TOOLS FOR PREDICTING CLEANING EFFICIENCY IN THE LHC

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Abstract

The computer codes Sixtrack and Dimad have been upgraded to include realistic models of proton scattering in collimator jaws, mechanical aperture restrictions, and time-dependent fields. These new tools complement long-existing simplified linear tracking programs used up to now for tracking with collimators. Scattering routines from STRUCT and K2 have been compared with one another and the results have been cross-checked to the FLUKA Monte Carlo package. A systematic error is assigned to the predictions of cleaning efficiency. Now, predictions of the cleaning efficiency are possible with a full LHC model, including chromatic effects, linear and nonlinear errors, beam-beam kicks and associated diffusion, and time-dependent fields. The beam loss can be predicted around the ring, both for regular and irregular beam losses. Examples are presented.

INTRODUCTION

The collimation system of the LHC [1] requires an excellent cleaning efficiency in order to avoid quenches of the super-conducting magnets. Various numerical tools used for prediction of cleaning efficiency were compared. The programs include generation of a primary beam halo, scattering of high energy protons through material and tracking of beam halos in the storage ring. The degree of agreement between different codes is discussed. Differences are used to assess possible systematic errors.

SCATTERING CODES

The physics of proton scattering in the material of collimator jaws has been implemented in various computer codes. The scattering routines track the protons through some length of a given material having them interacting with the proper cross-sections. The protons receive transverse kicks $\Delta\theta_x$, $\Delta\theta_y$ and offsets Δx, Δy and some momentum loss $\delta = \Delta p/p_0$. Note that a full shower calculation is not required for predicting the cleaning of ”primary” beam protons. The primary protons in the LHC have energies from 450 GeV at injection to 7 TeV at top. The scattering routines must correctly describe the interactions over the full range of energies, allow for different jaw materials, and include the correct jaw geometry, as protons impact at very close distance from the edge of the jaw.

Three different scattering routines were compared:

1. K2 was developed in the 1990’s by Jeanneret and Trenkler for studies of LHC collimation [2].

2. STRUCT was developed in the 1980’s by Baichev et al, among others for studies of LHC and SSC collimation [3].

3. FLUKA is a general purpose scattering and showering code ([4] and references therein).

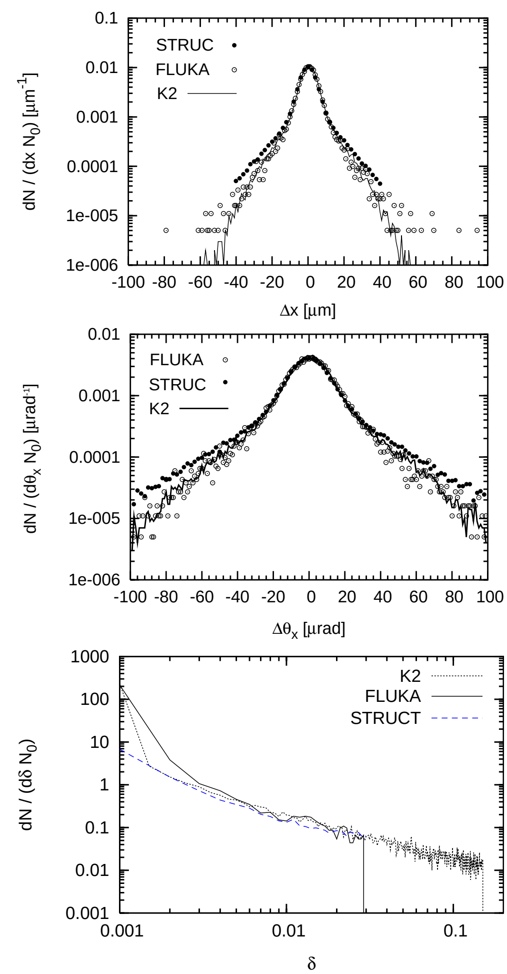

Figure 1: Scattering probabilities for one 7 TeV proton impacting on a 0.5 m long Cu jaw. Change in position (top), angle (middle) and energy (bottom).

A test case was defined: A 7 TeV pencil beam with zero angle ($y' = 0$) impacting $y = 1$ μm from the edge of a 0.5 m long vertical collimator, made of Cu. The changes in particle offsets, angles and momentum were recorded. The comparison of the different scattering routines shows good agreement, Fig. 1. Note that for FLUKA a 6.8 TeV energy cut was used. A probability function $dN/(dxN_0)$ is introduced with N_0 being the number of protons impacting on the jaw. Only a fraction of protons "survive" the passage through the jaw, the others are fragmenting. The results shown here refer to the horizontal plane which is symmetric contrary to the vertical plane where the 1 μm impact parameter introduces a pronounced asymmetry. The symmetry in the horizontal plane allows more easy interpretation of the effect on cleaning efficiency.

