ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL048

PERFORMANCE OF A DOUBLE-CRYSTAL SETUP FOR LHC FIXED-TARGET EXPERIMENTS*

K. A. Dewhurst†, M. D'Andrea, P. D. Hermes, D. Mirarchi, S. Redaelli, CERN, Geneva, Switzerland
M. Patecki, Politechnika Warszawska, Warsaw, Poland

Abstract

The Physics Beyond Colliders (PBC) studies at CERN address the possibility to utilise protons in the Large Hadron Collider (LHC) for a fixed-target program beyond the colliding-beam physics. As part of PBC, a double-crystal test stand is considered for installation in the LHC off-momentum collimation Insertion Region (IR) 3. In this PBC experiment, a first silicon crystal deflects beam-halo protons from the main beam onto a fixed-target. A second crystal, providing bending angles in the mrad range, is located immediately downstream of the target to deflect target-produced secondary particles onto a detector that will measure the electric and magnetic dipole moments of short-lived baryons. The LHC test stand will serve as a proof-of-principle machine experiment to assess the performance of new crystals at LHC energies and to address a number of critical machine aspects related to this complex setup. In this paper, simulations in MAD-X and SixTrack are used to predict the performance of the proposed double-crystal layout for the LHC Run 3 test-stand and the LHC Run 4 final experiment.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN produces the highest energy proton beams in the world, currently reaching 6.8 TeV [1, 2] with plans to reach 7 TeV, as well as upgrade to a high-luminosity (HL) design by 2030 [3]. The Physics Beyond Colliders (PBC) studies [4] aim to utilise the CERN accelerator complex for applications beyond colliding-beam physics. As part of PBC, the LHC fixed-target (FT) working group is investigating gas target and in-beam fixed-target experiments in various regions of the LHC [5, 6]; in-beam FT experiments based on bent crystals are considered for the off-momentum collimation region IR3, and the LHCb experiment region IR8 [7–13]. In this paper, we compare three layouts for a double-crystal experiment in IR3 and evaluate their performance based on particle tracking simulations and operational considerations.

A proof-of-principle (PoP) test stand is being designed for installation in IR3 to validate the double-crystal concept, providing input to future PBC layouts. The PoP test stand will provide both technical and operational experience of the setup in preparation for a final PBC experiment that aims to measure the electric and magnetic dipole moments of rare baryons. Additionally, the test stand will characterise the new silicon crystals with proton beams in the TeV range. The setup is designed in upgradable stages, beginning with the PoP test stand for use in Run 3 that can later be enhanced, without moving key components, for the final experiment with HL-LHC, starting in LHC Run 4. In both cases, a first crystal (Target Collimator Crystal for Splitting - TCCS) steers some protons from the halo of the main beam towards a fixed-target with an adjacent second crystal (Target Collimator Crystal for Precession - TCCP). The first crystal (TCCS) has the same parameters as those currently used in the LHC for ion collimation with a bend angle of 50 µrad [14]. The second crystal (TCCP) has a significantly larger bend angle of 7000 µrad. The parameters of these crystals have recently been specified in a Functional Specification document [15] for their manufacture. The PoP experiment aims to characterise these new crystals by measuring their proton channelling efficiency at TeV range energies. The final HL-LHC setup uses a target immediately before the TCCP (installed as part of the TCCP assembly) to produce short-lived baryons, such as Λ_c [16]. Baryon decay products will precess inside the TCCP and be detected downstream, allowing the first measurement of the electric and magnetic dipole moments of these rare baryons.

We consider three potential layouts for the double-crystal experiments in IR3 (A, B and C); two positions for the first crystal are investigated for beam 1 (A and B) and a similar setup, symmetrical to B, is considered for beam 2 (C).

POP EXPERIMENT - THE TEST STAND

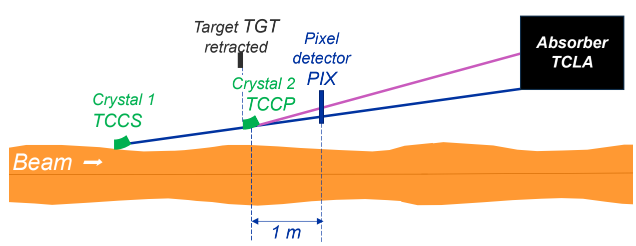

Figure 1: Layout of the PoP experiment. The TCCS is aligned with the edge of the main beam (orange) channelling protons (blue) onto the TCCP. Some protons are also channeled by the TCCP (purple) so that a double-spot forms on a pixel detector (PIX) 1 m downstream. Any remaining channeled protons are absorbed by a downstream collimator (TCLA). The target (TGT) can be retracted independently.

