# ANALYSIS OF THE DEPENDABILITY OF THE LHC QUENCH DETECTION SYSTEM DURING LHC RUN 2 AND FURTHER SYSTEM EVOLUTION

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*Abstract*

The quench detection system (QDS) of the LHC superconducting circuits is an essential part of the LHC machine protection and ensures the integrity of key elements of the accelerator. The large amount of hardwired and software interlock channels of the QDS requires a very high system dependability in order to reduce the risk of affecting the successful operation of the LHC. This contribution will present methods and tools for systematic fault tracking and analysis, and will discuss recent results obtained during the LHC production run in 2016. Measures for maintaining and further improving of the system performance will be explained. An overview of the further evolution of the LHC QDS also in view of the upcoming High Luminosity Upgrade of the LHC will be given.

## INTRODUCTION

Superconducting magnet circuits with associated bus-bars and links are the core technologies that enable to maintain and control a trajectory of particles in CERN's Large Hadron Collider (LHC) [1, 2]. Since the LHC is designed to collide protons at 7 TeV level, its main dipoles are required to produce a bending magnetic field of around 8.3 T in order to keep particles on the track. Numerous auxiliary magnet circuits operating within a broad range of magnetic fields, but much lower than the main bending magnets, are used to steer the beams, perform trajectory corrections, and introduce beam conditioning. An impressive amount of electromagnetic energy of about 11 GJ is stored in the whole magnet system of the LHC during its operation. The superconducting magnets are vulnerable to the quench phenomenon, which is a transition from the superconducting to the resistive state. It leads to the dissipation of the stored energy in a limited volume that in general can damage the affected magnet coil and may cause subsequent quenches in neighbouring circuits. Therefore, a highly dependable quench protection system (QPS) is necessary. It is based on the QDS supplemented by active and passive magnet protection means. The energy extraction system and quench heaters circuits fall into the active protection category, whereas the cold bypass diodes and parallel resistors into the passive means. The active systems are interlocked to the QDS. The present topology enables to detect promptly all dangerous situations and to execute the required steps in order to protect the LHC superconducting magnet system.

## QUENCH DETECTION SYSTEM

Taking into account the total number of required electronic circuit boards and the specific environment, where they are implemented, a number of constraints is set for the QDS. First of all the system is dealing with various quench detection modes, such as individual magnet, symmetric, bus-bar and current lead quenches [3, 4]. Additionally, an implementation of the detection technique depends on a given magnetic circuit and its topology. In general two main configurations are used: bridge and differential detection. The bridge configuration is implemented by a classic analogue approach or by digital signal processing. It is a robust technique applied to individual magnets. The differential numerical detection is used to protect circuits where the bridge technique cannot be applied. The digital detection enables to use nonlinear filtering, numerical inductance compensation and to vary detection parameters as a function of the circuit current. Table 1 summarizes an overall number of protection systems for various types of magnets used in the LHC. Each of the listed systems consists of multiple boards that enable to monitor magnets, bus-bars, current leads and quench heater circuits. They utilize more than 29000 active and custom made circuit boards, and provide above 14000 hardware interlocks required for dependable protection.

Table 1: Quench Detection Units in the LHC

| Name | Number | Description |
|---|---|---|
| nQPS | 436 | Main dipoles and quads |
| QDSIPQDT | 76 | Insertion region and inner triplet magnets |
| QDS600 | 114 | 600 A corrector magnets |
| QDSRB | 1232 | Main dipoles |
| QDSRQ | 392 | Lattice quads |
| QDSRBQ | 16 | Main dipoles and quads |

## DATA ACQUISIITON AND SUPERVISION

The QDS provides two different modes of data acquisition: the accelerator logging service (CALS) and the post-mortem (PM) system. All protection systems located in the tunnel are connected to the supervision layer by a WorldFIP™ interface that currently enables to transfer data every 100 ms. It enables to transfer in a real time 77792 digital indicators and 31924 analogue values to the supervision applications [5]. A part of the transferred signals is also used as software interlocks. Currently 132264 signals are transmitted between the QPS and the LHC accelerator control system at rates equal to 0.1, 5 or 10 samples per second. Due to its limited time resolution the CALS data is not sufficient for the analysis of critical events. Therefore, selected signals are sampled with a

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substantially higher sampling rate and stored in the local memory of the detection boards. Every event that causes a fast power abort triggers a PM data transfer and the locally stored information is sent over the WorldFIP. An important part of the data acquisition system is the supervision unit for the quench heater circuits, because their integrity has a direct impact on the reliability of the protection for the majority of the magnets. The supervision system performs an acquisition of voltages and currents in heaters circuits during a discharge. The provided data enables an early detection of quench heater failures. Furthermore, in case of a malfunction of the quench heater circuit during normal operation a slow power abort is triggered.

