POWERING TESTS AND MAGNET TRAINING

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Abstract

In this paper the powering tests and magnet training during the hardware commissioning campaigns of Run 2 are discussed, and the implications of running at 7 TeV from a magnet training and reliability perspective are given.

During Run 2, the efficiency of powering tests has steadily increased due to enhanced control software, more automatic analysis, and more experienced CERN personnel. The MP3 Intervention Matrix, used for documenting requalification procedures after interventions, is presented. Given that the main dipole circuits are considered the main bottleneck for reaching 7 TeV operation from a magnet training perspective, training of these circuits is discussed in detail with regards to training efficiency and electrical integrity.

The training campaign of December 2018 comprised training of the main dipole circuit in sector 12, all main quadrupole circuits, the individually powered dipoles and quadrupoles, and the inner triplets of points 1 and 5. Due to time constraints, the training targets were only partially reached. In general the observed training behavior was encouraging, although training on the main dipole circuit in sector 12 was slower than expected. Also considering that all dipoles have previously reached a quench current of at least 12 kA before installation into the LHC, no showstopper was identified for reaching 7 TeV operation.

With regards to reliability of magnet operation at 7 TeV, no problems are expected in terms of flattop quenches, but the sensitivity to UFO-induced quenches is expected to increase significantly.

INTRODUCTION

This paper follows a presentation given at the 9th LHC Operations Evian Workshop on the 30th of January 2019 which addressed the topic of powering tests and magnet training during Run 2 as well as the implications of potential future operation at 7 TeV.

In light of input received from the organizing committee, this paper seeks to provide answers to the following topics and questions:

- Have we become more efficient in executing powering tests during hardware commissioning campaigns?
- How are circuits requalified after interventions?
- What causes the necessity of training the magnets in order to reach higher operational performance?
- How can training be done efficiently?
- What measures are undertaken to ensure safe future training of the main dipole circuits?
- Will we be able to run at 7 TeV?
- Will operation at 7 TeV be as reliable or less reliable?

This paper addresses these questions in the order as given above.

EFFICIENCY OF POWERING TESTS DURING RUN 2

During Run 2, the powering tests benefitted from the application of enhanced circuit control software, enhanced automatic analysis software, and steady accumulation of experience by the CERN personnel. This has resulted in a steady increase in efficiency throughout Run 2.

Powering tests were executed with the Accelerators Testing Framework during Run 2, also known as AccTesting [3]. Amongst other functions, this framework allows for the configuration of circuit powering rules through which incompatible powering tests may be avoided. If two circuits are inductively coupled then an energy-extraction discharge (a common feature of powering tests) of one circuit can result in spurious quench detection of the concurrently powered second circuit, resulting in an interruption of the powering tests. By avoiding incompatible powering tests, the fraction of tests that fail is reduced, so that unnecessary analysis and repeats are avoided. As shown in Table I, the fraction of failed powering tests has steadily decreased.

Table 1: Powering test statistics during period 2014-2018, following [2]. Note that this table does not yet include the powering tests in December 2018.

Hardware commissioning starting in	**Failed test fraction [%]**	**Automatic test fraction (excluding signed-only tests) [%]**
Sept. 2014	15	36
Mar. 2015	8	66
Apr. 2016	8	68
Mar. 2017	6	77

Enhanced automatic analysis with the Post Mortem Event Analyzer (PMEA) and Embedded Domain Specific Language (eDSL) has resulted in a decreased amount of manual analysis effort. Automatic analysis is performed immediately after completion of tests, independent of the time of day, thus avoiding delays that may block progress of the overall powering tests. This results in a faster overall analysis and thus a reduction in the time required for the powering tests. During Run 2 a significant increase in the

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fraction of automatically analyzed powering tests was observed (Table 1).

REQUALIFICATION OF CIRCUITS AFTER INTERVENTIONS

The requalification procedure after interventions is described in the LHC Magnet Circuits, Powering and Performance Panel (MP3) Intervention Matrix [4]. The procedures outlined in this matrix are the result of ongoing discussions between the MP3 and experts for the various equipment upon which interventions take place. The purpose of these discussions and the subsequent documentation is to document and subsequently apply interventions in a consistent manner.

