ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL031

COMMISSIONING STRATEGIES OF HOLLOW ELECTRON LENS RESIDUAL KICK COMPENSATION*

M. Rakic†[2], R. Bruce[1], M. Giovannozzi[1], P. Hermes[1], G. Kotzian[1], S. Redaelli[1], M. Soderen[1], D. Valuch[1]
[1] European Organisation for Nuclear Research, Meyrin, Switzerland
[2] Ecole Polytechinque Federale de Lausanne, Lausanne, Switzerland

Abstract

Hollow electron lenses (HELs) could be used in the CERN High Luminosity Large Hadron Collider (HL-LHC) to selectively remove halo particles from the circulating beams. Although the ideal design should leave the particles in the beam core unaffected, in reality, core particles will be exposed to a small residual kick, which could induce transverse-emittance blow-up, if not properly compensated, while the HEL is operated in pulsing mode. As a possible solution, the HEL pulsing could be coupled to the adjacent HL-LHC transverse damper (ADT). The principle consists of exerting an oppositely directed kick with the ADT at each turn the HEL is switched on, thus compensating the HEL residual kick on the beam core. In this contribution, we simulate the performance of this compensation scheme and possible commissioning scenarios, with the aim of reliably setting up the compensation scheme if the direction and amplitude of the residual kick are a priori unknown.

INTRODUCTION

The Large Hadron Collider (LHC) is a 27 km long collider, designed to store proton beams with particle energies of up to 7 TeV [1]. To maximise the achievable luminosity, the LHC is preparing for an important upgrade, called High-Luminosity LHC (HL-LHC), with the aim of increasing luminosity five times by doubling the beam current and reducing the beam emittance [2].

Measurements carried out in the LHC have shown that particles at large transverse amplitudes, i.e. ($> 3\,\sigma$), which make the beam halo, comprise up to 5% of the total stored beam energy in the LHC [3, 4]. Simple scaling to the stored beam energy of HL-LHC [5] suggests that around 35 MJ would be stored in the beam halo. If this amount of energy was deposited in the collimation system in a short time, as can be induced by orbit jitters, serious damage could be caused. Furthermore, overpopulated halos increase the risk of beam dumps, which would reduce the integrated luminosity that can be produced. Therefore, it was concluded that the HL-LHC beam-halo population needs to be decreased in a controlled way. Hollow Electron Lenses (HEL) [5, 6] could be used to serve this purpose and were integrated in the upgrade baseline in 2019 [5]. They generate a hollow-shaped electron beam moving coaxially to the proton beam. It induces a transverse kick to halo particles of the order of 0.1 µrad, increasing their diffusion rate, and ultimately steering them to the collimators where they are absorbed.

The efficiency of the halo-depletion process depends on the pulsing mode in which the HEL is operated. Random pulsing is the mode in which the electron beam is switched on and off randomly at each turn with fixed current [5, 6] and is among the most efficient operational modes in terms of halo depletion. With a perfectly symmetric electron beam, particles in the beam core would be unaffected by the HEL. However, in reality, the electron beam is not expected to be perfectly symmetrical partially due to asymmetries induced at the HEL extremities. The asymmetric electron beam will cause a higher-order, non-zero field. In this work, we focus on the first-order dipole residual kick to the circulating beam core. From beam stability considerations [7], a maximum tolerable residual kick of 1.0 nrad was defined provided that the ADT [8] is active. The latter measures beam oscillations and kicks the beam to dampen them. The transverse feedback has typical damping times of a few tens of turns [9].

Compared to unknown random noise sources, the residual kick imparted by the HEL is deterministic and known when it acts on the beam. Therefore, as an alternative solution, the HEL pulsing could be coupled to the adjacent ADT, which would deliver an oppositely directed kick to the residual kick every time the HEL is switched on. In the commissioning phase, the optimal parameters for the coupling of these two elements would have to be found. In this contribution, we present possible commissioning scenarios and simulate their performance. We conclude whether reliable commissioning is possible, compare different schemes, and probe the sensitivity of the compensation to HEL noise.

SIMULATION SETUP

Simulation Tools

The simulations were performed using `Xsuite` [10, 11] and its sub-package `XTrack` – a collection of Python packages used to provide six-dimensional symplectic particle tracking tools. The simulations were run on the HTCondor CERN batch service [12], using Graphic Processing Units (GPUs). Primary collimators are included as perfect absorbers. The HEL is simulated using the `XTrack` implementation allowing for simultaneous simulation of the kick acting on the halo particles and the residual dipole kick on the core particles (with radii smaller than the radius of the inner electron beam) [11]. The ADT is simulated as a thin dipole.

