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

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Abstract

Collimation with hollow electron beams or lenses (HEL) is currently one of the most promising concepts for active halo control in HL-LHC. In previous studies it has been shown that the halo can be efficiently removed with a hollow electron lens. Equally important as an efficient removal of the halo, is also to demonstrate that the core stays unperturbed. In this paper, we present a summary of the experiment at the LHC and simulations in view of the effect of the HEL on the beam core in case of a pulsed operation.

INTRODUCTION

For high energy and high intensity hadron colliders like the HL-LHC, halo control becomes more and more relevant, if not necessary, for a safe machine operation and control of the targeted stored beam energy in the range of several hundred MJ. Past experiments at the Fermilab Tevatron proton-antiproton collider [1] demonstrated a successful halo control with hollow electron beams or hollow electron lenses (HELs) in DC mode.

Simulations of the HEL performance for LHC and HL-LHC [2–4] show a sufficiently high halo removal rate if beams are colliding, but only very low halo removal rates if the beams are separated. In order to clean the tails efficiently and in a short time-span also in case of separated beams, the halo removal rate can be increased by pulsing the HEL [2,4,6], where two different pulsing patterns are 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.

One of the main reservations about pulsing the e-lens is the possibility of emittance growth due to noise induced on the beam core by the HEL.

For an ideal radially symmetric hollow electron lens with an S-shaped geometry, the beam core would experience a zero net kick and thus no noise would be induced on the core. In the presence of imperfections in the HEL bends and in the e-beam profile, the kick at the center of the beam is non-zero. First estimates of the residual kick yield 0.142 nrad from the HEL bends assuming 10% current modulation and 16 nrad due to profile imperfections based on profile measurements of the current HEL e-gun prototype [5]. In case of DC operation of the HEL the kicks are static and could thus be corrected, if even necessary. However, for a pulsed operation, the tolerable kick amplitudes are much smaller as the pulsing frequency overlaps with the frequency spectrum of the beam itself. In case of random pulsing, white noise is induced driving all orders of resonances. In case of a resonant pulsing, only certain resonances are driven, explicitly for pulsing every *n*th turn only the *n*th order resonances are driven.

In order to obtain a first estimate on the tolerable profile imperfections in case of the resonant excitation[1], an experiment including preparatory simulations was conducted in August 2016 at the LHC, of which we will present the related simulation results and also first experimental results. The excitation for the MD was generated with the transverse damper system (ADT) of the LHC [7]. Details can be found in [5].

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 try was performed at injection energy. Expected effects of the resonant excitation are losses and emittance growth. To minimize the emittance growth due to intra-beam scattering, low intensity bunches are used instead of nominal bunches. For nominal single bunches with $N_b = 1.2\times10^{11}$, $\epsilon_N = 1.6\ \mu$m the expected emittance growth due to IBS is around 24.3 %/hour, while for the requested low

Table 1: 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}	-
number of bunches	$12\times4=48$	-
$\beta^*_{\mathrm{IP1/5}}$	11	m
working point (x/y)	64.28/ 59.31	-
chromaticity	15	-
octupole current (MOF)	19.6	A

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[1] For white noise analytical formulas and measurements exist. Due to very limited time for experiments at the LHC, the priority was therefore set on the resonant excitation.

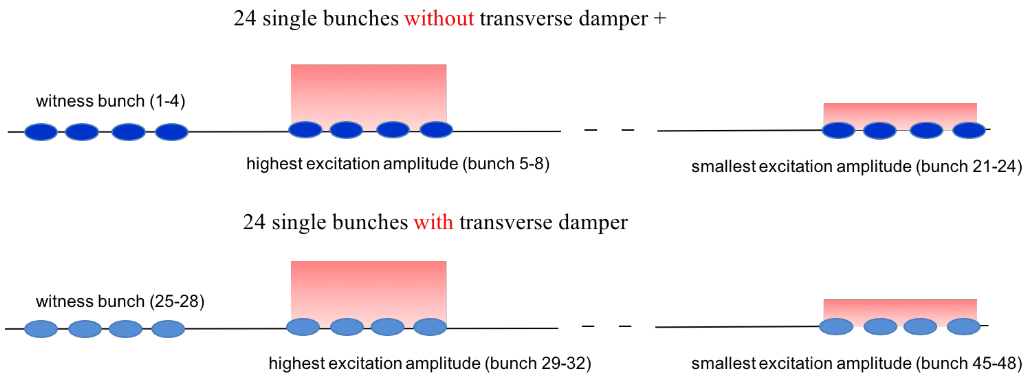

Figure 1: Filling scheme used in the LHC experiment: The dark blue ellipses indicate bunches which are not damped by the transverse feedback system, the light blue ellipses indicate bunches which are damped by the feedback system. The red square indicates the amplitude of the excitation, where the first 4 bunches of each batch of 24 bunches are used as witness bunches and do not see any excitation.

