QUENCH PROTECTION SYSTEM

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Abstract

The evaluation of the performance of the Quench Protection System (QPS) focuses on the overall availability of the system and its impact on the accelerator infrastructure in years from 2015 to 2018 that constitute Run 2. This contribution provides an insight into the evolution of the system throughout Run 2 and analyses major limitations encountered in this period. Subsequently, a discussion of planned optimizations and new installations is presented. Finally, the impact of the evolution of the QPS in LS2 on future accelerator operation is evaluated.

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). Since these components operate in the superconducting mode, they are vulnerable to a quench phenomenon. Therefore, a highly reliable Quench Protection System (QPS) is crucial for safe operation of the accelerator infrastructure. The system is based on a Quench Detection System (QDS) complemented by active and passive magnet protection means. Energy extraction systems and quench heaters circuits are attributed to the active protection category, whereas cold bypass diodes and parallel resistors to the passive means. The QDS is interconnected to the active protection system, and as well to a Powering Interlock Controller (PIC), which provides further connection to a Beam Interlock System (BIS) and Power Converters (PC). The BIS enables to request the removal of the particle beam, while the QPS and the PIC trigger all necessary steps to protect a superconducting magnet circuit. An adequate level of redundancy applied to the QPS ensures its reliability and safety of magnets throughout the operation.

QUENCH PROTECTION SYSTEM

The LHC is built from a vast number of superconducting magnets of different types in order to enable beam steering and applying corrections to the desired trajectory. Therefore, the QPS implements different building blocks in order to provide an exact solution for a magnet type and enables to deal with various quench detection modes, such as individual magnet, symmetric, bus-bar and current lead quenches [1,2]. An overview of the QPS hardware is presented in Table 1.

Table 1: QPS hardware overview

Name	Items	Description
EE13kA	32	13 kA energy extraction
EE600	202	600 A energy extraction
HDS	6084	Heater discharge power supplies
QDSRB	1232	Dipole quench detection
QDSRQ	392	Quadrupole quench detection
nQPS	436	13 kA symmetric quench detection
QDSIPX	76	Individually powered magnets
QDS600	114	600 A quench detection
Total	**8568**	

A functional overview of the QPS system in the LHC tunnel is presented in Fig. 1. The protection system for main 13 kA circuits consists of Energy Extraction (EE) systems located in caverns and quench detection units together with heater discharge power supply units distributed along the tunnel. Quench detection is comprised of individual magnet quench detection units for dipoles (QDSRB), individual magnet quench detection units for quadrupoles (QDSRQ) and symmetric quench detection units for main circuits (nQPS). In total QDSRB and QDSRQ crates are equipped with respectively 2464 and 1568 interlocking quench detectors. Symmetric quench detectors utilize 1632 symmetric and 4096 bus-bar interlocking quench detectors.

Most of the protection and detection devices for 6 kA and 600 A circuits are located in caverns, which makes them less vulnerable to radiation but they are not completely isolated from it. HDS units are an exception as they are located underneath the magnets it the tunnel. Inner triplets, individually powered dipoles and individually powered quadrupoles belong to 6 kA circuits. Their protection is solely based on quench heaters. Detection systems for these circuits use in total 360 individual magnet quench detectors for individually powered magnets, 48 individual magnet quench detectors for inner triplets and 1124 current lead quench detectors. 600 A corrector magnets are protected by Energy Extraction systems or means implemented on the Power Converter side depending on the total inductance of a circuit. Quench detection systems are equipped with 836 individual magnet quench detectors, as of which 212 are radiation tolerant designs, and 1672 current lead quench detectors.

In overall, this results in 13800 active interlocks, necessary to provide the required protection level. Furthermore, a large number and a variety of components used in the QPS require special precautions during design and operation not to impair the availability level of the system.

