ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK033

LAYOUTS FOR FEASIBILITY STUDIES OF FIXED-TARGET EXPERIMENTS AT THE LHC

P. D. Hermes*, K. Dewhurst, A. Fomin, D. Mirarchi, S. Redaelli
European Organization for Nuclear Research (CERN), Geneva, Switzerland

Abstract

The Physics Beyond Colliders (PBC) study investigates means of exploiting the potential of the CERN accelerator complex to complement the laboratory's scientific programme at the main Large Hadron Collider (LHC) experiments. The LHC fixed-target (FT) working group studies new experiments at beam energies up to 7 TeV. One of the proposed experiments is based on a bent crystal, part of the collimation hierarchy, to extract secondary halo particles and steer them onto a target. A second bent crystal immediately downstream of the target is used to study electric and magnetic dipole moments of short-lived baryons. The possibility to install a test stand in the LHC off-momentum collimation Insertion Region (IR3) to demonstrate the feasibility and performance of this challenging scheme is currently under investigation. The integration of a spectrometer magnet into the present layout is particularly critical. In this contribution, we study a possible test setup which could be used in LHC Run 3.

INTRODUCTION

The CERN Large Hadron Collider (LHC) is the world's largest collider, designed to accelerate protons to energies of up to 7 TeV [1]. The Physics Beyond Colliders (PBC) study explores the opportunities offered by the CERN accelerator complex, including the LHC and its High Luminosity upgrade HL-LHC [2], to complement the goals of the main experiments of the laboratory's collider programme. The LHC fixed-target (FT) working group addressed gas-target and in-beam fixed-target experiments [3–5]. Different possible implementations in various regions of the LHC are currently under investigation for in-beam targets based on bent-crystals: the LHC momentum collimation region IR3 [6] or IR8, housing the LHCb experiment [7] are considered for the so-called double-crystal setup [8–13], while IR2, hosting the ALICE experiment [14, 15], is considered for conventional targets [16]. The integration of a proof-of-principle setup in IR3 is considered for beam tests at the LHC to collect important information for the validation of the layouts and their performance and to demonstrate the feasibility of these implementations.

Figure 1 illustrates the considered concept for the integration of the FT setup compatibly with the collimation hierarchy. It relies on planar channelling in bent crystals: charged particles channelled between the crystalline planes are forced to follow the geometrical bending of the crystal [17]. A first crystal (CRY1) intercepts particles in the secondary beam halo (produced by the betatron collimators in IR7 [6]) to create sufficient separation between channelled protons and the main beam, such that they hit a solid target, e.g. made of tungsten, located downstream at a safe transverse distance. The double-crystal setup involves a second crystal (CRY2) immediately adjacent to the target, to study the electric and magnetic dipole moments of short-lived baryons like the Λ_c^+, see [5] and references therein. One or multiple collimators are needed to intercept and safely absorb the channelled halo. A test has demonstrated the principle of the double-channelling setup with protons in the CERN SPS at 270 GeV [18]. Experimental data for higher beam energies has to be gathered, in particular to demonstrate the feasibility of this scheme in the specific LHC beam conditions. CRY1 in the IR3 layout is similar to the crystals used at the LHC for crystal collimation [19, 20] while CRY2 needs to provide a larger bending angle of 5 mrad [21, 22].

GOALS OF LHC BEAM TESTS

Given the complexity of the double-crystal setup in the LHC, crucial information could be gathered by a test under realistic conditions with beam in the LHC in the Run 3 at the planned operating energy of 6.8 TeV. Various high-priority goals are identified. The performance of the large-bending crystal shall be assessed in the energy range relevant for the LHC experiments. The baryon energy of interest is in the order of 1-2 TeV. This range is only accessible at the LHC, and the proposed setup shall enable the characterization at even larger beam energies.

