EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 1169

THE CONTROL SYSTEM FOR THE CRYOGENICS IN THE LHC TUNNEL

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Abstract

The Large Hadron Collider makes extensive use of superconductors, in magnets for bending and focusing the particles, and in RF cavities for accelerating them, which are operated at 1.9 K and 4.5 K. The process automation for the cryogenic distribution around the accelerator circumference is based on 16 Programmable Logic Controllers, each running 250 control loops, 500 alarms and interlocks, and a phase sequencer. Spread along 27 km and under ionizing radiation, 15 000 cryogenic sensors and actuators are accessed through industrial field networks. We describe the main hardware and software components of the control system, their deployment and commissioning, together with the project organization, challenges faced, and solutions found.

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Presented at the ICEC 22 - ICMC 2008 Conference
21-25 July 2008, Seoul, Korea

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 21 July 2008

The control system for the cryogenics in the LHC tunnel

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INTRODUCTION

The Large Hadron Collider (LHC) at CERN is a 27 km proton-proton accelerator-collider, lying some 100 m underground; it will soon be operational and will eventually reach the unprecedented energy of 7 TeV per beam and luminosity of 10^{34} $cm^{-2}s^{-1}$ [1].

The LHC (Fig. 1) has eight Insertion Points (**IP**s), separated by sectors of about 3.3 km each. Four of these points are dedicated to the main experiments (P1-ATLAS, P2-ALICE, P5-CMS, P8-LHCb), while two others are used for beam cleaning (P3, P7), one for the beam dump (P6), and another for the RF accelerating system (P4).

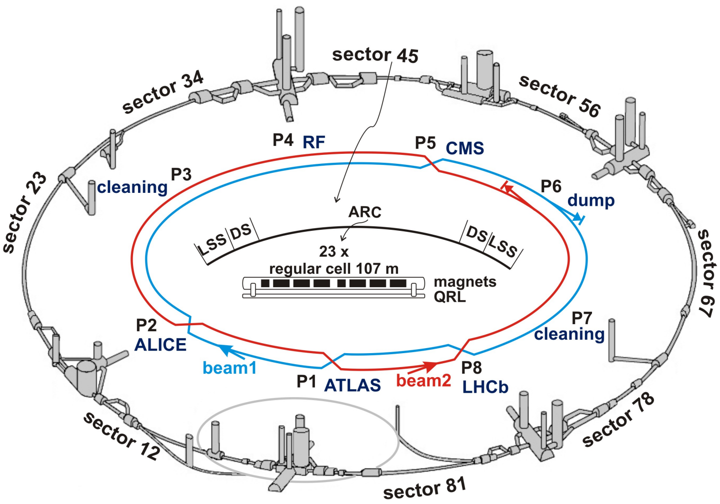

Fig. 1: the 8 LHC sectors, the 2 beams, the ARC and its cells

Each **sector** comprises: a curved section of 2 460 m (called **ARC**), with 23 regular cells of 107 m in a continuous cryostat; a dispersion suppressor (**DS**, 170 m) at each extremity of the ARC, and a long straight section (**LSS**, 270 m) near each IP.

In the ARC, every cell contains two sets of 3 steering dipoles and 1 focusing - defocusing quadrupole; all the ARCs and DS together comprise 1 232 main dipoles and 392 main quadrupoles. Both of these types of superconducting magnets operate in superfluid helium at 1.9 K, in order to reach respectively a field of 8.3 T, and a field gradient of 223 T/m, when powered to 11.8 kA. Associated to these main magnets, there is a great number (4 800) of smaller superconducting corrector magnets.

In the LSS there is a wide diversity of dipoles, quadrupoles and multipole correctors, with various functionalities: 86 quadrupoles, cooled at 4.5 K; 20 separation dipoles and 32 “inner triplet” quadrupoles near the experiments, cooled at 1.9 K; 114 conventional warm dipoles and quadrupoles, in high radiation areas where the heat loads are too high for safe operation of superconducting magnets.

A cryogenic distribution Line (**QRL**), running alongside the magnets, feeds them with helium through jumper connections (every 107 m in the ARC). Scattered along the LHC circumference, 10 000 sensors and actuators are mounted either in the magnets or in the QRL.