The differences in the results were analyzed in detail. It was found that the momentum loss shows a variation of $\pm$ 15% between different codes which is used to assign a systematic error on this observable. Large scattering angles and offsets exhibit differences of up to a factor of 3, as visible in Fig. 1. The large angle probabilities (above 25 μrad) affect cleaning efficiency and were approximated by fitting them, as shown in Fig. 2:

$$\begin{aligned} dN/d\,(d\theta_x N_0) &= e^{-6.25-0.058\theta_x} \quad \text{K2} && (1) \\ &= e^{-6.70-0.042\theta_x} \quad \text{STRUCT} && (2) \end{aligned}$$

Note that θ_x is to be given in units of μrad. The fraction of particles above a given angle θ_x^0 is easily obtained from the integral:

$$\begin{aligned} \frac{N}{N_0}(\theta_x > \theta_x^0) &= -0.033 \cdot e^{-0.058\theta_x^0} \quad \text{K2} && (3) \\ &= -0.029 \cdot e^{-0.042\theta_x^0} \quad \text{STRUC} && (4) \end{aligned}$$

Integrating above 10 $\sigma_{x'} \approx 25\mu$rad it is seen that in K2 about $7.8 \cdot 10^{-3}$ of the impacting protons would be kicked to above 10 $\sigma_{x'}$, while in STRUCT $10.3 \cdot 10^{-3}$ of the impacting protons would reach 10 $\sigma_{x'}$. It is seen that the factor three difference in large angle probabilities would at maximum amount to a 30% difference in cleaning efficiency.

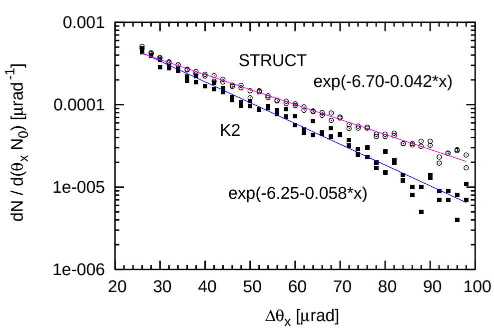

Figure 2: Large angle scattering probabilities for a 7 TeV proton impacting on a 0.5 m long Cu jaw with STRUCT and K2. The functional dependence is fitted.

TRACKING WITH COLLIMATORS

Halo cleaning is a multi-turn process. Particles can have multiple interactions in collimator jaws and in addition can perform many turns between subsequent hits of a collimator jaw. Speed requirements are important: The target cleaning efficiency ($10^{-3} - 10^{-4}$) requires large particle ensembles ($10^5 - 10^6$) that must be tracked for many turns (20-1000). Several tools have been set-up, each with specific advantages and limitations.

Colltrack with K2

Historically the design of the LHC collimation system relies on the K2 scattering procedure and linear transfer matrices (obtained from Twiss functions calculated with MAD). Recently an updated COLLTRACK program was written, relying on K2. The advantage of this approach is a very fast algorithm, allowing to track very large particle ensembles over many turns. Multiple imperfections are implemented. This allows for example the study of very short primary collimators, where halo protons stay in the machine for up to thousand turns after the first interaction in a primary collimator. Drawbacks are the limited description of chromatic and dispersive effects, the absence of nonlinearities, coupling, and beam-beam effects. Results from linear tracking with K2 can for example be found in [5].

Sixtrack with K2

The Sixtrack program [6] is the standard tracking tool for the LHC. For example, the LHC dynamical aperture is calculated with Sixtrack that includes all relevant imperfections, linear and non-linear fields, beam-beam kicks, and other errors for the LHC. It performs fully chromatic and coupled tracking, allowing the treatment of time-dependent field errors and the inclusion of the LHC aperture. The K2 scattering module has been included for proper treatment of beam scattering in collimators. Results of SIXTRACK with collimators are published in [7] for collimation efficiency during the snapback at the start of the LHC ramp.

Dimad with STRUCT

Dimad is based on second order Transport maps with kicks describing the action of higher order multipoles and also accepts symplectic ray tracing [8]. To describe propagation of TeV protons in materials a new collimator element was created, based on the main block of STRUCT[3] , and also a new `set collimator` operation which exists along with standard Dimad operations: field errors, misalignment, orbit correction and analysis of geometric and chromatic aberrations [1]. The original Dimad source is kept, with the new executable provisionally named Dimcol.

A highlight of Dimad is the possibility to study beam loss distributed in an aperture. An example radial aperture R=2 cm was set at all drift entrances.

