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Main Consolidations and Improvements of the Control System and Instrumentation for the LHC Cryogenics

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Abstract

Operation of the LHC during 2010 and 2011 with 3.5 TeV beam energy and luminosity up to $3.65\text{x}10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$, led to radiation-induced failures of micro-electronic devices used in the cryogenic control system. Mitigating actions addressed equipment relocation and corrective patches on electronics and software. Driven by the technical requirements and by feedback from the cryogenic operation team, numerous consolidations and improvements were implemented on-the-fly, enhancing availability and operability of the LHC cryogenics. Furthermore, additional diagnostic tools, test benches, technical procedures and trainings have been provided to strengthen first line support services.

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INTRODUCTION

LHC Cryogenics

The Large Hadron Collider (LHC) at CERN is a 27 km particle accelerator-collider. It makes extensive use of superconducting materials, in order to achieve high fields for accelerating and guiding the beam. Magnets and RF cavities are operated at temperatures of 1.9 K and 4.5 K respectively. The refrigeration power is provided by eight independent cryogenic plants installed at points P1.8, P2, P4, P6 and P8 (Figure 1). Helium cooling fluids are distributed along the LHC machine over 3.3 km, feeding each adjacent tunnel sectors, which are operated autonomously.

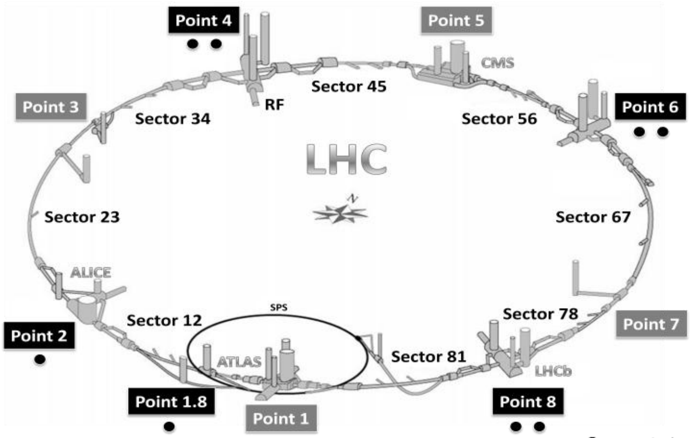

Figure 1 LHC machine layout

Control system

The highly distributed control system architecture follows the structure of the cryogenics for the LHC. It is based on the standard automation pyramidal organization with field instrumentation, control and supervision layers, integrated by CERN industrial control frameworks UNICOS and FESA. About 20’000 of cryogenic instruments are distributed over the 27 km LHC tunnel and at surface and underground cavern areas. The instrumentation readout is performed though two main types of field-buses: Profibus®, that is not meant to operate within radioactive environment, and WorldFIP® that carries the data from the tunnel instrumentation, thanks to its radiation-tolerant design. Front-End Computers (FEC) are used as a gateways between the WorldFIP® I/O modules and the Programmable Logic Controllers (PLC), while the Profibus® remote I/O are accessed directly by the PLCs. Two man-machine interfaces are built on with PVSS® application: the Supervisory Control and Data Acquisition (SCADA) and the Cryogenic Instrumentation Expert Tool (CIET). Detailed description of the control system architecture and used technology is given in [1, 2, 3, 4].

AVAILABILITY

The major radiation-induced failures, observed in 2011 during LHC operation, were due to Single Event Effects (SEE) on electronic equipment [5]. They occur when the beam is present and are driven by the beam integrated luminosity (see Figure 2), by collimation losses or by beam interactions with residual gas. The cryogenic control equipment suffered various types of events, either destructive or non-destructive. 45 radiation-caused failures, classified in Table 1, lead to 25 beam dumps and ~210 hours of cryogenic downtime [6]. Together with CERN Radiation Working Group (RadWG) and on the basis of failure analysis, radiation monitoring, simulation data and radiation tests, the most critical zones with sensitive electronics were identified.