The achievable performance in terms of protons on target is estimated with complex simulations of the multi-turn dynamics of the LHC beam halo, in presence of the tight betatron collimation hierarchy. A validation of these simulations shall be carried out to provide a solid experimental benchmark. This will provide important input for the specification of operational scenarios and performance estimates that critically depend on simulations and are potentially affected by unknown machine imperfections.

Various operational challenges, e.g., the alignment strategy of CRY2, to establish reference positions with respect to the circulating beam and the split halo produced by CRY1, are to be assessed experimentally before relying on this scheme. One crucial aspect to be studied with beam is the possibility of aligning the CRY2 using the main proton beam at low intensity and then to set it to achieve double-channelling reliably at the LHC energies, with adequate efficiencies. Other operational challenges that can be addressed involve the setup of orbit and optics changes that are studied on paper to optimize the performance.

* pascal.hermes@cern.ch

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK033

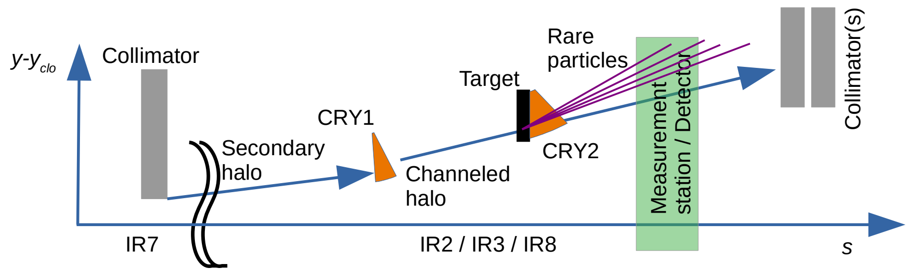

Figure 1: Double-crystal setup: the secondary beam halo scattered out of the primary collimator in the LHC betatron collimation region IR7 is guided by the splitting crystal CRY1 onto a target (T) with adjacent CRY2. Particle detection is provided by an existing detector (IR2/IR8) or dedicated measurement station (IR3) equipped with spectrometer (SPEC). Collimator(s) further downstream finally absorb the channelled halo. The vertical axis shows the vertical position w.r.t. the closed orbit y_{clo}.

The layouts for IR3 are also conceived to allow some preliminary measurements, eventually, with the assumption that a dedicated measurement system could be added.

REQUIREMENTS AND BEAM LINE INTEGRATION

The test setup inevitably requires installing two new crystals (CRY1 and CRY2) with their goniometers. The possibility to install a target adjacent to the CRY2 is being studied and will depend on the possibility to deploy effective measurement stations. For the latter, either a pilot detection device with spectrometer, or an existing detector has to be used. As discussed in [22], the experimental setup in IR8 requires comparably large bending angles (150 μrad for CRY1 and 14 mrad for CRY2). IR3 is more versatile in terms of the types of crystals which could be tested, which makes it our straight section of choice. In principle, both beams could be used but here we discuss the possibility of integration for LHC Beam 1 (circulating in clock-wise direction), to be aligned with the IR3 setup discussed in [22]. The study of a layout for Beam 2 is also planned.

Crystal1(CRY1) The setup was chosen to be realized with crystals acting in the vertical plane, because of possibly slightly relaxed requirements from hardware integration and collimation. Space availability and constraints imposed from hardware integration aspects led to the choice of the position at a distance s = 6430 m from Interaction Point (IP) 1, which is in an empty drift space in cell 7 left of the mid-point of IR3. We consider the bending radius of CRY1 to be 50 μrad, equivalent to the IR3 CRY1 parameter proposed in [22].

Spectrometermagnet While the installation of the two crystals is crucial for the beam test, a fully developed measurement station with spectrometer is currently not foreseen for integration during LHC Run 3. However, a simplified setup can be envisaged if one of the existing LHC dipole corrector magnets [1] were used to provide the magnetic dipole field required for momentum reconstruction. Ideally, the chosen corrector dipole would provide sufficient space both up- and downstream to have space for the installation of the target and CRY2 assembly (T/CRY2) and the detector, respectively. However, in order to maximize their efficiency for orbit correction, they are located immediately adjacent to the quadrupoles where the β-functions are maximum, such that no corrector dipole can fulfill both requirements in the current beam line layout.

