A COMPARISON OF INTERACTION PHYSICS FOR PROTON COLLIMATION SYSTEMS IN CURRENT SIMULATION TOOLS

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Abstract

High performance collimation systems are required for current and proposed high energy hadron accelerators in order to protect superconducting magnets and experiments. In order to ensure that the collimation system designs are sufficient and will operate as expected, precision simulation tools are required. This paper discusses the current status of existing collimation system tools, and performs a comparison between codes in order to ensure that the simulated interaction physics between a proton and a collimator jaw is accurate.

INTRODUCTION

For future higher energy and higher luminosity hadron colliders, beam cleaning systems become critical. Higher per-particle beam energies and higher beam currents result in far higher stored beam energies.

In order to protect the machine components, including the superconducting magnets and the experimental detectors, highly efficient collimation systems are a core design requirement. Relevant parameters for envisioned future colliders are shown in Table 1.

Since a small fraction of the beam stored energies listed in Table 1 can cause damage, the cleaning efficiency of the required collimation systems must be higher than any current collimation system. The high cleaning efficiency required must be verified beforehand by simulations due to the damaging nature of high energy beams. Therefore large high precision simulations must be run to ensure that no damage or quench will occur in all realistic operational scenarios to an operational accelerator and that the system performance will be sufficient. A number of different simulation codes are available which can perform these sorts of simulations. This paper will perform an evaluation and comparison of a selection of these codes using the FCC-hh [1-6] as a test case.

SIMULATION CODES AND PHYSICS MODELS

Multiple codes exist which can be used to simulate hadron machine collimation systems. For this study, the thin lens tracking code SixTrack [6] has been used for the magnetic tracking. This allows the same input configuration and tracking to be used which removes a number of possible sources of differences between codes, unlike in previous studies [7].

Different physics models for particle-matter interactions in the collimators have been integrated with the SixTrack code. The default collimation physics in SixTrack was taken from the code K2 [8–10], and has been used for many years for simulations of the LHC collimation system.

More recently, the multipurpose code FLUKA [11–13] has been coupled to SixTrack [14]. Here particles are tracked with SixTrack, and upon reaching a collimator, they are passed over to the FLUKA code where they are tracked through the full geometry of a collimator, then are returned to the SixTrack code for further tracking. For this work FLUKA has been run using the DPMJET-III generator.

The physics models [15] from the code Merlin [16] have also been transported into SixTrack. In this case, the relevant C++ classes were directly inserted into the SixTrack code, where they are called from Fortran via a C layer. The models used in this case are the Merlin total, total elastic, total single diffractive, and the differential cross sections for elastic and single diffractive scattering [17]. In addition the Merlin ionisation models with straggling were also used.

Finally, the code geant4 [18, 19] was linked to SixTrack. Here upon reaching a collimator in SixTrack, a simple geometry is constructed in geant4 of two appropriately spaced blocks of collimator material, and protons are tracked one by one through the material. Both the FTFP_BERT and QGSP_BERT physics lists can be used. Simulations used geant4 version 10.3-p1.

In both geant4 and FLUKA, all generated particles that are not protons are killed, and an energy cut of 30% energy loss is applied to the protons, resulting in a cut at 35 TeV in the FCC-hh case.

COLLIMATION SYSTEM SIMULATIONS

First simulations were performed with a simple test case, an isolated 60 cm carbon block, in order to simulate the primary jaw material. A test beam of 12.8 M, 50 TeV protons was fired into the jaw at an impact of 5 mm and the outgoing particle phase space was dumped by SixTrack after a 9.7 m drift - the distance to the next collimator in the FCC-hh lattice. The resulting distributions are shown as histograms in Figure 1. As can be seen, there are large variations between codes, especially for the outgoing energy distribution. K2 gives the smallest outgoing exit angle, followed by Merlin and then FLUKA. Following these, there is a large jump to the wider distributions provided by geant4 models. For the energy distribution, there are large variations, especially

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Table 1: A table showing parameters relevant to collimation system designs for the LHC [2], the high luminosity upgrade [3], the high energy LHC [4], the SPPC [5], and the nominal FCC-hh baseline [1]. The interaction energy is the available energy when a proton collides with a fixed target nucleon in a collimator.

Parameter	LHC	HL-LHC	HE-LHC	SPPC	FCC
Proton energy (TeV)	7	7	12.5-13.5	37.5	50
Number of bunches	2808	2808	2808	10080	10600
Protons per bunch ($\times 10^{11}$)	1.15	2.2	2.5	1.5	1
Stored energy (GJ)	0.36	0.69	1.4	9.1	8.4
Interaction energy (GeV)	115	115	153-159	265	306

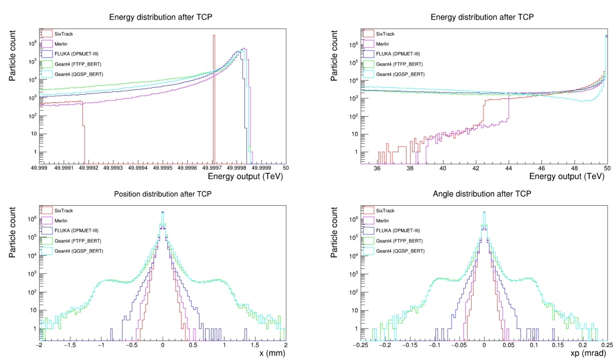

Figure 1: Histograms showing the outgoing phase space distributions from 50 TeV protons impacting a single test collimator jaw.

