64th ICFA ABDW on High-Intensity and High-Brightness Hadron Beams HB2021, Batavia, IL, USA JACoW Publishing
ISBN: 978-3-95450-225-7 ISSN: 2673-5571 doi:10.18429/JACoW-HB2021-MOCC3

FIRST EXPERIENCE OF CRYSTAL COLLIMATORS DURING LHC SPECIAL RUNS AND PLANS FOR THE FUTURE*

M. D'Andrea[1,2†], V. Avati[1,3], R. Bruce[1], M. Butcher[1], M. Di Castro[1], M. Deile[1], B. Dziedzic[4], H. Garcia Morales[1,5‡], Y. Gavrikov[1,6], K. Hiller[7], S. Jakobsen[1], J. Kašpar[1,8], K. Korcyl[4], I. Lamas Garcia[1], A. Masi[1], A. Mereghetti[1§], D. Mirarchi[1,9], S. Redaelli[1], B. Salvachua Ferrando[1], P. Serrano Galvez[1], M. Solfaroli Camillocci[1], N. Turini[10]
[1]CERN, European Organization for Nuclear Research, Geneva, Switzerland
[2]Università degli Studi di Padova, Padova, Italy
[3]AGH University of Science and Technology, Kraków, Poland
[4]Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland
[5]Royal Holloway University of London, Egham Hill, Egham, United Kingdom
[6]Petersburg Nuclear Physics Institute, NRC "Kurchatov Institute", Gatchina, Russia
[7]Deutsches Elektronen-Synchrotron, Hamburg, Germany
[8]Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[9]The University of Manchester, Manchester, United Kingdom
[10]Università degli Studi di Siena and Gruppo Collegato INFN di Siena, Siena, Italy

Abstract

Bent crystals can deflect charged particles by trapping them within the potential well generated by neighboring crystalline planes and forcing them to follow the curvature of the crystal itself. This property has been extensively studied over the past decade at the CERN accelerator complex, as well as in other laboratories, for a variety of applications, ranging from beam collimation to beam extraction and in-beam fixed target experiments. In 2018, crystal collimators were operationally used for the first time at the Large Hadron Collider (LHC) during a special high-β^* physics run with low-intensity proton beams, with the specific goal of reducing detector background and achieving faster beam halo removal. This paper describes the preparatory studies carried out by means of simulations, the main outcomes of the special physics run and plans for future uses of this innovative collimation scheme, including the deployment of crystal collimation for the High-Luminosity LHC upgrade.

INTRODUCTION

The CERN Large Hadron Collider (LHC) is routinely used to accelerate and collide high-intensity proton beams [1]. Throughout Run 2 (2015-2018), it was operated at a top energy of 6.5 TeV, with typical beam populations of a few 10^{14} protons per beam. In addition to the high-intensity, high-energy operation, special runs with dedicated machine and beam configurations were also performed in order to achieve specific experimental conditions.

In October 2018, one of the aforementioned special runs was carried out at the injection energy of 450 GeV, using low-intensity beams (up to about $6 \cdot 10^{11}$ protons per beam) and a special optics with a β^* (i.e. the optical function at the Interaction Points, IPs) larger than in normal operation. This special run was requested by the forward physics community to measure the proton-proton elastic cross section and extrapolate its nuclear part towards low values of momentum transfer [2]. Dedicated detectors housed in movable Roman Pots (XRPs) [3] are transversely placed very close to the circulating beams in order to intercept particles scattered at small angles as result of collisions with low momentum transfer at the IP. Two sets of XRP stations are installed downstream of IP1 and IP5, and are operated by the ATLAS (ALFA) [4] and TOTEM [5] collaborations respectively. Only the vertical two-sided stations, whose layout is schematically illustrated in Fig. 1, were used for this run.

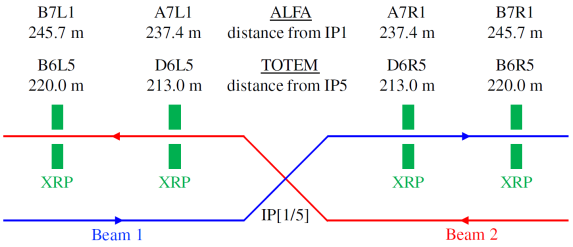

Figure 1: Illustrative layout of the vertical ALFA and TOTEM XRPs stations around IP1 and IP5 [6].

