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THE LHC CONTROL SYSTEM

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ABSTRACT

A new control system for the LHC machine has been developed building on the existing controls infrastructure of the CERN accelerators. While the primary target for this development is the LHC the aim is to deploy this system on the other accelerators at CERN starting with the LHC pre-injectors. All layers of the control system have been redeveloped. In the Front Ends FESA is a new software infrastructure using the CMW package to communicate with high level JAVA applications running in the Control Room. These developments support both 2 and 3 tier software architectures. The accelerator timing system has been renewed at the hardware level and extended to meet the needs of the LHC pre-injectors. In order to deal with the unparalleled complexity of the LHC, new database structures were put in place to describe the equipment, functional layout, installed configuration and to manage the operational data. Industrial components such as PLCs and SCADA have been selected for control of the cryogenic plant, the vacuum system, the quench detection system and are heavily employed in the machine protection systems (beam dump, collimators and interlocks). Various measures are necessary to integrate these developments into the traditional controls infrastructure. These developments are progressively validated during the commissioning of the LHC injection lines and the ion accumulator – LEIR- and during the commissioning of the LHC hardware.

The presentation will describe the different layers of this control infrastructure and be an introduction for the more detailed reports to be presented in the further sessions of this conference. It will also report on the current status of the work and the remaining milestones before LHC operation.

INTRODUCTION

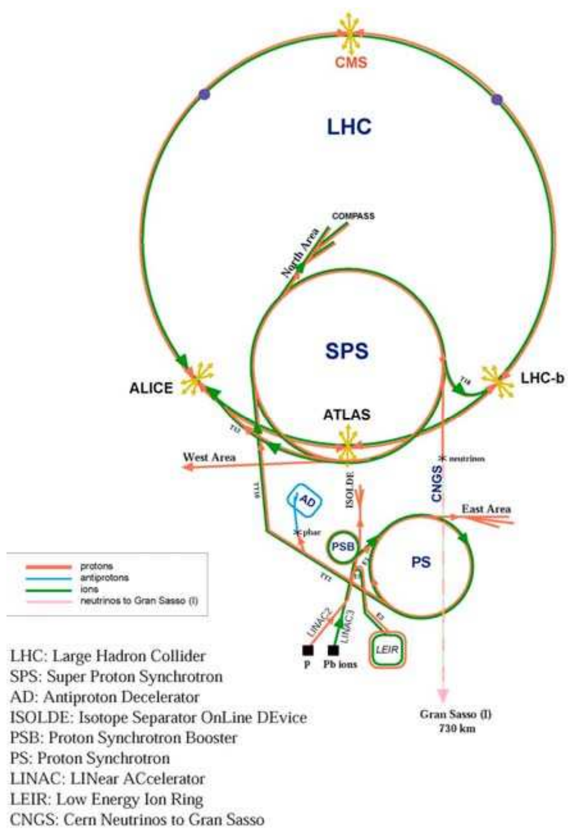

Figure 1 : The CERN accelerators

The CERN Large Hadron Collider (LHC) receives its beams for a complete chain of machines often referenced as "LHC pre-injectors". These machines - Linac2 (H^+) or Linac 3 (Pb 54^+), the PS Booster, the PS and the SPS - exist since a number of years. The PSB, the PS and the SPS have their own physics experiments. All these machines have been modified to be able to provide the beam characteristics needed for LHC but will continue to feed their own clients when they are not used to provide the beam for LHC. At last, a new accumulator ring is being rebuilt from the former LEAR machine - the Low Energy Ion Ring (LEIR) - to accumulate the lead ions for LHC before extracting them towards the PS Booster. Fig.1 shows all these machines and their experimental areas.

In January 2003, several years after the LHC project started at CERN, the PS and SL Divisions that were each in charge of CERN machines were merged into the AB Department. The two Operations Groups were put together and a new Controls Group was constituted from the PS and SL former controls groups together with the IAS (Industrial and Automation Systems) Group of the former LHC Division. The goal of the merging was to get to a better efficiency for realizing the LHC, simplifying the hierarchical relations and unifying the technical solutions. An additional goal was set:

to drive the LHC and its pre-injectors from a single control room and with a unified control system. The new control system for LHC was designed in this new frame.

