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PREDICTING THE MULTI-TURN CHANNELLING EFFICIENCY OF A 7 mRAD-BENDING SILICON CRYSTAL IN THE LARGE HADRON COLLIDER FOR TeV-RANGE PROTON ENERGIES

K. A. Dewhurst*, C. Maccani, M. D'Andrea[1], P. D. Hermes, D. Mirarchi, S. Redaelli
CERN, Geneva, Switzerland
[1]now at INFN-LNL, Legnaro (PD), Italy

Abstract

A double-crystal fixed-target experiment is planned for installation in CERN's Large Hadron Collider (LHC). This experiment features a 7 cm-long bent silicon crystal, with 7 mrad bend-angle to deflect particles produced by proton interactions with a target. As this crystal is more than an order of magnitude longer than any other installed in the LHC, it requires specific characterization, alignment, and testing. Testing will begin using the LHC's proton beam at different beam energies, before considering studies of interactions with particles out scattered from a target. Using a particle tracking program, we simulate the expected signals from the angular alignment of this unique crystal with multi-turn halo particles of the circulating LHC proton beam. A range of beam energies is considered to evaluate the performance, as particles with a spread of energies are anticipated downstream of the target following the interactions of the 7 TeV proton beams in the final experiment. The simulation results predict the crystal's multi-turn efficiency as a function of energy and serve as a benchmark for the commissioning process to integrate this long crystal into the LHC.

INTRODUCTION

As part of the Physics Beyond Colliders (PBC) studies at CERN [1], a fixed target experiment is proposed for Insertion Region (IR) 3 (momentum collimation [2, 3]) of the Large Hadron Collider (LHC) to measure the spin-precession properties of short lived baryons, such as the Λ_c^+ [4, 5]. The proposed spin-precession experiment incorporates two bent silicon crystals: a first crystal to deflect LHC protons onto a fixed target, and a second to bend the trajectories of the rare baryons produced from the target, causing their precession. The first crystal, TCCS (Target Collimator Crystal for Splitting), has the same parameters as those already installed in the LHC for beam collimation purposes [6], with 4 mm length and 50 µrad bend angle [7]. Whereas, the second crystal, TCCP (Target Collimator Crystal for Precession) is 70 mm long with a significantly larger bend angle of 7 mrad. In preparation for the spin-precession experiment, a proof-of-principle test-stand TWOCRYST [8–10], is planned to test the double crystal channelling configuration and characterise the TCCP.

One objective of TWOCRYST is to measure the multi-turn channelling efficiency of each crystal. Particles entering a bent crystal within a critical angle θ_{crit} can become captured in the potential well between the crystalline planes and thus are channelled along the crystal [11]. Some particles will undergo other interactions with the crystal lattice, such as amorphous (Coulomb) scattering, which can cause a particle in channelling to become dechannelled [11]. The channelling efficiency ϵ_{ch} is defined as the proportion of channelled particles compared to the total number of particles impacting the crystal with the potential to be channelled (i.e. those entering within $\pm\theta_{crit}$);

$$\epsilon_{ch}[\%] = \frac{\text{no. particles channelled}}{\text{total no. particles}} \times 100. \quad (1)$$

In the spin-precession experiment, 7 TeV protons impacting the tungsten target are expected to produce a significant yield of Λ_c^+ particles in the energy range of 1 TeV to 6 TeV [4]. At the same time, the TCCP crystal is designed to allow for particle channelling up to a maximum energy of 5.2 TeV, so that it cannot steer 7 TeV beam protons directly into the downstream experimental detector in the final experiment. Therefore, it is important to characterise the channelling behaviour of the TCCP at such intermediate energies. A Machine Development (MD) study has recently confirmed that the LHC energy ramp from injection 450 GeV to flat top 6.8 TeV can be carried out with intermediate steps [12]. This allows the LHC to be efficiently set-up for crystal measurements with a proton beam at 2-4 intermediate energies whilst avoiding the lengthy recovery periods required if one had to perform a different ramp cycle for each energy value of interest. In this paper, we explore a proposed method to measure the multi-turn channelling efficiency of the TCCP in operation for the TWOCRYST experimental set-up. We use multi-turn channelling simulations for the TCCP in the particle tracking program SixTrack [13–15] to predict the expected multi-turn channelling efficiency of the TCCP as a function of energy. Our results serve as predictions for the TWOCRYST measurements planned for 2025.

