Recent developments and applications of the crystal channeling at the Large Hadron Collider

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Acknowledgements

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— See details on our study at the Crystal Collimation Day: https://indico.cern.ch/event/752062

CERN groups involved in these crystal studies:
(support from many: vacuum, diagnostics, operations, services…)

Funding of LHC crystal installation:

UA9 collaboration: Physics Beyond Collider:


Recent PhD thesis works at CERN (simulations and/or measurements):

V. Previtali: CERN-THESIS-2010-133 (2010, PhD)
R. Rossi: CERN-THESIS-2017-424 (2014, PhD);
P. Schoofs: CERN-THESIS-2014-131 (2014, PhD, FLUKA team)
Planar channeling in bent crystals

Pure crystals with regular lattices

If the protons have $p_T < U_{\text{max}}$

Critical angle

$LHC\ 450\ \text{GeV} = 9.4\ \mu\text{rad}$
$LHC\ 6.5\ \text{TeV} = 2.4\ \mu\text{rad}$
$FCC-hh\ 50\ \text{TeV} = 0.9\ \mu\text{rad}$
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**Critical angle**

$$\theta_c = \sqrt{\frac{2U_{\text{max}}}{pv}}$$

**LHC 450 GeV** = 9.4 μrad

**LHC 6.5 TeV** = 2.4 μrad

**FCC-hh 50 TeV** = 0.9 μrad

Mechanical bending of crystal produces a net kick of trajectories of the particles trapped between planes.

Equivalent magnetic field for 50μrad at 7 TeV proton beams: **310 T** (4 mm crystal)
Planar channeling in bent crystals

Pure crystals with regular lattices

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$$\theta_c = \sqrt{\frac{2U_{\text{max}}}{pv}}$$

Table of critical angles:

- LHC 450 GeV = 9.4 $\mu$rad
- LHC 6.5 TeV = 2.4 $\mu$rad
- FCC-hh 50 TeV = 0.9 $\mu$rad

Mechanical bending of crystal produces a net kick of trajectories of the particles trapped between planes.

Equivalent magnetic field for 50 $\mu$rad at 7 TeV proton beams: 310 T (4 mm crystal)
Coherent interactions in bent crystals

From test beam on the CERN-SPS extraction line H8:  
(in the framework of the UA9 experiment)

See for an extensive overview Phys. Rept. 815 (2019) 1-107
Table of contents

- Introduction
- Crystal collimation at the LHC
  - LHC challenges
  - Crystal collimation layouts
  - Highlight results from LHC Run II
- Low-background run in 2018
  - 450 GeV run for Roman pot physics
  - Crystal collimation to optimise backgrounds
- Crystals for LHC fixed-targets
- Conclusions
The High-Luminosity LHC (HL-LHC) upgrade project aims at increasing the stored energy by another ~ factor 2!

1232 NbTi superconducting dipole magnets – each 15 m long
Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium)

Superconducting coil: $T = 1.9$ K, quench limit ~ 20-30 mJ/cm$^3$

Factor up to $9.7 \times 10^9$
Aperture: $r = 17/22$ mm

LHC design: 362 MJ
HL-LHC: 700 MJ
Achieved = 300 MJ
Three-stage cleaning in warm **cleaning insertions**: betatron (IR7) and off-momentum (IR3); local “tertiary” collimators at inner triplet.

Well-defined **collimation hierarchy** that integrates injection and dump protection collimators (as well as Roman pots). **Five stages**!

Machine aperture sets the scale for collimation hierarchy

Critical **beam-based alignment** to determine local orbit and beam size.
LHC multi-stage collimation

Three-stage cleaning in warm cleaning insertions:
- Betatron (IR7) and off-momentum (IR3)
- Local "tertiary" collimators at inner triplet

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Collimation cleaning (protons)
The crystal collimation concept
(replacing the 3-stage system for betatron cleaning)

Crystal-based betatron halo cleaning
— Bent crystal replaces horizontal and vertical primary collimators
— A single massive absorber (per plane) intercepts the channeled halo
— Potentially needs some additional shower absorbers downstream

Promises: Improvement of cleaning, with fewer collimators, in particular for heavy ion beams (suppress of fragmentation/dissociation!)

