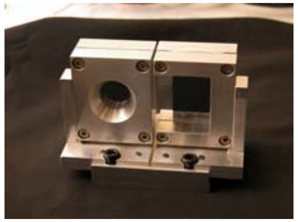


OBSERVATION OF PROTON REFLECTION ON BENT SILICON CRYSTALS AT THE CERN-SPS

Walter Scandale *CERN*

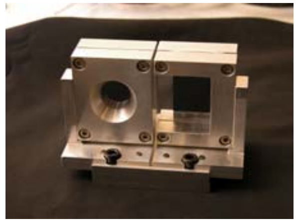
For the H8-RD22 collaboration

(CERN, FNAL, INFN, IHEP, JINR, PNPI)

BEAM 07

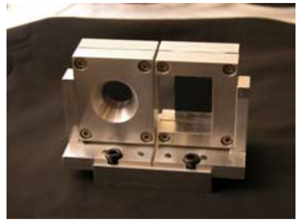
30 September 2007

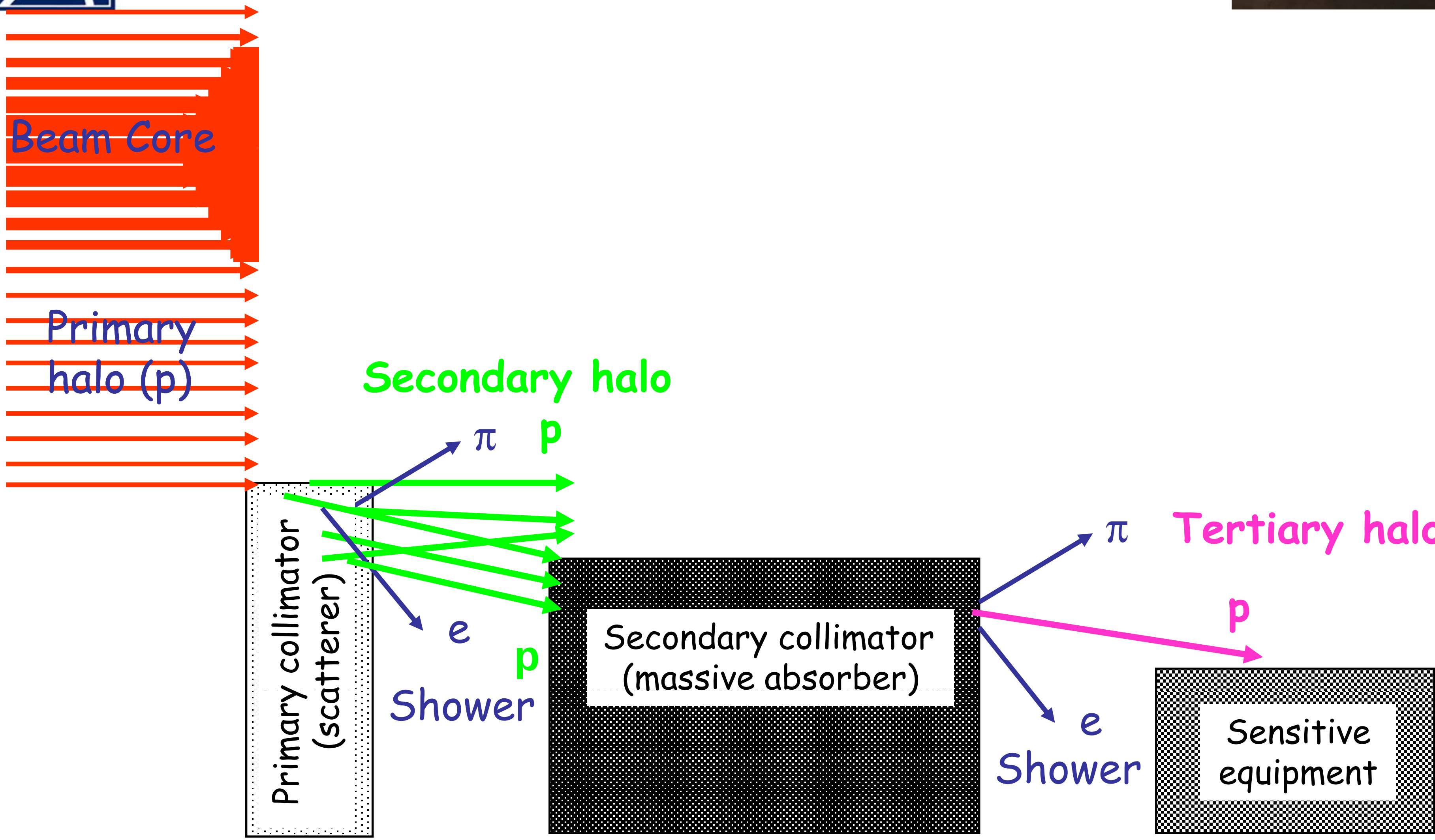
Outlook



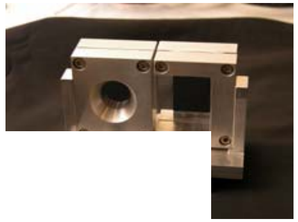
- Why using crystals in hadron colliders
- The H8-RD22 experiment at CERN
  - Experimental layout
  - High precision goniometric system
  - Tracking detectors
  - Silicon crystals(Strip and Quasi-Mosaic Crystals)
- Interaction with 400 Gev proton beam
  - Observation of volume reflection and channeling
  - Deflection angles
  - Single-pass efficiency
  - Multi-crystal volume reflection
  - Axial channeling
- Conclusions

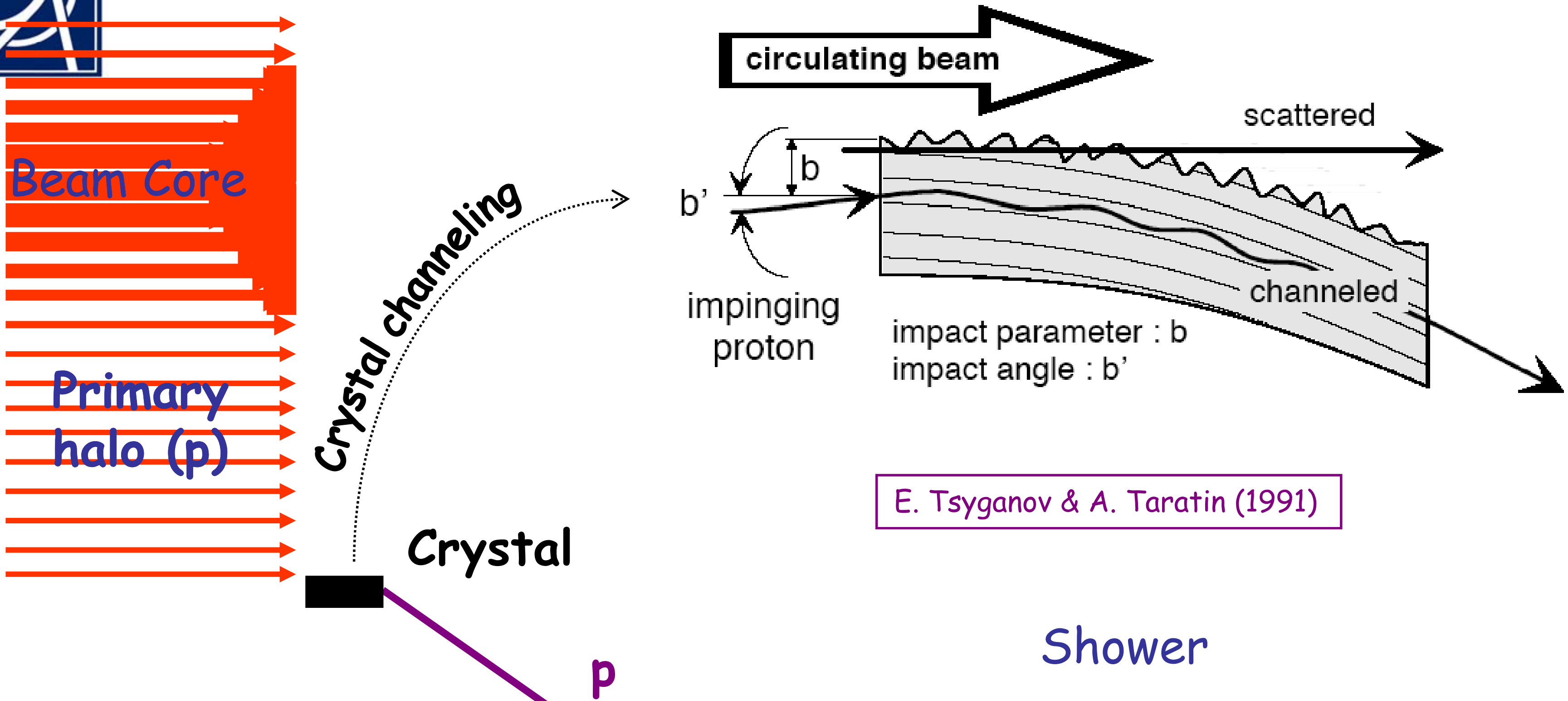
Two stage collimation

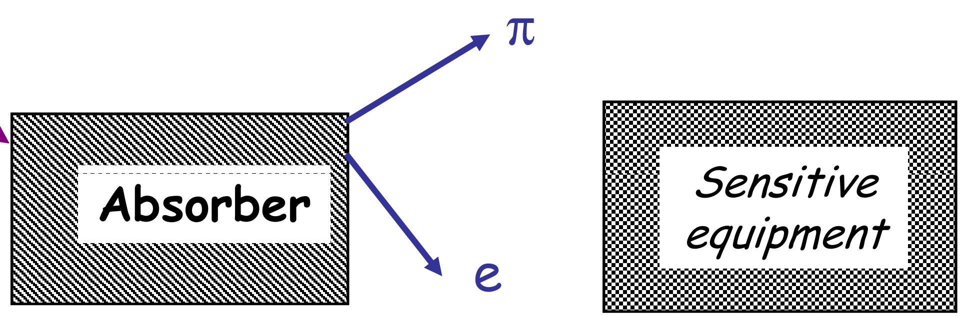




Crystal collimation



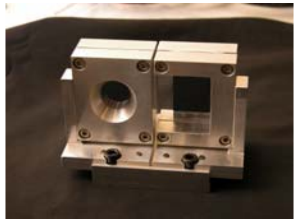




- Primary halo directly extracted!
- Much less secondary and tertiary halos
- Larger gap in the secondary collimators

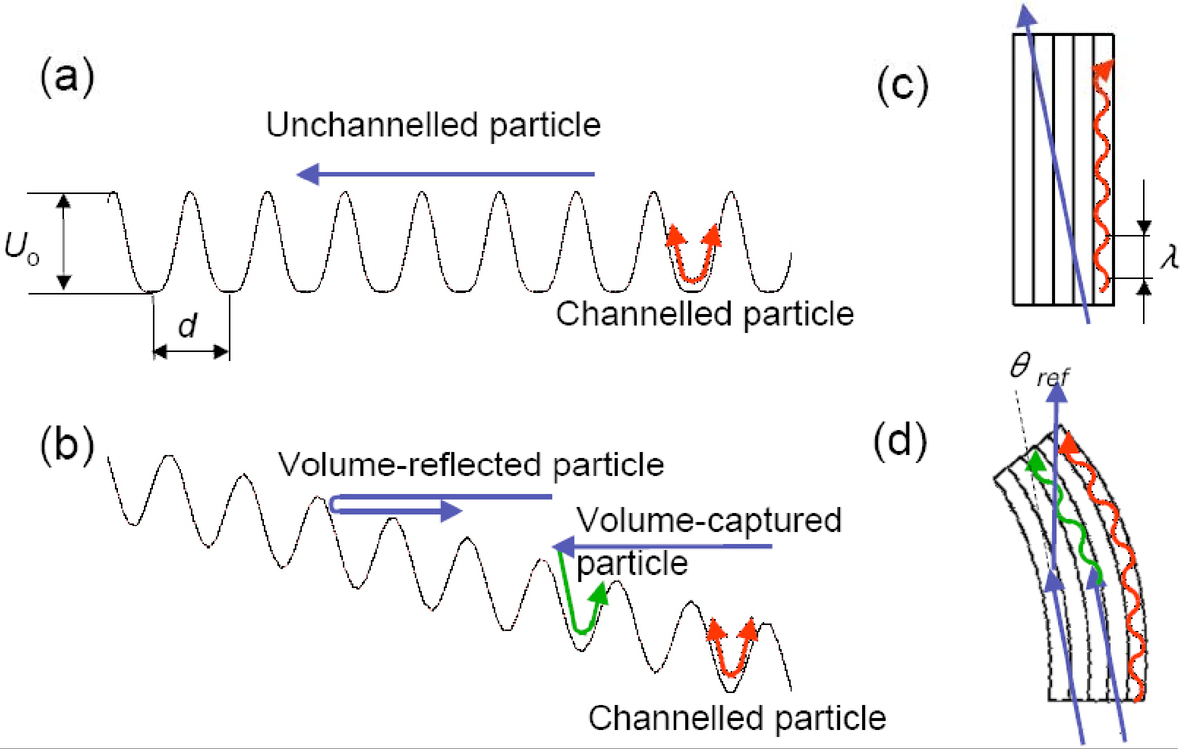
…but not enough data available yet to substantiate the idea…

