BENT CRYSTALS in the LHC
a way to improve the collimation efficiency in modern hadron colliders

Walter Scandale CERN
For the UA9 collaboration

Erice
October 29 2008
Outlook

- Why using crystals in hadron colliders
- The H8-RD22 experiment at CERN
  (test in a single-pass beam-line)
  - Experimental layout
  - Main results
- The UA9 experiment at the CERN-SPS
  (test in a circular accelerator)
  - Layout
  - Expected efficiency
- Conclusions
Two stage collimation
in a circular collider

How it works?

- Short scatterer deflects the primary halo (ap. $r_1 = N_1 \sqrt{\beta_{TWISS}} \varepsilon$)
- Long collimator intercepts the secondary halo (ap. $r_2 = N_2 \sqrt{\beta_{TWISS}} \varepsilon$)
- Halo particles captured through amplitude increase via multiple scattering and multi-turn effect.

Capture condition: $\delta x' > \sqrt{\left(\frac{N_2^2 - N_1^2}{\gamma_{REL.} \beta_{TWISS}}\right)} \varepsilon_N$ \hspace{1cm} $\varepsilon_N = \varepsilon \beta \gamma$

W. Scandale 3
Requirements for LHC

Nominal beam power: 362 MJ

**Super-Conduting Environment**

Proton losses into cold aperture

- Local heat deposition
- Magnet can quench

<table>
<thead>
<tr>
<th>Energy [GeV]</th>
<th>Loss rate (10 h lifetime)</th>
<th>Quench limit [p/s/m] (steady losses)</th>
<th>Cleaning requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>8.4e9 p/s</td>
<td>7.0e8 p/s/m</td>
<td>92.6 %</td>
</tr>
<tr>
<td>7000</td>
<td>8.4e9 p/s</td>
<td>7.6e6 p/s/m</td>
<td>99.91 %</td>
</tr>
</tbody>
</table>

Capture (clean) lost protons before they reach cold aperture!

Required efficiency: ~ 99.9 % (assuming losses distribute over 50 m)

Control transient losses (10 turns) to ~1e-9 of nominal intensity (top)!

**Courtesy of R. Assmann**
Nominal ion beam in LHC has 100 times less beam power than proton beam, but ~20 times higher probability of nuclear interactions respect to $\pi^0$.

<table>
<thead>
<tr>
<th>Physics process</th>
<th>Proton</th>
<th>$^{208}\text{Pb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$dE/dx$ due to ionisation</td>
<td>-0.12 %/m</td>
<td>-9.57 %/m</td>
</tr>
<tr>
<td></td>
<td>-0.0088 %/m</td>
<td>-0.73%/m</td>
</tr>
<tr>
<td>Mult. Scattering (projected r.m.s. angle)</td>
<td>73.5μrad/m$^2$</td>
<td>73.5μrad/m$^2$</td>
</tr>
<tr>
<td></td>
<td>4.72μrad/m$^2$</td>
<td>4.72μrad/m$^2$</td>
</tr>
<tr>
<td>Nucl. Interaction length</td>
<td>38.1 cm</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>≈fragment. length for ions</td>
<td>38.1 cm</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>Electromagnetic dissociation length</td>
<td>-</td>
<td>33 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19 cm</td>
</tr>
</tbody>
</table>

High probability of nuclear interactions in the scatterer ➔ strong reduction of the 2-stage collimation efficiency

---

A new disturbance respect to p

Hadronic Fragmentation cross sections for $^{208}\text{Pb}$ on $^{12}\text{C}$

Electromagnetic Dissociation cross sections for $^{208}\text{Pb}$ on $^{12}\text{C}$

_fragmented nuclei, Monte Carlo estimate of the x-sections_

loss 1 n (59%) → $^{207}\text{Pb}$
loss 2 n (11%) → $^{206}\text{Pb}$

Curtesy of Bellodi
Crystal collimation

- Primary halo directly extracted!
- Much less secondary and tertiary halos!?

..but no enough data available to substantiate the idea...

