The International Conference “Channeling 2014”

Quasi-mosaic Silicon Crystal Deflectors for LHC Beams

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Capri – Naples, Italy, 11 October 2014

Reflection of Gamma-Rays From Bent Quartz Plates

[1] Lind, West and DuMond, Phys. Rev. 77, 475 (1950).

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IN INVESTIGATING the coherent reflection of x- and γ-rays from the $13\bar{4}0$ planes of quartz plates cut from an α-quartz single crystal so that the $13\bar{4}0$ planes were normal to the plane of the plate and the side edges were parallel to the optical axis of the crystal, Lind, West and DuMond[1] found that the dependence of the integrated reflection coefficient on the wavelength for plates elastically bent to a cylinder of 2 meters radius is close to quadratic. Their measurements of the integrated reflection coefficient for the same plate in the unstressed state led to a dependence close to the linear, *i.e.*, the dependence characteristic of ideal crystals. Lind *et al.* do not attempt to give an explanation of the observed effect noting only that "... the quartz might, however, become mosaic-like in structure in some elastically reversible way not now understood."

We felt it would be of interest to verify the quadratic dependence of the reflection coefficient on the wavelength discovered by Lind, West and DuMond and to find an explanation of the effect. The measurements were carried out on the two-meter crystal-diffraction spectrometer of the All-Union Scientific

Lind, West and DuMond assumed that the initially flat reflecting planes remain plane when the plate is bent. This in general is not correct. Actually when a plate of arbitrary cross section is bent by the application of a bending moment M_1 acting in the yoz plane (Fig. 2) the displacements in the

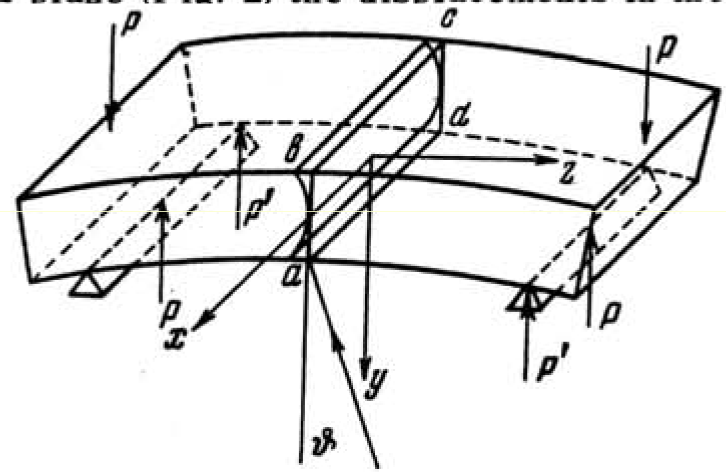

FIG. 2.

[3] S. G. Lekhnitskii, *Theory of Elasticity of an Anisotropic Body*, GTTL, Moscow 1950.

direction of the z-axis in the case of anisotropy of the general form are determined by the familiar relation[3]

$$W = (M_1 / 2I_1)[a_{35}xy + a_{34}y^2 + a_{33}y(2z - l)], \quad (1)$$

where M_1 is the effective bending moment, I_1 is the

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moment of inertia about the x-axis and the a_{ij}'s are strain coefficients. If a_{34} and a_{35} differ from zero, the cross sections are distorted by the bending into second-degree surfaces. With $a_{35}=0$ the planes bend along the parabolas:

$$z = k_1 y^2, \quad k_1 = M_1 a_{34} / 2I_1.$$

If $a_{35} \neq 0$, Eq. (1) becomes invalid for cases of bending of the crystal plate between cylindrical mirrors or by application of moments by the method of Borovskii-Gil'varg.[4,5] Actually if $a_{35} \neq 0$, in addition to bending, the plate tends to twist. However, the design of the crystal holder prevents twisting with the result that in addition to the moment M_1 (couple PP in Fig. 2) the plate is subjected to a moment M_t opposing the torsion (forces PP' in Fig. 2). The deformation of a plate loaded in this manner is satisfactorily approximated by the following expression

$$W = \frac{a_{35}}{2\rho\,[a_{33} - a_{35}^2 / (a_{44}b^2/a^2 + a_{55})]\,(a_{44}b^2/a^2 + a_{55})} \times \left\{a_{45}\frac{b^2}{a^2}x^2 - \left[a_{45} - \frac{a_{34}}{a_{35}}\left(a_{44}\frac{b^2}{a^2} + a_{55}\right)\right]y^2 + 2\frac{b^2}{a^2}a_{44}xy\right\}, \quad (2)$$

which is rigorously valid for a plate of elliptic cross section (in which case a and b are the axes of the ellipse) bent to a cylinder of radius ρ. Neglecting the terms with b^2/a^2 (in our case $(b/a)^2 \approx 2.5 \times 10^{-3}$), we obtain

$$W = \frac{1}{2\rho\,(a_{33} - a_{35}^2/a_{55})}\left(a_{34} - \frac{a_{45}}{a_{55}}a_{35}\right)y^2 \quad (3)$$

The intensity of reflection from the entire lamina will be proportional to

$$[r_0 p\,(F/v)\,\lambda\Delta y/\cos\vartheta]^2. \quad (9)$$

The width of the diffraction peak will obviously be

$$\Delta\vartheta_\Sigma = 2k_2T, \quad (10)$$

where T is the thickness of the plate and the integrated reflection coefficient

$$R_\vartheta \sim 2k_2T\left[r_0p\left(\frac{F}{v}\right)\frac{\Delta y}{\cos\vartheta}\right]^2 \sim \frac{p^2}{\cos^2\vartheta}r_0^2\left(\frac{F}{v}\right)^2 dT\lambda^2 \quad (11)$$

This relation is identical with the expression for the integrated reflection coefficient for a mosaic crystal. Computing Δy from (7) with $k_2 = 0.226 \times 10^{-}$

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Thus we see that the quadratic dependence of the reflection coefficient of an elastically bent quartz plate on the wavelength can be explained naturally without recourse to any additional hypotheses. The bent plate actually does become similar to a mosaic crystal in consequence of bending of the reflecting planes.

