Muon Channeling and the Need to Investigate Negative Particle Channeling and Collimation

Dick Carrigan
Fermilab

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Landscape for TeV-scale channeling

“Recent” developments

collimation
volume reflection, capture
Vorobiev & Taratin
RHIC
Tevatron
famous CERN H8
short crystals

LHC collimation
protons from 1-7 TeV
very active ...

Everything else

extraction, e. g. at LHC
collimation at an ILC, e+-
but really not so hard,
also later
muon collider
even further away
Fermilab 99/069 study
crystal collimation
not appropriate
but may be different at
high energy
Update on Tevatron crystal collimation studies

History
2005 – Reproduced RHIC results with “O” crystal
2007 – tried 3 mm, 150 μrad bend, problems -…
2008 – “O” back, better goniometer, instrumentation

T980 – CCE Crystal Collimation Experiment
Fermilab, LARP, CERN, BNL, INFN, IHEP, PNPI, JINR, RINP-BSU, Chicago, …
several phases over 2008-2010 for collimation in 1, 2 planes,
possible single particle, simulation, etc.
linked with SPS collimation experiment
artificial halo, single particle, …
Oct. 29 half day workshop at Fermilab on channeling collimation
in conjunction with LARP CM11 and session here today
Dean Still and others have made significant progress in Sept, Oct.
Crystal collimation at LHC: Ralph Assmann’s concerns (from Channeling 2006)

Crystals are an interesting advanced technology for phase 2 of LHC collimation. To evaluate benefit in detail the following information is required:

- How to handle different LHC energies from 450 GeV to 7 TeV?
- Probability spectrum for proton deflections (channeling and others). Include all effects down to 10^{-5} probability!
- Sensitivity to beam angle and angular spread?
- Number, opening (impedance) and locations of absorbers. Damage limit of crystal for instantaneous shock beam impact (expect ~3MJ, 0.2×1.0 mm, 200 ns).
- Damage limit of crystal for integrated dose (expect ~5×10^{16} p/year at 7 TeV).
- Handling of crystal during normal operation: 500 kW power impact.
- Requirements for alignment and operational set-up (tolerances, time, …)?

(missing from list – crystal questions)

Recent LHC incident may increase emphasis on collimation even more!
Incomplete TeV-scale channeling topics

Negative particle channeling and bending
hadrons, relation to $e^-$ and channeling radiation
not important for LHC collimation – pp collider

Muon channeling for futuristic possibilities
(collimation for muon colliders – Tollestrup)
Negative particle channeling

**early eighties thinking:**
large discrete angular deflections like external beam.

**collimation is different**
any kick, provided it is more than multiple scattering
multi-pass channeling helps.
high energy helps

*We need more information on negative channeling, negative bending!*

Could one channel and collimate antiprotons at the Tevatron?
Could one collimate e⁺/e⁻ at ILC?
In TOTEM, etc. at LHC could one deflect negative particles such as antiprotons?
Functional form of planar dechanneling

$$\lambda_D = 1.62 \frac{\psi_{cp}^2}{\langle \Theta^2 \rangle_c}$$

where

$\psi_{cp}$ is planar critical angle

$\langle \theta^2 \rangle_c$ is the mean square mult scat angle in channel

(see Feldman & Appleton, PRB8, 935 (1973), Carrigan FN-454,
Biryukov, Chesnokov, and Kotov (BCK))

For (+) BCK treatment (1.50) leads to:

$$\lambda_D = \frac{256}{9\pi^2} \frac{p \nu}{\ln(2m_e c^2 \gamma / I) - 1} \frac{a_{TF} d_p}{Z_i r_e m_e c^2}$$

$\lambda_D = 51$ cm for (+) @ 1 TeV (roughly ~ E - note log term, ~20% effect)
Potentials for $+$ and $-$ particles to get $\psi_p$

[see, e. g., Taratin and Vorobiev, Phys. Lett A119, 425 (1987)]
Some Aarhus +/- results showing $\psi^- < \psi^+$

Implanted radioactive $^{64}$Cu in a Cu crystal –
(E. Uggerhoj, Andersen, Can. J. Phy. 46, 543 (1968))

For antiproton axial channeling find critical angle is about 0.6 of the critical angle for protons. Agrees with theoretical calculations
Negative hadronic channeling

Then for

\[ \lambda_D = 1.62 \frac{\psi_{cp}^2}{<\Theta^2>_c} \]

Where \(<\Theta^2>_c\) follows from

\[ \frac{d^2\Omega}{dx_e} = \frac{d^2\Omega}{dx_n} = \frac{(m_e / 2M_iE)(4\pi e^4 / m_e v^2)N Z L_t}{(M_i / M_iE)(4\pi Z^2 e^4 / M_i v^2)NL_n} = \frac{L_e}{2ZL_n} \Rightarrow \frac{X_0^n}{X_0^e} \]

where \(L_i\) are the log terms in multiple scat. Set \(L_n/L_e = 2\).

