ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST024

A LOCAL MODIFICATION OF HL-LHC OPTICS FOR IMPROVED PERFORMANCE OF THE ALICE FIXED-TARGET LAYOUT*

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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 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 using 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. Production of physics events depends on the particle flux on target. The machine layout for the fixed-target experiment is being developed to provide a flux of particles on a target high enough to exploit the full capabilities of the ALICE detector acquisition system. In this paper, we discuss a method of increasing the system's performance by applying a local modification of optics to set the crystal at the optimal betatron phase.

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 opposite beams of protons (p) and lead ions (Pb), allowing for unprecedentedly high centre-of-mass energies of up to 14 TeV and 5.5 TeV, respectively. The ALICE fixed-target (ALICE-FT) programme [2] is proposed to extend the research potential of the LHC 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 channelling 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 ($\sqrt{s_{NN}}$) of 115 GeV. By using high-density targets, a high luminosity, in the order of an inverse femtobarn, can be achieved, allowing for an intensive study of rare processes, quark and gluon distributions at high momentum fraction (x), sea quark and heavy-quark content in the nucleon and nucleus and the quark-gluon plasma, including the QCD phase transition. Most of these phenomena are not accessible otherwise. Details on the physics potential of the ALICE-FT programme are summarised in the AFTER@LHC study group [2, 8].

The problem that we address is to design the machine layout that provides a number of protons on a 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 of the ALICE-FT layout [9] 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 [10, 11]. We also profit from the preliminary designs reported in [12, 13] 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[14]. In this paper, we give an update on the ALICE-FT machine layout. We report on a local optics modification in the insertion hosting the ALICE experiment (IR2) that provides an increased flux of particles on a target by setting the crystal at the optimal betatron phase. This method is independent of the crystal location, allowing for a crystal installation in a place with good space availability.

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) [15], 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 two, 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 [16] to protect its elements, especially superconducting, from impacts of particles from the beam. The 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 based on primary collimators (TCP), secondary collimators (TCSG)

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* This project has received funding from the European Union's Horizon 2020 research and innovation programme, acronym: FixedTargetLand, grant agreement: 101003442.

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Table 1: Some parameters of the future HL-LHC beams important for the ALICE-FT experiment, referred to as *standard* in [15].

Beam energy in collision	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

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 [17], 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

The halo splitting scheme is to be embedded into the transverse hierarchy of the betatron collimation system (see Fig. 1), in between the primary and secondary stage of IR7 collimators, such that the collimation system efficiency is not affected. A fraction of secondary halo particles redirected toward the target can be used for fixed-target collisions instead of disposing them at the absorbers.

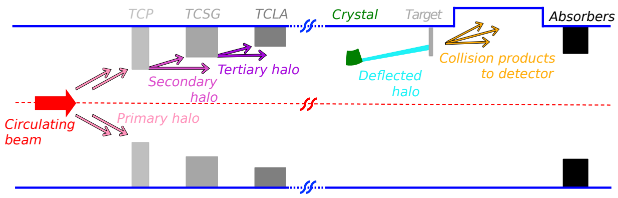

Figure 1: Working principle of the crystal-based fixed-target experiment (right side of the graphics) being embedded into the multi-stage collimation system (left side of the graphics). Graphics based on [14].

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, which can handle in the order of 10^7 protons on target per second [8]. Possible losses originating from the crystal+target assembly are intercepted by downstream absorbers. More details on design assumptions and constraints are given in [9]. The proton flux on target of the recent version of the layout [9] is estimated to reach about 5×10^5 p/s, and the machine is expected to be safe in terms of additional beam losses. However, issues related to space availability for the crystal assembly installation were reported [9]. A possible solution is described in the following paragraphs.

The crystal assembly can be moved from the longitudinal coordinate 3217.5 m (with 0 at IP1) to a location at 3259 m (already proposed in [12]), characterised by good space availability [18, 19]. As shown in Fig. 2, local aperture conditions at 3259 m allow for a common bending angle of the crystal of 200 µrad for both polarities of ALICE detector, which was not the case for the layout at 3217.5 m, where two crystal assemblies with different bending angles were envisioned [9]. On the other hand, for the nominal optics (HL-LHC v1.5 [20]), at 3259 m the number of protons intercepted by the crystal is largely reduced, at least by a factor of four compared to the scenario with the crystal at 3217.5 m, resulting in a significant reduction of the proton flux on target [19]. This is because of the unfavourable phase advance between the primary vertical collimator at IR7 and the crystal at 3259 m, close to $k\pi$, k is a natural number. Therefore, a local modification of IR2 optics is proposed to set an optimal betatron phase at the crystal.

