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HL-LHC layout for fixed-target experiments in ALICE based on crystal-assisted beam halo splitting

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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 Z TeV, where Z is the atomic number. ALICE is one of the experiments optimised for heavy-ion collisions. A fixed-target experiment in ALICE is being considered to collide a portion of the beam halo, split using a bent crystal inserted in the transverse hierarchy of the LHC collimation system, with an internal target placed a few metres upstream of the existing detector. This study is carried out as a part of the Physics Beyond Collider effort at CERN. Fixed-target collisions offer many physics opportunities related to hadronic matter and the quark-gluon plasma to extend the research potential of the CERN accelerator complex. Production of physics events depends on the particle flux on the target. The machine layout for the fixed-target experiment is developed to provide a flux of particles on the target high enough to exploit the full capabilities of the ALICE detector acquisition system. This paper summarises the fixed-target layout consisting of the crystal assembly, the target and the downstream absorbers. We discuss the conceptual integration of these elements within the LHC ring, the impact on ring losses, and expected performance in terms of particle flux on target.

1 Introduction

Advancements in the knowledge of fundamental constituents of matter and their interactions are usually driven by the development of experimental techniques and facilities, with a significant role of particle accelerators. The Large Hadron Collider (LHC) [1] at the European Organization for Nuclear Research (CERN) is the world's largest and most powerful particle accelerator colliding beams of protons (p) and lead ions (Pb), allowing for unprecedented high centre-of-mass energies of up to 14 TeV and 5.5 TeV per nucleon, respectively. An ALICE fixed-target (ALICE-FT) program [2] is being considered to extend the research potential of the LHC and the ALICE experiment [3]. The setup of in-beam targets at the LHC is particularly challenging because of the high intensity of LHC beams [4].

Fixed-target collisions in the LHC are designed to be operated simultaneously with regular head-on collisions without jeopardising the LHC efficiency during its main physics program. Several unique advantages are offered with the fixed-target mode compared to the collider mode. With a high-density target, high yearly luminosities can be easily achieved, comparable to luminosities delivered by the LHC (in the collider mode) and Tevatron [5]. In terms of collision energy, the ALICE-FT layout would provide the most energetic beam ever in the fixed-target mode, with the centre of mass energy per nucleon–nucleon of 115 GeV for proton beams and 72 GeV for lead ion beams [5], between the nominal Relativistic Heavy Ion Collider (RHIC) and Super Proton Synchrotron (SPS) energies. Thanks to the boost between the colliding-nucleon centre-of-mass system and the laboratory system, access to far backward regions of rapidity is possible with the ALICE detector, allowing the measurement of any probe even at far ranges of the backward phase space, which is uncharted with head-on collisions [5]. Moreover,

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the possibility of using various species of the target material extends the variety of physics cases, in particular allowing for unique neutron studies [5]. The physics potential [2,5] of such a fixed-target program covers an intensive study of strong interaction processes, quark and gluon distributions at high momentum fraction (x), sea quark and heavy-quark content in the nucleon and nucleus, and the implication for cosmic ray physics. The hot medium created in ultra-relativistic heavy-ion collisions offers novel quarkonium and heavy-quark observables in the energy range between the SPS and RHIC, where the quantum chromodynamics (QCD) phase transition is postulated.

A significant innovation of our proposal is to bring particles of the high-energy collider to collisions with a fixed target by splitting part of the beam halo using a bent crystal. Particles entering the crystal with a small impact angle ($\leq$ 2.4 µrad for silicon crystals and proton energy of 7 TeV [6]) undergo the channelling process resulting in a trajectory deflection equivalent to the geometric bending angle of the crystal body [7,8]. Such a setup enables an in-beam target at a safe distance from the circulating beam. The halo-splitting technique can profit from the circulating beam halo particles that are not contributing to the luminosity production and are typically disposed of by the collimation system. This type of advanced beam manipulation with bent crystals builds on the experience accumulated in different accelerators, for example at the Brookhaven National Laboratory (BNL) [9,10], Fermi National Accelerator Laboratory (FNAL) [11,12] and CERN [13,14]), in particular the successful results achieved in the multi-TeV regime for beam collimation at the LHC [15–17].

