BEAM-INDUCED ENERGY DEPOSITION ISSUES IN THE VERY LARGE HADRON COLLIDER*

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Abstract

Energy deposition issues are extremely important in the Very Large Hadron Collider (VLHC) with huge energy stored in its 20 TeV (Stage-1) and 87.5 TeV (Stage-2) beams. The status of the VLHC design on these topics, and possible solutions of the problems are discussed. Protective measures are determined based on the operational and accidental beam loss limits for the prompt radiation dose at the surface, residual radiation dose, ground water activation, accelerator components radiation damage and quench stability. The beam abort and beam collimation systems are designed to protect accelerator from accidental and operational beam losses, IP region quadrupoles from irradiation by the products of beam-beam collisions, and to reduce the accelerator-induced backgrounds in the detectors.

1 BEAM LOSS AND RADIATION

1.1 VLHC Specific

The VLHC beam [1], with about 3 GJ of kinetic energy, is almost an order of magnitude larger than the LHC. Under normal circumstances roughly 50% of this energy is gradually dissipated in beam-beam collisions at the interaction regions (IR). A few percent of the energy is lost diffusely due to beam-gas interactions around the ring, intercepted by beam collimation inserts, and dissipated in the RF loads as the beam is decelerated. Somewhere between 40% (intentional beam abort at the end of the store at normal operation) and 100% (unintentional beam abort at certain circumstances) of the beam energy can be deposited in the external beam absorbers. A beam collimation system is used to scrape away beam halo keeping most of the circumference beam loss "free", with just several regions where special care should be taken to mitigate the beam loss induced effects. The collimation region and IRs are the hottest regions in the machine and require special consideration.

Under accidental conditions, there is enough energy to cause severe damage to the machine and detector components and environment. Obviously, if such a beam of a millimeter size goes astray, it will melt a hole through a magnet and do further damage outside the machine. The VLHC beam carries enough energy that in principle it could liquefy 400 liters of steel. Experience with Tevatron and our studies for LHC and VLHC show that with highly reliable beam abort system, highly efficient beam collimation system, local shields and a some additional measures, the machine, detector and environmental can be safely protected.

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On a large scale, muon fluxes around the machine can drive the complex layout and other related issues. Many other radiation issues, such as radiation damage to electronics and other sensitive equipment in the tunnel, radiation streaming to the surface through access and ventilation shafts, unsynchronized beam abort etc., are or will be attacked. Here we consider just a few most important issues.

1.2 Superconducting Magnets

The warm-iron design of the transmission line magnet of the Stage-1 [1] is less sensitive to radiation-induced quenches than ordinary magnets. To determine tolerable beam loss in the arcs, detailed MARS14 [2] simulations are done in the lattice both at injection (1 TeV, $\sigma_{x,y}$=1.4 mm, α_{inc}=0.7 mrad) and top energy (20 TeV, $\sigma_{x,y}$=0.3 mm, α_{inc}=0.15 mrad), where α_{inc} is a grazing angle of a Gaussian beam on the beam pipe. Corresponding materials and magnetic field have been implemented into a 3-D model of the arc cell. Inward and outward beam losses were considered both for inner and outer beam-pipes (Fig. 1).

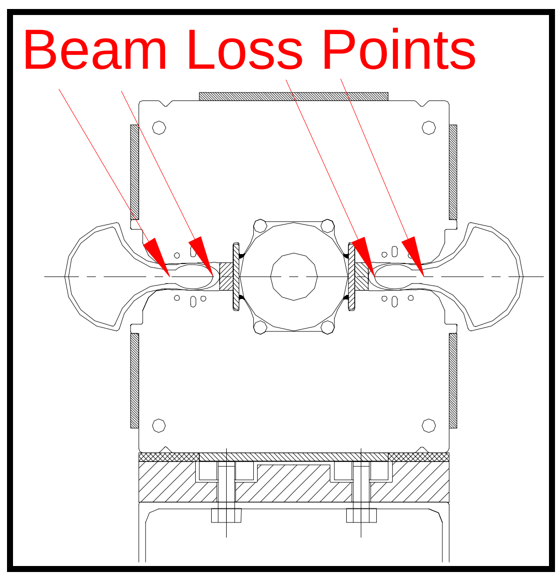

Figure 1: Beam loss points in the VLHC Stage-1 magnet.

Simulations show that the superconductor (SC) in the transmission line magnets is rather well protected radially by warm iron. The energy deposition is diffuse and the peak temperature is relatively low at the hottest spot in the showers downstream of where the proton hits the beam pipe. Therefore, the tolerable beam loss is significantly higher than in a conventional cosine-theta type magnets. Tab. 1 shows fast (<1 msec) and slow (>0.1 sec) beam loss rates needed to initiate a SC quench at injection and top energy in the Stage-1 ring. For comparison, the values for the Tevatron are shown. This comparison assumes that the quench limits are the same in the VLHC conductor and the Tevatron dipoles. This assumption is probably pessimistic since the braided cable of the VLHC can re-route the current around a quenched region on the magnet mid-plane, whereas a cosine-theta magnet cannot.