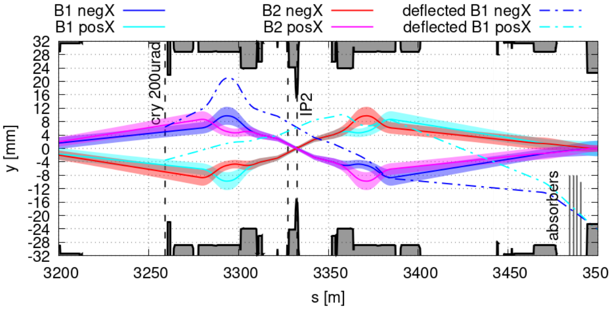

Figure 2: The proposed layout of the ALICE-FT experiment. Both beams (B1 and B2) with their envelopes (7.3σ) are given with solid lines for both ALICE solenoid polarities (posX and negX). Deflected beams are given in dashed blue lines. Machine aperture is given in solid black lines. Vertical dashed lines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

MODIFICATION OF IR2 OPTICS AND EXPECTED PERFORMANCE

IR2 optics modification has been implemented into the MAD-X [21] model of the HL-LHC by changing strengths of IR2 quadrupole magnets labelled with natural numbers from 4 to 10 (lower the number, closer the magnet to the IP2), on both sides of the IP2. Quadrupoles upstream of the IP2 were constrained only 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. Such defined machine models were used as an input to multi-turn particle tracking simulations in SixTrack [22] 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 [23]. Sixtrack simulations were used to estimate 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. About two million protons were used in each simulation scenario, initially distributed over a narrow ring of radius $r + dr$ slightly above 6.7σ in the normalised transverse vertical position-angle phase space (y, y').

By scanning the betatron phase at the crystal, the optimal phase shift of about −65° has been found. The corresponding optical β_y function in IR2 is given in Fig. 3 and changes in strengths of quadrupoles are summarised in Table 3.

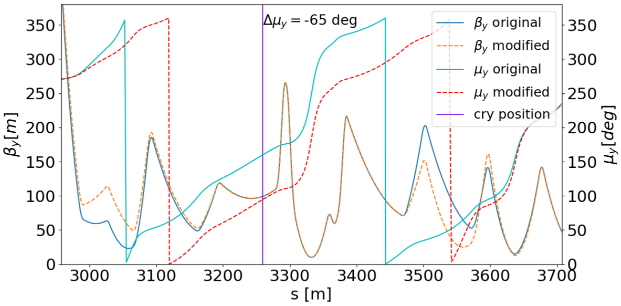

Figure 3: Vertical β function and betatron phase for nominal (solid lines) and modified (dashed lines) optics. Position of the crystal is marked with a vertical purple line.

A crystal set at the optimal betatron phase intercepts significantly more protons, nearly by a factor of seven, compared to the scenario with nominal optics. It results in an increased proton flux on target, in the order of 10^6 p/s, being twice as much as for the crystal at 3217.5 m (a method for the flux estimation is the same as described in [9]). However, no optimisation of betatron phase was done for the crystal at 3217.5 m, and we expect the difference in flux to disappear after phase optimisation in that location. No issues with collimation system efficiency were found due to introduced optics modifications, see Fig. 4. A reference loss map for comparison can be found in [9].

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

	Quadrupole strength k_1 $[10^{-3}\ \mathrm{m}^{-2}]$			
Quadrupole	IR2 left		IR2 right	
number	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

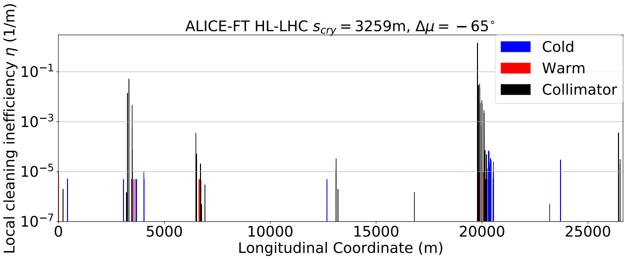

Figure 4: Loss map for the machine containing the ALICE-FT layout, including optics modifications that set the optimal betatron phase at the crystal. The local cleaning inefficency is a measure of the number of protons not intercepted by the collimation system and impacting the machine aperture. The simulation limit of 1 proton lost in the aperture corresponds to $5 \times 10^{-7}\ \mathrm{m}^{-1}$ in a 10 cm longitudinal bin.

CONCLUSIONS AND OUTLOOK

Installation of the crystal at the longitudinal coordinate 3259 m is advantageous in terms of space availability and local aperture conditions. However, for nominal optics, the expected flux of protons on target is very low in this configuration. In this paper, we have summarised a mitigation method based on a local IR2 optics modification that sets an optimal betatron phase at the crystal. It allows reaching a high flux of protons on target, in the order of 10^6 p/s, which is twice as much as reported in [9] and one order of magnitude less than the design goal. Works are in progress to reach the design performance.

ACKNOWLEDGEMENTS

We want to acknowledge the support provided by members of the ALICE Fixed-Target Project meetings [24] and Physics Beyond Colliders Fixed-Target Working Group [25], especially C. Hadjidakis, L. Massacrier and M. Ferro-Luzzi.

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