At every IP, several electrical feed boxes (**DFB**) hold and cool the superconducting current leads, through which the magnets are powered; overall, 52 DFBs are equipped with 5 000 cryogenic instruments.

At P4, the two counter-rotating proton beams will each be accelerated up to 7 TeV, by 2x8 superconducting RF (400 MHz) cavities (**ACS**), operating at 4.5 K, and including 200 cryogenic instruments.

HARDWARE

Fieldbuses

As the cryogenic instruments are distributed over large distances, they are accessed by industrial field networks. These fieldbuses allow considerable simplification in cabling and maintenance, compared to classic point-to-point connections between process controllers and field devices; in addition, they offer the capability of remote diagnosis and configuration.

Whenever possible, the Cryogenic Distribution Control System (CDCS) is based on well-known [2] standard industrial equipment, like high-end S7® Programmable Logic Controllers (**PLC**) and Profibus® remote-IO stations, both from Siemens™. Nevertheless, specific developments were necessary:

1. A large part of the front-end electronics has been designed at CERN [3], to include high-accuracy signal conditioning for thermometry, and to be radiation tolerant (rad-tol) in order to cope with the high level of ionizing radiation in the LHC tunnel. Each sector has (Table 1) more than 100 rad-tol electronic crates, with **WorldFIP**® bus interfaces and signal conditioner cards for temperature, pressure, level sensors and for electrical heaters. Some 80% of the crates are evenly distributed, placed under the ARC and DS magnets, whereas the remainder is concentrated in radiation-protected areas (UA, UJ, RR) near the IPs, because they cannot withstand the radiation in the tunnel LSS.
2. Under CERN's requirement, Siemens developed a version of their **Profibus** "intelligent" valve positioner [4] with its electronics, which is radiation sensitive, split from the valve pneumatic actuator. In each sector there are about 180 such positioners, grouped in 4 radiation-protected areas: 2 (UA, UJ) near the IPs and 2 (RE) in the ARC (Fig. 2).

Table 1: amount of instrumentation and control components

	TT	CV	PV QV	PT	LT	EH	total	FIP crates	FIP segments	Profibus segments	PLC	CCL	alarms interlocks
average / sector	1 000	325	90	90	65	310	1 880	100	8	5	2	2x250	600+500
total all-sectors	8 000	2 600	720	720	520	2 480	15 040	800	68	42	16	4 000	8 800

Per sector, eight WorldFIP network segments (1 Mbit/s) access data from most of the thermometers (TT), pressure sensors (PT), level gauges (LT), and digital inputs (like on-off valves end-switches or pressure switches), and convey the commands for electrical heaters (EH).

Also per sector, five Profibus network segments (1.5 Mbit/s) are used for the command of on-off valves (QV, PV), for the command and feedback of analog valves (CV) and of some heaters (EH), and to access "intelligent" instruments in general.

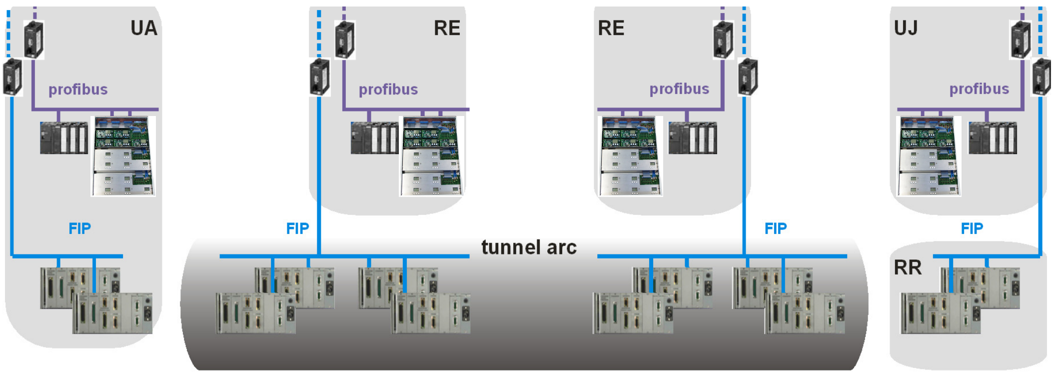

Fig. 2: Profibus and WorldFIP layout in tunnel and protected areas

The commissioning of the hardware components has already been reported elsewhere [3, 5, 6, 7, 8].

