SIXTRACK SIMULATION OF OFF-MOMENTUM CLEANING IN LHC

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Abstract

In the LHC, high-amplitude particles are cleaned by either betatron collimators or momentum collimators. Previously, betatron losses have been studied more in detail since considered as a possible performance limitation of the machine. Measurements during the first years of operation show high losses also in the off-momentum cleaning insertion. This causes a significant radiation dose to warm magnets downstream of the collimators. Our work in this paper aims at simulating with SixTrack the off-momentum particles, driven into the momentum collimators by radiation damping outside the RF system acceptance. The results are an important ingredient in assessing the effectiveness of new passive absorbers to protect the warm magnets.

INTRODUCTION

Unavoidable beam losses in the LHC [1], of particles with a large betatron amplitude in the transverse plane or an energy offset, need to be safely intercepted in order not to quench superconducting magnets. Therefore, a collimation system [1, 2, 3, 4], is placed in dedicated cleaning insertions, called IR7 and IR3, for betatron and momentum cleaning respectively. Primary collimators (TCP) are closest to the beam, followed by secondaries (TCS) and absorbers (TCLA). Additional collimators are also installed in other IRs. The cleaning efficiency for off-momentum particles by the collimation system has been not extensively studied so far, since it was not posing immediate performance limitations. Measurements of doses to warm magnets in 2011 indicated that a better model of IR3 losses is needed to address magnet lifetime issues.

During the first three years of the operation of the LHC, losses higher than expected have been measured in IR3, which could induce radiation damage to warm magnets [5]. The main aim of this study is, therefore, to provide more accurate simulated loss maps in IR3, based on synchrotron radiation losses. Once the loss distribution is obtained, it can be used for further studies of energy deposition on the collimator jaws and warm magnets, and also to quantify the gain of additional passive absorbers.

A second but not less important goal is to determine the typical impact parameter distribution in IR3, which will aid in developing faster simulations for off-momentum cleaning for studies of future machine scenarios.

To achieve these goals, SixTrack [6, 7] simulations have been performed at 7 TeV, taking into account the energy that particles lose turn by turn due to the emission of synchrotron radiation. Eventually these particles have an energy offset large enough to hit the IR3 TCP.

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SYNCHROTRON MOTION IN THE LHC

In a storage ring, a reference particle with nominal energy E_0 and synchronous momentum p_0 follows an ideal closed orbit. The energy E of the particle can deviate from E_0 and perform synchrotron oscillations around it. Therefore, the beam is made of particles with momenta distributed around the synchronous energy E_0.

The *energy offset* δ is defined as:

$$\delta = \frac{\Delta E}{E_0} = \frac{E - E_0}{E_0}, \tag{1}$$

that is usually distributed in the bunch as Gaussian or parabolic. In the LHC, at 7 TeV and nominal collimator settings, $\delta = \pm 0.0013$, i.e. $\Delta E \simeq \pm 9$ GeV, will make a particle hit the IR3 primary collimator.

Because of the ultra-relativistic energies in the LHC, we have the relativistic $\beta \simeq 1$ and hence the momentum is $p \approx E/c$. We can therefore use either E or p in Eq. (1).

Particle trajectories in longitudinal phase space can be derived from a Hamiltonian given by [8] :

$$\mathcal{H} = \frac{1}{2}\dot{\phi}^2 - \frac{\Omega^2}{\cos\psi_s}[\cos(\psi_s + \phi) - \cos\psi_s + \phi\sin\psi_s], \tag{2}$$

where ϕ is the phase, Ω is the synchrotron frequency and ψ_s, the synchronous RF phase. In this paper, a stored beam at 7 TeV energy are considered, so we can set $\psi_s = 0$.

