CHANNELING AND VOLUME REFLECTION IN BENT CRYSTAL

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Spokes person of the UA9 Collaboration

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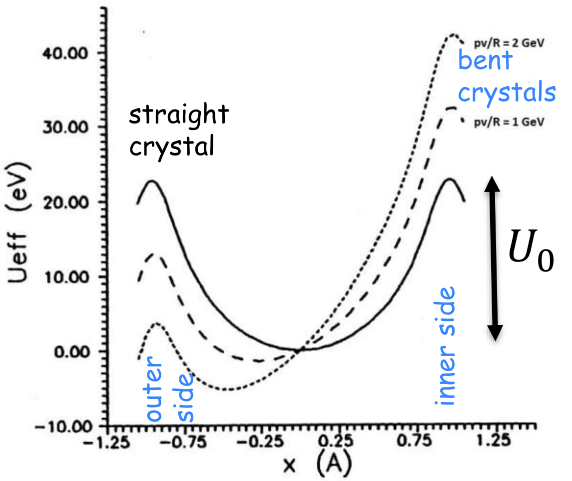
outlook

- Crystal-particle interactions
- Planar channeling
- Deflection efficiency
- UA9 as a test bed for crystal-particle interactions
- Short crystals
- Volume reflection
- Multi volume reflection
- Applications in circular accelerators

Particle-crystals interactions

Crystal inter-nuclear potential



$$U_{eff} = U_0 + \frac{pv}{R}x$$ Effective potential in a bent crystal

$$\alpha = \ell/R$$ bending angle

$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$ critical angle

$$R_c = \frac{pv}{U'(x_{max})} \approx \frac{pvx_{max}}{2U_{max}}$$ critical radius

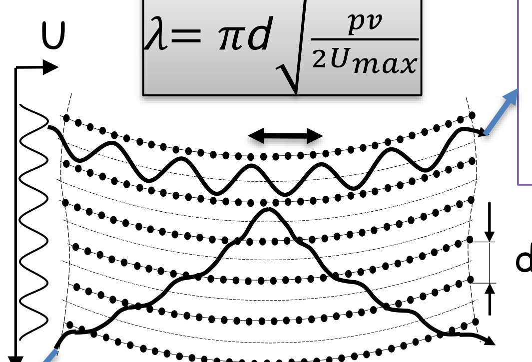
Coherent interactions

- Channeling
- *volume reflection*

Incoherent interactions

- multiple scattering
- volume capture
- dechanneling

$$\lambda = \pi d\sqrt{\frac{pv}{2U_{max}}}$$

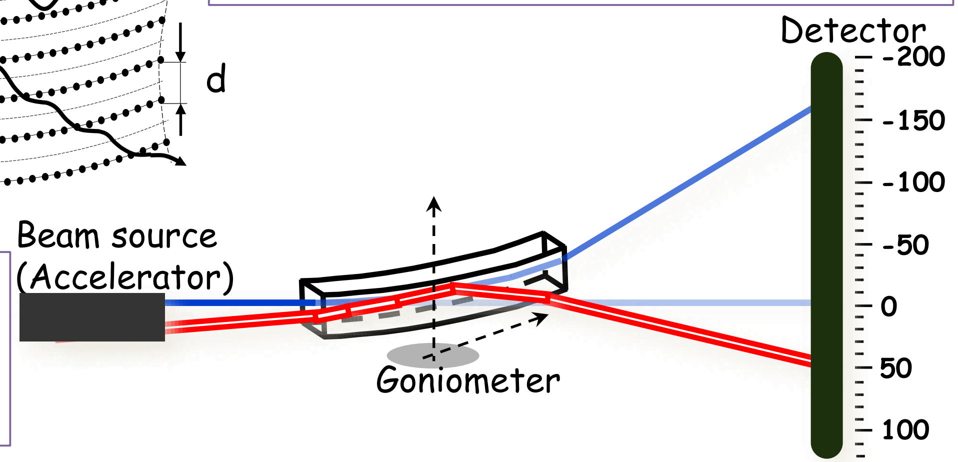


Planar channeling
- J. Lindhard, Dan. K., Vidensk. Selsk. Mat. Fys. Medd. 34 (14) (1965)
- E.N. Tsyganov, FNAL, TM-682 (1976).

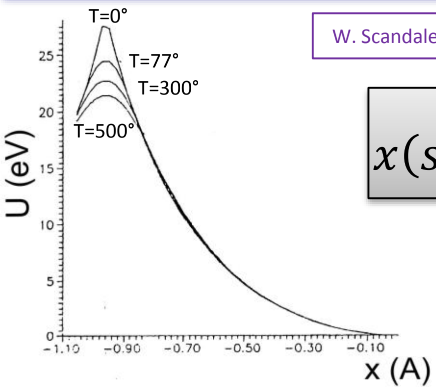
First Experiments:
- A.F. Elishev et al., Phys. Lett. 88B (1979) 387.
- J, Bak et al., Phys. Lett. 93B (1980) 505.

Volume reflection
- M. Taratin and S. A. Vorobiev, Phys. Lett. A **119**, 425 (1987);

First Experiments
- Y. M. Ivanov *et al.*, Phys. Rev. Lett. **97**, 144801 (2006).
- Y. M. Ivanov *et al.*, JETP Lett. **84**, 372 (2006).
- W. Scandale et al., PRL **98**, 154801 (2007)



Planar channeling

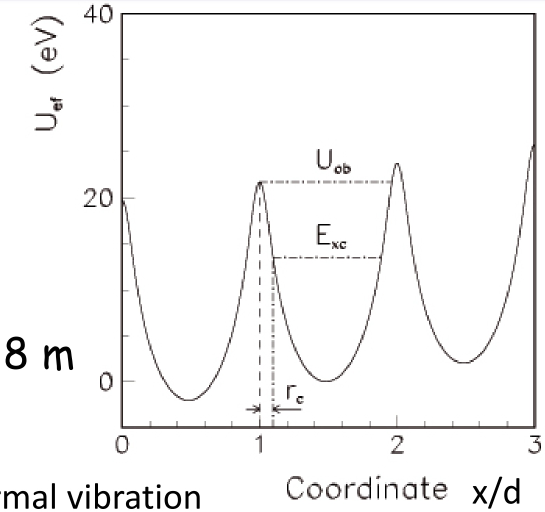


W. Scandale and A. Taratin, Physics Reports 815 (2019) 1–107

$$x(s) = \frac{d}{2}\sqrt{\frac{E_t}{U_0}} sin\left(\frac{2\pi s}{\lambda} + \phi\right)$$

$$\lambda = \pi d\sqrt{\frac{pv}{2U_{max}}}$$

$$E_t = \frac{pv}{2}\theta^2 + U(x)$$



for (110) si-crystal at T=300° with R= 38 m

$d = 1.92$ A is channel width

$u_1 = 0.038 \times d = 0.076$ A is RMS amplitude of the thermal vibration

$r_c = 2.5 \times u_1 = 0.187$ A is the screening distance from the point-like nuclear charge

$x_{mc} = d/2 - r_c = 0.77$ A is the boundary amplitude of the stable channeling states

$U_{ob} = 21.7$ eV is the depth of the planar potential well

$U_{xc} = 13.5$ eV is the critical transverse energy for stable channeling states

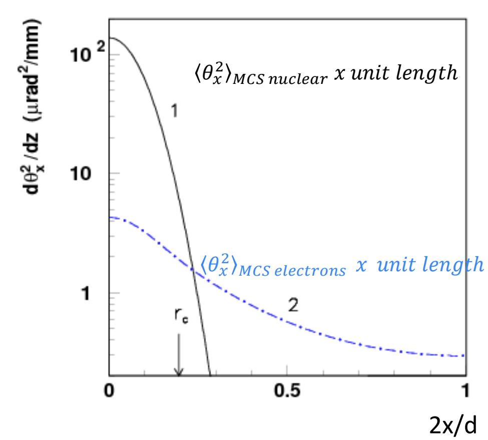
Nuclear density distribution

$$P_n(x) \sim exp\left(-\frac{x^2}{2u_1^2}\right)$$

If $x_{max} \le x_{mc}$ channeling + MCS on electrons (channeling corridor) $N_{ch}(s) \sim exp\left(-\frac{s}{L_e}\right)$

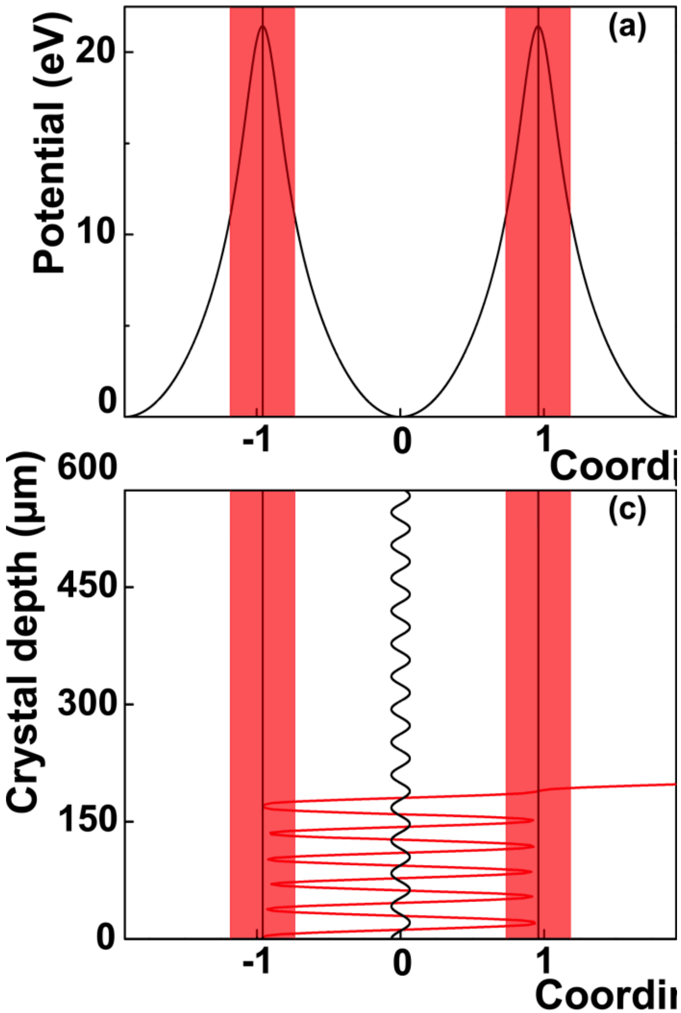
If $x_{max} > x_{mc}$ channeling +INI + MCS on nuclei and e^- (nuclear corridor) $N_{ch}(s) \sim exp\left(-\frac{s}{L_n}\right)$

$$L_n \ll L_e$$



Channeling and nuclear corridors

Scandale et al., PLB 680, 129 (2009)



$$N_{CH}(s) \approx N_{unstable} e^{-s/L_n} + N_{stable} e^{-s/L_e}$$

$L_n \sim$ sqrt(p) : at 7 TeV $L_n \sim$ 0.6 cm

$L_e \sim$ p : at 7 TeV $L_e \sim$ 400cm

Deflection efficiency

Deflection efficiency P_d = capture efficiency P_c x probability of channeling P_{ch}

$$P_d(R) = \underbrace{exp\left(-\frac{\ell}{L_e(R)}\right)\int_0^{E_{xc}(R)} f(E_{x0})dE_{x0}}_{\text{channeling corridor}} + \underbrace{exp\left(-\frac{\ell}{L_n(R)}\right)\int_{E_{xc}(R)}^{U_{ob}(R)} f(E_{x0})dE_{x0}}_{\text{nuclear corridor}}$$