SOVIET PHYSICS JETP VOLUME 27, NUMBER 5 NOVEMBER, 1968

EXPERIMENTAL INVESTIGATION OF THE ELASTIC QUASI-MOSAIC EFFECT

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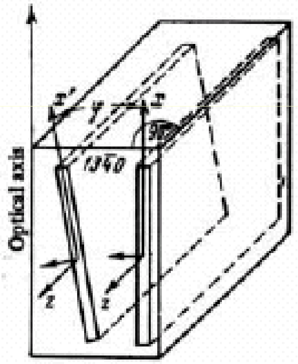

FIG. 4. Position of compared plates in the single-crystal quartz block.

ent orientations (the indices of the planes coinciding with the normal cross sections are indicated on the curves)[9].

The purpose of the present paper is to present a comparison of the experimental and calculated parameters of the diffraction process for different values of the flexure coefficient $k(\varphi)$, and particularly a verifica-

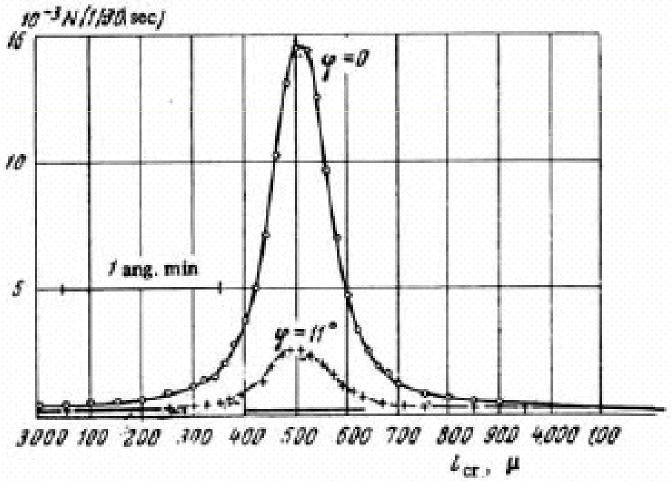

FIG. 5. K_{α_1} Sn x-ray line obtained with a two-meter Cauchois spectrometer using compared plates of 1 mm thickness. Receiving slit ≈ 250μ; N – number of γ quanta registered in 30 sec; l_{cr} – linear displacement of the end of the one-meter arm of the crystal drive. The vertical scale is doubled for the = 11° line.

Quasimosaic effect in silicon

- Calculations of deformed crystal plate done by **V.M.Samsonov** **(Preprint No. 278, LIYaF AN SSSR, 1976).**
  - Resulted in predictions of elastic quasimosaic effect for some other quartz and silicon plate orientations
  - Large elastic quasimosaicity for (011) plane of silicon predicted
- Zero result in the first experiments in 1999
- New calculations using Samsonov approach and new measurements:
  - (111) plane, not (011)
  - **published in JETP Letters 81, 99, 2005**

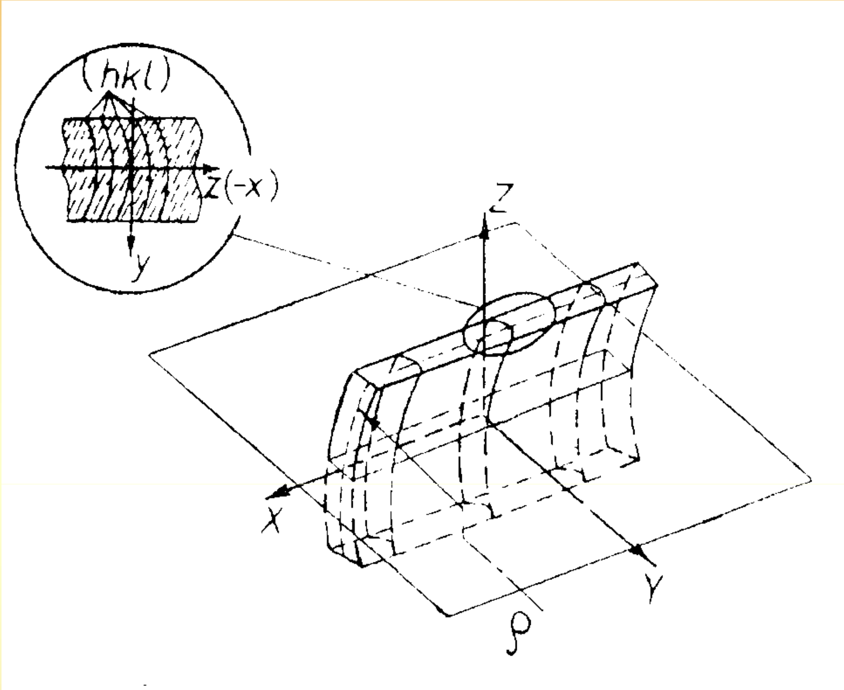

Figure from article: V.M.Samsonov and E.G.Lapin, On some possibilities and pequliarities of a curved crystal use in crystal diffraction instruments, Preprint No. 587, LIYaF AN SSSR, 1980

Quasi-Mosaic Effect Applications

- Improvement of efficiency of X-ray focusing crystal-diffraction spectrometers by two orders (chemical shifts of atomic levels)
- Possibility to optimize focusing crystal-diffraction spectrometers according to structure and width of line under investigation (world best measurements of pi-minus, K-minus, and Sigma-minus masses)
- Record resolution of gamma-ray focusing crystal-diffraction spectrometers (~1 microradian)
- Possibility to increase efficiency of X- and gamma-ray double flat crystal spectrometers

New Application of Quasi-Mosaic effect started from Crystal Beam Multi-Turn Extraction Experiments at IHEP (1997-2001)

Письма в ЖЭТФ, том 67, вып.10, стр.741 - 745

ПЕРВЫЕ РЕЗУЛЬТАТЫ ЭКСПЕРИМЕНТОВ ПО ВЫСОКОЭФФЕКТИВНОМУ ВЫВОДУ ПРОТОНОВ ИЗ У-70 С ПОМОЩЬЮ МОНОКРИСТАЛЛА

А.Г.Афонин, В.М.Бирюков, В.А.Гаврилушкин, В.Н.Гресь, Б.А.Зеленов, В.И.Котов, В.А.Маишеев, А.В.Минченко, В.Н.Терехов, Е.Ф.Троянов, Ю.А.Чесноков[1)], М.Г.Гордеева, А.С.Денисов*, Ю.М.Иванов*, А.А.Петрунин*, В.В.Скоробогатов*, Б.А.Чунин**