Challenges: Quality and performance of crystal assembly
Angular control within sub-micro radians
Safe and efficient disposal of channeled halo
LHC layouts for beam tests

Four crystals installed in the LHC: two per beam, one per plane

Same specifications for all crystals, two different producers and technologies

Complete layout: both beams and planes — allow thorough investigations and operational tests
LHC layouts for beam tests

Four crystals installed in the LHC: two per beam, one per plane

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Complete layout: both beams and planes — allow thorough investigations and operational tests

TCP = primary collimator
TCSG = secondary collimator
TCLA = shower absorber
History of beam tests: key milestones

2015
- Installation on beam 1 only (horizontal and vertical)
- Observation p channeling at the LHC: 450 GeV and 6.5 TeV
- Observation Pb channeling at the LHC: 450 Z GeV

2016
- Continuous channeling during energy ramp
- First assessment of cleaning performance with p beams
- First observation Pb channeling at the LHC: 6.37 Z TeV

2017
- Added 2 crystals on beam 2 (horizontal and vertical)
- Channeling of Xe at 450 Z GeV 6.5 Z TeV, together with assessment of cleaning performance

2018
- Continuous channeling during squeeze and collision
- First operational use in a physics run
- Operational tests with 6.37 Z TeV Pb beams with high intensity

Total “Machine Development” (MD) time: 58h with protons, 34h with ions
Channeling observations at 6.5 TeV

Key measurements: crystal angular scans and linear collimator scans

(1) **Angular scan**: strong reduction of local losses in channeling compare to amorphous.

Example: scan at 450GeV

- Loss rates in amorphous:
- Reduced losses in channeling: \( \approx 1/30 \)

(2) **Linear collimator scan**: measures the profile of the channeled halo.

Example: scan at 6.5TeV

- Secondary collimator position [mm]
- Losses at collimator [a.u.]
- Beam core
- Channeled halo
- Offset at collimator
Channeling observations at 6.5 TeV

Key measurements: crystal angular scans and linear collimator scans

(1) **Angular scan**: strong reduction of local losses in channeling compare to amorphous.

Example: scan at 450 GeV

Loss rates in amorphous

Reduced losses in channeling

~1/30

(2) **Linear collimator scan**: measures the profile of the channeled halo.

Example: scan at 6.5 TeV

Critical: Achieved the required angular control of better than ~1 μrad (A. Masi et al.)
Measurements and simulations, 6.5 TeV

Comparison: beam losses downstream of crystal in an angular scan vs simulated nuclear interactions in the crystal. Experimental input from measurements: crystal bending angle (65μrad).

See CERN Yellow Book CERN-2018-011-CP for details on simulation tools.
Collimation cleaning for proton beams

- Achieved up to a factor ~10 cleaning improvement at critical locations
- For protons, this is a “demonstrator setup”, compatible only with low beam intensities
- HL-LHC: design losses of ~1MW require a dedicated beam absorber!

Not considered for cleaning upgrade!
Collimation cleaning for Pb ion beams

- Overall reduction of losses around the ring.
- Tested with high ions intensities (~600 bunches)!
- Cleaning improvement up to a factor 7 (more with optimised settings).
- Not the same improvement with all crystals — to be understood.

(measurements available for a broad variety of settings)
Collimation cleaning for Pb ion beams

**Without crystals**

- Overall reduction of losses around the ring.
- Tested with high ions intensities (~600 bunches)!
- Cleaning improvement up to a **factor 7** (more with optimised settings).
- Not the same improvement with all crystals — to be understood.

