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QUALITY ASSURANCE OF LHC CRYOGENIC INSTRUMENTATION DURING INSTALLATION AND COMMISSIONING

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Abstract

The operation and monitoring of the LHC requires a cryogenic instrumentation system of an unprecedented size (800 instrumentation crates, holding 15000 sensors and actuators), with strict constraints on temperature measurement uncertainty and radiation hardness for all sensors and actuators. This paper presents the applied procedures of quality assurance and the specific hard- & software tools used to meet and track the mentioned requirements during its lifetime (fabrication, installation, commissioning, operation and maintenance); within the given constraints of time schedule, accessibility and coordination with other teams.

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Quality assurance of LHC cryogenic instrumentation during installation and commissioning

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The operation and monitoring of the LHC requires a cryogenic instrumentation system of an unprecedented size (800 instrumentation crates, holding 15000 sensors and actuators), with strict constraints on temperature measurement uncertainty and radiation hardness for all sensors and actuators. This paper presents the applied procedures of quality assurance and the specific hard- & software tools used to meet and track the mentioned requirements during its lifetime (fabrication, installation, commissioning, operation and maintenance); within the given constraints of time schedule, accessibility and coordination with other teams.

TEMPERATURE SENSORS. CALIBRATION AND ANALYSIS

Temperature is a control parameter for the LHC that requires metrological grade accuracy within a large scale machine. Its measurement has thus very stringent requirements [1], involving a long development effort to obtain the required performance [2-7].

The temperature sensors are used for controlling and monitoring the temperature during the cool-down, warm-up and normal operation of the superconducting magnets, cryogenic distribution lines, electric distribution boxes, radiofrequency acceleration cavities. They are also used by the control system to generate warnings or interlocks in case the temperature of a critical component is out of its normal operational range.

Two types of resistive temperature sensor were selected to comply with the LHC requirements: platinum 100 ohm type (Pt-100) for the range 50 K to 300 K, and Cernox™ type (CX) for the range 1.5 K to 300 K [8]. Both types of sensor were tested for radiation hardness up to almost 10^{15} n/cm^2. While all the Pt-100 sensors follow a standard curve defined by IEC 751, the CX sensors need to be calibrated individually.

The Cernox™ thermometers were calibrated in the "Institute de Physique Nucléaire" (IPN), in Orsay, France, according to a predefined procedure [9]. Depending on the thermometric block type where they had been mounted, long or short (see Figure 1), the thermometers were calibrated only in a vacuum test facility or in both helium (for the range 1.6 K to 4.2 K) and vacuum (up to 300 K) test facilities, respectively. Table 1 shows the quantities of thermometers calibrated in the different calibration facilities from 1999 to 2005.

Table 1 Overview of IPN contribution

Cernox thermometers calibrated	6749
Number of calibration runs	171
Vacuum runs	128
Helium runs	43

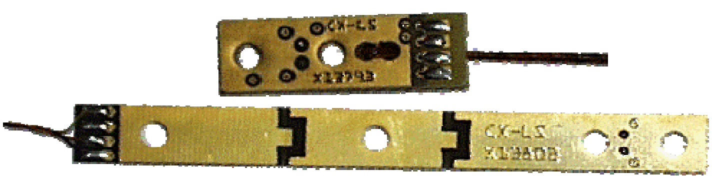

Figure 1 CX sensor in a short thermometric block (up) and in a long thermometric block (down)

