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FLUKA coupling to Sixtrack

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Abstract

SixTrack [1] and FLUKA [2,3] are simulation tools regularly used at CERN to perform LHC collimation studies. Until recently the communication between the two codes was weakly based on the use of file exchange. The present paper describes the current status of the FLUKA – SixTrack coupling, a TCP/IP interface to provide seamless communication between them and to finally behave like a single running program.

Keywords
FLUKA, SixTrack, coupling, collimation losses

1 Introduction

SixTrack is a single particle tracking code for long-term, 6D tracking in high-energy rings, while FLUKA is a general-purpose particle physics Monte Carlo code used in particular for machine protection, design of accelerator components, radiation to electronics (R2E), activation, and collimation studies. These imply energy deposition calculation with description of electro-magnetic (EM) showers as well as account of multi-turn effects and call for a synergy between the two codes. The standard work path for predicting collimation loss maps up to now required a dedicated version of SixTrack complemented with simplified interaction routines [4]. These loss maps, consisting of primary inelastic interactions, were provided to FLUKA to describe the particle shower development by microscopic models. The FLUKA-SixTrack coupling aims at combining the two codes and using each one in the respective domain of application.

1.1 History

The idea of the coupling dates back to 2006, when a first version was created by V. Vlachoudis using a toy tracker (single-turn matrix) communicating with FLUKA through network ports. That system was based on the assumption that the tracking was faster than FLUKA, so emphasis was given on the creation of a dedicated server that was weight balancing the work load of multiple tracker and FLUKA clients. In 2007, S. Gilardoni and R. Bruce developed another solution, in which FLUKA was called as system routine inside IcoSim [5], a MatLab-based tracker featuring a complete 4D tracking implementation (up to sextupoles, with no higher-order multipoles, no skew elements/solenoids/crab cavities…). The coupling code was working through file exchange and was performing a full FLUKA run on each turn. The initialization of FLUKA on each turn was inducing an excessive overload in the tracking time.

The present coupling is based on the FlukaIO library created in 2010 by V. Vlachoudis and D. Sinuela Pastor, i.e. an independent C++ TCP/IP library allowing the communication of any tracking code with FLUKA (or other Monte Carlo code). The first application was performed by F. Cerutti and A. Mereghetti for the SPS scrapers with the use of IcoSim and FLUKA [6]. Thanks to the further work of P. Hermes, A. Mereghetti, P.G. Ortega and V. Vlachoudis in the context of the LHC Collimation Working Group [7], the code was extended to SixTrack with main focus on LHC applications.

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2 Motivation and benefits

The coupling defines a clean separation line between the two codes:

- Particle tracking through the accelerator lattice is performed by SixTrack
- Beam-matter interaction is simulated by FLUKA

This allows a realistic multi-turn approach with the state-of-art account of physics processes, leading to more accurate predictions. It avoids rough simplifications in the modelling of complex interactions such as single-diffractive scattering or ion dissociation and fragmentation. It limits human intervention (removing the need to manually check every time file content, adopted units, etc.), as a consequence the overall process is less error-prone. It can handle moving beam-intercepting devices runtime, with the possibility to use any roto-translation of 3D geometries, and it can deal with energy ramping. Last but not least, it can benefit from the regular development of both codes and their tools.

Furthermore, the FLUKA-SixTrack coupling becomes very attractive when dealing with heavy ions and, in perspective, crystal channelling, as discussed in the following.

2.1 Heavy ion beams

Heavy ions when passing through matter, as in the collimator jaws, can undergo both electromagnetic dissociation and nuclear inelastic interactions, typically leading to lighter fragments that can in turn re-interact in the collimator materials. It is not enough to know the probability for generating a given fragment, since its momentum is not fixed. This makes fragments nominally far from the nominal beam rigidity to fall in reality inside the machine acceptance (e.g., tritium ions). Moreover, the cross sections are energy dependent and ionization plays for ions a non-negligible role in changing their energy along their path in matter. The energy loss evaluation needs a treatment significantly more sophisticated than a simplified Bethe formula, as adopted in some tracking codes. Landau fluctuations and Mott corrections have to be taken into account, as well as bremsstrahlung and pair production in addition [8]. Thus, the tracking of heavy ions requires a careful treatment and the coupling intrinsically overcomes all above issues, relying on their proper treatment.

