MEASURED AND SIMULATED CHANNELED-HALO DISTRIBUTIONS FOR THE TWOCRYST EXPERIMENT AT THE LHC

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Abstract

The TWOCRYST experiment at the CERN Large Hadron Collider provides a unique setup to study the behaviour of high-energy beam particles channelled by bent crystals. Two two-dimensional detectors in Roman Pots enable direct observation of channelled protons at energies from 0.45 TeV to 6.8 TeV. We present measured channelled-beam distributions for two bent silicon crystals with 50 µrad and 7000 µrad bending and compare them to combined beam-dynamics and particle–crystal interaction simulations including the full LHC lattice. The measured positions of the channelled beam is compared with beam-position-monitor data of the main beam to assess the sensitivity of the channelled-beam trajectory to realistic orbit drifts, providing key input for the requirements of future bent-crystal-based fixed-target experiments.

INTRODUCTION

The TWOCRYST experiment [1, 2] was installed at the Large Hadron Collider (LHC) [3] in 2025 to demonstrate the feasibility of spin-precession fixed-target experiments within CERN's Physics Beyond Colliders initiative [4]. The ultimate physics goal of such experiments is the first direct measurement of the electromagnetic dipole moments of short-lived charm baryons by exploiting the channeling phenomenon of positively charged particles in bent crystals [5] — an idea first proposed for the LHC in 2016 [6, 7] and since developed into a concrete experimental design that could be implemented in the HL-LHC era [8].

In a bent crystal, the intense electric fields between atomic planes act on a relativistic particle as an effective magnetic field orders of magnitude stronger than conventional magnets, simultaneously deflecting the trajectory and inducing a measurable spin precession before decay [9].

TWOCRYST is designed as a proof-of-principle test of this experimental concept — first demonstrated by the E761 collaboration at the Tevatron in 1992 [10] — applied to the new LHC setup. Initially considered for integration in the LHCb experiment [6], the focus shifted to a dedicated setup in the LHC collimation insertion IR3 [11] for improved performance. Installed on LHC Beam 2, the experiment consists of two silicon crystals bent in the vertical plane [12], a tungsten fixed-target, and two tracking detectors housed in Roman Pots [13] (RP). All devices can be independently moved, allowing for a broad variety of test conditions.

The first crystal — the Target Collimator Crystal for Splitting (TCCS) — deflects particles by 50 µrad. 120 m downstream of the TCCS, the target and the 7 mrad precession

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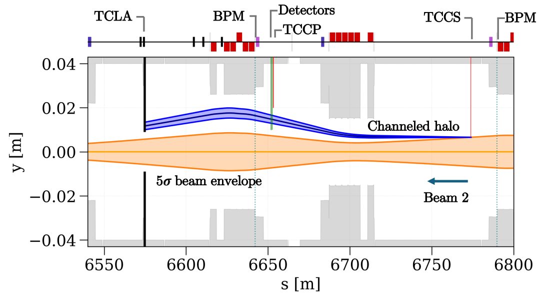

Figure 1: Vertical dynamics of the TWOCRYST setup at 450 GeV for channeling measurements as a function of the longitudinal position s. The 5σ main beam envelope is shown in orange, and channeled particles are shown in blue. Vertical dashed lines indicate the two Beam Position Monitors (BPMs) closest to the setup.

crystal (TCCP) are installed, followed by two Roman Pots that house the two different detectors: a silicon pixel detector [14] and the TWOCRYST Fiber Tracker (TFT) [15]. A downstream vertical collimator (TCLA) absorbs the channeled halo. Figure 1 shows the experiment layouts and illustrates the propagation of a channeled beamlet from its source at the TCCS to its absorption in the TCLA.

Beyond its role in validating the fixed-target physics concept, the two-dimensional imaging in TWOCRYST offers unprecedented insight into channeling physics and multi-turn beam dynamics. This work presents a comparison between measurements and simulations to characterize the channeling profiles at the LHC energy and study their multi-turn dynamics.

