BEAM INDUCED QUENCHES OF LHC MAGNETS

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Abstract

In the years 2009-2013 LHC has been operated with the top beam energies of 3.5 TeV and 4 TeV instead of the nominal 7 TeV, with corresponding reduced currents in the superconducting magnets. To date only a small number of beam-induced quenches have occurred, with most of them being specially designed quench tests. During normal collider operation with stored beam there has not been a single beam induced quench. This excellent result is mainly explained by the fact that the cleaning of the beam halo worked very well and, in case of beam losses, the beam was dumped before any significant amount of energy was deposited in the magnets. However, conditions are expected to become much tougher after the long LHC shutdown, when the magnets will be working at near nominal currents in the presence of high energy and intensity beams. This paper summarizes the experience to date with beam-induced quenches. It describes the techniques used to generate controlled quench conditions which were used to study the limitations. Results are discussed along with their implication for LHC operation after the first Long Shutdown.

INTRODUCTION

The seventeen beam-induced quenches which took place during LHC Run 1 are listed in Table 1. Only a few of them were operational quenches, the others took place during dedicated experiments (Machine Development time) or a Machine setup. The operational quenches took place exclusively during the injection process.

The low number of operational quenches in comparison to other superconducting accelerators: HERA [1], Tevatron [2] and RHIC is explained by better orbit stability, better beam tail cleaning efficiency, sophisticated interlocks and by running at about 50% of the design current. After Long Shutdown 1 (LS1) LHC will be running at the nominal energy and more beam-induced quenches are expected.

Four quenches were generated at flat top energies, i.e. 3.5 TeV or 4 TeV. One quench test was performed with a magnet current corresponding to 6 TeV beam energy, giving an outlook to quench limits at energies after LS1.

Half of the beam-induced quenches were deliberately provoked. So called *quench tests* took mainly place at the end of 2010 (numbers 6-10 in Table 1) and during 48 hours after Run 1 in February 2013 (numbers 15-17). The main goals of these tests were to calibrate beam abort thresholds of the Beam Loss Monitoring (BLM) system and to investigate machine performance limits. Not all quench tests ended with quenches. In this paper special emphasis is put on the last quench test period, as the previous tests are already described in literature (references in the text). However, the detailed analyses of the last tests are ongoing and will be published separately.

QUENCH LIMITS

The maximum amount of energy which can be deposited in a superconducting cable without provoking the transition to a normal-conducting state is called the quench limit. This limit depends on the type of the superconducting cable, its position inside the coil, its electric current (which is proportional to the beam energy in case of the dipoles) and on the spatial distribution and duration of the beam loss. The dependence on loss duration is illustrated in Fig. 1. There are three main regimes:

- for short duration beam losses ($<\sim 1$ ms) the quench limit is determined by the enthalphy margin of a dry cable, without contribution from liquid helium,
- for intermediate duration losses (1 ms $-$ 1 s) the superfluid helium inside and around the insulated conductor plays a crucial role because of its large heat capacity,
- for steady-state losses ($>\sim 1$ s) the heat is constantly removed with a rate determined by the properties of the helium channels inside the coil.

Because of multiple mechanisms of heat transfer between cable and helium which depend on the properties of

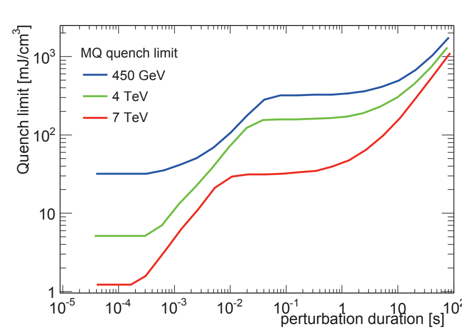

Figure 1: Quench limit as a function of energy perturbation duration (beam loss), for injection beam energy (450 GeV), 4 TeV and 7 TeV according to the algorithm from [3].

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the cable insulation, the estimation of the quench limit is difficult. Several numerical and phenomenological models lead to different results, especially for intermediate duration losses.

In the following the beam-induced quenches are discussed for three timescales of loss duration: fast, intermediate and steady-state.

FAST LOSSES

The four operational quenches involving multiple magnets (number 5,11,13,14 in Table 1) took place during physics beam injection. The first was due to injection with a wrong current in the main quadrupoles, the second and the fourth due to a flashover in the injection kicker magnet and the third due to strong orbit oscillations at injection.

The quenches number 1 to 4 were due to orbit errors (first turn quenches) [4]. Quench number 12 was similar, but it has been done on purpose, with the goal to cross-calibrate BLMs and radiation monitors [5].

In July 2011 and February 2013 dedicated tests have been done in order to investigate the quench limits for energies above 4 TeV [6]. In these tests the injected beam hits a closed collimator (TCLIB) and the generated particle shower heated the coil of the quadrupole magnet behind the collimator (Q6). The current in this magnet was increased in steps and corresponded to beam energies higher than the injection energy. In 2011 the test was stopped before quenching the magnet, but in 2013 the quench was achieved for a current corresponding to a beam energy of about 6 TeV.

The advantage of this test was a very well defined loss pattern (beam intercepted completely by the collimator), which allows preparation of a very precise particle shower simulation in order to determine the energy deposition in the magnet coil during the quench. It is expected that ongoing analysis of this test will give an outlook on the number of magnets that risk to quench during a dump system failure leading to an asynchronous dump.

MILLISECOND LOSSES

The LHC operation in years 2010-2013 was affected by a phenomenon of millisecond-duration beam losses, observed by the BLM system. These losses are suspected to be provoked by dust particles falling into the beams. They are called "Unidentified Falling Objects" (UFO) [7, 8]. They lead to losses strong enough to potentially quench LHC magnets. No quench was provoked during Run 1, but the quench limit is expected to be 2-4 times smaller for 7 TeV beams, while the energy deposition due to beam interaction with UFOs is expected to be 2-3 times higher.