The calibration data of each thermometer were recorded at CERN in Thermbase, the Oracle database system that stores data of the lifecycle of the cryogenic thermometers before final installation. At CERN, the calibration data were analyzed in order to obtain the mathematical function that better approximates the behavior of each individual thermometer. The approximation procedure required an elaborate analysis of the calibration points of both, the reference thermometers and the calibrated thermometers, to eliminate the outliers. The final computed points of temperature and resistance of each thermometer were fitted by using 9-degree polynomials:

$$\log_{10} T(R) = \sum_{0}^{9} A_i * \frac{1}{(\log_{10} R)^i}$$

equivalent to:

$$T(R) = 10^{\left(\sum_{0}^{9} A_i * \frac{1}{(\log_{10} R)^i}\right)}$$

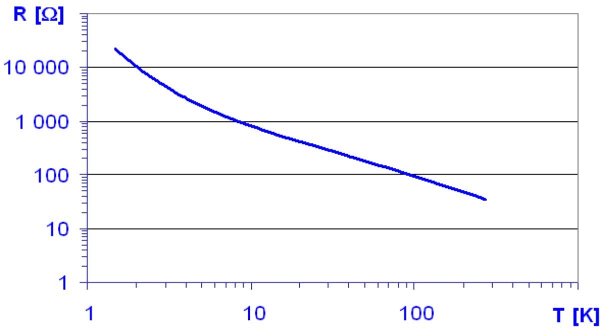

Figure 2 Example of a fit curve, T(R), log scale

The residuals obtained by using function *T(R)*, are within the uncertainty requirements given in Table 2.

Table 2 Uncertainty requirements as a function of the temperature range (including electronics and sensors uncertainty)

	Temperature Range [K]					
	1.6-2.2	2.2-4	4-6	6-25	20-50	50-300
Uncertainty	± 0.01 K	± 0.02 K	± 0.03 K	± 1 K	± 5 K	± 5 K

The LHC is operated by using Programmable Logic Controllers (PLCs) and the available processing power is not compatible with the execution of thousands of 9^{th} degree polynomials. The real-time temperature readout is based in a linear interpolation table of 65 pairs of points {R T} obtained from the fit function of each thermometer. The interpolation points are distributed logarithmically and to reduce linearization errors, the tables have been enhanced to make the interpolation points lay outside the fit function. As for the fit functions, there is at least one interpolation table for each thermometer.

Computed points, fit functions and interpolation tables of each individual thermometer, as the calibration and test data, are stored in Thermbase.

INSTALLATION AND TRACKING

The stringent requirements of the cryogenic thermometer uncertainty have determined the very particular manufacturing, assembly, calibration, test and analysis procedures. The CERN "Engineering Data Management System", EDMS, compiles the documentation relative to the different procedures applied, the engineering specifications and test reports.

The tracking of the thermometer during all this lifecycle is decisive to guarantee the correct identification of each thermometer once installed in the final assembly, considering furthermore that several teams are involved in time [10].

For this reason, in addition to Thermbase, the thermometers are also identified in the LHC general databases: Layout Database that stores the functional positions of the equipments, and the Manufacturing and Test Folder, MTF, that contains the tracking of the manufacturing steps, the test data and the equipment characteristics. The three databases are linked together.

In the Layout Database a particular slot is given to the main LHC equipment and indirectly to the instrumentation attached. This assigned slot represents the location of all the instrumentation installed around the LHC ring.

MTF Database stores information regarding the thermometers lifecycle and its consistency is crucial to avoid errors in allocation of the calibration data. The LHC instrumentation appears in the MTF tree as "child equipment" attached to the corresponding "parent equipment". This "Assembly Tree" with the "Assigned Slot" allows the complete definition of the location of the instrumentation and in particular, of the thermometers.

MTF database contains also information about the status of the equipment. In the case of the thermometers the states defined are: “Good”, “Defective”, and “Broken” (see Table 3).

Table 3 States of Cernox ™ thermometers installed in the LHC

CX thermometers installed	Good	Defective	Broken
5076	4987	64	25
	98.25 %	1.26 %	0.49 %

Within the most important information that is found in MTF database regarding the thermometers, are the “Travelers” and the “Non conformity Reports (NCRs)”.

