

# PARTICLE TRACKING FOR COLLIMATION STUDIES

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## *Abstract*

The collimation quench tests performed with circulating beam in the LHC in Run I give both empirical limits on the allowed beam loss rates as well as data that can be used for a deeper understanding of the underlying physics. In order to simulate the beam losses during the collimation quench test, a 3-step simulation is used, consisting of tracking, shower calculations, and electro-thermal simulations. This paper focuses on the first step and gives an overview of the main tracking tool used for collimation studies, SixTrack with collimation, which was also used during the initial design of the LHC collimation system. As an application, simulation results for the 2013 quench test are shown and compared to measurements..

## INTRODUCTION

The Large Hadron Collider (LHC) is designed to store proton beams with a total energy of 362 MJ. Therefore, the LHC beams are highly destructive. If protons deviate from the wanted trajectory so much that they hit the inside of the vacuum chamber, the induced heating can cause quenches and possibly material damage. Even a local beam loss of a fraction of a few  $10^9$  of the full physics beam in a magnet could cause a quench.

Therefore, the LHC needs a very efficient collimation system [1–3] to safely intercept unavoidable beam losses. This puts very high demands on the LHC collimation system to control beam losses and avoid quenches of superconducting magnets. Therefore, about 100 movable collimators are installed. Most collimators are placed in insertion region 7 (IR7) for betatron collimation, or in IR3 for momentum collimation. The collimators are ordered in a strict hierarchy, starting with the primary collimators (TCP) followed by secondary collimators (TCSG). Further out from the beam, tertiary collimators or additional absorbers are placed to intercept tertiary halo or provide local protection.

In order to qualify the performance of the collimation system, so-called loss maps are routinely carried out. During a loss map, a safe low-intensity beam is injected and excited, and the beam losses around the ring are measured using beam loss monitors (BLMs). Usually the highest losses are observed at the TCP and, since the collimation system cannot absorb all incoming losses, a small tail of protons is leaking out to the downstream cold magnets, in particular to the dispersion suppressor (DS) in IR7. This is the limiting location for the LHC intensity reach from collimation cleaning.

## COLLIMATION QUENCH TESTS

When beam losses occur during regular operation, the beam is dumped if signal on any cold BLM, in particular on the magnets in the IR7 DS, would exceed the thresholds that are set beforehand to avoid quench. In order to probe this limit, and estimate at what level of leakage from the collimators the DS magnets would really quench, collimation quench tests were carried out at the LHC in 2011 [4] and 2013 [5]. They were performed by provoking very high beam losses with the full collimation system in place, similarly to regular loss maps, but with much higher intensity.

The measured loss distribution around the LHC is during the 2013 test shown in Fig. 1. A peak beam loss rate of about 1 MW was achieved on the TCP and the measured BLM signals in the DS were about 3 orders of magnitude lower than at the TCP [5]. In fact, the DS BLM signals at the moment of the peak losses were up to a factor 5 higher than the predicted quench limit. In spite of these very high losses, which were much higher than any previous observation in Run I, no quench occurred.

This type of test allows to examine the quench behaviour in the DS under realistic operational conditions, which could directly be used to conclude on the minimum allowed beam lifetime as well as for setting BLM thresholds. For example, the DS thresholds could be directly increased to the signals that were achieved without quench in the experiment.

The quench test result can also be used in order to validate the theoretical models for quench limits. To do this, a multi-stage simulation is necessary. The first step consists of a tracking simulation, where a proton halo is propagated through the magnetic lattice of the LHC, including also the scattering in the collimators. The second step [6] takes the losses of primary protons generated by the tracking as input, calculates the shower through the magnets, and the flux of particles reaching the BLMs. The output of this second step can be used both to compare to the measured BLM signals, as well as to estimate the actual deposited energy in the superconductors. This is used as input for the third step [7], which consists of electro-thermal simulations to assess the achieved temperature as well as the quench behaviour of the superconductors. The main focus of this paper is the first step with tracking.

