

First observation in the LHC of beam-beam-induced crabbing

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The first experimental observation of a crabbing orbit induced by beam-beam interaction in the presence of a finite crossing angle in a high-energy proton beam is presented. This measurement required both the design of a dedicated experiment in the large hadron collider (LHC) and careful calibration and optimization of the beam instrumentation to produce and detect such a subtle effect. To also measure the dependence of this effect on the crossing angle, this parameter is varied from positive to negative values, further showing the reproducibility of the effect. Tracking simulations were performed to corroborate the experimental results, showing good 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 High-Luminosity LHC (HL-LHC) upgrade.

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I. INTRODUCTION

Ever since the early 2000s, with particle accelerators reaching record energies and luminosities, the need to minimize long-range beam-beam (LRBB) effects and optimize luminosity has pushed increasingly complex machine designs. Perhaps one of the most important developments from this era is the crab cavity (CC), a radio-frequency device used to tilt particle bunches transversely as a function of the longitudinal position to allow head-on overlap at the collision point even when there is a finite crossing angle. Initially developed during the 1980s and first installed at KEKB in Tsukuba, Japan [1], CCs are now part of the baseline design of next-generation facilities such as the High-Luminosity Large Hadron Collider (HL-LHC) at CERN [2] and the future Electron-Ion Collider (EIC) in the United States [3]. However, the study described here differs in its perspective on the crabbing effect. Rather than relying on specialized rf cavities to induce the crabbing of the beam, we explore

a subtler phenomenon: beam-beam-induced crabbing [4,5] in the presence of a finite crossing angle. As discussed in the next section, the underlying transverse-longitudinal coupling vanishes in the strict head-on limit ($\theta_c \rightarrow 0$) and arises specifically from the combination of the beam-beam interaction with a nonzero crossing angle. These interactions, intrinsic to the physics of colliding beams, have long been studied for their role in tune shifts and emittance growth, yet their capacity to mimic the effect of CCs has remained theoretical.

Here we share the first measurement of a crabbing orbit due solely to beam-beam interactions in the presence of a finite crossing angle [6], using the LHC. The amplitude of the induced crabbing is shown to be dependent on the intensity and crossing angle of the beams and inversely proportional to transverse beam size, as expected from the models and discussed in the next section. To identify machine configurations that could maximize this effect, we employed simulations using Xsuite [7]. The measurement was performed with dedicated wideband beam position monitors [8], namely, Head-Tail (HT) monitors, optimized to detect the change in the transverse orbit along the bunch, allowing us to capture the crabbing signature of two counterrotating bunches. This result is crucial in demonstrating the potential of this diagnostic to detect not only disruptive effects (e.g., large crabbing due to a CC

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failure [9]) but also imperfections in the closure of the crabbing orbit coming from a nonexact π -phase advance between the CCs located before and after the Interaction Point (IP), as well as voltage errors and cavity tilts. The structure of the paper is as follows. After defining crabbing dispersion, we describe the setup of the experiment, the diagnostics, and the results. The second part of the paper presents the numerical simulations that predicted the measured signal. We then complete the study by comparing the expected residual crabbing around the machine in the HL-LHC lattice due to CCs with the measured crabbing in our experiment.

A. An introduction to the concept of crabbing through beam-beam

In this section, the matrix formalism [7,10–12] is introduced as an effective way to study transverse-longitudinal coupling. This approach is then used to explain how beam-beam can induce crabbing. The analytical derivation of the effect is performed and used in the paper together with numerical simulations to analyze the experimental results.

The variables of our system are $(x, p_x, y, p_y, z, \text{ and } \delta)$, but we restrict ourselves to 4D transverse-longitudinal systems, as we are interested in the coupling of the longitudinal variables to a single transverse plane. A thin linear crabbing is defined by the following kick:

$$\begin{cases} \Delta p_y = kz \\ \Delta \delta = ky \end{cases}, \quad (1)$$

for some parameter k that will vary depending on the specific effect that is tilting the beam. The particles ahead ($z > 0$)/behind ($z < 0$) the reference particle will get a change in p_y , so the bunch is given a vertical tilt that depends on the longitudinal position. The symplecticity condition imposes an equal kick in δ that depends on y .

This thin lens is therefore described by a matrix M of the following kind:

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{bmatrix}, \quad (2)$$

where the coupling between y and z is given by the element $M_{2,3}$ and the symplecticity is ensured by the element $M_{4,1}$.

As a cross-check of this analysis, we consider the Hamiltonian of a thin CC [13,14]:

$$H_{\text{crab}} = \frac{qV}{P_s} \sin\left(\phi_s + \frac{\omega z}{c}\right) y, \quad (3)$$

where q is the particle charge, V is the voltage, P_s is the particle energy, ω is the frequency of the CC, c is the speed

of light, and ϕ_s is the synchronous phase of the crab-cavity rf wave. To simplify the form of this Hamiltonian, we restrict ourselves to the case of $\phi_s = 0$. The kick can be calculated from Hamilton's equations:

$$\begin{cases} \{-H, p_y\} = -\frac{\partial p_y}{\partial p_y} \frac{\partial H}{\partial y} = -\frac{qV}{P_s} \sin\left(\frac{\omega z}{c}\right) \\ \{-H, \delta\} = -\frac{\partial \delta}{\partial \delta} \frac{\partial H}{\partial z} = -\frac{qV}{P_s} \frac{\omega}{c} \cos\left(\frac{\omega z}{c}\right) y \end{cases}. \quad (4)$$

This map is symplectic by construction. Its Jacobian, and hence its first-order linearization, is also symplectic. If we define $k = -\frac{qV\omega}{P_s c}$, the linearized map coincides with the matrix M of Eq. (2).

Now we can understand how to produce crabbing through the beam-beam interaction [12]. The problem is studied in the weak-strong regime [15] with the two bunches colliding in the vertical plane with a total crossing angle of θ_c . Under the hypothesis of a very slow synchrotron oscillation ($\nu_s \ll 1$), the z coordinate of the particles can be considered quasi-static. This hypothesis is satisfied in the LHC scenario of our experiment, where $\nu_s \sim 0.07$. As the weak beam crosses over the strong beam, it will receive a vertical kick that depends on z . A graphical representation of the effect on a single particle of the weak beam is shown in Fig. 1, where the direction of the forces on the weak beam can be seen.

An analytical estimation of the crabbing on a particle that has coordinate (y, z) with respect to the center of the weak bunch can be obtained as a function of the beam-beam strength and of the crossing angle θ_c . Let σ_x, σ_y , and σ_z be the transverse and longitudinal beam sizes of the bunch and β_x^*, β_y^* be the β function values at the IP. In our experiment, the beams are round, so $\sigma_x = \sigma_y = \sigma$ and $\beta_x^* = \beta_y^* = \beta^*$. In the ultrarelativistic limit, the electric and

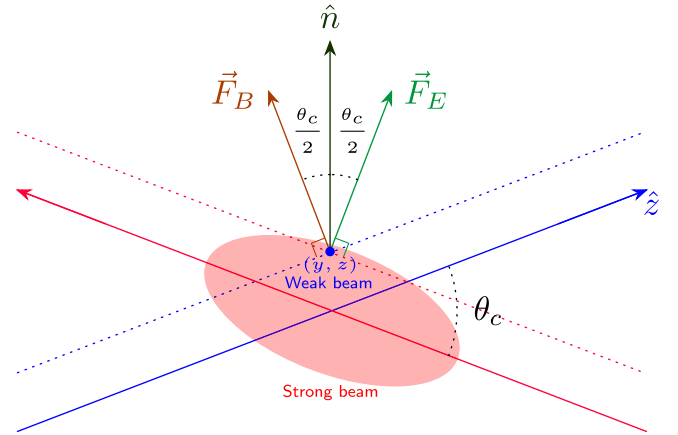


FIG. 1. Representation of the collision of the weak beam (blue) with the strong one (red). The particle with coordinates (y, z) with respect to the center of the weak beam is shown (dashed line). The electric (green) and magnetic (brown) forces generated by the strong beam are represented, and the net beam-beam force is directed in the $\hat{n}$ direction.

