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**THE DEVELOPMENT OF THE CONTROL SYSTEM
FOR THE CRYOGENICS IN THE LHC TUNNEL**

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Abstract

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This paper reviews the control system architecture and the main hardware and software components; presents the hardware commissioning and software production methodologies; and illustrates some of the problems faced during development, commissioning and nominal cryogenics operation, together with the solutions applied.

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Keywords: LHC, cryogenics, control system, PLC, commissioning.

1. INTRODUCTION

The LHC (Fig. 1) is the world's largest and most powerful particle accelerator, designed to collide two proton beams head-on at the energy of 7 TeV per beam. Four main detectors: ATLAS, ALICE, CMS, and LHCb have been built to identify the particles produced in collisions.

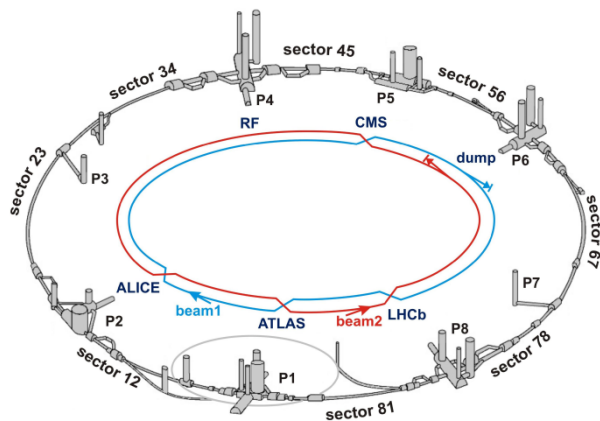


Fig. 1. Layout of 8 LHC sectors, RF and main detectors

The LHC is a 27km ring located about 100 meters underground. It is divided into eight 3.3 km long sectors. A single sector is made of a curved part (ARC) with one long straight section (LSS) at each extremity.

The beams are guided along the tunnel by superconducting magnets and accelerated by superconducting radio frequency cavities (RF). The current is supplied to the magnets through electrical feed boxes (DFB). All cryogenic equipment is maintained at 1.9 K or 4.5 K by helium supplied through a cryogenic distribution line, which runs along the magnets and is linked to 8 cryogenic plants, grouped in 5 technical sites. Each plant is comprised of warm compressors, refrigeration units, transfer lines and cold interconnection boxes.

2. CONTROLS ARCHITECTURE

The process automation for the cryogenics in the LHC tunnel follows a hierarchical industrial control system architecture (Fig. 2). It is composed of remote input / output modules (RIO), Programmable Logic Controllers (PLC), and a Supervisory Control And Data Acquisition (SCADA)

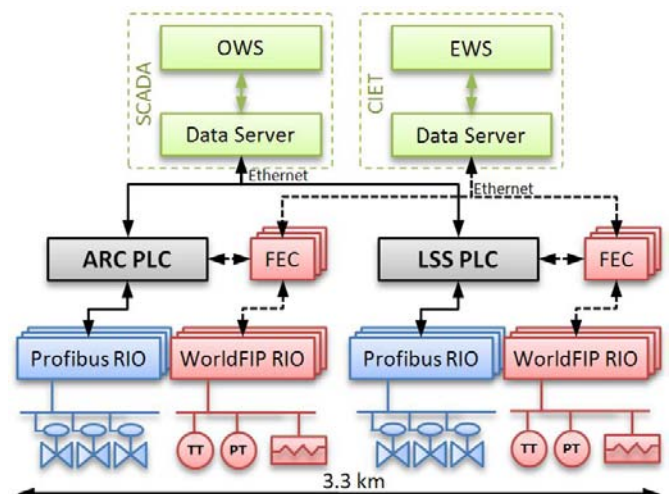


Fig. 2. Control system layout for one LHC sector.

2.1 Cryogenic Instrumentation & Remote I/O

About 10 000 sensors and 5 000 actuators have been installed, in order to keep the LHC tunnel cryogenics at nominal conditions (Table 1). Cryogenic process status is provided by sensors measuring temperature (TT), pressure (PT) and the level of liquid helium (LT). The process is controlled via analog and digital cryogenic valves and analog heaters. Additionally, the control system is equipped with several types of diagnostic devices and hardware interlocks, both represented by digital signals.