Particle-crystal interaction



Possible processes:

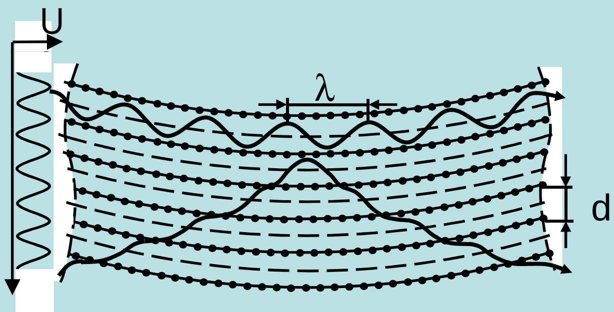
- multiple scattering
- channeling
- volume capture
- de-channeling
- *volume reflection*



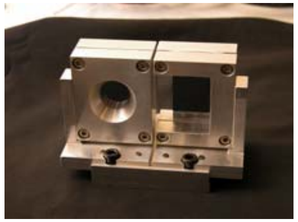
Volume reflection

Prediction in 1985-'87 by
A.M.Taratin and S.A.Vorobiev,

First observations in 2006 (IHEP - PNPI - CERN)

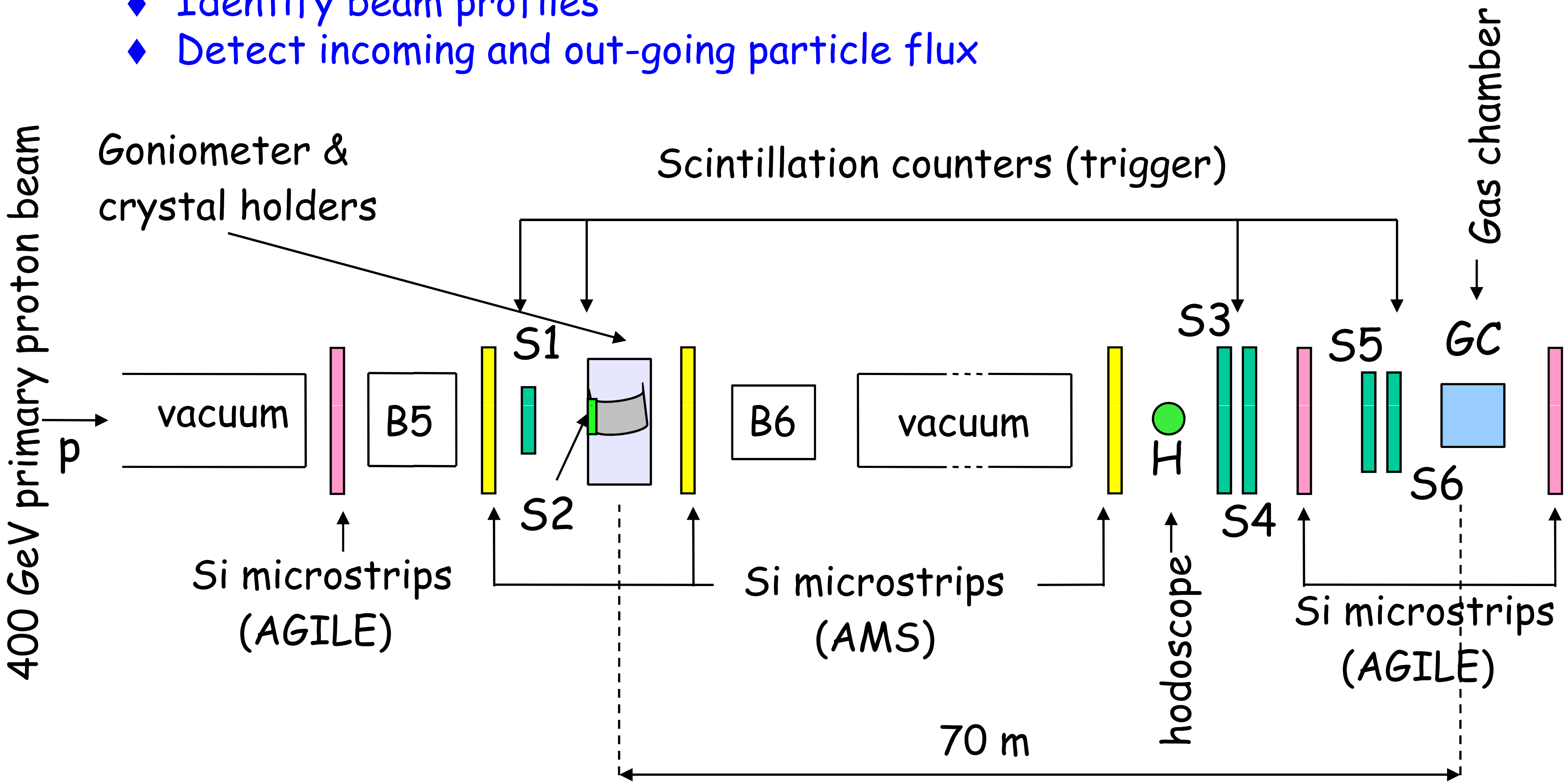


The basic H8RD22 apparatus

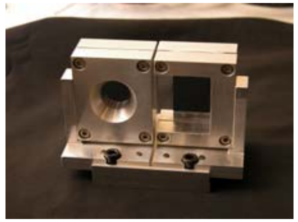


Main functionality:

- Identify direction and slope of the incoming and out-going tracks
- Identify beam profiles
- Detect incoming and out-going particle flux



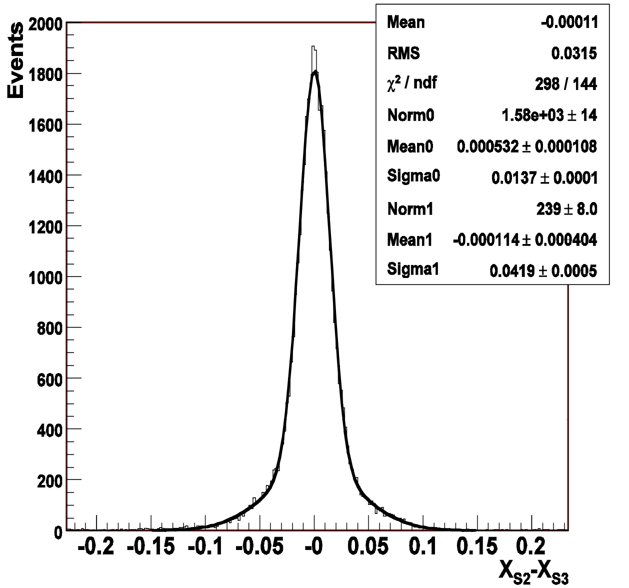
Si microstrips



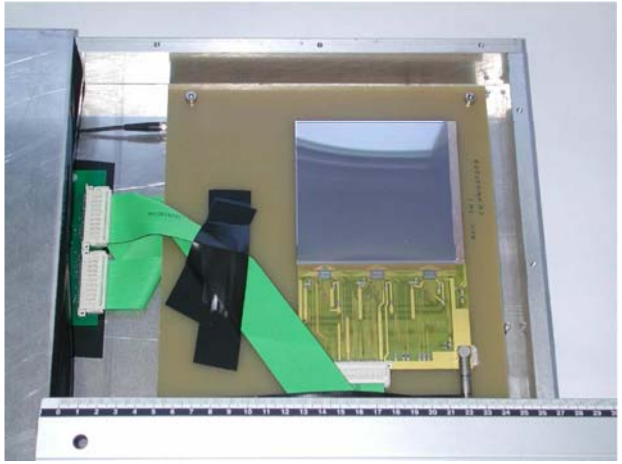
AMS

Built at INFN - Perugia

pitch 110 μm, σ =14μm

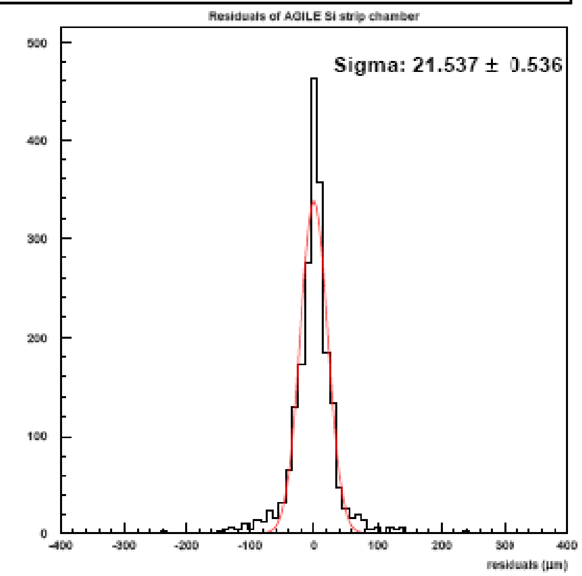


AGILE

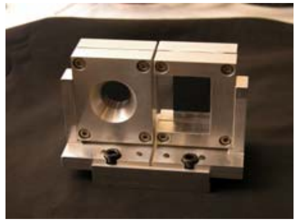


Built at INFN - Como & Trieste

pitch 242 μm, σ =22μm

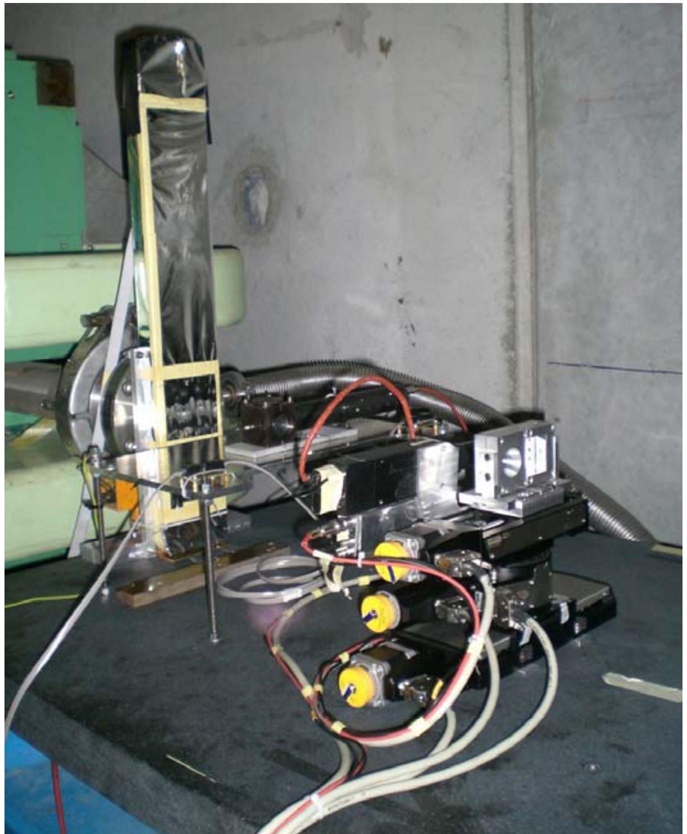


Goniometer

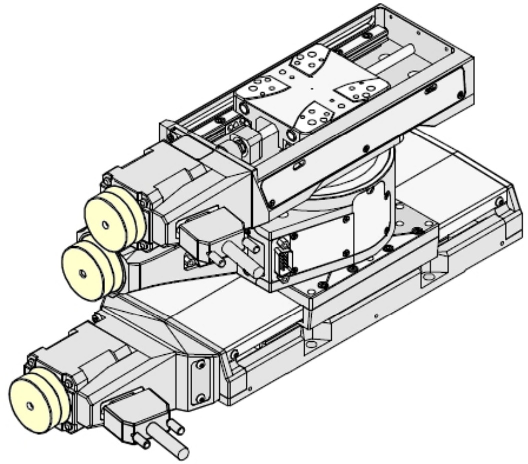


Assembled at INFN - Legnaro

- Two motors for translations
  - 2 μm repeatability
  - 102 mm range (upper stage)
  - 52 mm range (lower stage)

