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ENERGY DEPOSITION AND QUENCH LEVEL CALCULATIONS FOR MILLISECOND AND STEADY-STATE QUENCH TESTS OF LHC ARC QUADRUPOLES AT 4 TeV

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Abstract

In 2013, beam-induced quench tests with 4 TeV protons were performed to probe the quench level of LHC arc quadrupole magnets at timescales corresponding to millisecond beam losses and steady-state losses. As the energy deposition in magnet coils cannot be measured directly, this study presents corresponding FLUKA simulations as well as estimates of quench levels derived with the QP3 code. Furthermore, beam loss monitor (BLM) signals were simulated and benchmarked against the measurements. Simulated and measured BLM signals are generally found to agree within 30 percent.

INTRODUCTION

The Large Hadron Collider (LHC) accommodates more than 1700 superconducting dipoles and quadrupoles, as well as several thousands of superconducting corrector magnets, which are maintained at operating temperatures of 1.9 K and 4.5 K [1]. A tiny fraction of the stored beam energy (360 MJ for nominal 7 TeV proton beams) released to a small volume in superconducting coils is sufficient to quench a magnet, i.e. to induce a transition from the superconducting to normal conducting state. Depending on the magnet type, magnet current, operating temperature and the duration of beam losses, quench levels of NbTi-cables used in LHC magnets typically span between a few mJ/cm^3 and a few hundreds of mJ/cm^3.

Before the first Long Shutdown (LS1) in 2013–2015, 17 beam-induced quenches occurred in the LHC, most of them due to deliberately generated beam losses during machine studies [2]. Operational quenches exclusively happened at injection energy (450 GeV) and were mainly caused by injection failures where magnets were exposed to secondary showers from injection protection devices [2,3]. With higher energy and intensity operation anticipated after LS1 (from 4 TeV in 2012 towards nominal energy) the risk of beam-induced quenches however increases due to nearly twice as high magnet current and higher stored beam energy.

Potential performance limitations could for example arise from beam losses induced by dust particles in the vacuum chambers, which have already caused tens of beam dumps in the first years of operation. In order to establish more accurate estimates of quench levels, which further allow to customize beam abort thresholds for BLMs, a series of quench tests with 4 TeV proton beams was performed in February 2013 [2]. Quench levels were probed for different magnets and different kinds of loss scenarios, with loss durations ranging from transient to steady-state timescales. These quench tests complemented other mitigation measures to improve the machine performance for post-LS1 operation, like the relocation of hundreds of BLMs in the LHC arcs which allow for an optimized detection of losses due to beam-dust particle interactions.

As the energy deposited in magnet coils cannot be measured directly, Monte Carlo codes like FLUKA [4, 5] represent an essential tool for the analysis of quench tests. In particular, the simulations allow to relate the induced energy density in coils with BLM signals, the latter typically being governed by the peripheral part of particle showers as BLMs are installed outside of magnet cryostats. In this paper, we present FLUKA simulations for two different quench tests of a main arc quadrupole (MQ.12L6), one covering millisecond (intermediate loss-duration) and the second steady-state beam losses (over 20 s). The loss duration addressed in the first test is typical for beam-dust particle interactions. Details of the experimental setup are described in Refs. [6–8]. In both cases, the losses were induced by means of an orbit bump and by exciting the beam with the transverse damper (ADT). The key parameters of the two tests are summarized in Table 1. In this paper, estimates of the energy deposition in the MQ coils are derived and compared against quench level calculations with the QP3 code [9]. In addition, FLUKA predictions of BLM signals are validated against measurements.

Table 1: Comparison of Key Parameters Between the Quench Tests

Loss duration	Millisecond	Steady-state
Beam energy	4 TeV	4 TeV
Magnet current	5600 A	5600 A
Helium temperature	1.9 K	1.9 K
ADT gain	200 %	15 %
ADT mode	positive feedback	white noise
Protons lost	4-8.2×10^8	2.7×10^8/s (average) 3.6×10^8/s (peak)

SIMULATION SETUP

Energy deposition simulations were based on a realistic geometry model of the MQ and neighbouring magnets, including a detailed description of beam screen, cold bore, coils, collars, yoke, cold mass shell, thermal shields and cryostat. For illustration, Fig. 1 shows the transverse cross section of the FLUKA MQ model. The beam line was assembled using a utility called LineBuilder [10]. The coils were

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modelled as a homogeneous mixture based on the relative mass fractions of superconductor, copper stabilizer, insulator (Kapton), and liquid helium, resulting in an effective material density of 6.9 g/cm^3 for the inner MQ coils.