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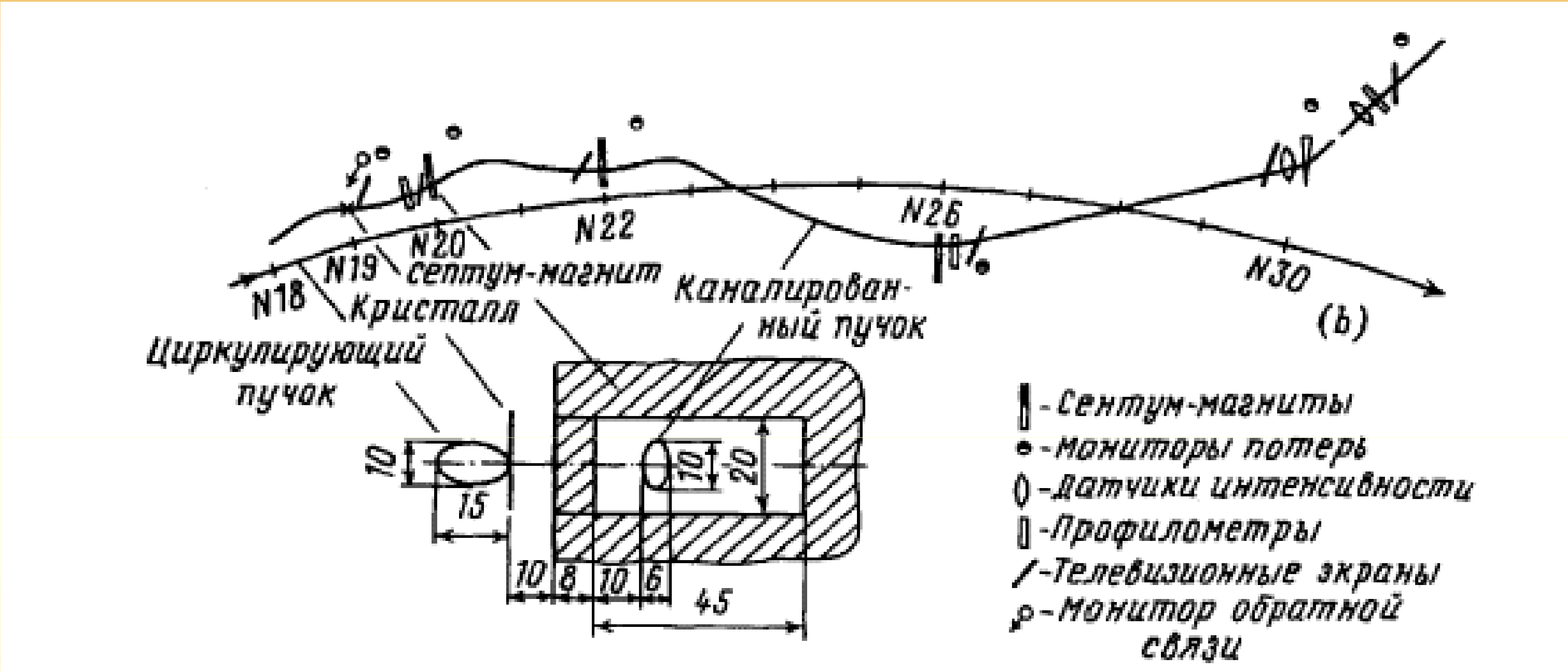
Поступила в редакцию 13 апреля 1998 г.

