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BEAM-INDUCED QUENCH TESTS OF LHC MAGNETS

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Abstract

At the end of the LHC Run1 a 48-hour quench-test campaign took place to investigate the quench levels of superconducting magnets for loss durations from nanoseconds to tens of seconds. The longitudinal losses produced extended from one meter to hundreds of meters and the number of lost protons varied from 10^8 to 10^{13}. The results of these and other, previously conducted quench experiments, allow the quench levels of several types of LHC magnets under various loss conditions to be assessed. The quench levels are expected to limit LHC performance in the case of steady-state losses in the interaction regions and also in the case of fast losses initiated by dust particles all around the ring. It is therefore required to accurately adjust beam loss abort thresholds in order to maximize the operation time. A detailed discussion of these quench test results and a proposal for additional tests after the LHC restart is presented.

INTRODUCTION

During the LHC Run 1 a total of 17 beam-induced quenches were observed. Most quenches occurred during quench tests or at beam setup time. The operational quenches took place exclusively during the injection process [1]. The low number of beam-induced quenches in comparison to other superconducting accelerators is explained partly by the low magnet currents, with the LHC running at just over half of its nominal energy. In 2015, after Long Shutdown 1, the LHC will be running close to its nominal energy of 7 TeV, with more beam-induced quenches expected. Therefore a good understanding of quench levels for various beam-loss scenarios is very important.

The quench level is defined as the minimum local energy deposition that, for a given beam-loss scenario, will result in a transition from the superconducting to normal-conducting state. Most quench level calculations to date have been based on a semi-empirical model [2], but a new electro-thermal model has been recently developed [3]. In Fig. 1 an example of quench level curves as a function of loss duration for a main LHC dipole magnet is estimated using the new model. The quench levels are computed with QP3 [3] on the horizontal plane of a main-dipole magnet, for the geometrical loss pattern in [4]. The higher beam energy results in lower quench levels. To validate the electro-thermal model the beam losses must be reproduced by means of simulation which needs to be validated with observable monitoring signals (mainly from Beam Loss Monitors (BLM)). The 17 beam-induced quenches in the LHC can be used to estimate upper bounds on quench levels in the quenching magnets. Adjacent magnets that did not quench, as well as beam-loss events that did not result in quenches at all, can serve to estimate lower bounds on quench levels. These analyses

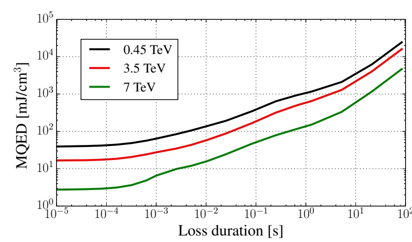

Figure 1: Quench level as a function of beam-loss duration for heat pulses of constant power for a main LHC dipole magnet, for magnet currents corresponding to injection beam energy (450 GeV), 3.5 TeV, and 7 TeV.

have been done and will be reported in [5]. Here the main lessons learned during this exercise are presented.

METHODOLOGY

Despite the different mechanisms of beam losses in the studied quench tests the analysis procedures are similar. The measurement data is provided mainly by the BLM system, the Quench Protection System (QPS), the Beam Position Monitors (BPM), and the fast beam-current transformer (FBCT). The analysis proceeds along the following steps (see Fig. 2):

1. The geometric loss pattern on a suitable interface is calculated with accelerator tracking codes. The interface may be the beam-screen surface, or a transverse plane, e.g., the frontal plane of a collimator. On the interface, the position- and the momentum distribution of the particles serves as an input for particle-shower simulations, which continue the tracking to the point where the particles hit dense matter.

2. Particle-shower simulations compute the energy deposition in the active volume of BLMs and inside the superconducting coil. These simulations are normalized with experimentally obtained numbers of lost particles.

