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MITIGATION OF EFFECTS OF BEAM-INDUCED ENERGY DEPOSITION IN THE LHC HIGH-LUMINOSITY INTERACTION REGIONS*

N.V. Mokhov, I.L. Rakhno, J.S. Kerby, J.B. Strait
FNAL, Batavia, IL 60510, USA

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Beam-induced energy deposition in the LHC high luminosity interaction region components is one of the serious limits for the machine performance. The results of further optimization and comprehensive MARS14 calculations in the IP1 and IP5 inner and outer triplets are summarized for the updated lattice, calculation model, baseline pp-collision source term, and for realistic engineering constraints on the hardware design. It is shown that the optimized layout and absorbers would provide a sufficient reduction of peak power density and dynamic heat load in the superconducting components with an adequate safety margin. Accumulated dose and residual dose rates in and around the region components are also kept below the tolerable limits in the proposed design.

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Beam-induced energy deposition in the LHC high luminosity interaction region components is one of the serious limits for the machine performance. The results of further optimization and comprehensive MARS14 calculations in the IP1 and IP5 inner and outer triplets are summarized for the updated lattice, calculation model, baseline pp-collision source term, and for realistic engineering constraints on the hardware design. It is shown that the optimized layout and absorbers would provide a sufficient reduction of peak power density and dynamic heat load in the superconducting components with an adequate safety margin. Accumulated dose and residual dose rates in and around the region components are also kept below the tolerable limits in the proposed design.

LHC IP1 AND IP5 REGIONS

The Large Hadron Collider (LHC) under construction at CERN, will produce pp collisions at center-of-mass energy $\sqrt{s}$=14 TeV and luminosity $\mathcal{L}$=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 majority of which is directed towards the low-β insertions. Studies [1, 2, 3] have identified this as a serious problem and proposed the ways to mitigate it. Here a brief summary of extensive studies of the IP1 and IP5 high luminosity insertions are presented based on the up-to-date LHC optics (version 6.4), better understanding of practical possibilities with quadrupole cooling and shielding, and upgraded MARS14 [4] modeling. Ref. [3] describes these studies in great details.

To protect SC magnets against debris generated in the pp collisions and in the near beam elements, a set of absorbers in front of the inner triplet, inside and between the low-β quadrupoles, and in front of the D2 separation dipole was designed on the basis of energy deposition MARS14 calculations. Fig. 1 shows the inner triplet configuration with the absorbers in. The two curves show the approximate "n1 = 7" beam envelope for injection and collision optics, including closed orbit and mechanical tolerances.

All essential components situated in the tunnel of the IP1(R) and IP5(R) regions of 215-m long are implemented into the MARS14 model with a detailed description of their geometry, materials and magnetic field distributions. The model includes all the beam line, cryogenic and protection elements, tunnel, first meters of rock (molasse) outside the tunnel, as well as near beam components and solenoid magnetic fields of the ATLAS and CMS detectors for the IP1 and IP5, respectively. Fig. 2 shows the interaction region beam elements and their placement in the tunnel as modeled in the code.

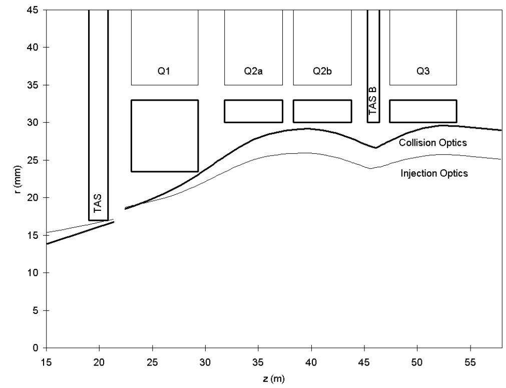

Figure 1: The LHC low-β insertions including absorbers: schematic view with the beam envelopes.

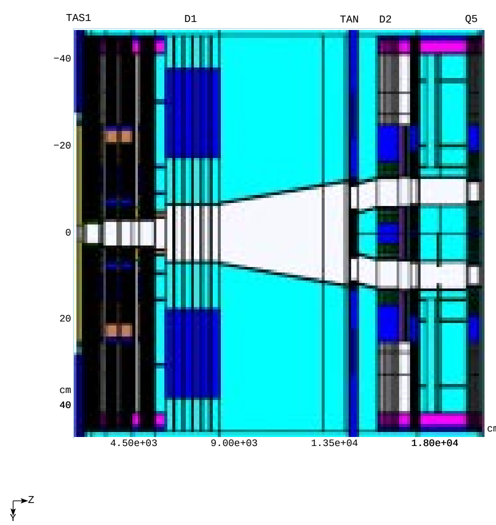

Figure 2: A fragment of the IP5 MARS model.

