# BEAM-INDUCED QUENCH TEST OF A LHC MAIN QUADRUPOLE

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*Abstract*

Unexpected beam loss might lead to a transition of the accelerator superconducting magnet to a normal conducting state. The LHC Beam Loss Monitoring (BLM) system is designed to abort the beam before the energy deposited in the magnet coils reaches a quench-provoking level. In order to verify the threshold settings generated by simulation, a series of beam-induced quench tests at various beam energies has been performed. The beam losses are generated by means of an orbit bump peaked in one of Main Quadrupole magnets (MQ). The analysis includes not only BLM data but also the Quench Protection System (QPS) and cryogenics data. The measurements are compared to Geant4 simulations of energy deposition inside the coils and corresponding BLM signal outside the cryostat.

## INTRODUCTION

The superconducting LHC magnets are in danger of damage due to the heat deposition causing destruction or quenching (transition from the superconducting state to the normal conducting state). The protection is provided by two independent and complementary systems. The Beam Loss Monitoring system measures the particle shower generated by any beam loss and dumps the beam before a quench can occur. The Quench Protection System measures the voltage generated on the magnet coil, detecting when a part of it becomes normal-conducting, and fires the quench heaters to dissipate the energy stored in the magnetic field over the whole volume of the coil.

The aims of the experiment were to understand the quench development and determine the quench level for beam losses on a 5-10 second timescale, and to correlate observables from various systems (mainly BLM and QPS) in order to create a consistent model for a quenching magnet. The results of the experiment can also be used to validate the QP3 heat transfer code [1].

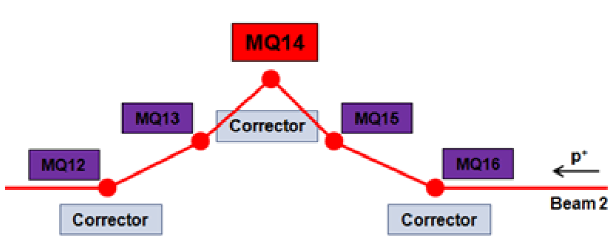


Figure 1: Layout of 3-corrector bump.

## EXPERIMENT

The quench test was performed in the LHC arc half-cell 14R2 (Figure 1) on the October 17, 2010. A three-corrector orbit bump was applied to divert the proton beam from its initial orbit to hit the aperture within the MQ magnet, which was focusing in the plane of the bump.

The beam energy was 3.5 TeV and the intensity was $1.85 \cdot 10^{10}$ protons. The circulating beam 2 was deflected in a vertical direction with an imposed bump set to reach a maximum deflection of 15 mm. The beam-abort thresholds on BLMs were increased by a factor of 3 in order not to dump the beam before the quench occurs.

## RESULTS

During the quench test about 58% of the initial beam intensity was deposited in the MQ (Figure 2) within approximately 6 s. Figure 3 shows QPS and BLM signals during the last second before the quench. The QPS registered a voltage drop (MQ.LOC:U_QS0_EXT signal) of approximately 160 mV before firing the quench heaters. The BLM detector signal is also observed to increase with time. The moment of the beam dump can be seen as a sudden drop in the quench heaters voltage and a corresponding steep decrease of the BLM signal.

The data registered by Beam Position Monitors (BPMs) indicate that the beam was dumped at around 14.65 mm before it reached the imposed maximum bump amplitude of 15 mm .

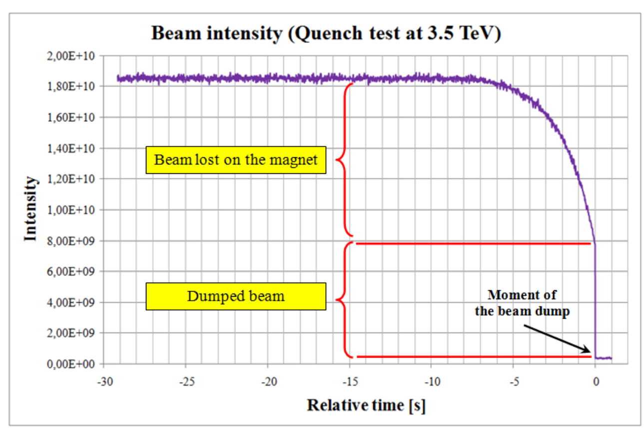


Figure 2: Beam intensity of the 3.5 TeV proton beam during the quench test as provided by the Beam Current Transformer (BCT).

