

# TEST AND SIMULATION RESULTS FOR QUENCHES INDUCED BY FAST LOSSES ON A LHC QUADRUPOLE

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## Abstract

A test program for beam induced quenches was started in the LHC in 2011 in order to reduce as much as possible BLM-triggered beam dumps, without jeopardising the safety of the superconducting magnets. A first measurement was performed to assess the quench level of a quadrupole located in the LHC injection region in case of fast (ns) losses. It consisted in dumping single bunches onto an injection protection collimator located right upstream of the quadrupole, varying the bunch intensity up to  $3 \times 10^{10}$  protons and ramping the quadrupole current up to 2200 A. No quench was recorded at that time. The test was repeated in 2013 with increased bunch intensity ( $6.5 \times 10^{10}$  protons); a quench occurred when powering the magnet at 2500 A. The comparison between measurements during beam induced and quench heaters induced quenches is shown. Results of FLUKA simulations on energy deposition, calculations on quench behaviour using the QP3 code and the respective estimates of quench levels are also presented.

## INTRODUCTION

The safe operation of the LHC relies on several protection levels. The main aim is to detect any anomaly in the hardware and/or beam behaviour and abort the beam before inducing quenches in the superconducting (sc) magnets. A dedicated system of about 3600 monitors (BLM) allows to surveil the beam losses around the LHC ring and trigger a beam abort when they are above a certain threshold. The definition of the BLM thresholds has to guarantee enough margin from the quench levels to insure the required protection, without compromising the machine performance and availability. A deep knowledge of the quench levels for the different families of LHC sc magnets is therefore crucial, especially in view of operation at higher energy after Long Shutdown 1 (i.e. 6.5 TeV).

At the LHC startup in 2009, the BLM abort thresholds were set according to the quench levels as predicted in [1] and [2]. Over the last years, new sophisticated electrothermal calculations have been performed which provide accurate estimates of the quench levels as a function of the beam energy and for different loss regimes. Several dedicated beam-induced quench tests were also carried out during Run 1 [3] to validate the tools used for calculations and, as a consequence, the quench level predictions at high energy. This paper contains the description and the results of a test performed in 2013 to investigate fast quenches above injection energy. The quench level of a quadrupole located in the injection region of Beam 2 (Q6: an MQM and MQML type quadrupole [4] hosted in the same cryostat and operating at

4.5 K), a few meters downstream of an injection protection collimator (TCLIB [5]), was measured. The test was the followup of a previous measurement performed in 2011 with lower beam intensity and magnet current [6].

## TEST SETUP AND MEASUREMENTS

The TCLIB collimator is located downstream of IP8 (Beam 2 counterclockwise direction) and, in case of failure of the injection kickers, it has to intercept primary protons escaping the main injection protection stopper (TDI [5]). One of the quench tests consisted in injecting a single bunch of  $6.5 \times 10^{10}$  protons and dumping it at the TCLIB. In order to fully intercept the beam, the collimator jaws were closed to the minimum allowed gap of 1 mm (anti-collision switches) and an offset of  $7 \sigma$  (measured beam size) was applied with respect to the beam centre. The particle showers produced at the TCLIB were partially absorbed at a fixed mask (TCLIM), located between the collimator and the Q6; nevertheless a non-negligible amount of energy was deposited on the magnet. A 20 MHz digital oscilloscope, connected in parallel to the Quench Protection System (QPS [7]), was used to measure the voltage drop across the sc coils of the magnet and detect any quickly developing normal conducting zone induced by the beam energy deposition. A linear correlation between the voltage rise and the bunch intensity was measured in 2011 [6].

The Q6 is individually powered; it was thus possible to increase the current of the magnet, at each beam injection (in consecutive steps of 500 A), and simulate operation at higher energies. A clear quench was provoked by the TCLIB showers on the Q6 when powering the magnet with 2500 A, which corresponds to operation at 6 TeV (injection optics).

