Power density in the triplet magnets for horizontal and vertical crossing angles: new simulation results by N. Mokhov

- Previous results
- New results
- Points to be clarified
- Some clarifications

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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project **LHC Project Report 477**

PROTECTING LHC COMPONENTS AGAINST RADIATION RESULTING FROM COLLIDING BEAM INTERACTIONS

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PROTECTING LHC COMPONENTS AGAINST RADIATION RESULTING FROM COLLIDING BEAM INTERACTIONS*

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Abstract

Beam-induced energy deposition in the LHC high luminosity interaction region (IR) components due to both pp 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. In this paper the results of further optimization and comprehensive MARS calculations are briefly described for the updated IP1 and IP5 layouts and a baseline pp-collision source term. Power density, power dissipation, accumulated dose and residual dose rates are studied in the components of the inner triplets including their TAS absorbers, the TAN neutral beam absorbers, separation dipoles, and quadrupoles of the outer triplets and possible collimators there. It is shown that the optimized absorbers and collimators provide adequate protection of all the critical components.

1 MARS MODELING IN IP1 AND IP5

The Large Hadron Collider (LHC) [1] under construction at CERN, will produce pp 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 [2, 3] have identified this as a serious problem and proposed the ways to mitigate it. Below selected results of extensive studies of the IP1 and IP5 high luminosity insertions, performed for the latest lattice (version 6.2) with the newest version MARS14 of the MARS code [4], are presented. All essential components situated in the tunnel of the IP1(R) and IP5(R) regions of 215 m long (up to the Q5 quadrupole) are implemented into the MARS14 model with a detailed description of their geometry, materials and magnetic field distribution (Fig. 1). Horizontal crossing is modeled in the IP5 with correspondingly oriented beam pipes, while it is modeled vertically in the IP1. Near beam details of the ATLAS and CMS detectors are put in the model for the IP1 and IP5, respectively. Consideration is limited to luminosity-driven energy deposition effects in the inner and outer triplets. Impact of the circulating and misbehave beam on the machine and detector components is considered elsewhere [5, 6].

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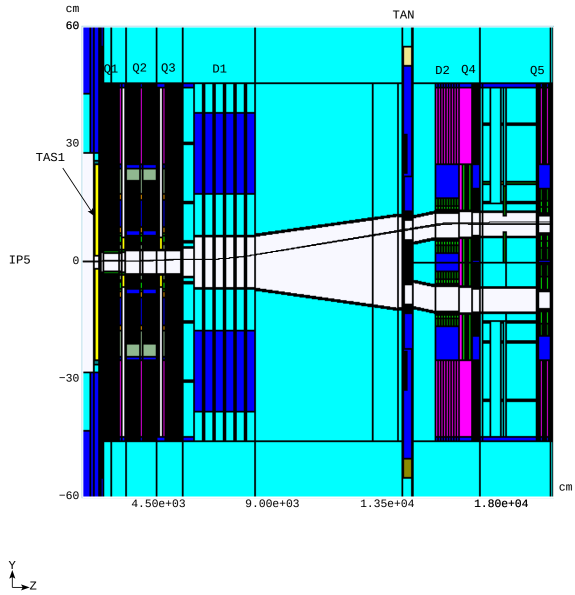

Figure 1: MARS model of the IP5 region. Proton tracks are shown in one ring.

2 INNER TRIPLET

The following protection system has been designed as a result of these studies: the TAS1 copper absorber (1.8-m long, 1.7 cm inner and 25 cm outer radii) at 19.45 m from the interaction point (IP), a stainless steel (SS) absorber (23.5<r<33.3 mm) inside the 35-mm radius Q1 aperture, a tapered SS liner in the MCBX, a TAS2 SS-copper absorber (1.1-m long, 25<r<60 mm) at 30.45 m from the IP in front of the Q2a quad, a TAS3 SS-copper absorber (1.2-m long, 33.3<r<60 mm) at 45.05 m from the IP in front of the Q3 quad, and a thicker beam pipe in the Q2a through Q3 region. Alternating magnetic field in the quads affects drastically the distribution of energy deposition ϵ in the inner triplet: ϵ peaks in horizontal and vertical planes and reaches maxima at a downstream or/and upstream end of the quads. There is a strong gradient in radial ϵ-behavior. Fig. 2 shows a longitudinal distribution of an azimuthal peak in the first layers of the superconducting (SC) coils in the IP1(R) and IP5(R) inner triplets. These results are applicable to the other sides of the IRs, inverting the IP1(R)-IP5(L) and IP5(R)-IP1(L) pairs. The power density reaches its maximum ϵ_{max}, obviously, at β_{max} in the Q2b-Q3 region. This value is further increased in Q2b due to horizontal (IP5(R)) and (IP1(L)) crossings. With all of the above protective measures, one can keep ϵ_{max} a factor of two to three—at the baseline luminosity—below the assumed quench limit of 1.2 mW/g.