The setup of this run posed several challenges from the accelerator physics point of view, requiring the design of dedicated beam optics [7] and collimation settings [8]. While machine protection requirements were relaxed thanks to the low stored beam energy of about 40 kJ (with respect to the stored energy of 350 MJ in nominal operation), the background induced at the detectors would have been intolerable without a dedicated halo collimation system. The feasibility of tight collimator settings necessary to position the XRPs as close as possible to the beam was identified as a major concern for the success of the run. In the standard LHC col-

---

[*] Work supported by the HL-LHC Project
[†] marco.dandrea@cern.ch
[‡] Currently at University of Oxford, Oxford OX1 2JD, United Kingdom
[§] Currently at Fondazione CNAO, Strada Campeggi 53, 27100 Pavia, Italy

limation system [9–11], multiple stages of amorphous collimators installed in two dedicated Insertion Regions (IRs) are used to progressively outscatter halo particles in a multiturn cleaning process. However, an innovative technique which makes use of crystal collimators has been extensively studied as a way to improve the efficiency of the LHC collimation system, promising a faster cleaning process via a reduced multiturn halo population [12]. The peculiar needs of this special physics run provided an ideal scenario for the first operational use of crystal collimation at the LHC.

CRYSTAL COLLIMATION AT THE LHC

Atoms in a crystal are arranged in a highly ordered microscopic structure, called a *crystalline lattice*. If the crystal is well oriented with respect to the trajectory of an impinging charged particle, the lattice is seen as a sequence of ordered planes of atoms. A particle impinging onto the crystal with specific impact conditions can then be trapped inside the electrostatic potential well generated by two neighboring planes and forced to travel in the nearly empty space between them for the full length of the crystal. This process is called *planar channeling*. If a particle is channeled by a bent crystal, its trajectory will be forced to follow the curvature of the crystalline planes. A few millimeter long crystal can thus be used to efficiently steer beam halo particles by tens of μrad, an effect corresponding to that of a magnetic field of hundreds of Tesla over the same length at nominal LHC beam energies. In a crystal-based collimation system, bent crystals are used as the primary collimation stage and deflect beam halo particles towards a single absorber, as schematically shown in Fig. 2. This innovative technique has been studied over the past decade to improve the performance of the LHC collimation system in view of its High-Luminosity upgrade (HL-LHC) [13–16], in particular for operation with nominal heavy-ion beam intensities.

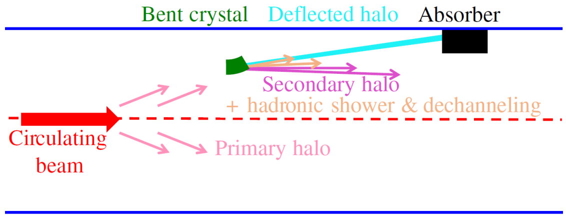

Figure 2: Schematic representation of the working principle of a crystal-based collimation system [6].

A test stand consisting of four silicon crystal collimators, two per beam and one per plane, is presently installed in the betatronic collimation Insertion Region (IR7) of the LHC [17]. The two vertical crystals used in the special physics run are provided by the UA9 collaboration and built at the Petersburg Nuclear Physics Institute (PNPI). Each crystal is mounted on a high-resolution goniometer, equipped with a piezo actuator and a stepper motor for the rotational and linear stage, respectively. The same high-performance motors with 5 µm resolution developed for standard LHC collimators are used for the linear movement. The piezo actuator provides an angular resolution below 0.1 µrad and an accuracy below 1 µrad [18]. These parameters are necessary in order to achieve and maintain channeling conditions throughout the entire machine cycle, as the channeling acceptance at LHC energies varies from about 9.5 µrad at 450 GeV to about 2.5 µrad at 7 TeV.

