Recent results on crystal collimation at the Large Hadron Collider

Stefano Redaelli, BE-ABP, on behalf of WP5
Acknowledgements

Collimation results are presented of behalf of the HL-LHC WP5 (collimation upgrade)
— Most plots/analyses prepared by D. Mirarchi, M. D’Andrea, R. Rossi
— See details on our study at the **Crystal Collimation Day**: [https://indico.cern.ch/event/752062](https://indico.cern.ch/event/752062)
— New results on crystal collimation of lead ion beams in Nov. 2019

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

**Funding of LHC crystal installation:**

**UA9 collaboration:**

Work on high-$\beta^*$ run: D. Mirarchi, R. Bruce, M. D’Andrea, H. Morales, S. Redaelli, A. Masi, M. Di Castro, P. Serrano, M. Butcher, with ATLAS-ALFA and TOTEM

**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

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

Critical angle

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

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

Pure crystals with regular lattices
Planar channeling in bent crystals

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**Straight crystal:** hadron oscillate, “trapped” between planes

**Bent crystal**

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

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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
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- Conclusions
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

<table>
<thead>
<tr>
<th>cold aperture</th>
<th>primary collimator</th>
<th>secondary collimator</th>
<th>shower absorbers</th>
<th>tertiary collimators</th>
<th>SC triplet</th>
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</thead>
<tbody>
<tr>
<td>protection devices</td>
<td></td>
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Three-stage cleaning in warm clean 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!

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Circulating beam

Collimation cleaning (protons)

R. Rossi
The crystal collimation concept
(replacing the 3-stage system for betatron cleaning)
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
The crystal collimation concept
(replacing the 3-stage system for betatron cleaning)

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Promises: Improvement of cleaning, with fewer collimators, in particular for heavy ion beams (suppress of fragmentation/dissociation!)
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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 radiants
Safe and efficient disposal of 0.5-1.0 MW 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

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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

Pics. courtesy of Y. Gavrikov

TCPCH.A5R7.B2
TCPCV.A6L7.B1
TCPCH.A4L7.B1
TCPCV.A6L7.B1

PNPI
INFN-Fe

Beam 1
Beam 1
Beam 1
Beam 1
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
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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
- Added 2 crystals on beam 2 (horizontal and vertical)
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2017
- **Continuous** channeling during **squeeze**
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Thanks to the HL-LHC project for supporting these studies and to MD coordination + LHC-OP.
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Channeling observations at 6.5 TeV

Key measurements: crystal angular scans and linear collimator scans

Beam core
Halo
Crystal
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
Channeling observations at 6.5 TeV

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

Example: scan at 6.5 TeV

S. Redaelli, 9th HL-LHC Collaboration Meeting, 16/10/2019
Channeling observations at 6.5 TeV

Key measurements: crystal angular scans and linear collimator scans

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Example:
- Scan at 450GeV

![Angular scan graph]

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

Example:
- Scan at 6.5TeV

![Linear collimator scan graph]
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

(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 (65\(\mu\)rad).

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

Crystal collimation

Conventional collimation

M. D’Andrea
Collimation cleaning for proton beams

Crystal collimation

- 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!

M. D’Andrea
Keep channeling in dynamics phases

Challenges:
- shrinking of beam size and change in angular distribution due to adiabatic dumping
- change in critical angle (from ~10 μrad to ~2 μrad) and acceptance

Functions need to be prepared to move the crystals: same formula used for standard collimators, but adapted also for rotational stage

\[ x(t) = x_c - \left[ n_{inj} + \frac{n_{ft} - n_{inj}}{\gamma_{ft} - \gamma_{inj}}(\gamma(t) - \gamma_{inj}) \right] \cdot \left[ \tilde{\sigma}_{inj} + \frac{\tilde{\sigma}_{ft} - \tilde{\sigma}_{inj}}{\gamma_{ft} - \gamma_{inj}}(\gamma(t) - \gamma_{inj}) \right] \frac{1}{\sqrt{\gamma(t)}} \]
Collimation cleaning for Pb ion beams

**Full ring**

- Without crystals
- With crystals

**Betatron cleaning region**

- Standard
- Crystal

S. Redaelli, 9th HL-LHC Collaboration Meeting, 16/10/2019
Collimation cleaning for Pb ion beams

**Full ring**

- 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)*

**Betatron cleaning region**

- **Without crystals**
  - Operational settings

- **With crystals**
  - Standard
    - $\eta=4.2\times10^{-13}$
  - Crystal
    - $\eta=7.8\times10^{-15}$

**Legend**

- Collimator
- Warm
- Cold
Collimation cleaning for Pb ion beams

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(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!