Table 1. LHC Tunnel Cryogenic Instrumentation

Instruments	Range	avg /sector	RF	Total
TT (temperature)	1.6- 300K	868	168	7 118
PT (pressure)	0-20 bar	105	14	855
LT (level)	Various	52	16	436
EH (heaters)	Various	297	10	2 392
CV (Control Valves)	0 - 100 %	323	18	2606
PV/QV (OnOff Valves)	On-Off	83	10	681
digital status signals	0-1	500	214	4 214

To cope with the distributed instrumentation, the Profibus-DP (Decentralized Periphery, Fig. 3), Profibus-PA (Process Automation, Fig. 4) and WorldFIP® (Fig. 5) fieldbuses are employed.



Fig. 3. Profibus DP: Remote IO

Profibus is used whenever the front-end electronics can be housed in radiation protected areas. The Profibus-DP RIO modules, driving digital valves or reading diagnostic signals, have been placed in those areas. The Profibus-PA intelligent valve positioners, normally attached to the pneumatic actuator, have also been moved into protected areas.



Fig. 4. Profibus PA: drawers of intelligent valve positioners

WorldFIP®, being radiation tolerant, is used where the front-end could not be moved away from radiation. To communicate with the upper level of the control system, it needs industrial computer gateways, called Front End Computers (FEC). The FECs capture raw signals from the conditioners and convert them into physical sensor information; and vice versa for commands.



Fig. 5. WorldFip: Remote IO

2.2 DCS & SCADA

Considering the large scale of the cryogenic system, it was necessary to distribute the PLCs over the eight LHC sectors. Each sector is controlled by two SIEMENS® S7-400™ PLCs (Fig. 6). The tunnel cryogenics is protected by 5 500 alarms and software interlocks and controlled by 3 600 Closed Control Loops (CCL) with a PID algorithm.

The phases of the process have been classified as four operational modes: cool-down; emptying; stand-by at 75 K

and warm-up. To handle the cool-down steps and transitions between them a phase sequencer has been designed. Around 35 000 functions, function-blocks and data-blocks were automatically generated in 15 000 source files, written in Structured Control Language (SCL) (Table 2).

Table 2. Software components

Type	avg /sector	RF	Total
SCL source files	1792	544	14 884
Functions, funct-blocks, data-blocks	4193	1 482	35 032
Alarms & interlocks	679	98	5 536
Closed Control Loops	444	51	3 610
SCADA synoptic panels	204	10	1 650



Fig. 6. Rack with 4 PLCs for 2 sectors (1 cryogenics site)

The SCADA layer is based on PVSS II™; it provides the classical features of a SCADA including the Human Machine Interface (HMI), through which the operators monitor and act on the cryogenic facilities, from local or central control rooms. It comprises around 1 650 panels with process synoptics, alarm and interlock handling, event logging, real-time and historical trend monitoring, navigation and global operation tools.

A specialized tool was created to configure and diagnose all the sensors located in the tunnel: the Cryogenics Instrumentation Expert Tool (CIET). This tool was developed using the same SCADA environment: PVSS II™; it allows instrumentation engineers accessing the full data of the WorldFIP® devices.

3. HARDWARE COMMISSIONING

3.1 WorldFIP® RIO test

In order to validate the FIP instrumentation, four Mobile Test Benches (MTB) were built and several test procedures were designed. The MTB automatically validates the signal conditioner cards, the communication interface and the attached sensors (PT, TT, and LT) and actuators (EH). A dedicated testing sequence is set up by the MTB for each RIO, according to information obtained from a Layout Database.

The testing procedure is split into a consistency test and an electrical test. During the consistency test, the MTB checks whether there is a correlation between the crate descriptions stored in the Layout Database and the components installed in the crate. The electrical test contains four parts: an instrumentation test that verifies the physical existence and proper wiring of sensors and heaters; verification of the electrical connection between sensors and crates; validation of the correct functionality of each of the electronic cards housed in the crate; and a check of all the components together. Finally, all test results are stored automatically in a database. The results are described by Penacoba et al. (2008)

3.2 Profibus RIO test

The test procedure of the control valves comprises two stages: the first is executed in the laboratory, and the second one executed in the LHC tunnel. In the laboratory, the configuration and automatic initialization of the positioner units are performed with a reference valve. In the tunnel, after the positioners have been connected to the corresponding valves, they are again initialised; the motion direction and the min-max positions were verified by manually operating each valve's positioner from its local command panel.