Controls Architecture

As the Profibus protocol is seamlessly integrated with the Siemens PLCs, these communicate directly with the Profibus remote-IO stations and valve positioners, confined in protected areas. Conversely, the WorldFIP protocol is unintelligible for the Siemens PLCs; the WorldFIP-PLC communication gateway is provided by dedicated Front-End Computers (**FEC**s) [9]; cycling at 500 ms, they perform data conversion to physical units, including the calculation of individual non-linear transfer functions.

Per sector, there are 2 PLCs (one for the ARC and DS and the other for both LSS); also cycling at 500 ms, they run some 250 Closed Control Loops (CCLs) and 500 alarms and interlocks. The CERN secured Ethernet Technical Network (TN) is used for the communication between the PLCs, the FECs, the SCADA, and with other systems' PLCs and SCADA (Fig. 3).

The PLCs and FECs are installed in surface buildings, close to each of the 5 cryogenic plants (at P18, P2, P4, P6, P8), and are connected to the underground Profibus and WorldFIP equipment via optical fibers, signal repeaters and copper cables.

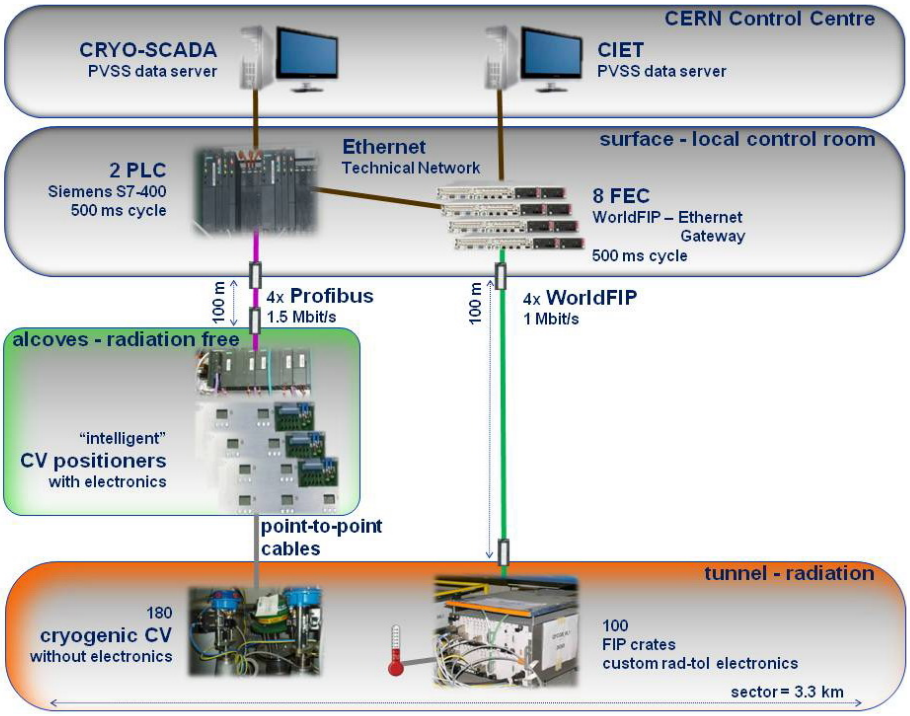

Fig. 3: controls architecture

The man-machine interface is based on two SCADA systems (Supervisory Control and Data Acquisition), built with PVSS® and running on data-servers hosted in the CERN Control Center (CCC):

1. CRYO-SCADA, used by the operators to access data and commands relevant to the cryogenic process, comprises synoptic panels (that provide navigation, monitoring and control for all instruments), alarms and interlocks handling, real-time and historical trends, data and event logging and archiving (Fig. 4);
2. CIET (Cryogenic Instrumentation Expert Tool), used by the control experts to remotely monitor, configure, parameterize, and reset the WorldFIP read-out channels.