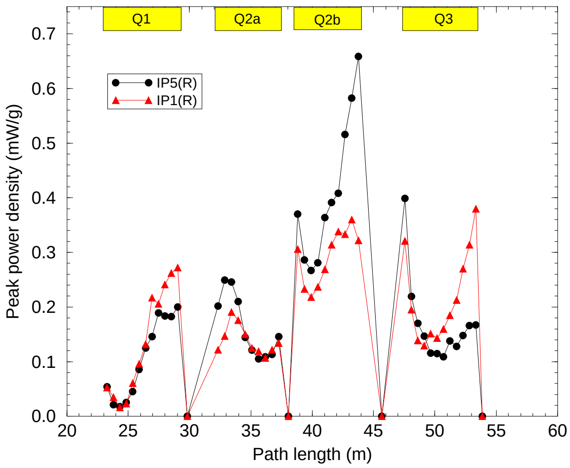

Figure 2: Peak power density in the first layer of the SC coils of the IP1 and IP5 inner triplet.

The absorbers do a very good job intercepting a significant fraction of the energy escaping the colliding detectors. The TAS1 alone absorbs 242$\pm$20 W on each side of the IP. The distribution of power dissipation in the IP5(R) inner triplet is shown in Fig. 3 separately for the coil regions, components inside the bore and for the remaining magnet mass. The Q1 inner absorber catches about 60% of power in this region. The dose accumulated in the inner triplet components is quite high. For the corresponding baseline luminosity profile over an operational year, it can be estimated as D (MGy/yr) = 7.8 ϵ (mW/g). The peak in the Q2b coil can be as high as 4.7 MGy/yr. Averaged over the coils it is about 100 kGy/yr, dropping down to several kGy/yr at the slide bearings supporting the yoke. The later assumes that a 2-cm gap around the TAS1 core is filled before the collider run. Residual dose rates are quite significant in the near beam region—especially on the absorbers—being below 0.1 mSv/hr (30 days irradiation and 1 day cooling) on contact at the vessel (Fig. 4).

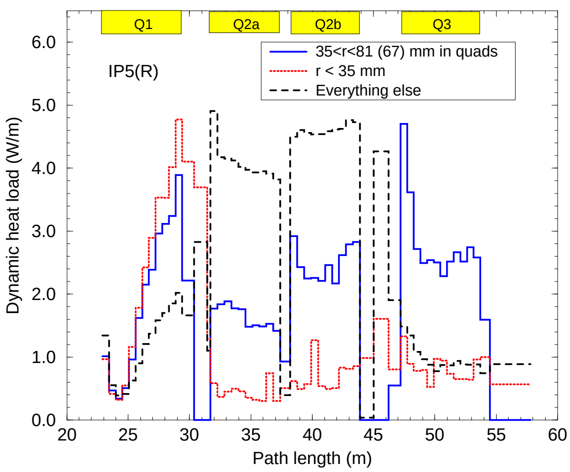

Figure 3: Power dissipation in the IP5 inner triplet.

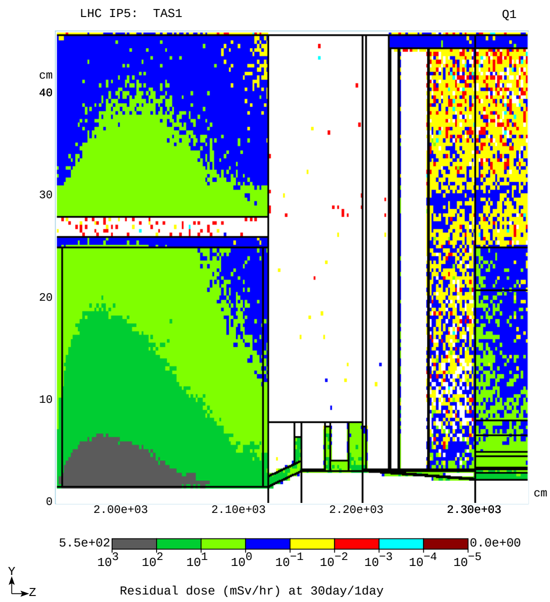

Figure 4: Residual dose (mSv/hr) for the IP5 TAS1-Q1.