As a baseline, we consider the vertical warm corrector dipole MCBWV.4R3.B1 (MCBW). More than twenty meters of free space are available upstream of this magnet. With the technical feasibility being currently under validation, a re-location of the MCBW by 10 m in the direction of IP1 could be envisaged[1] to free up the space required for equipping the setup with a preliminary detection device between the MCBW and the subsequent quadrupole magnet (new MCBW position at 6674.9 m from IP1). We studied the implied reduction of efficiency for beam orbit correction from a simple scaling with the square root of the β-functions, yielding a rather moderate reduction of 15%, which is likely compatible with the regular operation of the LHC.

Target+Crystal2(T/CRY2) The position of T/CRY2 is constraint by the position of the MCBW, serving as spectrometer, and is currently assumed to be 50 cm upstream of it (at 6674.5 m from IP1). The assumed bending radius of 5 mrad is aligned with the IR3 configuration discussed in [22]. Other crystal types could be tested as well. The decision to include a target for the test setup is currently pending and a setup in which only CRY2 is installed for testing purposes might be considered instead.

Absorbingcollimator We plan to employ the existing vertical absorber TCLA.A5R3.B1 to intercept the channelled halo downstream of the T/CRY2. Beam dynamics studies (see next section), have shown that this can be achieved with TCLA settings of 20 σ (where σ is the RMS beam size assuming a proton energy of 6.8 TeV, foreseen for LHC Run 3, and normalized emittance of 3.5 μm rad) or below. For the low proton intensity beam tests planned for Run 3, we do not expect to risk damaging this device if it is used for this purpose.

[1] This implies to move its Beam 2 counterpart MCBWH.4R3.B2 as well.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK033

Table 1: Parameters of key devices for the IR3 test setup

Element	Position (m)	Comment
CRY1	6430.0	50 μrad bending
T/CRY2	6674.5	5000 μrad bending
MCBW.4R3.B1	6674.9	-10m w.r.t. nominal

Possible locations of key devices are shown in Table 1. The proposed layout would be compatible with a future upgrade including the installation of a detector.

BEAM DYNAMICS SIMULATIONS

Simulations were carried out using the beam dynamics and accelerator design tool MAD-X [23, 24]. We consider the MCBW to be operated at maximum current, with an integrated field of 1.87 Tm bending the beam trajectory into the positive vertical direction [1]. The effect on the orbit has to be compensated with the remaining vertical IR3 corrector dipoles. The currents of the surrounding vertical orbit corrector magnets (one normal conducting MCBW and three superconducting MCBC) were matched, employing four corrector magnets, with the required currents being within their limits. Note that the effect on the beam orbit, and its compensation, would be similar if the IR3 FT-setup for HL-LHC were to be realized. Figure 2 shows the simulated vertical beam orbit of the main proton beam, the channelled halo extracted with the splitting crystal CRY1 (assumed to be at 5 σ with a bending angle of 50 μrad), as well as the $\pm 5\ \sigma$ beam envelope. The optical configuration corresponds to the state after the energy ramp and before starting with the squeeze. The position of the key devices used in the simulation corresponds to those presented in Table 1, including the assumed re-location of the MCBWV.5R4.B1 10 m upstream of its initial position.