$f(E_{x0})$ is the distribution of initial transverse energy

$E_{xc}(R)$=$E_{eff}(r_c,R)$ is the critical transverse energy for stable channeling

W. Scandale, et al., Phys. Rev. Lett. 102 (2009) 084801.

In long crystals ($\ell \gg L_n$)

- only the particles in the channeling corridor can be deflected ($E_{x0} < E_{xc}$)
- the channeling efficiency is limited by the MCS on the electrons

$$P_d(R)=P_{ch} \times P_c(E_{x0} < E_{xc}) = exp\left(-\frac{\ell}{L_e(R)}\right)\int_0^{E_{xc}(R)} f(E_{x0})dE_{x0}$$

Upper limit for the capture (and the channeling) efficiency in a long straight crystal

$P_d(R)<P_c(E_{x0} < E_{xc})$ Deflection efficiency smaller than capture efficiency

$P_c = 1 - {2r_c}/{d_p}$ Asymptotic value of P_c for a parallel beam

$P_c = 0.805$ for (110) si-crystal straight (or large R) with $\ell \gg L_n$ at T=300°

Detectors for UA9 in the North Area

Two measurement arms – 10m length in each

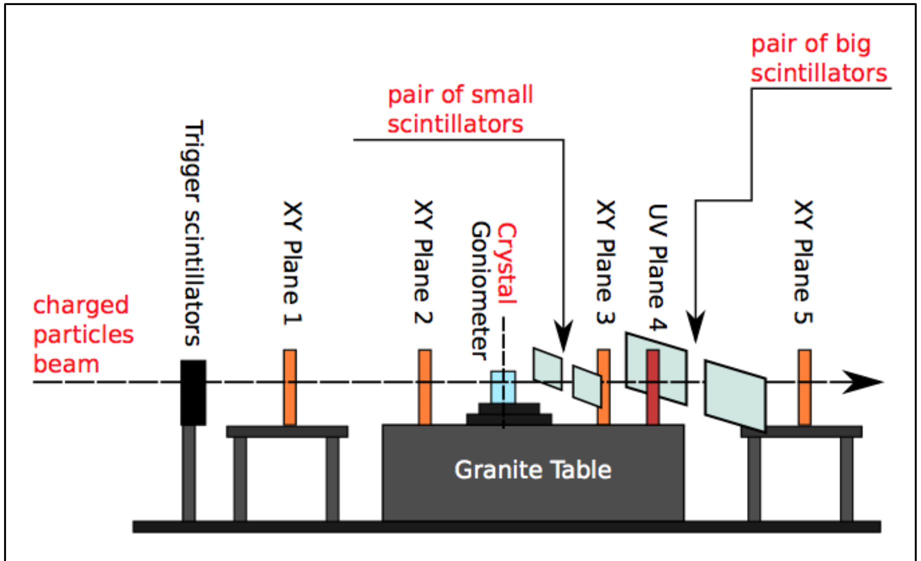


FIG. 1: Experimental layout in the H8 beam line.

Operational runs

- Use a low-divergence incoming beam
- **Alignment run:** only the tracking stations are in the beam line
- **Linear scan:** crystals are placed on the beam line
- **Fast angular scan:** scan of a large angular range to find the channeling orientation
- **Detailed angular scan:** ~10^5 events/step are acquired around the channeling orientation
- **High statistics run:** the crystal is left in the optimal channeling for a stat. of ~10^6 p

Observables

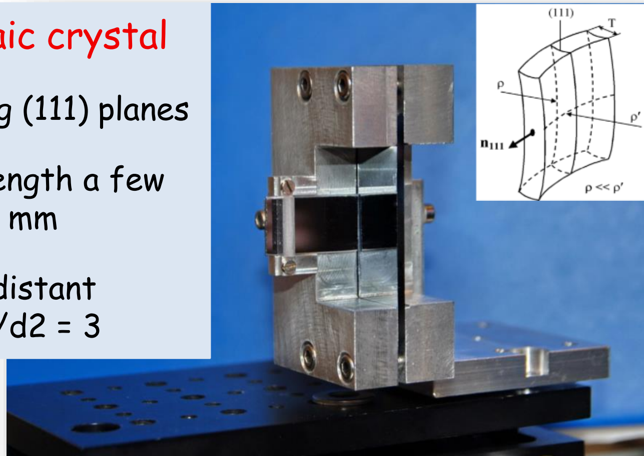
- Detect the incoming direction of each particle
- Detect the outgoing direction after the interaction with the crystal
- Detect inelastic events

W. Scandale et al., REVIEW OF SCIENTIFIC INSTRUMENTS **79**, 023303 (2008)

Bent crystals for UA9

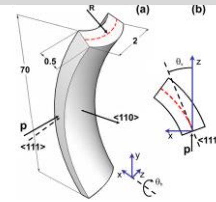
Quasimosaic crystal

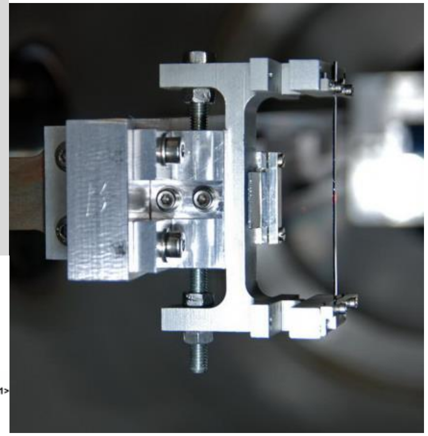
- ❑ Bent along (111) planes
- ❑ Minimal length a few tenths of mm
- ❑ Non-equidistant planes d1/d2 = 3



Strip crystal

- ❑ Bent along (110) planes
- ❑ Minimal length ~ 1 mm
- ❑ Equidistant planes



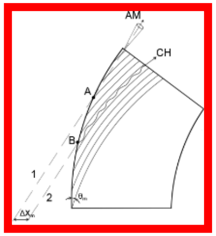


Crystals

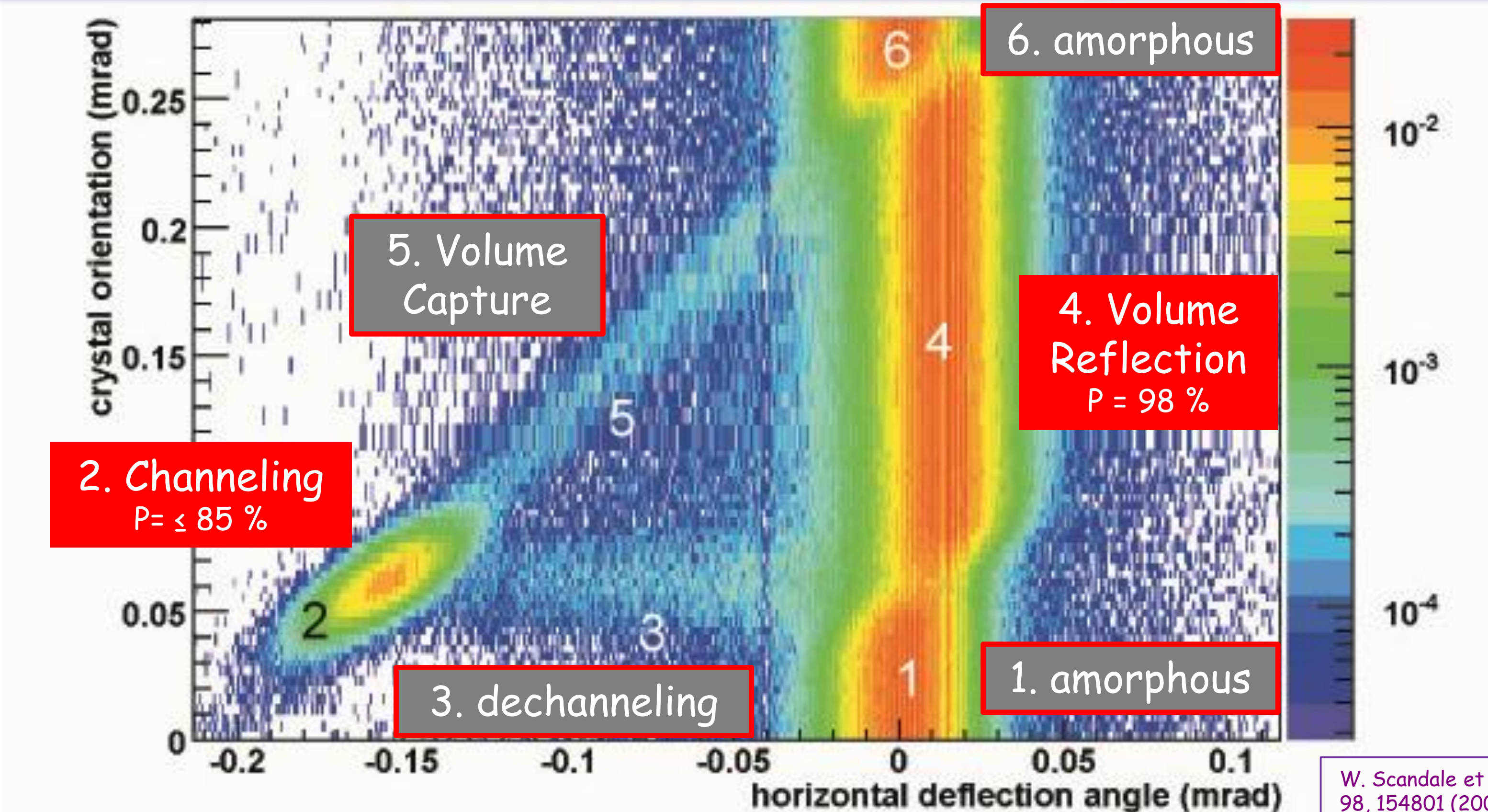
- ❑ Dislocation-free silicon crystals plates or strips
- ❑ for optimal channeling efficiency
  - ✓ short length (few mm)
  - ✓ moderate bending radius 45 ÷ 70 m

