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Simulating off-momentum loss maps using SixTrack

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Abstract
The Large Hadron Collider was designed to collide proton beams with unprecedented energy in order to extend the frontiers of the high-energy physics. The beam is not monochromatic and each particle deviates slightly from the nominal energy. Some particles follow an orbit which differs from the design orbit and, in some cases, they can reach the aperture and may quench the superconducting magnets. Therefore, these particles must be safely removed from the machine before losses in cold sections occur. A dedicated off-momentum collimation to capture these particles. In this paper we present a new set of tools to simulate off-momentum cleaning in order to better understand the dynamics of such particles and to try to improve the off-momentum collimation cleaning efficiency.

Keywords
LHC, collimation, off-momentum, simulations, Sixtrack.

The Large Hadron Collider (LHC) is designed to collide protons up to an energy of 7 TeV with a total stored energy of about 362 MJ per beam. This huge amount of energy presents a serious hazard to the superconducting magnets, which must be adequately protected to ensure reliable operation. Even a small fraction of particles lost in the superconducting aperture could quench the magnet. For this purpose, a multistage collimation system [1] was installed, in order to intercept unavoidable beam losses in a safe way. Two out of the eight Interaction Regions (IRs) of the LHC are devoted to beam collimation (Fig. 1). In IR7, the betatron cleaning section intercepts particles with large amplitudes while in IR3, the momentum cleaning section captures particles with large energy deviations.

Betatron cleaning has been already studied in detail since it is quite straightforward to implement in simulations. On the other hand, momentum cleaning has been studied with less detail due to that

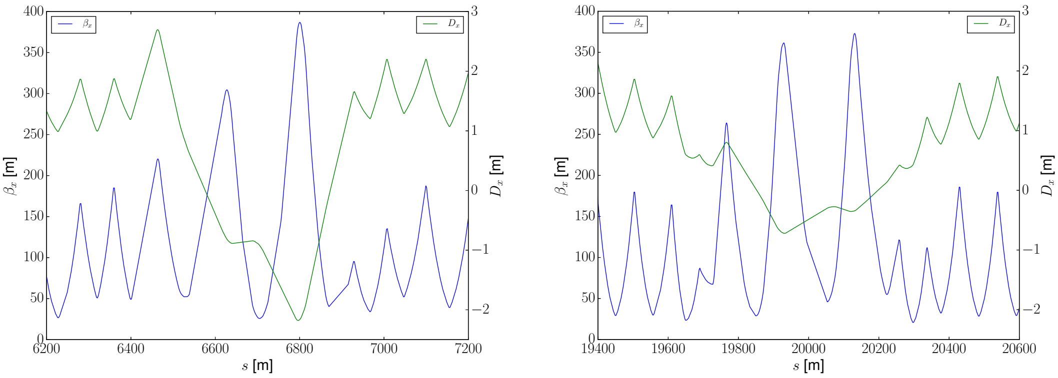

Fig. 1: Optical functions β_x and D_x in both collimation sections: momentum cleaning section (left) and betatron cleaning section (right).

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the simulation setup requires a dynamical manipulation of the elements of the machine and tools were not available until recently. In addition, a large number of turns need to be simulated with respect to the betatron cleaning simulations, which makes it more CPU demanding. In this paper, we show how off-momentum simulations can be carried out using SixTrack [3].

1 Betatron cleaning

The efficiency of the betatron cleaning is evaluated by means of the so called loss maps. Betatron loss maps are acquired during LHC regular or dedicated operation by using the electric transverse damper (ADT) to blow up the beam in such a way that the beam tails become more populated and eventually reach the betatron collimator cut. From the loss pattern obtained, we can study the performance of the collimation system. To simulate the betatron cleaning of the LHC collimation system we use SixTrack, which performs a thin lens element-by-element tracking. When a particle enters a collimator, a built-in Monte Carlo code is used to simulate the particle-matter interaction [2]. A particle is considered lost when it interacts inelastically inside a collimator (excluding single diffractive events) or if it hits the aperture. The simulation output contains the coordinates of all loss locations that allow us to reconstruct the loss pattern along the ring and compare it to measurements.