MEASURED BEAMLET PROFILE

Four measurements of the channeled halo profile from the TCCS were recorded across three separate sessions in 2025 (June 21, 22, and October 9) at injection energy of 450 GeV. The TCCS was aligned to the $5\sigma_y$ main envelope, where σ denotes the RMS beam size assuming a normalized emittance of 3.5 µm rad. The four sets of 2-dimensional hit distributions at the pixel detector are displayed in Figure 2. Except for the second measurement, the data was collected while utilizing the LHC Transverse Damper [16] (ADT) to induce white noise and excite the beam in the vertical plane.

The outgoing angular distribution of particles channeled by a crystal is determined by its critical angle, which for a crystal with the specifications of the TCCS at 450 GeV is $\theta_c = 9.12$ µrad. In Figure 1, this is represented by the blue envelope: the central line represents the trajectory of a particle that has received a kick of $\theta_{\text{bend}} = 50$ µrad from the TCCS, while the upper and lower lines correspond to

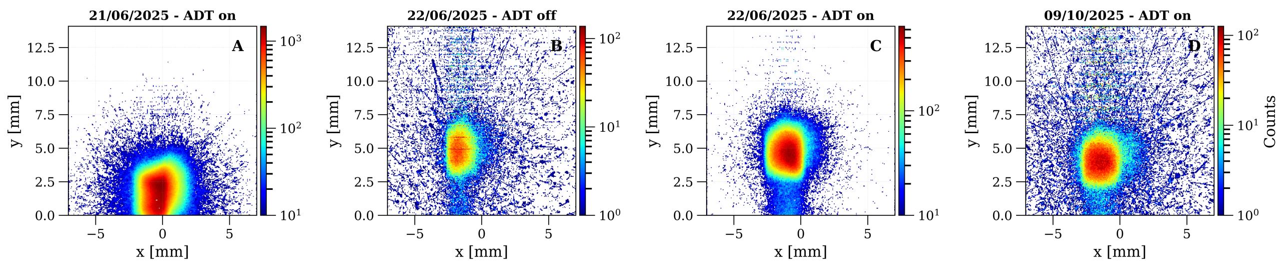

Figure 2: 2D hit distribution of the channeled halo from the TCCS recorded by the pixel detector at 450 GeV. The coordinates are shown in the detector's reference frame.

particles that have received a kick of $\theta_{\text{bend}} \pm \theta_c$. Given the presence of the quadrupole magnet between the TCCS and the detectors, this angular spread is subject to vertical broadening. In the horizontal plane, the crystal intercepts the full beam distribution, whose RMS size is $\sigma_x = 0.765$ mm at the TCCS position. In Table 1, the mean absolute horizontal position and the standard deviations in both x and y are reported for each measurement, providing an estimate of the spot dimensions. The absolute mean y is not reported, as the pixel modules are movable and the measurements are expressed in the detector reference frame.

Table 1: Mean horizontal position and horizontal and vertical standard deviations at 450 GeV of the halo channeled by the TCCS, for four measurement at the pixel detector.

	A	B	C	D	Mean
x_0 [mm]	-0.17	-1.44	-0.92	-1.46	-0.9 ± 0.3
σ_x[mm]	0.87	0.82	0.90	0.83	0.85 ± 0.02
σ_y[mm]	1.02	1.06	1.08	1.01	1.04 ± 0.01

An unexpected negative horizontal offset is consistently observed in the channeled distribution across all measurements, which is unexpected given that the beam reference orbit is expected to be zero-centered in both transverse planes. Analysis of data from the nearest Beam Position Monitors — one 16 m upstream of the TCCS and one 10 m downstream of the detector — reveals no indication of such offset at the pixel sensor.

TCCP single channeling measurements were also collected, removing the TCCS and aligning the long crystal to the edge of the $5\sigma_y$ beam envelope. Channeled particles acquire a 7 mrad kick and, given the short distance of 0.65 m to the pixel detector, they are expected to be concentrated in a single line of pixels with no transverse spread. The measured distribution is reported in Figure 3. On top of the ~ 1.3 mm wide line of activated pixels, a lower-density shadow is visible, stemming from multi-turn interactions, which can occur over the full vertical extent of the crystal. The characteristic s-shape of the distribution observed at the pixel sensor can be attributed to the torsion of the crystalline planes arising from the mechanical bending of the crystal.

