Simulating and Analysing Crystal Channelling in the Large Hadron Collider

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Introduction

Crystal collimation is a type of advanced beam cleaning where bent silicon crystals are used to steer beam halo particles toward an absorber. Crystals are materials with a highly organized atomic structure, so when charged particles interact with a crystal at the right impact conditions, they become trapped in the potential well generated by neighboring crystalline planes. These particles are forced to follow the direction of the atomic lattice, oscillating in the relatively empty space between the planes. This phenomenon is referred to as "channeling."

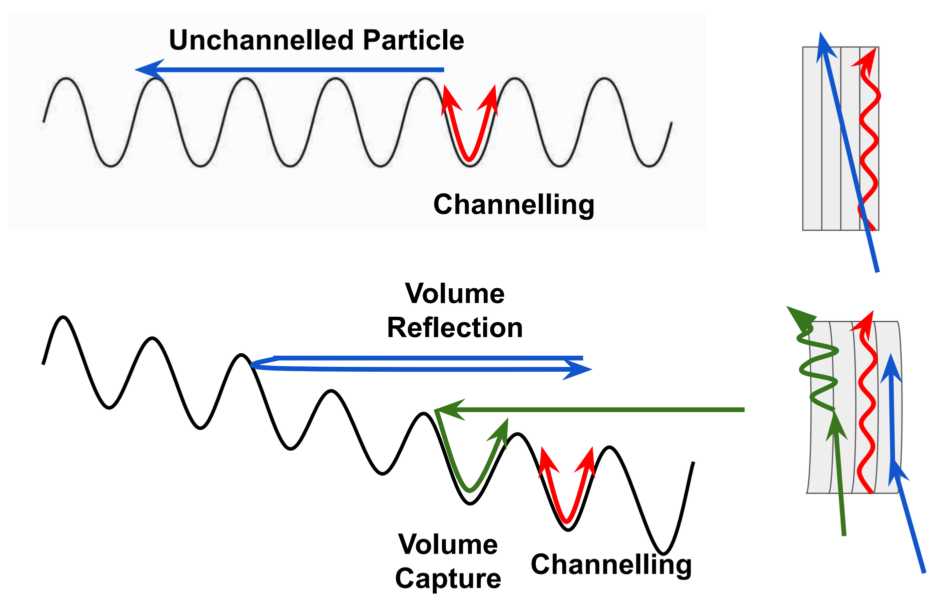
The current work done in the Non-linear Dynamics and Collimation (NDC) group uses bent crystals to channel beam halo particles in the Large Hadron Collider. It is particularly useful for channeling lead ion beams, as the crystal applies the same steering angle for intact lead ions and fragments. For this reason, crystal collimation is being implemented for the High Luminosity-LHC project to improve the ion collimation cleaning efficiency [1].

Phenomena from Crystal Particle Interactions

Besides channeling, there are other types of behaviors that may occur:

- Volume Reflection
- Volume Capture
- Dechanneling
- Amorphous scattering

These phenomena show up in very specific ways when you graph the relative incident angle (the angle at which the particles enter the crystal) vs. the kick angle (the deflection of each particle).



Finding the "Channelling Efficiency"