As an example the replacement of an energy extraction switch on a 600 A circuit is considered. In this case the MP3 Intervention Matrix states that the system is to be cycled three times followed by a so-called PLI3.b1 powering test. During this test, a field team is present to locally measure the voltage drop over the new breaker.

GENERAL DISCUSSION OF TRAINING OF THE MAIN DIPOLE CIRCUITS

Necessity of magnet training

The necessity of training of the superconducting magnets used in the LHC is due to the reduction in quench current that superconducting magnets undergo after thermal cycles, so-called “memory loss”.

As an example, every main dipole magnet was trained to at least 12 kA before installation into the LHC (Fig. 1), but after installation the quench current of the circuit was well below 12 kA. As shown in Fig. 2, along with the training behavior of the other RB circuits, the influence of thermal cycles is illustrated in the training behavior of main dipole circuit RB.A56. Before Long Shutdown 1 (LS1) this was the only main dipole circuit trained to above 11 kA. After the thermal cycle during LS1 the quench current of the circuit has dropped by about 700 A, and about 20 training cycles were required to retrain the circuit.

Therefore, after a thermal cycle the main dipole circuits are very likely to require retraining during hardware commissioning, thus enabling operation with minimal training quenches.

Efficient training through the avoidance of spurious quenches

The main bottleneck for future operation of the LHC at 7 TeV from a superconducting magnet perspective is the training of the main dipole circuits. This is in part due to the time required to cool down the circuit to 1.9 K in between training quenches, which is expected to be about 12 hours for future training campaigns up to 12 kA [7].

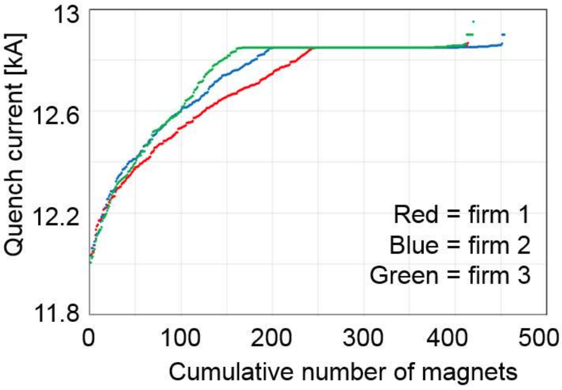

Figure 1: Achieved quench current of virgin main dipole magnets in SM18 [5].

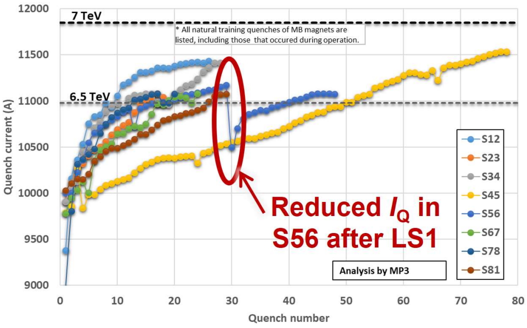

Figure 2: Training behavior of the RB circuits after installation [6].

The amount of time required to cooling the magnets down between training quenches increases with the amount of energy that is dissipated in the cold mass. Specifically, past experience has shown that a ten-fold increase in the amount of deposited energy results in a four-fold increase in the required cooling time (Fig. 3, [7]). To reduce the time required to cool down the magnets between training quenches it is important to avoid spurious secondary quenches.

Spurious secondary quenches are detected by either the initial QPS (iQPS) system that monitors the voltage difference between the two apertures of the dipole, or the new QPS (nQPS) system that compares the voltages over electrically adjacent dipoles and monitors the busbars between them.

Spurious secondary quench detection in the main dipole circuits occurs in part due to electrical “ringing” after powering supply deactivation and subsequent activation of the energy extraction systems [9, 10]. In addition, spurious quench detection is often observed on magnets that neighbor a quenching magnet. A likely explanation is that the voltage taps that monitor the spuriously quenched magnet are inductively coupled to the diode leads of the actually quenching magnet [11].

An example of a spurious quench detection is shown in Fig. 4. Here, 170 ms after an actual quench the nQPS detection threshold of 0.7 V was exceeded on a magnet neighboring the quenching magnet [8].