The problem that we address is the design of a machine layout that provides a number of protons on the target high enough to exploit the full capabilities of the ALICE detector acquisition system without affecting the LHC availability for regular beam–beam collisions. Our proposal for the ALICE-FT layout [18] follows general guidelines on technical feasibility and impact on the LHC accelerator of potential fixed-target experiments provided by the LHC Fixed Target Working Group of the CERN Physics Beyond Colliders forum [4,19]. We also profit from the preliminary designs reported in [20,21] and from the design study of an analogous fixed-target experiment at the LHC proposed to measure electric and magnetic dipole moments of short-lived baryons [22]. Our studies are based on numerical simulations, profiting from the experience collected within the CERN Collimation Team. Strong agreement between simulations and measurements was previously demonstrated both for regular operations with proton beams [23] and for experiments with bent silicon crystals [14,24]. Furthermore, the key concepts of this research will be experimentally tested at the test stand currently under development in the LHC's off-momentum collimation Insertion Region (IR) 3 [25].

In this paper, we summarise the ALICE-FT machine layout. We report on the conceptual integration of its elements (crystal and target assemblies, downstream absorbers), their impact on ring losses, and expected performance in terms of particle flux on target. We also discuss a method for increasing the flux of particles on the target by setting the crystal at the optimal betatron phase by applying a local optics modification in the insertion hosting the ALICE experiment (IR2). This method is independent of the crystal location, allowing for a crystal installation in a place with good space availability. Moreover, it enables the recovery of the maximum performance of the system in case of changes in beam optics in the LHC.

2 Machine configuration

A potential installation of the ALICE-FT setup could coincide with a major LHC upgrade in instantaneous luminosity, commonly referred to as the High-Luminosity LHC (HL-LHC) project [26], taking place in the Long Shutdown 3 (2026–2028). Some of the expected beam parameters with a direct impact on the ALICE-FT experiment performance are given in Table 1. One key beam parameter to be upgraded is the total beam current, which will increase by a factor of nearly 2, up to about 1.1 A, leading to about 0.7 GJ of total beam energy stored in the machine.

A highly efficient collimation system is therefore required in the LHC [27] to protect its elements, especially the superconducting magnets. The collimation system is organised in a precise multi-stage transverse hierarchy (see Table 2) over

Table 1 Proton-beam parameters of the future HL-LHC beams important for the ALICE-FT experiment, referred to as *standard* in [26]

Colliding-beam energy	E	7 TeV
Bunch population	N_b	2.2×10^{11}
Maximum number of bunches	n_b	2760
Beam current	I	1.09 A
Transverse normalised emittance	ε_n	2.5 [µm]
β^* at IP2		10 m
Beam crossing angle at IP2		200 µrad

Table 2 HL-LHC collimation settings expressed in units of RMS beam size (σ), assuming a Gaussian beam distribution and transverse normalised emittance $\varepsilon_n = 2.5$ µm

Coll. family	IR	Settings (σ)
TCP/TSCG/TCLA	7	6.7/9.1/12.7
TCP/TSCG/TCLA	3	17.7/21.3/23.7
TCTP	1/2/5/8	10.4/43.8/10.4/17.7
TCL	1/5	14.2
TCSP/TCDQ	6	10.1/10.1

two dedicated insertions (IRs): IR3 for momentum cleaning and IR7 for betatron cleaning. Each collimation insertion features a three-stage cleaning based on primary collimators (TCPs), secondary collimators (TCSGs) and absorbers (TCLAs). In addition, dedicated collimators are present in specific locations of the ring to provide protection for sensitive equipment (e.g. TCTP for the inner triplets), absorption of physics debris (TCL) and beam injection/dump protection (TDI/TCDQ-TCSP). The collimation system will be upgraded, as described in [28], to be compatible with HL-LHC requirements, but the general working principle remains the same. The system is designed to sustain beam losses up to 1 MJ without damage and quenching of superconducting magnets.

The halo-splitting scheme relies on placing a crystal into the transverse hierarchy of the betatron collimation system, between the primary and secondary stages of the IR7 collimators, such that the collimation system efficiency is not affected. Placing the splitting crystal closer to the beam than the primary collimators would not be possible without designing a downstream system capable of withstanding the collimation design loss scenarios. Retracting the crystal at larger amplitudes avoids this problem while still allowing the interception of a significant fraction of the multi-stage halo, as shown below. In this scheme, a fraction of secondary halo particles redirected towards the target can be used for fixed-target collisions instead of disposing of them at the absorbers, in a safe manner. For this scheme to work, the crystal does not need to be installed in IR7. In fact, the halo splitting is done in the vicinity of the experiment, where the target needs to be located.