DESIGN CONSTRAINTS

The protection system design constraints used in the study are as follows:

1. Baseline luminosity of 10^{34} cm^{-2}s^{-1}.
2. Keep *geometrical aperture larger than "n1 = 7"* for injection and collision optics, including closed orbit and mechanical tolerances.

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† mokhov@fnal.gov

3. *Quench stability:* keep peak power density ϵ_{max}, which can be as much as an order of magnitude larger than the azimuthal average, below the quench limit with *a safety margin of a factor of 3*.

4. Use *1.6 mW/g as a quench limit*. For many years, the estimated quench limit for the LHC high-gradient quadrupoles was 1.2 mW/g. Tests of porous cable insulation systems and recent calculations concerning the insulation system to be used in the Fermilab-built LHC IR quadrupoles (MQXB) have shown that up to about 1.6 mW/g of heat can be removed while keeping the coil below the magnet quench temperature.

5. Rely on *radiation-hard materials*. With the above levels, the estimated lifetime will exceed 7 years at the baseline luminosity even in the hottest spots.

6. Keep *dynamic heat loads below about 10 W/m*.

7. *Hands-on maintenance:* keep residual dose rates on the component outer surfaces below about 0.1 mSv/hr.

8. Always obey *engineering constraints*.

PROTECTION SYSTEM

A protection system on each side of the IP1 and IP5 has been designed over the years on the basis of comprehensive MARS calculations. It includes:

- The TAS front copper absorber at L=19.45 m (1.8 m long, 34-mm ID, 500-mm OD).
- A 7-mm thick stainless steel (SS) liner in Q1.
- The SS absorber TASB at L=45.05 m (1.2-m long, r=33.3-60 mm). Proposed in earlier studies a TASA absorber at L=30.45 m (1.1-m long, r=25-60 mm) is eliminated from the design.
- A ~3-mm thick SS liner in the Q2A through Q3.
- 40-cm long SS masks at L=23.45 m, r=250-325 mm to protect the Q1 slide bearings.
- The neutral particle copper absorber TAN at 140 m.
- The 1-m long TCL SS collimator at 191 m from IP.

The TAS absorbers in front of the first low-β quadrupoles are designed as a front-line system to protect the inner triplet by catching the particles originating from the IP and the cascades initiated by them. TAS's parameters were optimized over years. Currently the TAS are at 19.45 m from the IP in the IP1 and IP5, made of copper, 1.8-m long and 1.7 cm inner and 25 cm outer radii. At design luminosity, they catch 184 W of collision power on each side of the IP, allowing only 5% of the incoming energy (outside TAS aperture) to penetrate through the absorber body.

It was shown in Ref. [1] that a ~7-mm thick liner in the Q1 quadrupole is needed to bring ϵ_{max} at the Q1 non-IP end below the design limit (see Fig. 3). The same exponential shielding effect in a material preceding the SC coils dictates a thicker beam pipe in the Q2A through Q3 region. An intermediate absorber TASB protects the Q3 quadrupole, as do the masks inside the cryostat for the Q1 slide bearings. A neutral particle absorber TAN at 140 m on each side of the IP, was designed to protect the separation dipoles D2 and the outer triplet quads against the neutral component from the IP (neutrons and photons predominantly) and charged and neutral particles generated in the near beam components on the 140-m way from the IP. An instrumented copper core (21×26×350 cm) with two 5 cm diameter beam holes is surrounded by massive steel shielding with a 30-cm steel / 30-cm marble albedo trap.

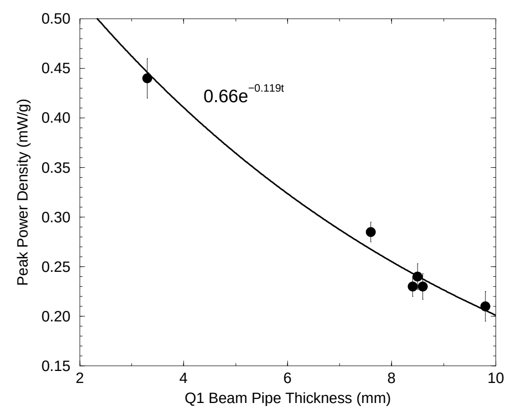

Figure 3: Peak power density in the Q1 inner layer *vs* liner thickness (beam screen together with cold bore).

POWER DENSITY AND HEAT LOAD

As a result of optimization of the above system parameters, it became possible to meet the design constraints. For quench stability, it was essential to perform a detailed 3D analysis of power density ϵ in the quadrupole coils, which varies strongly in longitudinal radial and azimuthal directions. There are pronounced peaks in the horizontal and vertical planes, with a difference between maximum and minimum values reaching a factor of 10 and between the peaks and azimuthally averaged values of a factor of 2.5 to 5.5. A longitudinal distribution of an azimuthal peak in the first radial bin of the SC coils (35<r<46.5 mm) is shown in Fig. 4. In the IP5, for the baseline horizontal crossing, the power density reaches its maximum ϵ_{max} = 0.45 mW/g at the Q2b non-IP end, a factor of 3.5 below the quench limit. In the SC separation dipole and outer triplet quadrupoles, the protection system provides a safety margin of 10 to 100.