> ❑ SPS at 120÷270 GeV 1÷2 mm length, 150÷170 μrad angle
> ❑ LHC 3÷5 mm length, 40÷60 μrad angle

- ❑ Mechanical holders with large C-shape frame imparting the main crystal curvature
  - ✓ Strip crystal: (110) planes are bent by anticlastic forces
  - ✓ Quasimosaic crystal: (111) planes are bent by 3-D anticlastic forces through the elasticity tensor
- ❑ Expected crystal defects:
  - ✓ Miscut: can be ≈100 μrad, but negligible effect if good orientation is applied
  - ✓ Torsion: can be reduced down to 1 μrad/mm ➔ UA9 data in the SPS North Area
  - ✓ Imperfection of the crystal surface: amorphous layer size ≤ 1 μm



Coherent interactions in bent crystals



W. Scandale et al, PRL 98, 154801 (2007)

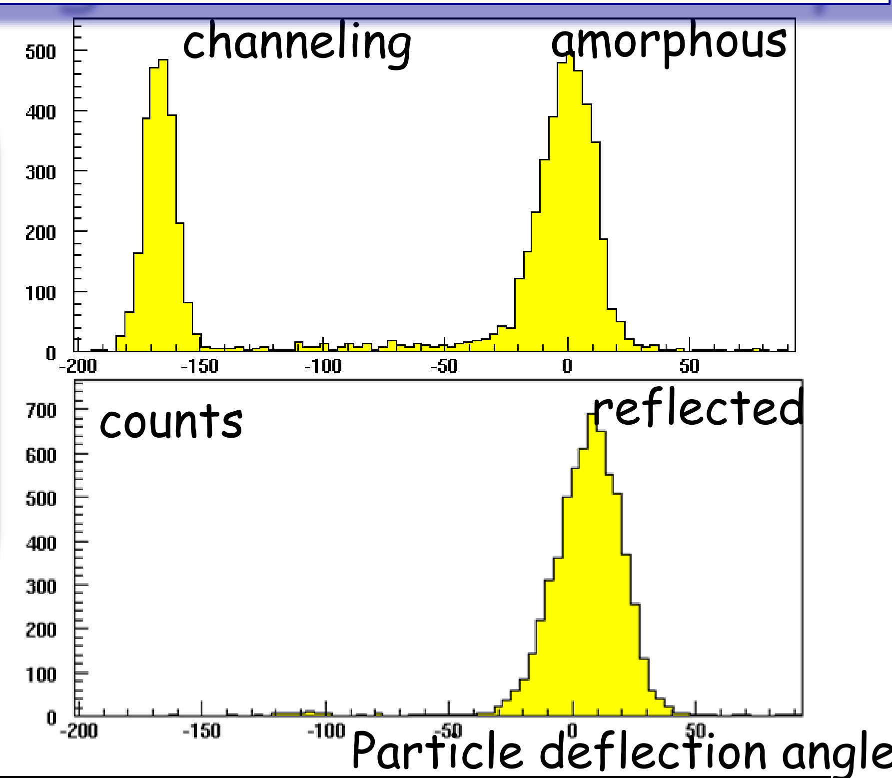
- Two coherent effects could be used for crystal-assisted beam deflection in particle accelerators:
  - ✓ Channeling ➔ larger deflection with reduced efficiency
  - ✓ Volume Reflection (VR) ➔ smaller deflection with larger efficiency
- SHORT CRYSTALS in channeling mode are preferred

W. Scandale et al., Nucl. Inst. and Methods B 268 (2010) 2655-2659.

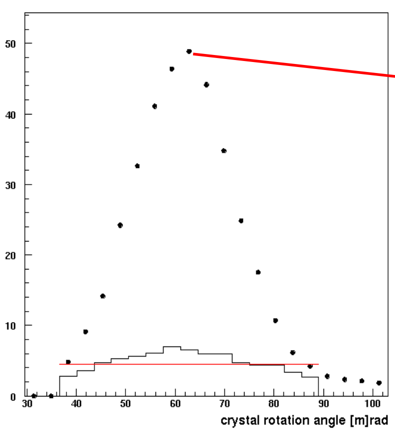
➔ ×5 less inelastic interaction than in VR or in amorphous orientation (single hit of 400 GeV protons)

Channeling and VR angle and efficiency

- Identify channeling, reflection and amorphous peaks of the angular profile distribution
- Compute the angular shift -> ***deflections***
- Integral of the events within $\pm 3\sigma$ around amorphous, channeling and reflected peaks
- Normalize the integrals to the incoming flux
- Ratios of channeling or deflection over amorphous normalized peak integrals -> ***efficiencies***



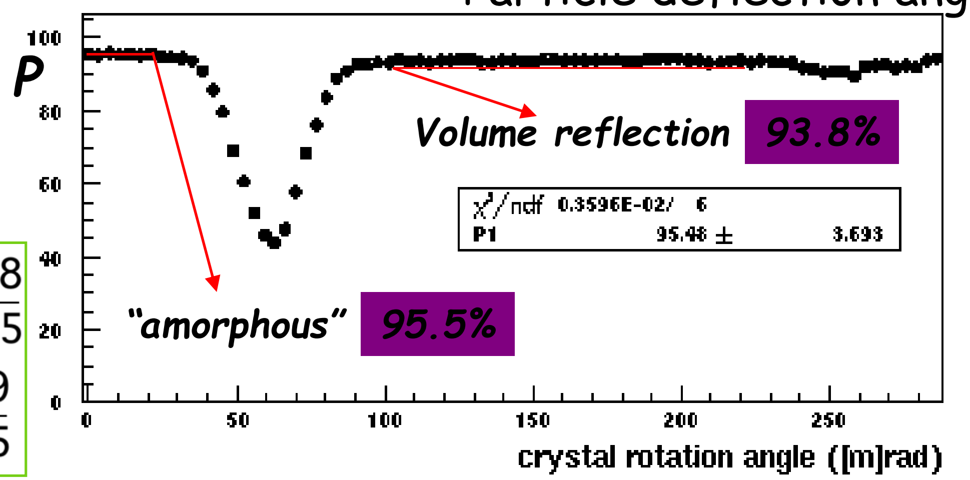
Example of efficiency estimate



Channeling

49.9%

$$
\begin{cases}
\varepsilon_{refl} = \dfrac{P_{refl}}{P_{amor}} = \dfrac{938}{955} \\
\varepsilon_{ch} = \dfrac{P_{ch}}{P_{amor}} = \dfrac{499}{955}
\end{cases}
$$

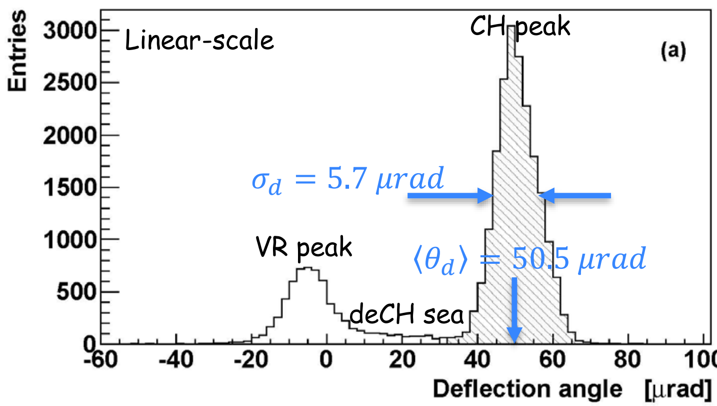


Short crystal features

$$Incoming\ beam: protons\ at\ 400\frac{GeV}{c}\ with\ angular\ divergences\ \ \sigma_x = 9.3\ \mu rad;\ \sigma_y = 5.2\ \mu rad$$

$$filtered\ at\ \sigma_x = \sigma_y \leq 5\ \mu rad$$

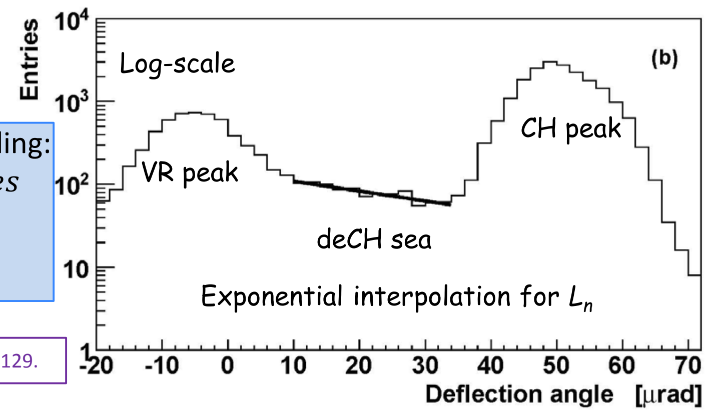
(110) si-crystal at T=300° 70×1.94×0.5 mm³ R= 38 m and with $\ell = 1.94\ mm \ll L_e$



Optimal orientation for channeling: incoming trajectory angles

$$\begin{cases} |\theta_{x0}| \leq 5\mu rad \\ |\theta_{y0}| \leq 5\mu rad \end{cases}$$

W. Scandale, et al., Phys. Lett. B 680 (2009) 129.



$$P_d(\delta\theta_x \geq \langle\theta_d\rangle - 3\sigma_d) = 75.2\ \%$$

$$L_n = 1.53\ mm$$

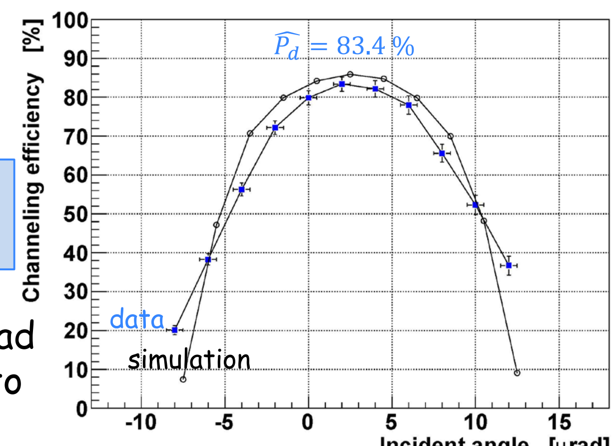
$$assuming\ \langle\theta_n^2\rangle \sim P_n(x) \rightarrow\ L_n = 1.5\ mm$$

Deflection efficiency as a function of the incident angle

for fraction of particles with horizontal incident directions inside contiguous angular windows each of 2 μrad

$$\widehat{P_d} = 83.4\ \%$$

The maximum value of the deflection efficiency exceeds the asymptotic limit for long crystals



Interpretation: angular window of 2 μrad « critical angle of 10.4 μrad

→the particles in the central bin travel very close to the channel axis without crossing the nuclear corridor

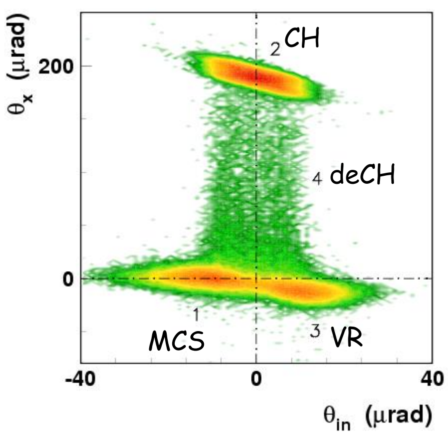
Dependence of L_n on incident angles θ_{x0}

W. Scandale, et al., Nucl. Instrum. Methods Phys. Res. B 268 (2010) 2655.
W. Scandale, et al., Phys. Lett. B 743 (2015) 440.