3 ALICE-FT layout

A general conceptualisation of the ALICE-FT layout is illustrated in Fig. 1. A fraction of secondary halo particles are intercepted by the crystal and steered towards the target. Collision products are registered by the ALICE detector, which can handle on the order of 10^7 protons on target per second [5]. Possible losses originating either from the crystal or

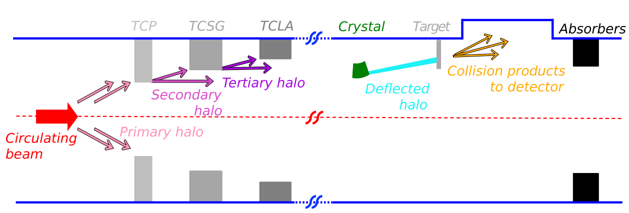

Fig. 1 Working principle of the crystal-based fixed-target experiment (right side of the graphics) being embedded into the multi-stage collimation system (left side of the graphics). Graphics based on [22], mostly by Mirarchi

from the target are intercepted by absorbers which would be installed downstream of the detector.

The ALICE-FT will act on the LHC beam 1 (B1) due to ALICE detector geometry. We assume the layout to be operated with the optics envisioned for the HL-LHC, although more optimised optics could be envisaged if needed. Since ALICE operates at low luminosities in proton runs, typically with offset levelling, this insertion does not demand tight optics constraints like the high-luminosity insertions for the general-purpose detectors [29]. Actually, a minor, local modification of the optics in the IR2 region is proposed to enhance the system performance by optimising the betatron oscillation phase at the location of the crystal. This will not affect the rest of the machine.

Safe integration of the crystal into the hierarchy of the collimation system is achieved by setting the crystal in the shadow of the IR7 primary collimators. As discussed in [22], the relative retraction of the crystal with respect to the IR7 primary collimator should not be smaller than 0.5 σ (RMS beam size), mostly to account for optics and orbit errors that, if not under control, could cause the crystal to accidentally become the primary collimator. The retraction should be kept as low as possible to maximise the number of protons impacting the target [4] as shown in Fig. 7. Similarly to [22], we also assume that, for machine safety reasons, the distance from the deflected beam to the aperture and the distance from the target to main beams are at least 4 mm. The system is to be installed in the vertical plane in order to avoid issues related to the beam dump system operating in the horizontal plane: this is the plane of the dump kickers and is subject to fast losses in case of an over-populated abort gap or in the (unlikely) case of dump failures [30,31]. In the case of a horizontal setup, larger aperture margins on settings would be applied to lead to lower rates of impinging halo, which we prefer to avoid.

The beam-crossing scheme at IP2 is also in the vertical plane. Furthermore, the main solenoid of the ALICE detector can be operated in two polarities, which affects the slope of both beams at IP2. We mark the negative slope of the LHC beam 1 at IP2 as *negX* and the positive slope as *posX*. Given the trajectory of B1 for both crossing schemes (*negX* and *posX*), aperture restrictions and space availability, the optimal longitudinal coordinate for crystal installation is 3259 m (with 0 at IP1). No other location in the area of interest in the LHC follows all the aforementioned requirements at the same time. The graphical illustration of the proposed layout is given in Fig. 2, and conditions inside the LHC tunnel are depicted in Fig. 3. As one can see, the chosen location is spacious and accessible, allowing for an easy integration of the crystal assembly into the LHC beamline.

We consider a 16-mm-long crystal made of silicon, with 110 bending planes and a bending radius of 80 m, providing a deflection of 200 µrad. This is the minimum deflection that can be safely used for both crossing schemes, ensur-

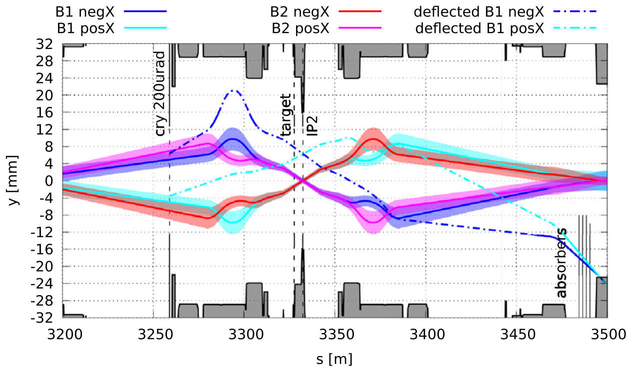

Fig. 2 The proposed layout of the ALICE-FT experiment. Both beams (B1 and B2) with their envelopes (7.3 σ) are given with solid lines for both ALICE solenoid polarities (posX and negX). Deflected beams are given in dashed blue lines. The machine aperture is given in solid black lines. Vertical dashed lines mark the locations of crystals, target and IP2, respectively. The location of absorbers is marked in the right bottom corner