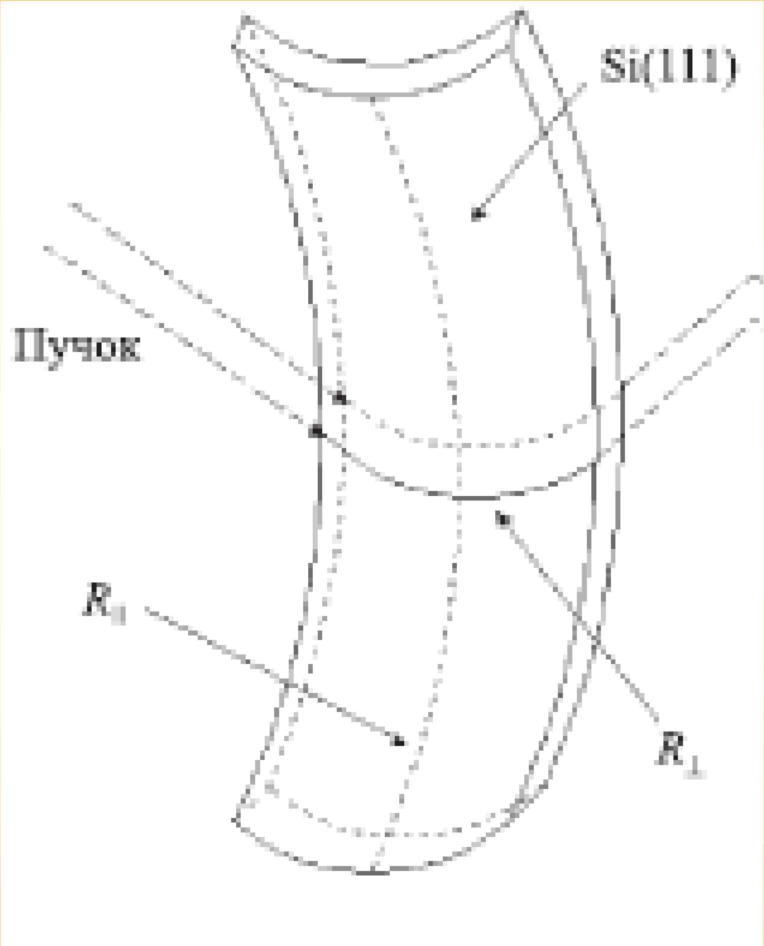
Crystal beam extraction at U-70

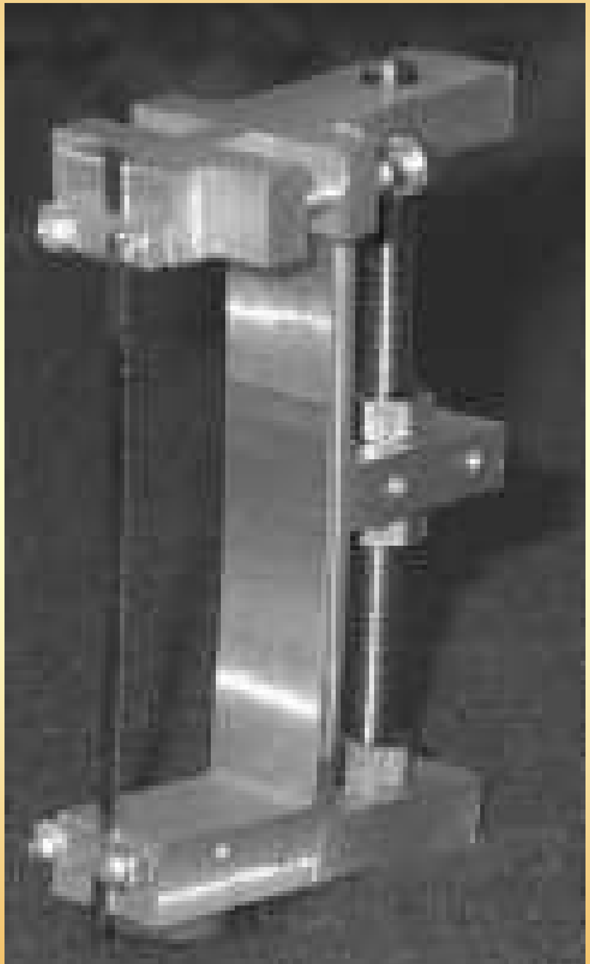


Bending angle (~ 0.4 – 1.0 мрад)

Small crystal legth along beam to provide multi-turn passage of 70 GeV protons

Strip crystals (IHEP)





Sizes ≈ 3 x 1 x 60 mm^3

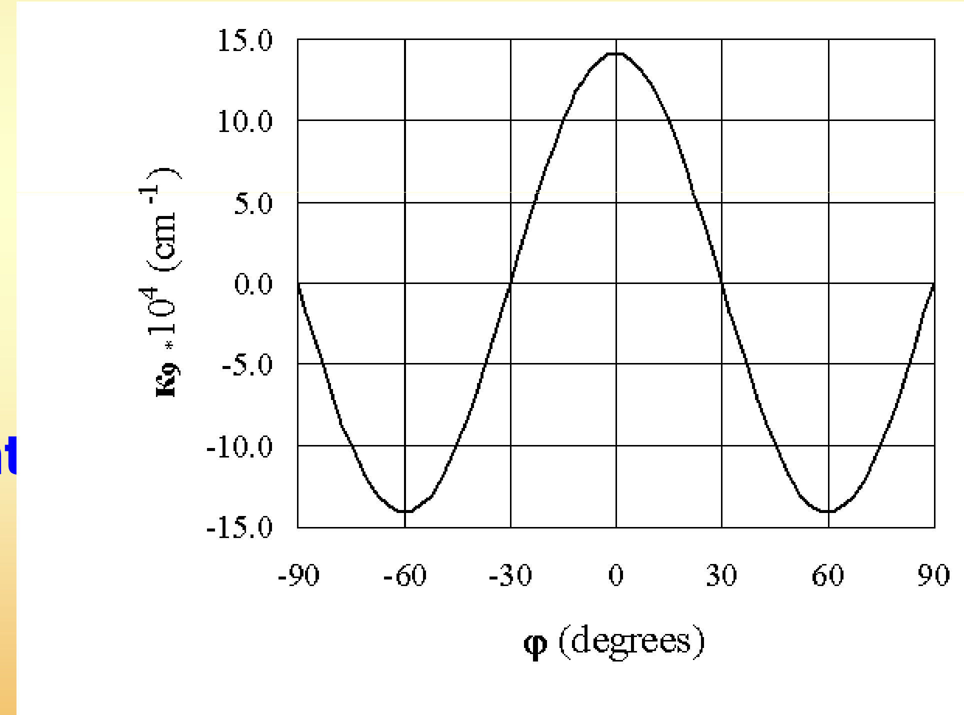
Elastic quasimosaic in dependence on cut angle for Si (111) plane