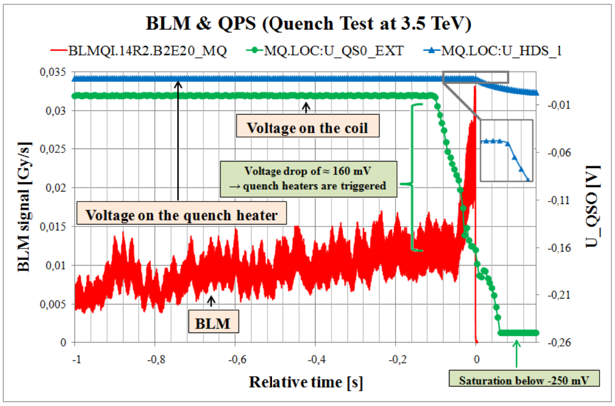


Figure 3: Comparison of signals during the quench. Red line – BLM, green line – voltage difference between apertures, blue line – voltage on quench heaters.

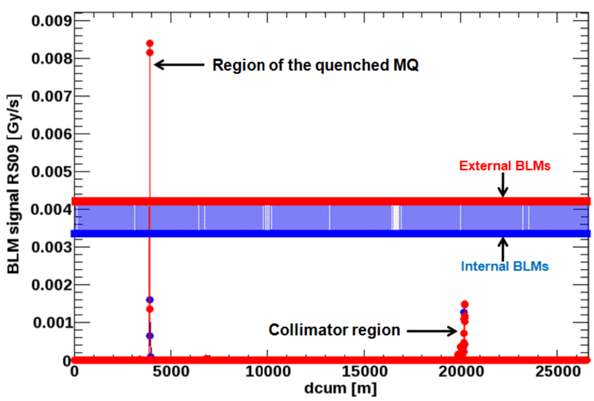


Figure 4: Beam losses along the LHC ring.

The BLM signals along the LHC ring are presented in Figure 4. Almost all beam losses appeared in cell 14R2 and were around eight times higher than those observed on the betatron cleaning collimators. The loss registered by the beam dump monitors is not shown on the plot.

## SIMULATIONS

A simplified Geant4 simulation of the quench test was performed with the implementation of a detailed representation of the LHC half-cell concerned. It included the main accelerator components: three downstream Main Dipoles (MBs), the MQ, interconnections and corrector magnets – MSCBB and MQT. In the simulation the loss location was chosen to be at the beam screen in the center of the main quadrupole. An impact angle of 202 μrad (vertical direction), calculated from the settings of the orbit bump, was chosen. The location of the BLMs with respect to the simulated loss point of impact is presented in Figure 5.

The simulation provides estimates of the energy deposition inside the superconducting coils, $E_{dep}$ and the signal from the BLMs mounted on the cryostat. The energy deposition in the coil is measured in cylindrical bins with size $\Delta\rho = 5.13$ mm, $\Delta\varphi = 4°$, $\Delta z = 9.83$ mm. It is important to note that the value of $E_{dep}$ cannot be derived directly from the experiment.

The BLM detectors were represented as long tubes along the cryostat to study the fluence of secondary particles, not only at the position of the installed monitors but also in the location of the dipoles.