magnetic forces have the same magnitude. However, the collision occurs with θ_c , and therefore the two forces are not in the same direction. Because of Lorentz's force, the electric force will be orthogonal to the strong beam trajectory, whereas the magnetic force is orthogonal to the weak beam trajectory. The net force will be directed toward $\hat{n}$ (as shown in Fig. 1):

$$\hat{n} = \hat{y} \cos \frac{\theta_c}{2} - \hat{z} \sin \frac{\theta_c}{2}. \quad (5)$$

If the beam-beam kick is linearized, the kick felt by the particle is:

$$\Delta \vec{p} = \xi \left(y \cos \frac{\theta_c}{2} - z \sin \frac{\theta_c}{2} \right) \hat{n}, \quad (6)$$

with a positive sign, since the two bunches have the same charge. The parameter ξ is defined as:

$$\xi = \frac{N_p r_0}{\epsilon \beta^*}, \quad (7)$$

where N_p is the number of protons per bunch, r_0 is the classical radius of the proton, and ϵ is the normalized emittance of the bunch.

Equations (7)–(10) below are obtained in the small Piwinski angle limit, where the finite longitudinal extent of the opposing bunch gives a negligible correction to the transverse beam-beam force. Strictly speaking, when integrated over s during the collision, the colliding beam presents an effective vertical size $\sigma_{y,\text{eff}} = \sqrt{\sigma_y^2 + ((\theta_c/2)\sigma_z)^2}$. In the experimental conditions considered here, the Piwinski angle, $\phi_{\text{piw}} \equiv (\theta_c/2)\sigma_z/\sigma_y^*$, is small: $\phi_{\text{piw}} \simeq 0.08$. The corresponding effective beam-size correction is therefore only $\sigma_{y,\text{eff}}/\sigma_y = \sqrt{1 + \phi_{\text{piw}}^2} \simeq 1.003$. This justifies neglecting this correction in the analytical treatment used to interpret the measured signal. The same approximation is not valid in higher Piwinski angle regimes, such as nominal HL-LHC operation, where ϕ_{piw} is of order 2.5–3.

The y component of the p_y kick is therefore:

$$\Delta p_y = \xi \left(y \cos \frac{\theta_c}{2} - z \sin \frac{\theta_c}{2} \right) \cos \frac{\theta_c}{2}. \quad (8)$$

By symplecticity, the δ variable will also be changed by the following amount:

$$\Delta \delta = \xi \left(y \cos \frac{\theta_c}{2} - z \sin \frac{\theta_c}{2} \right) \sin \frac{\theta_c}{2}. \quad (9)$$

This beam-beam kick can then be represented by the following matrix map:

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ \xi \cos^2 \left(\frac{\theta_c}{2} \right) & 1 & \xi \sin \left(\frac{\theta_c}{2} \right) \cos \left(\frac{\theta_c}{2} \right) & 0 \\ 0 & 0 & 1 & 0 \\ \xi \sin \left(\frac{\theta_c}{2} \right) \cos \left(\frac{\theta_c}{2} \right) & 0 & \xi \sin^2 \left(\frac{\theta_c}{2} \right) & 1 \end{bmatrix}. \quad (10)$$

If we now compare this matrix with the general crabbing matrix in Eq. (2), then $k = \xi \sin \left(\frac{\theta_c}{2} \right) \cos \left(\frac{\theta_c}{2} \right)$. For comparison, achieving the same effective crabbing strength k with our beam would require an equivalent CC voltage of about 9.6 kV. Notice again that, in the limit $\frac{\theta_c}{2} \rightarrow 0$, M is the classic beam-beam defocusing quadrupolar matrix. The crabbing effect scales linearly on the intensity and inversely on the emittance and the β^* .

In the context of accelerator physics, differentials (such as the vertical dispersion dy) can be mapped through a given lattice to calculate their value at each element. In this case, the matrix in Eq. (10) is calculated at the location of the beam-beam, and its effect on both the variables and the differentials is obtained. When this element is included in the lattice, its propagation generally produces several transverse-longitudinal terms in the complete transfer matrix. These terms are all retained in the full 6D Twiss calculation presented in Sec. III. For the analytical treatment presented here, we use the slow synchrotron oscillation approximation and treat z as a parameter. In this limit, $M_{2,3}$ identifies the source of vertical crabbing dispersion ζ_y at the IP, and one can calculate it as:

$$\zeta_y(\text{IP}) = \frac{\beta^* M_{2,3}}{2} \cot \pi \nu_y, \quad (11)$$

with ν_y the vertical tune. Finally, we can propagate $\zeta_y(\text{IP})$ at any other location to obtain:

$$\zeta_y(s) = \frac{\sqrt{\beta^* \beta(s)} M_{2,3}}{2 \sin \pi \nu_y} \cos(\pi \nu_y - |\psi(s) - \psi(\text{IP})|), \quad (12)$$

where the phase advance between the IP and the s location is taken into account. The vertical offset of the bunch for the longitudinal coordinate z_0 at location s can then be easily evaluated as $\Delta y(z_0) = \int_0^{z_0} \zeta_y dz = \zeta_y \times z_0$. In particular, it is convenient to evaluate $\Delta y(1\sigma_z)$, which is the crabbing offset at $1\sigma_z$.

The closed-form expressions in Eq. (12) are obtained under the frozen-longitudinal-coordinate approximation ($\nu_s \rightarrow 0$) and represent a leading-order analytical estimate. A more general formalism that includes the finite synchrotron tune is available in Ref. [10]. Although in our experiment, $\nu_s \simeq 0.07$ is finite, the validity of the frozen approximation in this regime is verified a posteriori by the multiparticle simulation in Sec. III, which includes full synchrotron motion and reproduces the analytical slope

(see Fig. 10). The quantitative comparison with the experiment is therefore based on the numerical model, while Eq. (12) is used to identify the expected sign, phase dependence, and scaling with the crossing angle, intensity, emittance, and beta-functions.

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 the analytical treatment is crucial to identify the main parameters of interest and how they come into play.

In summary, we have introduced a matrix formalism to describe transverse-longitudinal coupling. This formalism can be used to represent both CCs and beam-beam-induced crabbing and to highlight the key parameters to generate crabbing dispersion. This framework serves as a basis for the experiment and the simulations presented in the following sections.

II. EXPERIMENT DESCRIPTION

A. Experimental setup

This section outlines the experimental setup, providing an overview of the main lattice parameters and the procedure followed to perform the measurement.

The experiment was performed in the LHC and was designed with lattice and beam parameters reported in Table I.

By using these parameters and Eq. (12), we see that, at the HT monitor location, a crabbing of about $\pm 10 \mu\text{m}$ at $1\sigma_z$ should be present.

The LHC has four dedicated IPs. During measurement, it was decided to use only one of these (IP1, corresponding to the ATLAS [16] experiment) where the crossing occurs in the vertical plane. This choice was motivated by the fact that there is an optimal phase advance between this IP and the location of the HT monitor that maximizes Eq. (12). IP5 (corresponding to the CMS [17] experiment) has a horizontal crossing in the current operational scenario.

TABLE I. Beam parameters.

