PERFORMANCE OF THE PROTECTION SYSTEM FOR SUPERCONDUCTING CIRCUITS DURING LHC OPERATION

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Abstract

The protection system for superconducting magnets and bus-bars is an essential part of the LHC machine protection and ensures the integrity of substantial elements of the accelerator. Due to the large amount of hardwired and software interlock channels the dependability of the system is a critical parameter for the successful operation of the LHC.

INTRODUCTION

The protection of the superconducting circuits of the LHC, i.e. magnets, bus-bars and current leads is ensured by electronic quench detection systems in combination with other active protection elements such as quench heater discharge power supplies and energy extraction systems [1][2]. In addition there are passive protection elements as cold by-pass diodes and cold parallel extraction resistors being not subject of this contribution. The active protection systems cover 544 superconducting circuits of the LHC with nominal current ratings from 550 A to 11870 A. The systems incorporate a large number of individual protection and data acquisition devices requiring very high levels of reliability and availability.

Table 1: Circuits Covered by the Protection System

Circuit type	Quantity
Main bends and quads	24
Inner triplets	8
Insertion region magnets	94
Corrector circuits 600 A	418
Total	**544**

Regarding only the interlocking channels, a mean time between failure (MTBF) of 24 hours for the complete system, which is hardly acceptable for accelerator operation, calls already for an individual device MTBF of $0.33 \cdot 10^6$ hours and an event free time of one week for $2.3 \cdot 10^6$ hours. It is noteworthy that the manufacturers of electronic components typically guarantee a component MTBF between 0.2 and $1.0 \cdot 10^6$ hours.

Table 2: Protection Equipment Installed in LHC

System type	Quantity
Quench detection systems	7568
Quench heater discharge power supplies	6076
Energy extraction systems 13 kA	32
Energy extraction systems 600 A	202
Data acquisition systems	2532
System interlocks (hardwired)	**13722**

FAULT CLASSIFICATION

The consequences of faults of the protection system span from minor disturbances being transparent to accelerator operation to the total loss of protection in coincidence with a resistive transition of a superconducting element. The latter case could have very serious consequences and imply a shutdown of the accelerator of several months.

SYSTEM TRIGGERS

Protection Triggers

With the LHC currently running at half of its nominal energy the superconducting circuits have not yet been commissioned to their nominal current. Thus the occurrence of training quenches is very unlikely and has not been observed during the hardware commissioning campaigns in 2010 and 2011.

Beam induced quenches have been only observed during injection due to abnormal high beam losses caused by erratic operation of the kicker system. In most cases such losses cause a recoverable resistive transition. As the quench detection systems need to react faster than the time needed to distinguish between a recoverable resistive transition and a real quench, also these events will cause a trigger of the protection systems.

During the LHC operation in 2011 several problems with the cryogenic system instrumentation led in a few cases to the insufficient cooling of superconducting elements like HTS current leads and superconducting bus-bars. The lack of cooling power caused the protection systems to trigger the hardware interlocks in order to prevent damage to the concerned equipment. These events underline that the quench protection system is a sine qua non for preserving the machine integrity.

Spurious Triggering of Hardware Interlocks

A significant amount of the observed spurious triggers is caused by problems related to the electro-magnetic compatibility (EMC) of the detection devices but there are as well cases provoked by accidental opening of 230 V mains circuit breakers, faulty electrical connections and radiation induced effects (see below).

The EMC related triggers occur most frequently with protection systems using very long instrumentation cables of 100 to 150 m length to transmit the signals from the superconducting circuits and are usually correlated to general perturbations of the electrical network, e.g. drop-out of power lines or thunderstorms.

Table 3: Beam aborts during stable beam periods caused by triggers of the quench detection systems in 2011 (data extracted mid August after 173 days of operation.)

Type of fault	**Occurrence**	**Affecting**
Radiation induced (Single Event Upset)	6	Digital signal processor
EMC problems	5	Analog to digital conversion
Hardware failure	1	Circuit board
Real quench	1	Superconducting bus-bar
Total	**13**	

Performance of the Enhanced Layer of the Protection System

The upgrade of the protection systems in 2009 [2] added among other items 2068 redundant high precision detection systems for the protection and diagnostics of the bus-bar splices of the main circuits. Despite the low detection threshold of $U_{TH} = 500\ \mu V$ these systems counted only for a limited amount of spurious triggers and provided valuable information on the state of the superconducting bus-bar joints.

MATERIAL FAILURES

Among the observed hardware malfunctions the most frequent problem is the failure of the mains switch of the quench heater discharge power supplies. The fault is caused by the mechanical breakdown of one of the plastic materials used for the construction of the switch, due to an excess of hardener in its composition [3]. By this the hardening process continues and the material becomes more and more brittle. In addition the effect gets more stringent with time. This explains that despite the progressing repair work and preventive maintenance the MTBF of these power supplies continues to decrease ($1.17 \cdot 10^6$ hours in 2010, $0.97 \cdot 10^6$ hours at the time of writing).

In order to overcome the problem a repair campaign has been launched in 2010 with the objective to replace all 6076 faulty switches during technical stops of the LHC until spring 2012. The MTBF of the repaired power supplies is more than $6.5 \cdot 10^6$ hours (no faults of this type observed after repair).

RADIATION INDUCED FAULTS

Due to functional requirements a significant amount of the protection equipment is exposed to radiation during LHC operation. The actual radiation load depends on location and LHC exploitation.