The Siemens PDM® tool provides remote initialization or restart of any valve positioner, in case of failure and despite tunnel access restrictions. A dedicated CERN application was also developed to use PDM for campaigns of simultaneously changing, automatically modifying or saving the parameters of several positioners.

Digital valves require a 24V DC command, reaching the valve farthest from the alcove, where the power supply is localized. These valves' operation was verified using a tool simulating the driving signal and simultaneously reading feedback from end switches.

Positioner units are connected to the Profibus DP through DP/PA Link + Coupler modules, while the command signals for the digital valves and the digital input signals are managed by Profibus DP RIO modules. All this equipment is housed in crates, which were electrically tested in the laboratory before installation.

Once installed in the alcoves, the network parameters were set up and the test procedure was executed using a portable PLCs. During the test, each RIO module was connected to the Profibus network in order to check consistency between the database and the physically installed components. The

parameters verified include: module type and version, address, and channel assignment. All test results were archived for future reference.

3.3 Valve automatic test

After the accessibility of each Profibus RIO component has been checked from the PLC, extensive tests of actuators operability were performed. The procedure aimed to repeatedly check the valve reaction time and the accuracy of the reaction to requests sent by PLC. Every second, for each tested valve the following information was registered: occurrence of an IO-error, valve reaction time, request-feedback difference, feedback position range. All data is gathered in the PLC and later copied into a spreadsheet for further analysis.

3.3 Coherence test

The final stage of hardware commissioning was the coherence test of all the instruments, using the complete system configuration. The aim of this test was to verify if all valves respond correctly to requests. The verification was performed by a team consisting of an operator responsible for sending requests and checking feedbacks on the SCADA synoptic and a technician present in front of the tested devices in the LHC tunnel.

4. SOFTWARE PRODUCTION

4.1 Unified Industrial Control System Framework (UNICOS)

UNICOS is a framework created at CERN to develop control applications. (Blanco, 2007). It allows a homogenization and simplification of the software production sequence corresponding to the two upper layers of a classical industrial control application. It provides the methodology, components, and tools for automatic production of PLC and SCADA code for processing IO channels; PLC process logic; code and PLC-PVSS communication middleware. The UNICOS package includes: a base functions library, templates for specification-documents, code skeletons and code generators.

A typical procedure for application development consists of the following steps: functional analysis of process; preparation of a specifications document; description of IO channels, field devices and Process Control Units (PCU), together with their associated parameters; completion of code skeletons based on process logic; validation of specification document imported to generator; code generation; creation of a PLC hardware configuration, respecting memory assignment in code; compilation of the code together with hardware configuration and UNICOS baseline library; software deployment.

4.2 Software Production

The cryogenics controls software relies on various automatic generation tools developed at CERN. The software is generated using data coming from several databases (DB) containing definitions of the cryogenic instrumentation, controls system components and process logic.

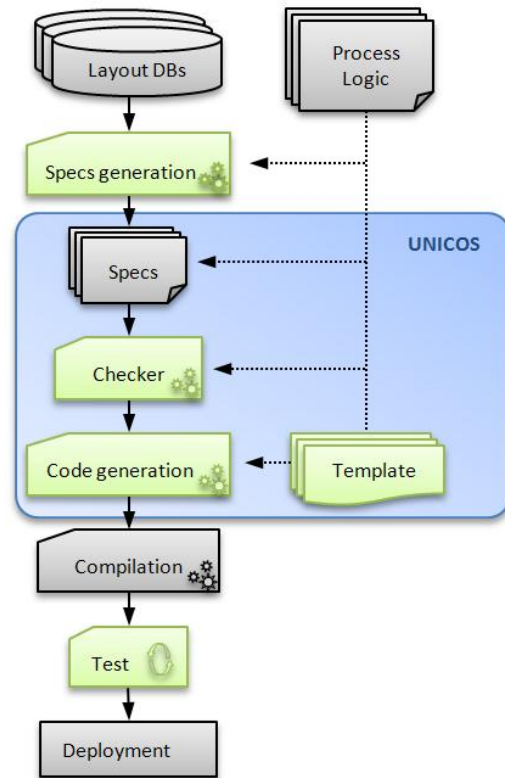


Fig. 7. Software production diagram

The software production process (Fig. 7) begins with the Specifications generation, using the view which combines data from several DBs and external spreadsheets. It extracts information required to produce a specification document and associated hardware configuration for PLC and then applies a set of rules and calculations to complete the objects, their parameters and dependencies.

