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Experience with the String2 Cryogenic Instrumentation and Control System

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Abstract

String2 was a 120 m full-scale model of a regular cell of the LHC accelerator arc. It was composed of eight superconducting main magnets, fed by a separate cryogenic distribution line (QRL); an electrical feed box (DFB) which supported the superconducting current leads that powered the magnets [1]. Bearing an intensive experimental programme, String2 was heavily instrumented. The cryogenic instrumentation and control system, whose complexity was close to a full 3.3 km LHC sector, have already been described in [2]. String2 was a useful facility to validate design choices and to gain knowledge on installation and commissioning procedures. This paper reports on the experience of four years of designing, installation, commissioning and maintenance, and outlines the lessons learned for the LHC.

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THE CRYOGENIC CONTROL SYSTEM ARCHITECTURE

About 700 cryogenic sensors and actuators were distributed along the 120 m length of String2; their signals were conveyed by seven fieldbus segments. Intelligent devices were directly connected to Profibus®-PA, whereas conventional devices were connected to analogue or digital modules on remote I/O stations, which communicated on Profibus®-DP. The cryogenic process automation was handled by two Siemens-S7® controllers (PLCs), running 126 closed control loops.

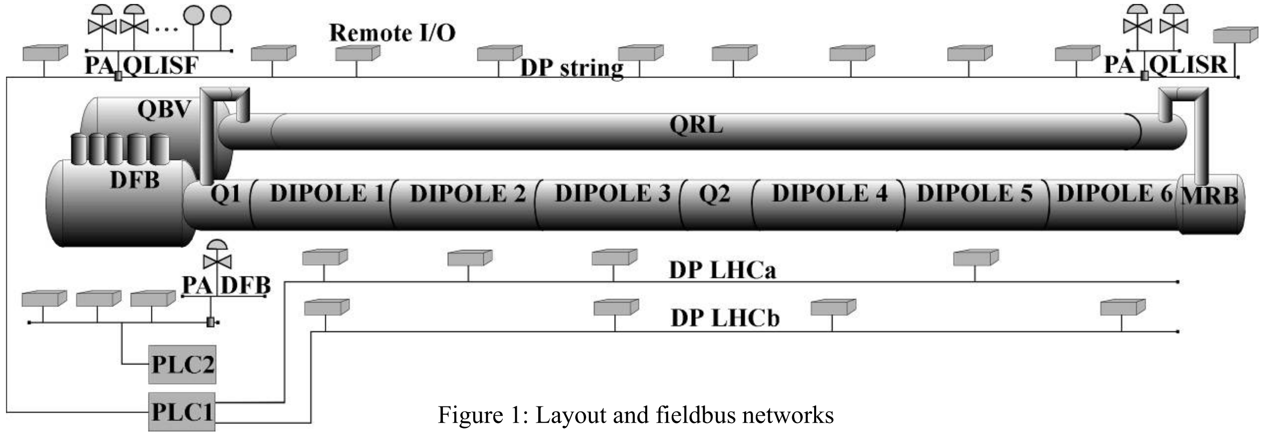

Figure 1: Layout and fieldbus networks

THE PROGRAMME

Design

The LHC cryogenic control system and instrumentation are based on commercially available components whenever possible; specific developments were necessary in some cases, such as for high accuracy electronic signal conditioning for thermometry [3], or to cope with the ionising radiation in the accelerator tunnel [4]. For String2, a particular effort was put to integrate components and systems as close as possible to their final LHC design. It was intended to investigate the accuracy and long-term behaviour of various types of sensors, validate signal conditioning units and their integration with fieldbuses, evaluate advanced control techniques, and the performance of the control system in general.

Installation

The deployment of the front-end electronics and fieldbuses for cryogenics started by the end of 1999, simultaneously with the first phase of the mechanical assembly. During more than one year, most of the String2 Phase1 components were installed (Figure 1): 2 quadrupole and 3 dipole prototype cryomagnets, the QRL, the DFB, and some ancillary systems (QBV, QLISF, QLISR, MRB).

Commissioning

While the last components were still being assembled, the commissioning started in April 2001: every instrument had its signal chain systematically verified; this included cabling, signal processing electronics, communication, synoptic view, and coherence between the databases of the PLC and of the supervision (SCADA).

Before the final closure of the String2 vacuum vessel, an important number of sensors was found to be swapped, damaged or malfunctioning, due to wires inverted, broken, or shorted to ground. They were repaired whenever the sensor or cables were still accessible.

Cool down & powering

In the beginning of August 2001 the cool down could start, as all the required instrumentation was available. At nominal operating conditions, the control loops were fine-tuned, and the main thermometers and pressure sensors were verified for high accuracy.

The process was gradually set into automatic mode, and eventually the facility could be left unattended, except during experiments or powering; the on-call cryogenic operator would be alerted by SMS, doubled by a hardwired general-fault alarm to a continuously manned central control room.

