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A NOVEL TOOL FOR BEAM DYNAMICS STUDIES WITH HOLLOW ELECTRON LENSES*

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Abstract

Hollow Electron Lenses (HELs) are crucial components of the CERN LHC High Luminosity Upgrade (HL-LHC), serving the purpose of actively controlling the population of the transverse beam halo to reduce particle losses on the collimation system. Symplectic particle tracking simulations are required to optimize the efficiency and study potentially undesired beam dynamics effects with the HELs. With the relevant time scales in the collider in the order of several minutes, tracking simulations require considerable computing resources. A new tracking tool, Xsuite, developed at CERN since 2021, offers the possibility of performing such tracking simulations using graphics processing units (GPUs), with promising perspectives for the simulation of hadron beam dynamics with HELs. In this contribution, we present the implementation of HEL physics effects in the new tracking framework. We compare the performance with previous tools and show simulation results obtained using known and newly established simulation setups.

INTRODUCTION

The CERN Large Hadron Collider (LHC) is designed to store and collide hadron beams of unprecedented intensities and particle energies up to 7 TeV [1]. The High-Luminosity LHC (HL-LHC) [2] upgrade, foreseen for installation after the LHC Run 3 (2022-25), aims to increase the collider's luminosity by reducing the value of β^* at the ATLAS and CMS insertions and an increase in beam brightness and intensity, thanks to the LHC Injectors Upgrade project [3], up to a total stored beam energy of 684 MJ per circulating beam. Such intense beams have a large damage potential in the event of uncontrolled beam losses. A high-performance multistage collimation system is installed in the LHC [4–6] and is being upgraded for the HL-LHC [7], in order to keep the collider protected against beam losses.

Measurements in the LHC [8,9] have shown that the transverse beam halo at amplitudes greater than 3 σ can constitute up to 5% of the total beam intensity. Estimated by simple scaling to the intensity of the desired proton beam, the energy in the beam halo of HL-LHC could reach the order of 34 MJ. Different failure scenarios could cause orbit offsets of up to 2 σ within a few turns [10], which could induce very high beam losses. Hollow electron lenses (HELs) have been integrated in the HL-LHC baseline to mitigate this risk by active depletion of the beam halo [10–12]. A HEL generates a hollow cylindrical shaped electron beam (e-beam) and steers it through a solenoid in the centre of which they move coaxially and oppositely directed to the proton beam. Perfectly symmetric hollow electron beams would leave particles at amplitudes smaller than the inner radius of the e-beam unaffected, while particles in the beam halo would be subject to a transverse kick from the electromagnetic field created by the e-beam. Exploiting this behavior allows to drive halo particles towards larger amplitudes in a controlled way, such that they are intercepted and disposed of by the collimators, whereby the population of the halo is reduced.

Operational scenarios for HEL are studied using symplectic tracking simulations, computing particle trajectories over a large number of turns (up to several millions) [13]. Of particular interest is the classification of turn-by-turn pulsing schemes in which the HEL is switched on and off according to a pre-defined time pattern. Examples of figures of merit to be studied in such simulations are the depletion efficiency, quantifying the percentage of the beam halo that is removed, and the emittance growth, a detrimental effect caused by the residual kick acting on the core of the main proton beam.

SixTrack [14–16], a single-particle symplectic tracking tool, provides the functionality of simulating HEL kicks [17], allowing the user to select different profiles $\rho(r)$ of the e-beam, and to simulate turn-by-turn pulsing of the HEL [18]. Simulation results obtained using this framework were presented in [13]. Since 2021, a new symplectic tracking framework, Xsuite [19], a collection of Python packages that can be run on CPUs and GPUs, is being developed. Simulations over a large number of turns in machines like the LHC can be carried out at significantly shorter simulation times when using GPU platforms. The Xtrack (XT) tracking package in Xsuite contains the symplectic tracking maps used in the simulation process.

This contribution describes the implementation of HEL physics in the Xtrack framework and the benchmark against SixTrack. Besides comparing the amplitude-dependent kick in the HEL, we verify the equivalence of both codes focusing on the two physical figures of merit: halo depletion efficiency and beam-core emittance growth.