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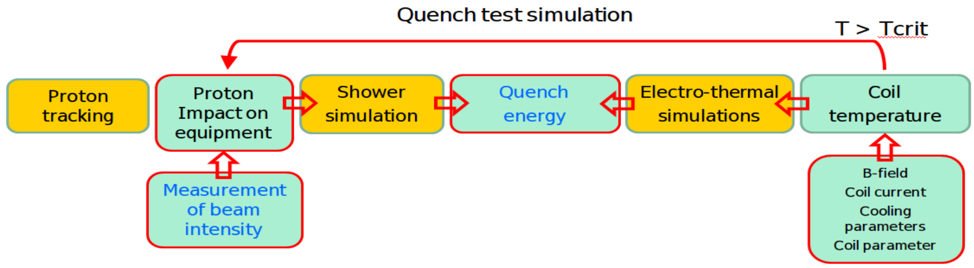

Figure 2: Steps of the quench test analysis.

A good agreement between the simulated and measured energy deposition in the BLMs gives a confidence in the simulated energy deposition in the coils.

3. An electro-thermal simulation yields quench level estimates in the most critical position of the coil. The inputs to the simulation are superconducting cable characteristics, the magnetic field, the shape of the radial profile of the energy density distribution (from particle shower simulations) and the normalized time-evolution signals from BLMs.

4. Consistency between particle-shower simulations and the electro-thermal modelling increases the confidence in the electro-thermal model as well as in the overall understanding of the event.

In the following sections each aspect of the quench test is briefly discussed. The list of quench tests performed is shown in Table 1. The first event was not an actual quench test but a beam setup event in which the beam trajectory could be precisely determined. Tests numbers 2, 8, 9, 10 did not result in a magnet quench.

EXPERIMENTAL SETUPS

The experiments can be divided into two classes, those with direct beam impact on the magnet and those using a target to generate the particle shower. In the first type of events the beam is deflected into the magnet aperture. In the early tests (6,7) this was done by means of an orbit bump that was slowly increased while in the recent experiments (5,11) the orbit bump was combined with transverse damper excitation to generate well controlled losses in the magnet of interest. In the second type of events the beam hits a target which produces secondary particles that then hit the magnet. The target can be a wire scanner (4), a single collimator (2, 3) or a whole hierarchy of collimators (8-10).

The last case, that of losing the beam on the collimation system, is the only test which actually corresponds to the operational loss scenario of a short beam lifetime. Other interesting operational scenarios, such as beam losses due to falling dust particles [6], cannot be generated in a controlled way, and therefore the experiments have a different setup which itself is unlikely to take place during the normal machine operation. These special setups produce losses on a small scale, using small beam intensities. It remains a challenge for future quench tests to generate controlled losses on the millisecond timescale. For many tests it is crucial to make sure of good synchronization between QPS and BLM systems and good control of the number of protons lost in the magnet. One strategy is to perform the test with a gradual increase of lost beam intensity, registering the evolution of all systems before the quench.

LOSS PATTERNS

The loss patterns obtained in the experiments vary from the obvious in cases like wire scanner test (4), to test 5, where a complex simulation needed to be developed and even then the agreement with observables (in this case with beam position and temporal loss pattern measurement) is moderate.

The biggest surprises encountered during the simulation of local loss patterns are: a strict relation of the particle impact angle with loss location along a quadrupole magnet and very large sensitivity to the impacted surface roughness [11]. A sub-milimeter knowledge of surface roughness is one of the key upgrades for the future quench tests with beam impacting directly on the magnet.

PARTICLE SHOWER SIMULATIONS

The first step of particle shower simulations is the introduction of the experimental setup into a simulation program. In the case of beam losses in an accelerator the main contribution is given by the material of the magnets. The amount of details included in the simulation depends on the required accuracy. For instance, in the case of BLMs installed next to the beam vacuum chamber, the radiation field gradient is such that even a one centimeter error in the radial position of the BLMs can result in large errors in the estimated signal. The simulations also include tunnel walls, mainly because they have a large impact on propagation of thermal neutrons, which contribute to the BLM signals at the percent level. Longitudinally, the simulation may cover a single magnet or a whole section of the accelerator.