intensity bunches with $N_b = 0.7 \times 10^{11}$, $\epsilon_N = 2.5$ μm the emittance growth is reduced to 4.6 %/hour. The beam and machine parameters used are summarized in Table 1. The same parameters were also used for the simulations.

The noise expected from the HEL can in first order be approximated by just a dipole kick. The transverse damper system (ADT) of the LHC [7] is capable of generating almost arbitrary patterns of kicks gated also on individual bunches. Based on the systems capabilities, the filling scheme illustrated in Fig. 1 was chosen for the experiment.

LIFETRAC SIMULATIONS

In preparation of the experiment, the attempt was made to predict the most sensitive pulsing pattern and also a first estimate of the dependence on the excitation amplitude in simulations with LifeTrac [8]. In order to obtain a realistic machine model, the latest LHC error tables as used for MADX [10] and SixTrack [11] 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 [9]. For this first test, only seed 1 has been simulated. As model of the beam core a 6D Gaussian distribution cut at 6 σ of 10^4 particles has been used, which was tracked over 10^6 turns. Based on earlier estimates of the estimated kick, simulations for 12 nrad 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 beam intensity for the different pulsing patterns is shown in Fig. 2. The largest losses are observed for pulsing every 7th and 10th turn, while for all other pulsing patterns hardly any losses are observed. For pulsing every 7th and 10th turn also the emittance initially increases due to a fast adjustment of the distribution over the first 10^4 turns. The bunch length decrease indicates that the losses are dependent on the momentum offset. The sensitivity to pulsing every 7th and 10th turn is also observed in the simulations without any errors and only sextupoles and octupoles leading to the conclusion that the excited resonances are driven by the sextupoles and/or octupoles. The FMA analysis for the case without errors (Fig. 3) furthermore reveals that the $7Q_x$ and $10Q_y$ resonance are driven.

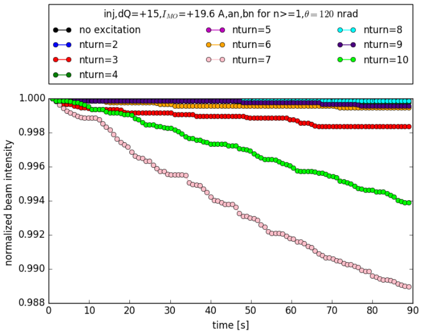

Figure 2: Time evolution of beam intensity for different pulsing patterns.

EXPERIMENT AT THE LHC

Based on the simulation results presented in this paper and the experimental time available, five different pulsing patterns were tried, explicitly pulsing every 7th turn in the horizontal plane (H) only, 10th turn in the vertical plane (V), 3rd turn in H, 3rd turn in V, 8th turn in H. For pulsing every 3rd turn H or V and every 8th turn in H with a maximum amplitude of 24 nrad, no losses or increase in emittance were observed. For pulsing every 7th turn, the maximum amplitude was increased in steps from initially 12 nrad to 24 nrad and ultimately 24 nrad, in which the drop in lifetime was already so large that the amplitude was not increased any further. The relative decrease in beam intensity per time:

$$\frac{\Delta I_{\text{rel}}}{\Delta t} = \frac{(I_{\text{start}} - I_{\text{end}})}{I_{\text{start}} \cdot (t_{\text{start}} - t_{\text{end}})} \tag{1}$$

measured with the fast beam current transformer (FBCT) and averaged over the four bunches experiencing the same excita-

