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THE MERLIN SIMULATION PROGRAM: NEW FEATURES USED IN STUDIES OF THE LHC COLLIMATION SYSTEM USING MERLIN

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Abstract

We present recent developments in the MERLIN particle tracking simulation code, originally developed at DESY. We have implemented differential scattering cross-sections based on a pomeron exchange model interpolated over experimental measurement data, and show that this model is important at the small scattering angles generated in the LHC collimators. Preliminary comparisons with previous simulations are presented.

INTRODUCTION

The MERLIN program was originally written at DESY [1] and applied to simulations of linear collider beam transport. Its use of C++ classes makes it easily extendable, which has enabled studies of the effects of geometric and resistive wake fields in collimators [2, 3] and we here present its extension to the collimation process itself.

COLLIMATION

The LHC collimation system is vital to its operation, and has been extensively studied to predict the loss positions of scattered particles [4, 5, 6]. A full simulation of the showering process can in principle be done using the GEANT4 package coupled to BDSIM [7]; however, this is extremely slow as many physics processes are considered. For many purposes such detail is unnecessary and a simple scattering model suffices. Those protons which interact inelastically in a primary collimator will develop a shower which will be safely caught by later absorbers. The more dangerous particles are those which interact only slightly, so they are only just outside the acceptance in angle or momentum, and may travel some distance through the accelerator before they finally strike either a collimator or an undesired more vulnerable component such as a superconducting magnet. Adequate study of this problem requires large statistics and accurate beam tracking, but only small-angle scatter need be considered: large-angle scatter is deemed to be 'safe'. These small effects comprise (i) energy loss and multiple Coulomb scattering and (ii) small angle elastic and quasi-elastic scattering off the nucleus. In the original MERLIN program a collimator was treated as a black absorber, and any particle that impinged on it was simply removed from the tracked particle set. We have modified MERLIN to simulate small-angle scatters.

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ENERGY LOSS

Charged particles lose energy through collisions with atomic electrons, and the mean energy loss (dE/dx) for different materials is given in many tables. However the standard values for 'minimum ionising' particles cannot be used directly for TeV energy protons, as the high energy terms - such as the relativistic rise - do make an appreciable difference. The energy loss of particles is a statistical process, and it is a more faithful simulation to apply a random loss to a particle (given by the Landau distribution) rather than a simple constant value; this has been implemented. An important feature of high-energy proton interactions is the significant probability of Bremsstrahlung emission: this is properly handled by a separate energy-loss algorithm rather than just folding it in to the total dE/dx loss.

ELASTIC AND SINGLE DIFFRACTIVE SCATTERING

A proton of mass m, energy E and momentum $\vec{p}$ collides with a target of mass M; the scattered proton has energy E' and momentum $\vec{p}'$ and the recoil target has mass M_X. The invariant t is defined as the squared difference in the 4 momenta

$$t = (E - E')^2 - (\vec{p} - \vec{p}')^2 \tag{1}$$

The energy loss is $\Delta E = \frac{t+M^2-M_X^2}{2M}$ and the scatterng angle θ is given, to a good approximation, by $\theta = \sqrt{t}/E$. The energy and direction of the outgoing particle (apart from a random azimuthal angle) are thus determined by the quantities t and M_X. If the scattering is elastic then M_X is equal to M.

The energy spread of the LHC is about 1.1×10^{-4}, and the spread in angle at the collimators is typically $\sigma_{y'} = 3.7\ \mu$ rad; this corresponds to a t of 0.0006. Any scatter much smaller than that will have no appreciable effect; any scatter much larger will result in a very large displacement at the secondary collimator and thus be lost. So the range of interest can be taken as $0.00001 \le t \le 0.01$ GeV^2.

For elastic scattering off a nucleon the energy loss for this range of t is between 0.000005 and 0.005 GeV. This value, divided by the incoming beam energy of 7 TeV, is very small compared to the 10^{-4} energy spread in the beam. Thus for elastic scatters, particles are not lost through energy loss but through angular deflection.

For inelastic scattering the mass-squared difference is much bigger than t. An energy loss of 0.77 GeV corresponds to a recoil mass of 1.6 GeV/c^2. The loss is proportional to the mass squared, so 4 GeV would clearly be more than adequate as an upper limit.