Table 1: Settings (in Beam σ) of Relevant Vertical Collimators for Different Configurations at Injection Energy

Collimator	**IR**	**Nominal**	**Special Run Standard**	**Special Run Crystal**
`TCTPV.4[R/L]1.B[1/2]`	2	13.0	2.7	13.0
`TCTPV.4[R/L]5.B[1/2]`	5	13.0	2.7	13.0/2.7
`TCP.D6[R/L]7.B[1/2]`	7	5.7	3.2	3.2
`TCPCV.A6[L/R]7.B[1/2]`	7	OUT	OUT	2.5
`TCLA.A6[R/L]7.B[1/2]`	7	10.0	2.5	2.7
`TCLA.C6[R/L]7.B[1/2]`	7	10.0	2.7	2.7
`TCTPV.4[R/L]8.B[1/2]`	8	13.0	2.7	13.0
`TCTPV.4[R/L]1.B[1/2]`	1	13.0	2.7	2.7/13.0

PREPARATION OF THE SPECIAL PHYSICS RUN

Dedicated settings for the LHC collimation system were devised in order to comply with the specific goal of reducing the background rate at the XRPs, placed close to the beams with an opening of 3 σ (where σ is the r.m.s. beam size, assuming a Gaussian distribution and normalized emittance $\varepsilon^* = 3.5\,\mu\text{m}$). The nominal settings of vertical primary (TCP), absorber (TCLA), tertiary (TCT) and crystal (TCPC) collimators for normal operation at injection are reported in Table 1 in units of σ, along with the two schemes developed for the special run.

In what will be referred to in the following as the *standard scheme*, tungsten collimators (TLCAs and TCTs) are deployed in a two-stage hierarchy characterized by the tightest normalized settings ever used in the LHC [8]. In particular, a 0.2 σ retraction is present between the primary and secondary stage, with an additional 0.3 σ retraction between the secondary stage and the XRPs. Tungsten collimators were chosen because of their higher absorption efficiency compared to all other collimators.

The *crystal scheme* was developed in parallel as an alternative way to achieve possibly even lower background rates [6]. The same settings as the standard scheme were taken as a starting point, but using a bent crystal as the primary stage. These settings were then optimized to relax margins and reduce the risk of small orbit drifts breaking the collimation hierarchy, while also improving the overall performance.

Semianalytic studies were carried out to evaluate if the channeled halo could be intercepted by the secondary stage even in these extreme conditions, by calculating the trajectory of deflected particles using the transfer matrix formalism. The final layout was then validated by complete multiturn tracking simulations performed with SixTrack, a

ISBN: 978-3-95450-225-7 ISSN: 2673-5571 doi:10.18429/JACoW-HB2021-MOCC3

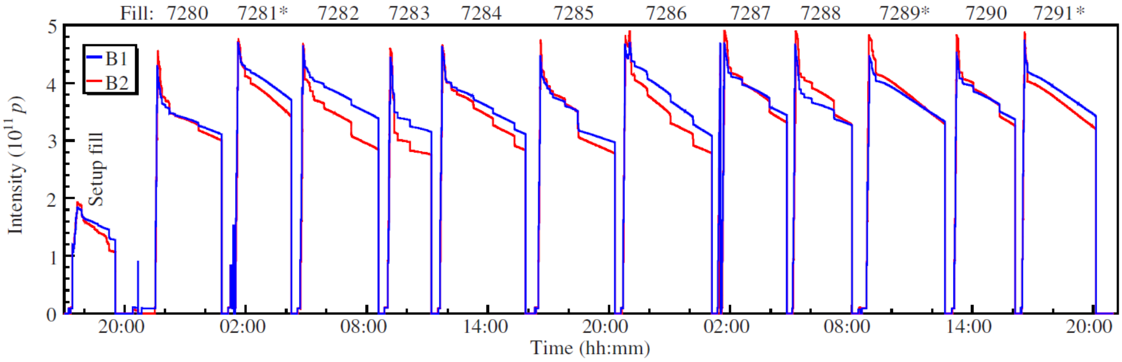

Figure 3: Beam intensity in fills performed during the special physics run. Crystal collimation fills are marked by * [6].

single-particle tracking code widely used at CERN for simulating beam dynamics in circular accelerators [19–23]. A dedicated Monte-Carlo simulation routine within SixTrack models the interaction between proton beams and crystal collimators [24–27]. This setup allowed the expected background at the XRPs and the improvement provided by crystals compared to standard collimation to be estimated.

An initial test run was carried out on 2 October 2018, during which promising results were obtained with both collimation schemes. In particular, the reference linear and angular positions to maximize the channeling performance were found for both crystals, allowing their deployment in operation interleaved with standard collimation settings.