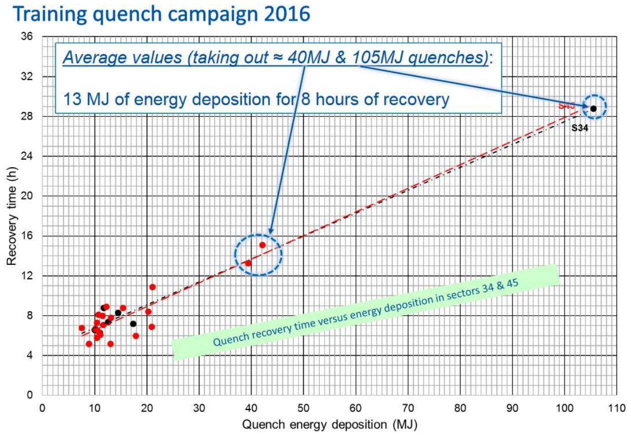

Figure 3: Relationship between deposited energy and recovery time during the 2016 training campaign, after [7].

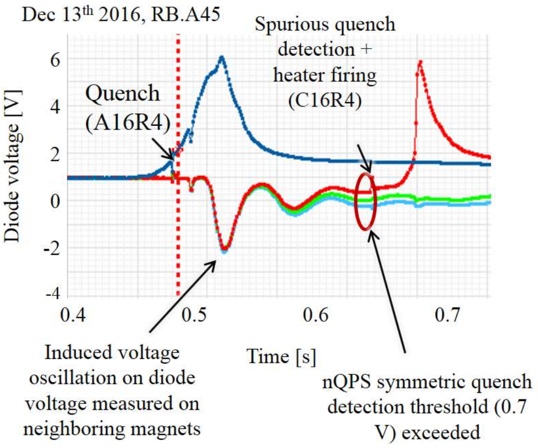

Figure 4: Quench event of the main dipole circuit of sector 45 on December 13, 2016, showing how a spurious quench detection resulted in quench heater firing and thus an unnecessary increase in dissipated energy, after [8].

During the HWC Dec 2018, adjusted nQPS settings were proposed and implemented, and the timing of the energy extraction activation was adjusted [8]. Whereas in previous hardware commissioning campaigns about two-thirds of the spurious quenches were due to nQPS triggering, during HWC Dec 2018 with the adjusted settings only 10% of spurious quenches resulted from nQPS triggering, with the remainder due to iQPS triggering. This implies a significant decrease in spurious quench detection due to the nQPS quench detection systems. During LS2 it is planned to investigate possible changes to the iQPS quench detection to further reduce spurious triggering.

Concluding, the efficiency of training of the main dipole circuit may be enhanced by avoiding spurious quench detection, thus reducing the amount of dissipation in the cold mass and the cryo-recovery time between quenches.

Efficient training through specialized training cycles

In addition to avoiding spurious secondary quenches, the amount of time required to train the main dipole circuits may also be reduced by increasing the amount of training quenches per training cycle.

Given that the amount of cryo-recovery time between training cycles is not proportional to the amount of dissipated energy (Fig. 3, [7]), it is advantageous from an efficiency perspective to perform multiple training quenches per training cycle. This may be achieved by adjusting the circuit response after quench detection: Rather than deactivating the power converter and discharging the circuit with energy extractors immediately after quench detection (Fig. 5, top), one may continue to ramp for a few more seconds, with the objective of quenching further magnets (Fig. 5, down). As an example, with continuing to ramp for three more seconds at 10 A/s one may expect to quench two to three more magnets, given that in HWC Dec 2018 the average increase in quench current was 15 A between consecutive training quenches.

From a starting point of 10 MJ, a three-fold increase in dissipated energy would result in a 80% increase in cryo-recovery time between training cycles and thus an expected 40% reduction in the average cryo-recovery time per training quench, assuming the dependency as shown in Fig. 3.

