Energy Deposition Issues in the Very Large Hadron Collider [*]

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1 INTRODUCTION

An energy deposition issues related to the radiation protection systems design for the VLHC are discussed. The status of the VLHC design on these topics, and possible solutions of the problems are discussed at the example of existing or designed high energy accelerators.

2 BEAM-INDUCED RADIATION EFFECTS AND LIMITS

Two types of beam loss in the collider must be considered at the design of radiation protection systems. They are operational and accidental beam losses.

2.1 Operational beam loss

Even in good operational conditions, a finite fraction of the beam will leave the stable central area of accelerator because of beam-gas interactions, intra-beam scattering, interactions in the IPs, RF noise, ground motion and resonances excited by the accelerator elements imperfection. These particles produce a beam halo which is traveling simultaneously with main beam, but outside the beam core. As a result of beam halo interactions with limiting aperture, hadronic and electromagnetic showers are induced in accelerator causing accelerator components heating, irradiation and background in the detectors. Collimation system is required to mitigate the effect of operational beam loss.

2.2 Accidental beam loss

The total stored beam energy in the beam at the collider top energy is equal to $1.5GJ$ for high field version and $13.6GJ$ for the low field version [1]. As the beam size is very small ($\sigma_{x,y} = 0.1-0.3mm$), an accidental loss of a small fraction of the beam during short time will melt a hole through the magnets and cause severe damage to the environment.

To protect accelerator and environment from damage the beam has to be aborted from the accelerator before been lost. But, if the process is very fast, there is no enough time to start the abort system. These fast processes were investigated for the SSC [3] and LHC machines which are close to VLHC with respect to the accumulated energy in the beam.

2.3 Beam loss limits (accidental and operational)

Operational and environmental radiation limits must be considered to determine the required accelerator tunnel depth, tunnel wall thickness and other protective measures like beam collimation system efficiency, beam abort line location, beam dump size and configuration. The main of these limits are:

prompt radiation dose at the surface (to protect general public)

- for accidental conditions (1 mrem/hr)
- for operational conditions (0.05 mrem/hr)

residual radiation dose (rate at the accelerator equipment, tolerable for personnel, 5-100 mrem/hr),

ground water activation (radionuclides in ground water),

accelerator components radiation damage (machine lifetime, kapton, polymide - 5000 Mrad, epoxy - 1000 Mrad).

3 PROTECTION FROM INSTANTANEOUS BEAM LOSS

We show here how accelerator can be protected from fast accidental loss at the example of LHC. Each of the LHC circulating beams at the top energy contains approximately 334 MJ of energy [2]. The abort kicker system consists of 14 pulsed magnets having a rise time of about 3μs. Normally this system is triggered during the 3 μs abort gap in the circulating beam. An accidental prefire of one of the abort kicker modules induces coherent oscillations of the circulating bunches with pretty large amplitude (Fig. 1). Starting from 70% of the kicker strength the disturbed protons hit the aperture of the IP5 elements. The low-β quadrupoles are heated behind the melting point.

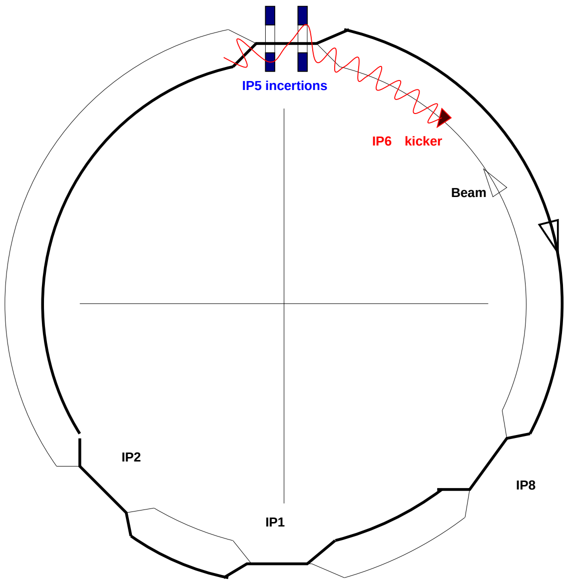

Figure 1: Schematic of the LHC abort kicker prefire.

