TOWARDS THE OPTIMAL LHC INTERACTION REGION: BEAM-INDUCED ENERGY DEPOSITION*

N.V. Mokhov and J.B. Strait, Fermilab, P.O. Box 500, Batavia, IL 60510 USA

Abstract

The overall machine and detector performances at the LHC are strongly dependent on the interaction region (IR) scheme and details. Beam-induced energy deposition in the components of the complex due to both p-p collisions and beam loss in the IR vicinity is a significant challenge for the design of the high luminosity insertions. It was shown in our previous studies that a set of collimators in the machine and absorbers within the low-beta quadrupoles would reduce both the peak power density and total heat load to tolerable levels with a reasonable safety margin. New optical configurations for the IRs developed in the past year may require changes in the absorber dimensions. In this paper we present studies of the radial and azimuthal distributions of the deposited power density and the dependence of peak power density on absorber thickness. These can be used to guide further studies of the optics and absorber systems.

1 INTRODUCTION

The Large Hadron Collider (LHC) [1] is designed to produce p-p collisions at $\sqrt{s}$=14 TeV and $L = 10^{34}$ cm^{-2}s^{-1}. The interaction rate of 8×10^{8} s^{-1} represents a power of almost 900 W per beam, the large majority of which is directed towards the low-β insertions. Previous studies [1, 2, 3] have identified this as a potentially serious problem. The quadrupole fields sweep the secondary particles into the coils preferentially along the vertical and horizontal planes, giving rise to local peak power density P_{max} as much as an order of magnitude larger than the average. Tests of porous cable insulation systems [4] and calculations concerning the insulation system to be used in the Fermilab-built LHC IR quadrupoles [5] have shown that up to about 1 mW/g of heat can be removed while keeping the coil below the magnet quench temperature. Since our previous studies [3], which presented an optimized set of absorbers to protect the magnets, the optics design of the IRs has changed and not all parameters of the new design are firmly established yet. We present here studies of the distribution of the the power density in radius and azimuth within the magnet coils and the dependence of P_{max} on the thickness of internal absorbers placed inside the magnet bore, which can be used to guide future studies of the optics and absorber systems.

2 INNER TRIPLET CONFIGURATION

The studies described in this paper are based mainly on the IRs in version 4.2 of the LHC optics [1]. In that design the triplet consists of four 5.5 m long, 70 mm coil aperture quadrupoles – Q1, Q2a, Q2b and Q3 – which are powered in series and operate at 225 T/m at the high luminosity IRs (points 1 and 5). Two 1.8 m long, 85 mm aperture trim quadrupoles adjacent to Q1 and Q3 (Q01 and Q03 respectively) operate at a maximum gradient of 120 T/m; they provide tunability and the additional strength required of the outer two elements of the triplet. Superconducting beam separation-recombination dipoles D1 and D2 are 11.5 m long, have an 88 mm coil aperture and operate at 4.3 T. Under injection (collision) optics β^* = 6 (0.5) m, and a half crossing angle of 100 μrad is specified.

Recently a new version 5 of the LHC optics [6] has been introduced, which eliminates the trim quadrupoles and lengthens Q1 and Q3 to 6.3 m. The separation between D1 and D2 is increased allowing the use of lower field or shorter dipoles. At the high luminosity IRs D1 is replaced by a room temperature magnet. The half- crossing angle is now proposed to be 200 μrad at injection and 175 μrad under collision optics in the high luminosity IRs, and a $\pm$2 mm transverse separation at injection has been introduced. Under injection optics β^* = 12 m, but might be increased further. The optimization of these parameters is the subject of on-going studies (for example [7, 8]). The new conditions require changes of the absorber dimensions, typically increasing their apertures due to the larger crossing angle.

To understand the impact of these changes on the energy deposition and to guide future work, we have studied the dependence of P_{max} on internal absorber thickness. These studies have been carried out using both version 4.2 and version 5 configurations. Since the distance of the triplet from the interation point is the same and the overall length of the triplet is only slightly greater in version 5 than version 4.2 (30.6 m versus 29.6 m), the relation between power density and absorber thickness is the same for the two configurations within calculational uncertainties.

