

FROM CONCEPT TO FEASIBILITY: OPTIMISED DESIGN STUDIES OF THE ALICE FIXED-TARGET CONFIGURATION FOR LEAD IONS AT THE HL-LHC

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Abstract

The ALICE fixed-target (ALICE-FT) programme uses crystal-assisted halo splitting to send a controlled flux of beam-halo particles onto an internal target upstream of the ALICE interaction point, enabling a rich fixed-target physics programme in parallel to collider running. We present the final feasibility assessment for operation with HL-LHC Pb beams.

Using SixTrack–FLUKA tracking with particle–matter interactions, we scan optics, crystal parameters and target/absorber geometry. The phase advance between the betatron collimation system and the ALICE-FT crystal, as well as the crystal bending angle and alignment, are optimised to maximise halo interception and channeling to the target while preserving the collimation hierarchy. The optimised layout increases the fraction of halo particles on target, delivers fixed-target luminosities compatible with the projected ALICE heavy-ion programme and keeps additional losses within machine-protection limits. We conclude with an operational scenario and prospects for an experimental demonstration of the concept.

INTRODUCTION

The Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) is the most powerful accelerator capable of accelerating protons and lead ions with the energies of 14 TeV and 5.5 TeV per nucleon, respectively [1]. One of the LHC main experiments, ALICE (A Large Ion Collider Experiment), is optimized for the detection of heavy-ion collisions, hence its research potential can be further increased through experiments based on fixed-target collisions [2]. The assembly proposed in this work, ALICE fixed-target (ALICE-FT), utilizes bent crystals at its base. When the particle impacts such crystal at the adequate angle, a crystal channeling phenomenon occurs, where the particle follows the path of bent crystalline planes. This deflection enables the interception of part of the beam halo and its redirection at the target (so called halo-splitting), resulting in the productive usage of the particles otherwise lost in the collimation system. This assembly follows guidelines provided by CERN Physics Beyond Colliders forum [3] and benefits from the studies of crystal collimation at CERN-LHC [4, 5], BNL [6, 7] and FNAL [8, 9].

Fixed-target based experiments for the ALICE detector provide particular advantages in comparison to the collider mode. Luminosity values comparable to ones in LHC col-

lisions can be achieved thanks to high-density target [10]. Collision energy possible to achieve in ALICE-FT of 72 GeV for lead ions is comparable to the collision energy in Super Proton Synchrotron (SPS) and Relativistic Heavy Ion Collider (RHIC). Contrary to head-on collisions, the fixed-target configuration enables access to far backward regions of rapidity and measurements at far ranges of the backward phase space [10]. Additionally, ALICE-FT can utilize different types of target material extending experimental possibilities of the set-up [10]. Possible studies with fixed-target assemblies include strong interaction processes, quark and gluon distributions at high momentum fraction, sea quark and heavy-quark content in the nucleon and nucleus, and research on cosmic ray physics [2, 10].

ALICE fixed-target assembly was already evaluated and adjusted for proton beam [11]. In this work, corresponding feasibility assessment is conducted for the lead ion beam. This is a cause of the additional challenge as the fragmentation of heavy ions and creation of different charge-to-mass particles results in the higher risk of leakage in the LHC collimation system [12]. Hence, the main focus of this work is to verify the performance of ALICE-FT assembly for the lead ion beam and to adapt it for the most efficient performance.

ALICE FIXED-TARGET CONFIGURATION

The assembly of ALICE fixed-target is considered for the operation of High-Luminosity (HL-LHC) beam B1 [13]. For the protection from high-energy particle losses, LHC utilizes multi-stage collimation system [14] placed in two interaction regions (IR): IR3 for momentum cleaning and IR7 for betatron cleaning. Collimators are placed in hierarchical pattern with primary collimators (TCPs) being placed closest to the beam halo, secondary collimators (TCSGs) and tertiary absorbers (TCLAs). Heavy-ion beam causes effective collimation to be more challenging compared to the proton beam because of ion fragmentation and production of particles with charge-to mass ratio different from that of the main beam. Hence, crystal collimation, previously developed as an R&D concept, was empirically found to be more efficient than standard LHC collimation. This system provides enough impact depth on absorbers limiting production of ion fragments. Such vertical crystal collimator placed in IR7 is crucial for ALICE-FT acting as a primary collimator for the assembly.