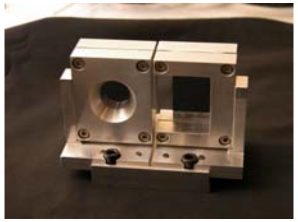


- One motor for H-rotations
  - 360° range
  - 1.5 μrad precision
  - 1 μrad repeatability
- One motor for V-rotations (added later)
  - > ±10° range
  - 1.5 μrad precision
  - 1 μrad repeatability

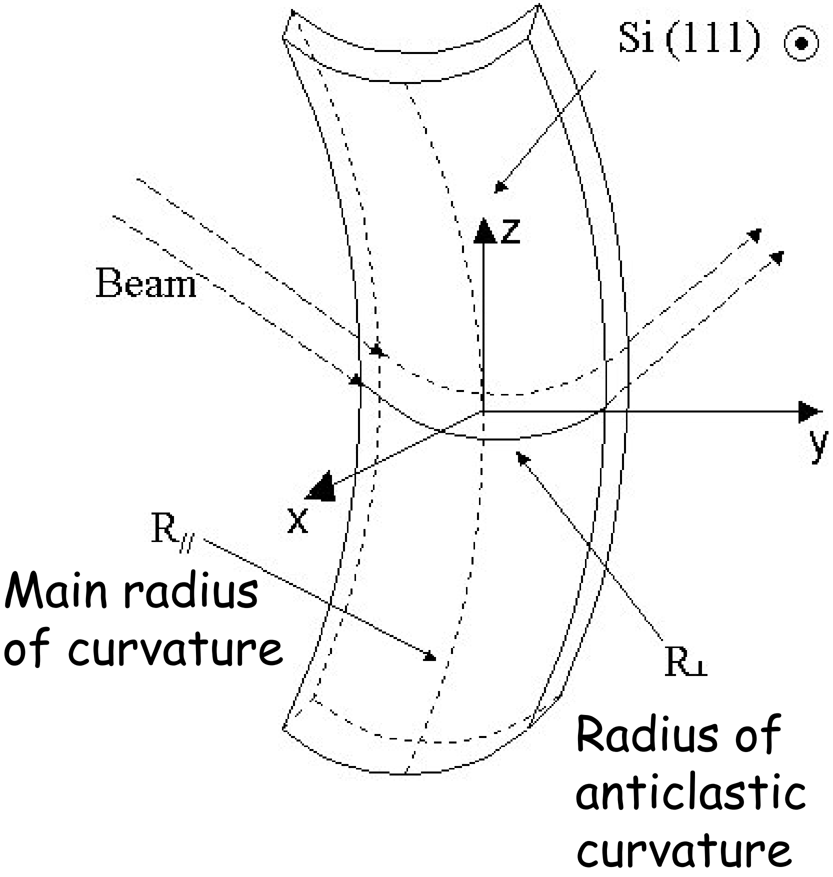


Strip crystals

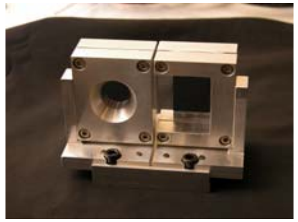
Built at IHEP - Protvino and at INFN - Ferrara



The main curvature due to external forces induces the anticlastic curvature seen by the beam

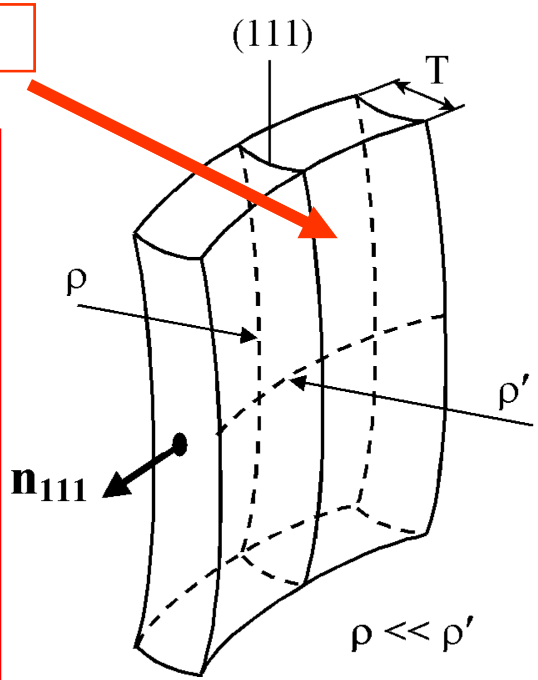


Quasimosaic crystals



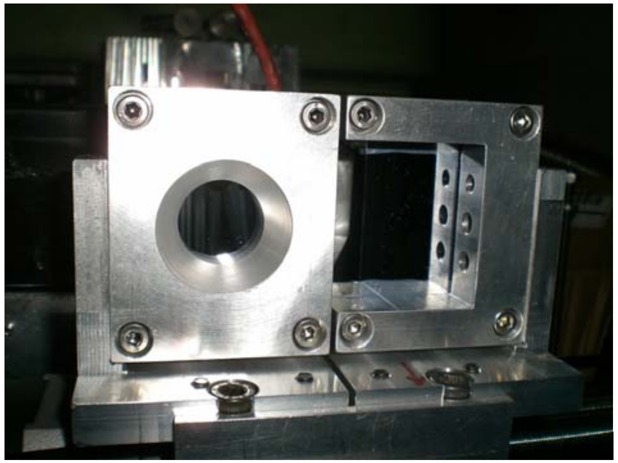
Built at PNPI - Gatchina

Beam direction



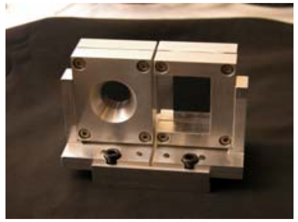
Quasi-Mosaic effect (Sumbaev , 1957)

- The crystal is cut parallel to the planes (111).
- An external force induce the main curvature.
- The anticlastic effect produces a secondary curvature
- The anisotropy of the elastic tensor induces a curvature of the crystal planes parallel to the small face.



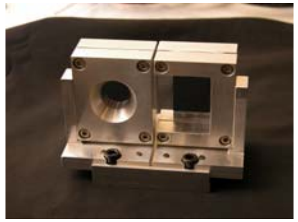
Crystal size: 0.7 x 30 x 30 mm^3

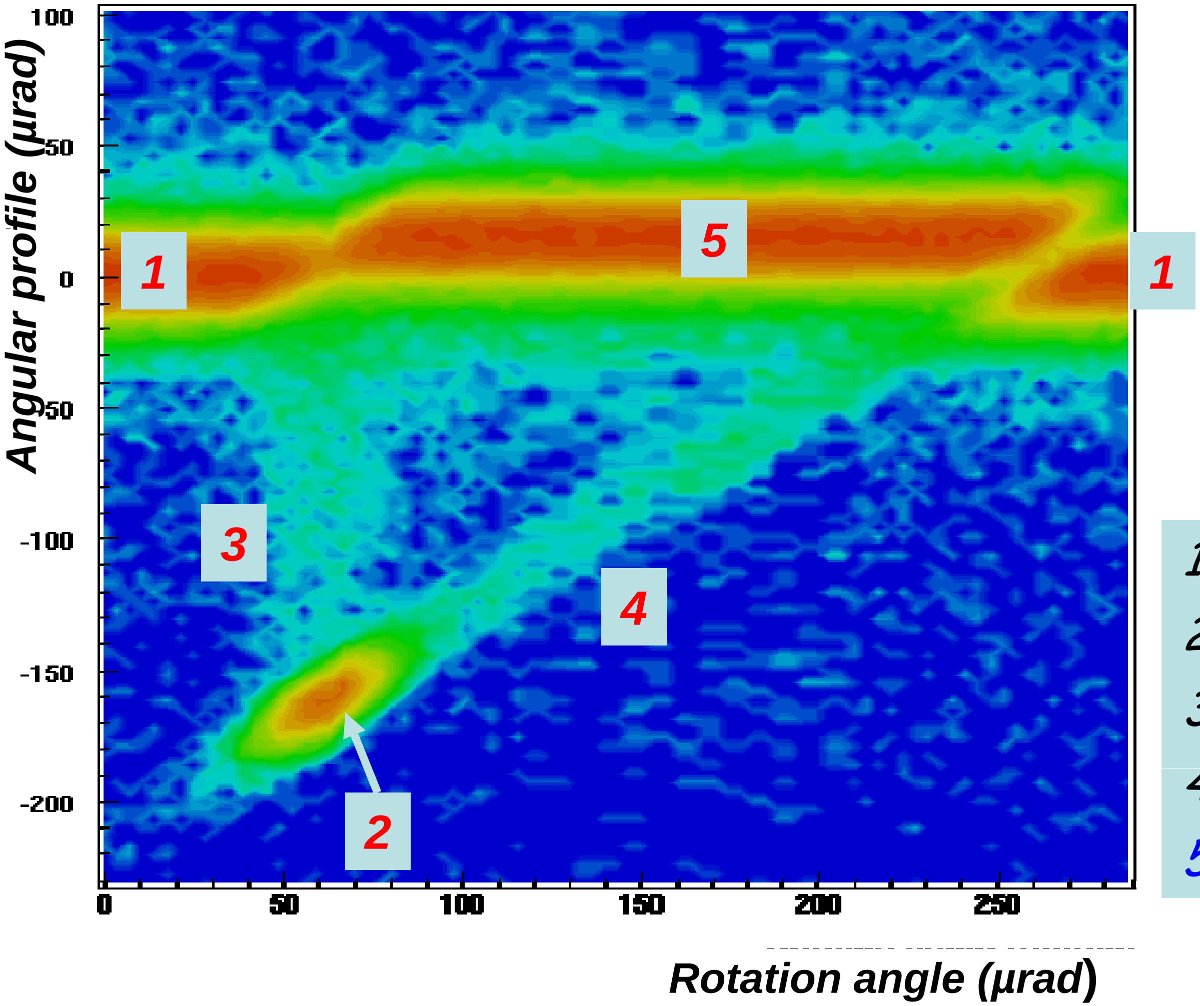
Data taking



- Pre-alignment of the crystal respect to the beam line using optical methods
- Fast alignment of the crystal to the beam direction through the hodoscope (pitch 2 mm): the channeling peak is well visible at about 1 cm from the non-deflected beam
- Fast angular scan using the gas chamber (pitch 200 μm) and a high intensity beam (10^8 proton per SPS pulse): the reflection region is well visible.
- High statistics scan with the Si microstrip, in the range predefined by the fast angular scan (10^4 protons per SPS pulse)

Angular beam profile as a function of the crystal orientation



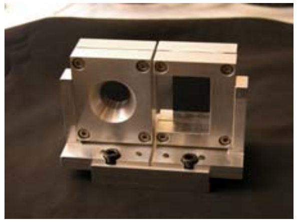


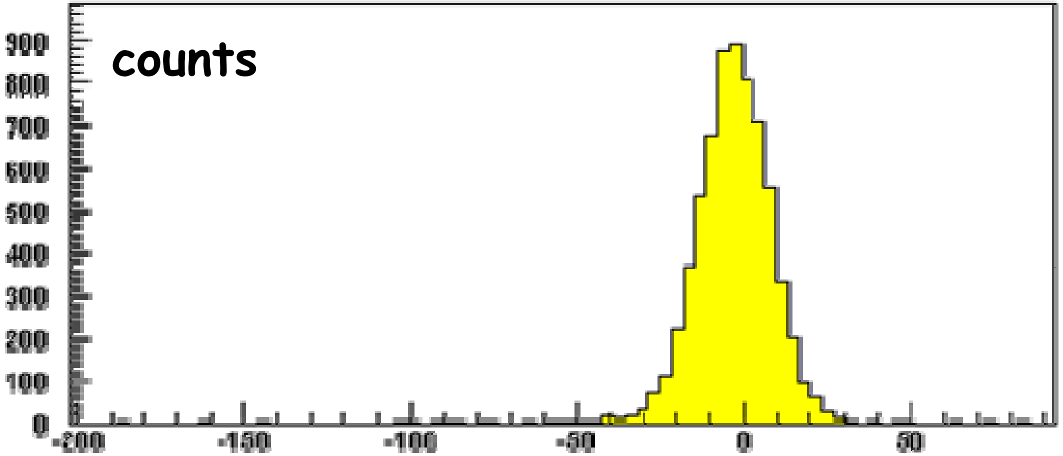
The **angular profile** is the change of beam direction induced by the crystal

