Proceedings of ICFA Mini-Workshop on Tracking for Collimation in Particle Accelerators, CERN, Geneva, Switzerland, 30 October 2015, CERN Yellow Reports: Conference Proceedings, Vol. 2/2018, CERN-2018-011-CP (CERN, Geneva, 2018)

Status of SixTrack with collimation

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Abstract

In this paper, we review the functionality and status of the collimation version of SixTrack. It is a simulation tool that contains both an accurate magnetic tracking of an ensemble of particles, as well as a model for particle-matter interaction inside collimators, in order to model the efficiency of a proton collimation system. We summarize recent upgrades and improvements and we review also a benchmark with measured data before finally discussing plans for future development.

Keywords

LHC; collimation; tracking simulations.

1 Introduction

The Large Hadron Collider (LHC) [1, 2] at CERN is designed to store and collide protons with an unprecedented beam energy of 7 TeV and a total stored energy of about 362 MJ per beam. For the upgrade of the LHC, HL-LHC [3], an increase of the stored energy to almost 700 MJ is foreseen. The LHC beams are highly destructive because of the high stored energy, and all beam losses must be tightly controlled. For this purpose, a multi-stage collimation system is used [1, 4–9], in order to intercept unavoidable beam losses in a safe way.

To assess the performance of the collimation system, a detailed understanding of the cleaning of beam protons by the collimators is needed. The collimators are not perfect absorbers and a certain fraction of the protons intercepted by the collimation system is outscattered and risks impacting on the cold magnets, where they could induce quenches. It is therefore crucial that the efficiency of the collimation system can be accurately modelled already on the design stage, in order to ensure that the accelerator is able to operate smoothly without lengthy interruptions caused by quenches or beam dumps.

Protons lost in the cold magnets have usually hit a collimator and afterwards have travelled some distance through the magnetic lattice of the ring—in many cases, protons are lost several turns after their first collimator impact. Therefore, we need accurate simulation tools that model both the tracking through the magnetic lattice as well as the particle-matter interaction inside collimators. The magnetic tracking is critical in particular because of the large amplitudes and energy deviations of the halo particles. SixTrack with collimation [10–14], which we in this paper simply call here "SixTrack", was developed for this purpose. In this paper, we review the functionality, status and future plans of this code.

2 Functionality and of SixTrack

SixTrack is a multi-turn tracking code, which takes the six-dimensional phase space into account in a symplectic manner [10–12]. SixTrack performs a thin-lens element-by-element tracking through the

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https://doi.org/10.23732/CYRCP-2018-002.1.

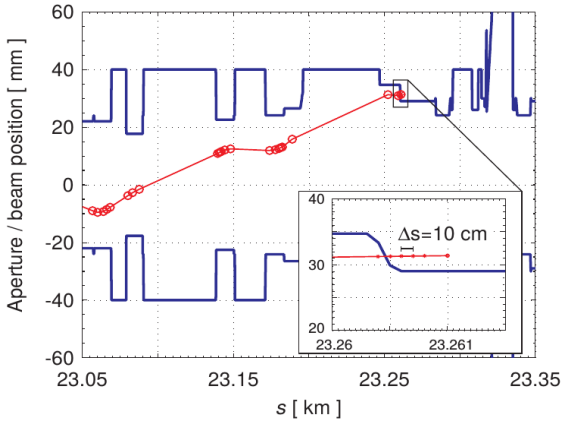

Fig. 1: Example of a halo particle (red line) that hits the LHC aperture (blue line) [17].

magnetic lattice, including multipoles up to order 20. Initially, SixTrack was developed for dynamic aperture studies where a very high numeric stability is needed when tracking particles over a large number of turns. During the design of the LHC, the K2 scattering routine was incorporated in SixTrack [13, 15]. When a particle is tracked around the magnetic lattice and encounters a collimator, this routine is called to simulate the particle-matter interaction inside the collimator material. SixTrack takes as input a database with information about all collimators (settings, material, length, angular orientation etc.), as well as a sequence of magnetic elements, which can be created by MAD-X [16]. This provides a tight integration with the LHC magnetic imperfection model.

