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THE COMMISSIONING OF THE INSTRUMENTATION FOR THE LHC TUNNEL CRYOGENICS

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Abstract

The Large Hadron Collider (LHC) at CERN is a superconducting accelerator and proton-proton collider of circumference of 27 km, lying about 100 m underground. Its operation relies on 1232 superconducting dipoles with a field of 8.3 T and 392 superconducting quadrupoles with a field gradient of 223 T/m powered at 11.8 kA and operating in superfluid helium at 1.9 K. This paper describes the cryogenic instrumentation commissioning, the challenges and the project organization based on our 2.5 years experience.

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ABSTRACT: The Large Hadron Collider (LHC) at CERN is a superconducting accelerator and proton-proton collider of circumference of 27 km, lying about 100 m underground. Its operation relies on 1232 superconducting dipoles with a field of 8.3 T and 392 superconducting quadrupoles with a field gradient of 223 T/m powered at 11.8 kA and operating in superfluid helium at 1.9 K. This paper describes the cryogenic instrumentation commissioning, the challenges and the project organization based on our 2.5 years experience.

KEYWORDS: LHC; hardware commissioning; cryogenics.

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Contents

1. Introduction

The Large Hadron Collider (LHC) is a 27 km superconducting accelerator and proton-proton collider designed to reach the unprecedented energy of 7 TeV per beam and luminosity of 10^{34} $cm^{-2}s^{-1}$ [1,2]. Its operation relies on 1232 superconducting dipoles with a field of 8.3 T and 392 superconducting quadrupoles with a field gradient of 223 T/m powered at 11.8 kA and operating in superfluid helium at 1.9 K The electrical supply to the superconducting magnets is provided by 52 electrical feed boxes (DFB) equipped with 1400 current leads carrying current between 120 A and 13 kA, which distribute current to several hundreds of different circuits. The electrical power is brought from room temperature to cryogenic temperature by High Temperature Superconducting (HTS) current leads, whose lower extremities are immersed in a bath of liquid helium, around 4 K.

The LHC (figure 1) has eight Interaction Points (IPs), separated by eight sectors of about 3.3 km each. Four of these points are dedicated to the main experiments, two others are used for beam cleaning systems capturing off-momentum and halo particles, another for the superconducting RF acceleration cavities and one for the beam dumping system.

Each sector consists of an arc (ARC, 2460 m), with 23 regular cells of 107 m, with a dispersion suppressor (DS, 170 m) at each extremity and a long straight section (LSS, 270 m) near each IP.

Every ARC cell contains two sets of 3 steering dipoles (15 m) and 1 focusing/defocusing quadrupole (5.5 m). In the LSS there is a wide diversity of dipoles, quadrupoles and multipole correctors, with various functionalities. So, while the eight ARCs are almost identical and repetitive the long straight sections are very different, which has a significant impact on the commissioning procedure.

The cryogenic system consists of gas storage, warm compressors and refrigerators on the surface and cold compressors in underground caverns. A cryogenic distribution line (QRL), parallel to the magnets, feeds them with helium through jumper connections (every 107 m in the ARC). The operation and monitoring of the LHC require a large amount of cryogenic instruments (most of them operating in radioactive environment) with a robust and reliable design. The cryogenic control system has to manage about 800 electronic crates and more than

16000 sensors (for temperature, pressure and liquid helium level measurements) and actuators (valves and heaters), distributed along the LHC circumference and in radiation protected areas.

The commissioning was performed sector by sector and in parallel without any interference related to the vacuum and cryogenic systems and magnet powering [3].

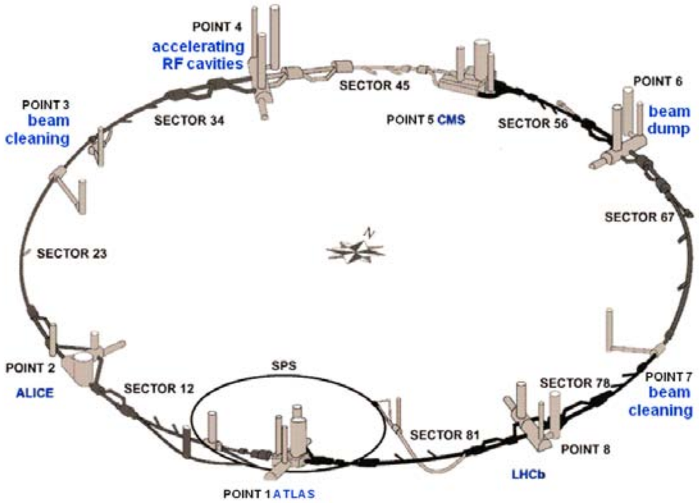

Figure 1. LHC points, P1: ATLAS detector, P2: ALICE detector, P3: Collimation system to capture off-momentum particles, P4: Radio Frequency superconducting acceleration cavities, P5: CMS detector, P6: Beam abort systems for the beams to be extracted safely and deposited onto external dump (absorbing the beam energy), P7: Collimation system to control the beam halo, P8: LHCb detector.