## SIXTRACK

To assess the collimation performance, we need a detailed understanding of the cleaning of beam protons by the collimators. Protons lost in cold magnets have usually hit a collimator and afterwards travelled some distance through the magnetic lattice of the ring—in many cases,

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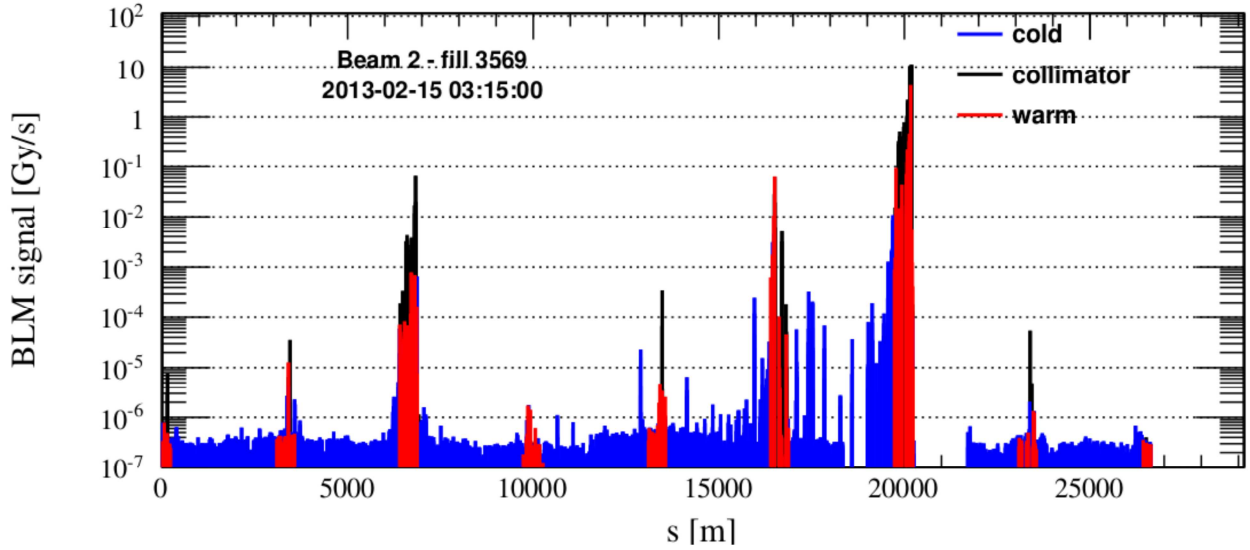


Figure 1: Beam loss distributions around the LHC as measured by BLMs during the collimator quench test on 2 February 15, 2013. The beam energy was 4 TeV and an the unsqueezed injection optics was used. The initial losses occur in the horizontal plane in B2 with a peak power of about 1 MW. Figure taken from Ref. [5].

protons are lost several turns after their first collimator impact. There fore, we need simulation tools that model both the tracking through the magnetic lattice as well as the particle-matter interaction inside collimators.

SixTrack with collimation was developed for exactly this purpose during the design of the LHC. It is based on the standard SixTrack [8, 9], which is a thin-lens tracking code that follows 6D trajectories of relativistic particles in circular accelerators in a symplectic manner. It accounts for magnetic non-linearities up to order 20 and the lattice input can be created using MAD-X, which provides a tight integration with the LHC magnetic imperfection model. SixTrack is used for dynamic aperture studies with high numeric stability, as well as for tune optimization. It is well-tested and experience with SixTrack has been accumulated over a few decades of code development at CERN [10]. It is still used both for the nominal LHC and its upgrades.

During the LHC design phase, the K2 Monte Carlo code [11] was included in SixTrack [12] to simulate the proton-matter interaction inside collimators. Ionization energy loss and multiple Coulomb scattering are included, as well as point-like processes: nuclear elastic scattering, nuclear inelastic scattering (where it is assumed that the proton disintegrates), single diffractive scattering, and Rutherford scattering. A particle is considered lost either when it hits the aperture—the particle coordinates are checked at a post-processing level against a detailed aperture model with 10 cm longitudinal precision—or if it disintegrates in an inelastic interaction inside a collimator. The simulation output contains all loss locations. It should be noted that the inclusion of the scattering is necessary to estimate the leakage out of the the collimators and extends the domain of applications beyond what can be achieved using pure tracking tools.

Recently, the built-in scattering routine has been improved [13]. 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. Routines for treating crystal collimation have also been incorporated [14].

The simulation starts with a distribution of halo particles, which already have sufficient betatron amplitudes to hit the primary collimators. Tracking also the core, including the diffusive processes that send particles onto the collimators, would make the computing time unfeasible. The starting distribution, which relies on assumptions from other input calculations, thus determines directly the impact parameter  $b$ .