HEL KICK

From Biot-Savart's law, one can derive the transverse kick θ that a hadron receives from the interaction with the oppositely directed HEL electron beam [20] as follows:

$$\theta(r) = \frac{1}{2\pi\epsilon_0 c^2}\frac{LI(1+\beta_e\beta_p)}{(B\rho)_p\beta_e\beta_p}\frac{1}{r}f(r)\,, \tag{1}$$

where L is the active length of the HEL, β_e and β_p are the relativistic factor of the electrons and protons, respectively, $(B\rho)_p$ is the magnetic rigidity of the proton beam

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and $r = \sqrt{x^2 + y^2}$ is the proton's transverse distance from the e-beam center. The profile function $f(r)$ corresponds to the fraction of the total electron current I that is enclosed by a circle of radius r, namely $f(r) = \frac{2\pi}{I} \int_0^r r\,\rho(r)\,\mathrm{d}r$. For a constant radial e-beam density $\rho(r) = \rho$, we obtain $f(r) = \min\left(\frac{r^2-r_1^2}{r_2^2-r_1^2}, 1\right) \times \left(\frac{\mathrm{sgn}(r-r_1)+1}{2}\right)$, with r_1 and r_2 being the inner and outer electron beam radii, respectively. Eq. (1) is implemented in SixTrack, with the parameters $L, I, E_{\mathrm{kin}}, r_1, r_2$ specified by the user, where E_{kin} denotes the kinetic energy of the electrons.

HEL IMPLEMENTATION IN XTRACK

Xtrack tracking maps are implemented in the C programming language and are controlled by the Python framework. The implementation of the HEL in Xtrack currently assumes a constant radial e-beam density (being one of the radial profiles implemented in SixTrack) and was initially benchmarked against Eq. (1). In addition to the functionality provided in SixTrack, the tool allows the user to assign a residual dipolar kick to particles that are at amplitudes below the inner e-beam radius r_1 (caused by e-beam asymmetries). This allows the user to carry out combined simulations of halo depletion and beam-core emittance growth.

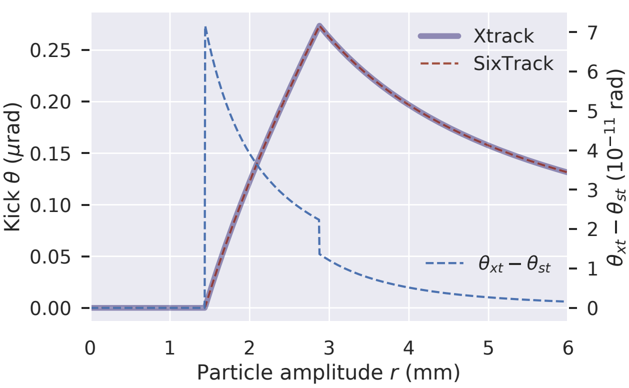

Figure 1: Kick θ received by 7 TeV protons moving through a Hollow Electron Lens of 3 m length with 10 keV electrons, at 5 A current and inner and outer e-beam radii of r_1 = 1.44 mm and r_2 = 2.88 mm as calculated with Xtrack (blue) and SixTrack (red). The difference between the two results is visible on the right axis.

The HEL kick exerted on particles of amplitudes r between 0 mm and 6 mm in Xtrack and SixTrack is shown in Fig. 1. Both codes agree up to a precision of $\pm 7 \times 10^{-11}$ rad, with the difference probably being caused by numerical noise. This assumption is supported by the observation that the numerical offset between the kicks differs in the regions $r < r_1$, $r_1 < r < r_2$ and $r > r_2$. In particular, at the transition $r = r_2$, the floating point computation of $f(r)$ is replaced by a fixed integer and, as expected, we observe a sudden decrease in the observed difference.

We conclude that both codes deliver physically equivalent results in the computation of the HEL induced kick.

