Erice, October 28th, 2008

"Channeling 2008"

Charged and Neutral Particles Channeling Phenomena

Observation of high-efficiency axial channeling of high-energy protons in a bent crystal

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Ettore Majorana foundation and centre for scientific culture
Erice, October 28th, 2008

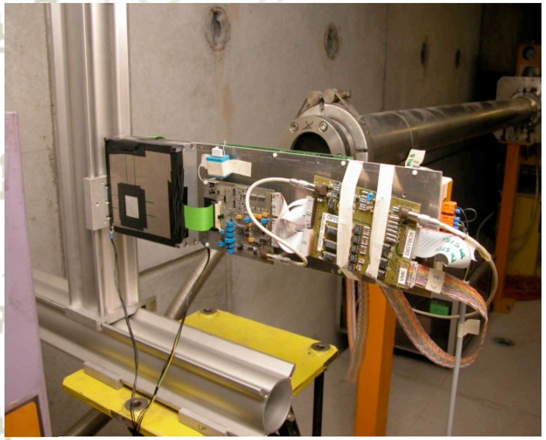
on behalf of the H8RD22 collaboration

CERN; IHEP, JINR, PNPI; INFN: FE, LNL, MI, PG, RM, TS

Outlook

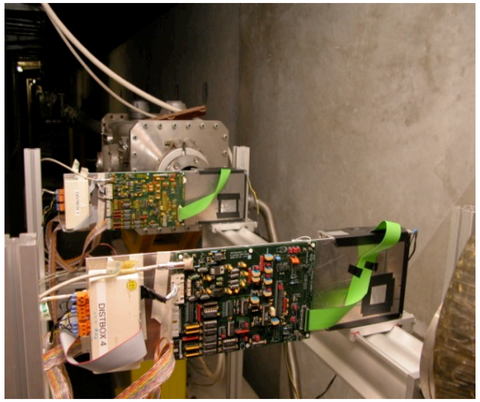
- Crystal preparation
- Crystal characterization
- Axial channeling with positive charges
- Axial channeling with negative charges
- Search for MVR in a single crystal
- Conclusions

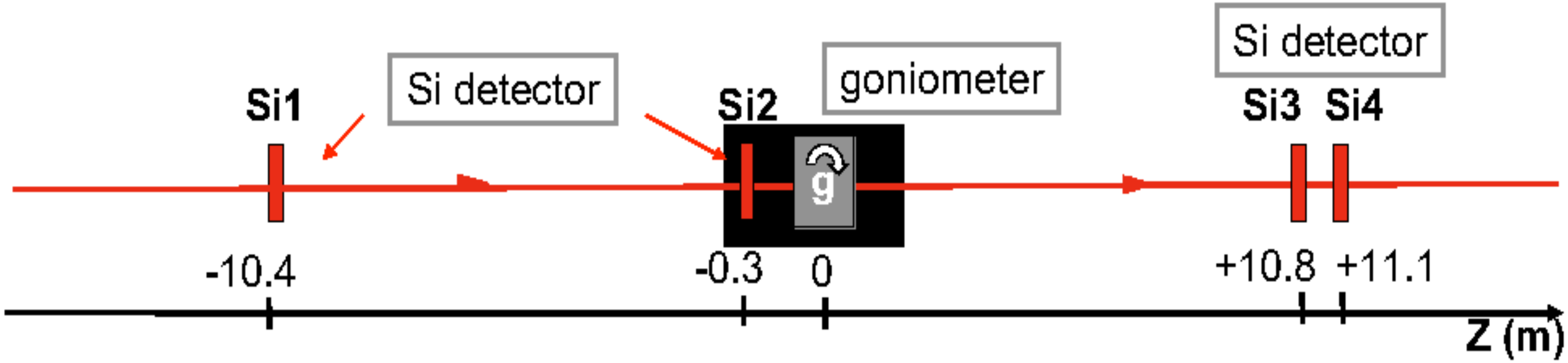
Experiment H8RD22



Spokesman: Dr. W. Scandale

- 1.92x1.92 cm^2 telescopes with reading steps 50 µm
- Spatial resolution:5 µ m

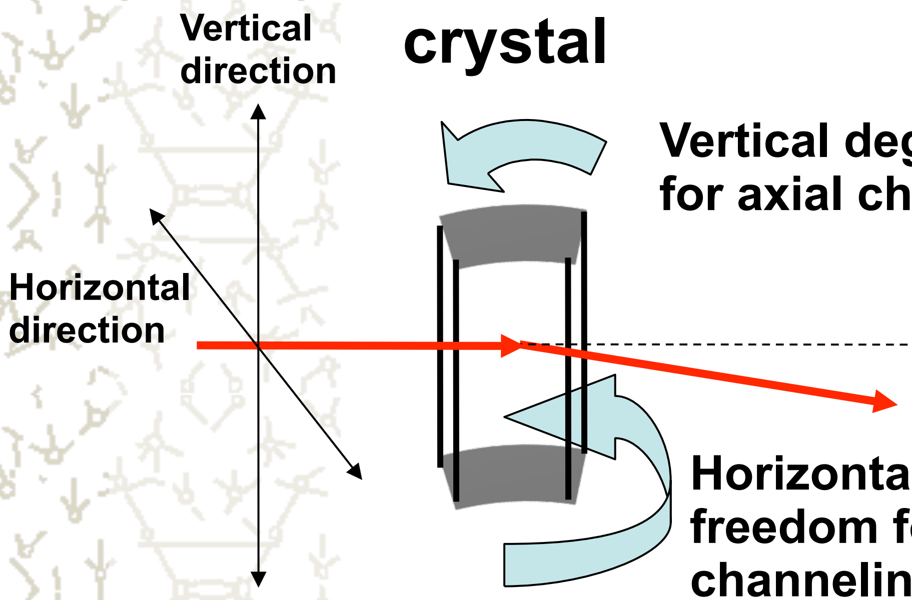




Telescope provided by Como-Trieste group

RSI **79** (2008) 023303

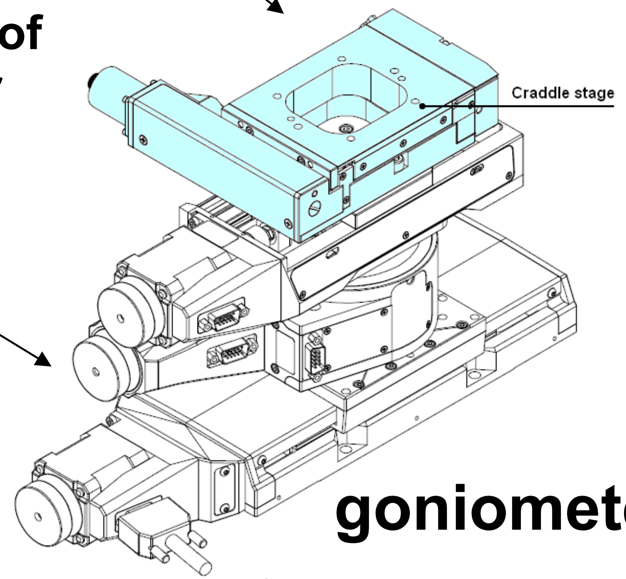
Goniometer



Vertical degree of freedom for axial channeling

Horizontal degree of freedom for planar channeling

±6.3° total range
0.25 μrad resolution
1 μrad repeatability
2 μrad accuracy

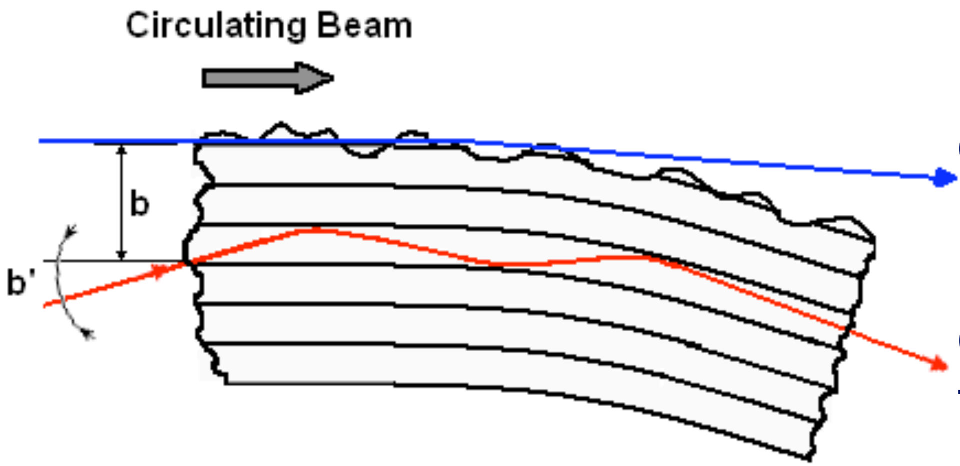


goniometer

Goniometer provided by LNL group

New kind of crystals

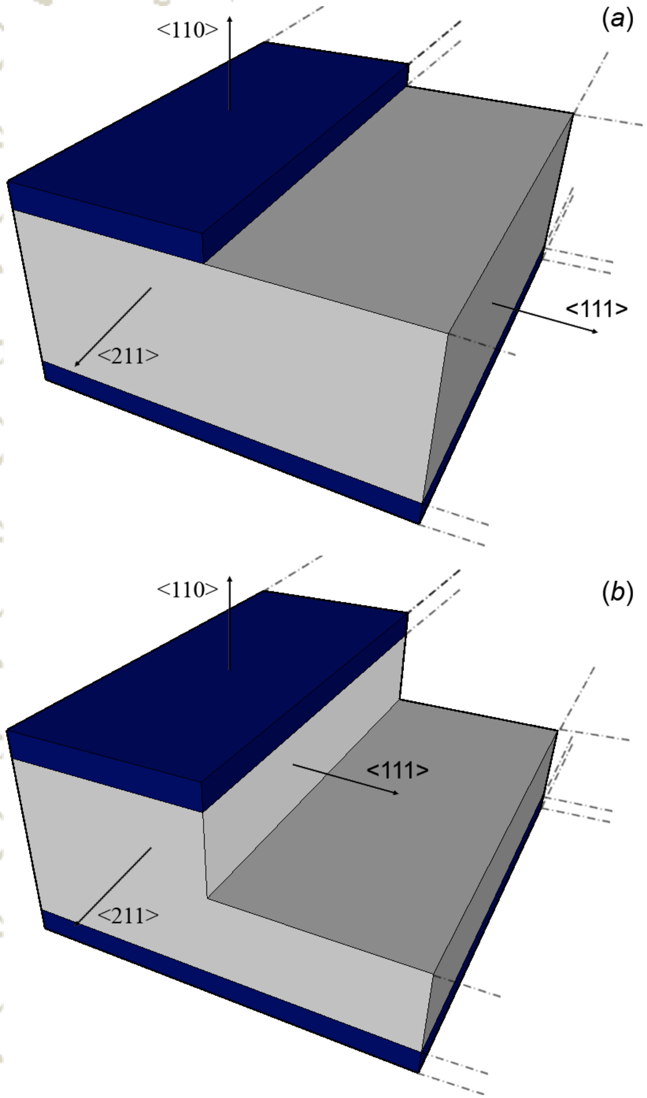
An application of crystals would be the collimation of beam halo in next generation of hadron machines (e.g. the LHC)