2 Momentum cleaning

The momentum cleaning section in IR3 is designed to intercept particles which deviate enough from the design energy with sufficient margin to the off-momentum aperture bottleneck of the machine to fit an efficient multi-stage system. To do that we take into account that the linear motion of a particle is the solution of the inhomogeneous Hill's equation that has two different contributions: the betatron component and the dispersive term. The horizontal spatial transverse coordinate of single particle, x, is given by,

$$x = x_\beta + x_\delta = \sqrt{\epsilon\beta_x(s)}\cos(\mu(s) - \mu_0) + \delta D(s), \tag{1}$$

where x_β is the pure betatron oscillation given by the β-function at a given s location, the beam emittance ϵ and the phase advance $(\mu(s) - \mu_0)$ and x_δ is the orbit deviation due to the particle energy offset $\delta = \Delta p/p$ and the dispersion D at this location. Particles with large enough energy deviation δ can be lost in the magnet aperture if no dedicated protection system is included. Therefore, in the momentum primary collimator, dispersion is by design relatively large in order to intercept particles with even small $|\delta|$.

Off-momentum loss maps are also acquired during regular or dedicated operation at the LHC. To do so, the RF frequency is trimmed to bring the beam to higher or lower energies towards the primary collimators in IR3. The frequency shift induces a phase shift in the RF voltage seen by the synchronous particle. The synchronous particle is not synchronous any longer for the new RF configuration and starts oscillating around the new bucket. If the frequency trim is applied adiabatically, the phase space from one turn to the next changes slowly enough to always keep the full beam captured the full beam and brings the full distribution towards the collimator cut. The loss pattern recorded during this process gives information about the efficiency of the momentum cleaning. Although off-momentum loss maps are important, they have never been simulated before. In the next sections we explain how these simulations can be implemented now using new options available in SixTrack.

3 RF-trim model

To simulate realistic off-momentum dynamics we need to take into account the longitudinal dynamics in the LHC. The RF frequency trim can be modeled by modifying the longitudinal mapping equations to take into account a phase shift term $\Delta\varphi$ that is added to every turn to the phase,

$$\delta_{n+1} = \delta_n + \frac{eV}{\beta^2 E}(\sin\phi_n - \sin\phi_s) \tag{2}$$

$$\phi_{n+1} = \phi_n + \Delta\varphi + 2\pi h\eta\delta_{n+1} \tag{3}$$

where η the slip factor, h the harmonic number, $\delta = \frac{\Delta p}{p}$ is the energy error of the particle, β is the particle speed in units of c, E is the energy, ϕ is the phase coordinate of the particle and ϕ_s is the synchronous phase that we take equal to zero for simplicity. For small shitf per turn, this formalism is suitable to model adiabatic RF trims. This adiabatic phase shift is given by a quadratic function of time in order to represent a linear shift in the frequency using the simple relation,

$$\varphi = \omega t \rightarrow \varphi + \Delta\varphi = (\omega + \Delta\omega)t \tag{4}$$

$$\Delta\omega \propto t \Rightarrow \Delta\varphi \propto t^2. \tag{5}$$

The exact coefficient of the second order term is given by the maximum phase shift $\Delta\varphi_{\text{max}}$ and the number of turns N_{turns} in which the trim will be applied. For instance, an RF frequency shift $\Delta\omega$ applied in two consecutive turns gives a phase shift $\Delta\varphi$ of,

$$\Delta\varphi(t = \tau) = \Delta\omega_{\text{RF}}\tau = \Delta\omega_{\text{RF}}\frac{2\pi}{\omega_0}. \tag{6}$$

where ω_{RF} is the angular frequency of the RF and ω_0 is the angular frequency of the particles around the ring. We can express it in terms of $f = \frac{\omega}{2\pi}$ and express the phase shift as a function of the frequency trim as,

$$\Delta\varphi = 2\pi\frac{\Delta f_{\text{RF}}}{f_0} \tag{7}$$

If one wants to apply this shift repeatedly during several turns, as it is the case for an adiabatic RF trim, an expression of the phases shift as a function of the number of turns is required. If we consider the function in Eq. (2) a quadratic increase of the phase shift is achieved by a linear model given by,

$$\Delta\varphi_{\text{map}}(n) = \frac{\Delta\varphi_{\text{max}}}{N_{\text{turns}}}n, \tag{8}$$

where $\Delta\varphi_{\text{max}}$ is the maximum phase shift given by the total frequency shift and N_{turns} is the total number of turns during the RF trim. However if one wants to apply the phase shift straight to the RF cavity phase where the reference phase stays constant an actual quadratic model is needed in order to take into account the cumulative behavior of the shift,

$$\Delta\varphi_{\text{cav}}(n) = \frac{\Delta\varphi_{\text{max}}}{2N_{\text{turns}}}n^2. \tag{9}$$

