Crystal Channelling Optimisation in the LHC Using Reinforcement Learning

A. Vella†,1,2, D. Mirarchi[1], G. Valentino[2], R.Cai[1], S. Redaelli[1],
[1] European Organization for Nuclear Research, Geneva, Switzerland
[2] University of Malta, Msida, Malta
†andrea.vella@cern.ch

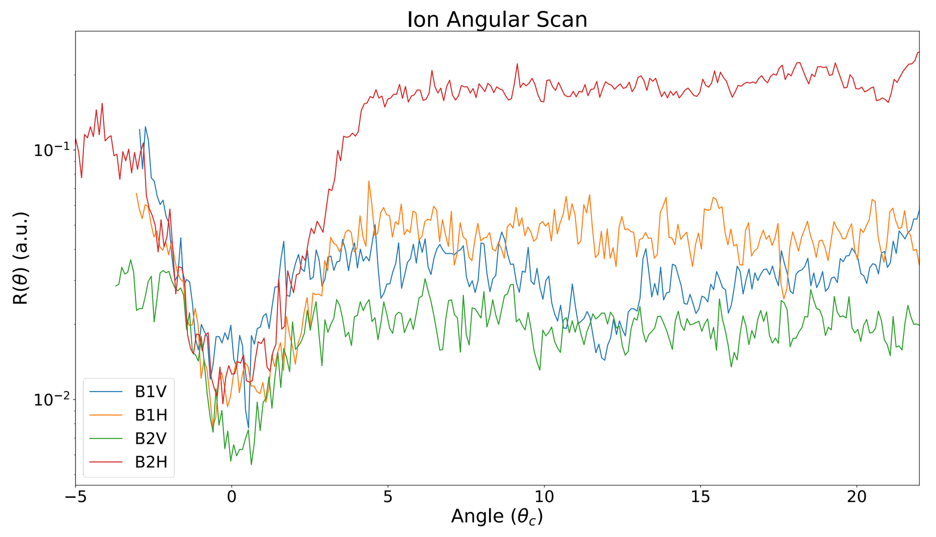
Abstract:

The Large Hadron Collider (LHC) requires a collimation system to ensure safe operation with both proton and heavy-ion beams. As of 2023, a crystal collimation scheme using bent silicon crystals was introduced to improve the collimation efficiency for heavy-ion beams.

However, drifts in the crystal angular position leading to the loss of cleaning performance during physics fills were observed. These drifts are thought to derive from mechanical deformation of the goniometer due to heating caused by beam impedance effects. A quadratic-fit based optimiser was deployed to compensate for such drifts using feedback from beam loss monitors.

This paper details the simulation environment to train reinforcement learning agents to maintain the optimal channelling position with increased reliability and reduced convergence time and presents the latest results obtained with lead ion beams.