ALICE Fixed-Target experiment requires placement of crystal, target and absorbers in the vicinity of ALICE detector - in IR2. Such set-up described and evaluated in [11] for protons is here adjusted for lead ion beam. Bent silicon crys-

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tal is placed in the vertical plane 73 m upstream of ALICE interaction point (IP) 2 — in the shadow of crystal in IR7 to intercept particles deflected by the latter crystal. 5-mm long carbon target is placed behind the crystal — 4.7 m upstream of IP2. Additionally, 4 absorbers are added 150 m downstream of IP2. A schematic overview of ALICE fixed-target assembly is shown in Fig. 1.

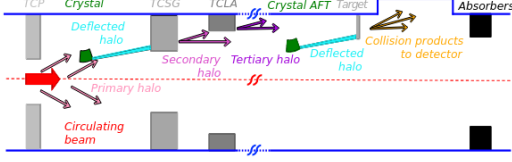


Figure 1: Principle of ALICE fixed-target assembly alongside collimation system. Adapted from [15].

In order not to interfere with the collimation hierarchy, crystal in IR2 half-gap should fall between primary crystal (TCP) in IR7 half-gap of 6.5 and secondary collimator (TCSG) with a half-gap of 8, where σ is one standard deviation of main beam core approximated with a normal distribution in a transverse vertical plane. Hence, crystal in IR2 was placed at the distance of 7.75 σ . Particle halo deflected by crystal in IR2 should also avoid nearby aperture, cross beam B1 center at a distance from the collision point to not impact ALICE main collisions and the particles that do not cause collisions should impact absorbers at a large enough depth. An optimal crystal of 8-mm length and 100-rad bending angle is chosen for meeting the requirements listed above most adequately. Deflected beam trajectory is shown in Fig. 2.

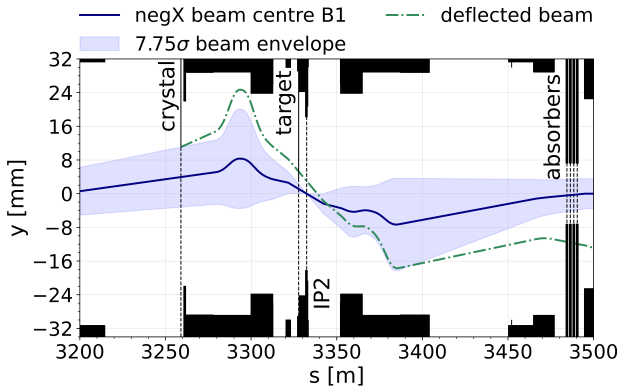


Figure 2: Beam B1 path alongside longitudinal direction s . The blue line and region are the main beam with its envelope of 7.75σ respectively. The dashed teal line is the beam deflected by crystal. Vertical dashed lines mark the ALICE Fixed-Target critical aperture in IR2 and IP2.

ALICE FIXED-TARGET FEASIBILITY

The performance evaluation of proposed ALICE fixed-target assembly for lead ion beam is conducted through a set of dedicated simulations based on SixTrack-FLUKA coupling state-of-the-art framework [16, 17]. Additionally, the initial beam optics parameters are generated using MAD-X (X is the current version) tool [18]. SixTrack (5.5.0) [16, 19]

is used for multi-turn tracking of a particle along the accelerator lattice and FLUKA (4-4.1) [20, 21] — for the particle interaction with the matter of accelerator aperture.