A DOUBLE-CRYSTAL MACHINE EXPERIMENT: TWOCRYST

The TWOCRYST test-stand is planned for installation in IR3 of the LHC using Beam 2, which circulates anticlockwise. The main components of the experiment include the TCCS, tungsten target, TCCP, several detector devices, and an existing TCLA collimator (Target Collimator Long Absorber). Amongst the detector devices it is foreseen to install one movable 2D pixel detector housed in a Roman

* kay.dewhurst@cern.ch

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Pot (RP) [16], and a Beam Loss Monitor (BLM) outside the beam pipe; approximately 1 m and 5 m downstream of the TCCP respectively. The set up is arranged so that channelled particles are deflected vertically; those from the TCCS can be intercepted by the TCLA and channelled particles from the TCCP can be detected with the BLM. The 2D-detector can be moved vertically to intercept the channelled beam from either crystal. The layout of components relevant to this study is shown in Fig. 1, for two configurations.

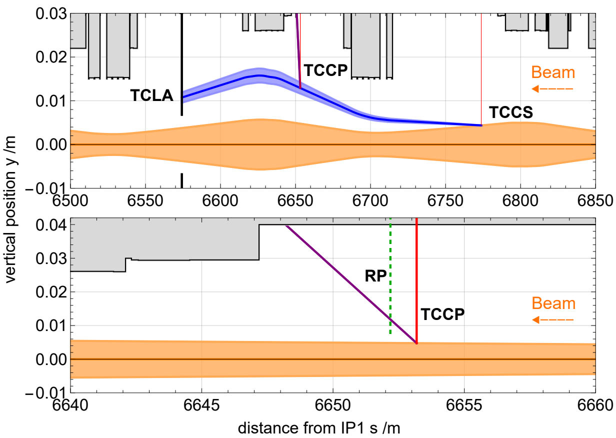

Figure 1: Layout of components in IR3, for a 1 TeV beam. Upper: Double-channelling configuration. Lower: Alignment of the TCCP with the main beam. Beam 2 (orange) travels from right to left. Particles channelled by the TCCS (blue) can be absorbed by the TCLA. Particles channelled by the TCCP (purple) pass through the pixel detector, housed in an RP, before being lost on the aperture (grey). A BLM outside the beam pipe will be placed to detect these losses.

MULTI-TURN CHANNELLING EFFICIENCY

Established Operational Procedure

Multi-turn channelling efficiency measurements have been carried out for the existing collimation crystals in the LHC [7]. The measurement procedure involves first, aligning the crystal to the edge of the main beam, and second, rotating the crystal in an angular scan to find the optimal channelling orientation. The angular alignment is performed while continuously inducing beam losses on the crystal using the LHC transverse damper (ADT) [17]. Finally, when the crystal is aligned in both position and angle, a downstream collimator is gradually moved toward the beam from its nominal position, intercepting the channelled, dechannelled, and scattered particles until it touches the edge of the main beam. The losses on the crystal and reference collimator are detected by their respective local BLMs.

This linear collimator scan enables the integrated losses to be plotted against transverse position. The resulting transverse profile is then fitted with an error function to calculate the number of channelled particles. The total number of particles entering the crystal is estimated by the sum of particles deflected outside of the main beam i.e. the intercept point with the spike from main beam losses. Further details of this method [18–20] and results for the existing LHC crystals are available in the references [7, 21]. As the channelled particles from the TCCS can be intercepted downstream by the TCLA (as shown in Fig. 1), this established procedure can be used to measure the channelling efficiency of the TCCS. However, a different approach is required for the TCCP, as channelled particles from this crystal cannot be intercepted by a collimator.