2. Cryogenic Control System

The cryogenic instruments, distributed over large distances are accessed by two industrial field networks. The Profibus® (by Siemens™), which is radiation sensitive, is used for the valve signals and some special heaters; and the WorldFIP®, which is radiation tolerant, transfers the data from sensors and actuators (figure 2). These fieldbuses allow considerable simplification in cabling and maintenance and offer the capability of remote diagnosis and configuration [4,5].

Per sector, there are eight WorldFIP® network segments per sector that access data at 1 Mbit/s from most of the thermometers (TT), pressure sensors (PT), level gauges (LT), and digital inputs (on-off-valves, end-switches or pressure switches) and transfer the commands for driving electrical heaters (EH). There are also five Profibus® network segments (1.5 Mbit/s), which are used for the command of on-off valves (QV, PV), for command and feedback of analog valves (CV) and of some particular heaters (EH) and to configure and parameterize “intelligent” valve positioners via PDM® (a software by Siemens™). Moreover there are two Siemens-S7® Programmable Logic Controllers (PLC) (one for the ARC and DS and the other for both LSS) per sector, cycling at 500 ms and running some 250 Closed Control Loops (CCLs) as well as 500 alarms and interlocks. Although the Profibus® protocol is integrated with the Siemens™ PLCs, the WorldFIP®-PLC communication gateway is provided by dedicated Front-End Computers (FECs) running Linux®, where the TT interpolation tables are located.

The man-machine interface is based on two Supervisory Control and Data Acquisition systems (SCADA), built with PVSS®: The CRYO-SCADA, which complies to the CERN-Unified Industrial Control System (UNICOS) framework, is used by the operators to access data and commands relevant to the cryogenic process, comprises synoptic panels (for navigation, monitoring and control of all instruments), alarms and interlocks handling, real-time and historical trends, data and event logging and archiving. The Cryogenic Instrumentation Expert Tool (CIET) is a tool used by the control experts to remotely monitor, configure, parameterize, and reset the WorldFIP® read-out channels.

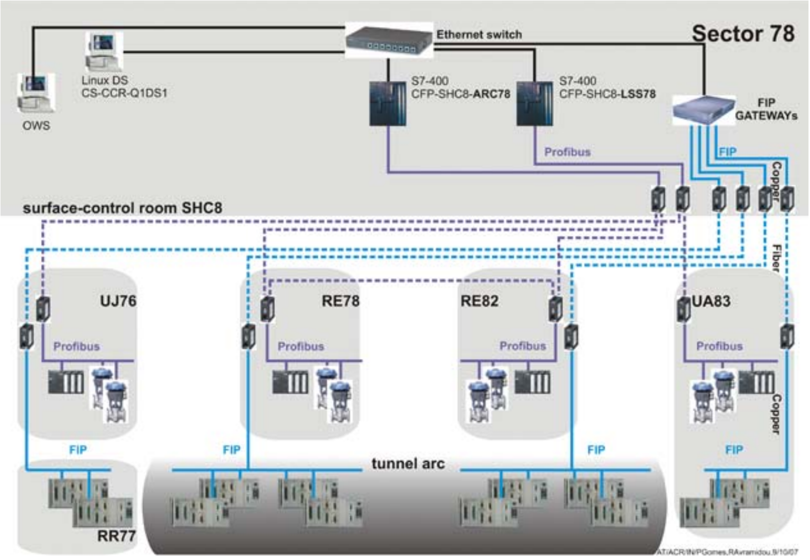

Figure 2. Controls architecture for LHC full sector. All valves are accessed through Profibus in protected areas and all other instruments accessed through WorldFip.