Plate bending radius R = 1 m

$$\Delta\theta = 2k_9 T \text{, where}$$

T – thickness of plate

k_9 – deformation coefficient

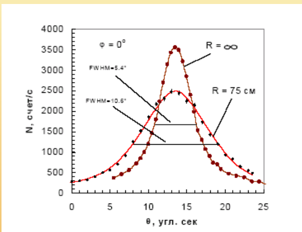


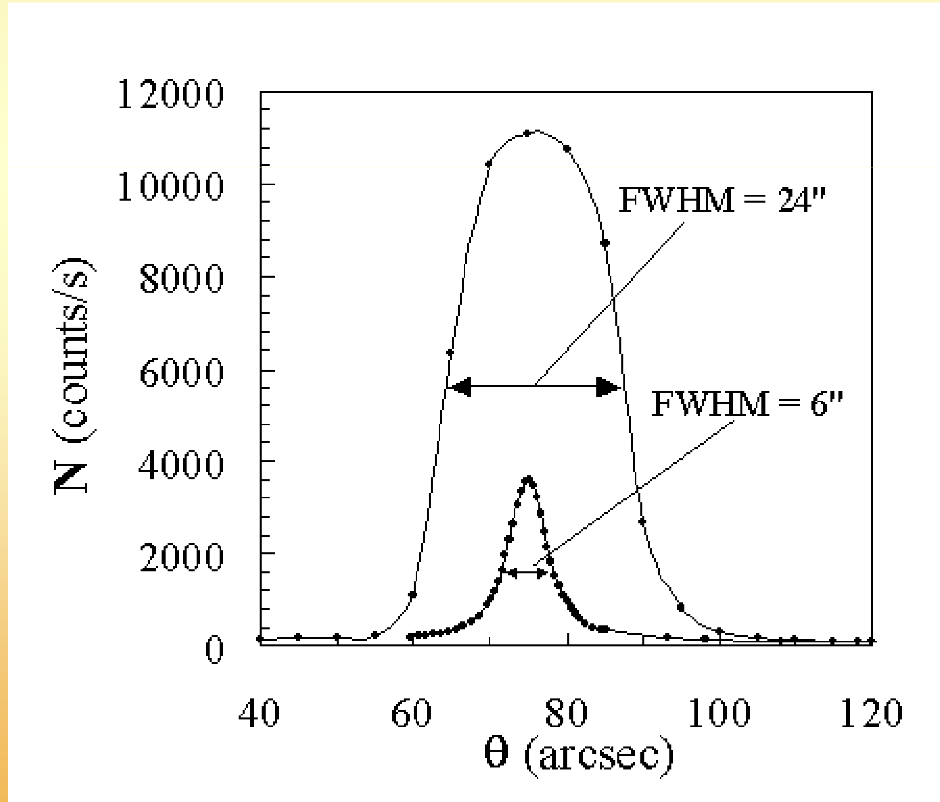
(formula taken from V.M.Samsonov, E.G.Lapin, Preprint No. 587, LIYaF AN SSSR, 1980)

Quasimosaic effect in Si with X-rays

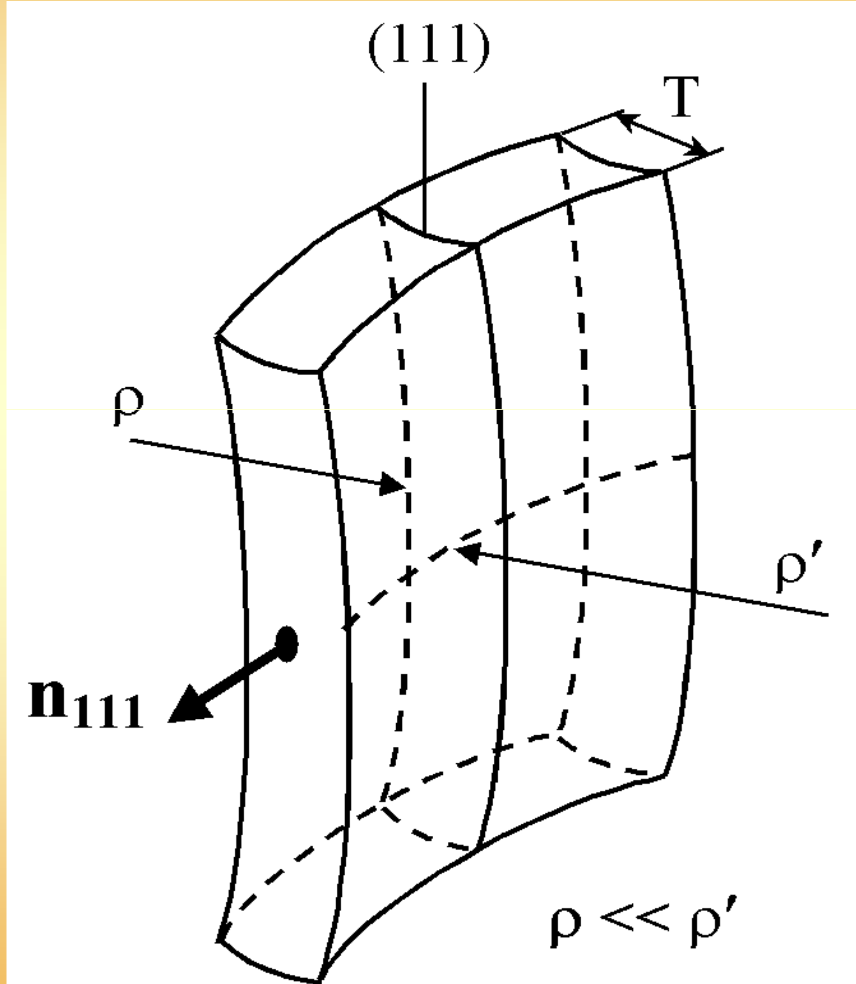
Rocking curves for Si plate with quasimosaic before and after bending.

Rocking curves for Si plate without quasimosaic before and after bending.