The manufacturing documents and cryogenic thermometer travelers trace the different conformity tests carried out at the different phases of the lifecycle of the thermometer: manufacturing, calibration and installation; but also after the shipments between manufacturer, CERN and IPN, and after every single intervention once the thermometer was installed at the final position of the assembly. These conformity tests consist on 4-wire and 2-wire measurements at room temperature. The resulting data is used to recognize if a manufacturing or electrical problem exists.

When a problem occurs during the installation or operation of a thermometer, it is declared as “Broken” or “Defective” and a non conformity report is created (for example: if the thermometer is grounded). In many cases, the thermometers are no longer accessible once installed in the LHC, except in case of a main repair. For this reason, redundant thermometers are installed for temperature measurements essential for the correct operation of the LHC.

Table 3 shows that the 1.75 % of the thermometers installed have NCRs (thermometer defined as “Broken” or “Defective”). Figure 3 shows the distribution of the 89 Cernox™ thermometers installed in the LHC where problems have been discovered. This quantity includes mainly low risk cases: diagnostic and foreseen thermometers whose measurement are not vital for the operation and control system. Also, thanks to the redundancy, almost 17 % of the problematic temperature measurements could be ensured. Finally there are two cases where both, principal thermometer and redundant thermometer have NCRs. Fortunately, a 3-wire or even 2-wire measurement is possible for the “Defective” ones.

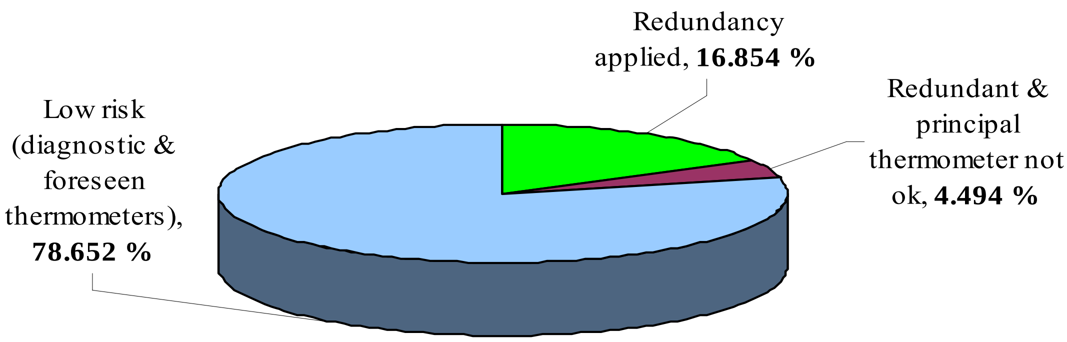

Figure 3 Distribution of the 89 Cernox ™ thermometers installed in LHC with problems

COMMISSIONING

Once the equipments and instrumentation were installed in the corresponding position along the eight sectors of the LHC, the commissioning phase began.

The commissioning of the cryogenic equipment started with a detailed inspection in order to detect inverted cables or broken equipment and was followed by tests performed by a mobile test bench (MTB). The MTB is a test rack to validate in situ all the channels of the electronic crates and also the sensors and actuators. It ensured coherency between databases and the field [10]. The first repairs in electronics and cabling were done as consequence of this first step of the commissioning.

The second phase of the commissioning was done from the ground level by using the Cryogenics Instrumentation Expert Tool (CIET). Thanks to this tool, all the channels of the cryogenic instrumentation used by the controls and cryogenic operation (valves, pressure sensors, level gauges, electrical heaters and temperature sensors) are monitored.

The first validation through CIET was done at ambient temperature, before the cool-down of each sector. The observed data provided an indirect measurement of the tunnel temperature, demonstrating the good sensitivity of the thermometers at room temperature and the adequate follow-up of the LHC quality assurance policy.

During the commissioning through CIET new problems of cabling (open and short circuits, wrong cable connections) electronics (noise, spikes, auto resets) and wrong identification of the thermometers in the database (and in consequence wrong interpolation tables used by the PLCs) were detected apart of those already found by the MTB. The problems were studied and solved when possible but a few cases remain unsolved or under study. Table 4 shows the availability of the channels based on Cernox™ thermometers used by the control system just before the cool-down of each sector. It also illustrates the percentages of non-conform Cernox™ thermometers due to manufacturing problems ("Broken" or "Defective") and due to problems in the electronics, cabling or definition in the databases that could not be solved before the cool-down of the sector.

