EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 596

RELIABILITY ANALYSIS FOR THE QUENCH DETECTION IN THE LHC MACHINE

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The Large Hadron Collider (LHC) will incorporate a large amount of superconducting elements that require protection in case of a quench. Key elements in the quench protection system are the electronic quench detectors. Their reliability will have an important impact on the down time as well as on the operational cost of the collider. The expected rates of both false and missed quenches have been computed for several redundant detection schemes. The developed model takes account of the maintainability of the system to optimise the frequency of foreseen checks, and evaluate their influence on the performance of different detection topologies. Seen the uncertainty of the failure rate of the components combined with the LHC tunnel environment, the study has been completed with a sensitivity analysis of the results. The chosen detection scheme and the maintainability strategy for each detector family are given.

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Presented at the Eighth European Particle Accelerator Conference (EPAC)
3-7 June 2002 - La Villette, Paris, France

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Geneva, 22 July 2002

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Abstract

The Large Hadron Collider (LHC) will incorporate a large amount of superconducting elements that require protection in case of a quench. Key elements in the quench protection system are the electronic quench detectors. Their reliability will have an important impact on the down time as well as on the operational cost of the collider. The expected rates of both false and missed quenches have been computed for several redundant detection schemes. The developed model takes account of the maintainability of the system to optimise the frequency of foreseen checks, and evaluate their influence on the performance of different detection topologies. Seen the uncertainty of the failure rate of the components combined with the LHC tunnel environment, the study has been completed with a sensitivity analysis of the results. The chosen detection scheme and the maintainability strategy for each detector family are given.

1 INTRODUCTION

Although reliability is already a very important requisite in accelerators working as subsystems of new technologies [1], existing research accelerators are not optimised from this point of view and all former studies show a lack of data and, above all, of methodology.

The Large Hadron Collider is a very complex superconducting machine, whose success will not be defined only by the two classical objectives in a high energy particle accelerator, energy and luminosity, but also by its reliability and availability performance. Together with these basic goals, there are aspects like the large energy stored in the magnets, the number of critical components and the long repair times, that give to the LHC reliability analysis a much more important role than it had for other accelerators.

Although there is experience in reliability engineering at CERN [2], until nowadays it has not been used as a general tool for complex accelerator design. A proper approach to the LHC reliability must take profit of the broad technical experience of the institute together with data from other laboratories in order to create models that will allow to predict the system reliability or, in other words, quantify the lack of knowledge [4]. Well known methods used in other fields like the space industry may be adopted [3].

Dependability analysis (including reliability, availability, maintainability and safety) are required in LHC for all systems related to personnel and equipment protection. In this respect, the quench protection system (QPS) represents a key element to prevent hardware damage from possible resistive transitions of superconducting elements.

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2 QUENCH DETECTORS

The LHC superconducting elements are equipped with electronic quench detectors [5], which are able to identify a resistive transition at any point of the superconducting coils, bus bars or current leads, and at any state of the accelerator powering cycle.

The general layout of a quench detector can be subdivided in several common functional blocks: instrumentation wires from the cold-mass to the quench detector racks, redundant quench signal generators (amplification, buffering and comparator), multichannel evaluation logic, time discriminator and powering. In addition, there is a small data acquisition and test system for diagnostics, power permit and post mortem analysis. A quench will be detected when a certain number k out of the n channels (k-*oo*-n) stay above a threshold voltage longer than a certain time period.

The reliability of such detectors has an important impact on the total LHC reliability. A non-detected quench can easily provoke an irreversible damage on the quenched element and an important loss of time and money for its removal and substitution. On the other hand, too safe designs could often generate false quench signals decreasing also the total available time of the machine.

2.1 Failure Modes

The quench detectors show three different failure modes:

- **False Quench (FQ):** Due to the fail safe design (negative logic), this is a safe failure mainly generated by powering trips, broken instrumentation wires or problems in the voltage references.
- **Unprotected Magnet (UM):** This dangerous failure occurs when a detector becomes blind and is unable to perform its basic function.
- **Missed Quench (MQ):** This is the main failure. The superconducting element quenches when the detector is blind.