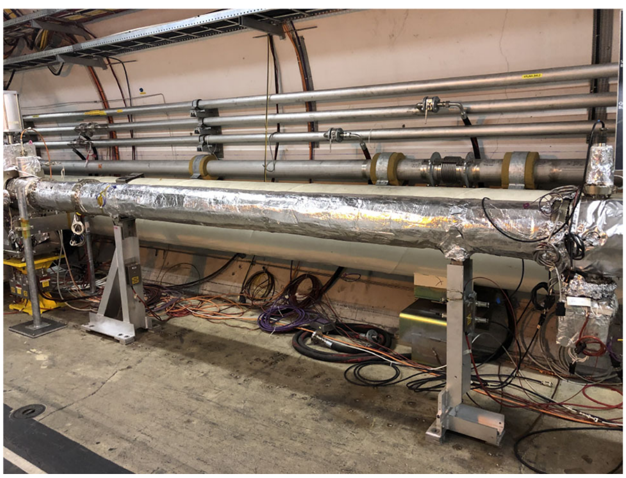

Fig. 3 Conditions inside the LHC tunnel at the proposed location. Good accessibility and space availability allow for easy installation of the crystal assembly

ing that the deflected beam fits within the available aperture. The bending radius was chosen to be the same as the bending radius of crystals already used in the LHC, following the parametric studies reported in [16] to ensure an optimum crystal channelling performance at the LHC top energy while keeping the nuclear interaction rate as low as possible. However, the crystals used in the LHC are 4 mm long and provide a deflection of 50 µrad. A further optimisation of crystal parameters in order to reduce the length could potentially be done at a later stage.

The target assembly is planned to be installed nearly 5 m upstream from IP2, with a target length of about 5 mm and made of either light or heavy material (e.g. carbon or tungsten), depending on the physics scenario considered. Details on target design studies can be found in [32].

Four absorbers, of the same design as collimators already used in the LHC, are proposed to be installed about 150 m downstream from the IP2. The first three are proposed to be made of 1-m-long carbon fibre-carbon composite jaws, as in the present TCSGs in the LHC, while the last one is to be made of 1-m-long tungsten jaws, as the present TCLAs in the LHC, similarly as in [22]. The difference is that in our study, we use a large opening of about 50 σ that still intercepts the channelled beam while being well in the shadow of the entire collimation system. Such a choice is driven by the desire to minimise the impact of these extra absorbers on the regular collimation system and machine impedance instead of searching for minimum gaps that maintain the collimation hierarchy. As will later be shown, we do not experience any cleaning-related issues. The proposed setup of absorbers follows a performance-oriented approach with the potential to reduce the number of required absorbers, based on the energy deposition study to be done in the future.

4 Expected performance

The MAD-X code [33] is used to manage the HL-LHC model, to prepare suitable lattice and optics descriptions used as input to tracking studies, and to calculate the trajectory of particles experiencing an angular kick equivalent to the crystal bending angle. Detailed evaluation of the layout performance is performed using multi-turn particle tracking simulations in SixTrack [34] that allow for symplectic, fully chromatic and 6D tracking along the magnetic lattice of the LHC, including interactions with collimators and bent crystals, and a detailed aperture model of the machine [35,36]. In our simulations, we use at least 2 million protons, initially distributed over a narrow ring of radius r + dr slightly above 6.7 σ in the normalised transverse vertical position-angle phase space (y, y'), which allows an estimation of the number of protons impacting the collimation system (including the crystal and the target of the ALICE-FT layout) as well as the density of protons lost per metre in the aperture with a resolution of 10 cm along the entire ring circumference.

The ALICE-FT experiment must be compatible with the standard physics programme of the LHC, meaning that it cannot add any operational limitations, mostly related to particle losses, which must stay within acceptable limits. This is demonstrated in Fig. 4, where a loss map of the machine including the ALICE-FT system does not contain any abnormal loss spikes compared to the reference loss map of the machine without the ALICE-FT system. The only new spikes correspond to protons impacting the elements of the ALICE-FT setup. A strong agreement between the simulated and measured loss maps has been demonstrated in the LHC [23], supporting our confidence in the conclusions drawn from our simulations.