Get for 1 TeV as an approximation neglecting details of nuclear density.

\[ \lambda_- = \left( \frac{\psi_-}{\psi_+} \right)^2 \frac{\lambda_+}{2Z(L_n/L_e)} = \left( \frac{0.48 A}{0.83 A} \right)^2 \frac{51 \text{ cm}}{2*14*2} = 3 \text{ mm} \]
Negative hadronic channeling - continued

But - potential well is not filled with ions, only ±u_T
a weighting might be

\[ Z_{\text{eff}} = \frac{2u_T Z + 2\left(\frac{d_p}{4} - u_T\right)}{d_p / 2} \]

so that Zeff = 3 rather than 14 for 1 TeV Si(110)
giving λ-(1 TeV) \~\ 14 mm

Of course, particle more in center of channel, …

This range (3 to 14 mm) is short but have used:
3 mm strip crystals
Quasimosaic crystals (.03, 1 mm at CERN H8, H4)

Scandale-H4,H8
Straight crystal dechanneling for negative particles

Going beyond hand waving (or hand wringing) need:

- a diffusion model treatment for the negative particle case
- or a simulation ala CATCH or BINCOL

Would like array of (+/-)

\[ E = 0.07, 0.4, 1, 7 \text{ TeV} \]
\[ R = 0.1, 0.25, 0.5 \, R_T \]

Little experimental information on straight negative hadronic dechanneling
Bending of negative particles

The critical bending or Tsyganov radius is:

\[
R_T \approx \frac{p_v}{\pi N d_p Z e^2} = \frac{p_v(GeV)}{5.7 GeV/cm[Si(110)]}
\]

At +1 TeV in Si is ~175 cm (BCK 2.17). For the negative case,

the effective \(d_p\) could be smaller and \(R_T\) larger

The bending dechanneling length is:

\[
\lambda_D(p_v, R) = \lambda_D,0 \left(1 - \frac{R_T}{R}\right)^2
\]

If \(R \gg R_T\) then for negative particles \(\lambda_D(p_v, R)\) will be the negative particle dechanneling length, so it will be short

Negative particle bending measurements do give a tool to measure dechanneling in principle
Negative hadron bending

Bak et al. did studies of negative particle axial deflection at 10 - 12 Gev with pions [S. Anderson et al., Nucl. Phys. B167, 1 (81), J. Bak, et al., Nucl Phys. A389, 533(82)]

Schiott simulated their data using BINCOL in Carrigan and Ellison (Relativistic Channeling, NATO 165, Plenum (87)). Saw only small effects on order of critical angle.

I extract an upper limit on the bending dechanneling length of O(2 mm) from Baurichter et al. studies of negative π- axial deflection at 200 Gev. [A. Baurichter et al., NIM B119, 172 (1996)]

\[0.6 < \lambda < 3 \text{ mm}\] from the formula and the ansatz for the planar case.

H4, H8 (Bolognini thesis-fig. 4.21a) gives O(1 mm) @150 GeV for (111) in a quasi mosiac crystal
Negative particle volume reflection

Taratin and Vorobiev (1987)
In computer model positive particle
deflect $\sim 2\psi_{cp}$ away from bend
negative particle somewhat less.


Tevatron simulations for proton and antiprotons.
Antiproton effect nearly as strong as proton in volume reflection

Maisheev – analytic treatment
[PRST 10, 084701 (2007)]
This can be used to extrapolate to different energies, radii
Angles for positive case are 1.8 times larger than negative.

For a contrary view on (-) case see

No experiments have been reported but CERN H4 now has info
Negative volume capture

Volume capture deflects in the direction of the bend
Volume capture is a feeding-in process that follows reversibility
   This means it will be characterized by a feeding-in length
       functionally similar to a dechanneling length
since negative particle dechanneling is stronger
   feeding-in will be stronger
   but once in a channel particle will also dechannel faster
The theory of negative particle volume capture has apparently not been discussed
   However simulations such has Biryukov’s should implicitly contain it.

