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Energy Deposition Studies for the Betatron Cleaning Insertion (IR7) of LHC

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Two insertions (IR3, IR7) of the Large Hadron Collider (LHC) are dedicated to beam cleaning with the design goals of absorbing part of the primary beam halo and of the secondary radiation. The tertiary halo which escapes the collimation system in IR7 may heat the cold magnets at unacceptable levels, if no additional absorber is used. In order to assess the energy deposition in sensitive components, extensive simulations were run with the Monte Carlo cascade code FLUKA. The straight section and the dispersion suppressors (DS) of IR7 were fully implemented. A modular approach in the geometry definition and an extensive use of user-written programs allowed the implementation of all magnets and collimators with high precision, including flanges, steel supports and magnetic field. This paper provides the number and location of additional absorbers needed to keep the energy deposition in the coils of the magnets below the quenching limit.

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INTRODUCTION. THE IR7 BETATRON CLEANING INSERTION OF LHC

The LHC is the most challenging accelerator being constructed. The projected proton energy for the LHC (7 TeV) surpasses the state of the art by a factor 7 with stored energies in each beam up to 350 MJ, two orders of magnitude above those of the forefront accelerators. Moreover, the nominal transverse energy density in the beams ($\frac{GJ}{mm^2}$) is 1000 times higher than in current proton storage rings. This renders the LHC beams highly destructive. Tiny losses of the beam suffice to quench any of the 5000 superconducting LHC magnets[1] while the entire beam loss would entail massive damages as it would have the equivalent energy to melt half a ton of copper.

In order to attain the luminosity performances and to meet the LHC requirements within such a sensitive superconducting environment, a Collimation System (CS) has been designed for years [1]. The role of the LHC CS in machine protection is to absorb the beam halo so as to avoid quenches of the superconducting magnets, to protect the accelerator elements and experiments from beam loss after a failure and to minimize halo-induced backgrounds in the particle physics experiments. The CS is concreted into two insertions, IR3 for momentum cleaning and IR7 for betatron cleaning, which shall be equipped with some 54 movable, two-sided collimators. From injection up to top energy, various beam dynamics processes breed the beam halo and thus limit the lifetime of the beam down to a value close to 0.2 h (equivalent to $4 \cdot 10^{11}\ \frac{p}{s}$ for a transient period of 10 s). The goal of the CS is that 7 TeV protons (primary halo) always touch the collimators first. Primary and secondary collimators (TCP, TCS) generate a secondary and tertiary halo, the cold aperture only been shielded from the latter by the so-called active absorbers (TCL).

[1] which, in turn would lead to a beam loss.

MONTE CARLO SIMULATIONS OF ENERGY DEPOSITION, METHODOLOGY

The energy density deposited by the showers that are generated at the interception of the primary halo by the collimators was extensively simulated with FLUKA [2, 3]. Each shower was initiated by a nuclear interaction of a proton with the coordinates/direction provided by the COLLTRACK V5.4[2] code [4].

The geometry implementation in FLUKA was rather sophisticated due to the complex nature of IR7. Indeed, the betatron cleaning insertion includes 4 quadrupoles (MQW), a first pair of warm bending magnets (MBW) that adds 3 cm of separation between the two beams and a second pair 340 m downstream to restore the offset to 19.4 cm, horizontal and vertical correctors (with MCBW dipoles) and, in the DS, cold quadrupoles (MQTL), orbit correctors (MCB), sextupoles (MCS), and bending magnets (MB). Each MQW is in turn composed of 5 MQWA and 1 MQWB modules. The MB's are 14.3 m long, 5 *mrad* curved objects, with a deflection field of the 8 Tesla. In total, over 200 elements of 23 different types are laid along a 1.5 km tunnel, segmented as an upstream arc (DS), a straight section (SS) and a downstream arc (DS). Objects were modeled with full details (including flanges, steel supports and magnetic fields) and stored in a "parking" area next to the tunnel for latter mapping via the LATTICE card of FLUKA. The modular approach allowed an accurate yet manageable description of the complex system. The beam lines, the surrounding tunnel and all beam line elements were automatically generated by a REXX [5] script that used the latest beam optics V6.5 [6].