Some crucial elements are difficult to be encode geometrically, such as for example the ends of the superconducting coils, which have a complicated form with additional spacers of various special shapes. In many loss cases the maximum of the energy deposited in the coil is expected to be in this

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Table 1: Overview of the Beam-Induced Quench Tests on LHC during Run 1

No	Date	Regime	Method	Type	Temp. [K]	I/I_{nom} [%]	beam energy [TeV]	Comment and reference
1	2008.09.07	short	kick	dipole	1.9	6	0.45	[4]
2	2011.07.03	short	collimation	-	-	-	0.45	no quench
3	2013.02.15	short	collimation	quadrupole	4.5	46/58	0.45	[7]
4	2010.11.01	intermediate	wire scanner	dipole	4.5	50	3.5	[8]
5	2013.02.16	intermediate	orbit bump	quadrupole	1.9	54	4	[9]
6	2010.10.06	steady-state	dyn. orbit bump	quadrupole	1.9	?	0.45	3 quenches
7	2010.10.17	steady-state	dyn. orbit bump	quadrupole	1.9	?	3.5	[5]
8	2011.05.08	steady-state	collimation	-	-	-	3.5	no quench
9	2011.12.06	steady-state	collimation	-	-	-	3.5	ions, no quench
10	2013.02.15	steady-state	collimation	-	-	-	4	no quench [10]
11	2013.02.16	steady-state	orbit bump	quadrupole	1.9	54	4	[9]

difficult region, leading to a significant error in the energy density estimation.

In general the BLM signals are simulated with particle shower programs to a satisfactory accuracy. Large discrepancies are observed for very low signals especially those generated by back-scattered particles. In some tests the generated BLM signals were saturated and these BLMs should be replaced by higher-range detectors in future tests.

A rigorous error estimation based on simulation to BLM signal agreement remains difficult to obtain. The low sensitivity of the current BLM system to variations in loss patterns limits the accuracy at which the energy deposition in the coil can be determined.

ELECTRO-THERMAL SIMULATIONS

Electro-thermal simulations describe the heat propagation from the superconducting cable through the insulation to the liquid helim bath. It takes as input the normalized radial distribution of the energy density in the coil obtained by the particle shower simulation and the temporal loss structure measured during the test. Because of the large impact of Helium II on the thermal properties of the magnet (large heat capacity and conductivity) a good knowledge is required of the amount of liquid helium in the coil. This is usually less well known in the magnet ends, where the quench often takes place.

The overall agreement of the experimental results with electro-thermal simulations is within a factor 2, except for millisecond losses for which the experiment suggests a 3-5 times higher value (5). This is probably due to the spiky loss structure observed, for which future work is needed to engineer and validate a predictive model.

The results for the steady-state case, test (11) suggests that the fishbone structure between the two layers of the coil is not efficient in increasing heat transfer from the coil. Experimental work to verify this point is ongoing.

CONCLUSIONS

To assess the future luminosity reach of the LHC and to determine quench-preventing BLM thresholds several

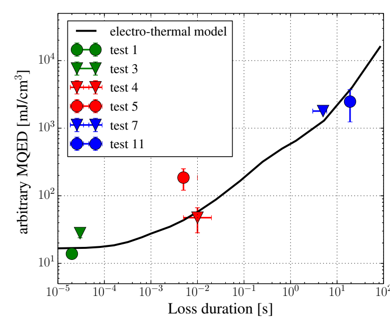

Figure 3: Illustration of results obtained during quench tests. Electro-thermal model is a quench level which is expected from heat transfer simulations. Note that it is a generic curve here, not representing a particular magnet type or current.

quench tests were performed during Run 1. Despite the fact that the methods used to produce the required loss patterns and loss durations were perfected over time, the errors in the procedure are still quite large as reflected in Fig. 3.

Among the lessons learnt for the future investigations is the importance of a proper tool for loss pattern simulations, for losses generated by an orbit bump. Because of the size of a particle shower and the limited potential of the current BLMs to distinguish various loss patterns, knowledge of precise energy deposition in the coil is limited. Radiation detectors placed closer to the magnet coil would help in overcoming these issues. Finally, the problem of generating losses on the millisecond-timescale similar potentially dangerous dust-particle events remains to a large extent unsolved. The tests performed to date generated losses about 10 times longer and with an irregular loss structure, so differing significantly to the observed dust event. It must be stressed that these conclusions are based on a very limited number of quench tests and should be revisited in the future, when more data becomes available. Further collimation tests are needed at higher energies and with ions to fully determine the LHC luminosity limits experimentally.

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