3. Cryogenic Instrumentation

The LHC magnet cryostats are fed with helium from the cryogenic distribution line (QRL) by 208 service modules (SM). A service module consists of two valve boxes (connected to 2-12 valves) and a jumper connecting the QRL to the LHC magnets. There are 2600 Control Valves (CV), which are analog valves using a range of 0 to 100 % and 720 Quench (QV) and Pressure Valves (PV), which are digital valves having two states (on/off). Intelligent positioners (communicating via Profibus-PA®) are used to control the opening of the cryogenic valves (CV analog valves) on the QRL. The electronic units are placed in radiation protected areas (figures 3, 4), while the radiation insensitive equipment that regulates the compressed air in the valve actuators is placed on the corresponding QRL-SM (figure 5) and comprises the potentiometer (that reads the stem position) and two piezo-valves (that pressurize and depressurize the pneumatic actuator).

The installation, configuration, initialization testing and troubleshooting of these electronic units for all 8 sectors has been completed at the early phase of commissioning. Before their installation in the field, all valve-positioner units were configured and tested in the laboratory, and after their installation, a verification procedure took place and pressurized air was supplied. The test procedure included already given parameters cross-checking, initialization with corresponding valves and electrical connections between positioner unit and pressure regulation block, motion direction and extreme positions verification, based on manual operation for each analog valve. The digital valves were also verified with a tool simulating the driving signal. The final stage of the valve commissioning was the coherence test for the verification of the proper valve response, by sending requests and receiving feedback on the supervisory system at one side and checking the valve under test at the other side.

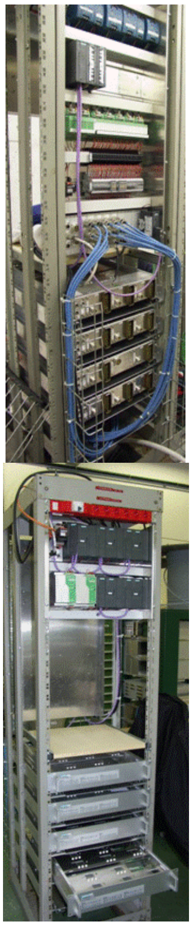

Figure 3. Rack with electronics for on/off (PV, QV) and analog (CV) valves for QRL (back and front side).

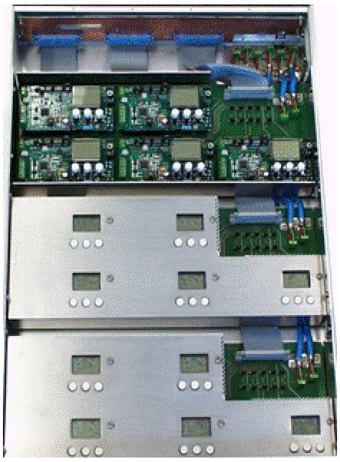

Figure 4. Drawer with fifteen intelligent valve positionners.

Figure 5. QRL Valves (3 types: Pneumatic on/off Valves-PV, Control Valves-CV, Quench Valve-QV).

Beside valves there are 2400 cryogenic heaters used as actuators. They are equipped with a resistant wire (25-100 Ohm) with heating power ranging from 25 W to 500 W (DC and/or AC - at a later stage they were limited to 25 W, consolidating the situation with improved design and materials) and they are installed inside the magnet cryostats and on the QRL elements.

The cryogenic process requires also temperature (TT), pressure (PT) and liquid helium level (LT) sensors. CERNOX^{TM} Resistive Temperature Sensor (50±20 Ohm at 300 K) very precise (few tens of mK) in low temperature range and Pt100 Platinum Resistance Thermometers (~ 100 Ohm at 0 ^{0}C) with sufficient accuracy over a wide temperature range (from -200 ^{0}C to +850 ^{0}C) are used as temperature sensors. The 720 pressure sensors are based on a metallic membrane, that slightly deforms under the applied pressure and a metal thin-film strain gauge, that senses the membrane deformation, incorporated in a resistive bridge topology. The 560 level gauges (LT), which are used for the liquid helium level measurements are made of a superconductive wire, connected in series with a small heating resistance. When current is applied to the gauge vertically positioned in the helium tank, the heating resistance warms the emerged part of the superconductive wire, which passes to the normal resistance state, while the immerged part remains into the superconductive state. Hence, a resistance measurement of the wire will provide the resistance value of the emerged part, from which the length of the immerged part can be calculated.

Cryogenic instrumentation crates house electronic cards for reading the temperature (TT), pressure (PT) and liquid helium level (LT) measurements, supply electrical power to the LHC cryogenic heaters (EH) and read the digital valve status. Approximately 800 of them (figures 6, 7) have been installed, connected and tested underground [6,7]. These crates communicate through a fieldbus, based on the WorldFip® protocol.

Figure 6. Instrumentation crate under the dipoles.

Figure 7. Instrumentation crates in the radiation protected areas.