The study of elastic and diffractive hadron scattering is well-established using simple models that predict cross-sections, the slope paramter b in t distributions $\frac{d\sigma}{dt} \propto e^{-bt}$, and the distribution in M_X . However, we now have more data from scattering experiments at energies above and below the c.m.s energy of $\sqrt{s} = 115$ GeV equivalent to 7 TeV collisions on a fixed target nucleon. The data have been fitted using a preliminary theoretical pomeron exchange model [9] which provides the differential cross-sections valid for beam energies of 3.5 and 7 TeV, and the relevant range of t.

We compare the elastic and single diffractive cross sections, and the dependence on t and M_X, from previous collimation studies, with improved pomeron exchange models. We do not consider here cases where the beam particle is excited (hence 'single diffractive' denotes excitation in the target nucleon): if an excited beam proton decays to a pion and a proton then that proton has a $\delta p/p$ such that it is lost in the next dipole, and does not join the halo (but such protons could give rise to other problems, a subject for later study).

MULTITHREADING AND OTHER PROGRAMMING IMPROVEMENTS

Calculation of particle transport and collimation can proceed independently of other particles in the tracked bunch, so speed can be enhanced by the use of multiple CPUs, implemented using e.g. MPI. For collective effects, such as wakefields and space charge, particle information must be exchanged between processes, and this limits the speed benefit of parallelisation.

In extending MERLIN simulations to millions of particles using parallelisation we encountered some interesting computational problems. To preserve accuracy in calculations for emittance and similar quantities, we needed to perform summations by using a running average rather than forming a total. Also the standard `erase` function proved a speed bottleneck, as it moves all subsequent elements down one at a time, and an alternative had to be constructed. Finally, we have checked that numerical errors are small by extracting beta functions from tracked particles for several hundred turns, and observe that they are stable.

A snapshot of particle tracking (at the LHC collimator TCP.B6L7.B1) is shown in Figure 1.

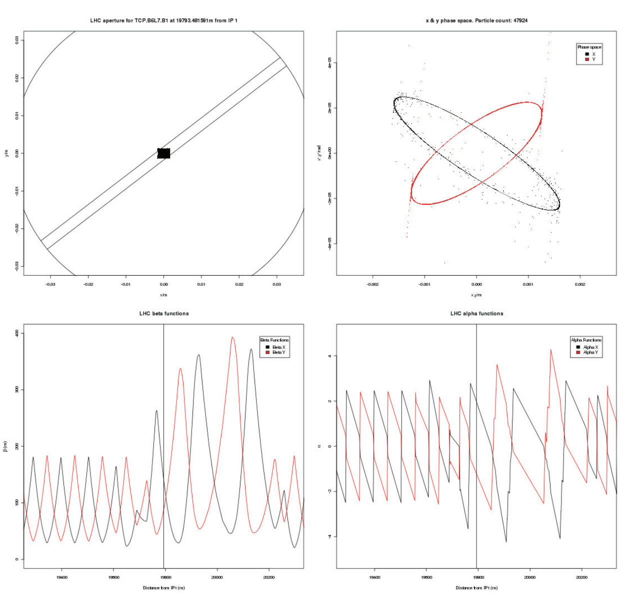

Figure 1: Simulation of scattering at an LHC collimator TCP.B6L7.B1, the first tilted primary collimator. The top left shows the x, y view of the collimator and a 6 σ pencil bunch used in generating loss maps. The top right shows the bunch partcle values for x, x' (in black) and y, y' (in red) at the collimator. The effect of scattering in two upstream primary collimators (TCP.D6L7.B1 and TCP.C6L7.B1) can be seen. The lower plots show the values for β and α in the nearby lattice.

RESULTS FOR THE LHC LATTICE

Figure 2 shows the particle loss map using a 400-turn simulation of 2×10^7 7 TeV protons, using the same K2 scattering model [8] as in previous studies [4, 5, 6]. The bunch tracked was a 6σ pencil beam with an impact parameter of 1 micron at the first primary collimator (TCP.D6L7.B1); the standard energy loss mechanism was used for these simulations. Lost particles are binned in 10 cm lengths through the circumference, starting at IP1.

The obtained map is similar to previous results, for example in [6], though a detailed comparison is not possible as our simulation used a pencil beam initial distribution which was 6σ in both x and y and their correlation, just impacting all three types of collimator, whereas the previous work studied horizontal and vertical halo particles separately. Nevertheless results are qualitatively compatible, with the major losses on the primary collimators in IR7. Differences, such as the losses we see on the tertiary collimators, can be understood from the different nature of the pencil beams used. A more detailed study is in progress.