Preparations have begun to install components for the PoP experiment during the current run of the LHC (Run 3). As shown in Fig. 1, the PoP experiment uses a pixel detector to view a single-channelled and double-channelled spot. The relative intensities of these spots will be used to determine the channelling efficiency of the TCCP. The experiment is

* This research is supported by the National Science Centre, Poland, project number: 2021/43/D/ST2/02761.
† kay.dewhurst@cern.ch

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL048

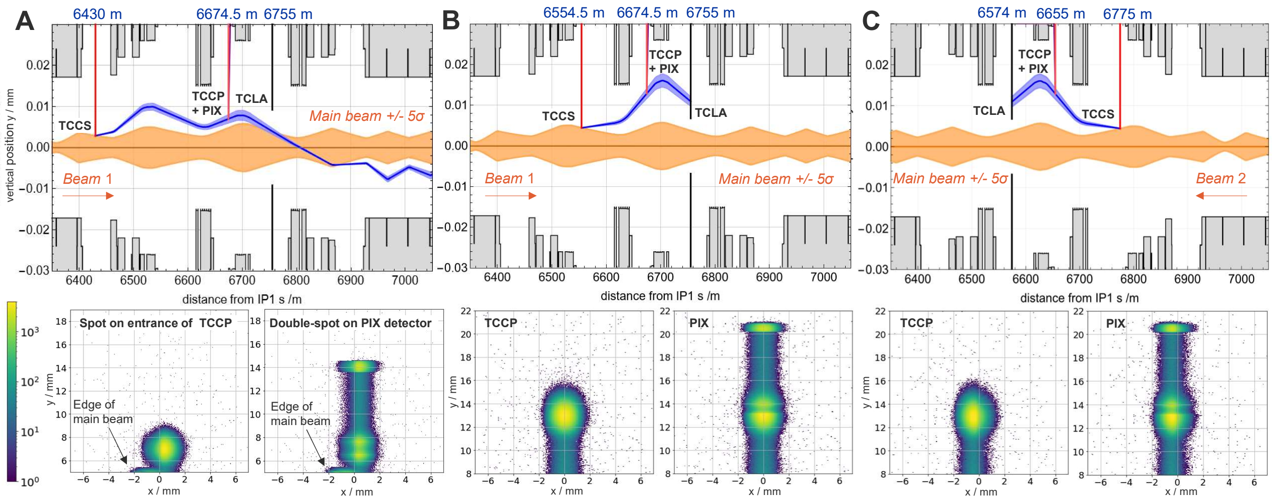

Figure 2: Three layouts (A, B, C) considered for the PoP experiment with a beam energy of 1 TeV and a main beam envelope of $\pm 5\sigma$ (orange), where σ is the r.m.s. beam size for the nominal normalized emittance of 3.5 µm rad. In each case, the TCCP is aligned with the channelled beam (blue) from the TCCS, and the pixel detector (PIX) is 1 m downstream of the given TCCP position. Below each trajectory are plots of the expected proton spot at the entrance of the TCCP and on the PIX; these plots have the same dimensions (14 mm × 14 mm) as the real pixel detector.

designed for protons with low-TeV energies; around 0.45 TeV to 3 TeV. Here we consider 1 TeV; the energy of interest for particles produced from the target in the final experiment.

The trajectories of the main and channelled beams for the three layouts (A, B, C) are shown in Fig. 2; these were found using the accelerator design program MADX [17], using Run 3 linear optics and crystals inserted as markers into the lattice. The channelled beam trajectory assumes a 50 µm kick with respect to the angle of the beam envelope at the transverse setting of the TCCS (located 5σ from the beam centre). A distribution of 4 000 000 particles was then tracked for 200 turns of the LHC using the particle tracking program SixTrack [18–20] to predict the expected proton distribution on the TCCP and PIX.

Figure 2 shows layouts B and C have some advantages over layout A. For case A, the channelled trajectory is close to the main beam edge at the TCCP position. Moreover, the edge of the main beam is apparent on the pixel detector plot. Both layouts B and C have the TCCS located at a position with a large beta-function (β_y) causing the channelled trajectory to be further separated from the main beam envelope than for layout A. Additionally, for cases B and C, the local vertical TCLA collimator can be used to absorb the channelled beam, whereas in A it would need to be absorbed by the next suitable collimator: the TCT in IR5.