Equation (9) is used in tracking simulations to dynamically change the RF cavity frequency as it is explained in following sections.

4 Off-momentum cleaning simulations

The RF trim is simulated trim using SixTrack tracking code with a collimation module to take into account impacts on the magnet aperture and the hits in the collimators. The next sections describe how to prepare the SixTrack input (`fort.2` and `fort.3`) to perform off-momentum cleaning simulations.

4.1 Lattice input (`fort.2`)

The lattice input file `fort.2` must contain the RF cavities. To include them, one must add the option `cavall` to the sixtrack conversion command in the MADX file. Once the file `fort.2` is generated, the voltage value must be set to a non-zero value. Otherwise SixTrack ignores the element.

4.2 Configuration input (`fort.3`)

DYNK [4, 5] is a module of the SixTrack code that allows the user to dynamically change some of the parameters of the simulation such as quadrupole strengths, RF cavity phase and voltage among many others. In this case the DYNK module is used to simulate the RF cavity phase shift. DYNK input requires to specify the parameter to be modified and its value at each turn. Although the DYNK module contains built-in functions, a simple script to generate the input phase for the simulations has been developed where the main input is the maximum frequency shift $f_{\max}$ that one wants to apply and the number of turns required to go from 0 to the $f_{\max}$. As a typical example, in Fig. 2 a frequency trim of +500 Hz has been applied for 10000 turns (around 1 second) and the resulting phase to be applied to the cavities is shown as a function of the turn number. As an example, the following lines describe the `DYNK` module to be incorporated in the `fort.3` file to apply the effective RF trim to the cavities and to simulate the off-momentum loss map. The rest of the settings of the file are the same used for standard betatron cleaning simulations. The initial beam distribution instead of the typical annular halo distribution, is that of a nominal bunch with a Gaussian distribution in dp/p with $\sigma_{dp/p} = 1.14 \cdot 10^{-4}$ standard deviation.

```
DYNK
FUN volt1 CONST 2.0
FUN harm0 CONST 35640.0
FUN lag1 FILELIN lag_values.dat
SET acsca.d5l4.b1 voltage volt1 1 10000 0
SET acsca.d5l4.b1 harmonic harm0 1 10000 0
SET acsca.d5l4.b1 lag_angle lag1 1 10000 0
NEXT
```

In the second and third line we define the constant voltage and the harmonic number of the cavity. In the fourth line we call the file `lag_values.dat` which contains the values of the cavity phase at each turn of the simulation represented in Fig.2. Since the calculation of the phase value is relatively complex, we use an external script to generate the input file and to have full control of the output. Nevertheless, we can define different functions within the DYNK module to perform the same calculation.

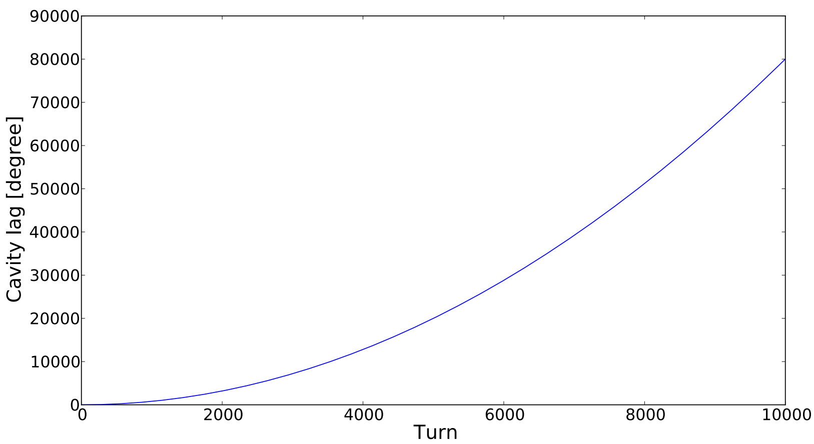

Fig. 2: Example of the phase applied to the RF cavity in the SixTrack simulation for 10^4 turns

