ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC21

FEASIBILITY STUDY OF THE ALICE FIXED-TARGET EXPERIMENT WITH HL-LHC LEAD ION BEAMS BASED ON CRYSTAL-ASSISTED BEAM HALO SPLITTING

M. Patecki*, M. Monikowska, Warsaw University of Technology, Faculty of Physics, Warsaw, Poland

Abstract

The Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) is the world's largest and most powerful particle accelerator colliding beams of protons and lead ions at energies up to 7 ZTeV. ALICE is one of the detector experiments optimised for heavy-ion collisions. A fixed-target experiment in ALICE is considered to collide a portion of the beam halo, split using a bent crystal, with an internal target placed a few meters upstream of the detector. For proton beams, we have already demonstrated that such a setup provides satisfactory performance in terms of particle flux on target and that it can be safely operated in parallel to regular beam-beam collisions. On the other hand, in the case of lead ion beams a beam halo is populated with nuclei of many species that may differ in terms of charge, mass and magnetic rigidity, which makes such a scenario more challenging to operate. In this paper, we summarize our first considerations of the feasibility of a fixed-target layout at ALICE to be operated with lead ion beams in the LHC.

INTRODUCTION

The study of fundamental particles and their interactions has significantly advanced due to the development of experimental facilities, with particle accelerators playing a crucial role. The Large Hadron Collider (LHC) [1] at the European Organization for Nuclear Research (CERN) stands at the forefront of these facilities, being the world's largest and most powerful particle accelerator. It enables collisions of protons and lead ions, achieving center-of-mass energies up to 14 TeV for protons and 5.5 TeV per nucleon for lead ions. The operation of lead ions, although limited to approximately one month per year, provides a unique opportunity to study the physics of collisions between larger atomic systems and to examine the properties of nuclear matter under extreme conditions. The ALICE (A Large Ion Collider Experiment) [2] at CERN, optimized to detect products of heavy-ion collisions, presents an opportunity to extend its research potential by performing fixed-target collisions in parallel to the main collider operations. Fixed-target collisions could be facilitated by utilizing beam halo splitting through a bent crystal [3, 4], which directs the deflected beam to collide with an in-beam target located inside of the ALICE detector [5]. This solution, commonly referred to as ALICE fixed-target (ALICE-FT), designed for LHC proton operations, is detailed in [6]. This innovative technique harnesses particles from the beam halo, which are otherwise not involved in primary collisions, thus maximizing the use of the LHC's beam without interrupting the main accelerator operations. The concept profits especially from the experience associated with the development of crystal collimation techniques in the LHC [7–11], but also collected at other accelerators laboratories like e.g. BNL [12, 13] and FNAL [14, 15].

The fixed-target mode offers several distinct advantages over collider mode operations. High-density targets enable the achievement of high annual luminosities, comparable to those produced by the LHC in collider mode and by the TeVatron [16]. In terms of collision energy, the ALICE fixed-target (ALICE-FT) configuration achieves the highest energy in fixed-target mode, providing center-of-mass energies of 72 GeV for lead ion beams [16], which sit between the energies available at the Relativistic Heavy Ion Collider (RHIC) and the Super Proton Synchrotron (SPS). The configuration also allows for exploring the far backward regions of rapidity, thanks to the relative boost between the colliding-nucleon center-of-mass system and the laboratory system, enabling the detection of phenomena at far ranges of the backward phase space that are not accessible in head-on collisions [16]. Additionally, the use of varied target materials broadens the range of physical phenomena that can be studied, particularly offering unique opportunities for neutron research [16].

The scientific potential [5, 16] of the ALICE-FT programme is extensive, encompassing rigorous studies of strong interaction processes, and the distributions of quarks and gluons at high momentum fractions. It also investigates the sea quark and heavy-quark content within nucleons and nuclei, with implications for cosmic ray physics. Furthermore, the intense conditions generated in ultra-relativistic heavy-ion collisions provide a new spectrum of observable phenomena related to quarkonium and heavy quarks, within the energy range that spans from the Super Proton Synchrotron to the Relativistic Heavy Ion Collider, where the QCD phase transition is hypothesized to occur.

The primary objective of this paper is to determine whether the ALICE-FT setup, originally developed for proton beams, can be adapted for use with lead ion beams at the LHC. There are a number of significant differences between these two cases, mostly related to the setup of the collimation system and the characteristics of the beam halo. The simulation setup is also different and generally more challenging than that for proton beams. Preliminary results of the feasibility study of the ALICE fixed-target layout operated with lead ion beams in the LHC are discussed in the following parts of this paper.