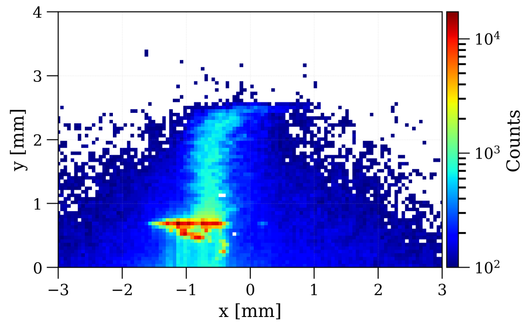

Figure 3: 2D hit distribution of the channeled halo from the TCCP recorded by the pixel detector at 450 GeV. The coordinates are shown in the detector's reference frame.

SIMULATED BEAMLET PROFILE

Detailed simulations were performed, in order to compare the measured against the expected distributions of the channelled beamlets. Element-by-element symplectic tracking was performed with the XTRACK package from the XSUITE software framework [17], while particle-matter interactions, including crystal physics, were modeled using the XCOLL package [18–20], also part of XSUITE. A model of the full LHC lattice with 2025 injection optics was used.

For both the TCCS and TCCP cases, an annular halo distribution of 1×10^5 particles was sampled from a narrow ring $[4.997\sigma_y, 5.001\sigma_y]$ in normalized y–p_y phase space, matched to the Twiss parameters at IP1, and combined with a 2D Gaussian horizontal profile in normalized x–p_x, centered at the origin ($x = 0$). Particles are tracked over 200 turns.

Results of the TCCS single-channeling tracking simulation are reported in Figure 4 alongside the experimental data, both binned using the same pitch dimensions as the pixel detector. The simulation yields a mean horizontal position of $x_0 = -0.33$ mm and dimension in standard deviations of $\sigma_x = 0.65$ mm and $\sigma_y = 0.88$ mm, slightly lower than the measured values in Table 1. The vertical cut due to $\pm\theta_c$ limits of outgoing angular distribution is sharp in simulation but less well-defined and broader in measurements. In both, a low-intensity halo to the right of the main beamlet is identified as a multi-turn effect.

TCCP single-channeling simulations are performed assuming a perfect crystal with no torsion. The simulated line of activated pixels (Figure 5) is broader than the observed one, and, while the multi-turn halo remains visible on top, the s-shape seen in the measurements is absent.

A horizontal shift of the TCCS beamlet is observed also in the simulated data (Figure 4). Analysis of multi-turn motion of the generated particles suggests that a transverse

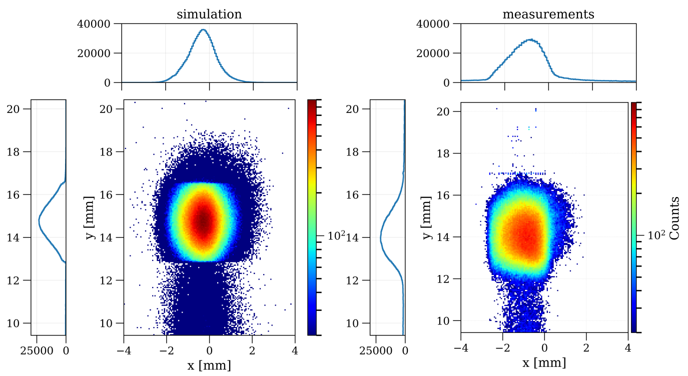

Figure 4: Comparison of simulated and measured 2D hit distributions with x and y projections.