The UNICOS automatic validation of the specifications was extended by a PERL checker. The aim of this tool was to shorten the code production cycle, by detecting most of the specification's errors at the very beginning. This way, we minimized the risk of having to repeat the software generation procedure. The PERL checker covers most of the aspects of the project, analyzing the specification for compliance with different rules i.e.: object dependencies and parameters, interlocks for given devices and completeness of the data.

Due to the specificities of the cryogenics process, a substantial piece of code had to be manually prepared by a programmer. Another PERL tool extends the UNICOS generator capabilities, in order to replace the programmer as much as possible. An example of automatically generated code is the calculation of minimal, average and maximal values for every cryogenic cell, where each calculation may be derived from one hundred arguments.

Automatic software generation required the creation of around 80 templates, based on the process logic and on the UNICOS skeleton. Any process logic modification forces the subsequent regeneration and compilation of the group of objects affected by the change. In order to avoid such situations, all recurrent pieces of code have been extracted from the templates and moved to external functions;

as a result only a single function is touched in case of logic update.

The last step before field deployment is the test of PLC and SCADA software, carried out by the process engineer on the development machines, to ensure the correctness of the translation from process functional analysis to machine code. Those development machines are not connected to the real instrumentation in the field; thus the check is performed by exploiting the UNICOS process state simulation features, by forcing the instruments status.



Fig. 8. synoptic in SCADA

In the cryogenics system there are circuits recurring multiple times; therefore, special generation tools were developed to replicate the corresponding panels (Fig. 8). Each sector has around 50 panels automatically produced from templates and around 150 static panels manually created on the basis of machine technical drawings and information collected in the Layout Database.

5. KEYS FOR CHALLENGING LARGE APPLICATIONS

5.1 Development

Even if UNICOS was a mature framework in the development of process control systems, a large adaptation was needed. The high-performance PLCs used in the cryogenics control were driven to their limits in terms of cycle-time and resources (memory and communications). UNICOS for SIEMENS S7 PLCs was totally revamped with the aim of optimizing resources and performance. This allowed the full deployment of the process control application.

The Industrial PCs, included in the control system layer, run a real time application based in a CERN in-house framework (FESA: Front-End Software Architecture). The development of this application imposed a block-design instead of a classic device-design. Dealing with such a large number of instruments imposed a logical grouping to keep treatment times coherent with a WorldFip sampling time of 500 msec. The application also included the automatic specification of the cryogenic instrumentation, both, sensors and actuators. Dedicated generators were developed to provide the required

capabilities and to accelerate the procedure of deployment. Demanding performance in the communication between PLCs and FECs also imposed an improvement of the Ethernet mechanisms and protocols.

The SCADA layer of the tunnel cryogenics is part of the complete LHC cryogenic control system. A distributed and high scalable system was designed due to the large quantity of exchanged data between the control and supervision layer (about 1 million of tags). A data server is employed to supervise each LHC sector. The whole SCADA includes 16 PVSS data servers (DS). The mechanisms for long-term archiving data, based on an Oracle database, have been largely improved in terms of performance. A nominal flow of 3.5 Gbytes/day is stored in such database.

5.2 Commissioning

Dealing with large systems imposes automatic procedures, not only during the developing phase but also for the commissioning; the time spent in this activity could be reduced as much as possible while keeping a high quality assurance standard. Having a common specification source as in the UNICOS framework is a key for coherence within the different controls components (PLCs, FECs, DSs). Moreover, the technical coordination of the commissioning became a challenging task, due to the involvement of several very specialized technical groups, solving highly complex problems. The experience shown that a great deal of problems were much easily solved when there was tight coordination of all commissioning teams, and effective communication between the responsible of the different equipment, such as: radiation-hard electronic crates, PROFIBUS & WorldFIP field bus, PLC architecture and PLC source codes and finally the Human Machine Interface.