Figure 1 shows the version 4.2 inner triplet configuration and indicates the minimum mechanical half aperture, accounting for all the various errors considered in [1]. The positions and apertures of each magnet are shown as well as internal absorbers that come to the limiting aperture [3].

3 ENERGY DEPOSITION

The p-p collisions and showers in the IR components are simulated with the DPMJET event generator [9] and the MARS code [10], version 13(96), respectively. Charged particles are tracked through the lattice and the fields within each magnetic element. The cut-off energies are 1 MeV (charged particles), 0.2 MeV (photons) and 0.5 eV (neu-

* Work supported by the U. S. Department of Energy under contract No. DE-AC02-76CH03000

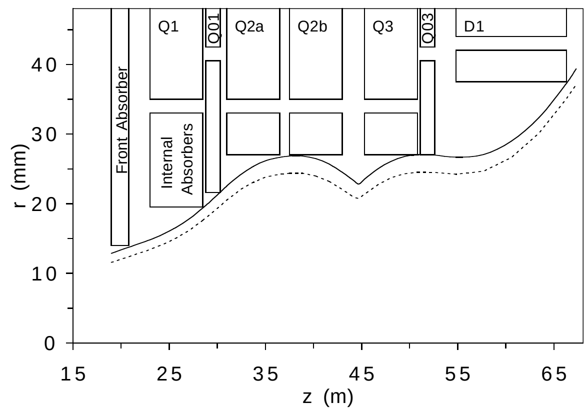

Figure 1: The LHC low-β insertions (version 4.2) including absorbers. The solid (dashed) curve is the approximate 10σ beam envelope for injection (collision) optics, including closed orbit and mechanical tolerances.

trons). Magnet coils are modeled with 4 radial bins of 8.5 mm depth, azimuthal bins varying from 5° at the horizontal and vertical planes to 15° between, and axial bins range between 1.1 m (Q1) and 3.8 m (D1) long. The magnet coils, which are a mixture of NbTi, copper, insulation and helium, are simulated as a homogeneous material with A=50, Z=23 and ρ=7 g/cm^3. Details such as cooling channels in the yoke and coil ends are not included. Statistical errors on the Monte Carlo calculation are estimated to be $\pm$15% for P_{max}, based on comparison of results from different runs with independent random seeds.

The longitudinal distribution of P_{max} has been studied in detail in [3] for several triplet and absorber configurations. With the front collimator in place, P_{max} is always peaked at the downstream end of Q1, upstream end of Q2a, upstream end of Q3 and downstream end of D1. With no internal absorber P_{max} = 1.2$\pm$0.2 mW/g in Q2, at or above the allowable limit. With individually sized 10σ absorbers as shown in Fig. 1, P_{max} is substantially reduced, giving a factor of 3-4 safety margin. Cases in which the absorbers have larger or smaller inner radius have been studied to determine the dependence of P_{max} on absorber thickness.

Typical azimuthal structure of power density in the coils is shown in Fig. 2 for the 10σ absorber, showing the strong peaking at the horizontal and vertical planes. Left-right and vertical-horizontal asymmetries are apparent due to the excess of positive high energy particles in the forward direction and the horizontal crossing plane assumed in this study. Both P_{max} and azimuthally averaged power densities drop rapidly with radius (Fig. 3), so outer coil layers are in a much better situation than the innermost.

4 DEPENDENCE ON ABSORBER THICKNESS

A 1.8 m long copper absorber is placed in front of the triplet and stainless steel absorbers (thick beam pipes) are placed within the magnet bores to minimize the energy deposition in the coils. The LHC design requires [1] that the physical aperture, including effects of dispersion, closed orbit errors, construction and alignment tolerances, and the crossing angle in the IRs be everywhere at least 10σ (except at the beam cleaning collimators), where σ is the *rms* beam size. (A new method of computing the geometric aperture has been recently introduced [11], which will be incorporated in future studies.) Fig. 1 shows the 10σ limit for injection and collision conditions and absorbers with inner radii at this limit. The outer radius of the absorbers is 2 mm less than $r_{\rm coil}$.

