HOLLOW ELECTRON BEAM COLLIMATION FOR HL-LHC – EFFECTS ON THE BEAM CORE*

M. Fitterer[†], G. Stancari, A. Valishev, Fermilab, Batavia, IL 60510, USA
R. Bruce, G. Papotti, S. Redaelli, G. Valentino, D. Valuch, C. Xu, CERN, Geneva, Switzerland
G. Valentino, University of Malta, Malta

Abstract

Collimation with hollow electron beams is currently one of the most promising concepts for active halo control in the High Luminosity Large Hadron Collider (HL-LHC). To ensure the successful operation of the hollow beam collimator the unwanted effects on the beam core, which might arise from the operation with a pulsed electron beam, must be minimized. This paper gives a summary of the effect of hollow electron lenses on the beam core in terms of sources, provides estimates for HL-LHC and discusses the possible mitigation methods.

INTRODUCTION

For high energy and high intensity hadron colliders like the HL-LHC, halo depletion is deemed necessary in order to control the targeted stored beam energy in the range of several hundred MJ [1]. Measurements at the LHC furthermore indicate strongly overpopulated tails. Explicitly, around 5% of the beam population is stored in the tails above 3.5 beam σ (compared to 0.22% in case of a Gaussian distribution) [2].

For a controlled depletion of the tails, the hollow electron lens (HEL) currently presents the best solution as it acts in amplitude space and not in tune space like other alternative solutions currently investigated at CERN [3–5]. In addition, the concept of halo control with a HEL has already been successfully demonstrated at the Fermilab Tevatron proton-antiproton collider [6]. A first conceptual design for an HEL for HL-LHC can be found in the CDR [7], and the most relevant parameters are summarized in Table 1.

Table 1: Hollow Electron Lens Parameters as in [7]

Parameter	Value	Unit
length L	3	m
desired range of scraping positions	4-8	σ_p
gun solenoid, B_g	0.2-0.4	T
main solenoid, B_g	2-6	T
compression factor ($k = \sqrt{B_m/B_g}$)	2.2-5.5	-
Peak yield I_e at 10 keV	5.0	A
inner/outer cathode radius, r_1/r_2	6.75/12.7	mm

EFFECTS OF THE HEL ON THE BEAM CORE

In the ideal case, the HEL is installed in a position with round protons beams and the electron beam is a uniform hollow distribution in radius $r = \sqrt{x^2 + y^2}$ with inner radius r_1 and outer radius r_2. For the HL-LHC, typical values are $r_1 = 4\sigma_p = 1.1$ mm, $r_2 = 7.5\sigma_p = 2.1$ mm yielding $\theta_{max} = 375$ nrad based on the HEL parameters listed in Table 1. Due to the radial symmetry, the field thus vanishes in this case for $r < r_1$ and the straight part therefore leaves all particles with $r < r_1 = 4\sigma_p$ unperturbed. Effects on the beam core can arise from the bends of the HEL and from residual electromagnetic fields also in the straight part of the HEL originating from imperfections in the electron beam profile, space-charge distortions and transport. In both cases the kick exhibited on the beam core is non-linear [8, 9]. In DC operation this effect is considered to be negligible based on experimental studies at the Tevatron proving a depletion of the halo without any distortion of the core [10]. For the HL-LHC HEL, the effect of the bends has been evaluated in simulations in [11] and is considered to be negligible. The non-linear effect of profile imperfections in DC mode has not yet been studied, but compared to other machine non-linearities present (e.g. field and alignment errors), the effect is likely to be negligible. The picture however changes drastically in case of pulsed operation of the HEL. In this case any residual field from the HEL introduces noise leading to a tightening of the tolerances by orders of magnitude to ensure no additional emittance growth or lifetime degradation. Pulsing is being considered to extend the range of depletion rates, if needed. This is in particular the case if no strong non-linearities like beam-beam or octupoles and high chromaticity are present [12–14]. For this purpose two different pulsing patterns are currently considered:

- **random:** the e-beam current is modulated randomly: at every turn the kick is varied between 0 and its maximum value following a uniform distribution,

- **resonant:** the e-lens is switched on only every n^{th} turn with $n = 2, 3, 4, \ldots$ and the maximum kick is applied.

The random mode introduces white noise on the beam which is in general very dangerous as it excites all frequencies and thus also the betatron frequency of the beam. The resonant excitation however only excites certain resonances, explicitly pulsing every n^{th} turn drives n^{th} order resonances. To obtain a first estimate of the tolerances on the profile imperfections and also the effect of the bends in case of pulsed operation,

only the dipole contribution is considered. Scaling in both cases the field to the HEL parameters listed in Table 1, i.e. $L = 3$ m, $I_e = 5.0$ A, $E_e = 5$ keV, $E_p = 7$ TeV, $B_g = 5$ T, one obtains [15]:

- **HEL bends:** $\theta_{\text{Bends}} = 0.5$ nrad (Under the assumption of 10% difference between entrance and exit bend and an S-shape of the HEL.)