ARCHITECTURE

The LHC control system architecture is largely based on standard components; however, two major changes took place for the LHC era:

- the consistent use of object oriented technologies for the control of beam-related systems.
- the wide use of industrial controls for the supervision of complete subsystems of the LHC.

Network

Two Ethernet networks exist at CERN: the General Purpose Network (GPN) and the Technical Network (TN). The first one is deployed over all the CERN buildings and accesses Internet; the second one is restricted to equipment control and does not access Internet. It is a highly sub netted, routed network based on a redundant Gigabit Ethernet backbone using fiber optical distribution.

The Technical Network is connected to the General Purpose Network through switches that can theoretically be opened in case of security problems but this configuration is not perceived as safe enough. A complete strategy to handle the security problems in control systems has been defined in 2005 [1] and should be progressively deployed in 2006 and 2007, before beam is injected into LHC.

Overall infrastructure

As shown in Fig 2, the LHC control system has 3 hierarchical layers of equipment communicating through the CERN Technical Network, a flat Gigabit Ethernet network using the TCP-IP protocol.

The Equipment access

- The VME Front End Computers: 350 VME computers are being added to the existing 300 crates already existing for the PS Complex and SPS, to deal with high performance acquisitions and real-time processing. They house a large variety of commercial or CERN-made I/O modules. These FECs run either the same LynxOS real-time operating system as those of the PS and of the SPS or Red Hat Linux. Mostly they are diskless to increase reliability and they boot over the network. Typically, the LHC beam instrumentation and the LHC beam interlock systems use VME front-ends.
- The Industrial PC Front End Computers: when simple functionality is needed, industrial PC Front-Ends running Linux have been substituted to the VME crates to reduce costs. Around 250 rackable PCs are being installed in the surface buildings of LHC. They typically contain one or two fieldbus interface boards and a PCI timing receiver board and are connected to the equipment in the tunnel and underground areas by optical fibres. The LHC power converters and the LHC Quench Protection System are interfaced through PC gateways.
- The PLC Front End Computers: PLCs traditionally used for controlling industrial equipment has been also introduced to control accelerator-specific systems. In a few cases, PLCs are accessed through VME FECs. Only PLCs from Schneider and Siemens are used for LHC as recommended CERN standards. In LHC, they are used for machine cryogenics, interlocks [2], vacuum, Radio-Frequency and beam extraction.
- Fieldbuses: two fieldbuses are supported by CERN, namely WorldFIP and Profibus. They are both used for LHC.
    - WorldFIP is selected when determinism (down to 10μs), robustness in severe environments and high data rates (1MBits/s and 2.5 MBits/s) are required. It is used for the LHC power converters, the Quench Protection System (QPS), the cryogenics temperature monitoring. The WorldFIP infrastructure consists of 350 km cabling, around 40000 passive and 1100 active elements among which modules specifically designed for hard radiation environment.
    - Profibus is selected for its simplicity of configuration, its large variety of remote I/O systems and its ease of integration with Siemens PLCs. Its capacity to be used as an

instrumentation bus (Profibus-PA) with a wide range of instrumentation products offering Profibus as standard means of connection. It is used for fast kicker magnets, cooling and ventilation, vacuum, cryogenics, magnet and power interlock controllers.

