Bent Crystal Proton Collimation: Now A Reality

Tevatron T-980 Experiment

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Outlook

- Physics
- Experiment
- Results
- Summary and Plans
What is *bent crystal*?

Crystal bending is accomplished through *anticlastic* deformation.
Five (!) Processes in Crystals

- **Unchanneled particle (scattered)**
- **Channeled particle**
- **Volume-reflected particle**
- **Volume-captured particle**
- **Volume reflection** was predicted by Taratin and Vorobiov in 1987

**Channeled particle de-channeled**
Single Pass Observations: SPS Beamline

1. Primary p+ beam
2. Channeling
3. Dechanneling
4. Volume reflection
5. Volume capture

Note the difference in acceptance:

- Channeling < 10 µrad
- Vol-reflection ~ 100 µrad

... and m.b. higher **efficiency**

... but smaller angle

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Circulating Beam Collimation

“Standard” 2-Stage Collimation

Primary beam

Primary collimator (scatterer)

Secondary collimator (absorber)

Amorphous Scattering
Collimation by Crystal Channelling

Primary beam

Bent crystal

Dechanneling

Channeling

Secondary collimator (absorber)
Collimation by Volume Reflection

Primary beam

Volume Reflection

Bent crystal

Crystal Reflection Collimation

Secondary collimator (absorber)
The concept of multiple VR

Repeated VRs in an array of parallel crystals results in larger deflection, e.g. at $E=1$ TeV:

*One crystal* \( \theta_{VR} = 8 \mu\text{rad}; \theta_{\text{bend}} = 200 \mu\text{rad} \)

*8 crystals* \( \theta_{VR} = 8 \times 8 = 64 \mu\text{rad} \)

8 Crystal “Strips”
Which Particles Move Onto Crystals?

Taking synchrotron motion in account:

\[ X_{co} + \sigma_x \cdot a_\beta + D \cdot \sigma_p \cdot a_S = X_{\text{crystal}} \]
How Halo Particles Move Onto The Crystal

- Four diffusion processes:
  - Vacuum and transverse noise $\sim 4 \text{ nm/} \sqrt{\text{turn}}$
  - RF noise $\sim 12 \text{ nm/} \sqrt{\text{turn}}$ (Hor) and $\sim 1 \text{ nm/} \sqrt{\text{turn}}$ (Vert)
  - Beam-beam/NL diffusion $\sim 10-40 \text{ nm/} \sqrt{\text{turn}}$
  - (abort gap DC beam only) TEL $\sim 7 \mu \text{m/turn}$
    
    …compare with:
  - 5 mm amorphous Si $\sim 200 \mu \text{m/} \sqrt{\text{turn}}$
  - 5 mm W primary target $\sim 1.2 \text{ mm/} \sqrt{\text{turn}}$

- Two orbit processes:
  - Transverse orbit oscillations $\sim 20 \mu \text{m}$, $\sim 15 \text{ Hz} = 3000 \text{ turns}$
  - Synchrotron motion near RF bucket
    $\sim 1 \text{ mm}$ (Hor) and $\sim 70 \mu \text{m}$ (Vert) at $\sim 35 \text{ Hz} = 1300 \text{ turns}$

Thus, range of “impact parameters “ (depth) of 0.3-30 $\mu \text{m}$
...That Makes Crystal Phenomena in Rings Very Different From Single-Pass

Crystal Surface Phenomena:

1. Surface Roughness: ~100 nm

2. Miscut Angle: ~120 µrad

In the crystal angular scan over the bending angle region of 410 µrad, there is always an impact parameter region where the particles are channeled with a reduced deflection angle.
Hence, Because Of These Differences, *The Experiment (T980)*

- One Horizontal O-shaped Crystal
- One Vertical Multi-Strip Crystal
- Both These Crystals At Once
Collimator Scans of Crystal Extracted Beams

- Move collimator into the beam halo
- Vary crystal angle to observe CC/VR beam
- Observe the losses vs collimator X position (indicates intensity)
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The T980 Experiment Hardware: Goniometers, etc

Up and Downstream Laser angle measurement instruments

Up and Downstream Motion control and LVDT
Installed new Vertical goniometer with 2 crystals 4 m upstream of the Horizontal goniometer

Also installed new detectors and hardware at F17 to detect volume reflected beam (VR)
Example of Angle Scan

Loss monitor near E03H collimator timed to count only during three 2.6 us abort gaps.
Example of Collimator Scan

Note: a) positions and widths are different
b) abort gap channeling only ~70% efficient
Collimator Scan of Vertical VR Beam

Position as expected for VR angle of ~64 urad
...somewhat wider...