$Incoming\ beam: protons\ at\ 400\frac{GeV}{c}\ with\ angular\ divergences\ \ \sigma_x = 9.3\ \mu rad;\ \sigma_y = 5.2\ \mu rad\ -\ filtered\ at\ \sigma_x = \sigma_y \le 5\ \mu rad$

(110) si-crystal at T=300° 70×1.94×0.5 mm³ R= 10.26 m, $\ell = 1.94\ mm \ll L_e$ and $\alpha = 189\ \mu rad$

$$\theta_c = 9.8\ \mu rad$$



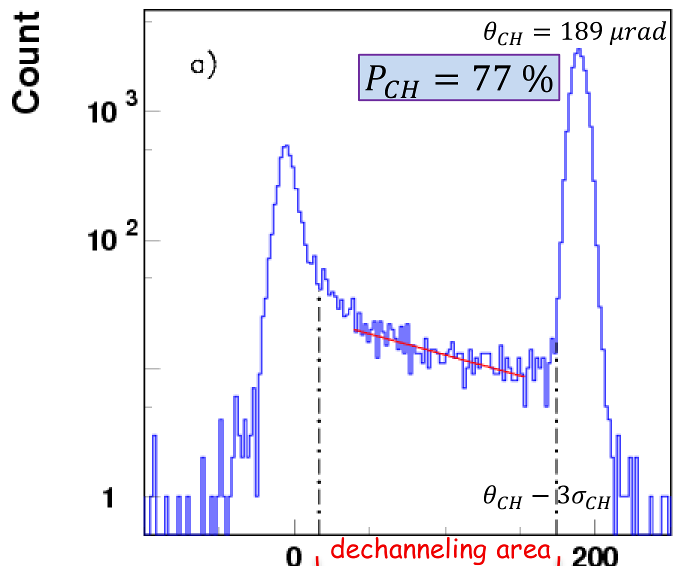
$$P_{deCH} = {N_{deCH}}/{N_{CH}}$$

Optimal orientation for channeling:
incoming trajectory angles

$$\begin{cases} \theta_{in} \in \theta_{in0} \pm \Delta\theta_{in} \\ \theta_{in0} = 0 \\ \Delta\theta_{in} = 1.75\ \mu rad \end{cases}$$

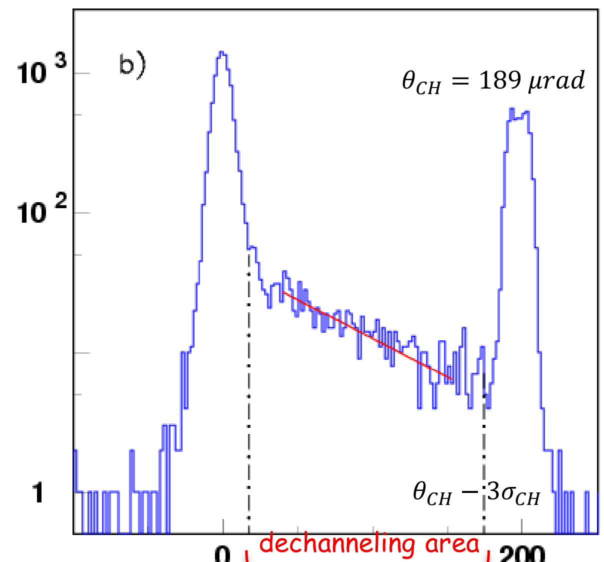
Orientation close to θ_c:
incoming trajectory angles

$$\begin{cases} \theta_{in} \in \theta_{in0} \pm \Delta\theta_{in} \\ \theta_{in0} = 8.75\ \mu rad \\ \Delta\theta_{in} = 1.75\ \mu rad \end{cases}$$



$$\begin{cases} P_{deCH} = 7.2\ \% \\ S_{deCH} = L_n = 1.4\ mm \end{cases}$$

θx (µrad)



$$\begin{cases} P_{deCH} = 23.5\ \% \\ S_{deCH} = L_n = 0.8\ mm \end{cases}$$

θx (µrad)

Dechanneling probability

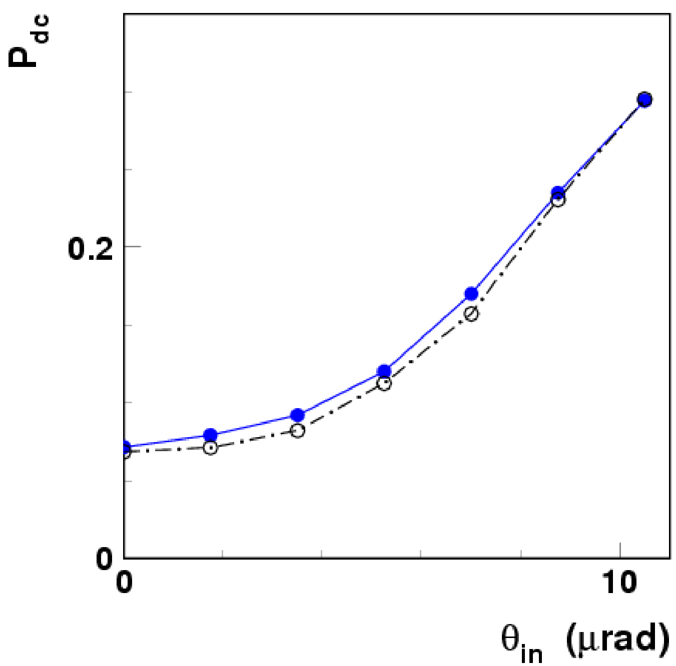
W. Scandale, et al., Nucl. Instrum. Methods Phys. Res. B 268 (2010) 2655.
W. Scandale, et al., Phys. Lett. B 743 (2015) 440.

$Incoming\ beam: protons\ at\ 400\frac{GeV}{c}\ with\ angular\ divergences\ \sigma_x = 9.3\ \mu rad;\ \sigma_y = 5.2\ \mu rad\ -\ filtered\ at\ \sigma_x = \sigma_y \leq 5\ \mu rad$

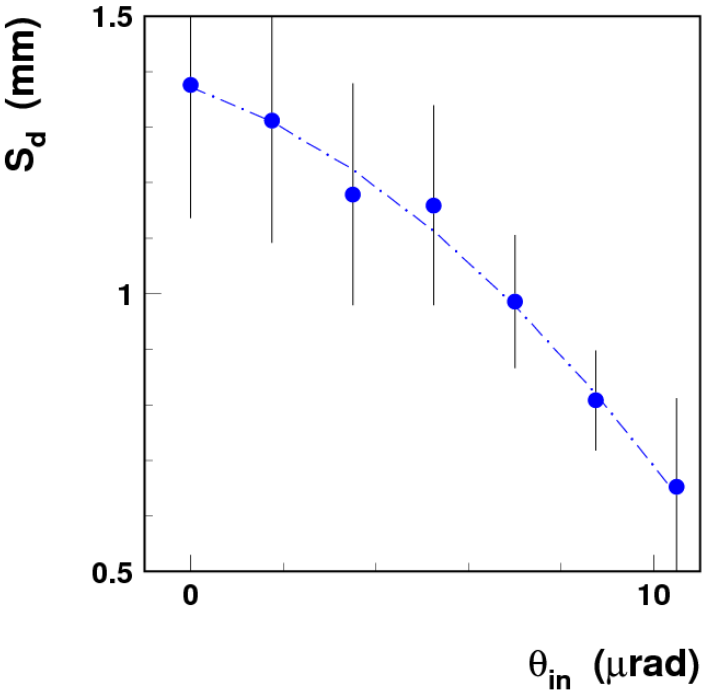
(110) si-crystal at T=300° 70×1.94×0.5 mm^3 R= 10.26 m, $\ell = 1.94\ mm \ll L_e$ and $\alpha = 189\ \mu rad$

