BENCHMARKING FLUKA SIMULATIONS OF DOUBLE CHANNELING AND CRYSTAL ALIGNMENT AGAINST THE TWOCRYST EXPERIMENT

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Abstract

The TWOCRYST experiment at CERN is a as a proof-of-principle installation designed to demonstrate the feasibility of a crystal-based fixed target experiment, part of the Physics Beyond Colliders programme. The setup comprises two bent crystals installed in the LHC beamline at Insertion Region 3 (IR3), the same as the momentum collimation system. In the double channeling configuration explored in this set up, a splitting crystal (TCCS) extracts particles from the beam through channeling, directing them onto a long crystal (TCCP) inside which particles can be channeled again. This paper presents the FLUKA simulations performed to assess the crystals alignment procedures for various beam and crystal configurations. Since crystal alignment is achieved mainly by monitoring the Beam Loss Monitor (BLM) signals in the vicinity of both bent crystals, the main objective of the simulations is to evaluate the corresponding BLM responses at each step of the alignment. These simulations aim to confirm the validity of the alignment process by demonstrating that the BLM signals can be reliably used to gauge proper crystal alignment. The simulation outcomes are presented here and were found to be consistent with experimental observations.

INTRODUCTION

The use of bent crystals in high-energy accelerators allows precise manipulation of particle trajectories through channeling in the crystal lattice [1]. The proposed ALADDIN experiment is designed to employ this technique to measure the magnetic and electric dipole moments of charm baryons by inducing spin precession within bent crystals [2, 3].

As a precursor to this experiment, TWOCRYST [4, 5] serves as a proof-of-principle installation, testing the operational feasibility of double channeling, probing the crystal efficiency, and determining the particles on target, one of the main metrics of the experiment. One of the challenges in the operation of such a setup is the very precise angular alignment needed, and the high-precision, fast and sensitive controls needed for this. This study makes use of FLUKA [6–8] simulations to evaluate whether variations in Beam Loss Monitors (BLM) signals can be used to align the crystals during channeling and amorphous conditions across a range of beam energies (450 GeV, 1 TeV, 3 TeV and 6.8 TeV).

Charged particles can become confined within the electrostatic potential wells formed by the lattice planes of a crystal. When such a crystal is mechanically bent, the channeled particles follow the curvature of the planes, resulting in a controlled deflection of the particles [1, 9].

Channeling is possible only if the energy of the transverse motion of an incoming particle is less than the depth of the channel electrostatic potential well. This condition leads to the existence of a maximum incident angle for channeling, called *the critical angle*, defined as

$$\theta_c = \sqrt{\frac{2U_e}{pv}}, \tag{1}$$

where U_e represents the potential energy well, p the particle momentum, and v the particle velocity.

TWOCRYST exploits the channeling capabilities of two bent crystals: the TCCS (4 mm-long with a 50 μrad bending) extracts a beamlet from the LHC halo, while the TCCP (70 mm-long with a 700 μrad bending) performs further deflection of the particles [10–12]. Two Roman Pot stations house a pixel detector and a fibre tracker (TFT) which measure the deflected beam properties. The layout is shown in Fig. 1. This is done for one of the two counter-rotating beams of the LHC (beam 2).

The movement of the goniometer supporting each crystal is assisted by BLMs to ensure precise alignment. In the case of the TCCS, the BLM is located 1 m downstream and should see a signal reduction when the crystal is in channeling as fewer nuclear interactions occur, and thus fewer secondaries reach it. On the other hand, the TCCP BLM is positioned at the location where the channeled beam exits the vacuum chamber, such that when the TCCP is in channeling, deflected particles will directly impact the BLM, resulting in a sharp signal increase. The BLM responses were compared to beam halo losses on the primary collimator (TCPs) [13–18] for different beam energies.

FLUKA MODEL

To reproduce the geometry of the TWOCRYST setup in detail, dedicated FLUKA models were developed for both crystals and their vacuum tanks [19]. Figure 2 shows the resulting assemblies. Two BLMs were included in the model near the crystal locations corresponding to the integration in the LHC tunnel.

Each study case starts takes as input a set of six-dimensional coordinates representing particles impacting either the TCCS, TCCP, or the primary collimator (TCP). These are generated beforehand in dedicated combined tracking and particle-matter interaction simulations performed with MADX [20].