Integral power dissipation distribution in components of the IP5 inner triplet is presented in Fig. 5, while Table 1 gives integral values for the the components in the entire 215-m region studied. Statistical uncertainty for each of the values in the Table does not exceed 1%. The integration with respect to radius for all the components was per-

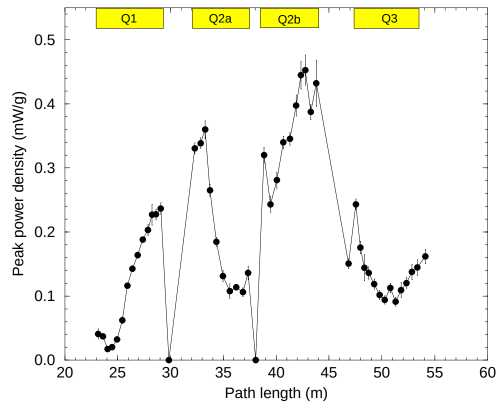

Figure 4: Longitudinal distribution of peak power density in the first radial bin of the IP5 SC coils in the IP5 quadrupoles.

formed from 0 up to 45.72 cm, *i.e.* through the vacuum vessel. Results for the IP1 are quite similar. The table also gives hadron fluxes and prompt dose on the vessel, useful for a beam loss monitor system design, and an estimate of radiation environment in the tunnel near the cryostat.

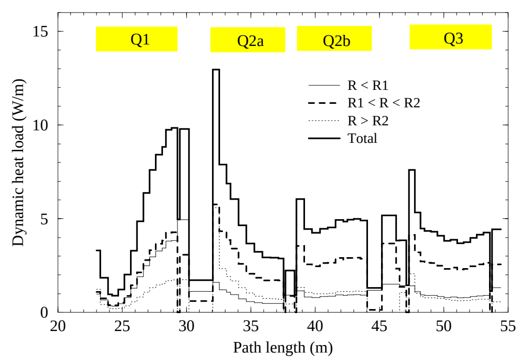

Figure 5: Power dissipation in the baseline IP5 inner triplet components. R_1=35 mm, R_2=81 mm in Q1 and Q3 and R_2=67 mm in Q2a and Q2b.

UNCERTAINTIES

Based on numerous international benchmarkings on micro and macro levels, status of the current event generators, thorough sensitivity analysis in the inner triplet over eight years (event generators, other physics input, geometry, materials, fields, crossing etc), numerous discussions and analyses of the results by the community over the same eight years, understanding of the Monte Carlo aspects, we believe that we predict the maximum power density in the coils with an accuracy better than 30%. This is true for the innermost layers of the coils (just a beginning of showers) for a particular configuration. The results, especially for local peak power deposition, can be quite sensitive to configuration changes, however. The uncertainty is higher at larger radii and larger distances from the IP, often because of statistics. Integral energy deposition and integral flux values such as azimuthal average, power dissipation (dynamic heat load) are predicted with about 10-15% accuracy. Residual dose rates are estimated within a factor of two to three.

Table 1: Dynamic heat load P (W) on the IP5 components, and prompt dose equivalent DE (Sv/hr) and hadron flux Φ (10^4cm^{-2}s^{-1} at E>14 MeV) on the vessel at longitudinal peaks at the nominal luminosity.

Element	P	DE	Φ
Absorber TAS	184		
Absorber TASB	5.7	18.12	91.84
Quadrupole Q1	30.7	12.44	92.72
Quadrupole Q2a	28.8	22.09	133.4
Quadrupole Q2b	26.6	5.184	40.91
Quadrupole Q3	27.7	12.61	93.76
Corrector MCBX1	6.9	17.55	144.6
Corrector MCBX2	1.6	4.202	32.67
Corrector MQSXA	2.0	15.85	106.0
Corrector MCBXA	3.1	4.712	41.58
Feedbox DFBX	6.92	6.670	39.31
Dipole D1	50		
Absorber TAN	189		
Dipole D2	1.96	2.079	11.08
Quadrupole Q4	0.39	0.243	1.696
Quadrupole Q5	1.79	1.466	9.104

CONCLUSIONS

The system described in this paper and developed under realistic engineering constraints will protect the LHC IP1/IP5 region components against luminosity-driven short- and long-term deleterious energy deposition effects with a good safety margin, at least at the design luminosity of 10^{34} cm^{-2}s^{-1}.

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