PERFORMANCE DURING THE SPECIAL PHYSICS RUN

The special physics run took place from 11 to 13 October 2018 with 450 GeV proton beams. After a first setup fill to validate the results obtained in the initial tests, two physics fills were dedicated to data taking with the standard and crystal collimation schemes, respectively. A preference for the standard scheme was expressed by ALFA, while TOTEM had better data quality with the crystal scheme but was also satisfied with the standard scheme. Thus, it was initially decided to keep the standard scheme for the subsequent fills. However, after four fills, it was necessary to recenter some of the collimators in order to keep the very tight margins between the primary and secondary collimation stages. As a result of this operation, the data quality for TOTEM was significantly worsened in the following fills. It was then decided to use the crystal scheme for two final fills, interleaved by a fill dedicated to ALFA using the standard scheme. A total of nine and three fills were carried out using the standard and crystal schemes, respectively. The beam intensity during each fill is shown in Fig. 3.

During each fill using the standard scheme, the background on the XRPs was observed to increase over time up to values that could have jeopardized the measurement. As a result, it was necessary to perform a rescraping of the beam – a deep cut of the beam tails down to 2 σ, as done at the beginning of every fill – about once every hour. The tungsten collimators are inserted towards the beam in order to dispose of the accumulated multiturn beam halo and bring the background rate down to a satisfactory level. During this operation, the ALFA XRPs needed to be retracted from the beam due to concerns for radiation to electronics. Thus, the whole procedure took about 6 minutes each time. The rescrapings can be seen in Fig. 3 as decreasing steps in beam intensity during fills which make use of the standard scheme. In the fills using the crystal scheme, on the other hand, the background rate was observed to increase much more slowly and no rescraping was needed, leading to a 10% more efficient data taking. Furthermore, crystals were quickly deployed using an automated sequence to insert them directly in optimal channeling using the reference positions and orientations identified during the test run. A quick check was nevertheless performed after each insertion, confirming that the crystals could reliably be deployed. These obervations are an important milestone, showing the efficiency of the current crystal collimator hardware and controls.

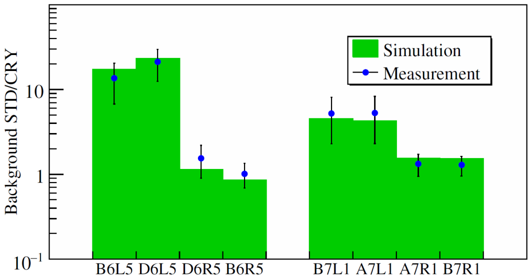

Figure 4: Comparison of the measured and simulated background ratio at the XRP stations [6].

The beam-related background with the two schemes was evaluated using non-colliding bunches, in order to remove the contribution of physics background coming from collisions. High-sensitivity data provided by ALFA and TOTEM were used to quantify the observed background rate. The ratio between the background measured with the crystal and standard system at the XRP stations is in very good qualitative and quantitative agreement with simulations, as shown in Fig. 4. The background rate is directly linked to the multiturn halo, formed by particles that keep circulating in the machine after their first interaction with the collimation system. These particles need to be absorbed as quickly as possible to achieve efficient cleaning. A dedicated simulation campaign showed that 99% of the particles impacting on