However, in addition to quench energy deposition, the distribution of quenching magnets over the cryo-cells also has an impact on the cryo-recovery time. In the case of fast secondary quenches (featured in the higher energy deposition cases shown in Fig. 3) where quenching magnets are located in the same cryo-cell the cryo-recovery is slower than for the case where the quenching magnets are distributed over different cryo-cells, as may be expected for the multiple training quenches resulting from this training scheme. The estimate of 40% reduction in cryo-recovery time per training quench is likely pessimistic.

This modified training scheme does have negative consequences. In particular, the heat load on the diodes and busbars increases, the impact of ramping during quenches on the regulation of the power supply is presently unclear, the probability of creating a (double) short to ground is increased (see next section), and there may be other implications where are presently not yet foreseen. In general, this concept is an interesting possibility, but it represents a trade-off between increased training efficiency versus risk. Careful consideration is required before proceeding with this option, and good electrical integrity is a necessity. This option is to be discussed by the MP3 during LS2.

Safe training through consolidation and analysis after quenches

An extensive training campaign with hundreds of training quenches in the main dipole circuits [12] would be required to reach 7 TeV operation. In order to train the magnets while minimizing the risk of permanent damage, efforts are underway to reduce the probability of shorts to ground.

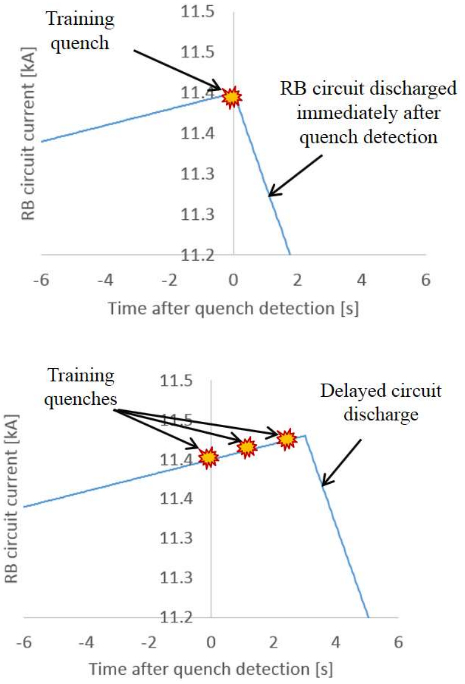

Figure 5: Standard (top) versus modified (bottom) training cycles of the main dipole circuit

It was previously observed that the diode boxes of the main dipoles contain metallic debris (Fig. 6, [13]), which is likely left over from the initial welding of the cold masses (note that the diode boxes are located at the bottom of the cold masses).

After a quench, the circuit is discharged over the energy extractors so that the voltage potential of the diodes with respect to ground is raised by up to 400 V. The dissipation of the stored energy of a quenching magnet into the helium bath results in turbulence in the helium bath, which can move the metallic debris around resulting in a conductive path between the diode and ground. This diode is then electrically connected to ground and the earth-current fuse at the power supply blows.

On December 8, 2016, this resulted in a sudden shift in circuit potential by about 400 V after the occurrence of the short to ground and followed by 22 main dipoles quenching, given that the quench detection systems are sensitive to sudden shifts in the voltage potential [14].

A single short to ground, with an expected 1% probability per training event [15] thus results in spurious triggering of dipole magnets, in addition to a required intervention with the so-called Earth Fault Burner [16]. A more serious case is a double short, with an expected 0.01% probability per training event [15], which results in internal arcing and severe damage to the main dipole circuit [14, 15].

In light of this issue, during LS2 the metallic debris will be removed, additional electrical insulation will be installed (see for instance [17]), and high resistance diode contacts will be consolidated [18]).

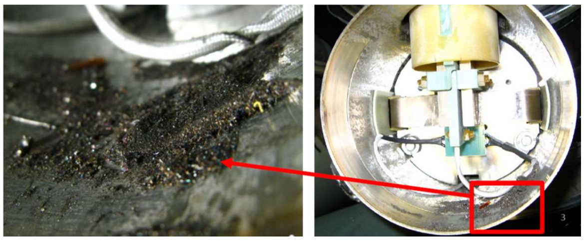

Figure 6: Diode boxes of the main dipole circuit, with metallic debris, after [13].

