On the possible use of crystals for extraction from the LHC

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Introduction

Strong fields from screened nuclei,
Continuum approximation

Strong fields with macroscopic extension

\[ \psi_c = \left( \frac{2U}{p\nu} \right)^{1/2} \]
Channeling in a curved crystal (I)

Centrifugal term

\[ U_{\text{eff}} = U(x) + U_{\text{cf}} = U(x) - pv\kappa x \]

Curvature, \( \kappa = \frac{1}{R} \)

Well ‘disappears’:

\[ \kappa_c = \frac{\pi Z_1 Z_2 e^2 N d_p}{pv} \]
\[ \kappa_c \propto \frac{Z_2}{pv} \]
Channeling oscillation wavelength: \( \lambda \)

\[ \theta(\lambda) < \psi \iff \kappa < \kappa_c = \pi Z_1 Z_2 e^2 N d_p / p v \]

or

‘Adiabatic condition’:

**Deflect less than the critical angle over one oscillation**

\[ \psi \propto (Z_2 / p v)^{1/2}, \quad \lambda \propto 1 / \psi \propto (p v / Z_2)^{1/2} \]

\[ \Downarrow \]

\[ \kappa_c \propto Z_2 / p v \]
Dechanneling

Multiple Coulomb scattering $\Rightarrow$ dechanneling

Dechanneling length:

\[ L_D \approx 0.9 \text{ m}\cdot\text{p[TeV/c]}, \text{ Si (110)} \]

Mechanical bending to $\approx 10$ mrad

$\downarrow$

High energies ($\geq$ few GeV)

Structural bending possible with much smaller $R$
– crystal undulator, MeV bending

\[ N = N_0 \exp(-x/L_D) \]
Curvature dechanneling

Decreased potential barrier: 
$$E_{\text{depth}}(\kappa) = E_{\text{depth}}(0) \left(1 - \frac{\kappa}{\kappa_c}\right)^2$$

Dechanneling fraction 
$$F \approx 3\frac{\kappa}{\kappa_c}$$

$$(1-F)$$ of phase-space stays channeled
Dechanneling in a curved crystal (II)

Multiple scattering dechanneling

Centrifugal term \( \Rightarrow \)

Equilibrium near nuclei

\[ \Downarrow \]

Decreased dechanneling length:

\[ L_D \propto E_{\text{depth}} \propto (1 - \kappa/\kappa_c)^2 \approx (1 - F/3)^2 \]

\[ L_D(F) = L_D(0)(1 - F/3)^2 \]
Model for deflection efficiency

\[ \varepsilon = \varepsilon_S \cdot exp\left(\frac{-L_S}{L_D}\right) \cdot exp\left(-\frac{L_B}{L_D(1-F/3)^2}\right) \cdot (1-F) \]
First extensive investigation at SPS

Si (111), 450 GeV protons

File: First extensive investigation at SPS.pdf

Deflection efficiency vs. Deflection angle [mrad]

Model

Experiment

Ulrik I. Uggerhøj, CC-2005
Heavy materials

Theoretical expectation:
Higher $Z$, Higher field, $L_D\kappa_c \propto Z^2$
$L_D\kappa_c = 0.3$, Si (110), weak energy dependence
At optimal length: $\varepsilon \approx \varepsilon_S(1-(3\theta/L_D\kappa_c)^{1/2})^2$
Higher $L_D\kappa_c \Rightarrow$ higher efficiency
Silicon ($Z=14$) in good agreement with model
How about germanium ($Z=32$)?
Higher Z

Ge (110), 450 GeV protons

Deflection efficiency vs. Deflection angle [mrad]

- Model, $\sigma_{\psi} = 3\mu\text{rad}$
- Experiment

450 GeV/c

2000 T !
Energy dependence

Germanium (110), 200 GeV $p^+$ and $\pi^+$

![Graph showing the energy dependence of deflection efficiency for Germanium (110) with 200 GeV $p^+$ and $\pi^+$. The graph includes data points and a line representing the model, $\sigma_\psi = 6 \mu$ rad.](b)
Nuclei