Table 2: A table showing relative loss counts in each named region relative to the default K2 scattering in SixTrack.

Region	Merlin	FLUKA	G4 FTFP	G4 QGSP
β TCP	1.001	1.011	0.9213	0.9394
β TCSG	1	1.267	1.447	1.318
β TCLA	0.921	1.497	2.367	1.91
β DS1	0.5086	0.5692	0.6822	0.06647
β DS2	0.4388	0.4465	0.5185	0.0321
β DS3	0.408	0.429	0.5093	0.02711
β DS4	0.4075	0.4466	0.4729	0.08615
δ TCP	0.4529	1.388	1.123	0.6897
δ TCSG	0.4913	1.36	1.236	0.7881
δ TCLA	0.5064	1.3	1.215	0.9174
Total	1	1.047	0.993	0.9928

with the low energy loss electromagnetic modelling. K2 provides a very simple model, the other codes will provide full ionisation straggling. The energy loss provided by single diffraction also varies. Merlin has a cut at 12% loss from a single interaction, and K2 at 15%. FLUKA and geant4 can provide additional methods of energy loss via proton inelastic interactions that Merlin and K2 do not simulate.

Following the single test jaw, full loss map simulations were performed. All simulations use the baseline FCC-hh May 2017 lattice, using a standard horizontal halo loss map configuration [20–22]. In each case 12.8 M particles were tracked for 200 turns. Results for each case are shown for the full ring in Figure 2. This shows the beam optics followed by the cleaning inefficiency calculated for each scattering code around the ring, and is defined as [24] $\frac{n_{\text{lost}}}{n_{\text{total}}\Delta s}$, where Δs is the binning size, in this case 0.1 m for aperture losses, and the collimator length for collimators, n_{lost} is the number of particles lost in a bin, and n_{total} is the total number of particles.

A visual inspection of the loss map shows that overall the loss distribution between each code is qualitatively similar. This provides confidence in the expected distribution. The variation is mostly in the magnitude of the loss peak sizes. A detailed comparison between the loss ratios in each region is given in Table 2. In each case this is shown as relative to the default K2 scattering model in SixTrack.

It shows the relative total losses, and is broken down into selected subgroups - each subset of collimators and the cold dispersion suppressor (DS) region following the betatron cleaning insertion. A number of loss spikes occur in the DS region, and these are numbered in the order they occur following the insertion.

Starting with the betatron collimation system, the primary collimator losses in K2, Merlin and FLUKA are in good agreement. Both geant4 models give a shift in losses from the primary to subsequent collimators. Due to the lack of any change in dispersion throughout the betatron collimation insertion, protons that have lost energy can pass through the collimation system and will be lost in the DS and beyond. The secondary collimators will catch elastically scattered protons. The increased losses in geant4 can be explained due to this; observing Figure 1 it can be seen that geant4 will generate a much wider transverse scattering distribution than the other codes. Also the difference in transmission through a single collimator is different in geant4. FLUKA and geant4, were configured to allow energy losses of up to 30%, but Merlin and K2 cannot generate energy losses of this size. Therefore in FLUKA and geant4, more losses are observed in the warm regions of the collimation sections due to the first warm dipole following the primary collimators acting as a spectrometer magnet. This is of no concern in these simulations since the warm region losses are dominated by the flow of secondary particles that are generated.

Following the betatron collimation insertion, the layout is matched into the arc in the DS region. Here the dispersion

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Figure 2: An image showing loss maps using each code for the FCC-hh collimation system, showing the full accelerator ring. Green losses are at collimators, red are warm magnets, and blue are at cold superconducting magnets. The upper plot shows the lattice optics, with the transverse beta functions being in red and blue, and the horizontal dispersion function shown in green. Further information is given in [22, 23].

rapidly rises and off-energy particles are lost in this small region. The loss rate depends on the energy distribution generated by each code. Merlin, FLUKA and geant4 with FTFP are in good agreement, at about 40 to 60% of the K2 value, with Merlin consistently giving values at the lower end of the range, and FTFP at the upper. On the other hand, geant4 with QGSP is very different, and only gives a very small loss rate. Again from Figure 1, it can be seen that there is a dip in the energy distribution from 46 to 49 TeV, which does not occur in the other codes. This reduces the loss rate to only a few percent of the other codes, thus if one is using this model they should be aware that all other codes do not agree.

Following the betatron collimation, particles can travel around the ring through each experiment until they reach the energy collimation insertion. Due to this being far downstream from the initial starting point, there is wide variation between all codes. For example, Merlin and FLUKA showed good agreement for losses in the betatron DS region, but on reaching the energy collimation, Merlin shows a 50% decrease over K2, but FLUKA shows a 33% increase. Overall, the total numbers of lost particles over 200 turns in each code show very good agreement.

CONCLUSIONS

As expected, performing simulations with different physics models gives a different result in each case. A full detailed analysis of why each case is different is beyond the scope of a single piece of work, but this can provide an estimate of the range of expected results. Using the QGSP based physics lists from geant4 for collimation may not currently be the best option. FTFP showed better agreement with other codes. It is promising that in each case the loss distribution is similar, and in critical loss regions such as the cold DS, Merlin, FLUKA and Geant4 with FTFP show good agreement. Differences between codes are mostly quantative. Determining the physically correct solution is difficult, and depends on many different factors, and more advanced simulations must be performed, including secondary particle generation and full modelling of accelerator components [25, 26].

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