An immediate firing the rest kicker modules (unsynchronized abort) mitigates the problem, but does not solve it,

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because it itself disturbs the beam during the kicker rise time and causes unacceptable losses, which initiates severe quench of IR quadrupoles.

The first method to protect the collider and detector components at an unsynchronized abort is to put a set of shadow collimators upstream of IP5 triplet (Fig. 2). The first shadow protects downstream elements from the primary beam. Second and third shadows are used to protect superconducting magnets from secondary particles emitted by the first shadow. Shadow collimators eliminate quench and decrease the detector components irradiation by 6 order of magnitudes.

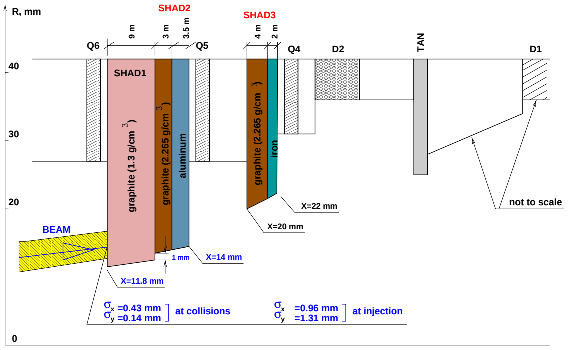

Figure 2: Shadow collimators location in the IP5 for low-β quads protection from overheating at accidental abort kicker prefire.

Another way is to compensate the prefired module by a special module charged with an opposite voltage (antikicker) (Fig. 3). The antikicker should be fired with a delay less than 1 μs after the kicker prefire. After this, the beam can be safely aborted using the abort gap. This method seems to be very attractive because it does not depend on the accelerator tune, closed orbit deviation, beam crossing scenario, and protects the entire accelerator from losses at unsynchronized abort.

4 BEAM ABORT SYSTEM

The collider beam may need to be aborted because of either high beam loss, large transverse injection errors, or other technical reasons, such as vacuum leaks, cryogenic failure, quench detection. etc.

Like the Tevatron, SSC and LHC, the VLHC [4] design (Fig. 4) uses fast kicker to move the circulating beam into an iron Lambertson magnet, which bends the beam vertically through the beam line to the absorber. To minimize the number of abort kicker and Lambertson magnet modules the extracted beam pass through a hole in the superconducting quadrupole cryostat.

The main requirements to the abort system are relating to beam energy and power. The first is to locate the muon vector at the site boundary, and the second to minimize instantaneous temperature rise in the absorber to acceptable level. This would require to place the absorber far from the extraction point, and to force beam size enlargement with blow-up quadrupoles and/or sweeping the beam across the

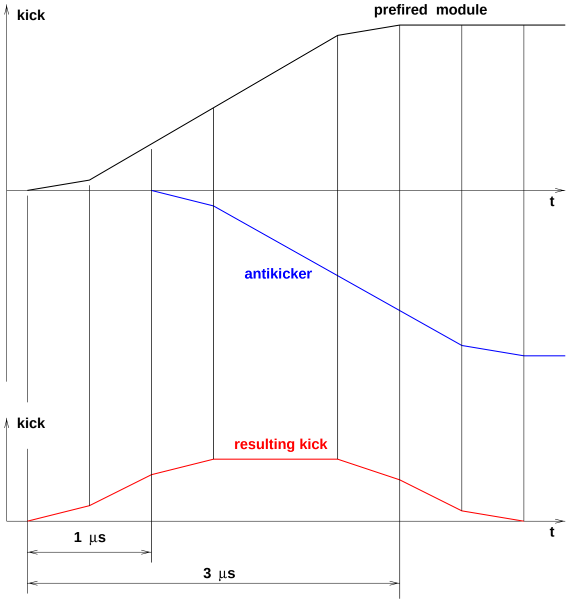

Figure 3: Resulting kick at accidental abort kicker prefire with antikicker scheme of compensation.

