SIMULATIONS OF THE LHC COLLIMATION SYSTEM

R. J. Barlow, R. B. Appleby, J. Molson, H. Owen, A.M. Toader,
Manchester University, UK and the Cockcroft Institute, UK

Abstract

Abstract The collimation system of the LHC will be critical to its success, as the halo of high energy (7 TeV) particles must be removed in such a way that they do not deposit energy in the superconducting magnets which would quench them, or showers in the experiments. We study the properties of the LHC collimation system as predicted by the Merlin and Sixtrack/K2 simulation packages, and compare their predictions for efficiency and halo production, and the pattern of beam losses. The sophisticated system includes many collimators, serving different purposes. Both programs include energy loss and multiple Coulomb scattering as well as losses through nuclear scattering. The MERLIN code also includes the effects of wakefields. We compare the results and draw conclusions on the performance that can be achieved.

INTRODUCTION

The Large Hadron Collider (LHC) is a proton-proton collider at CERN, Geneva, and has a nominal beam momentum of 7 TeV/c per beam. The design luminosity of the LHC ($10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in 7 TeV p-p mode) requires 2808 bunches, of $1.15{\cdot}10^{11}$ proton per bunch, in each of the two beams, resulting in a beam energy of 362 MJ, which is enough to present a considerable risk to the operation and to the elements of the machine. As a result, the LHC will be operated with a multi-stage collimation system to avoid quenching of superconducting elements and provide protection from beam damage, with staged collimators at increasingly further distances from the beam to collimate protons over successive turns.

The successful operation and upgrade of the LHC means it is important to obtain an understanding of the performance of the LHC collimation system as the machine builds to higher intensities. This requires a simulation of the various scattering processes in a flexible code, combined with a detailed machine model and the estimation of wakefield effects in the near-beam collimators. The MERLIN code [1] is well suited for this purpose, and in this paper we continue to develop its use for this application, starting with a description of the scattering model in MERLIN, followed by the bench marking of MERLIN against FLUKA [2] for a Copper collimation and then the study of an LHC primary Carbon collimator. Finally, we draw our conclusions.

PHYSICS OF SCATTERING PROCESSES

In this section we describe the scattering model of MERLIN, and present the differential cross sections relevant for proton scattering in a collimator.

Following [3], we distinguish five different scattering processes, in which a particle of 4-momentum p produces an outgoing particle with 4-momentum p'. The process cross sections and kinematics depend on the variables $t = -(p-p')^2$ and s, the total cms energy squared.

- Elastic proton-nucleon scattering, with the differential cross section

$$\frac{d\sigma}{dt} \propto \exp(-b(s)t), \tag{1}$$

  where $b(s,t)$ is the slope factor, with parameterised form [4],

$$b(s) = 8.5 + 1.086\ln(\sqrt{s}), \tag{2}$$

- Elastic proton-nucleus scattering, which is similar to proton-nucleon scattering but the slope b, which is a function of s, is different.

- Single diffractive scattering $pp \to pX$, where the proton survives the interaction and stays in the machine after the collimator. The target mass increases to some value M_X, and the differential cross section is given, for small values of t, by

$$\frac{d^2\sigma}{dt\,dM_X^2} \propto \frac{\exp(-b(M_X))t}{M_X^2}, \tag{3}$$

  This is valid in some range $M_1 < M_X < M_2$, and the distribution is generated from a uniform random number u by the transformation $M_X = \frac{M_1 M_2}{M_2 - u(M_2-M_1)}$. Following [4] we take $M_1^2 = 2\ \mathrm{GeV}^2$ and $M_2^2 = 30\ \mathrm{GeV}^2$ so that the slope b is constant over the region.

- Rutherford scattering, for which

$$\frac{d\sigma}{dt} \propto \frac{1}{t^2} \tag{4}$$

  To avoid the singularity we consider only t values down to some value t_{min}, and the cross section incorporates this. The distribution is generated by $t = \frac{t_{min}}{1-u}$, where u is uniformly distributed from 0 to 1.

- Inelastic scattering of a proton with a nucleon, resulting in a large momentum transfer and the production of many secondaries. The products of such a collision are produced with energies significantly lower than the nominal beam momentum which therefore do not travel far in the machine. We therefore take the energy of such particles as being lost in the collimator where the interaction occurs.

