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FIRST PROTON CRABBING AT THE LHC VIA HEAD-ON BEAM-BEAM INTERACTION *

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Abstract

The first experimental observation of a crabbing orbit induced by head-on collisions with a non-zero crossing angle in a high-energy proton beam at the Large Hadron Collider (LHC) is presented. This challenging measurement required both the set up of a dedicated experiment and a careful calibration of the beam instrumentation to produce and detect such a subtle effect. To measure the dependence of this effect on the crossing angle, this parameter is varied from positive to negative values. Tracking simulations were performed to corroborate the experimental results, showing excellent agreement with the measured crabbing amplitudes. This experiment highlights the potential of the existing wideband beam-position monitors to diagnose crabbing effects, which will be crucial in the HL-LHC upgrade.

INTRODUCTION

Modern colliders started implementing Crab Cavities (CCs) [1] to intentionally introduce crabbing for luminosity purposes. CCs have been used in KEK [2] and are part of the baseline for HL-LHC [3] and Electron-Ion Collider [4]. This work, however, investigates a different crabbing mechanism: crabbing induced by Head-On Beam-Beam (HOBB) interactions [5, 6].

We present the first experimental observation of a crabbing orbit induced by head-on collisions with a non-zero vertical crossing angle (θ_c) in the Large Hadron Collider (LHC) [7]. Machine parameters have been optimised using Xsuite [8] and MAD-X [9] simulations. The wideband beam-position monitors [10] were calibrated and utilized to measure the induced crabbing, which was estimated to be approximately 10 µm at $1\sigma_z$.

After introducing the definition of crabbing dispersion, the first part of this paper details the experimental setup and measurement techniques, while the second part focuses on the numerical simulations used to predict the crabbing effect.

An effective way to study HOBB induced crabbing is to use a matrix formalism as in [8, 11–13]. The variables of interest of our system are (y, p_y, z, δ) since the effect was induced in the vertical plane in our experiment. We want to find $\zeta_y(\mathrm{s}) = \frac{dy}{dz}$ in a linear approximation of the beam-beam force. The problem is studied in the weak-strong regime [14] with the two bunches colliding with a total crossing angle θ_c.

An analytical estimate of the crabbing induced on a particle at (y, z) in the weak bunch can be derived assuming round beams. Under these assumptions the beam-beam parameter simplifies to $\xi = \frac{N_p r_0}{\epsilon \beta^*}$, where N_p is the bunch intensity, r_0 the classical proton radius, ϵ the normalized emittance, and β^* the optical function at the IP. The crabbing effect is therefore directly proportional ξ.

The beam-beam kick can then be represented by the following 2D matrix map:

$$\mathcal{M} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ \xi\cos^2(\frac{\theta_c}{2}) & 1 & \xi\sin(\frac{\theta_c}{2})\cos(\frac{\theta_c}{2}) & 0 \\ 0 & 0 & 1 & 0 \\ \xi\sin(\frac{\theta_c}{2})\cos(\frac{\theta_c}{2}) & 0 & \xi\sin^2(\frac{\theta_c}{2}) & 1 \end{bmatrix}. \quad (1)$$

The element $\mathcal{M}_{2,3}$ is what produces a crabbing through HOBB by coupling y and z planes. The vertical crabbing dispersion ζ_y at the IP will then be given by:

$$\zeta_y(\mathrm{IP}) = \frac{\beta^* \mathcal{M}_{2,3}}{2} \cot \pi \nu_y, \quad (2)$$

with ν_y the vertical tune. One can then propagate $\zeta_y(\mathrm{IP})$ at any other location to obtain:

$$\zeta_y(\mathrm{s}) = \frac{\sqrt{\beta^* \beta(s)}\mathcal{M}_{2,3}}{2\sin \pi\nu_y} \cos(\pi\nu_y - |\psi(\mathrm{s}) - \psi(\mathrm{IP})|), \quad (3)$$

where the phase advance between the IP and the s location is taken into account. The vertical displacement of the bunch for the longitudinal coordinate z_0 at location s can then be easily evaluated as dy = $\zeta_y(\mathrm{s}) \times z_0$.