Early on,  $b$  was estimated theoretically to be of the order of  $1 \mu\text{m}$  during physics operation [15]. With the machine in place, the LHC halo diffusion speed has been measured using a collimator scan [16]. These studies indicate  $0.02 \mu\text{m} < b < 0.3 \mu\text{m}$  with single bunches during stable physics conditions, but  $b$  is likely to be larger during beam instabilities and fast losses. Recent simulations indicate that  $b$  during loss maps could instead be of the order of  $10 \mu\text{m}$  [17] but also that  $b$  only has a minor influence on the loss distribution up to about  $b \approx 100 \mu\text{m}$ .

The simulation flow in a typical collimation simulation with SixTrack is summarized in Fig. 2. The simulation inputs are the machine configuration, in terms of optics and layout, and detailed data of all collimators. The hits

on the aperture are extracted using post-processing tools and a detailed aperture model of the full ring [18]. Usually a total of about  $6 \times 10^6$  halo protons are tracked for a few hundred turns, which is enough for the vast majority of them to be lost.

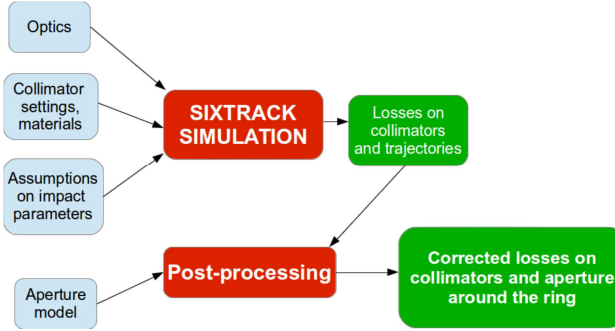


Figure 2: Schematic illustration of the flow, inputs and outputs of a typical collimation simulation with SixTrack.

## SIMULATIONS OF THE 2013 QUENCH TEST

In order to prepare the 2013 collimation quench test, a series of SixTrack studies were performed in order to find suitable settings of the IR7 collimators. Several settings were evaluated and the most promising options were further studied in an experimental pre-study with low-intensity loss maps. In order to have a high enough leakage to the DS, so that a quench was a priori possible, it was decided to use collimator settings that were significantly more open than the ones used during the 2012 physics run [19]. This is in itself a remarkable result, as it demonstrates the very high efficiency of the standard settings. The chosen settings, shown in detail in Ref. [5], are the relaxed settings used in 2011 in mm, with an additional  $1 \sigma$  retraction of the TCSGs in IR7 and the dump protection IR6.

The simulated losses of primary protons, taken from the SixTrack simulation using the actual quench test settings, are shown in Fig. 3, together with the measurement results. As can be seen, there is a qualitatively very good agreement between the two, with the highest loss at the beginning of IR7 at the TCPs and the losses decaying along the insertion. Losses a few orders of magnitude lower than the TCP loss are observed at the cold magnets in the DS at the limiting loss location.

Some differences can be observed: the measurement indicates a much denser loss pattern, with higher losses in the warm section, but also in the cold arc. However, the BLMs do not measure the direct proton losses shown for the simulation, but the secondary particles produced in the showers caused by the primary losses. The BLM signal per locally lost primary 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. This is especially important for the warm BLMs, which are

likely to intercept secondary shower particles created in upstream collimators.

Therefore, one cannot expect a high quantitative accuracy when comparing the BLM signals with the number of lost primary protons on the aperture or collimators. To do this, a shower calculation, discussed in further detail in Ref. [6], is necessary. In order to illustrate the level of achieved agreement after this step, we show in Fig. 4 the comparison between the measured BLM signals and a FLUKA [20, 21] shower simulation [22], based on the SixTrack results shown in Fig. 3. When the showering is included, the level of quantitative agreement improves significantly and is typically within a factor 2–3.

A similar 2-step simulation with SixTrack and FLUKA has been benchmarked in detail with the operational losses during the 2011 run in Ref. [17]. These results are typically within a factor 2 from the measurements, even when the final loss locations is far from the initial impact on a collimator, such as for the tertiary collimators close to the experiments. This can be considered an excellent agreement, in view of the complexity of the full simulation chain and the fact that the losses around the ring span 7 orders of magnitude.