Table 4 Availability of the Cernox ™ thermometers before the cool-down by sector

SECTOR	OK	NCR	cabling-electronic-definition problems
Sector 1-2	96.84 %	0.88 %	2.28 %
Sector 2-3	94.46 %	1.91 %	3.63 %
Sector 3-4	94.84 %	1.91 %	3.25 %
Sector 4-5	94.14 %	0.18 %	5.68 %
Sector 5-6	90.45 %	1.69 %	7.87 %
Sector 6-7	95.97 %	1.81 %	2.22 %
Sector 7-8	95.45 %	1.52 %	3.04 %
Sector 8-1	95.94 %	0.88 %	3.17 %

OPERATION AND MAINTENANCE

Apart of being an essential tool during the commissioning phase, the CIET application has been fundamental for the support provided to the technicians working underground once the cool-down of the sectors started. New failures in the electronics, cabling and sensors which appeared after the commissioning at ambient temperature are being detected and solved using CIET as diagnostic tool.

The thermometer performance at room temperature, before the cool-down, was assessed by the readout of tunnel temperature. During the operation period it is assessed by the readouts given by the thermometers installed at the same temperature level or on the same distribution header. For instance, in nominal conditions, the main magnets operate in superfluid helium and thanks to the excellent thermal conduction, the 107 m LHC standard cells can be considered as isothermal to within ± 10 mK dispersion.

An evaluation of the overall accuracy of the sectors that have already reached operation temperature (~1.9 K) was done by analyzing the dispersion of temperature for the different thermometers in a given cryogenic cell, considering that each cell is isothermal at stable conditions [4]. Figures 4 and 5 illustrate the dispersion obtained in two of the cells of sector 8-1.

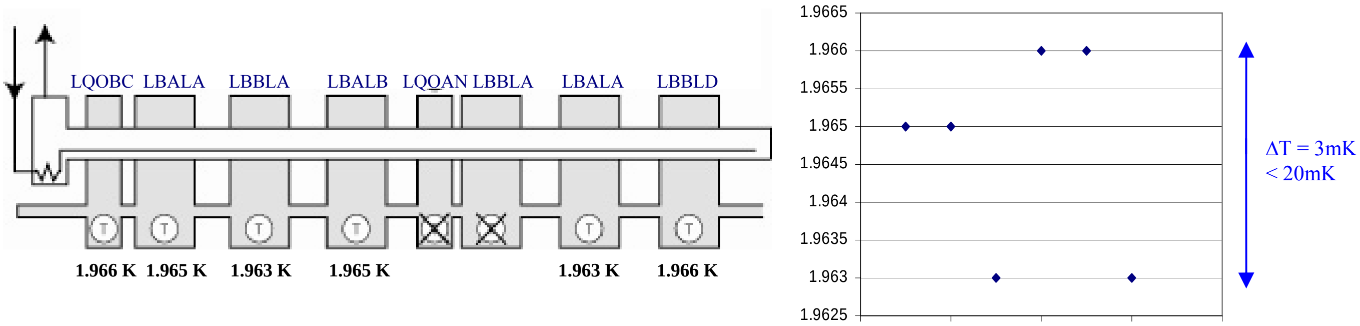

Figure 4 Cryogenic cell 29L1 (sector 8-1) and dispersion between TT821 thermometers. Within specifications