The peak of energy deposition inside the coil occurs at about 40 cm from the loss location while the highest number of secondary particles, therefore the highest BLM signal, is registered by BLMs at around 2 m from the loss location (Figure 6). The radial distribution of energy density in the most exposed azimuthal and longitudinal position was fitted by a power law function [2]

$$E_{dep} = p_0(r - p_1)^{p2} \qquad (1)$$

where $r$ is the distance from the coil centre and $p_0$, $p_1$, $p_2$ are the fit parameters (Figure 7).

A calculated maximal energy density of $3.9\cdot10^{-6}$ mJ/cm$^3$ per proton occurred on the inner surface of the coil while the average energy density per superconducting cable was found to be approximately $6\cdot10^{-7}$ mJ/cm$^3$ per proton.

Fluences $F$ of secondary particles have been convoluted with response functions $R$ given by [3] to provide variables comparable with the BLMs. The convolution is expressed by the following equation

$$Q = \sum_{i=1}^{5}\left(w_i \cdot \sum_j \sum_k R_{i,j,k} F_{j,k}\right) \qquad (2)$$

where index $i$ corresponds to the angle of the incoming secondary particle (15º, 30º, 45º, 60º, 90º) and $w$ is the weight related to the number of particles in an angular bin

$$w_i = \frac{I_i}{I_{total}} \qquad (3)$$

$I_i$ is an integrated area assigned to a particular angle and $I_{total}$ is an integral of the angular distribution (Figure 8). The index $j$ iterates over the particle types ($p^+$, $e^-$, $e^+$, $\pi^-$, $\pi^+$, n, γ) while $k$ iterates over secondary particles in the energy range from 10 keV to 10 TeV. In case of neutrons the lowest energy bound is 0.2 meV.

Table 2 summarizes a comparison between experimental data and Geant4 simulations. The differences observed could be attributed to the simplification of the loss scenario.

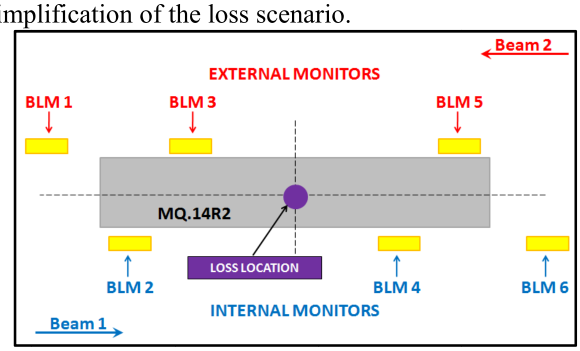


Figure 5: Each MQ is equipped with six monitors, - the three external BLMs (with respect to the LHC ring centre) survey beam 2 while the three internal detectors observe beam 1.

Table 2: Revision of Geant4 simulation results and comparison with the quench test. BLM data with a 1.3s integration time.

| BLM | Name | G4 simulations BLM signal [Gy/s] | Quench test BLM signal [Gy/s] | Ratio [-] |
|---|---|---|---|---|
| 1 | BLMQI_14R2_B2E30_MQ | $1.72\cdot10^{-2}$ | $1.79\cdot10^{-2}$ | 0.96 |
| 2 | BLMQI_14R2_B1I10_MQ | $8.02\cdot10^{-3}$ | $3.49\cdot10^{-3}$ | 2.30 |
| 3 | BLMQI_14R2_B2E20_MQ | $2.55\cdot10^{-2}$ | $1.47\cdot10^{-2}$ | 1.74 |
| 4 | BLMQI_14R2_B1I20_MQ | $9.66\cdot10^{-4}$ | $1.41\cdot10^{-3}$ | 0.69 |
| 5 | BLMQI_14R2_B2E10_MQ | $4.97\cdot10^{-4}$ | $2.74\cdot10^{-3}$ | 0.18 |
| 6 | BLMQI_14R2_B1I30_MQ | $2.37\cdot10^{-4}$ | $2.08\cdot10^{-4}$ | 1.14 |

## QP3

The Geant4 result of radial energy distribution has been combined with experimental data of the beam loss temporal distribution and used as an input to the QP3 code. The preliminary results have shown that the simulations significantly overestimate the energy deposited inside the superconducting cable by a factor of 11. $E_{avg}$ obtained from QP3 is about 0.5 J/cm$^3$ while the value based on the Geant4 simulation is about 6.06 J/cm$^3$ for the considered lost protons.