OPERATION IN RUN 2

General overview

The overall level of availability throughout Run 2 for the QPS system was 98.51 %, while the LHC reached a level of 83.18 %. Despite the high value of dependability, it was considerably affected by the year following LS1 that turned out to be visibly worse for the whole infrastructure, because

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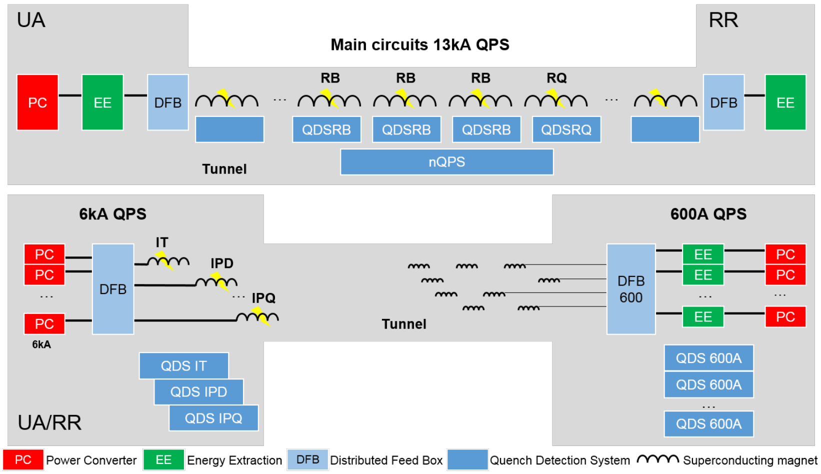


Figure 1: Layout of the QPS system in the LHC.

a significant amount of time was needed for an adaptation to the updated systems. Detailed analysis of the overall availability is presented in Table 2.

Table 2: Overall availability in Run 2

	LHC	QPS
2015	77.90 %	96.89 %
2016	83.39 %	99.29 %
2017	88.83 %	99.14 %
2018	82.59 %	98.73 %

A year to year comparison of the proton run availability statistics serves as a more comparable and convenient method of evaluating the system performance as working conditions are relatively stable in time, while its duration enables to gather a representative set of data. The proton run availability analysis is presented in Fig. 2.

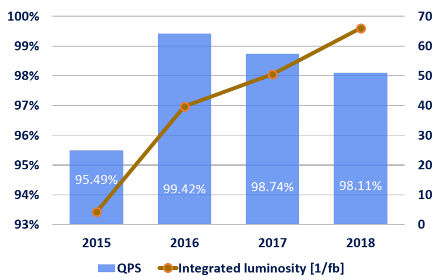
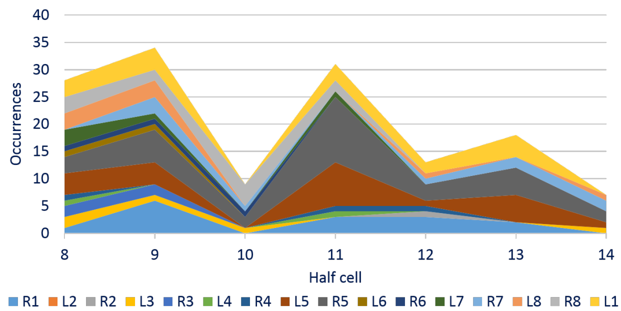
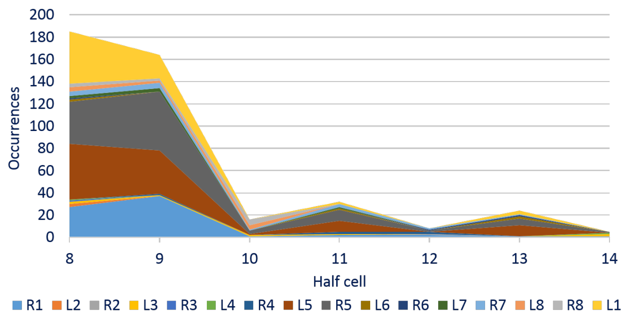


Figure 2: Proton run availability of the QPS.

The data clearly shows the impact of radiation to electronics issues in 2015 on the QPS system. It affected in the biggest extent the bus-bar splice protection units, which were specially installed for a high resolution evaluation of the splice connections before Run 2 and later a decision was made to keep them in the installation. They were replaced by dedicated units during TS2 in 2015, after which no significant issues have been observed. Additionally, increasing levels of radiation in RRs started to affect the performance of 600 A quench detectors. Therefore, they were replaced by an FPGA based radiation tolerant design in YETS 15/16. During the same yearly stop, Energy Extraction systems were inspected and maintained. For the 600 A systems it was a general maintenance, and 13 kA systems required an inspection and a service of energy extraction switches that showed integrity problems. These actions resulted in the exceptional availability on a level of 99,42% in 2016. It is worth to mention that the system during this year experienced a very low number of random failures.



(a) Events in 2017



(b) Events in 2018

Figure 3: Radiation induced events registered by the QPS.