* Research supported by the HL–LHC project.
† milica.rakic@cern.ch

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL031

Machine Settings

We used the HL-LHC V1.5 flat top optics (after energy ramp and before squeezing the beams for collisions), at the nominal beam energy of 7.0 TeV. The initial distribution of the particles used in the tracking was sampled as a Gaussian distribution of 30 000 protons with an HL-LHC design emittance of 2.5 µm [2]. The total number of turns per simulation is typically in the order of one to a few millions, requiring substantial computing resources. This is the reason why the usage of GPUs, which is enabled through `XTrack`, is beneficial. The HEL inner radius is set to 4.7 σ (where σ is the RMS beam size for the design emittance), providing 2 σ clearance with respect to the primary betatron collimators (TCP) positioned at 6.7 σ. The HEL is turned on randomly with 50% probability at every turn. When it is turned on, the residual dipole kick acts on the beam particles in the core. HEL and ADT are located in insertion region 4, at 9056 m and 9128 m respectively from IP1, with their associated optical parameters presented in Table 1.

Table 1: Optical parameters (betatron function β and phase advance ϕ) of the HEL and ADT, located in HL-LHC IR4.

Element	β_x [m]	β_y [m]	ϕ_x [rad]	ϕ_y [rad]
HEL	280	280	7.53	6.78
ADT	213	336	7.58	6.82

APPROACH AND GOALS

The underlying hypothesis of the study is that the emittance will grow stronger if the correct ADT compensation value is not met for the given HEL residual kick. Once the ADT kick optimally compensates for the residual kick, the emittance growth will be minimal. Since the residual kick is expected to be strongest in the vertical plane, this case is simulated and studied in detail, but we expect the results to be representative for the horizontal plane as well.

The ideal ADT kick that would perfectly compensate for a known residual kick in the HEL can be computed as [13]:

$$\theta_{\mathrm{ADT}} = -\theta^{r}_{\mathrm{HEL}} \sqrt{\frac{\beta_{\mathrm{HEL}}}{\beta_{\mathrm{ADT}}}} \cos \Delta\phi, \qquad (1)$$

where θ_{ADT} and $\theta^{r}_{\mathrm{HEL}}$ are ADT and HEL kicks, β_{HEL} and β_{ADT} their betatron functions, and $\Delta\phi$ is the phase advance between these two elements. From this formula, and using the optics parameters at HEL and ADT, listed in Table 1, the theoretical compensation required by the ADT for a vertical residual kick of 1.0 nrad strength is −0.91 nrad.

We study the identification of the optimal compensating ADT kick by performing a scan over different ADT kick strengths. We calculate the emittance in different stages of the simulation using the β-function and the calculated coordinates for all particles. Two scenarios were tested. First, using separate bunches, assuming that each data point is recorded with a new bunch, starting at the initial emittance of 2.5 µrad. As a second method, we studied the use of a single bunch: the same bunch is used throughout the scan, and the emittance is not reset after each kick amplitude step. In doing so, the goal is to test the commissioning feasibility of this approach and explore if the same bunches can be used to reduce the required measurement machine time.

SIMULATION RESULTS

Identification of Ideal ADT Kick

We scanned different compensating ADT kicks sequentially, in the range from −5.0 nrad to 5.0 nrad and in fixed steps of either 0.25 nrad or 1.0 nrad. The emittance is recorded after 10 s of operating in this mode, and the ADT kick is changed to the next value in the given range. The final emittance obtained after each 10 s interval is plotted against the compensating kick applied and the data is fitted to obtain the ADT kick corresponding to the minimum emittance growth. The data points are fitted using a non-linear least-squares method to fit the user-defined function to a data set (`Python 3.0 SciPy`, with the function `curve fit`).

The simulation results, showing the emittance growth over 10 s for each step are shown for both single and separate bunches in Fig. 1. Both have a parabolic shape with a clear minimum, thus we conclude that the scan method is effective in identifying the ideal compensation kick. The minima were