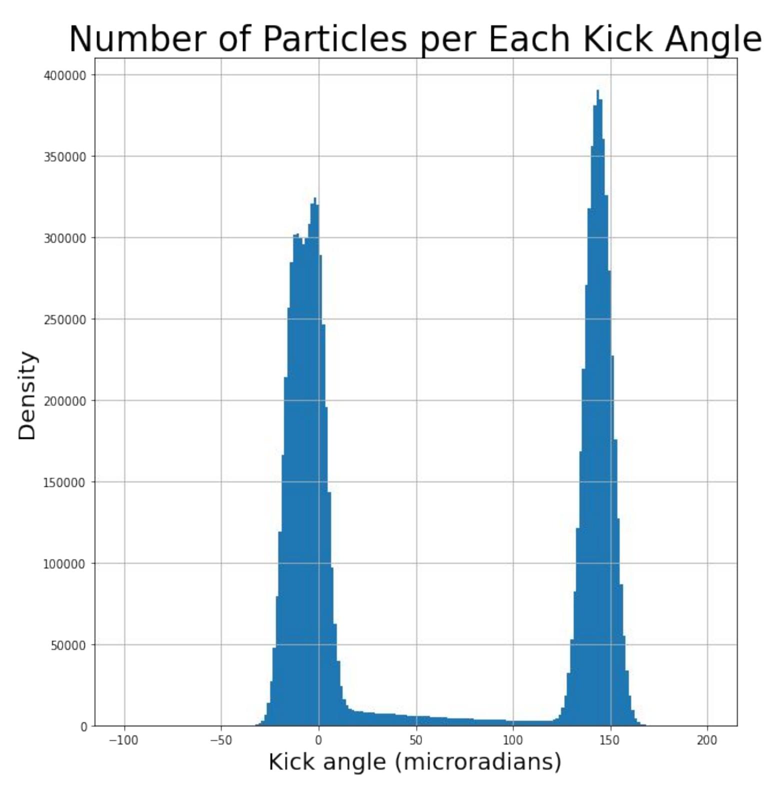
By isolating the peaks with the highest kick angles we can view just the particles that experienced either Volume Capture or Channelling.

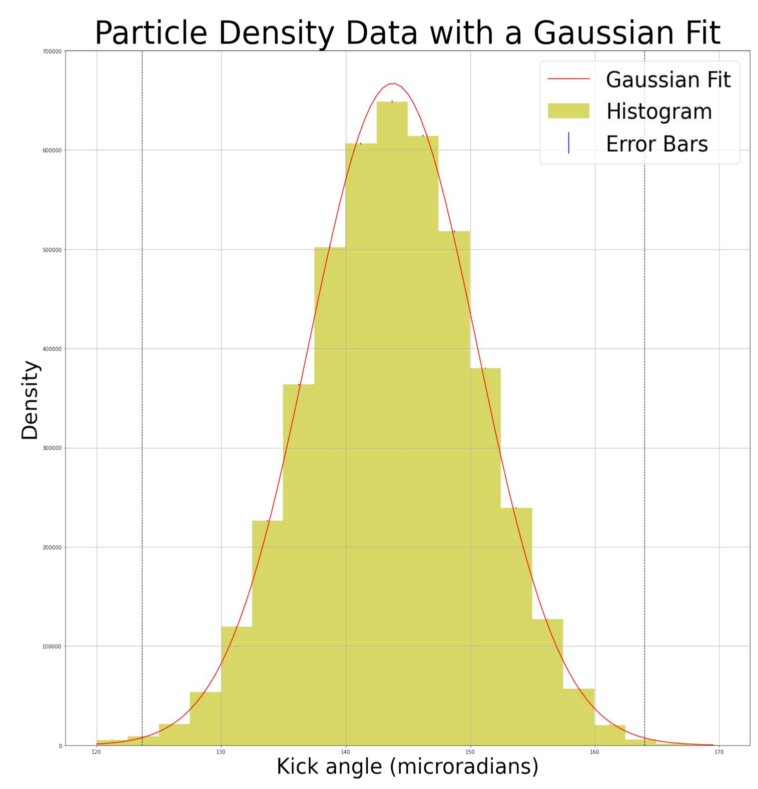
I further isolated the channeling peak, and fit it with a Gaussian curve. I then determined which points land within three sigma of the peak value. This is the range where particles are considered channeled.