* marcin.patecki@pw.edu.pl

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC21

ALICE-FT CONFIGURATION IN THE LHC

The ALICE-FT setup was considered to be operated with High-Luminosity LHC (HL-LHC) beams [17]. Table 1 lists some expected parameters for the lead beam operation. For proton beams, the LHC employs a sophisticated multi-stage collimation system [18] to protect the machine against high-energy losses. This system, organized transversely over two dedicated insertions—IR3 for momentum cleaning and IR7 for betatron cleaning—features a three-stage cleaning process involving primary collimators (TCPs), secondary collimators (TCSGs), and absorbers (TCLAs). Additional dedicated collimators are strategically positioned around the ring to protect sensitive equipment (e.g., TCTP for the inner triplets), absorb physics debris (TCL), and ensure beam injection/dump protection (TDI/TCDQ-TCSP). As outlined in [19], this collimation system will undergo upgrades to meet HL-LHC standards, though its fundamental operating principles will remain unchanged. It is designed to withstand beam losses up to 1 MJ without causing damage or quenching the superconducting magnets.

Table 1: Some parameters of the future HL-LHC lead beams important for the ALICE-FT experiment [17].

Beam energy in collision	E	7 TeV
Bunch population	N_b	1.8×10^8
Number of bunches	n_b	1240
Beam current	I	33 mA
Stored beam energy		20.5 MJ
Transverse normalised emittance	ε_n	1.65 µm
β^* at IP2		0.5 m

Collimating lead beams poses additional challenges [20] due to the fragmentation of heavy ions within the collimators, which often results in significant leakage of particles with charge-to-mass ratios different from the main beam. Consequently, crystal collimation [20] is employed as the baseline method for lead beams, incorporating bent crystals to act as primary collimators (TCPCs). This setup benefits from the substantial angular kick experienced by halo particles during the channeling process, directing them towards a downstream absorber. The impact depth is sufficient to minimize out-scattering, thereby enhancing the overall efficiency of the collimation system. Settings of the crystal collimation system used with lead ion beams is given in Table 2.

The ALICE-FT setup [6] assumes to place an additional crystal roughly 70m upstream from the ALICE detector to interact with the LHC beam 1. The crystal is set in the shadow of the IR7 primary collimators, with the same retraction as TCSGs at IR7, to prevent accidental hierarchy breakage and to profit from the secondary beam halo. The installation is considered to be vertically oriented to avoid issues related to horizontal beam dump operations. The system uses a several-mm long silicon crystal with a 110 bending plane and an 80 m bending radius, providing a safe deflection of

Table 2: HL-LHC crystal collimation settings [20] for lead beams expressed in units of RMS beam size (σ), assuming a gaussian beam distribution.

Coll. family	**IR**	**Settings (σ)**
TCPC/TCP/TSCG/TCLA	7	5.0/6.0/6.5/8.0
TCP/TSCG/TCLA	3	15.0/18.0/20.0
TCT	1/2/5/8	10.5/13.0/10.5/15.0
TCL	1/5	44.0
TCSP/TCDQ	6	10.3/7.4

up to 200 µrad. Nearby, a target assembly approximately 5 mm in length made from materials such as carbon or tungsten will be installed inside the ALICE detector, approximately 5 m upstream from IP2. Further downstream, about 150 m from IP2, four absorbers designed similarly to existing LHC collimators are planned. These include three 1 m long carbon-fibre-carbon composite jaws and one tungsten jaw, each featuring a large opening to effectively intercept the channeled beam without impacting the regular collimation system or machine impedance. This setup aims to optimize performance and potentially reduce the number of required absorbers, with future energy deposition studies expected to guide further adjustments. The schematics of the ALICE-FT is shown in Fig. 1.

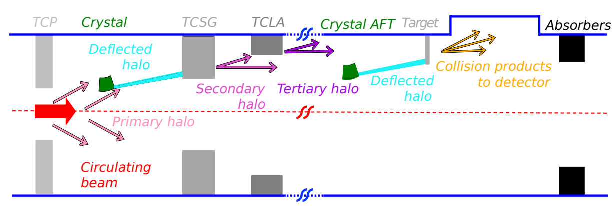

Figure 1: Working principle of the crystal-based fixed-target experiment (right side of the graphics) being embedded into the crystal collimation system (left side of the graphics). Graphics based on [21], mostly by D. Mirarchi.

