FIRST ATTEMPTS AT USING ACTIVE HALO CONTROL AT THE LHC*

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Abstract

The beam halo population is a non-negligible factor for the performance of the LHC collimation system and the machine protection. In particular this could become crucial for aiming at stored beam energies of 700 MJ in the High Luminosity (HL-LHC) project, in order to avoid beam dumps caused by orbit jitter and to ensure safety during a crab cavity failure. Therefore several techniques to safely deplete the halo, i.e. active halo control, are under development. In a first attempt a novel way for safe halo depletion was tested with particle narrow-band excitation employing the LHC Transverse Damper (ADT). At an energy of 450 GeV a bunch selective beam tail scraping without affecting the core distribution was attempted. This paper presents the first measurement results, as well as a simple simulation to model the underlying dynamics.

INTRODUCTION

The possibility to implement mechanisms to control and deplete actively the beam halos at the LHC is considered as an important possible upgrade of the collimation system in view of the operation at high intensity. In LHC Run I, several beam dumps occurred during squeeze due to orbit jumps causing scraping of beam tails at the collimators [1,2]. Such drifts would be mitigated if a depletion of the beam tail is carried out in a controlled way so that no beam would be scraped off. In addition, and looking towards the future LHC upgrade (HL-LHC) [3], if tails are depleted, fast crab-cavity failures pose lower risk to send beam onto sensitive elements.

In order to increase the diffusion speed of the halo, while leaving the core unaffected, three different methods have been proposed: electron lenses [4,5], tune modulation [6] and ADT narrow-band excitation. By means of the latter method with the ADT we can create a narrow-band excitation at a given frequency relating to a certain betatronic tune Q_{ADT}. Relying on the amplitude detuning by which particles with different amplitudes have different tunes, we can resonantly kick just particles at a certain amplitude, driving them to larger amplitudes until they are intercepted by a primary collimator (TCP). It is expected that if this excitation is made in a controlled manner and the dominating source of tune spread comes from the amplitude detuning, the tails can be depleted while the core of the beam remains unperturbed. Other aspects of this mechanism are described in [7].

This article presents the measurement results with 450 GeV proton beams from the very first trials with this method in the LHC [8]. Furthermore the parallel studies by means of simulations are described.

MEASUREMENTS

MAD-X [9] was used to calculate the range of expected fractional tunes where an ADT excitation could be performed in the measurements, corresponding to amplitudes between 0 and 6σ. This gave the ranges of $Q_x \approx 0.2715$ to 0.291 for the horizontal and $Q_y \approx 0.3015$ to 0.3215 for the vertical plane. The ADT software was prepared so that excitations could be applied separately in both planes either as a frequency scan via step wise increase of the excitation tune (corresponding to a given ADT frequency) in increments of ΔQ_{ADT} with a time Δt between steps or at a fixed frequency Q_{ADT}. The maximum applicable kick amplitude per turn A amounted to ≈ 1.93 µrad (i.e. 0.36 σ).

In order to demonstrate that only particles of the targeted amplitude region are depleted the experiment was carried out with a *three-bunch scheme*, see Fig. 1. Three bunches of the same intensity were injected in the LHC. The ADT excitation window affected two bunches, #1500 and #1700. The third bunch #0 circulated outside the ADT window. This *reference bunch* served as a probe for other sources of emittance growth. Bunch #1500 was blown-up by ADT white noise before the actual narrow-band excitation to populate its tails and is therefore referred to as *blown-up bunch*. This

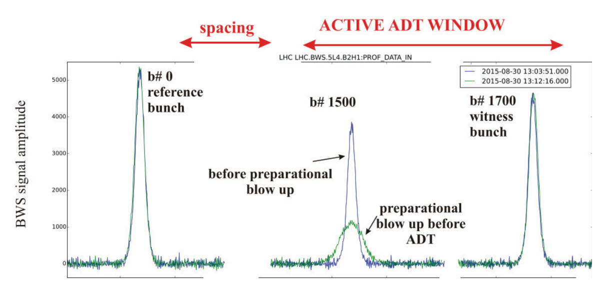

Figure 1: Wire scanner profiles illustrating the *three-bunch scheme*. In blue the profiles show the state before the preparatory blow up of bunch #1500 and green afterwards.

should provide significant signal for observable beam intensity decrease and losses compared to the standard bunch #1700 which should display as a *witness bunch* whose core should not be affected by the excitation. The TCPs were

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set to 5.7σ. During all series of excitations with the ADT the individual intensities and emittances, bunch profiles and beam losses were constantly monitored.

Initially a measurement of horizontal detuning with amplitude was carried out with the AC dipole as in [10,11] with higher statistics and octupole current at 10 A. This gave refined estimates of relevant ADT excitation frequencies. The result is shown in Fig. 2 with fitted parameters of the model $\Delta Q_x = \Delta Q_0 + b \cdot \sigma^2_{\text{nominal}}$ where ΔQ_0 corresponds to a perfectly centered particle and a value of $\epsilon_{\text{norm.}} = 3.75\,\mu\text{m}$ is chosen.

