Experience with Multi-TeV Beam Channeling and Crystal Extraction at the LHC

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CERN, BE-ABP
LHC crystal extraction options

- In-beam targets (small angle) vs dedicated line (bigger);
- New line vs implementation in existing LHC dump line;
- Existing experiment(s) as experimental apparatus?
- Dedicated operation with crystals as primary beam restriction vs parasitic operation in shade of LHC collimation system.

No specific implementation discussed here († next talk), rather illustration of how the developed know-how and experience with hardware can steer design work.
Outline

☑ Introduction
☑ UA9 results with SPS beams
☑ LHC collimation studies
☑ LHC crystal extraction
☑ Spill control mechanisms
☑ Conclusions
Acknowledgements

This talk is given on behalf of the members of the UA9 collaboration (SPS, H8 data) and LHC collimation team.

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

Funding of LHC crystal installation:

Recent thesis works (simulations and/or measurements):
- V. Previtali: CERN-THESIS-2010-133 (2010, PhD)
- D. Mirarchi: CERN-THESIS-2011-136 (2011, master);
  CERN-ACC-2015-0143 (2015, PhD)
- R. Rossi: CERN-THESIS-2014-187 (2014, master);
  PhD ongoing
- P. Schoofs: CERN-THESIS-2014-131 (2014, PhD, FLUKA team)

Hadron interactions with bent crystal

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

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

Forced to oscillate in a relatively empty space

$$x(z) = \frac{d_p}{2} \sqrt{\frac{E_t}{U_{\text{max}}}} \sin\left(\frac{2\pi z}{\lambda} + \phi\right)$$

Straight crystal: hadron “trapped” between planes

Bent crystal

Key parameters for Si crystals

<table>
<thead>
<tr>
<th>Case</th>
<th>Energy [GeV]</th>
<th>$\theta_c$ [μrad]</th>
<th>$\lambda$ [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS coast</td>
<td>120</td>
<td>18.3</td>
<td>33.0</td>
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<tr>
<td>SPS coast</td>
<td>270</td>
<td>12.2</td>
<td>49.6</td>
</tr>
<tr>
<td>H8</td>
<td>400</td>
<td>10.0</td>
<td>60.3</td>
</tr>
<tr>
<td>LHC inj.</td>
<td>450</td>
<td>9.4</td>
<td>64.0</td>
</tr>
<tr>
<td>LHC top</td>
<td>6500</td>
<td>2.5</td>
<td>243.2</td>
</tr>
<tr>
<td>LHC top</td>
<td>7000</td>
<td>2.4</td>
<td>252.3</td>
</tr>
</tbody>
</table>

FCC (50TeV) < 0.9 μrad

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

Equivalent magnetic field for 50μrad at 7 TeV proton beams: 310 T (4 mm crystal)
Single-pass measurements in SPS-H8

UA9 experimental setup in the SPS-H8 line (400GeV)

Detailed set of measurements: crucial for code development and characterisation of crystals; several new effects observed.
Single-pass measurements in SPS-H8

Planar channeling (simplest):
Five (5!!) different processes

Detailed set of measurements: crucial for code development and characterisation of crystals; several new effects observed.
SPS channeling of circulating beams

UA9 experiment setup installed in the SPS-LSS5: hardware from UA9 and collimation project

Additional complexity:
- Edge effects on crystal surface;
- Beam dynamics of particles with larger amplitudes/energy errors;
- Scattering on other collimators;
- Details of aperture models.
Simulations versus measurements

First high-dispersion area area

QF.52410

- Sim. Data
- Exp. data

R~8

R~18


PhD work by D. Mirarchi
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Concept of crystal collimation

Crystals as primary collimators: **large angles** and **reduced change of rigidity** (diffractive losses and ion fragmentation).

**Challenges for the LHC:**
- small angular acceptance \(\sim 2 \mu\text{rad}\);
- localization of losses up to **1.0 MJ** in one single collimator absorber.

**Present multi-stage collimation**
- Primary collimator
- Secondary collimators
- Shower absorbers

**Crystal collimation**
- Absorber
- Shower absorbers
- Crystal
- Channelled halo beam
- Circulating beam
- Primary beam halo
Concept of crystal collimation

Crystals as primary collimators: **large angles** and **reduced change of rigidity** (diffractive losses and ion fragmentation).

**Challenges for the LHC:**
- small angular acceptance $\sim 2 \mu$rad;
- localization of losses up to **1.0 MJ** in one single collimator absorber.