2.2 Maintainability

In order to increase the availability of the detection system, two different checks are foreseen:

- **Coherency Test (CT):** The redundant channel signals and the quench signal are connected to a XOR gate that will send a warning (coherency flag) to the control room when any of the signals is different from the others. This increases the reliability against false quenches.

- **Quench Test (QT):** A simulated quench signal is sent from the control room setting all the channels at 'Quench' level. If one or more do not change, the coherency flag will provoke the generation of a warning message. If all the channels are blind, the output of the quench detector will show the failure staying at 'No Quench' state. If the check is followed by a repair of the damaged element the availability of the system is set to 1 ("as good as new"). Since this test implies the discharge of the quench heater power supplies, it can only be performed when the magnets are cold and not powered.

The design and maintainability of the quench detectors has been set according to the different properties of the protected superconducting elements and circuits, which can be classified in five families: main dipoles and lattice quadrupoles, insertion and final focusing magnets, corrector circuits, current leads and bus bars.

3 RELIABILITY MODEL

3.1 RESQP: REliability Software for Quench Protection studies

Our objective is to create an analytical model for a general protection system whose components and outputs not only have the usual *'works'* and *'does not work'* states, but also intermediate ones for predicting different system failures. The model has to include the possible maintenance policies and their effects on different topologies. In order to choose the best solution a cost has to be given to each failure. This cost does not have to be necessarily constant and can change depending on the state of the accelerator (e.g. a false quench signal will have a different running cost impact before injection than during collisions at top energy). Moreover, the model has to include possible screening between component failures (e.g. a powering problem will generate a false quench even in a blind detector due to the negative logic) and dependencies between failures (e.g. a quench can not be missed if the detector has not become blind first).

The relative simplicity of the electronic boards and the repetitive structure along all the machine makes the system suitable to be modelled analytically. On the other hand, the multiple failure modes of components, the risk and cost time dependencies and the complex maintenance strategy recommend the use of Monte Carlo methods. Nevertheless, the high precision of the results obtained with Monte Carlo will fade due to the high uncertainty on the reliability data of the electronic devices. This makes the Monte Carlo code complexity and computing time not worthwhile [6].

The analytical approach has been chosen [7]. Using the Markov State-Space methodology, the different states of each component are defined together with their transition probabilities and their influence on the state of the complete system. In order to provide a tool for this implementation and related computations, the simulation program RESQP (REliability Software for Quench Protection studies) has been developed. This program manages the implementation of the structure function of the system and computes the expected downtime for each topology with the different maintenance strategies. After computing each failure probability, the program gives the expected downtime for the whole machine with the confidence level set by the user.

3.2 Input Parameters of the Model

The input values to be introduced by the user can be divided in two groups: those related to the LHC performance and those related to the reliability performance of the electronic components used in the quench detectors.

The first group comprises the total lifetime of the machine, the expected operational time per year, the number of superconducting elements, etc. These parameters are properly defined in the LHC Baseline documents. The most difficult to estimate is the expected quench rate for the different elements. In some cases, like for the main dipoles and quadrupoles and the insertion magnets, the minimum number of quenches for which the most sensitive hardware elements are designed has been used. In the case of other elements like the current leads or the corrector circuit magnets, an estimation is very difficult. Therefore, a broad sensitivity analysis has been carried out computing the expected number of missed quenches for different quench rates.

The reliability data on electronic components are the principal input parameters. The two main sources are the Military Handbook (MIL-HDBK-217F) widely used and accepted in very different fields and the data provided by the manufacturers. The values are usually given with a 60% confidence level at $25°C$. They have been corrected up to a 95% level at $35°C$ using the provided accelerated test data with the Chi-Square distribution and the Arrhenius formula.

