Crystals for collimation

W. Scandale

Presentation layout

- Why crystals?
- The history of crystal collimation
- Silicon and other materials

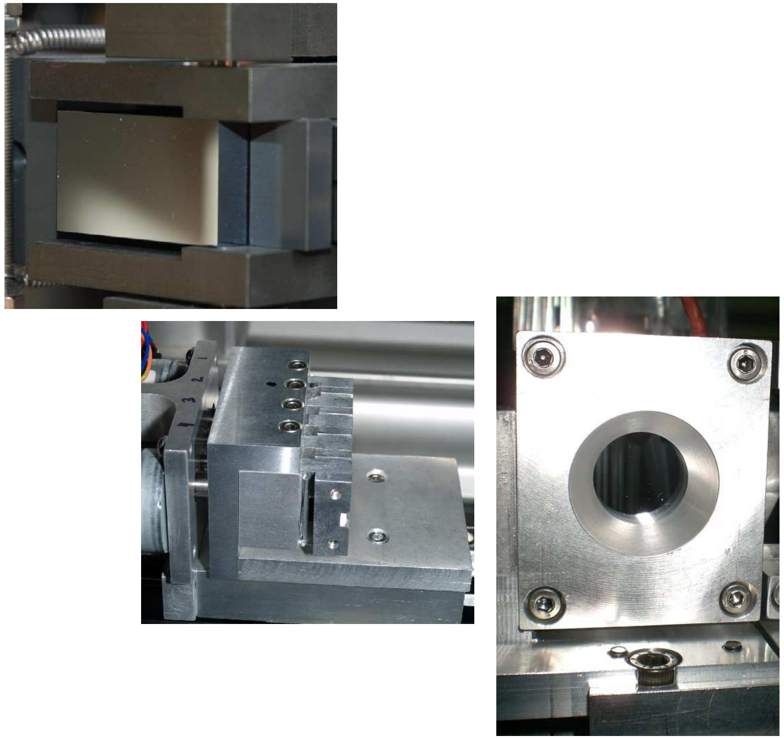
Why crystals?

PROS

- easy to use and compact
- efficient
- reliable and predictable
- radhard
- advanced test phase

CONS

- complex alignment
- sensitive to the particle impact position and angle



STILL UNDER STUDY

- channeling vs volume reflection
- different materials
- single turn vs multi turn
- effect of the amorphous layer

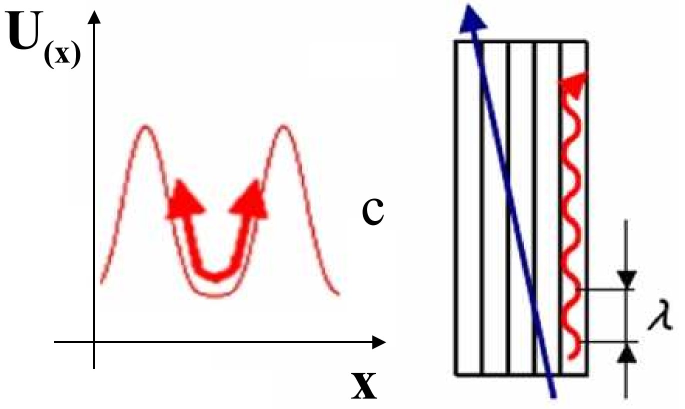
→ ***Dedicated tests on circular machines***

The idea: Tsyganov (1976)

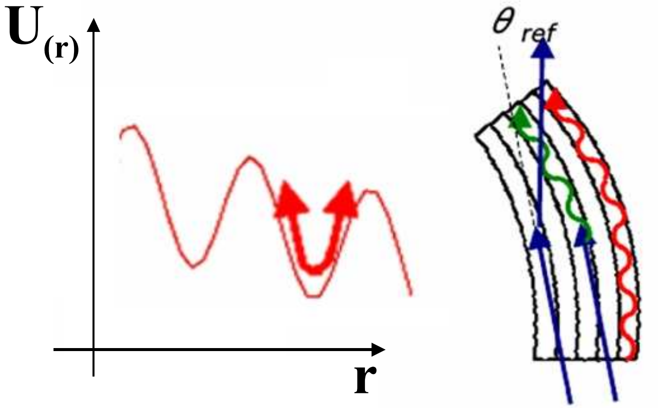
- *1912 - J. Stark*: some directions in a crystal are more transparent to charge particles wrt an amorphous material
- *1976 - E. N. Tsyganov*: channeling in bent crystals

Tested at FNAL in 1979

Interplanar potential



Effective potential



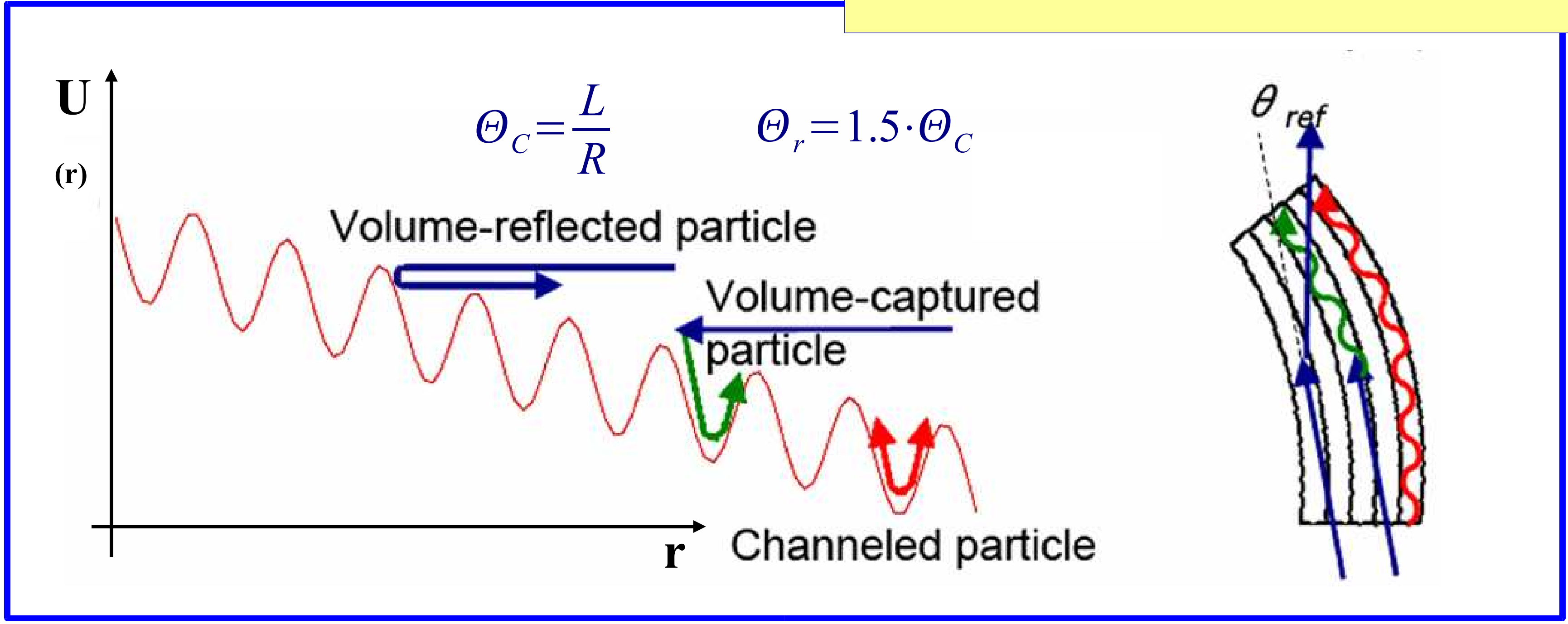
$$\Theta_C = \frac{L}{R}$$

A few years later .....

New phenomena → an initially misaligned particle becomes *tangent* with a channel →

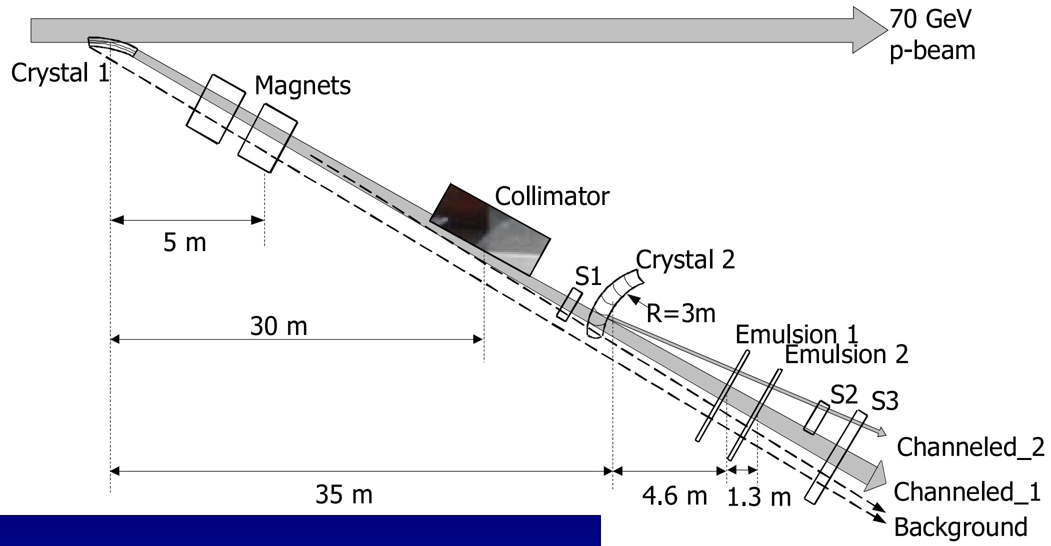
- ***volume capture*** **if the particle enters in channeling losing energy**
- ***volume reflection*** **if the effective potential reflects it**