Due to the complexity of the LHC lattice a full set of simulations has been developed and described later in this paper to precisely evaluate this effect, but this analytical treatment is crucial to identify the main parameters of interest and how they come into play.

EXPERIMENT

Experimental Setup

The experiment has taken place in the LHC and designed with the beam parameters reported in Table 1.

LHC has four dedicated Interaction Points (IP1, IP2, IP5, IP8). During the measurement, it was decided to use just IP1 where the crossing occurs in the vertical plane. For this particular filling scheme bunches could not collide in IP2 and IP8 and were separated in IP5. The parameters are chosen to maximise ξ staying within the safety limits of the LHC machine. The measurement involved just one bunch per

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Table 1: Beam Parameters For Both Beams

Parameter	Value
N_p [ppb]	2.3×10^{11}
E_b [GeV]	450
$(\epsilon_{n,x}, \epsilon_{n,y})$ [µm]	2.0, 2.0
σ_z [ns]	0.32
$\frac{\theta_c}{2}$ [µrad]	(170, 0, -170)
f_{rev} [s^{-1}]	~ 11245.0

beam, referred to as B1 or B2 in the following. In this paper two different conditions for B1 are presented, corresponding to a positive and a negative value of $\frac{\theta_c}{2}$. In the experiment B1 is injected in the LHC and circulates in the machine; B2 is injected directly in collision with B1 with $\frac{\theta_c}{2} = 170$ µrad. After the collision the crossing angle is changed to −170 µrad. Both the intensity and the emittance of each beam have been monitored, with DC current transformers [15] and Beam Synchrotron Radiation Telescopes [16], respectively.

To detect the crabbing signal wideband beam-position monitors, referred to as head-tail (HT) monitors [10], were used. The system is based on the high speed acquisition of a dedicated 40 cm "stripline" type vertical beam-position monitor (BPM), positioned at a location with high β_y function. Every turn two signals are produced, the analog sum (Σ) and difference (Δ) of each pair of electrode signals. The Σ signal contains information regarding the total charge of the bunch, whereas the Δ signal is used to retrieve asymmetries between the head and tail of the bunch. To obtain the information needed the Δ signal must be normalized to the corresponding Σ signal:

$$\Delta_n = \frac{\Delta(z)}{\Sigma(z)}. \tag{4}$$

This normalised difference is then converted to a displacement through a calibration factor $C_f = 4545.45$ µm:

$$dy(z)[\mu m] = C_f \times \Delta_n(z). \tag{5}$$

Experimental Results

If a crabbing effect is present, then the bunch will continue to be tilted by the same amount at the HT location in the lattice. This in turn produces a turn-by-turn static signal. It is possible to leverage on this property to average over many consecutive turns ($\mathcal{O}(10^3)$) to get a better signal to noise ratio. An example of a set of these consecutive acquisitions is reported in Fig. 1. All the acquisitions obtained in this way are then put in the form of Eq. (5) and plotted in a histogram like the one shown in Fig. 2 together with the bin by bin standard deviation. A linear fit is then applied to the data to retrieve the crabbing in the range $z \in [-1\sigma_z, +1\sigma_z]$.

In each plot, the head of the bunch is always on the left part of the plot and the intensity of the colormap used has a maximum in the maximum $\langle\Sigma\rangle$ signal of each set of acquisitions, so that the bunch intensity is visible on the plot.

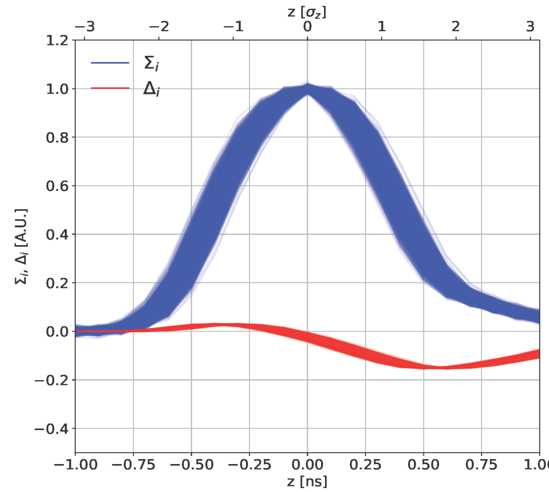

Figure 1: Example of Σ and Δ signals for 2000 consecutive turns.