The proximity of the channelled beam to the main beam envelope becomes more of an issue at lower beam energies as the 5σ beam envelope is naturally larger. For layout A, this prevents alignment of the crystals at injection energy (450 GeV) as the channelled trajectory is not separate from the main beam at the TCCP position. It is beneficial operationally to align the crystals at injection energy, as new bunches can be injected from the accelerator chain if required and ramping the beam to higher energy requires extra preparation and recovery time. Layout A is a feasible option as crystal alignment could be carried out at 1 TeV but layouts B and C provide advantages of simpler operation for alignment and time-saving.

Based on these PoP simulations, layouts B and C appear favourable. However, the suitability of the proposed layouts must also be considered for the final PBC experiment.

FINAL PBC EXPERIMENT - DOUBLE-CRYSTAL AND FIXED-TARGET

In the final PBC experiment, the target will be inserted in front of the TCCP crystal; a 4 T m spectrometer magnet will be installed immediately downstream of the TCCP as part of the detection system; and additional collimators (three TCSGs and a TCLA) will be added to intercept the channelled beam and decay products from the target. An overview of the scheme and the new components to be installed are described in a previous article [21], their positions are shown in Fig. 3. The final experiment will use the intense 7 TeV HL-LHC beam, and we consider the nominal normalized emittance in HL-LHC of 2.5 µm rad. The TCCS is not aligned with the edge of this main beam but instead with a secondary halo in IR3. This halo is formed by impacting protons onto the primary collimator; the TCP in IR7. This allows the TCCS to be located $+0.5\sigma$ beyond the edge of the main beam. To compare the layouts A-C for the final PBC experiment, we consider the trajectories as well as the expected number of protons impacting the target (Protons on Target - PoT).

The inclusion of a spectrometer causes a kick to the main beam which must be corrected locally in IR3 by vertical corrector magnets. For each layout, A-C, the main beam trajectory was matched back to the nominal closed orbit

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL048

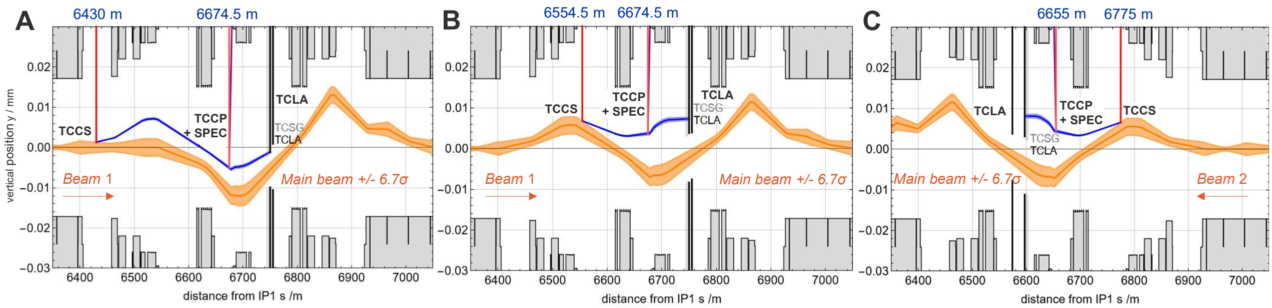

Figure 3: Three layouts (A, B, C) considered for the final PBC experiment with a beam energy of 7 TeV and a main beam envelope of $\pm 6.7\sigma$ (orange). In each case, the TCCS is aligned with a secondary halo at a transverse setting 7.2σ from the main beam centre ($+0.5\sigma$ from the main beam envelope). The TCCP is aligned with the channelled beam (blue) from the TCCS. Immediately after the TCCS, the beams experience an upward kick caused by the spectrometer magnet (SPEC).

by varying the strengths of local corrector magnets within their design limits using the downhill-simplex algorithm in MADX. The resulting orbit bump can be seen for the three layouts in Fig. 3.

Two collimation options exist for HL-LHC; tight settings with a beam envelope of $\pm 6.7\sigma$ (as in Fig. 3), and relaxed settings with a beam envelope of $\pm 8.5\sigma$ [22]. The transverse setting of the primary collimator, the TCP in IR7, determines the extent of the beam envelope. Both collimation options were investigated for the three layouts, giving six Proton-on-Target (PoT) values for comparison. In each case, the TCCS is located $+0.5\sigma$ from the edge of the main beam envelope.

