# Design of the LHC Beam Dump

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### *Abstract*

The severe constraints on the beam dumping system for the proposed Large Hadron Collider (LHC) arising from the beam energy (7.7 TeV) and intensity ($5 \times 10^{14}$ protons) call for unusual procedures to dilute the beam. Sweeping the beam in a circle over the front face of the absorber reduces the absorbed energy densities, but used alone it is not sufficient to keep the maximum temperature rise in the dump below an acceptable level, given other constraints due to available kicker magnet technology and tunnel length. Previous Monte-Carlo cascade simulations which calculated the effectiveness of thin scatterers placed upstream of the main absorber have been corrected and updated. Results are also presented concerning the optimization of the thicknesses of such scatterers. These show that a combined sweeping plus double-scatterer system gives a reasonable safety margin. Finally a system is discussed which combines the sweeping procedure with a dump where the absorber blocks are interleaved with air gaps in which 1 Tesla dipole fields occur. This system could produce comparable dilution of the deposited energy.

## 1 INTRODUCTION

Each of the circulating beams of the proposed Large Hadron Collider (LHC) will contain up to $4.7 \times 10^{14}$ protons at an energy of 7.7 TeV, giving a maximum stored energy per beam of 583 MJ [1]. The LHC beam dumping system must be able to accommodate this energy. Graphite has been chosen for the principal energy absorbing material because of its very favourable physical properties [2]. Sweeping the beam over the front face of the dump alone is insufficient unless the tunnel leading to the dump is lengthened well beyond its proposed 750 m, or the performance of the kicker magnets which sweep the beam are pushed to unrealistic levels. Assuming 2200°C as the maximum tolerable temperature rise for the graphite core and a sweeping radius in the range 5 to 10 cm a further reduction in the peak energy density of the order of a factor of 3 or more is required if reasonable safety factors are to be applied.

Three different schemes are described here which can provide sufficient extra dilution. Two of them make use of graphite scatterers placed in the extracted beam in between the sweeping kickers and the dump itself to dilute the beam, mainly because of nuclear inelastic interactions. In the first scheme, two relatively thin (20 cm) graphite scatterers are used. A second scheme optimizes the double-scatterer solution in such a way as to obtain the same peak energy density in each of the scatterers as in the dump itself. The third scheme separates the main dump block into several sections and interleaves the blocks with air gaps in which there are uniform magnetic fields of 1 Tesla. Since most of the energy in the core of the cascade is deposited by electrons and positrons, a moderate magnetic field should have some effect in diluting the cascade.

## 2 DESCRIPTION OF THE CALCULATIONS

All the calculations presented in the following have been performed using the latest version of the FLUKA code [3]. Despite the extensive benchmarking of the code that has been performed in the last two years, there are inevitable uncertainties arising from the extrapolation of known physics to LHC energies. It must be stressed that most of the energy deposition is due to the electromagnetic component of the cascade which follows $\pi^0$ decay. FLUKA relies on QED formulas which are believed to be reliable also in this energy range. The only important modification to standard expressions for electron and photon cross-sections is the onset of the Landau-Pomeranchuk-Migdal effect [4, 5]. At these energies this affects only bremsstrahlung from electron and positrons and it should be negligible for low Z materials like graphite: nevertheless it has been explicitly introduced in the new FLUKA version. The main uncertainties concern hadron-nucleus inelastic interactions at high energies. However LHC beam energies correspond to centre of mass energies in hadron-nucleon collisions for which experimental data from present colliders are available.

Previous results [1, 6] were obtained with thresholds of 10 MeV and 2 MeV for $e^+/e^-$ and $\gamma$ transport respectively. However a 10 MeV electron has a csda range in graphite of the order of 3.5 cm and the mean free path for a 2 MeV photon is of the order of 13 cm. Since we are interested in energy deposition in radial intervals as small as 0.1 cm the choice of such high thresholds could be questioned. The present calculations have been performed using 1 MeV and 0.5 MeV energy thresholds for $e^+/e^-$ and $\gamma$. To avoid dramatic increases of the required CPU time, which could be as large as 2 hours of CERN accounting units per primary proton, variance reduction techniques have been therefore extensively used in all the calculations.

The present calculations consider a 750 m long dump tunnel, with the sweeping system placed 110 m downstream of the extraction point and scatterers placed 280 and 140 m upstream of the dump. In most calculations the actual beam emittance has been taken into account.