HALO DEPLETION SIMULATIONS

Simulations of halo depletion provide crucial input to evaluate the efficiency of the HEL in different operational configurations. It is currently foreseen to operate the HEL with a random turn-by-turn pulsing, randomly switching the e-beam current on to the full current or off to zero current at each turn. The scheme has the advantage of depleting the beam halo very efficiently, but comes along with the disadvantage of inducing emittance growth in the case of an imperfect symmetry of the e-beam that creates a residual kick at the beam core.

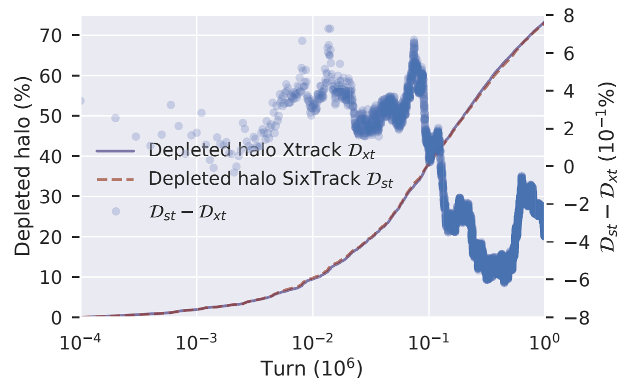

Figure 2: Halo depletion in HL-LHC with HEL in random pulsing in Xtrack (blue line) and SixTrack (red line). The blue dots represent the absolute difference between the two. Identical pulsing pattern, initial distribution, optics and normalized collimator settings were used.

We benchmark halo depletion efficiency simulations by comparing the number of surviving particles simulated in the two frameworks. Both simulations were carried out for protons in HL-LHC V1.5 at flat-top energy of 7 TeV. We considered the primary horizontal and vertical collimators in IR7 to be at 5.7σ as perfect absorbers, that is, without calculating particle-matter interaction. Both frameworks calculate optics and closed orbit to set and align the collimator jaws based on internal computations. The initial distribution, used for both simulations, was based on a double Gaussian with 65% at 1 σ and 35% at 2σ and we selected only particles that pass the electron beam at least once within the first 200 turns, which ensures that no computing resources are used for particles that are not influenced by the HEL.

Tracking was carried out for 3×10^4 initial particles over 1×10^6 turns, and the same HEL random pulsing pattern is applied, resulting in the depletion curves shown in Fig. 2. The curves show a very good agreement, with the halo depletion differing by less than 1 % at any value of the turn number in the abscissa. The remaining differences can be related to numerical differences from floating-point operations, resulting in slightly different geometrical collimator gaps, alignments and beam orbits simulated by the two frameworks. This analysis demonstrates that the codes deliver equivalent results in the simulation of transverse halo depletion.

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CORE-BEAM EMITTANCE GROWTH SIMULATIONS

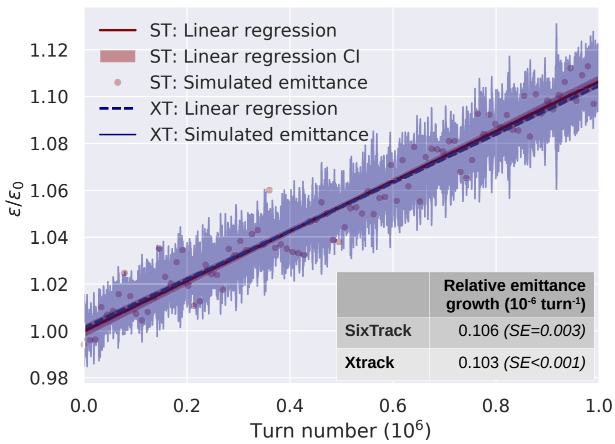

Figure 3: Simulated relative core-beam emittance growth ϵ/ϵ_0 in SixTrack (ST) and XTrack (XT) assuming an uncompensated residual dipolar kick of 1 nrad at the HEL. The core-beam emittance growth estimated via a linear regression agrees within one standard error (SE).

