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STATUS OF LAYOUT STUDIES FOR FIXED-TARGET EXPERIMENTS IN ALICE BASED ON CRYSTAL-ASSISTED HALO SPLITTING*

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Abstract

The Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) is the world largest and most powerful particle accelerator colliding beams of protons and lead ions at energies up to 7 TeV and 2.76 TeV, respectively. 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 by means of a bent crystal with an internal target placed a few meters upstream of the detector. 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. This paper summarises our progress in preparing the fixed-target layout consisting of crystal assemblies, a target and downstream absorbers. We discuss the conceptual integration of these elements within the LHC ring, impact on ring losses, conditions for a parasitic operation and expected performance in terms of particle flux on target.

INTRODUCTION

The ALICE fixed-target (ALICE-FT) programme [1] is proposed to extend the research potential of the Large Hadron Collider (LHC) [2] and the ALICE experiment [3]. The concept is based on steering onto a solid internal target a fraction of the proton beam halo split by means of a bent crystal, similar to crystals being developed for beam collimation at the LHC [4–6]. Splitting the beam is performed by exploiting the channeling process occurring inside a bent crystal, resulting in a trajectory deflection equivalent to the geometric bending angle of a crystal body [7]. Such a setup, installed in the proximity of the ALICE detector, would provide the most energetic proton beam ever in the fixed-target mode with centre-of-mass energy per nucleon-nucleon ($\sqrt{s_{\mathrm{NN}}}$) of 115 GeV offering a possibility to study the hadronic matter and to provide inputs for cosmic ray physics as summarised by the AFTER@LHC study group [1, 8].

Our proposal of the ALICE-FT layout 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 [9, 10]. We also profit from the preliminary designs reported in [11, 12] 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 [13].

In this report, we summarise the status of the ALICE-FT layout, including 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, taking into account parasitic and dedicated operation modes.

MACHINE CONFIGURATION

A potential installation of the ALICE-FT setup will coincide with a major LHC upgrade in terms of instantaneous luminosity, commonly referred to as the High-Luminosity LHC (HL-LHC) [14], taking place in the Long Shutdown 3 (2025-2027), to make it ready for Run4 starting in 2027. Some of the expected beam parameters, having a direct impact on the ALICE-FT experiment performance, are given in Table 1. Among beam parameters being a subject of the upgrade, we highlight the total beam current increase nearly by a factor of 2, up to about 1.1 A, leading to more than 0.7 GJ of total beam energy stored in the machine. A highly efficient collimation system is therefore present in the LHC [15] and it will be upgraded for the HL-LHC [16]. Its role is to intercept the beam halo and to protect the cryogenic aperture from beam losses as some tens of mJ/cm^3 deposited in a superconducting magnet can cause an abrupt loss of its superconducting properties, i.e. a magnet quench. The halo splitting scheme is to be embedded into the transverse hierarchy of the betatron collimation system, as shown in Fig. 1, such that the collimation system efficiency is not affected. A fraction of secondary halo particles redirected towards the target can be used for fixed-target collisions instead of disposing them at the absorbers. The present collimation system is organised in a precise multi-stage hierarchy (see Table 2) over two dedicated insertions (IRs): IR3 for momentum cleaning and IR7 for betatron cleaning. Each collimation insertion features a three-stage cleaning

Table 1: Some Parameters of the Future HL-LHC Beams Important for the ALICE-FT Experiment, Referred to as *Standard* in [14]

Beam energy in collision	E	7 TeV
Bunch population	N_b	$2.2 \cdot 10^{11}$
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

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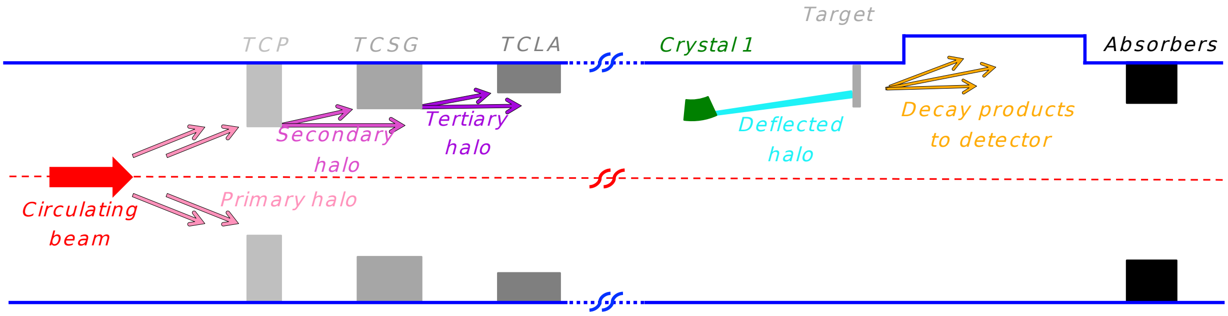