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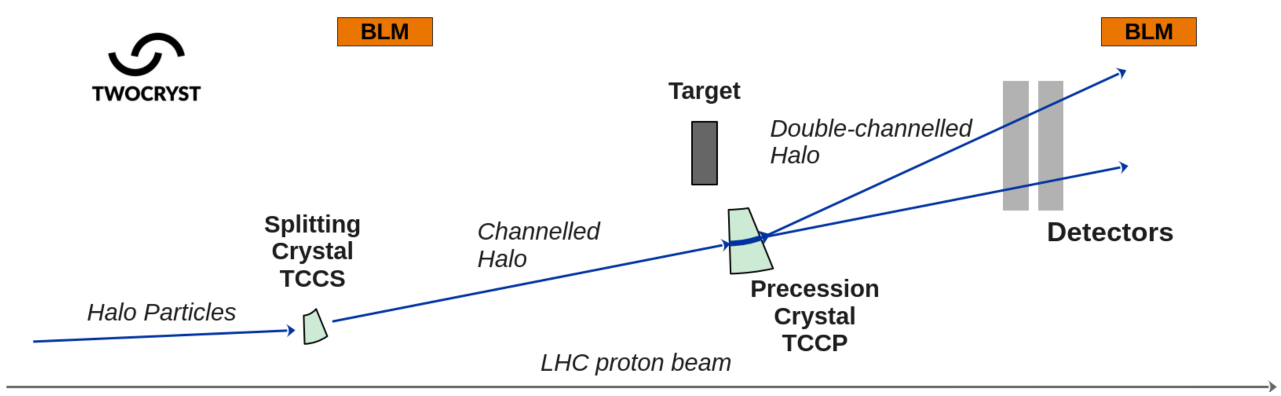

Figure 1: Schematic TWOCRYST layout showing positions of TCCS, TCCP, BLMs, and downstream detectors (TFT and pixel detector). A tungsten target, used in the ALADDIN experiment and removed for TWOCRYST is also indicated.

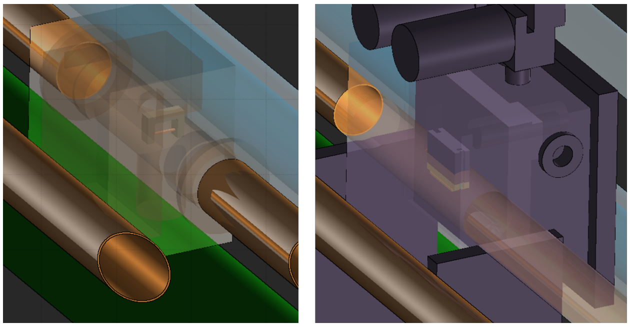

Figure 2: FLUKA model of TCCS (left) and TCCP (right) crystal assembly and tank.

Initial runs with 10 simulated particles were used to assess the beam–crystal alignment. The crystal tilt was tuned to match the average incoming beam angle, ensuring it lay within the critical channeling angle range. The position (half-gap) of the second crystal was refined such that the beam intersected the crystal region. This alignment and tuning procedure was performed for each energy configuration to optimise channeling efficiency in the FLUKA simulation.

Previous comparisons with experimental data [21] indicate that FLUKA tends to overestimate channeling efficiency for long crystals such as TCCP, which was considered when interpreting results. Shorter crystals such as the TCCS generally achieve higher efficiencies (60–80%), while longer crystals like the TCCP show lower values (30–50%) due to de-channeling along the length of the crystal.

SIMULATION RESULTS

The experiment consisted in an angular scan of the crystals orientations with respect to the beam. The crystal would be rotated slowly, using the BLM signal to determine which orientation the crystal was in. To assess if this was feasible in FLUKA, six configurations would be simulated. An additional reference case, with both crystals out and both LHC beams impacting on their respective TCP was used as a baseline for normalisation.

BASE: Baseline case. Standard configuration with the beam in both beam pipes and no crystals inserted. The first impact per turn on collimators in IR3 after scattering in IR7 was recorded as the source term. Simulations were summed for contributions from both Beam 1 and Beam 2.

TCCS AM: The TCCS is inserted in amorphous orientation, acting as the bottleneck while the TCCP is retracted.

TCCS CH: The TCCS is inserted in channeling orientation while the TCCP is retracted.

CH-AM: The TCCS intercepts and channels the primary halo, while the TCCP is positioned downstream to intercept and scatters the deflected beam in amorphous.

CH-CH: Double channeling configuration. The TCCS intercepts and channels the primary halo, while the TCCP is positioned downstream to intercept and re-channel the deflected beam, directing onto the downstream BLM.

TCCP AM: The TCCP acts as the bottleneck, with the TCP retracted and the TCCS out. The TCCP is rotated to its amorphous orientation scattering rather than channeling the beam.

TCCP CH: Identical to the previous configuration, except that the TCCP is in channeling orientation steering the primary halo.

The relative BLM signal (normalised to the baseline case) was extracted for both monitors: the BLM signal at the TCCS and at the TCCP. The corresponding results are summarised in Table 1 and Table 2.