The simulations serve not only to reproduce the measurements for a better understanding. Given the very good agreement, another important application is to predict the loss levels and quench behaviour in future machine configurations. This has been done to assess the efficiency of the collimators at higher energy [22–24], both by studying the primary losses, the energy deposition or the predicted quench behaviour. At each level of the three-step approach (tracking, shower calculations, and electro-thermal simulations) different observables can be predicted or compared to previous measurements. This is schematically illustrated in Fig. 5, which also shows the output of each step which is used as input in the following one.

## OUTLOOK AND FUTURE IMPROVEMENTS

Several improvements to the SixTrack code have been recently implemented: updated scattering [13], a new halo modelling [17], and crystal collimation [14]. Other improvements, such as modelling of off-momentum losses, are under study [25].

There is also an ongoing collaboration between the FLUKA team and the LHC collimation team at CERN to develop an alternative SixTrack version, which completely replaces the K2 scattering by online calls to FLUKA [26–28], in order to describe all kinds of interactions taking place in beam intercepting devices. The 3D geometry of the latter ones is explicitly modelled in FLUKA, replacing the respective item in the SixTrack lattice.

It should be noted that integrated simulation tools with a functionality similar to the collimation version of

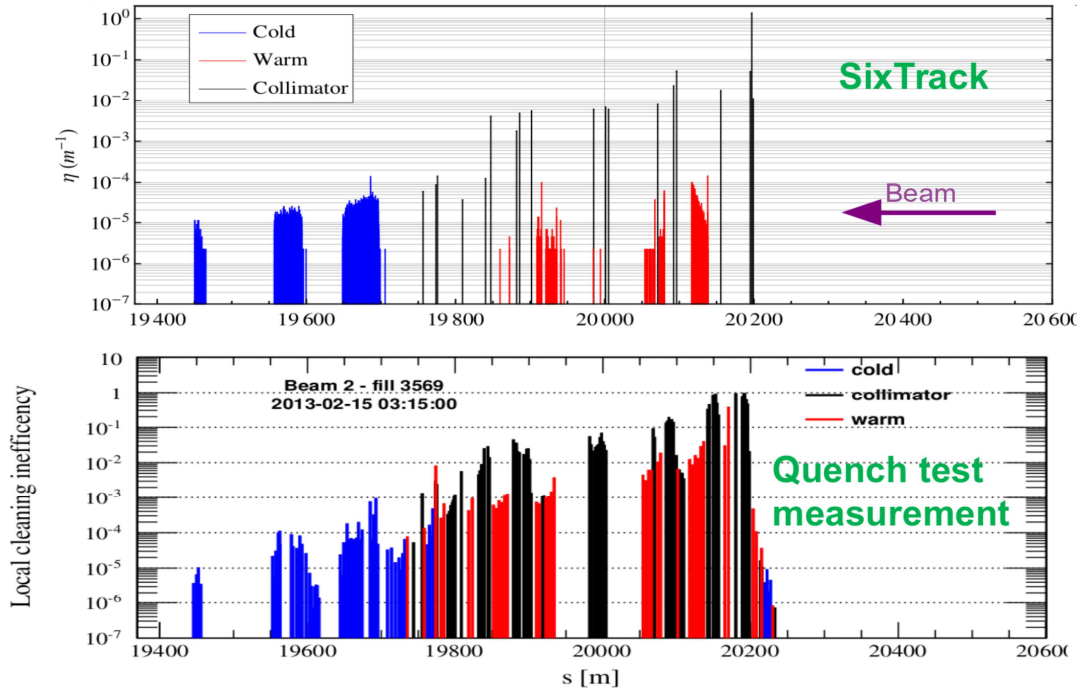


Figure 3: The distribution of primary proton losses simulated with SixTrack in IR7 for the 2013 quench test configuration (top) and the BLM signals from measurements during the 2013 collimator quench test at 4 TeV (bottom) [5]. For the measurement, the cleaning inefficiency was estimated by normalizing all BLM signals to the highest one (close to the primary collimator).

