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FLUKA ESTIMATIONS CONCERNING OBSTACLES IN THE LHC MAGNETS

M. Brugger, F. Cerutti, A. Ferrari, V. Vlachoudis
AB-ATB-EET, CERN

Abstract The effect of the impact of the full energy LHC proton beam with an object left in the beam pipe is investigated in order to assess the conditions for a superconducting magnet's quench. FLUKA simulations indicate that a quench would happen about 20 m downstream from the impact for a current through the object being several orders of magnitude lower than the nominal beam current. If such a strict current limit (decreasing with increasing obstacle's thickness) is not exceeded in operational conditions, the obstacle might be destroyed without causing any quench, being the vaporization time dependent on its shape and movement. However, any rise of the traversing current above the mentioned limit would result in a beam dump and the obstacle remaining in the machine.

1. Introduction

In view of LHC commissioning, any accidental reduction of the machine physical aperture has to be carefully avoided. Within the mandate of quality assurance of all assembly works, an inspection activity addressed to the beam pipe is going on. In particular, since April 2006 every magnet, prior to lowering and interconnection in the tunnel, is pre-inspected on the surface using two different methods: visual inspection and microwave reflectometry. The examination of 80% of about 500 installed dipoles and quadrupoles indicated the presence of 19 magnets with potential risk of obstacles [1, 2]. Most of the identified objects are polyethylene and metal swarfs, but steel and Kapton pieces also have been found (see Fig. 1).

Figure 1. Some of the objects found along the beam pipe in the LHC magnets [3].

The aim of this note is to evaluate the effect of a possible collision of the proton beam with one of these obstacles in the vacuum pipe, investigating the possibility of a superconducting magnet to quench due to heat deposition by the showers originated from nuclear interactions of primary particles traversing the object.

2. Simulation of the interaction of beam particles with an obstacle

The straight section and the Dispersion Suppressors (DSs) of the Insertion Region 7 (IR7) in LHC were modeled with the Monte Carlo code FLUKA [4, 5].