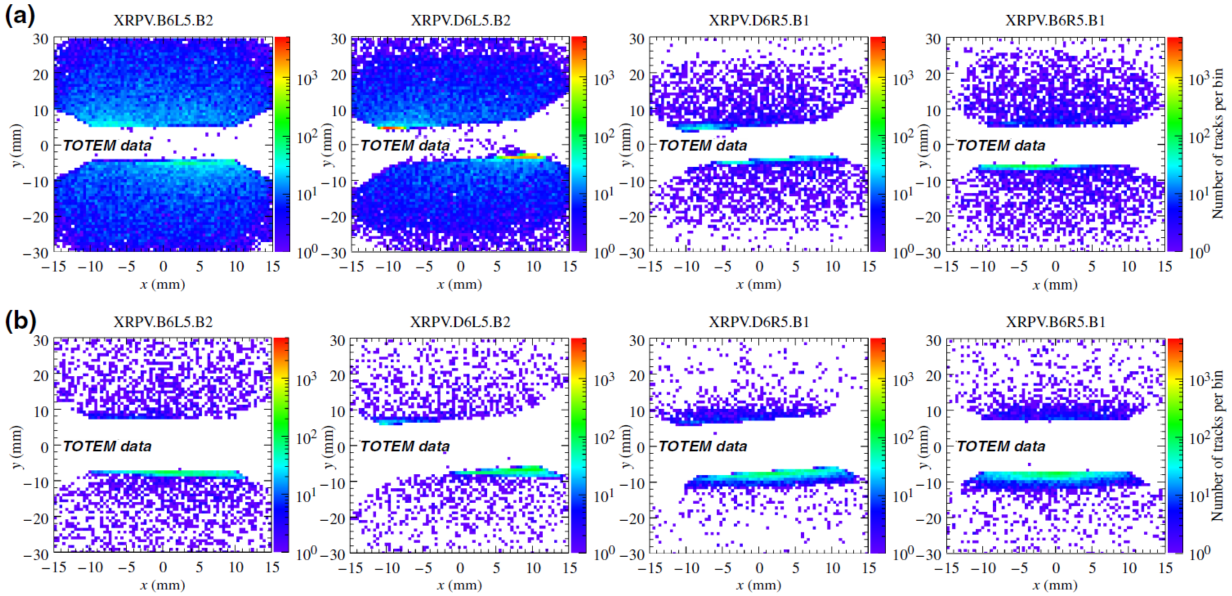

Figure 5: Measured background hit pattern at the TOTEM XRP stations using standard (a) and crystal (b) collimation [6].