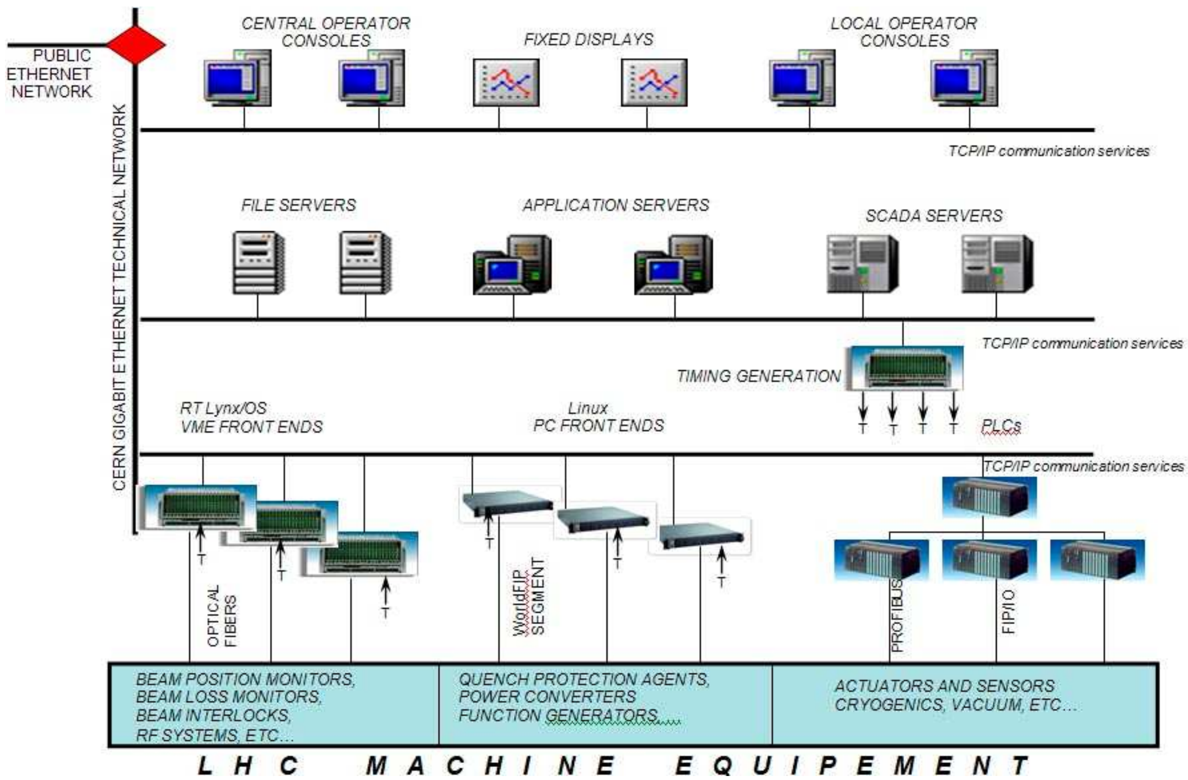

Figure 2: The LHC Controls architecture

Servers

- UNIX application servers are used to run the LHC middle-tier software, to host operational programs and data files, and also to offer specific services (web services for operation, fixed displays, SCADA servers, Database servers, …). They run the Linux operating system. Emphasis has been put on the hardware reliability and cost issues rather than on the pure performance aspects. Mirroring and RAID techniques are used to ensure data integrity and error recovery. Apart from some large SUN computers used for databases, the servers are usually HP Pro-Liant machines. Around 50 of them will be located in the new CERN Control Center (CCC).

- The Central timing is a complex VME based system that acts as a server for timing and synchronization data for all the machines, including the timestamping of all the LHC data.

Processes running in these servers communicate with the equipment access machines using various mechanisms and protocols such as the Common Object Request Broker Architecture (CORBA) and TCP-Modbus.

Operator Consoles and Fixed Displays

- As shown in Fig. 2, the upper layer of the LHC control system consists of operation consoles and fixed displays that may be located in the CCC or in the technical buildings. These operation machines are one or 3 screen display PCs running Linux. Some of them run Windows mainly to operate the general technical services of CERN. They present the interactive GUIs of the applications that run in the servers. Forty of them will be located in the CCC and an equivalent number will be located in the technical buildings. They are all connected to the Technical Network of CERN.

- Fixed Displays is the generic term for displays showing status information on a process, a machine or a beam. These signals are elaborated in PCs located centrally and widely distributed across CERN either on the Ethernet network or via CATV networks. For LHC, 20 additional Fixed Displays are being elaborated for use in the CCC and in the technical buildings.