Two different conditions are studied: $\frac{\theta_c}{2} = \pm 170$ µrad, which, according to $\mathcal{M}_{2,3}$, should be equal in module and opposite in sign. When B1 is put in collision with B2 with the positive crossing angle, a positive displacement at 1 σ_z of 10 µm is present, as shown in Fig. 2. By changing the

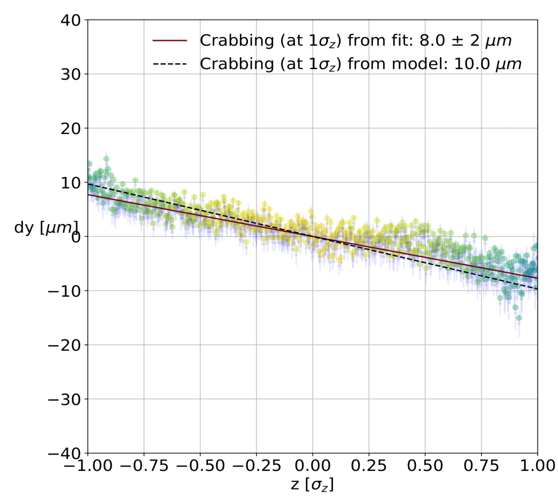

Figure 2: Crabbing signal for B1 at $\frac{\theta_c}{2} = 170$ µrad.

crossing angle to $\frac{\theta_c}{2} = -170$ µrad, a negative displacement at 1 σ_z of −10 µm can be seen in Fig. 3.

We can anticipate that both cases are in agreement with the numerical simulations shown in Fig. 4.

SIMULATIONS FOR LHC AND HL-LHC

To analyse the experiment, Xsuite simulations have been employed using a realistic lattice of the LHC at injection energy. HOBB interactions [17] were modeled using a weak-strong [18, 19] approach, with a 6D lens in IP1 [20]. The 6D closed orbit of the system is computed to obtain the magnitude of the effect at the HT monitor location. Thanks to

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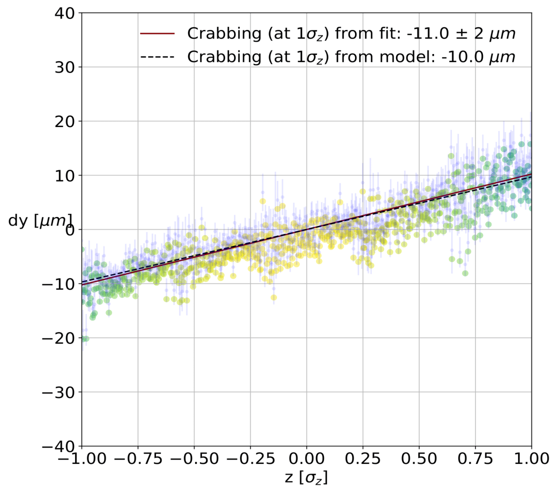

Figure 3: Crabbing signal for B1 at $\frac{\theta_c}{2} = -170\,\mu$rad.

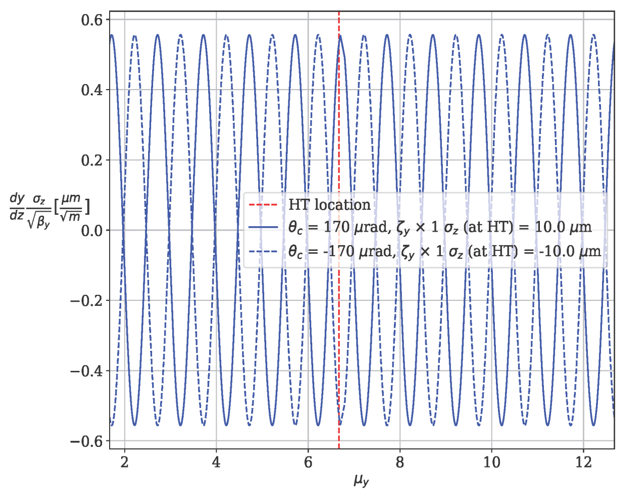

Figure 4: $\zeta_y(\mu_y)$ with $\frac{\theta_c}{2} = \pm 170\,\mu$rad and HOBB for B1. The value of the crabbing at the HT monitor location is also shown. All the functions are normalized with the $\sqrt{\beta_y(s)}$.