E. Tsyganov & A. Taratin (1991)

W. Scandale 6
Particle-crystal interaction

Possible processes: (a)
- multiple scattering
- channeling
- volume capture
- de-channeling
- volume reflection

Volume reflection
Prediction in 1985-'87 by A.M. Taratin and S.A. Vorobiev,
First observation 2006 (IHEP - PNPI - CERN)
The H8RD22 apparatus:
Single pass tests in the SPS-North Area

- 3-stage goniometer (2 lateral + one rotation)
- precision = of the order of 1μrad

- double sided silicon strip detector with 50μm pitch
- dimensions = 1.92x1.92 cm²
- SNR = 80:1 with a 5 MHz readout clock and 25m cables
- Residual = better than 5 μm
- DAQ rate = 2.1kHz → 10k events per spill
The main curvature due to external forces induces the anticlastic curvature seen by the beam.

Crystal size: 0.9 x 70 x 3 mm$^3$
Quasi-Mosaic effect
(Sumbaev, 1957)

- The crystal is cut parallel to the planes (111).
- An external force induces the main curvature.
- The anticlastic effect produces a secondary curvature.
- The anisotropy of the elastic tensor induces a curvature of the crystal planes parallel to the small face.
Angular beam profile as a function of the crystal orientation

9mm long Si-crystal deflecting 400GeV protons

The angular profile is the change of beam direction induced by the crystal

The rotation angle is the angle of the crystal respect to beam direction

The particle density decreases from red to blue

1 - “amorphous” orientation
2 - channeling (50%)
3 - de-channeling (1%)
4 - volume capture (2%)
5 - volume reflection (98%)

W. Scandale 11
Multi-crystals

multiheads crystal (PNPI)  multistrip crystal (IHEP and INFN-Ferrara)

Several consecutive reflections

- enhance the deflection angle
- keep large cross section
5 heads multi-cryystals

- Volume reflection angle 53 µrad
- Efficiency ≥ 90 %

Steps to align the five crystals

High statistics
Multi-strips

- Volume reflection angle ~100 μrad
- Efficiency ~ 90 %

INFN-Ferrara IHEP
Other results of H8RD22

PROTON BEAM (400GeV/c),
- Volume reflection dependence from the curvature of the crystal
- Axial channeling

ELECTRON/POSITRON BEAM (180GeV/c),
- Volume reflection with electrons and positrons
- Radiation emission with e+/e- beams in channeling condition
The underground experiment in the SPS

Approved by the CERN Research Board of the 3 Sept 2008

Goals:
- Demonstrate high efficiency collimation assisted by bent crystals (loss localization)
- Follow single particle dynamics in crystal-collimation system

CRYSTAL experiment layout

Approximately to scale in s[m]

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Roman Pot 1</th>
<th>Roman Pot 2</th>
<th>Secondary collimator (TAL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si?</td>
<td>QF.518</td>
<td>QD.519</td>
<td>QF.520</td>
</tr>
<tr>
<td>5186.713</td>
<td>5182.000</td>
<td>5218.711</td>
<td>5250.708</td>
</tr>
</tbody>
</table>

CERN
INFN
PNPI
IHEP
JINR
SLAC
FNAL
LBNL
Jan-Feb 09: area reserved for magnet repair

Installation week 3 Jan 09

Installation week 25 Jan 09

600 mm long
30x30 mm² wide
RD22 tank

Quartz windows:

Laser table for crystal alignment

Concerns:
- Optimal energy
- Alignment
- Feed-troughs

Concerns:
- Out-gassing
- RF noise
- Feed-troughs

Beam axis
The SPS beam

- Possible energy range from 70 to 270 GeV.