The scattering routine accounts for multiple Coulomb scattering and ionization energy loss, as well as several point-like processes: nuclear elastic scattering, nuclear inelastic scattering, single diffractive scattering (treated separately from other inelastic processes), and Rutherford scattering. If a proton undergoes a nuclear inelastic interaction, which is not single diffractive, it is assumed that the proton disintegrates and it is considered lost on the collimator. The induced hadronic and electromagnetic showers are not modelled by SixTrack.

If any of the other physical processes takes place, where the interacting beam proton survives, the tracking continues through the collimator material. There is a possibility that the tracked proton can exit the collimator jaw, after having received kicks in energy and angle by the scattering processes. In this case, that proton is injected again into the magnetic tracking.

A particle is considered lost either when it undergoes an inelastic interaction, as detailed above, or if it hits the aperture. The particle trajectories are written out by SixTrack in all elements and checked in a post-processing step against a detailed aperture model with 10 cm longitudinal precision [17]. This requires a detailed aperture model of the machine. The aperture check is illustrated in Fig. 1, where both the interpolated trajectory and the aperture model are shown.

For simulations of beam cleaning, the starting conditions are particle coordinates in the halo, which have already an amplitude large enough to hit a collimator. The diffusion that initially sends particles onto the collimators is not modelled. This has the advantage that it is possible to track many millions of halo particles to achieve sufficient statistics so that losses significantly below the quench level can be resolved, and also at less exposed locations. Typically, at least 6.4×10^6 halo protons are tracked for 200 turns. If the simulation would include diffusion and track the full beam core, the needed computing time would rise by many orders of magnitude and the simulation would become impractically long. On the other hand, a full beam distribution is tracked for other applications, such as failure studies.

The simulation output contains coordinates of all loss locations, which can be used either to directly assess the loss pattern and the cleaning efficiency, or as inputs to further simulation studies of energy deposition. An example of the simulated loss pattern is shown in Fig. 2, where the losses are

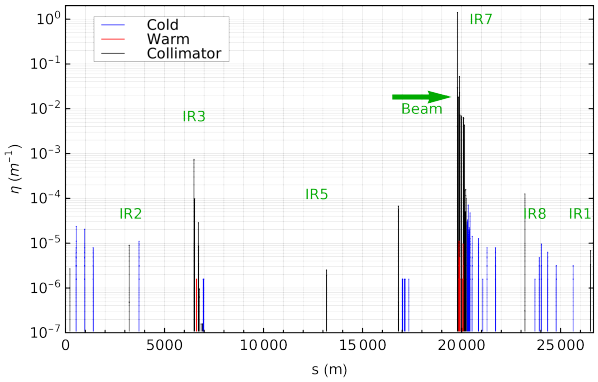

Fig. 2: Cleaning inefficiencies around the LHC obtained SixTrack, for a horizontal halo in B1, assuming the machine configuration used in the 2015 run of the LHC [18, 19].

expressed in terms of the local cleaning inefficiency η:

$$\eta = \frac{N_{\mathrm{loc}}}{N_{\mathrm{tot}}\Delta s}. \tag{1}$$

Here N_{loc} is the local losses over a distance Δs and N_{tot} is on total losses on collimators.

3 Recent improvements

Several improvements have recently been implemented in SixTrack with collimation, which we summarize below.

In the original version of SixTrack, the starting distribution was generated at IP1, at the start of the ring. The matched phase space in the collimation plane is populated uniformly in a thin segment around the normalized betatron amplitude corresponding to the TCP half opening. The shape in phase space is thus a thin hollow ellipse. This has the disadvantage that not all protons hit the primary collimator on the first turn. The halo can then deform due to non-linear fields such as sextupoles, which makes it difficult to control well the impact parameters.

Therefore, a new type of halo has been implemented, which we call direct halo [20]. The starting conditions are then created directly at the collimator. It is identical to the annular halo except that particles in the collimation plane are generated only in the areas of the phase space that are outside the collimator cuts. Thus, with the direct halo, all halo particles hit the TCPs on the first turn, so that the impact distribution on the TCPs is much easier to control and it is usually also more efficient in terms of computing time. Example distributions of the phase space at the TCP for the two cases are shown in Fig. 3.