3 TAN, D2 AND OUTER TRIPLET

A "neutral beam" absorber TAN at 140 m on each side of the IP, is designed to protect the separation dipoles D2 and the outer triplet quads [7]. Its parameters were optimized based on detailed MARS14 calculations. An instrumented copper core (21$\times$26$\times$350 cm) with two 5 cm diameter beam holes is surrounded by massive steel shielding with a steel/marble albedo trap (Fig. 5). The power dissipated in the core is about 200 W and is brought primarily by energetic neutrals (45% neutrons and 45% photons) generated at the IP and in the near beam components on a 140-m way from the IP. Residual dose rate on contact at the TAN outer surface of the steel shielding (y=+55 cm in Fig. 5) is shown in Fig. 6 for irradiation from 1 day to 20 years continuosly as a function of cooling time. In realistic operation, the dose is below 0.1 mSv/hr about a day after shutdown.

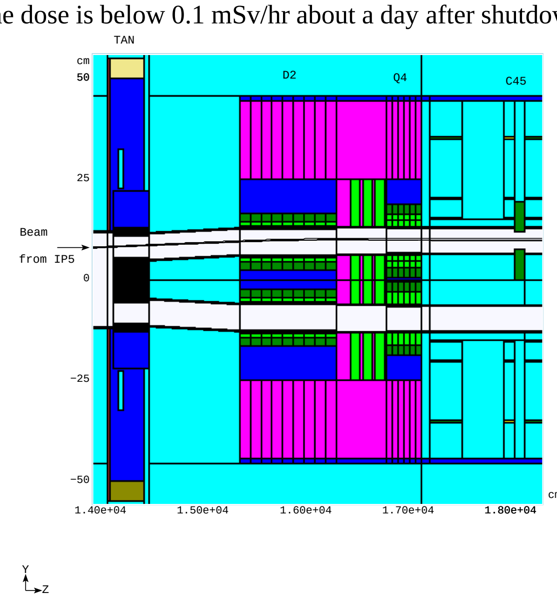

Figure 5: MARS model of the IP5 TAN and beginning of the outer triplet. Proton beam from the IP is shown.

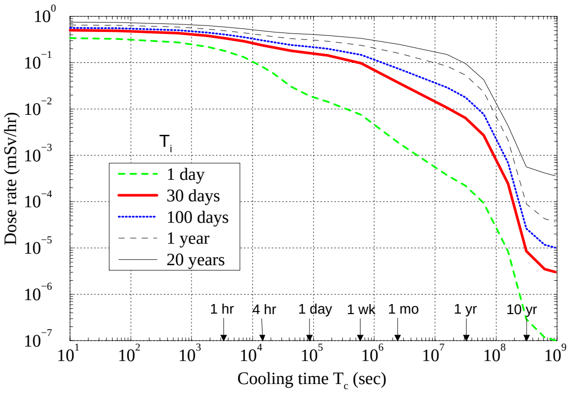

Figure 6: Residual dose (mSv/hr) averaged over the IP5 TAN shielding surface (y=+55 cm) vs cooling time.

The TAN protects nicely the D2 dipole (Fig. 7) and Q4 quadrupole (Fig. 8), with the peak ϵ_{max} in the SC coils—which occurs again in a tiny azimuthal bin in the horizontal plane of the inner coil—almost a factor of hundred below the tolerable limit, with less than 1.75 W and 0.4 W of power dissipated in D2 and Q4, respectively. At the same time, calculations have shown that the peak power density in the Q5 SC coils was rather close to the allowable limit of 1.2 mW/g. It was found that an additional steel collimator C45 (19.4×19.4×100 cm), situated between Q4 and Q5 at 180.5 m from the IP and with a 21.3 mm aperture for the outgoing beam (see Fig. 5), solves this problem. Fig. 9 shows that both the peak power density in the SC coils and power dissipation in the Q5 quadrupole calculated with such a collimator are similar to those in D2 and Q4.

