EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 1077

CALIBRATION OF CRYOGENIC THERMOMETERS FOR THE LHC

Ch. Balle[1], J.Casas-Cubillos[1], N. Vauthier[1] and J.P. Thermeau[2]

Abstract

6000 cryogenic temperature sensors of resistive type covering the range from room temperature down to 1.6 K are installed on the LHC machine. In order to meet the stringent requirements on temperature control of the superconducting magnets, each single sensor needs to be calibrated individually. In the framework of a special contribution, IPN (Institut de Physique Nucléaire) in Orsay, France built and operated a calibration facility with a throughput of 80 thermometers per week.

After reception from the manufacturer, the thermometer is first assembled onto a support specific to the measurement environment, and then thermally cycled ten times and calibrated at least once from 1.6 to 300 K. The procedure for each of these interventions includes various measurements and the acquired data is recorded in an ORACLE®-database. Furthermore random calibrations on some samples are executed at CERN to crosscheck the coherence between the approximation data obtained by both IPN and CERN. In the range of 1.5 K to 30 K, the calibration apparatuses at IPN and CERN are traceable to standards maintained in a national metrological laboratory by using a set of rhodium-iron temperature sensors of metrological quality.

This paper presents the calibration procedure, the quality assurance applied, the results of the calibration campaigns and the return of experience.

1 CERN, Accelerator Technology Department, Geneva, Switzerland
2 IPN, Technologie des accélérateurs et détecteurs, Orsay, France

Presented at the 2007 Cryogenic Engineering Conference and International Cryogenic Materials Conference
CEC-ICMC2007
16-20 July 2007, Chattanooga, USA

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 10/12/2007

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Ch. Balle[1], J.Casas-Cubillos[1], N. Vauthier[1] and J.P. Thermeau[2]

[1]CERN
Geneva, CH-1211, Switzerland

[2]IPN, Technologie des accélérateurs et détecteurs
Orsay, F-91406, France

ABSTRACT

6000 cryogenic temperature sensors of resistive type covering the range from room temperature down to 1.6 K are installed on the LHC machine. In order to meet the stringent requirements on temperature control of the superconducting magnets, each single sensor needs to be calibrated individually. In the framework of a special contribution, IPN (Institut de Physique Nucléaire) in Orsay, France built and operated a calibration facility with a throughput of 80 thermometers per week.
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KEYWORDS: cryogenic thermometer, calibration, LHC.

INTRODUCTION

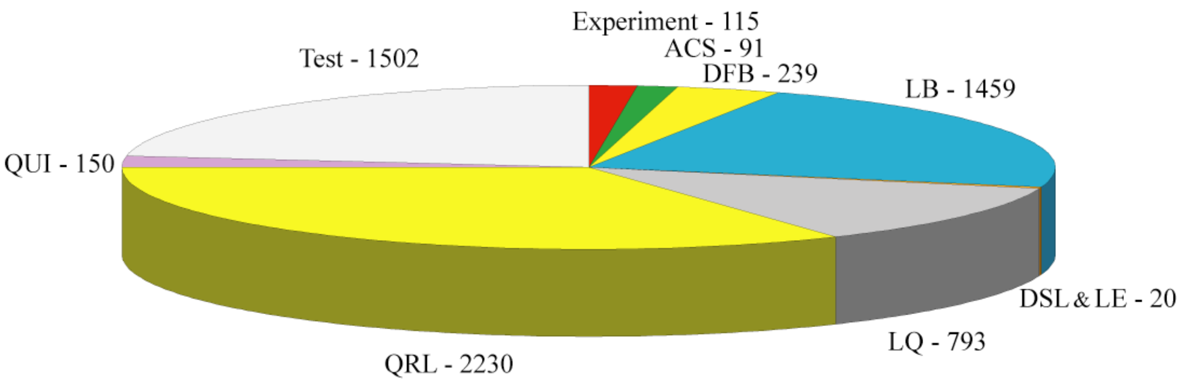
The 27-km LHC accelerator requires the world largest cryogenic system. To control and monitor the various LHC machine components during the different operation phases such as cool-down, beam-run, quench and more, 6000 low-temperature sensors are necessary. FIGURE 1 shows the thermometers requested and deployed for prototypes, test facilities and experiments in- and outside CERN.

CALIBRATION REQUIREMENT

The main parameters defining the stringent requirements are environment, industrial installation, small uncertainty band and reliability. To fulfill these requirements, firstly a dedicated support carrying the sensor has to be developed and secondly the best fitting sensor available on the market has to be selected.