Figure 1: Working principle of the crystal-based fixed-target experiment (right side of the graphics) being embedded into the multi-stage collimation system (left side of the graphics). TCP, TCSG and TCLA stand for primary, secondary and tertiary stage of collimation, respectively. Graphics from [13].

based on primary collimators (TCP), secondary collimators (TCSG) and absorbers (TCLA). In addition, dedicated collimators are present in specific locations of the ring to provide protection of 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 undergoes an upgrade, as described in [16], to make it compatible with HL-LHC requirements, but the general working principle will remain the same.

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
TCT	1/2/5/8	10.4/43.8/10.4/17.7
TCL	1/5	14.2
TCSP/TCDQ	6	10.1/10.1

ALICE-FT LAYOUT

A general concept of the ALICE-FT layout is illustrated in Fig. 1. A bent crystal is embedded into the collimation system and intercepts a fraction of the beam halo, which is deflected towards the target based on the crystal channeling process. Collision products are registered by the ALICE detector. Possible losses originating from the crystal+target assembly are intercepted by downstream absorbers. The main goal of the ALICE-FT layout is to provide a number of protons on target (N_{PoT}) high enough to exploit full capabilities of ALICE detector acquisition system, while keeping the losses on superconducting magnets within tolerable limits. At the moment it is not clear if both regular beam-beam collissions and additional fixed-target collisions can be registered by the ALICE detector in parallel. On the other hand ALICE anticipates to reach its luminosity goal for beam-beam proton-proton collisions after one year of data taking in the Run4 [17]. Afterwards, the ALICE detector could be dedicated to fixed-target collisions while the LHC is operated with proton beams. As estimated in [8], the ALICE detector can handle in the order of 10^7 protons on target per second; an exact number depends on the final implementation of the target [18], which is under investigation.

We assume the layout to be operated with the presently planned HL-LHC optics (version 1.5 [19] at the moment), as the overhead would become too large if new optics needs to be commissioned. Similarly, we assume that the ALICE-FT layout will not violate the multi-stage cleaning hierarchy, in particular the crystal will be in the shadow of IR7 primary collimators. As discussed in [13], 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, but it should be kept as low as possible to maximise the number of protons impacting the target [10].Similarly to [13], 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 should be 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; otherwise, larger margins on settings would be required. The crossing scheme at IP2 is also in the vertical plane. Furthermore, the main solenoid of ALICE can be operated in two polarities which affect the slope of both beams at IP2. We mark the negative slope of the LHC beam 1 (B1) at IP2 as *negX* and the positive slope as *posX*. Both polarities are covered by our layout, but all the numbers reported in this paper correspond to *negX* scenario as the difference is minor. The ALICE-FT will act on B1 due to ALICE detector geometry. The graphical illustration of the proposed layout, that fulfils all above requirements, is given in Fig. 2.

We consider crystals made of silicon, with 110 bending planes and a bending radius of 80 m, the same as a bending radius of crystals already used in the LHC, following the parametric studies reported in [5] to ensure an optimum crystal channeling performance at LHC top energy, while keeping the nuclear interaction rate as low as possible. The optimum crystal bending angle depends on the ALICE solenoid polarity: 100µrad for *negX* and 175µrad for *posX* meaning that, at the moment, we consider an installation of two crystal assemblies next to each other. The longitudinal co-

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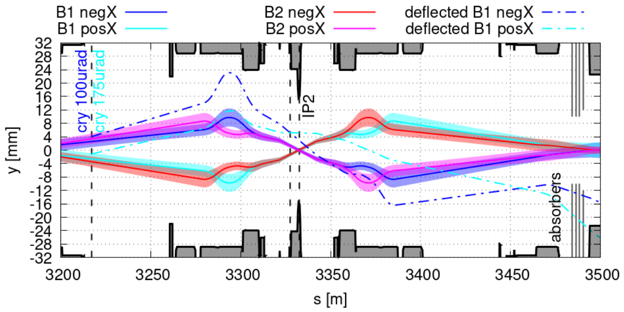

Figure 2: The proposed layout of the ALICE-FT experiment. Both beams (B1 and B2) with their envelopes (7.3 σ) are given with solid lines for both ALICE solenoid polarities. Deflected beams are given in dashed blue lines. Machine aperture is given in black solid lines. Vertical dashed lines mark locations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

ordinate for the crystal installation is 3217.5 m (with 0 at IP1), chosen to maximise the number of protons impacting the crystal due to local phase-space conditions of secondary beam halo [20]. However, preliminary integration considerations indicate that this location will be challenging for the crystal installation, as this region is already crowded with other equipment and complex from the point of view of vacuum systems [21]. Moving the crystal downstream is considered as a possible mitigation method at the cost of reduced system performance due to unfavourable phase advance with respect to the primary collimator at IR7, resulting in a lower number of protons impacting the crystal.

