PROCEEDINGS OF SCIENCE

Update on TWOCRYST: the feasibility of double-crystal fixed-target experiments at the LHC

P. Hermes,[a] C. Antuono,[a] G. Arduini,[a] L. Bandiera,[d] M. Benettoni,[d] R. Cai,[a] M. Calviani,[a] S. Cesare,[e] S. Coelli,[e] M. D'Andrea,[a] D. De Salvador,[g] Q. Demassieux,[a] K. Dewhurst,[a] M. Di Castro,[a] L. Esposito,[a] M. Ferro-Luzzi,[a] A. Fomin,[b] J. Fu,[i] P. Gandini,[e] M. Giorgi,[h] V. Guidi,[d] H. Havlikova,[a] S. J. Jaimes Elles,[c] S. Jakobsen,[a] G. Lamanna,[h] S. Libralon,[c] C. Maccani,[a] L. Malagutti,[d] D. Marangotto,[e] F. Martínez Vidal,[c] J. Mazorra de Cos,[j] A. Mazzolari,[d] A. Merli,[e,m] H. Miao,[i] D. Mirarchi,[a] R. Negrello,[d] N. Neri,[e] M. Patecki,[k] A. Perillo Marcone,[a] S. Redaelli,[a] P. Robbe,[b] M. Romagnoni,[d] B. Salvant,[a] I. Sanderswood,[j] R. Seidenbinder,[k] G. Simi,[g] E. Soria,[a] M. Sozzi,[h] E. Spadaro Norella,[h,l] A. Stocchi,[b] A. Triossi,[g] G. Valentino,[j] M. Zanetti[g] and C. Zannini[g]

[a] *CERN, Geneva, Switzerland*
[b] *IJCLab, Orsay, France*
[c] *Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia, Spain*
[d] *INFN Ferrara & University of Ferrara, Italy*
[e] *INFN Milano & University of Milano, Italy*
[g] *INFN Padova & University of Padova, Italy*
[h] *INFN Pisa & University of Pisa, Italy*
[i] *University of Chinese Academy of Sciences, Beijing, China*
[j] *University of Malta, Malta*
[k] *Warsaw University of Technology, Department of Physics, Warsaw, Poland*
[l] *now INFN Genova & University of Genova, Italy*
[m] *now EPFL, Lausanne, Switzerland*

E-mail: pascal.hermes@cern.ch

PoS(ICHEP2024)844

A setup of two bent crystals and a fixed target in the CERN Large Hadron Collider (LHC) could enable the study of the magnetic (MDM) and electric (EDM) dipole moments of short-lived charm baryons with unprecedented accuracy. At the core of the experiment is a bent crystal in which particles of interest, such as the Λ_c^+ and Ξ_c^+ particles, can be confined between the crystalline planes, inducing a deflection that enforces spin precession measurable by detectors. The setup requires a fixed target inside the LHC vacuum to create the charmed baryons. A first crystal serves to split beam halo particles from the circulating beam, allowing the target to be placed at a safe distance. TWOCRYST is a proof-of-principle experiment to be installed in the LHC to demonstrate the feasibility of such an experimental setup. Scheduled for operation in 2025, TWOCRYST aims to deliver crucial data needed to prepare the experiment and gather experience in operating the double-crystal setup. The TWOCRYST test stand features a simplified setup compared to the final experiment but will include all essential components within the LHC beam vacuum: two crystals and one target with the final specifications. Two 2D detectors, one silicon pixel detector and one fiber tracker, installed in movable Roman pots, will allow observation of the crystal channelling and provide important information on the crystal performance at different beam energies up to about 5 TeV. We review the project, all key devices, and the program of machine tests foreseen for TWOCRYST.

ICHEP 2024
17-24 July 2024
Prague, Czech Republic

1. Introduction

The study of the magnetic (MDM) and electric (EDM) dipole moments of particles, especially short-lived charm baryons like the Λ_c^+, could deliver crucial input for the exploration of physics beyond the Standard Model. Due to their short lifetimes, such as 2×10^{-13} s for the Λ_c^+, inducing measurable spin precession using conventional magnets is not feasible. These limitations could be overcome by integrating two bent crystals [1] into the CERN Large Hadron Collider (LHC) [2]. Bent crystals can deflect charged particles by planar channelling between the atomic planes [3]. In the double-crystal arrangement, the first crystal (TCCS: Target Collimator Crystal for Splitting) splits halo particles from the circulating beam onto an in-vacuum target to produce, amongst other products, the Λ_c^+ particles of interest. Channelling and deflecting these particles by means of a second bent crystal (TCCP: Target Collimator Crystal for Precession) induce spin precession, enabling its measurement with a dedicated detector downstream. The concept is compatible with the high-intensity operation at the LHC and planned to be operated parasitically to the standard operation with proton-proton luminosity production.