The **rotation angle** is angle of the crystal respect to beam direction

The **particle density** decreases from red to blue

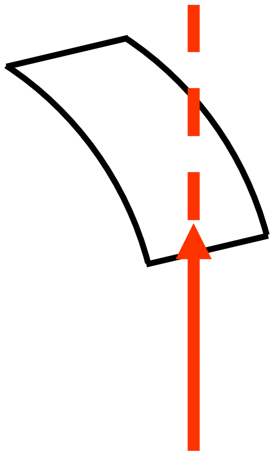
1 - "amorphous" orientation
2 - channeling
3 - de-channeling
4 - volume capture
5 - volume reflection

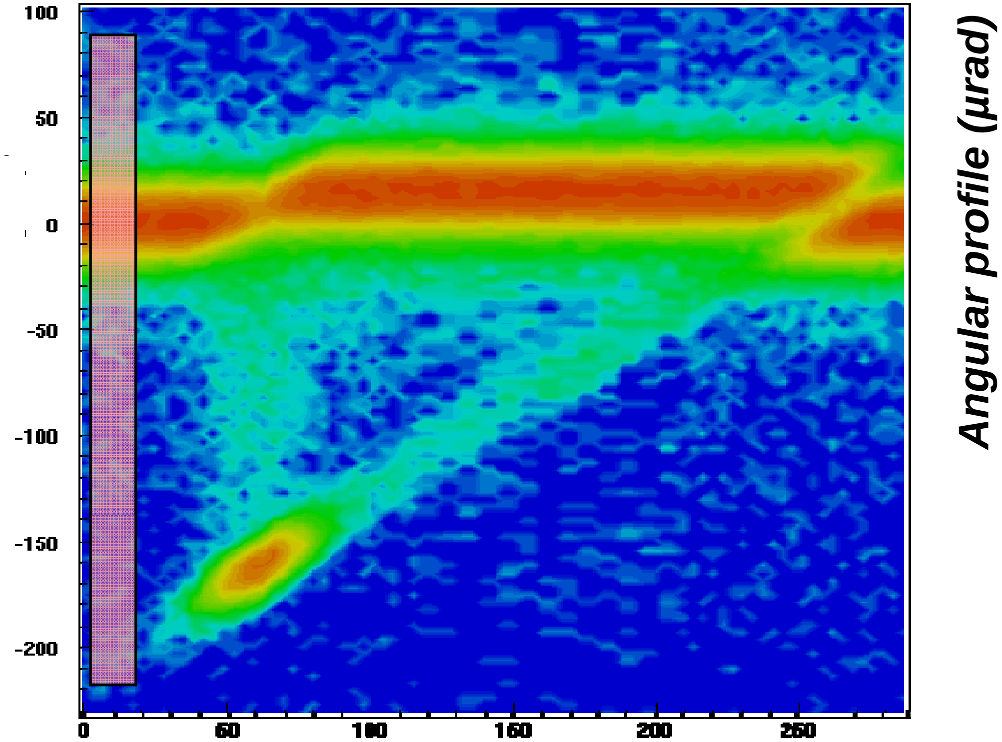


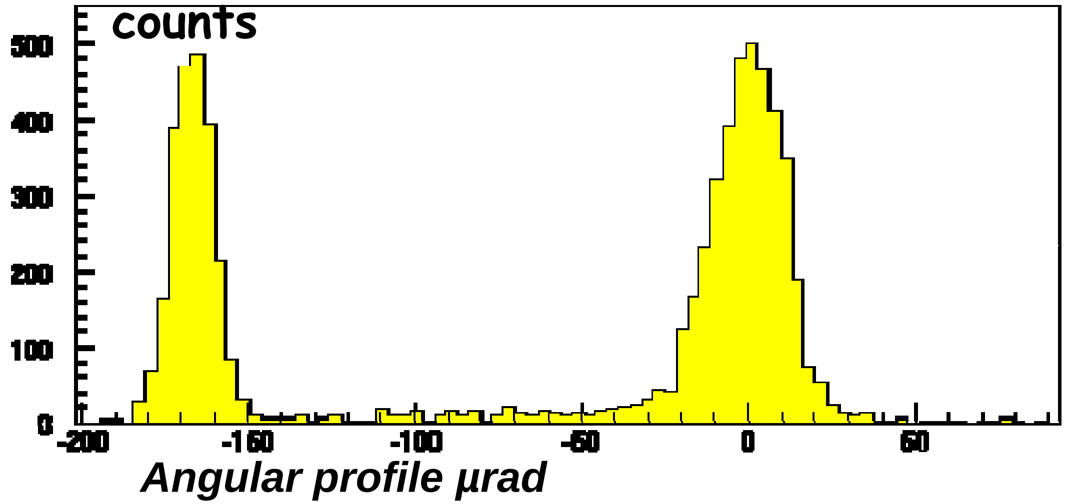


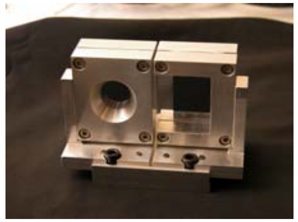
Angular profile µrad

Amorphous

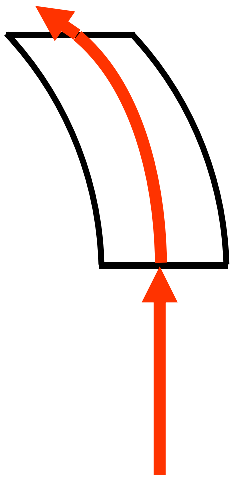


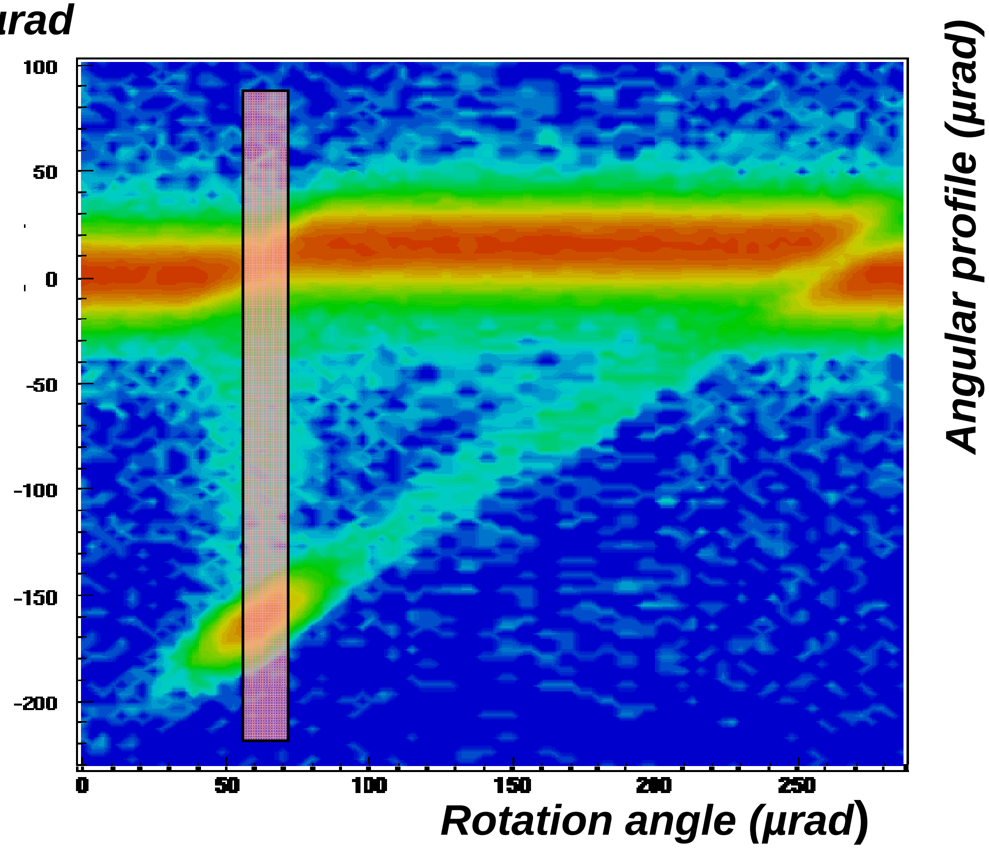


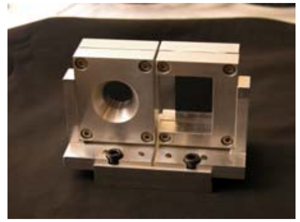

counts
500
400
300
200
100
0
-200
-150
-100
-50
0
50
Angular profile µrad

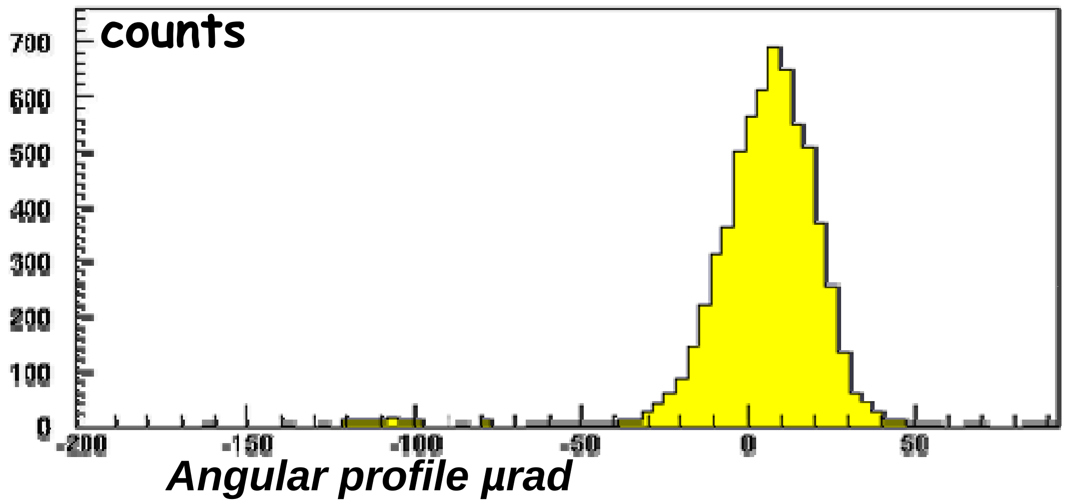


Channeling

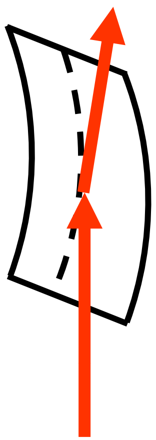


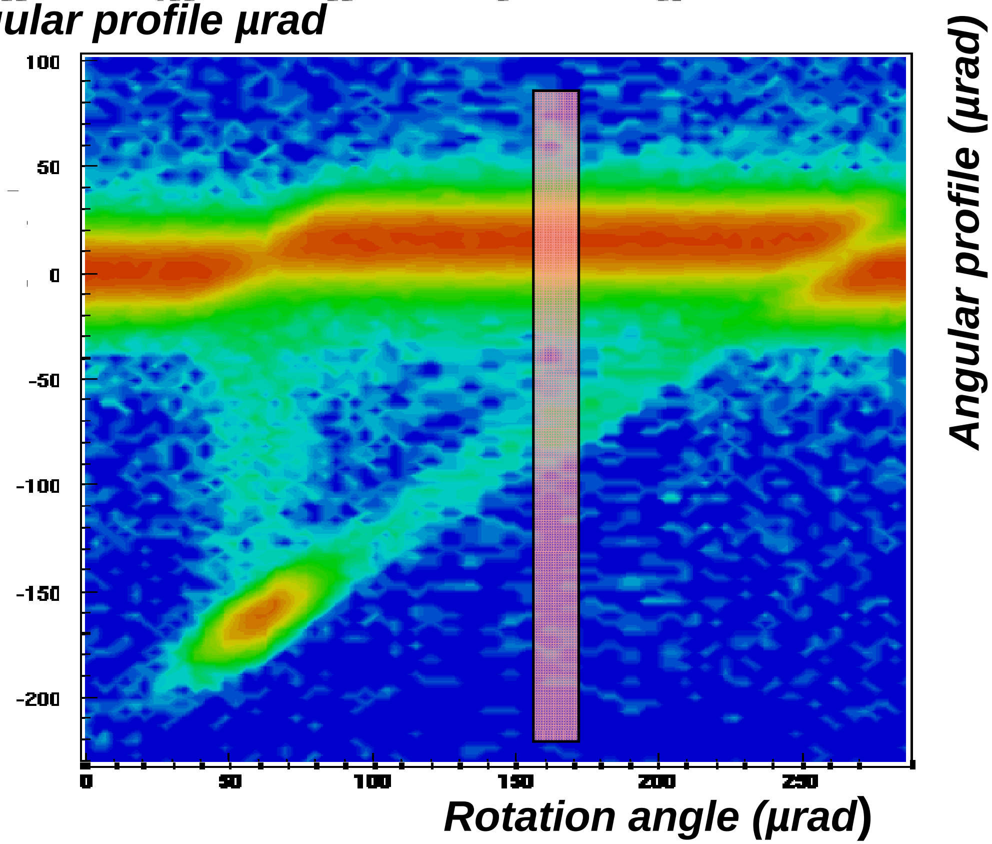

100
50
0
-50
-100
-150
-200
0
50
100
150
200
250
Rotation angle (µrad)
Angular profile (µrad)



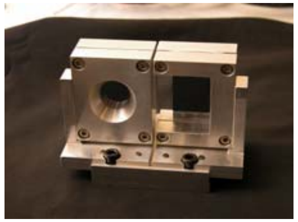


Volume Reflection

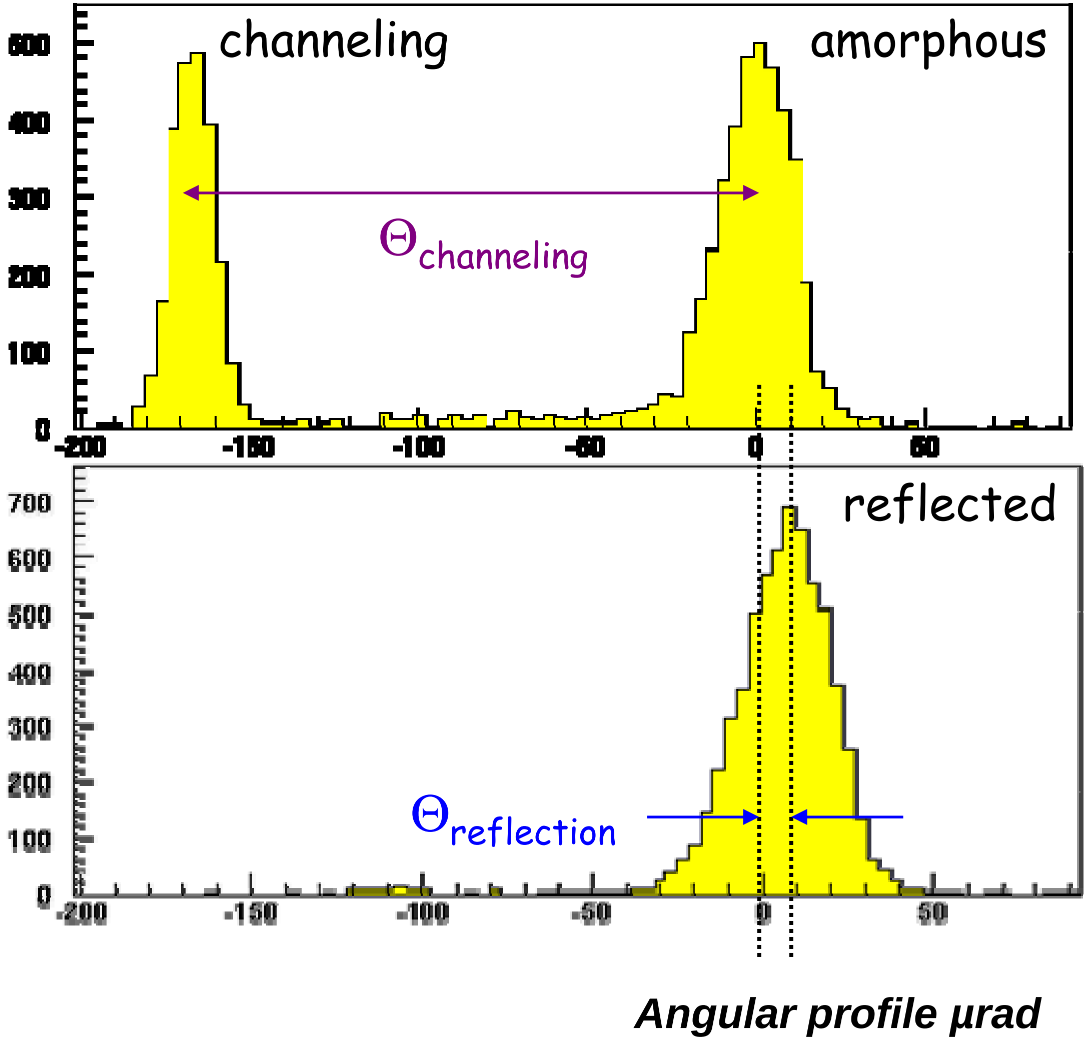


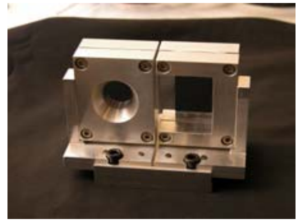


Deflection



- Identify channeling, reflection and amorphous peaks of the angular profile distribution