MACHINE TIMING AND SEQUENCING

Central timing

- From a Global Positioning System (GPS) time receiver, a UTC referenced date and time and a very accurate 1 Pulse Per Second tick are produced. A 10 MHz clock with a 10^{-10} stability locked onto these ticks, is used as source for all the machine timing.
- UTC time is provided to the equipment to timestamp the data with a 25 ns resolution. Using an optional CERN-developed chip the resolution can be brought down to 1 ns. Adjustable delays of 25 ns resolution are used to compensate for the lengths of the cables.
- NTP (Network Time Protocol) servers are used to synchronize the PLCs with typical accuracies of a few milliseconds on LANs and of up to a few tens of milliseconds on WANs. Some PLCs that require higher precision use the high precision 1PPS tick from the GPS; in this case NTP is used only to relate this tick to UTC time.

Central Beam and Cycle Management

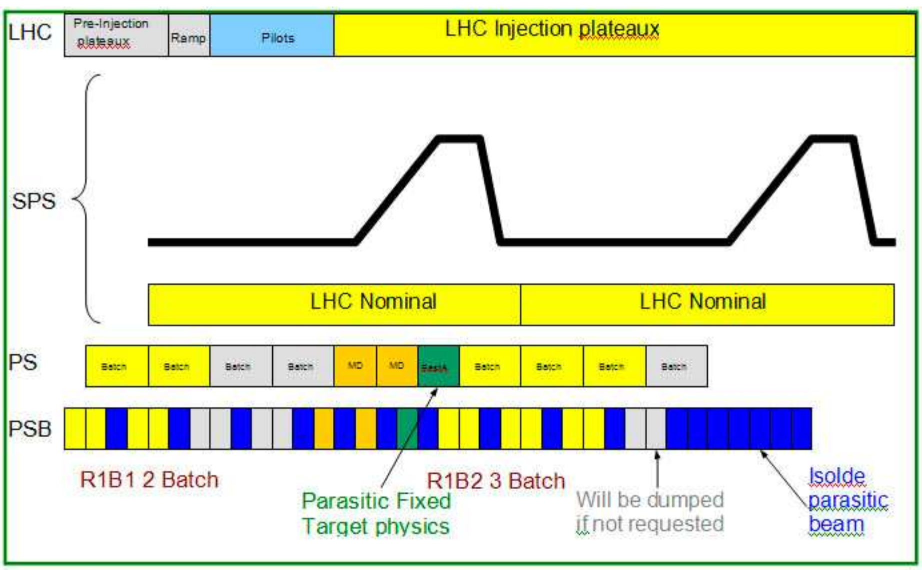

Fig 3. Typical LHC filling scheme

The Main Timing Generator (MTG) that existed already for the machines of the PS Complex was upgraded in 2004 to incorporate the SPS. In 2005 a new Central Beam and Cycle Management (CBCM) was developed to handle the production and processing of the LHC beams all along the accelerator chain and allowing for a fast switching to non-LHC physics (Isolde, REX, AD, CNGS, PS and SPS fixed target physics). Fig.3 shows a sequence providing 2 consecutive injections into LHC, with interleaved beams being produced by the PS Booster (PSB) and the PS for non-LHC physics.

The systems provides all the timing events needed to process the beam and to synchronize the machines; it also provides sequencing data known as "telegrams" specific to each machine. The central timing system is constituted of 4 VME subsystems: one redundant CBCM driving all the LHC pre-injectors, one redundant CBCM for LHC, one system to handle the machine software interlocks and one system used as a gateway to broadcast the telegrams and some key timing events on the Ethernet Technical Network. All these subsystems share the same configuration data, thanks to the reflective memory technology.