Table 1: Quench-inducing beam loss thresholds for the Stage-1 and Tevatron magnets.

	Fast (ppp)	Slow (p/sec)
VLHC, 0.9 TeV	9×10^8	3×10^9
VLHC, 20 TeV	2.5×10^7	7.5×10^7
Tevatron, 0.9 TeV	4×10^7	3×10^8

Heat load in the IR quads from radiation resulting from colliding beam interactions—although several times higher than in the LHC—will be handled the same way [3] via the IR design, a set of collimators and inner absorbers in the inner and outer triplets and a neutral beam dump. The distributed dynamic heat load—with the collimation system on—is dominated by beam-gas scattering and is expected to be <5 mW/m, less than 8% of the 4.5 K cryogenic heat load.

1.3 Worst-Case Beam Accident

The assumption is that some unspecified agent causes the beam to be kicked out of the machine with a rise time fast compared to the revolution frequency, so that the normal beam abort does not have time to act. Such a beam will rapidly melt a hole in the magnet and impact the tunnel wall at near grazing incidence (∼5 mrad). Fig. 1 shows results of a MARS14 calculation for a 20-TeV beam under the assumption that both the rock and beam position remain fixed. One sees that a region 8-m long and about 15 cm in radius is heated to the melting point of dolomite. Obviously it will splatter to the floor.

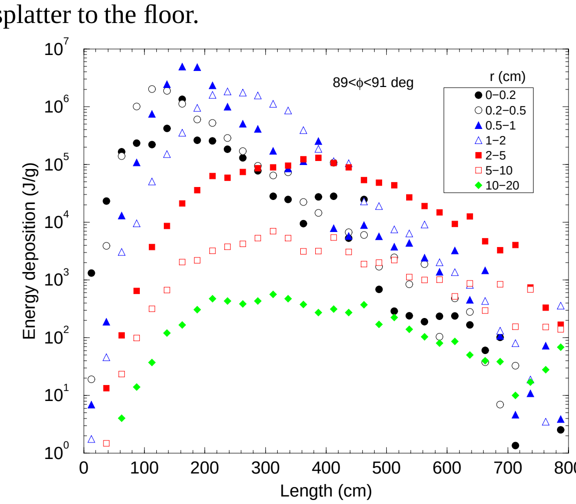

Figure 2: Longitudinal distribution of energy deposition in concrete wall in a semi-cylindrical region at several radii for a full 20-TeV beam.

2 BEAM ABORT SYSTEM

It turns out to be quite straight forward to kick the beams out of the machine towards absorbers (Fig. 3). Like the Tevatron, SSC and LHC, a single-turn extraction is used to switch the circulating beam from the field-free hole to the field gap of the Lambertson magnets, which extract the beam from the machine. Separation of the circulating and extracted beams is 25 mm at the entrance to the Lambertson magnets. Special large-aperture warm quadrupoles are used upstream of the Lambertsons so that no aperture restriction and quench problem exist. To protect the Lambertson septa and some other critical components from accidental destruction by the beam, resulting from a kicker timing error, it was proposed to put a graphite shadow right in front of these components [5]. The shadow piece, a few cm across and 4-m long at 20 TeV, is an inert device with an aperture the same as that of the adjacent component which it protecting.

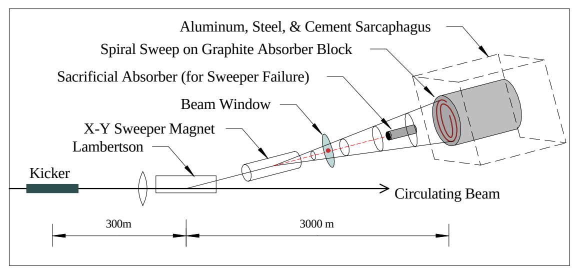

Figure 3: Schematic layout of beam abort channel.

For TeV beams, the natural choice for the absorber is graphite, as at the Tevatron, SSC and LHC. The major difficulty lies in making the beams big enough that they will not crack an absorber. An absorber consists of a graphite core, contained in an aluminum jacket with water cooling, followed by adequate steel and concrete to protect ground water [4]. The graphite core is rectangular, with dimensions 10×1.2×1.2 m. The thickness of steel shielding around the aluminum container is about 1.3 m on each side and is about 3 m downstream. A “4-in-1” design is considered where extracted beams from both directions hit absorber core in a common sarcophagus. The Stage-1 and Stage-2 share common absorbers. The average beam power is 300 kW, the same as for the Fermilab Main Injector absorber.