No experiments have been reported

[discussions of positive particle volume capture have been given by
 Sumbaev (circa 79), Samsonov (C&E-87), and BCK sec 2.3.1]
Studying negative particle channeling

**Tevatron – anti protons (Dean Still)**
- prefer <1 mm thick crystal, 5 mm might work
- redo proton, antiproton helices locally at E0 (goniometer)
  or remove proton store. Both need serious setup
- need a nearby antiproton downstream collimator, detector – something exists at E0 for Tevatron

**Fermilab Meson Area Beams**
Meson test beam – a problem is energy fairly low
MIPP – also a problem with low beam energy
Other possibilities for negative particle channeling

CERN
H4- this last summer did 150 GeV negative π, k, µ mesons
used thin crystals (~1 mm thick). Also used H8 in fall 2007

Serpukhov
lower energy beams than CERN

KEK
ATF – Endo et al, expression of interest – with 1.3 GeV tightly focused
electron beam
problem – channeling radiation
Muon channeling

Does high energy muon channeling answer fundamental questions?
Not really!
Point is that dechanneling length does not depend on nuclear interactions

\[ L_{\text{col}} (\text{Si}) = 30 \text{ cm}, \quad \] 
\[ L_+ [\text{Si}(110)] \sim 51*E(\text{TeV}) \text{ cm}, \quad \text{equal at } \sim 0.6 \text{ TeV} \]
\[ L_- [\text{Si}(110)] \sim 3 \text{ mm}*E(\text{TeV}). \]
nuclear density higher for negatives \( O(d_p/4u_T) \) or factor of 6
\[ L_{\text{col}} \text{ is still 100 times longer at 1 TeV, 15 times at 7 TeV} \]
weakly interacting particle does not teach anything

Critical energy for muons in Si is 470 GeV

Bremsstrahlung cross section

\[ \sigma_\mu = \sigma_e \left( \frac{m_e}{m_\mu} \right)^2 \]
so much less radiation/unit length
but negative muons in high \( Z^2 \) region
Muon channeling - continued

Potentially might be interesting for collimation in a **futuristic** muon collider or **neutrino factory**

50 on 50 GeV “low” energy muon colliders collimation **no challenge** (see Drozhdin et al. FERMILAB-Conf – 99/069)

But for higher energies more of a problem short quasimosiac bends using axial channeling might begin to be useful

Available information

  little experimental muon channeling data, mostly from pion implantation
  no theoretical evaluations?
Muon channeling experiments

Particle identification
use a hadron absorber in front of detector
typically 8 – 10 nuclear interaction lengths or 1.5 m iron.
At 50 GeV: $\Theta_{ms} = 800 \, \mu\text{rad}$ compared to $\psi_{cp} = 28 \, \mu\text{rad}$

Muon beams
Muon beams are tertiary beams
process is $\text{p} \rightarrow \text{pions} \rightarrow \text{muons and neutrinos}$
(450 GeV) (50 GeV) (<25 GeV)
Need space for pion decay
but even an ordinary pion beam has some muon contamination
But want information at TeV scale!
Rate lower at higher energy, but for channeling may be OK

Muon experiments at CERN?
per Gatignon: M2/COMPASS @ 160 GeV/c has $2E^8$/spill (+, /3 for -),
$\Theta \sim 600 \, \mu\text{rad}$, $\sigma \sim 20 \, \text{mm}$
I hear that in the H4 run @CERN this summer the beam was 50% muons
Summary

Negative hadronic channeling studies interesting for:
- planar and axial cases for normal bending
- volume reflection
- volume capture

Short crystals via anticlastic or quasimosaic techniques important

Muons:
- difficult experimentally but H4 ran last summer @ CERN
- not clear there is much interesting channeling physics
- no mid-range applications

For more Fermilab channeling information see:
- Channeling home:
  http://home.fnal.gov/~carrigan/Channeling/Channeling_master.htm
- Channeling Formulary:
  http://home.fnal.gov/~carrigan/Channeling/Channeling_formulary.htm
Questions?
Negative hadron and $e^+/e^-$ channeling?

e$^+/e^-$ channeling

- channeling radiation impact must be considered
- crystal lengths must be short
- not so much dependence on charge
- little of no experimental information at high energy, particularly for bending
e\(^+\)/e\(^-\) dechanneling lengths (microns, normalized to 1 GeV)

Critical energy for e\(^+\)/e\(^-\) in Si is 53 MeV but not so significant for channeled particle

