INTERACTIONS BETWEEN MACROPARTICLES AND HIGH-ENERGY PROTON BEAMS


Abstract

A known threat to the availability of the LHC is the interaction of macroparticles (dust particles) with the LHC proton beam. At the foreseen beam energy of 6.5 TeV during Run 2, quench margins in the superconducting magnets will be 2-3 times less, and beam losses due to such interactions may result in magnet quenches. The study introduces an improved numerical model for such interactions, as well as Monte-Carlo simulations that give the probability of such events resulting in a beam-dump during Run 2.

INTRODUCTION

The phenomenon of UFOs (Unidentified Falling Objects), i.e., interactions of falling macroparticles (dust particles) with the proton beam, is well documented [1, 2]. Similar effects are known from other, mostly electron and anti-proton machines [3, 4, 5]. The LHC is the first proton machine where this phenomenon can be found. Figure 1 shows observations of UFO rates during the LHCs Run 1 with beam energies up to 4 TeV. With up to 13 UFOs per hour during a 25-ns bunch-spacing test run, falling macroparticles were estimated to become a significant threat to the availability of the LHC when operating at 6.5 TeV [6]. Such interactions produce particle showers that deposit energy in the adjacent superconducting magnets, possibly leading to magnet quenches. The current strategy to mitigate the effects this phenomenon is to detect the beam-losses with beam-loss monitors, and to trigger a preventative beam dump as soon as a threshold is exceeded.

Figure 1: Number of arc UFOs per hour during stable beams in 2011 and 2012. Courtesy T. Baer.

NUMERICAL MODEL

A typical interaction between a macroparticle and the high-energy proton beam interaction - commonly referred to as a UFO event, is described as follows:

- A macroparticle (dust) falls from the beam screen or vacuum chamber.
- The macroparticle is ionized by elastic collisions with the proton beam releasing free electrons.
- Inelastic collisions result in particle showers recorded by BLMs, and potential quenches.
- The macroparticle is repelled by the beam’s electric field.

Equation of Motion

The macroparticle’s acceleration $\ddot{\vec{r}}$, with $\vec{r}$ the transverse position vector, is determined by gravity and by the force exerted by the electric field of the beam $\vec{E}$ on the macroparticle charge $Qe$,

$$\ddot{\vec{r}}(x, y, t) = \frac{Q(t)e}{m} \vec{E}(x, y) + \vec{g}, \quad (1)$$

with $e$ the electron charge, $m$ the macroparticle mass, $g$ the gravitational constant, and $\vec{E}$ modeled by the Bassetti-Erskine formula [11] with recommendations for numerical stability from [12]. The total beam charge per unit length is given by $N_pe/C$, with $C$ the LHC circumference and $N_p$ the total number of protons in the beam.

Macroparticle Charge Rate

Elastic interactions with the macroparticle lead to ionization. As a result, the charge rate, $\dot{Q}$, determines the beam’s electric field influence. The charging formula, which is related to the Bethe-Bloch formula, is derived from the distribution $N_e$ of knock-on electrons found in [13] with appropriate approximations,

$$\frac{\partial^2 N_e}{\partial T \partial z} \approx 2\pi r_e^2 c_e^2 n_1 \frac{1}{T^2}. \quad (2)$$
where $T$ is the kinetic energy transferred to the electron, $z$ is the incident proton’s path length through the material, $r_e = e^2/(4\pi\varepsilon_0 m_e c^2_0)$ is the classical electron radius, with $m_e$ the electron mass, $c_0$ the vacuum speed of light, $n = (N_A Z \rho)/(AM_u)$ is the electron density, with $N_A$ Avogadro’s number, $Z$ and $A$ the atomic number and relative atomic mass of the macroparticle material, respectively, $\rho$ its mass density, and $M_u$ the molar mass constant, and $m_e$ is the electron mass. In [14, p. 7] we find an empirical fit for the practical range $\ell(T)$ of an electron in a given material as a function of its kinetic energy. This relation can be inverted to give the minimum energy required for a given distance, $T(\ell)$. Assuming that electrons at the minimum escape energy travel perpendicularly to the path of the incident proton, the average path length to escape the macroparticle is $\ell_{\text{esc}} = 0.736 T$. The minimum energy-transfer for ionization $T_{\text{min}}(Q(t), R)$ is the sum of $T(\ell_{\text{esc}}(R))$ and the Coulomb potential of the macroparticle at its radius $R$. The resulting charge-rate formula reads

$$Q(x, y, t) = \int_a \int_S J(x, y) \frac{\partial^2 N_e}{\partial T \partial z} \, dT \, dz \, da,$$

where $a$ is the macroparticle’s cross-sectional area, $S$ the average path-length of the incident proton through the particle, and $J$ is 2-D Gaussian beam-current density with a total current of $N_p e f$, where $f$ is the LHC revolution frequency. Evaluation, under the assumption that the particle-size is small compared to the beam size, gives

$$\dot{Q}(x, y, t) = -\frac{2N_p f R^3 \pi N_A \sigma_y^2 m_e c^2_0 \rho}{3\sigma_x \sigma_y T_{\text{min}}(Q(t), R) M_u} e^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}},$$

where $\sigma_{x,y}$ are standard deviations of the 2-D Gaussian beam. The beam size is related to the beta function $\beta$ (see Fig. 2) and the emittance $\epsilon$ via $\sigma_{x,y}(T_p, s) = \sqrt{\beta(s)\epsilon(T_p)}$, with $T_p$ the proton’s kinetic energy. Furthermore, dispersion and momentum offsets are taken into account. From (4), one can derive the average charge per proton, $Q_{pp} = \dot{Q}/ \int_a J \, da$, on an uncharged macroparticle, i.e., $T_{\text{min}} = T_{\text{min}}(0, R)$, and compare it to the same value computed with the Garfield++ software [16]. Comparing both