2.2 Crystal channeling

The use of bent crystals for beam manipulation to different purposes, such as collimation, is an option actively pursued and systematically investigated on the LHC [9]. In this context, the development of a microscopic description of the coherent effects featuring their interaction with hadron beams, to be integrated in accelerator simulation tools of wide application, is a fruitful investment. This motivation triggered the recent implementation of crystal channelling in an event generator based on FLUKA that was benchmarked against the UA9 experiment data for proton beams [10]. The present version includes planar channelling of any positively charged particle, crystal torsion and miscut, nuclear interaction suppression, dechanneling, volume reflection and volume capture.

Figure 1 shows a comparison between a typical measurement and the current model, giving an overview of all the most relevant effects.

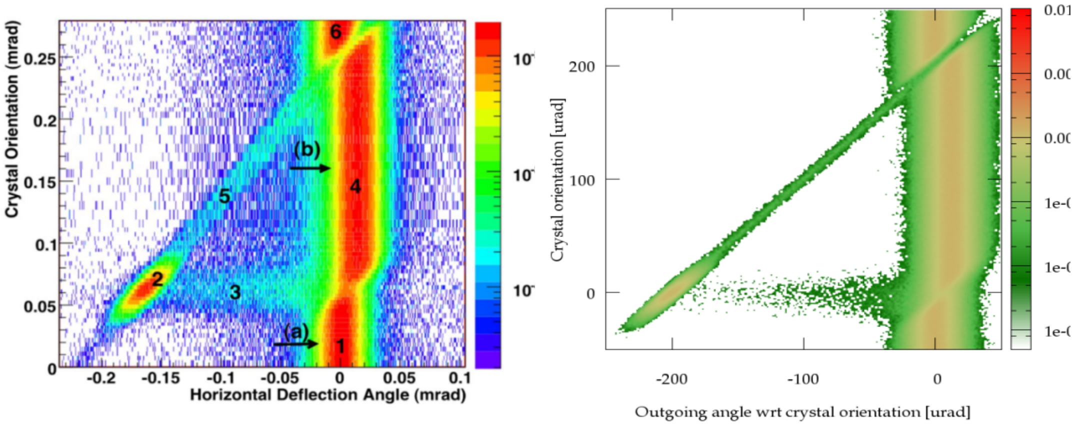

Fig. 1: Comparison of UA9 measurement [11] (left) and simulation (right).

3 Key ingredients

The FLUKA-SixTrack coupling requires a FLUKA input file describing the concerned insertion regions, even if they are restricted to the bare intercepting device of interest. Moreover, if a second simulation stage with FLUKA is required (e.g., to compute energy deposition in sensitive elements), then it is convenient that the same detailed geometries of beam-intercepting devices used in the second simulation stage are used also in the first one. Hence, the FLUKA input file for FLUKA-SixTrack coupling simulations is normally prepared with the FLUKA element database (FEDB) and the Line Builder [12]. These two tools provide a powerful way of building automatically beam line geometries perfectly complying with tracking requirements.

3.1 The FLUKA Element Database (FEDB)

We have been performing FLUKA calculations for the LHC machine since 2004. To optimize the workflow, we have created a dedicated database called "*FLUKA element database*", which nowadays consists of FLUKA models of relevant objects from all CERN accelerators starting from the LINAC injector up to the LHC (see an example in Fig. 2). It offers flexibility and ease in modelling accelerator components as standalone objects, crucial when adding additional degrees of detail, following the evolution of the design of future devices, or comparing different technical solutions. Moreover, it minimizes errors and duplication of work since all models are stored as common and shared resources under a revision tracking system (SubVersioN repository). Lastly, it offers portability, with prompt propagation of updates, as improvements are inherited by all the people concerned.