Simulations in SixTrack were carried out to find the PoT values for each of the six scenarios. In each case, a pencil beam of 20 000 000 particles incident on the vertical TCP in IR7 with an impact parameter of 2 µm, produces the local distribution of secondary halo particles at the TCCS. First, an angular scan of the TCCS determines its best orientation to align with the secondary halo. The beam is then tracked for 200 turns and the results are collated to find the PoT value.

The following equation for PoT is used to calculate the integrated PoT over a fill time of 10 h ($\int^{10} PoT(t)dt$) [7]:

$$PoT(t) = \frac{1}{2}\frac{I(t)}{\tau}exp\left(-\frac{t}{\tau}\right)\frac{N_{imp}^{TCCS}}{N_{sim}}\epsilon_{CH}^{TCCS}, \qquad (1)$$

where τ is the beam lifetime, $I(t)$ is the intensity, t is the fill time, N_{imp}^{TCCS} is the number of protons impacting the TCCS, N_{sim} is the total number of protons impacting any device in the simulation and ϵ_{CH}^{TCCS} is the proportion of protons channelled by the TCCS. The intensity is assumed to follow an exponential decay based on an initial intensity I_{tot} and a burn-off time τ_{BO}, such that $I(t) = I_{tot}exp(-t/\tau_{BO})$. We use the same assumptions to calculate the PoT as in [7], including a beam lifetime of 200 h, an initial intensity of 2.8×10^{14} protons and a burn-off time of 20 h. The results are summarised in Table 1 and align with previous findings [7].

Table 1 shows that for all three layouts, the PoT is slightly improved with tight collimator settings (TCP at 6.7σ). Layout C, using beam 2, shows the best channelling efficiency of the TCCS at 57 % to 58 % suggesting more of the protons impinging on the TCCS in this scenario have the correct incoming angle to be channelled. However, despite a lower channelling efficiency for layout B of 30 % to 35 %, more protons impact the TCCS compared to layout C, resulting in a higher PoT value. For the final PBC experiment, the number of PoT is a significant parameter that will determine the yield of rare baryons produced for the electric and magnetic dipole measurements. Layout B, using beam 1, is therefore the layout we recommend for the double-crystal experiment in IR3.

Table 1: Protons-On-Target (PoT) for each Layout

Layout (Beam)	TCP y[σ]	TCCS s[m]	TCCP s[m]	Proportion channelled	PoT (10h) [$\times 10^{10}$]
A (1)	8.5	6430	6674.5	0.17	0.11
B (1)	8.5	6554.5	6674.5	0.35	1.40
C (2)	8.5	6775	6655	0.58	1.19
A (1)	6.7	6430	6674.5	0.39	0.52
B (1)	6.7	6554.5	6674.5	0.30	1.55
C (2)	6.7	6775	6655	0.57	1.26

CONCLUSION

Three potential layouts were investigated for a double-crystal fixed-target experiment in IR3 of the LHC. Considering both a PoP test stand and a final PBC experiment, the three layouts were compared based on beam trajectories and the predicted number of protons-on-target from simulations. Issues with alignment at injection energy and a low number of PoT makes layout A (TCCS at 6430 m) using beam 1 less favourable. Symmetrical layouts (B and C) for beams 1 and 2 both show favourable trajectories for the PoP, as well as suitable trajectories and a good number of PoT for the PBC experiment; both are suitable layouts. Layout B using beam 1 (TCCS at 6554.5 m) shows the greatest number of PoT from simulations. Therefore, we recommend work to install the double-crystal experiment in IR3 of the LHC moves forward using layout B.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL048

REFERENCES

[1] *LHC Run 3: Physics at record energy starts tomorrow*, 2022. https://home.cern/news/news/physics/lhc-run-3-physics-record-energy-starts-tomorrow

[2] ATLAS Collaboration, *ATLAS Experiment records "first physics" at new high-energy frontier*, 2022. https://atlas.cern/Updates/Press-Statement/Run3-first-collisions

[3] L. Rossi and O. Brüning, "Introduction to the HL-LHC Project," in *The High Luminosity Large Hadron Collider*, vol. 24, 2015, pp. 1–17. doi:10.1142/9789814675475_0001

[4] J. Jaeckel, M. Lamont, and C. Vallée, "The quest for new physics with the Physics Beyond Colliders programme," *Nat. Phys.*, vol. 16, no. 4, pp. 393–401, 2020. doi:10.1038/s41567-020-0838-4

[5] S. Redaelli, M. Ferro-Luzzi, and C. Hadjidakis, "Studies for Future Fixed-Target Experiments at the LHC in the Framework of the CERN Physics Beyond Colliders Study," in *9th International Particle Accelerator Conference, Vancouver, Canada*, 2018, TUPAF045. doi:10.18429/JACoW-IPAC2018-TUPAF045

[6] C. Barschel *et al.*, "Report from the LHC Fixed Target working group of the CERN Physics Beyond Colliders forum," *CERN-PBC-REPORT-2019-001*, 2019. http://cds.cern.ch/record/2653780

[7] D. Mirarchi, A. Fomin, S. Redaelli, and W. Scandale, "Layouts for fixed-target experiments and dipole moment measurements of short-lived baryons using bent crystals at the LHC," *The European Physical Journal C*, vol. 80, no. 10, pp. 1–16, 2020.