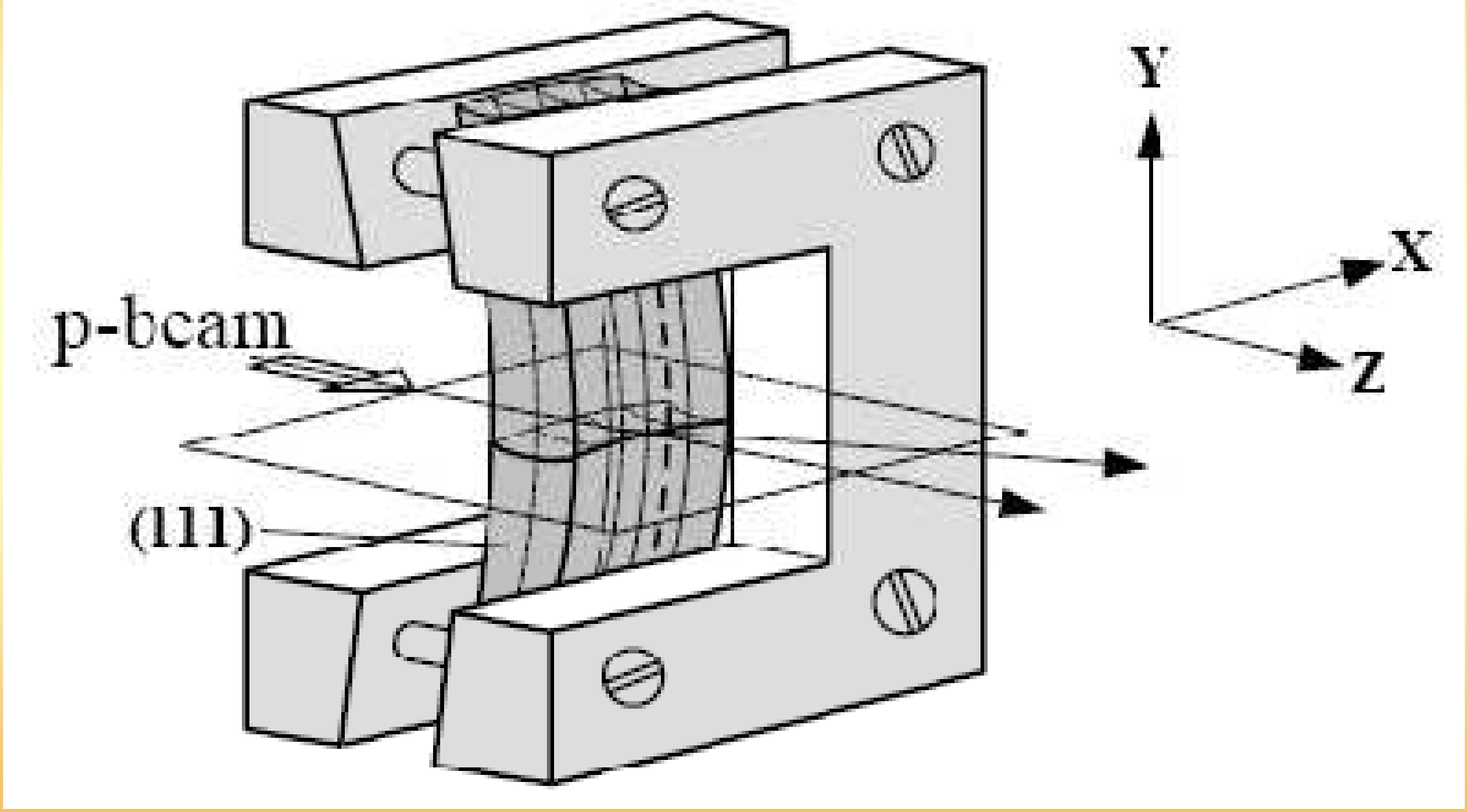




Shape of bent Si plate with elastic quasimosaic



Bending device



First quasimosaic silicon crystal prepared in 2002 for channeling experiment with 70 GeV protons

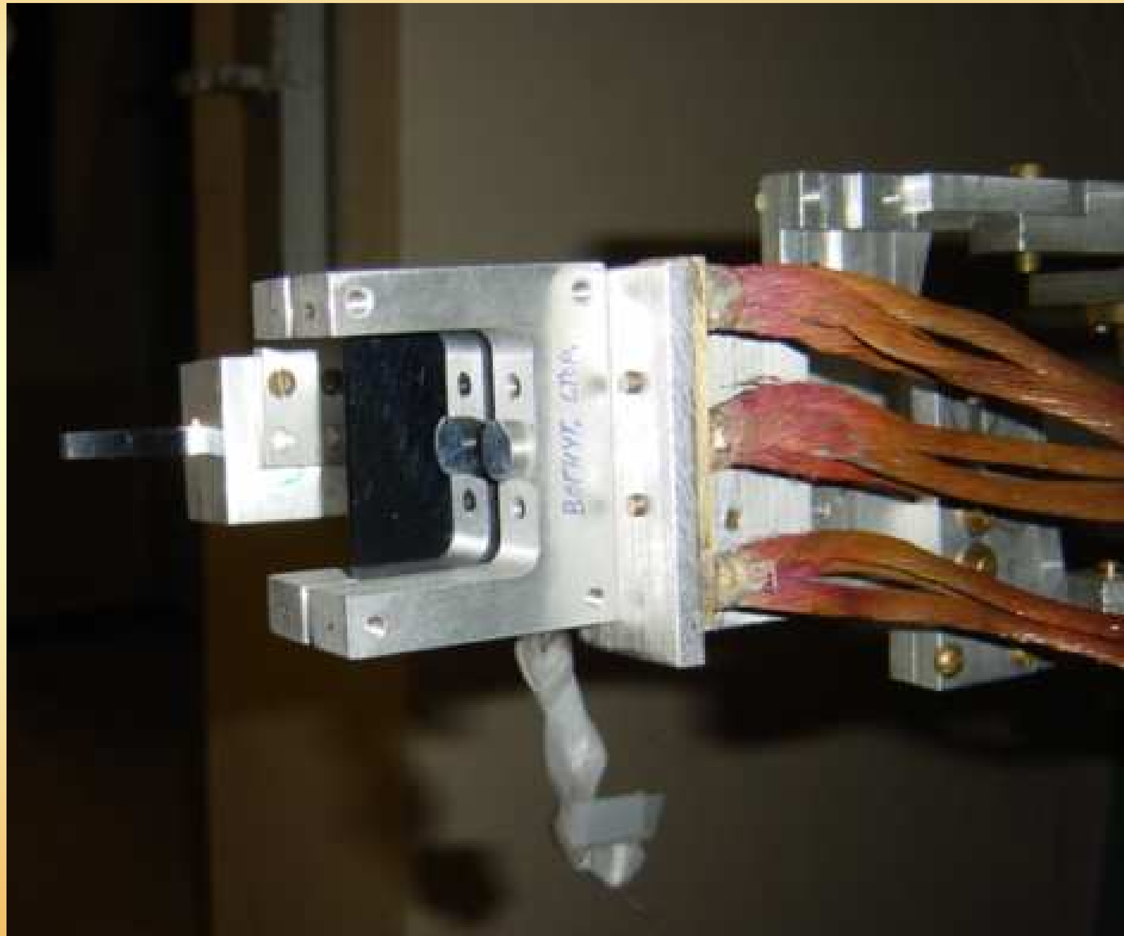
Samples 0.3 mm and 2.7 mm with ~0.4 mrad bending angle