Furthermore, some updates have been carried out on the K2 scattering routine [14]. The changes concern the proton-proton single diffractive cross section, considering a recent parametrization based on the renormalized pomeron flux exchange, the proton-nucleus inelastic and total cross sections, using recent data from the Particle Data Group, and the proton-proton elastic cross section, based on TOTEM data. Furthermore, the carbon material properties have been revised based on the composite material used in the collimators. The ionization energy loss and the multiple Coulomb scattering models have also been improved.

The scattering routine must also handle all possible materials of LHC collimators. The present system contains jaws made of carbon fibre composite (CFC), tungsten, or copper. For HL-LHC, it is planned to install collimators made of new advanced materials for improved impedance and robustness [22]. In order to estimate the cleaning performance with these new materials, they have been recently implemented in the SixTrack scattering routine [23, 24].

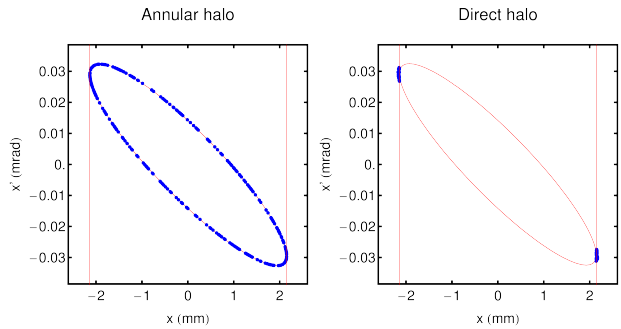

Fig. 3: Examples of the horizontal phase space of the starting distributions at the TCP for annular halo (left) and direct halo (right). Each blue point represents a single particle, and the red ellipse the matched 5.7 σ envelope. The vertical red lines represent the cuts of the TCP jaws. The figure is taken from Ref. [20] under the creative commons license [21].

As an alternative to the built-in scattering routine, the option of linking SixTrack to the particle physics Monte-Carlo code FLUKA [25, 26] has been implemented, the so-called SixTrack-FLUKA coupling [27–29]. The details of this are, however, beyond the scope of this paper, since another contribution to these proceedings is dedicated to this [30]. SixTrack has also been linked to the MERLIN scattering library [31, 32], as well as to Geant4 [33, 34]. Several scattering models are therefore available to the user, and a comparison of them can be found in Ref. [35].

The choice of scattering model can be particularly important for new regimes in energy, such as for the Future Circular Collider [36], for which SixTrack is also used to assess the collimation performance [37]. These studies triggered further improvements and generalizations to SixTrack, e.g. to handle machines with a very large number of elements, as well as automatic calculations of global inefficiencies for the off-momentum halo. Further details on these studies are given in another article in these proceedings [38].

Another important update concerns the check of losses against the aperture model, which in the original SixTrack version was done using post-processing, as described above. A new implementation does this aperture check online, within the main SixTrack code. This allows an improvement in terms of needed computing time, and a less complex simulation setup. However, the possibility of using the same trajectories with many random imperfections on the aperture is lost. This can however be done with yet another improvement, which writes the trajectories into a more efficient binary format (HDF5) instead of as a text file [39].

There has also been a recent implementation in the main version of SixTrack of a dynamic kick module, called DYNK [40, 41], which allows settings of machine elements, such as magnets or RF cavities, to be changed dynamically during the simulation. A detailed description of the present state of this functionality is given in Ref. [41], however, we highlight in this paper that the DYNK module can be used to extend the range of applications of SixTrack with collimation.

For example, certain beam failures such as asynchronous beam dumps can now be simulated with SixTrack. During an asynchronous beam dump, the extraction kickers fire at the wrong moment, when beam is passing. This means that the protons moving through the kicker fields receive intermediate kicks, which risk sending them directly onto sensitive elements without hitting the primary collimators first. This accident scenario has been very important for the LHC, since the risk of damaging machine components has limited the reach in β^* [42, 43]. With the DYNK module, the rising field of the misfiring extraction kickers can be included in SixTrack. Since every passing bunch would receive a different kick, many bunches are simulated separately and the results are summed in the end. An example of the simulated loss distribution is shown in Fig. 4.