Collimators and absorbers owe special remarks as they are key elements in the halo cleaning system. The TCP are meant to act as the bottleneck of the beam, the inter-jaw half-aperture being at 6 σ, while this value reaches 7 and 10 σ for the TCS and TCL, respectively. Since σ depends on the beta function, whence on the position, the aperture and

[2] a multi-turn beam optics program that computes a map of protons lost in the collimators by tracking up to 100 turns the 7 TeV beam at low beta settings.

the orientation is adapted at runtime through the LATTIC.F routine so that the same prototypes can be used all over. As for the optimum materials, the jaws in the collimators are made of graphite (a detailed discussion can be found in [7]) and comparison between Cu and W shows that the latter makes the TCL more effective. Other relevant parts of the collimators like springs, RF-Fingers, collars, cooling pipes etc have being included and their collected doses surveyed.

Each LHC magnet has an associated magnetic field[3], the mapping of which is provided by the formerly mentioned REXX script, which ensures the correctness of the beam optics and of the beta functions.

Heat deposition in critical hot elements

Normal losses are less likely to damage hot elements than superconducting components, but they can easily hinder their functionalities and, consequently, increase the dose in the cold elements. A brief check-list follows.

HEAT IN THE COLLIMATOR JAWS The hottest collimator, regardless of the TCL (downstream) is TCSG.A6L7.B1 where the total simulated dose reaches 22 kW. [8] prove that both AC-150-K-C/C-2D and R4550 graphite jaws withstand the estimated share of heat (25 %) still maintaining their robustness and flatness within specifications. [9]

HEAT IN THE COLLIMATOR COUPLING FINGERS The 80 fingers at each end-cap of the collimators are distributed around the beam forming a collar of inner radius 5.0 cm and outer radius 5.1 cm. The total heat deposited in the back fingers of TCSG.A6L7.B1 was 80 W for the whole collar. The heat distribution is tabulated in table 1. These values don't compromise the operation of the collimators.

Table 1: Heat distributions $[\frac{W}{cm^3}]$ in sensitive elements of the TCSG.A6L7.B1 (downstream components).

Element	**45°**	**90°**	**135°**	**180°**	**TOT** $[W]$
Fingers	1.7	1.8	2.3	2.2	59
Inner Flange	1.6	1.9	2.5	1.9	325

HEAT DEPOSITION IN THE FLANGES The flanges are the pieces that couple different parts of the vacuum equipment. If the thermal stress caused by radiation is strongly inhomogeneous, then the flanges may be asymmetrically deformed and the joints may lose their tightness. Table.1 shows the estimated heat distribution in the flanges of TCSG.A6L7.B1 for different transverse directions. The total heat and the anisotropy remain tolerable.

[3]Analytically or as a bi-dimensional interpolation grid with certain symmetries.

HEAT DEPOSITION IN THE MBW The life time of an MBW is inversely proportional to its annual absorbed dose. The most critical elements of the MBW are the two insulators that separate the coils. In the simulated geometry, each insulator (left and right) has a volume of 20400 cm^3. The total energy deposited in the two insulators of MBW.6L7.B1 is 860 W (beam 1) and 3 W (beam 2). To be on the safe side, the energy deposited in the insulators by *beam 1* can be thought to be concentrated in the nearest insulator and the contribution from *beam 2* may be neglected. This assumption casts an average energy density of $\frac{860\ W}{20400\ cm^3} = 42.1 \frac{mW}{cm^3}$, equivalent[4] to a relatively moderate dose rate of $105.7 \frac{mGy}{h}$.

HEAT IN THE ELECTRONIC EQUIPMENTS The ionizing radiation causes, among other effects, malfunctioning (fake electric pulses) and progressive degradation (atomic displacements) of the electronics. The design of appended galleries and of architectonic barriers as well as all additional measures taken to protect the electronics constitute a project in itself that, cooperatively with IR7 magnet protection, has converged towards safer solutions with doses up to 1-2 mGy/year [10].