**Operational settings**

( measurements available for a broad variety of settings)

- Being considered for the HL-LHC upgrade!
Other measurements of channeling

- Very extensive set of measurements
- Energies up to 6.5 TeV
- Proton, lead and xenon beams
- Continuous channeling during dynamics machine phases (energy ramp, optics changes)
- Channeling of secondary beam halos

Channeling of Xe beams at 6.5 TeV!
Table of contents

- **Introduction**
- **Crystal collimation at the LHC**
  - LHC challenges
  - Crystal collimation layouts
  - Highlight results from LHC Run II
- **Low-background run in 2018**
  - 450 GeV run for Roman pot physics
  - Crystal collimation to optimise backgrounds
- **Crystals for LHC fixed-targets**
- **Conclusions**
2018 special run “high-\(\beta^*\)” at 450 GeV

Challenges for total p-p cross section measurements
- Short run of only a few days, at injection energy \(s^{1/2} = 900\) GeV
- New optics with large colliding beam sized in ATLAS/CMS
- Roman pots of ATLAS-ALFA and TOTEM as close as possible to the beam
- High background rates observed in beam tests, putting in question the feasibility of this run in 2018.

*Note: low beam intensities planned for this run!*

Two collimation schemes proposed:
1. “Tight settings” scheme with tungsten collimators protecting the pots
2. Crystal collimation at tight settings

Both requiring complex operational procedures.
With crystal collimation:

— Significant background suppression for TOTEM!

\textit{Much simplified analysis, lower data rejection.}

— ATLAS-ALFA: problematic distributions at some pots

\textit{Understood later in simulations how to fix this, but not in time for the short data taking period.}

— Both experiments acknowledged a significant bckg reduction as a function of time, with no need for frequent re-shaping of beam halos!

\textit{Courtesy of TOTEM (preliminary)}
Background evolution in time

Crystal collimation

~2.5 h

Standard collimation

~1 h

Courtesy of ATLAS (preliminary)

Scheme by C. Schwicz
Background evolution in time

Crystal collimation

![Crystal collimation graph]

Standard collimation

![Standard collimation graph]

Crystal collimation

![Crystal collimation graph]

Conventional collimation

![Conventional collimation graph]

Courtesy of ATLAS (preliminary)

Courtesy of TOTEM (preliminary)
No need for frequent scraping when crystal collimation is used!

1 setup fill: confirmed alignment STD and Cry coll.

Re-align needed for STD
Bad bkg to TOTEM following fills
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Scheme for halo splitting and fixed targets

Basic idea:
— A crystal inserted in the transverse collimation hierarchy can deflect part of the beam (secondary or tertiary) halos, otherwise disposed of by the collimation system
— Further downstream, this “split halo” impinges onto an in-beam-vacuum fixed target
— Additional absorbers downstream needed to intercept the collision products
— “Double-crystal setup”: a second crystal is attached to the target to study the magnetic and electric dipole moment precession of short lived barions (Lambda_c)

Studies are part of the PBC study at CERN: see PBC-FT (“LHC fixed target”) working group.

See also: Eur.Phys.J. C77 (2017) no.12, 828
Layouts in LHC IP8 (LHCb)

— Being studied with the UA9 collaboration and the SELDOM team. Under evaluation by LHCb (not yet approved).

— The PBC-FT team is actively working on a final assessment of achievable protons on target for measurements of MDM and EDM. WG summary document out this summer.

— Some members of ALICE Collaboration are studying a similar layout, with a conventional target and no second crystal (see ESPP proposal: https://cds.cern.ch/record/2671944). Interested also in using this concept with heavy ion beams,

— Studying also alternative layouts in the LHC ring, see for example IR3 (arXiv:1906.08551).
Conclusions

- Reviewed the main results obtained with bent crystals at the high-energy frontier at the LHC.
  A 4-crystal scheme was available during the LHC Run II at 6.5 TeV. Extensive beam tests were done: proton beams, Pb ion beams, Xe ion beams. Driven by the study of upgraded beam halo collimation.

- Very promising results obtained for beam halo cleaning.
  Observation of channeling at unprecedented beam energies, showing that we master the technology to control angles with the required accuracy. Promising performance with heavy ion beams, being considered for the upgrade!

- In 2018, we had a first operational use of crystal collimation in a physics run, to reduce backgrounds for the p-p cross section
  High-β⁺ run in 2018 profited from the availability of crystals for low backgrounds.

- Simulations combining crystal interactions, optics, aperture and scattering in other collimators are well advanced (for protons). Various developments ongoing for ions.

- Promising results obtained motivated new ideas!
  New idea of halo splitting being considered for LHC fixed-target implementations.