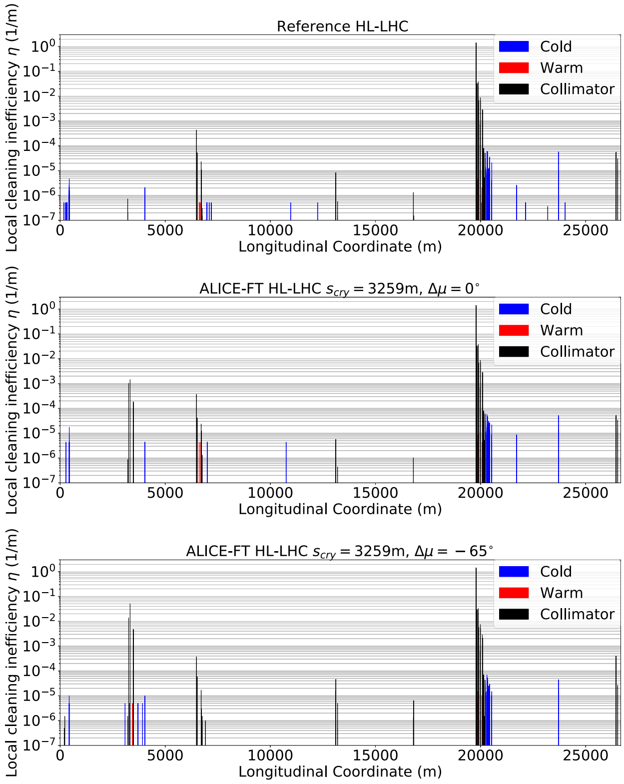

Fig. 4 Comparison of loss maps for the machine without the ALICE-FT system (top), with the ALICE-FT system without the optics optimisation (middle) and with the ALICE-FT system with the optics optimisation (bottom). The local cleaning inefficiency (vertical axis) is a measure of the number of protons not intercepted by the collimation system and impacting the machine aperture. The simulation limit of one proton lost in the machine aperture corresponds to $5 \times 10^{-7}\,\mathrm{m}^{-1}$ in a 10 cm longitudinal bin. No abnormal loss spikes are present in the loss maps

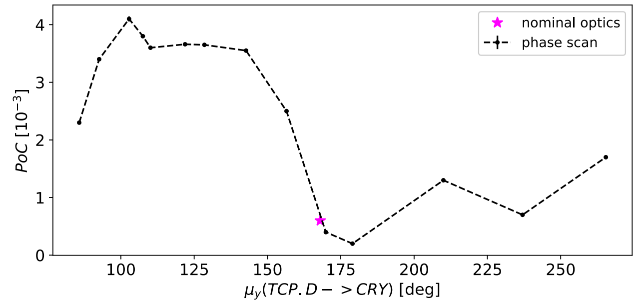

Fig. 5 The dependence of the fraction of the number of protons impacting the crystal over the number of protons impacting the primary collimator (PoC) on the betatron phase from the primary vertical collimator in IR7 (TCP.D) to the IR2 crystal (CRY). Crystal retraction is 7.9 σ. Statistical errors are on the order of 1%, which makes the bars hardly visible

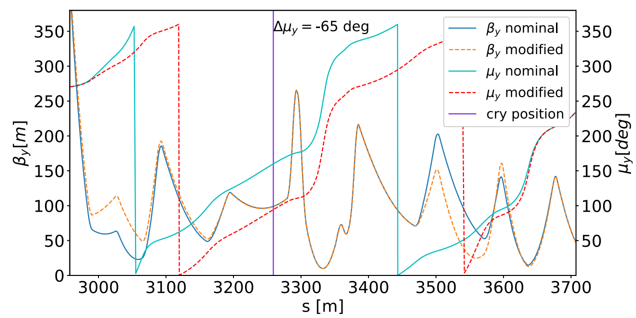

Fig. 6 Vertical β function and betatron phase for nominal (solid lines) and modified (dashed lines) optics. Position of the crystal is marked with a vertical purple line

Table 3 Normalised strengths of quadrupoles for nominal and modified optics. IR2 left and IR2 right stand for regions upstream and downstream of the IP2, respectively

Quadrupole number	Quadrupole strength k_1 $[10^{-3}\ \mathrm{m}^{-2}]$			
	IR2 left		IR2 right	
	Nominal	Modified	Nominal	Modified
10	− 6.39	− 6.15	7.30	7.30
9	7.01	6.89	− 6.60	− 6.82
8	− 5.41	− 3.59	6.71	6.30
7	7.60	7.42	− 6.36	− 7.47
6	− 4.91	− 4.17	4.33	4.20
5	2.99	2.88	− 3.63	− 4.09
4	− 2.80	− 2.67	3.74	2.60