Timing distribution

- The timing events and the sequencing data are distributed to the FECs and to the servers onto dedicated RS 485 timing networks. Hardware modules are needed to decode the sequencing information and to produce the timing pulses used either to trigger equipment or to act as interrupt in R-T FECs. These modules have been developed at CERN in VME, PCI and PMC formats.
- The LHC timing network also distributes some additional parameters known as "Safe LHC Parameters" (SLP). These parameters allow the equipment to behave safely as a function of the intensities and energies of the circulating beams. A special study is being made on this specific network to guarantee a very high reliability.
- The sequencing data are also broadcast on the Ethernet Technical Network to be used by any non R-T machine not physically connected to the RS485 networks. It is the case of the console computers used by the operators or by the equipment specialists.

DATA MANAGEMENT

Over 100,000 signals are generated by the cryogenics, machine protection and beam monitoring systems. The quantity of data to be recorded for diagnostics after a "beam abort" has been estimated as a few Gigabytes. Operation of the machine will rely on stringent control of the hardware settings. A complete beam operational history will be created in order to build a long term understanding on the accelerator performance. To handle such a variety and volume of data Oracle has been selected as the strategic choice for data management at the LHC.

Offline & Online Data Repositories

As shown in Fig 4, this data infrastructure consists of :

- Physical Equipment description data (offline)
- Machine layout data (offline)
- Controls configuration data [3], [4]
- Operational data

Among the LHC layout data, the powering layout involving 1612 electrical circuits and about 80,000 connections required a dedicated database to ensure the correctness of the final layout.

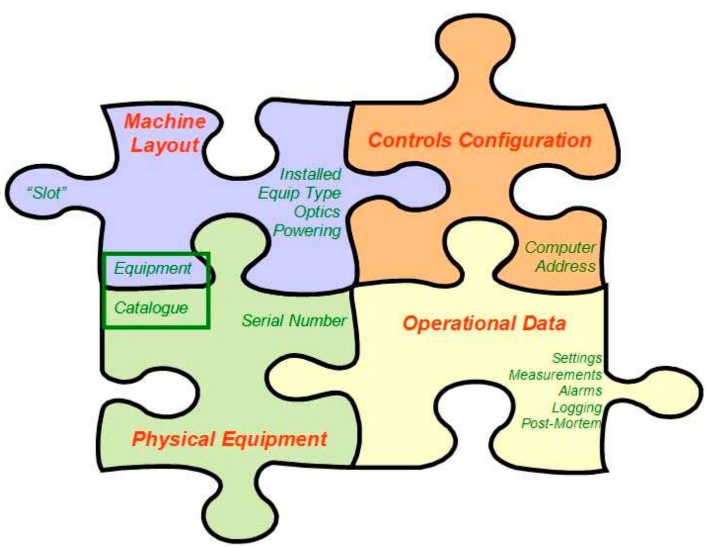

Figure 4: The four domains of data for LHC

COMMUNICATIONS

The Controls Middleware (CMW) [5] is the ensemble of protocols, Application Programming Interfaces (API) and software frameworks, which allow seamless communication between the software entities of the control system. Two conceptual models are supported: the device access model and the messaging model. The device access model is mainly used in the communication between the resource and middle tiers while the messaging model is mainly used within the business tier or between the business tier and applications running in the presentation tier (Fig. 5).

Device Access Model

The typical use of this communication model is between Java applications running in the middle tier and CMW equipment servers running in FECs. These processes communicate through an API [13]

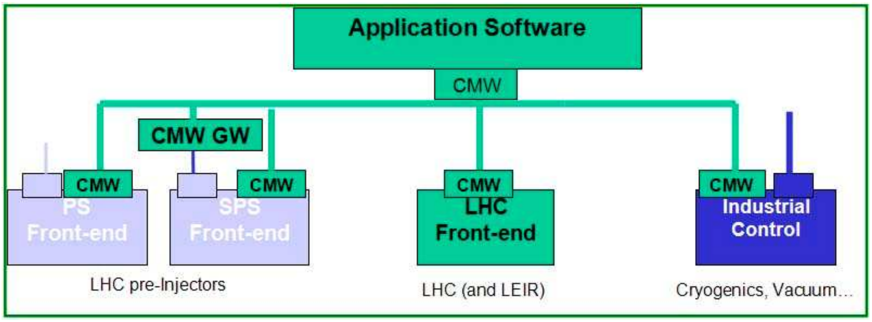

Figure 5: Controls Middleware implementation

which is available for both Java and C++.