With increasing beam intensity in 2010 first problems with data acquisition systems (DAQ) leading to stalled data transmission have been observed. The fault could be traced down to a malfunction of a capacitive digital isolator. The particular fault state has not been revealed during radiation test campaigns as it turned out to depend on the operational mode of the device. The problem however could be mitigated by the development of a dedicated firmware version for this type of DAQ system.

In 2011, with peak luminosities of the order of $2.1 \cdot 10^{33}\ cm^{-2}s^{-1}$, the first spurious radiation induced triggers of the quench detection system have been observed. The detailed analysis of those events revealed that the program execution of the digital quench detection systems stopped. The systems were then consequently reset by the on-board watchdog circuits. As the circuit trip occurs due to the reset procedure investigations are currently ongoing whether this process can be optimized in order to allow a smooth restart of the detection system.

All faults observed so far have been categorized as soft errors not causing any hardware damage. In two cases the redundancy of the protection system was lost but the circuit protection was always assured.

Table 4: Radiation Induced Faults

Equipment	**Type of fault**	**Events**
Data acquisition system	Permanent trigger	**62**
Data acquisition system	Spurious trigger	**4**
Data acquisition system	Loss of fieldbus communication	**2**
Quench detection system for 600 A circuits	Spurious trigger	**6**
Quench detection system for insertion region magnets	Spurious trigger	**1**
Splice protection system	Stalled system (loss of redundancy)	**2**

The ongoing firmware upgrade of the DAQ systems allowed already to mitigate 49 out of the 62 observed permanent trigger events (79 %).

STAND-BY SERVICE

During the LHC exploitation a round-the-clock support to operation in case of system faults is ensured by a stand-by service team formed by equipment specialists. In the event of a hardware fault the performance of the stand-by service is crucial in order to minimize the machine downtime.

Intensive training and growing experience of the team members allowed to reduce the average time for an intervention from 2.3 hours in 2010 to 1.7 hours in 2011 [4].

FAULT STATISTICS

The two tables below show system hardware faults requiring access to the LHC tunnel for re-starting systems or exchanging hardware. With respect to the LHC run in 2010 the MTBF of the quench detection hardware has increased by about 30 percent. This can be explained by the fact that during the early phase of LHC exploitation in 2010 a number of initial hardware related problems has been successfully re-solved.

Table 5: Faults Statistics in 2010 (280 Days of Operation)

Equipment	Faults	Availability [%]	MTBF [hours]
Quench heater power supplies	26	99.998	1145760
Quench detection systems	19	99.999	3362135
DAQ caused by radiation (SEU)	12	99.997	828240
DAQ all faults combined	20	99.997	774792

Table 6: Faults Statistics in 2011 (Data Extracted Mid August After 173 Days of Operation)

Equipment	Faults	Availability [%]	MTBF [hours]
Quench heater power supplies	26	99.998	970290
Quench detection systems	7	99.999	4488905
DAQ caused by radiation (SEU)	18	99.996	584048
DAQ all faults combined	19	99.996	553308

MEASURES FOR MITIGATION AND UPGRADES

While some faults, like the radiation induced problems with some DAQ systems, require short term mitigation measures, most of the system upgrades are foreseen to be implemented during the first long shutdown of the LHC scheduled for 2013/2014.

Enhanced Diagnostics

Based on the experience gained within the LHC exploitation so far and taking into account requests by equipment specialists a number of several possible extensions of the supervision of the protections systems have been identified. The enhanced supervision capabilities, e.g. for the quench heater circuits, will allow performing more detailed diagnostics of the superconducting circuits and facilitating the event analysis by automatic tools and equipment specialists.

Electro-Magnetic Compatibility

It is planned to reroute and regroup the instrumentation cables of the most sensible protection systems and to separate the protection of the superconducting magnet and bus-bars. By this measure, affecting about 50 systems, the number of spurious trigger should be significantly reduced.

Radiation Tolerant Electronics

The further development of radiation tolerant digital quench detection systems is essential also with respect to the increasing number of discontinued electronic components. Prototypes of more radiation tolerant digital quench detection and data acquisition systems are currently under tests and the production is foreseen to be launched end of 2012. In addition some of the radiation exposed electronics will be moved to protected zones during the first long shutdown.

SUMMARY

During the LHC exploitation in 2010 and 2011 the protection system for superconducting circuits of the LHC demonstrated its reliability and capability to ensure the integrity of the protected superconducting elements. The system reached already in the initial phase of exploitation a high level of availability, essential for successful accelerator operation. The maintenance of the system will require a continuous effort and further developments will be necessary to adapt the system to the evolution of the LHC.

REFERENCES

[1] K. Dahlerup-Petersen, R. Denz, K. H. Mess, “Electronic Systems for the Protection of Superconducting Devices in the LHC”, EPAC’08, Genova, June 2008.
[2] R. Denz, K. Dahlerup-Petersen, F. Formenti, K. H. Meß, A. Siemko, J. Steckert, L. Walckiers (CERN Geneva), J. Strait (Fermilab, Batavia, Illinois), “Upgrade of the Protection System for Superconducting Circuits in the LHC”, PAC’09, Vancouver, May 2009.
[3] G. Arnau Izquierdo, private communication, June 2011.
[4] G.-J. Coelingh, private communication, June 2011.