4. Cryogenic Instrumentation Commissioning with MTB

Two test benches running LabVIEW™ have been developed at CERN to verify the correct functionality of the field instrumentation [8, 9]. They have been used at the card manufacturer's premises and at CERN. A portable test system for the WorldFip® crates has been used for in-situ diagnostics or special tests. The commissioning of the cryogenic instrumentation (electronics, cabling, sensors, actuators) in the tunnel was done by three Mobile Test Benches (MTB) and an additional one in the lab for parallel problem solving and software upgrades (figure 8). The MTB is a valuable tool for finding most problems with cables, sensors and connectors (i.e. wrong or not connected cables to the field instrument, wrong grounding/shielding in the cables or connectors, bad contacts, short circuits, open circuits, blown fuses, damaged cables or connectors, missing connections and mismatches with specifications and database, missing info in the database). The MTB is based on a PXI platform, running LabVIEW™ application. The PXI® rack houses:

- An embedded controller by National Instruments™, running Windows XP®.
- Two FIP® communication cards for the top and bottom level of the crates with different FIP® addresses.
- A 276×8 matrix module by Pickering™ for the switching of connections between the MTB instrumentation and the cards/cables under test.
- One programmable resistor module by Pickering™ for the simulation of the various sensors during the card tests.

- Various other cards (power supply card, multimeter card).

Other important components of the MTB are:

- One Keithley™ 2400 SourceMeter® for resistance measurements in 2-wire mode and current sourcing for the 4-wire measurements.
- One Keithley™ 2182 Nanovoltmeter® for accurate voltage sensing for the 4-wire measurements.
- A connector panel, which provides the physical interface between the MTB instrumentation and the cards/cables under test.
- One heater card test box, which houses power relays, used to route power from the heater card to the load during the heater card test.
- One UPS (Unbreakable Power Supply), which supplies all MTB electronics with AC mains power (to avoid shut down during short removals from one crate to another).

The following tests were performed:

- Consistency test. Purpose of the test is the comparison of matching of the crate configuration with the CERN Layout DataBase.
- Card test. Purpose of the test is the validation of the correct functionality and accuracy of each electronic card. This is the only test for which the criteria pass/fail (reference values, tolerances, etc) are hard-coded in the MTB software, implemented for every card type.
- Instrument test. Purpose of the test is the verification that each instrument (sensor/actuator) is physically present at the machine, correctly wired and properly connected and it has the expected resistance value, given the instrument type and the machine conditions. The test (for TT, PT, LT) is based on the 4-wire method, which uses two pairs of wires, one pair for excitation current application and another pair for the voltage drop measurement across the sensor for the noise reduction.
- Pin-to-Pin test. Purpose of the test is the detection of the electrically measurable errors in cable/instrument (short circuits and low insulation resistance) measuring the resistance between all pin combinations of a cable connector and the resistance between each pin of the connector and ground in 2-wire mode.
- FIP® test. Purpose of the test is a final cross check of the full readout chain (sensor+electronics) as it requires all the cables to be connected back to the crate. The FIP functionality is already checked during the card test. During this test the sensor 4-wire resistance value is returned and comparison with the 4-wire measurement of the instrument test takes place.

Beside these tests, monitoring which is not actually a test, but rather a useful tool before testing start, that shows all the measurements the crate performs (crate not powered, missing or not connected cable, instrument improperly installed and electronic card not operational) is necessary to take place. It provides an overview of all data that the crate feeds to the FIP network (sensor measurements, noise levels, card state etc).

The troubleshooting tools that have been used or developed in order to solve the problems arising from MTB and its components are the stand-alone loads (connectors with discrete resistors internally connected), digital multimeter matrix relay test and cabling test. Purpose of the matrix relay test is to check the MTB matrix for stuck open relays or relays with worn out contact based on the all possible paths (relay combinations) measurements and report of all paths with resistance value higher than a predefined limit. Purpose of the cabling test is the identification of possible short circuits in the MTB wiring including the matrix, the connector panel and the MTB cables.

The MTB project uses Perforce®, a Software Configuration Management (SCM) tool that provides a centrally managed storage area for all files of a project, keeps detailed track of the history of each managed file (versions, changes, bug-fixes, comments, etc.) and allows collaboration amongst users. More specifically Perforce® helps to manage the LabVIEW™ software distribution from the developer team to the operator team, individual crate configuration files and also the results for all cryogenic instrumentation crates. All crate data stored in layout database. XML® data files (CIDs, FIP® addresses, type of cards, active channels, cable numbers, type of sensors etc) are useful to overcome constraints such as size and complexity of layout database, network presence and speed at the tunnel. The results are stored locally in the corresponding folder of the crate and after the completion of tests are submitted to the Perforce® server and MTF - a database that stores the data related to the management of the LHC equipment. Information about electronics and instrumentation is stored in Layout Database.