In order to understand the results presented in the following sections, they must be compared with the maximum allowed energy density for graphite set to $\epsilon_{max} = 0.055$ GeV/cm$^3$ per proton. This figure is derived from an adiabatic temperature rise of $\Delta T_{max}$ of 2200°C for an LHC beam containing $4.7 \times 10^{14}$ protons.

## 3 THIN SCATTERERS

The effectiveness of two 20 cm thick scatterers placed at 280 and 140 m in front of the dump has already been investigated [6, 1]. Four physical processes contribute to diluting the beam via interactions in the scatterers:

- Multiple Coulomb scattering. The effect can be shown to be negligible at these energies.
- Nuclear elastic interactions. These are however relatively infrequent ($\lambda_{el} = 114$ cm for 7.7 TeV protons in graphite) and the resulting deflection is insufficient to cause a significant dispersion of the beam.
- Nuclear inelastic interactions. The interaction length for 7.7 TeV protons in graphite is $\lambda_{inel} = 42$ cm, and the typical transverse momentum of the outgoing particles has a mean value of $\approx 400$ MeV/$c$. Typical pion energies are several GeV corresponding to an emission angle of the order of 100 mrad, large enough to make particles to miss the dump after a distance of 100 metres. Even leading secondary particles with an energy of 2 TeV would experience enough deflection to be displaced radially by 2 cm after 100 m, which would prevent them from contributing significantly to the peak energy deposition which is highly localized.
- Decay in flight. 300 m corresponds to the decay length of a 5 GeV pion, so most of the soft pions and a significant fraction of the most energetic ones will decay along the path between the scatterers and the dump without contributing to the cascade build-up in the dump.

The radial profiles of the energy deposition at cascade maximum in the dump for a pencil beam ("zero" emittance) with 0, 1 and 2 scatterers are presented in Figure 1. These curves update those presented in a previous report [6] where an error was present in the cascade simulation and which gave a higher value for the effectiveness of the scatterers. It must be pointed out that the ratios of the maximum energy deposited are very close to the 1:0.62:0.38 relation which would be expected if the maximum energy deposition in the dump were determined only by the number of uncollided protons impinging on it. When folded with a 10 cm sweeping radius and with the actual beam emittance the resulting peak density would be just below the allowed limit [1]. The peak energy density in the scatterers is much lower than in the dump and does not represent a serious problem with a sweeping radius in excess of few centimetres.

## 4 OPTIMUM SCATTERERS

The temperature rise in 20 cm scatterers is very much lower than the limiting value and it is also clear that nearly all protons inelastically interacting in the scatterers can be disregarded when considering the peak energy deposition in the dump. An attempt was therefore made to find the "optimum" scatterer thickness for which the peak energy deposition in the scatterers and in the dump are equal. The energy density distributions computed for these optimal thicknesses of 50 cm for the first scatterer and 90 cm for the second one and a 5 cm sweeping radius are presented in Figure 2. The peak energy densities are in the range 0.035–0.04 GeV/cm$^3$ in each of the three components. These values are about 25% smaller than the limiting one and represent a substantial gain (roughly a factor ten) over the "no" scatterer solution with the same sweeping radius.

However there are significant penalties associated with all scatterer solutions. Actually these scatterers are no longer beam spoilers but important portions of the dump itself split in such a way to exploit the tunnel length to minimize the buildup of the cascade and therefore have to be constructed in the same way as the dump itself.

## 5 SPLIT DUMP PLUS MAGNETIC FIELDS

In order to avoid these inconveniences, a new scheme is at present under investigation. The basic idea is to split the dump into several slabs and to achieve the required dispersion of secondaries between subsequent slabs by using 1 Tesla magnetic fields orthogonal to the beam direction. Such fields can only be effective in sweeping out charged particles of moderate energy. However most of the energy is carried by the electro-magnetic component of the cascade which rapidly develops into a situation where a significant fraction of the energy is carried by electrons and positrons of relatively low energy. It is interesting to realise that the bending radius of a 1 GeV/$c$ charged particle in a 1 Tesla field is of the order of 300 cm, corresponding to a radial displacement of 3 cm for a 1 metre long magnetic field.