The cross sections for each process are evaluated separetely and stored in a materials database. The total cross section (not including Rutherford scattering) on a nucleus of mass number A is obtained using

$$\sigma^T_{pN} = \sigma^T_{pp} A^{0.77}. \quad (5)$$

A proton may elastically or single diffractively interact with a nucleon in a nucleus, but this is restricted to those on the surface and the cross sections are given by

$$\sigma^{el}_{pn} = n_{eff}(A)\sigma^{el}_{pp}, \quad (6)$$

$$\sigma^{SD}_{pn} = n_{eff}(A)\sigma^{SD}_{pp}, \quad (7)$$

with $n_{eff}(A) = 1.6A^{1/3}$.

The elastic cross section on the nucleus is obtained by subtraction of all other processes from the total cross section.

In addition to these processes, multiple Coulomb interactions scatter the position and direction of tracks and degrade their energy. This process was already implemented in Merlin.

The cross sections used for a Copper target are shown in Table 1.

Table 1: Cross sections values for point-like interactions for a Copper target with density 8.98 g/cm^3 and a proton beam momentum of 7 TeV.

Process	σ**(mb)**
σ^{SD}_{pp}	4.9
σ^{el}_{pp}	7.98
σ^{tot}_{pN}	1232
σ^{in}_{pN}	782
σ^{el}_{pn}	50.95
σ^{el}_{pN}	367.77
σ^{SD}_{pn}	31.28
σ^{R}_{pN}	1.53

In terms of particle energies and angles, the 4-momentum transfer t can be written as

$$t = -(E-E')^2 + (\vec{p}-\vec{p}')^2 \approx 2pp'(1-cos\theta) \approx pp'\theta^2 \quad (8)$$

Conservation of energy gives $E - E' = E_X - m$, m being the original target mass, and one obtains the relation.

$$\Delta E = -\frac{t + m^2 - M^2}{2m} \quad (9)$$

where m is the initial mass of the target (i.e. the nucleon or nucleus mass) and M is the recoil mass (the same as m for elastic scattering). Thus in all processes the variable t is computed, followed by the energy loss ΔE and then the scattering angle. The azimuthal angle of the scattered proton is sampled uniformly between 0 and 2π.

The distance between two interactions is obtained from the total point-like interaction mean free path λ,

$$\Delta s = -\lambda \ln(u), \quad (10)$$

where u is a uniform random number from 0 to 1. After Δs the interaction which occurs is chosen from the partial cross sections, and over Δs multiple Coulomb scattering is taken into account.

SCATTERING IN A COLLIMATOR

A Copper Collimator in MERLIN and FLUKA

In order to benchmark the particle scattering routines in MERLIN, a test calculation was performed of the interaction of a 7 TeV proton beam in a 50 cm Copper collimator. The beam was taken to be a mono-energetic pencil beam incident far from the edge of the collimator, and the position, angle and momentum was scored of the protons streaming from the end of the collimator material. Note that many of the protons did not survive the collimator, and only intact final protons were scored. Following [5] only protons with momentum greater than 6.8 TeV were scored.

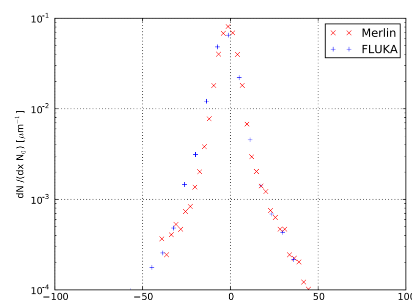

Figure 1: The distribution of change in proton position after scattering through 0.5 m of Copper collimator.

Figs. 1 and 2 shows the change in horizontal position and angle of the surviving protons, obtained with the MERLIN scattering in red and with FLUKA [2] in blue. The differential probability function dN shows the amount of protons in the position and angular range dx or dθ at the end the collimator. The figures show the agreement in the proton distributions after 0.5 m of Copper collimator and validates the updated MERLIN scattering routines for the scattering in collimators.