The LHC completed the first full year of physics production in 2016, and with following years the value increased further, which resulted in an increased radiation exposure of the QPS devices. During the YETS 17/18 UPS connectors of the 13 kA energy extraction systems were reviewed as one faulty unit (RQD.A12) created significant contribution to the overall downtime of the QPS system in 2017. The operation in 2018 showed increased radiation levels in half-cells 8 and 9 due to the intentional TCL collimators settings change. A comparison of radiation induced events registered by the dipole and quadrupole detection systems in consecutive years in the dispersion suppressor regions is presented in Fig. 3. A noticeable change in the radiation distribution around points 1 and 5 resulted in a considerably higher number of radiation related events on data acquisition. These events were transparent to the operation, but there were observed also 8 events on data acquisition that required an intervention in comparison to 1 in 2017. More importantly, the higher radiation deposition caused 6 spurious triggers in the main circuits. Eventually, these events were responsible for 34.1 % of the QPS downtime in 2018. The impact of radiation on the availability in 2017 and 2018 is compared in Fig. 4.

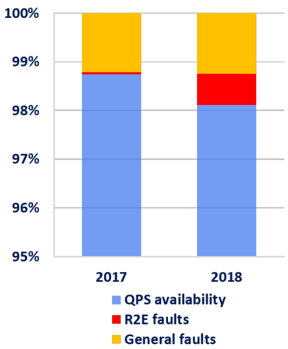
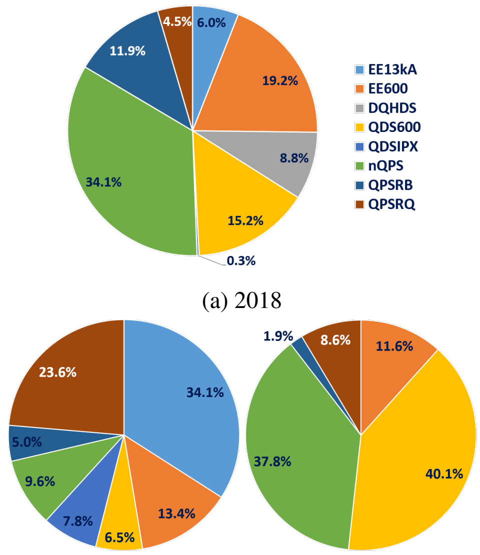


Figure 4: Radiation impact in 2017 and 2018.

The biggest contributors to the radiation induced downtime were bus-bar protection boards that used a photoMOS based interlocking relay, which turned out to be susceptible to total integrated dose and caused spurious dumps. The most exposed boards were equipped with electro-mechanical relays during TS2 in 2018 and this step enabled to continue operation without further major problems. Further replacements in the machine are possible if the anticipated radiation load is going to increase in the affected half cells. Elevated radiation conditions in half cells 8 and 9 are comparable with the HL-LHC radiation level baseline.

Subsystem level analysis

An overall fault distribution among subsystems of the QPS in 2018 is presented in Fig. 5a, and previous years in Fig. 5b and 5c. A substantial contributor to the overall downtime of the QPS in 2018 was the nQPS layer. However, as already explained, all faults were caused by the bus-bar protection, which is a part of this system. The system showed also usual problems with internal communication, but these problems are generally transparent for operation.



(a) 2018

(b) 2017 (c) 2016

Figure 5: Fault distribution in QPS.

The energy extraction system for 600 A circuits was the second main contributor to the overall downtime. It was not possible to distinguish a particular fault mode or a responsible component. In general, faults were equally distributed among all units installed, and usually a recovery period was long for a single fault as it required an access. Furthermore, the participation of the EE600 system in the downtime of the QPS has been increasing for 3 consecutive years, which suggests that the system slowly approaches the end of its useful life time. The system will be maintained during LS2 according to observed failures. Moreover, a decision regarding bypassing energy extraction systems in circuits operating below 300 A is going to be taken. This campaign will be mostly transparent for operation, and as a result a further availability increase can be expected.