The initial halo distribution is generated at the entrance of crystal in IR7 with the impact parameter of 1 m. The total of $2.8 \cdot 10^6$ Pb particles are injected into the system. With nominal settings, 1025 (0.028%) of initial particles impact the crystal in IR2. To achieve more favorable interception rate, phase scan is conducted following the methodology described in [11]. The number of particles flux depends on the betatron oscillation phase advance between crystal in IR7 and crystal in IR2 — μ_y . It is possible to adjust phase advance value through quadrupole strengths modification. As the change is done only on the small part of the accelerator lattice (vicinity of IP2) and the parameters are set back to the nominal ones after the adjustment, global beam optics parameters remain the same as shown in Fig. 3. Additionally,

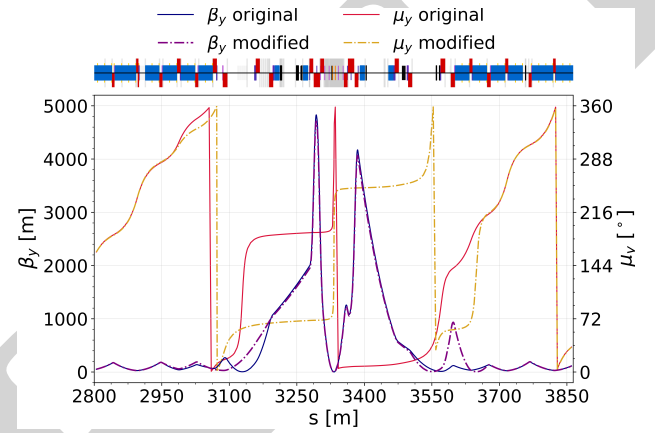


Figure 3: Comparison of betatron function and betatron phase for nominal and optimal phase advance value. Downstream and Upstream of ALICE fixed-target experiment, the parameters are the same providing no global interference with phase matching scheme.

optics parameters at the ALICE collision point are kept the same regardless of phase advance value. To locate the maximum particle on crystal (PoC) value, simulations are conducted for phase advance values covering the full range of 360° . Results of such phase scan are shown in Fig. 4 and it is apparent that the nominal phase advance provides one of the lowest PoC fraction. The maximum PoC is found to be at $\mu_y = 107^\circ$ providing the PoC value of $5.074 \cdot 10^{-3}$, which means over 18 times increase compared to the nominal value.

The angular acceptance of a crystal is 2rad, which means that the vertical tilt of a crystal impacts its channeling efficiency. For each simulation, the angular scan is performed (phase-space distribution of particles on crystal for angular scan is shown in Fig. 5) and the tilt value providing the most particles at the optimal angle is found. Vertical tilt of a crystal provides increase in channeled particles rate from 0% to 40% (401 particles) for nominal phase advance and from 5% to 40% (32540 particles) for optimal phase advance. Lossmaps are the way to verify impact of a modification in

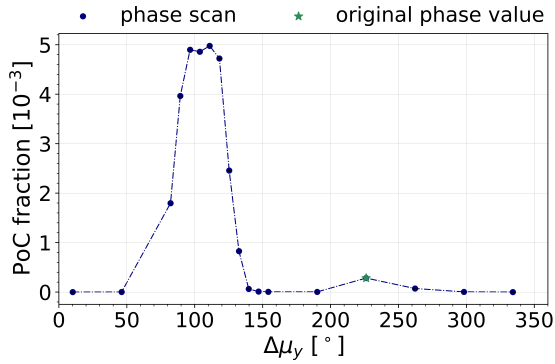


Figure 4: Phase scan for ALICE fixed-target assembly. Number of particles impacting the crystal as fraction is calculated for phase advance values μ_y over the whole range of 360° . The PoC fraction for nominal phase advance is marked as a green star.