The PVSS data-servers are accessible all over the CERN site, via the TN, on clients locally running Human Machine Interfaces (HMI): Operator Work Stations (OWS) or Engineering Work Stations (EWS). The data-servers regularly send all data to long-term central storage (Logging) for off-line analysis.

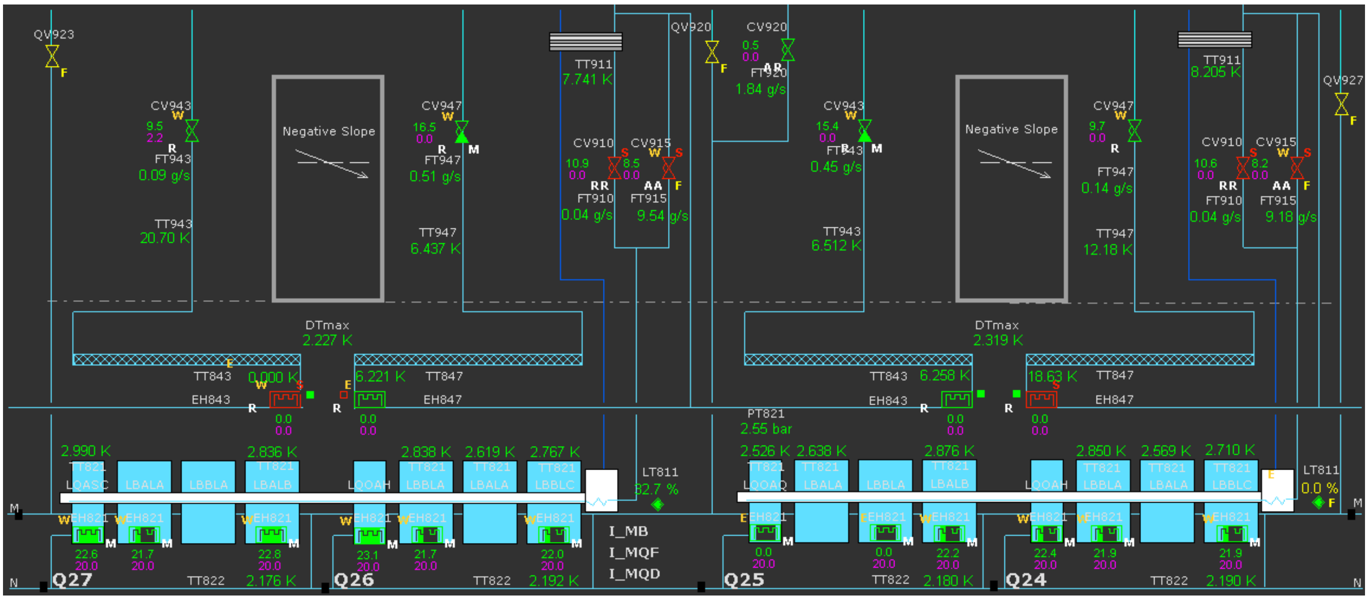

Fig. 4: part of synoptic screen in CRYO-SCADA, showing two ARC cells fed from the QRL

SOFTWARE

Databases

Because of the number and diversity of the cryogenic instrumentation, several databases (DBs) are intensively used to manage the characteristics and the relations of instruments; they are the knowledge source for front-end hardware (WorldFIP and Profibus) manufacturing, installation and test; moreover, the automated software production depends totally on information directly extracted from DBs. Furthermore, web interfaces offer human access to those DBs, to manually store or retrieve data.

The **LHC Layout DB** [10] manages the information on all LHC equipment topology, and logical or physical relationships; we have stored there the whole cryogenic instrumentation and controls infrastructure: cables, connectors, pin-outs, electronic modules, crates, racks, fieldbuses, and logical instrumentation channels; it can be directly accessed by the electronics manufacturer to configure the crates, by the test stations in the field, and by the automated generator of specifications for the control software.