For the simulation of the core-beam emittance growth, we consider an ensemble of 3×10^4 particles, Gaussian distributed, with an initial emittance of 2.5 μm, tracked in the same ring lattice, and applying the same random HEL pulsing pattern as studied previously. In SixTrack, the HEL is modelled as a vertical dipole kick of 1 nrad. In Xtrack, we use the implementation of the residual kick at $r < r_1$ in the HEL tracking map (described in the implementation section). In order to make the simulation results comparable, we set r_1 to a large value of 2 cm, such that all particles receive only the residual kick of 1 nrad and do not interact with the electron beam. The tracking is carried out for 1×10^6 turns with both tools. It is noteworthy that in operation the residual kick will be compensated with the LHC transverse damper, which is currently expected to reduce the emittance growth by a factor of at least ten, which is not taken into account in this simulation for code-comparison purposes.

As illustrated in Fig. 3, the results obtained with the two codes show a very good agreement. We use a linear regression to derive the slope of the relative emittance vs. time, which quantifies the relative core-beam emittance growth. The regression based on the Xtrack simulation data delivers a slope of 0.103×10^{-6} per turn. For the SixTrack data, a value of $0.106^{0.101}_{0.112} \times 10^{-6}$ per turn was obtained. The sub- and super-scripted figures correspond to the 2.5% and 97.5% quantiles derived from the regression, respectively. The confidence interval (CI) calculated for Xtrack is less than 10^{-3}, due to the large number of points, which is why we do not list it. The SixTrack linear regression line with the boundaries from the 2.5% and 97.5% CI is also shown in Fig. 3. The comparison demonstrates that the physical results simulated with the two codes are equivalent within the statistical limits.

COMPUTING SPEED COMPARISON

Xtrack performed the tracking of all 3×10^4 particles over 10^6 turns in a single run in approximately 11.5 h when executed on GPU (NVIDIA Tesla V100S with 5120 CUDA cores). The SixTrack simulations were split into jobs of four particles each, for a total of 7.5×10^3 simulations, using the CERN batch system employing HTCondor [21, 22]. These jobs required approximately 2.6 h for the simulation of the halo depletion . A summary of the number of particle turns per second achievable in SixTrack and Xtrack is given in Table 1, which shows a drastic improvement in the tracking speed with Xtrack on GPU. For comparison, we also show the computation speed of Xtrack on CPU, which is in the same order of magnitude as SixTrack. Both were run using a CPU at 2.4GHz from 2014. The simulation speed for a full study ultimately depends on the availability of CPUs and GPUs on the batch system.

The possibility to simulate a larger sample of particles per job in Xtrack allows calculating physical figures of merit online instead of deriving them from post-processed data gathered in parallel simulations. Consider the calculation of the core-beam emittance in the example above. Using Xtrack, all particles are simulated in a single job, such that the core-beam emittance can be computed during the simulation on a turn-by-turn basis and only the aggregated figure is saved. The distributed simulation with SixTrack requires an offline analysis based on the stored particle coordinates, requiring a larger amount of disk space. To sample the emittance on a turn-by-turn basis in the example above, approximately 95 GB of disk space would be needed, compared to only a few kB required when using Xtrack.

Table 1: Tracking speed with SixTrack and XTrack based on tracking of 10^6 turns in HL-LHC

	Processing	Particles	Time (s)	$\frac{\text{particle turns}}{\text{s}}$
ST	CPU	4	≈9000	444
XT	CPU	4	≈8040	497
XT	GPU	30000	41400	724’637

CONCLUSIONS AND OUTLOOK

Based on three examples (single-turn kick, beam halo depletion, and core-beam emittance growth computation), we have compared the simulation results obtained with SixTrack and the new tool Xtrack. All study cases have demonstrated the equivalence of the two tools for the physics studied with HELs. Compared to SixTrack, Xtrack allowed orders of magnitude faster simulations with greater flexibility and reduced storage space requirements. Xtrack will be used as a baseline tool for production runs in the future, and several upgrades of the HEL functionality are currently under development (considering measured radial profiles to calculate $f(r)$ and considering higher orders than dipolar residual kicks via Chebychev polynomials [23]).

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