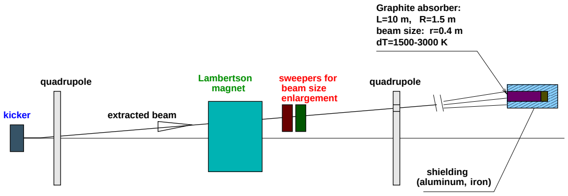

Figure 4: Abort system location in the VLHC utility straight section.

face of absorber during spill time over 30 cm. A 10 m long and 1.5 m in radius graphite absorber is considered. This gives temperature rise in the graphite of $1300^o - 3300^oC$ depending on the method of beam enlargement.

Another thermal consideration which must be kept in mind is that a thin titanium vacuum window will melt, just from dE/dx, if the beam σ is less than 5 mm. This automatically means that window can be installed just before the absorber, and large aperture beam line is necessary for a beam line with beam pipe diameter of 1.5 m at the absorber location.

The absorber, must also protect the environment from ground water activation. This is done by several meters of iron shield surrounding the graphite core.

5 BEAM COLLIMATION

The collimation system is necessary to protect superconducting magnets against quench and accelerator components from overheating, to reduce accelerator related backgrounds in the detectors, and to protect accelerator components, environment and personnel from irradiation.

A two-stage [6] beam collimation system is designed for the VLHC to localize most of losses in the utility straight section [7] specially designed to match the requirements of beam collimation and abort systems. The collimation system consists of horizontal and vertical primary collimators and a set of secondary collimators placed at an optimal phase advance, to intercept most of particles outscattered from the primary collimators during the first turn after particle interaction with primary collimator. Two more supplementary collimators are placed in the IR in the distance of 270m upstream and downstream of quadrupoles to decrease particle losses in the low-β quadrupoles. Particle impact parameter on a primary collimator is of the order of 1μm [8]. A thin primary collimator increases proton amplitude as a result of multiple Coulomb scattering and thus effects in drastic increase of particle impact parameter on the downstream secondary collimators. This results in a significant reduction of the outscattered proton yield and total beam loss in the accelerator, decreases collimator jaws overheating and mitigates requirements to collimators alignment.

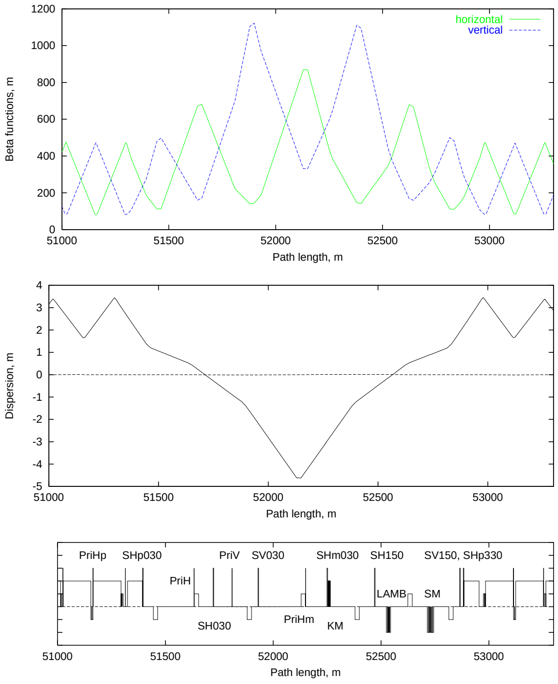

Figure 5: Beta functions and dispersion in the collimation system location.

Collimation system location in the utility section is shown in Figure 5. KM, LAMB and SM are kicker, Lambertson and septum magnets of the beam abort system.

Proton transverse populations in the primary collimator PriHp, used for off-momentum particles collimation, and in the secondary collimators are shown in Figure 6. In our simulations particles first time interact primary collimator with a small (about 3μm) impact parameter. As a result of multiple Coulomb scattering in the primary collimator, the impact parameter at the secondary collimators, increases to about 0.1mm (Figure 7).