3.2 The Line Builder (LB)

The Line Builder [12] is a tool developed by A. Mereghetti, which allows to assemble FLUKA geometries of beam lines taking as input the accelerator lattice sequence, magnet strengths and optical parameters. It offers:

- flexibility, through the automatic synchronization with the machine optics, essential ingredient for a sound modelling of the line;
- consistency, protecting against wrong settings of the beam line, e.g. misplacements, wrong orientations, mismatches in magnetic fields and collimator aperture;
- portability, thanks to the automatic use of the last updates of the FEDB.

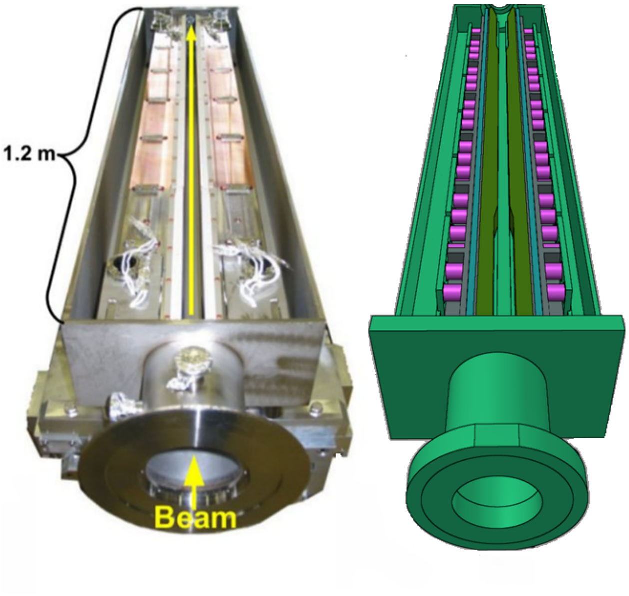

Fig. 2: An LHC collimator (left) and its FEDB model (right).

3.3 Users' settings

FLUKA simulations can be very CPU-intensive for detailed energy-deposition studies in large LHC geometries at *TeV* beam energies. This is because one has to apply low secondary particle production and transport cuts down to *MeV* energies or less, in particular for electrons, positrons and photons, and needs many fine-grained scoring meshes, to calculate point-like quantities that are necessary, for instance, to compare to quench levels or stress limits.

For tracking study purposes, CPU time can be quite significantly optimized by adopting high cuts and switching off unnecessary physics processes ($e^-/e^+/\gamma$ production and transport, inelastic collision product generation and transport). Transport thresholds must be carefully set in FLUKA, to properly describe particles which can still propagate in the machine, and hence contribute to the global loss map, while suppressing the local shower development, this way achieving sound results in reasonably short times.

4 Workflow

The coupling is a third-party library to the two codes (FLUKA and SixTrack) that allows the communication through the use of TCP/IP messages. FLUKA and SixTrack run at the same time in parallel, either on the same computer or different ones, talking to each other over the local network. One or more portions of the accelerator lattice are labelled for transport in FLUKA, whereas the rest is handled by SixTrack (Fig. 3). The beam particles are transported turn by turn by SixTrack throughout the lattice. When they reach a labelled element, they are transferred to FLUKA for transport in its 3D geometry, simulating the interaction with accelerator components. At the end of the FLUKA insert, marked by a geometry interface, particles are sent back to SixTrack. The exchange of particles is performed at run-time, through a network port using the dedicated FlukaIO library. This loop continues until the particles are either lost in the FLUKA portion or in the rest of the machine.