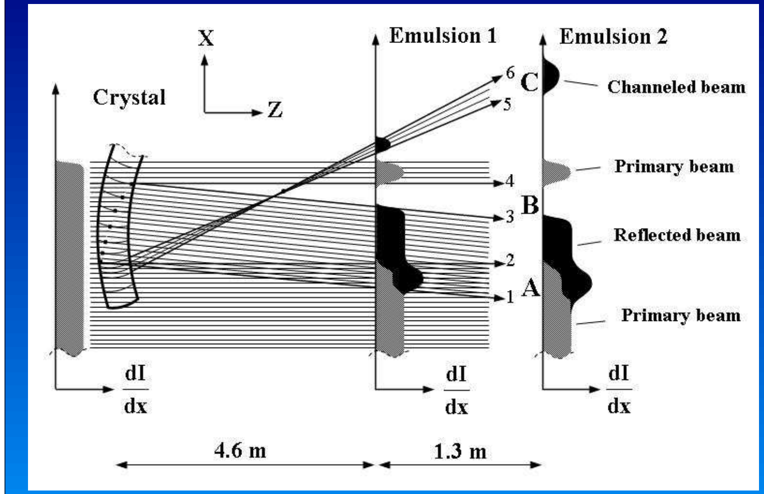
- ***large (and adjustable) angular acceptance***
- ***favourable scaling properties with energy ($\theta \propto 1/\sqrt{E}$ instead of 1/E as in channeling and multiple scattering)***
- ***high efficiency***

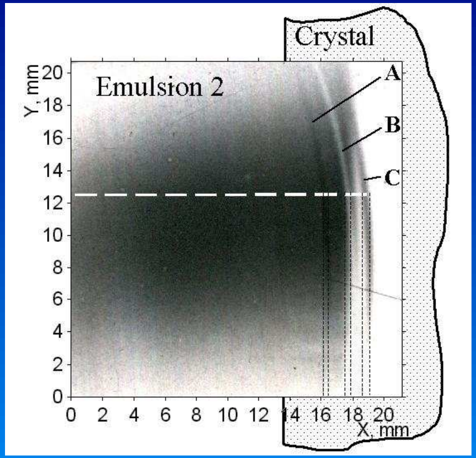

$$\Theta_C = \frac{L}{R} \qquad \Theta_r = 1.5 \cdot \Theta_C$$

First observation: IHEP (2002)

- U-70 accelerator
- 70 GeV/c protons
- quasimosaic crystal:
  - 0.72 mm (along the beam)
  - area of 20x60 mm^2
  - bending angle of 423 μrad

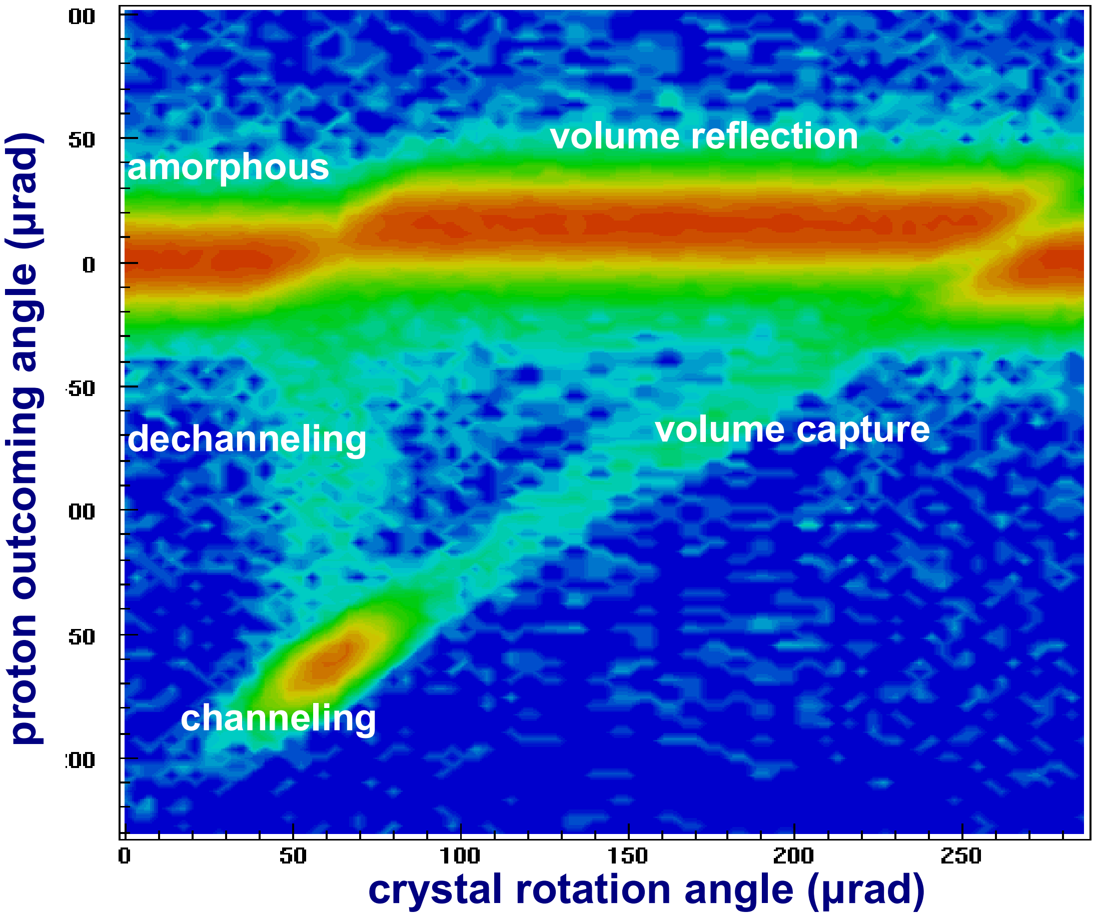




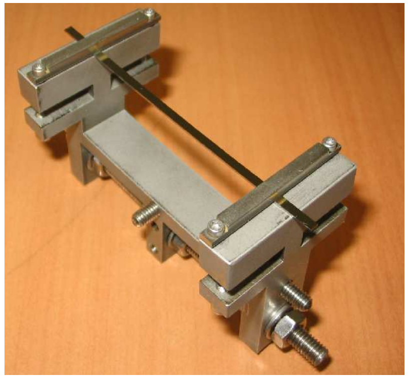


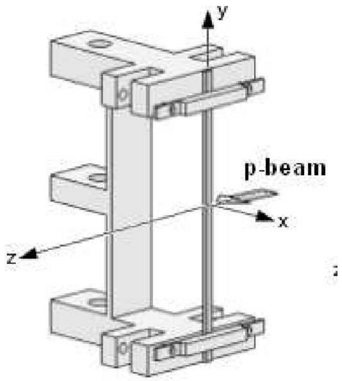
becoming

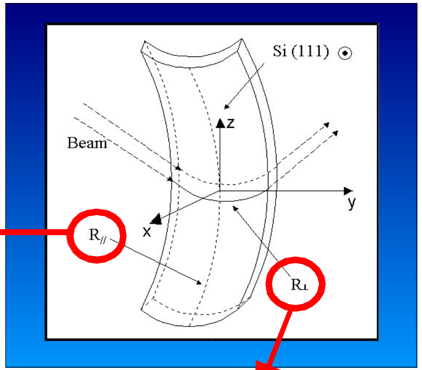
First observation @400GeV/c: CERN (2006)



Single strip crystal





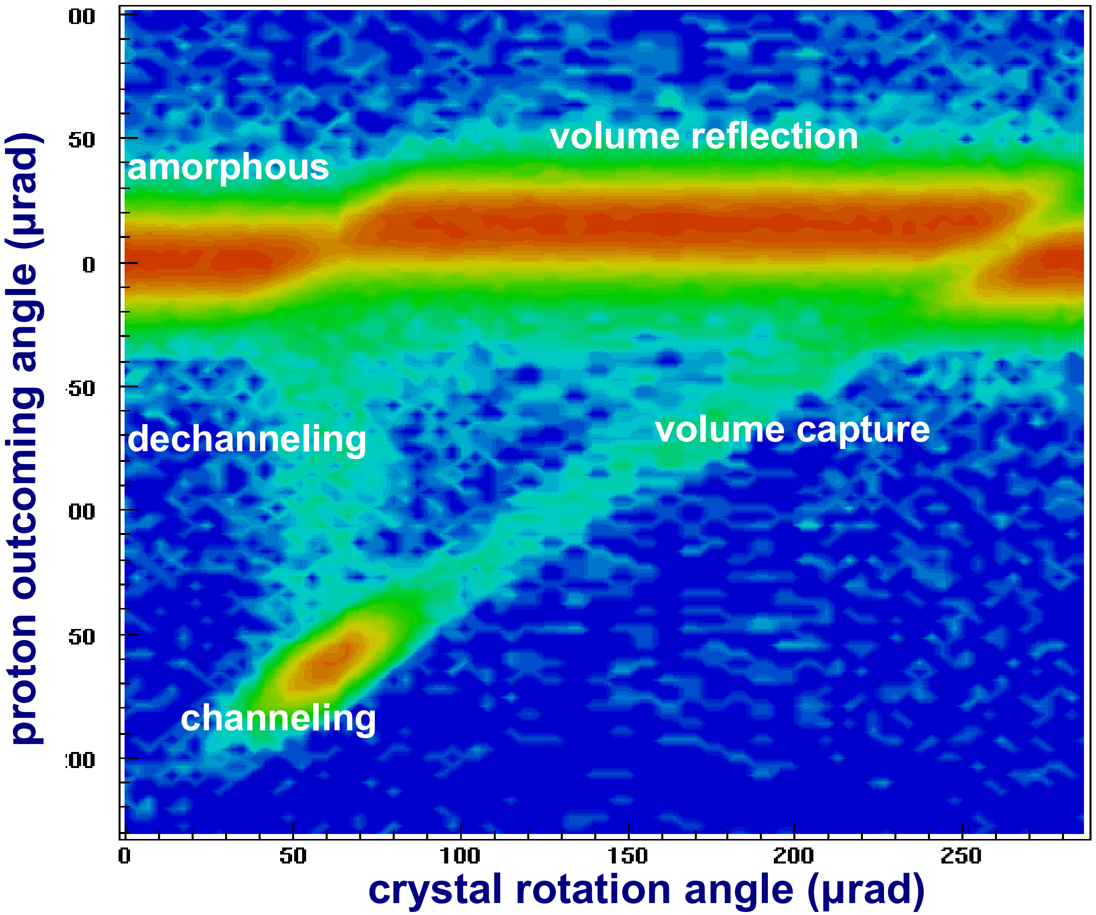


primary curvature

secondary curvature generated by the anticlastic forces

INFN Ferrara and IHEP

First observation @400GeV/c: CERN (2006)