Parameter	Value
N_p (ppb)	2.3×10^{11}
E_b (GeV)	450
$(\epsilon_{n,x}, \epsilon_{n,y})$ (μm)	2.0, 2.0
β^* (m)	11
$\beta(\text{HT})$ (m)	405
ν_y	0.31
σ_z (ns)	0.32
$\frac{\theta_c}{2}$ (μrad)	(170, 0, -170)
f_{rev} (s^{-1})	11 245.0
$ \psi(\text{HT}) - \psi(\text{IP1}) $	38.198
ϕ_{piw}	0.08
$\sigma_{y,\text{eff}}/\sigma_y$	1.003
ξ (m^{-1})	1.60×10^{-2}

Although it is possible in principle to rotate the crossing angle in IP5 to make it vertical and therefore useful to increase the amplitude of our crabbing signal, this was avoided to simplify the experimental procedure due to the limited beam time allocated for it. However, by LHC design, every bunch that collides in IP1 will also collide in IP5, so the bunches were separated to avoid interactions in IP5.

The parameters are chosen to maximize beam brightness, N_p/ϵ , keeping a reasonable lifetime. The measurement involved just one bunch per beam, with the two beams referred to as B1 or B2 in the following. The two bunches are put in collision with a vertical crossing angle $\frac{\theta_c}{2} = +170 \mu\text{rad}$ at 450 GeV. The angle is then varied from positive to negative values to demonstrate that, according to $M_{2,3}$, the crabbing changes sign.

Both the intensity and the emittance of each beam have been monitored, with dc current transformers [18] and Beam Synchrotron Radiation Telescopes [19], respectively. For a given optics, these two beam parameters are the fundamental contributors to the induced amplitude in the crabbing, since the beam-beam force is proportional to N_p and inversely proportional to ϵ_y , as shown in Eq. (7). A comprehensive plot with the evolution of both beams and the $\frac{\theta_c}{2}$ changes during the measurement is shown in Fig. 2.

Both beams start with the desired N_p and ϵ_y but are subject to proton losses and emittance growth due to the collisions. For this reason, the crabbing is expected to slightly change with time, with both effects contributing to a reduction of the bunch tilt.

B. Head-tail monitor

To detect the crabbing signal, dedicated wideband beam position monitors (BPMs) [8] were used. The HT system, shown as a simplified block diagram in Fig. 3, is based on the high-speed acquisition of a 40-cm “stripline” type BPM.

The system has been used primarily in the LHC for the detection of intra-bunch motion due to its large bandwidth, but it was also employed to measure the crabbing orbit in a dedicated series of CCs experiments in the SPS [20].

In this experiment, the dedicated vertical plane stripline is used, placed in a location with a 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 complete information needed, the first step is to normalize the Δ signal to the corresponding Σ signal:

$$\Delta_n(t) = \frac{\Delta(t)}{\Sigma(t)}, \quad (13)$$

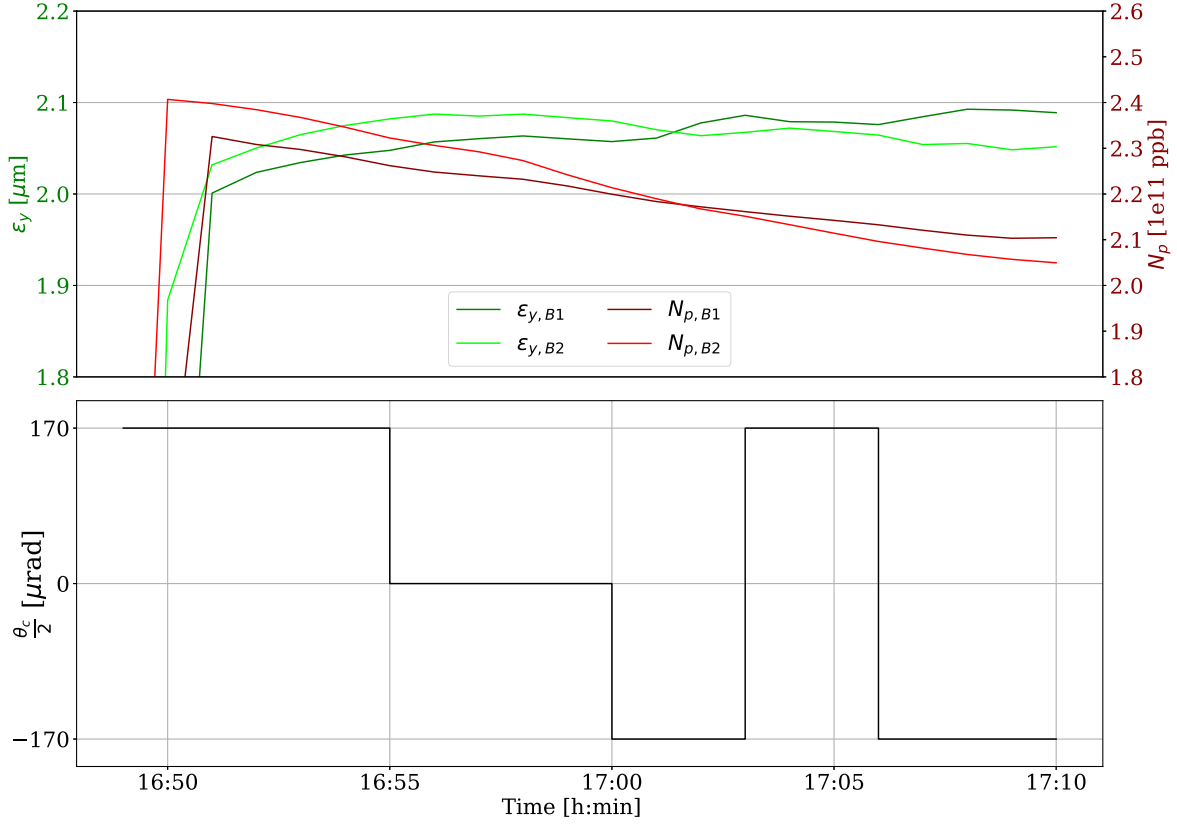


FIG. 2. ϵ_y (green), N_p (red), and $\frac{\theta_c}{2}$ (black) evolution during the experiment for both beams.

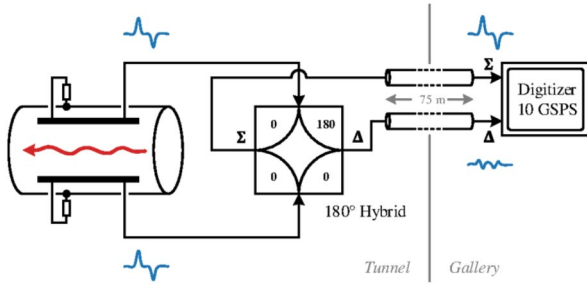


FIG. 3. The principle of the LHC HT. The Σ and difference Δ of the electrode signals of a long stripline-type BPM are obtained using a 180° hybrid and sampled by a high-speed digitizer located in a service gallery (courtesy of [8]).

where t is expressed in ns. This difference can then be converted to a displacement in μm through a calibration factor of $C_f = -4545 \mu\text{m}$ (Appendix A).

Measuring absolute position changes is complicated, so the HT monitor is designed to detect relative changes in the beam. The crabbing is therefore always retrieved as a difference between a reference measurement on one bunch in certain physical conditions (e.g., condition A, $\frac{\theta_c}{2} = 0 \mu\text{rad}$, $\Delta_{n,A}$) and a second measurement on the same bunch in a different condition (e.g., condition B,

$\frac{\theta_c}{2} = +170 \mu\text{rad}$, $\Delta_{n,B}$). In this study, the reference signal will always be the one taken at $\frac{\theta_c}{2} = 0 \mu\text{rad}$. This is because we know from the theory that the expected crabbing for this angle is zero, so the retrieval of the crabbing at any other angle is trivial.