FEASIBILITY EVALUATION

Tracking simulations were done to evaluate the performance of the ALICE-FT setup operated with lead ion beams. The SixTrack-FLUKA Coupling [22, 23], the leading tool for heavy-ion collimation simulations at the LHC, was used for this purpose. SixTrack [24, 25] is utilized for multi-turn magnetic tracking, and FLUKA [26, 27] manages the particle-matter interactions within the collimators and bent crystals. The collimators hierarchy was set as in the Table 2 and the primary beam halo was initialized at the entry of the TCTPCV with an impact parameter of 10 um and with the position-angle distributions defined by optical parameters at that location. At this stage, the elements of the ALICE-FT system were not added to the simulation setup but the ALICE-FT crystal is treated as a black absorber, namely particles that hit the crystal are immediately lost and their coordinates are recorded. The distribution of such registered particles is given in Fig. 2. 1.31M of particles were injected

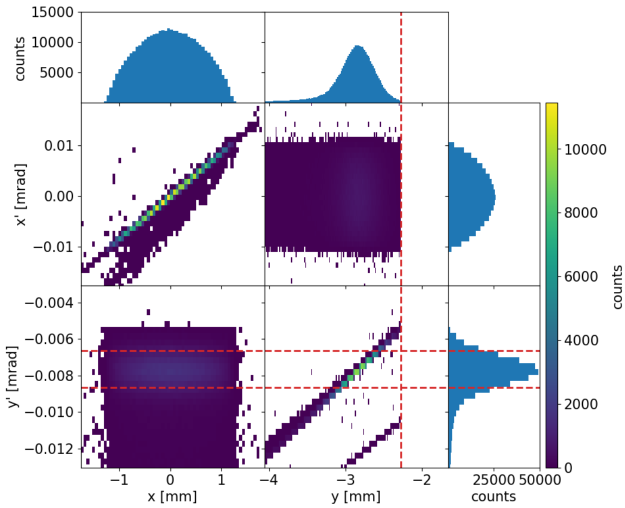

Figure 2: Distribution of beam particles at the location of a potential crystal installation with respect to the beam centre. x, y denote horizontal and vertical position, x', y' denote horizontal and vertical angle. Horizontal dashed lines indicate the angular acceptance of the crystal. The vertical dashed line indicates the minimum distance of the crystal edge from the beam centre such that collimation system hierarchy is not violated.

into the simulation, 0.37M of particles hit the ALICE-FT crystal represented by a black absorber and 0.24M of particles fit its angular acceptance. Contribution from particles other than Pb-208 is negligible. The upper limit of vertical halo particles that enter the crystal collimation system and consequently can be channeled by the ALICE-FT crystal is estimated to roughly 18 %, which is a very encouraging number. For the ALICE-FT proposal based on proton beams, the corresponding number is significantly smaller, about 0.4 %. A potential explanation for such a difference is that in case of proton beams a conventional (not based on crystals as primary collimators) collimation system is used which relies more on multi-turn effects and gradually growing betatron amplitude causing a larger dilution of the secondary beam halo. In case of lead beams, all particles that can be intercepted by the ALICE-FT crystal, are intercepted at the same turn as the interaction with the IR7 crystal, making the beam splitting scheme more performant.

SUMMARY

The feasibility study based on particle tracking simulations indicates that the ALICE-FT not only can be adapted for the operation with lead ion beams, but also the ratio of particles that can be deflected towards the target, with respect to the total beam halo entering the crystal collimation system, is significantly higher than in case of protons beams, with an upper limit of about 18 %. It sets a solid motivation for further feasibility studies covering the full ALICE-FT setup included into the simulation setup to investigate the expected flux of particles on target and cleaning efficiency of the collimation system in such a configuration. These results are expected to be obtained soon.

ACKNOWLEDGEMENTS

We thank for the support provided by members of the CERN BE-ABP-NDC Section, mostly: S. Redaelli, R. Bruce, R. Cai, B. Lindstrom. This research was funded by the National Science Centre, Poland, project number: 2021/43/D/ST2/02761.

REFERENCES

[1] O. S. Brüning *et al.*, *LHC Design Report*. CERN, 2004. doi:10.5170/CERN-2004-003-V-1

[2] K. Aamodt *et al.*, "The ALICE experiment at the CERN LHC. A Large Ion Collider Experiment", *J. Instrum.*, vol. 3, S08002. 259 p, 2008, Also published by CERN Geneva in 2010. doi:10.1088/1748-0221/3/08/S08002

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

[4] A. M. Taratin, "Particle channeling in a bent crystal", *Physics of Particles and Nuclei*, vol. 29, no. 5, pp. 437–462, 1998. doi:10.1134/1.953085

[5] F. Galluccio *et al.*, "Physics opportunities for a fixed-target programme in the ALICE experiment", 2019. https://cds.cern.ch/record/2671944