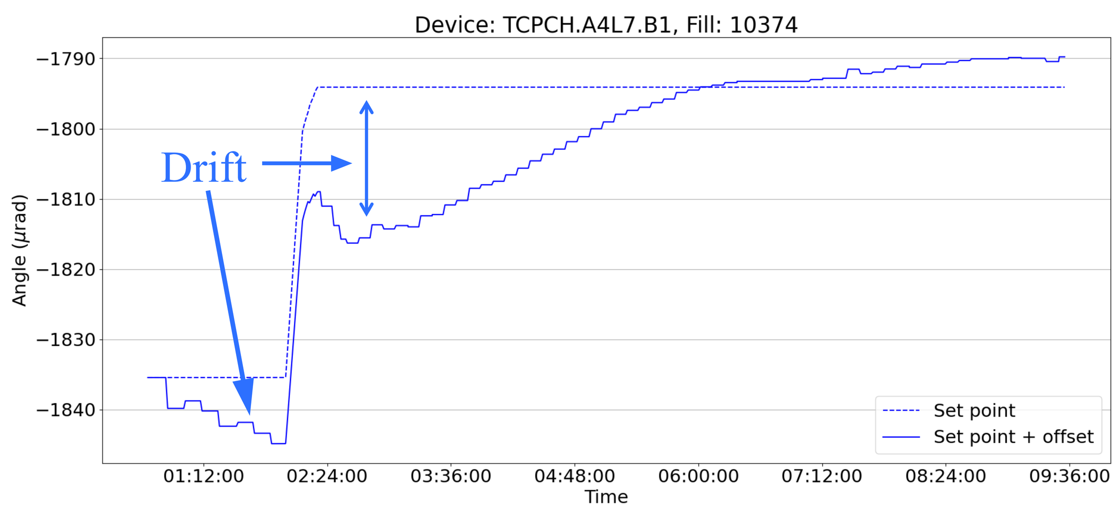
Alignment



Angular scans:

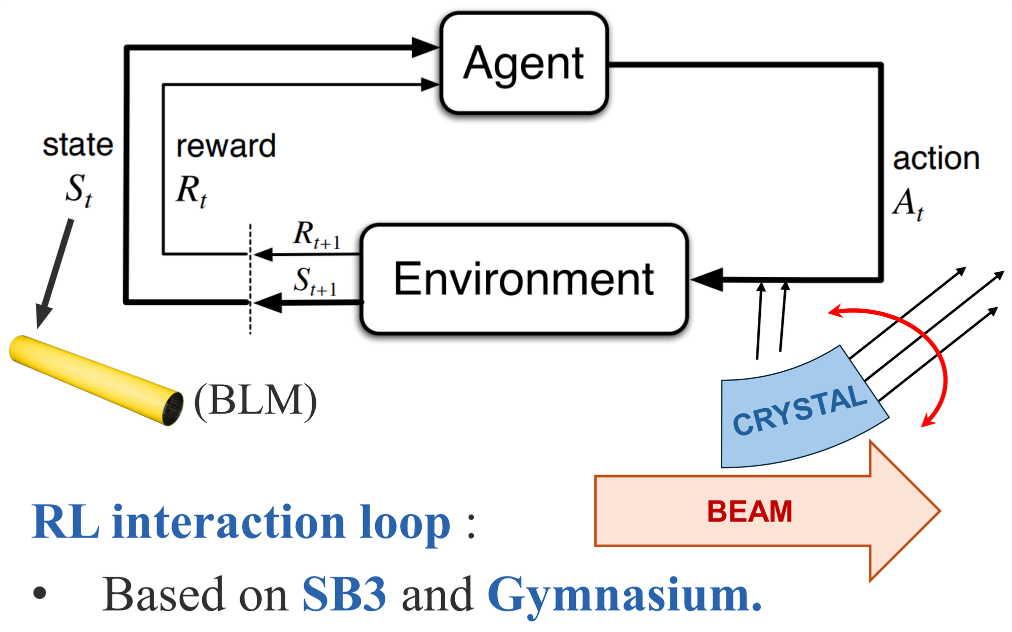
- Characterise crystal profiles.
- Performed in **physical units (µrad),** converted to units of **critical angle (θ_c).**
- Optimal channeling orientation **validated with loss maps**.

Crystal Drift



- **Attributed to heating** of the crystal goniometer.
- **Analytical modelling limited** due to statistical uncertainty.
- **Requires feedback** to track channeling.