The setup is developed to provide as many protons as possible impacting the crystal (N_{PoC}) in order to maximise, for a given channelling efficiency, the number of protons on the target. For a given crystal retraction relative to primary collimators, the proton flux on the crystal strongly depends on the betatron oscillation phase advance between the primary collimators at IR7 and the IR2 crystal. With the nominal optics, the phase advance is nearly least favourable, leading to a low N_{PoC}. This can be corrected by a minor, local modification of the IR2 optics, implemented by changing strengths of the IR2 quadrupole magnets labelled with natural numbers from 4 to 10 (the lower the number, the closer the magnet to the IP2) on both sides of the IP2. Quadrupoles upstream of the IP2 were constrained to shift the phase advance at the crystal while keeping the IP2 optics parameters unchanged. Quadrupoles downstream of the IP2 were constrained to recover the same optical parameters, including the betatron phase, as in the nominal optics. The maximum N_{PoC} was found for phase advance shifted by $-65°$, as shown in Fig. 5.

The corresponding optical β_y function in the IR2 is given in Fig. 6, and changes in strengths of quadrupoles are summarised in Table 3. Such an optics modification is quite feasible for implementation at the IR2 and does not affect the rest of the machine, especially losses along the ring as shown in Fig. 4.

The number of protons hitting the target depends on the number of protons hitting the crystal, their phase-space distribution at the crystal entry face, the parameters of the crystal,

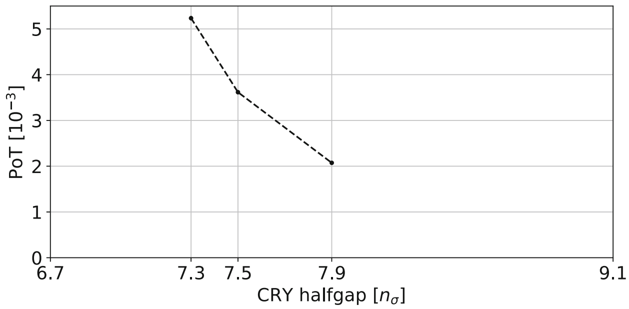

Fig. 7 Fraction of the number of protons impacting the target over the number of protons impacting the primary collimator (PoT) for some values of crystal half-gap expressed as the number of beam σ. Limits of the horizontal axis correspond to half-gaps of primary and secondary collimators in IR7. Statistical errors are on the order of 1%, which makes the bars hardly visible

and the crystal position and orientation inside the beam pipe. All these phenomena are treated by the simulation code we use. Protons hitting the crystal emerge from the collimation system. Therefore, their number and phase-space distribution are subject to a complex multi-turn process which is also simulated. As a result, we obtain PoC and PoT as fractions of protons hitting the crystal or the target (respectively) over all protons intercepted by the collimation system. Three values of PoT resulting from simulations performed and depending on the relative crystal retraction are given in Fig. 7.

These scaling factors allow us to estimate the actual number of protons hitting the crystal and (more interestingly) the target under realistic conditions of the beam, where the most important factors are beam intensity and lifetime. An exponential decrease in the beam intensity is assumed, characterised by the time coefficient τ interpreted as a beam lifetime, which depends on beam parameters and machine state. A dominant contribution to the total beam lifetime comes from the beam burn-off due to collisions (τ_{BO}), while the number of protons on the target $\mathrm{N}_{\mathrm{PoT}}$ depends mostly on τ_{coll} corresponding to beam core depopulation towards tails that are intercepted by the collimation system. Following the same assumptions as in [22], where I_0 is the initial beam intensity, time coefficients $\tau_{\mathrm{BO}} \approx 20\,\mathrm{h}$ and $\tau_{\mathrm{coll}} \approx 200\,\mathrm{h}$, the number of protons impacting the target per 10-h-long fill ($\mathrm{T}_{\mathrm{fill}}$) in 2018 operating conditions can be estimated as:

$$\mathrm{N}_{\mathrm{PoT}} = \frac{1}{2} PoT \int_0^{T_{fill}} \frac{I_0}{\tau_{\mathrm{coll}}} exp\left(-\frac{t}{\tau_{BO}}\right) exp\left(-\frac{t}{\tau_{\mathrm{coll}}}\right) \mathrm{d}t \approx 2.7 \times 10^{10}. \tag{1}$$

This corresponds to an average flux of protons on target of 7.5×10^5 p/s, being roughly one order of magnitude from the design goal of 10^7 p/s (summary given in Table 4). Therefore, further optimisation of the design would be needed to maximise the physics gain of the considered setup. On the other hand, the intensity of HL-LHC beams will be about a factor of 2 larger, which most probably will result in a larger proton flux on target, much closer to the design goal. However, the actual lifetime and beam loss pattern must be known for the final assessment of the performance of the proposed design. The experimental test stand being set up at the off-momentum collimation insertion (IR3) [25] will be used to verify the concepts discussed in this paper, and to offer a more accurate estimate of the anticipated performance.

