SixTrack FOR CLEANING STUDIES: 2017 UPDATES

A. Mereghetti*, R. Bruce, F. Cerutti, R. De Maria, A. Ferrari, M. Fiascaris, P. D. Hermes,
D. Mirarchi, E. Quaranta, S. Redaelli, D. Sinuela Pastor, K. N. Sjobak, V. Vlachoudis,
CERN, Geneva, Switzerland
J. Molson, LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
Y. Zou, IHEP, Beijing, China, P. Garcia Ortega, University of Salamanca, Salamanca, Spain

Abstract

SixTrack is a single particle tracking code for simulating beam dynamics in ultra-relativistic accelerators. It is widely used at the European Organisation for Nuclear Research (CERN) for predicting dynamic aperture and cleaning inefficiency in large circular machines like the Super Proton Synchrotron (SPS), the Large Hadron Collider (LHC) and the Future Circular Collider (FCC). The code is under continuous development, to both extend its physics models, and enhance performance.

The present work gives an overview of recent developments, specifically aimed at extending the code capabilities for collimation studies. They mainly involve: the online aperture check; the possibility to perform simulations coupled to advanced Monte Carlo codes like FLUKA or using the scattering event generator of the Merlin code; the generalisation of tracking maps to ion species; the implementation of composite materials of relevance for the future upgrades of the LHC collimators; the physics of interactions with bent crystals. Plans to merge these functionalities into a single version of the SixTrack code will be outlined.

INTRODUCTION

SixTrack [1–4] is a tracking code for simulating transverse and longitudinal single particle beam dynamics. It is widely used at CERN for predicting dynamic aperture in large storage rings [5] like the Large Hadron Collider (LHC) [6] or its upgrade as foreseen by the High Luminosity LHC Project (HL-LHC) [7, 8]. The code was extended [9] to predict the performance of a collimation system in terms of loss pattern and cleaning inefficiency. Nowadays, it is regularly used for optimising the performance of existing cleaning systems, like those of the LHC [10] or of the Relativistic Heavy Ion Collider (RHIC) at BNL [11]. SixTrack is also an essential tool for the design of future cleaning systems, like the one for off-momentum cleaning being designed for the Super Proton Synchrotron (SPS) at CERN [12], or the upgrade of that of LHC in the context of the HL-LHC project [7, 8, 13], or the one proposed for the Future Circular Collider (FCC) [14].

The code is in continuous development [15], not only to improve its accuracy in predicting loss patterns in circular machines, but also to address the performance of novel technologies proposed for future cleaning systems. The present work gives an overview of recent developments, with examples of results.

COUPLING TO FLUKA

FLUKA [16, 17] is widely used for particle-matter interaction studies; at CERN, studies cover the entire accelerator complex. In the context of collimation studies the focus is mainly on collimators and nearby equipment, e.g., energy deposition in downstream superconducting magnets or signals induced in Beam Loss Monitors (BLMs). Studies used to be carried out by loading in FLUKA losses at collimators previously estimated with SixTrack [9].

An active coupling between FLUKA and SixTrack has been recently set up [18], where the two codes run separately while communicating with each other via a TCP/IP communication protocol [19]. Hence, the accurate tracking through accelerator lattices of SixTrack is combined with the detailed physics of particle-matter interactions of FLUKA, and multi-turn effects, relevant for collimation studies, can be simulated in great detail. The same detailed collimator geometries and material definitions used for the energy deposition calculation are deployed; moreover, being the scattering physics the same in both simulation stages, the degree of consistency of results is greatly increased. In addition, as input to energy deposition calculations, the coupling generates the list of particles at their first impact on the collimation system at any turn. This allows to properly take into account single diffractive interactions and the contribution from ionisation to peak energy deposition values in collimators, which can be up to a factor 3 larger than what estimated in the past [20] for a mesh of 5 μm transversally and 1 cm longitudinally. The FLUKA-SixTrack coupling is now regularly used for generating input to energy deposition studies (e.g., see [21]). A recent benchmark of the accuracy of results generated with the coupling can be found in [22], for both proton and ion (see later) beams.

The system is flexible enough to allow for the on-line estimation of energy deposition, i.e. during tracking through the lattice. Moreover, the FLUKA geometry can be extended at will. Figure 1 shows a quantitative benchmark of BLM signals against measurements during tests of beam scraping in the SPS [23]. An external routine for beam sampling is available, with many types of distributions (e.g., double-Gaussian, linear scans in amplitude and angle, K–V and water-bag distributions [24]).