Quench detection systems for 600 A circuits suffered from random trips during flat tops and ramp downs, and these events were mainly responsible for the downtime. Furthermore, as presented in Fig. 6, the unit fault duration is relatively high among other subsystems. Random trips can be split into two categories: triggered by the behaviour of a power converter when crossing zero and an electromagnetic interference vulnerability of QPS current sensors. Trips of the QPS in the former category, are from a system specification point of view, the correct behaviour of the quench detection system. An additional filtering applied on the quench detection level might decrease the sensitivity of the system and thus the safety margins. All registered events happened during ramp downs, so at rather low current in a circuit, and they posed mainly inconvenience during the operation. In contrary, trips in the latter category were occurring in all phases of the operation of the machine and they were responsible for a main part of the downtime attributed to the subsystem. Signals from current sensors are used to numerically calculate derivative components in order to compensate for inductive voltage components in the protected circuits. Therefore, the process is highly susceptible to noise and an EMI can cause a circuit to trip. In order to mitigate this problem, current sensors that showed to be more susceptible are going to be replaced by a sensor type that has been currently evaluated. Other sensor are going to be reviewed regarding shielding integrity problems.

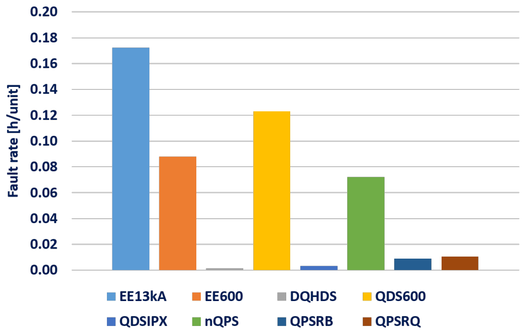


Figure 6: Unit fault duration for QPS systems in 2018.

The quench detection system for the main dipoles (MB) finished at fourth position in 2018. However, the unit fault duration was very small and comparable to the quench detection system for the main quadrupoles (MQ). Actually, these systems are very similar from a hardware perspective and they differ mostly in size. They showed a good performance with relatively negligible issues. During operation, problems with the "QPS OK" flags were observed, but they were mostly solved by remote interventions in case of the MB units. As remote maintenance options of the quadrupole detection units were limited, these problems required masking and scheduling interventions during convenient periods. This will disappear with a renovation program that takes place in LS2. Additionally, systems were responsible for generating artificial, radiation triggered Post Mortem (PM) data dumps. The problem was transparent for the operation, but could pose small inconveniences. Most of the remaining problems will be addressed by improved remote maintenance procedures or suppressed on the real time application level.

Heater discharge power supplies were not responsible for a great amount of the downtime and the unit fault duration was very small. Despite the fact that current statistics do not indicate the end of useful life of the system, capacitors used to store energy were evaluated. The investigation revealed that the end of a useful lifetime for 36000 capacitors is not earlier than LS3.

Energy extraction systems for 13 kA circuits had the highest unit fault duration, but eventually did not create a great impact on the overall downtime of the QPS. This means that faults were rare, but in most cases they required an access and the average is biased by the small overall number of devices. A general consolidation and maintenance program is going to be launched during LS2 in order to target 256 circuit breakers, dump resistors and control units. The anticipated life time after the successful campaign is 15 years.

The detection system for individually powered magnets was responsible for the smallest amount of the downtime. Its main problem is a subsystem for individually powered quadrupoles, which shows a sensitivity to thunderstorms. In fact, the cause of the problem lays in the electrical power distribution. Although, the problem was not prominent during the operation, usually during thunderstorms other systems are faster and when an IPQ trips the beam is already gone, it will be addressed during LS2 by separating a magnet and bus-bars protection. An existing limitation of the IPQ subsystem is the lack of a symmetric quench detection, and magnet safety is ensured by lowered thresholds of Beam Loss Monitors (BLM). Research and development work has been ongoing in order to develop a current derivative sensor that could be used to detect symmetric quenches of a magnet assembly.

Despite the fact that current lead heater controllers do not belong to the quench protection, they provide active interlocks and they are maintained by the group. They are located in the UA and RR areas, and the total number of installed units is 1350. An analysis of fault statistics, see Fig. 7, revealed that the number of failures of units installed in RRs started to increase. These units are exposed to small radiation doses and the obtained data suggest that radiation exposure shortens the useful life time. Therefore, a campaign to develop a radiation tolerant current lead heater controller has been launched.

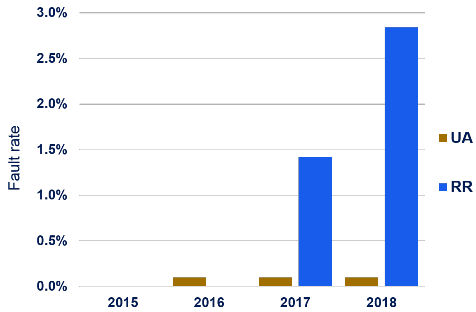


Figure 7: Fault rate of current lead heater controllers.