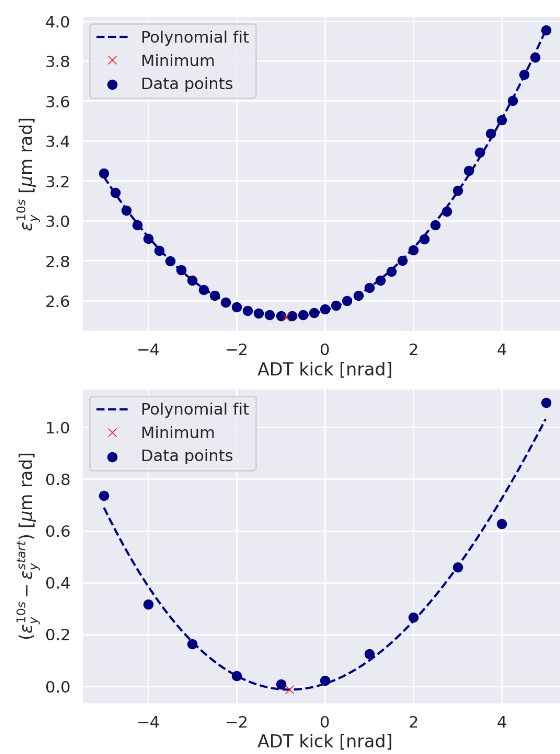

Figure 1: Emittance change over 10 s as a function of ADT kick strength, with 0.25 nrad step size for separate bunches (top) and 1.0 nrad step size for single bunch (bottom). Data are fitted by a quadratic regression (dashed line). From the fit, the minimum is estimated (red cross).

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL031

identified, based on the fit parameters, as −0.89 nrad (multi-bunch scan), and −0.80 nrad (single-bunch scan). The result obtained from the multi-bunch method is closer to the ideal value (relative error of 2.8 %) than the result of the single-bunch method (12 %). The observed discrepancy is probably produced by the limited statistics due to the finite number of simulated particles.

The same procedure is repeated with different values of residual kick and is presented in Table 2. These results show that the estimation of the optimal compensation is possible with both separate and single bunches for various HEL residual kick strengths. Furthermore, we could not identify a systematic difference in the accuracy of both approaches, as shown in Table 2. We conclude that single bunches can be used and should be preferred since this approach requires less machine time. If the required granularity of the ADT kick strengths cannot be reached with a single bunch, a hybrid method can be considered.

Table 2: Relative errors in the estimation of the ideal ADT compensating kick with respect to the theoretical value. Different values of HEL residual kick were tested with the separate (SE) and single (SI) bunch scheme.

θ^{r}_{HEL}	$\Delta\theta^{SE}$	$\Delta\theta^{SI}$
0.5 nrad	11.4 %	4.0 %
1.0 nrad	2.8 %	12.0 %
2.0 nrad	11.1 %	/

Required Number of Data Points

We evaluated the sensitivity of the approach (assuming the separate-bunch scheme), identifying the minimal required scan size for reliable results. Details can be found in [13], and we just present some key results here.

In simulations, varying the sample density from 11 to 44 points (step size of 0.25 nrad instead of 1 nrad in the range from −5 nrad to 5 nrad) does not significantly improve the precision of the ideal kick estimation. A more structured approach was done using a bootstrapping approach, applying the fit to differently sized sub-samples of a dense single-bunch scan. Reliable estimates were consistently obtained with at least ten measurement points. It was also shown that significantly increasing the number of samples beyond 20 points does not produce better estimates. Altogether, we conclude that the approach can be used reliably and in a shorter time, requiring only a small number of scan points.

Impact of Noise

The robustness of the proposed commissioning scenario was tested against noise on the HEL residual kick. The residual HEL kick was varied at each turn as follows:

$$\theta_{\mathrm{HEL}} = \theta^{0}_{\mathrm{HEL}} \cdot \left(1 \pm \frac{\Delta_n[\%]}{100}\right), \qquad (2)$$

where $\theta^{0}_{\mathrm{HEL}}$ is the HEL residual kick without any noise. It is set to 1.0 nrad. Δ_n is the noise level in % sampled from the (0, n_{max}) range, using a uniform distribution. The maximum noise level n_{max} is defined for each simulation and was probed up to a level of 100 %. The ideal compensating kick is first identified using the separate-bunch scheme. The compensating kick identified was very similar to the study without noise. This is expected because the mean value of the residual HEL kick across the simulation is equal to $\theta^{0}_{\mathrm{HEL}}$.

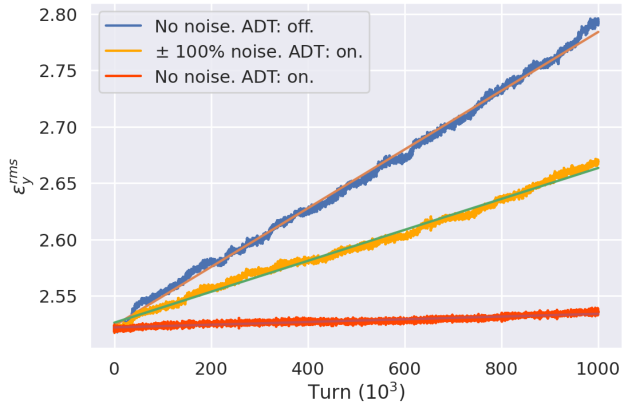

Figure 2: Emittance evolution within 10^6 turns with different operations of ADT: without compensation in blue, with noise (100 % noise level) in orange and without noise and ideal ADT compensation in red.