Proposed Method for the TCCP

The initial TCCP alignment and its angular scan can be carried out in the standard way; with losses from an angular scan detected by the local BLM. We propose to find the transverse profile information using the signal on the 2D detector, instead of using a linear collimator scan. The detector is based on the VeloPix design [22, 23] with 256 × 256 pixels of 55 µm width, giving a sensitive area of 14 × 14 mm^2. We will explore the application of this proposed method to predict the multi-turn channelling efficiency of the TCCP.

SIMULATION AND ANALYSIS

Using the particle tracking program SixTrack, the TCCP was set to 5 nominal beam σ (with nominal normalized emittance of 3.5 µm rad) to intercept the edge of the main beam. The betatron primary collimators (TCPs in IR7) that usually define the beam envelope were retracted to 6σ. A distribution of 1×10^7 particles with a Gaussian profile in x, px and an annular halo (width of $\delta y = 0.005\sigma$) around 5σ in y, py, was initialised at the entrance of the TCCP. Particles were tracked for 200 turns using the 2024 LHC optics setting from the combined ramp-and-squeeze closest to the desired energy [24]. Beam energies of 450 GeV (injection), 1 TeV, 2 TeV and 3 TeV were considered.

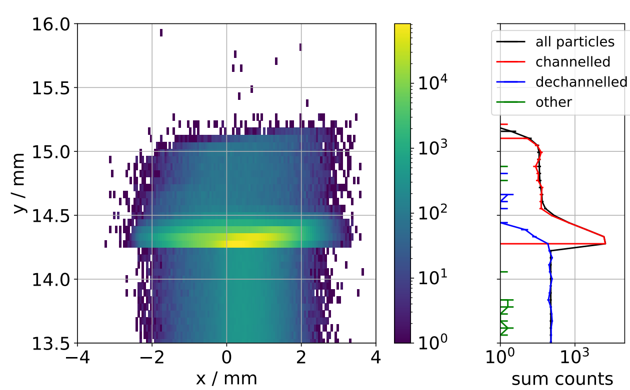

Figure 2: Left: Beam spot at the pixel detector (sum of all turns) for 450 GeV protons from a full simulation (10^7 particles). The displayed bin width is equal to the 55 µm pixel size of the detector. Right: The sum of counts from each pixel row for one simulation run (10^5 particles), showing the contribution of each crystal interaction process to the observed distribution on the detector. Log scale on x-axis.

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Figure 2 shows a typical beam spot at the pixel detector for the 450 GeV case. Particles channelled from the main beam edge form a well-defined peak at 14.3 mm, with dechannelled particles below. A small proportion of particles undergo a first interaction with the crystal (most often volume reflection) which increases their oscillation amplitude, and are channelled from a larger initial y-position in a later turn. This produces the highest (above 14.5 mm) particle positions on the detector.

The main channelled peak (at 14.3 mm in Fig. 2) is expected to have a Gaussian profile. However, the spread of channelled particles exiting a bent crystal from a point source is around $\pm\theta_{crit}$ (values listed in Table 1). As the detector is 1 m downstream, this profile only covers a range of $\tan(2\theta_{crit}) = 17.9$ µm in the 450 GeV case, which alone is not observable on the 55 µm resolution detector at this close range. Instead, the peak width is determined by the y-positions of particles from the incoming distribution (few 10s of µm). Therefore, we do not attempt a Gaussian fit, instead we sum all counts in the main channelled peak to estimate the number of channelled particles (N_{ch}^{pix}).

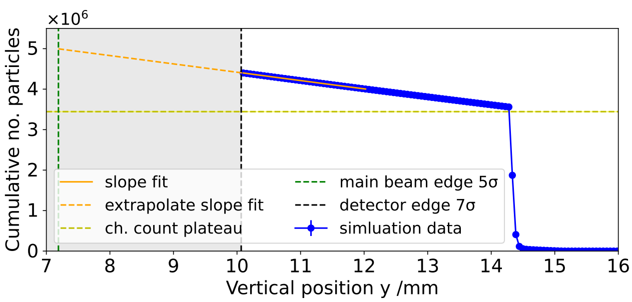

Figure 3: Integrated number of particles above each y-position for a 450 GeV beam. The number of channelled particles is shown as a plateau. An approximation of the total particles is made by extrapolating a linear fit to intercept the main beam edge.