Essential for the on-line evaluation of energy deposition in devices, the mechanical acceptance of the machine is checked during tracking. The implementation extends what set up in the past [9], adding new shapes like the octagon (relevant for HL-LHC and FCC), and giving the possibility

---

* alessio.mereghetti@cern.ch

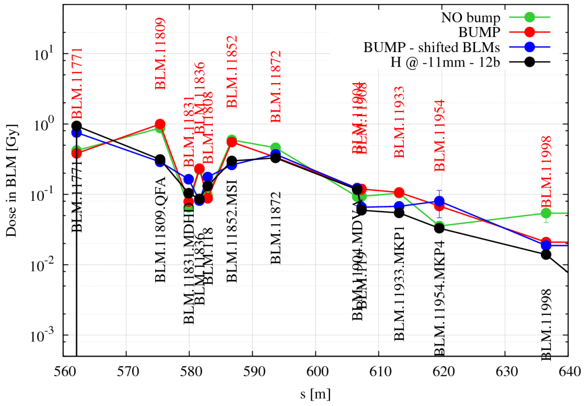

Figure 1: Benchmark of BLM signals estimated with the FLUKA-SixTrack coupling (colors represent different simulation settings) against measurements (black curve) during tests of beam scraping in the SPS [23].

to specify transverse offsets (horizontal and vertical) and angles about the longitudinal axis. The bisection method, faster than the original one, is used to determine the final loss point, down to any desired accuracy.

HEAVY-ION TRACKING

FLUKA, used as scattering engine, proved to give accurate results also with heavy-ion beams. As an example, during the LHC Pb-ion operation in 2015, it was possible to relate the high background measured in the Insertion Region (IR) 2 to a secondary ion beam generated in Electro-Magnetic Dissociation (EMD) reactions in the left jaw of the horizontal primary collimator in IR7. Simulations were carried out with the “SixTrack with Ion-Equivalent Rigidities” (STIER) [25], where the interaction of Pb ions with the collimator jaws are simulated in FLUKA, and the generated out-scattered particles are loaded in SixTrack and tracked by means of protons of equivalent magnetic rigidity.

The FLUKA-SixTrack coupling has been extended to deal with ion beams [25]; in particular, the tracking maps implemented in SixTrack had to be generalised to treat ions of any species. This version of the coupling (Heavy-Ion SixTrack-FLUKA) has been applied to the design of the HL-LHC collimation system, considering also scenarios of beams made of other ion species [25].

OTHER SCATTERING ENGINES

SixTrack is being extended [26] importing scattering engines different from the original one. Presently, those implemented in Merlin [27] or in Geant4 [28] have been ported [26]. This approach allows to re-use a long-standing simulation set up (i.e. the native SixTrack for collimation studies) while exploring results from different scattering models. Moreover, being the scattering engines embedded in the SixTrack executable without external codes to be coupled with, they are suitable for running cleaning studies with the BOINC platform for volunteer computing [29]. In addition, the collimation code has been separated from the rest and a general clean-up is under way [26, 30].

As an example, Fig. 2 compares the average local cleaning inefficiency downstream of the LHC betatron collimation system as from the original scattering routine of SixTrack, the Merlin engine, and the FLUKA-SixTrack coupling [31]. These results indicate an overall good agreement between the different codes and an indirect validation of the original version of the scattering, recently updated [32].

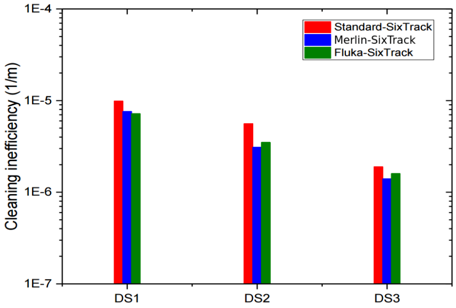

Figure 2: Average local cleaning inefficiency at the main clusters of losses downstream of the betatron collimation system (DS1 and DS2) and upstream of the momentum one (DS3) as predicted by SixTrack with two different scattering engines and by the FLUKA-SixTrack coupling [31]. The results were obtained for cleaning horizontal tails of Beam 2 in the case of 2016 LHC configuration with squeezed beams.