Deflection of 33 TeV Pb$^{82+}$ (1997)

Small EM dissociation, nuclear interaction
Heavy ion deflection ($\text{In}^{49+}$)

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
$\theta$ [mrad] & $\sigma(\theta)$ [$\mu$rad] & $\varepsilon$ [%] \\
\hline
7.5$\pm$0.3 & 34$\pm$1 & 3.0$\pm$0.2 \\
11.9$\pm$0.2 & 35$\pm$1 & 2.0$\pm$0.1 \\
19.8$\pm$0.2 & 26$\pm$7 & 0.4$\pm$0.1 \\
\hline
\end{tabular}
\end{table}

Dechanneling for increasing curvature
Heavy ion deflection

- Nuclear-charge pickup, $n + \gamma \rightarrow p + \pi^-$

- Ions predominantly ($\approx 99\%$ for realistic thicknesses) exit in the same charge state as they enter
Summary

Deflection phenomenon in bent crystal:
- Light material, Si, eff. up to 50%
- Heavy material, Ge, eff. up to 60%
- Dependence on curvature
- Energy dependence
- Radiation sensitivity (for protons, 6%/10^{20} p^+/cm^2)
- Nuclei, Pb^{82+}
- Nuclei, In^{49+}

Possible applications
- Extraction of p^+ or Pb from LHC
- Extraction of Au from RHIC

Heavy ions???
Only remaining ‘big’ exp. question for deflection in bent crystals
LHC – what’s new?

• …Since the LHB proposal LHCC/93-45:
  – Accelerator lattice
  – Twiss parameters (more or less fixed now)
  – Warm and cold sections
  – Dump scheme
  – Beam parameters
  – Exact layout (technical drawings)
  – Crystal radiation damage:
    \[ 10^{13} \text{ p}^+/\text{day, } 10^{-5} \text{ cm}^2, \text{ limit: } 10^{20} \text{ p}^+/\text{cm}^2 => \]
    about 100 days (then remote displacement, 0.1 mm)
LHC dump, IP6
LHC dump, IP6

- Only cold section
- Extracted (dumped) beam
Tunnel cross section

Circulating beams
Kicker section, dump, IP6

- Possible location of bent crystal(s)

- $d_{IP6} = 192710$ mm

- $\beta$-function: appr. 200 m
Bending efficiency (single pass)

Including 90% surface transmission

- 17 cm (Si)

Efficiency [%]

Normalized length, $L/L_D$

Angle in mrad
Multi-pass

High efficiency multi-pass proton beam extraction with a bent crystal at the SPS


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b CERN, Geneva, Switzerland
c ESRF, Grenoble, France
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• Multi-pass: Shorter crystals (Biryukov et al.)
What do we get?

• Beam loss from LHC: about $10^9$ p$^+$/s
• Assuming efficiency in multi-pass mode 50%
• $5 \times 10^8$ p$^+$/s, $\sqrt{s} = 115$ GeV
• Likely impact parameters on the crystal: about 10 µm (difficult estimate), critical angle: 2 µrad
  \[
  \text{emittance (v): } 20 \times 10^{-6} \text{ mm } \cdot \text{ mrad}
  \]

• Beam size at dump (in extraction direction): 0.3 mm
Possible problems (and possible solutions)

- Dechanneling losses in regions of increasing curvature (ZnO coating on first few mm)
- Heavy ion radiation damage to crystal?
- High-intensity beam during dump (fast dipole)
Additional advantages

- Deflection angle independent on energy:
  - Extraction possible at any energy 0.450-7 TeV
  - Insensitivity to small energy errors (could be catastrophic for MKD dump): Slow dump by means of crystals (?)
  - (Smart) collimation
  - Beam stability – extracted beam intensity
  - Beam monitoring

Strong crystalline fields – a possibility for extraction from the LHC

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Extraction (collimation) device – complete with power supply etc.
... an even intersection” (RF, Dump, ALICE, LHC-B)