Particles in the halo drift outwards at the rate of ~2 nm per turn. Since the tune is not integer, the particles will hit the crystal every ~10-20 turns and thereby the first impact parameter of the particles onto the crystal will be in the range of ~100 nm (courtesy of V. Previtali and R. Assmann)

It demands a crystal with a roughness lower than 100 nm on the lateral faces of the crystal

Anisotropic etching



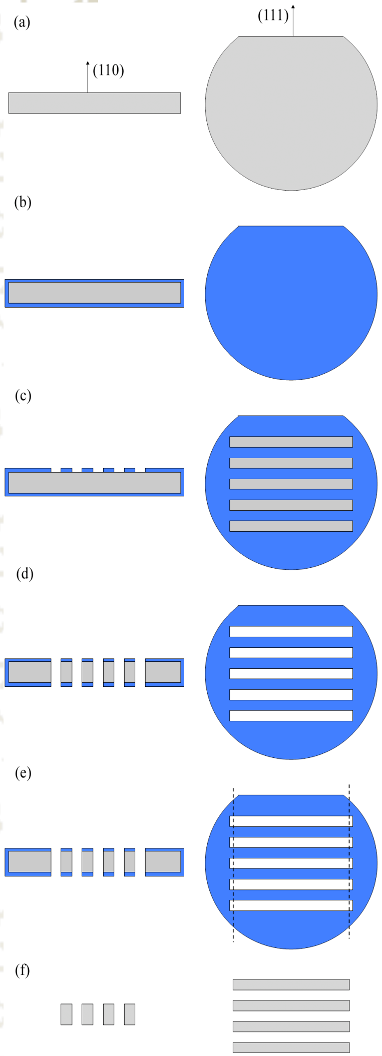
Anistropic chemical etching is a feasible way to realize sub-surface damage free crystals entirely by wet chemical methods

Etch rate on different silicon planes for KOH 20% at 40 °C

(100)	(110)	(111)
7.1 μm/h	10.7 μm/h	Negligible

Sensor and Semiconductor Laboratory

Photolythography



a) (110) silicon wafer as starting material:

b) LPCVD deposition of silicon nitride thin layer

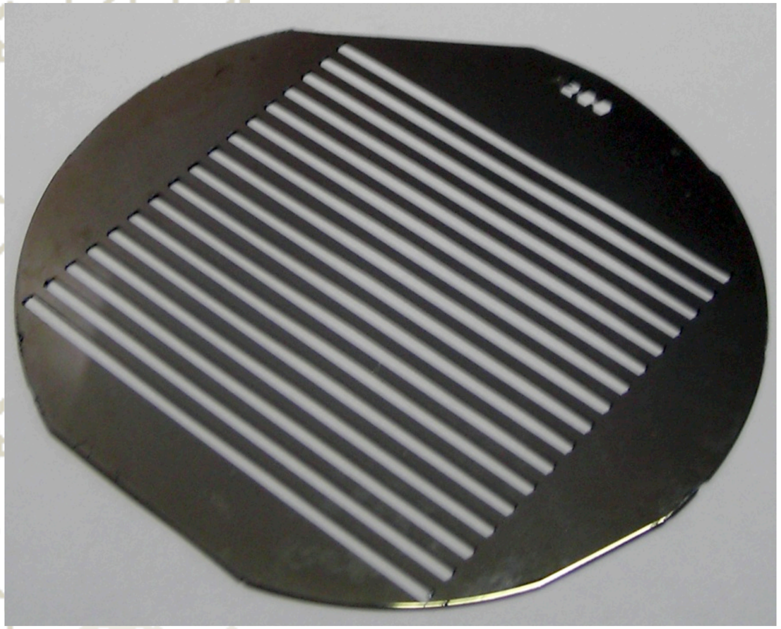
c) Silicon nitride patterning

d) Etching of Si in KOH solution, silicon nitride acts as masking layer

e) Silicon strips release

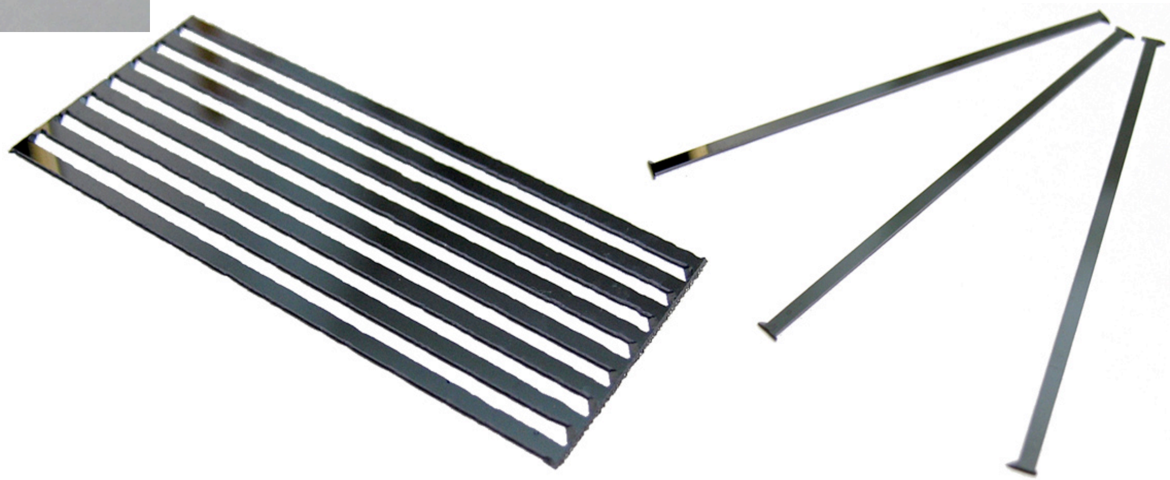
f) Removal of silicon nitride

Fabrication of crystals



Fabrication of either a multistrip or a batch of strips is possible through wet chemical methods

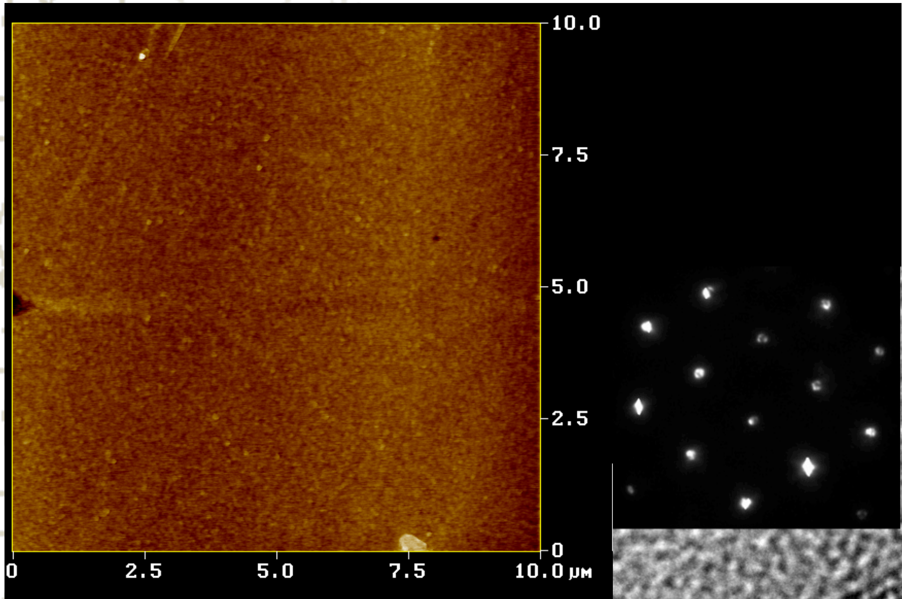
To appear in a forthcoming issue of JPD: Appl. Phys.



More details are in poster PS2-9 by A. Mazzolari et al.

Structural characterization

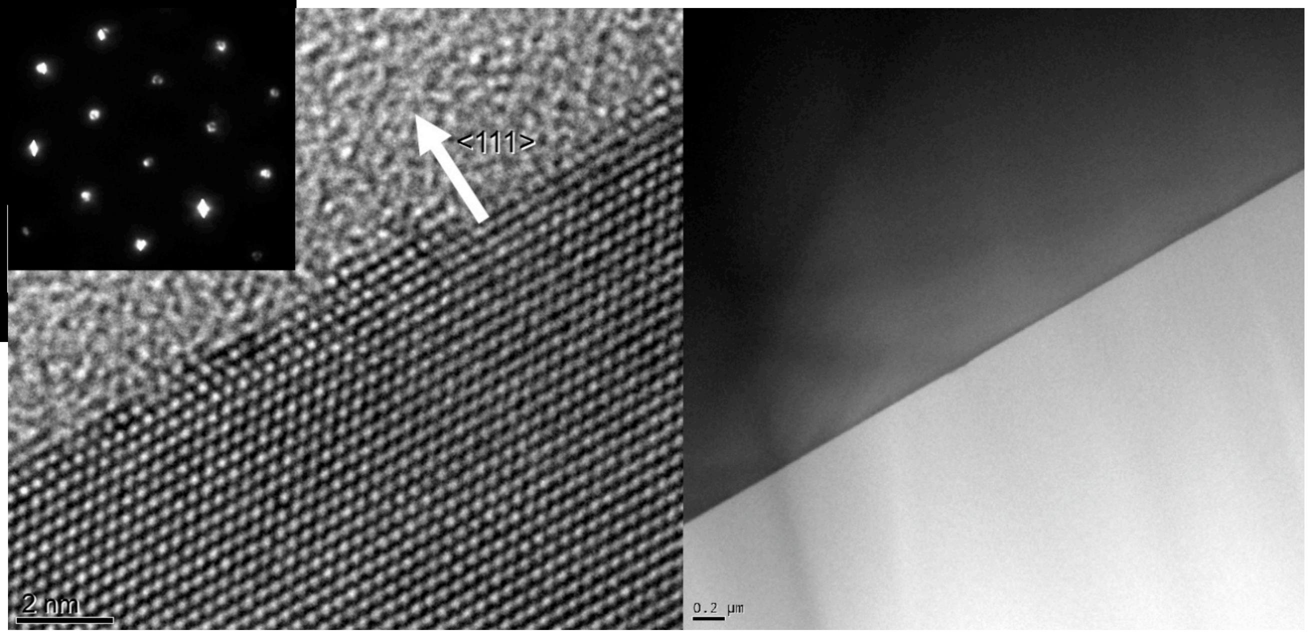
Lateral surface (AFM)