Sample 10 mm with ~100 μrad bending angle

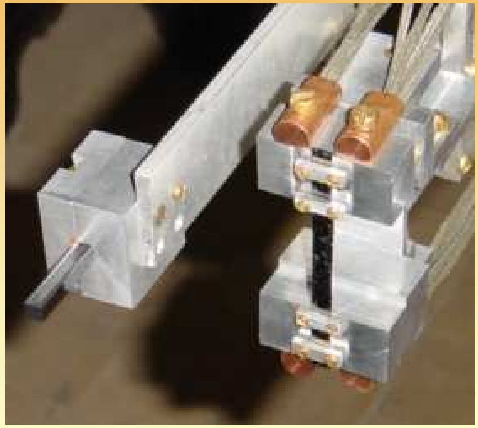
Crystals for experiment on extraction of high entensive proton beam at IHEP

Plane	**(111)**
Length along beam	**2.65 mm**
Bending angle	**400 μrad**

Quasi-mosaic crystal installed at gonio



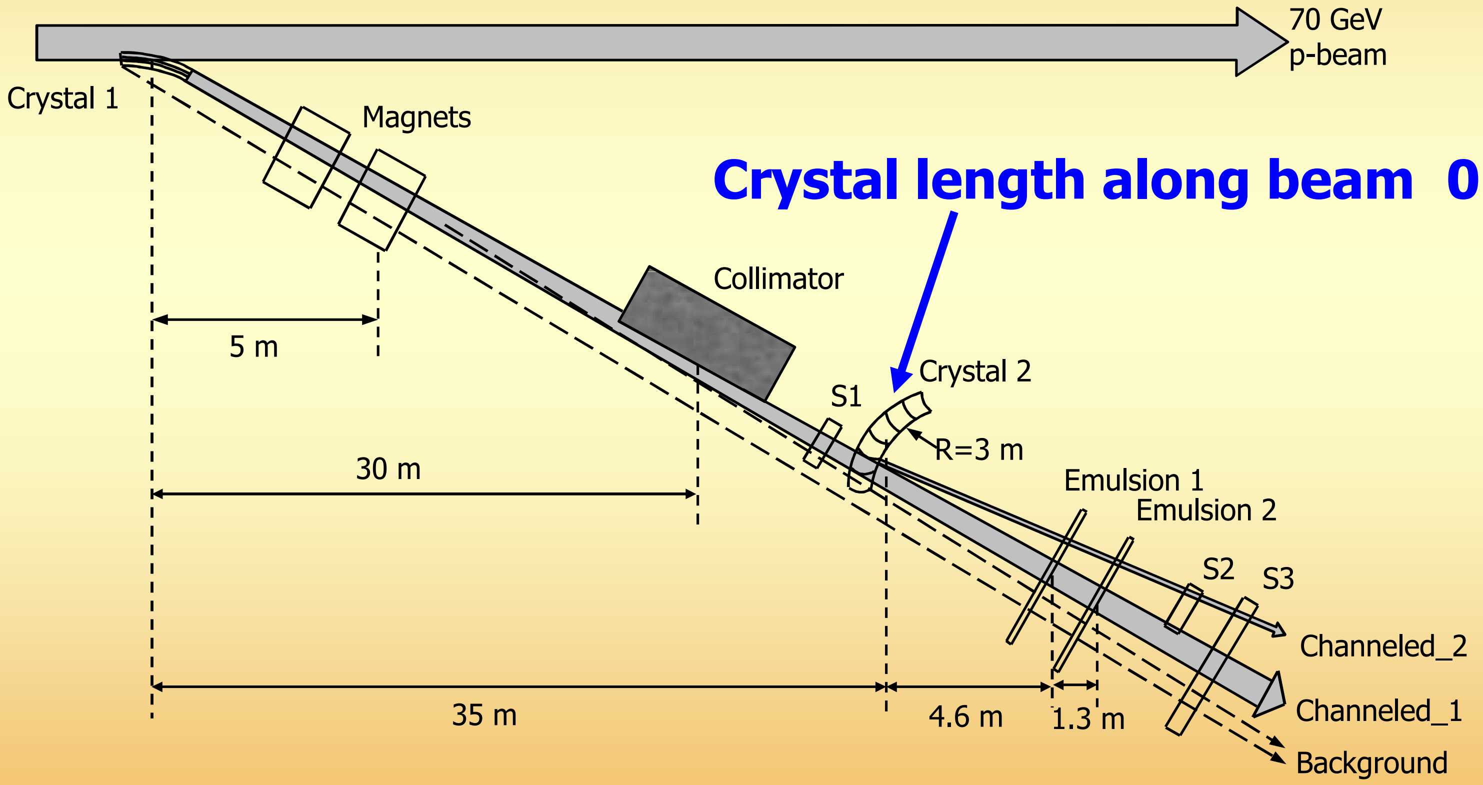
Crystal installation at U-70



Beam extraction from U-70

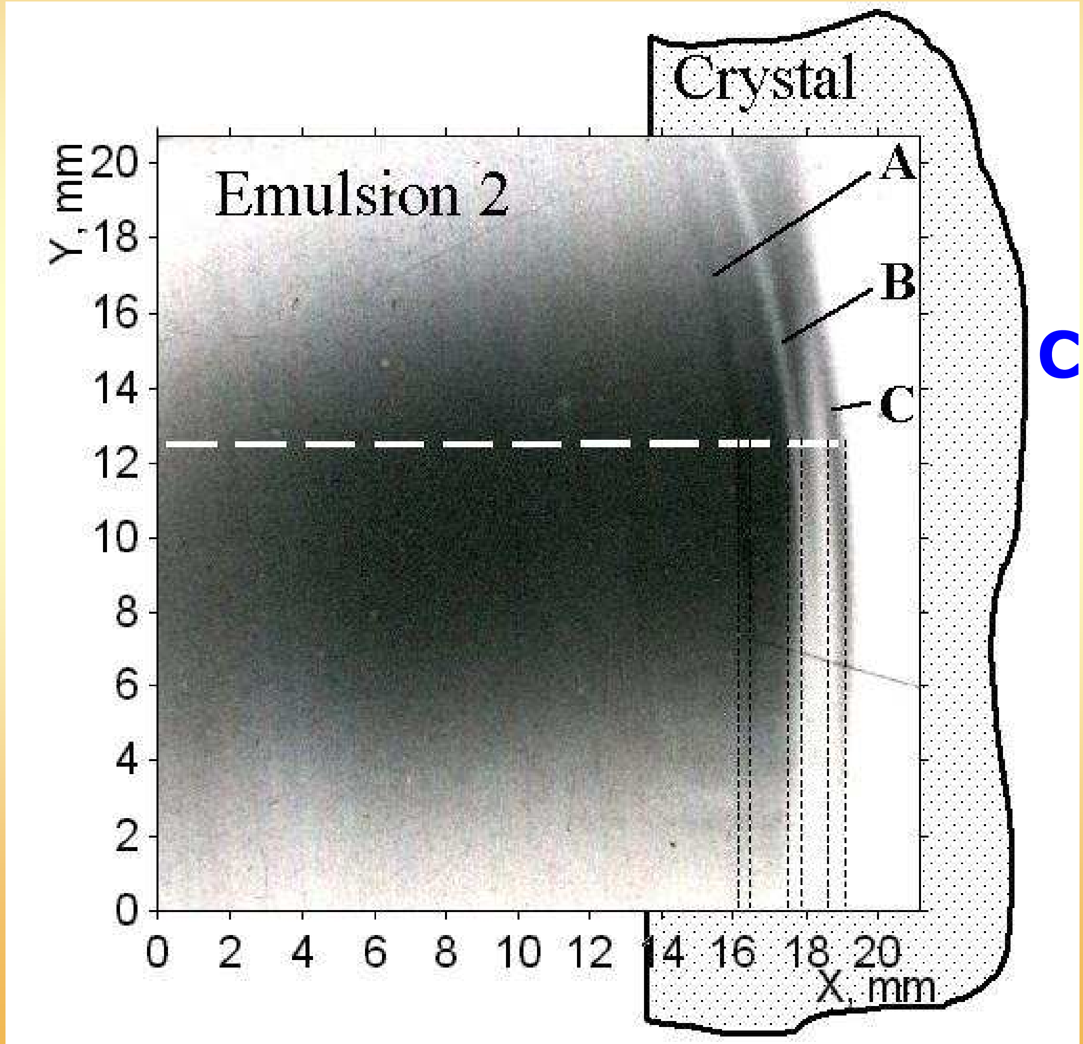
Number of protons in the ring	**$5.5 \cdot 10^{12}$ p**