Single strip crystal

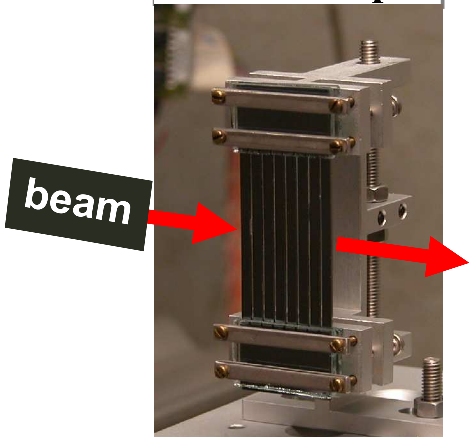
- ***First measurement*** **of the volume reflection effect with a proton beam of 400 GeV/c**

EFFICIENCY	VALUE
VOLUME REFLECTION	**98.2 ± 0.1%**
CHANNELING	**51.2 ± 0.7%**
VOLUME CAPTURE	**1.3 ± 0.1%**
DECHANNELING	**5.0 ± 0.4%**

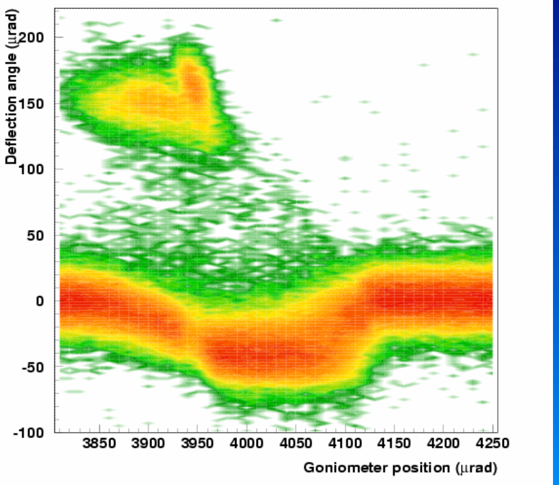
to arrive to

The multireflection idea : CERN (2007)

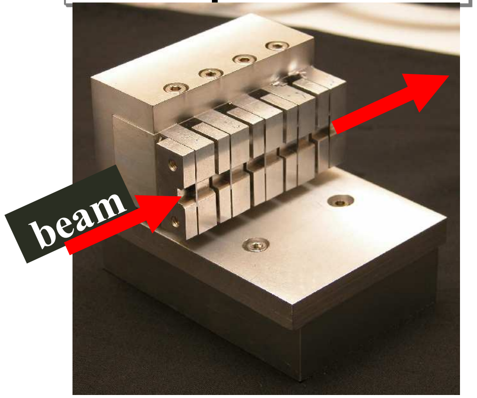
Multi strip



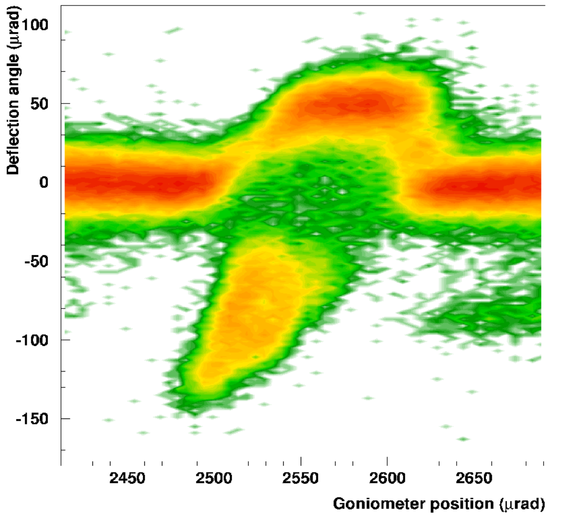
4 out of 8 aligned



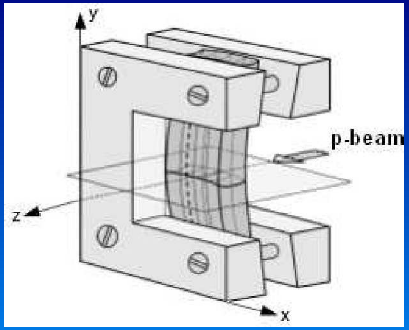
Multi quasimosaic



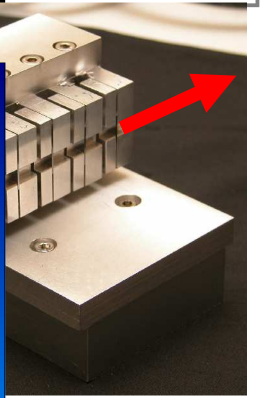
5 aligned



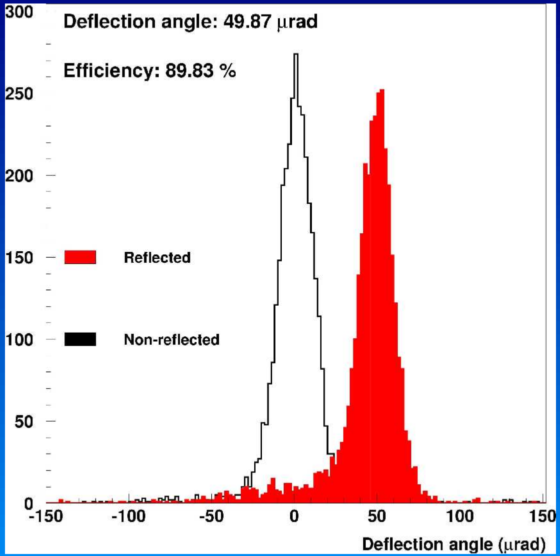
The multireflection idea : CERN (2007)



Multi quasimosaic



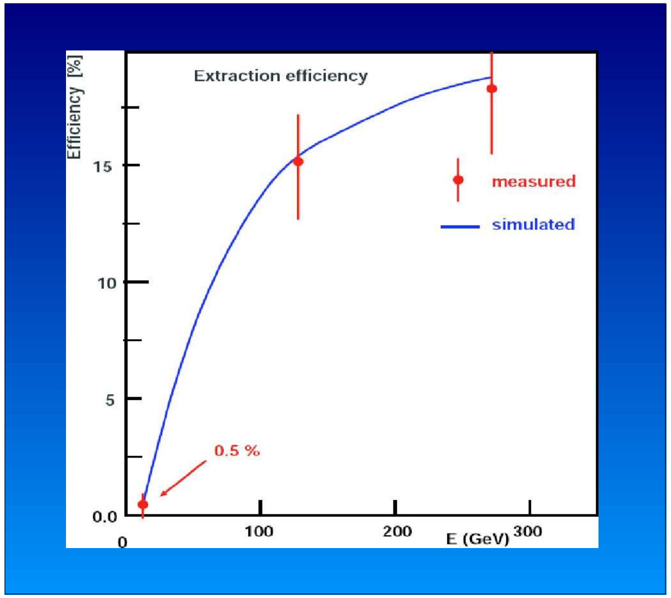
- elastic quasi-mosaicity
- prepared in form of small plates → the (111) planes are normal to the large face and parallel to its edges
- *primary curvature* bending the yz plane
- *secondary curvature* (produced by anticlastic forces) in the xz plane
- quasimosaic effect → *due to crystal anisotropy*

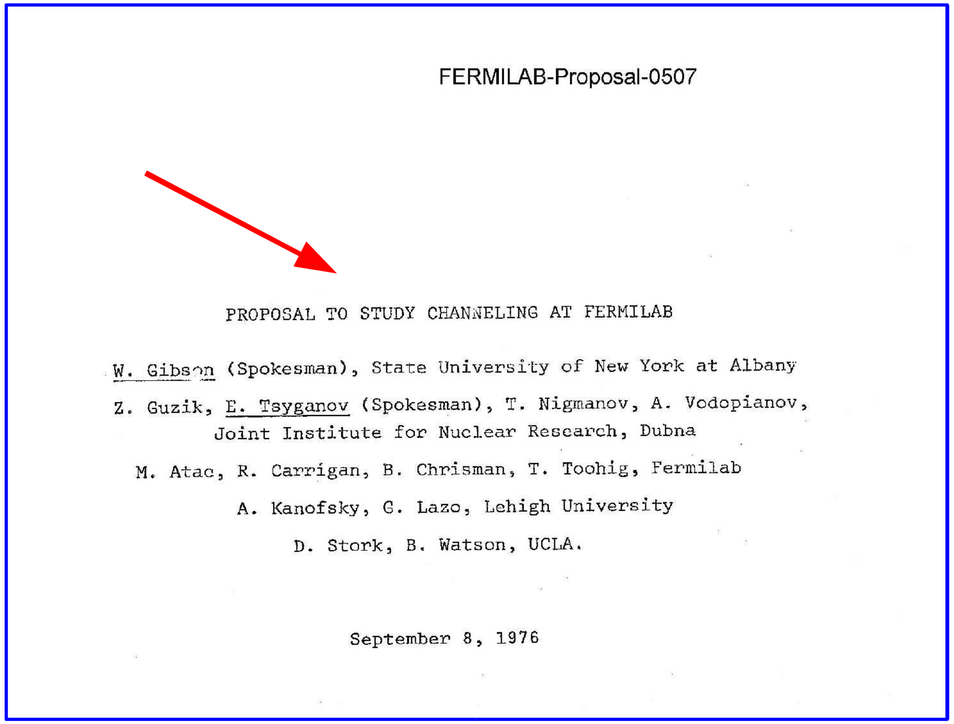


Going through ......