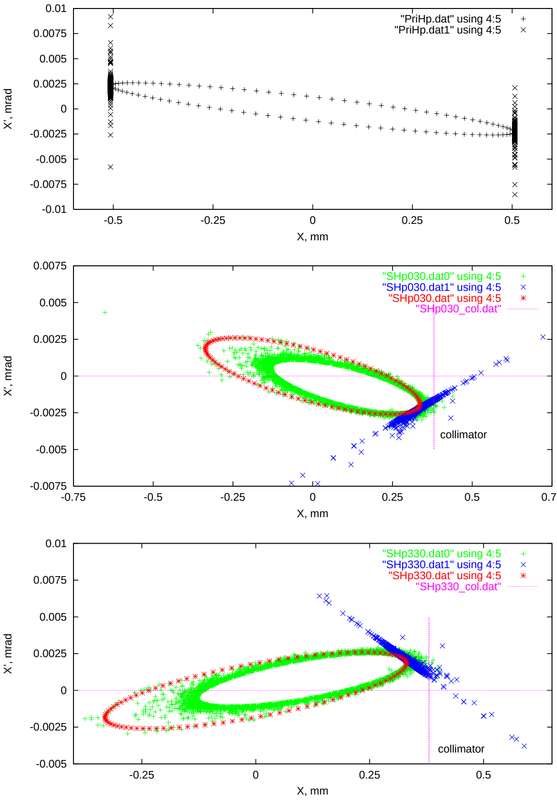

Figure 6: Horizontal halo population at the primary PriHp collimator exit (top), in the secondary collimator SHp030 (middle), and in the secondary collimator SHp330 (bottom). Ellipse represents 5σ envelope on the phase plane. Black crosses represent particles at the first turn after interaction with the primary collimator (without secondary collimators).

After the first interaction with primary collimator high amplitude particles are intercepted by the secondary collimators, but large number of particles survive, and will interact with primary collimator again. Average number of particle interactions is equal to 1.4 if primary collimators are placed at 5 σ and secondary at 6.2 σ. Particles with amplitudes smaller than 6.2σ are not intercepted by the secondary collimators, and survive during several tens turns until they increase amplitude at the next interactions with primary collimator. These particles occupy region inside the 6.2σ envelope.

Although primary collimators are placed at 5σ and secondary collimators are at 6.2σ from the beam axis, the tail of halo is extended behind 6.2σ. Halo particles population and amplitude distribution in the accelerator aperture are shown in Figure 8. Large amplitude particles, which escape from the cleaning system at the first turn, are able to circulate in the machine, before being captured by the collimators on the later turns. This defines the machine geometric aperture.

Beam loss distribution in the VLHC is presented in Figures 9. The beam collimation utility section is designed using normalconducting magnets. The beam loss in the utility section amounts 240 W/m, which is not a big problem for normalconducting elements. The maximum beam loss in the superconducting part of accelerator occurs in the first magnets behind the collimation system. Beam loss rate in this magnet is equal to $0.089\ W/m$ or $1.11 \cdot 10^4 p/(m \cdot sec)$.

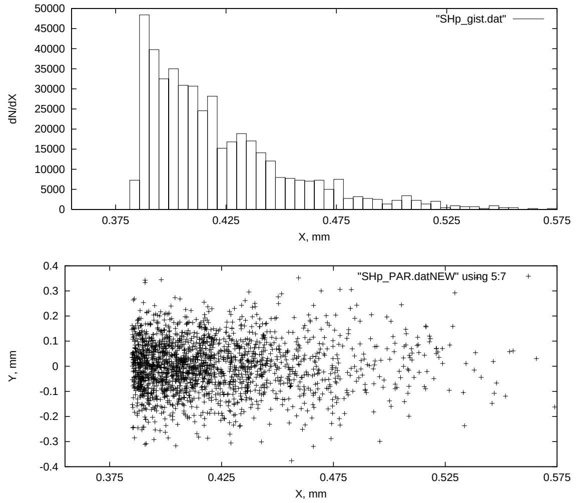

Figure 7: Proton transverse population in the secondary collimator SHp030.