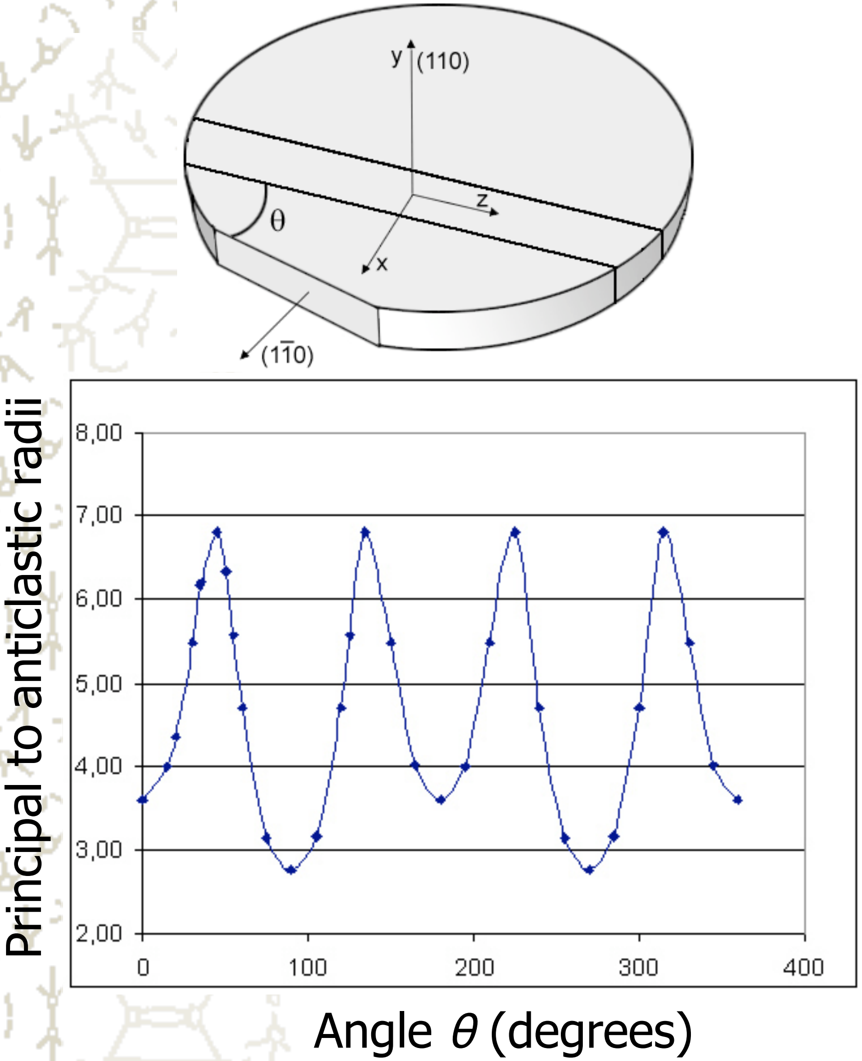
Sub-nm roughness
was achieved

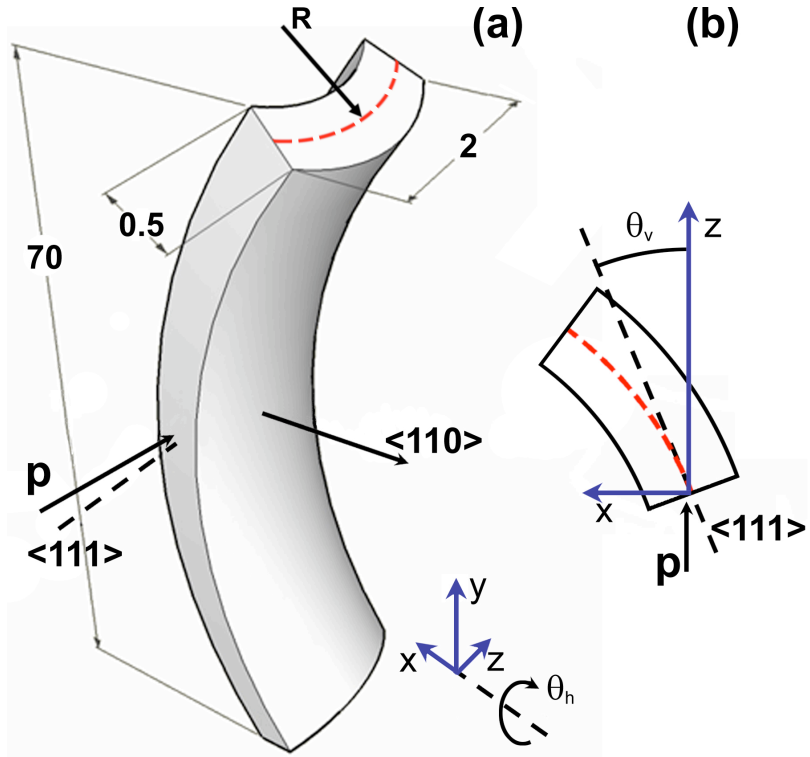
High-quality surfaces
achieved via ACE

Entry surface (HRTEM)



Crystal bending

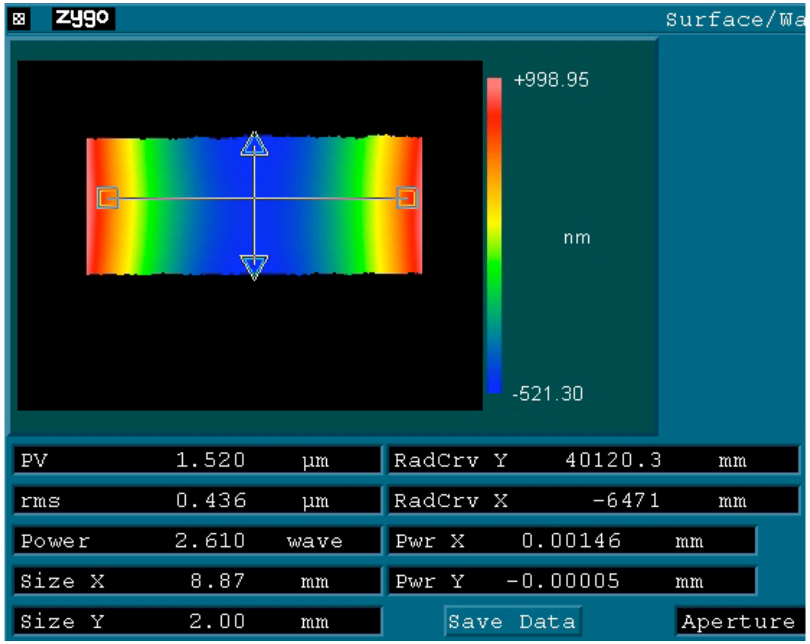


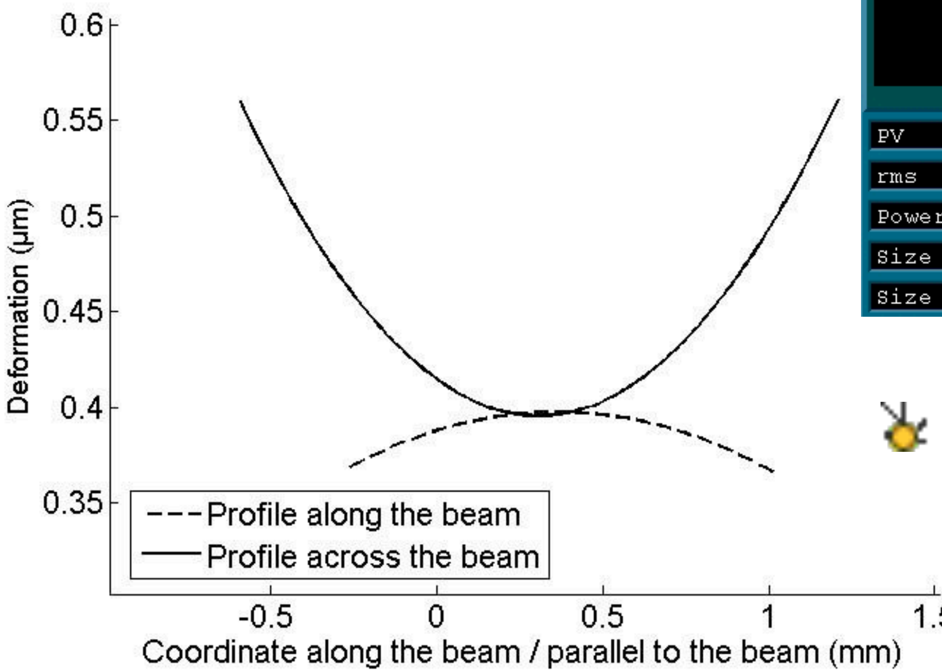


- Crystal bending is accomplished through anticlastic deformation

Optical characterization

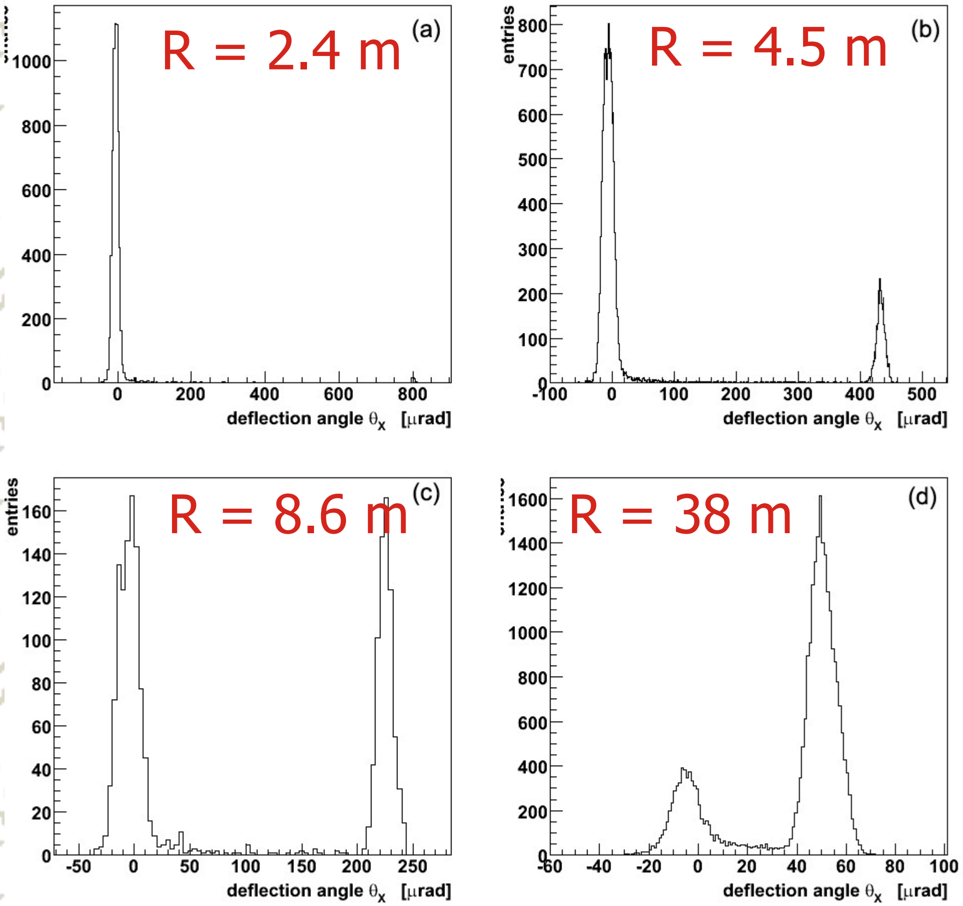
- Optical profilometry with 2 nm resolution