The temperature sensors were installed either in the insulation vacuum of the LHC-machine or directly immersed in the cryogenic fluid. Accordingly three different types of sensor supports were developed at CERN [1] and produced by Anco in Greece and Air Liquide in France. Once the sensor is mounted on its support the assembly is called long, short or finger thermometer according to the type of supports. The design of the different assemblies is shown in TABLE 1.

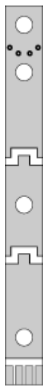
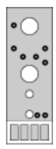
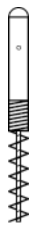
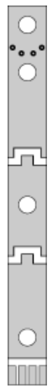
The selection of the sensor was restricted to the family of resistive temperature detectors (RTD), which are well known and used since decades in all kind of technical applications [2]. After investigation on calibration, irradiation and thermal cycling at CERN and IPN [3-4] two types of sensors were selected for the LHC-machine: a thin film zirconium oxynitride sensor with the brand name Cernox™, manufactured by Lake Shore Cryotronics and an industrial platinum RTD of type Pt100. The latter covers a range from 50 to 300 K and follows a standard response curve within a defined class of tolerance according to the European norm IEC 751. Therefore it is interchangeable and no individual calibration is needed. The chosen Cernox™ -model CX-1050 shows a monotonic R-T behavior from 1.6 K to 300 K, has a sensitivity of at least 1000 Ω/K below 4 K, and requires an individual calibration for every single sensor.



ACS	Superconducting Cavities	DFB	Electrical Feed Box
DSL	El. Superconducting Link	LB	Dipole Magnet
LE	Connection Cryostat	LQ	Quadrupole Magnet
QRL	Cryogenic Distribution Line	QUI	Cryogenic Interconnection Box

FIGURE 1. Cryogenic thermometer quantities requested for the LHC main components, experiments and tests.

TABLE 1. Thermometer requirements as a function of the LHC main components.

Requirements & Solutions	**Interconnect, DFB, DSL, QRL, ACS, QUI, DSL, LE**	**Magnet**	**QRL**	**QRL**
Temperature Range [K]	1.6..300	1.6..300	1.6..300	50..300
Installation in	vacuum	He	He	vacuum
Interchangeability	✗	✗	✓	✗
Quench-resistant	✗	✓	✗	✗
Lifetime	20 years	20 years	20 years	20 years
Thermal Cycle 300..1.8 K	≥ 1/year	≥ 1/year	≥ 1/year	≥ 1/year
Radiation	$\geq 5 \times 10^{11}$ neutrons / cm^2 over 10 years			
Non-expert installation	Yes	Yes	Yes	Yes
Uncertainty below 4 K	± 5 mK	± 5 mK	± 5 mK	± 5 mK
Uncertainty above 4 K	1%	1%	1%	1%
Secure wire connection	✓	✓	✓	✓
	⇩	⇩	⇩	⇩
Sensor selected	Cernox ™	Cernox ™	Cernox ™	Pt100
Support type				

From a logistic point of view, the platinum RTD is a standard supply. Since the standard calibration satisfies the requirements where it is installed, the platinum RTD will be ignored in the following sections. The choice of the Cernox™ RTD with its singularity had a deep impact regarding logistics, procedures and tools to be used along the lifetime of the thermometer. Consequently a dedicated cryogenic thermometer database and a calibration facility was build-up.

The Oracle® 8i thermometer database, called ThermBase, stores the curriculum vitae of every thermometer including the calibration and test data. Also the LHC control database and CERN equipment database are pointing to the thermometer database for enabling downloads of calibration tables to the Front-End Controller (FEC) [5].

A cryogenic thermometer calibration facility was designed and constructed at CERN for the sensor selection campaign, for validating the supports and for small series calibrations [6]. Compared with test facilities in industry and other laboratories, the CERN insert is designed to fix the LHC cryogenic thermometer directly on it. Thus calibration under LHC installation conditions is ensured.

The gained knowledge and experience was transferred to IPN (Institut de Physique Nucléaire) in Orsay, France within the framework of a special contribution. A system of two automatic calibration benches was built to calibrate the thermometers for the LHC machine [3]. All the calibrations were made by comparison with working standard thermometers of rhodium-iron type. Those standards are maintained at CERN by means of secondary standards and a calibration apparatus from the Institute for Physical Research VNIIFTRI, Moscow, Russia. The secondary standards are maintained once per year by the Italian national metrological institute INRIM (Istituto Nazionale di Ricerca Metrologica) in Torino, Italy. They are traceable in the range of 1.6 K to 30 K and have an uncertainty of ± 2 mK to ± 5 mK. For temperatures above 30 K, the calibration of the working standards is followed by a platinum standard thermometer coming from NPL (National Physical Laboratory) in Teddington, England.