Table 4 Expected proton flux on target based on 2018 operating conditions compared with expected capabilities of ALICE detector acquisition system. The first number may grow up to a factor of 2 for HL-LHC conditions due to two times larger initial beam intensity

	Proton flux on target [p/s]
Estimated	7.5×10^5
ALICE acquisition system	10^7

5 Conclusions and outlook

This paper summarises the layout for ALICE fixed-target experiments based on crystal-assisted beam halo splitting. By using numerical simulations, we have demonstrated that it can be operated safely without affecting the availability of the LHC for regular beam–beam collisions. The estimated proton flux on target is roughly one order of magnitude away from the design goal of 10^7, with a possible improvement resulting from larger intensities of HL-LHC beams, allowing us to exploit of the full capabilities of the ALICE detector acquisition system. An experimental verification of the concepts discussed in this paper will be performed at the experimental test stand in the LHC, which will also enable a more precise estimation of the expected performance of the proposed design.

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Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: All the relevant data are either reported in the paper or can be derived analytically using the formalism described and using open-source software cited.]

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References

1. O.S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock, *LHC Design Report, CERN Yellow Reports: Monographs* (CERN, Geneva, 2004). http://cds.cern.ch/record/782076
2. F. Galluccio, C. Hadjidakis, A. Kurepin, L. Massacrier, S. Porteboeuf, K. Pressard, W. Scandale, N. Topilskaya, B. Trzeciak, A. Uras et al., Physics opportunities for a fixed–target programme in the ALICE experiment (2019). https://cds.cern.ch/record/2671944
3. K. Aamodt, A. Abrahantes Quintana, R. Achenbach, S. Acounis, D. Adamova, C. Adler, M. Aggarwal, F. Agnese, G. Aglieri Rinella, Z. Ahammed et al. [ALICE Collaboration], JINST **3**, S08002 (2008). Also published by CERN Geneva in 2010
4. C. Barschel, J. Bernhard, A. Bersani, C. Boscolo Meneguolo, R. Bruce, M. Calviani, V. Carassiti, F. Cerutti, P. Chiggiato, G. Ciullo et al., Tech. rep. (CERN, Geneva, 2019). https://cds.cern.ch/record/2653780
5. C. Hadjidakis, D. Kikoła, J. Lansberg, L. Massacrier, M. Echevarria, A. Kusina, I. Schienbein, J. Seixas, H. Shao, A. Signori et al., Phys. Rep. **911**, 1 (2021)
6. D. Mirarchi, *Crystal Collimation for LHC* (2015). https://cds.cern.ch/record/2036210
7. V.M. Biryukov, Y.A. Chesnokov, V.I. Kotov, Crystal channeling and its application at high-energy accelerators (1997). ISBN 978-3-642-08238-2
8. A.M. Taratin, Phys. Part. Nuclei **29**, 437 (1998)
9. R. Fliller, A. Drees, D. Gassner, L. Hammons, G. McIntyre, S. Peggs, D. Trbojevic, V. Biryukov, Y. Chesnokov, V. Terekhov, Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms **234**, 47 (2005). Relativistic Channeling and Related Coherent Phenomena in Strong Fields
10. R.P. Fliller, A. Drees, D. Gassner, L. Hammons, G. McIntyre, S. Peggs, D. Trbojevic, V. Biryukov, Y. Chesnokov, V. Terekhov, Phys. Rev. ST Accel. Beams **9**, 013501 (2006)
11. N. Mokhov, G. Annala, A. Apyan, R. Carrigan, A. Drozhdin, T. Johnson, A. Legan, R. Reilly, V. Shiltsev, D. Still et al., Int. J. Mod. Phys. A **25**, 98 (2010)
12. V. Zvoda, G. Annala, R. Carrigan, A. Drozhdin, T. Johnson, S. Kwan, N. Mokhov, A. Prosser, R. Reilly, R. Uplegger et al., Int. J. Mod. Phys. A **25** (2012)