During cool-down, the analysis of the profiles of temperature vs. time and vs. location showed additional inversions and misidentifications in all the 32 current leads of the DFB. An extra effort was therefore deployed in order to power the magnets to nominal current in September.

Phase 2 & Phase 3

During the 2002-03 winter shutdown, the String2 was completed to a full cell by addition of 3 LHC pre-series dipoles, introducing some 30 new analogue channels. Cool down took place in May 2002 and powering started in the following month. For the third and final run in 2003, several upgrades were made on the control system, in order to move closer to the final LHC configuration, hardware and software wise.

THE EXPERIMENTS & THE LESSONS

Instrumentation

The String2 instrumentation was particularly complex and non-regular as most components were prototypes, from multiple origins, and with frequently changing specifications. There were many unexpected problems, which took too much time and resources to identify and repair.

After one month of commissioning, only 64% of the thermometers in the magnets and QRL were acknowledged to perform within specifications; three months later, 24% more became operational. Only after 8 months of commissioning the instrumentation diagnosis could be frozen; for the 215 thermometers in the magnets and QRL: 64% OK since day one, 26% repaired, 7% working with reduced performance, 3% lost; for the currents leads (220 thermometers): 0% OK at day one, 90% identified as permutated in several ways, and 10% lost. Other instruments were in smaller amount and had fewer problems.

This laborious commissioning of the instrumentation emphasized the risk of degrading or losing the control of several magnets temperatures, and stimulated urgent actions within different teams:

- magnet reception test procedures were reviewed in order to avoid thermometer damage;
- thermometer owners or installers were urged to thoroughly follow installation guides and to properly document all phases of assembly;
- emphasis was put on the thermometry databases, in order to finally have working interfaces for inserting and analysing thermometer calibrations and for assembly follow-up, and also to have automatic generation of PLC interpolation tables; otherwise there was a high risk of having temperatures measured in ohm;
- people became aware that commissioning time must not be neglected and that it cannot be entirely squeezed in the shadow of other activities; the goal is to have a machine running within specifications and to minimise the interventions and the down time.

EMC

Unexpectedly, when the main superconducting magnets were powered, their temperature measurement was found to be strongly correlated to the magnet current. Several studies and measurements showed:

- a magneto-resistance phenomenon would have required a magnetic field of about one Tesla at the thermometer location; this was ruled out by the magnet designers;
- when two independent magnet circuits were powered, the individual temperature offsets were adding up quadratically; this hinted at the cumulative effect of two uncorrelated noise sources;
- the power converters voltage to ground and current indeed exhibited high-frequency noise, with amplitude increasing with the current; this noise was also seen at the thermometer leads, superimposed to the DC thermometer excitation; this meant electromagnetic coupling from magnet coils into the thermometer, and was confirmed by direct signal injection on the current leads;
- the temperature offset was proportional to the noise power, indicating Joule effect; this was compatible with previous laboratory measurements (30-100 mK / μW);
- for higher noise power, the signal conditioner's input reaches its saturation threshold.

This temperature dependence on magnet current (Figure 2) was solved by adding capacitive filters to the power converters; they will therefore be also required for the LHC.

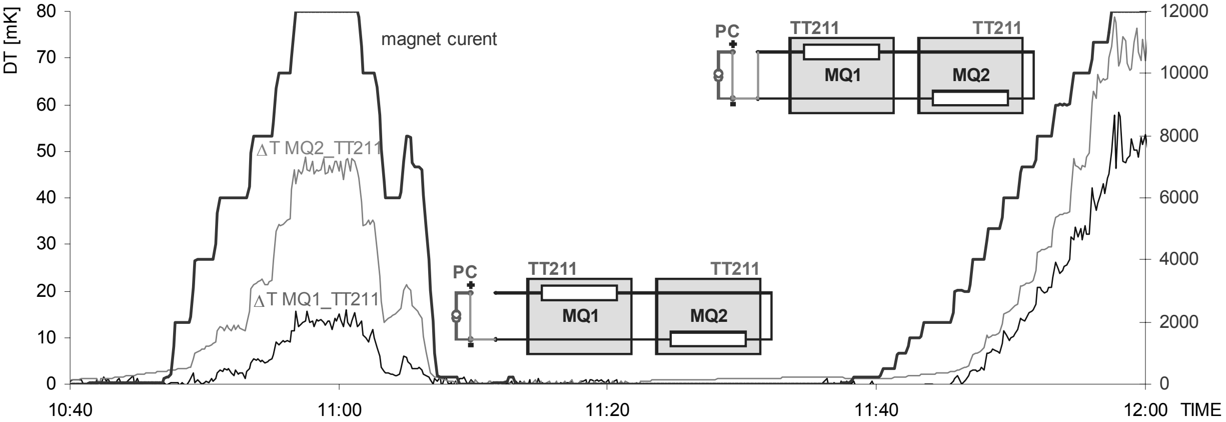

Figure 2: Correlation between the quadrupoles temperatures offset and the DC current in short-circuited Power Converter

Further electromagnetic compatibility were performed, to seek for possible effects of the electrical noise generated by kicker magnets and their pulsed power supplies. These experiments confirmed the stronger interference rejection of double shielded cables, when compared to single shielded ones. Otherwise, a digital communication board was blocked by every kicker pulse, if its auto-restart was not enabled; this warns that the radiated power is still a real concern for electronics near the kickers.