The CERN Engineering and Equipment Data Management System (**EDMS** [11]) provides storage and management of all engineering documents and equipment information; the application **MTF** (Manufacturing and Test Folder [12]) is thoroughly used to store and track individual equipment data, comprising: calibrations, results of test measurements, status flags, and strict follow-up of the steps of manufacturing, assembly & test procedures.

Our **Controls Layout DB** provides an interface between MTF, LHC Layout DB, and **Thermbase** (the dedicated DB where we have loaded the calibration data, fitting functions and interpolation tables for all thermometers in the LHC). In addition to instruments data, Controls Layout also contains additional parameters such as instrument relations in control loops, PID coefficients, alarms and interlocks thresholds. We are currently developing **Sensorbase DB**, as an upgrade of Thermbase, in order to consistently gather all the metrological data of thermometers, pressure sensors and level gauges.

UNICOS baseline

The control software (for FEC, PLC, CIET, and CRYO-SCADA) is mostly based on the CERN UNICOS framework (UNified Industrial COntrol System [13]), which provides methodology, components, and tools to design and program industrial control systems; it includes: base functions library (with modular PID algorithm), skeleton templates and code generators / replicators, which allow rapid prototyping of the control system while minimizing human intervention and error sources.

The information from the various DBs is combined in specific views of the Controls Layout DB (Fig. 5), to be easily accessed by the **specifications generator** that was built to produce files with:

1. hardware configuration for the PLCs and Profibus front-end;
2. Excel® tables for the code generators; grouped by UNICOS object type, these spreadsheets list all instrumentation channels, associated parameters, calibration IDs, and logical connections.

The specifications for one PLC contain 5 600 objects of 16 types. For each object, the **UNICOS S7-Generator** creates the memory assignment for PLCs and SCADA, the PLC source code for the objects and for the process logic, and the code for the PLC-SCADA communication middleware. The source code of a single PLC typically contains 250 000 lines of SCL (Structured Control Language); it is compiled together with the **UNICOS Library**; the machine code loaded in the PLC memory amounts to more than 3 MByte.

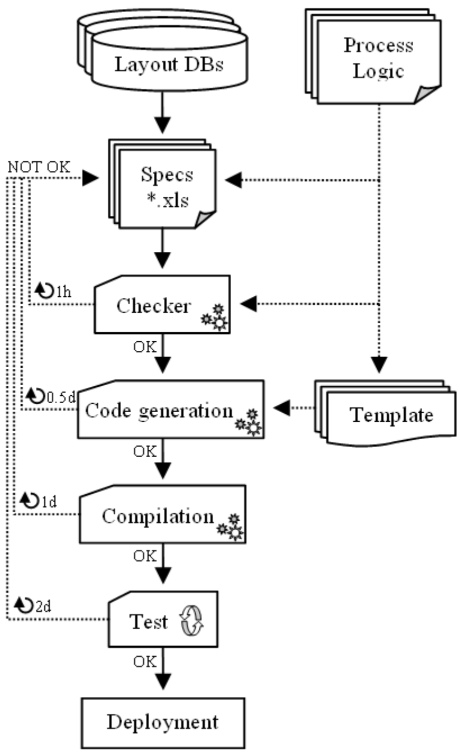

Fig. 5: PLC code production cycle

PLC code production

After the development and commissioning of PLC code for the first LHC sector, it became clear that the UNICOS baseline generators had to be adapted and extended to cover the singularities of the LHC machine, especially in the LSS [14]. An **additional code generation tool** handles process specificities not covered by the UNICOS generators, such as: data blocks for communication with external systems (700 variables per sector); logic for magnet powering interlocks (10 per sector, calculated from up to 250 signals, which now takes a few minutes to code instead of several days; logic for the process sequencer (Fig. 6); calculation of min/max/avg values for families of instruments (4 200 functions with up to 250 arguments).

The standard UNICOS validation tools did not cover the newly defined parameters, which had to be manually checked; many errors were found close to the end of source code generation or even later, during compilation or during operation; therefore, the production-verification-correction cycle could take several days. For the following sectors, a newly built **specifications validation tool** permitted to automatically check: communication variables, logic parameters, object dependencies, completeness of the data, and the integration of the LHC singularities; most errors could thus be discovered within an hour.