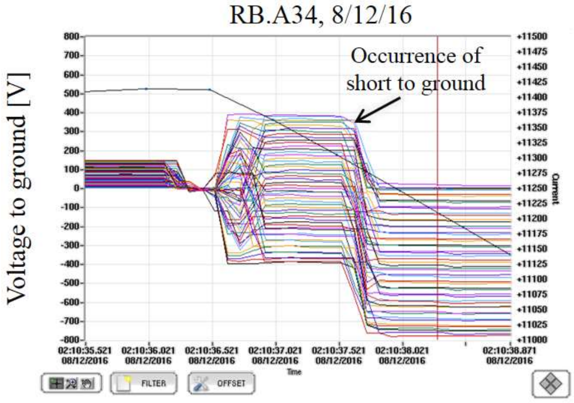

Figure 7: Measured voltages to ground in the RB circuit of sector 34, on December 8, 2016, after [14].

Besides consolidation efforts to mitigate problems with electrical integrity, after every quench the quench behavior of the circuits is evaluated by the MP3. Through early detection of problems and subsequent mitigation efforts, the occurrence of severe problems is minimized so that training of the circuits can be done in a safe and efficient manner.

TRAINING AND COMMISSIONING CAMPAIGNS DURING HWC DEC 2018

Training of the main dipole circuit in sector 12

During HWC Dec 2018, RB.A12 was trained in an effort to reach the training target of 12 kA (equivalent to 7 TeV + margin). The purpose of these tests was to get an indication of how many training steps are required to train all main dipole circuits to 7 TeV + margin, and to see whether the observed amount of training quenches is in line with expectations.

The training campaign was stopped after 16 training quenches, due to a combination of slower training than expected and time constraints. A quench current of 11.4 kA was reached (Fig. 8, [6]).

While the observed training was slower than expected, nevertheless no showstopper for reaching 7 TeV + margin was identified [19, 20].

Training of the main quadrupole circuits

All main quadrupole circuits were trained during HWC Dec 2018 with the objective of training up to 11.75 kA, (equivalent to 7 TeV + margin, see Fig. 9, [6]).

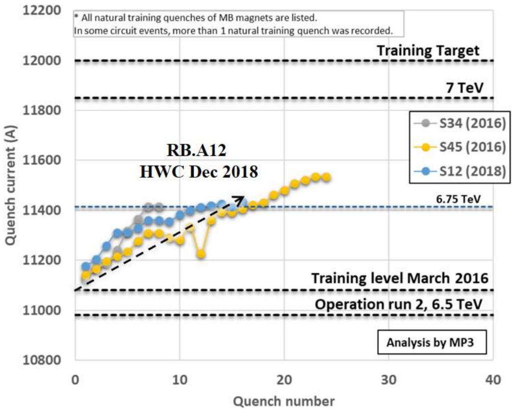

Figure 8: Training of the RB.A12 circuit during HWC Dec 2018, compared to previous training campaigns of circuits RB.A34 and RB.A45 [6].

Due to time constraints this target was not reached. Nevertheless, the observed training behavior showed that the main quadrupole circuits are not a bottleneck for reaching 7 TeV + margin, also considering the much smaller cryo-recovery time on the order of 1 hour.

Training of the individually powered dipoles and quadrupoles

During HWC Dec 2018 the individually powered dipoles and quadrupoles were trained with the objective to reach the current required for 7 TeV operation.

The 16 individually powered dipoles all reached the target current after two training quenches in total.

Of the 78 individually powered quadrupoles 53 reached the target current, for four circuits the target current was reduced after multiple training quenches, 14 circuits were not trained, and 7 more were partially trained due to time constraints [1].

Commissioning of the inner triplets at points 1 and 5

The inner triplets of points 1 and 5 were ramped to the equivalent current of 7 TeV + margin [21] and maintained at this current for 30 minutes without quenches. This means that all inner triplets are proven to operate at 7 TeV.

Feasibility of LHC operation at 7 TeV + margin from a quench current perspective

Of the superconducting magnets in the LHC the main dipoles are considered the bottleneck for reaching the equivalent current for 7 TeV + margin. From the training campaign of the main dipole circuit in sector 12 during HWC Dec 2018 it became clear that training was slower than expected. Nevertheless, no showstopper was identified, also considering that all installed dipoles have reached a quench current of at least 12 kA before installation in the LHC (Fig. 1).