Two experiments were designed to investigate the quench limit for this timescale of losses: a wire scanner quench test [9] (number 10) and fast loss test using the transverse damper (ADT) (number 16). The preparation of the beam excitation procedure for last one is described

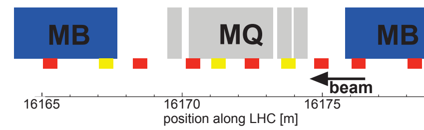

Figure 2: The location of additional beam loss monitors in the cell around the quadrupole magnet 12L6 (MQ). Yellow boxes are regular BLMs mounted on every quadrupole while the orange ones represent additional monitors.

in [10]. Seven additional beam loss monitors, one diamond detector and an oscilloscope registering the Quench Protecion System (QPS) signals were installed nearby the targeted magnet, as shown in Fig. 2.

In Fig. 3 the post-mortem high-granularity data from BLM and QPS systems are presented. The total duration of losses was about 10 ms but the quench started after about 5 ms when about $5 \cdot 10^8$ protons were lost. A challenge of this test were the measurements of beam intensity and emittance of bunches with about 10^8 protons per bunch, more than 10 times lower than intensities for which the LHC beam instrumentation was designed.

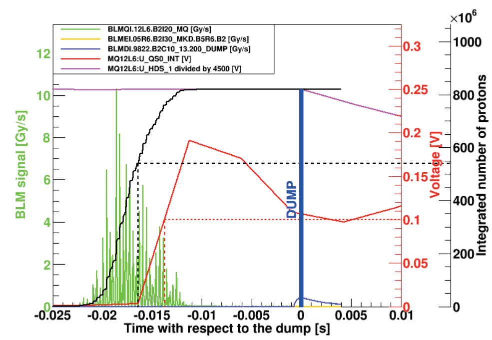

Figure 3: Synchronized BLM (green) and QPS (red) signals registered during quench number 16. The quench occurred after about $5 \cdot 10^8$ protons hit the magnet.

STEADY-STATE LOSSES

Five beam-induced quenches from Table 1 can be qualified as steady-state: 6-9 and 17, but several other attempts have been undertaken. These attempts were performed in 2011 and 2013 by generating a controlled beam loss on the collimation system [11, 12]. In the very last attempt the peak power of the beam hitting the primary collimators reached 1 MW and still no quench occurred. This last test has demonstrated that the multi-stage LHC collimation system is able to protect cold magnets from quenches even in cases of very large beam instabilities.

The second method to investigate the steady-state quench limit is based on the generation of a local orbital bump touching the aperture of the magnet. The experiment

Table 1: List of beam-induced quenches of LHC magnets in years 2008-2013.

No	date	beam energy [TeV]	loss duration	quenched magnet	location	remark
1	2008.08.09	0.45	∼ ns	MB	8L3	beam setup
2	2008.09.07	0.45	∼ ns	MB	10R2	beam setup
3	2009.11.20	0.45	∼ ns	MB	12L6	beam setup
4	2009.12.04	0.45	∼ ns	MB	15R2	beam setup
5	2010.04.18	0.45	∼ ns	MB+	20R1	wrong main quad current
6	2010.10.06	0.45	1 s	MQ	14R2	quench test
7	2010.10.06	0.45	1 s	MQ	14R2	quench test
8	2010.10.06	0.45	1 s	MB	14R2	quench test
9	2010.10.17	3.5	6 s	MQ	14R2	quench test
10	2010.11.01	3.5	10 − 40 ms	MBRB	5L4	quench test
11	2011.04.18	0.45	∼ ns	MB+	IP8	kicker flashover
12	2011.07.04	0.45	∼ ns	MB	14R2	test
13	2011.07.28	0.45	∼ ns	MQXB+	IP2	injection oscillations
14	2012.04.15	0.45	∼ ns	MB+	IP8	kicker flashover
15	2013.02.15	0.45/6	∼ ns	MQM	6L8	quench test
16	2013.02.15	4.0	5 − 10 ms	MQ	12L6	quench test
17	2013.02.16	4.0	20 s	MQ	12L6	quench test

of 2011 (number 9) is described in [13, 14]. It was repeated in February 2013 on a different magnet, generating a horizontal loss with much longer duration (20 seconds) and excitation with ADT for a precise control of the beam blowup. Comparison of BLM signals, shown in Fig. 4, clearly demonstrates the advantage of the use ADT.

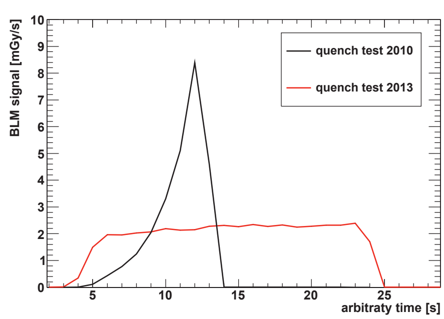

Figure 4: Comparison of BLM signals (averaged over 1.3 seconds) for the 2010 and 2013 tests (number 9 and 17).

CONCLUSIONS

There were 17 beam induced quenches of LHC superconducting magnets during Run 1. Half of them were during dedicated tests. The only operational beam-induced quenches of LHC magnets during Run 1 took place at injection. Analysis of the quench tests is complicated and involves intensive particle-shower simulations. A direct benefit of these tests was the tuning of BLM thresholds. Furthermore, the detailed analysis of the experimental studies allows a quantitative benchmark of codes and a more precise extrapolation of quench margins to 7 TeV. The last series of quench tests shows larger than expected quench limits in millisecond-scale losses and an important dependence of the BLM signal on the loss pattern.

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