Based on the UNICOS skeleton, 140 **logic templates** were written for families of controllers, valves, heaters, and also for global logic, process sequencer, alarms & interlocks. Additionally, pieces of code that are common to several templates were replaced by calls to external functions with argument passing; modifications of process logic are thus faster to implement and less error-prone.

Before deployment in the production machines connected to the field, the project is loaded in a test PLC, with simulated instruments, for thorough tests by the process engineers.

The UNICOS automated checking and generation tools proved to be essential for flexible and robust PLC code generation; the additional tools that we developed improved the code reliability, by minimizing human mistakes, reduced the production cycle to 2 days, and simplified long term maintenance.

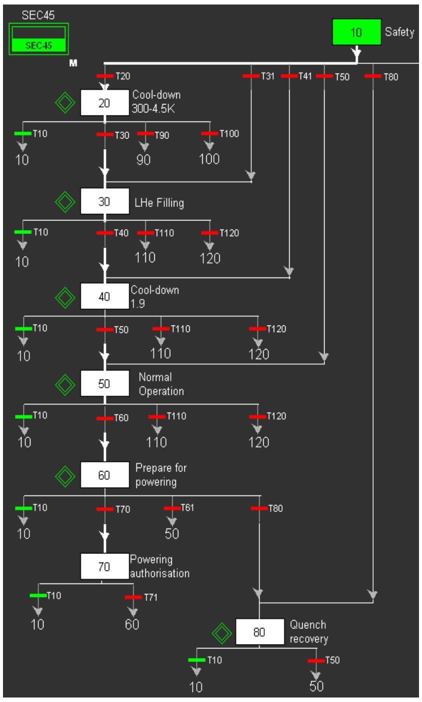

Fig. 6: command panel for sequencer

SCADA

In every sector, the SCADA contains some 200 different panels, of which 40 contain synoptic diagrams (Fig.4), 35 are bar-graphs, 35 concern the process sequencer (Fig.6), and 60 are dedicated to alarms and interlocks. Half of the synoptic panels are in the ARC and present similarities between themselves in one sector, and from one sector to another. We have created a few generic **template panels** with only static drawings and each one with a rather complex PVSS initialization script. Every time a panel is loaded on the HMI, its script reads a string of parameters with information of what instrument widgets to add to the panel, and where to position them, according to which ARC cell it corresponds. The different strings of parameters were previously created by a **parameter generator**, directly accessing the Layout and Controls DBs to know which instruments have to be visualized in a given panel.

Using this methodology of parameterizing repeated occurrences of similar screens, we have reduced by a 15 fold the number of different ARC panels in the whole LHC, thus dramatically shrinking the development time. Unfortunately, the panels of the tunnel LSS and of the DFBs are not repetitive and could not be parameterized; they have all been manually designed.

The instruments that are flagged in the DBs as not connected to the control system are automatically made **invisible** by the parameter generator, who just does not add them to the parameter string. Furthermore, when a damaged instrument must be removed from the panel, its reference can manually be deleted from the parameter string, until a new string generation can be automatically done from an updated DB.

In order to visualize the geographical profile of physical variables, each sector needs 35 **bar-graph** panels; they are also based on a very small number of template panels, with a script to read the parameters containing the names of variables to be plotted. The same bar-graph templates are used in all sectors, in conjunction with the appropriate set of parameters.

Likewise, the visualization in CIET of the contents of the individual **FIP crates** is based on one single template and 800 different strings of parameters.

Perl® scripts were developed to convert panels from CRYO-SCADA to CIET; because, although the static graphics are the same, variable names are slightly different between the two systems; these scripts are used to copy and convert fixed synoptic panels, parameterized synoptic panels or bar-graph panels. The parameter generator has also been extended to CIET crates, synoptics and bar-graphs.

All these tools and generators have been integrated in a Panels Maintenance Framework (PMF), from which can also be launched the PVSS HMI and Graphical Editor. Moreover, many dedicated PVSS scripts were written for easy application repetitive operation commands to families of SCADA objects.