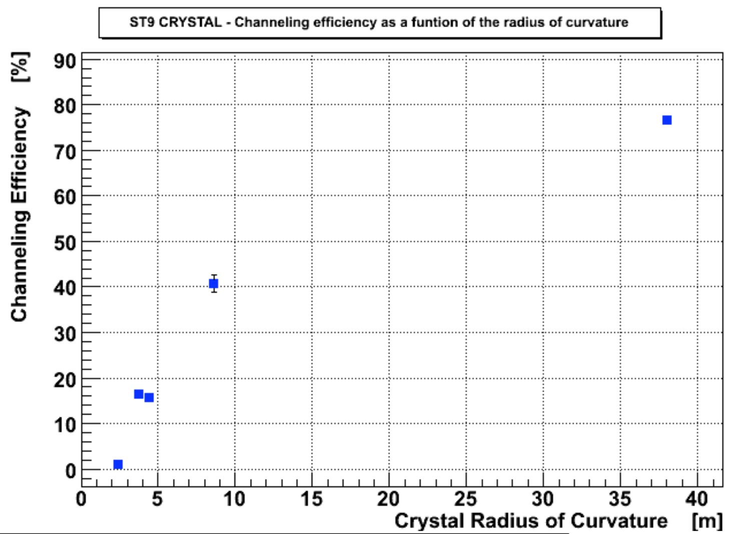
- Determination of the primary and anticlastic curvatures

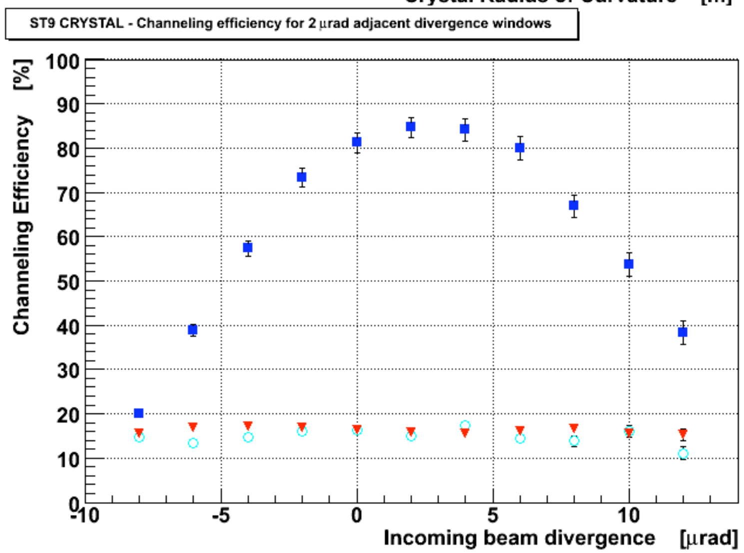
On-beam characterization



- ST9 crystal was characterized with 400 GeV protons in the external line H8 in the SPS
- Planar channeling efficiency is very high

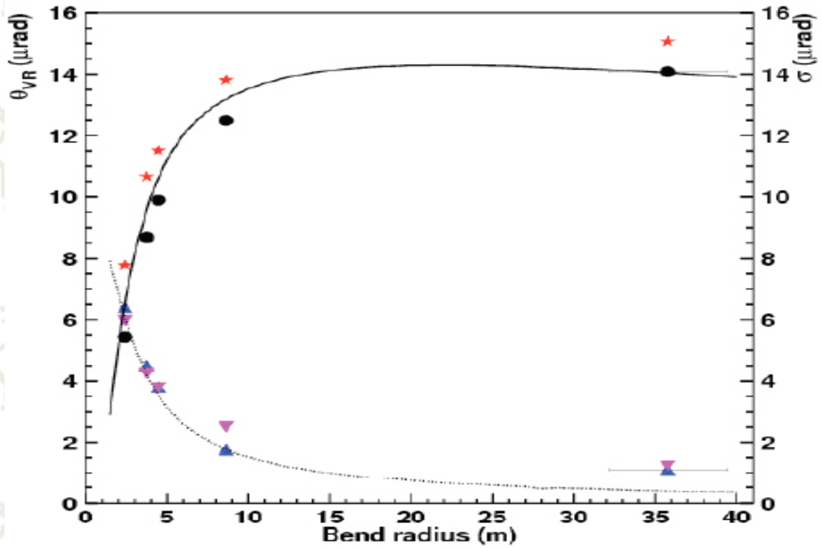
On-beam characterization





- Single-pass efficiency of planar channeling exceeds 75% and 85% with quasi-parallel particles

Study on VR



- Dependence of VR defection angle and its spread vs. crystal curvature
- Comparison with theoretical model

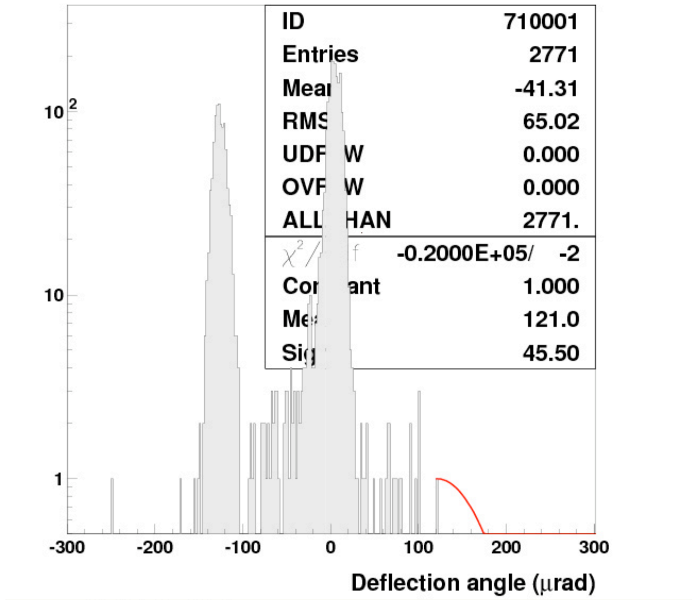
To appear in a forthcoming issue of PRL

V. Maisheev Phys. Rev. ST Accel. Beams 10 (2007) 084701

Crystal-size scaling

2006 -> 2 mm strip ST9
2007 -> 1 mm strip ST10
2008 -> 0.5 mm strip ST14

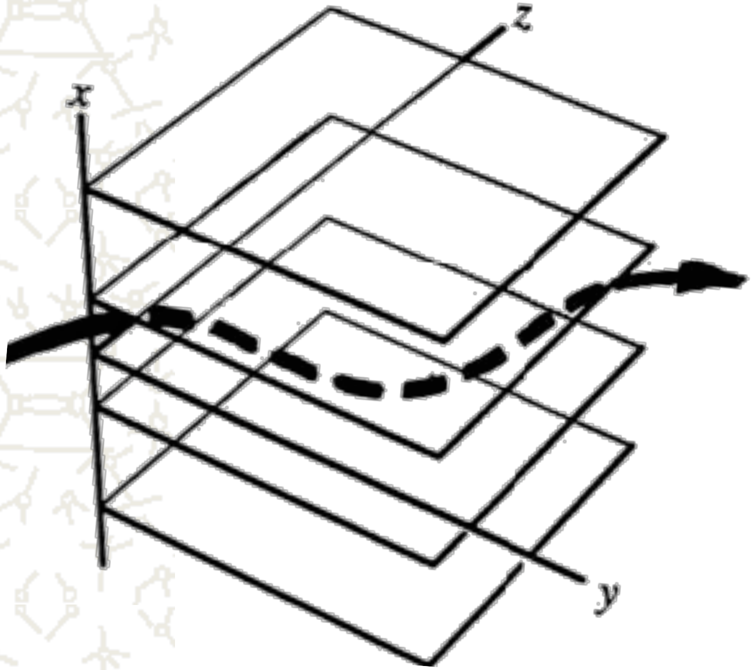
Observation of high-efficiency planar channeling and volume reflection in a 0.5 mm single silicon strip.
New miniaturization limit reached.

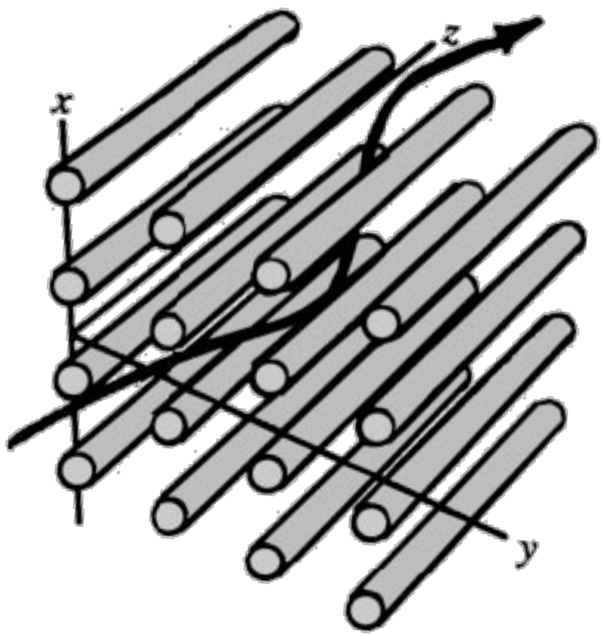


Radius of curvature is *R*=4 m
Tsyganov radius is *R*=0.6 m

Channeling

Channeling is the confinement of charged particles traveling through a crystal within atomic planes (planar or axial modes)