$$\theta_c = 9.8\ \mu rad$$

$P_{deCH} = {N_{deCH}}/{N_{CH}}$

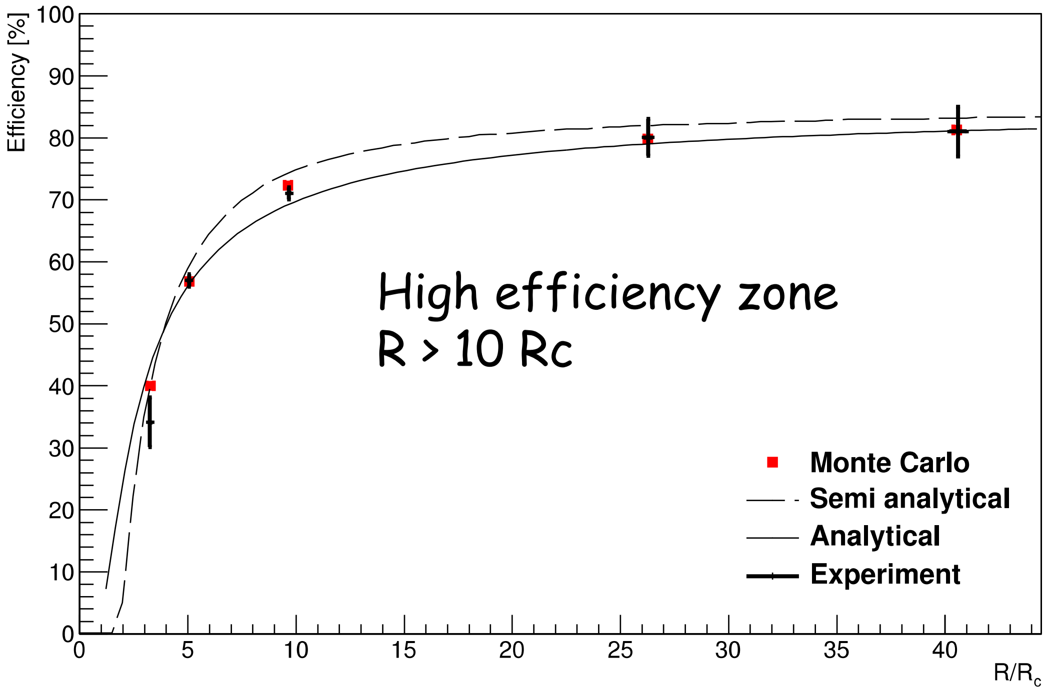


$S_{deCH} = L_n$



Channeling efficiency versus R_c

E. Bagli et al., Eur. Phys. J. C (2014) 74:2740



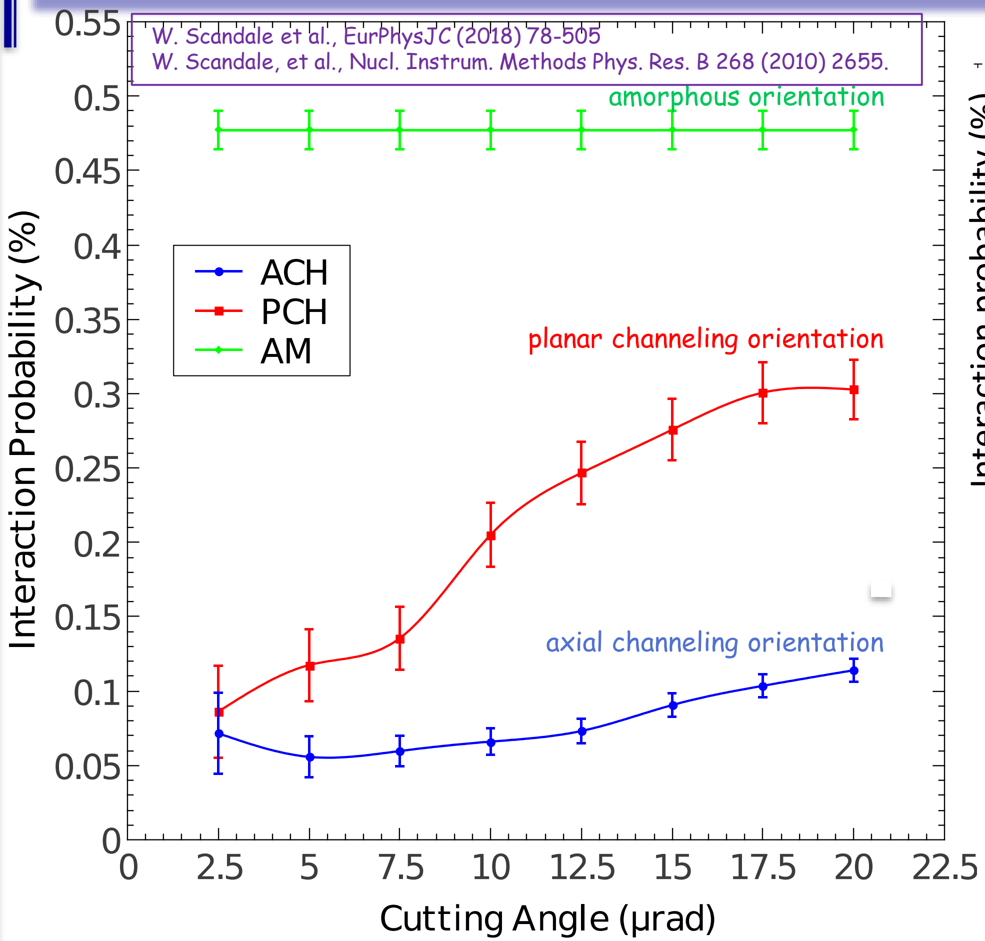
- Experiment (H8 and SPS):
  - Si bent crystal (L =0.2cm)
  - (1 1 0) plane
  - 400 GeV/c protons

Si (110):

R_c = 12m at pb = 7 TeV

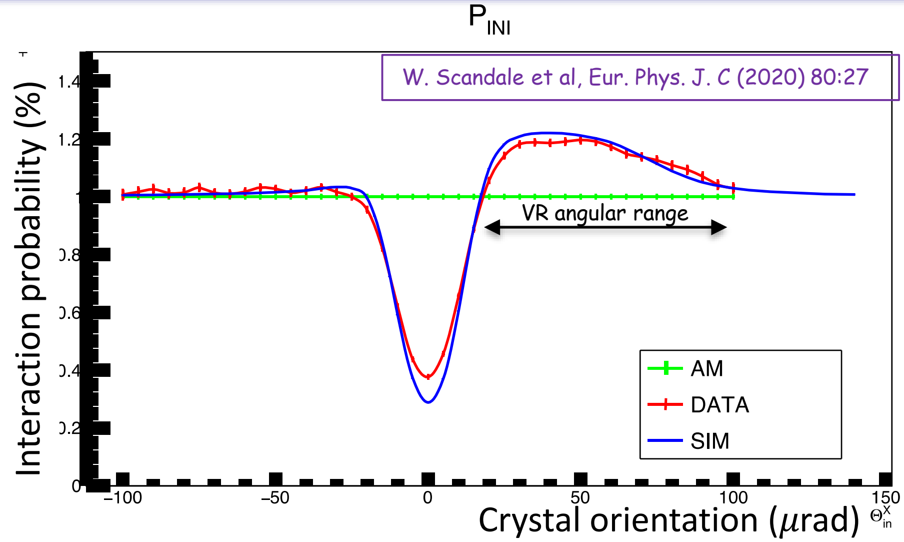
~1 mrad deflection requires ~12cm long Si crystal

Inelastic nuclear interactions



Probability of nuclear interactions as a function of the cutting angle.

- The crystal orientation is fixed to maximize the channeling.
- The angular half-range (cutting angle) of the incoming particles is varying.



Probability of nuclear interactions as a function of the crystal orientation.

- The crystal orientation is varying
- The angular range of incoming particles is fixed at ± 2.5 μrad.

VR parameters as a function of R

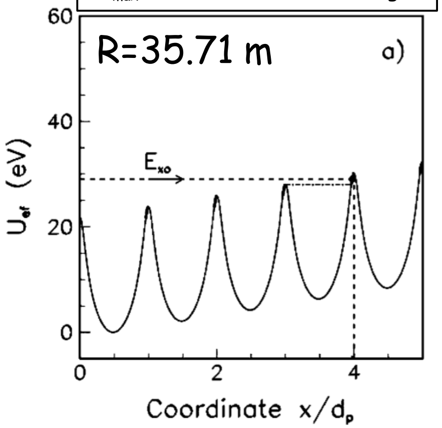
Volume reflection (VR) and volume capture (VC) are competing process

The VC probability dependence on the crystal radius R is approximately linear due to a linear increase of the tangency region length with increasing R

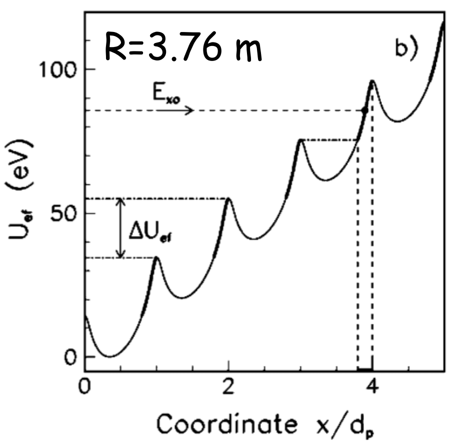
$$P_{VC}(R) \approx R\theta_c / L_d \quad P_{VR}(R) = 1 - P_{VC}(R)$$