A copy of the CERN thermometer database was installed at IPN, where several upgrades and modifications of the structure and the Oracle® Forms user-interface were made. A fast transfer of IPN calibration data to CERN was possible thanks to a direct connection between both laboratories.

PROCEDURE

A network composed of several suppliers and laboratories was created to take advantage of their competencies and experience (See TABLE 2).

Assembling

Over a period of 2 years Lake Shore Cryotronics® supplied to CERN a total of 7000 Cernox™ sensors of type CX-1050-SD with the characteristic R(1.7 K) = 22500 Ω ± 5000 Ω. An electronic file, containing the resistive values at room, liquid-nitrogen and liquid-helium temperature of the batch of sensors supplied was attached to every shipment. The sensor was carefully soldered by hand to a support, specific to the measurement environment and supplied by Anco. Like for the sensors, the support deliveries were accompanied with a test sheet listing the resistive values of the conductors. The serial number of the assembled thermometer is graved on it to avoid any mistake. An automatic electrical continuity test and a 4-wire resistance measurement at room temperature compared with the values supplied by Lake Shore Cryotronics® could validate the thermometer conformity. The data acquired during these tests and the type of support are added to the file coming from Lake Shore Cryotronics®.

The above-mentioned tests were repeated every time the thermometer undergoes an intervention such as installation and shipping, or in case the thermometer shows an unexpected behavior. This set of data is called thermometer traveler.

TABLE 2. List of suppliers and laboratories and their contribution.

Collaborators	Contribution
Lake Shore Cryotronics®, Westerville, USA	Cernox™-RTD manufacturing
Anco, Athen, Greece	Support manufacturing
INRIM, Torino, Italy	Secondary standard calibration facility Data analyzing Calibration plateau definition
IPN, Orsay, France	Thermal cycling facility Mass calibration facility Data pre-analyzing Oracle® 8i database

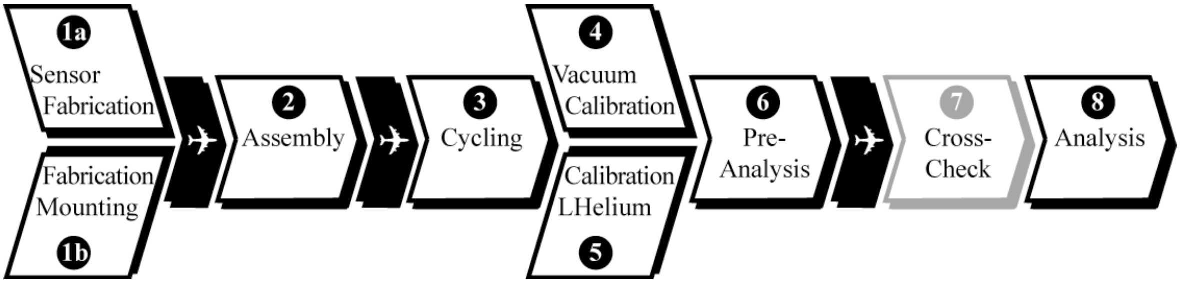


FIGURE 3. The main steps of the procedure from an off-shelf sensor to a calibrated LHC thermometer.

Thermal Cycling

After assembly, each thermometer was packed in a foam-cushioned box. In parallel, an electronic file containing its data was send to IPN. At IPN this file is imported to ThermBase. Then a fully automatic reception test was executed on the thermometers; the data compared and recorded. An alarm was sent out if the difference was out of tolerance.

In order to improve the long-term stability of the sensors, each thermometer was thermally cycled ten times between 4.2 K and 300 K with an automatic cycling facility [4]. No thermometer data were acquired during cycling.

Calibration

IPN was running two facilities: one for calibrations in liquid helium and the other under vacuum conditions. The long thermometers were calibrated at least once under vacuum over the full temperature range from 300 K to 1.6 K. This corresponds to step 4 in the FIGURE 3. The short and finger thermometers underwent step 4 and 5 of the FIGURE 3. They were calibrated in liquid helium in the range from 1.6 to 4.2 K, their future working conditions, and under vacuum up to 300 K so that they can be used for monitoring during cool-down and warm-up operation. Both calibrations were automatically driven by a Programmable Logic Controller (PLC).