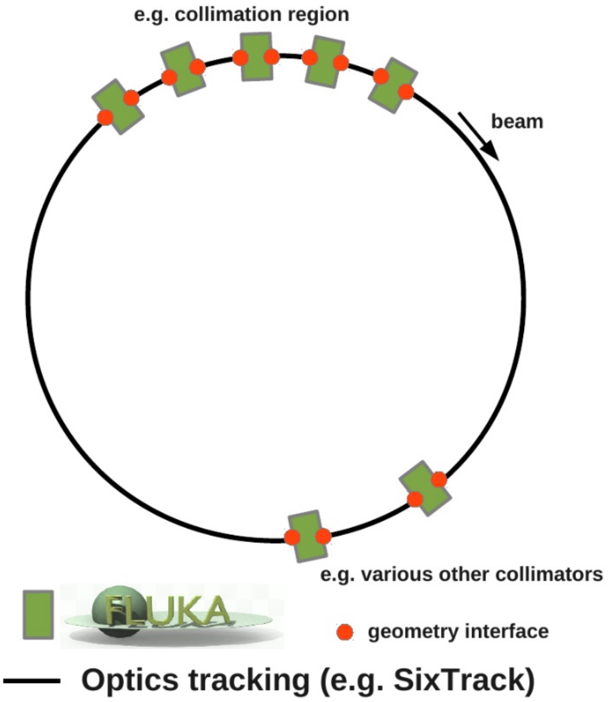

Fig. 3: Schematics of the SixTrack-FLUKA coupling.

5 Present Status

The present version of the code is able to perform the coupling with an accelerator lattice description in either thin or thick lenses. Both 4D and 6D tracking including RF acceleration are supported. More than one insertion and more than one element per insertion can be flagged for coupling. The starting beam distribution is provided by an external generator. Each particle is assigned a unique ID for off-line analyses of chained interactions in different collimators. The aperture checking must be performed on-line, otherwise unphysical particle distributions hitting beam-intercepting devices will be tallied. Hence, this is an essential ingredient for both loss maps around the ring and energy deposition onto beam-intercepting devices. The on-line aperture checking greatly expands the functionalities of the LIMI block native to SixTrack, including also the most common LHC aperture type RECTELLIPSE. Although pre-processing tools are used to prepare most of the necessary input files, it is the user's ultimate responsibility to guarantee the integrity of input information, e.g. the transformations from the local SixTrack reference system to the global one of FLUKA and vice-versa, as well as the length of the FLUKA geometry and the synchronous length declared in input to SixTrack (to correctly handle the longitudinal dynamics in the FLUKA insertions).

Additional features one can benefit from are: the application of dynamic kicks in SixTrack to magnetic elements, e.g. to simulate the raising of magnetic bumps or current ripples in power supplies; moving FLUKA bodies run-time, to simulate beam-intercepting devices with impact parameters varying with time; useful information dumps for monitoring the simulation progress and the evolution of key quantities of the beam being tracked; the use of complex 3D geometries of portions of beam lines, including also magnetic elements with their fields.

5.1 Repository

The necessary material (i.e. the coupling code, with the associated SixTrack and FLUKA user routines, the LB library and the FEDB) is available in a shared project space at

/afs/cern.ch/project/fluka through an access list. Otherwise, every repository (i.e. coupling, FEDB, LB) can be manually checked out by authorized users from the central CERN SVN service:

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svn co svn+ssh://svn.cern.ch/reps/fedb
svn co svn+ssh://svn.cern.ch/reps/LB
svn co svn+ssh://svn.cern.ch/reps/fluka_coupling
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6 LHC applications

It is often the case that a qualitative comparison of loss maps with Beam Loss Monitor (BLM) signal patterns is done to provide a first feedback on the loss locations and amplitude, especially when verifying the running configuration of the collimation system for data taking. However, for a quantitative benchmarking of the level of accuracy the simulation chain provides, a second especially meticulous step is required after the tracking, to proceed into full shower development simulations and evaluation of measurable quantities such as the BLM recorded dose.

