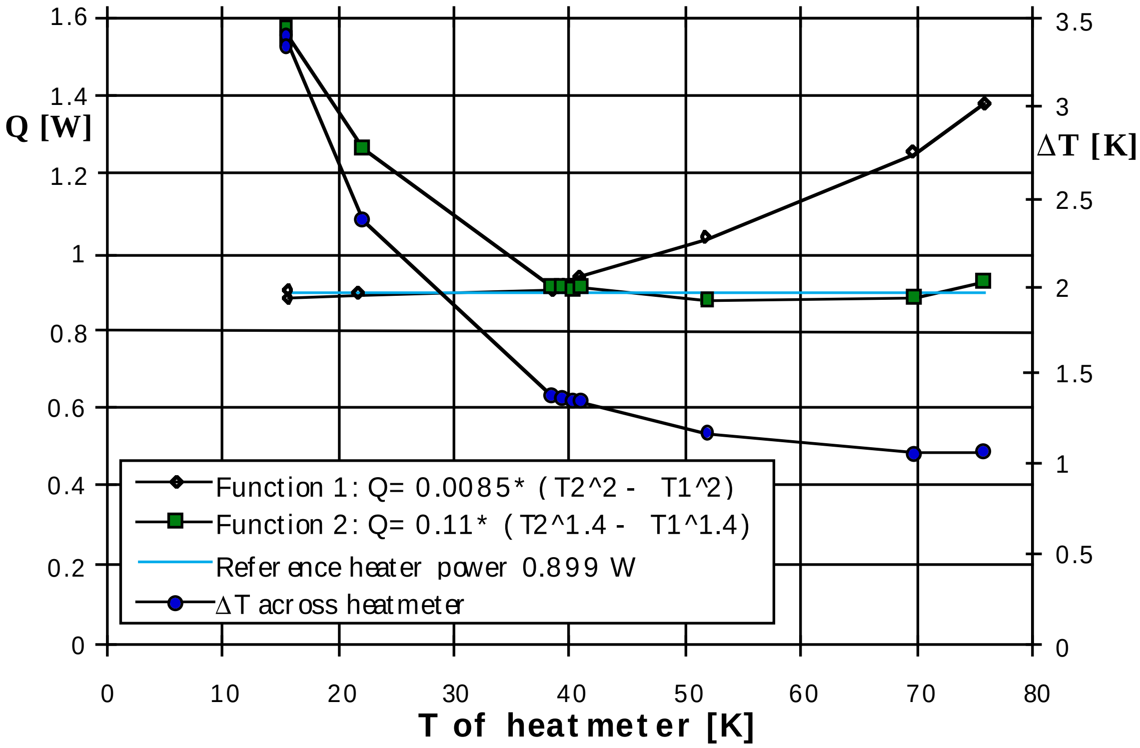

Figure 3. Two calibration functions for two temperature intervals

Table 3. Estimated precision $\Delta\dot{Q}$ of the heatmeter

T [K]	n	C [W/(m·K^{n+1})]	ΔT [K]	$\Delta\dot{Q}$ [W]
4	1	0.0085	0.004	0.0008
20	1	0.0085	0.02	0.014
40	1	0.0085	0.04	0.056
40	0.4	0.11	0.04	0.056
80	0.4	0.11	0.1	0.14

Table 3 shows the calculated precision of this heatmeter due to the uncertainty of the temperature measurement using equation (11).

The real precision of the heatmeter is better than estimated above. This is due to the fact that in the calculation the uncertainties of the two sensors are considered uncorrelated. However, the sensors that are used were calibrated together which eliminates partly systematic calibration errors.

Note, that the calculated precision concerns the absolute precision of the heatmeter which is limited by the calibration of its temperature sensors. The heat sensitivity is mainly limited by the instrumentation (stability of current source, precision of voltmeter etc.) and can reach values much better than those calculated above.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to Vladimir Datskov for the many helpful discussions on precise thermometry and the supply of the calibrated carbon ceramic temperature sensors.

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