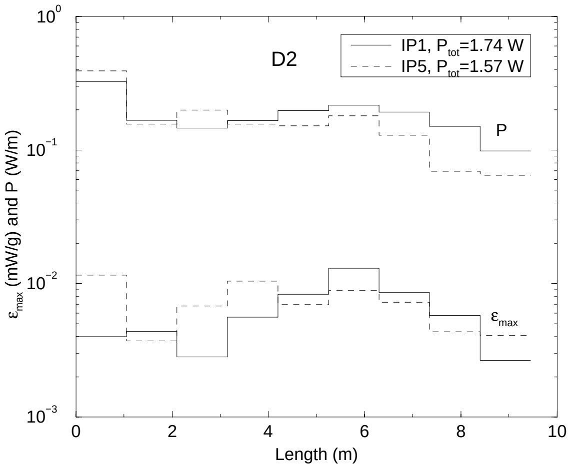

Figure 7: Peak power density ϵ_{max} and dynamic heat load P vs length in the IP1 and IP5 D2 separation magnet.

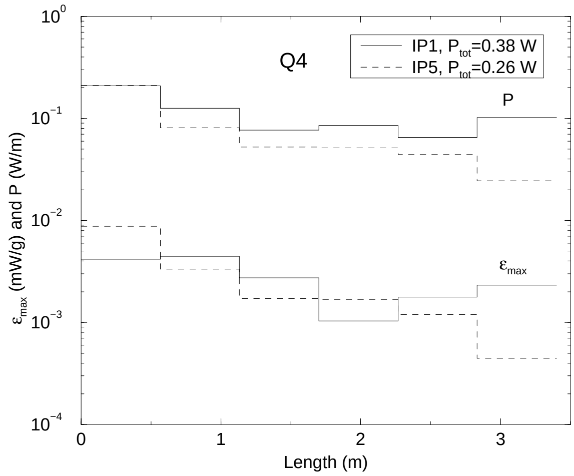

Figure 8: Peak power density ϵ_{max} and dynamic heat load P vs length in the IP1 and IP5 Q4 outer triplet quadrupole.

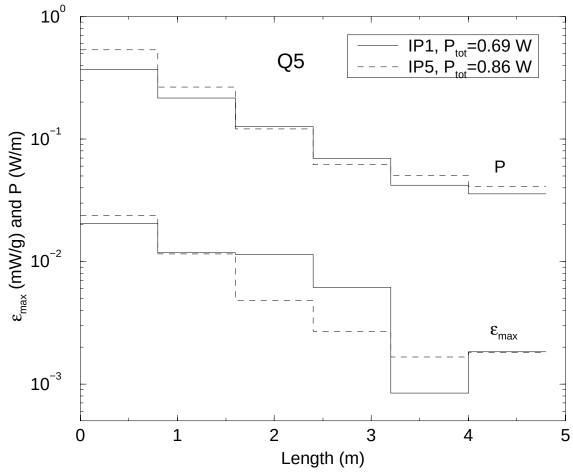

Figure 9: Peak power density ϵ_{max} and dynamic heat load P vs length in the IP1 and IP5 Q5 outer triplet quadrupole.

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Vertical *vs* Horizontal Crossing in IP5

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The effect of the IP5 crossing plane orientation on energy deposition in the inner triplet is shown. The results of power density calculations with the MARS14 code [1] are given for the nominal luminosity of 10^{34} cm^{-2}s^{-1} at $\sqrt{s}$=14 TeV for a half crossing angle α=150 μrad. All the details of the current design – including optimized TAS, TASB and Q1-MSBX absorbers, slide bearing masks etc [2] – are in the MARS14 model as shown in Fig. 1. Two high-statistics runs have been performed: for the horizontal and vertical crossings with the beam screen in Q2A through Q3 as shown in Fig. 2. All the other parameters in these runs are the same.