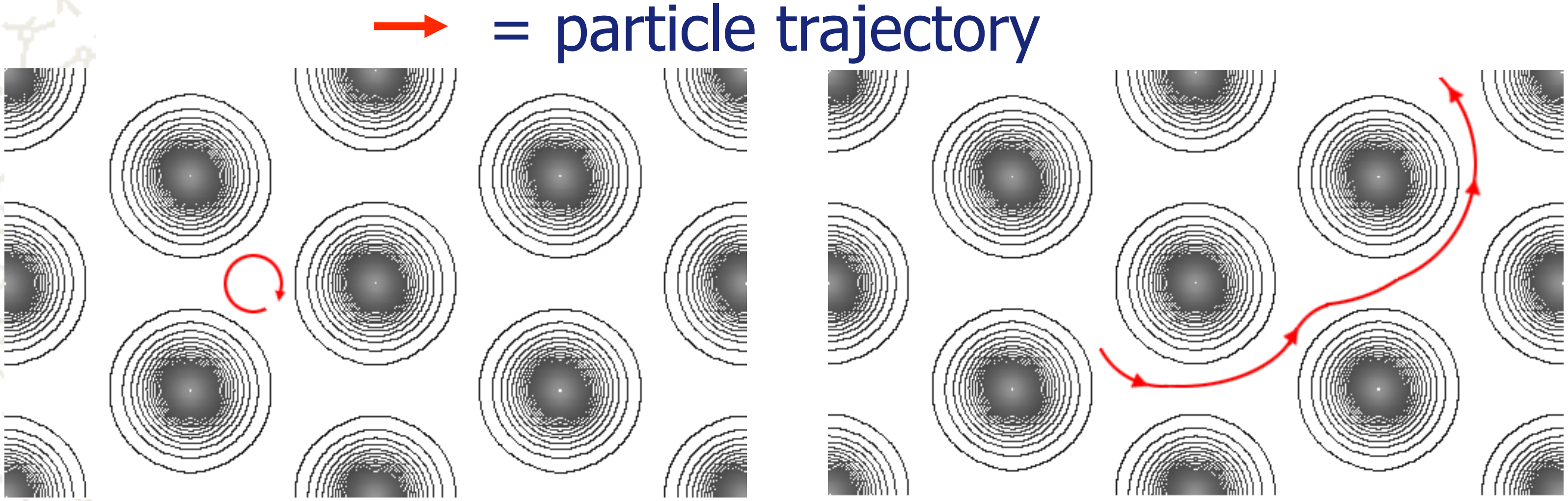


Channeling occurs as the trajectory of a particle forms a angle lower than the critical angle

$$\psi_c = \left(\frac{4 Z_1 Z_2 e^2}{p v d} \right)^{1/2}$$

Axial channeling

Axial channeling consists of particle confinement through two modes



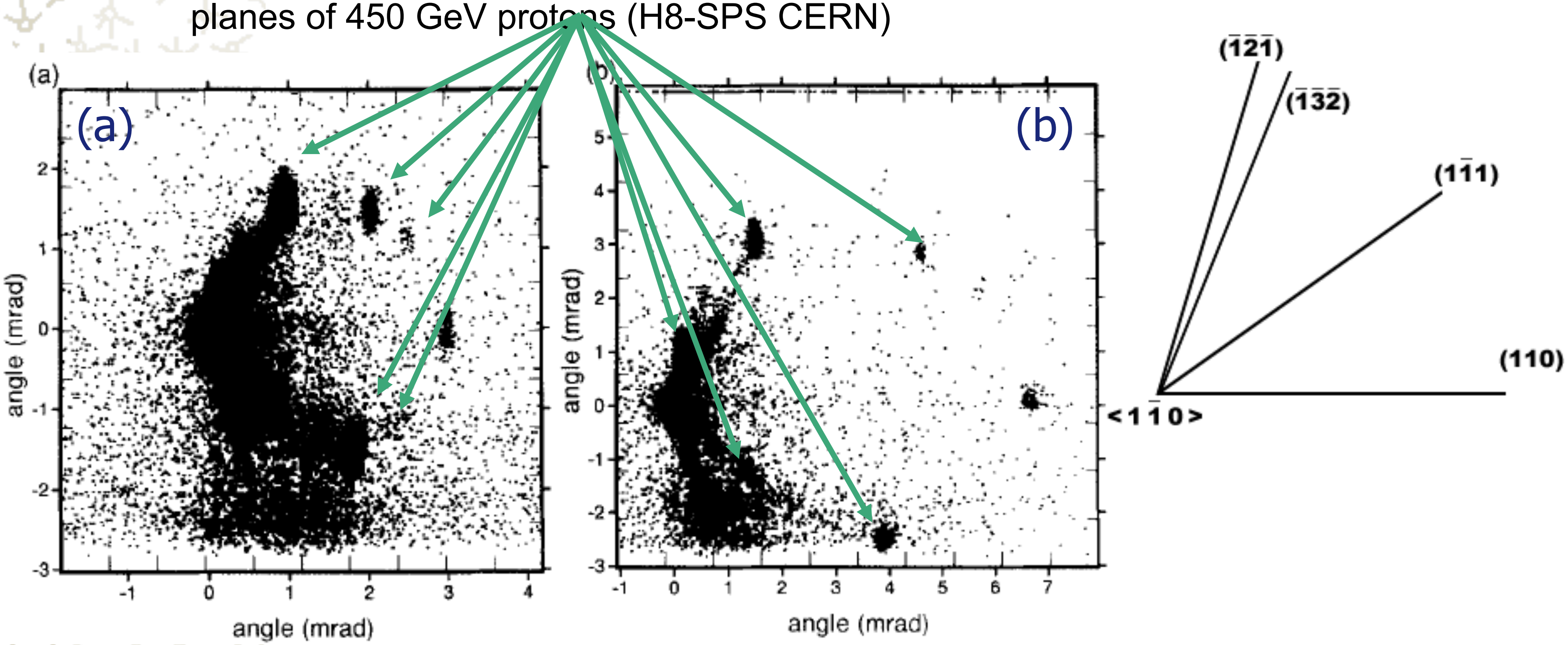
Hyperchanneling Doughnut scattering

AC in a bent crystal

- AC in a bent crystal was studied by A.M. Taratin and S.A. Vorobiev [Pis'ma Zh. Tekh.Fiz. 4 (1978) 947] as a method to steer particles.
- The simulation relying on binary-collision model demonstrated wide spectrum of deflection up to full bending.
- Deflection was ascribed mainly to doughnut scattering rather than to hyperchanneled particles

Earlier experiments

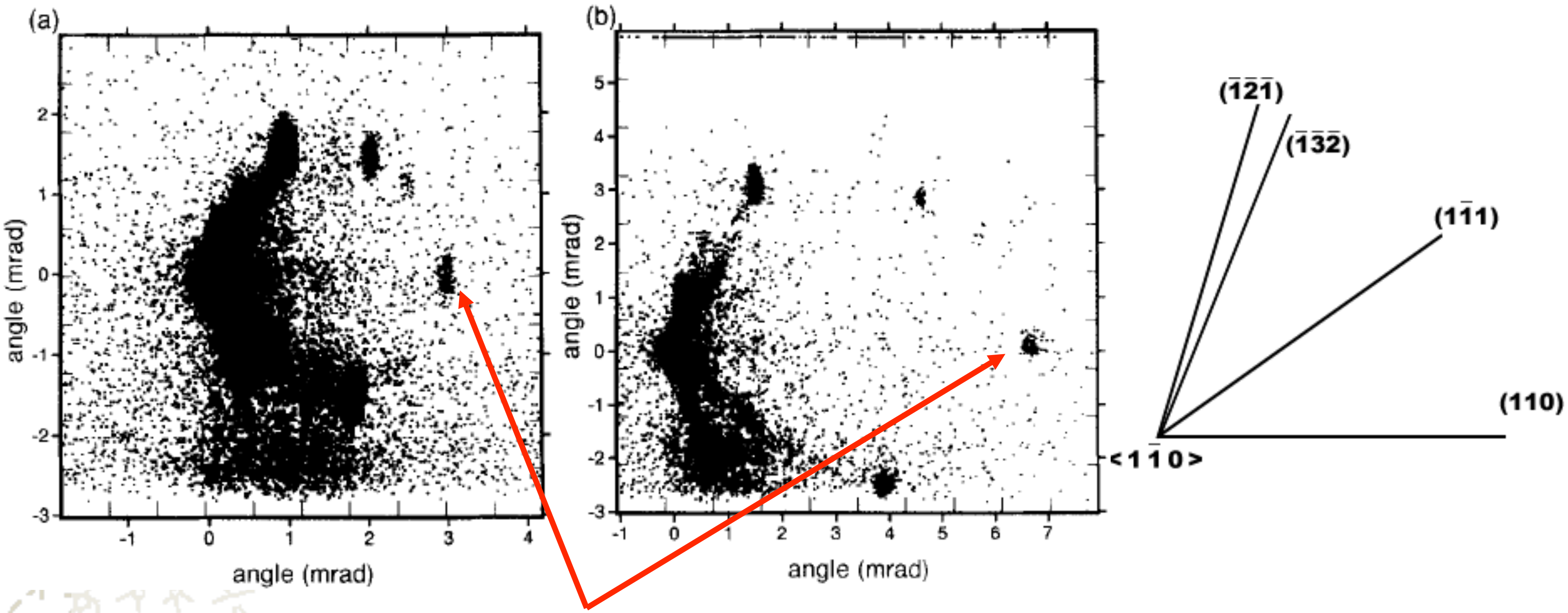
Deflection due to planar channeling by skew planes of 450 GeV protons (H8-SPS CERN)



Axial bending for the <110> axis in silicon. The crystal was bent 3.1 mrad in (a) and 6.7 mrad in (b)

A. Baurichter et al, NIM B **119** (1996) 172

Earlier experiment



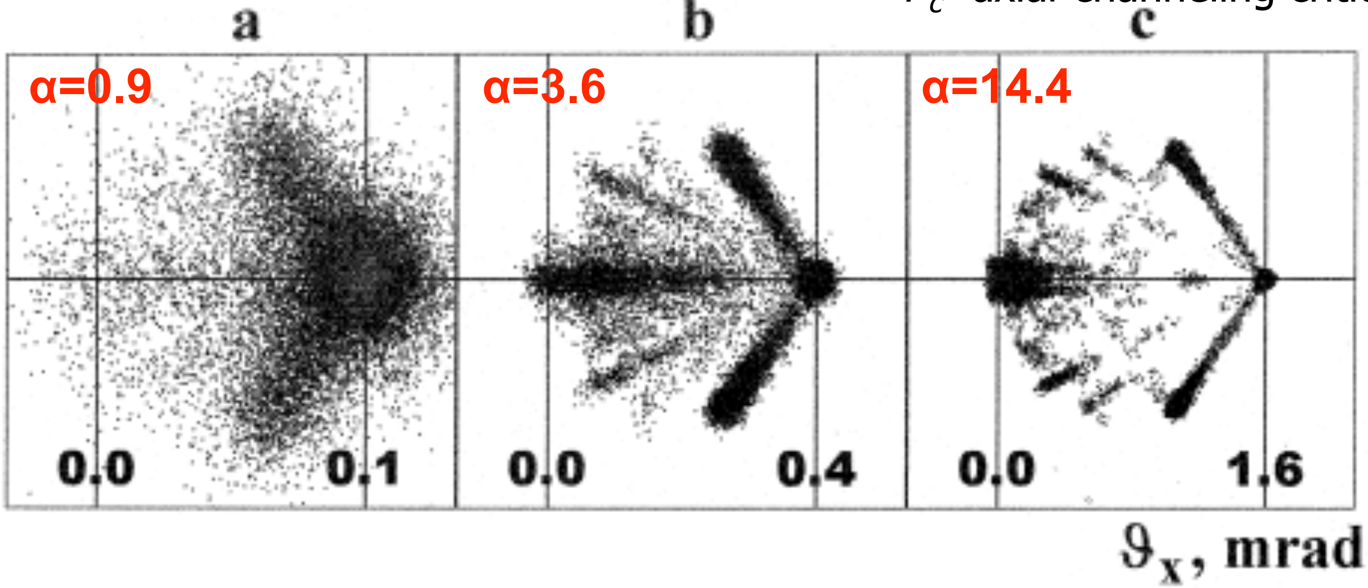
Particles subjected to hyperchanneling along the <110> atomic string

Axial bending for the <110> axis in silicon. The crystal was bent 3.1 mrad in (a) and 6.7 mrad in (b). In case (a) it resulted in $\alpha = 34.6$