Total number of particles in the cut: 6,824,780

Number of particles within ±3σ: 4,509,501

Channelling Efficiency: 66.08%

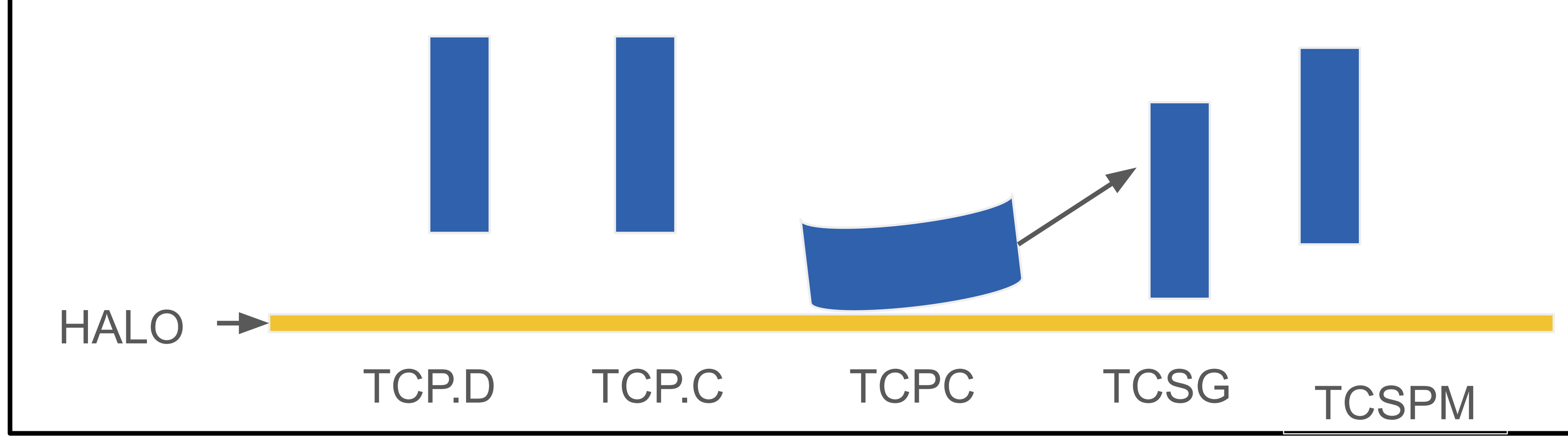




Overview of My Project

For my project, I am using the simulation program SixTrack to simulate the results of a recent Machine Development (MD) study in the LHC from May 15th, 2024. The main collimators and crystal used for this simulation are shown below.