HEAT DEPOSITION IN SUPERCONDUCTING MAGNETS

There are two main types of cold elements in IR7: quadrupole and dipole magnets (MQ and MB). These objects are to lose their superconducting properties if the spurious power densities reach about 1 and 5 $\frac{mW}{cm^3}$, respectively [5]. In order to protect these fragile components, 5 TCL were ordered and a systematic study was launched to maximize the shielding efficiency of the absorber system for different configurations (locations and orientations).

Seven candidate positions negotiated with the *beam integration group* where allocated for the TCL; *A4* and *A6* between the interaction point IP7 and the first downstream dogleg bending magnet MBW.D6L7.B1, *C6* between the two downstream dogleg bending magnets, *E6* and *F6* after the second downstream dogleg bending magnet but upstream of MQ6, and *A7 or B7* between MQ6 and DS. A primary set of simulations scanned through the efficiency of the first 5 TCL in terms of the dose computed for the MQ6 group and, in particular, for the first subcomponent MQTLH.A6R7.B1. *A4* was soon discarded (too far away), while *A6*, *C6* and *E6* were retained. Moreover, it was verified that an alternating angle scheme was best filtering the showers, so the starting configuration was frozen as $A6_vC6_hE6_v$[6]. Initially, when $5\ \frac{mW}{cm^3}$ was taken as threshold, the 3 TCL could comply with specifications ($\rho_E \sim 2.5\ \frac{mW}{cm^3}$), but after the stringent $1\ \frac{mW}{cm^3}$ level was established, it became clear that a fourth absorber ($F6_h$) would be needed to shield MQTLH.A6R7.B1. Once the

[4]The density of the epoxy in the insulator is $1.43 \frac{g}{cm^3}$.

[5]Values of 30 $\frac{mW}{cm^3}$ are sometimes accepted [11]

[6](v) stands for vertical and (h) for horizontal orientation of the TCL.

spiky convergent results properly deemed, the peak value in the MQ6 approached $0.8\ \frac{mW}{cm^3}$, leaving scarce margin for contingencies. Improvements could be tentatively found by placing W insertions in the Cu jaws. Simulations were therefore rerun to check this exploit and results proved enormously encouraging, with peak densities as small as $0.25\ \frac{mW}{cm^3}$.

The previous situation left one absorber available at *A7* or *B7* to provide extra shielding for the MQ's and MB's of the DS. Simulations were carried out for each of the two positions with horizontal and vertical jaws and the goodness of each solution was judged through the total and peak doses in MQ7-MQ13 and MB.A8R7.B1-MB.C13R7. The best solutions, equivalent within statistical fluctuations, were those containing $A7_h$ or $B7_h$, compared in fig. 1. The magnetic field was refined several times for

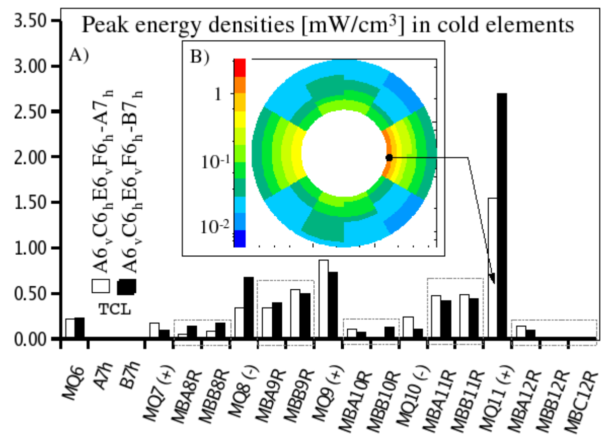

Figure 1: A.) Energy density $[\frac{mW}{cm^3}]$ in MQ and MB for $A7_h$ (□) and for $B7_h$ (■). B.) Energy density in MQ11.

an optimum tracking in the MB's, but the results remained stable in the range of small corrections, which affirmed the confidence in the calculations. Moreover, fig. 1.A seems coherent with the expected beam optics, with a broader horizontal beam (and thus higher doses) in the MB's that follow an h-defocusing quadrupole (-). It is remarked that not only the doses remain mainly under the quench limits, but also the z-derivatives show that the beam delivered beyond IR7 should not be destructive. For MQ11 (fig. 1A and B), however, special actions may have to be taken in the future.