Bending radius close to critical value: high dechanneling population and low efficiency

~20%
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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!*
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**Figure:**

- **Nominal** and **Tight** stages for various collimation elements:
  - TCT
  - TCLA
  - Dump protection
  - TCSG
  - TCP

- **Primary stage at 2.5 $\sigma$**
- **Secondary stage at 2.7 $\sigma$**
- **Roman Pots at 3 $\sigma$**

* Tightest collimation ever in the LHC!*

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**R. Bruce**
2018 special run “high-$\beta^*$” at 450 GeV

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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.
Reduced background with crystals

**Conventional collimation**

**Crystal collimation**

Simulations
Reduced background with crystals

With crystal collimation:
— Significant background suppression for TOTEM! *Much simplified analysis, lower data rejection.*
— ATLAS-ALFA: *problematic* distributions at some pots *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!

*Courtesy of TOTEM (preliminary)*
Background evolution in time

Crystal collimation

Standard collimation

~2.5 h

~1 h

Elastic+background rates

Signal+Bkg

Bkg

Signal+Background rates

Scraping

Background rates

1/19/2018

1/19/2018

Scheme by C. Schwicz

Courtesy of ATLAS (preliminary)
Background evolution in time

Crystal collimation

~2.5 h

Standard collimation

~2.1 h

Crystal collimation

~3.2 h

Conventional collimation

~1.6 h

Courtesy of ATLAS (preliminary)

Courtesy of TOTEM (preliminary)
Overall view of the high-$\beta^*$ run

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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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-\(\beta^*\) 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.
Reserve slides
TOTEM data quality (preliminary)

- **Standard collimation:** background at sensor edges, removed with **full off-line cut**

- **Crystal collimation:** no background evident, removed with **first off-line cut**

COURTESY OF J. CASPAR
Understanding ALFA background in simulations

Very high statistics needed: $96 \times 10^6$ p simulated

- History of each particle reconstructed to understand the hit pattern:

  Beam 2

  1. Particles get dechanneled and escape from IR7

  2. $\sim 10$ turns in the machine

  3. Impact on TCLA.A5L3.B2 closed at $2.7\sigma$

  4. Emerge from TCLA and impact on ALFA-XRP at the same turn

\[
\Delta \mu_x^{XRP-TCLA} \sim 4^\circ, \quad \Delta \mu_y^{XRP-TCLA} \sim 244^\circ
\]

\[
\frac{\Delta y(\theta)}{\Delta x(\theta)} = \frac{\theta \sqrt{\beta_y^{TCLA} \beta_y^{XRP} \sin(\Delta \mu_y^{XRP-TCLA})}}{\theta \sqrt{\beta_x^{TCLA} \beta_x^{XRP} \sin(\Delta \mu_x^{XRP-TCLA})}} \sim 20
\]
Evolution of LHC layouts

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

Same design specifications for all crystals, two different producers and technologies

<table>
<thead>
<tr>
<th></th>
<th>Beam 1</th>
<th></th>
<th>Beam 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal</td>
<td>Vertical</td>
<td>Horizontal</td>
<td>Vertical</td>
</tr>
<tr>
<td>2015</td>
<td>Strip-INFN</td>
<td>QM-PNPI</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>2016</td>
<td>Strip-INFN</td>
<td>QM-PNPI</td>
<td>QM-PNPI</td>
<td>QM-PNPI</td>
</tr>
<tr>
<td>2017</td>
<td>Strip-INFN</td>
<td>QM-PNPI</td>
<td>QM-PNPI</td>
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<td>QM-PNPI</td>
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</table>

Complete layout to allow thorough investigations and operational tests
Details of crystal angular scans

The crystal device is aligned to the beam halo and rotates around its axis.

**What we look at:**
- decreased losses at the crystal
- increased losses at the absorber

**What we look for:**
- optimal channeling orientation
- reduction factor

Background subtracted, normalization to lost particles flux and amorphous level.

Measured angular scan - B1V INJ

Reduction factor: 11.088
Details of crystal linear scans

The absorber is retracted and inserted until it touches the primary beam, with the crystal in channeling orientation.

**What we look at:**
- losses at the absorber as a function of its transverse position

**What we look for:**
- multiturn channeling efficiency
- characterization of channeled beam and crystal bending angle

Distance between channeled and primary beam is converted into deflection angle using the transfer matrix.
Motivation for the double-crystal setup

Use bent crystals for measuring the magnetic moment of the charmed charged hadrons starting from $\Lambda_c^+ (\text{ct}_0(\Lambda_c^+) \sim 60\text{mm})$

The same technique could be also used to measure the magnetic moment of the lepton $\tau$

Anomalous magnetic moment of charmed and/or beauty quarks may account for the compositeness of those quarks

PBC kickoff, Sep. 2016:

Measuring magnetic moments with bended crystal

Achille Stocchi | LAL Orsay – Paris Sud/IN2P3

Many people contribute to this presentation (discussions/ideas/work)


Figure 1. Spin rotation in a bent crystal

Magnetic moment of channeled particles should precess in a bent crystal

$$\theta_{\text{spin}} = \frac{g-2}{2} \gamma \theta_{\text{crystal}}$$

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.
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).

5 mm long target made of W at 2.4 m from IP8; Cry2 bending angle = 14 mrad, length = 7cm.