Messaging Model

The LHC control system software relies on the Java Message Service (JMS). The JMS specification adds a standard and vendor-independent API that enables the development of portable, message-based applications in the Java programming language. Moreover, JMS is a strategic technology for the Java 2 Platform Enterprise Edition (J2EE).

SOFTWARE FRAMEWORKS

The FEC software framework

- The software running in the LHC FECs was developed using a specific framework, known as FESA. This framework is a complete environment for the equipment specialists to design, develop, test and deploy real-time control software for the FECs. This framework implemented in C++ is also the new standard for the LHC injector chain [6], [7], [8].
- The FESA framework is built for LynxOS and Linux platforms. The software tools are written in Java and are thus platform independent. No commercial software requiring a run-time license has been used.

The J2EE framework for accelerator controls

A 3-tier architecture [9] was implemented to get a clear separation between the GUI (the user interface), the control (the core business of the application and the abstract model of the accelerator control) and the devices (the physics equipment) that are controlled. The middle-tier is responsible for providing all services and for coordinating the client applications running on the operator consoles. To achieve this new programming model, the J2EE platform was selected to support the middle-tier and a unified Java API for Parameter Control (JAPC) was developed to access all types of parameters [10].

The UNICOS framework for industrial controls

The UNICOS framework (UNified Industrial COntrol System) [11] builds on a classic industrial controls architecture using PVSS [12], the SCADA product recommended at CERN, in the Supervision layer, Schneider or Siemens PLCs for process control at the Control layer and to connect process channels in the Field layer. Communication is based on Ethernet and FIPIO. In the UNICOS concept the object implementation is split into a GUI programmed in the SCADA and a process programmed in the PLC [13].

In order to optimize the communication bandwidth between the PLCs and the SCADA, an event-driven protocol based on TCP-Modbus has been developed.

The UNICOS and the J2EE frameworks share the same conventions for the graphical symbols used at the GUI level.

THE CONTROL ROOM SOFTWARE

For the LHC beam operation

The LHC control room applications are based on a set of common control system services and components, in order to avoid duplication of effort and solutions. The operational software development process relies on common development tools, guidelines and procedures for the construction, testing, integration, deployment and change management [13].

While the generic application programs are developed by the Controls Group, the programs with a large content of beam physics and of operations experience are developed in the frame of an Operations-Controls project team known as LHC Application Software (LSA) [14].

For the LHC industrial systems

Several LHC accelerator industrial subsystems will be accessible from the CCC consoles via PVSS.

The SCADA development process, in particular when based on frameworks such as UNICOS, can be based mostly on configuration and graphic editors rather than programming. A unique device configuration database contains all characteristics of the devices, including device addressing, alarm and data logging parameterization. Software bridges allow for both industrial and accelerator systems exchange data and access the equipment setting parameters.

GENERAL SERVICES FOR OPERATIONS

Analogue signals

On top of hundreds of digitized signals appearing in application GUIs, some 500 signals in the 1 kHz to 50 MHz range need to be visualized in real-time to ensure a proper adjustment of the LHC in the same way that it has been done for the other CERN accelerators. A system known as OASIS (Open Analog Signals Information System) [15], [16] has been implemented based on the same principles as the existing systems: analog multiplexing and digitization close to the equipment and triggered by GMT timing pulses, transmission through Ethernet to control room consoles and Java GUI applications to monitor them in four-channel “virtual oscilloscope” screens.

Alarms

The detection, collection, management and distribution of information concerning all abnormal situations require one global alarm system. The system accepts information concerning any problem associated with the CERN accelerators and technical services and offers this information, in a structured way, to any interested party. The core part of this system is the LHC Alarm SERvice (LASER), [17]. As for the other systems, a 3-tier architecture was chosen and is now implemented according to the J2EE specification. The middle-tier will collect Fault States using a subscribtion mechanism. A number of services and facilities is offered at this level, as persistence, logging, reduction management, browsing and interaction. A presentation tier will cater for clients interested in those services via a Java client interface.