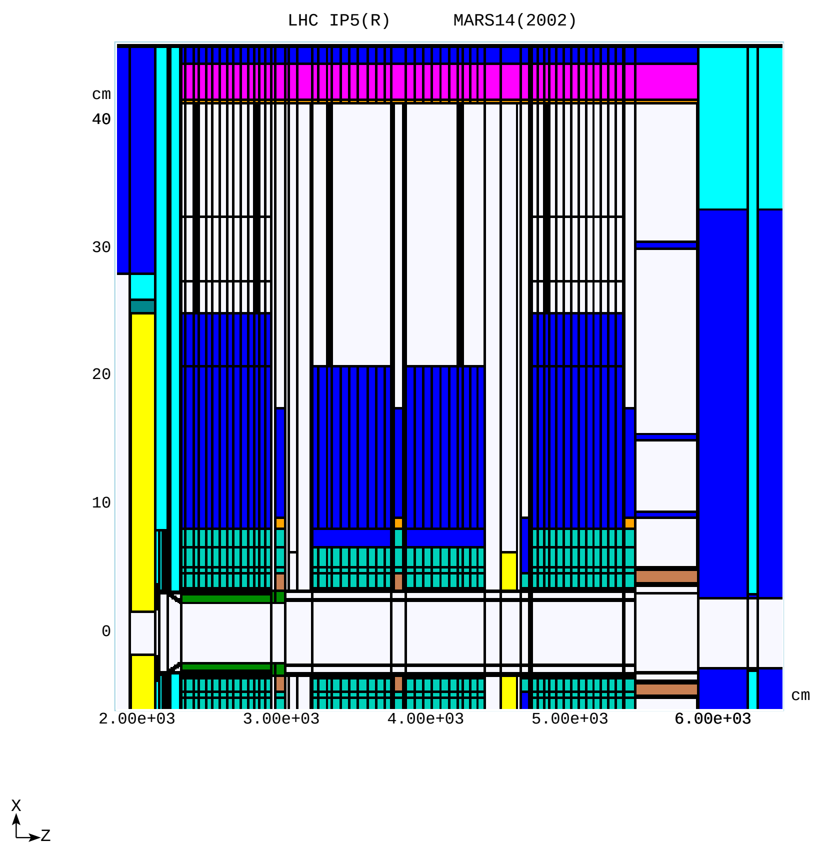

Figure 1: IP5 low-β insertion MARS model.