This approach has improved a lot the commissioning process showing its best results for the rapid comprehension of the origin of the different errors and the dispatch of the required solutions.

The long commissioning phase started with a detailed inspection aimed at detecting installation and cabling errors, and was followed by automatic tests to ensure coherency between databases and the field. The commissioning of the instrumentation was done from the surface by using CIET; thanks to this tool, most of the channels of the cryogenic instrumentation used by the controls and cryogenic operation are monitored and validated.

After a period of cryogenic operation, the cool-down sequence was simplified, by organizing it in only two phases instead of the original eight, in order to improve the global operability. The improvement of the behaviour of the system was reached in different ways: through the implementation of median filters on all sensors, to avoid spikes; through first-order low-pass filter at the input of control loops; through control loops identification; and through optimisation of software interlocks list, where the non-essential ones were moved into the actuators' logic.

5.3 Deployment

Due to frequent changes in the LHC schedule, the tasks related to hardware commissioning had to be executed simultaneously in all LHC sectors. In 2007 it turned out that the period allocated to software preparation was not sufficient to take into account all the requirements coming from the functional analysis of the process and new proposals coming from LHC operators aiming to improve the system. After examining possible scenarios, the decision was to prioritize the main tasks. The software responsible for human and machine safety was given the highest priority. The process automation software was defined as necessary to operate system with second priority. Finally it was reasonable to assume that all system improvements that addressed only the comfort of work for the operators were postponed to future updates. As a result, in March of 2008 the software production procedure for the last LHC sector was put into practice.

The LHC cryogenics control system was deployed and fully operational before the LHC beam start-up in 2008. After that, reorganization from development mode to maintenance mode was carried out. The resources were reduced to just a few people taking care of system maintenance and updates. In September 2008 one of the LHC subsystems was damaged, which resulted in stopping the collider for more than a year. This time period was used to redefine process logic, taking into account the experience gained in the preceding phase.

The new functional analysis of the process (called Logic Phase II) brought improvements in safety, better operability through a major logic simplification and better availability of the LHC machine. The details are described by Gomes (2009). Preparing the redeployment took 6 months; during this time all databases, automatic generation tools and code skeletons were adapted to the new requirements. Regeneration of all software was performed during a period of 4 months, and the deployment time was reduced from 5 days in first sector to 3 days in the last 3 sectors. The presence of cryogenic temperatures in the tunnel and limited time window for deployment intervention forced all actions to be synchronized. The PLCs, SCADA and FECs software was uploaded simultaneously and started individually. The LHC tunnel cryogenics controls system was again fully operational, with the new logic, in September 2009.

6. CONCLUSIONS

Since the beginning of the project we took advantage of the CERN/UNICOS main features, such as reduced effort and software production time, increased code reliability, minimized risk of human mistakes, and simplified long-term maintenance.

Even if UNICOS was a mature framework in the development of process control systems, a large improvement was triggered by the specificity of the cryogenic installation in terms of: large number of instruments (physical IOs and IO software objects); integration of the WorldFip fieldbus (using FECs

and FESA); optimization of PLC resources and performance; demanding communication mechanisms between PLCs and FECs (using Ethernet).

During the commissioning phase, the technical coordination resulted in a challenging task, due to the involvement of several very specialized technical groups dedicated to solve highly complex problems. A significant improvement was obtained by introducing a global coordination of all commissioning teams.

During the operation phase, the main challenge has been to maintain a high-reliability standard, taking into account that some operational conditions might cause failure of the control system and, as a consequence, increase the downtime of the LHC machine.

In the last 2 years, after the first LHC operation in nominal cryogenic conditions, we have evolved towards simplicity in process control, databases, and generator of specifications; the control system is now more reliable and user friendly and much adapted to regular operation.

Taking into account the experience gained in the preceding phase, a major redefinition of the process logic was undertaken. The new functional analysis of the process brought improvements in safety, better operability through a major logic simplification and better availability of the LHC machine.

Like any large scale system, the LHC cryogenic control system is a living machine, which needs continuous high-level controls support and a very accurate and detailed technical documentation, in order to minimize the interventions need in terms of time and manpower.

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