1.1 TWOCRYST as a proof-of-principle

TWOCRYST is a proof-of-principle of the double-crystal setup. It is foreseen to be installed in Insertion Region 3 (IR3) of the LHC during the year-end technical stop (YETS) 2024/2025 and intended to be operated in machine development (MD) studies during 2025. It is a critical step towards realising a double-crystal based physics experiment by addressing several important open questions:

TCCP channelling efficiency In the EDM/MDM experiment, the greatest yield of Λ_c^+ particles is expected in the energy range between 1 TeV and 5 TeV [4]. These particles must be channelled by the TCCP crystal to induce spin precession. The crystal is specified for a required length of 7 cm and a deflection of 7000 µrad [5]. Such crystals have been tested in the CERN SPS extraction lines at energies up to 180 GeV, but experimental data in the multi-TeV energy range of interest are still unavailable. Performance estimates for a final implementation presently rely only on simulations that are particularly challenging for the new long crystals. One key objective for TWOCRYST is the characterization of the TCCP crystal channelling efficiency at 1000 GeV, 3000 GeV, and 5000 GeV - energies only accessible in the LHC.

Operational feasibility The operation of the double-crystal setup requires a simultaneous high-precision linear and angular alignment of the two crystals, to enable an efficient splitting of beam halo particles and subsequent channelling of the particles of interest, ensuring that the setup remains transparent to the high-intensity operation. A tangible demonstration of the operational feasibility of this setup can only be achieved by using operational LHC beams in dedicated machine tests, which is the main aim of the TWOCRYST project.

Performance estimates The physics reach of the double-crystal experiment strongly depends on the achievable number of protons on target (PoT). Sophisticated simulations combining beam dynamics and particle-matter interaction are used to derive PoT estimates [4, 6]. The data recorded in the TWOCRYST MDs will provide a solid benchmark of simulation-based PoT estimates, allowing to derive robust predictions and efficiently optimise the PoT in simulations.

1.2 Conceptual Design

Reaching the TWOCRYST goals requires the installation of the TCCS, TCCP, and at least one 2D detector in the LHC for operation in 2025. The concept of the TWOCRYST setup is illustrated in Figure 1, which depicts the double-channelling configuration to estimate the TCCP channelling efficiency. The installation in LHC Beam 2 (the beam circulating in counter-clockwise direction) in LHC IR3 is ideally suited to meet the TWOCRYST goals and is compatible with the constraints from machine integration side. After thorough study and optimisation in beam dynamics simulations [6], the selected positions of the TCCS and TCCP are at 6773.9 m and 6653.3 m from LHC IP1 (ATLAS), respectively. This setup benefits from the low radiation levels and high space availability in this region. The setup is designed to allow for measurements of each individual crystal directly on the circulating proton beams. The EDM/MDM physics experiment could be installed at identical positions.

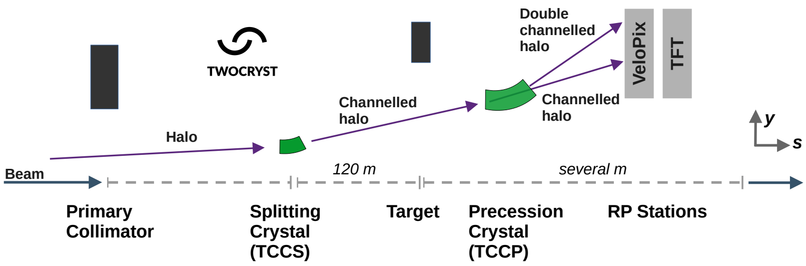

Figure 1: TWOCRYST setup in double channelling mode: Halo particles are deflected to a large amplitude by the splitting crystal (TCCS). The precession crystal (TCCP) is positioned to channel these particles again. The two 2D detectors (VeloPix and TFT) downstream observe the distribution of single- and double-channelled particles, enabling analysis of the TCCP channelling efficiency.

2. Hardware and Instrumentation

2.1 Crystals and Goniometers

Both crystals are made of silicon. The TCCS is specified to be 4 mm long with a design bending angle of 50 µrad. Crystals with identical specifications have been used in the LHC with proton and heavy-ion beams at top energy [7, 8]. The specified length of the TCCP crystal was set to 70 mm with a deflection of 7.0 mrad. Both crystals were manufactured and delivered to CERN for TWOCRYST in 2023 by the institute INFN, Ferrara section, Italy. They were subject to a series of validation tests. X-Ray crystallography was used to identify the bending and the stability of the crystal properties under repeated thermal cycling from room temperature to 250 °C. A hadron beam test in the CERN North Area using 180 GeV pions was successfuly completed. The efficiency in channelling the 180 GeV pions was measured as 62% for the TCCS and 16% for the TCCP [9]. Both are considered as appropriate for installation in the LHC.