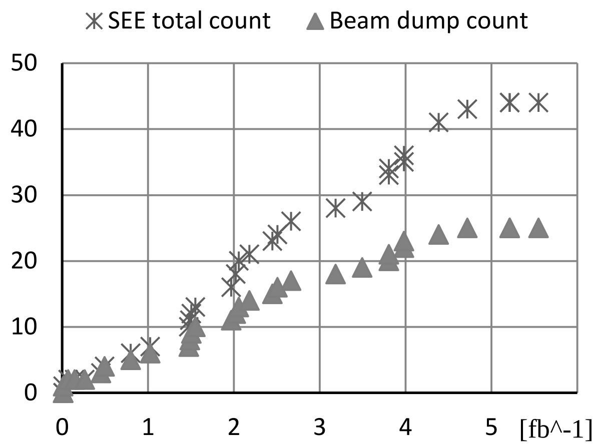

Figure 2 Cryo SEE vs. integrated luminosity

Table 1 Basic failure statistic

Affected equipment	Nr. events	Dumps	Events type	Critical areas
Cryogenic plants PLC	7	7	non-destructive	caverns of P8, P6 &P4
Current lead temperature	17	9	non-destructive	LHC tunnel
Current lead valves	19	9	non-destructive	LHC technical galleries
24VDC Power Supplies	2	0	destructive	LHC technical galleries

<u>Equipment Relocations</u>

Failures of cryogenic plants PLCs, potentially caused by non-destructive Single Event Upsets (SEU), had a major contribution to system downtime. Various tests have confirmed a high radiation sensitivity of PLCs' Central Processing Units (CPU). To improve the availability of the cryogenic plant in P8, the most sensitive PLCs together with the electrical control cabinets were relocated into radiation protected areas, during winter stops. A dozen electrical cabinets were reviewed and adapted to new position. The intelligent positioners, usually located close to valves they control, were split to allow relocation of the sensitive electronics. Also in P4 and P6, the CPUs were relocated "on-the-fly", following recent events and recommendations from RadWG.

<u>Corrective Patches on hardware and software</u>

Wrong temperature readings on the current-leads had triggered several beam dumps. This was due to an error on the selection of the measurement range, owing to an SEU on a digital insulator. The range-selection functionality was masked by a software patch on the FEC; since then, 8 beam dumps were avoided. A definite solution was provided during last winter stop: some 1200 cards were consolidated with straps blocking unnecessary functionality on sensitive element

The availability of the current lead cooling valves, controlled thought Profibus remote I/O, was affected by non-destructive single-events on the communication module. An automatic reset routine, detecting communication failure and then executing a power-cycle reset was successfully tested and implemented in the PLCs as a short term solution. Twelve automatic resets were triggered since the patch was deployed, all without losing cryogenic nominal conditions or circulating beams. The relocation to the protected areas was chosen as the final solution, to be executed during long shutdown of 2013.

Destructive single-events on 24VDC-supplies short-circuited their outputs, leading to a power-loss on the associated remote I/O modules. A review of the tunnel cryogenics power-supply architecture conducted to a new design, with better redundancy and faster protections; it was implemented during the last winter stop and will inspire the final solution to be implemented in 2013.

OPERABILITY

Controls

The beam injections into the LHC induce peaks of heat load on the Beam Screen (BS) cooling circuit of the Inner Triplets superconducting magnets. This transient over-heating provoked instabilities in the vacuum of the beam pipe. Driven by the operation team, the control logic of BS cooling was improved in 2011. The standard PID controllers, which are normally tuned to smooth beam operation, were complemented by additional logic; this detects the beam injection thermal effect and allows higher opening of the control valve (CV), to increase the BS cooling (Figure 3). Furthermore, a prototype of the new control loop, preventing decreasing of the mass flow, was recently implemented and is being tested.