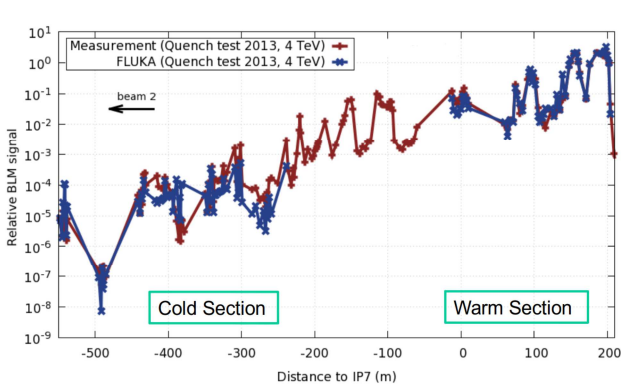


Figure 4: The BLM signals from measurements during the 2013 collimator quench test shown together with the results of a two-step simulation with SixTrack and FLUKA [22].

SixTrack are also being developed within the framework of the Hi- Lumi project [27]. These include MERLIN [29–31], which is a thick-lens particle tracking code in the form of a C++ physics library, and BDSIM [32,33], which is the integration of a particle tracking tool with the Geant4 physics libraries.

### SUMMARY

Because of the very high stored beam energy in the LHC, it is necessary to have a highly performing

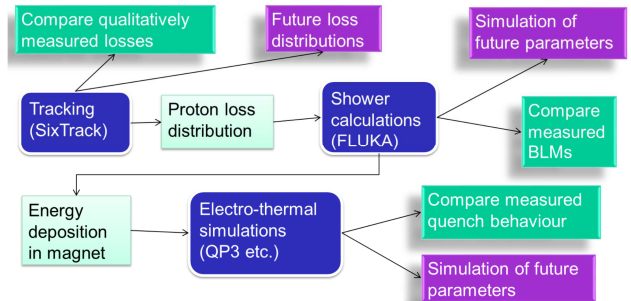


Figure 5: The BLM signals from measurements during the 2013 collimator quench test shown together with the results of a two-step simulation with SixTrack and FLUKA [22].

collimation system. Although the collimation system has so far been very successful in protecting the cold parts of the ring, it is unavoidable that a small leakage of beam losses ends up on superconducting magnets. In order to probe the actual quench limit of the most exposed magnets, collimation quench tests were performed during Run I, where high beam losses were provoked with the full collimation system in place.

The collimation quench test results can be used to empirically decide boundaries on the allowed maximum loss rate, as well as on the BLM thresholds, since they were performed in machine conditions close to what could be expected in physics operation. They can also be used to benchmark simulation tools, which gives a deeper understanding of the underlying physics. To simulate the collimation quench test, a 3-step simulation is used,

consisting of tracking with SixTrack, shower calculations with FLUKA [6] and electrothermal simulations [7].

SixTrack simulates the the loss distribution of beam halo particles around the ring, combining a high-precision tracking through the magnetic lattice with a built-in Monte Carlo that treats the scattering inside collimators. SixTrack results for the 2013 collimation quench tests are in a very good qualitative agreement with measurements, however, in order to perform a quantitative comparison, a shower calculation is needed. Including this step, the

typical agreement with measurements is within a factor 2–3. This is an excellent result, considering the complexity of the simulation and the fact that the losses span 7 orders of magnitude. The good agreement gives us confidence in the simulation tools, which are also used to predict the performance of the collimation system in future machine configurations at higher energy. Furthermore, several improvements to the simulation tools are ongoing.