CONCLUSIONS

More than 5 CPU · year computation power has been required to find an optimum shielding configuration where $\frac{mW}{cm^3}$ density peaks are scored in tiny volumes located 1.5 km downstream the interception regions. Results look encouraging, especially if W jaws are used in the TCL. The heat in sensitive hot elements remains moderate, cold elements are reasonably protected and the beam at the end or IR7 is almost loss-free[7].

Future works [12] will investigate what is the effect of the showers caused by that small fraction of the primary halo which escapes the primary collimators and first collides with the TCL.

REFERENCES

[1] R. Assmann, C. Fischer, J.B. Jeanneret, R. Schmidt, "Summary of the CERN Meeting on Absorbers and Collimators for the LHC". LHC Project Note 282.

[2] A. Fassó, A. Ferrari, P.R. Sala, "Electron-photon transport in FLUKA: status", Proceedings of the MonteCarlo 2000 Conference, Lisbon, October 23-26 2000, A. Kling, F. Barao, M. Nakagawa, L. Tavora, P. Vaz - eds., Springer-Verlag Berlin, p.159-164 (2001).

[3] A. Fassó, A. Ferrari, J. Ranft, P.R. Sala, "FLUKA: Status and Prospective for Hadronic Applications", Proceedings of the MonteCarlo 2000 Conference, Lisbon, October 23-26 2000, A. Kling, F. Barao, M. Nakagawa, L. Tavora, P. Vaz - eds., Springer-Verlag Berlin, p.955-960 (2001).

[4] G. Robert-Demolaize, R. Assmann, S. Redaelli, F. Schmidt, "A New Version of SixTrack with Collimation and Aperture Interface", to be published in Particle Accelerator Conference 05 proceedings, Knoxville, May 16-22 2005.

[5] V. Vlachoudis, "BRexx Overview", Rexx Symposium 2001, Research Triangle Park, NC May 2001.

[6] O. Brüning et al.,"LHC Design Report. Volume I The LHC Main Ring", 4 June 2004 CERN-2004-003.

[7] V. Vlachoudis, A. Ferrari, M. Magistris, M. Santana-Leitner, E. Tsoulou, "Consequences of Regular and Irregular Beam Impact on the LHC Collimators", The Monte Carlo Method: Versatility Unbounded In A Dynamic Computing World, Chattanooga, Tennessee, April 17-21, 2005. American Nuclear Society, LaGrange Park, IL (2005).

[8] A. Bertarelli et al., "Mechanical Design for Robustness of the LHC Collimators", to be published in Particle Accelerator Conference 05 proceedings, Knoxville, May 16-22 2005.

[9] R. Assmann et al., "Requirements for the LHC Collimation System", Proceeding of 8^{th} European Particle Accelerator Conference (EPAC02), La Vilette, Paris, France 3-7 June 2002 E.P.S., Geneva, 2002 pp 197. LHC Project Report 599.

[10] K. Tsoulou, V. Vlachoudis, A. Ferrari, "Studies for the radiation levels and shielding in RR73, RR77 and UJ76 in IR7 for collimation phase 1", LHC project Note, to be published.

[11] J.B. Jeanneret, D. Leroy, L. Oberli and T. Trenkler. LHC Project Report 44 (1996).

[12] Magistris M., Ferrari A., Santana M., Tsoulou K. and Vlachoudis V., "Studies for magnet and electronics protection in the LHC Betatron-Cleaning Insertion", to be presented in the International Conference on Accelerator Applications (AccApp), 29 August - 1 September 2005, Venice (Italy).

[7] Note, however, that due to statistical and systematic uncertainties, a safety factor 3-5 is advisable for downstream doses