The target assembly is planned to be installed nearly 5 m upstream from IP2 with a target made of either light or heavy material as, e.g. carbon, tungsten of about 5 mm of length. Details on target design studies can be found in [22].

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 made of 1 m long carbon-fibre-carbon composite jaws, as the present TCSGs in the LHC, while the last one is made of 1 m long tungsten jaws, as the present TCLAs in the LHC; similarly as in [13]. The difference is that in our study we use a maximum opening of about 50 σ that still intercepts the channeled beam to keep the absorbers in the shadow of the entire collimation system and therefore to minimise their impact on the regular collimation system and on the machine impedance, instead of searching for minimum gaps that maintain the collimation hierarchy. As will be shown later, we do not experience any issues related to cleaning. The proposed setup of absorbers follows a performance-oriented approach with a potential to reduce the number of required absorbers, based on a detail energy deposition study to be done in the future. An optimisation of absorbers design will be done if it turns out to be needed.

The main parameters of the proposed layout are summarised in Table 3.

Table 3: Main Parameters of the ALICE-FT Layout; Cry Stands for a Crystal and Abs Stands for an Absorber

	position **[m]**	**length** **[cm]**	**mat.**	**half-gap** **[mm]**	**bending angle** **[µrad]**
cry$_{negX}$	3217.5	0.8	Si	1.4	100
cry$_{posX}$	3217.5	1.4	Si	1.4	175
target	3327.6	(5,10)	C/W	3.8	—
abs1	3484.4	100	C	9.9	—
abs2	3486.4	100	C	10.3	—
abs3	3488.4	100	C	10.7	—
abs4	3490.4	100	W	12.4	—

EXPECTED PERFORMANCE

The MAD-X code [23] is used to manage the HL-LHC model, to prepare suitable lattice and optics descriptions used as input to the 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 done using multi-turn particle tracking simulations in SixTrack [24] that allows a 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 [25]. In our simulations, we use at least two 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. 3 where a loss map of the machine including the ALICE-FT system does not contain any abnormal loss spikes comparing 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.

Loss maps presented in Fig. 3 refer to the case with the crystal at 7.3 σ, i.e. close to the minimum allowed retraction with respect to the primary collimator in IR7. This is a conservative choice from the cleaning point of view as it corresponds to a larger number of protons impacting the crystal (N_{PoC}) and therefore also a larger number of protons impacting the target (N_{PoT}) comparing to larger crystal retractions. The dependence of a fraction of the beam halo intercepted by the crystal (PoC) or by the target (PoT) over all protons intercepted by the collimation system on the relative

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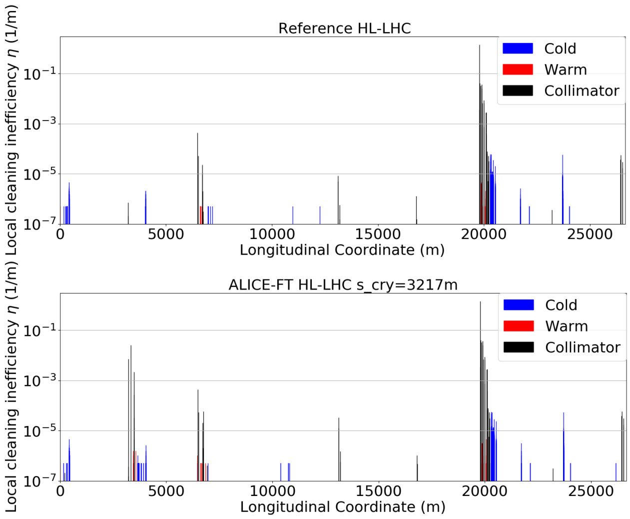

Figure 3: Comparison of loss maps for the machine with (bottom) and without (top) the ALICE-FT system. The local cleaning ineffiency is a measure of the number of protons not intercepted by the collimation system and impacting the machine aperture. The simulation limit of 1 proton lost in the machine aperture corresponds to $5 \cdot 10^{-7} \mathrm{m}^{-1}$ in a 10 cm longitudinal bin.

crystal retraction is given in Fig. 4. PoT is lower than PoC due to limited angular acceptance of the crystal leading to the channeling process (about 2.5 μrad for 7 TeV protons) and due to crystal channeling efficiency, which is lower than 1.