The displacement needed is therefore obtained by calculating:

$$\Delta y(z) = -C_f \times (\Delta_{n,B} - \Delta_{n,A}). \quad (14)$$

Note that, by construction, any contribution that is independent of the crossing angle cancels identically in this difference.

If a crabbing effect is present, then the bunch will continue to be tilted by the same amount at the HT location on every turn. This in turn produces a turn-by-turn static signal. It is possible to take advantage of this property to collect many consecutive turns ($\mathcal{O}(10^3)$) to obtain a better signal-to-noise ratio. Notice that during these turns, it is true that due to burn-off and emittance growth, the crabbing is not staying exactly constant, but by looking at Fig. 2, one can see that a sensible change is measurable only on greatly larger timescales ($\mathcal{O}(10^6)$ turns). An example of these consecutive acquisitions is reported in Fig. 4.

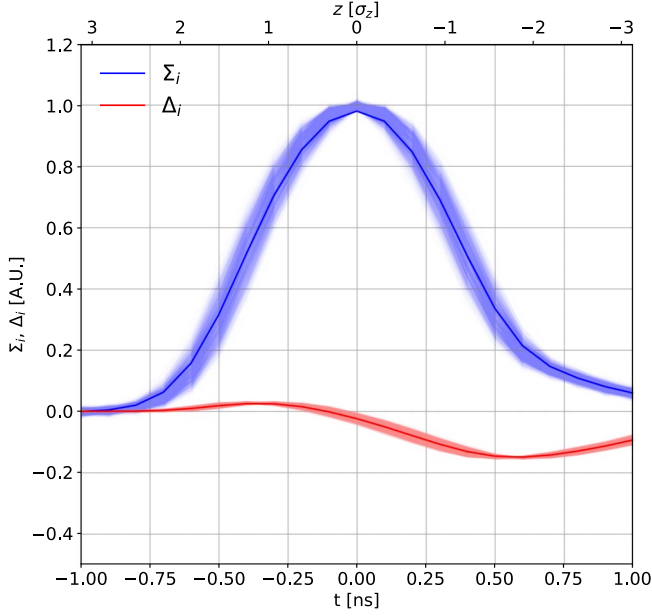


FIG. 4. Example of Σ and Δ signals for 2000 consecutive turns. The oscilloscope sees the head of the bunch first.

To finally obtain the crabbing signal, the delay between the Σ and Δ signals is calculated and subtracted. Then the stream of acquisitions is aligned to correct the rms. jitter of about 0.1 ns between consecutive signals. The signals are numerically resampled with a 1 ps period along the z coordinate, and the bin-by-bin value described in Eq. (14) is obtained. This bin width is chosen to better visualize the bunch profile in the plots that will follow. All the averages obtained in this way are then plotted in a histogram like the two shown in Fig. 5 together with the bin-by-bin standard deviation. The average Σ signal in the stream of acquisition is then fitted with a Gaussian to obtain the longitudinal σ_z as seen from the HT monitor. A linear fit in the range $z \in [-1\sigma_z, +1\sigma_z]$ is then applied to the data to retrieve the crabbing.

The reproducibility of this reconstruction chain was assessed with a null test: processing with the same procedure the difference between the first and the second 1000-turn subsets of the reference acquisition at $\frac{\theta_c}{2} = 0$ μrad yields a residual crabbing of 2 ± 2 μm at $1\sigma_z$, consistent with zero. This value sets the scale of the systematic uncertainty of the reconstruction.

C. Experimental results

In this section, the experimental results for each beam are presented. The angle scan for both B1 and B2 is shown, together with the expected simulated crabbing model described later in the paper. The intensity of the colormap used for both beams has a maximum in the maximum $\langle \Sigma \rangle$ signal of each acquisition, so the bunch intensity is visible in the plot.

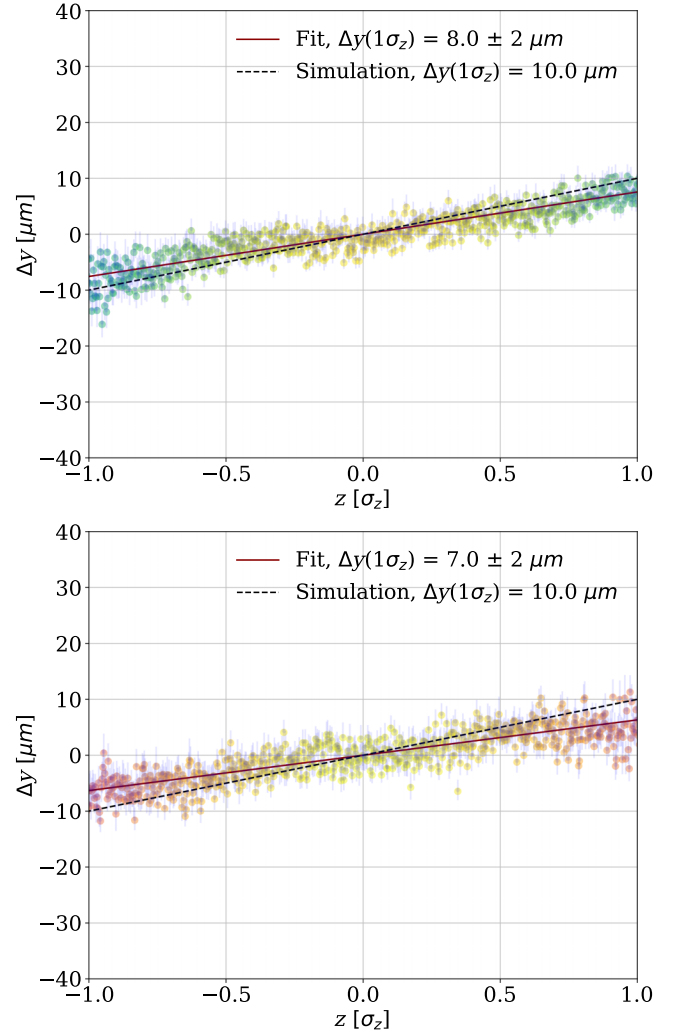


FIG. 5. Crabbing signal for B1 (top) and B2 (bottom) at $\frac{\theta_c}{2} = +170$ μrad . The expected crabbing from simulations is also shown (dashed line) and compared to the linear fit of the measurements (solid line).

At the beginning of the experiment, as shown in Fig. 2, B1 is put in collision with B2 with a positive crossing angle. This in turn produces a positive displacement at $1\sigma_z$ of about $+10$ μm , as shown in Fig. 5.

The phenomenon is explained using Eqs. (8) and (12): for B1, by colliding with B2 with a $\frac{\theta_c}{2} > 0$, a positive Δp_y is produced at the IP. This Δp_y is then rotated by the lattice map and becomes a $\zeta_y > 0$ at the HT location, as will be shown in Fig. 7. So, the simulated model described later in the paper for both B1 and B2 is in agreement with the measured signal showing a positive crabbing at the HT location. The study then continued, as shown in Fig. 2, with the angle variations that led to the full scan for both beams, reported in Fig. 6.