- **profile imperfections:** $\theta_{\text{Bends}} = 15$ nrad estimated from measured current-density profiles.

The contribution from the bends is, thanks to the S-shape of the HEL, therefore negligible compared to the profile imperfections. The estimate of the profile imperfections is based on measurements of the 1-inch gun prototype built at Fermilab, which might be pessimistic as misalignments and orbit errors could present a considerable contribution. There is currently a serious effort ongoing to mitigate these imperfections and provide better measurements for the new e-gun built at CERN. The approximation by a simple dipole field is also done in view of cross-checking the simulations with experiments as in the LHC almost arbitrary spectra of dipole noise can be generated with the transverse damper (ADT) [16]. The results of this first experiment and the comparison with simulations are summarized in the following sections and further details can be found in [15, 17].

DESCRIPTION OF THE LHC EXPERIMENT

As experiments at top energy are always not very efficient because of the long recovery times in case of beam losses, this first experiment has been performed at injection energy. To minimize the emittance growth due to intra-beam scattering, low intensity bunches have been used instead of nominal bunches, in which case the estimated emittance growth is approximately 5%/h instead of 24.3%/h [18]. The beam and machine parameters are summarized in Table 2. The 48 single bunches were grouped in batches of 4. Each batch of 4 bunches experienced the same excitation amplitude with in total 5 excitation amplitudes plus 4 references bunches. In addition, the damper was active for 24 bunches and not active for the other 24 bunches in order to study if the observed effects can be mitigated with the transverse damper. The same parameters were also used for the simulations.

LIFETRAC SIMULATIONS

In order to obtain a realistic machine model, the latest LHC error tables as used for MADX [19] and SixTrack [20] have been used and all $a_i, b_i, i \leq 2$ errors have been scaled to obtain around 1 mm rms orbit and 15% average peak beta-beat, which are the values currently measured at injection [21]. For this first test, only one seed has been simulated. As model of the beam core a 6D Gaussian distribution cut at $6\,\sigma$ of 10^4 particles has been used, which was tracked over 10^6 turns using the tracking code Lifetrac [22]. Based on earlier estimates of the estimated kick, simulations for 12 nrad

Table 2: Machine and Beam Parameters for LHC Experiment

Parameter	Value	Unit
Energy	450	GeV
norm. emittance	2.5	μm
bunch length (4σ)	1.0	ns
bunch intensity	0.7×10^{11}	p
number of bunches	$12 \times 4 = 48$	-
$\beta^*_{\text{IP1/5}}$	11	m
working point (x/y)	64.28/ 59.31	-
chromaticity	+15	-
octupole current (MOF)	+19.6	A

and 120 nrad maximum kick amplitude were conducted. For 12 nrad kick amplitude no effect on emittance, losses, bunch length and beam distribution were observed. For 120 nrad, the largest losses are observed for pulsing every 7th and 10th turn, while for all other pulsing patterns hardly any losses are observed [15]. The same observation is also made in case of the emittance. However, no continuous emittance growth is observed, but rather a change of the distribution within the first 10^4 turns to a new steady state with larger emittance. The sensitivity to pulsing every 7th and 10th turn can be illustrated with the FMA analysis (Fig. 1) which reveals an excitation of the $7Q_x$ and $10Q_{x/y}$ resonances. Both resonances are driven by the sextupoles and octupoles as the same observations are made for the case without errors and only sextupoles and octupoles.
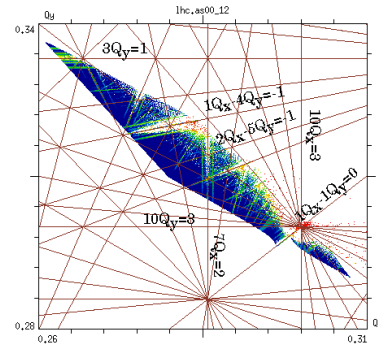

Figure 1: FMA analysis for the case without any errors. For 7th turn pulsing the $7Q_x$ resonance is driven and for 10th turn pulsing the $10Q_{x/y}$.