![Figure 2: $\beta$ function and dispersion in an LHC arc cell [15].](image)

**Beam Losses**

The BLM signal during an interaction is calculated by the product of the BLM response at a given location and the proton loss rate,

$$\text{BLMSignal}(t, s) = \tilde{N}_p(\vec{r}(t)) \cdot \text{BLMResponse}(T_p, s),$$

where $s$ is the longitudinal position, $\text{BLMResponse}(T_p, s)$ (see Fig. 4 for a FLUKA [17, 18] simulation) is the BLM signal due to a single inelastic proton-nucleus interaction for a proton of kinetic energy $T_p$. The proton loss rate $\tilde{N}_p$ is equal to the rate of inelastic collisions produced by incident protons as they pass through the macroparticle,

$$\tilde{N}_p(x, y) = \int_a \int_S J(x, y) \Sigma_{\text{iel}} \, ds \, da,$$

where $\Sigma_{\text{iel}} = \sigma_{\text{iel}} \rho_A$ is the macroscopic cross-section of inelastic interactions, $\sigma_{\text{iel}}$ the microscopic cross-section, and $\rho_A = (N_A \rho)/(AM_u)$ the atom density. The resultant formula is thus

$$N_p(x, y) = \frac{2N_p f \sigma_{\text{iel}} R^3 N_A \rho}{3\sigma_x \sigma_y AM_u} e^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}}.$$

![Figure 4: FLUKA-modeled BLM response for the Run-2 configuration, for an inelastic collision of a 6.5-TeV proton with a Carbon nucleus at a given longitudinal location along an arc cell [19].](image)

**MONTE-CARLO SIMULATIONS AND 6.5 TeV PREDICTIONS**

The numerical model was implemented in Mathematica. Figure 5 shows typical flight paths for different initial transverse locations. Figure 6 demonstrates that the BLM signals of measured UFO events can be reproduced with
realistic input parameters, i.e., a particle of $R = 45 \, \mu m$ with copper as macroparticle material drops at a plausible location in a standard LHC arc cell. Monte-Carlo simulations were carried out to re-create the recorded UFO events throughout 2012 at 4 TeV beam energy. Figure 7 shows a cumulative histogram of peak BLM signals recorded in three BLM positions, as well as the Monte-Carlo simulated equivalent. The resultant fit required for macroparticle radii distribution, see insert in Fig. 7, using copper as the particle-material (unknown), was, however, produced with physically plausible radii $1 < R < 50 \, \mu m$.

Throughout Run 2, BLM thresholds will be set at, or just below, the magnet quench limits defined by

$$\text{BLMSignal@Quench}(E, t_{\text{int}}) = \frac{\text{BLMResponse}(E) \cdot \text{QuenchLevel}(E, t_{\text{int}})}{\text{EnergyDeposit}(E)}$$

where $t_{\text{int}}$ is the integration time of the BLM signal, EnergyDeposit the average energy deposition in the peak-location of the coil, computed with the same FLUKA model as the BLMResponse, and the QuenchLevel is the minimum energy required to quench. A weakness of the studies predictions, however, is the remaining uncertainty of the QuenchLevel, of a factor of four, quantified in the analysis of dedicated quench tests [20].

Using the same distributions for location and radii, it was possible to extrapolate to 6.5 TeV by altering beam-related input parameters to the necessary equivalents. Comparing of the upper inserts in Fig. 7 and 8, one can also see the relocation of BLMs for Run 2. This configuration allows for a better sensitivity of the BLM system to UFOs in the dipole magnets.

The improved model of macroparticle-beam interactions, in combination with a detailed FLUKA simulation of particle showers, allows the generation of a set of UFO events that reproduces 2012 measured data. Adjusting the model parameters allowed for the extrapolation to 6.5 TeV beam energy. Results show that the QuenchLevel uncertainty has a significant impact on the predictions, however, initial Run 2 statistics will be used to negate the uncertainty. To conclude, the model is well suited to simulate such interactions, for making predictions of their influence at higher beam energies and or investigating mitigation strategies.

**SUMMARY**

The improved model of macroparticle-beam interactions, in combination with a detailed FLUKA simulation of particle showers, allows the generation of a set of UFO events that reproduces 2012 measured data. Adjusting the model parameters allowed for the extrapolation to 6.5 TeV beam energy. Results show that the QuenchLevel uncertainty has a significant impact on the predictions, however, initial Run 2 statistics will be used to negate the uncertainty. To conclude, the model is well suited to simulate such interactions, for making predictions of their influence at higher beam energies and or investigating mitigation strategies.
REFERENCES