FIRST TRIALS

- *1979, FNAL*: **channeling efficiency of 1%**
- *1996, RD22*: **extraction of 120 GeV diffusing protons at the SPS → efficiency of 10-20% →** ***MULTITURN enters in the game***




FERMILAB-Proposal-0507

PROPOSAL TO STUDY CHANNELING AT FERMILAB

W. Gibson (Spokesman), State University of New York at Albany

Z. Guzik, E. Tsyganov (Spokesman), T. Nigmanov, A. Vodopianov,
Joint Institute for Nuclear Research, Dubna

M. Atac, R. Carrigan, B. Chrisman, T. Toohig, Fermilab

A. Kanofsky, G. Lazo, Lehigh University

D. Stork, B. Watson, UCLA.

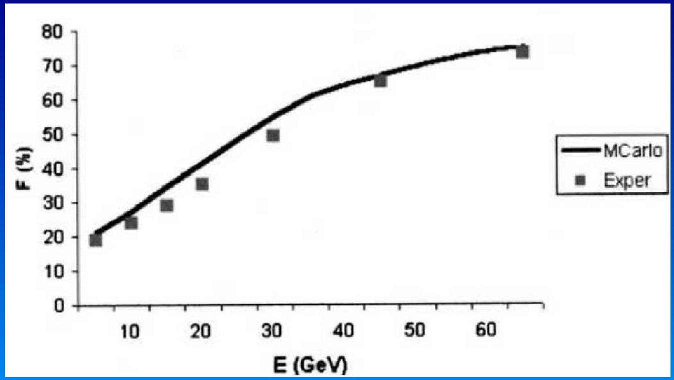
September 8, 1976

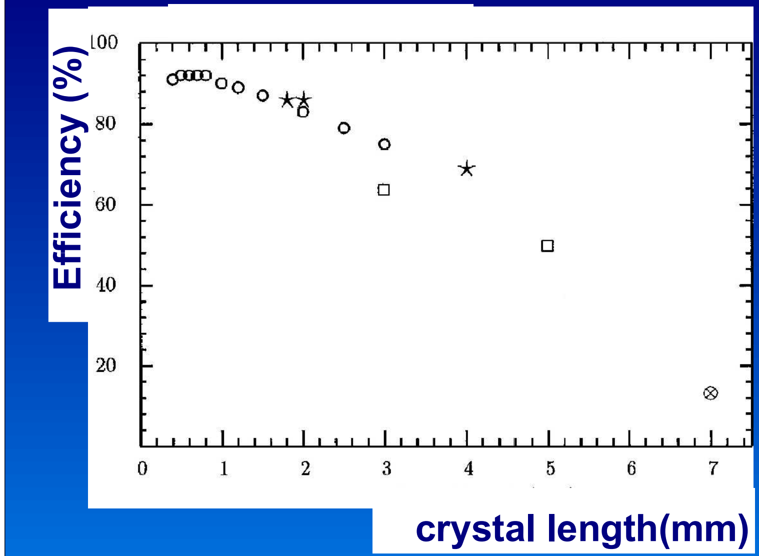
V.M.Biryukov et al., NIMB 53 (1991): ***the reduction of the crystal size in the beam direction increases the average nr of crossings of the particle thus increasingchanneling efficiency***

IHEP experiments

IHEP: 1997-2000

- ➔ extraction and collimation experiments on the U-70 synchrotron ring
- ➔ very short crystals + multipass → max efficiency of ~85% (2mm crystal)
- ➔ *short crystals == STRIP crystals*
- ➔ tests at different energies (during the acceleration phase)



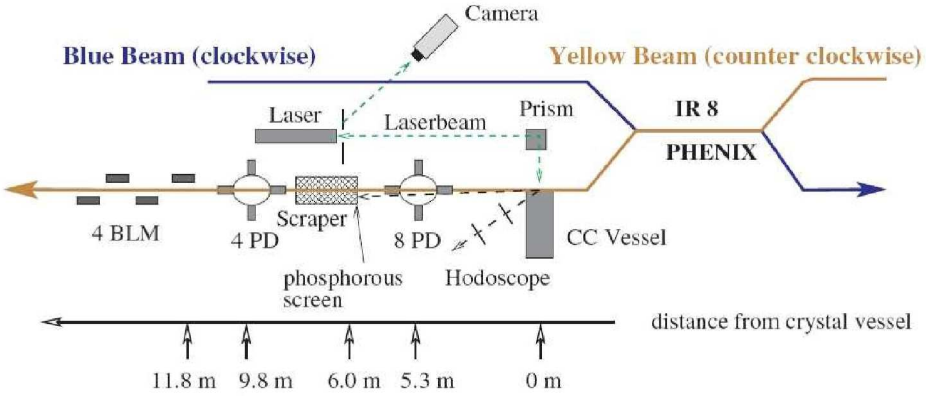


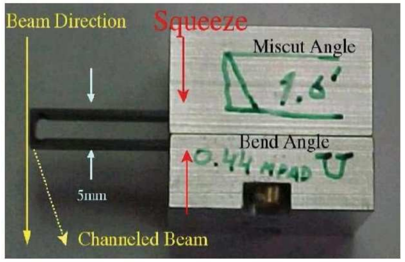
- ✔ * and circle with cross = strip crystal
- ✔ box = O shaped crystal
- ✔ circle = Montecarlo prediction

next step: effect on background

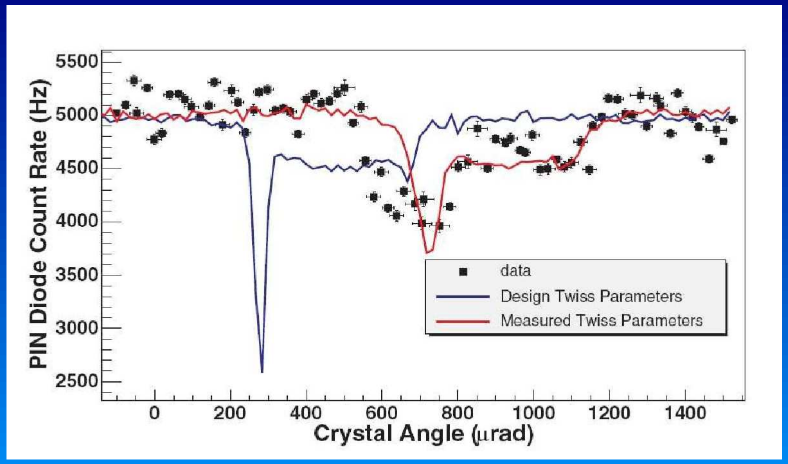
The RHIC experience (2003)

- ➔ O-shaped crystal (PNPI) installed before 2003: 5mm along the beam direction, 1mm wide and with a bending angle of 440 μrad
- ➔ angle wrt beam changed by a piezoelectric inchworm
- ➔ detectors = PIN diodes, ionization beam monitors





2001 run

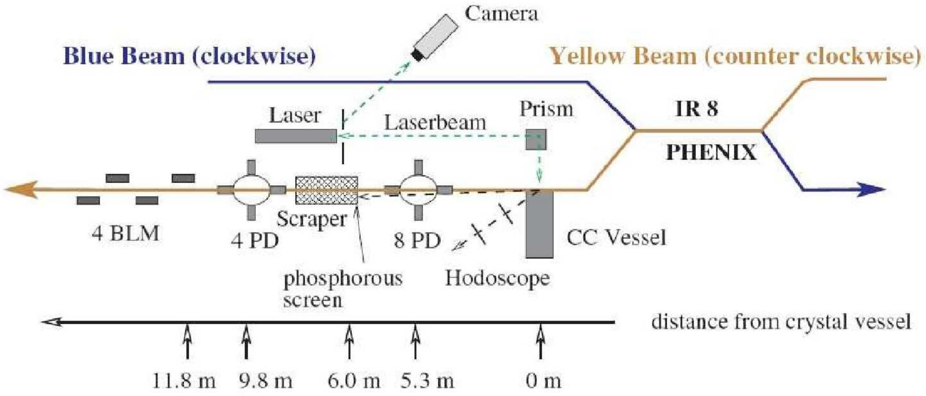


- ➔ blue curve = from design parameters (after 20 turns it reaches the expected efficiency of 56%)
- ➔ data not in agreement → rotation of the phase space ellipse
- ➔ red curve = simulation with the real ellipse (efficiency of 25%)
- ➔ first evidence of volume reflection?