## DATA ANALYSIS

### *Oscilloscope Data Analysis*

During each loss event, induced by the beam impacting on the TCLIB, an electrical signal was recorded across the magnet's coil at the oscilloscope. The observed signal had the shape of a narrow voltage spike and was always followed by a drop of the current in the magnet by about 0.5 A. Up to 2000 A the magnet could recover and the quench heaters [7] did not fire. At 2500 A, the initial spike was followed by a slow voltage rise that exceeded the threshold of the quench detectors after about 12 ms and the quench heaters were fired (Fig. 1). Data of a quench induced with the quench heaters, while powering the magnet with 2500 A, are also shown in Fig. 1 for reference. The two curves show the same behaviour with a rapidly developing resistive zone at 40 ms,

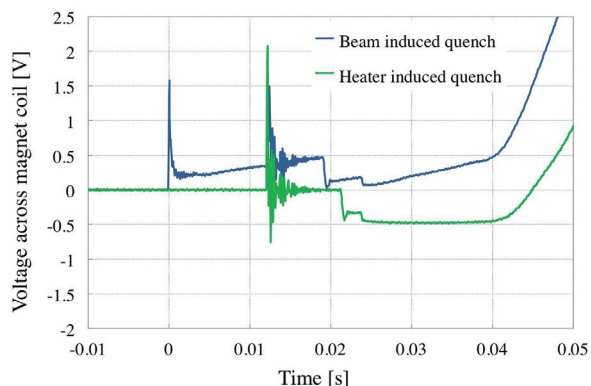


Figure 1: Comparison of electrical signals measured across quenching magnet coils: quench provoked by quench heaters and beam induced quench. The graphs are synchronised by the moment of the quench heater firing.

when the magnet coils are reached by the heat coming from the quench heaters.

The beam induced quench signal is unambiguous but the mechanism causing the narrow voltage spike, at the moment of the losses, and the following current drop are not fully understood. The particles hitting the Q6 magnet indeed interacted with the coil and provoked the quench. Nevertheless, the involved process seems to be more complex than the simple creation of a resistive zone due to the heat deposition. Further investigations are ongoing.

### FLUKA and QP3 Calculations

Particle-shower simulations with FLUKA [8] [9] were carried out in order to evaluate the energy deposition on the Q6 coils. An accurate representation of the geometry of

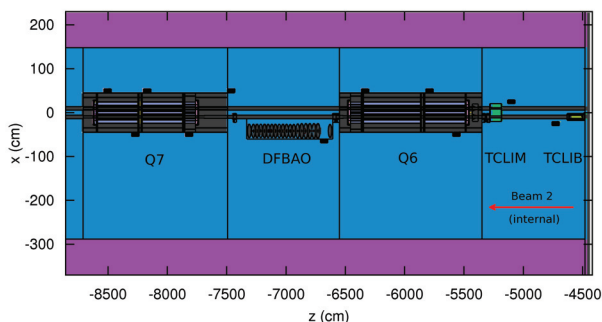


Figure 2: Geometric model implemented in FLUKA for the Q6 energy deposition calculations.

the LHC section, from the TCLIB until the first quadrupole downstream of Q6 (Q7: two MQM type magnets in the same cryostat), was implemented in the FLUKA model (as shown in Fig. 2). Details on apertures, beam screens, vacuum modules, cold/warm transitions (DFBAO) and diagnostics were included in the calculations as well as the quadrupole magnetic field corresponding to the applied current. FLUKA calculations were done starting from a particle distribution,

matched with respect to the nominal optics parameters at the entrance of the TCLIB and the measured emittance in the SPS (0.5 mm mrad). The knowledge of the absolute position and aperture of the TCLIB allowed a precise estimate of the beam impact point on the jaw. The beam intensity, measured in the SPS before each extraction towards the LHC, was used as normalisation factor to quantify the actual beam load on the TCLIB and the consequent showers on the downstream elements. At 450 GeV, about 90% of the impacting protons experience an inelastic nuclear interaction inside the 1 m long graphite jaws of the TCLIB; only 10% of the incident proton energy is absorbed in the jaw. Simulations