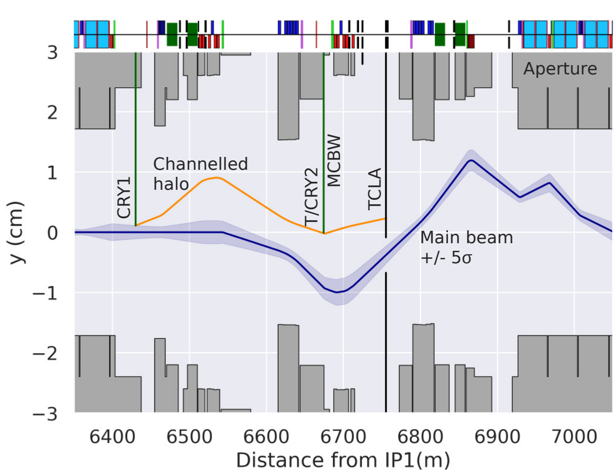

Figure 2: Simulated orbit of the main proton beam (blue) and channelled halo (orange) for a possible Run 3 beam test, assuming a beam energy of 6.8 TeV and normalized emittance of 3.5 μm rad.

The offset between main beam and target is roughly 8 mm, demonstrating that the setup can indeed provide a safe separation between target and main beam. The TCLA, aligned around the closed orbit of the main beam with the two jaws intercepts the channelled beam halo. Comparing beam orbits and envelope to the aperture of the beamline elements, it can also be concluded that the setup is not limited by the available aperture in the vertical plane.

Tracking simulations with SixTrack [25–27], including particle-matter interaction in collimators and crystals, were carried out to test the efficiency at which particles can be guided onto the target. The machine configuration is as before with the collimator settings as listed in Table 4 of [22]. The initial distribution is set up such that all particles impact on the vertical primary collimator in IR7 (TCP7), set to 5 σ. CRY1 is also set to 5 σ in this example, comparable to the scenario presented in Table 5 in [22]. Figure 3 shows the spot size of the channelled halo impacting the target. The quantitative analysis unveils that 18% of the protons that were initially impacting the TCP7 hit the CRY1, out of which 72% are channelled and impact the target. We conclude that the setup is effective in simulations in serving the purpose of testing the double crystal setup at LHC energies.

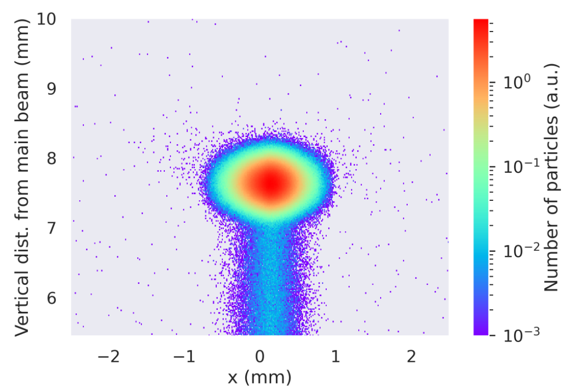

Figure 3: Transverse distribution of protons impacting the target in the proof-of-principle setup. The colour indicates the number of particles.

CONCLUSIONS AND OUTLOOK

The LHC momentum collimation region IR3 offers the possibility of hosting a test stand in LHC Run 3 to prepare for potential fixed target experiments based on single- and double-crystal channelling in HL-LHC. It relies on the installation of a set of two new bent crystals, and ideally also of a dedicated measurement station (under study). The deployment of such setup would enable assessing key open points, identified as important milestones prior to the integration in the LHC of a FT experiment. The studies in simulation indicate that the proposed layout is suitable to achieve this goal. Future simulations will be carried out to study how beam optics changes could increase the number of protons on the target, as well as to study possible strategies to establish double channelling.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK033

REFERENCES

[1] O. S. Brüning, *et al.*, "LHC design report v.1 : The LHC main ring," *CERN-2004-003-V1*, CERN, Geneva, Switzerland, 2004.

[2] G. Apollinari, *et al.*, *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1*. CERN Yellow Reports: Monographs. CERN-2017-007-M, CERN, Geneva, Switzerland, 2017.