13. W. Scandale, A. Taratin, Phys. Rep. **815**, 1 (2019)
14. W. Scandale, G. Arduini, R. Assmann, C. Bracco, M. Butcher, F. Cerutti, M. D'andrea, L. Esposito, M. Garattini, S. Gilardoni et al., Int. J. Mod. Phys. A **37**, 2230004 (2022)
15. W. Scandale, G. Arduini, M. Butcher, F. Cerutti, M. Garattini, S. Gilardoni, A. Lechner, R. Losito, A. Masi, D. Mirarchi et al., Phys. Lett. B **758**, 129 (2016)
16. D. Mirarchi, G. Hall, S. Redaelli, W. Scandale, Eur. Phys. J. C **77**, 424 (2017)
17. S. Redaelli, M. Butcher, C. Barreto, R. Losito, A. Masi, D. Mirarchi, S. Montesano, R. Rossi, W. Scandale, P. Serrano Galvez et al., Eur. Phys. J. C **81**, 142 (2021)
18. M. Patecki, A. Fomin, D. Kikoła, D. Mirarchi, S. Redaelli, *Proceeding to the 64th ICFA Advanced Beam Dynamics Workshop, MOP26*
19. Kickoff Meeting for the Physics Beyond Collider study (2016). https://indico.cern.ch/event/523655
20. F. Galluccio, FTE@LHC and NLOAccess STRONG 2020 joint kick-off meeting, 8.11.2019
21. A. Fomin, 21st meeting of the PBC-FT working group, 16.12.2020. https://indico.cern.ch/event/981210/
22. D. Mirarchi, A. Fomin, S. Redaelli, W. Scandale, Eur. Phys. J. C **80** (2020)
23. P. Hermes, R. Bruce, J. Jowett, S. Redaelli, B. Salvachua Ferrando, G. Valentino, D. Wollmann, Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc Equip. **819**, 73 (2016)
24. M. D'Andrea, Applications of Crystal Collimation to the CERN Large Hadron Collider (LHC) and its High Luminosity Upgrade Project (HL-LHC) (2021). Presented 23 Feb 2021. https://cds.cern.ch/record/2758839
25. K. Dewhurst, Performance of a double-crystal setup for LHC fixed-target experiments, in *Proc. IPAC'23*
26. G. Apollinari, I. Bejar Alonso, O. Bruning, P. Fessia, M. Lamont, L. Rossi, L. Taivan, *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1, CERN Yellow Reports: Monographs* (CERN, Geneva, 2017). https://cds.cern.ch/record/2284929
27. R.W. Assmann, O. Aberle, G. Bellodi, A. Bertarelli, C. Bracco, H. Braun, M. Brugger, S. Calatroni, R. Chamizo, A. Dallocchio et al., Revised version submitted on 2006-09-15 14:36:59 (2006)
28. S. Redaelli, R. Bruce, A. Lechner, A. Mereghetti, pp. 87–114 (2020)
29. O. Aberle, I. Béjar Alonso, O. Brüning, P. Fessia, L. Rossi, L. Tavian, M. Zerlauth, C. Adorisio, A. Adraktas, M. Ady et al., *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report, CERN Yellow Reports: Monographs* (CERN, Geneva, 2020). https://cds.cern.ch/record/2749422
30. E. Carlier, Safe Injection into the LHC (2003). https://cds.cern.ch/record/642470
31. R. Filippini, E. Carlier, L. Ducimetière, B. Goddard, J. Uythoven, Reliability Analysis of the LHC Beam Dumping System (2005). https://cds.cern.ch/record/841092
32. K. Pressard, Joint workshop "GDR-QCD/QCD@short distances and STRONG2020/PARTONS/FTE@LHC/NLOAccess", 2.06.2021
33. H. Grote, F. Schmidt, MAD-X: An Upgrade from MAD8, CERN-AB-2003-024-ABP (2003). http://cds.cern.ch/record/618496
34. G. Ripken, F. Schmidt, Tech. Rep. CERN-SL-95-12. CERN-SL-95-12-AP. DESY-95-063, CERN, Geneva (1995). https://cds.cern.ch/record/281283
35. 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, CERN (CERN, Geneva, 2018). https://cds.cern.ch/record/2646800
36. A. Mereghetti, F. Cerutti, R. De Maria, B. Goddard, V. Kain, M. Meddahi, O. Mete, Y. Papaphilippou, D. Sinuela Pastor, V. Vlachoudis et al., Conf. Proc. C **130512**, WEPEA064 (2013)
37. ALICE Fixed-Target Project meetings. https://indico.cern.ch/category/11595/
38. Physics Beyond Colliders Working Group. https://indico.cern.ch/category/8815/