Nevertheless, the performance of the compensation scheme is reduced in the presence of noise. The results presented in Fig. 2 show that, without any ADT compensation, the total emittance growth is the highest (blue plot). Without noise and with ideal ADT compensation, the emittance growth is reduced by a factor of 21 (red plot). In the presence of high noise (±100%), the emittance growth can still be reduced, but the reduction drops to a factor of 2.

CONCLUSIONS AND OUTLOOK

In this article, it was shown that the deterministic compensation of the HEL residual kick with the ADT is effective in numerical simulations. The ideal compensating kick can be established without prior knowledge through dedicated scans using a limited number of recorded data points. When the HEL residual kick is noisy, assuming that the noise characteristics are stable, the optimal compensation can still be identified, albeit the emittance growth mitigation is reduced.

From an operational perspective, it is expected that the scheme can be applied without a detrimental effect on the efficiency of the ADT feedback. When the feedback system is taken into account, even lower emittance growth rates can be expected, which is planned to be studied in the future. The expected emittance growth with ADT compensation included and assuming moderate noise levels (below 100%) is shown to be tolerable over the 5 minutes for which the HEL is intended to operate in random mode. Based on our findings, we conclude that the proposed HEL-ADT commissioning scheme is a promising perspective for usage in real operation.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL031

REFERENCES

[1] O. S. Brüning *et al.*, "LHC design report v.1 : The LHC main ring," *CERN-2004-003-V1*, CERN, Geneva, Switzerland, 2004.

[2] G. Apollinari *et al.*, *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1*. CERN, Geneva, Switzerland, 2017. doi:10.23731/CYRM-2017-004

[3] G. Valentino *et al.*, "Beam diffusion measurements using collimator scans in the LHC," *Phys. Rev. ST Accel. Beams*, vol. 16, p. 021 003, 2 2013. doi:10.1103/PhysRevSTAB.16.021003

[4] A. Gorzawski *et al.*, "Probing LHC halo dynamics using collimator loss rates at 6.5 TeV," *Phys. Rev. ST Accel. Beams*, vol. 23, p. 044 802, 2020. doi:10.1103/PhysRevSTAB.23.044802

[5] S. Redaelli *et al.*, "Hollow electron lenses for beam collimation at the High-Luminosity Large Hadron Collider (HL-LHC)," *J. Instrum.*, vol. 16, no. 03, P03042, 2021. doi:10.1088/1748-0221/16/03/p03042

[6] D. Mirarchi *et al.*, "Nonlinear dynamics of proton beams with hollow electron lens in the CERN high-luminosity LHC," *Eur. Phys. J. Plus*, vol. 137, p. 7, 2021. doi:10.1140/epjp/s13360-021-02201-5

[7] X. Buffat, *Instability latency with the e-lens residual dipole kicks*, Presentation at the HL-LHC WP2 Meeting, CERN, Geneva, Switzerland, 2021. https://indico.cern.ch/event/1026380/contributions/4309563/attachments/2223502/3775305/2021-04-09_ELensLatency.pdf

[8] W. Hofle, G. Arduini, R. de Maria, G. Kotzian, D. Valuch, and V. Lebedev, "Suppression of emittance growth by excited magnet noise with the transverse damper in LHC in simulation and experiment," 2011. https://cds.cern.ch/record/1378470

[9] W. Hofle, *Transverse Feedback in the LHC High Lumi Era*, Presentation at the HL-LHC Era 5th Joint HighLumi LHC - LARP Meeting, CERN, Geneva, Switzerland, 2015. https://indico.cern.ch/event/400665/contributions/1843455/attachments/1177876/1703859/LHC_TFB_HighLumi_era.pdf

[10] *Xsuite Readthedocs*. https://xsuite.web.cern.ch

[11] P. D. Hermes *et al.*, "A Novel Tool for Beam Dynamics Studies with Hollow Electron Lenses," in *Proc. IPAC'22*, Bangkok, Thailand, 2022, pp. 176–179. doi:10.18429/JACoW-IPAC2022-MOPOST045

[12] *HTCondor Website*. https://research.cs.wisc.edu/htcondor/

[13] M. Rakic, "Compensation of residual field from hollow electron lens asymmetries in the Large Hadron Collider," Presented 30 Jun 2022, M.S. thesis, Ecole Polytechnique Fédérale de Lausanne, 2022.