Channelling of charged particles in bent crystals can only be established if the angle of incidence w.r.t. the crystal lattice is within a given range, defined by a critical angle θ_c, which for silicon

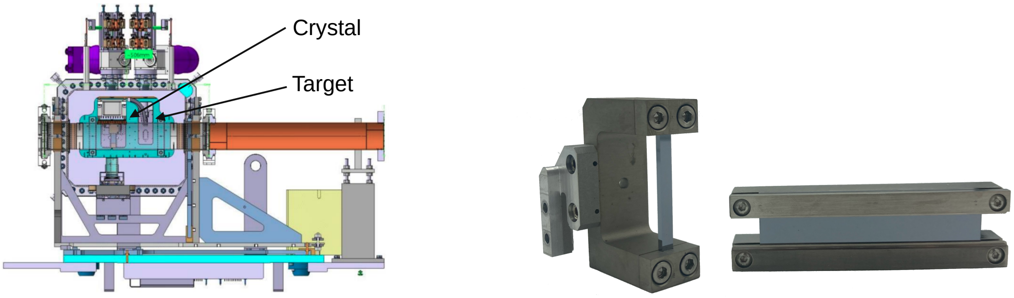

Figure 2: Left: Side view of the TCCP assembly with movable crystal and target. The beam direction is from right to left. Right: TWOCRYST TCCS and TCCP crystals in their mechanical bender.

crystals is approximately 10 µrad at LHC injection energy of 450 GeV and 2 µrad at top energy of 7 TeV. Therefore, both crystals must be mounted in high-precision goniometers, allowing for angular alignment in the sub-µrad range, while also providing the capability for linear motion of the crystal. Given the identical specifications, the TCCS crystal is planned to be installed in a high-precision goniometer that was previously used in the LHC for crystal collimation (TCPC) [8].

For the heavier TCCP crystal, the same angular precision is needed and an additional movable target must be placed immediately upstream at a distance smaller than 1 mm. These unprecedented constraints have required the design of a new combined target and TCCP crystal goniometer assembly, depicted in Figure 2. It provides the functionality of a fully independent motion of target and crystal, both separated longitudinally by only 200 µm. The TCCP crystal can be aligned with an angular precision of 0.1 µrad, providing the required flexibility for operation in double-channelling mode and when aligned directly on the circulating beam. The TWOCRYST MD studies are going to be carried out with low intensity beams. The crystal and target will be in "parking" positions (e.g. at the furthest possible distance to the circulating beam) during the 2025 high intensity operation with potentially more than 5×10^{14} protons at 6.8 TeV. The TCCP device design had to meet the strict LHC impedance requirements, in order to avoid device heating and beam instabilities due to wakefields created by beam particles. The TCCS assembly and the recovered Roman Pot stations were already installed in the LHC and optimized for impedance prior to their initial installation.

2.2 Detectors and Roman Pots

The TWOCRYST measurements require at least one movable 2D detector. Roman Pots (RPs) will be used to house and position two detectors in a secondary vacuum close to the circulating beams. The RPs were previously used at the LHC and have been provided to TWOCRYST by the ATLAS-ALFA collaboration [10]. Both will be installed within less than 2 m of the TCCP crystal such that the particles deflected by 7 mrad can be measured before reaching the beam pipe.

ATLAS-ALFA has further supported TWOCRYST by lending a decommissioned 2D fibre tracker (now TWOCRYST Fibre Tracker, TFT) and the required auxiliary equipment to operate in one RP. The TFT is composed of a mesh of scintillating fibres that allow a 2D reconstruction of the point of impact of a charged particle. The other RP will be equipped with a 2D silicon pixel detector (SPD) providing three chips with 256×256 pixels each, with an active area of 1.6×1.6 cm^2 each. The SPD detector package will consist in three layers of silicon sensors, inserted in a support structure that will provide mechanical support and thermal conductivity for heat removal of the roughly 40 W produced by the SPD in operation, which will be provided by a Peltier element.