Logging

The process of capturing and recording information on the operation of the LHC is generally referred to as “LHC Logging”. The information of interest that needs to be logged commonly concerns values of variables that evolve over time. The total number of logging variables is in the order of 10^5-10^6 with logging frequencies up to 0.1 Hz. The recorded data is stored in order to permit comparison of historical data, off-line analysis to search for data correlations, and compilation of operational statistics.

Fault State from the LASER system and data captured by the logging system are carefully time stamped, using UTC time, down to the microsecond level if needed, to enable precise correlations.

Post Mortem

The Alarms and Logging systems are not sufficient to provide all the facilities required for the understanding of quenches and beam losses in the LHC. This, together with the large risks of breaking equipment, precludes learning by trial and error as practiced with normally conducting machines. A Post Mortem System [18][19] is thus required to interpret the circumstances of Beam and Power Aborts. The system will capture data from all systems (OASIS, LASER, Logging) plus transient data acquired on a specific trigger generated for instance from beam losses measurements or machine interlocks. Analysis programs will then help in understanding the few Gigabytes of data captured.

LARGE SYSTEMS FOR LHC

As for any accelerator, the control system drives all the power supplies of the LHC magnets through high precision function generators linked to WorldFIP; it connects all the beam instrumentation through 60 VME crates and drives the vacuum equipment with Schneider PLCs. The cryoplants and the cryogenic distribution system are based on UNICOS using a total of total of 130 Schneider PLCs. Besides these classical large systems, the LHC comprises the following specific systems:

Real-Time feedback loops

Real-time feedbacks will be required in the LHC for orbit and tune and possibly for chromaticity. The requested sampling frequencies of the feedbacks lie in the range of 10 to 100 Hz. From the point of view of infrastructure, robust operation of feedbacks concerns mainly networks and FECs. A global orbit feedback in particular will involve more than 100 FECs of the beam instrumentation and power converters. Tests performed on the SPS and simulations show that these systems can be deployed across the Technical Network using only a small part of the available bandwidth.

LHC collimation system

130 objects (collimators, movable absorbers, diluters and scrapers) are needed to protect the machine equipment, to clean or to shape the beam. Among those 70 collimators will need to be moved synchronously within a few 10 μm precision, taking into account the local orbit and losses. This makes a very complicated system that has to be extremely reliable [20].

Powering interlock system

The powering interlock system permits powering of magnets if several conditions are met. In case of a failure, the powering interlock system must ensure a safe stop of powering ("power abort") and a discharge of the magnet energy, and request a beam dump if necessary. The powering interlock system has been implemented as 28 subsectors that are controlled each by one or two PLCs linked to the Technical Network (36 PLCs in total). Interlocks generated by the system are connected to the Beam Interlock system [2].

Beam interlock system

The beam interlock system [21] firstly permits injection into the LHC when all systems are ready for beam and secondly, with beam is circulating, transmits any request to dump the beam to the beam dumping system. The system consists of 2 optical fiber loops per beam connecting 16 VME controllers that receive interlocks from many LHC subsystems (beam loss monitors, vacuum, access, powering,...) [22]. When an interlock occurs on one of the controllers one of the loop opens and the system provides a dump request for the corresponding beam. The system is supervised trough a Java client communicating with the controllers via the standard CMW communication.

Quench protection system

This system receives data from a large number of sensors connected to a 1Mbit/sec WorldFIP bus that communicates through 35 VME gateways with the control system. It links to. The supervision layer resides in a PVSS data server that communicates with the LHC logging, alarms, and post-mortem systems. A GUI for experts completes the system.