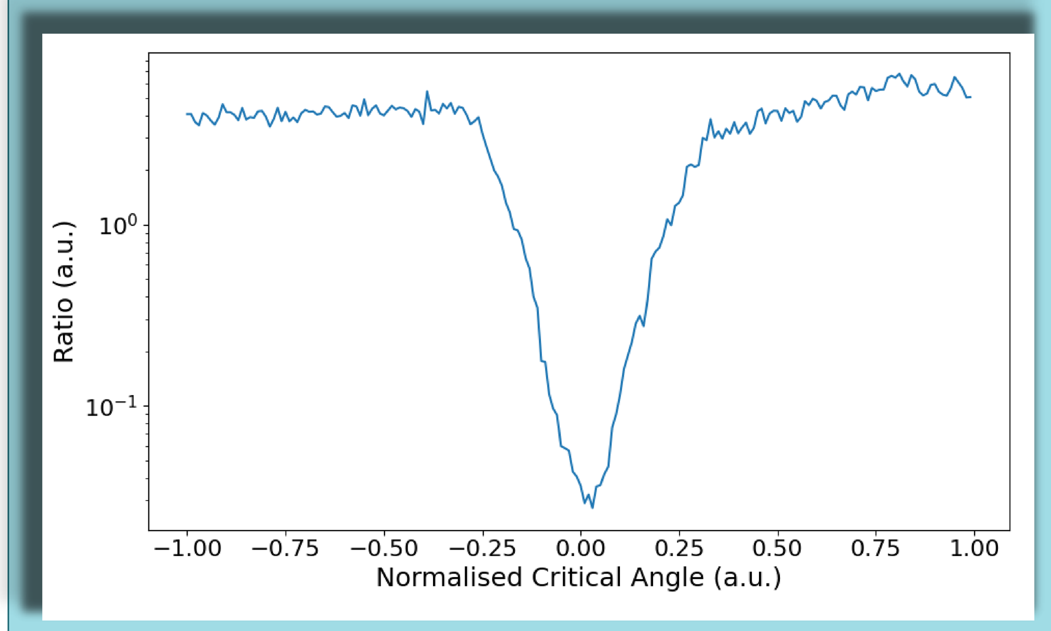
RL Environment



RL interaction loop :

- Based on **SB3** and **Gymnasium.**
- Controls the updates and policy architecture of the agents.
- Standard methods tested for **SAC**, **TRPO** and **PPO.**