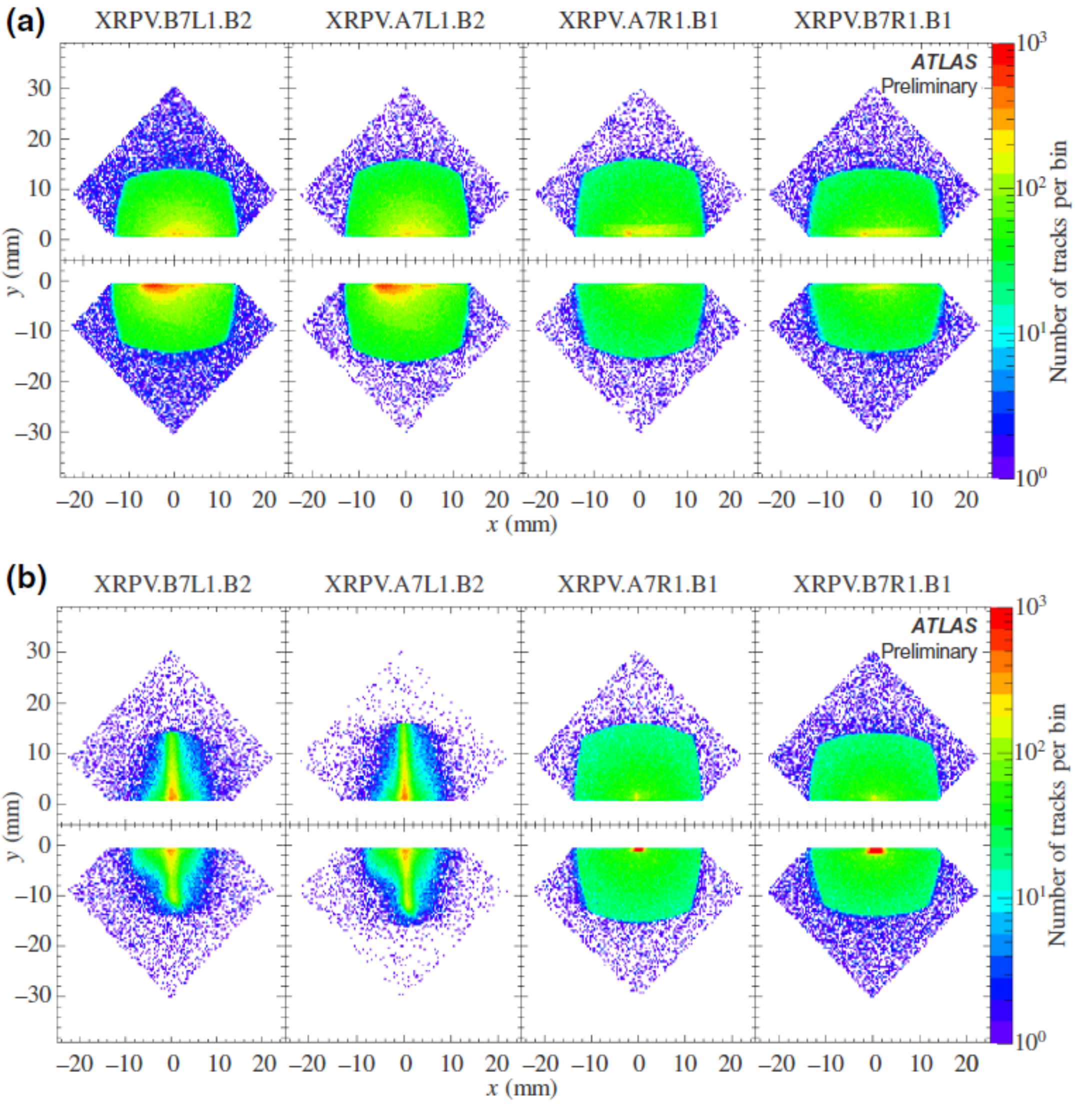

Figure 6: Measured background hit pattern at the ALFA XRP stations using standard (a) and crystal (b) collimation [6].

a crystal primary collimator are absorbed by the collimation system in the same turn, while this percentage is reduced to only 66% for a standard primary collimator. The observed performance provides evidence for the faster halo removal achievable with crystals. More details can be found in [6].

Figures 5 and 6 show the background hit pattern measured with non-colliding bunches at the TOTEM and ALFA XRPs respectively, using the two collimation schemes. In both cases, the observed pattern is in very good agreement with simulations [6]. In particular, structures due to the multiturn halo hitting the detector edges facing the beam are significantly suppressed when crystals are used. This enabled efficient offline event reconstruction and an improved data quality for TOTEM. For ALFA, however, the hit pattern on the Beam 2 XRPs when crystals are used is more focused on the central region, where the physics signal is expected, leading to a less efficient offline background subtraction. This problematic feature of the background distribution was not identified during preliminary studies as the main focus was the optimization of the background rate, rather than the hit pattern. A full offline analysis showed that the irreducible background is increased from about 0.5% with the standard scheme to about 1.5% with the crystal scheme, which is still satisfactory for the measurement. Nevertheless, a dedicated simulation campaign was carried out after the physics run in order to understand this behavior and investigate possible mitigation solutions. The source of the hit pattern was found to be particles that undergo dechanneling after hitting the crystal in IR7 and bypass the secondary stage because of the lower deflection acquired. These particles then circulate in the machine for about 10 turns before hitting a tungsten collimator in IR3. A fraction of these particles escape the collimator and finally hit the ALFA XRPs in Beam 2 on the same turn. The peculiar shape of the hit pattern is related to the fractional betatron phase advance between the collimator and the XRPs. Simulations show that retracting the IR3 collimator would have removed the problematic distribution and led to an even larger background rate reduction for ALFA, while the gain would have been reduced for TOTEM. More details can be found in [6].

FUTURE PROSPECTS OF CRYSTAL COLLIMATION

The performance achieved by the crystal scheme in the special physics run is a crucial milestone, proving the maturity and reliability reached by this innovative collimation technique, as well as by the associated hardware and control systems. Furthermore, the good qualitative and quantitative agreement between observed results and simulations is a good indicator of the accuracy of the currently available tools. The predictive power of simulations could make it possible to achieve even better performance should this scheme be defined as baseline for future low-intensity special runs.

The main challenge for the use of crystal collimation in operation with high-intensity proton beams is the safe disposal of the power from channeled halo particles that can reach up to 500 kW, requiring the design of a special absorber. However, much lower power depositions are expected with high-intensity ion beams, allowing the channeled halo to be safely intercepted with a standard secondary collimator [28]. The good outcome of the special physics run and the demonstration of the cleaning improvement provided by crystal collimation with Pb ion beams [15] were key ingredients in the decision to include crystal collimation in the HL-LHC upgrade baseline programme for use in operation with ion beams starting in Run 3 [29, 30].

Bent crystals are highly versatile tools that lend themselves to a variety of purposes aside from collimation, including advanced techniques of beam extraction and manipulation, as well as applications to fixed target experiments currently studied in the Physics Beyond Colliders framework [31–33]. The outcome of this special physics run shows that crystals can be deployed safely and efficiently in these highly specialized scenarios.