The real time application running on front-end computers (FEC), which broadcasts timing and manages data traffic on QPS fieldbuses, together with upper software layers enables to provide all necessary supervision and data acquisition for the correct system operation. Problems encountered during the operation were minor and usually transparent. The increasing radiation load showed that hardware crate controllers installed in the QPS devices, which create data nodes on the fieldbuses, are vulnerable to radiation. This can interrupt the communication with an agent or affect data integrity. Safety of a circuit is ensured by hardware detection modules, but in case of a protection event, data that enable to perform a proper analysis of the event are potentially not stored. Therefore, a development has been started to design a radiation tolerant crate controller. Several freezes of the real time application were observed during the operation, but this did not cause any downtime. Additionally, few cases of missing PM data were observed. This usually happens during powering tests or machine commissioning, and mainly IPQ and 600 A devices are affected. Both problems should be addressed by ongoing refactoring and modernization of the real time application. This activity aims on removing unused code, and optimizing data processing and the implemented state machine controller. Furthermore, an automatic fault recovery is planned to be added in order to facilitate regular maintenance of the system. As the controls software stack and some of the controls hardware components are being renovated, compatibility of the real time application must be ensured during LS2. Finally, a set of tools used for supervision and maintenance will be targeted in order to provide a proper decoupling between operational and expert tools. Tools for an automatic analysis of the state of health of the system are as well in the scope of future improvements.

NEW INSTALLATIONS

During LS2 two new major installation campaigns are planned. A DYPQ consolidation project is driven by a lifecycle management, and concerns the replacement of the existing main quadrupole magnet protection system with a newly developed one. This upgrade targets the Local Protection Interface Module (DQLIM) units and Local Protection Units (DQLPUB). Heater Discharge Power Supplies (DQHDS) will be reused from the existing installation. The DQLIM implements an interface between quench detectors and magnet taps, redundant power supplies for quench detector units and current transformers for an accurate heater discharge analysis. Furthermore, the new unit supports redundant mains powering. The DQLPUB quench detector unit [3] introduces new features in order to provide the improved availability, maintainability and data accuracy. This family implements for the first time, fully simultaneous data to facilitate analysis and slightly improve the timing resolution. Improved timing synchronization to the global timing was an important objective during the design of the system. Additionally, the system enables to execute considerably more remote maintenance procedures than the former MQ protection system. Finally, the new protection system was tested in radiation to be ready for the HL-LHC baseline specification.

A quench protection system for 11 T dipole magnets and trim circuits is a second installation planned for LS2. The scale is substantially smaller than DYPQ project, and a baseline is to provide protection equipment for 4 circuits. The equipment consists of heater discharge power supplies (HDS) for 11 T magnets, an HDS controller unit, a trim leads protection unit, and a UQDS [4] based new generation quench detection unit. HDS units provide a local magnet protection by quench heaters, and the HDS controller enables to distribute trigger lines from quench detectors and perform data acquisition of heater discharge curves. The trim circuit protection supervises superconducting leads of an 11 T magnet that are used to trim the magnet's current with respect to the main dipole circuit current. The unit monitors voltages over the leads and current distribution. Finally, the 11 T quench detection unit provides protection against asymmetric and symmetric quenches of a magnetic assembly, and bus-bars monitoring as well. The unit introduces high definition data acquisition and fast interlocks needed to protect the 11 T system. All planed units are going to be fully integrated with the existing QPS supervision and controls stack.

CONCLUSION

The quench protection system showed a very good performance during Run 2. Very high availability of the system enabled to decrease its impact on the availability of the overall accelerator infrastructure, and contributed to a very successful physics production run. Nevertheless, radiation levels to which the system is exposed still need careful evaluation and validation as it was revealed in the case of the readjusted TCL collimators. The system undergoes several consolidation programs that are aimed on maintaining the life cycle of the equipment and eliminating selected limitations detected during Run 2. Additionally, new equipment will be installed in order to protect new magnetic circuits and to phase out older equipment. Finally, significant changes in the supervision layer are to be expected as many software technologies will be updated, but also new features from the QPS perspective will be introduced.

In conclusion, the operational experience gathered during Run 2, careful planning of executed campaigns, and new hardware and software solutions will ensure good perspectives for restarting the system for Run 3. The QPS system should be able to maintain its availability level.

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