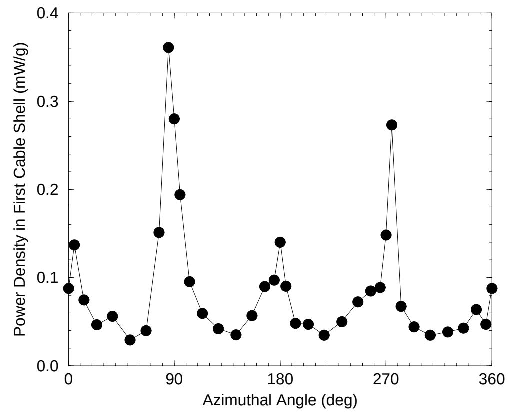

Figure 2: Azimuthal distribution of power density in the first cable shell at the downstream end of Q1. (0° is up.)

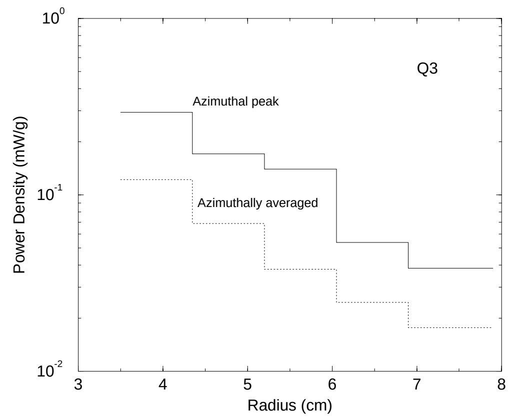

Figure 3: Radial distribution of P_{max} and azimuthally averaged power density at the upstream end of Q3.

Results on P_{max} for different triplet and absorber configurations, studied over 1995-1997, are collected in Fig. 4 through Fig. 6. The power density within a particular part of the triplet depends not only on the thickness of the absorber at that point but also on the apertures of the upstream absorbers. In Fig. 4 the aperture of the front absorber is r = 14 mm for the first three data points, and r = 12 mm for the last point. In Fig. 5 the pairs of data points at 8 mm and 9.5 mm thickness correspond to different absorber apertures in Q1 (Q1 aperture set to be the same as in Q2-Q3 or to the smallest allowed at its own location). Again, the right-most points correspond to a smaller front absorber aperture than the others. Here it is apparent that the effect of varying upstream apertures is comparatively

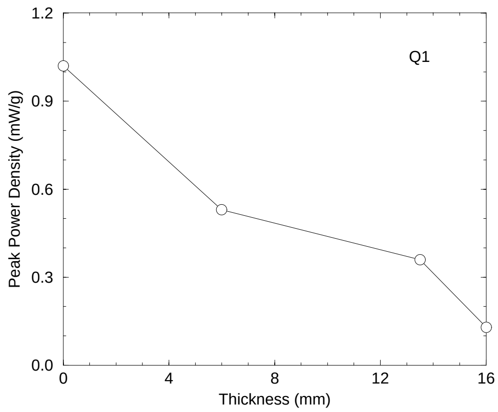

Figure 4: P_{max} in Q1 as a function of thickness *d*.

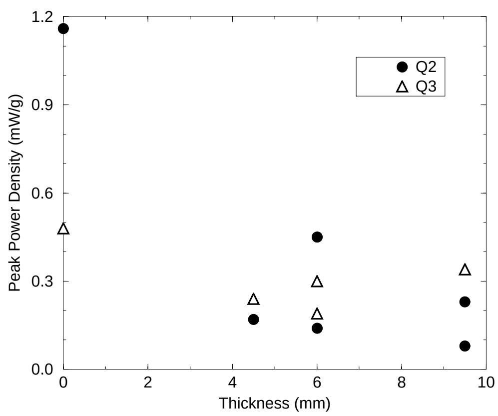

Figure 5: P_{max} in Q2 and Q3 as a function of thickness *d*.

local: P_{max} is less sensitive to front absorber aperture in Q2-Q3 than in Q1, especially for the case of a smaller Q1 absorber aperture. Similar trends are observed in Fig. 6 for D1.