Fig. 4 shows the FLUKA geometry of the LHC IR7 Long Straight Section (LSS) assembled with the use of the Line Builder and the FEDB, with which energy deposition simulations were carried out. For the collimator jaws and tanks, the same model is used for this second step as for the previous SixTrack-FLUKA coupling step, boosting the consistency between the two simulation steps. In order to properly evaluate the BLM signals and other quantities of interest, various machine elements have also been modeled in detail in FLUKA, such as the LSS warm dipoles and quadrupoles, passive absorbers, collimator supports, BLMs, tunnel walls, Super Conducting (SC) dipoles and quadrupoles, etc.

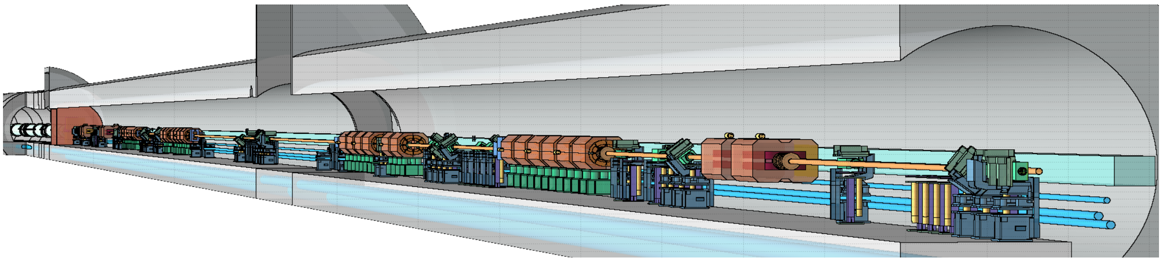

Fig. 4: LHC IR7 LSS FLUKA geometry visualised with Flair.

Fig. 5 shows the comparison between simulated BLM signals and measurements taken during the 2013 proton collimation quench test carried out at 4 TeV beam energy [13, 14]. The source term, i.e. the distribution of inelastic interactions at the collimators (including single diffractive events), was generated with the SixTrack-FLUKA coupling, as an alternative to the older approach using SixTrack with its embedded interaction models. In this case the two simulation approaches provide alike results, since the original proton loss distributions were pretty similar and BLMs are sensitive to the development of the secondary particle cascades, described by FLUKA in both simulation set-ups. An excellent agreement can be observed between simulated and experimental BLM signals for more than one hundred BLMs in the IR7 LSS with signals spanning over a few orders of magnitude, apart from an underestimation tendency in the Beam 2 active absorber region on the left end.