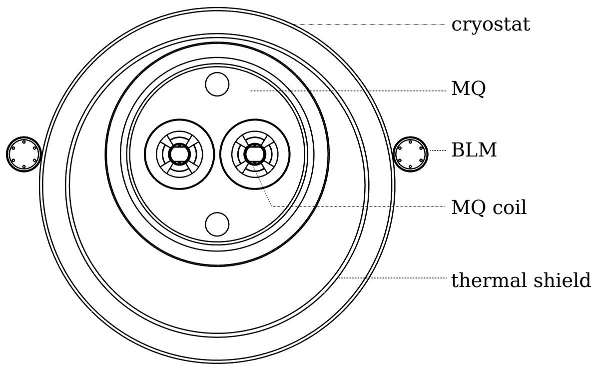

Figure 1: Transverse cross section of the magnet geometry.

A series of BLMs was incorporated in the simulation geometry at locations of standard LHC BLMs and mobile BLMs (the latter having been specifically installed for the quench tests). The FLUKA BLM model (see Fig. 2) accurately renders the electrodes, alumina spacers and stainless steel housing of real LHC BLMs (ionization chambers filled with ~1500 cm^3 of nitrogen gas).

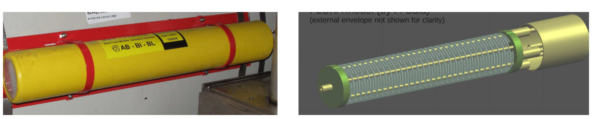

Figure 2: BLM mounted on cryostat and FLUKA model of BLM (external envelope not shown for clarity).

The FLUKA simulations were based on proton loss distributions on the magnet beam screen from MAD-X tracking calculations. A detailed account of these tracking studies is presented in Ref. [11]. In order to estimate the energy density in MQ coils, a cylindrical mesh with bin sizes of ΔR=0.2 cm, ΔPhi=2° and ΔZ=10 cm was superimposed on the coil geometry. The BLM response was derived by calculating the energy deposition in the active gas volume between electrodes.

RESULTS

Millisecond Beam Loss Quench Test

Figure 3 compares simulated and measured BLM dose values for the millisecond beam loss quench test, together with the longitudinal impact distribution of protons on the beam screen from MAD-X [11]. For BLMs located downstream of the proton impact distribution, simulations and measurements agree within 20%. The good agreement validates the energy deposition simulations by FLUKA but also verifies the loss profile predicted by the beam dynamics simulations.

Figure 4 shows the simulated longitudinal peak energy density profile in MQ coils, time-integrated over the entire

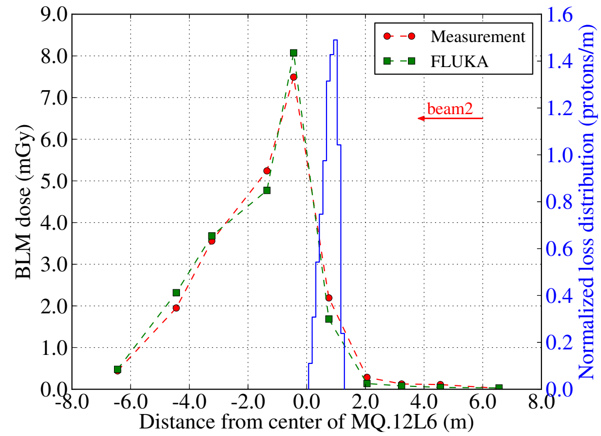

Figure 3: Comparison of simulated and measured BLM dose during the millisecond quench test. Dose values are normalized to 8.2×10^8 protons. The histogram indicates proton loss distribution on the MQ beam screen as predicted by MAD-X studies [11].

loss duration (~10 ms). The estimated maximum energy density of 405 mJ/cm^3 represents an upper limit to the quench level as the duration between the onset of losses and the onset of quench is not exactly known. A preceding attempt to quench the magnet with about half the beam intensity (4×10^8 protons) had failed, hence setting a lower limit to about 200 mJ/cm^3.

In the millisecond regime the heat transfer from individual strands to the small helium reservoirs within a Rutherford cable plays a decisive role [12]. Boiling effects on the strand surface into these voids are difficult to estimate. Initial simulations predicted a quench level of 50-100 mJ/cm3, well below the lower bound computed by the MAD-X/FLUKA model of 200 mJ/cm3 [9].

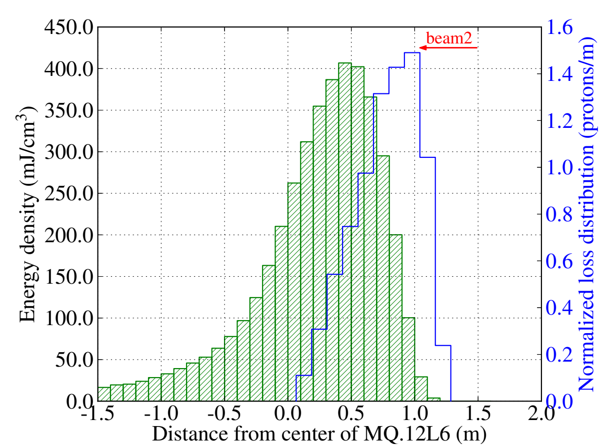

Figure 4: Peak longitudinal profile of energy density in MQ coils during the millisecond quench test. Dose values are normalized to 8.2×10^8 protons. Loss distribution as predicted by MAD-X studies [11].