## REFERENCES

- [1] O. S. Brüning et al. LHC design report v.1 : The LHC main ring. CERN-2004-003-V1, 2004.
- [2] R.W. Assmann. Collimators and Beam Absorbers for Cleaning and Machine Protection. Proceedings of the LHC Project Workshop - 'Chamonix XIV', Chamonix, France, page 261, 2005.
- [3] R.W. Assmann et al. The Final Collimation System for the LHC. Proc. of the European Particle Accelerator Conference 2006, Edinburgh, Scotland, page 986, 2006.
- [4] R.W. Assmann et al. Collimator losses in the DS of IR7 and quench test at 3.5 TeV. CERN-ATS-Note-2011-042 MD, 2011.
- [5] B.Salvachua et al. Collimation quench test with 4 TeV proton beams. CERN-ACC-NOTE-2014-0036, 2014.
- [6] A. Lechner et al. Particle shower simulations for LHC quench tests: methodology, challenges and selected results. Proceedings of the Workshop on Beam-Induced Quenches, CERN, Geneva, Switzerland, 2014.
- [7] A. Verweij et al. Electro-thermal simulations of superconductors in case of beam losses. Proceedings of the Workshop on Beam-Induced Quenches, CERN, Geneva, Switzerland, 2014.
- [8] F. Schmidt. SixTrack. User's Reference Manual. CERN/SL/94-56-AP, 1994.
- [9] <http://sixtrack-ng.web.cern.ch/sixtrack-ng>.
- [10] R. de Maria et al. Proceedings of IPAC'13, 2013.
- [11] N. Catalan Lasheras. Transverse and Longitudinal Beam Collimation in a High-Energy Proton Collider (LHC). PhD thesis, University of Zaragoza, 1998.
- [12] G. Robert-Demolaize et al. A new version of sixtrack with collimation and aperture interface. Proc. of the Particle Accelerator Conf. 2005, Knoxville, page 4084, 2005.
- [13] C. Tambasco. An improved scattering routine for collimation tracking studies at LHC. Master's thesis, Università di Roma, Italy, 2014.
- [14] D. Mirarchi et al. Improvements of the crystal routine for collimation studies. Proceedings of the International Particle Accelerator Conference 2014, Dresden, Germany, page 886, 2014.
- [15] R. Assmann, F. Schmidt and F. Zimmermann. Equilibrium beam distribution and halo in the LHC. Proc. of the European Particle Accelerator Conf. 2002, Paris, France, page 1326, 2002.
- [16] G. Valentino et al. Beam diffusion measurements using collimator scans in the lhc. Phys. Rev. ST Accel. Beams, 16:021003, 2013.
- [17] R. Bruce et al. Simulations and measurements of beam loss patterns at the cern large hadron collider. Phys. Rev. ST Accel. Beams, 17:081004, Aug 2014.
- [18] S. Redaelli, R. Assmann and G. Robert-Demolaize. LHC Aperture and Commissioning of the Collimation System". Proceedings of the LHC Project Workshop - 'Chamonix XIV', Chamonix, France, page 268, 2005.
- [19] R. Bruce et al. Collimator settings and performance in 2011 and 2012. Proceedings of the LHC Performance Workshop - Chamonix 2012, 2012.
- [20] A. Ferrari et al. FLUKA: a multi-particle transport code. CERN Report CERN-2005-10, 2005.
- [21] G. Battistoni et al. The FLUKA code: Description and benchmarking. Hadronic Shower Simulation Workshop 2006, Fermilab 6–8 September 2006, AIP Conference Proceeding, 896:31–49, 2007.
- [22] E. Skordis et al. Energy deposition simulations for quench tests. Presentation in the LHC collimation review 2013, 2013.
- [23] R. Bruce, A. Lechner and S. Redaelli. Beam-halo simulations. CERN-ACC-2013-008, 2013.
- [24] R. Bruce, A. Lechner and S. Redaelli. Energy deposition simulations for upgraded collimation layouts. CERN-ACC-2014-0009, 2014.
- [25] E. Quaranta et al. SixTrack Simulation of Off-momentum Cleaning in LHC. Proceedings of IPAC13, Shanghai, China, 2013.
- [26] A. Mereghetti et al. Sixtrack-FLUKA active coupling for the upgrade of the SPS scrapers. Proceedings of the International Particle Accelerator Conference 2013, Shanghai, China, page 2657, 2013.
- [27] R. Bruce et al. Integrated Simulation Tools for Collimation Cleaning in HL-LHC. Proceedings of the International Particle Accelerator Conference 2014, Dresden, Germany, page 160, 2014.
- [28] P. Garcia Ortega. Status of SixTrack-FLUKA coupling. presentation in the LHC Collimation Working Group, 2014.10.06., 2014.

- [29] J. Molson et al. MOABC3. Proceedings of ICAP12, 2012.
- [30] M. Serluca et al. Comparison of MERLIN/SixTrack for LHC collimation studies. Proceedings of the International Particle Accelerator Conference 2014, Dresden, Germany, page 185, 2014.
- [31] M. Serluca et al. Hi-lumi LHC collimation studies with MERLIN code. Proceedings of the International Particle Accelerator Conference 2014, Dresden, Germany, page 784, 2014.
- [32] I. Agapov et al. NIMA, 606:708, 2009.
- [33] S. Boogert et al. WEPC46. Proceedings of IBIC 2013.