- Compute the angular shift -> ***deflections***
- (underlying hypothesis: the incoming beam follows a stable direction)

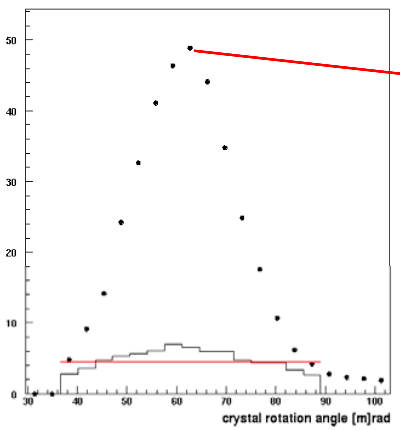




Efficiency

- 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***
- (underlying hypothesis: the incoming beam flux is stable)

Example of efficiency estimate

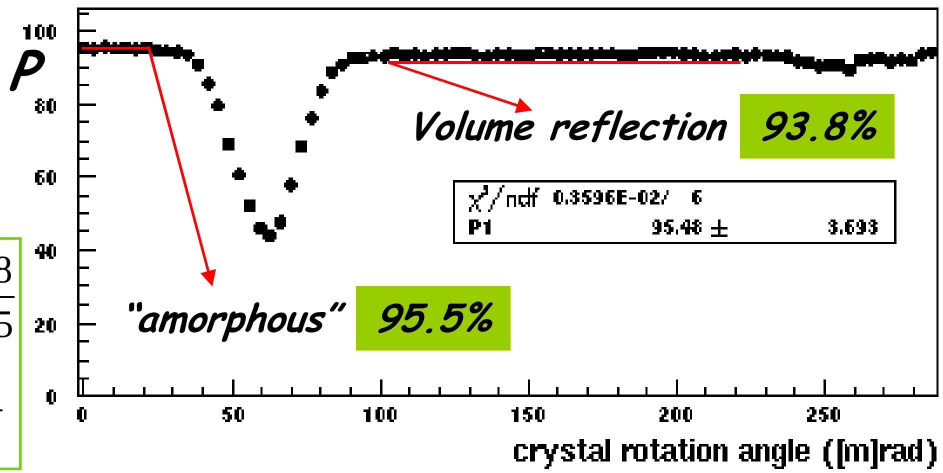


Channeling

49.9%

$$\varepsilon_{refl} = \frac{P_{refl}}{P_{amor}} = \frac{93.8}{95.5}$$

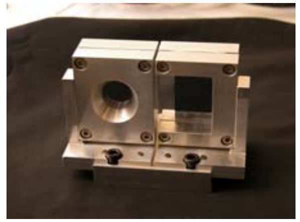
$$\varepsilon_{ch} = \frac{P_{ch}}{P_{amor}} = \frac{49.9}{95.5}$$



Volume reflection ***93.8%***

"amorphous" ***95.5%***

Typical results



QM2 quasimosaic crystal

ε (reflection) = 98.2 %

ε (channeling) = 52.7 %

$\Theta_{channeling}$ = 73 μrad

$\Theta_{reflection}$ = 12 μrad

ST4 strip crystal

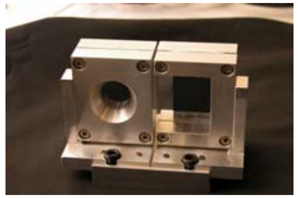
ε (reflection) = 98.2 %

ε (channeling) = 51.2 %

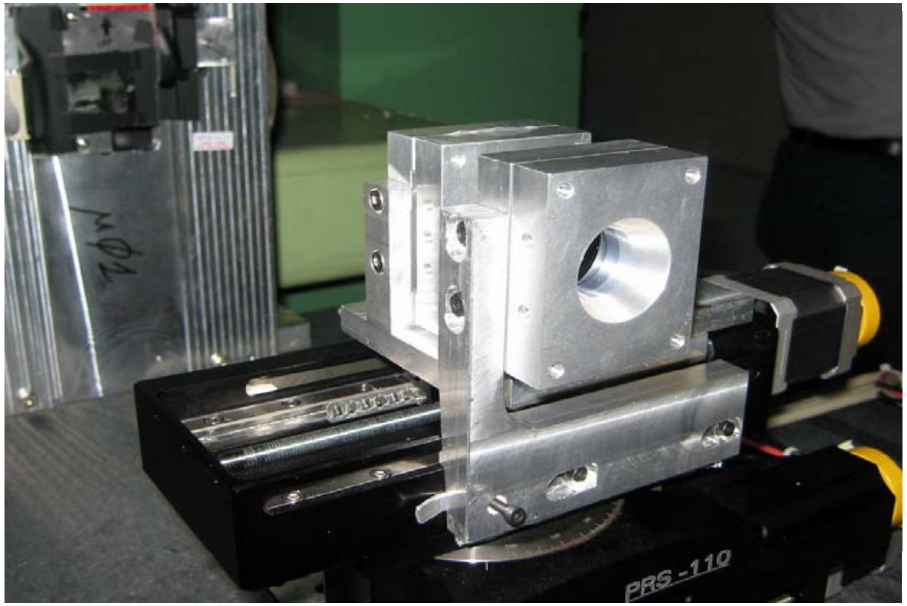
$\Theta_{channeling}$ = 163 μrad

$\Theta_{reflection}$ = 14 μrad

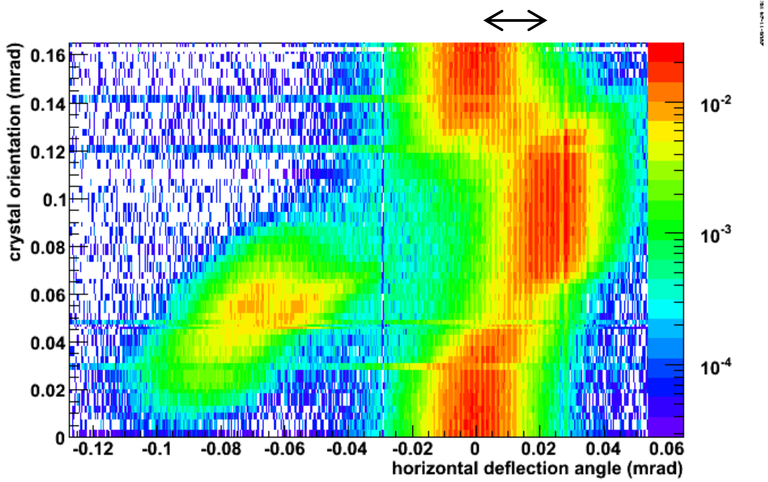
Double Reflection on Quasi-Mosaic Crystals