During HWC Dec 2018 the main quadrupole circuits were trained but did not reach their target current. In spite of this, no showstopper was identified and these circuits are not believed to be a bottleneck.

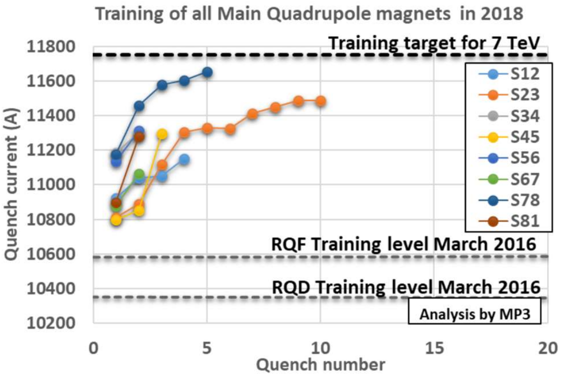

Figure 9: Training of the RQ circuits during HWC Dec 2018 [6].

All individually powered dipoles, most individually quadrupoles and the inner triplets of points 1 and 5 were commissioned at 7 TeV + margin.

RELIABILITY OF OPERATION AT 7 TEV

The reliability of magnet operation at 7 TeV is discussed in terms of flattop operation and UFO-induced quenches.

The strategy for avoiding flattop quenches during operation is to train up to the operational current plus a margin (typically 100 A for RB and RQ) during the hardware commissioning campaigns. After reaching the current target that includes the margin, the circuits are ramped to the operational current and kept at this current for a period of eight hours. If no quench occurs during this period then this implies that the margin level was sufficient and the training campaign is completed. With respect to the main dipoles and quadrupoles, no limitation for operation from flattop quenches is expected [22].

Regarding UFO-induced dumps and quenches, the increase in energy from 6.5 to 7 TeV results in an expected 12% increase in deposited energy in the coils per proton lost, along with a 20-30% decrease in the amount of energy required to quench a magnet. This results in an expected two- to fourfold increase of the amount of UFOs that have potential to induce a quench [22]. For reference, in the period of 2015 and 2016 there were 37 beam dumps without quench and 6 quenches resulting from UFO-induced increases in heat load on the magnets [22]. Concluding, operation at 7 TeV has the potential to significantly increase the amount of UFO-induced beam dumps quenches with respect to 6.5 TeV operation.

CONCLUSION

This paper gives an overview of powering tests and magnet training during Run 2 and discusses its implications for potential future operation of the LHC at 7 TeV from a magnet training and reliability perspective.

The efficiency of the powering tests during the hardware commissioning campaign has increased during Run 2, due to enhanced control software, more automatic analysis of measurements after the tests, and a general increase in experience and skill on the part of the CERN personnel.

The procedure to requalify the LHC circuits after intervention is discussed in terms of the MP3 Intervention Matrix.

A general discussion of training of the main dipole circuits is presented, given that these circuits are believed to be the main bottleneck for reaching operation at 7 TeV from a training perspective. Methods to enhance the efficiency of the training campaign are discussed, and the efforts to enhance the electrical integrity during LS2 are presented.

As part of the powering tests during the December 2018 hardware commissioning campaign, various circuits were trained to study the feasibility of future operation at 7 TeV from a superconducting magnet perspective. In this training campaign no showstopper for reaching 7 TeV was identified. The main dipole circuits are expected to be the main bottleneck for future operation at 7 TeV and the training of main dipole circuit RB.A12 was slower than expected. The individually powered dipoles were trained up to the target current. Training of the main quadrupoles and the individually powered quadrupoles was partially completed due to time constraints, but nevertheless the results were encouraging and these circuits are not expected to be a bottleneck for operation at 7 TeV. The inner triplets at points 1 and 5 were commissioned at 7 TeV + margin so that all inner triplets are proven to operate at 7 TeV.

Regarding reliability at 7 TeV operation, no significant increase in flattop quenches are expected. Nevertheless, the amount of UFOs which have potential to induce a quench is expected to increase by a factor two to four.

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