COMPOSITE MATERIALS

In the context of the HL-LHC upgrade, an intense R&D programme has been launched, to identify jaw materials with low impedance while standing the higher damage potential of HL-LHC beams. The most interesting materials under consideration are compounds [33], and the original scattering routine implemented in SixTrack had to be modified, since it only dealt with elemental materials.

An approximated treatment was implemented [34], such that the physics of particle-matter interactions is simulated on fictitious materials, the physical properties of which are weighted averages calculated on the components. This treatment is applied not only to events involving the bulk material (e.g., ionisation and multiple Coulomb scattering), but also to point-like nuclear interactions. A careful benchmark against Merlin [35] has shown that no relevant differences are found for collimation studies. This treatment was extensively used to characterise, in terms of cleaning inefficiency and absorption capability, the performance of the HL-LHC collimation system when different jaw materials were considered for the secondary collimators [34,36], which account for a relevant fraction of the overall impedance budget [37].

Figure 3 shows an example of application of the discussed implementation to the optimisation of material and length of the FCC primary collimators [38].

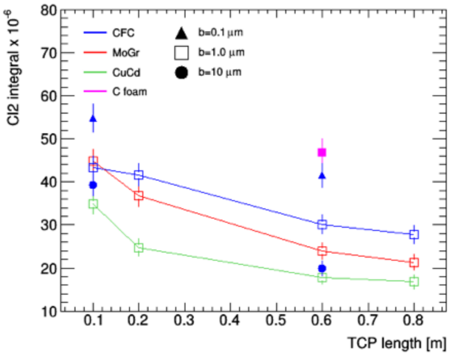

Figure 3: Local cleaning inefficiency in the second cluster of losses downstream of the betatron collimation system proposed for FCC as a function of material and length of primary collimators [38]. *b* is the average impact parameter, i.e. the average depth at which particles hit the collimator jaw.

CRYSTAL CHANNELLING

The deployment of crystals as primary collimation stage is a promising solution to substantially reduce the impedance of the collimation system and the local cleaning inefficiency downstream of the collimators. The physics of crystal channelling and related phenomena have been already imported in SixTrack [39] and recently updated [40, 41]. The original routine was benchmarked against single pass measurements; its update was also benchmarked against data taken in SPS [41]. When applied to the LHC [41] (see Fig. 4), crystals are expected to improve the cleaning inefficiency by a factor of 10 with respect to the regular cleaning system. Crystals were installed in the LHC during the Long Shutdown 1 (LS1) on Beam 1, and first promising measurements were taken in 2015 and 2016 [42, 43]. Installation on Beam 2 took place during the 2016 Extended Year End Technical Stop.

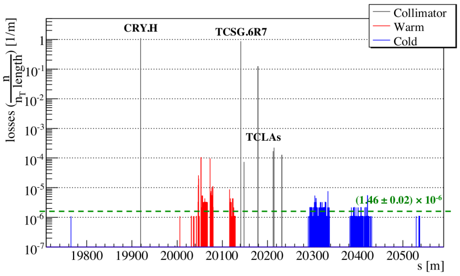

Figure 4: Losses in the region of the LHC collimation system at 6.5 TeV as predicted by SixTrack for a horizontal crystal in channeling orientation and one secondary collimator [41].

ELECTRON LENSES

The deployment of electron lenses [44] as tool for depleting tails in a controlled way is another appealing solution to enhance the collimation performance by actively controlling loss rates of halo losses and by controlling the static tail population [45]. Simulations play a key role in optimising the performance of the system. The original implementation in SixTrack allowed to have first simulation results for the SPS [46]. A review of the code has recently started [30].

CONCLUSIONS AND OUTLOOK

SixTrack for collimation studies has demonstrated a high degree of reliability, accuracy and flexibility. Nevertheless, many of the lines of development are not under the same revision tracking system. Hence, it is planned to port them under github [47], the revision tracking service where the main code release is maintained.

Priority will be given to importing the on-line aperture checking, extending it to thick tracking [48]. This is necessary to run CPU-intensive cleaning studies (e.g., for electron lenses or for crystals when used in amorphous orientation) on the BOINC platform for volunteer computing.

All the other implementations not yet incorporated in the main SixTrack release will follow, starting from the FLUKA-SixTrack coupling and the extension of the tracking maps to ion species. At the same time, the various methods presently available for sampling the initial beam distribution will be unified, with the routine of the FLUKA-SixTrack coupling taken as basis. The physics of interactions with bent crystals will be incorporated as well. Finally, a major merging of the code for collimation studies into native variables and functions will be performed.

