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ENERGY DEPOSITION STUDIES AND ANALYSIS OF THE QUENCH BEHAVIOR IN THE CASE OF ASYNCHRONOUS DUMPS DURING 6.5 TeV LHC PROTON BEAM OPERATION

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Abstract

The CERN LHC beam dumping system comprises a series of septa and fast-pulsed kicker magnets for extracting the stored proton beams to the external beam dumps. Different absorbers in the extraction region protect superconducting magnets and other machine elements in case of abnormal beam aborts, where bunches are swept across the machine aperture. During Run 2 of the LHC, controlled beam loss experiments were carried out at 6.5 TeV probing the particle leakage from protection devices under realistic operation conditions. This paper presents particle shower simulations analyzing the energy deposition in superconducting coils and assessing if the observed magnet quenches are compatible with the presently known quench limits.

INTRODUCTION

For all LHC filling schemes, an abort gap $\sim 3\,\mu$s long without beam is present between circulating bunch trains. In case of a beam dump request, the LHC extraction kickers (MKDs) rise up their magnetic fields during this abort gap in order to achieve an extraction of the beams with minimal particle losses on machine components [1]. That requires a precise synchronization of the kicker triggering and the position of the abort gap in the LHC ring. However, asynchronous beam dump (ABD) events can be caused by a spontaneous triggering of one of the 15 MKDs followed by an immediate re-triggering of the remaining 14 MKDs, or by a synchronization error of the kickers with the abort gap [2]. In both cases, a fraction of the stored bunches can experience the magnetic field during the kicker rise time and receive a kick not strong enough for a proper extraction to the dump. The particles swept across the aperture are intercepted then by dedicated protection absorbers at strategic positions, which prevent damage to septa and/or superconducting magnets. The absorbers are made of low-density materials like carbon-reinforced carbon (CfC) composites, which are robust enough to sustain the impact of the swept beams.

By design, asynchronous beam dumps are considered acceptable failure cases of the LHC Beam Dumping System (LBDS) [1]. Nonetheless, the quenching of superconducting magnets due to scattered protons or the leakage of particle showers from the absorbers is unavoidable. Until now, no ABD occurred with high-intensity beams, but reliability tests of the kickers showed that such events cannot be excluded. A thorough understanding of the particle leakage and energy deposition in superconducting magnets is therefore essential.

An asynchronous beam dump test with low-intensity 6.5 TeV proton beams was carried out in 2016, resulting in the quench of several superconducting magnets in the dispersion suppressor next to the LBDS insertion region (IR6). No quenches occurred in the insertion region itself. This paper offers an explanation for the occurrence (and absence) of quenches by means of particle shower simulations with the FLUKA Monte Carlo code [3, 4]. The obtained energy densities in superconducting coils are assessed against presently known quench levels.

The quench level of matching section quadrupoles in IR6 were tested previously in a controlled beam loss experiment carried out in 2015 [5]. This experiment also allowed for a cross-check between shower simulation estimates and quench level predictions obtained with electro-thermal model simulations (QP3). The energy deposition results for this quench test serve also as a basis for the ABD analysis and are briefly reviewed in the first part of the paper.

MODEL OF THE EXTRACTION REGION

In order to estimate the energy density in superconducting magnets deposited by the secondary showers, a FLUKA model of the LHC extraction region IR6 was implemented. The geometry model comprises collimators, vacuum chambers and superconducting magnets, ranging from the one-sided absorber TCDQ (Target Collimator. Dump Quadrupole) in the long straight section (LSS) to the quadrupole MQM.9R6 (Q9) in the dispersion suppression (DS) region. Figure 1 shows the upstream part of the FLUKA model, from the TCDQ to the quadrupole MQY.4R6 (Q4). During an ABD, beam particles hit the front face of the TCDQ. The TCDQ is divided into three modules. Each module has a total absorber length of 3 m and consists of 12 absorber blocks made of CfC with a density of either 1.4 g/cm^3 or 1.75 g/cm^3. The lower density CfC blocks are arranged such that they cover the region of the shower maximum, which reduces the peak temperature in the absorber. The remaining protection absorbers downstream of the TCDQ are the two-sided collimator TCSP (1 m long, made of CfC with a density of 1.67 g/cm^3) and the fixed-aperture mask TCDQM (1 m long, made of stainless steel) directly in front of the Q4.