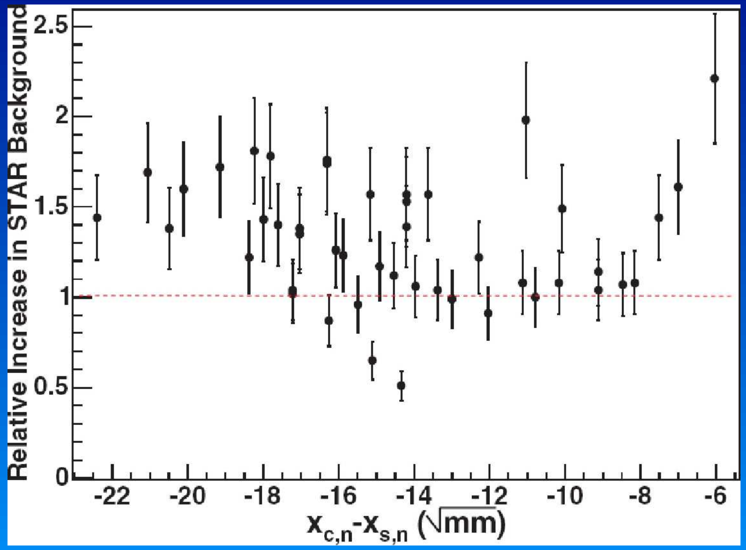
The RHIC experience (2003)

Pb: low channeling efficiency → large amount of scattering that cannot be removed by the scraper

Need:
- knowledge of the beam phase space
- small beam divergence at the entry of the crystal face to match the acceptance



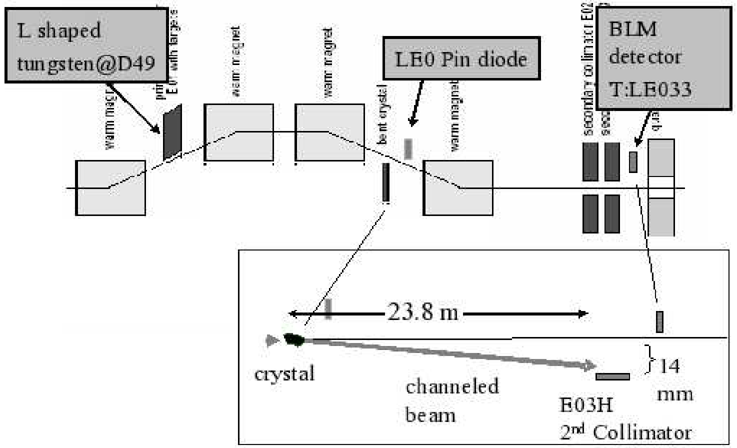
Relative background measured by STAR vs the distance between crystal and secondary colllimator



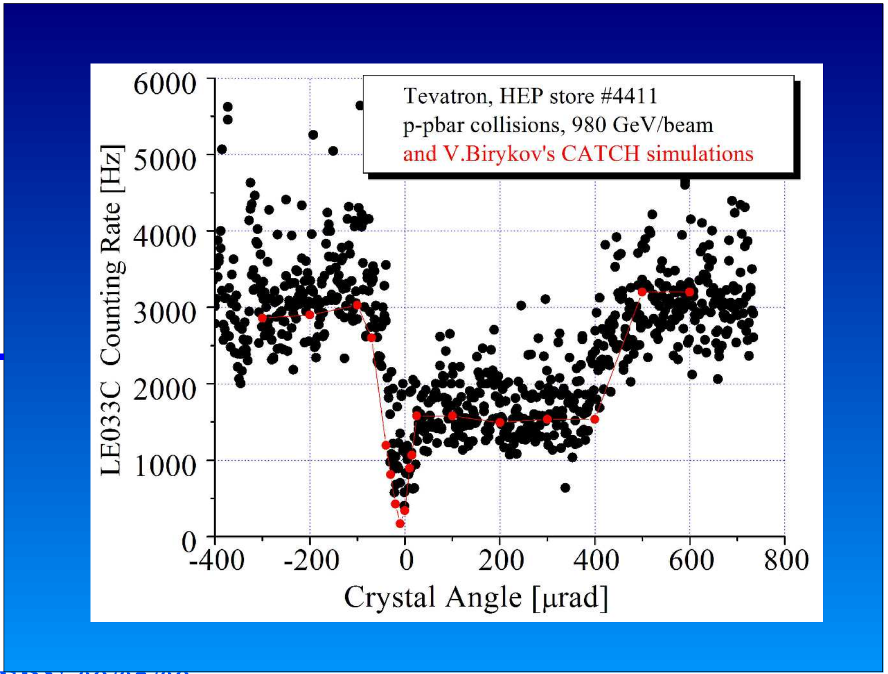
- background normalized to the uncollimated one
- negative = crystal closer to the beam wrt the scraper
- unsuccessful result

The FNAL experience (2005)

- ➔ same O-shaped crystal (PNPI) of RHIC
- ➔ detectors = PIN diodes, ionization beam monitors
- ➔ PIN diode used to measure the large angular scattering (*that is a scattering rate proportional to the nuclears interaction inside the crystal*)



- ➔ dip = channeling; it is due to the suppressed rate of nuclear interactions + the particle steered towards the secondary collimator where it is absorbed
- ➔ channeling efficiency ~78%
- ➔ evidence of volume reflection?



W. Scandale, CERN-08/02/08

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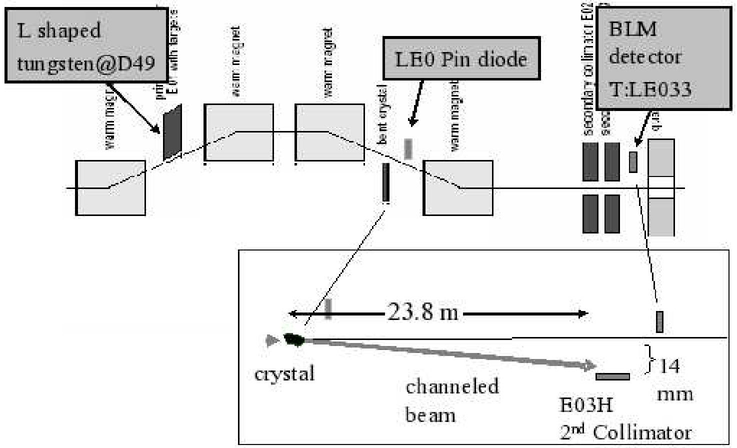
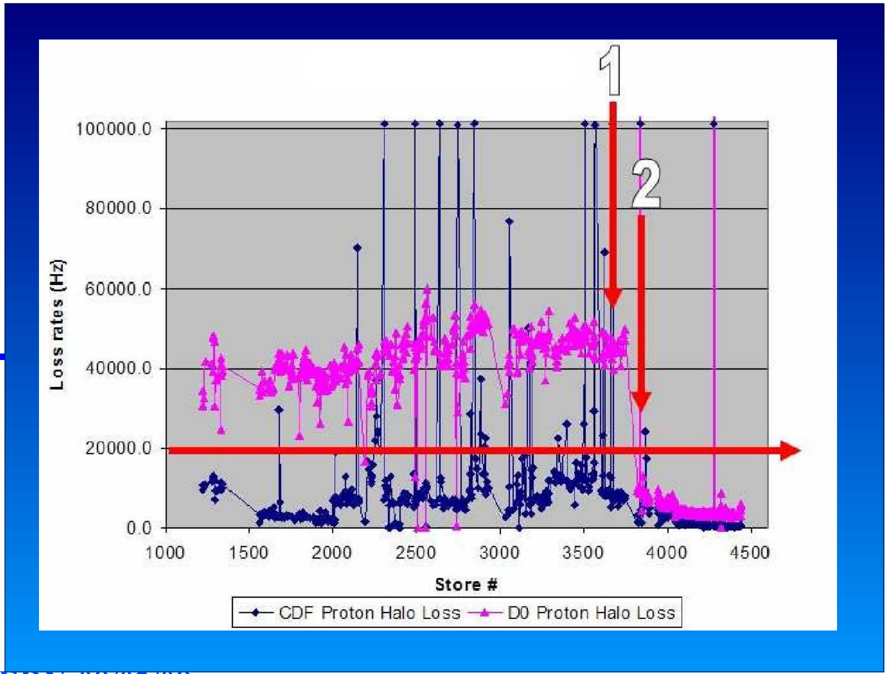
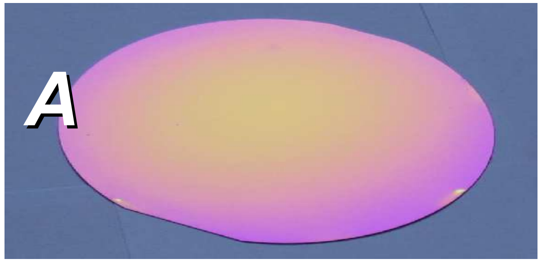


- ***effective reduction of the background***
- ***horizontal line = proton halo loss limit***
- ***vertical ones = machine developments to reduce background:***
  - ***1 = installation of a double scraper***
  - ***2 = improvement of the vacuum system + alignment + installation of the crystal***



How you build a crystal (INFN - Fe)



A

wafer with minimal impurities → cleaning procedure:

- degrease the wafer in trichloroethylene, acetone and isopropanol
- clean in solution of water, hydrogen peroxide and ammonium hydroxide (5:1:1)
- dip in diluted hydrofluoric acid
- wash in water, hydrogen peroxide and hydrochloric acid → *ready to be diced*

B

dicing with a diamond blade saw:

- diamond grain size = 4-6 μm
- density = 62%
- dicing speed = 0.5mm/min

↓

surface layer with scratches, line defects, dislocations and anomalies (of the order of the blade size) → have to be removed