RESULTS OF THE EXPERIMENT AT THE LHC AND EXTRAPOLATION TO HL-LHC

In this first experiment, the two pulsing patterns featuring the strongest losses and emittance growth, 7th turn in horizontal (H) and 10th turn vertical (V), were tried together with pulsing patterns showing no or only a very small effect, 3rd turn H, 3rd turn V, 8th turn H. As the kickers of the transverse damper are not synchronized in time, the pulsing could only be applied in one plane in order to ensure a clean frequency spectrum. During the experiment the losses were measured

with the Fast Beam Current Transformer (FBCT) and the emittance and transverse profiles with the Beam Synchrotron Radiation Telescope (BSRT). In addition, a q-Gaussian fit:

$$f_{q-\text{Gauss}} = c + a \cdot \frac{\sqrt{\beta}}{C_q(q,\beta)} e_q(-\beta(x-\mu)^2)$$

has been applied to the BSRT profiles (for details see [17]). Here c and a are parameters introduced to model the background of the profiles and q,μ and β the q-Gaussian fit parameters. A value of $q > 1$ indicates overpopulated tails with respect to a Gaussian distribution and $q < 1$ underpopulated tails. For $q \rightarrow 1$ the distribution becomes Gaussian. The following main observations could be made:

- **7th turn H:** large losses (10-20% for 15 nrad excitation amplitude, see Fig. 2), no or very small emittance growth, depletion of the large amplitude tails (decrease of c in the q-Gaussian fit to the BSRT profiles) and increase in the middle of the distribution (increase of σ of the q-Gaussian fit)

- **10th turn V:** small losses (3% for 15 nrad excitation amplitude), strong emittance growth (43% for 15 nrad excitation amplitude), change of beam distribution visible in BSRT profiles (see Fig. 3).

- **3rd turn H**, **3rd turn V**, **8th turn H:** no losses nor emittance growth was observed, however measurements should be repeated with un-perturbed beams before drawing firm conclusions.

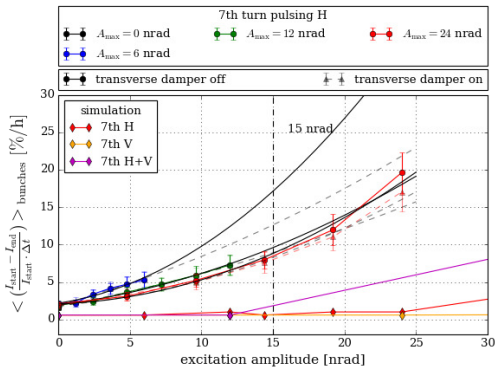A detailed analysis of the experiment can be found in [17].

Figure 2: Relative losses measured with the Fast Beam Current Transformer (FBCT). The maximum excitation amplitude was increased from 6 nrad to 24 nrad during the 7th turn H pulsing shown in blue, green and red. For each case the average loss rate over the 4 bunches with the same excitation amplitude is shown together with the quadratic fit. The simulation results are shown with diamonds and underestimate in general the measurements.

Based on the experiment showing an underestimation of the effect in simulations, simulation have been performed
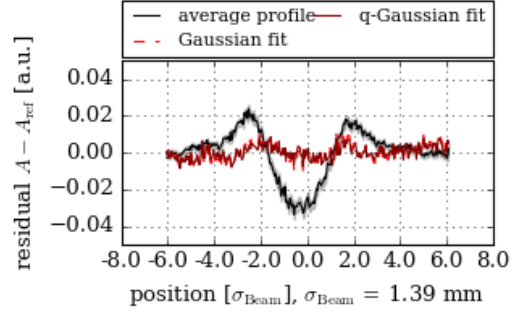
Figure 3: Residual defined as profile after excitation ($A_{\text{max}} = 96$ nrad) minus profile before excitation ($A_{\text{max}} = 0$) for excitation 10th turn V. A clear depletion of the center of the distribution and increase in the middle is visible. The red lines are the deviation from the Gaussian and q-Gaussian fit indicating that the distribution also becomes slightly non-Gaussian.

for HL-LHC for the same reference value as used for the experiment simulations of 120 nrad yielding additional losses, emittance growth and ultimately also luminosity loss for all pulsing patterns (for details see [11]).

CONCLUSION AND OUTLOOK

Effects on the beam core from the HL-LHC HEL might arise due to the HEL bends and e-beam profile imperfections. For DC operation, this is not expected to lead to any performance degradation. In pulsed operation, the residual non-linear field however introduces noise on the proton beam. A first experiment at the LHC taking only the dipole contribution into account showed that for the current estimate of approx. 15 nrad at 7 TeV applied at injection, losses and emittance growth arise for 7th and 10th turn pulsing. The simulations in general underestimate the effect. The next steps towards a better specification of the tolerances on the profile imperfections and contribution from the bends are the repetition of the LHC experiment for other pulsing patterns and at 7 TeV, improvement of the HEL model (bends, profile imperfections) and an investigation of the differences between simulations and experiments. In parallel, studies are also ongoing in order to eliminate any systematic effects from misalignment and orbit distortion on the profile measurements, which could contribute considerably to the current estimate of the kick.