QM1+QM2, normalized, sliced beam



double reflection angle: ~ 20 μrad

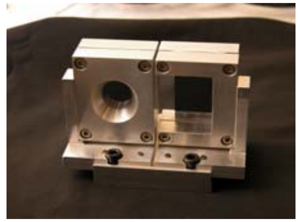


G. Ambrosi   Roma, Nov. 2006

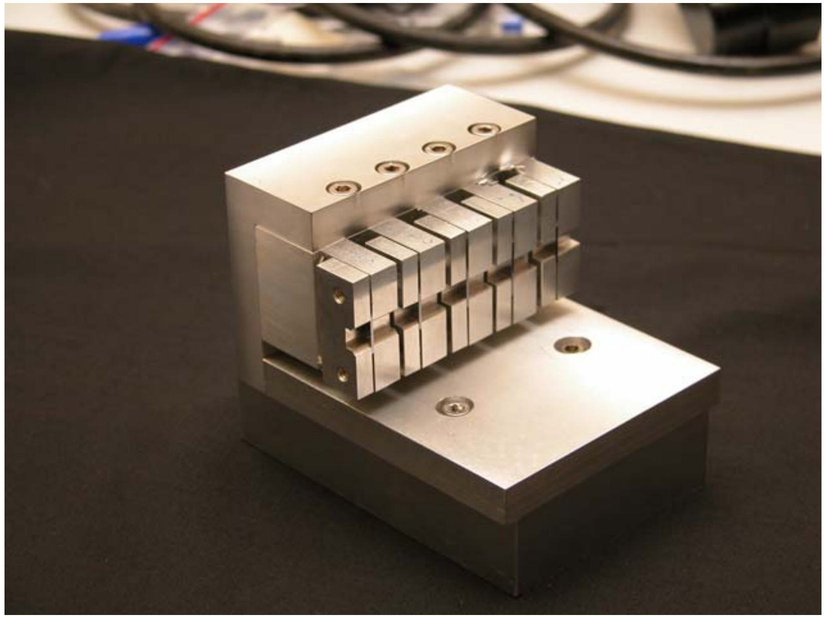
Experimental procedure:

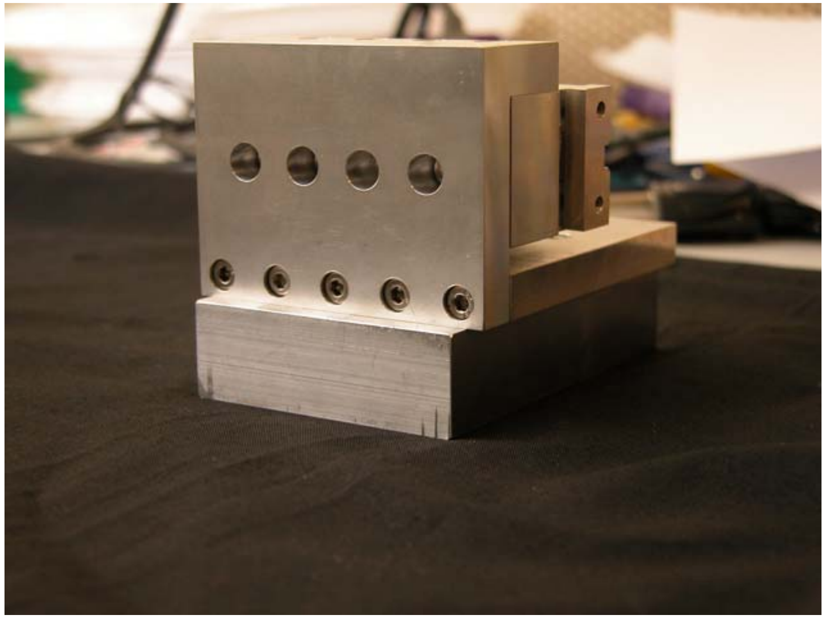
- alignment of the first crystal though the H-rotational stage
- alignment of second crystal though the upper linear stage (anticlastic bend)
- many steps for finding optimal alignment

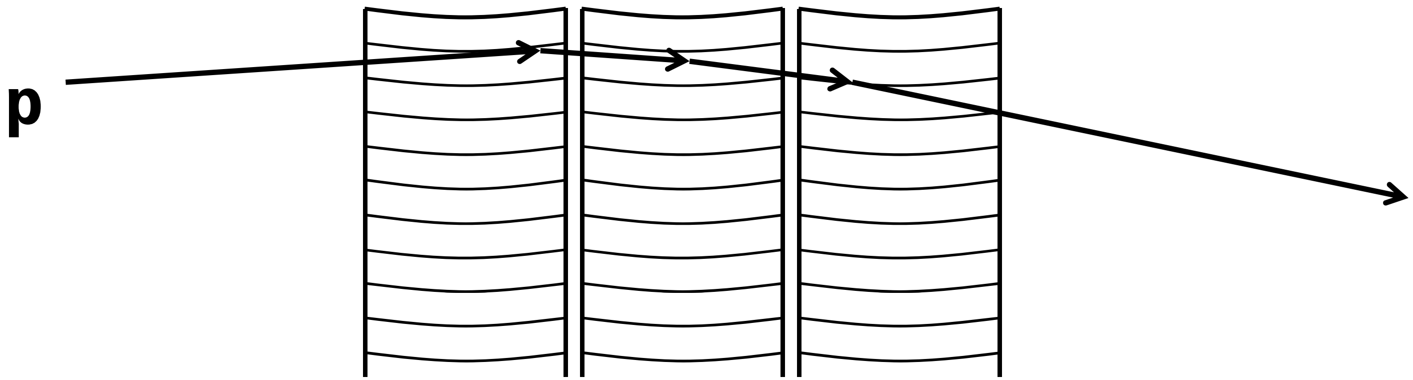
Multi Reflection on Quasi-Mosaic Crystals (1)



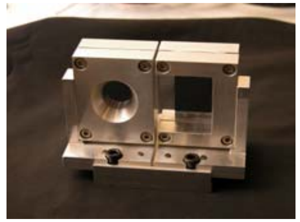
5 heads multi-crystal crystal (PNPI)



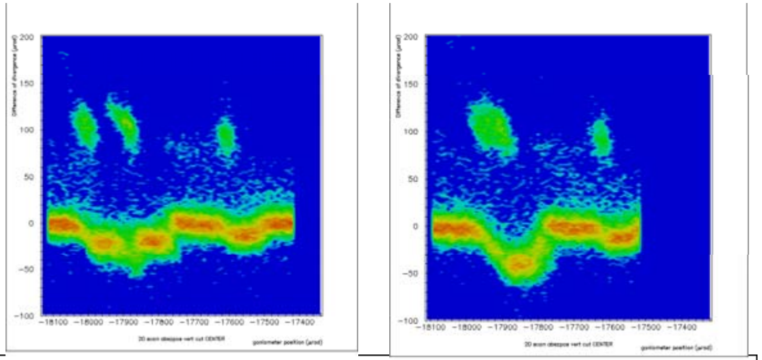




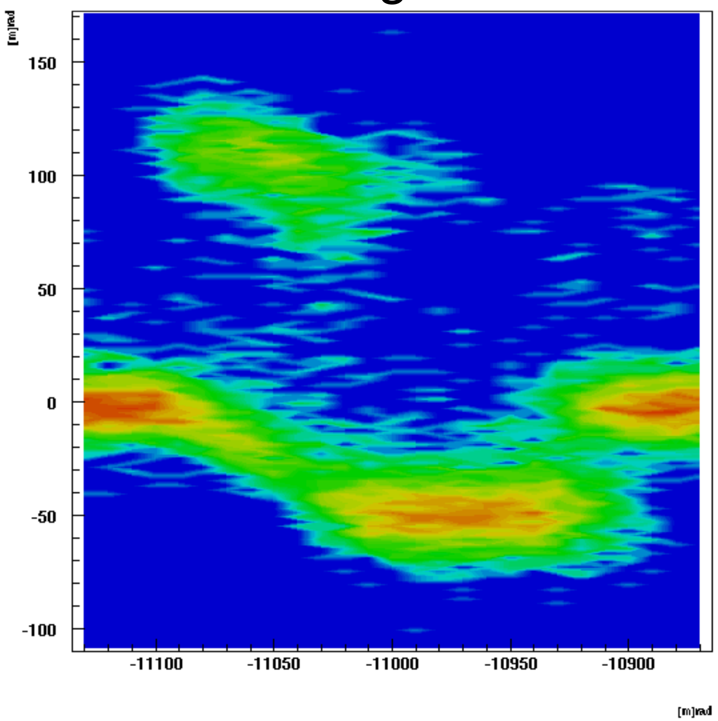
Multi Reflection on Quasi-Mosaic Crystals (2)