REFERENCES

[1] F. Schmidt, "SixTrack version 4.2.16 single particle tracking code treating transverse motion with synchrotron oscillations in a symplectic manner", CERN, Geneva, Switzerland, Rep. CERN/SL/9456, 2012.

[2] G. Ripken and F. Schmidt, "A symplectic six-dimensional thin-lens formalism for tracking", CERN, Geneva, Switzerland, Rep. CERN/SL/95–12(AP), 1995.

[3] R. De Maria *et al.*, in *Proc. IPAC'13*, pp. 948–950.

[4] SixTrack, `http://sixtrack.web.cern.ch/SixTrack`

[5] M. Giovannozzi *et al.*, in *Proc. IPAC'15*, pp. 705–709.

[6] O. Brüning *et al.* (eds), "LHC design report", Vol. I, CERN, Geneva, Switzerland, Rep. CERN-2004-003-V-1, 2004.

[7] O. Brüning, L. Rossi (eds.), "The High Luminosity Large Hadron Collider", World Scientific Press, 2015.

[8] G. Apollinari, I. Bejar Alonso, O. Brüning, M. Lamont, L. Rossi (eds.), "High Luminosity Large Hadron Collider (HL-LHC) Technical Design Report V.01", CERN, Geneva, Switzerland, EDMS n. 1723851 v.0.71, `https://edms.cern.ch/ui/file/1723851/0.71/HL_TDR_V07.0.2016.10.05.Version15.2h.pdf`

[9] G. Robert-Demolaize, R. Assmann, S. Redaelli, F. Schmidt, in *Proc. PAC'05*, pp. 4084–4087.

[10] R.W. Assmann *et al.*, in *Proc. EPAC'06*, pp. 986–988.

[11] G. Robert-Demolaize and A. Drees, "Simulations of collimation losses at RHIC", in *Proc. Tracking for Collimation Workshop*, CERN, Geneva, Switzerland, Oct. 2015, unpublished.

ISBN 978-3-95450-182-3

[12] M. Patecki, A. Mereghetti, D. Mirarchi, and S. Redaelli, "SPS collimation studies", presented at the SLAWG meeting, 5th Apr. 2017, CERN, Geneva, Switzerland, https://indico.cern.ch/event/621754/contributions/2507952/attachments/1440650/2217920/sps_coll_SLAWG_mpatecki_5apr17.pdf

[13] D. Mirarchi *et al.*, in *Proc. IPAC'16*, pp. 2494–2497.

[14] M. Fiascaris, R. Bruce, D. Mirarchi, and S. Redaelli, in *Proc. IPAC'16*, pp. 2423–2426.

[15] S. Redaelli (ed.), "Proceedings of the tracking for collimation workshop", CERN, Geneva, Switzerland, Oct. 2015, unpublished.

[16] A. Ferrari, P.R. Sala, A. Fassò, and J. Ranft, "FLUKA: a multi-particle transport code", CERN, Geneva, Switzerland, Rep. CERN-2005-010, Oct 2005.

[17] G. Battistoni *et al.*, "Overview of the FLUKA code", *Ann. Nucl. Energy*, vol. 82, pagg. 10–18, 2015.

[18] A. Mereghetti *et al.*, in *Proc. IPAC'13*, pp. 2657–2659.

[19] FlukaIO, twiki.cern.ch/twiki/bin/view/FlukaTeam/FlukaIO

[20] E. Skordis, "Effect of non-inelastic interactions (EM and nuclear elastic) of primary protons in TCP", presented at the LHC CWG meeting, 7th Mar. 2016, CERN, Geneva, Switzerland, https://indico.cern.ch/event/504706/contributions/1182927/attachments/1239673/1824598/2016_-_07_-_03_Collimation_Working_Group_-_TouchesVsInelastic_-_E._Skordis.pdf

[21] M.I. Besana *et al.*, "Energy deposition in the betatron collimation insertion of the 100 TeV Future Circular Collider", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper MOPAB003, this conference.

[22] E. Skordis *et al.*, "Study of the 2015 top energy LHC collimation quench tests through an advanced simulation chain", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper MOPAB012, this conference.