In Fig. 1 each contour line shows the particle motion for a different value of $\mathcal{H}$ in the longitudinal phase space: the area within the separatrix [8] is commonly called RF-bucket describing where particles are in stable motion. When a particle receives a kick and passes that line, its motion becomes unbounded. To allow a good representation, a proper conversion of the variable of Eq. (2) in the phase space coordinates (δ and longitudinal coordinate inside the RF-bucket s) has been done.

To illustrate the longitudinal phase space motion, a comparison between SixTrack simulation and the analytic result has been performed, as shown in Fig. 1. Each green line refers to a particle starting with a slightly different energy offset around 7 TeV that has been tracked by the code, without taking into account the synchrotron radiation effect.

SIMULATION SETUP

For this study, the simulation has so far been run only for Beam 1.

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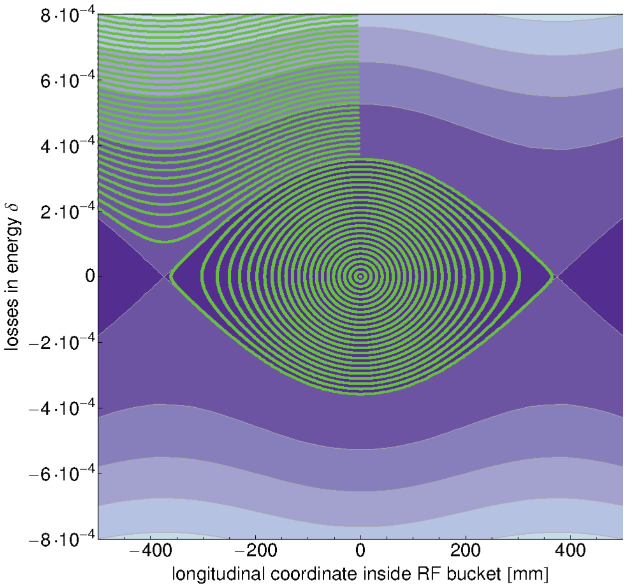

Figure 1: Comparison between Hamiltonian and SixTrack simulation in the longitudinal phase space, without radiation damping.

The main settings for SixTrack simulation are shown in detail in Table 1.

Table 1: Main Parameters used for SixTrack Simulation

SixTrack Parameter		**Input**
Number of particles	[protons]	$1.25 \cdot 10^5$
Energy	[TeV]	7
Number of turns	[turns]	$> 1.3 \cdot 10^6$
RF voltage	[MV]	16
RF frequency	[MHz]	400.8
Synchrotron angular frequency	$[rad/s^{-1}]$	144.5
Bucket half height ($\Delta E/E$)		$0.36 \cdot 10^{-3}$
IR3 TCP setting	$[\sigma]$	12
IR3 TCSG setting	$[\sigma]$	15.6
IR3 TCLA setting	$[\sigma]$	17.6
IR7 TCP setting	$[\sigma]$	6
IR7 TCSG setting	$[\sigma]$	7
IR7 TCLA setting	$[\sigma]$	10

At nominal 7 TeV operation, the energy loss per turn due to synchrotron radiation is 6.71 keV per turn [1]. As the energy loss scales with the fourth power of the relativistic γ, we apply every turn to each particle in SixTrack an energy loss ΔE_s of:

$$\Delta E_s = 6.71\,\text{keV} \cdot \frac{\gamma^4}{\gamma_0^4}. \tag{3}$$

Particle starting conditions are randomly generated using a Mathematica script. Betatron coordinates are sampled from a Gaussian distribution; in the longitudinal phase space, instead, δ is sampled from an uniform distribution between the separatrix and 20% outside in energy. We set $s = 0$, since the synchrotron motion anyway makes all particles pass all phases.

The performed simulations are extremely demanding in terms of computing time, since more than 10^6 turns are needed before all particles have lost enough energy to hit the IR3 TCP (see Fig. 3). Due to the energy and phase space conditions chosen, large number of turns has been needed to make the particle hit the collimator due to synchrotron radiation: about 4 computing days to terminate a 64 particles simulation.