QUENCH TEST OF IR6 QUADRUPOLES

On 4th November 2015, a controlled beam loss experiment was performed to probe the quench level of IR6 matching quadrupoles for ultra-fast (ns) beam losses [5].

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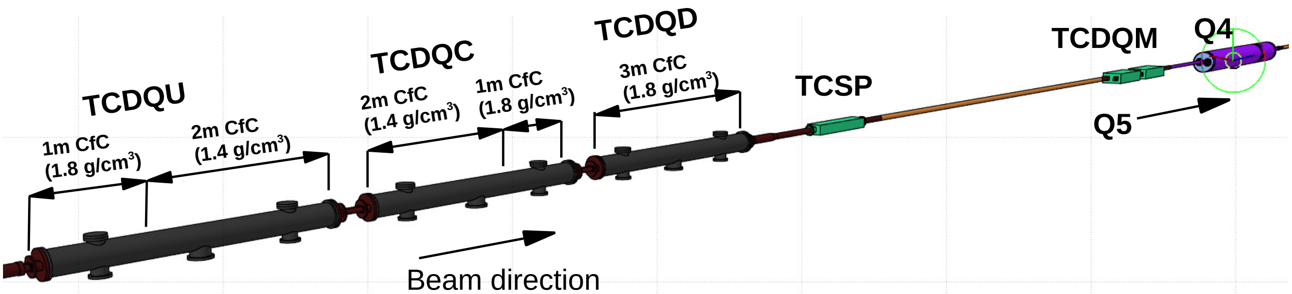

Figure 1: FLUKA model of the IR6 insertion region, from the TCDQ to the MQY.4R6 (Q4). The CfC-absorber blocks of the TCDQ with a lower density of 1.4 g/cm^3 are located around the shower maximum in the absorber.

Probe bunches with intensities of 5–7×10^{10} protons were injected and dumped on the closed TCSP upstream of the Q4 (MQY.4L6). The Q4, which is operated at a temperature of 4.5 K, was powered at different currents to mimic different operation energies, see Table 1.

The last shot lead to a quench of the Q4 whereas the injection cycle before, done with a lower bunch intensity while the magnet was operated with the same electrical current of 3150 A, did not result in a quench. To estimate the energy deposition in the superconducting coils needed to cause a quench, FLUKA simulations were carried out for cycles 6 and 7 using the geometry model described before. The calculations resulted in a peak energy density in the Q4 coils of ~ 16 mJ/cm^3 and ~ 23 mJ/cm^3 for cycle 6 and 7, respectively. The lower bound of the MQY quench level estimated from cycle 6 is about 50 % higher than the quench level predicted by thermo-electrical calculations with the computer code QP3 [6] (10.7 mJ/cm^3 for a current of 3150 A). The agreement is nevertheless acceptable considering the uncertainties in the modeling approaches. The uncertainty of the shower simulations for the estimation of point-like quantities like the energy density in coils is extremely difficult to predict, but is estimated to be roughly factor of two.

ABD TEST

For the asynchronous beam dump test on 15. May 2016, carried out at 6.5 TeV, the RF was switched off allowing particles to de-bunch and drift into the abort gap. In this way, a synchronous beam dump sweeps the particles in the abort gap over the machine aperture imitating an asynchronous dump. The abort gap population at the time of the dump was estimated to consist of 1.35×10^{11} protons for Beam 1 [7]. Most of these particles recirculated for another turn, hit the septum protection absorber (TCDS) or were extracted. About 3.2×10^{10} protons, however, were intercepted by the TCDQ. Four magnets in the neighboring dispersion suppressor quenched, whereas no quenches were observed in the IR6 matching section. In the following, simulation results are presented and analyzed for all the magnets in order of distance to the TCDQ, see also Table 2.