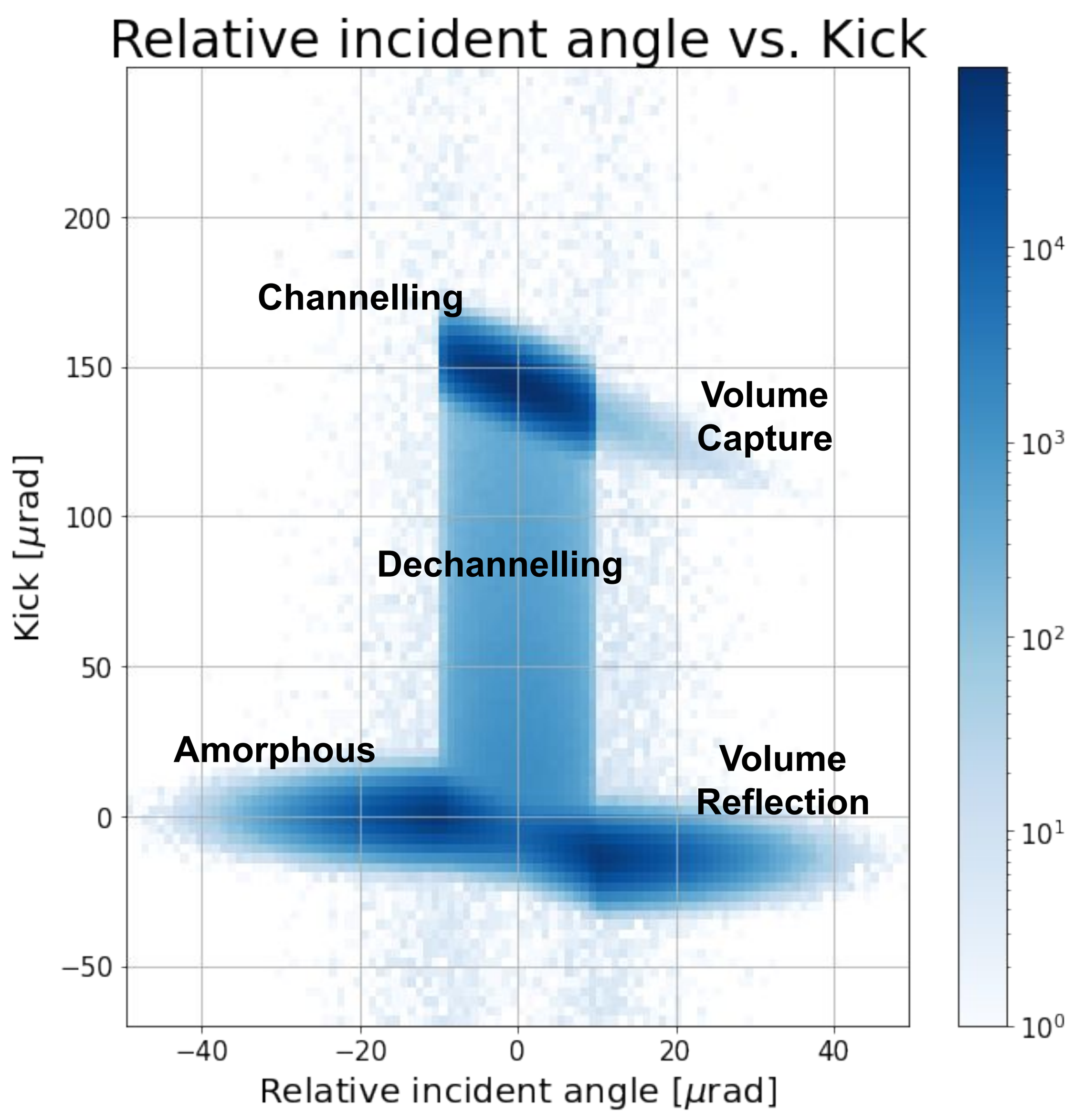
My first step was to develop an analysis algorithm, which calculates the channeling efficiency, or the percent of particles channeled by the crystal. To build this script, I used data from an existing SixTrack simulation.



Recognizing Phenomena

This 2D plot shows the presentation of each phenomenon in graphical form.

Because channeling and Volume Capture have a similar Kick Angle, they can be difficult to differentiate if the density of each phenomenon is so different (as in this data).