[3] C. Boscolo Meneguolo, *et al.*, "Study of beam-gas interaction at the LHC for the Physics Beyond Collider Fixed-Target study," *CERN-PBC-Notes-2019-001*, CERN, Geneva, Switzerland, 2019.

[4] 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*, TUPAF045, 2018. doi:10.18429/JACoW-IPAC2018-TUPAF045

[5] C. Barschel, *et al.*, "LHC fixed target experiments: Report from the LHC Fixed Target Working Group of the CERN Physics Beyond Colliders Forum," *CERN-PBC-REPORT-2019-001*, CERN, Geneva, Switzerland, 2019.

[6] R.W. Assmann *et al.*, "The Final Collimation System for the LHC," *Proc. of the European Particle Accelerator Conference* 2006, Edinburgh, Scotland, p. 986, 2006.

[7] The LHCb Collaboration, "The LHCb Detector at the LHC," *J. Instrum.*, vol. 3, no. 08, p. S08005, 2008.

[8] W. Scandale, *et al.*, "Optical layout for the measurement of Short Living Baryon Magnetic Moment using Bended Crystals at LHC," *Physics Beyond Colliders Kickoff Workshop*, CERN, Geneva, Switzerland, 2016.

[9] 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.

[10] 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.

[11] 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.

[12] 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.

[13] J. Fu *et al.*, "Novel Method for the Direct Measurement of the τ- Lepton Dipole Moments," *Phys. Rev. Lett.*, vol. 123, no. 1, p. 011801, 2019.

[14] The ALICE Collaboration, "The ALICE experiment at the CERN LHC," *Journal of Instrumentation*, vol. 3, no. 08, p. S08002, 2008.

[15] A. Kalweit, "Highlights from the ALICE experiment," *Nuclear Physics A*, vol. 982, pp. 1–7, 2019. The 27th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions: Quark Matter 2018.

[16] M. Patecki, *et al.*, "Status of Layout Studies for Fixed-Target Experiments in Alice Based on Crystal-Assisted Halo Splitting," *HB2021,* Fermilab, Batavia, Illinois, USA,pp.146–150, 2022.

[17] A. M. Taratin, "Particle channeling in a bent crystal," *Phys. Part. Nucl.*, vol. 29, pp. 437–462, 1998.

[18] W. Scandale *et al.*, "Double-crystal measurements at the CERN SPS," *Nucl. Instrum. Methods Phys. Res., A*, vol. 1015, p. 165747, 2021.

[19] W. Scandale, *et al.*, "Observation of channeling for 6500 GeV/c protons in the crystal assisted collimation setup for LHC," *Physics Letters B*, vol. 758, pp. 129 – 133, 2016.

[20] S. Redaelli *et al.*, "First observation of ion beam channeling in bent crystals at multi-TeV energies," *Eur. Phys. J. C*, vol. 81, no. 2, p. 142, 2021.

[21] S. Aiola *et al.*, "Progress towards the first measurement of charm baryon dipole moments," *Phys. Rev. D*, vol. 103, no. 7, p. 072003, 2021.

[22] D. Mirarchi, *et al.*, "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.

[23] "MAD-X program." http://cern.ch/mad/, CERN, Geneva, Switzerland.

[24] W. Herr and F. Schmidt, "A MAD-X primer," *CERN-AB-2004-027-AB, CERN, Geneva, Switzerland*, 2004.

[25] F. Schmidt, "SixTrack. User's Reference Manual," CERN/SL/94-56-AP,CERN,Geneva,Switzerland ,1994.

[26] R. De Maria *et al.*, "Sixtrack version 5: Status and new developments," in *Proc. of IPAC19,* Melbourne, Australia, May 2019, pp. 3200-3203, paper WEPST043.

[27] R. Bruce, *et al.*, "Status of SixTrack with collimation," *CERN-2018-011-CP, Proceedings of the ICFA Mini-Workshop on Tracking for Collimation,* CERN, Geneva, Switzerland,p.1, 2018.