4.3 Full simulation

It is important to note that off-momentum loss maps simulations are carried out separately for B1 and B2 while it is usual to have both beams in the machine when off-momentum loss maps are acquired. There-

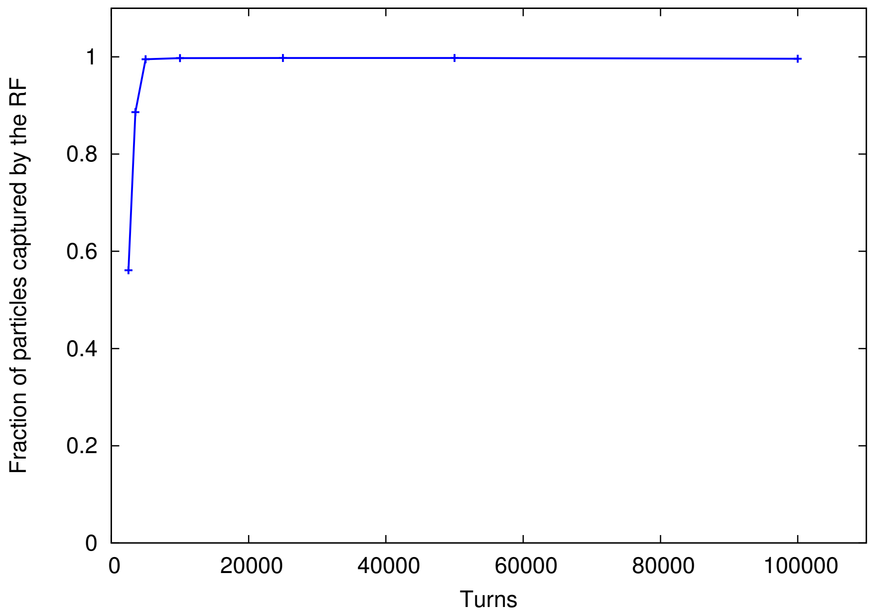

Fig. 3: Fraction of particles captured by the RF bucked and lost in collimators or aperture after RF frequency trim simulation as a function of number of turns simulated. For low number of turns the RF bucket moves fast and some particles of the bunch jump out of the bucket.

fore, to have a full representation of the off-momentum loss maps for comparison with the measured data, one must simulate both beams and combine the result.

5 Simulation speed

The off-momentum loss map acquisition in the LHC takes about 15 seconds. During this time the protons in the LHC perform more than $1.5 \cdot 10^5$ turns. If one wants to simulate the full procedure a large amount of CPU time and disk space is required. In order to reduce the simulation time simulations we take just 10^4 turns, this is less than one second real machine time and the current maximum number of turns allowed by the software. We risk to spoil the results due to the high speed of the frequency trim. To check that this speed reduction does not affect the final result of the loss pattern, different simulations using different number of turns have been performed.

In Fig. 3 the total number of particles lost in the aperture or collimators is plotted as a function of the total number of turns of the RF frequency trim. A clear reduction of the number of lost particles is observed for fast simulations i.e. for a frequency trim with performed during a small number of turns.

6 Benchmarking simulations

A simulated off-momentum loss map for the 2016 LHC optics is shown in Fig. 4 for B1 and B2. The frequency trim is -500 Hz for 10^4 turns. These simulations have been benchmarked by comparing the results with the acquired off-momentum loss maps during LHC operation as can be seen in the results published in [6]. Main losses occur in IR3 primary collimator as expected. The ratio between IR3 losses and IR7 losses is also in agreement with the measurements. One can also observe the losses in the DS around IR3 and some losses in IR4 which were also observed in the machine and reported in [7].