W. Scandale et al., PRL 101, 234801 (2008)

Small deflection region close to U_{max} → maximal reflection angle



Large deflection region → large spread on the reflection angle



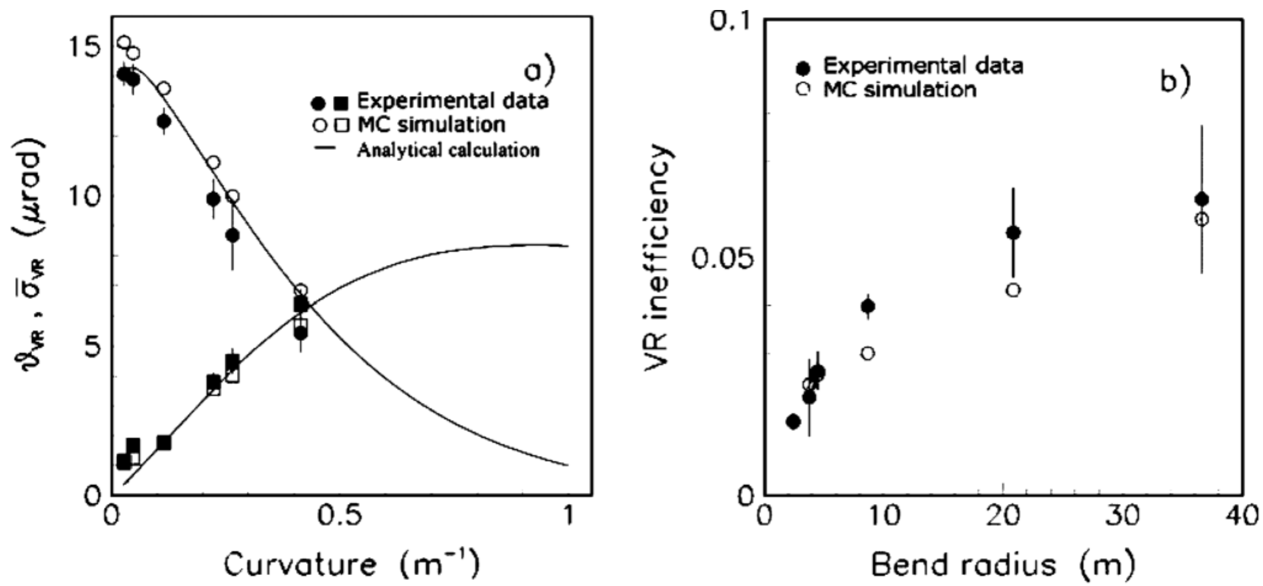
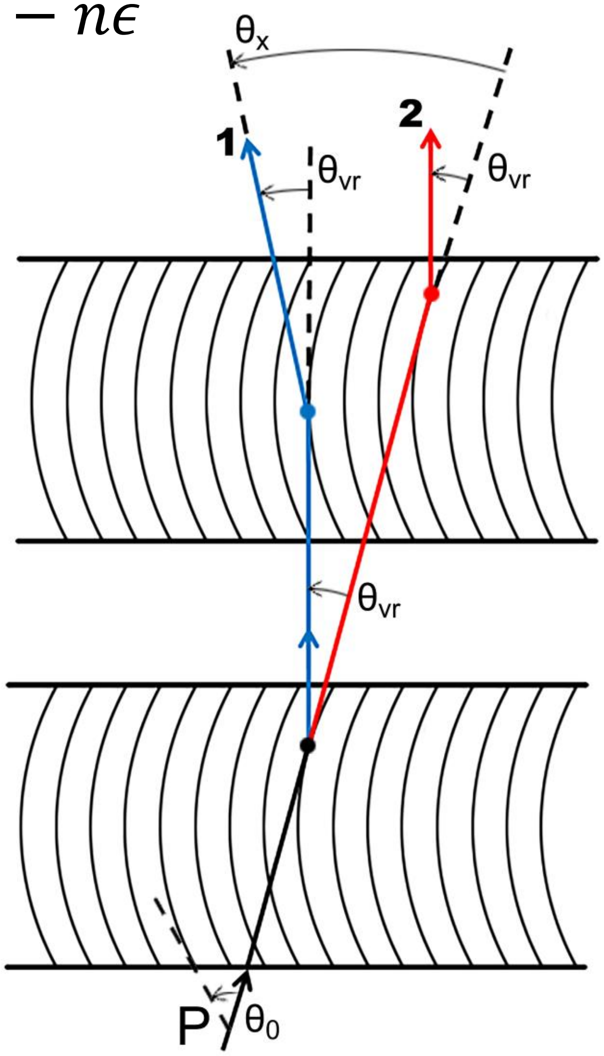


FIG. 4. The dependencies of the VR parameters on the crystal curvature and the bending radius R: (a) the deflection angle θ_{vr} (dots) and its rms deviation due to the potential scattering $\bar{\sigma}_{vr}$ (squares), (b) the VR inefficiency ε.

MULTI - VR

Deflection angle $\alpha_{MVR} \approx n \times \alpha_{VR}$

Deflection efficiency $P_{MVR} \approx P_{VR}^{n} = (1-\epsilon)^{n} \approx 1 - n\epsilon$



Sequence of two bent crystals with the particle trajectories.

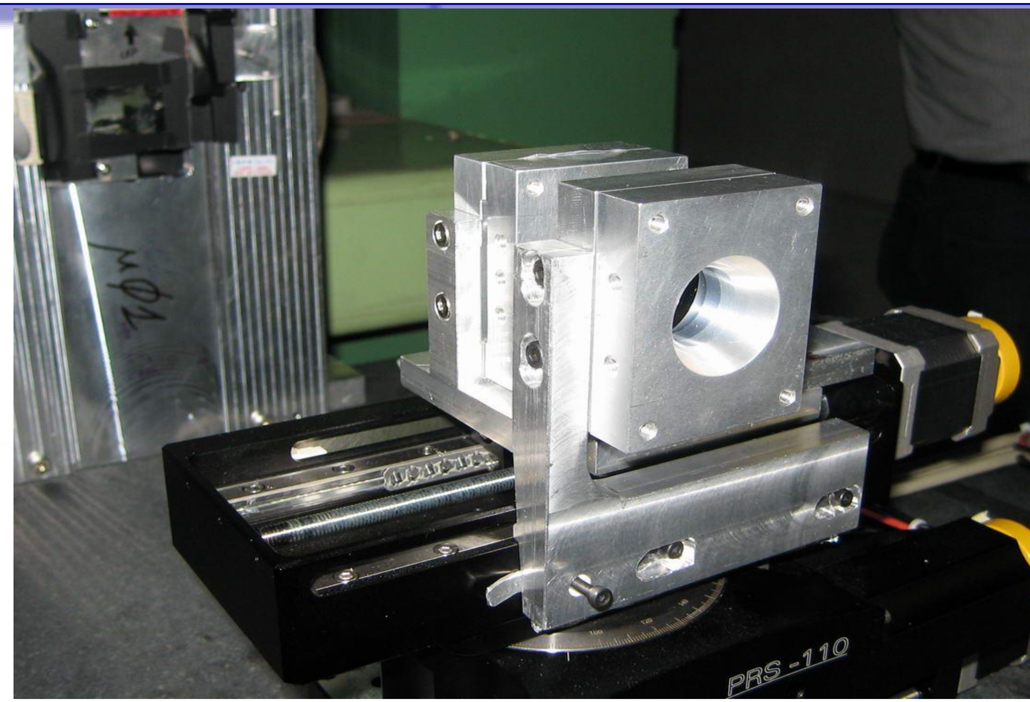
1. Particle **1** has volume reflections in both crystals near the tangency points with bent planes.
2. Particle **2** is volume captured in the first crystal and then volume reflected in the second one

MVR allows increasing the reflection angle at the cost of a reduced deflection efficiency

Double-reflection experiment

Experimental setup:

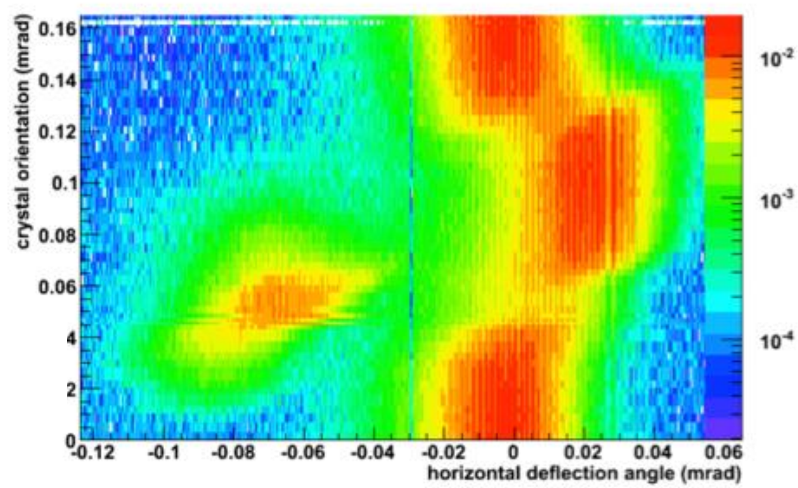
- QM1 on the rotational stage for off-axis alignment of the first crystal (preliminary scan)
- QM2 on the upper linear stage for alignment of second crystal (thanks to the anticlastic bend)
- many iterations for finding perfect alignment conditions



Experimental observations

QM1
$\alpha_{QM1} = 78\ \mu rad$
$\theta_{VR} = 11.9\ \mu rad$
$\eta_{VR} = 97.8\ \%$

QM2
$\alpha_{QM2} = 69\ \mu rad$
$\theta_{VR} = 11.7\ \mu rad$
$\eta_{VR} = 98.3\ \%$



double reflection angle: ~ 23 µrad
double deflection efficiency: ~ 96.7 %

W. Scandale et al, Physics Letters B 658 (2008) 109–111

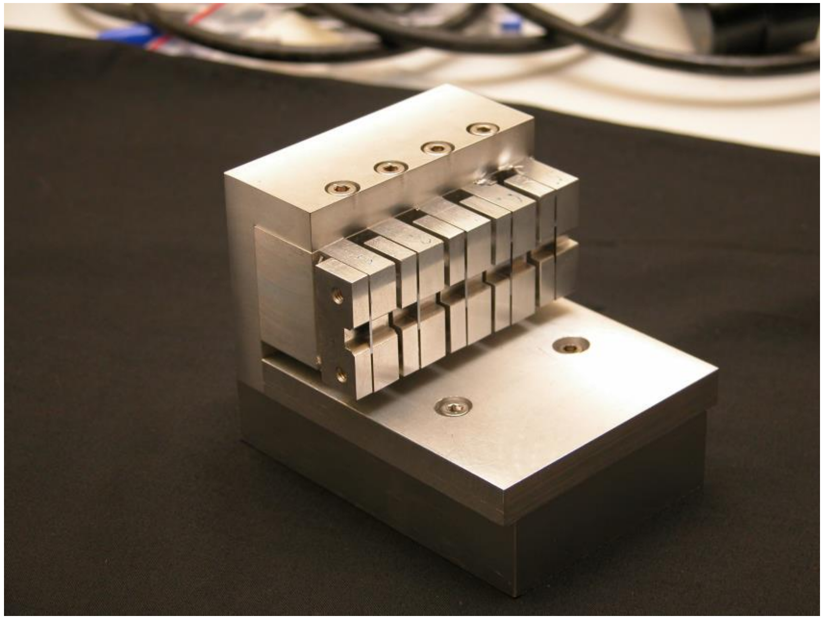
Multi-crystals

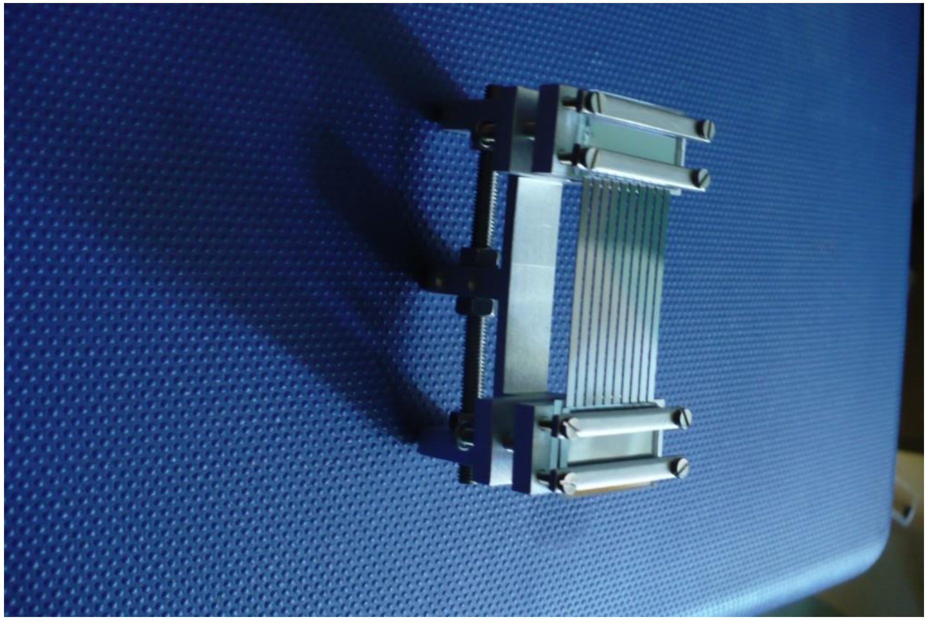
Several consecutive reflections

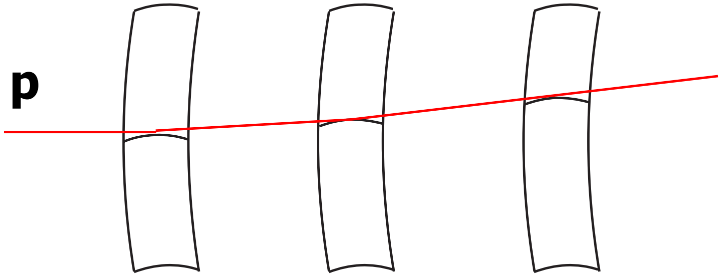
- enhance the deflection angle
- keep large cross section