Since in reality the chamber geometry varies along the ring and the losses do not occur in one point, the exact permeter occupancy cannot be found in this way. One can however estimate losses over large sections of the ring, and

[1] Scattering of GeV protons was first introduced in Dimad during the KAON factory studies with the collimator treated during tracking as an `arbitrary element` [9], [10]

Ideal system – fraction of halo lost				
in colli-mators	on the 2 cm aperture			
	RDS7	IP6	IP1,2,5	arcs
Collision: 10^6 part., 300 turns				
0.9986	$6 \cdot 10^{-4}$	0	$4 \cdot 10^{-4}$	0
Injection: 10 seeds $\times 10^5$ part., 150 turns				
0.9985	$1.3 \cdot 10^{-3}$	$8 \cdot 10^{-5}$	0.	$8 \cdot 10^{-5}$

Table 1: Halo fractions absorbed in collimators and lost on the 2-cm radial aperture (drift entrances) in different ring sections. The injection values are averages of 10 seeds.

such were chosen to be: the two collimator occupied sections in IR7 and IR3, the Right Dispersion Suppressor in IR7 (RDS7), the IP6, the high-beta IP-s (IP8,1,2,5) and all the arcs. The resulting losses are summarized in Table 1. It is seen that at collision no particles reach the arcs and a fraction $4 \cdot 10^{-4}$ reaches high-beta locations in the IP-s. Here, however, the real chamber size will be larger. More detailed studies are underway.

COMPARING INEFFICIENCY

The cleaning efficiency for the 7 TeV LHC has been studied in detail with the linear Colltrack(K2) code and Dimad [11][2]. The goal was to assess the size of possible differences. K2 and Sixtrack were compared for injection energy. No aperture limitations are set besides collimators. Coordinates and momenta are stored at some location s, which yields the *integrated inefficiency* curve $F(A_r)$, defined to be the fraction of halo lost on an absorber standing at radial amplitude $A_r = \sqrt{A_x^2 + A_y^2}$, where $A_x^2 = 2J_x/\epsilon$ (similar for y). Here $J_{x,y}$ are the transverse action invariants, hence $F(A_r)$ is independent on the lattice location chosen. The following results were obtained for the integrated inefficiency at radial amplitudes of $A_r > 10\sigma$:

Energy	Disp.	Dimad	Colltrack	Sixtrack
7 TeV	0 m	$0.6 \cdot 10^{-3}$	$0.6 \cdot 10^{-3}$	-
7 TeV	2 m	$3.0 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	-
.45 TeV	0 m	-	$1.6 \cdot 10^{-3}$	$4.7 \cdot 10^{-3}$

Note that the SIXTRACK result is for the LHC with realistic errors and non-linear fields. The Dimad results refer to a machine with corrected linear chromaticity. The other results refer to an unperturbed machine.

An exact agreement is seen between Colltrack and Dimad at a location with zero dispersion. At a 2 m dispersion location the predicted inefficiency is larger by a factor 2.5 in Dimad than in the simplified Colltrack approach. The scattering routine could explain a factor of about 1.3. The rest is due to the more realistic Dimad tracking of off-momentum particles.

At injection Sixtrack predicts a 3 times larger inefficiency than Colltrack, relying on the same K2 scattering routine. This may be explained by the realistic tracking in Sixtrack and the errors on the LHC settings (orbit, coupling and non-linear field errors).

[2]the results in [11] are obtained in the case of a detuned optics i.e. injection optics with collision emittance.

CONCLUSION

A number of numerical tools have been set up to predict the LHC cleaning efficiency. They rely on different scattering routines that transport the protons through the collimator jaw. These routines show discrepancies of up to a factor of three for large angle scattering. This can amount to changes of up to 30% in predicted cleaning inefficiency. In addition variations of up to $\pm 15\%$ are seen in the predicted momentum loss, with resulting systematic errors of $\pm 7\%$ in inefficiency.

The direct comparison of predicted cleaning inefficiency, however, shows more important differences. It is seen that the simplified linear tracking underestimates cleaning inefficiency by a factor of 2 to 3. The more accurate tracking in Dimad and Sixtrack finds larger inefficiencies. In addition, Sixtrack includes realistic LHC errors (coupling, orbit, non-linear field errors). The errors moderately increase the inefficiency. Note that the imperfections in the Sixtrack study did not include imperfect set-up of the collimation system.

The Dimad program was used to analyze the distribution of losses around the ring. It was shown that less than 10^{-4} of the primary halo is lost in the high-beta insertions. A more accurate model of aperture is expected to show even smaller losses.

The overall agreement in the results is quite reasonable. The available tools can be employed with decent certainty in the reliability of results, choosing the most appropriate tool for a particular study.

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