As a reference we can consider the LHC admissible limits for superconducting magnets, which is equal to $7 \cdot 10^6 p/(m \cdot sec)$ [2] for $7 TeV$ and scale it by a ratio of accelerators energy (50/7=7). The VLHC collimation system permits to decrease losses in the superconducting magnets to a level which is two order of magnitude below the admissible limit.

A beam loss analysis has shown that the accelerator related background in the detector is originated by particle loss in the inner triplet region. A supplementary collimator located in 358 m from the IP at 10σ is used to decrease particle flux in the low-β quadrupoles. Particle loss rate in the supplementary collimator from one beam is equal to $1.36 \cdot 10^7 p/sec$.

5.1 *Collimation using bent crystal*

A possibility to improve collimation system efficiency using a bent channeling crystal instead of a thin scattering target was studied in the Tevatron.

Number of particles passed through the Roman Pots upstream of DØ and CDF detectors with primary tungsten collimator, and with crystal instead of primary collimator are presented in Table 1 for different thickness of amorphous layer. Number of particles nuclear interacted with primary collimator or the crystal is very important because it defines radiation level in the accelerator. These values are shown in the last two lines of the table. As shown in the table crystal can reduce seven times background in the detectors, and decrease four times accelerator irradiation.

6 INTERACTION REGION ISSUES

6.1 *Low-β quadrupoles protection from IP products*

This problem became very important in the LHC because of high luminosity and large energy of the collider. In the LHC 1200 W of power is leaving an IP in each direction in collision products. A front absorber (Figure 10) is located upstream of the first quadrupole to protect the triplet quadrupoles against intensive particle fluxes from the IP. The neutral beam absorbers is located between the separation dipoles in 150 m from the interaction point for neutral hadrons and photons interception.

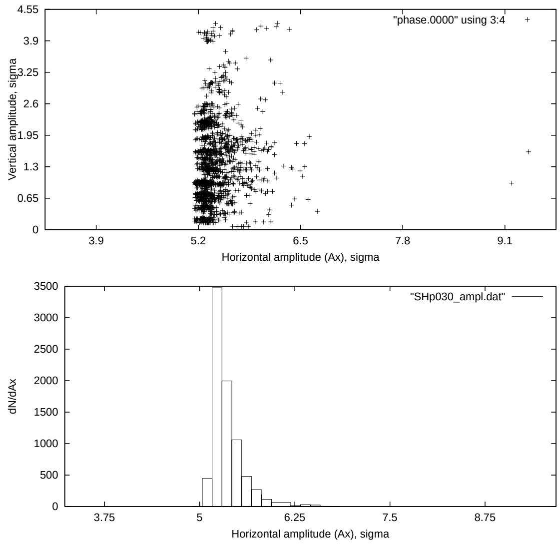

Figure 8: Halo particles population and amplitude distribution in the VLHC aperture at collimation of protons with equilibrium momentum.

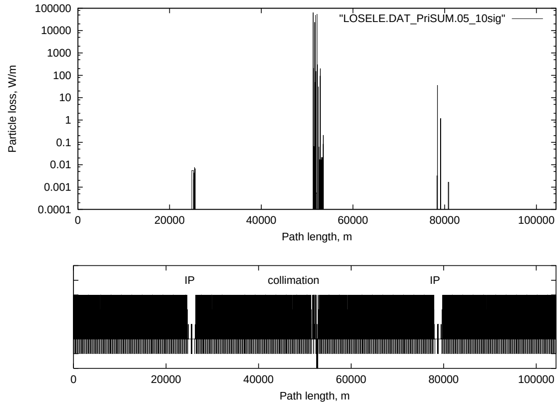

Figure 9: Beam loss distribution along the accelerator at proton beam collimation with primary collimators at 5σ, secondary collimators at 6.2σ and supplementary collimators at 10σ.