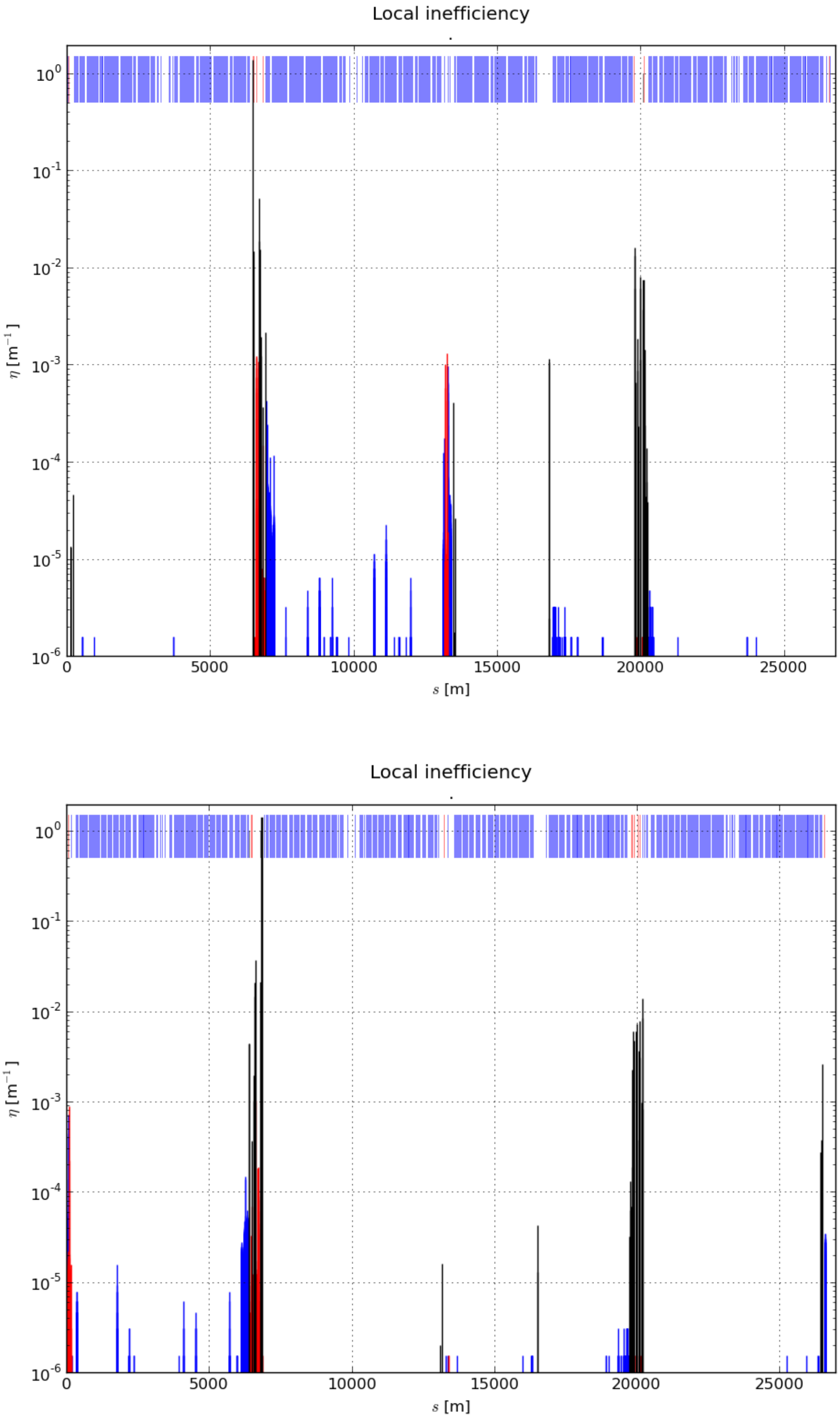

Fig. 4: Simulated off-momentum loss map for B1 (top) and B2 (top) with a -500 Hz frequency trim for 10^4 turns

7 Conclusions

A novel set of simulations of the off-momentum cleaning in the LHC have been presented. With these new implementation we are able to simulate the momentum cleaning not only of the LHC but also of any other machine such as HL-LHC and FFC-hh. These simulations would allow us to better optimize the momentum cleaning insertion of any hadron collider as well as to establish the basis for other future simulations related to off-momentum dynamics.

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