Table 1: Q4 quench Test Parameters (4th Nov. 2015)

Shot	Intensity (# p+)	MQY current (A)	Quench
1	$5.6 \cdot 10^{10}$	163	No
2	$6.7 \cdot 10^{10}$	650	No
3	$5.8 \cdot 10^{10}$	1150	No
4	$5.7 \cdot 10^{10}$	1650	No
5	$5.7 \cdot 10^{10}$	2650	No
6	$\mathbf{4.7 \cdot 10^{10}}$	**3150**	**No**
7	$\mathbf{6.7 \cdot 10^{10}}$	**3150**	**Yes**

Figure 2 shows the transverse energy density distribution in the Q4 coils for beam 1 at the position of the maximum energy density. The energy density map shows a peak in the horizontal plane because of energetic charged hadrons from the TCDQ and TCSP, which leak through the TCDQM mask. These hadrons are deflected onto the beam screen by the quadrupole field, leading to a maximum energy density of approximately 22 mJ/cm^3 at a depth of 1.2 m. The Q4 was powered at a current of 2389 A during the ABD test, which means that the minimum energy density to induce a quench was higher than in the quench test described in the previous section. The QP3 code predicts a MQY quench level of around 16 mJ/cm^3 for this magnet current. Based on this value, a quench would have been expected from the FLUKA results, but the absence of the quench during the ABD test is still explainable given the simulation uncertainty.

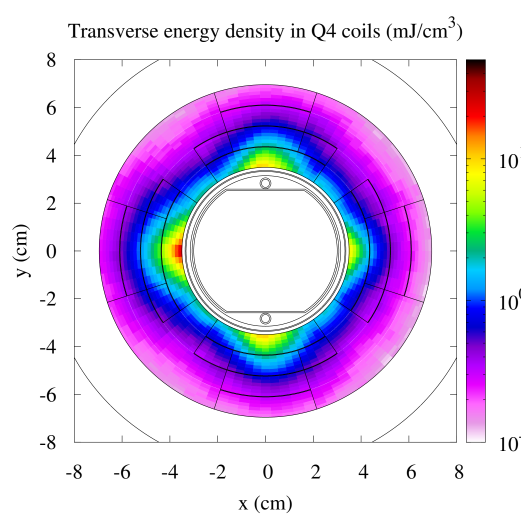

Figure 2: Simulated transverse energy density distribution in the Q4.R6 coils at the position where the maximum energy deposition of ~ 22 mJ/cm^3 occurs.

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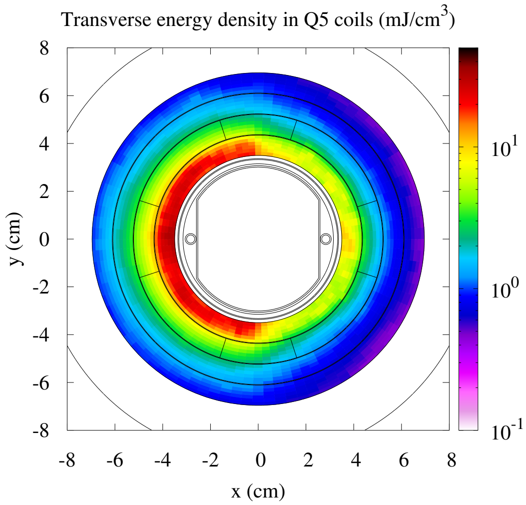

Figure 3: Simulated transverse energy density distribution in the Q5.R6 coils at the position where the maximum energy deposition of ~ 33 mJ/cm^3 occurs.