Greenenko-Shul'ga condition

$$\alpha = \frac{l_\perp}{R\psi_c}\frac{l}{R\psi_c} < 1$$

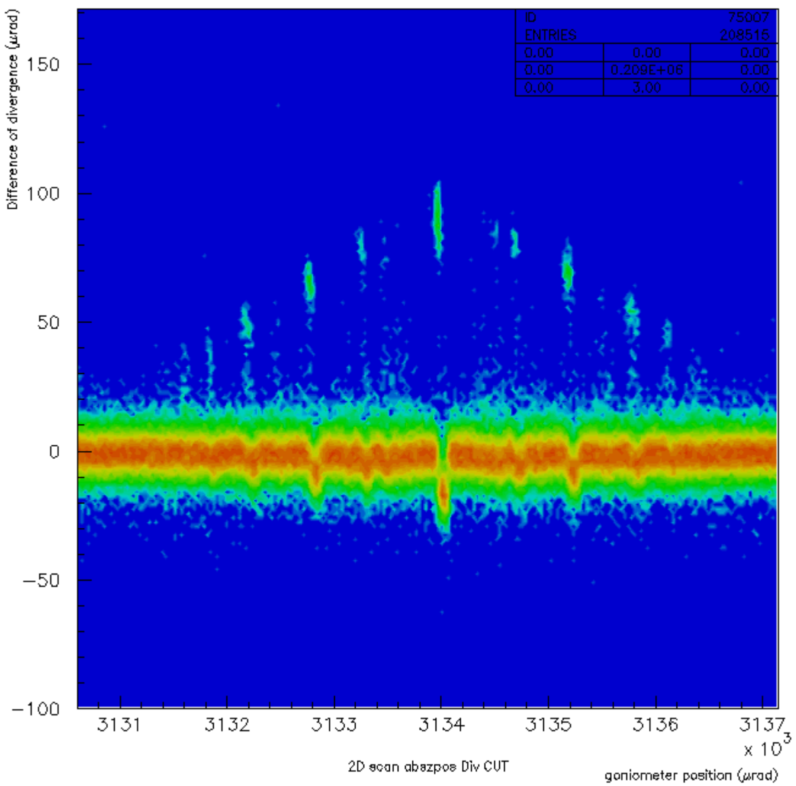
l=crystal lenght along the beam
$l_\perp$=equalization length
R=bending radius
Ψ_c=axial-channeling critical angle



450GeV proton beam angular distribution at the exit of a bent silicon crystal with the curvature radius R=30 m near (110) axis:
(a) l=3 mm; α=0.9; (b) l=12 mm; α =3.6; (c) l=48 mm; α =14.4

A.A. Greenenko, N.F. Shul'ga, NIM B **173** (2001) 178

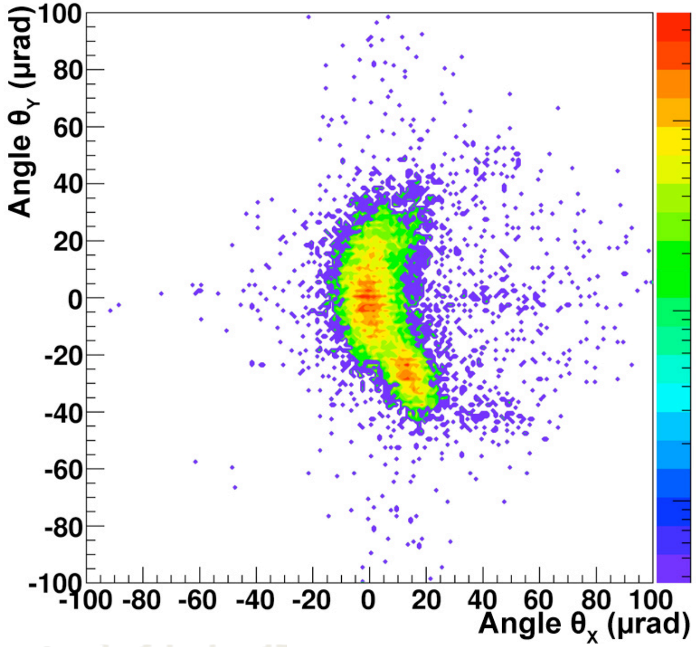
Search for axial channeling

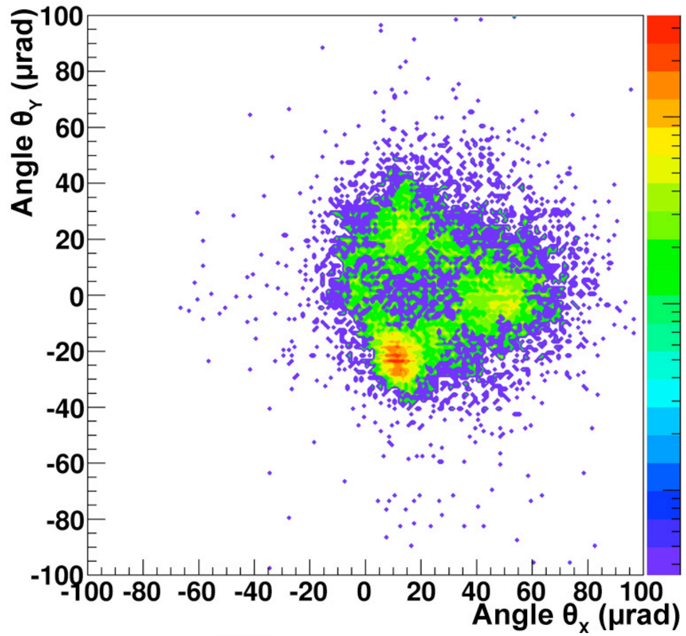


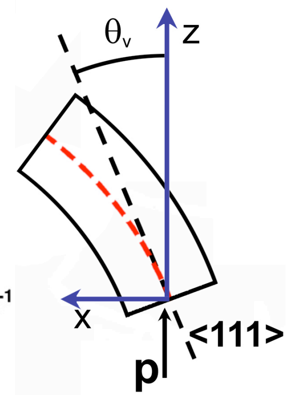
- 400 GeV protons at H8
- Beam divergence was 8 μrad
- Planar channeling is achieved first
- Scanning with the cradle
- Near the axis the “Christmas tree” is obtained
- On the axis, all the spots collapse into a single spot