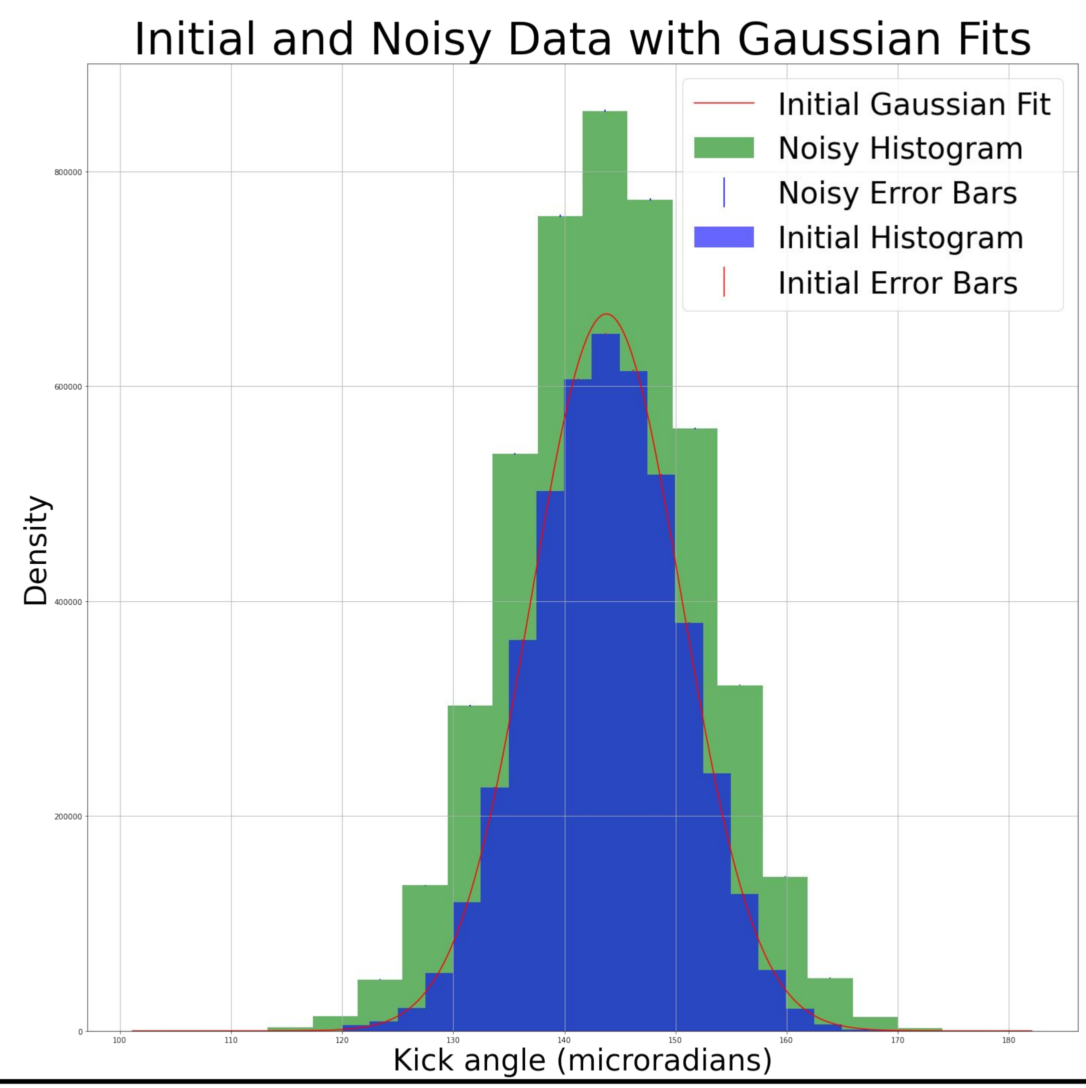
Including Resolution

An experimental resolution is included by adding random gaussian noise to the simulated deflections at the same level that noise occurs in the experiment. The effect of this resolution can be seen in the next graph as the light green buffer around the data.

Total number of particles in the cut: 6,824,780

Number of particles within ±3σ: 4520869

Channelling Efficiency: 66.24%



Conclusions and Next Steps

I found that the results of my simulation analysis match up well with results from a corresponding NDC paper [2], which validates the simulation tool and my analysis script. I am currently using SixTrack to simulate a test of a TCPC crystal in the LHC. I have completed the first simulation using particles at 450 GeV and will repeat the process considering crystal channeling at higher energies of 1 TeV, 3 TeV, and 5 TeV. I will then use the analysis script described here to find the channeling efficiency at each energy, so it can be compared to the collected data from the MD measurements.

Acknowledgements and Sources

[1] M. D'Andrea, O. Aberle, R. Bruce, M. Butcher, M. Di Castro, R. Cai, I. Lamas, A. Masi, D. Mirarchi, S. Redaelli, R. Rossi, and W. Scandale, "Operational performance of crystal collimation with 6.37 Z TeV Pb ion beams at the LHC," 2024

[2] D. Mirarchi, G. Hall, S. Redaelli, W. Scandale, "A crystal routine for collimation studies in circular proton accelerators," 2015

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