CONCLUSIONS

Crystal collimation was used in operation at the LHC for the first time during a special high-β^* physics run. Crystals were aligned during preparatory tests and automatically deployed in channeling orientation during the physics fills. Data provided by the ATLAS (ALFA) and TOTEM collaborations show that the experimental background at the detectors was significantly reduced thanks to the faster halo cleaning process provided by the crystal collimation scheme. This led to a more efficient data taking and an improved data quality with respect to the standard collimation scheme. Additional simulation studies show that the background hit pattern could be improved by adjusting the settings of other collimators, leaving room for further optimization in view of future runs. The good performance achieved in this run was a crucial milestone demonstrating the maturity reached by this innovative collimation scheme, as well as that of the associated hardware and control system, allowing bent crystals to be safely and efficiently used for beam manipulations in state-of-the-art machines such as the LHC. This opens the way for more synergies between accelerator and high-energy physics, and, along with the demonstrated cleaning performance with high-intensity ion beams, was a contributing factor in the decision to include crystal collimation in the baseline for the next runs of the LHC and HL-LHC.

ACKNOWLEDGEMENTS

The experimental data gathered during the special physics run were kindly provided by the ATLAS (ALFA) and TOTEM collaborations. Crystal collimation tests at the LHC are carried out with the support of the UA9 collaboration, which provided and characterized the bent crystals prior to the installation in the machine. The crystals used in the special run were manufactured by PNPI. Research on crystal collimation for the LHC is supported by the HL-LHC Project. Crucial contributions from the CERN BE-ABP, BE-CEM, BE-OP and SY-STI groups to the preparation and carrying out of the run are also kindly acknowledged.

REFERENCES

[1] O. Brüning *et al.*, "LHC Design Report", in *CERN Yellow Reports Monographs*, 2004. `doi:10.5170/CERN-2004-003-V-1`

[2] G. Antchev *et al.*, "First determination of the ρ parameter at $\sqrt{s} = 13$ TeV: Probing the existence of a colourless C-odd three-gluon compound state", *Eur. Phys. J. C*, vol. 79, p. 785, 2019. `doi:10.1140/epjc/s10052-019-7223-4`

[3] M. Oriunno *et al.*, "The Roman Pot for the LHC", in *Proc. EPAC'06*, Edinburgh, UK, 2006, paper MOPLS013, pp. 562–564.

[4] S. A. Khalek *et al.*, "The ALFA Roman Pot detectors of ATLAS", *J. Instrum.*, vol. 11, p. 11013, 2016. `doi:10.1088/1748-0221/11/11/P11013`

[5] G. Anelli *et al.*, "The TOTEM experiment at the CERN Large Hadron Collider", *J. Instrum.*, vol 3, p. 08007, 2008. `doi:10.1088/1748-0221/3/08/S08007`

[6] D. Mirarchi *et al.*, "Reducing Beam-Related Background on Forward Physics Detectors Using Crystal Collimation at the Large Hadron Collider", *Phys. Rev. Applied*, vol. 14, p. 064066, 2020. `doi:10.1103/PhysRevApplied.14.064066`

[7] H. Burkhardt, "High-Beta Optics and Running Prospects", *Instruments*, vol. 3, p. 22, 2019. `doi:10.3390/instruments3010022`

[8] H. Garcia Morales *et al.*, "Tightest collimation system in the LHC", (to be published).

[9] R. Assmann *et al.* "The final collimation system for the LHC", in *Proc. EPAC'06*, Edinburgh, UK, Jun. 2006, paper TUODFI01, pp. 986–988.

[10] R. Bruce *et al.* "Simulations and measurements of beam loss patterns at the CERN Large Hadron Collider", *Phys. Rev. Spec. Top.-Accelerators Beams*, vol. 17, p. 081004, 2014. `doi:10.1103/PhysRevSTAB.17.081004`

[11] S. Redaelli, R. Bruce, A. Lechner, and A. Mereghetti, "Chapter 5: Collimation system", in *CERN Yellow Reports Monographs*, vol. 10, pp. 87–114, 2020. `doi:10.23731/CYRM-2020-0010.87`

[12] W. Scandale and A. Taratin, "Channeling and volume reflection of high-energy charged particles in short bent crystals. Crystal assisted collimation of the accelerator beam halo", *Phys. Rep.*, vol. 815, pp. 1-107, 2019. `doi:10.1016/j.physrep.2019.04.003`

[13] W. Scandale *et al.*, "Observation of channeling for 6500 GeV/c protons in the crystal assisted collimation setup for LHC", *Phys. Lett. B*, vo. 758, p. 129, 2016. `doi:10.1016/j.physletb.2016.05.004`

[14] R. Rossi, "Experimental assessment of crystal collimation at the Large Hadron Collider", Ph.D. thesis, Università La Sapienza di Roma, Roma, Italy, 2017.