[23] A. Mereghetti, "Performance evaluation of the SPS scraping System in view of the High Luminosity LHC", Ph.D. thesis, University of Manchester, Manchester, UK, 2015.

[24] Y. Papaphilippou and N. Catalan Lasheras, "Phase space concepts", presented at the USPAS, 20th Jun. – 1st Jul. 2005, Cornell University, Ithaca, NY, US, https://yannis.web.cern.ch/yannis/teaching/phasespace.pdf

[25] P.D. Hermes, "Heavy-ion collimation at the Large Hadron Collider - simulations and measurements -", Ph.D. thesis, University of Münster, Germany, 2016.

[26] J. Molson *et al.*, "A Comparison of interaction physics for proton collimation systems in current simulation tools", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper WEOBA1, this conference.

[27] R.B. Appleby, R.J. Barlow, J.G. Molson, M. Serluca, and A. Toader, "The practical pomeron for high energy proton collimation" Eur. Phys. J. C, vol. 76, p. 520, October 2016.

[28] S. Agostinelli *et al.*, "Geant4 – a simulation toolkit", Nucl. Instrum. and Methods A, vol. 506, p. 250–303, July 2003.

[29] M. Giovannozzi *et al.*, in *Proc. IPAC'12*, pp. 505–507.

[30] K. Sjobak *et al.*, "New features of the 2017 sixTrack release", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper THPAB047, this conference.

[31] Y. Zou et al, "Checks of Merlin scattering routine in SixTrack for LHC", presentation at the LHC CWG, 21st Apr 2017, CERN, Geneva, Switzerland, https://indico.cern.ch/event/623918/contributions/2517825/attachments/1430976/2198075/Preliminary_comparison_among_three_versions_of_SixTrack_YeZou.pdf.

[32] C. Tambasco, "An improved scattering routine for collimation tracking studies at LHC", MS.C. thesis, Universitá La Sapienza, Roma, Italy, 2013.

[33] A. Bertarelli *et al.*, "Thermo-physical and mechanical characterisation of novel materials under development for HL-LHC beam-intercepting devices" presented at IPAC'17, Copenhagen, Denmark, May 2017, paper WEPVA113, this conference.

[34] E. Quaranta *et al.*, in *Proc. IPAC'15*, pp. 2068–2071.

[35] A. Valloni *et al.*, in *Proc. IPAC'16*, pp. 2514–2517.

[36] E. Quaranta, "Investigation of collimator materials for the High Luminosity Large Hadron Collider", Ph.D. thesis, Politecnico di Milano, Milano, Italy, to be published.

[37] N. Mounet *et al.*, in *Proc. IPAC'13*, pp. 1817–1819.

[38] M. Fiascaris, R. Bruce, S. Redaelli, "Collimation system status", in *EuroCirCol Meeting*, 7th–9th November 2016, Barcellona, Spain.

[39] V. Previtali, "Performance evaluation of a crystal-enhanced collimation system for the LHC", Ph.D. thesis, EPFL, Lausanne, Swuitzerland, 2010.

[40] D. Mirarchi *et al.*, in *Proc. IPAC'14*, pp. 886–889.

[41] D. Mirarchi, "Crystal collimation for LHC", Ph.D. thesis, Imperial College, London, UK, 2015.

[42] R. Rossi *et al.*, "Status of crystal collimation studies at the LHC", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper MOPAB007, this conference.

[43] W. Scandale *et al.*, "Observation of channelling for 6500 GeV/c protons in the crystal assisted collimation setup for LHC", *Phys. Lett. B*, vol. 758, pp. 129–133, 2016.

[44] V. Shiltsev, "Electron Lenses for Super-Colliders", Springer, 2016.

[45] S. Redaelli *et al.*, in *Proc. IPAC'15*, pp. 2462–2465.

[46] V. Previtali, G. Stancari, A. Valishev, and S. Redaelli, in *Proc. IPAC'13*, pp. 990–992.

[47] SixTrack GitHub Repository, https://github.com/SixTrack/SixTrack

[48] A. Mereghetti, R.De Maria, M. Giovannozzi, and S. Redaelli, "Overview of needs for SixTrack on-line aperture check", presentation at the HSS section meeting, 8th Mar 2017, CERN, Geneva, Switzerland, https://indico.cern.ch/event/618960/contributions/2498367/attachments/1424029/2183686/2017-03-07_AM.pdf