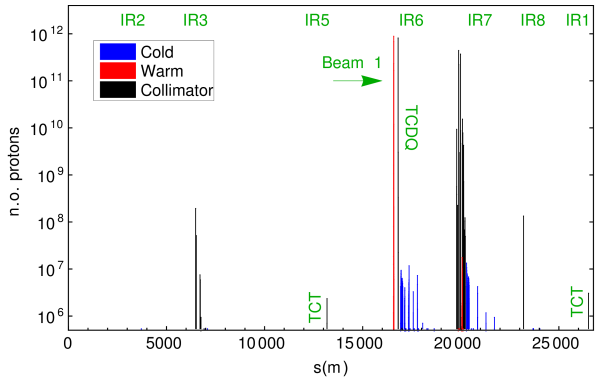

Fig. 4: Loss distribution around the LHC ring for B1 during an asynchronous beam dump, as simulated with SixTrack using the DYNK module for the 2015 standard physics configuration. Only 20 bunches, which are kicked onto amplitudes where they risk to damage equipment in the ring, were simulated and summed. If all bunches would be included, higher losses would be expected in IR6. The figure is taken from Ref. [43] under the creative commons license [44].

Another use of the DYNK module is to simulate the losses occurring during a shift of the RF frequency, similarly to what is performed operationally when the off-momentum cleaning is qualified with loss maps. These studies are described in detail in another paper of these proceedings [45]. Further applications include failures of crab cavities in HL-LHC [46–48].

Furthermore, alternative collimation schemes can be studied with SixTrack, which has required updates to the code. Firstly, the scheme of using a bent crystal instead of a standard primary collimator has been investigated [49]. If a proton hits the crystal at a specific angle, it can travel in the potential well between the parallel planes of the crystal, with a very small probability of interacting. Since the planes are bent, the proton can exit the crystal with a significant angular offset, which is enough to make the proton hit a downstream absorber with a large impact parameter. In order to simulate this collimation scheme, physics routines for the proton-crystal interaction have been implemented, with details given in Refs. [50, 51].

Another new collimation scheme under study is the use of a hollow electron lens to increase the diffusion speed of the halo, inside the cut of the primary collimator [52–56]. This allows depletion of the halo in a controlled way, thus avoiding spurious dumps if beam is scraped on the primary collimators during orbit jitters. SixTrack studies on this collimation scheme are being set up, and the hollow electron lens has been implemented as an element in SixTrack. A rich simulation program is planned to fully explore the performance.

Finally it should also be noted that an effort has been made to perform collimation studies with heavy ions using SixTrack, where the main difficulty arises from the different particle-matter interaction of heavy ions. A first approach used starting conditions from FLUKA of scattered and fragmented ions exiting the primary collimator and assumed all downstream collimators to be perfect absorbers [57]. A further development of the heavy-ion simulations included new tracking maps in SixTrack for heavy ions, based on a Hamiltonian formalism that includes both the mass and the charge of the particles [58], and also a full coupling with FLUKA to have particle-matter interactions sampled online in all collimators, as for protons. More details are given in Ref. [59].

Apart from the more extensive updates described above, an active development has recently led to improved output files that store more information of the history of the protons, as well as various optimizations, simplifications, and fixes of the collimation routines and sanity checks of the inputs.