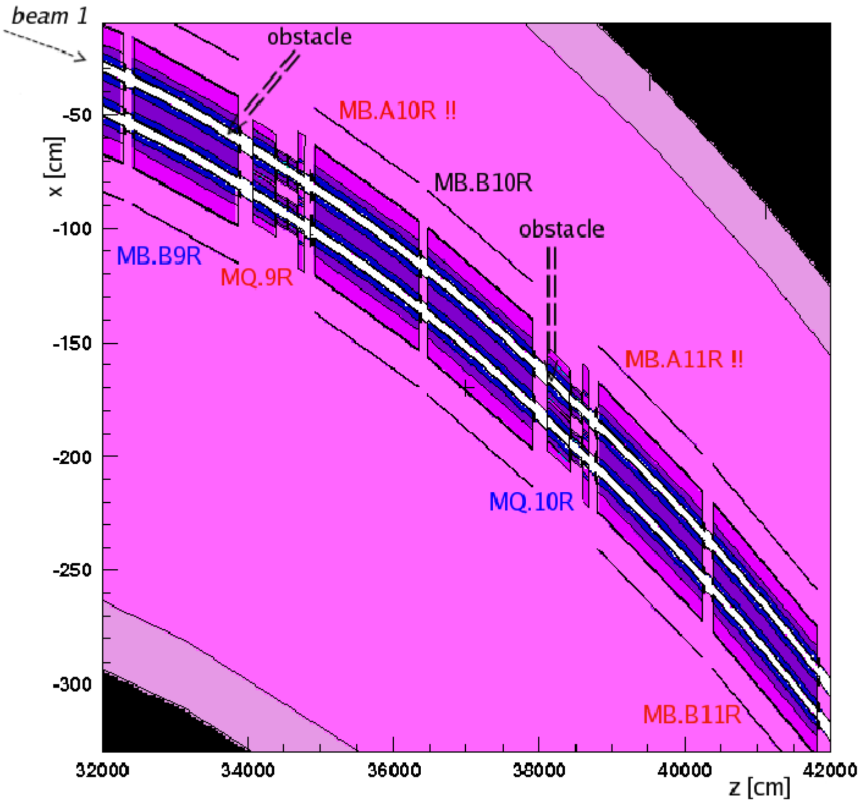

Figure 2. Horizontal section of a part of the DS on the right of IR7, as implemented in the FLUKA geometry, where an obstacle is located as indicated by the arrow. The z-axis is parallel to the direction of the beam axis in the IR7 straight section and the origin of the reference frame is placed in the Interaction Point 7 (IP7). The exclamation marks identify the quenching magnet for the different obstacle's positions.

All relevant components and details were implemented up to realistic limits thanks to a modular approach to the geometry definition and a systematic use of user-written routines providing a precise description of all magnets and collimators. In the past extensive simulations allowed to assess the energy deposition in sensitive components as already previously illustrated in numerous studies for the betatron collimation region (see Ref. [6] and references therein).

In this work we consider beam 1 and suppose that the obstacle is located in a superconducting magnet installed in the DS downstream from IR7 (MB.B9R7.B1 or MQ.10R7.B1, see Fig. 2). We did not insert into the geometry any approximate shape of the object, but simulated the collision by forcing a 7 TeV proton to undergo a nuclear interaction in iron or polyethylene at a given point of its orbit inside the magnet. This means that the incident proton interacts with a nucleus selected according to the material composition and nuclear cross sections, and the reaction products are then transported along the machine. The addition of a realistic obstacle would allow the calculation of the energy deposition in the object itself on the basis of the distribution of the impinging protons, but will only have negligible effects on the spectrum of secondary particles reaching delicate elements. As a function of the obstacle's location and material, FLUKA is used to calculate the map of energy deposition density per interacting primary proton for all concerned magnets, thus providing an evaluation of the peak in the coils and the integral value in an entire magnet. Table 1 summarizes the results.

MATERIAL	LOCATION			MOST AFFECTED MAGNETS		
	magnet	ℓ	d		peak [pJ/(pr·cm^3)]	total [nJ/pr]
iron	MB.B9R	0.892	0	MB.A10R	90.2	595.4
				MQ.9R	51.8	183.3
iron	MB.B9R	0.858	1.15 mm ($\simeq 5.5\ \sigma$)	MB.A10R	83.8	540.6
				MQ.9R	57.0	200.9
iron	MQ.10R	0.05	0	MB.A11R	97.1	814.2
				MB.B11R	23.9	80.7
polyethylene	MB.B9R	0.892	0	MB.A10R	85.7	576.0
				MQ.9R	52.9	158.8

Table 1. Maximum energy deposition density in the coils and total heating for the most affected magnets in case of interaction of a 7 TeV proton inside an obstacle of the indicated material at the given position. ℓ represents the spatial coordinate of the obstacle along the beam axis in units of the magnet pipe length (ℓ=0 corresponds with the magnet entry point, ℓ=1 with the magnet exit point) and d is its distance from the beam axis.

The cases examinated so far indicate that the most affected magnet is the first dipole after the one containing the obstacle and the maximum local heating in the coils, occurring about 20 m downstream from the collision point, ranges between 83.8 (impact along an orbit significantly far from the beam axis) and 97.1 pJ/(pr·cm^3). Assuming as a quench limit the (conservative) value of 4 mW/cm^3 in Ref. [7], one gets that the number of *interacting* protons must not exceed 4.78 and 4.13 10^7 *pr*/s, respectively. On the other hand, looking at the dipole total heating, the quench limit of 14 W (i.e. about 1 W/m [8]) is reached with a current of *interacting* protons equal to 1.72 (2.59) 10^7 *pr*/s in the worst (best) case. If the obstacle is an iron object 0.1 mm thick in the beam direction, the interaction probability for the impinging protons is about 0.065%, so the maximum acceptable current through the obstacle comes out to be in the range $2.6 \div 3.9\ 10^{10}$ *pr*/s.