## CONCLUSIONS

The three-corrector bump technique has proven to be a successful method to induce a controlled quench of a magnet. The experiment has shown the correlation between losses detected by ionization chambers and the voltage on the superconducting coils.

Experimental data have been compared with Geant4 simulations and, although only a simplified loss scenario was simulated (a point-like loss impacting in the centre of the quadrupole) the agreement with experimental data is encouraging. The difference with respect to QP3 predictions need further investigation.

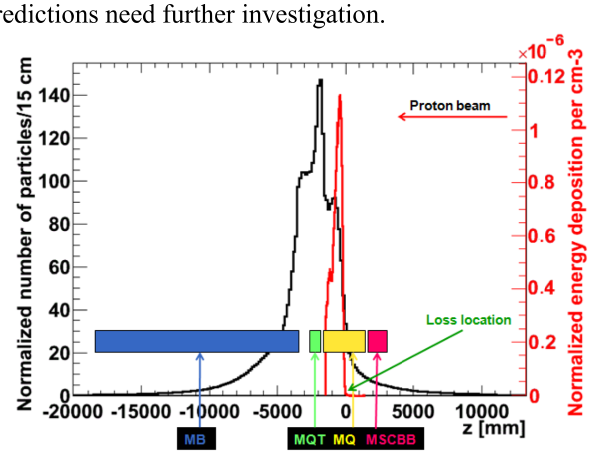


Figure 6: Energy deposition along a coil cable (for a region where $E_{dep}$ reaches a maximum) and the number of particles registered outside the cryostat. Main magnets have been marked.

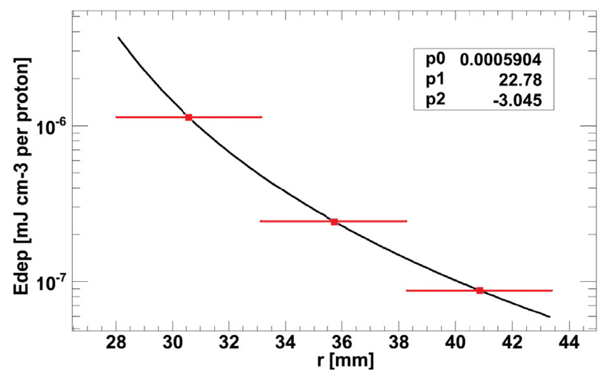


Figure 7: Radial distribution of the energy deposition.

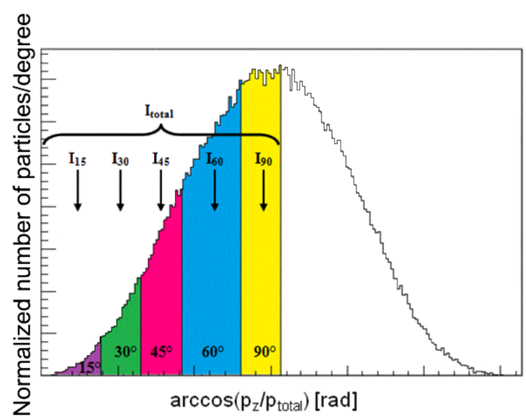


Figure 8: Angular distribution of secondary particles scored by the detectors. Scheme of weight *w* calculations.

Further study of the beam loss distribution is foreseen as well as analysis of a similar quench test performed at a beam energy of 450 GeV.

## REFERENCES


[1] A. Verweij,"QP3: Users Manual", CERN/EDMS 1150045.

[2] Jeanneret J.B., Leroy D., Oberli L., Trenkler T., *Quench levels and transient beam losses in LHC magnets*. LHC Project Report 44.

[3] Stocker M., CERN-THESIS-2008-099.