3.3 Solution for the local quench detectors

A quench in one of the main magnets is detected by a floating bridge detector [5], known as DQQDL, which continuously compares the voltages across the two apertures (dipoles) or two poles (quadrupoles). Each potential level is routed out from the superconducting element by two redundant instrumentation wires. An instrumentation amplifier, a voltage reference and a comparator complete the generation of the channel signal. The studied topologies are:

- Redundant Analog Part: The signal is treated by a *k-oo-n* active redundancy. Since the voting circuit is not redundant, checks will not prevent from failures at the logic level.

- Redundant analog and logic part: It has been observed that increasing the number of channels (e.g. *2oo3* or *2oo4*) does not mean necessarily less unprotected magnets. This is due to the higher complexity of the logic part. This topology tries to compensate this effect. Schemes like *2oo4d* (*d* refers to doubled logic) show a good reliability but the price to be paid is a high complexity in both, the analog and the logic part.
- Two detectors in series redundancy: The whole detector, with a simple scheme (e.g. *1oo2*) is duplicated and the cards are connected by an AND gate (wired logic). Results show that a simple topology like two *1oo2* detectors linked by an AND (*1oo2and1oo2*) gives a reliability level almost as good as the complex *2oo4d*.
- Two detectors in parallel redundancy: In order to improve the unprotected magnet reliability two simple detectors (e.g. *2oo2*) are linked by an OR gate (wired logic). Two *2oo2* detectors connected with an OR (*2oo2or2oo2*) show almost as good results as *2oo4d*. The simple topology makes it the preferred option.

Failures for yearly quench tests and monthly coherency tests are listed in Table 1 (90% confidence level). The last column shows the mean downtime in days. The main parameters used have been [8]: 2016 magnets, 24 quenched magnets per operational week, 20 years lifetime and maximum yearly operation of 5110 hours.

Table 1: 90% confidence interval for the number of false quenches, unprotected magnets and missed quenches for the DQQDL detectors in 20 years of LHC operation. Yearly quench tests and monthly coherency tests have been applied.

topology	*FQ*	*UM*	*MQ*	*downtime*
1oo2	408-462	3-10	0-3	132 days
2oo3	193-233	11-23	0-5	117 days
2oo4	199-240	18-32	1-7	157 days
2oo3d	198-557	2-9	0-2	73 days
2oo4d	210-252	0	0	48 days
1oo2and1oo2	187-227	6-15	0-4	99 days
2oo2or2oo2	197-238	3-11	0-2	73 days

It is important to notice that in the best case the number of false quenches is around 10 per year. Pareto studies show that they are mainly due to problems with powering. Redundant power supplies have been considered. The effect of this will be an increase in the number of FQ in *2oo2or2oo2*, while a reduction of this number in *1oo2and1oo2*. On the other hand, the latter topology has a higher cost and a larger number of MQ. A study [9] has been carried out concluding a pay-back period for the investment not lower than seven years within the most favourable conditions. This result discourages to take this option.

For the other quench detector families similar studies have been carried out. Due to the lower expected quench rates (except for the insertion magnets) and fewer detectors per family, *2oo3* and *1oo2* topologies perform well enough. The first one has a lower missed quench reliability but, on the other hand, the individual powering for each channel reduces almost to zero the total number of false quenches. Nevertheless, the space for these detectors in the accelerator tunnel is more restricted than it was for the local quench detectors. This constraint makes the *1oo2* with common powering the preferred solution in all these families.

3.4 Sensitivity Analysis

In order to check the robustness of the model and to look for strong interaction between inputs, the sensitivity of the results to the reliability data of the components has been studied. The different failure rates have been simultaneously drifted up to 100% of their nominal values. The same has been done for external parameters like the quench rate. No big changes on the results or strong dependencies have been found.

4 CONCLUSIONS

Reliability analysis is a very powerful and useful tool for optimising the LHC performance. Reliability, availability and maintainability play a major role in all the quench protection subsystems like the quench detectors. The code RESQP has been developed for optimising the QPS hardware and the maintenance strategies. The design phase of all the quench detector families is now completed and prototypes are being produced.

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