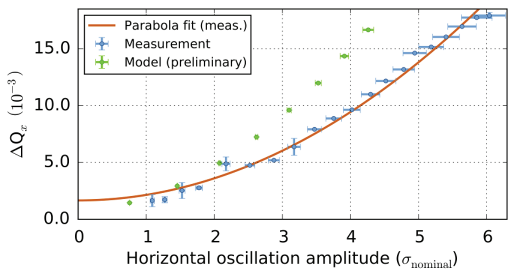

Figure 2: Detuning with amplitude measurement fitted by $\Delta Q_0 = 1.7{\pm}0.2{\cdot}10^{-3}$, $b = 0.52{\pm}0.13{\cdot}10^{-3}$ and preliminary model.

Several scans in ADT excitation frequency were performed, which initially went through the whole amplitude range between 0 and 6σ. This allowed to study losses as a function of excitation frequency and to give further input to the frequency range and amplitude chosen when attempting to clean the halo only, which were tried in subsequent frequency scans. The fractional tune at zero amplitude amounted to $Q_x \approx 0.278$. An example result of

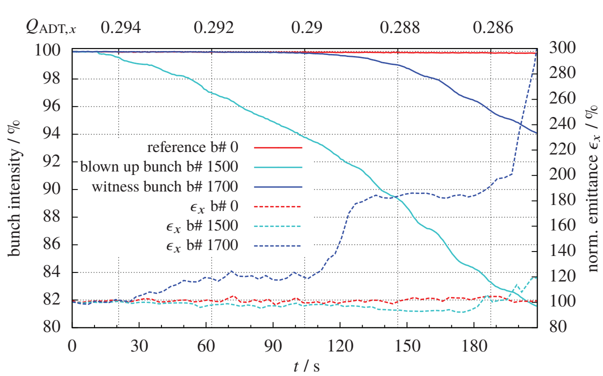

Figure 3: Individual bunch intensities and emittances during an ADT frequency scan of $Q_{\text{ADT},x} = 0.285 \leftarrow 0.295$, $\Delta t = 2\,\text{s}$ and $A = 6.53 \cdot 10^{-3}\sigma$ approaching the cores.

the obtained bunch intensities and emittances is shown in Fig. 3, where the blown-up bunch experienced the scraping of particles earlier than the witness bunch, which starts dropping around $Q_{\text{ADT},x} = 0.290 \approx 4.5\sigma_{\text{nominal}}$. By contrast the reference bunch is not affected during the whole scan. This result represents in the first approximation the distributions of the bunch profiles taken with the beam wire scanners (BWS), shown in Fig. 4, considering that the excitation affects all particles and depending on the ADT amplitude a narrow-band exists within particles are scraped. However the individual emittances in Fig. 3, measured continuously with a synchrotron radiation monitor, display that there is a perturbation for the witness bunch even far from the core. Focussing on the tune range where the witness

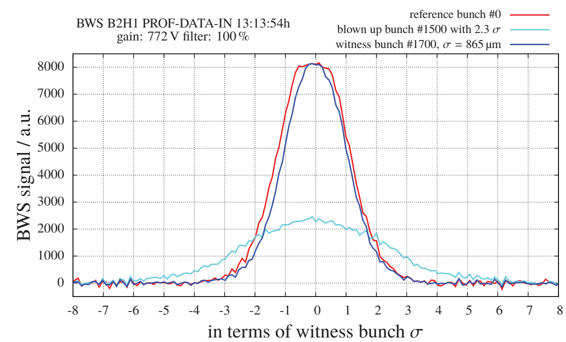

Figure 4: Beam wire scanner profiles before the ADT excitation refering to the frequency scan in Fig. 3.

bunch was not affected in terms of intensity and emittance, excitations with a fixed ADT frequency and the same ADT amplitude was performed. An example result is illustrated in Fig. 5. During the whole excitation of 120 s the witness bunch shows no loss of particles and the curve overlaps with the reference bunch. For the blown-up bunch a depletion of 2 % in the region of $Q_x = 0.295 \approx 5.4\ \sigma_{\text{nominal}}$ was achieved. Furthermore no emittance growth for the witness bunch was observed demonstrating that its core remained unaffected. This has to be verified for larger time scales in the future. However, subsequent excitations with larger ADT amplitudes caused losses also on the witness bunch.

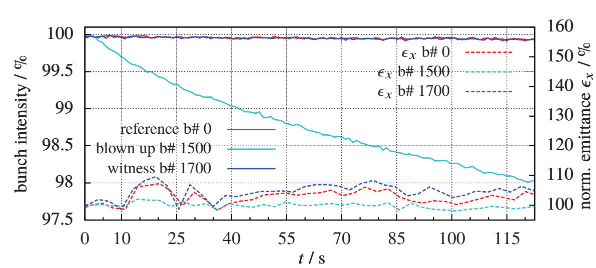

Figure 5: Individual bunch intensities and emittances during an ADT excitation with fixed frequency of $Q_{\text{ADT},x} = 0.295$ and $A = 6.53 \cdot 10^{-3}\sigma$.