8 strip crystal system

collimator out
collimator in

Graph:
- LE033 Mar 17 2010; Volume Reflection, F17 in
- erf fit $Y_0 = -1.76$ mm, $w = 1.12$ mm
Collimator Scan of Vertical CH Beam

same 8 strip crystal at E0 F17 collimator (1km away)

Position is not what’s expected for 200 urad channeled beam (-5.7mm)

?? Interception??

F1LBNC

erf fit, $Y_0 = -1.9\text{mm}$, $w = 0.78\text{ mm}$

Loss rate Near F17 Collimator F1LBNC (Hz)

Vertical F17 Collimator Position F12VCP (mm)
Computer Modeling: Beams @ Collimators

At the Hor Crystal

At E03H Collimator

At F172H Collimator
Compare MS Data with Simulations

![Graph showing experimental data and simulations](image)

- **Experimental data**
- **Simulations**

**Y-axis:** Loss Rate at the Intercepting Collimator LE033 (arb. units)

**X-axis:** Crystal Angle (μrad)
Compare MS Data with Simulations

Loss Rate at the Intercepting Collimator LE033 (arb.units)

- - - Experimental data
- - - Simulations

Volume Reflected
Beam Hits Collimator

Crystal Angle (μrad)
Compare MS Data with Simulations

- Experimental data
- Simulations

Loss Rate at the Intercepting Collimator LE033 (arb.units)

Crystal Angle (μrad)
1st Attempt of 2 Plane Crystal Collimation

Hor Crystal in Channeling & 8 Strip Vert Crystal in VR

Improvement seen due to Hor CC, but very little due to Vert MS Volume Reflection
Summary Crystal Collimation in Tevatron

- Crystal collimation has been used during many collider stores in 2009-10
- In 2009, old O-shaped crystal in horizontal goniometer was replaced with new 0.36-mrad O-shaped one (IHEP) with negative 0.12-mrad miscut angle; PLUS, new vertical push-pull goniometer installed 4-m upstream, housing two crystals: 8-strip (IHEP) and old O-shaped ones → therefore, we now have crystals for BOTH planes
- Instrumentation added: eg scintillation telescopes installed at E0 and F17
- A successful fast/automatic insertion of the crystals has been achieved.
- Success in using vertical multi-strip crystal: (1) easy to work with; (2) observed both multiple-VR beam at E03 collimator and a channeled beam at F17 collimator; (3) decent agreement with simulations.
- A reduction of ring losses was reproducibly observed along with local loss effects on the collimator due to crystal channeling.
- First ever attempts of 2 plane crystal collimation … (modest results so far)
- Quantitative discrepancies btw simulations/expectations and observations
New Hardware and Plans (2010-11)

- In summer 2010 shutdown, old O-shaped crystal in vertical goniometer will be replaced with new Quasi-Mosaic crystal (PNPI), and 8-strip IHEP crystal will be replaced with advanced 16-strip crystal (INFN, Ferrara), keeping a possibility to alternate them remotely.

- High-resolution pixel telescopes will be installed in front of E03 and F17 collimators to measure channeled and VR beam profiles at those locations with resolution ~5 μm.

- Broad experimental program with this enhanced system is planned starting September 2010 through October 2011 for thorough study of two-plane crystal collimation efficiency in EOS and full collider stores. It aims at demonstration of improved reproducible beam loss localization in collimation region, reduction of beam losses around the ring, and specifically in the CDF and D0 collider detector regions.