RESULTS

The resulting losses along the ring on collimators, as simulated by SixTrack, are shown in Fig. 2. As expected, the highest losses are observed in IR3 but significant peaks appear also in IR7. In both regions the collimation hierarchy is well respected. No losses on the aperture are observed, which is still to be understood. However, as the total fraction of simulated particles reaching the aperture is usually of the order of 10^{-3}, it is a negligible correction to the losses on the collimators, which therefore can be trusted.

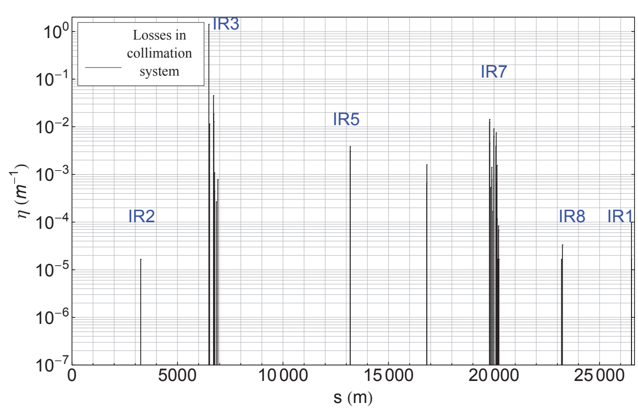

Figure 2: Beam loss map from SixTrack simulation at 7 TeV with synchrotron radiation effect.

All particles hit first the TCP in IR3. The turn of the hit is distributed as in Fig. 3. The average impact parameter is about 2 μm and the impact angle on the collimator jaw, -0.044 mrad, is in perfect agreement with the value from $x'(s) = D'(s) \cdot \delta$, where $x'(s)$ is the impact angle as function of the longitudinal coordinate and $D'(s)$ is the derivative of the dispersion function.

The resulting spatial distribution of inelastic interactions in the IR3 TCP is shown in Fig. 4. This distribution can be used for further dose studies with other codes such as FLUKA. Since particles are losing energy through synchrotron radiation, only one TCP jaw has been hit. As shown in the Fig. 4, most protons are absorbed in the

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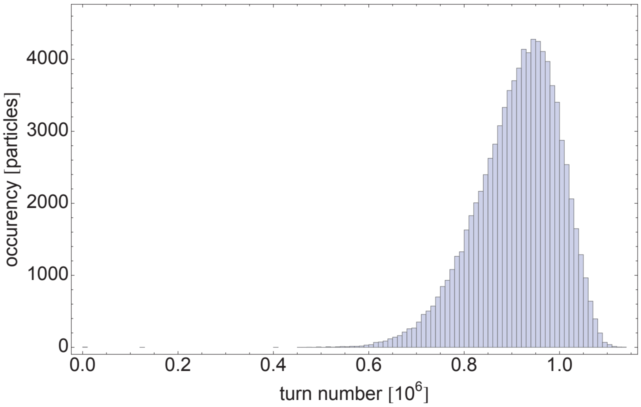

Figure 3: Histogram of the number of turns after that the first hit of the IR3 TCP jaw occurs.

first hundred micrometers deep inside the material and are mainly concentrated in the first half length of the jaw.