SIMULATIONS

Standard tracking simulation codes allow a precise description of the beam dynamics. Nevertheless, in order to illustrate the physics of the narrow-band excitation and to have a very fast simulation model that allows for parametric studies we have created a simpler one dimensional model to

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test the principle. In addition, this simpler model is much faster than tracking codes like SixTrack [12]. It is composed of a one turn map including the octupolar contribution to generate a tune spread plus an oscillating kick given by the ADT. Other features have been included in the model in order to make it more similar to the real measurement. For instance, the ADT amplitude signal can be ramped up and down adiabatically in order to avoid emittance blow-up. Also, frequency scans can be done continuously or in steps. The octupole strength has been varied until tracking simulations fit the curve given by the detuning with amplitude measurement in Fig. 2. The amplitude of the ADT signal has been calculated accounting for the calibration of the ADT.

As an example, we simulate the fixed frequency excitation measurement of Fig. 5. In this case an ADT frequency of $Q_{\mathrm{ADT}} = 0.295$ was chosen. The excitation during the

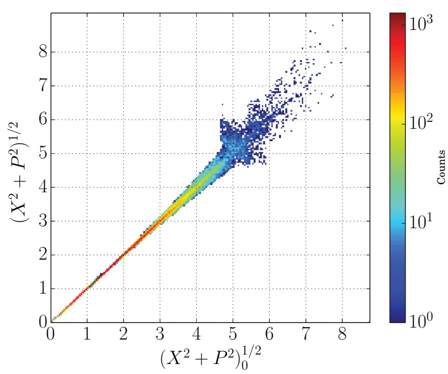

Figure 6: Final amplitude distribution as a function of the initial amplitude for a fixed ADT frequency of $Q_{\mathrm{ADT}} = 0.295$.

measurement lasted for about 120 seconds with an intensity reduction of about 2%. We have simulated the same excitation under similar circumstances for 10^6 turns that corresponds to approximately 90 seconds. The blown-up bunch is modelled by a distribution 2.5 times wider than the reference distribution. In Fig. 6 the final amplitude of the particles in the blown-up bunch is plotted as a function of the initial amplitude in σ, calculated via the normalized betatron coordinates X, P. The excited amplitude (around 5.6σ) is clearly affected while the core remains unaltered. In Fig. 7 the relative intensity of the bunch population below 5σ is shown as a function of the number of turns. We observe an intensity reduction of 1.5% which is close to the measurements, however the shape of the graph does not coincide, which may be caused by non-implemented diffusion.

In another case we simulate a frequency scan from $Q_{\mathrm{ADT}} = 0.290$ to 0.295 along $5 \cdot 10^4$ turns (fast scan), see Fig. 8. The blown-up bunch is represented by a distribution 2 times wider than the nominal. One can observe a clear cut at the start of the initial excitation frequency and a clear tail depletion. A non negligible amount of particles is excited from 4-5σ to 5-7σ. Some particles still remain in the

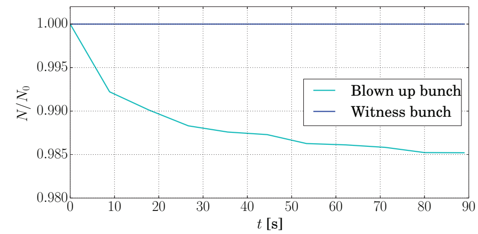

Figure 7: Relative intensity evolution during 90 seconds for a fixed ADT frequency of $Q_{\mathrm{ADT}} = 0.295$.

tail but globally there is an intensity reduction in the bunch tail although the core is clearly affected but without a clear emittance growth. This result points in the same direction of the measurements and motivates future experiments. In spite of the promising results, we nevertheless plan also to perform further simulations of selected cases using more accurate 6D tracking simulations that include also other nonlinearities.

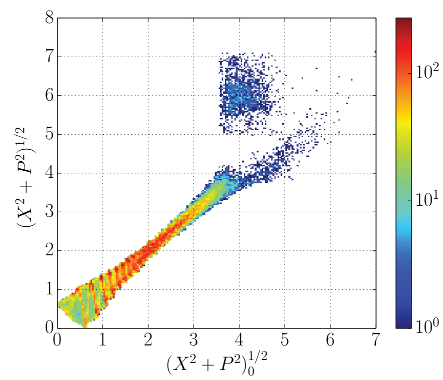

Figure 8: Final amplitude distribution as a function of the initial amplitude for an ADT frequency scan of $Q_{\mathrm{ADT}} = 0.290 \rightarrow 0.295$.

CONCLUSION

The very first attempt of using active halo control in the LHC by means of the transverse damper at injection energy showed first promising results. For the application of the ADT useful settings have been proposed which deliver similar results in a simplified 1D simulation tool. A detuning with amplitude measurement was successfully carried out. The presented measurements of excitations use an original experimental method referred to as *three-bunch scheme* that can be very useful also for other halo studies. In spite of some promising results, some tests were inconclusive. Before conclusions can be drawn on the feasibility of the method for operational halo control, the measurements would have to be repeated, to demonstrate a reliable reproducibility, and new tests have to be envisaged in more complex operational conditions with multiple bunches. Furthermore, more detailed simulations are planned.

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