THE CERN CONTROL CENTER (CCC)

A new control room is being finalized on the Prévessin site that will act as the unique CERN Control Center (CCC) for all the CERN machines and for the technical services of both sites. The technical services and the restart of the PS and SPS machines will be performed from this place from March 2006. Then the hardware commissioning of LHC will take place there leading to beam commissioning in 2007. It consists in a single 625 m2 room containing 40 console units split in four circles disposed as a four-leaved clover. The PS complex, the SPS, the LHC and the technical services (including the

Figure 6: The CERN Control Center layout

cryoplants of LHC) are each parts of this room (Fig. 6). A working place is generally made of 2 console modules joined together and housing two 3-screen Linux PC for interactions, one Windows PC for administrative tasks and 3 to 5 additional screens to display "fixed display" status information. Several dedicated console for access control complete the equipment in each circle and 16 large 42' displays on the walls repeat the status information of general interest.

STATUS

Hardware commissioning has already started in the LHC tunnel, beam commissioning is expected to begin in August 2007.

Infrastructure installation

Basic infrastructure	conception	implementation	comments
Network	done	done	security strategy to be applied
VME FECs	purchased	done	LEIR: 100%, LHC Hardw. Comm :50%
PC gateways	purchased	done	LHC Hardw. Comm. : 50%
PLC FECs	purchased	done	Cryogenics : 60%, Powering Interlock system : 30%
WorldFIP	done	done	Tunnel & Surface buildings: deployed 100%, qualified : 35%
Profibus	done		
remote reboot	done	done	sectors 7-8, 8-1
Servers	purchased	provisional installation	to be installed in CCC < Feb 2006
Consoles	equipment defined and purchased		Nov 2005 - March 2006 for CCC Installed in Field CR - UA83
Central Timing	done	done	< March 2006
Timing distribution & receivers	done	done for all modules	done in Points 1, 7 & 8

Table 2: Status of the LHC controls infrastructure installation

The installation of the controls infrastructure is being done at full speed and the software components are being tested thoroughly on the current projects. Table 2 gives an overview on the readiness of the infrastructure. Globally, 50% of the controls infrastructure will be installed by the end of 2005. The other half will be completely installed in 2006.

Subsystem status

The strategy decided in 2003 that is to deploy the LHC controls components on any new development was applied: the transfer lines from SPS to LHC, CNGS, LEIR and the upgrades of the LHC pre-injectors were all used as benches to test the new LHC system So, most of these components have been already tested, on a smaller scale though than for LHC. Table 3 shows the subsystems that were tested in that way. Currently, with the commissioning of LEIR with beam [23] and with the hardware commissioning of the first sector of LHC, practically all of the software infrastructure for LHC will have been tested by the end of 2005. The restart of the PS and SPS in March 2006 after 18 month stop will allow finalizing the upgrading of the LHC pre-injector chain and in particular the new timing system.

At last the commissioning with beam of one sector of LHC by the end of 2006 will provide an excellent opportunity to get a first full size test of the whole system. The challenge which remains to be met is the production of a large number of specific application programs for operations and equipment specialists for which specifications do not exist yet and that will have to be delivered in a very short time.

Control subsystems / Test opportunities	Post Mortem	Logging	Timing	Alarms (LASER)	Powering interlocks	Automated test procedures	OASIS	CMW FESA	PVSS UNICOS	AP & LSA software
TT40/TI8	NO	YES	Partial	NO	YES	NO	YES	BOTH	BOTH	BOTH
LEIR beam commissioning	NO	YES	YES	YES	YES	NO	YES	BOTH	BOTH (vacuum)	BOTH (partial)
1st QRL tests	NO	YES	NO	YES	NO	NO	NO	NO	YES	NO
QPS surface tests	YES	NO	NO	NO	NO	NO	NO	FESA	NO	NO
LSS8L tests	YES	YES	YES	YES	YES	YES	NO	BOTH	YES	BOTH
Large electrical circuit commiss.	YES	YES	YES	YES	YES	YES	NO	BOTH	YES	BOTH
SPS/TI2/CNGS	YES	YES	YES	YES	YES	NO	YES	BOTH	YES	BOTH

Table 3: Readiness of LHC controls subsystems *(Green = done; Yellow = in progress)*

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