A spiral beam sweeping scheme similar to the SSC and LHC is adopted to spread the beam energy across the absorber face [4]. A horizontal and a vertical sweeper, 90° out of phase, both oscillate with decaying amplitudes. Ideally, the frequency should increase as the radius of the spiral decreases in order to keep the temperature rise constant. A suitable compromise is to limit the inner radius of the spiral to half that of the outer radius and accept a factor of two higher temperature rise at the inner radius. An estimate indicates that an outer radius of 30 cm would be adequate to keep the temperature below 1500°C. If the beam sigma was 0.5 cm in both planes, the frequency of these sweepers would be 9.7 kHz.

A 4-m long, 5-cm diameter sacrificial graphite rod is positioned immediately upstream of the main absorber at its axis to protect the absorber in case that sweepers fail. Normally the extracted beams will spiral around this rod without hitting it. If the beam is extracted with the sweeping magnets off, the beam damage will be confined to the sacrificial rod, housed in a metal box to prevent the spread of radioactive debris. A beam window will not be protected at such a failure, if the effective beam sigma on the window is less than 0.5 cm. The ring vacuum can be preserved by rapid-acting gate valves, multiple windows acting in series or differential pumping with wire meshes.

3 BEAM COLLIMATION SYSTEM

The design strategy of the VLHC is that the beam losses are localized and controlled as much as possible with a dedicated beam collimation system [6]. The collimation system, designed for the Stage-1 as a result of thorough simulations with the STRUCT code [7], consists of horizontal and vertical primary collimators (5 mm of tungsten) and a set of secondary collimators (3-m long L-shaped copper) placed at optimal phase advances and aligned parallel to the circulating beam. The secondary collimators intercept most of the particles outscattered from tungsten during the first turn after beam interaction with primary collimators. From the very beginning, the lattice is designed to provide a warm collimation region with enough space to accommodate the system and provide large dispersion for those collimators which intercept the off-momentum protons. The primary collimators are positioned at 7σ and secondary ones are at 9.2σ from the beam axis.

Eight supplementary collimators are placed in the next long straight section to decrease particle losses in the low-β quadrupoles. These collimators are positioned at $14\sigma_{x,y}$ to intercept particles outscattered from the secondary collimators. Beam loss distributions in the collimation region are presented in Fig. 4. Beam losses in the conventional magnets of the collimation section are quite acceptable. There are only several SC magnets in the arcs with beam loss rate of 0.3 to 1 W/m, the rest of the arc is clean in our calculations. Total beam loss in the low-β quadrupoles is 61 W (Fig. 5) without supplementary collimators. This is quite high and might be unacceptable from the detector background standpoint. Adding the supplementary collimators, one reduces these losses by about an order of magnitude.

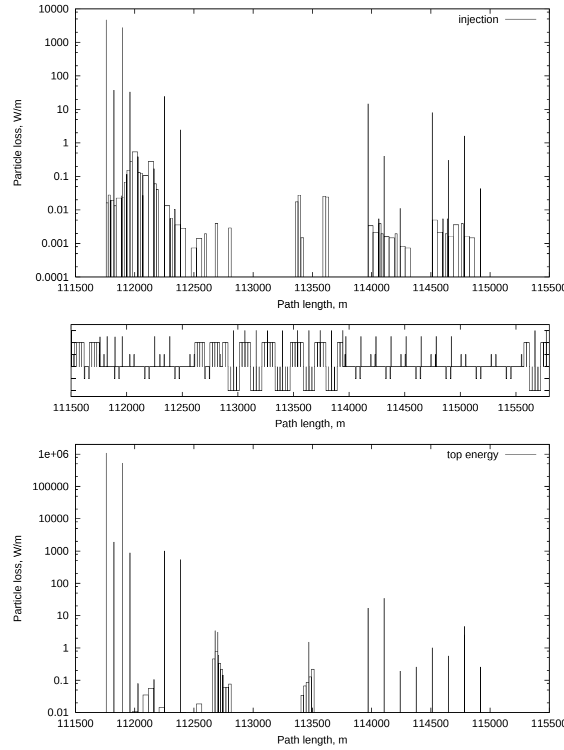

Figure 4: Beam loss distributions in the collimation section at injection (top) and at collisions (bottom).

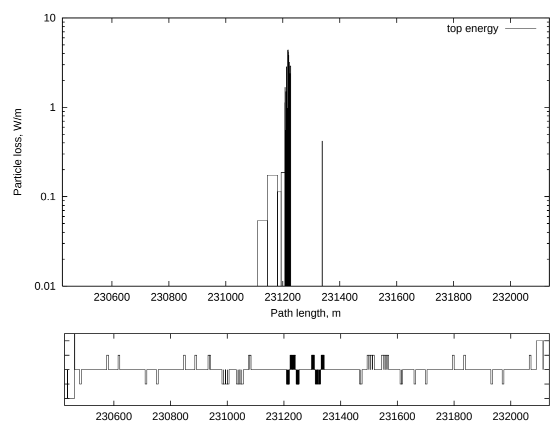

Figure 5: Beam loss distributions in the IR at collisions.

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