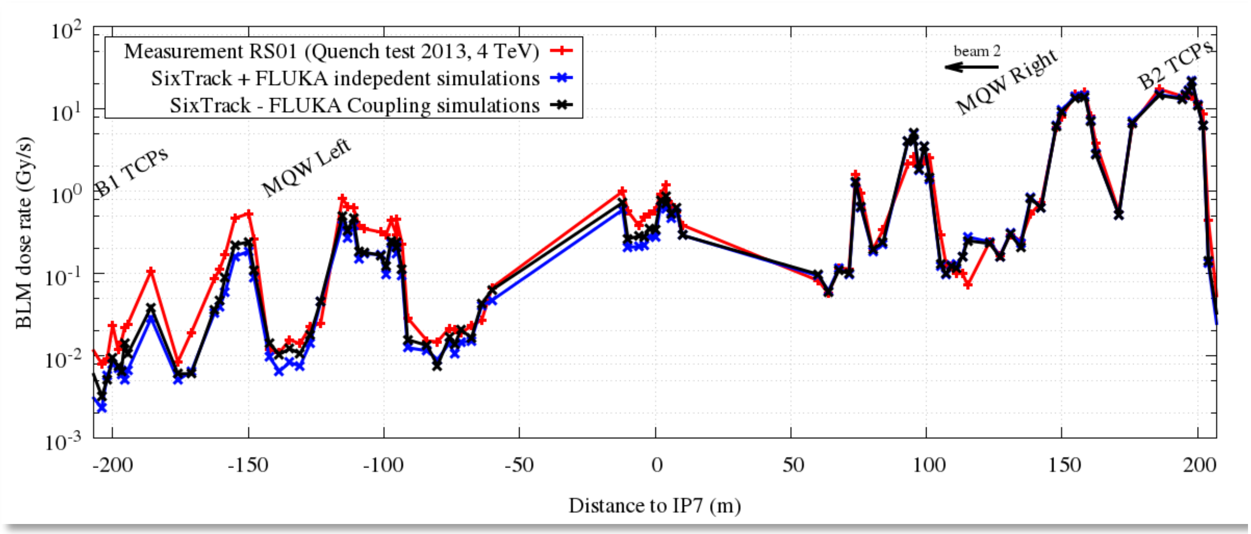

Fig. 5: Benchmarking of the simulated BLM signals against measurements taken during the 2013 proton collimation quench test at 4 TeV beam energy.

Another usage of this two-step method is the evaluation of the BLM response per proton lost in a specific collimator. By considering only the losses occurring on the latter, it is possible to calculate the signal produced in the BLM corresponding to the same collimator (primary signal) as well as the induced crosstalk signal recorded by the upstream and downstream BLMs (Fig. 6). Table 1 shows an example of a simulated BLM response matrix for losses on the vertical and horizontal primary collimators in IR7 that can be used in order to obtain the loss plane decomposition from measured signals. Table 2 provides the response matrix of losses on the horizontal and vertical tertiary collimators, where the apparent increase in response mainly originates from the different jaw material (Tungsten instead of Graphite) as well as the different BLM position with respect to the impacted jaws.

The tables highlight that for losses on different collimators, even of the same family, a different primary BLM response is to be expected, as well as that the crosstalk plays a very significant role. For instance, we see that the response of the BLM at the TCP.C (horizontal primary collimator) is increased by 80% if losses move from the horizontal to the vertical plane, first impacting the preceding collimator. Consequently, the actual loss plane combination cannot be directly identified by the measured BLM signals, but implies the response matrix application.

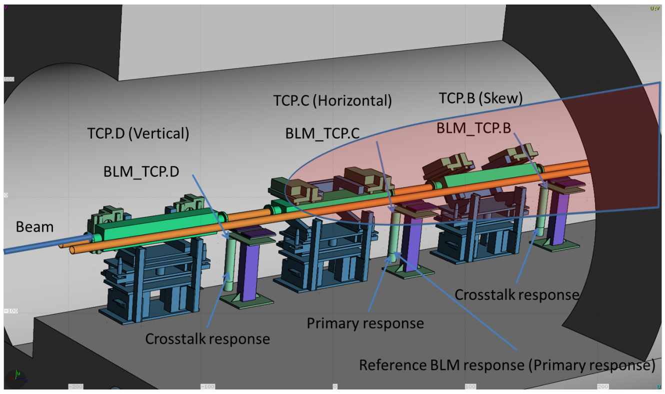

Fig. 6: FLUKA model of the IR7 vertical (TCP.D), horizontal (TCP.C) and skew (TCP.B) collimators, with a figurative proton interaction in the TCP.C inducing primary and crosstalk BLM responses.

Table 1: BLM response matrix for the IR7 primary collimators at 3.5 TeV proton beam energy. Primary and crosstalk responses appear in **Bold** and *Italic,* respectively. Values are normalised to $4.6\ 10^{-12}$ Gy/p, i.e. the primary response of BLM_TCP.C.