As the angle changes from positive to negative values, it is possible to calculate that the crabbing changes its amplitude and sign following the model in Fig. 7. For both

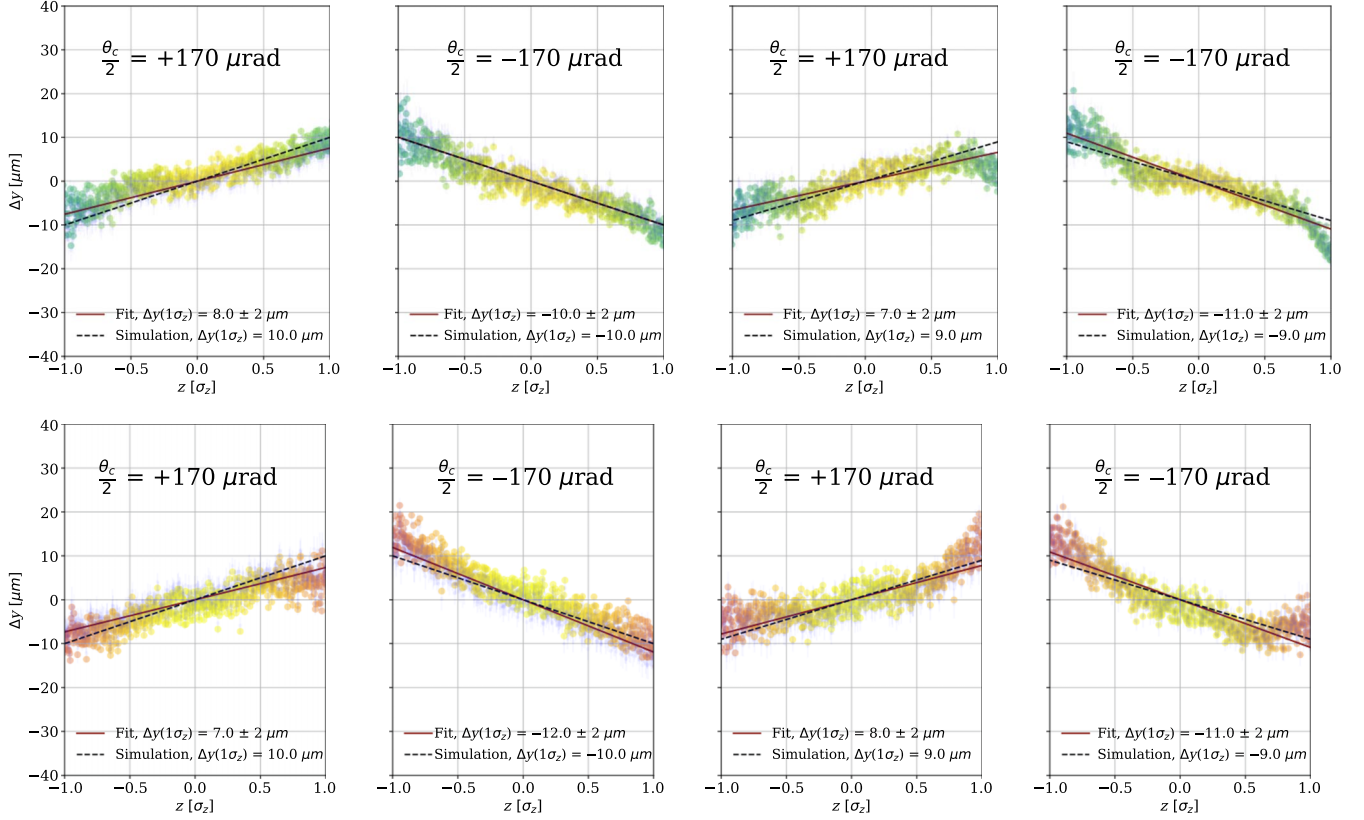


FIG. 6. Crabbing signal for B1 (top) and B2 (bottom) during the scan at $\frac{\theta_c}{2} = +170, -170, +170, -170 \mu\text{rad}$.

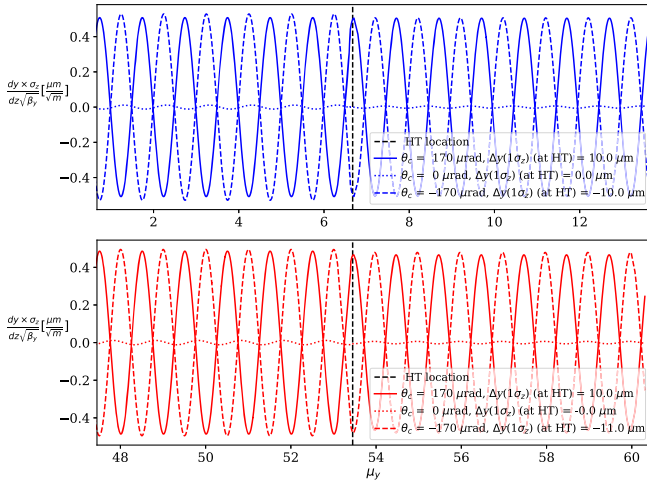


FIG. 7. $\zeta_y(\mu_y)$ function under three different conditions: $\frac{\theta_c}{2} = 0$ and $\frac{\theta_c}{2} = \pm 170 \mu\text{rad}$ for both B1 and B2. The three curves illustrate the expected sign reversal of the crabbing dispersion when the crossing angle is reversed and the near-zero beam-beam-induced crabbing for $\theta_c = 0$. The value of the crabbing at the HT monitor location is also shown. All the functions are normalized with the $\sqrt{\beta_y(s)}$, with $\sqrt{\beta_y(\text{HT})} \simeq 20.1 \text{ m}^{1/2}$. The variable μ_y denotes the cumulative vertical betatron phase advance used by the lattice model.

beams, it was possible to demonstrate that this is the case, showing the capacity of the HT monitor to measure effects of this order of magnitude.

The simulations reproduce the sign reversal and the expected magnitude of the measured crabbing signal, although a small signed offset remains visible across the scan in Fig. 6. The simulation gives a larger absolute amplitude at a positive crossing angle but a smaller absolute amplitude at a negative crossing angle. This behavior indicates an additive offset rather than a systematic overestimate of the beam-beam crabbing strength. To separate these contributions, the measured amplitudes are decomposed into components that are odd and even under reversal of the crossing angle. In this sense, the crossing-angle-odd component of the data follows the simulated beam-beam crabbing, whereas the remaining even component is compatible with a small reconstruction offset of less than $2 \mu\text{m}$. Because the same zero-angle acquisition is used as the reference for every measurement, a residual reconstruction slope in this acquisition shifts all reconstructed amplitudes in the same direction. The magnitude of the even component is consistent with the $2 \mu\text{m}$ systematic scale obtained from the null test. We therefore interpret the measurement-simulation difference as a reconstruction-level systematic associated with the

common reference rather than as a discrepancy in the predicted beam-beam crabbing strength. Possible sources include residual Σ/Δ synchronization, acquisition-chain imperfections, and orbit or rf-related changes between the reference and signal acquisitions.

Now we turn our attention to the simulations that were used to both design the experiment and predict the effect.

III. SIMULATIONS

Xsuite simulations have been employed using a realistic MAD-X [21] lattice of the LHC at injection energy. Head-on beam-beam interactions (HOBB) [22] were modeled using a weak-strong [23–26] approach, with one 6D lens in IP1. This type of simulation simplifies beam-beam interactions by assuming a rigid Gaussian distribution for the strong beam. As a complementary cross-check, we also performed a self-consistent strong-strong simulation: the result is reported in Appendix B and is found to agree with the weak-strong prediction at the 2% level, in line with the small Piwinski angle expectation. The parameters used as inputs in this section are reported in Table I.