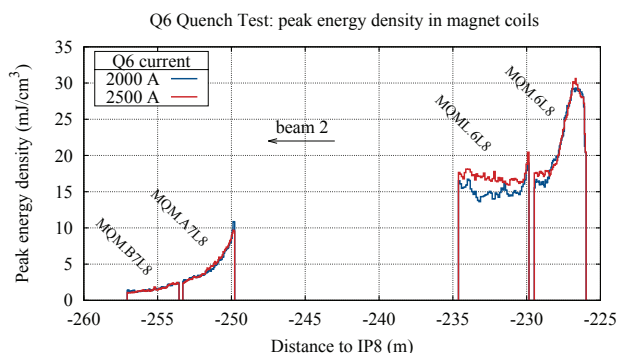


Figure 3: Peak energy density at Q6 and Q7 quadrupoles when impacting the TCLIB with  $6.5 \times 10^{10}$  protons at 450 GeV. The cases with a current of 2000 A and 2500 A are considered.

were performed for a Q6 supply current of 2000 A (74 T/m corresponding to operation at 4.91 TeV) and 2500 A (93 T/m corresponding to operation at 6.13 TeV). The result of the peak energy density calculations along the Q6 and Q7 magnets is shown in Fig. 3 for the two scenarios. The two profiles are almost identical as the beam intensity and energy is the same in both cases. A small discrepancy can be appreciated only for the Q6 magnet, where the different applied fields affect the behaviour of the showers development along the quadrupole. The FLUKA model predicted a maximum energy density of 29 mJ/cm<sup>3</sup> and 31 mJ/cm<sup>3</sup> on the magnet coils powered with 2000 A and 2500 A respectively; the magnet quenched only in the second case. The estimated maximum energy density is located in the horizontal plane on the inner coil diameter as shown in Fig. 4. The energy density radial profile was used to define the location, shape and size of the heat pulse for the electrothermal calculations with QP3 [10]. Losses occurred in a few ns and, according to simulations, no dependence of the quench level on the loss duration is expected for losses shorter than 100 μs. A quench level between 16-20 mJ/cm<sup>3</sup> is estimated with QP3 at 2500 A, in perfect agreement with FLUKA predictions on energy deposition. Instead, for the measurement at 2000 A (when no quench occurred), QP3 calculations give a quench level of 20-23 mJ/cm<sup>3</sup>, about 50% lower than FLUKA estimates. Taking into account the uncertainties in FLUKA

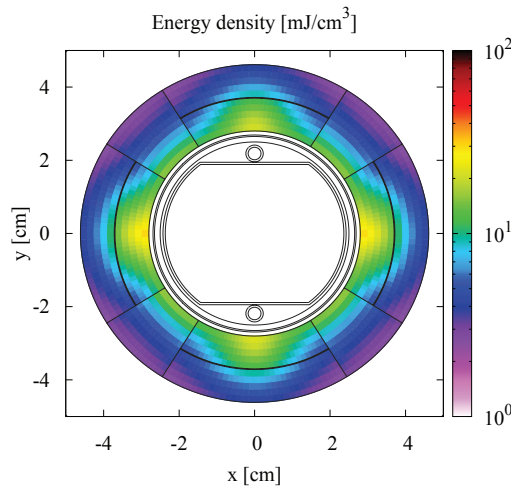


Figure 4: Transverse energy density distribution in Q6 coils (2500 A) at the position where the maximum energy deposition occurs. Spatial coordinates are with respect to the center of the vacuum chamber.

(mainly the geometry definition) and QP3 calculations, the agreement in the quench level evaluation is satisfactory.