Process Control

The temperature of the superconducting magnets is a control parameter with tight operating constraints, which implied the development of an advanced process regulator based on the Model-Based Predictive Control paradigm (MBPC), in order to reduce the control band and improve stability [5].

The dynamics involved in the magnet temperature regulation presented the following characteristics:

- asymmetric inverse response, where temperature excursion initially reacts opposite as expected;
- variable dead-time depending mostly on the heat load situation;
- non-uniform cold mass temperature across magnets, due to a constrained heat transfer through the cold mass interconnections.

These complex characteristics, together with the severe operational constraints, suggested the need of a more advanced control technique than a simple proportional, derivative and integral controller (PID) or any other linear regulator. String2 operation evidenced the poor performance of PID regulation where re-tuning was absolutely necessary every time the heat load varied. LHC will have more than 200 temperature regulators and tuning becomes a fundamental issue.

Extensive MBPC tests showed a better wide-range performance than the PID. Fig 3 compares the response of both controllers under the same heat load disturbance; MBPC is able to halve the initial temperature excursion and to stabilize the temperature twice faster than the PID regulator [6].

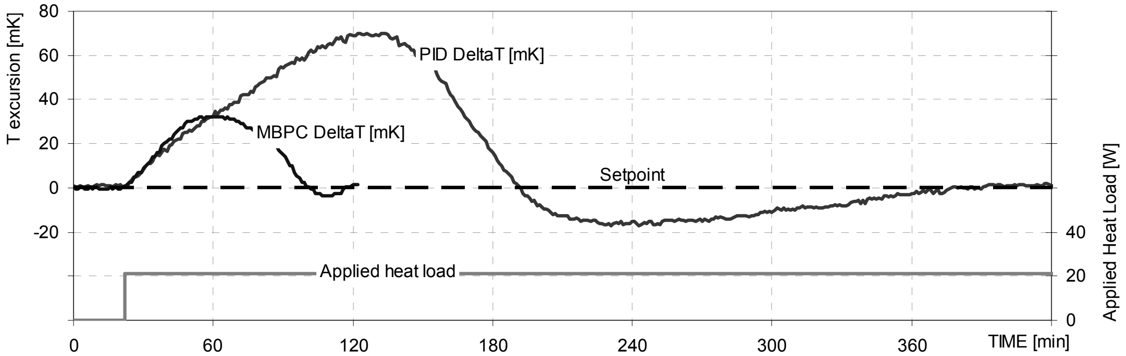

Figure 3: Temperature excursion of MBPC vs. PID, following a step in applied heat load

Closer to the LHC

Due to the high level of ionising radiation in the LHC tunnel, all front-end electronics for cryogenics has been designed to be radiation tolerant. Thus, new WorldFIP® fieldbus interfaces [7] and signal conditioners, for temperature and pressure, were introduced in String2, together with a gateway between WorldFIP® and the PLCs; they performed flawlessly.

Under CERN's request, Siemens developed a version of their intelligent valve positionners that allows the pneumatic actuator to be separated from the electronics, which must be out of the tunnel radiation. In String2, a set of these conditioners was introduced, with 1 km of cable.

Furthermore, a large part of the control system was migrated into the standard LHC control framework (UNICOS [8]), which comprises new programming methodology, new PLC and new SCADA. Specification and reception were performed by our team, and implemented by the UNICOS team.

FOR THE LHC…

The installation and commissioning of String2 cryogenic instrumentation and controls was very educative and will have a direct impact on the commissioning of the LHC sectors, permitting to save precious time.

The String2 facility provided validation and additional knowledge for instruments, front-end electronics, electromagnetic compatibility, fieldbus and PLC architectures, remote electronics positionners, control algorithms, programming methodology, and SCADA.

In some cases weaknesses were highlighted, triggering improvements in issues such as inter-team communication, respect of instrumentation installation procedures, and documentation production or access. It was also clear that wireless access to local area network will be essential in the LHC tunnel.

All in all, the skills of the involved teams and the robustness of components and process allowed keeping an overall cryogenics availability of more than 97% of total operation time [6]. Furthermore, no correction of the thermometers transfer function was ever needed, due to the quality of the original calibrations, the performance of the built-in thermalisation and the accuracy of the signal reading chain.

We wish to express our acknowledgement to the Operators, the UNICOS team and other String2 crews, who gave us valuable help during the commissioning of instruments and control system, contributing for the success of the String2 venture.

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