C

mechanical polishing: the sample is fixed on a special slide put on a rotating plane covered with different abrasive cloths

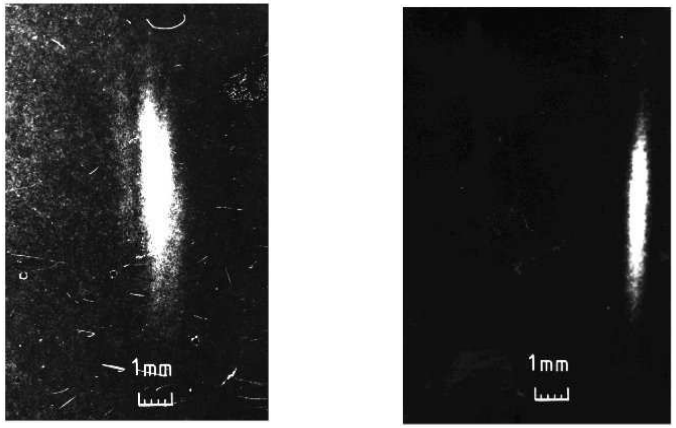
chemical (planar) etching (2 methods):

- protect largest surface with Apiezon wax
- wet planar etching (HF, HNO_3, CH_3COOH (2:15:5))
- timing for etching depth of 30 μm
- remove wax coating

***GOOD CRYSTAL** == roughness below 100nm and lack of crystalline defects*

Analysis with:
- *Atomic Force Microscope (AFM)*
- *Rutherford BackScattering in channeling condition (c-RBS)*

Importance of etching


mechanically polished ***chemically etched***

**IHEP - 70 GeV proton beam
V.M. Biryukov et al., RSI 73 (9), 3170 (2002)**

Evaluation parameters:
- *(from AFM) standard surface roughness R_a*

$$R_a = \frac{1}{n x m} \sum_i \sum_j \left| z(i,j) - \bar{z} \right|$$

→ z(i,j) = height max of a nxm image and $\bar{z}$ the average one

- *(from c-RBS) surface X_{min} defined as :*

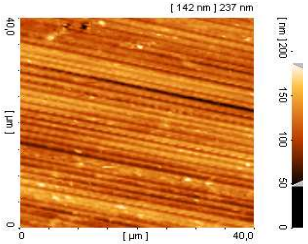
$$X_{min} = \frac{RBS\ yield\,(channeling)}{RBS\ yield\,(random\ conditions)}$$

→ The higher the degree of crystalline order the lower X_{min} (because dechanneling is reduced)

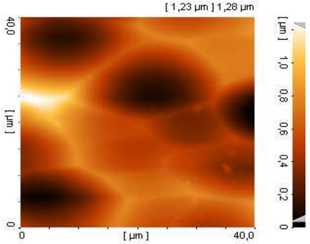
- *S. Baricordi et al., APL 87, 094102 (2005)*
- *A. Vomiero et al., NIMB 249, 903 (2006)*
- *S. Baricordi et al., APL 91, 061908 (2007)*

AFM analysis - examples

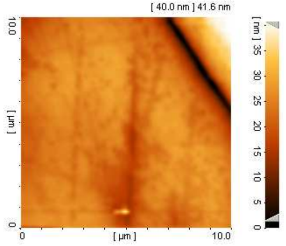
CUT



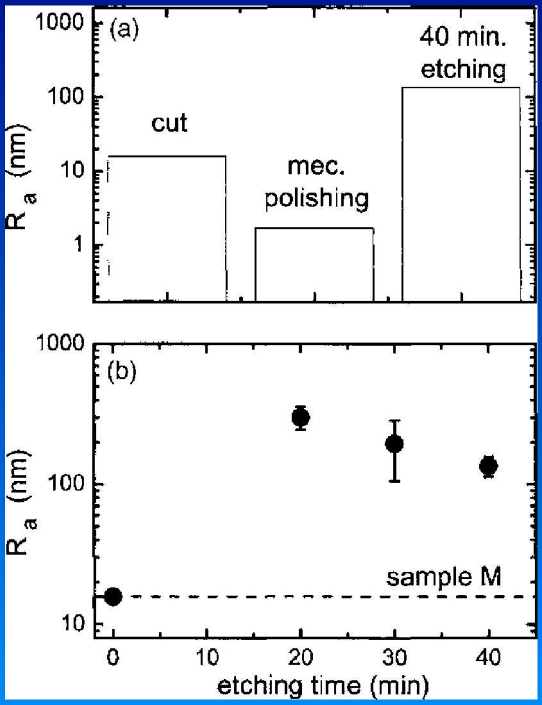
ETCHED - 1st mode



MECHANICALLY POLISHED



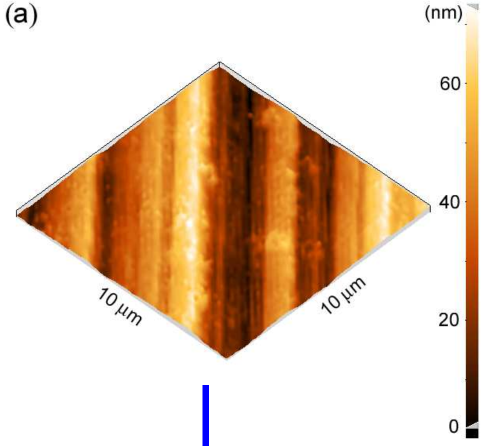
Roughness increases with etching!



MODIFIED ETCHING ...

AFM analysis - examples

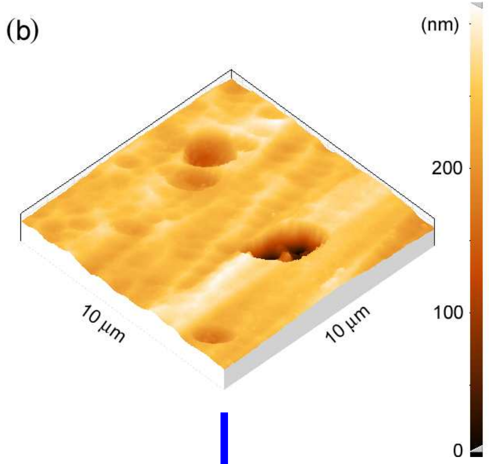
CUT



Scrapes due to the blade

$R_a = 15 \pm 5$ μm

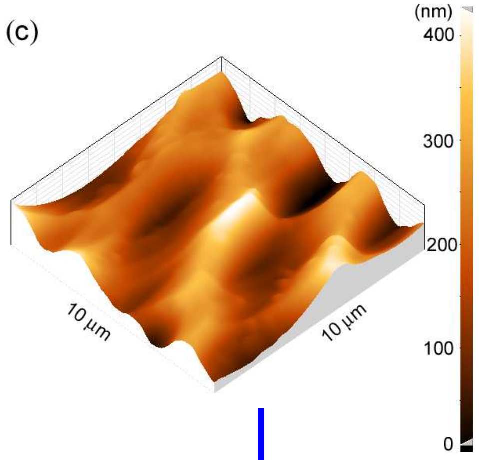
1st etching type



Undesired crates worsening the surface flatness

$R_a = 135 \pm 10$ μm

2nd etching type



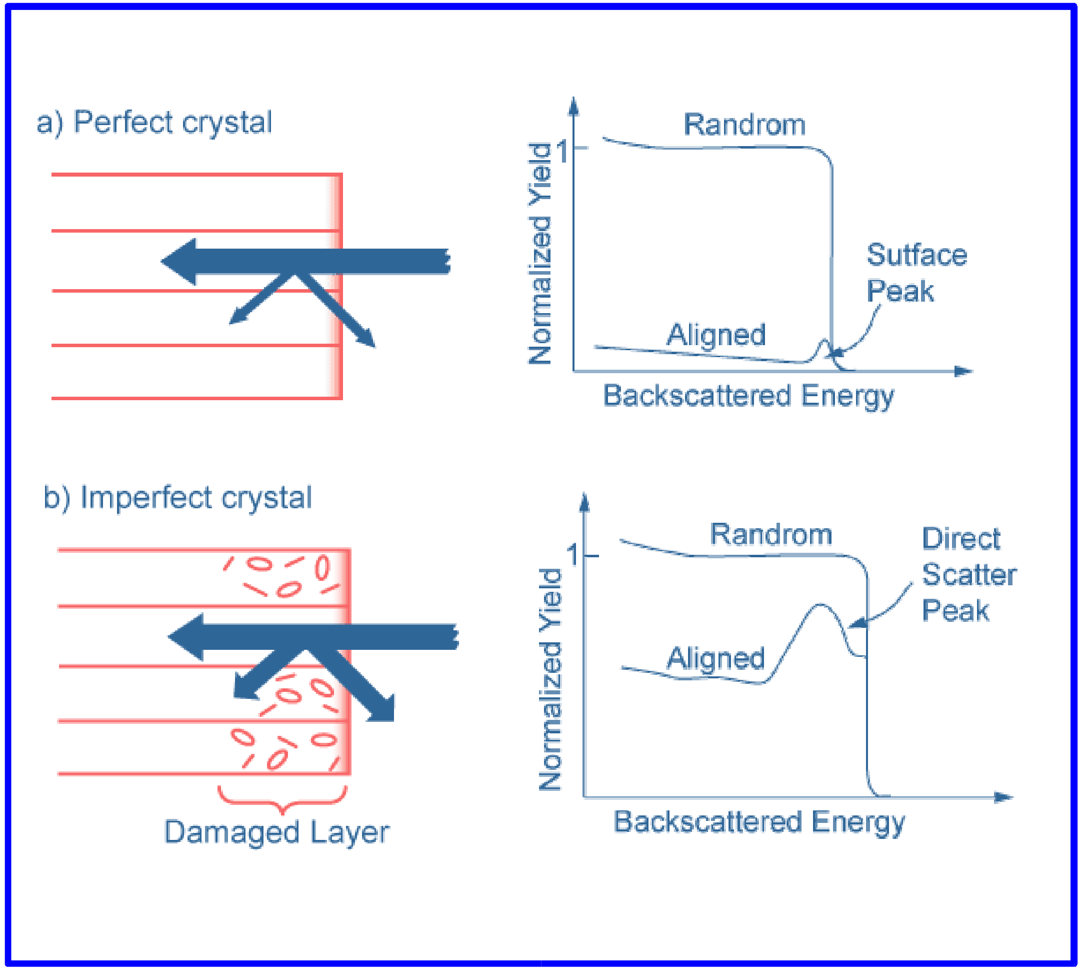
New etching procedure:

- **fast and homogeneous oxidation of silicon**
- **erosion of silicon dioxide**

$R_a = 23 \pm 5$ μm

R_a becomes a factor 5 better

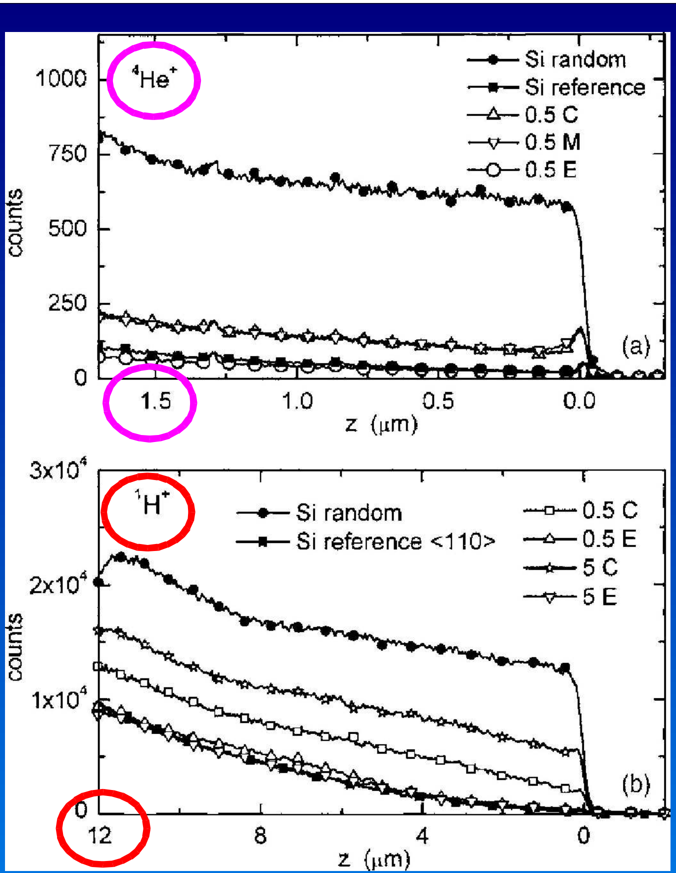
c-RBS analysis - examples



- signal of the impurity and host lattice in RBS spectra is separated by kinematics
- beam of *low energy alpha particles* or *protons*
- *angular yield curve as a function of the energy of the scattered particles or the depth in crystal*

- AN2000 Van Der Graaf accelerator in Laboratori Nazionali di Legnaro
- Spot dimension = 0.2x1 mm^2
- Solid state silicon detector
- Typical energy = 2 MeV
- Alpha particles → max penetration depth = 1.5 μm
- Protons → max penetration depth = 12 μm

c-RBS analysis - examples



- ➔ E = etching; C = cut; M = mech. polished
- ➔ 0.5 = etching speed of 0.5mm/min
- ➔ 5 = etching speed of 5mm/min

- two reference spectra: *RANDOM* and *PERFECTLY ALIGNED*
- surface silicon peak because of surface scattering
- sample 0.5E and reference = similar
- 0.5C and 0.5M : longer tails towards the bulk → disordered structure
- Regular shape → homogeneous distribution of defects in depth
- *0.5M and 0.5C are equal but 5 times larger than 0.5E → improved crystalline order in 0.5E even if worse roughness*

- 5C worse than 0.5C → higher speed, higher disorder
- 0.5E = 5E → etching compensates for dicing → *chemical etching is fundamental to remove surface damaged layers*

X_{min} (cut) = 16 ± 1% →

X_{min} (2nd etching method) = 2.2 ± 0.2%

Radiation hardness

Several tests:

- ➔ 1994: S. I. Baker et al. (NIMB 90, 119-123)
- ➔ 1996: C. Biino et al. (CERN-SL-96-30-EA)
- ➔ 2005: V.M. Biryukov et al. (NIMB 234, 23-30)

NA48 results

- radiation damage: no
- flux of 5×10^{20} p/cm^2 lead to 31±4% loss in deflection efficiency

YEAR	LOCATION	ENERGY (GeV)	EXPOSURE (part/cm^2)	RESULT
1983	FNAL	400	1.0×10^{17}	Reduced dechanneling length
1983	FNAL	400	6.0×10^{16}	Minimum yield increase <1%
1987	FNAL	400	5.0×10^{16}	Little or no damage
1987	BNL	28	1.0×10^{18}	No damage
1992	Serpukhov	70	1.0×10^{19}	No damage
1994	BNL	28	4.1×10^{20}	Minimum yield increase (1.8±0.6)% @2MeV

….. and power deposit

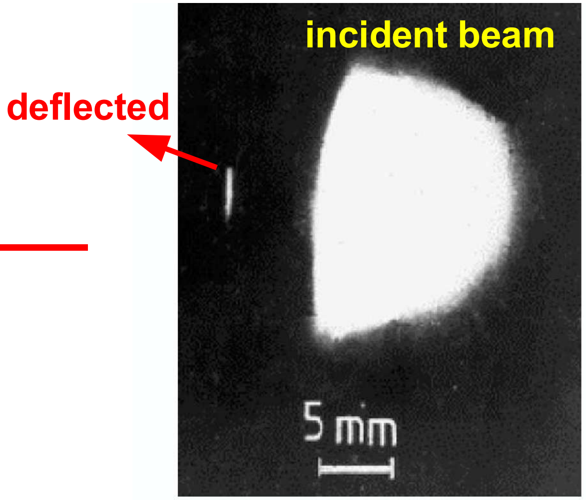
Particle hits can induce

- thermal shock
- radiation damage
- life reduction

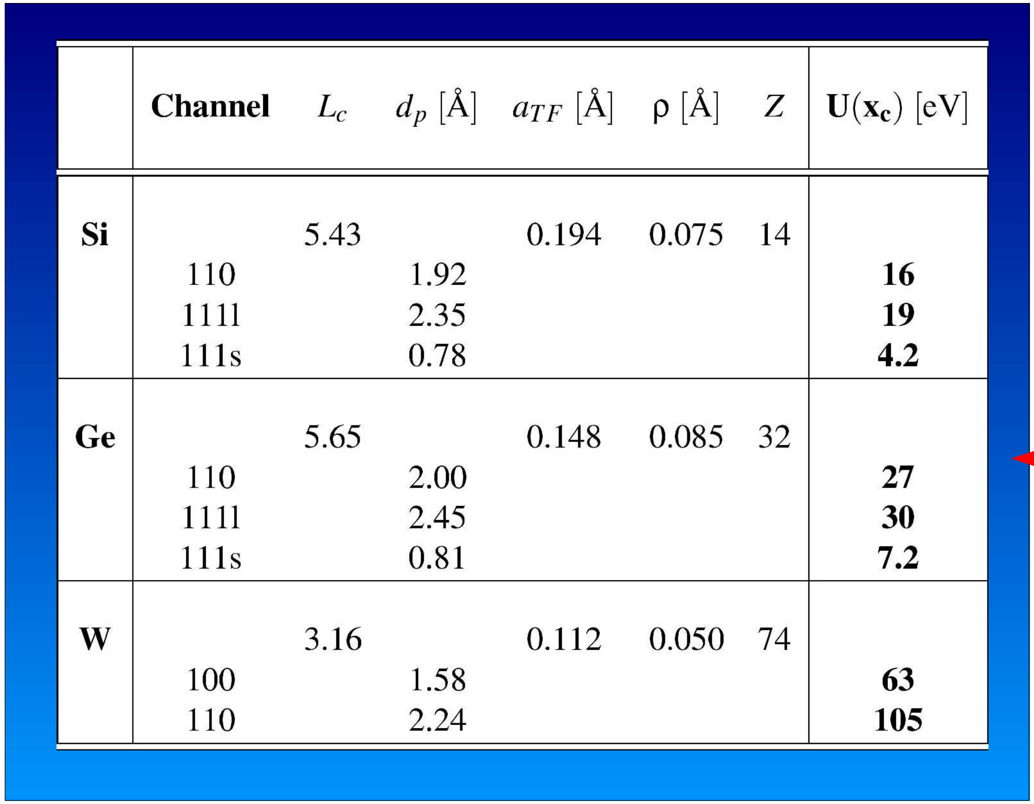
- test at IHEP U-70
- 5 mm long crystal upstream of the U-70 cleaning area
- ~ 10^{14} protons per 50 ms spill with a repetition period of 9.6s
- afterward, test on an extracted line observing the deflected beam with a photo emulsion

IN LHC TERMS:

- one bunch = 1.1 x 10^{11} protons
- the IHEP crystal survived an instant dump of 1000 bunches