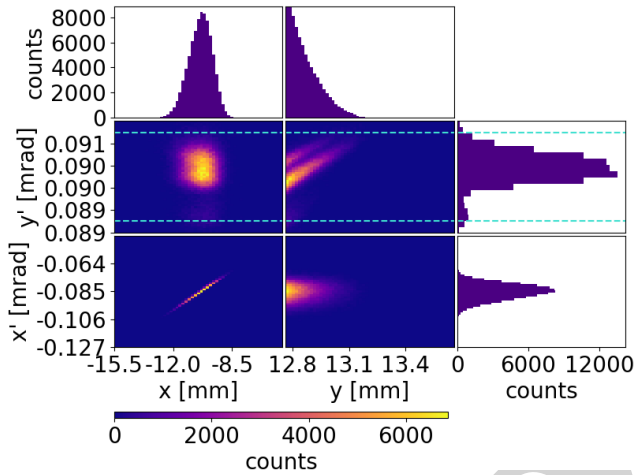


Figure 5: Phase-space distribution of particles impacting the crystal in IR2. Dashed blue lines mark the crystal angular acceptance.

the LHC on the entire machine. They determine the fraction of the entire energy lost in superconducting and regular magnets, as well as collimators, at the specific longitudinal position. Ideally, any change should not cause significant increase in losses. Practically, it is assumed by the rule of thumb, that they should not exceed $10^{-5} \frac{1}{m}$, while exact values are usually found by doing detailed Monte Carlo studies of losses in the region of interest. Lossmaps shown in Fig. 6 compare cleaning inefficiency for HL-LHC without ALICE Fixed-Target experiment and HL-LHC with ALICE fixed-target experiment with nominal and optimal phase advance. The noticeable increase in cold and warm losses occurs with added ALICE-FT assembly, though these picks seem to be at the limit of what can be accepted. From the results of conducted simulations, one can safely assume that the HL-LHC can operated in a controlled way with added ALICE-FT. However, final assessment should be made with MC Simulations of particle impacts in the region of interest and with experimental validation.

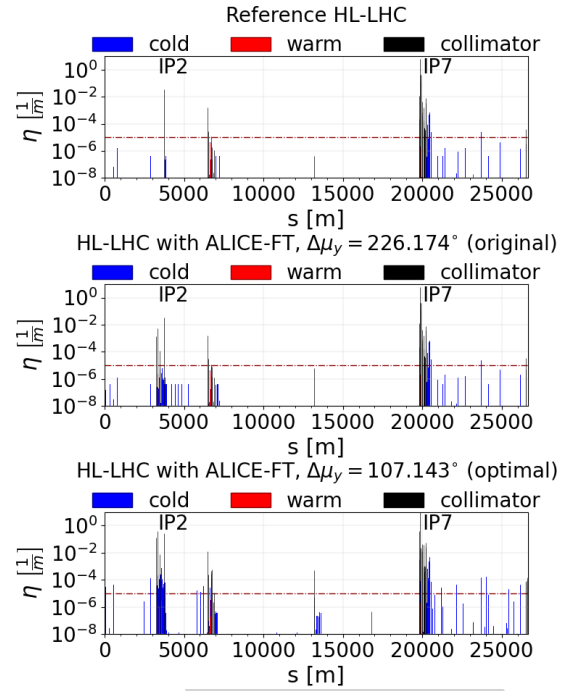


Figure 6: Comparison of lossmaps between HL-LHC without ALICE fixed-target experiment serving as the reference one, HL-LHC with ALICE Fixed-Target experiment with nominal phase advance between crystals in IR7 and IR2 and — with the optimal phase advance value. Vertical blue lines respond to cold losses on superconducting magnets, vertical red lines respond to losses on regular magnets and vertical black lines — to losses on collimators. Horizontal red dashed line relates to a limit usually considered as safe.

CONCLUSIONS

Through the feasibility evaluation conducted in this study, ALICE fixed-target experiment assembly has demonstrated strong capability for efficient integration with the HL-LHC lead ion beam. With the satisfactory particle ratios achieved and the system initially validated for the HL-LHC safe performance, the substantial fundamentals were established for the experimental implementation possibility.

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