As for transient beam losses, the quench limit of 0.8 mJ/cm^3 in the coils [9] implies that the number of protons interacting in the object within a time interval of 3 ms must be less than $0.825 \div 0.956\ 10^7$ *pr.* This means that the maximum number of protons allowed to traverse a 0.1 mm thick iron obstacle over that time is $1.2 \div 1.4\ 10^{10}$ *pr.*

Table 2 lists these limits.

QUENCH LIMITS	INTERACTING PROTONS	PROTONS THROUGH THE OBSTACLE	
		iron	polyethylene
continuous heating	[10^7 *pr*/s]	[10^9 *pr*/s]	
4 mW/cm^3 in the coils	$4.13 \div 4.78$	$4.92/t \div 5.70/t$	$3.16/t$
1 W/m	$1.72 \div 2.59$	$2.05/t \div 3.09/t$	$1.64/t$
transient heating	[10^7 *pr*]	[10^9 *pr*]	
0.8 mJ/cm^3 in the coils	$0.825 \div 0.956$	$0.98/t \div 1.14/t$	$0.63/t$

Table 2. Number of interactions of primary protons in an obstacle leading the most affected superconducting magnet to quench and corresponding number of primary protons traversing the obstacle, as a function of material and thickness t expressed in g/cm^2. The range covers the considered initial conditions, with the left limit corresponding to the impact in MQ.10R7.B1 on the beam axis (third row of Table 1) and the right one corresponding to the impact in MB.B9R7.B1 out of the beam axis (second row of Table 1).

3. Approximate evaluation of the obstacle's heating

In case further analyses concerning the possible carbonization of the obstacle, generating dust particles in the machine, are required, more detailed information about its shape and the distribution of particles impinging on it is needed. On the other hand, a rough estimation of the temperature increase ΔT inside the object can be easily obtained for the transient case supposing that a 7 TeV proton incurs an energy loss per travelled thickness

$(\Delta E/\Delta t) \simeq 2$ MeV/(g/cm^2). One immediately gets

$$\Delta T = \frac{\Delta E}{\Delta t}\,\frac{N_{pr}}{c\,\Delta A}$$

where N_{pr} is the number of protons instantaneously hitting the obstacle over a section of area ΔA perpendicular to their path and c is the obstacle's specific heat. If we look again at a 0.1 mm thick iron or polyethylene object and assume $\Delta A = \pi\sigma^2$ with $\sigma \simeq 0.2$ mm, the minimum value of N_{pr} causing the first dipole downstream to quench (as given in the last line of Table 2) leads to $(\Delta T)_{Fe}$=7 K and $(\Delta T)_{polyeth.}$=13 K (with c_{Fe}=0.44 J/(gK) and $c_{polyeth.}$=1.3 J/(gK)), i.e. to a quite unsignificant temperature rise.

An operational regime can be achieved only if the current through the obstacle remains below the presented limits. Ideally keeping this condition, after some time, depending on current density and heat diffusion, the obstacle would be destroyed and no magnet would have quenched. However, a displacement relative to the beam could very easily increase the traversing current beyond the quench threshold, leading to a beam dump without eliminating the obstacle.

4. Conclusions

The hypothetical collision of the full energy LHC beam with a 0.1 mm thick iron (polyethylene) obstacle in the beam pipe, can cause a superconducting dipole to quench for a current through the obstacle 8 (7) orders of magnitude lower than the total nominal beam current of 3.75 10^{18} pr/s.

An ideal continuous irradiation on the obstacle below this limit (even stricter for larger thickness), eventually would disintegrate it avoiding the quench. Nevertheless, an uncontrollable rise of the traversing current might rapidly quench a magnet leaving the object in the beam pipe. Also, in the transient scenario a cold magnet's quench happens well in advance of the possible carbonization of the obstacle.

The quench is expected to take place about 20 m downstream from the obstacle location.

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