#### FLUKA Calculations of BLM Dose

FLUKA simulations were also used to try to reproduce the measured dose in the BLMs installed at the TCLIB and at the downstream elements. The BLMs close to the TCLIB and the Q6 magnet saturated at each injection and this made the comparison challenging. Since the losses propagated further downstream of the Q6 magnet, the data at the BLMs located up to 70 m after the TCLIB were considered for the comparison with the simulations. A difference of more than one order of magnitude was found (as shown in Fig. 5). One

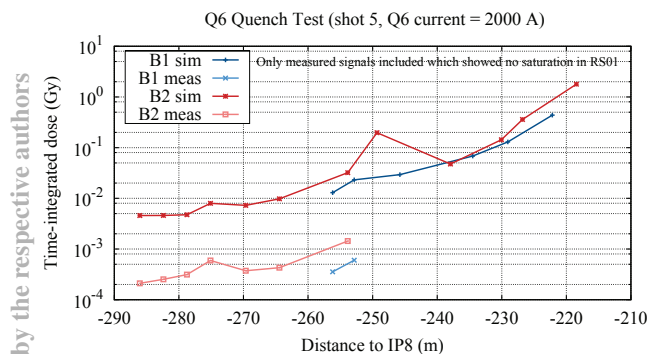


Figure 5: Comparison between FLUKA simulation results (sim) and BLM data (meas) for time-integrated dose at the elements downstream of the TCLIB (-217 m from IP8). Monitors for both Beam 1 (B1) and Beam 2 (B2) are considered.

possible explanation is that the saturation of all the monitors close to the TCLIB and Q6 affected the BLMs on the same power distribution line making their data reading doubtful. Despite this discrepancy, the reliability of the FLUKA model

was proven from other experiments (where an agreement between 20% and 30% could be achieved) and the good agreement with QP3 calculations.

## CONCLUSIONS

A campaign of beam induced quench tests was performed during Run 1 to validate the models used to calculate the quench levels of the LHC sc magnets and extrapolate them to operation at 6.5 TeV. One test consisted in investigating fast quenches above injection energy in a MQM type quadrupole located in the injection region. A clear quench, induced by the TCLIB showers on the Q6 when powering the magnet with 2500 A (6 TeV), was observed. Still, the process inducing the quench in the sc coils is not fully understood and further analysis is needed. FLUKA and QP3 calculations were carried out to evaluate the quench level of this magnet and an agreement was found within 50%. The attempt of reproducing BLM dose measurements with FLUKA simulations was also done. A discrepancy of more than one order of magnitude was found but BLM data could have been affected by the saturation of a large number of monitors on the same powering line. In general, the results of this test validate the calculation tools and their predictions for quench induced by fast beam loss within the expected uncertainty.

## REFERENCES

- [1] J.B. Jeanneret et al., "Quench level and transient beam losses in LHC Magnets", CERN-LHC-Project-Report-44, CERN, Geneva, Switzerland, 1996.
- [2] D. Bocian et al., "Modelling of quench limit for steady state heat deposit in LHC magnets", IEEE transactions on applied superconductivity, VOL. 18, No. 2, CERN, Geneva, Switzerland, 2008.
- [3] M. Sapinski et al., "Beam induced quenches of LHC magnets", Proceedings of IPAC2013, Shanghai, China, 2013.
- [4] "LHC Design Report", chapter 8 "Insertion Magnets", p. 219-250, CERN, Geneva, Switzerland, 2004.
- [5] V. Kain, "Machine protection and beam quality during the LHC injection process" CERN-THESIS-2005-047, Vienna Tech. U., 2005.
- [6] C. Bracco et al., "Experiments on the margin of beam induced quenches for LHC superconducting quadrupole magnet in the LHC", Proceedings of IPAC2012, New Orleans, USA, 2012.
- [7] R. Denze et al., "Upgrade of the protection system for superconducting circuits in the LHC", Proceedings of PAC09, Vancouver, CAN, 2009.
- [8] A. Ferrari et al., "FLUKA: A multi-particle transport code", CERN-2005-010, CERN, Geneva, Switzerland, 2005.
- [9] G. Battistoni et al., "The FLUKA code: Description and benchmarking", Proc. of the Hadronic Shower Simulation Workshop 2006, AIP Conf. Proc. 896, p. 31-49, 2007.
- [10] A. Verwein, "QP3: User Manual", EDMS-1150045, CERN, Geneva, Switzerland, 2008.