[8] A. Fomin *et al.*, "Feasibility of τ-lepton electromagnetic dipole moments measurement using bent crystal at the LHC," *High Energy Phys.*, vol. 2019, no. 3, p. 156, 2019.

[9] J. Fu *et al.*, "Novel Method for the Direct Measurement of the τ- Lepton Dipole Moments," *Phys. Rev. Lett.*, vol. 123, no. 1, p. 011 801, 2019.

[10] W. Scandale, D. Mirarchi, S. Redaelli, and A. Stocchi, "Optical layout for the measurement of Short Living Baryon Magnetic Moment using Bended Crystals at LHC," *Physics Beyond Colliders Kickoff Workshop*, 2016.

[11] A. Stocchi *et al.*, "Measurement of Short Living Baryon Magnetic Moment using Bent Crystals at SPS and LHC," *Physics Beyond Colliders Kickoff Workshop, CERN, Geneva, Switzerland*, 2016.

[12] F. Botella *et al.*, "On the search for the electric dipole moment of strange and charm baryons at LHC," *Eur. Phys. J. Plus*, vol. 77, no. 3, p. 181, 2017.

[13] E. Bagli *et al.*, "Electromagnetic dipole moments of charged baryons with bent crystals at the LHC," *Eur. Phys. J. Plus*, vol. 77, no. 12, p. 828, 2017.

[14] R. Rossi *et al.*, "Status of crystal collimation studies at the LHC," in *Proceedings of the 8th Int. Particle Accelerator Conf. (IPAC 17)*, 2017, pp. 84–87. doi:10.18429/JACoW-IPAC2017-MOPAB007

[15] Q. Demassieux *et al.*, *[TCCS/TCCP] Functional and Operational Conditions for the Double-Crystal setup in the LHC IR3*, Restricted access, 2022. https://edms.cern.ch/document/2742008/1.0

[16] A. S. Fomin *et al.*, "Feasibility of measuring the magnetic dipole moments of the charm baryons at the LHC using bent crystals," *J. High Energ. Phys.*, vol. 2017, no. 8, 120(1–27), 2017. doi:10.1007/JHEP08(2017)120

[17] H. Grote, R. Ghislain, and F. Schmidt, *The MAD-X Program (Methodical Accelerator Design)*, 2022. http://madx.web.cern.ch/madx/

[18] R. De Maria *et al.*, "SixTrack Version 5: Status and New Developments," in *Proceedings of the 10th Int. Particle Accelerator Conf. (IPAC 2019)*, 2019, pp. 3200–3203. doi:10.18429/JACOW-IPAC2019-WEPTS043

[19] D. Mirarchi, S. Redaelli, and W. Scandale, "Crystal implementation in SixTrack for proton beams," *CERN Yellow Reports: Conference Proceedings*, pp. 91–108, 2020. doi:10.23732/CYRCP-2018-002.91

[20] M. D'Andrea, A. Mereghetti, D. Mirarchi, V. Olsen, and S. Redaelli, "Release of Crystal Routine for Multi-Turn Proton Simulations within SixTrack v5," in *Proceedings of the 12th Int. Particle Accelerator Conf. (IPAC 2021)*, 2021, pp. 2648–2651. doi:10.18429/JACoW-IPAC2021-WEPAB024

[21] P. Hermes, K. A. Dewhurst, A. Fomin, D. Mirarchi, and S. Redaelli, "Layouts for Feasibility Studies of Fixed-Target Experiments at the LHC," in *Proceedings of the 13th Int. Particle Accelerator Conf. (IPAC 2022)*, 2022, pp. 2134–2137. doi:10.18429/JACOW-IPAC2022-WEPOTK033

[22] B. Lindström, R. Bruce, P. Hermes, and S. Redaelli, "Update on the High Luminosity LHC collimation performance with proton beams," presented at IPAC'23, Venice, Italy, May 2023, paper MOPA126, this conference.