The quadrupole fields sweep the secondary particles into the coils. The inner absorber configuration has been designed which keeps energy deposited in the quad coils below the quench level. It consists of a thick beam pipe in the quadrupoles and two supplementary 1.5 m long absorbers.

6.2 *Beam-induced effect on the detector backgrounds and performance*

This problem is shown here at an example of the Tevatron DØdetector. The particle flux distributions [9] in the DØ region are shown in Figure 11 for charged hadrons,

loss location	with primary collimator	with crystal		
		amorphous layer thickness		
		10 μm	5 μm	2 μm
	particles number, $10^4 part/s$			
DØ CDF	11.5 43.6	1.35 5.40	1.60 3.20	1.15 3.43
nuclear interactions in crystal		82.4	70.6	50.3
nuclear interactions in primary collimator	270			

Table 1: Number of particles passed through the Roman Pots upstream of DØ and CDF detectors with primary 2.5 mm long tungsten collimator, and with crystal instead of primary collimator, for different thickness of amorphous layer. Number of particles nuclear interacted with primary collimator and the crystal. Crystal angle with respect to the beam is equal to -0.108 mrad. Crystal length is equal to 5 mm.

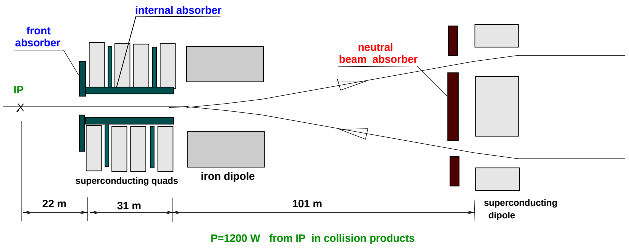

Figure 10: Location of absorbers in the LHC interaction region.

electromagnetic showers, and muons. Two concrete walls are placed here upstream the IP. The second wall placed behind the final focus triplet decreases particle fluxes as much as by one order of magnitude.

7 CONCLUSIONS

The energy deposition issues become extremely important ones for the VLHC because of huge energy stored in the beam. Accelerator protection systems which are desirable in the existing machines are absolutely necessary for the VLHC. Such as accidental kicker prefire in the Tevatron effects a quench, but it destroys the accelerator and causes severe damage of environment in the VLHC.

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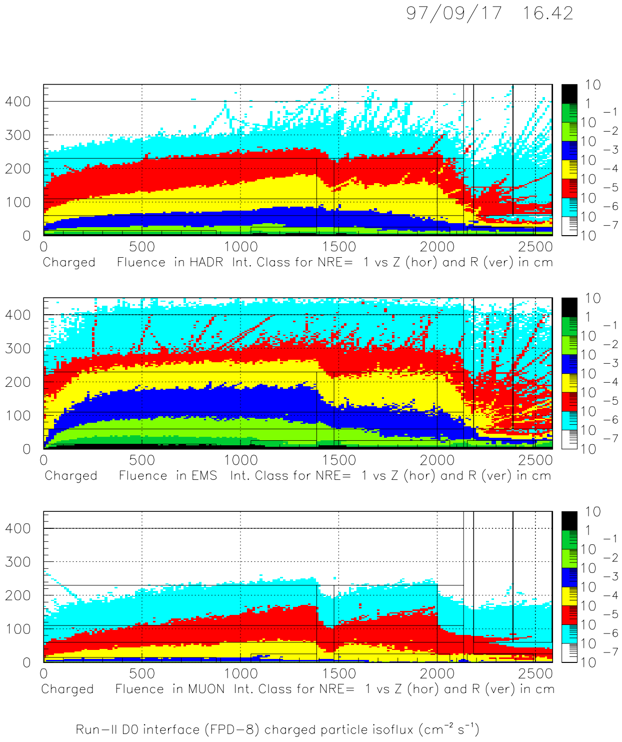

Figure 11: Particle flux distributions in the DØ region for charged hadrons, electromagnetic showers, and muons.

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