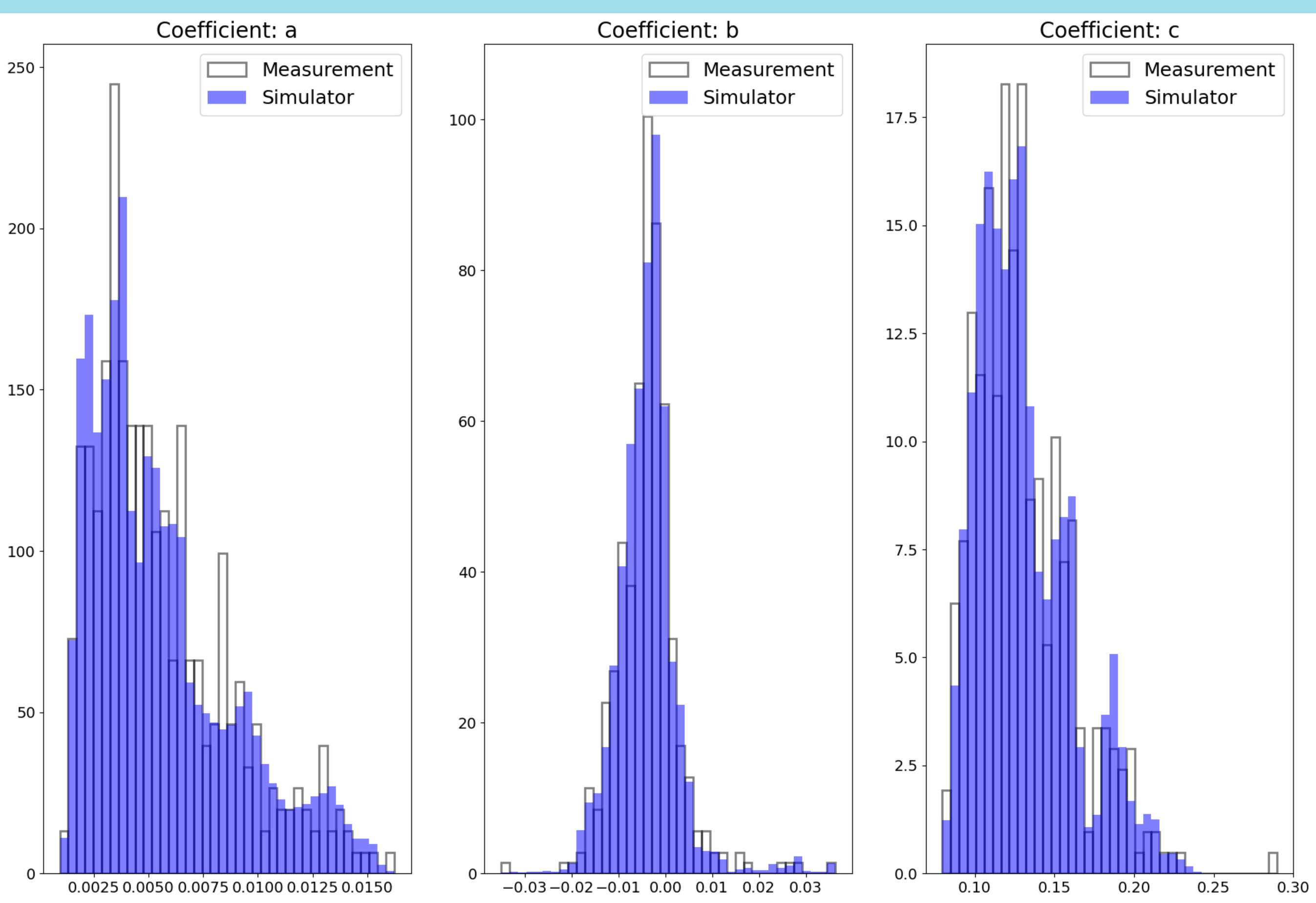
Environment #1 - Angular Scan Modelling



- ✓ Based on SixTrack-FLUKA simulation data.
- ✓ Added **Gaussian noise** based on historical data.
- ✓ **Limited historical data**, as they are performed during commissioning activities.

Environment #2 – Operation Data Modelling

- ✓ Based on quadratic fits derived from **operation data** taken in 2024.
- ✓ Simulation environment takes the operational data acquired with the classical optimisation method and **fit a model to simulate the response**.
- ✓ Compared a SimGAN and VAE generator, adopted **SimGAN** method.



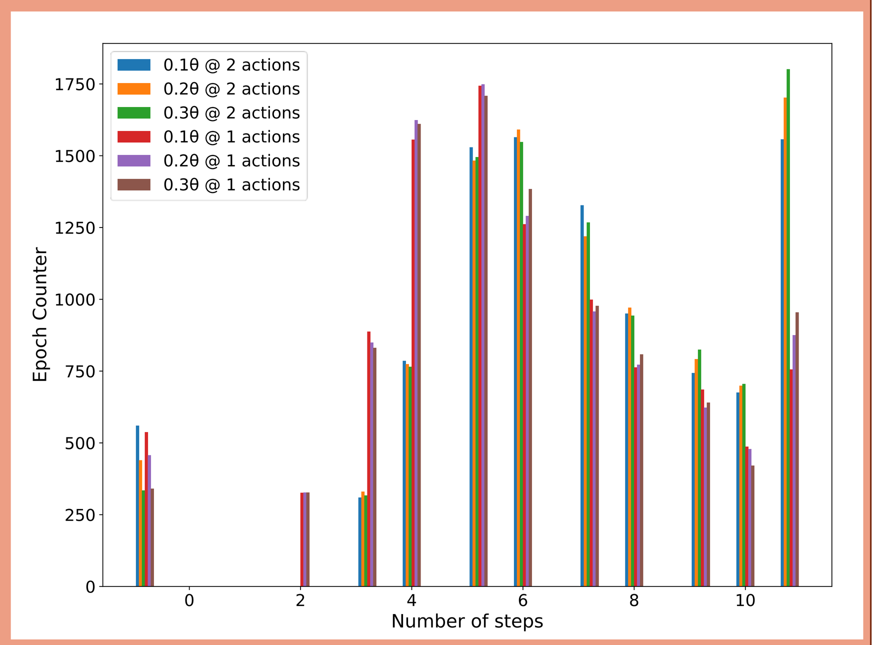
Methods Investigated

Methods[3]	Pro	Con	
Gradient Descent	Simple algorithm	Susceptible to noise	Based on performance requirements and crosstalk, ES and BO do not facilitate a sustainable method for operational optimisation. RL methods were selected to investigate both their industrial and academic value.
Extremum Seeking	Optimum Tracking while in channelling	Requires continuous sampling	
Bayesian Optimisation	Robust to modelling variations	Requires samples to form internal model	
Reinforcement Learning	Allows for sample efficient algorithms	Limited by reliability of simulation data	