Preliminary calculations have been performed using a dump divided into four sections of 50, 50, 100 and 1000 cm length. In between two sections there is a gap of two metres in which two separate magnetic fields are assumed to occur, each of 1 metre length and with one field in the vertical plane and the other one in the horizontal plane. This configuration was designed to provide an approximate cylindrical symmetry which is vital in order to have good statistical accuracy in the Monte-Carlo simulations.

A 5 cm sweeping radius has been assumed as before. The variation with depth of the maximum radial value of the energy density determined in these preliminary calculations is shown in Figure 3. It can be seen that peak values in all slabs are approximately equal. There has been no optimization of the slab thicknesses so far and in the present calculations the energy density in the third slab is somewhat higher than the "allowed" limit. These results suggest that with only slight improvements (*e.g.* simply splitting this third slab into two parts) it should be possible to reduce peak densities to below the nominal limit.

It must be pointed out that a large fraction of the beam energy (about 50%) is swept out from the dump by the magnetic field, and the effect of this on the magnet system must be evaluated. However this energy is spread out over large areas and with proper shielding should not present major problems. However a slightly longer cavern will be required in order to house the dump and there will be the extra complication of providing the necessary magnetic fields.

## 6 CONCLUSIONS

Three possible solutions have been discussed which achieve the beam dilution needed in order to dump the proton beam from the proposed Large Hadron Collider. A system which sweeps the beam in a circle over the front face of the dump is common to all solutions. Two of them make use of graphite scatterers of various thicknesses placed upstream of the dump. With an optimal choice of these scatterers extra reduction factors as large as a factor ten can be achieved. A third solution involving the use of 1 Tesla magnetic fields in the dump to dilute the electromagnetic component of the cascade appears to provide suitably low levels of energy deposition.

## 7 REFERENCES

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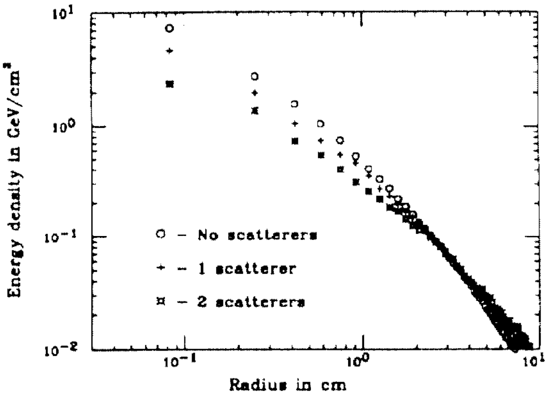

Figure 1: The radial profiles of energy density at cascade maximum in the dump for a pencil beam.

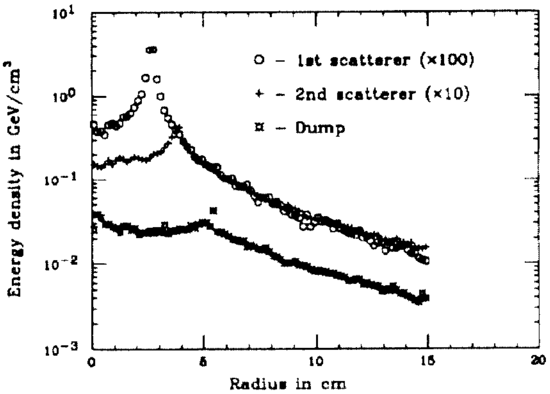

Figure 2: The maximum radial energy density distributions in the components of an "optimal" two-scatterer system.

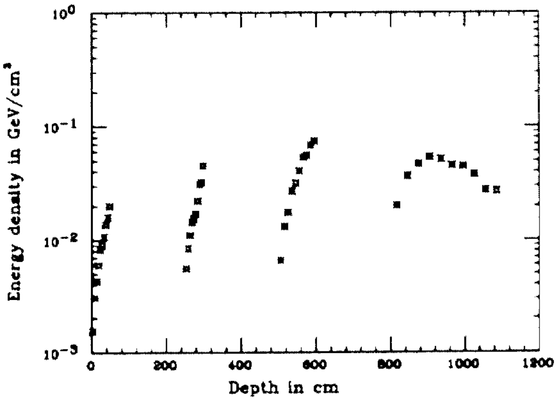

Figure 3: The variation with depth of the maximum radial value of the energy density for a split dump with 1 Tesla magnetic fields.