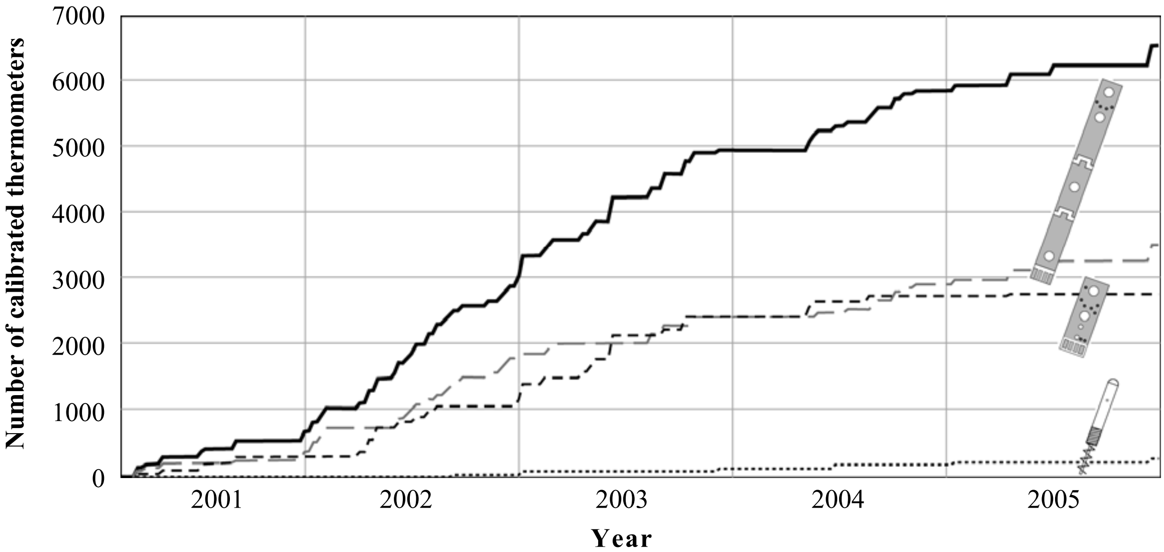


FIGURE 4. The bold curve represents the sum of calibrated long, short and finger thermometers over 5 years. Up from May 2002 the calibration rate is higher, because the second additional vacuum insert is under operation.

A personal computer (PC) running LabVIEW™ from National Instruments® acquired the measurement and process data and wrote them directly to the database. The calibration time was short compared to the time of the operator for installing and connecting up to 90 thermometers on the insert, entering the configuration set-up (i.e. channel, position and serial-number) and bringing the system into operation. Therefore a second insert for the calibration under vacuum was constructed and put in place in May 2002. The increase of the calibration rate due to this second insert is shown in FIGURE 4. An optimized set of calibration temperature setpoints was computed by INRIM after having analyzed the calibration curve progression of 300 thermometers.

Data Analysis

After calibration the IPN operator pre-analyzed the acquired data with a software tool developed at IPN and written in LabVIEW™. Every thermometer had at least one approximation function of its temperature-resistance (T-R) characteristic, which is typically a polynomial function of several degrees. No calibration data were removed from the database. Non-conforming measurements were simply flagged-out. Before shipping the thermometers back to CERN a final electrical test was executed and recorded at IPN. Finally all the newly acquired data are transferred to ThermBase at CERN.

At CERN, a linear interpolation function for the FECs was deduced from the polynomials. INRIM has developed a method to generate cubic spline functions for better approximating the thermometer T-R points without the risk of oscillations, which are characteristic for polynomials. However this method was abandoned owing to the lack of robustness when one or more anchor points were not performed. The present polynomial interpolation obtained is satisfactory.

RESULTS

Crosscheck Calibration

CERN executed random calibrations on some calibrated thermometers coming from IPN in order to crosscheck the coherence between the approximation data obtained by IPN and CERN. FIGURE 5 shows the difference ($\Delta T = T_{CERN}(R) - T_{IPN}(R)$) of 6 thermometers