[3]Thanks to F. M. Velotti for external input

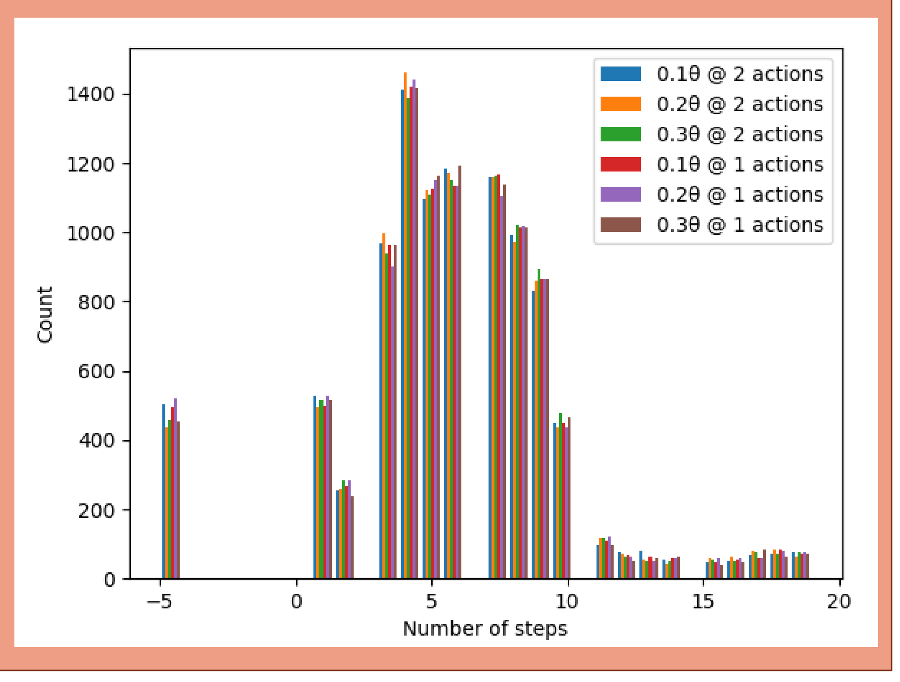
Environment #1 Results

- ✓ Simulation **convergence** rate **≈92%**
- ✓ Generated models for SAC and TRPO.
- ✓ Best model based on SAC architecture
- ✓ Testing with machine resulted **in non-convergent behaviour**.
- ✓ Error attributed with **state difference compared to the simulation suite.**



Environment #2 Results

- ✓ Simulation **convergence** rate **≈95%**
- ✓ Generated models for SAC and PPO.
- ✓ Selected PPO with continuous fitting to improve reliability.
- ✓ **Positive machine results**, but long convergence time. Additional statistics planned for the 2026 run.



Conclusion:

- **Crystal collimation** has been integrated in the LHC and has **achieved** the required **cleaning performance** with heavy ion beams as per the HL-LHC upgrade, **exceeding 20MJ** of target stored beam energy during LHC Run 3.
- Firmware upgrades allow for **real-time control** of the drift along the LHC cycle based on **optimiser feedback**.
- **Testing of the environment suite** based on simulation data showed promising results, however transfer from the simulation to application yielded **mixed outcomes using RL techniques**.
- Continued **efforts** are **aimed** to **improve the simulation** modelling with historical data and supplementing with 100Hz data (introduced in 2025).

Sponsored by Research, Innovation & Development Trust (RIDT) and the University of Malta (UM)

L-Università ta' Malta
Faculty of Information & Communication Technology
Department of Communications & Computer Engineering

HiLumi HL-LHC PROJECT

LHC Collimation Project CERN

Beams Department | Operation