Approaching the <111> axis

Bending was imparted to achieve **α=0.126**





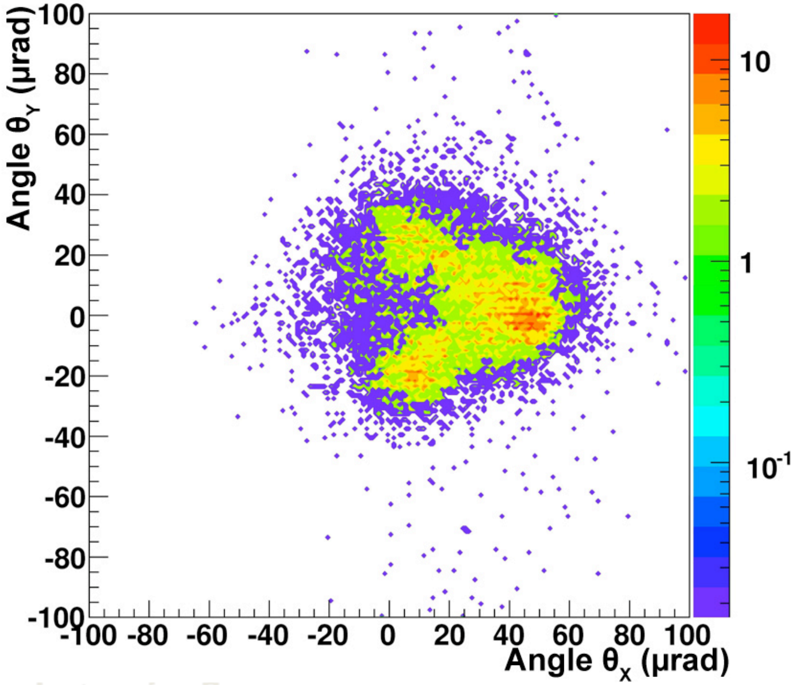


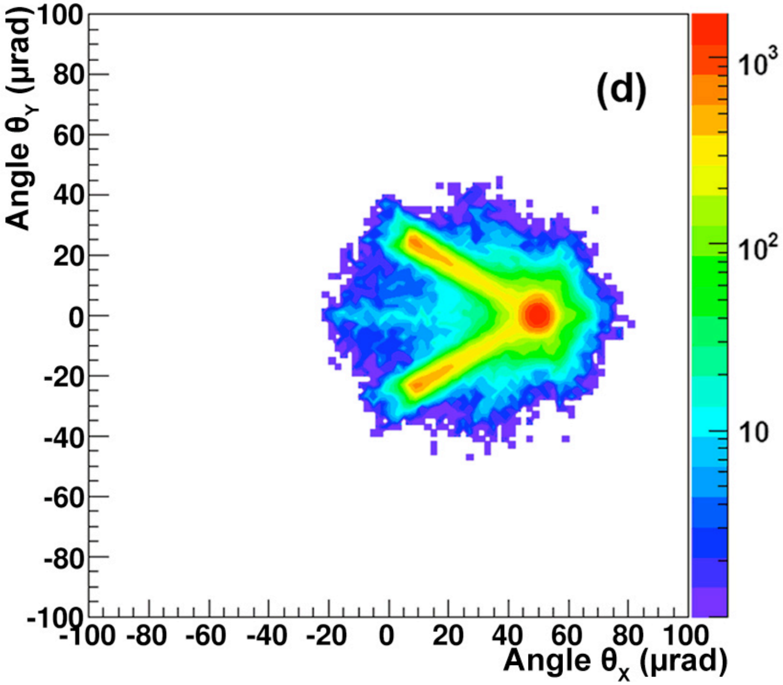
θ_v=40 μrad

θ_v=15 μrad

ψ_c=21 μrad

Axial channeling

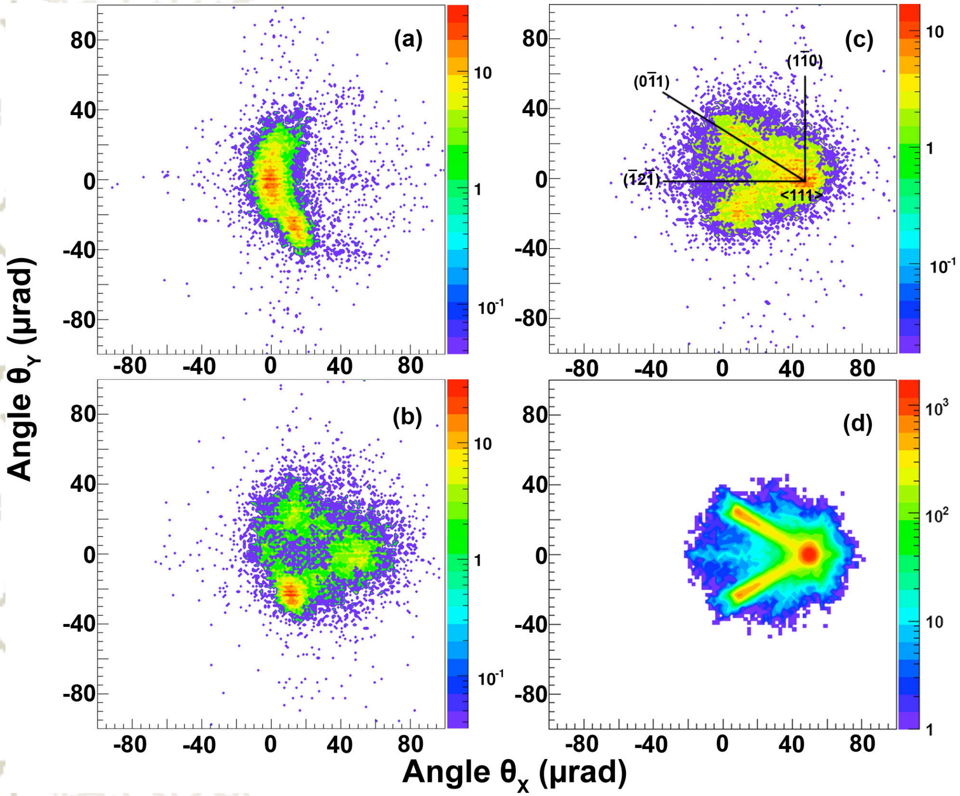




θ_v=0 μrad

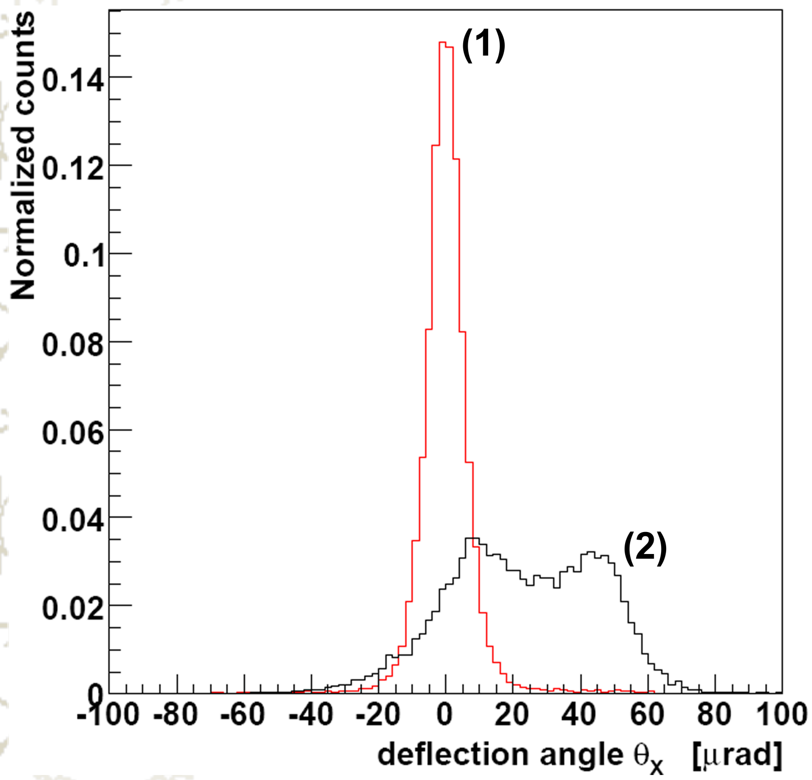
Simulation under the same condition as in the experiment

Summary



- Particles start interacting with the potential of AC <111>
- AC begins deflecting the particles
- Partial feed-in of skew planes occurs (α<<1)

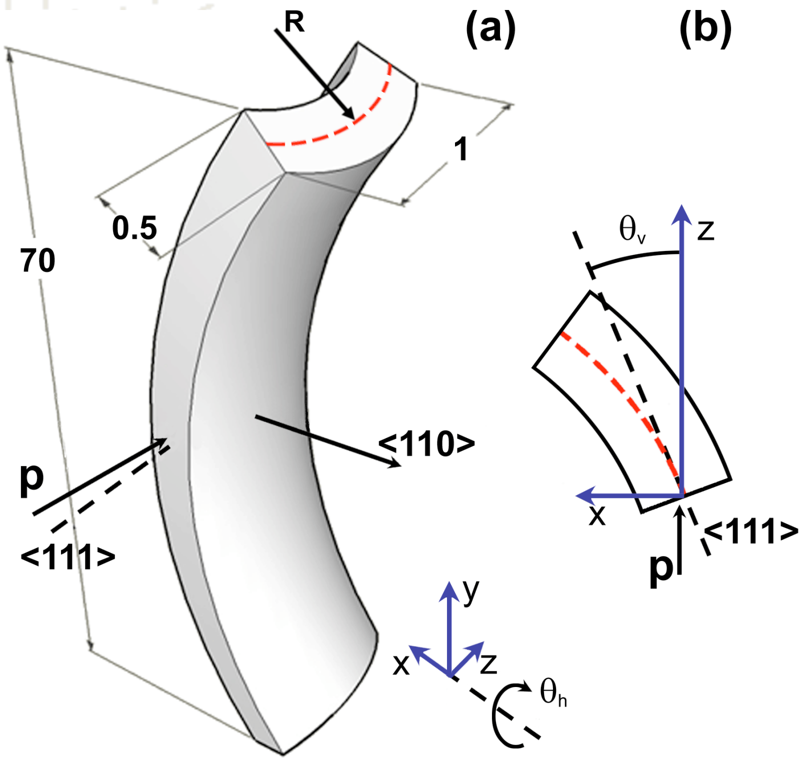
AC efficiency



- Efficiency of axial channeling is larger than 30%
- Its capability to deflect particles toward one side is about 90%
- Hyperchanneling contributed to about 2% according to the theory

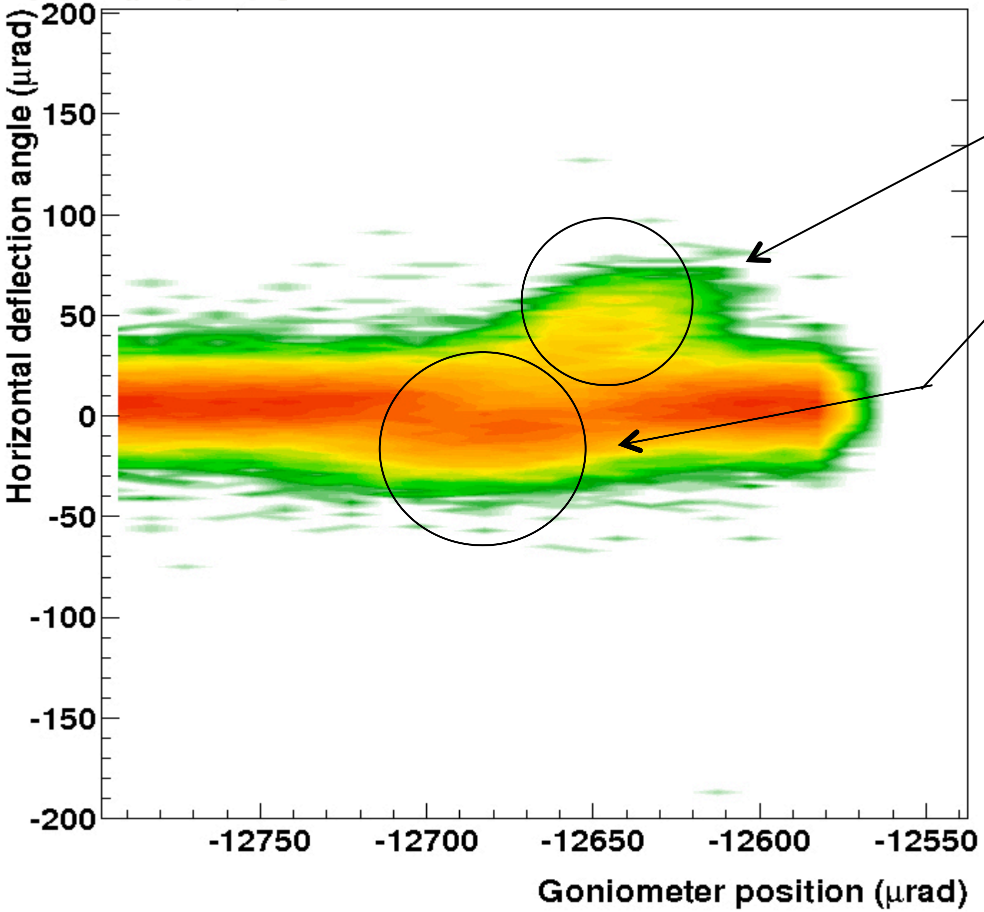
PRL **101** (2008) 164801

Channeling with negative particles



- Experiment in the external line H4 at the SPS - CERN
- Mixture of μ^- and π at 150 GeV
- Beam divergence about 30 μrad
- Crystal ST10 (1 mm along the beam)

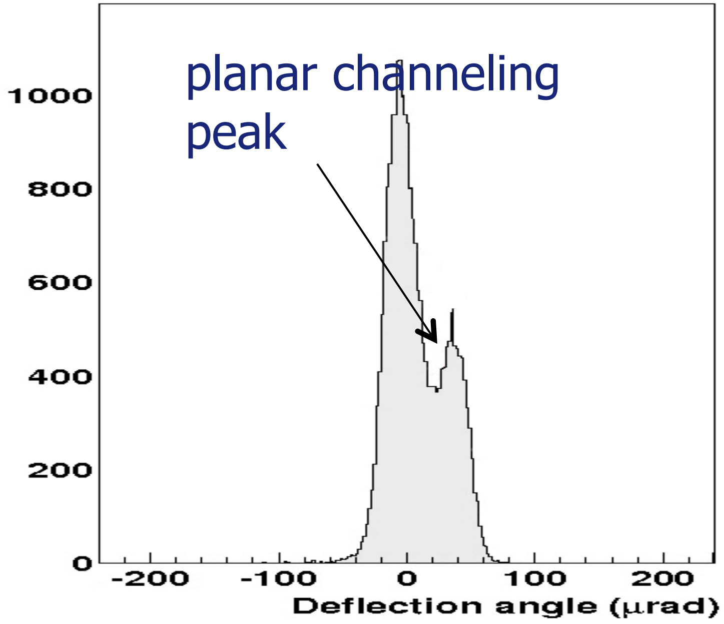
Planar channeling and VR



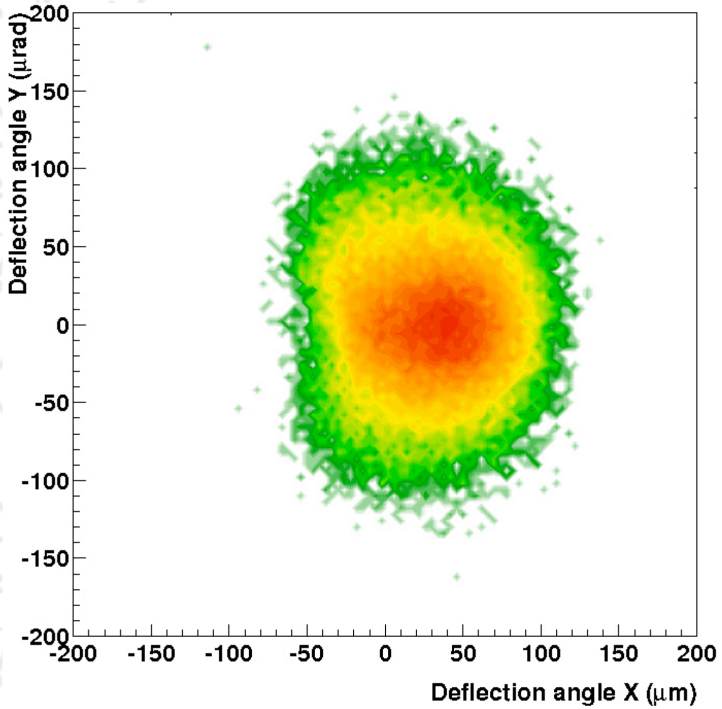
Observation of:

- <u>planar channeling</u>
- <u>volume reflection</u>

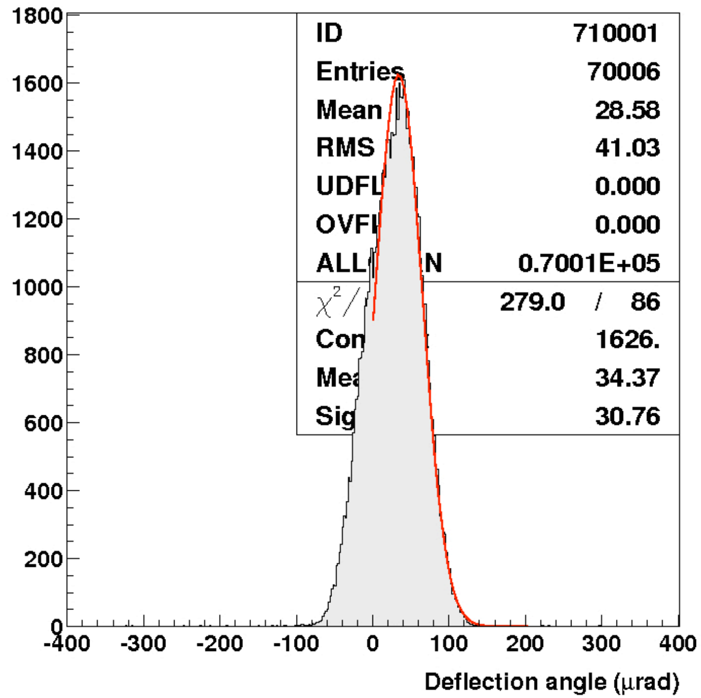
(planar channeling efficiency about 23%)



Axial channeling

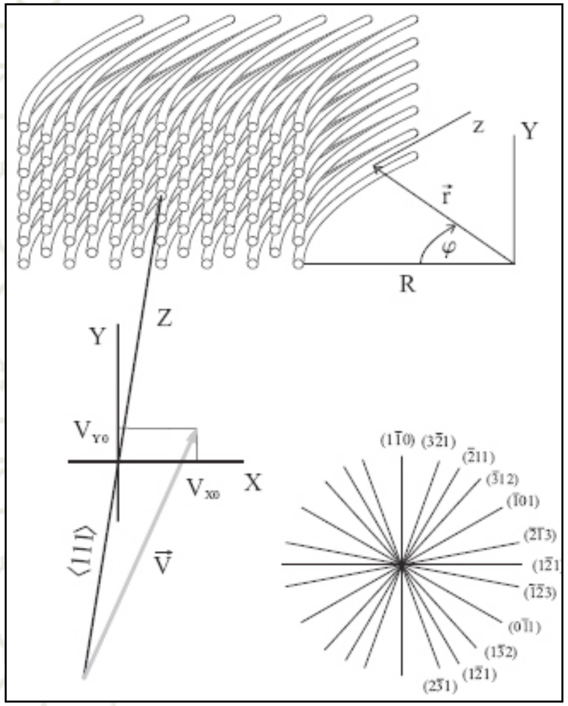


Observation of axial channeling with negative hadrons



It opens up new possibilities to manipulate negatively charged particles beams

Multiple volume reflection in a single crystal

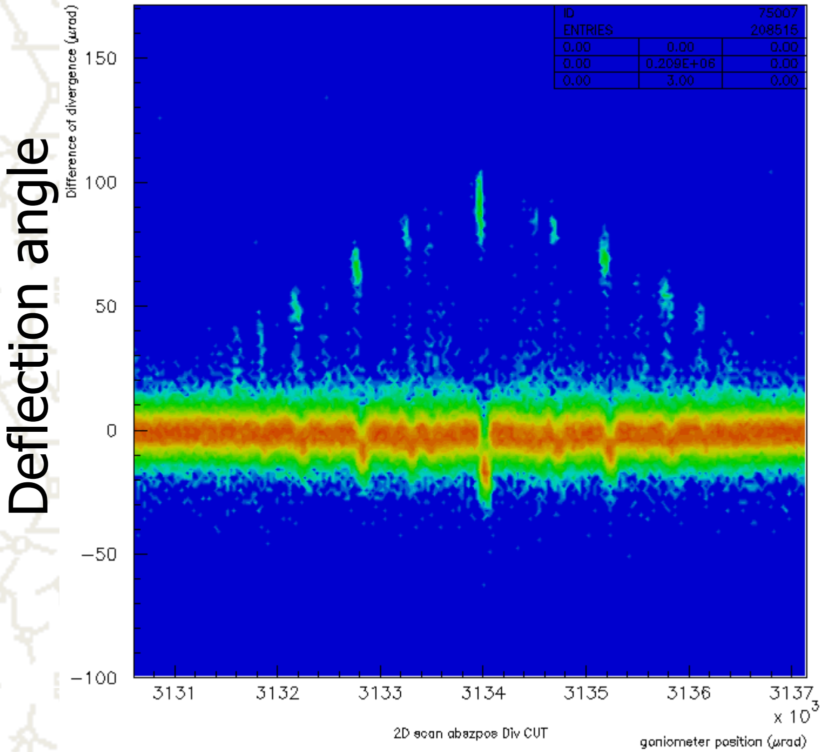


A crystal axis is the intersection of several planes

If a particle beam impinges onto the crystal at appropiate angle, it is subject to volume reflections from subsequent planes

Proposed by V. Tikhomirov
PLB **655** (2007) 5

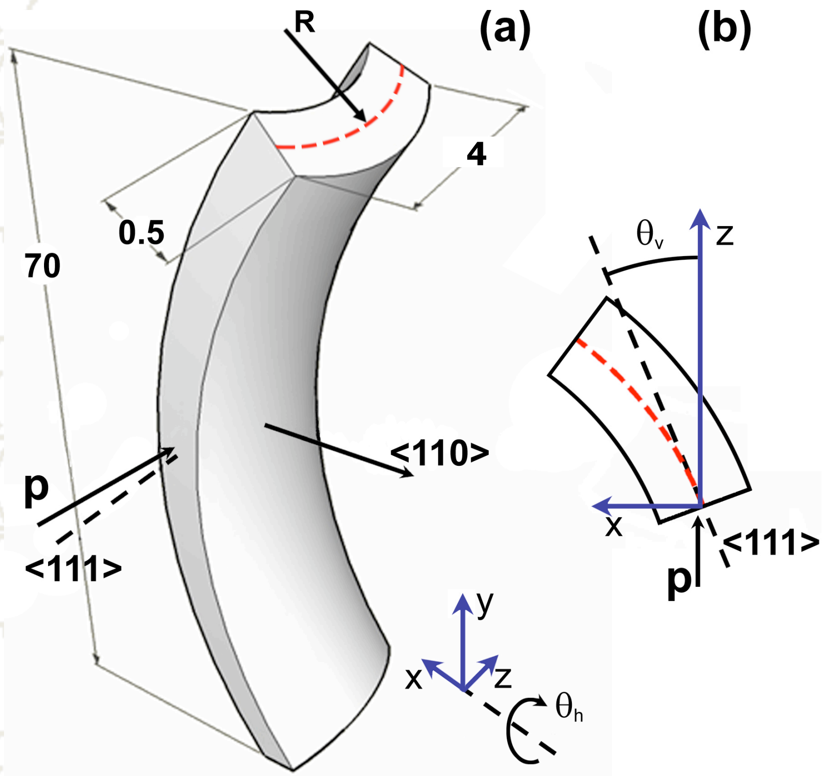
Multiple volume reflections



Horizontal angle

- Near-axis condition with ST9 crystal
- Observation of volume reflection by skew planes

Crystal for MVR

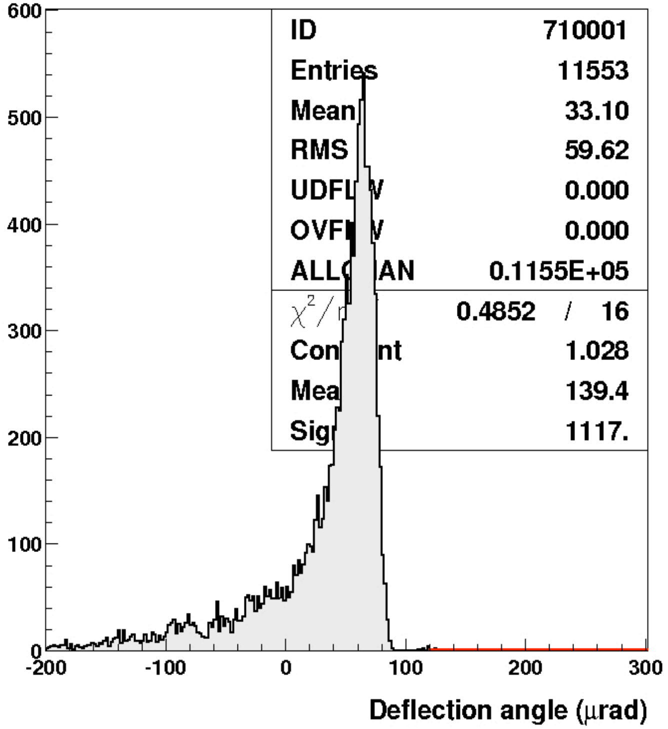


For observation of MVR, the optimal orientation of the crystal with respect to beam is

$$\theta_h = \frac{\theta_v}{2}; \theta_v = \frac{\theta}{2}$$

θ = 400 μrad being the bending angle

Observation of MVR



Clear observation of multiple volume reflection in a single strip crystal

Very high deflection efficiency, acceptance range to be measured

Systematic study in 2009

Conclusions

- Fabrication of crystals for channeling
- Observation of high-efficiency axial channeling with protons
- Observation of axial channeling with negative charges
- Observation of MVR with protons
- AC and MVR as new schemes for collimation in hadron machines other than PC and VR

Thank you

Thank you for attention!