## DEPENDABILITY

The high energy stored in superconducting magnet circuits and the vulnerability of magnets to the quench phenomenon call for a high dependability level of the QDS. Particularly important is the reliability of the system. Since, undetected quenches are an unacceptable situation, adequate redundancy was applied in the QDS. However, this approach increases the probability of producing false triggers. Spurious quench signals are triggering a beam dump and induce an energy dissipation in the affected magnet which creates an impact on the cryogenic system. This might lead to several hours of recovery. In order to ensure the availability of the system with applied redundancy, a higher mean time between failures (MTBF) must be taken into account during the development process. Current assessment of the MTBF yields to $4x10^6$ hours for a single active QPS element installed in the LHC. The availability of the system is also reinforced by digital signal processing techniques that enable mitigation of effects coming from power converters, magnets and EMI radiation from equipment installed in the vicinity.

In case of a system that is distributed over large underground areas, the maintainability during operation is a crucial contributor to the overall downtime. Every access to the LHC tunnel in order to perform corrective maintenance requires at least two hours. A direct improvement is based on remote acquisition and control systems that enable fault prediction and plan maintenance during technical stops. Remote actions can be triggered to restore the availability of the system. The developed control and acquisition system is a core part of the strategy that enables to maintain dependability of a whole infrastructure on the expected level. It is complemented by a number of software applications used in different contexts of accelerator operation. Dedicated software tools cover regular supervision activities and the commissioning process. Troubleshooting tools are based on PM and CALS data analysis that enables to diagnose problems in the accelerator infrastructure.

The effects of ionizing radiation to electronics have been a major concern for electronics for the LHC infrastructure since 2011 when the first radiation induced faults were observed. During the LHC run 1 radiation induced faults were responsible for significant number of spurious beam aborts triggered by the QDS [6]. Since then, all registered events were single event effects (SEE), specifically single event upsets (SEU). This effect is responsible for malfunction of digital devices affecting microprocessors, FPGAs, memories, buffers and isolators. The SEU effects are non-destructive and the effect disappears after a reset or a power cycling. However, they are responsible for beam dumps, which affect the availability of the LHC. Since expected radiation levels in the LHC are increasing [7], multiple campaigns to mitigate radiation effects were launched [4]. They were based on two approaches: a relocation of the affected equipment and deployment of hardened electronics. The later technique is based on usage of radiation qualified devices, which required to conduct a number of radiation tests of the developed circuits. Digital circuits that are still susceptible to SEUs are protected by coding or triplication techniques. The deployment process for the critical units has been completed and it resulted in a significant drop of false beam dumps triggered by the QDS.

## DEPENDABILITY ANALYSIS

The LHC availability in 2016 experienced a remarkable improvement. The availability reached 74% of overall time compared to 69% in 2015 [8]. The accelerator spent 16% more time in a stable beam mode in a comparison to the 2015 run [9]. The stable beam duration was almost doubled. Since the QDS underwent a modernization campaign against radiation induced faults, its impact on the LHC downtime was significantly reduced. A plot of the QDS availability and impact fault time in consecutive months in 2016 is presented in Fig. 1.

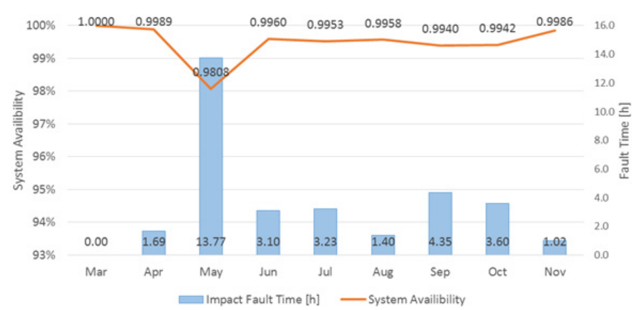


Figure 1: QDS availability and fault time in 2016 [10].

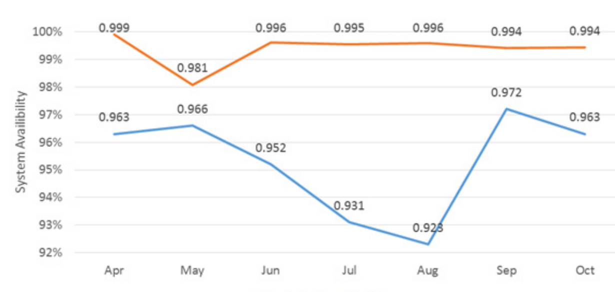


Figure 2: QDS availability pp-run in 2016 and 2015 [10].

