H8-RD22 Experiment to test Crystal Collimation for the LHC

Walter Scandale CERN
For the H8-RD22 collaboration
(CERN, FNAL, INFN, IHEP, JINR, PNPI)

LHC seminar
15 March 2007
Outlook

- Reminder of the concept of collimation
- Why using crystals
- The H8-RD22 experiment at CERN
  - Silicon crystals
  - Experimental layout
  - High precision goniometric system
  - Tracking detectors
- The results of the 2006 run
  - Crystal Angular Scans (Strip and Quasi-Mosaic Crystals)
  - Double Reflection Effect
- Concluding remarks and future plans
Two stage collimation

Beam Core

Primary halo (p)

Secondary halo

π
p

Primary collimator (scatterer)

Shower

Secondary collimator (massive absorber)

Tertiary halo

π
p

Sensitive equipment
Requirements for LHC

Super-Condacting 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>
<th>Control transient losses (10 turns) to ~1e-9 of nominal intensity (top)!</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>
<td></td>
</tr>
<tr>
<td>7000</td>
<td>8.4e9 p/s</td>
<td>7.6e6 p/s/m</td>
<td>99.91 %</td>
<td></td>
</tr>
</tbody>
</table>

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

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

Courtesy of R. Assmann
IR3 and IR7 insertions are equipped with 54 collimators made of carbon-carbon.

Open problems:

- Resistive impedance (up to 100 times the whole LHC)
- Electron cloud (local concentration)
LHC stability diagram

All the machine with Cu coated (5 µm) collimators

Without collimators (TCDQ+RW+BB)

Re(ΔQ)

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-0.0008 -0.0006 -0.0004 -0.0002
0.000025
0.00005
0.000075
0.0001
0.000125
0.00015

- Im(ΔQ)

0.00015
0.000125
0.0001
0.000075
0.00005
0.000025

Courtesy of E. Metral
Crystal collimation

- Primary halo directly extracted!
- Much less secondary and tertiary halos!?
Crystal collimation: a smart approach for primary collimation

- A bent crystal deflects halo particles toward a downstream absorber:
  - the selective and coherent scattering on atomic planes of an aligned Si-crystal may replace more efficiently
  - the random scattering process on single atoms of an amorphous scatterer.

The hope is to get

- Larger collimation efficiency
- Larger gap of the secondary collimator --> reduced impedance
RD 22: extraction of 120 GeV protons (SPS: 1990-95)

- Large channeling efficiency measured for the first time
- Consistent with simulation expectation extended to high energy beams
- Experimental proof of multi-turn effect (channeling after multi-traversals)
- Definition of a reliable procedure to measure the channeling efficiency

<table>
<thead>
<tr>
<th></th>
<th>Crystal 1</th>
<th>Crystal 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam intensity (protons)</td>
<td>$(7.0 \pm 0.1) \cdot 10^{11}$</td>
<td>$(3.7 \pm 0.1) \cdot 10^{11}$</td>
</tr>
<tr>
<td>beam lifetime (hrs)</td>
<td>$20 \pm 2$</td>
<td>$12 \pm 1$</td>
</tr>
<tr>
<td>protons lost per second</td>
<td>$(6.7 \pm 0.6) \cdot 10^5$</td>
<td>$(8.9 \pm 0.7) \cdot 10^5$</td>
</tr>
<tr>
<td>protons detected per second</td>
<td>$5.6 \cdot 10^5$</td>
<td>$6.6 \cdot 10^5$</td>
</tr>
<tr>
<td>background (%)</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>detection efficiency (%)</td>
<td>$78 \pm 12$</td>
<td>$78 \pm 12$</td>
</tr>
<tr>
<td>extraction efficiency (%)</td>
<td>$10.2 \pm 1.7$</td>
<td>$9.3 \pm 1.6$</td>
</tr>
</tbody>
</table>

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E853: extraction of 900 GeV protons (Tevatron: 1993-98)

- Extracted significant beams from the Tevatron parasitic, kicked and RF stimulated
- First ever luminosity-driven extraction
- Highest energy channeling ever
- Useful collimation studies
- Extensive information on time-dependent behavior
- Very robust
Crystal collimation at RHIC

STAR Background during crystal collimation test at RHIC

4 crystal scans with different scraper positions - $x_s$

The observed increase of background (black and red plots) was unexplained
Crystal collimation at FNAL

Using the crystal, the secondary collimator E03 can remain further (-1 mm or so) from the beam and achieve almost a factor of 2 better result!