Three mobile test benches have been used, working in parallel, having two shifts per day (morning/evening), when necessary.The test duration varied between 2 and 10 hours/crate, depending on the crate equipment and complexity. The rate achieved was ~2-3 crates/MTB/shift in average for the ARC (tunnel) and ~1 crate/MTB/shift for the LSS (protected areas), while the commissioning duration was 2-3 weeks per sector (tunnel) and 1 week for protected areas depending on problems. The increased experience accelerated the procedure to this level. The extra iterations after the repairs have not been taken into account. Due to the peculiarities of LSS the electronic crates in corresponding protected areas needed a higher investment of testing time and number of iterations, as shown in figure 9. The average retesting iterations was 1.6 for the electronic crates in the tunnel and 2.4 for the ones in the protected areas (PA).

The most common problems found were related to electronic cards, instruments, cables, bad contacts, short circuits, open circuits, wrong grounding, database views refresh state, missing info in the database, FIP® communication or components of the MTB itself. Noisy channels/cards have been found in the 14 % of the electronic crates in the tunnel and 6 % of the corresponding ones in the protected areas. The latter was quite common at the early stages of the commissioning and during the commissioning of the Sector 34 (figure 1) that was characterized by relatively higher level of humidity. This fact has caused extended testing times, not included in the above mentioned estimation.


Figure 8. Mobile Test Bench in action.

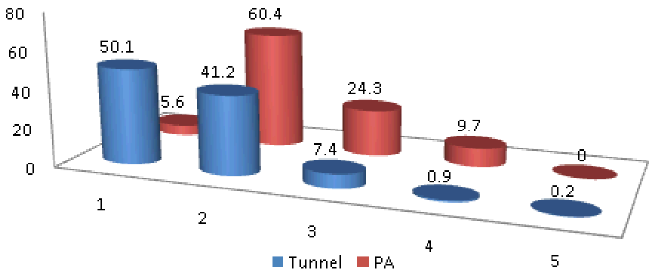

Figure 9. Percentage of instrumentation crates versus number of iterations for the tunnel and the protected areas.

5. High Voltage Tests

The LHC electrical feed boxes (figure 10) are liquid helium cryostats, which support and cool the high temperature superconductor current leads operating between 600 A and 13 kA. These current leads provide the electrical link between the warm cables (at room temperature) and the cold superconducting electrical circuits. In order to monitor those temperatures, two thermometers are mounted on each current lead. The fact that some of the wires carrying the signals from the TTs are in galvanic connection with the circuits that supply the magnets, requires high voltage qualification tests to be performed on the related cables, patch panels and electronic cards.

The aim of the tests is to check for conformance of the entire electrical line related with the temperature read-out from the TTs on the DFB current leads.

The test procedure consists of three main steps:

- Verification of grounding of the cable shields.
- Measurement of insulation resistance between all signal wires and the ground, through the complete chain.
- Measurement of insulation resistance between the signal wires of each current lead (8 active wires + 4 shieldings) and the signal wires of the other current leads.

For the ground continuity test, the acceptable resistance is below 1 ohm. The duration of all the insulation tests is set to one minute and the acceptable maximum leakage current is 60 nA. The test voltage is 1.9 kV for the cables related to 13 kA current-leads and 600 V for the others.

In total 185 cables and 929 channels have been tested. High voltage breakdown has been detected at the level of 7.6 %. All the cases have been repaired and in most cases the reason was humidity in the cables. In most cases the measured leakage current was below 20 nA.

Figure 10. High Voltage tests in one of the 52 DFBs of various types.

6. Conclusions

The cryogenic instrumentation commissioning necessary to ensure that all relevant elements work properly, although very demanding in terms of time and manpower investment has been successfully completed. The operational performance (within specifications) has exceeded 98 % for thermometers and ~100 % for other instruments.

The MTB was a valuable tool for finding most problems with cards, cables, sensors and connectors. It was a relatively complicated tool with long debugging period for exhaustive checks. Increased responsibility of the operator for results interpretation/evaluation and reporting was necessary for the commissioning of approximately 800 electronic crates and more than 12000 cryogenic sensors and actuators.

Acknowledgment

We would like to deeply thank our colleagues from AGH University of Science and Technology in Krakow and all the members of the CERN LHC cryogenics instrumentation team for their help, contribution and fruitful collaboration.

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