ACKNOWLEDGMENTS

REFERENCES

[1] "Review on the needs for a hollow e-lens for the HL-LHC," `https://indico.cern.ch/event/567839/`, CERN, Geneva, Switzerland, October, 2016.

[2] G. Valentino, "What did we learn about halo population during MDs and regular operation?", Review of the needs for a hollow e-lens for the HL-LHC, `https://indico.cern.ch/event/567839/timetable/#20161006`, October, 2016.

[3] S. Redaelli *et al.*, "Plans for Deployment of Hollow Electron Lenses at the LHC for Enhanced Beam Collimation," *Proc. 6th International Particle Accelerator Conf. (IPAC15)*, Richmond, USA, May 2015, paper WEBB1.

[4] J. Wagner *et al.*, "Active halo control through narrow-band excitation with the ADT at injection," CERN-ACC-NOTE-2016-0062, April, 2016.

[5] H. Garcia-Morales et al., "Status of tune ripple MD analysis," ColUSM82, `https://indico.cern.ch/event/610855/`, February, 2017.

[6] G. Stancari, A. Valishev, G. Annala, G. Kuznetsov, V. Shiltsev, D. A. Still and L. G. Vorobiev, "Collimation with Hollow Electron Beams," in *Phys. Rev. Lett.*, vol. 107, no. 8, p. 084802, Aug., 2011.

[7] G. Stancari, V. Previtali, A. Valishev, R. Bruce, S. Redaelli, A. Rossi, B. S. Ferando,"Conceptual design of hollow electron lenses for beam halo control in the Large Hadron Collider", FERMILAB-TM-2572-APC, CERN-ACC-2014-0248, 2014.

[8] G. Stancari, "Calculation of the Transverse Kicks Generated by the Bends of a Hollow Electron Lens," FERMILAB-FN-0972-APC.

[9] I. Morozov, "Simulation of Hollow Electron Beam Collimation in the Fermilab Tevatron Collider," *Proc. 5th International Particle Accelerator Conf. (IPAC12)*, New Orleans, USA, May 2012, paper MOEPPB008.

[10] G. Stancari *et al.*, "Collimation with Hollow Electron Beams," *PRL* 107, 084802, August, 2011.

[11] M. Fitterer *et al.*, "Hollow Electron Lens for HL-LHC: Effect on core," Joint LARP CM28/HiLumi Meeting, `https://conferences.lbl.gov/event/76/session/6/contribution/35`, April, 2017.

[12] A. Valishev, "Simulation Study of Hollow Electron Beam Collimation for LHC," Fermilab, Batavia, USA, Rep. FERMILAB-TM-2584-APC, 2014.

[13] V. Previtali, G. Stancari, A. Valishev, "Numerical simulations of a proposed hollow electron beam collimator for the LHC upgrade at CERN," Fermilab, Batavia, USA, Rep. FERMILAB-TM-2560-APC, 2013.

[14] M. Fitterer, G. Stancari, A. Valishev, "Simulation study of Hollow Electron Beam Collimation in HL-LHC," Fermilab, Batavia, USA, Rep. FERMILAB-TM-2636-AD, 2016.

[15] M. Fitterer, G. Stancari, A. Valishev, "Effect of pulsed hollow e-lens operation on the beam core," Fermilab, Batavia, USA, Rep. FERMILAB-TM-2635-AD, 2016.

[16] P. Baudrenghien, W. Höfle, F. Killing, I. Kojevnikov, G. Kotzian, R. Louwerse, E. Montesinos, V. Rossi, M. Schokker, E. Thepenier, D. Valuch, E.V. Gorbachev, N.I. Lebedev, A. A. Makarov, S.V. Rabtsun, V.M. Zhabitsky, "LHC Transverse Feedback System and its Hardware Commissioning," in *Proc. 11th European Particle Accelerator Conf. (EPAC'08)*, Genoa, Italy, June 2008, pp. 3266-3268, paper THPC121.

[17] M. Fitterer *et al.*, "Effect of a resonant excitation on the evolution of the beam emittance and halo population," CERN-ACC-NOTE, to be published.

[18] F. Antoniou, private communication, Jul. 2016.

[19] MADX, `https://mad.web.cern.ch/mad/`

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

[21] R. Tomás, private communication, May 2016.

[22] A. Valishev, Y. Alexahin, V. Lebedev and D. Shatilov, "Simulation of beam-beam effects and Tevatron experience," *Journal of Instrumentation*, vol. 7, no. 12, p. P12002, 2012.