ATTENUATION AND EMITTANCE GROWTH OF 450 GEV AND 7 TEV PROTON BEAMS IN LOW-Z ABSORBER ELEMENTS

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Abstract

The intensity of the LHC beams will be several orders of magnitude above the damage thresholds for equipment. Passive protection of accelerator equipment against failures during beam transfer, injection and dumping of the beam with diluters and collimators is foreseen. These protection devices must be robust in case of beam impact, and low-Z materials such as carbon are favored. In these diluters, the reduction of the energy density is determined both by the attenuation due to inelastic nuclear collisions and by the emittance growth of the surviving protons due to elastic scattering processes. The physics principles leading to attenuation and emittance growth for a hadron beam traversing matter are summarised, and FLUKA simulation results for 450 GeV and 7 TeV proton beams on low-Z absorbers are compared with these predictions. Design criteria for the LHC absorbers are derived from these results.

INTRODUCTION

The destructive potential of the LHC beam, even at 450 GeV injection energy, requires the use of diluter devices in the SPS [1], the SPS to LHC transfer lines [2] and in the LHC itself [3], to protect against mis-steered beams. The diluters must reduce the energy deposited in downstream elements to a safe level, and should themselves survive the beam impact. This robustness criterion imposes the use of low-Z materials such as graphite.

We show that relatively short low-Z diluters can be effective at 450 GeV. The energy deposition in downstream elements can be reduced to a safe level by the attenuation through nuclear inelastic interaction combined with the emittance growth of the surviving protons by scattering.

We compare the predicted attenuation and emittance growth with nuclear simulations for carbon diluter elements, at proton energies between 450 GeV and 7 TeV, diluter lengths between 20 and 700 cm, and carbon density between 1.77 and 3.00 g/cc. The overall dilution efficiency is derived using a simulation of the peak energy deposition variation with beam emittance.

SCATTERING PROCESSES

For an increase in the angular spread of the beam by $\Delta\theta$ the emittance growth $(\epsilon_{new}/\epsilon_0 - 1)/\beta = \Delta\theta^2/\epsilon_0$ where β is the conventional Twiss parameter and ϵ_0 the initial emittance.

Inelastic nuclear scattering Inelastic scattering is characterised for our purposes by an interaction length λ_I, with the primary protons removed from the beam by the interaction. For the energies under consideration, λ_I is typically 45 cm in carbon. After traversing a length L of the diluter, the attenuation $N_0/N(L)$ of the primary proton beam is exp(L/λ_I).

Elastic nuclear scattering For elastic scattering the interaction length is typically 100 cm in carbon. The proton survives and is scattered with a relatively large angle. The process can be described by an optical diffraction model, with an RMS scattering angle θ_e in each of the two transverse planes given by [4]:

$$1 \,/\, \theta_e^2 = 1/3\ A^{2/3}\ (p \,/\, 0.135)^2 \text{ [rad]}$$

where A is the atomic number of the target and p the proton momentum in GeV. The probability P of observing N interactions in a length L with interaction length λ_e given by:

$$P(L/\lambda_e, n) \;=\; e^{-L/\lambda_e}\ (L/\lambda_e)^n \,/\, n!$$

After n scattering events each of angle θ_e, the total angle is $\sqrt{n}\ \theta_e$.

Multiple Coulomb scattering The multiple Coulomb (Rutherford) diffusion process is treated statistically, and after traversing a length L of the diluter, an approximately Gaussian angular distribution is obtained with the RMS proton scattering angle θ_{mc} [rad] in each of the two transverse planes given by [4]:

$$\theta_{mc} = 0.0136 \,/\, p\ \sqrt{L/X_0} \text{ [rad]}$$

where p is the proton momentum in GeV and X_0 the radiation length, typically 20 cm for carbon.

FLUKA SIMULATION

The primary beam attenuation and emittance increase, as a function of carbon density, diluter length, beam energy and the geometry, were calculated with FLUKA [5]. A pencil beam with zero initial divergence was incident perpendicular to the front face of a carbon jaw. The number and exit angles of the surviving primary protons were recorded.

The main systematic error contribution is associated with the reaction cross-section. From comparison with experimental data for graphite, this error is well below 10% for the energy range considered. Statistical errors are of the

ρ = 1.77 g/cc						
Energy (TeV)	0.45	1	2	3	5	7
λ_I (cm)	46.1	44.9	44.4	43.9	43.0	42.1
λ_E (cm)	118	113	109	107	102	99.0
E = 0.45 TeV						
ρ (g/cc)	1.77	1.88	2.0	2.25	2.5	3.0
λ_I (cm)	46.1	43.4	40.8	36.2	32.6	27.2
λ_E (cm)	118	111	105	92.9	83.6	69.7

Table 1: Inelastic (λ_I) and elastic (λ_E) interaction length vs. beam energy and carbon density ρ for protons impacting a carbon diluter

order of 1% for most of the simulations, except for long diluter lengths, where the error reaches 15% for 500 cm length. Statistical error bars have been included in the plots.