Distinct patterns were observed across the two monitors:

BLM after TCCS: The signal consistently decreased compared with the amorphous case when TCCS was in the channeling configuration. The channeling signal, compared to amorphous - shows a reduction factor $\sim$3 at 450 GeV and 1 TeV. In the amorphous configuration the inelastic collisions

Table 1: Relative BLM signal after the TCCS (normalised to the baseline) for each configuration and beam energy.

Case	**450 GeV**	**1 TeV**	**3 TeV**
BASE	1.00	1.00	1.00
TCCS AM	3.58(38)	3.10(18)	1.42(17)
TCCS CH	1.30(15)	1.18(09)	0.77(12)
CH-AM	1.25(14)	1.18(07)	0.75(11)
CH-CH	1.26(15)	1.20(08)	0.79(10)
TCCP AM	0.79(08)	0.73(04)	0.61(07)
TCCP CH	0.79(08)	0.73(04)	0.61(07)

Table 2: Relative BLM signal after the TCCP (normalised to the baseline) for each configuration and beam energy.

Case	**450 GeV**	**1 TeV**	**3 TeV**
BASE	1.00	1.00	1.00
TCCS AM	3.55(23)	2.06(23)	1.77(30)
TCCS CH	1.01(29)	1.73(29)	1.86(18)
CH-AM	$3.49(31)\times10^2$	$5.89(31)\times10^2$	$2.48(14)\times10^2$
CH-CH	$6.26(75)\times10^3$	$1.42(75)\times10^4$	$1.98(11)\times10^3$
TCCP AM	$4.54(33)\times10^1$	$6.30(33)\times10^2$	$2.40(13)\times10^2$
TCCP CH	$1.69(16)\times10^4$	$2.96(16)\times10^4$	$6.68(37)\times10^3$

cause particle cascades that result in a signal increase on the BLM, in channeling the beam is neatly deflected away. For TCCP in the main beam, the signal on the TCCS BLM was only the background contribution from beam 1.

BLM after TCCP: The signal increased sharply compared to the TCCP in amorphous case , demonstrating that the deflected beam was indeed hitting the BLM.

At 6.8 TeV, only TCCS AM and TCCS CH were simulated with only 20% of the particles on target being channeled, due to a greater distribution of the incident angle, and decrease in θ_c. No measurable BLM signal change was detected, indicating that BLM-based alignment is not feasible at such high energies.

EXPERIMENTAL BENCHMARK

We compare these results with experimental measurements obtained at CERN during dedicated beam time allocated to the TWOCRYST Collaboration. A comprehensive description of the experimental setup, methodology, and results is provided in [22]. Here, we refer to those results only insofar as they are relevant for comparison with the present simulations.

As shown in [22], the TCCS BLM signal decreases when the TCCS enters the channeling regime, as nuclear interactions, the dominant contribution to local losses, are suppressed. At 450 GeV, a reduction by approximately a factor of eight is observed. Conversely, the signal of the TCCP BLM, located along the trajectory of the double-channeled beam, increases by a factor of 2.5 when both crystals are aligned for channeling.

The simulated BLM signal observed for the TCCS underestimated the value shown in the experiment by a factor of ~ 3. It should be noted that accurately modeling the noise in such complex configurations remains particularly challenging, thereby limiting the reliability of quantitative predictions for the observed increases and reductions. Further investigation of these effects is therefore warranted. Additional sources of uncertainty in the comparison include a possible overestimation of the channeling efficiency for long crystals in the FLUKA model, an incomplete description of crystal manufacturing defects, imperfect alignment of the channeled beam with respect to the TCCP BLM, and a broader angular distribution of particles incident on the target under experimental conditions. The influence of crystal torsion on the signal, as well as its contribution to the observed reduction in the experimental signal, is discussed extensively in [5]. These aspects constitute important directions for future work and will be investigated in upcoming studies.

CONCLUSION

The crystal-related capabilities of the FLUKA code make it possible to reproduce the alignment steps of the TWOCRYST experiment where two crystals are in turn aligned to the LHC Beam 2 in order to achieve double-channeling. Due to this complex setup, the alignment procedure relies on multiple configurations of crystal positions and alignment. FLUKA simulations were conducted in 7 of those configurations, including a base case used for result normalisation. The results confirmed the expected BLM response around the TWOCRYST experimental setup, thus validating ahead of the data taking that BLM signals could be used to assess crystal alignment. Channeling of TCCS led to a reduction of the BLM signal by a factor 2-3 and channeling of TCCP led to an increase of the second BLM reading by a factor 50-400, qualitatively consistent with experimental observations trends up to 3 TeV. At 6.8 TeV, where the TCCP can only channel secondaries, no measurable variation was observed for either BLM, indicating BLM-based alignment is not possible in all conditions. Overall, the results validate BLM-based alignment as a reliable method for the TWOCRYST experiment as well as for future ALADDIN related investigations.

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