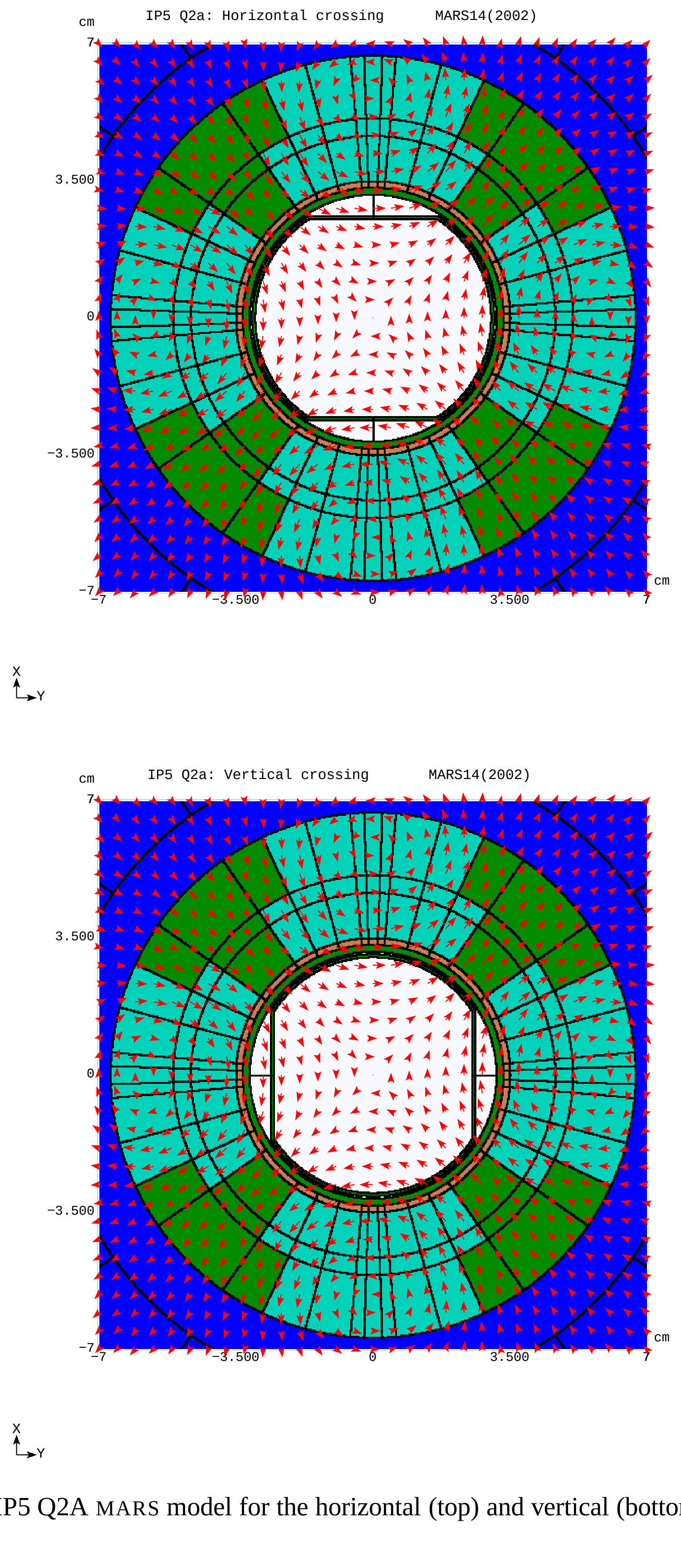

Figure 2: IP5 Q2A MARS model for the horizontal (top) and vertical (bottom) crossings.

Figs. 3–4 show azimuthal distributions of power density in the IP5(R) quadrupole coils at the hottest (longitudinally) spots, calculated both for horizontal and vertical crossings. One sees 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) in the IP5(R) inner triplet is shown in Fig. 4 (bottom). For the baseline horizontal crossing, the power density reaches its maximum ε_{max} at the Q2B non-IP end. For the vertical crossing, there are two equal peaks – at the IP end of Q2A and at the non-IP end of Q3 – which are slightly lower than the one for the horizontal crossing case.