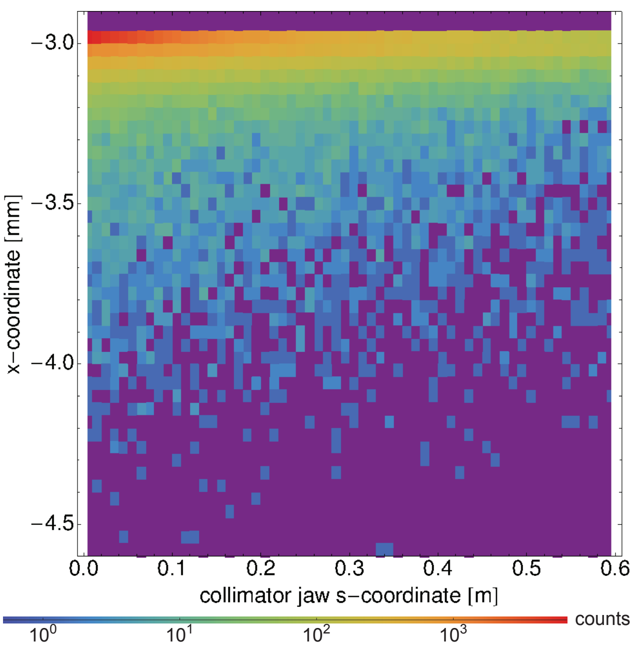

Figure 4: Density plot of particle impact parameter as function of longitudinal coordinate in IR3 TCP right jaw.

One more relevant aspect to mention is the choice of the initial energy offset.

As mentioned above, a uniform distribution in δ was used, since the real distribution of δ is not well known. This is compatible with the assumptions in Ref. [9]. To justify this assumption, we study the correlation between the initial δ and the impact coordinates on the IR3 TCP. As shown in Fig. 5, no correlation can be identified: due to δ, the particles will reach the collimator at different time but it does not influence their distribution inside the jaw. Therefore, the assumption of a uniform initial distribution in δ does not affect the final result.

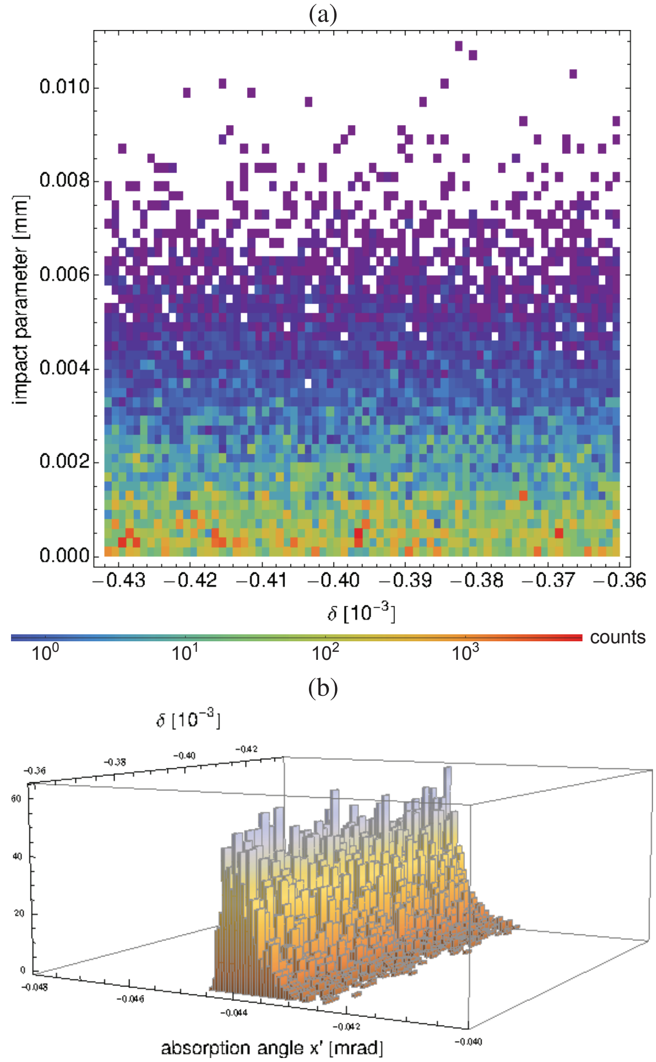

Figure 5: Correlation between the initial energy offset δ and the impact parameter (a), the impact angle (b).

CONCLUSIONS

Seen the significant results obtained with this study, they can be a useful starting point for future FLUKA simulations of the radiation damage in IR3. As further work, we intend to improve the simulations and find a way to speed them up to get equivalent results in shorter time.

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