RESULTS

Two of the most important parameters are the elastic and inelastic nuclear interaction lengths. The values in carbon obtained from FLUKA are shown in Table 1, as a function of beam energy and material density, assuming that the attenuation depends on the length as described above.

Emittance growth by scattering

The angular distribution from FLUKA of the surviving protons for the impact of 450 GeV protons on a 1.2 m 1.77 g/cc carbon jaw is shown in Fig.1. The two distinct scattering processes produce a double-peak effect. The expected curves from the formulae quoted above are also shown, with the superposition shown in red of the expected angular distributions considered for n = 1, 2 ... multiple elastic scattering events per proton - for 0 elastic scattering events the angular distribution is given by the multiple Coloumb scattering alone. To extract a quantitative figure, an equivalent Gaussian giving the same proton density at the centre of the distribution was computed (dashed line) - this has an RMS of 152 μrad. For a typical beta function of 50 m and the nominal emittance of 3.75 μrad, this corresponds to a beam emittance increase of a factor of about 150.

In Figs.2 to 4 the emittance growth $(\epsilon_{new}/\epsilon_0 - 1)/\beta$ for protons impacting carbon diluter are shown as a function of the diluter length, beam energy and diluter density respectively. It should be noted here that the values shown need to be multiplied by the β value at the diluter location to calculate the actual emittance increase.

Overall dilution efficiency

The overall dilution efficiency is determined by the attenuation in the diluter and the divergence of the surviving proton beam. To evaluate this effeciency, the energy deposition as a function of the transverse beam size for energies of 450 GeV and 7 TeV, for a proton beam impacting a copper target, was simulated with FLUKA for a range of beam

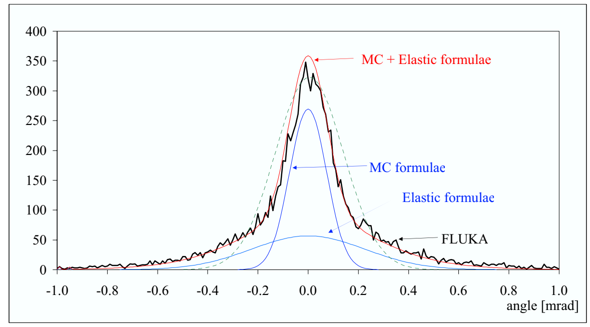

Figure 1: Angular distribution of 450 GeV protons traversing a 1.2 m long, 1.77 g/cc carbon diluter.

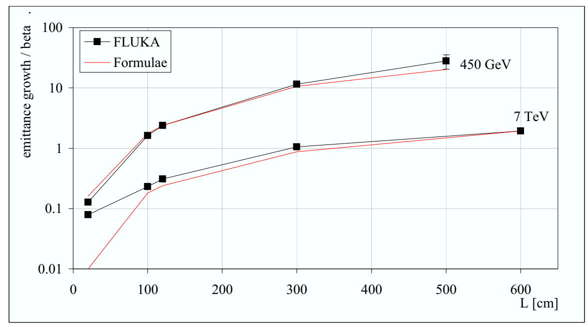

Figure 2: Effective emittance growth / β for 450 GeV and 7 TeV protons after traversing a 1.77 g/cc carbon diluter, as a function of length.

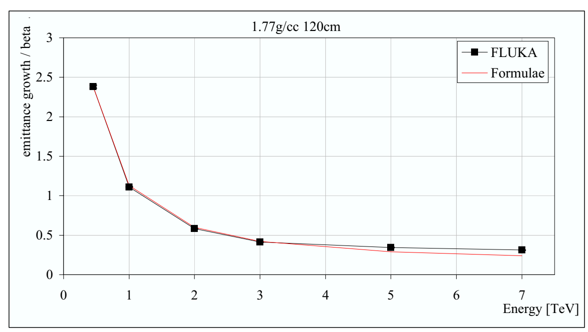

Figure 3: Effective emittance growth / β after traversing a 1.2 m long 1.77 g/cc carbon diluter as a function of proton energy.

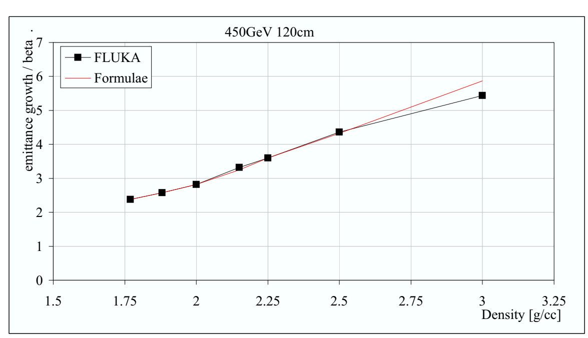

Figure 4: Effective emittance growth of 450 GeV protons traversing a 1.2 m carbon diluter, as a function of density.

emittances, with typical transverse β values of 50 m (corresponding to nominal beam-sizes of 0.6 mm for 450 GeV and 0.2 mm for 7 TeV). The results are shown in Fig.5.