The integrated profile in y can be used to estimate the total number of particles interacting with the TCCP. An example plot, reminiscent of the usual BLM plot from a collimator scan, is shown in Fig. 3. The lower edge of the pixel detector is estimated at 7σ as, being housed within the RP, the active area will not reach the beam edge. Therefore, data in the grey region is not available from measurement.

As an approximation, we extrapolate a linear fit of the dechannelled particle slope to intercept the main beam; estimating the total number of particles impacting the crystal (N_{tot}^{int}). However, a linear fit does not accurately reflect the particles in the grey region, as it excludes amorphous scattered particles close to the main beam. By comparing to the number of impacting particles in our simulation (N_{tot}^{sim}), we find this method underestimates the number of impacting particles by a factor ranging from 1.3 (at 450 GeV) to 1.8 (at 3 TeV), resulting in an overestimate of the channelling efficiency (final column Table 1). Further work can explore whether the estimate of the total impacting particles from this technique can be scaled based on physics models to give an improved estimate for use with operational measurements. A benchmark could be made using the TCCS, as its multi-turn channelling efficiency can be measured by both scanning with the downstream TCLA and using the 2D detector. Previously, an approach with two similar methods was taken to measure the multi-turn channelling efficiency of a crystal (CR2) in the SPS [25].

Table 1: Predicted Multi-Turn Channelling Efficiency of the TCCP from SixTrack Simulations

Beam energy [TeV]	**Critical angle** [µrad]	**Ch. efficiency** [%] **true** $N_{ch}^{sim}/N_{tot}^{sim}$	**pix. count** $N_{ch}^{pix}/N_{tot}^{sim}$	**pix. count & int.** $N_{ch}^{pix}/N_{tot}^{int}$
0.45	8.95	54.1	54.0	69.0
1.0	5.36	56.2	57.8	75.0
2.0	2.96	45.5	48.3	69.0
3.0	1.74	25.5	29.5	52.2

SixTrack can directly report the total number of particles interacting with the crystal during a simulation (N_{tot}^{sim}) and the total number channelled (N_{ch}^{sim}); this gives the expected (*true*) values of the channelling efficiency, shown in Table 1. The efficiency from counting the channelled peak bins on the pixel detector (pix. count) compared to both the total from simulation (N_{tot}^{sim}) and the intercept (N_{tot}^{int}) are also reported.

The pixel-count approach better estimates the true number of channelled particles at lower energies because the channelled spot size decreases with energy, e.g. at 3 TeV the main channelled peak only covers the width of 2 pixels, increasing the uncertainty of the reported count from this method. A high signal intensity over only a few pixel rows is a concern for operation, as it may damage the detector. An acceptable intensity impacting a single pixel needs to be defined ahead of the TCCP multi-turn efficiency measurements.

CONCLUSIONS

Particle tracking simulations were carried out to predict the multi-turn channelling efficiency of a 7 mrad bent silicon crystal, planned for installation in the LHC as part of the TWOCRYST experiment. First measurements will be done directly with a circulating proton beam. The proposed measurements using a pixel detector give good estimates of the number of channelled particles, especially at lower energies where the channelled spot size is larger. However, difficulties in measuring the total number of particles interacting with the crystal are likely to produce measured efficiencies that overestimate the true efficiency of the crystal. The multi-turn efficiency is expected to be highest at 1 TeV, with a true efficiency of $\epsilon_{ch} = 54$ % and lowest at 3 TeV, with $\epsilon_{ch} = 26$ %. The decrease in efficiency at energies above 1 TeV is driven by the decreasing angular acceptance (critical angle) of the crystal. Further studies will be useful to enable better estimates of the impacting particles from measurements and subsequently, the true channelling efficiency.

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