Xsuite, the differential quantity ζ_y is computed and mapped through the LHC lattice, with the result shown in Fig. 4. The crabbing orbit is identical for $\frac{\theta_c}{2} = \pm 170\,\mu$rad, but with a π phase between the two cases. The crabbing predicted by the derivative mapping at the HT monitor location is in very good agreement with the measured one.

HL-LHC Simulation

This measurement is part of the effort towards the LHC [7] upgrade, that, after more than 10 years of operation, will be upgraded to the High Luminosity LHC (HL-LHC) [3, 21] with the aim to increase the yearly integrated luminosity by at least a factor 3 with respect to the current LHC operational scenario. Four CCs [22] per beam and per IP will be installed in the two main experiments, ATLAS [23] and CMS [24]. The phase advance between the CCs on the opposite side of each experiment leaves a residual crabbing in the machine. The detection of this effect is crucial in the context of orbit

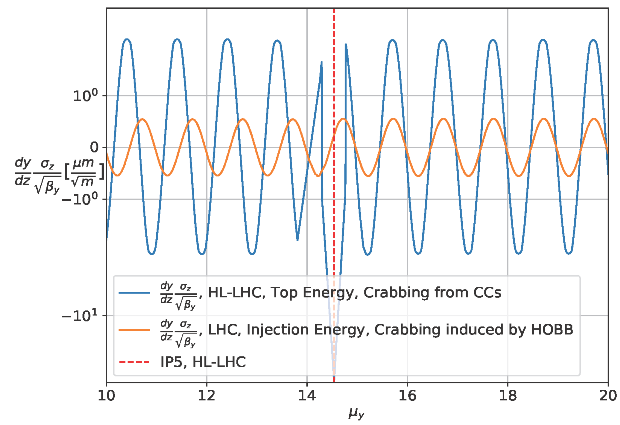

Figure 5: Comparison between residual crabbing in HL-LHC and induced crabbing via HOBB interaction in the experiment. IP5, where the vertical kicking CCs will be installed is shown. Symmetric logarithmic scale.

diagnostics and machine protection. This residual crabbing has been numerically calculated and is visible in Fig. 5. The fundamental information is that the crabbing induced around the machine in the case of our experiment that was successfully detected by the HT monitor is one order of magnitude lower than the one due to the residual crabbing coming from CCs in the HL-LHC. This result is crucial to demonstrate the potential of this diagnostics to detect not only disruptive effects (e.g. large crabbing coming from a CC failure [25]), but also imperfections in the closure of the crabbing orbit.

CONCLUSIONS AND FUTURE WORK

This study presents the first experimental observation of a 10 µm crabbing at $1\sigma_z$ induced by the HOBB interaction with a crossing angle at the LHC. We successfully calibrated diagnostics and conducted dedicated experiments with two colliding bunches at 450 GeV. The crabbing effect was induced and measured, and its dependence on the crossing angle ($\frac{\theta_c}{2}$) was experimentally verified.

The analytical and numerical models accurately predicted the observed crab crossing values. As the LHC undergoes the HL-LHC upgrade with the installation of 16 crab cavities, the ability to measure and localize residual crabbing becomes crucial. The HT monitor, as demonstrated in this study, offers a promising diagnostic tool for this task.

Future experiments, such as inducing horizontal collisions at IP5, can further explore the capabilities of the HT monitor and quantify the minimum detectable crabbing signal in both planes. This would provide valuable insights into the limitations and potential of this diagnostic technique, in particular in the presence of dispersion.

Overall, this study highlights the effectiveness of the HT monitor and numerical modeling in understanding and addressing crabbing effects in the LHC.

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