Figure 3 shows the particle loss map for the same beam and lattice with the new pomeron-exchange model. Loss positions are broadly similar but there are differences in exact locations, showing that a more accurate scattering model makes a difference: it is important to us the best theoretical model available.

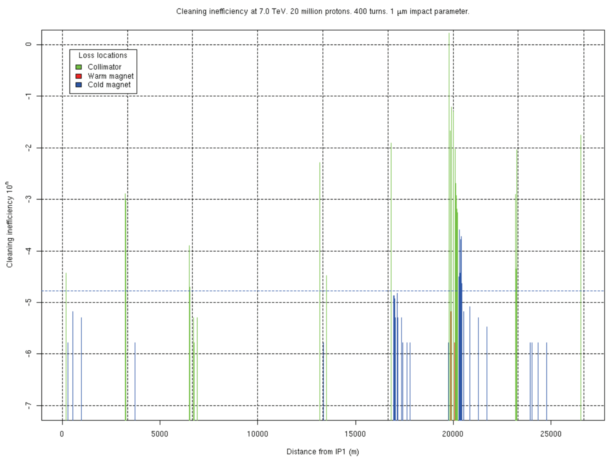

Figure 2: Particle loss map using the K2 model for elastic and single-diffractive scattering. Blue represents losses in the cold magnets, red in the warm magnets, and green in the collimator.

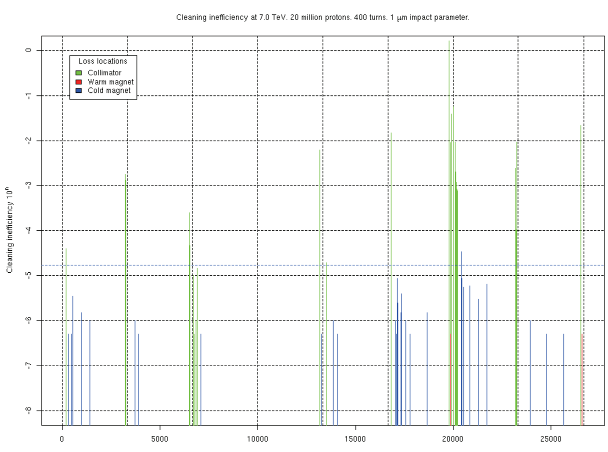

Figure 3: Particle loss map using pomeron-exchange model for elastic and single-diffractive scattering.

We show in Figure 4 the loss map for protons at 3.5 TeV (the current LHC energy) using 10^9 particles over 400 turns. This was done using 1000 CPUs of the UK Northwest Grid [10] and was achieved with only 1 hour's running. This demonstrates the possibility of repeated running of high statistics simulations with this code.

CONCLUSIONS

The MERLIN code can be used to simulate the collimation system in the LHC, thanks to improvements in the code speed and accuracy, and the addition of a simple and fast description of the physics of scattering at LHC energies and small angles. We have implemented both a traditional scattering model, and one based on up-to-date experimental data, the latter predicting significant differences in the detailed loss positions

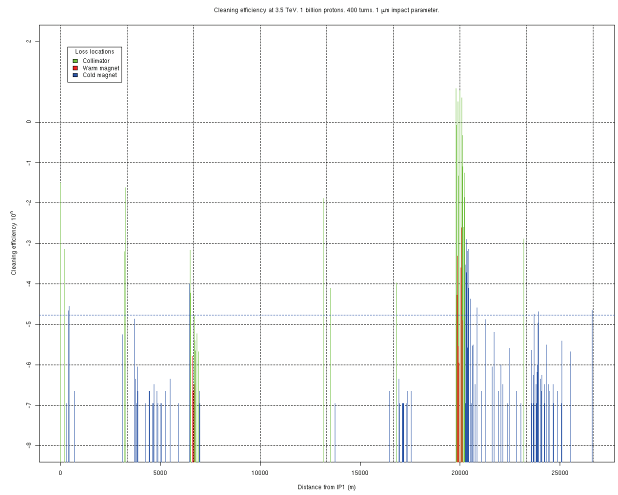

Figure 4: Loss map for 3.5 TeV beams using 10^9 particles.

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