[6] M. Patecki *et al.*, "HL-LHC layout for fixed-target experiments in ALICE based on crystal-assisted beam halo splitting", *Eur. Phys. J. C*, doi:10.1140/epjc/s10052-023-12140-3

[7] W. Scandale *et al.*, "Observation of channeling for 6500 GeV/c protons in the crystal assisted collimation setup for LHC", *Physics Letters B*, pp. 129–133, 2016. doi:10.1016/j.physletb.2016.05

[8] Mirarchi, D., Hall, G., Redaelli, S., and Scandale, W., "Design and implementation of a crystal collimation test stand at the Large Hadron Collider", *Eur. Phys. J. C*, vol. 77, no. 6, p. 424, 2017. doi:10.1140/epjc/s10052-017-4985-4

[9] Redaelli, S. *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. doi:10.1140/epjc/s10052-021-08927-x

[10] 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.

[11] W. Scandale *et al.*, "Feasibility of crystal-assisted collimation in the cern accelerator complex", *Int. J. Mod. Phys. A*, vol. 37, no. 13, p. 2 230 004, 2022.

[12] R. Fliller *et al.*, "Rhic crystal collimation", *Nucl. Instrum. Meth. Phys. Res, Secti. B*, vol. 234, no. 1, pp. 47–56, 2005, Relativistic Channeling and Related Coherent Phenomena in Strong Fields. doi:10.1016/j.nimb.2005.03.004

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC21

[13] R. P. Fliller *et al.*, "Results of bent crystal channeling and collimation at the relativistic heavy ion collider", *Phys. Rev. ST Accel. Beams*, vol. 9, p. 013 501, 1 2006. doi:10.1103/PhysRevSTAB.9.013501

[14] N. MOKHOV *et al.*, "Crystal collimation studies at the tevatron (t-980)", *Int. J. Mod. Phys. A*, vol. 25, no. supp01, pp. 98–105, 2010. doi:10.1142/S0217751X10049943

[15] V. Zvoda *et al.*, "Advanced bent crystal collimation studies at the tevatron (t-980)", *Int. J. Mod. Phys. A*, vol. 25, 2012. doi:10.1142/9789814307017_0015

[16] C. Hadjidakis *et al.*, "A fixed-target programme at the LHC: Physics case and projected performances for heavy-ion, hadron, spin and astroparticle studies", *Phys. Rep.*, vol. 911, pp. 1–83, 2021. doi:10.1016/j.physrep.2021.01.002

[17] G. Apollinari *et al.*, *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1*. CERN, 2017. doi:10.23731/CYRM-2017-004

[18] R. W. Assmann *et al.*, "The final collimation system for the LHC", 4 p, 2006, revised version submitted on 2006-09-15 14:36:59. http://cds.cern.ch/record/972336

[19] S. Redaelli, R. Bruce, A. Lechner, and A. Mereghetti, "Chapter 5: Collimation system", pp. 87–114, 2020. doi:10.23731/CYRM-2020-0010.87

[20] R. Cai, "Studies of crystal collimation for heavy ion operation at the LHC", Presented 02 May 2024, École Polytechnique Fédérale de Lausanne, 2024. https://cds.cern.ch/record/2896673

[21] 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, 2020. doi:10.1140/epjc/s10052-020-08466-x

[22] S. Redaelli, "ICFA Mini-Workshop on Tracking for Collimation in Particle Accelerators", 2018. doi:10.23732/CYRCP-2018-002

[23] E. Skordis *et al.*, "FLUKA coupling to Sixtrack", ICFA Mini-Workshop on Tracking for Collimation in Particle Accelerators. doi:10.23732/CYRCP-2018-002.17

[24] G. Ripken and F. Schmidt, "A symplectic six-dimensional thin-lens formalism for tracking", CERN, Tech. Rep. CERN-SL-95-12. CERN-SL-95-12-AP. DESY-95-063, 1995. https://cds.cern.ch/record/281283

[25] *ICFA Mini-Workshop on Tracking for Collimation in Particle Accelerators: CERN, Geneva, Switzerland 30 Oct 2015. ICFA Mini-Workshop on Tracking for Collimation in Particle Accelerators*, 2018. doi:10.23732/CYRCP-2018-002

[26] A. Ferrari, P. R. Sala, A. Fassò, and J. Ranft, *FLUKA: A multi-particle transport code (program version 2005)*. CERN, 2005. http://cds.cern.ch/record/898301

[27] G. Battistoni *et al.*, "The FLUKA code: Description and benchmarking", *AIP Conf. Proc.*, vol. 896, no. SLAC-REPRINT-2007-184, 31–49. 19 p, 2007. http://cds.cern.ch/record/1088761