Thanks to the protective measures implemented into the inner triplet design [2], one keeps peak power density ε_{max} a factor of about three – at the baseline luminosity – below the LHC high-gradient quadrupole quench limit of 1.2 mW/g, both for horizontal and vertical crossings in the IP5 with appropriate orientation of a "racetrack" beam screen. Note that the above limit is assumed in the project for last seven years and was recently updated to 1.6 mW/g for MQXB on the basis of thorough thermal analysis of the Fermilab quadrupoles [3].

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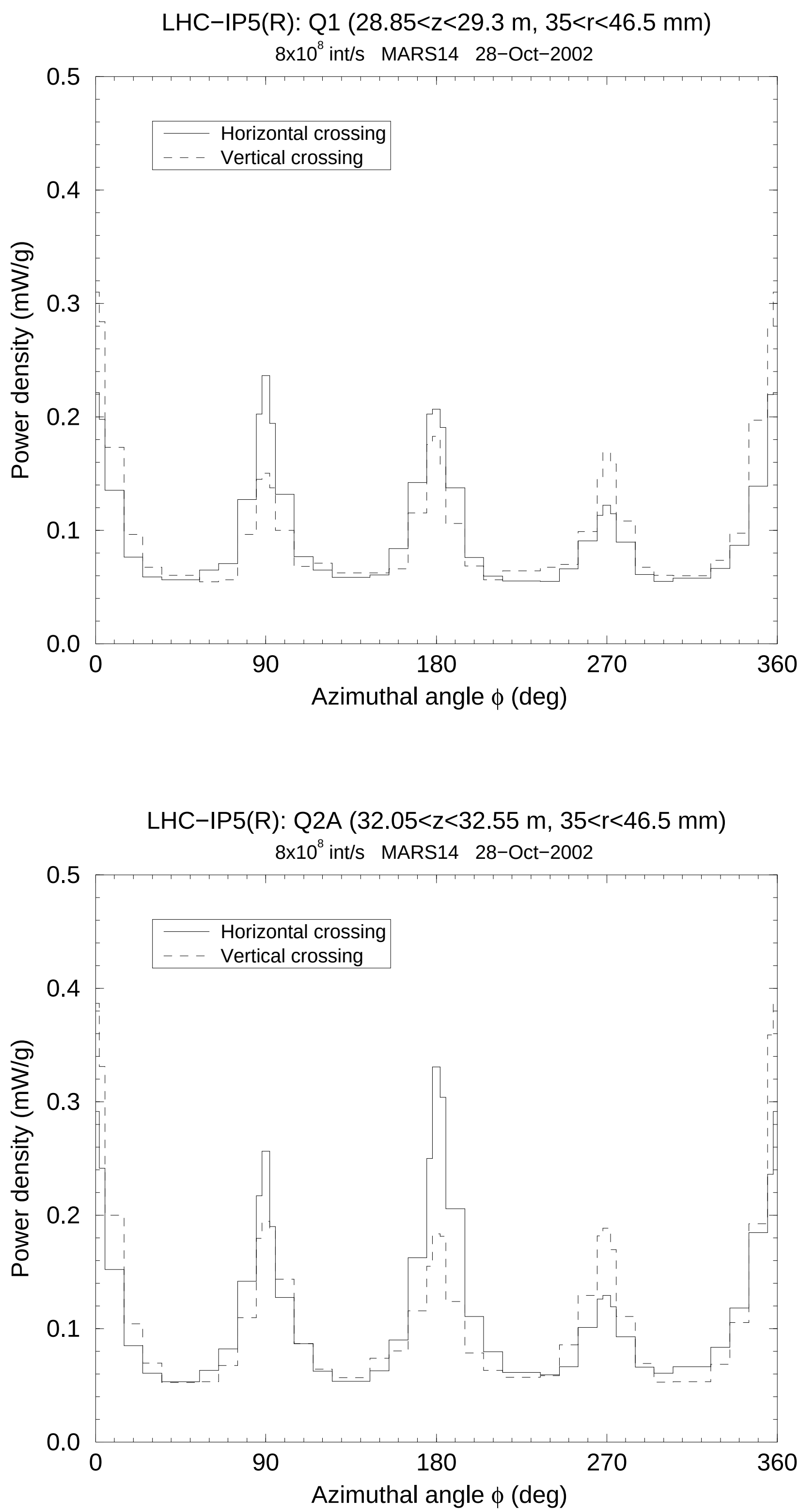