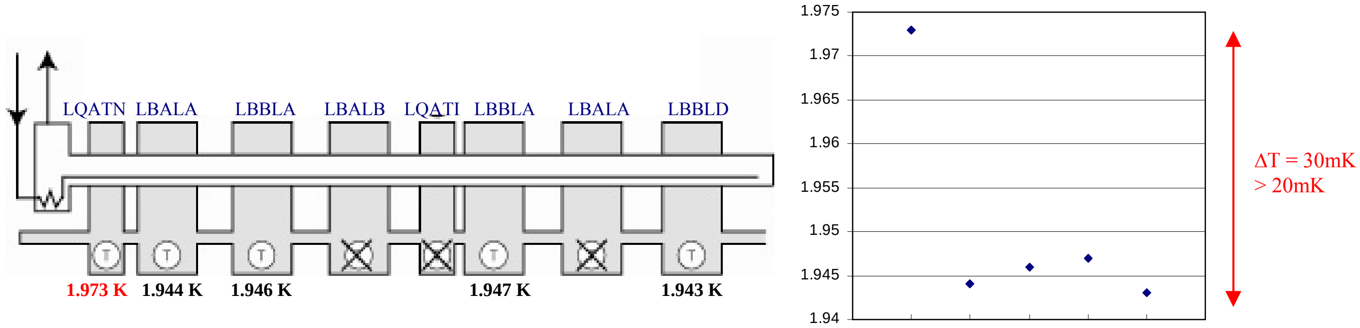

Figure 5 Cryogenic cell 19R8 (sector 8-1) and dispersion between TT821 thermometers. Outside specifications

Considering the example of sector 8-1, only 3 of the 27 cryogenic cells constituting the arc are outside specifications for the LHC, with dispersion bigger than 20 mK (see Figure 6).

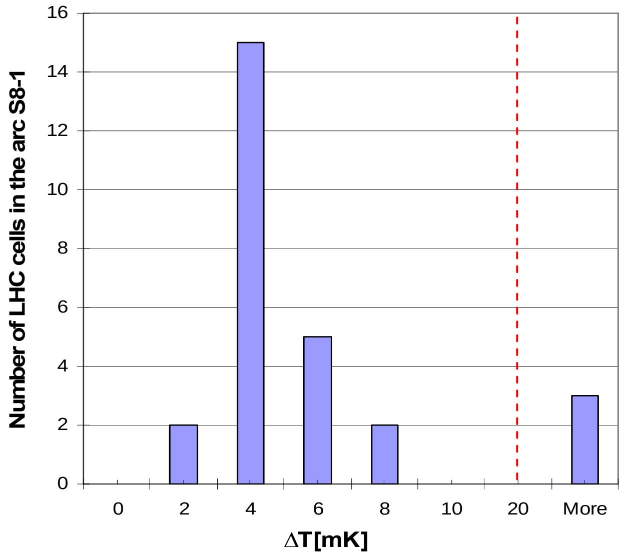

Figure 6 Dispersion per cell at 1.9 K on arc cells of sector 8-1

In most cases, cells containing thermometers clearly outside the tolerance usually correspond to channels already detected as non-conform during the commissioning phase.

CONCLUSIONS

The observed performance of the cryogenic instrumentation shows very few divergences between the field and the databases parameters, indicating that the quality assurance procedures were all well applied during the manufacturing and commissioning of the LHC.

In particular, the temperature sensors type Cernox™, with more that 5000 units installed, have required some of the most meticulous procedures of quality assurance since they involved the generation of individual calibrations, fit functions and interpolation tables.

The commissioning of the temperature channels was also particularly hard and tedious, considering that each channel was analyzed separately in order to verify not only that the channel had an output (no cabling or electronic problems affecting the measurement) but also that the value of temperature given was coherent with the temperature of the machine.

However, the right identification of certain thermometers installed is still under investigation. To understand location and database mismatches a detailed analysis of the fabrication reports is required; this is a very complex task because it includes not only the evaluation of electronic documents but also hand-written fabrication reports, sometimes created by other teams. Fortunately, those cases represent less than 2 % of the thermometers installed, and thanks to the redundancy and extra channels foreseen, they will not imply a risk to the normal performance of the LHC.

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