A. Beam-beam model study

In the introduction, we derived the matrix M that represents the beam-beam kick, Eq. (10). In this section, we compare our numerical model to the analytical one. We begin by calculating the transfer matrix for a single longitudinal slice of the 6D HOBB map installed in IP1 to compare it with Eq. (10). The nontrivial elements of the transfer matrix $\mathcal{M}$ are:

$$\begin{aligned}\mathcal{M}_{p_y, y} &= 1.60 \times 10^{-2} \text{ m}^{-1}, \\ \mathcal{M}_{p_y, z} &= \mathcal{M}_{\delta, y} = 2.72 \times 10^{-6} \text{ m}^{-1}, \\ \mathcal{M}_{\delta, z} &= 4.65 \times 10^{-10} \text{ m}^{-1}.\end{aligned}$$

Using the parameters in Table I, the resulting crabbing values agree with the analytical estimate. This result is expected to be essentially independent of the number of slices in the small Piwinski angle regime of this experiment. Indeed, this was verified numerically by recomputing the transfer matrix with up to 51 slices: the relative variation of $\mathcal{M}_{p_y, z}$ saturates at the level of 3.4×10^{-4} , negligible with respect to all other uncertainties of the analysis.

Now we can study the kick propagation around the machine. The analytical model in Eq. (12) reveals a crabbing of about $\pm 10 \mu\text{m}$ at $1\sigma_z$ at the HT monitor location for both beams, respectively, for a $\frac{\theta_c}{2} = \pm 170 \mu\text{rad}$. The case with $\frac{\theta_c}{2} = 0 \mu\text{rad}$ corresponds to an absence of crabbing.

The differential mapping described in the Introduction can now be numerically performed by transporting the

value of ζ_y around the LHC lattice, with the result shown in Fig. 7.

One can immediately see that the values of crabbing predicted by the theory agree with the result of the computation. However, the case $\frac{\theta_c}{2} = 0 \mu\text{rad}$ shows residual crabbing. Furthermore, the sinusoid predicted by Eq. (12) appears to be distorted as if another effect is present on top of the crabbing induced by the beam-beam. This distortion is caused by an effect coming from the rf accelerating cavities. During the experiment, crabbing dispersion produced by an rf cavity located in a dispersive location [27] was also present. To show the magnitude of this effect, a comparison between crabbing from the HOBB lens and from rf cavities is shown in Fig. 8.

The figure shows the presence of a second crabbing bump at the rf location, an effect that is more than one order of magnitude smaller than the one coming from beam-beam interaction. The relevant lattice vertical dispersion at the rf location is $\eta \simeq -0.04 \text{ m}$, which, combined with the rf kick, produces the small additional

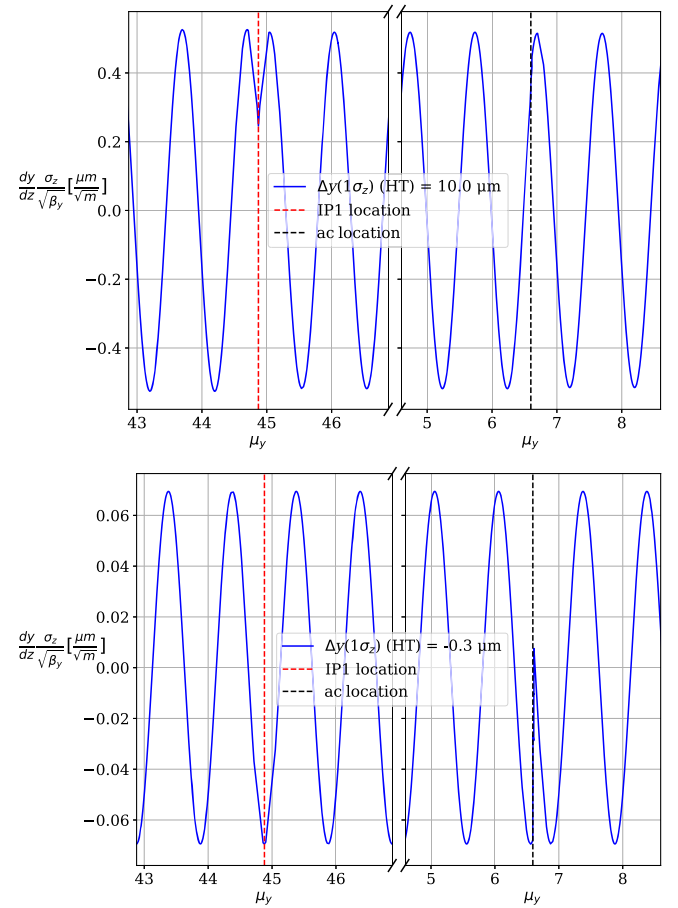


FIG. 8. Crabbing dispersion around the machine with (top) and without (bottom) beam-beam at IP1 around the lattice. It is possible to see the crabbing bump at the IP1 location in the first case and at the rf location in the second case.

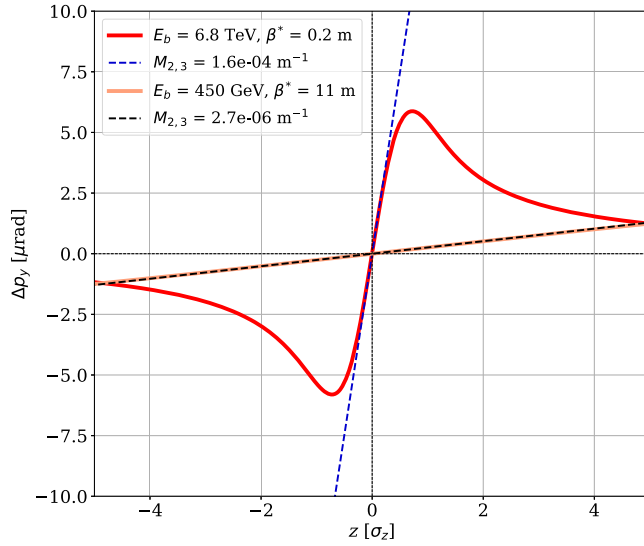


FIG. 9. Δp_y as a function of the longitudinal coordinate z , obtained from a single-particle, single-pass scan around the z -dependent closed orbit, for $\epsilon_n = 2.0 \mu\text{m}$, $N_p = 2.3 \times 10^{11}$ ppb, $\frac{\theta_c}{2} = 170 \mu\text{rad}$ with different E_b ($E_b = 450 \text{ GeV}$ and $E_b = 6.8 \text{ TeV}$) and β^* ($\beta^* = 11 \text{ m}$ and $\beta^* = 0.2 \text{ m}$). The analytical model has been calculated in both cases, and the corresponding linear kicks are plotted as dashed lines. The longitudinal range is restricted to $\pm 5\sigma_z$ to focus on the physically relevant region.

contribution visible in Fig. 8. This effect is taken into account in the models shown in Figs. 5 and 6.

The last step is to move from the linear to the nonlinear problem of the crabbing induced by beam-beam. Until now, we linearized the problem in z assuming that the nonlinearities of the HOB force do not affect the core of the bunch where we performed the measurements. The last part of this section is dedicated to both demonstrating this and comparing it with the same type of interaction but in a more complicated scenario. We take into consideration collisions in the LHC but with 6.8 TeV optics. This second scenario is studied in a simulation using the same parameters used for the study at injection energy, except for the energy itself and the $\beta^* = 0.2 \text{ m}$, to be compared with the 11 m one of our experiments. The methodology is similar to the one used before for the computation of the matrix, but in this case, the kick is computed with respect to a 4D closed orbit dependent on the z coordinate. Specifically, Fig. 9 is obtained from a single-particle, single-pass scan of the beam-beam kick as a function of the longitudinal coordinate z , evaluated around the corresponding z -dependent closed orbit. By changing the z coordinate, one can then obtain the corresponding p_y coordinate displacement.