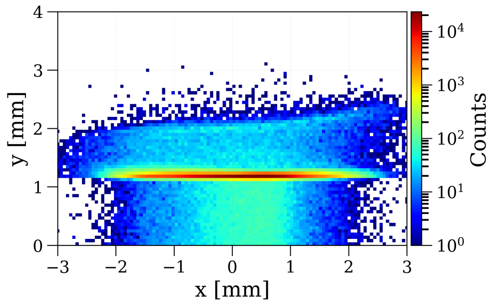

Figure 5: Simulated 2D hit distribution of the channeled halo from the TCCP at 450 GeV using XCOLL, assuming a perfect crystal model with no torsion.

x-y coupling can be responsible for the offset. A single-particle simulation over 7000 turns through the LHC lattice, initialized at the TCCS location with $x = p_x = 0$ and vertical coordinates matching the $5\sigma_y$ vertical beam envelope, confirms that machine non-linearities induce a consistent negative horizontal shift at the crystal amplitude, though hardware-related effects cannot be excluded. In the long crystal case, an analogous single-particle simulation initialized at the TCCP reproduces the horizontal distribution seen in Figure 5. In this case, however, the shift observed in measurements of Figure 3 can be attributed to crystal torsion: in a crystal with torsion, the channeling acceptance depends not only on the vertical alignment and y position, but also on x. As the orientation angle varies, the spatial region satisfying the channeling condition shifts horizontally. Figure 6 shows turn-by-turn positions at the TCCS and at the TCCP.

CONCLUSION

The TWOCRYST setup was successfully used for high-resolution profiling of channeled beamlets. TCCS measurements provide a valuable benchmark for crystal channeling models in the XSUITE simulation framework, with potential for deeper refinement through further analysis. A variability of order 2 mm in the beamlet position was observed and linked, via simulations, to multi-turn non-linear beam dynamics. Unlike vertical offsets, which can be mitigated by mechanically repositioning the devices, the horizontal shifts identified here cannot be operationally corrected and

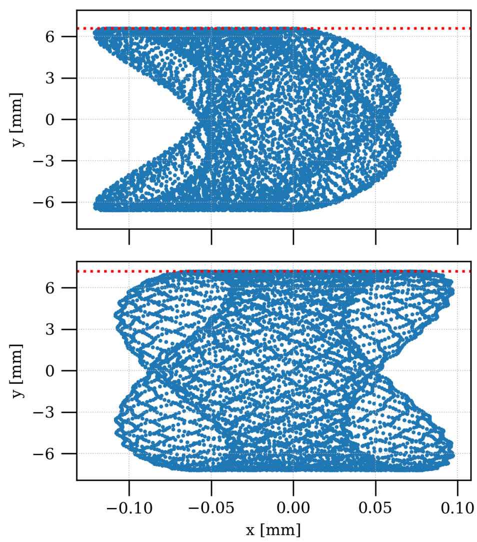

Figure 6: Turn-by-turn x-y positions at the TCCS (upper) and TCCP (lower) location for a single particle tracked over 7000 turns. The red dotted line indicates the vertical amplitude of the crystals ($5\sigma_y$)

must therefore be accounted for in the design of future spin-precession fixed-target experiments. TCCP measurements reveal a torsion effect not yet modelled by XCOLL, but its implementation within the framework is foreseen.

ACKNOWLEDGMENTS

TWOCRYST is carried out under the Physics Beyond Colliders (PBC) Fixed-Target Working Group and is a collaboration of the institutes CERN, INFN (Italy), IFIC (University of Valencia-CSIC, Spain), IJCLab (France), the University of Malta, the Institute of Nuclear Physics of the Polish Academy of Sciences, Warsaw University of Technology (Poland), and UCAS (China). The project acknowledges support from the PBC project; the HL-LHC project; the ATLAS-ALFA collaboration; the ERC SELDOM Grant No. 771642; the INFN CSN5 project OREO; the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU under Project Title PRIN 202277EWLW; contributions from the AICRYSCON project funded by Xjenza Malta through the FUSION: R&I Research Excellence Programme; support from MICIU, AEI, and GVA (Spain) under projects PID2022-139842NB-C22, CIPROM/2022/36, ASFAE/2022/030, and NextGenerationEU; and funding from the National Science Centre, Poland (project No. 2021/43/D/ST2/02761).

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