CONCLUSIONS

The control software production relies on a set of databases and on a package of automatic generation tools, which have been developed to create data and code in several steps, according to a well established methodology.

By the end of 2007, two sectors have successfully reached nominal conditions and passed several magnet powering tests [15]. The software production cycle had then to be reviewed, in order to cope with the tight schedule required for the following sectors; applying extra effort on automatic code production and check, we managed to reach a rate of 1 new sector every 2 weeks, while in parallel giving support and performing modifications on sectors already in operation.

The Closed Control Loops performance depends on the quality of Ethernet communications between PLCs and Front-End Computers; thanks to the low network occupancy, the high availability of the Technical Network infrastructure, and the effort put in topology optimization, the controls performance is not hampered by the fact that Ethernet is not a deterministic network like the fieldbuses.

All eight sectors are now cold and they are expected to reach nominal temperature and magnet current this summer, ready for the first particle injections. The operational performance, within specifications, of the different instrumentation channels before cool-down has exceeded 95% for thermometers (and about 100% for other instruments) for the 3 first sectors. [6, 7]

The experience gained with the past LHC-String projects [2] has set a valuable ground for the definition of the hardware & software architectures, and of the procedures for building and testing them.

We wish to express our gratitude to the colleagues from industrial support and from the collaborating Institutes, for their motivation and professionalism – without them, this venture would have never been possible; acknowledgements also to Prof. Evangelos Gazis from NTU-Athens, to Dr. Jan Kulka from AGH-Kraków, and to Dr. Roberto Saban from CERN, who put in place the Hardware Commissioning Collaboration; and finally to the cryogenic operation team, for their help in the commissioning and for their patience while waiting for our improvements or repairs.

REFERENCES

1. Brüning O et al, LHC design report Vol. I, CERN-2004-003 (2004)
2. Gomes P et al, Experience with the String2 Cryogenic Instrumentation and Control System, ICEC20, Beijing, China (2004)
3. Vauthier N et al, First Experience with the LHC Cryogenic Instrumentation, CEC-ICMC2007, Chattanooga, USA, (2007)
4. SIEMENS, Electropneumatic Positioner with external Operating and Control unit, SIPART PS2 PA, 6DR59xx (2004)
5. Fluder C et al, Experience in Configuration, Implementation and Commissioning of a Large Scale Control System, ICCC2008, Sinaia, Romania (2008)
6. Penacoba G et al, Outcome of the Commissioning of the Readout and Actuation Channels for the Cryogenics of the LHC, EPAC08, Genoa, Italy (2008)
7. Lopez A et al, Quality Assurance of LHC Cryogenic Instrumentation at Installation and Commissioning: Practical Experience, ICEC22, Seoul, Korea (2008)
8. Avramidou R et al, The commissioning of the instrumentation for the LHC tunnel cryogenics, IEEE NSS-MIC 2007, Honolulu, Hawaii, USA (2007)
9. Blanco E et al, LHC Cryogenics Control System: Integration of the Industrial Controls (UNICOS) and Front-End Software Architecture (FESA) Applications, ICALEPCS07, Knoxville, Tennessee, USA (2007)
10. Le Roux P et al, The LHC Functional Layout Database as Foundation of the Controls System, ICALEPCS07, Knoxville, Tennessee, USA (2007)
11. Boyer T et al, The CERN EDMS An Engineering and Equipment Data Management System, EPAC02, Paris, France (2002)
12. Delamare C et al, Manufacturing and Test Folder: MTF, EPAC02, Paris, France (2002)
13. Gayet Ph et al, UNICOS a Framework to Build Industry-like Control Systems Principles Methodology, ICALEPCS05, Geneva, Switzerland (2005)
14. Fluder C et al, An Automatic Approach to PLC Programming for a Large Scale Slow Control System, ICCC2008, Sinaia, Romania (2008)
15. Serio L et al, Validation and Performance of the LHC Cryogenic System through Commissioning of the First Sector, CEC-ICMC2007, Chattanooga, USA, (2007)