A LHC Carbon Collimator

The primary collimators in the LHC are made of 1 m of Carbon. To begin the study the LHC collimation perfor-

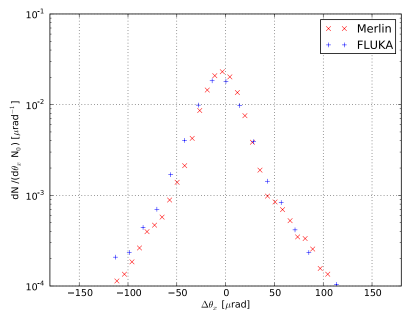

Figure 2: The distribution of change in proton direction after scattering through 0.5 m of Copper collimator.

mance and study the impact on a 7 TeV proton beam, we have made a similar calculation to the Copper benchmark on a LHC primary collimator. The surviving proton position and angular distributions are shown in Figs. 3 and 4.

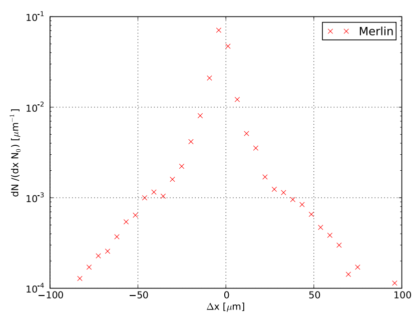

Figure 3: The distribution of change in proton position after scattering through 1 m of Carbon collimator.

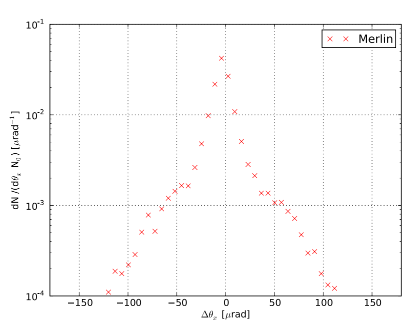

Figure 4: The distribution of change in proton direction after scattering through 1 m of Carbon collimator.

The impact on a 7 TeV proton beam by 1 m of Carbon is to stop many of the protons (inelastic proton-nuclear interaction), and the small surviving protons emerge with a angular distribution arising from the point-like processes in the scattering chain. These surviving protons are known as a secondary halo. Note the single diffractive process described in section gives rise to a off-momentum contribution in the secondary halo, potentially causing large orbit deviations in the arcs and dispersion suppressor of the LHC.

CONCLUSIONS

The LHC collimation system has shown great performance with beam in 2009 and 2010 [6], with exciting challenges to overcome at higher intensities.

In this paper we have described the extension of the MERLIN program to include scattering in collimators, specifically for the study of the nominal and upgrade LHC collimation system. We have shown the code is consistent with proton scattering in a collimator in FLUKA, and presented the first MERLIN study of scattering in a nominal LHC Carbon collimator and formation of the secondary halo. This is a major step forward in the development of a new tool for LHC collimation study. MERLIN also include a model of collimator wakefields [7], giving the possibility of novel study the impact of wakefields on the LHC beam over many turns and in conjunction with the formation of the beam halo through collimator scattering processes.

The studies of the 7 TeV nominal LHC collimation scheme will continue, with the aim of including wakefield effects on the collimator loss maps around the ring. Following this, MERLIN will be applied to the study of LHC collimator upgrades, focusing on the use of novel collimating materials, the collimation of the off-momentum halo in cold parts of the machine and wakefield effects.

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REFERENCES

[1] The MERLIN code is described at `http://www.desy.de/~merlin`.

[2] A. Fasso, A. Ferrari, J. Ranft, and P.R. Sala, "FLUKA: a multi-particle transport code", CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.

[3] G. Robert-Demolaize, "Design and performance optimization of the LHC collimation system", LHC Project Report 981, 2006.

[4] K. Goulianos, "Diffractive interactions of hadrons at high energies", Physics Reports vol. **101** pp. 171-219, 1983.

[5] R. Aßmann *et al*, "Tools for predicting cleaning efficiency in the LHC", in Proc. PAC03, Portland, Oregon, USA.

[6] D. Wollmann *et al*, "First cleaning with LHC collimators", these proceedings.

[7] A. Toader and R. Barlow 'Computation of Resistive Wakefields for Collimators', in Proc. PAC09, Vancouver, Canada.