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The H8-RD22 experiment

3rd mini-workshops on crystal collimation organized by CARE-HHH-ADP

- 3rd CC, CERN, 9-10 Mar. 2006

<table>
<thead>
<tr>
<th>organization</th>
<th>scientific themes</th>
</tr>
</thead>
<tbody>
<tr>
<td>♦ 20 participants</td>
<td>♦ Recent result on channeling at IHEP and PNPI</td>
</tr>
<tr>
<td>♦ 5 institutions</td>
<td>♦ Layout and detector of the SPS crystal experiment in the H8 line</td>
</tr>
<tr>
<td>♦ 23 talks</td>
<td>♦ Simulation of the expected results in H8</td>
</tr>
</tbody>
</table>

Main outcomes:
♦ Launching of the collaboration H8-RD22 (CERN-INFN-FNAL-IHEP-JINR-PNPI), for the SPS experiment on channeling in the H8 beam.
♦ Definition of the beam parameters and the experimental layout for H8-RD22.
♦ Cooperative effort of HHH with EU-INTAS-CERN programme to support the networking need of H8-RD22.
♦ Crystals as possible tools to enlarge the physics potential of TOTEM.
♦ Support for main components (beam, detectors, crystals and goniometer) requested to INFN-CSN1, INFN-NTA-HCCC and CERN
The H8 line

- goniometer in 2006
- upstream Si det
- bending magnets
- goniometer in 2007
The H8-RD22 apparatus

Variant for 2007

Angular resolution $\sim 2 \mu\text{rad}$, $\delta \Theta \sim \sqrt{2} \sigma/l \leq 0.5 \mu\text{rad}$

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Strip silicon crystals

Crystals sizes: 0.9 x 70 x 3 mm$^3$ and 0.5 x 70 x 3 mm$^3$

- Strip Crystals have been fabricated in the Sensors and Semiconductor Laboratory (U. of Ferrara)
- Mechanical bending exploits anticlastic forces
Quasi-mosaic silicon crystals

Quasi-Mosaic Crystals fabricated in PNPI (Gatchina, Russia)

- the mechanical bending of the crystal induces the bending of the atomic planes (initially flat and normal to large faces of plate) due to anisotropy
- $\rho$ depends on the choice of crystallographic plane and on the angle of $n_{111}$ respect to the crystal face

Crystal plate sizes: $\sim 1 \times 30 \times 55 \text{ mm}^3$

critical angle for 400 GeV/c protons: $\theta_c \approx 10 \mu\text{rad}$
High precision goniometer

- Silicon detector
- Goniometer
- Granite Block
- Scintillator
- Crystals

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AMS Silicon Detectors

Detector upstream of the crystal (on the granite block):
- 1 double-sided silicon microstrip detector:
  - Resolution ~ 10 µm in bending direction (X coordinate)
  - Resolution ~ 30 µm in non-bending direction (Y coordinate)
  - Active area ~ 7.0 x 2.8 cm²

Detector downstream of the crystal (on the granite block):
- 1 BABY double-sided microstrip detectors (IRST):
  - Resolution better than 10 µm in bending direction
  - Resolution better than 20 µm in non-bending direction
  - Active area ~ 1.9 x 1.9 cm²

DOWNSTREAM TELESCOPE (at 65 m from crystal location):
- 4 AMS LADDERS:
  - Resolution ~ 10 µm in bending direction
  - Resolution ~ 30 µm in non-bending direction
  - Active area ~ 4 x 7 cm²
AGILE Silicon Detectors

- Single-sided silicon strip detectors
- Built by Agile (INFN/TC-01/006)
- Active area 9.5 x 9.5 cm$^2$
- Spatial resolution: ~ 40 µm at normal incidence (~ 30 µm for tracks at 11°)
- Silicon thickness: 410 µm

- Upstream detector (before goniometer)
  - 2 silicon detectors at 90° (corresponds to 1 X-Y plane)

- Downstream detector 1 (at 65 m from crystal location):
  - 4 X-Y silicon planes