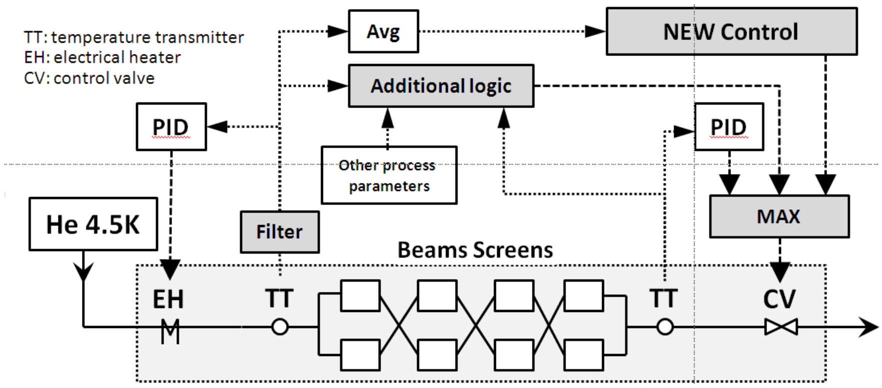

Figure 3 Inner Triplet BS logic

The first months of operating the RF cavities, in cryogenic nominal conditions (2010), had triggered an optimization of the process functional analysis, which lead to revisions of the logic and of machine protection. During the winter stop 2010-2011 the logic was considerably rebuilt: the new structure of the Process Control Objects supervising process logic was implemented; available option modes, phase sequencers as well as individual objects logic where upgraded, in order to meet RF process thermal dynamic requirements. At the same time the software interlocks protecting machine were optimized. The normal operation period in 2011 proved that the applied patches are better adapted to process specificities. Nevertheless, further improvements of the RF cool-down phase were necessary; an additional pressure controller was successfully implemented during last winter stop, allowing for smoother cool-down of the RF cavities.

In case of an extensive communication failure of a large number of Profibus® distributed I/Os, the respective PLC will be flood by an avalanche of events on the bus. While trying to process that amount data, the PLC may overrun the maximum allowed program cycle time. To prevent it, the bus electrical connections were consolidated; the PLCs were reconfigured to handle up to 12 seconds cycle. Moreover, functionality was implemented to prevent loss of the machine settings in case of PLC “cold” restart.

Instrumentation

After a few months of operation, the current lead cooling valves started to develop excessive friction in the bearings, impairing smooth operation. New, friction free valves were tested with very good response in real LHC operation. A road-map was put in place to progressively replace 1258 valves and to calibrate the corresponding instrumentation channels, while minimising the impact on the cryogenics availability [7]. This consolidation was completed during the last winter stop.

Due to budgetary restrictions, the LHC started with only the vital magnet temperature reading channels. In order to improve the accuracy of the superconducting magnet temperature regulation, 750 channels were progressively equipped with the missing electronic cards. The CIET panels accessing those cards were reconfigured, the channels were activated in the PLC and the SCADA synoptic was updated.

SUPPORT

The large scale of the control system, reflected on a great number of components and a complex relationship between them, poses a challenge for the first-line technical support: a given symptoms may have many possible causes. Additional measures were taken to improve support reliability: a common diagnostic of all 24VDC supplies in the LHC tunnel was implemented on the SCADA; the Profibus® control valves of the cryogenic plant were equipped with communication gateways allowing remote diagnostic and configuration; SCADA plants-map navigation was developed, to help in the localisation of hundreds of electrical control cabinets. Furthermore, several step-by-step intervention procedures were prepared by technical experts; around 150 electrical diagrams were homogenized. All documentation was classified by installation, localisation and equipment type in the web navigation interface: procedures, electrical diagrams, manufacturers' documentation and parameter files. To ensure proper execution of the intervention procedures, several test benches (Figure 4) were built and used to support trainings and to test and validate spare components.

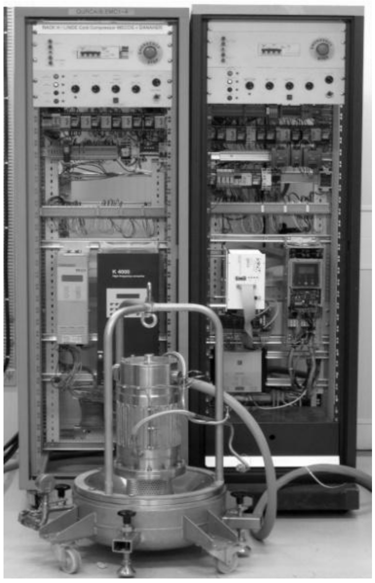

Figure 4 Compressor test bench

CONCLUSION

Implementation of mitigation actions and on-line patches improved robustness of equipment; 20 known radiation-induced failures, which could have led to beam dumps, were avoided. The presented consolidations and improvements rendered the control system more reliable and better adapted to regular operation. Additional diagnostic tools, procedures and trainings were essential to provide an efficient first line support for the LHC cryogenics.

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