A comparison between availability for the QDS for proton runs in the LHC in 2015 and 2016 is shown in Fig. 2. A visible drop in the system availability in 2015 was related to radiation to electronics. It was solved, by exchanging the affected type of electronic boards with radiation tolerant versions, during a technical stop (TS2). The improved availability resulted in a significant drop of the number of interventions. In 2015 101 remote and 42 tunnel interventions were required, while in 2016 13 remote and 15 access interventions were carried out. The raw fault time of the QDS subsystems listed in the Table 1 is shown in Fig 3. The presented comparison focuses on downtime of installed subsystems in consecutive months of operation and defines an overall availability of the system. Taking into account the number of elements installed in every subsystem group, the 600 A QDS requires more attention, because it was responsible for the longest downtime period per device installed. A comparison between downtime periods per device installed is shown in Fig 4.

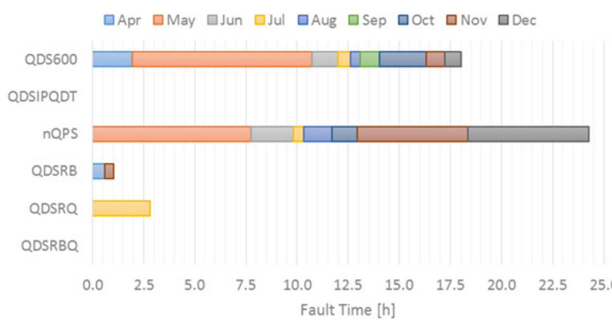


Figure 3: QDS fault time by system in 2016.

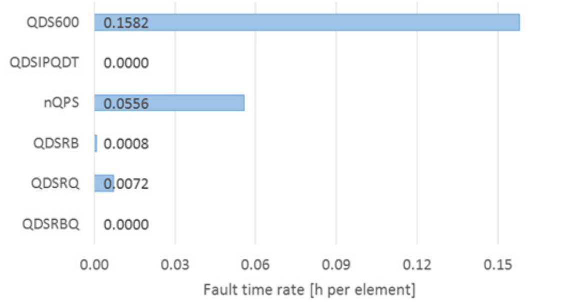


Figure 4: Fault time per device by QDS system in 2016.

## EVOLUTION OF THE QDS

Further evolution of the QDS is carried on two levels. The first level comprises of modifications required by a regular maintenance of the system. In this case electronic boards are upgraded in order to increase the overall dependability and replace components that are approaching their end of life. Software tools are also an area of improvements on this level. First of all, a more strict security policy is being applied for expert tools in order to isolate expert level development from operation and to protect the LHC from unintentional changes of the configuration. An important aspect of the software tools development is the process of automation of performed analyses. A number of tools, especially for hardware commissioning has been deployed, but there is still a great demand for automatic analysis of events. The development in this area is ongoing as the next improvement in the field of the dependability can be made by early detection of issues in the magnet circuit instrumentation and accelerator infrastructure. The second level of evolution of the QDS is related to hardware changes that require a substantial amount of resources. As mentioned previously in order to properly analyse the quench events a higher amplitude and time resolution of signals is required. Furthermore, to fully profit from the automatic tools the timestamping accuracy is crucial. A long term project is being conducted in order to replace the WorldFIP infrastructure with a radiation hardened interface that can provide data throughput in the range of hundreds of megabits and is synchronized to better than 1 ms. Another important aspect is the development of an isolated analogue to digital measurement channel with a programmable gain, a wide bandwidth (100 kHz), a broad input range (40 Vpp) and a high dynamic range that allows to use an identical analogue approach for most applications [11]. Once qualified, this hardware will be used in conjunction with an FPGA in order to fulfil various quench detection tasks by a software defined approach. The migration from analogue to digital detection enables to use sophisticated linear and non-linear filtering to supress noise coming from neighbouring infrastructure and provides high immunity to spurious triggers. It is especially valid for magnets of the new $Nb_3Sn$ superconductor type, which are considered for a future use in the HL-LHC [12]. Digital filtering and detection techniques have been already validated for QDS600 [13]. Digital detection units will be also used to protect superconducting links planned for the HL-LHC.

## CONCLUSION

The QDS is a fundamental part of the LHC's machine protection system. It is used to protect the majority of superconducting circuits that require tailored topologies and protection schemes. The QDS infrastructure is still undergoing a development in order to fulfil requirements of higher beam energies and luminosity given by the LHC evolution process. A fast quench detection requires sensitive electronics and reliable interlocks to protect the superconducting infrastructure. Data acquisition systems offering high resolution are required for the correct analysis of operations data. Altogether, existing constraints make the design process of the system complex, because it has to fulfil two contradictory conditions: a provision of high safety level for the superconducting magnet circuits and at the same time an assurance of the high availability of the system. Therefore dependability studies are an important part of the development process for the QDS. The development work performed so far resulted in a substantial improvement of the dependability of the system. It resulted in a significant contribution to the successful run 2 and the overall availability of the LHC. Further developments will be focused on maintaining this level of performance for the HL-LHC and providing tools that simplify the control and monitoring process of the LHC quench detection system.

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