**Promises of crystal collimation:**
1. Improve **collimation cleaning efficiency**, in particular for **heavy ion** beams;
2. Reduce electro-magnetic perturbations of collimators to the beams **(impedance)**.
Layout of LHC crystal collimation setup

- Two crystal technologies (strip and quasi-mosaic);
- Optimized for collimation studies for ions and protons, all energies;
- Feasibility tests, compatible with low-intensity beams.

<table>
<thead>
<tr>
<th>Name</th>
<th>s [m]</th>
<th>Collimation plane</th>
<th>Bending [µrad]</th>
<th>Length [mm]</th>
<th>Mat.</th>
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<tbody>
<tr>
<td>TCPC.4L7.B1</td>
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<td>4</td>
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<td>Si</td>
</tr>
</tbody>
</table>

Hardware developed by EN/STI with industry (goniometer sub-microrad resolution)
First proton channeling at 6.5 TeV

Critical: Achieved the required angular control of better than ~1 μrad (A. Masi et al.)

(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

Beam losses at crystal [ a.u. ]

Loss rates in amorphous

Reduced losses in channeling

~1/30
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IR7 layouts and beam tests

- Present setup: 2 crystals with design angles of 50 μrad (measured: ~40 μrad in V and ~65 μrad in H);
- Aperture compatible with angles of ~200 μrad (V) and 500 μrad (H);
- A well instrumented setup that can be used for new crystal’s characterisation after completion of collimation studies (earliest: 2018).

Any ideas for a detector that can be installed into a 1.48m slot available for collimation upgrades?
Implementation in dump insertion

Bending of 230 \(\mu\text{rad}\) could extract beams into the present dump line, in analogy with kicker magnets (relies on kicks from Q5/Q4). 

*Probably need a different angle to separate channeled beam from standard dump — integration in dump line would have to be studies.*

First look at crystal as primary restriction (low-intensities scenario).
Beams downstream of crystal

Ex.: 3 nominal bunches ($3 \times 10^{11} p$) ➣ spill of $\sim 10^7 p/s$ (1h lifetime)

These particles must be safely disposed of!

D. Mirarchi
Loss distributions (crystal as primary)

Only compatible with low intensities!
Loss distributions (crystal as primary)

Only compatible with low intensities!
Operation with crystal as secondary

This scheme would not perturb the standard cleaning mechanisms in the collimation insertion. Implication for dump insertion clearly to be assessed.

Crystals at the transverse amplitude of secondary collimators would intercepts a (broader) distribution of tertiary halo particles. Might work with higher intensities!
Achievable spill rates with full LHC

Nominal LHC: $3.2 \times 10^{14}$ particles, 1 hour and 10 hours lifetime, with a crystal in IP6 at 7.5 sigmas.

Preliminary
Controlled beam depletion
(studied as active halo control for beam collimation)

- **Tune noise** through ripple of quadrupole power supplies. 
  *Ongoing beam tests: LHC + SPS*


- **Hollow electron lenses** for halo control. 
  *Upcoming HL-LHC project review: Oct. 6th.*

**Graphs and Notes:**
- **Small loss rates of about 1e7p/s (required for long crystal scans)**
  - R. Rossi

- **Losses at crystal**

- **High losses in controlled quench tests**
  - > 2 full Tevatron beams!
  - B. Salvachua

**Graph:**
- SPS tune ripple: 0.5 A at 1kHz
  *(Tested in beam tests on Aug. 3rd)*
Conclusions

☑ Reviewed where we are with channeling of multi-TeV hadron beams

  Very promising recent results at the LHC, profiting from several years of studies by UA9.

☑ We have operational experience and simulation tools, and the hardware for angular control — validations at SPS and LHC, broad energy range.

  "So simple that it cannot be true", but the devil is in details!

  Present understanding relies on several years of studies and measurements.

  Very fertile field for students and post-docs — see list of PhD thesis of recent years!

☑ We are confident that we can master this technology up to 7 TeV.

  Still: outstanding test program at the LHC to be completed, but results are encouraging.

☑ Outlined some possible applications to LHC extracted beam experiments.

  First look indicates promising possibilities, clearly more studies would be needed.

  Extension to other machines — lower or higher energies — is possible.

☑ Proposed methods to control spill rates: strong synergy with ongoing studies of active loss controls for LHC collimation upgrades.

  Tune resonances from quadrupole ripple, transverse damper, hollow e-lenses.

☑ Contact us to discuss if you have ideas on how to use crystals!

  Present installation in collimation insertion: unique setup to test new crystal ideas.