3. TWOCRYST Machine Studies

The TWOCRYST study program will be completed in dedicated LHC machine development (MD) periods. We distinguish three broad categories of TWOCRYST MDs:

Preparatory MDs Preparatory beam tests are required to pave the way for TWOCRYST's main studies. In May 2024, the first TWOCRYST MD was conducted, during which an optimized LHC energy ramp was successfully tested. In the latter, the energy ramp is interrupted at predefined intermediate energies where the TCCP crystal shall be tested. Within a single fill, particle momenta of 1 TeV, 3 TeV, and 5 TeV were achieved and maintained. The channelling efficiency of existing collimation crystals was studied, as a test for future studies with the TCCP. This development is crucial for efficient measurements, as otherwise lengthy pre-cycles of the superconducting magnets after the measurement at each energy would be needed. Once the TWOCRYST hardware is installed, the 2D detectors will be commissioned with the beam in a dedicated MD, and the crystals will be aligned to the circulating beam for the first time. This alignment at the injection energy of 450 GeV will calibrate the crystal angle with the control system, facilitating future alignments.

TCCP Crystal Characterization The angular alignment of the TCCP using the local BLM while intercepting the main circulating beam will help to identify the central angle in the channelling condition and characterize the crystal channelling at the energies of interest (between 1 TeV and 5 TeV). By measuring the width of the volume reflection plateau, the crystal deflection can be estimated. The 2D detectors will then allow to deduce the multi-turn channelling efficiency. Based on the previously identified optimal TCCP angles, the double-channelling (TCCS - TCCP) configuration can be set up to observe the single- and double-channeled halo on the 2D detectors, thereby studying the TCCP single-pass channelling efficiency.

Performance Estimates With the TWOCRYST hardware installed at locations suited for a future experiment, the number of PoT can be determined in TWOCRYST by positioning the TCCS crystal into the operational position (in the secondary beam halo) and monitoring the protons striking the 2D detectors while the target and TCCP are retracted. In an optional MD, simulation based techniques for PoT improvement could be cross-validated, in particular the optimization of PoT by inducing a change in betatron phase. All the measurements above also serve as a unique collection of data that will be used as inputs for a detailed benchmark of the different simulations codes used to model the multi-turn dynamics of the collimation halos and their interactions with the crystals.

4. Conclusions

The TWOCRYST project is a crucial demonstrator to validate the feasibility of future double-crystal fixed-target experiments at the LHC. Scheduled for operation in 2025, TWOCRYST will test the efficiency of the required long bent crystal at various energies, demonstrate the operational feasibility, and provide performance estimates by benchmarking simulations against experimental

PoS(ICHEP2024)844

data. The experiment will employ high-precision goniometers and two 2D detectors housed in Roman Pots, installed in the IR3 region of the LHC. Successful completion of TWOCRYST will validate the double-crystal approach, paving the way for a possible future experiment, which could contribute to our understanding of fundamental particle properties and advance the field of particle physics by enabling precise studies of charm baryons. A new collaboration is being formed to prepare a future experiment and it will be scrutinized by the LHC physics committees. The results expected by TWOCRYST provide a critical input in this decision-making process.

Acknowledgments

TWOCRYST is supported by the Physics Beyond Colliders Study Group. Financial support for crystal development was provided by the SELDOM project, funded by the European Research Council under Grant Agreement 771642. The TWOCRYST collaboration expresses its gratitude to the ATLAS-ALFA collaboration and the HL-LHC project for their significant hardware contributions.

References

[1] L. Burmistrov et al., *Measurement of Short Living Baryon Magnetic Moment using Bent Crystals at SPS and LHC.*,CERN-SPSC-2016-030 ; SPSC-EOI-012.

[2] O. S. Brüning et al., *LHC Design Report*, CERN-2004-003-V1.

[3] V. M. Biryukov, Yu. A. Chesnokov, and V. I. Kotov, *Crystal channeling and its application at high-energy accelerators*, Springer (1997).

[4] D. Mirarchi et al., *Layouts for fixed-target experiments and dipole moment measurements of short-lived baryons using bent crystals at the LHC*, Eur. Phys. J. C 80, 929 (2020).

[5] P. Hermes, S. Redaelli, et al., *[TCCS/TCCP] Functional and Operational Conditions for the Double-Crystal Setup in the LHC IR3*, EDMS 2883108, LHC-TCxC-ES-0001 (2023).

[6] K. Dewhurst et al., *Performance of a double-crystal setup for LHC fixed-target experiments*, JACoW IPAC 2023, MOPL048 (2023).

[7] M. D'Andrea et al., *Crystal collimation performance at the LHC with a 6.8 TeV proton beam*, JACoW IPAC 2023, MOPL023 (2023).

[8] S. Redaelli et al., *Crystal collimation of heavy-ion beams*, JACoW IPAC 2024, FRXN3 (2024).

[9] S. Cesare et al., *Performance of short and long bent crystals for the TWOCRYST experiment at the Large Hadron Collider*, Unpublished (2024).

[10] S. Abdel Khalek et al., *The ALFA Roman Pot Detectors of ATLAS*, JINST 11 (2016), P11013 (2016).