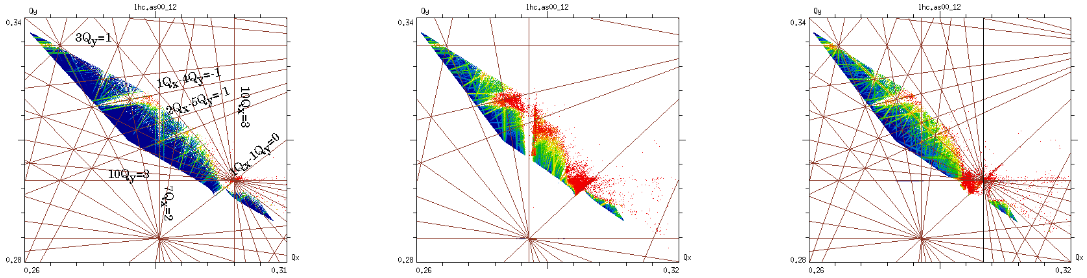

Figure 3: FMA analysis for the case without any errors: (left) no excitation, (center) pulsing every 7th turn, (right) pulsing every 10th turn.

tion is shown in Fig. 4. The relative decrease in intensity and thus the beam losses increase approximately quadratically with the excitation amplitude while no losses are observed in all cases without any excitation. For pulsing every 10th turn in V a similar behavior is observed, but not with such a clear scaling as in the case of pulsing every 7th turn. In the case of pulsing every 10th turn also a clear increase in emittance measured with the transverse synchrotron radiation telescopes (BSRT) is visible (Fig. 5). For pulsing every 7th turn H no increase in emittance was found. Fig. 6 collects only the bunches experiencing the highest excitation amplitude and shows a comparison of the expected $\frac{\Delta I_{\mathrm{rel}}}{\Delta t}$ from simulations scaled linearly with the values obtained during the experiments indicating a qualitative agreement of measurements and experimental results considering that the amplitude was scaled linearly while a quadratic scaling appears to be more adequate (Fig. 4) and the simulations were only done for one seed thus representing only one machine configuration.

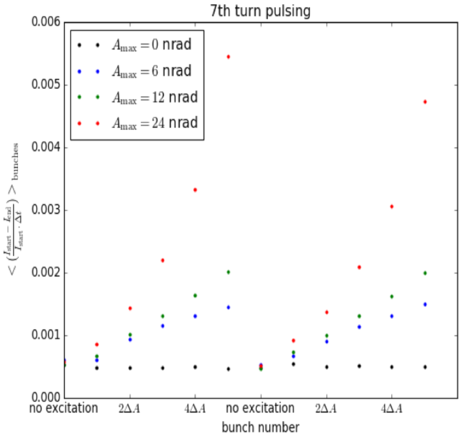

Figure 4: Scaling of losses with excitation amplitude for pulsing every 7th turn H measured with the FBCTs.

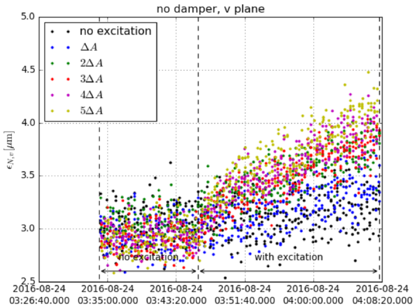

Figure 5: Emittance measured with the BSRT without excitation and with pulsing every 10th turn in V.

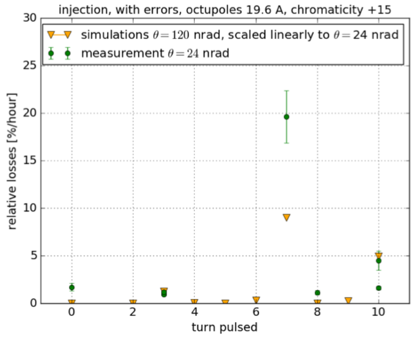

Figure 6: Emittance measured with the BSRT without excitation and with pulsing every 10th turn in V.

CONCLUSION AND OUTLOOK

A first experiment at the LHC testing the effect of a resonant excitation on the beam core has been performed. Losses were observed for pulsing every 7th turn in H (max. kick 24 nrad) and 10th turn in V (max. kick 96 nrad) and no losses for the other pulsing patterns tested. This observation is consistent with simulations. However, the LHC beam appears to be more sensitive in terms of amplitude than predicted in simulations. In future experiments it is foreseen to test the remaining resonant excitation pulsing patterns using the same beam and optics conditions and most importantly also the random mode in order to compare the two modes.

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