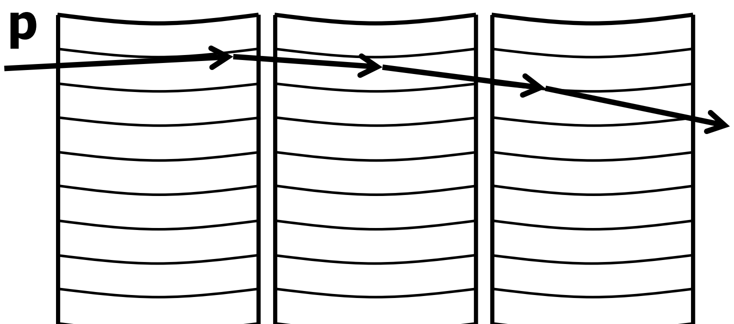
Multi-heads QM crystal (PNPI)

multistrip crystal (IHEP and INFN-Fe)



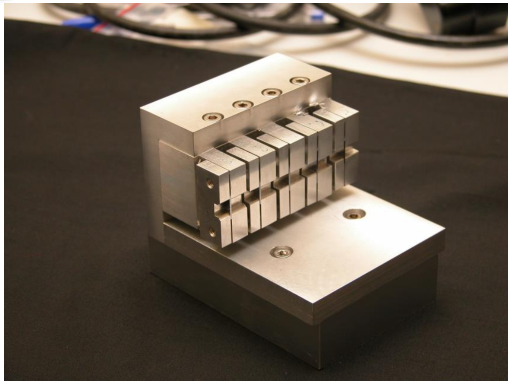






5-heads multi-QM-crystals

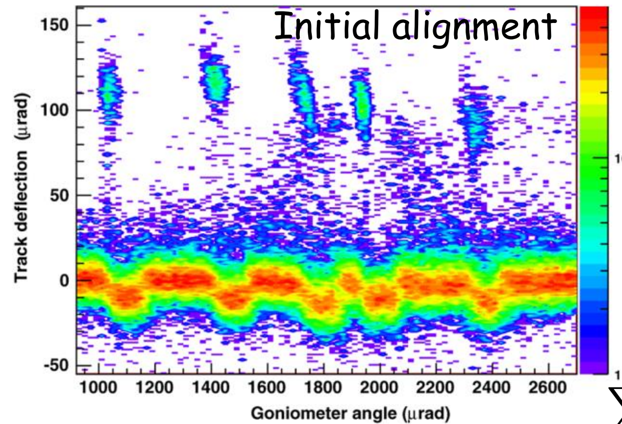
W. Scandale et al., PRL 102,084801 (2009)



Quasimosaic deflector

- Five (111) crystal plates
- Size 14x10x0.65 mm^3
- $\alpha = 110\ \mu rad$
- Cylindrical frame with R=2.7 m
- Individual alignment by piezo elements
- Opening area 5x3 mm^2

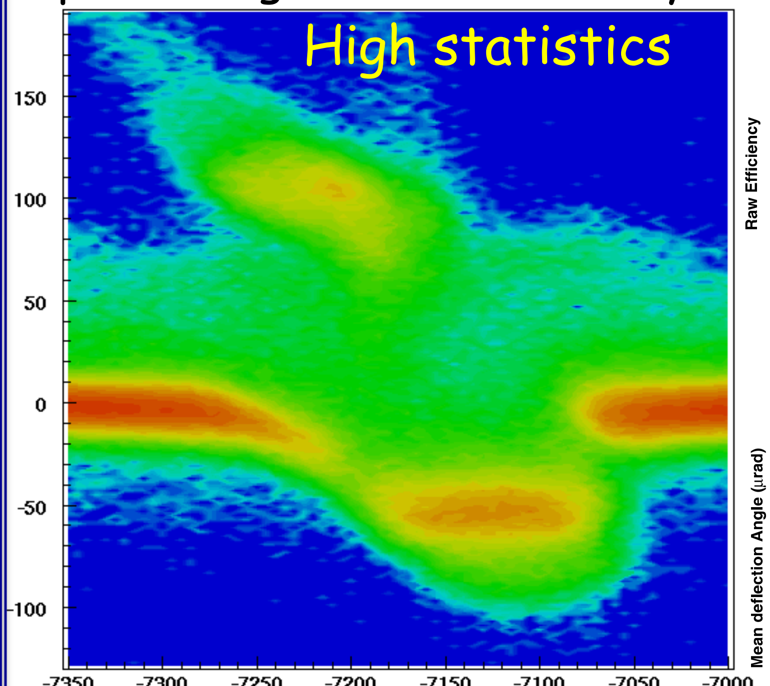
$\theta_{CH} \geq 100\mu rad \quad \theta_{VR} \geq 9.5\mu rad$

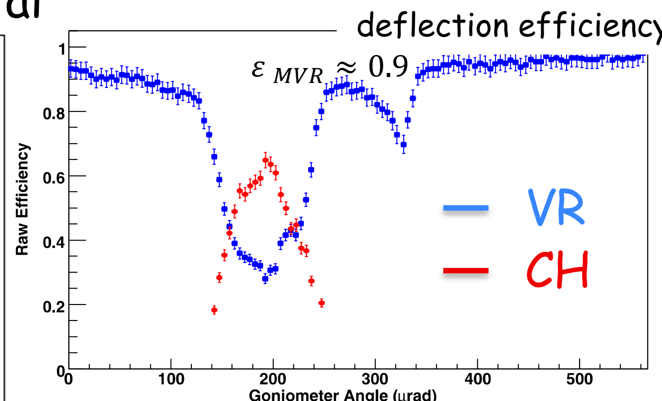


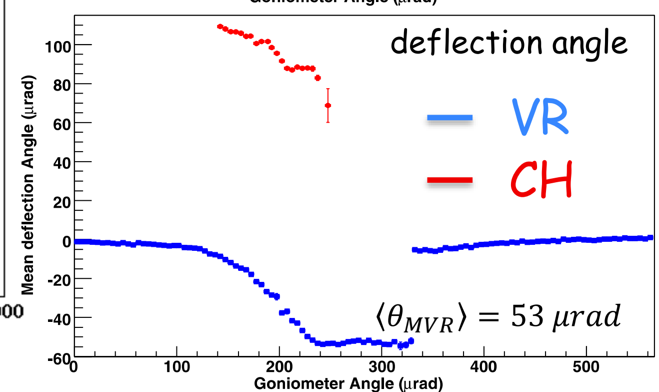
θ_{VR} (μrad)
9.6 ± 0.3
9.6 ± 0.3
12.5 ± 0.4
10.2 ± 0.4
11.8 ± 0.4

$\sum_{1}^{5} \theta_{VR}^{i} = 53.5\mu rad$

Optimal alignment of each crystal







Similar tests with a similar frame and a sequence of multi-strip crystals

CASE 1

8 strips crystals (111)

$\ell = 2.25\ mm, \alpha = 300\ \mu rad$

Measured values:

$\theta_{MVR} = 70\ \mu rad \quad \varepsilon_{MVR}=0.85$

CASE 2

6 strips crystals (110)

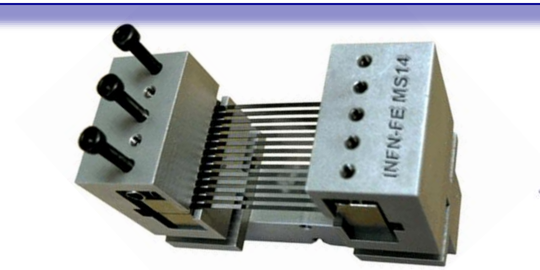
$\ell = 2\ mm, \alpha = 150\ \mu rad$

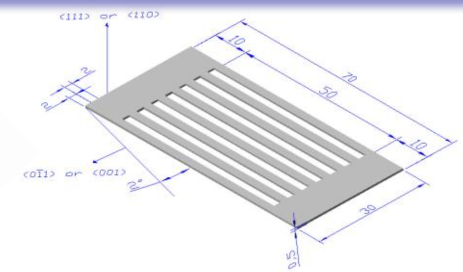
Measured values:

$\theta_{MVR} = 40\ \mu rad \quad \varepsilon_{MVR}=0.93$

MULTISTRIP

- MST 14 R=4.61 m
- Volume reflection angle ~100 μrad
- Efficiency ~ 90 %





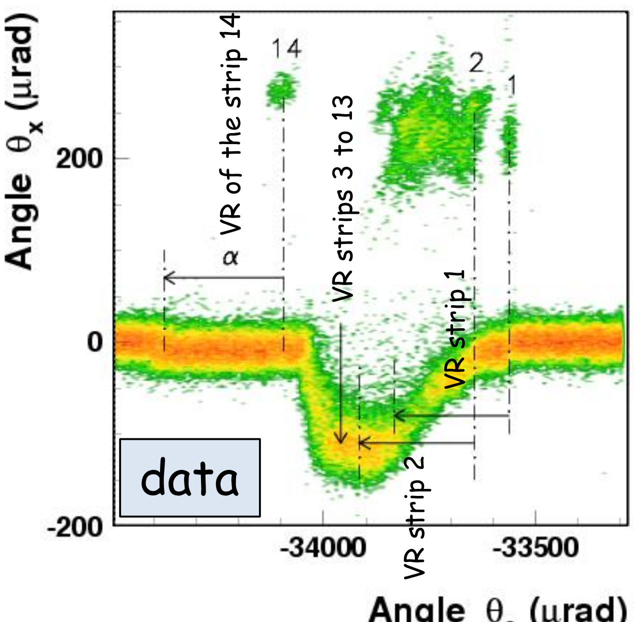
MVR effect of the strips 3 to 13

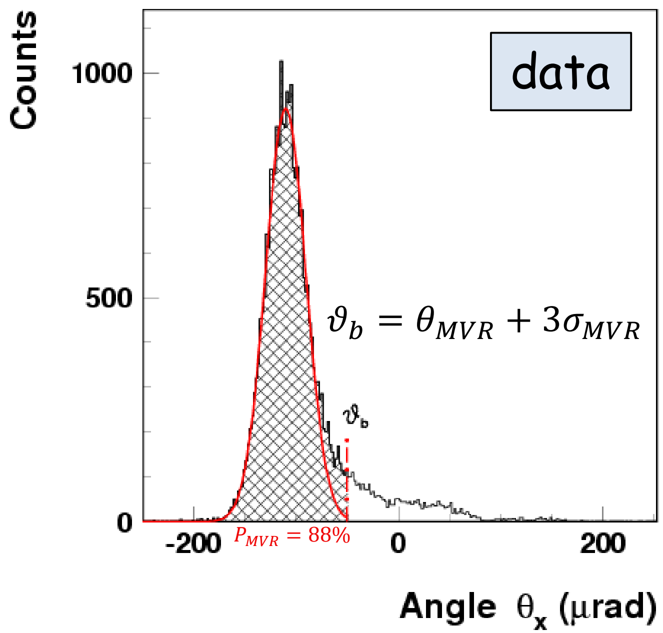
- $\theta_{MVR} = 110.6\ \mu rad$
- $\sigma_{MVR} = 19.7\ \mu rad$
- $P_{MVR}(\theta_x \le \vartheta_b) = 88\ \%$
- $P_{MVR}(\theta_x \le 0) = 94\ \%$

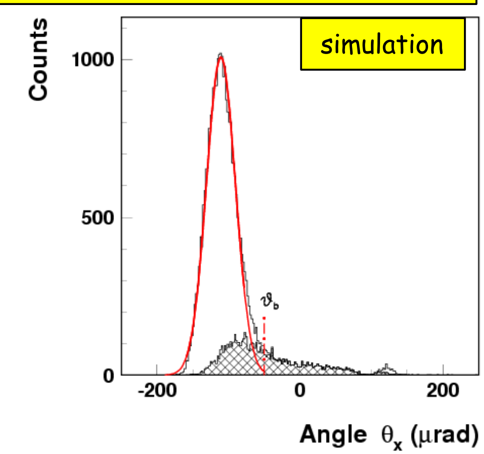
Single VR inefficiency (simulation) $\varepsilon \approx 1.91$
→Approximate value of the MVR efficiency 79 %

MVR simulation of the strips 3 to 13

- $\theta_{MVR} = 110.7\ \mu rad$
- $\sigma_{MVR} = 20.2\ \mu rad$
- $P_{MVR}(\theta_x \le \vartheta_b) = 91.2\ \%$



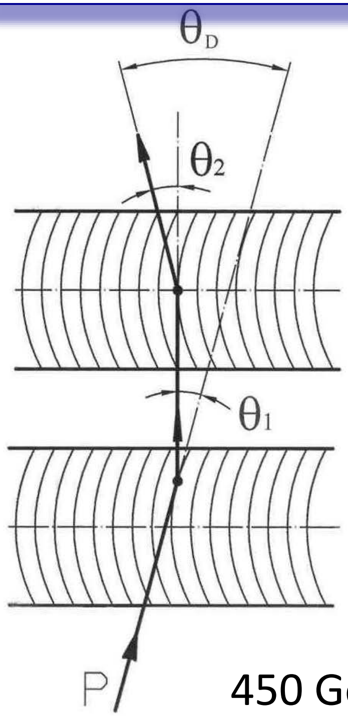




In the hatched area there are the particles with at least one volume capture event.
They are 11.7 % of the total.

Optimizing the MVR

A.M. Taratin, W. Scandale, Nucl. Instrum. Methods Phys. Res. B 262 (2007) 340.

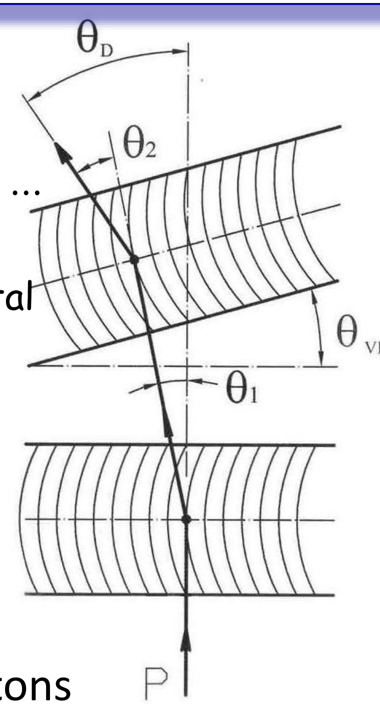


parallel sequence

- the location of the tangency points are different for each crystal of the sequence
- it will become closer and closer to the entry face
- $\theta_{MVR} \leq \alpha$

unparallel sequence

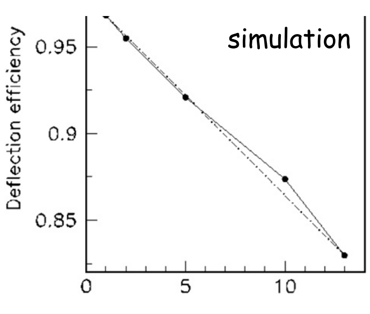
- chose $\theta_{VR} = \theta_1 = \theta_2 = \cdots$
- tangency points not changing from a crystal to another
- $\theta_{MVR} = n\theta_{VR}$

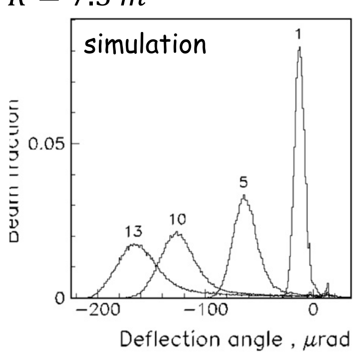


450 GeV protons

(110) si-crystals, n ≤ 20

$\theta_c = 10\ \mu rad;\ R_c = 0.77\ m;$
$\ell = 1.5\ mm;\ \alpha = 200\ \mu rad;$
$R = 7.5\ m$



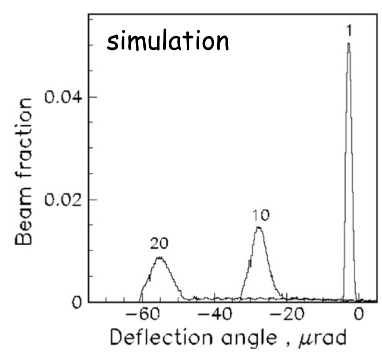


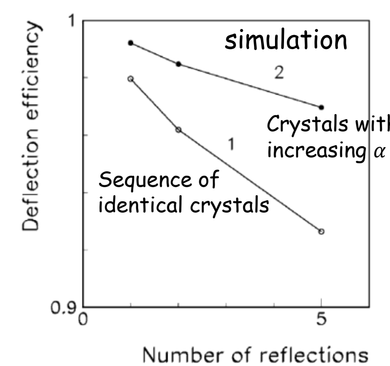
Planar channeling onset at n=13

7000 GeV protons

(110) si-crystals, n ≤ 20

$\theta_c = 2.55\ \mu rad;\ R_c = 11.89\ m;$
$\ell = 1.2\ mm;\ \alpha = 12\ \mu rad;$
$R = 100\ m$





Other results

Crystal specifications to assist collimation in LHC	V.M. Biryukov et al., Nucl. Instrum. Methods Phys. Res. B 234 (2005) 23-30.
Axial channeling of high-energy protons	W. Scandale et al., PRL 101, 164801 (2008). W. Scandale et al. PLB B 693 (2010) 545-550
Radiation emitted by electrons and positrons in a bent crystal	W. Scandale et al., Phys. Rev. A 79, 012903 (2009).
Axial channeling of negative particles	W. Scandale et al., PLB B 680 (2009) 301-304 .
Planar channeling and VR of negative particles	W. Scandale et al., PLB B 681 (2009) 233-236 .
MVR by different planes in one si-crystal for high-energy protons	W. Scandale et al., PLB B 682 (2009) 274-277.
MVR by different planes in one si-crystal for negative particles	W. Scandale et al., EPL, 93 (2011) 56002 .
Parametric X-rays produced by 400 GeV protons in a bent crystal	W. Scandale et al., PLB B 701 (2011) 180-185 .
Probability of EM dissociation for well channeled ions	W. Scandale et al., PHYSICAL REVIEW ST-AB16, 011001 (2013).
Dechanneling length of high-energy negative particles	W. Scandale et al., PLB B 719 (2013) 70-73.
Focusing of 400 Gev Proton beam with bent crystals	W. Scandale et al., PLB B 733 (2014) 366-372 . W. Scandale et al., NIM B 414 (2018) 104-106 W. Scandale et al., PHYSICAL REVIEW ST-AB 21, 014702 (2018) W. Scandale et al., NIM B 446 (2019) 15-18
Mirroring of 400 Gev Protons with ultra-thin straight crystal	W. Scandale et al., PLB B 734 (2014) 1-6 .
Comparison of MVR for positive and negative particles	W. Scandale et al., Pis'mavZhETF,vol.101,iss.10,pp.755-760
Multiple scattering on 400 GeV protons in bent si-crystals	W. Scandale et al., NIM B 402 (2017) 291-295 W. Scandale et al., Eur. Phys. J. C (2019) 79:993
Dechanneling of 400 GeV protons in a long bent si-crystals	W. Scandale et al., NIM B 438 (2019) 38-41
Performance of highly irradiated si-bent crystals	W. Scandale et al., Eur. Phys. J. C (2019) 79:933

Conclusive remarks

UA9 experiments in the North Area of the SPS have brought fundamental information on the interaction of high-energy particles with bent crystals.
In parallel UA9 has proposed, implemented and conducted experimental work on applications in high-energy accelerators:

- For crystal-assisted collimation in the SPS (see R. Rossi talk)
- For crystal assisted-collimation in the LHC (see S. Redaelli talk)
- For beam extraction assisted by bent-crystals (see F. Velotti talk)

Tank-you for your attention