The computational model shows the expected linear behavior for both cases. In the case of the 6.8 TeV optics, the nonlinear part of the phenomenon is already visible after about $1\sigma_z$, whereas in our experimental case, the response remains essentially linear over the whole range

shown in Fig. 9, with significant deviations only appearing at much larger z (around $10\sigma_z$, well outside the bunch core). This is expected due to the difference in β^* in the two cases: at large z , even if the longitudinal density is low, the transverse field from the core of the opposing beam in our experimental case is still strong enough to give a kick, as the test particle is still “seeing” part of the broad transverse profile. This plot shows that in our experiment, we are only probing the linear part of the interaction, and this is why the treatment of Eq. (8) is sufficient. We emphasize that the experimental fit window $z \in [-1\sigma_z, +1\sigma_z]$ used to extract the crabbing amplitude is set by the signal-to-noise of the HT monitor, which becomes noise-dominated outside the bunch core, and not by the onset of nonlinearity in the beam-beam force, which only becomes appreciable at much larger z in the present regime. Notice that for the time allocated for the experiment, it was not possible to accelerate the bunches to top energy and put the bunches in collision, so this study is only related to injection energy.

The model developed in Eq. (12) is a single-particle model. To finally reproduce the expected signal at the HT monitor location, we simulated the bunch evolution in the LHC lattice. This is interesting since, by means of a statistical approach to the problem, the crabbing can be retrieved from tracking an ensemble of initial conditions and looking at the average motion of the distribution. We simulate $\mathcal{O}(10^5)$ particles with a Gaussian distribution matched to the rf bucket in the longitudinal plane ($\sigma_z = 9.5 \text{ cm}$) and a uniform distribution centered around the z -dependent 4D closed orbit of the beam-beam interaction in the transverse planes. This sampling is preferred to a fully Gaussian transverse distribution because it concentrates statistics near the closed orbit, reducing the number of turns needed to retrieve the crabbing from the histograms. The bunch of Beam 1 is then sliced along the z coordinate to obtain a histogram of the type shown in the various measurements, and after averaging over 1000 turns, the vertical position of each slice is calculated and shown in Fig. 10 at the location of the HT monitor. The simulation includes full synchrotron motion and the 6D beam-beam lens.

It is clearly visible from the graph that the multiparticle simulation, performed under idealized numerical conditions, is in good agreement with what is measured by the HT monitor in Fig. 5.

B. HL-LHC and residual crabbing

This measurement is part of the effort toward the LHC [6] upgrade, which, after more than 10 years of operation, will be upgraded to the HL-LHC [2,28], aiming to increase the yearly integrated luminosity by at least a factor of 3 with respect to the current LHC operational scenario. To achieve this result, the bunch intensity will be increased to 2.3×10^{11} protons, together with a reduction of β^* to

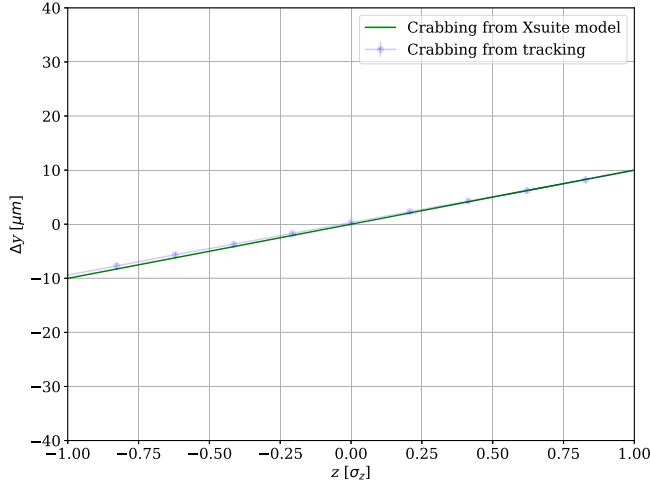


FIG. 10. Multiparticle simulation with $\frac{\theta_c}{2} = +170 \mu\text{rad}$ at the HT monitor location. Slice-by-slice statistical uncertainties on the reconstructed mean vertical position are shown.

15 cm. Critical LRBB effects [15] will be present in this scenario, which will be alleviated by deploying a large crossing angle scheme ($\frac{\theta_c}{2} = 250 \mu\text{rad}$), possibly thanks to the new large aperture final focusing system [28]. 4 CCs [20] per beam and per IP will be installed to restore the geometrical luminosity loss in the two main experiments, ATLAS [16] and CMS [17]. The CC kick before entering the IP, in the ideal case, is compensated by the other CC after the IP, installed at an exact π -phase advance with respect to the first one [13]. In the real lattice, however, this condition is never exactly satisfied, and a residual crabbing is present in the machine. The detection of this effect is crucial in the context of orbit diagnostics and machine protection. This residual crabbing has been numerically calculated and is shown in Fig. 11.

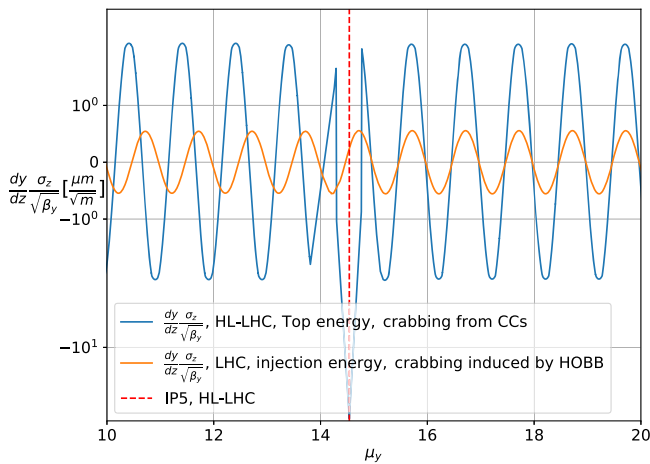


FIG. 11. Comparison between residual crabbing in HL-LHC and induced crabbing in the experiment. IP5, where the vertical kicking CCs will be installed, is shown. The plot is in a symmetric logarithmic scale.

The key result is that the crabbing produced in our experiment, and successfully detected by the HT monitor, is an order of magnitude smaller than the residual crabbing expected from the CCs in the HL-LHC. This demonstrates the capability and sensitivity of this diagnostic in the analysis of crabbing orbit problems.

IV. CONCLUSIONS AND FUTURE WORK

In this study, we report the first experimental observation of a crabbing amplitude of approximately $10 \mu\text{m}$ at $1\sigma_z$, induced by the beam-beam interaction in the presence of a finite crossing angle at the LHC. Using two colliding bunches at 450 GeV, we successfully calibrated the diagnostics for both beams and measured the induced crabbing. The observed dependence on the crossing angle ($\frac{\theta_c}{2}$) was consistent with theoretical expectations: the effect changes sign as the crossing angle is reversed and is consistent with zero in the strict head-on limit, as predicted by the model. Both analytical and numerical models reproduce the magnitude and sign of the effect within the fit uncertainty.

Beyond the proof of principle, this result is significant for several reasons. First, it demonstrates that beam-beam interactions in the presence of a finite crossing angle can act as an effective source of crabbing, mimicking the action of a CC with an equivalent voltage in the order of 10 kV. Second, the successful detection of such a small and controlled effect shows that existing wideband beam position monitors are sensitive enough to characterize crabbing dispersion. This capability is particularly relevant in the context of the HL-LHC, where imperfect closure between crab cavities will generate residual crabbing that is an order of magnitude greater than the effect observed here. HT monitors are therefore validated as diagnostic tools for the HL-LHC era, where unintended orbit tilts could have operational consequences.

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 information on the limitations and potential of this diagnostic technique, in particular, in the presence of dispersion.