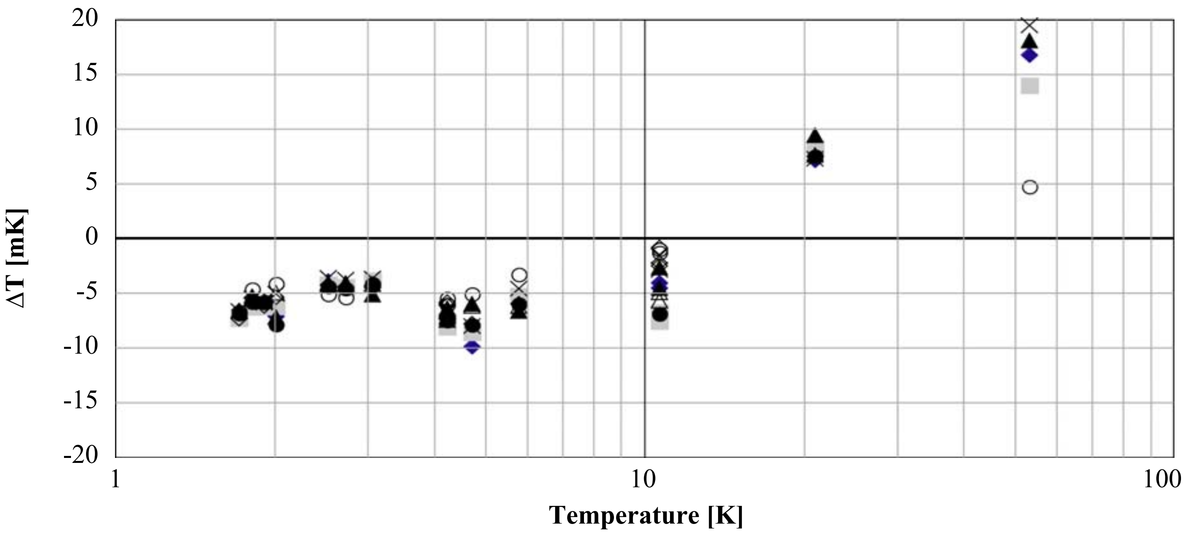


FIGURE 5. Crosscheck between IPN and CERN calibration. ($\Delta T = T_{CERN}(R) - T_{IPN}(R)$)

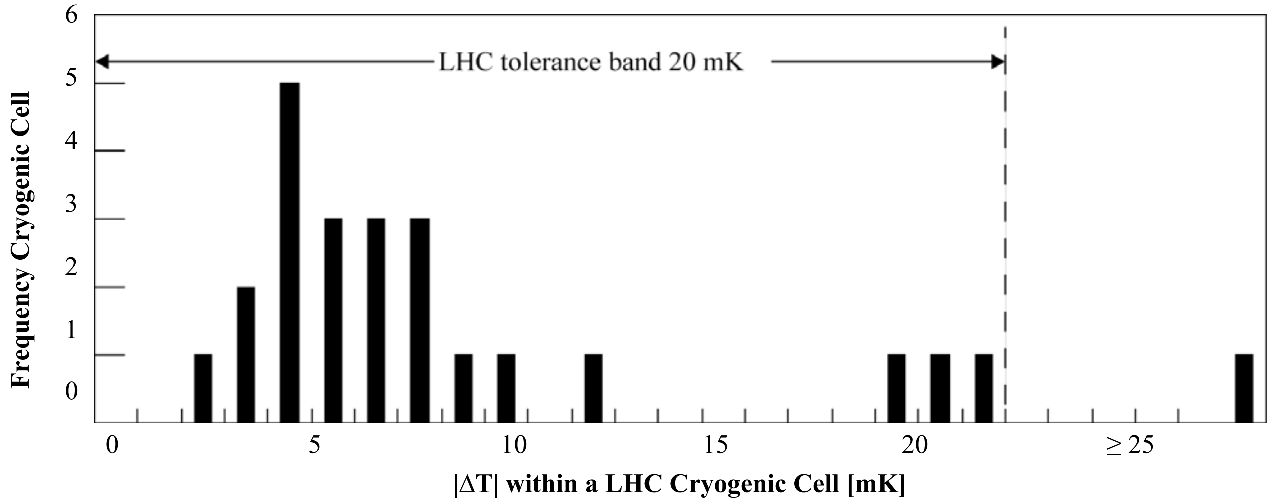


FIGURE 6. Absolute temperature spread of thermometers within a LHC cryogenic cell at 1.95 K, assuming that the gradient of temperature of a cell is zero.

at a given temperature. Below 10 K a systematic deviation of - 5 mK can be observed This anomaly was constant over the full production period. Further investigations have to be made to understand the reason.

Thermometer in LHC Operation

During cool-down of the first sector of the LHC-machine the performance of the thermometers was within the expectations. As an example FIGURE 6 shows that the temperature spread within 24 isothermal cryogenic cells is, with one exception, inside the tolerance band.

CONCLUSION

From the years 2001 to 2005 more than 6500 cryogenic thermometers equipped with Cernox™-RTD have been calibrated for the LHC-machine and for other applications. The feedback from users and the first readings of the cooled sector of the machine are positive.

The high number of sensors to be assembled, cycled and individually calibrated, together with severe environmental conditions and tight uncertainties specification, made this thermometer project a great challenge. Well-defined procedures were necessary to guarantee the requirements.

ACKNOWLEDGEMENTS

We thank all the people inside and outside CERN who participated to this project. We appreciated the constructive feedbacks from the end-users in the field, as well as the encouragement of our colleagues and the availability and precise work of the technicians involved.

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