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Steady-state Beam Loss Quench Test

In this test, the lower ADT gain leads to a sharper loss distribution (see Fig. 5, 6) compared to the millisecond beam loss quench test. It could be possible that the sharper distribution is affected by any surface roughness in the beam screen. Two simulations were done to evaluate the sensitivity of such a roughness, in the first one assuming a smooth beam screen surface and in the other one implementing a 10 cm long rectangular step with the amplitude of 30 μm [11] in the beam screen.

The simulated BLM dose is compared with the measured dose in Fig. 5. For the simulation assuming that the beam screen has a smooth surface, the simulated values underestimate the experimental ones by about a factor of 2 for central BLMs. For the simulation with the bump implemented, measured and simulated values agree better than 30 % for BLMs downstream of the proton impacts.

Implementing a similar step for millisecond quench test simulation did not alter the results of the energy deposition simulations significantly, implying that only steady-state quench test is sensitive to surface roughness in beam screen. This is probably due to the broader loss distribution that could smear out any surface roughness effects.

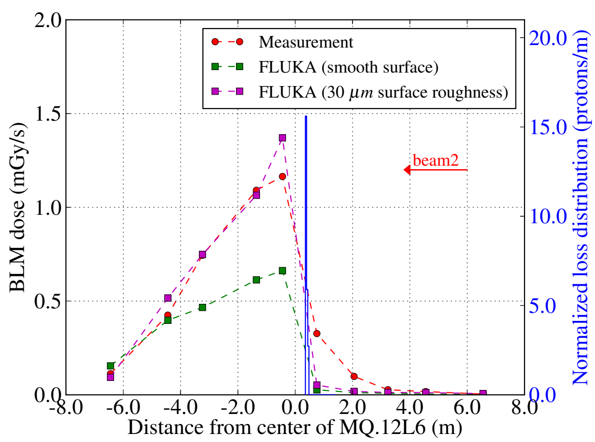

Figure 5: Comparison of simulated and measured BLM dose during the steady-state quench test. Dose values are normalized to 2.7×10^8 protons/s. Loss distribution as predicted by MAD-X studies [11] for the case with surface roughness.

Figure 6 shows FLUKA predictions of the peak power density radially averaged over the inner MQ coils and time-averaged over the entire loss event. Maximum radially averaged power densities in the magnet are about 39 mW/cm^3 and 65 mW/cm^3, respectively for smooth and rough surface.

For steady-state beam losses, the quench limit depends on the heat removal rate [2]. The electro-thermal model for steady-state heat deposition is based on experimental work [13]. A conservative approach (no steady-state cooling to the helium reservoirs in the inter-layer spacers called "fishbones") yields a quench level estimate of 70 mW/cm3 [9].

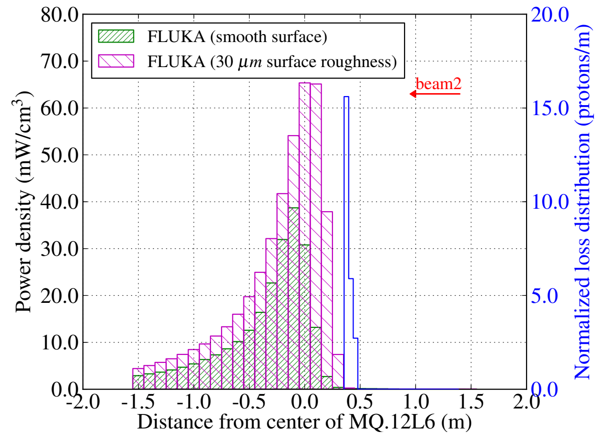

Figure 6: Peak longitudinal profile of power density in MQ coils during the steady-state quench test. Dose values are normalized to 2.7×10^8 protons/s. Loss distribution as predicted by MAD-X studies [11] for the case with surface roughness.

CONCLUSION

FLUKA simulations of BLM dose and energy density are presented in this paper for two quench tests that implemented orbit bump to quench a quadrupole magnet, namely millisecond and steady-state beam loss quench tests. Quench level estimations derived with the QP3 code is also reported.

Estimation of dose values and maximum energy densities is a step closer to update the BLM thresholds in order to ensure good performance of the machine within its limits.

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