Figure 3: Azimuthal distributions of power density in the first radial bin of the SC coils in the IP5 Q1 (top) and Q2A (bottom) quadrupoles at longitudinal peaks for the horizontal and vertical crossings.

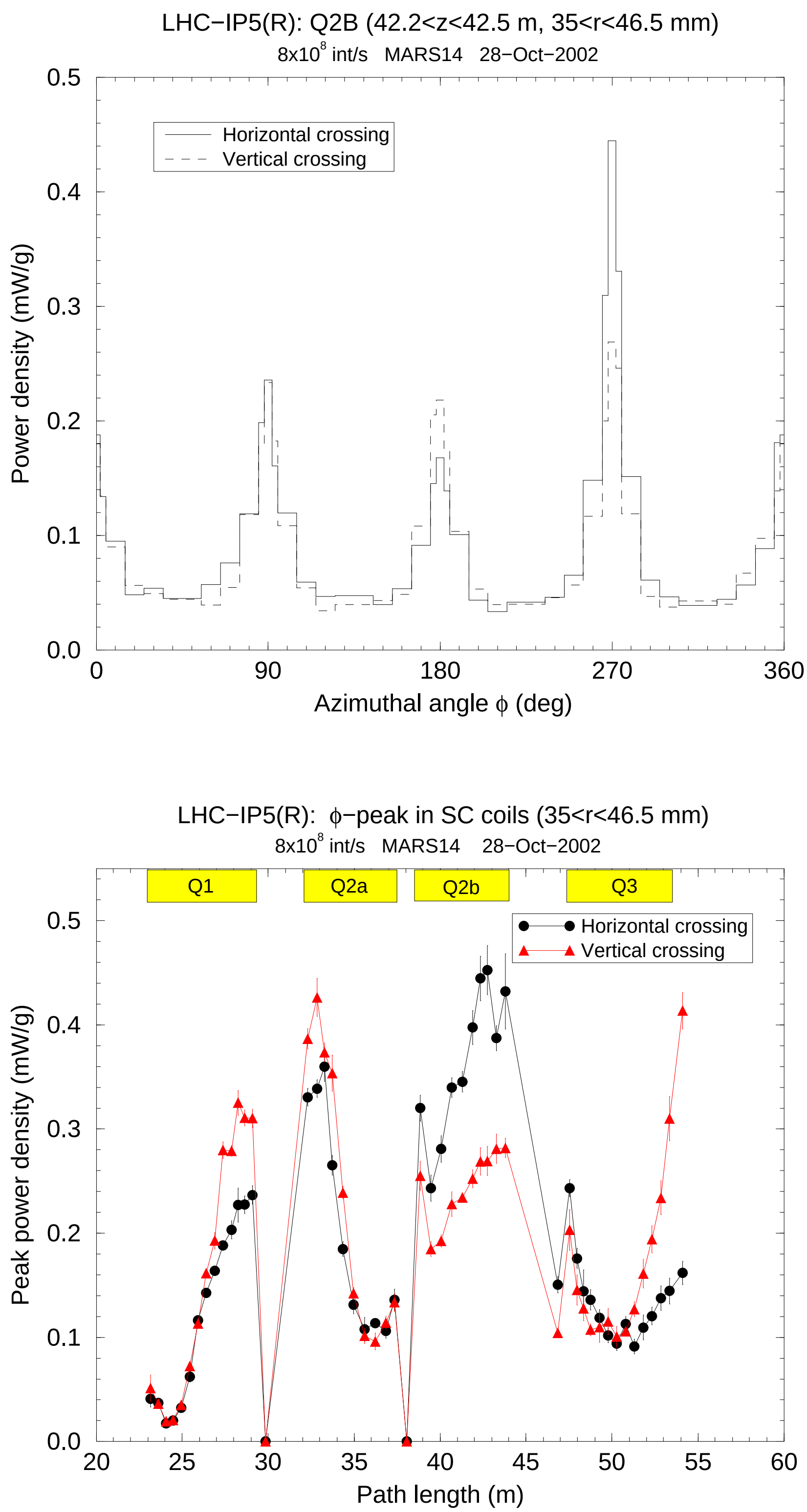

Figure 4: Azimuthal distribution of power density at longitudinal peak in Q2B quadrupole (top) and longitudinal distribution of peak power density (bottom) in the first radial bin of the IP5 SC coils in the IP5 quadrupoles for the horizontal and vertical crossings.

Points to be clarified: questions collected at LEMIC and outside LEMIC

1. Estimated error on the peak power density in the coils and sensitivity to the physics model used to generate interactions at 14 TeV in the center of mass
2. Estimated quench limit and errors
3. Beam screen in Q1
4. Simulation of the V and H crossing scheme at IP5 (is the MCBX taken into account?)

It would be nice to get the detailed geometry used in the simulation and a comparison with the previous results

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Some clarifications from N. Mokhov and J. Strait

1. Based on numerous international benchmarkings on micro and macro levels, status of the current event generators, thorough sensitivity analysis in the inner triplet over last seven years (event generators, physics other than event generators, geometry, materials, fields, crossing etc), numerous discussions and analyses of the results by the community over same seven years, understanding of the Monte Carlo aspects, I would claim that we predict the maximum power density in the coils with an accuracy better than 20-25%. Integral energy deposition and flux values in the inner triplet components such as azimuthal average, power dissipation (dynamic heat load) are reliable within about 10%. Residual dose rates are estimated within a factor of two to three. All my studies on the LHC last decade are based on DTUJET (early days) and DPMJET (later) as an event generator. The results given in that note, are based on the state-of-the-art DPMJET-3 code, as I recall version 3.0-2 of mid-spring 2001 or may be even a newer version (3.1?) after Hannes' visit at Fermilab in August 2001.

2. The quench limit is calculated for the given coil material and cooling channels using power density profile (MARS), thermal analysis (ANSYS) and model of quench propagation etc Results on power density are normalized per 8.e8 non-elastic pp-interactions per second, there is no other time structure involved. For details on the thermodynamics models see paper by A. Zlobin et al presented at EPAC'02 (MOPLE017) and cited in my note. For many years, the estimated quench limit for the LHC high-gradient quadrupoles was 1.2 mW/g. It is shown in the above EPAC paper that it is most likely 1.6 mW/g for the MQXB quadrupole. Unfortunately, we do not have a thermal model for MQXA, and I think all we can say is that we expect its thermal margin to be comparable to that of the MQXB. Based on uncertainties with the quench limit, larger uncertainties in the calculations in early years and Tevatron experience, our design goal always was to keep the peak power density in the inner triplet SC coils a factor of 3 below the quench limit, i.e. < 0.4 - 0.45 mW/g.

3. Instead of the beam screen, the Q1 has a thick beam tube designed to provide an adequate power density reduction in the Q1-Q2A. A detailed

description can indeed be found in the draft report I showed you a month ago. The model is a simplification in which the ID in his model is equal to the ID of the circular part of the beam screen, the OD is equal to the OD of the thick beam tube, thereby slightly overestimating the amount of material between the beam and the coil. Comparing different runs in which different Q1 beam tube thicknesses were simulated, the overestimate of the material does not affect the results presented in the technical note.

4. As described in my short note, the vertical crossing in the IP5 was modelled just by rotating by 90 degrees the crossing plane and the beam screen in the Q2A through Q3.

5. As we expected, the above is the only reason for different energy deposition distributions in the IP1 and IP5. The ATLAS and CMS fields and other "near-beam" differences in the detectors do not affect the peak energy deposition in the inner triplet SC coils.

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