Unlike the Q4, the downstream Q5 is not protected by a fixed-aperture mask, which would suppress the shower-induced peak load at the magnet entrance. For this reason, the maximum energy density in the Q5 (about 33 mJ/cm^3) is estimated to be located in the return coils close to the front face of the magnet. The energy density in the transverse plane, shown in Fig. 3 is hence more uniformly distributed than in the Q4. The energy density is lower in the right coil, which is in the direct shadow of the TCDQ. The Q5 is a MQY-type magnet like the Q4, but was powered at a higher current (3230 A). The quench level can therefore be expected to be similar as in the quench test described in the previous section (i.e. around 11 mJ/cm^3). The estimated peak energy density is about a factor of three higher, but no quench was observed. Because of the complex design of the magnet, especially of the end parts including the return coils, the geometry model as well as the FLUKA scoring mesh had to be simplified for those regions. Considering these simplifications, the peak energy density in the coils was likely overestimated. In addition, the minimum quench energy can vary across the coil depending on the local field. These factors can possibly explain the absence of quench in the Q5.

Table 2: Overview about calculated peak energy densities in the superconducting magnet coils, their expected and observed quench behavior. Magnets in order of distance from IP6. Operation temperatures in second column.

	Temp. [K]	[mJ/cm^3]	Quench exp.	Quench obs.
MQY.4R6	4.5	22	**Yes**	No
MQY.5R6	4.5	< 33	**Yes**	No
MB.A8R6	1.9	< 73	**Yes**	**Yes**
MB.B8R6	1.9	< 12	No	**Yes**[a]
MQML.8R6	1.9	1.4	No	**Yes**[b]
MB.A9R6	1.9	< 0.2	No	No
MB.B9R6	1.9	< 0.2	No	No
MQM.9R6	1.9	< 0.2	No	**Yes**[b]

[a] Due to heat propagation from the quenching upstream dipole
[b] Due to EM coupling with the discharge of the dipole circuit next by or its bypass diode opening

A similar simulation uncertainty is expected for the first dipole in the dispersion suppressor (MB.A8R6), where the highest energy deposition occurs also at the magnet entrance. Here, however, the calculated maximal energy density of 73 mJ/cm^3 exceeds by far the quench limit for fast beam losses of around 18 mJ/cm^3 for MBs operated at 6.5 TeV, based on QP3 calculations and empirical correction factors from Run 1 quench tests [8]. Hence, a quench had to be expected even considering the uncertainty of the estimated peak energy density.

The peak in the energy density in the second dipole (MB.B8R6), on the other hand, is estimated to be less than 12 mJ/cm^3, which is below the threshold for quench. The magnet quenched, however not because of particle showers but because of heat propagation from the upstream MB.A8R6. Also the calculated peak energy density values in all remaining magnets downstream are below the corresponding quench levels, see Table 2. The Q8 (MQML.8R8) and Q9 (MQM.9R6) quenched, however, most likely because of EM-coupling with the discharge of the dipole circuits and/or with the opening bypass diode. These effects were not subject of the FLUKA simulations and were therefore not part of the considerations whether magnet quenches had to be expected or not.

CONCLUSIONS

The results of the FLUKA simulation are generally compatible with the observed quench behavior of the magnets during the ABD test. The MB.A8R6 quenched as expected while the absence of quench in the Q4 and Q5 can possibly be explained by simulation uncertainties although the predicted energy densities are above the expected quench level. Error sources can for example be simplifications of magnet or collimator geometries, imperfections in the aperture description, or uncertainties in the physics models of the FLUKA code itself. In general, also quench levels are subject of uncertainties, e.g. discussed in [8]. Another uncertainty factor is that the number of particles eventually hitting the TCDQ or other protection elements cannot be fully controlled by the described test procedure. For this reason, another asynchronous beam dump test has been proposed and performed on 3rd December 2017 where bunches were injected directly into the abort gap by adapting the abort-gap protection settings [9]. In this way, bunches have a clearly defined intensity and a clearly defined position inside the abort gap. In addition, off-momentum effects can be excluded. This allows to verify our understanding of the quench behavior and the current beam and FLUKA models. Corresponding Monte Carlo simulations and energy deposition studies with FLUKA are currently ongoing.

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