Looking for other materials



	Channel	L_c	d_p [Å]	a_{TF} [Å]	ρ [Å]	Z	**U(x_c)** [eV]
Si		5.43		0.194	0.075	14	
	110		1.92				**16**
	111l		2.35				**19**
	111s		0.78				**4.2**
Ge		5.65		0.148	0.085	32	
	110		2.00				**27**
	111l		2.45				**30**
	111s		0.81				**7.2**
W		3.16		0.112	0.050	74	
	100		1.58				**63**
	110		2.24				**105**

The critical angle dependence:

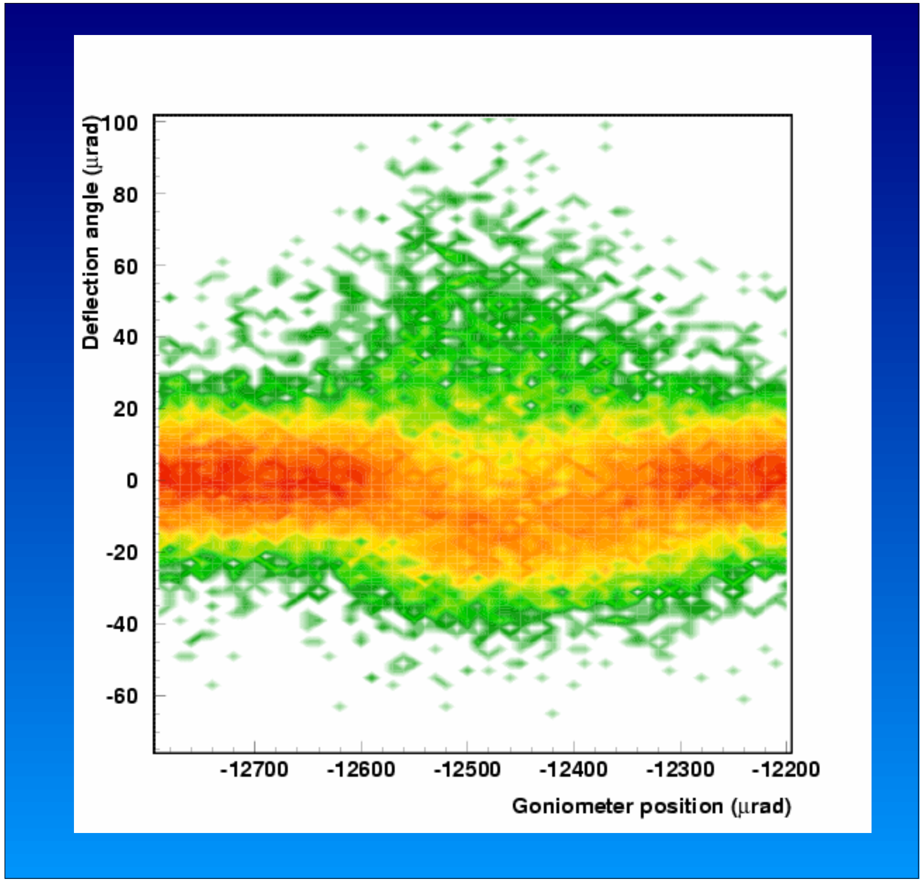
$$\theta_c = \sqrt{\frac{2U}{pv}}$$

The U dependence:

$$U(x) \propto Z_{mat}$$

Look for new materials:
GERMANIUM, DIAMOND,
TUNGSTEN

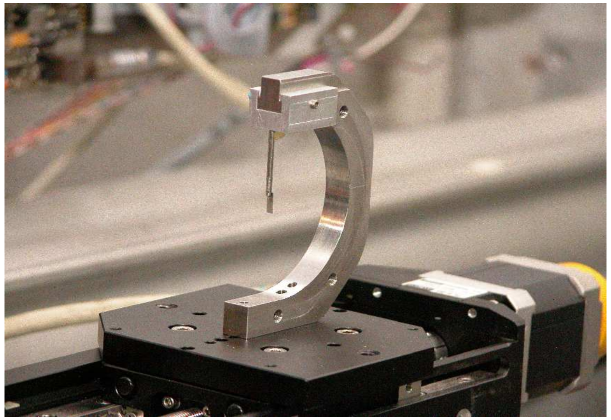
From silicon to germanium: 1st trial

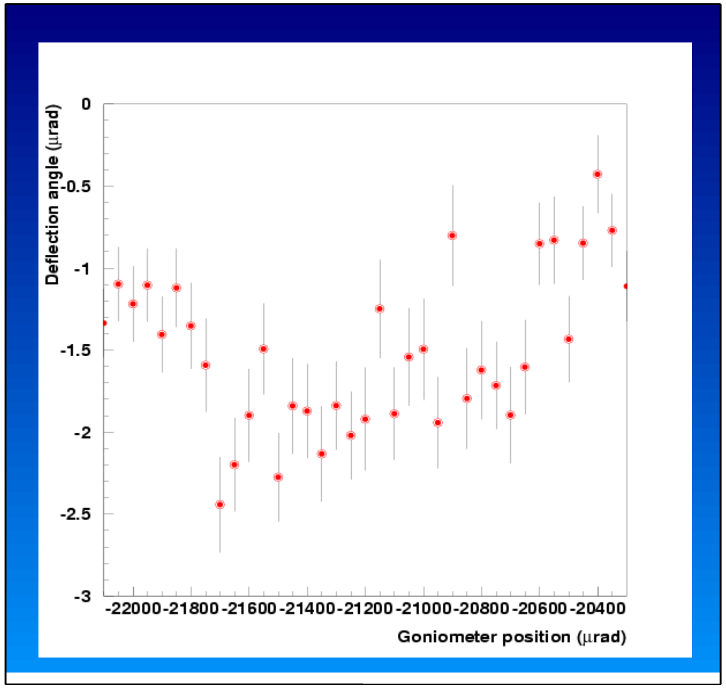


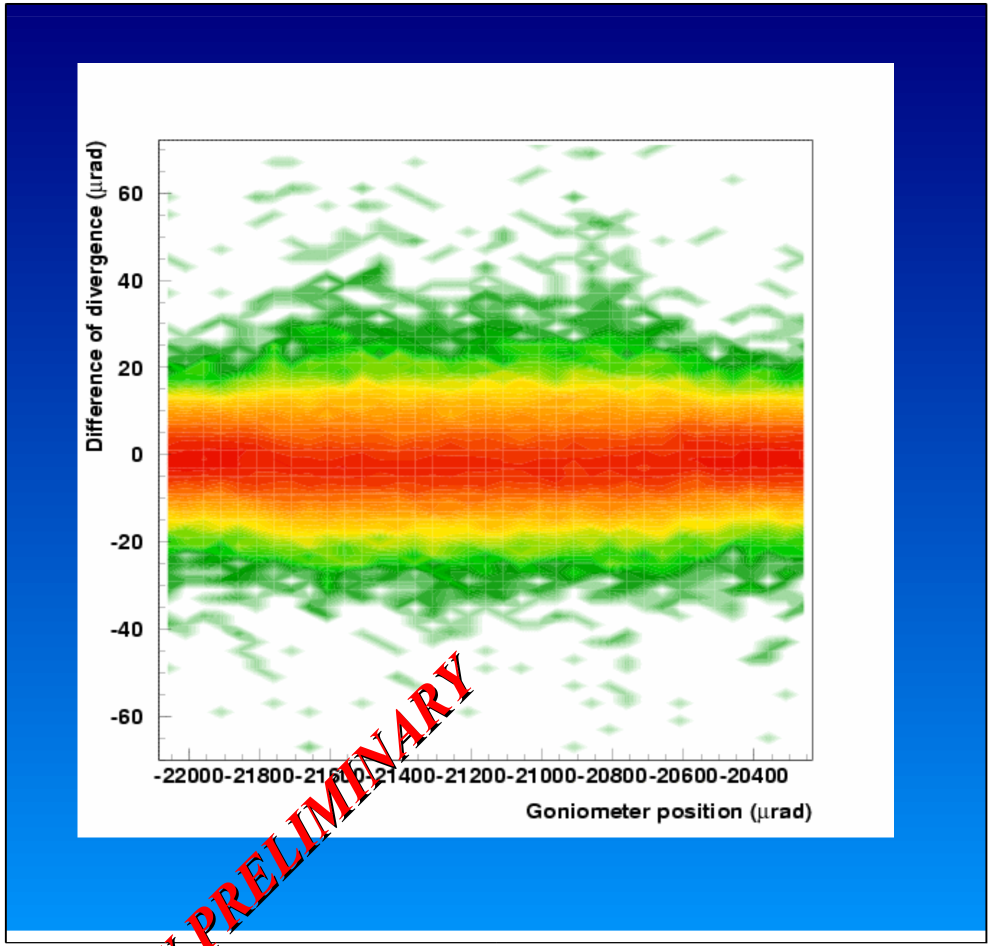
- tested in May 2007
- volume reflection is present
- the crystal was not perfect → no channeling; everything goes into dechanneling because of lattice defects

- non negligible problem: high cost

From silicon to diamond







VERY PRELIMINARY

(U. Uggerhoj; diamond produced by DeBeers)

CONCLUSIONS

- ✔ *silicon crystals tested in terms of:*
  - ➔ *radiation hardness*
  - ➔ *power deposit*
  - ➔ *efficiency of all the physical effects*
  - ➔ *surface features*
- ✔ *studies on new materials just started; first test on:*
  - ➔ *germanium*
  - ➔ *diamond*
- ✔ *tests performed with:*
  - ➔ *low and high energy proton beams*
  - ➔ *electron and positron beams (just started)*

➔

While going on with collimation tests with silicon crystals, we need to:

- ➔ **understand surface influence and say the last word on surface specifications**
- ➔ **perform more tests on radiation hardness, power resistance and temperature**
- ➔ **try do develop new materials which will require dedicated efforts**