The dilution efficiency is defined as the ratio of the energy deposition for an undiluted beam with nominal normalised LHC emittance of 3.75 μm, to the actual energy deposition for a beam having traversed the diluter. This was calculated for various diluter configurations using Fig.5. The results are shown in Figs.6 to 8 as a function of the diluter length for 450 GeV and 7 TeV, and also as a function of the carbon density for 450 GeV.

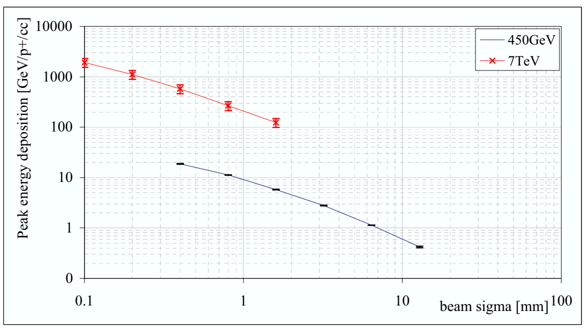

Figure 5: Peak energy deposition E in GeV/p+/cc in a copper target vs. beam size σ for 0.45 and 7 TeV. In both cases, E$\propto 1/\sigma$.

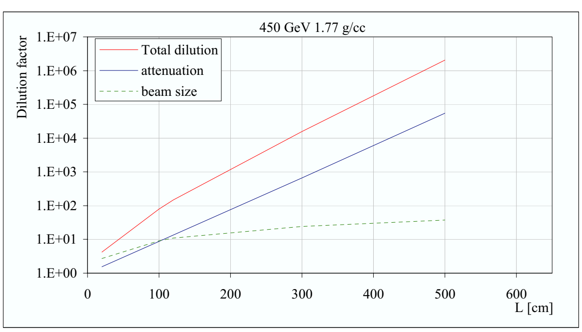

Figure 6: Dilution efficiency vs. diluter length for 450 GeV protons traversing 1.77 g/cc carbon.

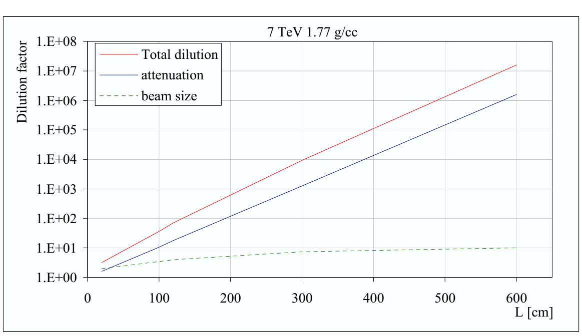

Figure 7: Dilution efficiency vs. diluter length for 7 TeV protons traversing 1.77 g/cc carbon.

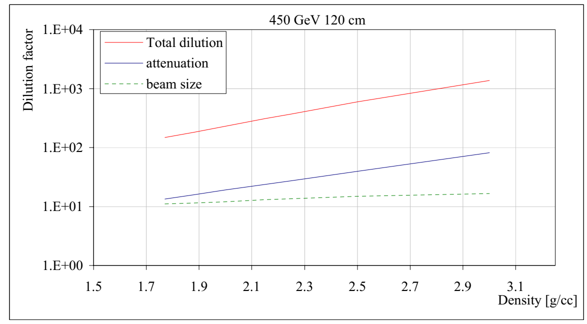

Figure 8: Dilution efficiency vs. carbon density for 450 GeV protons traversing 1.2 m diluter.

DISCUSSION

The beam intensity required to damage the accelerator components being protected varies with beam size and energy, and when this is taken into account an overall dilution effectiveness can be derived. The results show that short ($\sim 1\ m$) diluters can be effective for beams injected into the LHC, since here the energy and intensity are low enough to allow sufficient energy density attenuation. This type of diluter will be used for LHC injection protection and for the SPS to LHC transfer lines. At higher beam energies, in the LHC ring proper, the required diluter length quickly becomes very long. In some particular applications where there is no alternative, low-Z (carbon) diluters of $\sim 6\ m$ length will be used, like the TCDS and TCDQ elements to protect against an unsynchronised beam dump [3].

CONCLUSION

An investigation of the effectiveness of short, low-Z diluters for the protection of the machine elements in the LHC and its injector chain show that, for injection energy, the emittance growth contributes significantly for particles having traversed diluter elements and should be taken into account as a criterion, along with the attenuation, for defining the length of diluters. The results demonstrate that short, low-Z diluters can be effective in the LHC transfer lines and injection systems, but that much longer objects are required at 7 TeV, even for very limited beam intensities.

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