Steps to align the five crystals

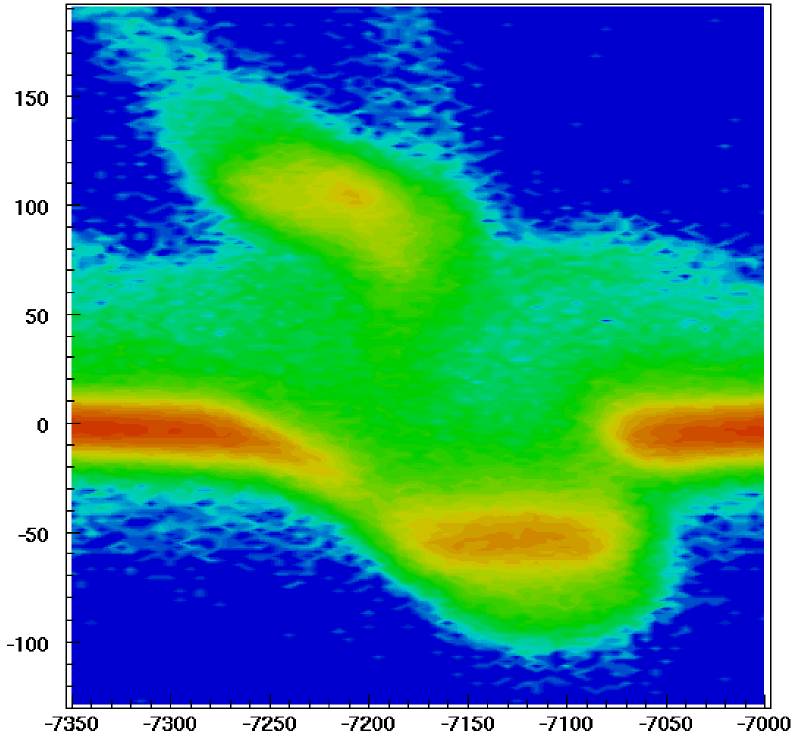


Best alignment



- Volume reflection angle 53 μrad
- Efficiency ≥ 90 %

High statistics

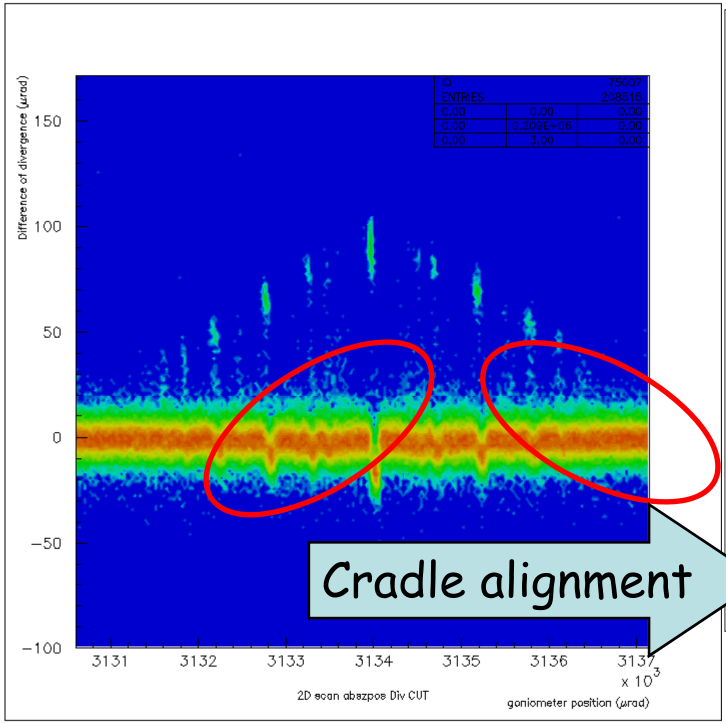


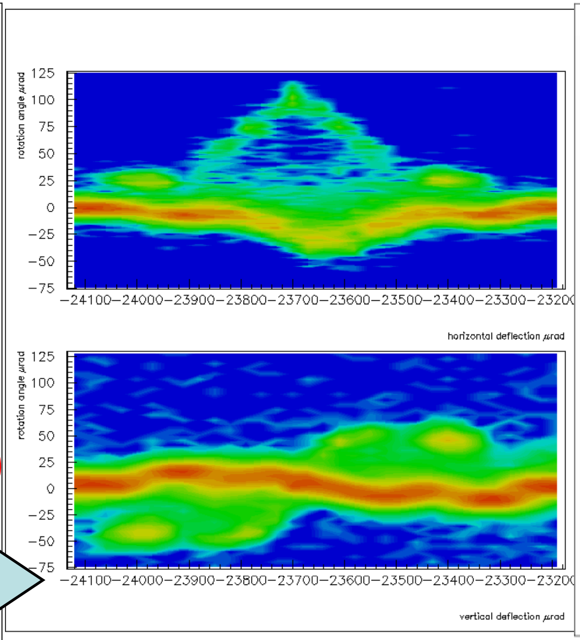
ection on bent

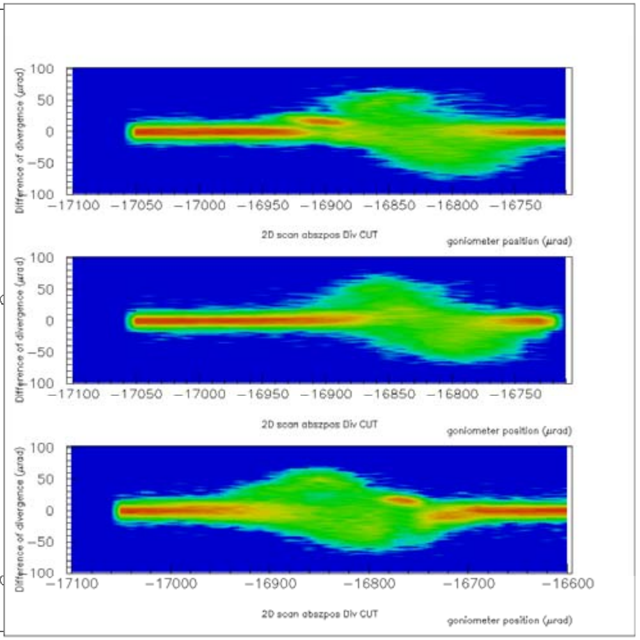
Axial channeling in a single crystal

Channeling from secondary crystal planes
Vertical beam profiles

- Planar-to-axial channeling transition
- Variation of VR effect with the vertical angle

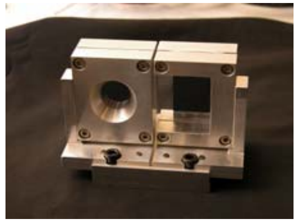






In axial channeling mode the crystal produces an angular spread of $\pm 50\ \mu$rad

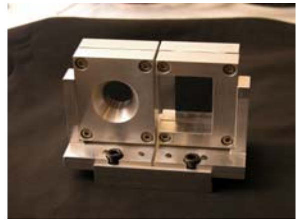
Conclusion



- High efficient reflection (and channeling) observed in single pass interaction of high-energy protons with bent crystals (0.5 to 10 mm long)
- Single reflection on a Si bent crystal deflects > 98 % of the incoming 400 Gev p beam by an angle 12÷14 μrad
- Multi-reflections on a sequence of aligned crystals to enhance the reflection angle successfully tested with two and five consecutive crystals.
- Axial channeling observed (scattering enhancement)

Very promising results for application in crystal collimation

Acknowledgments



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- the INTAS program
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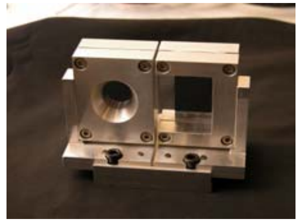
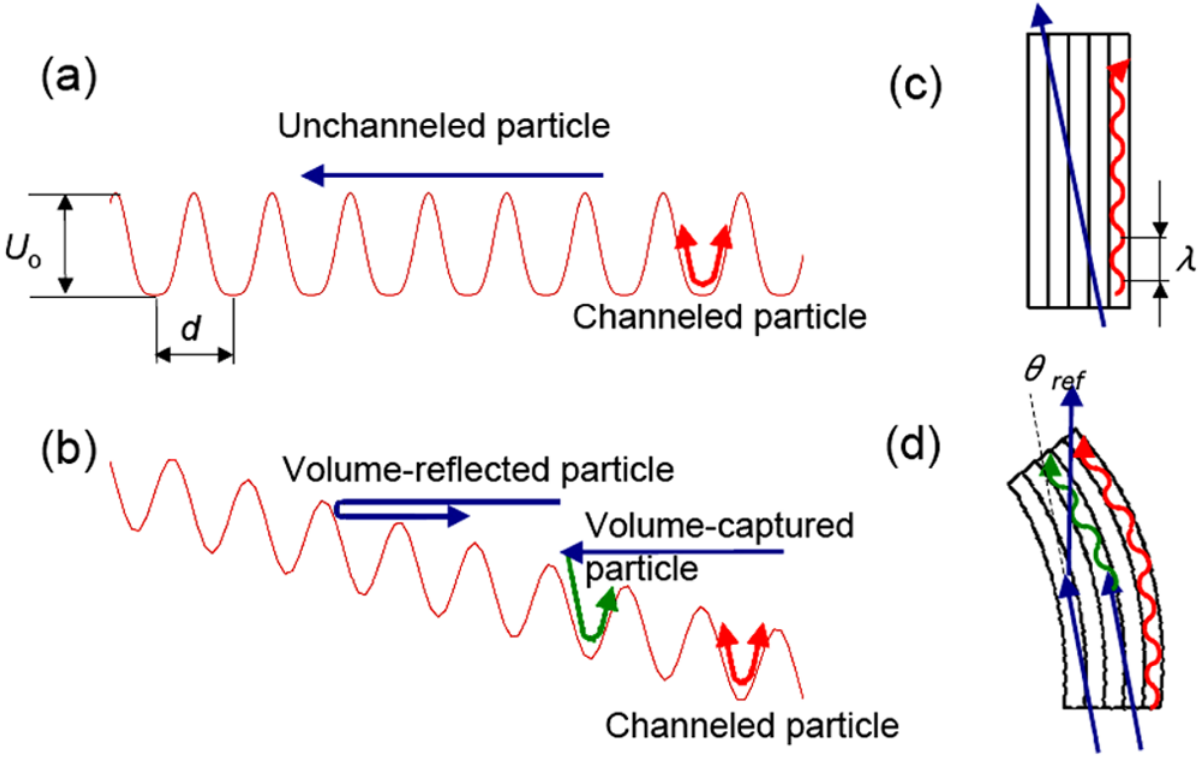
- The Program "Physics of Elementary Particles and Fundamental Nuclear Physics" of Russian Academy of Sciences.
- INFN: NTA program

Particle-crystal interaction



Possible processes:

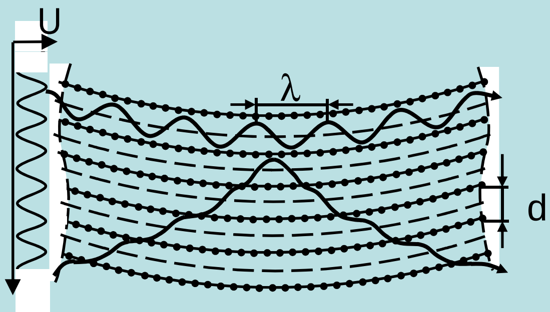
- multiple scattering
- channeling
- volume capture
- de-channeling
- *volume reflection*



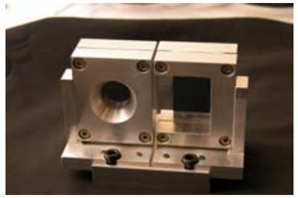
Volume reflection

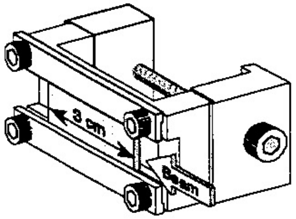
Prediction in 1985-'87 by A.M.Taratin and S.A.Vorobiev,

First observation 2006 (IHEP - PNPI - CERN)



RD 22: extraction of 120 GeV protons (SPS: 1990-95)





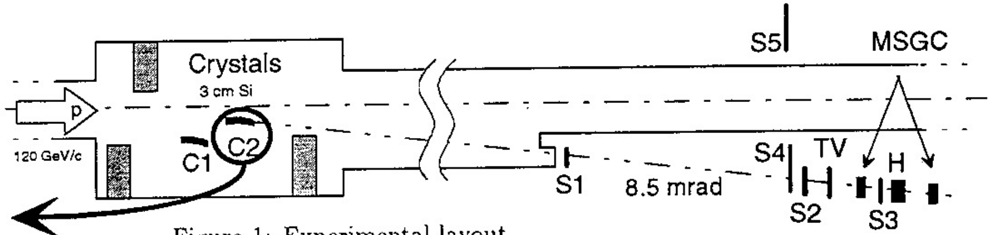
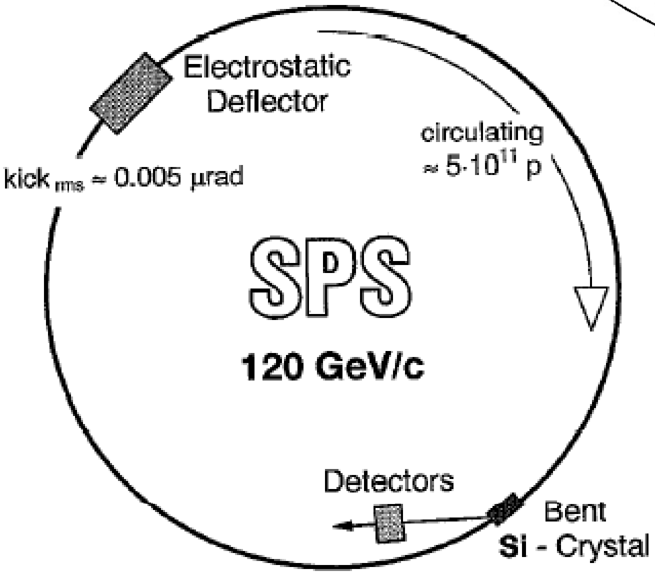


Figure 1: Experimental layout

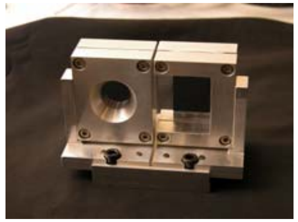


The RD22 Collaboration, CERN DRDC 94-11

	Crystal 1	Crystal 2
beam intensity (protons)	$(7.0 \pm 0.1) \cdot 10^{11}$	$(3.7 \pm 0.1) \cdot 10^{11}$
beam lifetime (hrs)	20 ± 2	12 ± 1
protons lost per second	$(6.7 \pm 0.6) \cdot 10^{6}$	$(8.9 \pm 0.7) \cdot 10^{6}$
protons detected per second	$5.6 \cdot 10^{5}$	$6.6 \cdot 10^{5}$
background (%)	5	2
detection efficiency (%)	78 ± 12	78 ± 12
extraction efficiency (%)	**10.2 ± 1.7**	**9.3 ± 1.6**

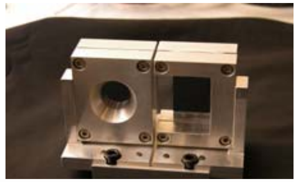
- *Large channeling efficiency measured for the first time*
- *Consistent with simulation expectation extended to high energy beams*
- *Experimental proof of multi-turn effect (channeling after multi-traversals)*
- *Definition of a reliable procedure to measure the channeling efficiency*