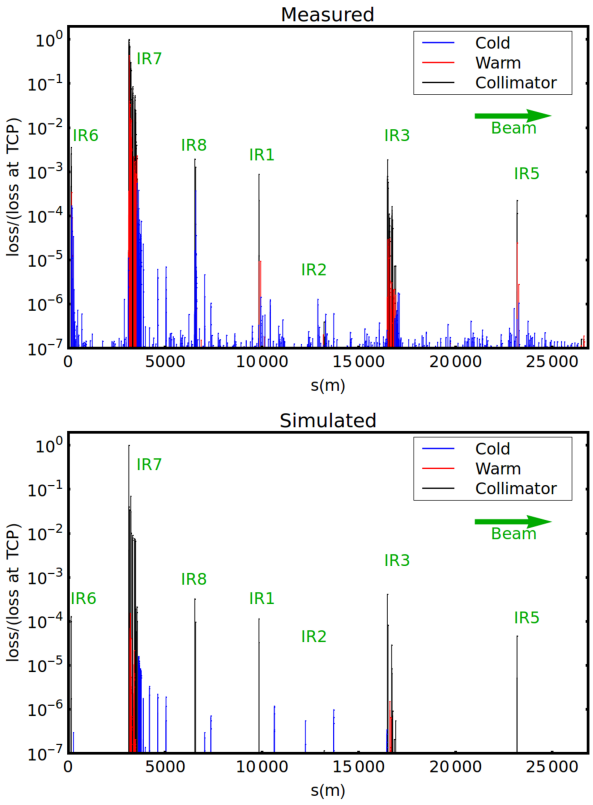

Fig. 5: Distributions of beam losses in the LHC ring as measured by BLMs during a 2011, (top) and from a SixTrack simulation (bottom), for the 2011 LHC machine configuration at 3.5 TeV and β^*=1.5 m. The simulation and measurement are both normalized to the highest loss, and the initial losses occur in the horizontal plane in B1. The figure is taken from Ref. [20] under the creative commons license [21].

4 Comparison with data

In order to be confident in the predictions by SixTrack for future accelerators, it is important to demonstrate its reliability by comparing to data from the present LHC. This is a continuous effort, which started when the first LHC data became available and is still ongoing. We summarize here one such comparison that was performed in Ref. [20].

In the lower part of Fig. 5, we show the simulated losses from SixTrack around the ring, for the case of a perfect machine without errors, using the 2011 machine configuration with a beam energy of 3.5 TeV and β^*=1.5 m. A 1 m binning of the the simulated losses has been used, except at the TCPs, which are considered as separate bins although they are only 60 cm long.

This simulation result is shown together with an example of measured losses during a qualification loss map, where controlled losses were excited with a low-intensity beam by approaching the third order resonance. It can be seen in Fig. 5 that there is a very good qualitative agreement between the measurement and the simulation. The highest losses occur at the collimators in the betatron cleaning insertion IR7 and the second most important loss location is the momentum collimators in IR3. The TCTs upstream of the experiments, as well as the beam dump protection collimators in IR6, also intercept significant losses. It can be seen that the simulation predicts all potentially limiting cold loss locations.

It should be noted, however, that there are some significant quantitative deviations between simulations and measurements, for example at the TCTs. In order to understand this, we note that the BLMs do not measure the direct proton losses that are shown for the simulation, but instead the shower particles produced by the primary losses. The BLM signal per locally lost proton could vary significantly between

loss locations, depending on the local geometry, materials, BLM location with respect to the loss position, and the spatial and angular distribution of the losses. Because of that, one cannot expect a high level of quantitative agreement when comparing the weighted convolution of all upstream showers in a BLM with the loss locations of primary beam protons. To do a quantitative comparison, it is therefore necessary to simulate also the showers in a second step, using e.g. FLUKA.

The details of such a comparison is shown in Ref. [20]. It is demonstrated that, if imperfections are included in SixTrack, a quantitative agreement within a factor 2–3 can be obtained between simulated and measured BLM signals for cleaning losses. More recent studies using the SixTrack-FLUKA coupling and a more updated FLUKA geometry for the shower simulation show a similar level agreement for the perfect machine [60]. An agreement of a factor 2–3 is also seen when comparing the SixTrack simulations of asynchronous dumps with BLM data [43,61]. In these cases, no dedicated FLUKA simulation was performed, but the BLM response was instead estimated from dedicated beam measurements [62].

The level of obtained agreement is still considered a very good, given the high complexity of the simulation chain, the many unknown imperfections, and the fact that the loss levels around the ring span 7 orders of magnitude. Nevertheless, this uncertainty should be kept in mind in the design of future machines when relying on SixTrack results.

5 Summary and outlook

We have given a summary of the functionality and status of the collimation version of SixTrack, which has been the standard tool for quantifying the collimation cleaning performance of the LHC. SixTrack has been shown to produce accurate loss patterns within the expected uncertainties, but further improvements are still possible. The development of SixTrack continues, and future work includes deeper studies of the scattering model and detailed comparisons to other codes, as well as general improvements in the code structure, input and output files, and a merging of different branches of SixTrack with special functionalities into one main version. The work on halo modelling continues as well, and it is planned to implement a general halo sampling that could also produce starting conditions for simulations of off-momentum collimation. Other important topics for future work are to adopt it better for large-scale simulations, using e.g. the BOINC system [63] with access to thousands of CPUs in parallel, and to continue and refine the comparison with data for other machine configurations.

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