[15] M. D'Andrea, "Applications of crystal collimation to the CERN Large Hadron Collider (LHC) and its High Luminosity upgrade project (HL-LHC)", Ph.D. thesis, Università degli Studi di Padova, Padova, Italy, 2020.

[16] HL-LHC Crystal Collimation Day, `https://indico.cern.ch/event/752062/`

[17] D. Mirarchi, G. Hall, S. Redaelli, and W. Scandale, "Design and implementation of a crystal collimation test stand at the Large Hadron Collider", *Eur. Phys. J. C*, vol. 77, p. 424. `doi:10.1140/epjc/s10052-017-4985-4`

[18] A. Masi *et al.*, "Goniometer and controls", presented at HL-LHC Crystal Collimation Day, 2018.

[19] SixTrack – 6D Tracking Code, `http://sixtrack.web.cern.ch/SixTrack/`.

[20] F. Schmidt *et al.*, "SixTrack users's reference manual, Version 5.4.3", CERN, Geneva, Switzerland, 2019.

[21] G. Ripken and F. Schmidt, "A symplectic six-dimensional thin lens formalism for tracking", CERN, Geneva, Switzerland, 1995, Rep. CERN-SL-95-12-AP.

[22] G. Robert-Demolaize, R. Assmann, S. Redaelli, and F. Schmidt, "A New Version of SixTrack with Collimation and Aperture Interface", in *Proc. PAC'05*, Knoxville, TN, USA, May 2005, paper FPAT081, pp. 4084–4086.

[23] R. Bruce *et al.*, "Status of SixTrack with collimation", in *CERN Yellow Report Conference Proceedings*, vol. 2, pp. 1–10, 2015. `doi:10.23732/CYRCP-2018-002.1`

[24] D. Mirarchi, S. Redaelli, and W. Scandale, "Crystal implementation in SixTrack for proton beams", in *CERN Yellow Report Conference Proceedings*, vol. 2, pp. 91–108, 2015. `doi:10.23732/CYRCP-2018-002.91`

[25] V. Previtali, "Performance evaluation of a crystal-enhanced collimation system for the LHC", Ph.D. thesis, EPFL, Lausanne, Switzerland, 2010.

[26] D. Mirarchi, "Crystal collimation for LHC", Ph.D. thesis, Imperial College, London, UK, 2015.

[27] D. Mirarchi, G. Hall, S. Redaelli, and W. Scandale, "A crystal routine for collimation studies in circular proton accelerators", *Nucl. Instrum. Methods Phys. Res. Sect. B*, vo. 355, pp. 278–382, 2015. `doi:10.1016/j.nimb.2015.03.026`

[28] C. Bahamonde, A. Lechner, and R. Rossi, "Crystal channeling of ions on different TCSG materials", presented at LHC Collimation Upgrade Specification Meeting, 2018.

[29] O. Aberle *et al.*, "High-Luminosity Large Hadron Collider (HL-LHC): Technical design report", in *CERN Yellow Reports Monographs*, vol. 10, 2020. `doi:10.23731/CYRM-2020-0010`

[30] M. D'Andrea *et al.*, "Crystal collimation of 20 MJ heavy-ion beams at the HL-LHC", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 2644–2647. `doi:10.18429/JACoW-IPAC2021-WEPAB023`

[31] J. Jaeckel, M. Lamont, and C. Vallée, "The quest for new physics with the Physics Beyond Colliders programme", *Nat. Phys.*, vol. 16, p 393, 2020.

[32] C. Barschel, "Report from the LHC Fixed Target working group of the CERN Physics Beyond Colliders Forum", CERN, Geneva, Switzerland, 2019, Rep. CERN-PBC-REPORT-2019-001.

[33] 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", *Eur. Phys. J. C*, vo. 80, p. 1, 2020. `doi:10.1140/epjc/s10052-020-08466-x`