BLM Collimator	BLM_TCP.D	BLM_TCP.C	BLM_TCP.B
TCP.C (Horizontal)	*0.01*	**1**	*2.53*
TCP.D (Vertical)	**0.58**	*1.80*	*2.13*

Table 2: BLM response matrix for the IR1 tertiary collimators (TCT) at 3.5 TeV proton beam energy. Primary and crosstalk responses appear in **Bold** and *Italic,* respectively. Values are normalised to $4.6\ 10^{-12}$ Gy/p, i.e. the primary response of BLM_TCP.C in Table 1.

BLM Collimator	BLM_H1	BLM_V1
TCT_H1 (Horizontal)	**7.2**	*1.15*
TCT_V1 (Vertical)	*0.4*	**3.25**

7 Summary and perspectives

The integrated FLUKA/SixTrack coupling offers an accurate tool for multi-turn simulations of cleaning systems. It benefits from sophisticated physics models, particularly relevant for single-diffractive scattering and ion interactions. With the use of appropriate transport settings in FLUKA, the CPU time can be kept reasonably low, even when simulating complex accelerators like the LHC. The FlukaIO library, providing the two codes with the communication infrastructure, is flexible enough to be linked with other tracking and Monte Carlo codes. Currently it is operational with FLUKA for SixTrack, IcoSim and IcoSim++.

Further improvements are represented by the operational integration in FLUKA of the crystal channeling event generator, the use of beam-beam collision products as embedded source term (allowing to track diffractive and elastically scattered protons or ion fragments generated at the experimental interaction points of a collider), the replacement of the FLUKA user routines by dedicated input cards, and the possible re-introduction of the external server mechanism to handle anisotropic computation times if needed.

References

[1] R. De Maria *et al.*, these proceedings

[2] G. Battistoni *et al.*, “Overview of the FLUKA code”, Annals of Nuclear Energy 82, 10-18 (2015)

[3] A. Fassò, A. Ferrari, J. Ranft, and P.R. Sala, “FLUKA: a multi-particle transport code”, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773

[4] R. Bruce *et al.*, these proceedings

[5] H. Braun *et al.*, “Collimation of heavy ion beams in LHC”, Proceedings of the 2004 European Particle Accelerator Conference, Lucerne, Switzerland, 551 (2004); N. Holden, “Development of the ICOSIM Program and Application to Magnetised Collimators in the LHC”, Technical Report CERN-AB-Note-2008-054, CERN, Geneva, Dec 2008. http://cds.cern.ch/record/1151294

[6] A. Mereghetti, “Performance Evaluation of the SPS Scraping System in View of the High Luminosity LHC”, PhD Thesis, University of Manchester, UK (2015)

[7] P. Garcia Ortega, “Status of SixTrack-FLUKA coupling”, Talk at the LHC Collimation Working Group #181, CERN, Geneva, Oct 2014. https://indico.cern.ch/event/343152

[8] U.I. Uggerhøj, “Penetration Phenomena at Relativistic Energies”, Matematisk-fysiske Meddelelser 52, 699 (2006)

[9] W. Scandale *et al.*, “Observation of Channeling for 6500 GeV/c protons in the crystal assisted collimation setup for LHC”, Phys. Lett. B 758, 129-133 (2016)

[10] P. Schoofs, “Monte Carlo Modelling of Crystal Channelling at High Energies”, PhD Thesis, EPFL, Lausanne, Switzerland (2014)

[11] W. Scandale *et al.*, “High-efficiency Volume Reflection of an Ultrarelativistic Proton Beam with a Bent Silicon Crystal”, Physical Review Letters 98, 154801 (2007)

[12] A. Mereghetti *et al.*, “The Fluka LineBuilder and Element DataBase: Tools for Building Complex Models of Accelerator Beam Lines”, proceedings of IPAC12, New Orleans, US (2012)

[13] B. Salvachua *et al.*, “Collimation quench test with 4 TeV proton beams”, CERN-ACC-NOTE-2014-0036 (2014)

[14] E. Skordis *et al.*, “Impact Of Beam Losses In The LHC Collimation Regions”, IPAC15, Richmond, USA