<table>
<thead>
<tr>
<th>Process</th>
<th>e(^+) dechan (microns)</th>
<th>e(^-) dechan (microns)</th>
<th>Energy MeV</th>
<th>Comment</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planar theory</td>
<td>500</td>
<td>130 qua, 13 pure</td>
<td>1000</td>
<td>Si(110),1/2</td>
<td>Belosh. &amp; Trik Kom.</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>130 qua, 13 pure</td>
<td>1000</td>
<td>Si(110),1/e</td>
<td>Belosh. &amp; Trik Kom.</td>
</tr>
<tr>
<td>Planar experiment</td>
<td>1100 (60 – oc len)</td>
<td>660 (36)</td>
<td>54</td>
<td>Si(110),1/e</td>
<td>Livermore Komaki Adejshvili</td>
</tr>
<tr>
<td></td>
<td>88 (31)</td>
<td>350</td>
<td>54</td>
<td>Si(110),1/e</td>
<td>Livermore Komaki Adejshvili</td>
</tr>
<tr>
<td></td>
<td>23 (28)</td>
<td>1200</td>
<td>54</td>
<td>Si(110),1/e</td>
<td>Livermore Komaki Adejshvili</td>
</tr>
<tr>
<td>Axial theory</td>
<td>13</td>
<td>1000</td>
<td>Si(&lt;111&gt;),?</td>
<td>Muralev Taratin &amp; Vorob</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18</td>
<td></td>
<td>Si(&lt;111&gt;),1/2</td>
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<td>Adejshvili</td>
<td></td>
</tr>
</tbody>
</table>

Problems: Old and incomplete data! consistency, agreement of experiments (angular divergence), too little data, statistical estimates on data, theory challenges but some recent work at 5 GeV for undulator possibility (Korol et al. Physics/0412101 v1)
# Summary of coherent bend effects

<table>
<thead>
<tr>
<th>Effect</th>
<th>Angle dist</th>
<th>Deflection</th>
<th>Magnitude</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume reflection</td>
<td>$\Theta_d \sim \phi_c \sim 1/(p\beta)^{1/2}$</td>
<td>Away from bend</td>
<td>Strength same as channeling</td>
<td>Cumulative with beam passes</td>
</tr>
<tr>
<td>Volume capture</td>
<td>Up to full bend</td>
<td>Toward bend</td>
<td>$w_s \sim \text{const} \frac{R}{(p\beta)^{3/2}}$</td>
<td>Small at high energy</td>
</tr>
<tr>
<td>Miscut</td>
<td>Lowers deflection</td>
<td>Toward bend</td>
<td>0 to full deflection</td>
<td></td>
</tr>
<tr>
<td>Relaxed bend</td>
<td></td>
<td>Smaller bend</td>
<td></td>
<td>Ruled out by whole arc</td>
</tr>
<tr>
<td>Something else</td>
<td></td>
<td></td>
<td></td>
<td>Keep an open mind</td>
</tr>
</tbody>
</table>

Muon and Negative Hadronic Channeling
Carrigan  http://home.fnal.gov/~carrigan/channeling/channeling_master.htm

Channeling 2008
October, 2008
Electrons

with innovative short bends might be able to do electron bending

this is a regime where GeV scale machines could contribute
electron/positron dechanneling below 1 GeV down to 10 – 20 MeV

old information may not be consistent
Muon collider schematic
(taken from Bruce King-BNL, 4th International Conference on the Physics Potential and Development of mu+mu- Colliders, San Francisco, 1997.)

Very intense
Large aperture
Six degrees of freedom
Does it work?

For channeling collimation:
problem is large decay emittance of muon

Very fast, large aperture
Negative hadron and $\text{e}^+/\text{e}^-$ channeling -continued


More recently Greenenko and Shul’ga [NIM B90, 179 (94)] studied negative deflection with a simulation program. For axial channeling at 400 GeV they saw deflection at the same scale as the Schiott simulation. Their distributions for 100 GeV hadrons bent in a 3 cm crystal are shown below:

Note that the negative deflection is of the same order as the positive case but very diffuse. Volume reflection or capture?

$$\Theta_b = 0.3 \ \text{mrad}, \ \psi_{ca} = 0.04 \ \text{mrad} \quad \Theta_{axis} = 0.3 \ \text{mrad}$$
Muon energy loss – small!

\[ \delta E_i = 3.43 \text{ GeV} \]