- Downstream detector 2 (at 65 m from crystal location):
  - 6 X-Y silicon planes interleaved with 300 µm tungsten planes
Gas Chamber and Scintillators

Gas Chamber

- Parallel plate chamber
- 0.6 × 12.8 mm² active area
- filled with Ar 70% + CO₂ 30%
- 64 strips (pitch equal to 200 µm)
- mounted on X-Y table
- able to withstand rates up to 10⁸ ppp

Scintillating detectors

- Finger scintillators: 0.1 × 1 × 10 mm³
- Scintillating hodoscope: 16 strips with 2 × 4 × 30 mm³ read-out by MAPMT (fast beam monitoring)
- Scintillator plates 100 × 100 × 4 mm³ used for triggering silicon detectors
Angular scan of a crystal (1)

Theoretical explanation of channeling and volume reflection phenomena

Involved processes:
- channeling
- volume capture
- de-channeling
- volume reflection

Angular scan of a crystal (2)

Results of the angular scan with Strip Crystal

measured volume reflection angle: 
\[ \sim 10 \, \mu \text{rad} \]
Angular scan of a crystal (3)

measured volume reflection angle: \( \sim 10 \, \mu \text{rad} \)
Scan of Quasi-Mosaic Crystal

- Orientation (111)
- Bending angle: ~ 80 µrad
- Crystal sizes: 30 x 58 x 0.84 mm³

QM2, normalized, no beam slice

QM2, normalized, sliced beam

measured volume reflection angle: ~ 10 µrad
Double Reflection on Quasi-Mosaic Crystals (1)

Experimental setup:

- exploited rotational stage for off-axis alignment of the first crystal (preliminary scan)
- used upper linear stage for alignment of second crystal
- many steps for finding perfect alignment conditions
Double Reflection on Quasi-Mosaic Crystals (2)

QM1+QM2, normalized, no beam slice

M1+QM2, normalized, sliced beam

double reflection angle: $\sim 20 \, \mu\text{rad}$
Double Reflection on Quasi-Mosaic Crystals (3)

Chan1 unperturbed

Chan2

Ref1

Ref12

Misaligned crystals -> two reflections angle: ~ 10 µrad
Conclusive remarks

- First observation of Volume Reflection Effect in bent silicon crystals with 400 GeV/c protons with efficiency close to unity
- Measurement of volume reflection angle: \( \sim 10 \, \mu \text{rad} \)
- First observation of Double Reflection using two crystals in series: combined reflection angle is \( \sim 20 \, \mu \text{rad} \) and efficiency close to 1
- Channeling and Volume Reflection phenomena studied with Strip and Quasi-Mosaic Silicon Crystals (different fabrication techniques)
- Measurement of crystals with different crystalline planes orientations: (111) and (110)

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- SPS-OP team

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- INFN-CSN1 and INFN-NTA
- CERN AB & AT departments
Open issues

- Crystal efficiency for channeling and volume reflection at both LHC injection (450 GeV) and top (7 TeV) energies.
- Probability spectrum of proton deflections at 0.45 to 7 TeV for all physics processes down to a $10^{-5}$ level.
- Damage limit of crystals for instantaneous shock beam impact at $\sim 15$ MJ/mm$^2$.
- Damage limit of crystals for integrated dose at $\sim 5 \times 10^{16}$ p/year at 7 TeV.
- Handling of crystals during normal operation at high-power impact.
- Number, opening (impedance) and locations of absorbers for extracted and scattered beam.
- Sensitivity to beam angle and angular spread in the TeV region.
- Requirements for alignment and operational set-up (goniometer conceptual design, tolerances, time, etc.).
Future plans

- 7 weeks beam time requested in 2007 at the SPS
  - protons (H8 beam-line) at 400 GeV
  - electrons and/or positrons at 300 GeV
  - ions during dedicated MDs
- Investigate edge-effect
- Test of multi-strip crystals (Ferrara Sensor and Semiconductor Laboratory) to increase the angle of volume reflection
- Test of germanium strip crystals and possibly zeolites
- Upgrade of goniometric system with cradle for investigation of axial channeling
- Upgrade and refurbishment of existing silicon microstrip detectors in order to increase spatial resolution

- CARE-HHH workshop CC 07 22-23 March 2007
- Proposal of LARP to create a working group aiming at a crystal experiment in the Tevatron