- We selected two energies of interest:
  - 120 GeV, as for the RD22 experiments (reference data in the literature);
  - 270 GeV, as for other planned experiment in the SPS (faster setting-up)

<table>
<thead>
<tr>
<th></th>
<th>High energy</th>
<th>unbunched</th>
<th>bunched</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Voltage [MV]</td>
<td>1.5</td>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td>Momentum P [GeV/c]</td>
<td>270</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Tune Qx</td>
<td>26.13</td>
<td>26.13</td>
<td>26.13</td>
</tr>
<tr>
<td>Tune Qy</td>
<td>26.18</td>
<td>26.18</td>
<td>26.18</td>
</tr>
<tr>
<td>Tune Qs</td>
<td>0.0021</td>
<td>0</td>
<td>0.004</td>
</tr>
<tr>
<td>normalized emittance (at 1 σ) [mm mrad]</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>transverse radius (RMS) [mm]</td>
<td>0.67</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>momentum spread (RMS) Δp/p</td>
<td>2 to 3×10^{-4}</td>
<td>2 to 3×10^{-4}</td>
<td>4×10^{-4}</td>
</tr>
<tr>
<td>Longitudinal emittance [eV-s]</td>
<td>0.4</td>
<td>≤0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

alternative tunes are those selected in RD22 (Qx=26.62, Qy=26.58).
The SPS beam

- Intensity a few $10^{11}$ up to a few $10^{12}$ circulating particles.
- Beam either unbunched or bunched in a few tens of bunches.
- Beam lifetime larger than 80 h, determined by the SPS vacuum.

- A halo flux of a few $10^2$ to a few $10^4$ particles per turn, which can be investigated with the detectors in the roman pots
  - evenly distributed along the revolution period (unbunched beam);
  - or synchronous to the bunch structure (bunched beam).
- Larger fluxes up to a few $10^5$ particles per turn, which should be studied using only the beam loss monitors.

Beam footprint in the crystal
Deflected beam

Particle trajectory with $\alpha=150 \, \mu\text{rad}$
Expected efficiency for $\alpha=150 \ \mu\text{rad}$

- **Optimal orientation for channeling**: VR ($-\alpha$)
- **Amorphous orientation**
- **Probability to hit the TAL**
- **Probability to hit the TAL and RP2**
- **Probability to hit the TAL, PR1 and RP2**

- **TAL hit**
  - Number of particles vs. position
  - Number of particles vs. angle

---

- **Efficiency** vs. Angle, $\mu\text{rad}$
Plans for 2009

UA9

• Installation in the SPS tunnel: Feb 09
• First run: June 09
• Loss localization experiment: Sept 09
• Observation of single particles and efficiency measurement: Nov 09

H8RD22

• 400GeV proton microbeam: Oct 09
• 150GeV electro/positron muon beam: Nov 09
Conclusion

- High efficient reflection (and channeling) observed in single pass interaction of high-energy protons with bent crystals (0.5 to 10 mm long)

- Single reflection on a Si bent crystal deflects > 98 % of the incoming beam by an angle $12\div14 \mu\text{rad}$

- Very promising for application in crystal collimation

- Multi-reflections on a sequence of aligned crystals to enhance the reflection angle successfully tested in the 2007 and 2008 runs. Efficiency > 90 %.

- Axial channeling also observed (scattering enhancement ?)

In 2009 the UA9 test planned in the SPS will provide us with the final word on crystal collimation for future hadron colliders
Recent Publications

- 2006–PhysRevLett_97_144801 Volume Reflection of a Proton Beam in a Bent Crystal
- 2007–NIMB54908 Volume reflection of high-energy protons in short bent crystals
- 2007–PRL98 High-Efficiency Volume Reflection of an Ultrarelativistic Proton Beam with a Bent Silicon Crystal
- 2008–NIMB55427 Efficiency increase of volume reflection of high-energy protons in a bent crystal with increasing curvature
- 2008–PLB 658 Double volume reflection of a proton beam by a sequence of two bent crystals
- 2008–RSI 79 Apparatus to study crystal channeling and volume reflection phenomena at the SPS H8 beamline
- 2008–SPSC–P–335 PROPOSAL OF THE CRYSTAL EXPERIMENT
Acknowledgments

We acknowledge partial support by

- The European Community-Research Infrastructure Activity under the FP6 “Structuring the European Research Area” program (CARE, contract number RII3-CT-2003-506395),
- the INTAS program
- The MIUR 2006028442 project,
- The Russian Foundation for Basic Research grant 06-02-16912,
- The Council of the President of the Russian Federation grant NSh-3057.2006.2,
- The Program "Physics of Elementary Particles and Fundamental Nuclear Physics" of Russian Academy of Sciences.
- INFN: NTA programme