To provide a reasonable margin with respect to expected quench level, the minimum absorber thickness should be 10-13 mm in Q1, 4.5-6 mm in Q2-Q3, and about 6 mm in D1. With this, the total power deposited in the inner triplet quadrupole cold mass is 82 Watts while the absorbers take about 60 Watts. One may consider cooling the internal absorbers at a higher temperature, as is done with the beam screen in the arcs. However, the insulating space required between a separate absorber and vacuum pipe would reduce the absorber thickness, making this option impractical.

5 CONCLUSIONS

Energy deposited in the superconducting magnets is an important issue in the overall design of the LHC IRs. Reducing P_{max} to an acceptable level requires the use of internal absorbers with the total thickness of 10-13 mm in Q1, 4.5-6 mm in Q2-Q3, and 6 mm in D1 (if this dipole is superconducting). Increasing the front absorber aperture above r = 14 mm will reduce the safety margin. Detailed analysis

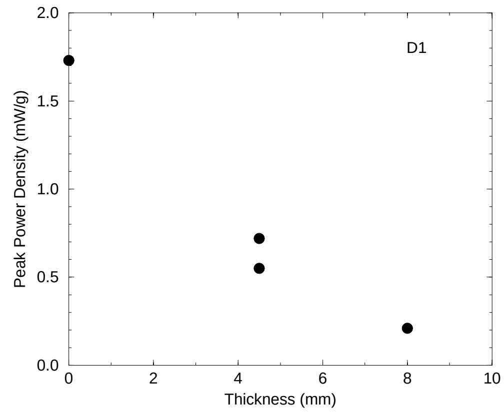

Figure 6: P_{max} in D1 as a function of thickness *d*.

of beam losses in the LHC high-luminosity interaction regions showed [12] that these contribute a few percent in the beam related energy deposition in Q2-Q3 quadrupoles and D1 and D2 dipoles, with pp-collisions as the main player.

6 REFERENCES

[1] 'The Large Hadron Collider Conceptual Design', CERN/AC/95-05(LHC), 1995, P. Lefèvre and T. Pettersson, editors.

[2] A. Morsch, R. Ostojic, T.M. Taylor, 'Progress in the Systems Design of the Inner Triplet of 70 mm Aperture Quadrupoles for the LHC Low-beta Insertions', Proc. 4th European Part. Accel. Conf., London, England, 1994.

[3] N.V. Mokhov and J.B. Strait, 'Optimization of the LHC Interaction Region with Respect to Beam-Induced Energy Deposition', EPAC96 and Fermilab–Conf–96/136, 1996.

[4] L. Burnod, et al., 'Thermal Modelling of the LHC Dipoles Funcitioning in Superfluid Helium,' Proc. 4th European Part. Accel. Conf., London, England, 1994.

[5] R. Bossert, et al., 'Development of a High Gradient Quadrupole for the LHC Interaction Regions,' IEEE Trans. Appl. Superconductivity **7**, 1997.

[6] A. Faus-Golfe, et al., 'A More Robust and Flexible Lattice for LHC,' submitted to the 1997 IEEE Part. Accel. Conf.

[7] M. Böge, et al., 'Overview of the LHC Dynamic Aperture Studies,' submitted to the 1997 IEEE Part. Accel. Conf.

[8] D. Ritson and W. Chou, 'Study of the Dynamic Aperture During Collisions in the LHC,' submitted to the 1997 IEEE Part. Accel. Conf.

[9] J. Ranft, Phys. Rev., D51, 64, 1995. Comput. Phys. Commun., **83**, p. 107, 1994.

[10] N.V. Mokhov, 'The MARS Code System User Guide, Version 13(95)', Fermilab–FN–628, 1995.

[11] J.B. Jeanneret and T. Risselada, 'Geometrical Aperture in LHC at Injection,' LHC Project Note 66, 23 Sept. 1996.

[12] A.I. Drozhdin, M. Huhtinen and N.V. Mokhov, Nucl. Instr. and Methods, A381, 531, 1996.