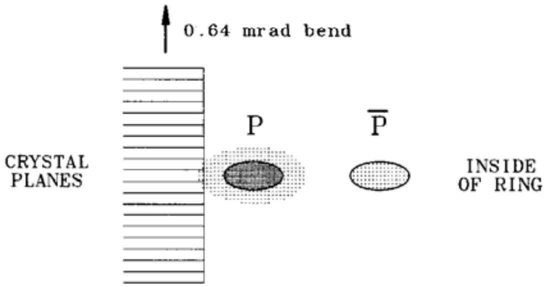
RD 22: extraction of ions (SPS: 1996-97)



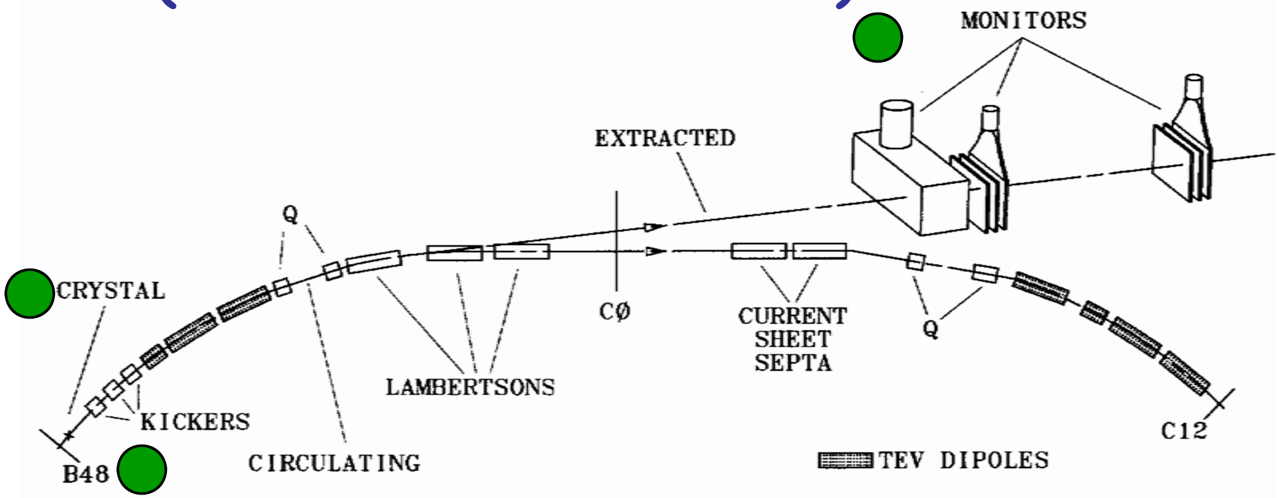
- **Single pass experiment – external beamline**
  - Very good agreement with theoretical model, corroborates expectations
  - Ion channelling demonstrated for the first time, with efficiency ~10-14%
- **Multi-pass experiment – SPS ring**
  - More complex problem with not so clear outcome
  - lack of knowledge on physics of nuclear interactions involved in multipass extraction
  - Narrower angular scan (suppressed contribution of multipass extraction?)
  - Lower deflection efficiencies (up to 10%) and bigger spread in values for different configurations
- **Open issues**
  - EMD suppression not proved experimentally (neutron loss?)
  - Radiation damage to crystal not investigated(much lower limit expected than for p)
  - Multi-pass ion interactions not clear (Si~amorphous material if channelling conditions are not satisfied..)

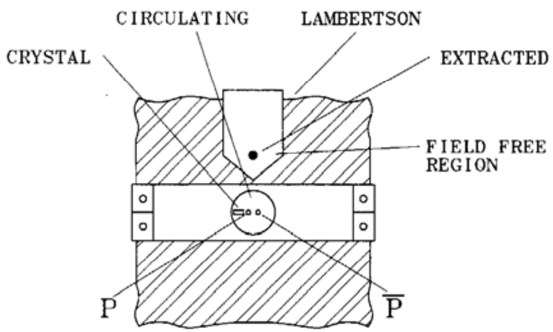
E853: extraction of 900 GeV protons (Tevatron: 1993-98)





At crystal

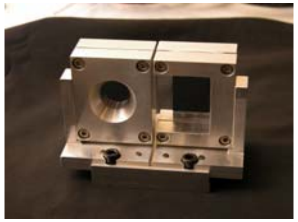




Lambertson, crystal

- Extracted significant beams from the Tevatron parasitic, kicked and RF stimulated
- First ever luminosity-driven extraction
- Highest energy channeling ever
- Useful collimation studies
- Extensive information on time-dependent behavior
- Very robust

Crystal collimation at RHIC



- Indirect experiment (measure particles disappearance) with Au and p runs
- Si crystal 5×1 mm with θ_B=465 mrad located in interaction region matching section
- Positioning not optimal (large beam divergence and $\alpha \neq 0$)
- Crystal bends in the same plane where it scrapes ⇒ sensitivity to horiz. halo

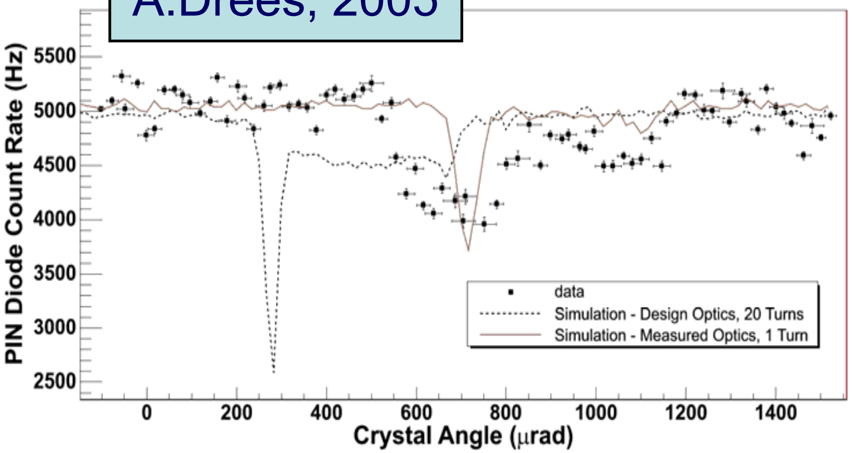
No clear interpretation of the results!

- Measured ch. efficiency (~25%) doesn't match theoretical predictions (56% with nominal machine optics). Better agreement and consistency when using measured beam divergence need accurate knowledge of lattice functions.
- Multipass physics and halo distribution models too simplistic?
- Low channelling efficiency ⇒ collimation not successful & increased backgrounds !!

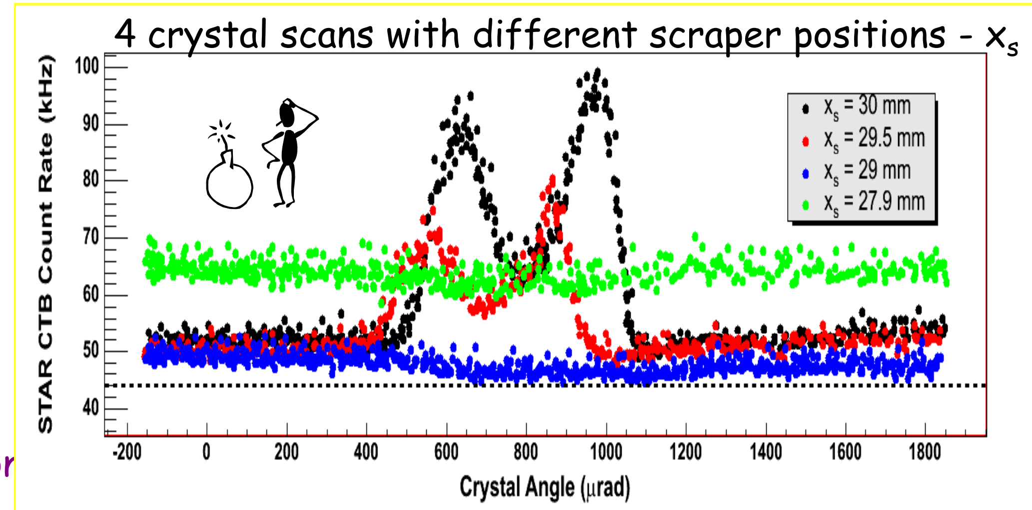
Not conclusive & abandoned !

R.Fliller III, A.Drees, 2005

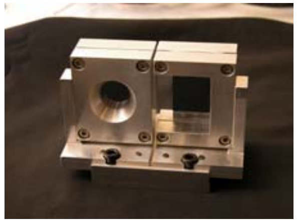
STAR Background during crystal collimation



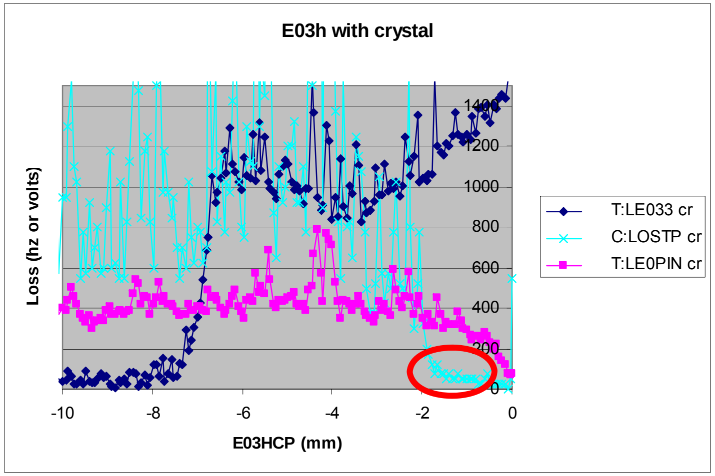
or



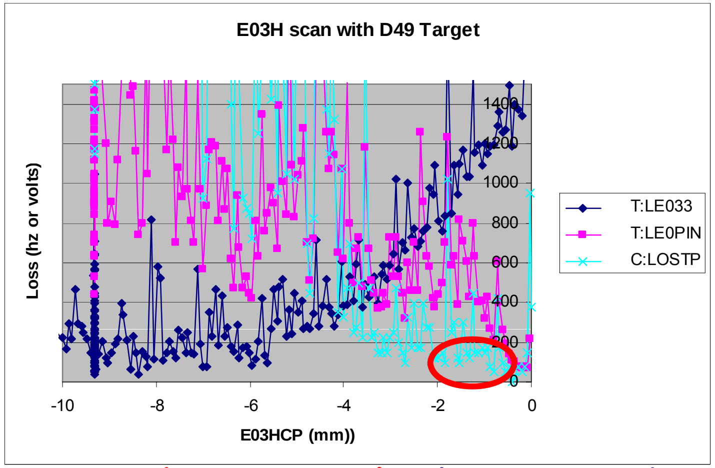
Crystal collimation at FNAL



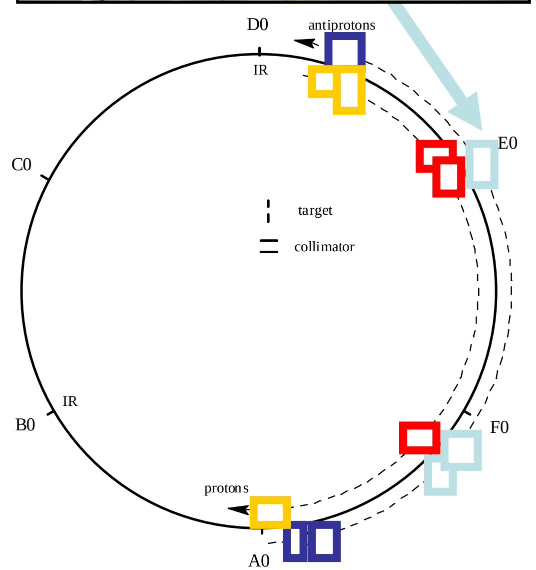
Crystal Collimator in E0 replacing a Tungsten Target (2005)



Crystal



Tungsten scatterer



Using the crystal, the secondary collimator E03 can remain further (-1 mm or so) from the beam and achieve almost a factor of 2 better result!