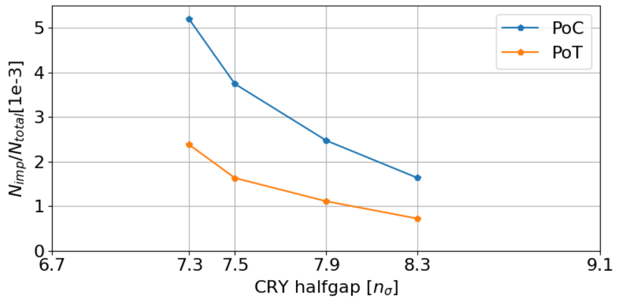

Figure 4: Fraction of beam halo intercepted by the crystal (PoC) and target (PoT) for some values of crystal halfgap expressed in the number of beam sigma. Limits of the horizontal axis correspond to halfgaps of primary and secondary collimators in IR7.

We define a *parasitic* mode of operation as a situation in which the fixed-target collisions at IP2 occur during the regular beam-beam collision mode of the LHC. The N_{PoT} scales with the number of protons impacting primary collimators at IR7 (see Eq. (1)), which depends on the beam intensity being a complex function of time, discussed in more detail in [13]. An exponential decrease of 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 N_{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 [13], with I_0 being the initial beam intensity, time coefficients $\tau_{BO} \approx 20$ h and $\tau_{coll} \approx 200$ h, the number of protons impacting the target per 10 h long fill (T_{fill}) in 2018 operation conditions can be estimated as:

$$N_{PoT} = \frac{1}{2} PoT \int_0^{T_{fill}} \frac{I_0}{\tau_{coll}} \exp\left(-\frac{t}{\tau_{BO}}\right) \exp\left(-\frac{t}{\tau_{coll}}\right) dt \approx 10^{10}. \qquad (1)$$

A more detailed statistical analysis of all 2018 fills of the LHC [26] indicates the N_{PoT} to be within the same order of magnitude, with an expected proton flux on target of about $5 \cdot 10^5$ p/s. This number may grow by a factor of two, to about 10^6 p/s, in the HL-LHC operation due to two times larger initial beam intensity, if the remaining parameters are the same, but an exact estimation is difficult to perform at the moment. This is about one order of magnitude lower than ALICE detector data acquisition capabilities, even if the target is extended to 10 mm length [8, 18].

A possible method to increase the proton flux on target is discussed in [26] where a special *dedicated* beam mode is proposed at the end of every LHC fill. The proposal is to extend these fills with several minutes long periods of a special beam excitation mode, during which the transverse beam emittance is increased in a controlled way by using the transverse damper. This allows increasing the number of protons impacting the primary collimators such that the proton flux on target can be increased up to a factor of 10, reaching the maximum capabilities of the ALICE detector acquisition system, see Table 4. The disadvantages of this method are a loss of an integrated luminosity (less than 1 % over a year) by the LHC experiments registering the beam-beam collisions and a larger impact of beam losses on the collimation system (but still within the design limits). Studies are ongoing to assess the feasibility of this method.

Other methods of increasing the proton flux on target, mostly in the *parasitic* mode, are under investigation.

Table 4: Order of magnitude of proton flux on target for *parasitic* and *dedicated* beam modes (estimated according to 2018 operation conditions) compared with expected capabilities of ALICE detector acquisition system. The first two numbers may grow by about a factor of 2 for HL-LHC conditions, due to two times larger initial beam intensity, but an exact estimation is difficult at the moment.

	proton flux on target [p/s]
beam *parasitic* mode	$5 \cdot 10^5$
beam *dedicated* mode	$5 \cdot 10^6$
ALICE acquisition system	10^7

CONCLUSIONS AND OUTLOOK

In this report, we summarise the status of layout studies for ALICE fixed-target experiment based on crystal-assisted beam halo splitting. The proposed layout allows for a *parasitic* operation without compromising machine safety. The preliminary estimation of flux of protons on target in the *parasitic* mode indicates a number about one order of magnitude lower (assuming the HL-LHC beam intensity) compared to capabilities of the ALICE detector acquisition system. Its full potential can be exploited by applying a special *dedicated* operation mode based on beam excitation techniques. Integration of the ALICE-FT system will be challenging for both crystal assembly and target assembly and requires further investigation. In case of severe difficulties, some backup solutions are being prepared (e.g. moving the crystal downstream, double-crystal setup), but their detailed description is out of the scope of this report.

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