In conclusion, this study provides the first direct evidence of beam-beam-induced crabbing with a finite crossing angle in the LHC, establishes the validity of analytical and numerical models, and demonstrates the readiness of the diagnostic tools that will be critical for controlling crabbing effects in the high-luminosity era.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this article are openly available [29].

APPENDIX A: CALIBRATION AND DELAYS BETWEEN SUM AND DELTA SIGNALS

To determine the amplitude of the oscillation in μm , the HT monitors were calibrated by inducing orbit bumps. The normalized position, derived from the ratio of the difference and sum signals at the bunch center, provides a beam position measurement independent of intensity. A linear fit of the calibration data reveals that a normalized position of 0.22 equals a physical displacement of 1 mm, as shown in Fig. 12, i.e., $C_f \simeq \frac{-10^3}{0.22} \mu\text{m} = -4545 \mu\text{m}$.

Since there may be a delay between the Σ and Δ signals, a correction procedure is needed. To correct this, the calibration dataset is used: by selecting the set of signals coming from a large bump, the Δ signals become very similar to the Σ signals. These signals can then be averaged ($\bar{\Sigma}$, $\bar{\Delta}$) and synchronized. The effect of the alignment is

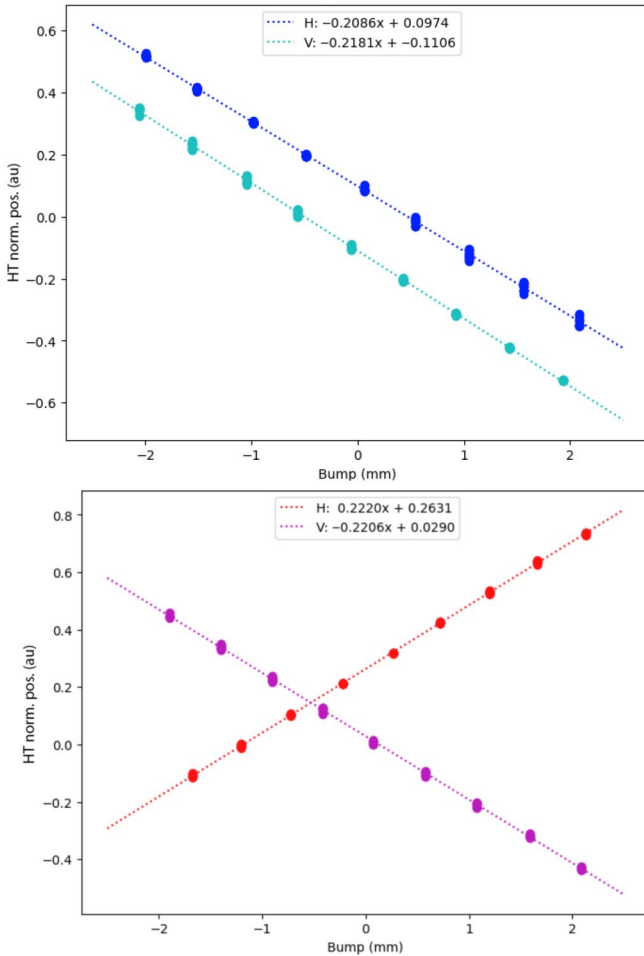


FIG. 12. Calibration of the head-tail monitor response using orbit bumps in the pickup in both planes.

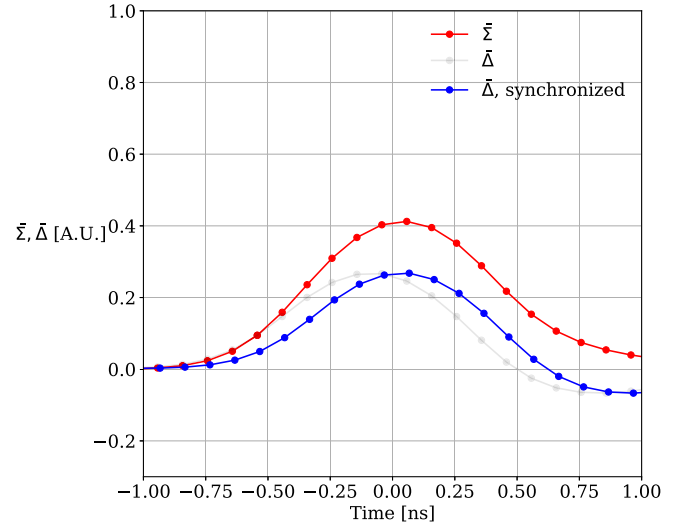


FIG. 13. Alignment of Σ and Δ signals for B1. A delay of about 0.2 ns is found between the two.

shown in Fig. 13, where a delay of about 0.2 ns is found for B1 (and 0.1 ns for B2).

APPENDIX B: STRONG-STRONG CROSS-CHECK OF THE WEAK-STRONG MODEL

The simulations used throughout this paper rely on a weak-strong description of the beam-beam interaction. As discussed in Sec. III, this approximation is justified in the experimental regime by the small Piwinski angle ($\phi_{\text{piw}} \simeq 0.08$, see Table I). To verify this argument numerically and to address the fact that the phenomenon is in principle a strong-strong effect, we performed a self-consistent strong-strong simulation as a complementary cross-check.

The simulation is performed using Xsuite [7]: both beams are tracked simultaneously through a one-turn linear lattice map matched to the IP optics ($\beta^* = 11 \text{ m}$, $\nu_x = 0.28$, $\nu_y = 0.31$, $\nu_s = 0.07$) and a 6D beam-beam element with parameters extracted from Table I. Each beam is initialized with 10^5 macroparticles drawn from a 6D matched Gaussian distribution and updated each turn, capturing any feedback between the two beams self-consistently. The system reaches equilibrium after a short transient of $\mathcal{O}(100)$ turns, after which the crabbing slope $\langle dp_y/dz \rangle$ at the IP is obtained from a linear fit of the perturbation ($z, \Delta p_y$) distribution, averaged over about 1000 turns. The result is summarized in Fig. 14.

The strong-strong crabbing converges to the weak-strong analytical value within a 2% agreement. In addition, the simulation is performed over $z \in [-2.5 \sigma_z, +2.5 \sigma_z]$, showing a linear trend even outside the region of interest for our measurement. This quantitatively confirms the small Piwinski angle argument: in the regime of the present experiment, treating the strong beam as a rigid

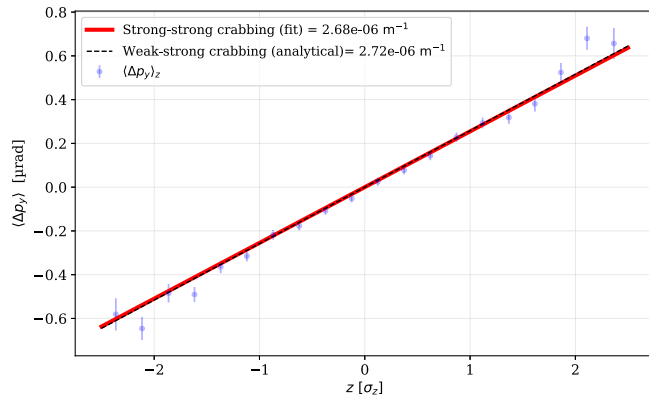


FIG. 14. Slice-averaged kick $\langle \Delta p_y \rangle_z$ from the strong-strong simulation (blue points, error bars from per-slice statistics) compared with the strong-strong linear fit (red solid) and the weak-strong analytical prediction (black dashed).

Gaussian source introduces a deviation that is well below the dominant systematic uncertainties of the measurement, and the weak-strong model used in the main text is therefore adequate.

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