Number of extracted protons	**$4.0 \cdot 10^{12}$ p**
Extraction efficiency	**~ 70%**

Experiment at IHEP with 70 GeV proton beam (2002)



Yu.M.Ivanov et al.PRL 97, 144801 (2006)

The beam distribution after quasimosaic crystal measured with photoemusions



C – channeling

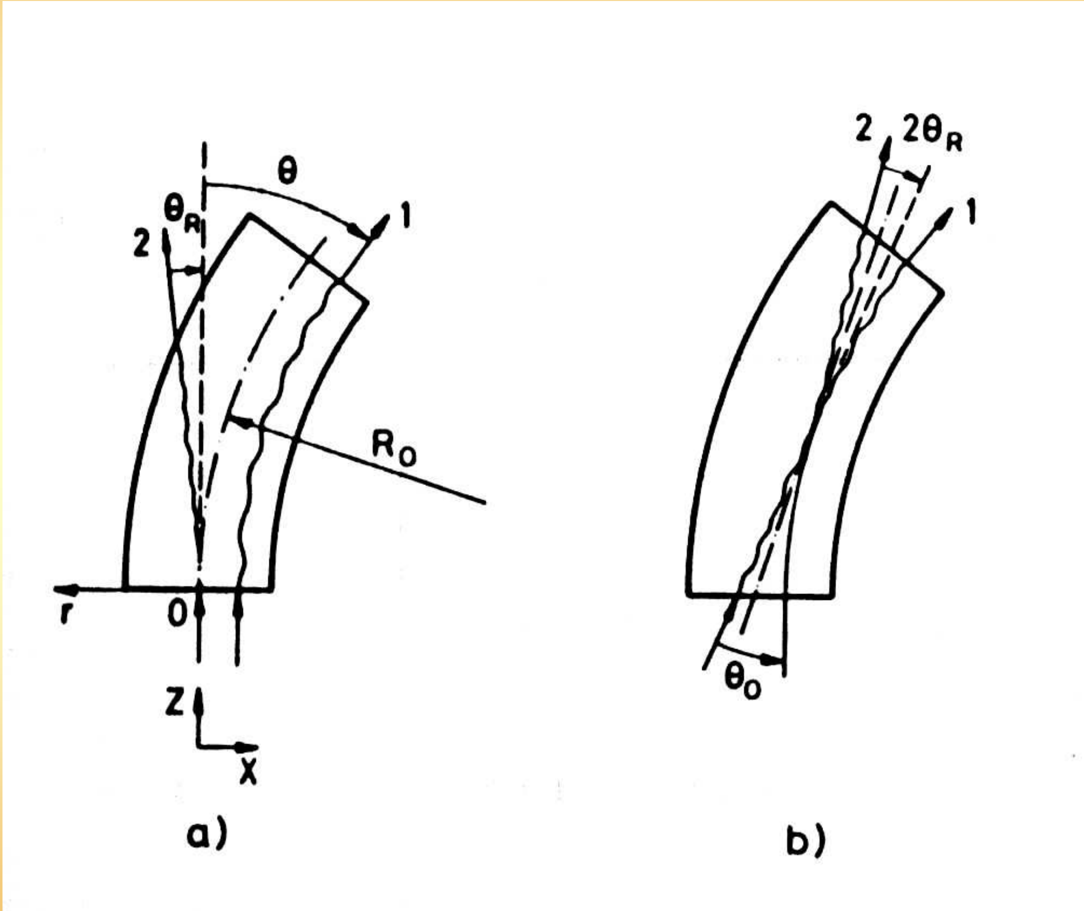
Why A и B ?

Volume Reflection Effect

A.M.Taratin and S.A.Vorobiev, Phys.Lett. A119 (1987) 425

and

A.M.Taratin and S.A.Vorobiev, NIM in PR B26 (1987) 512

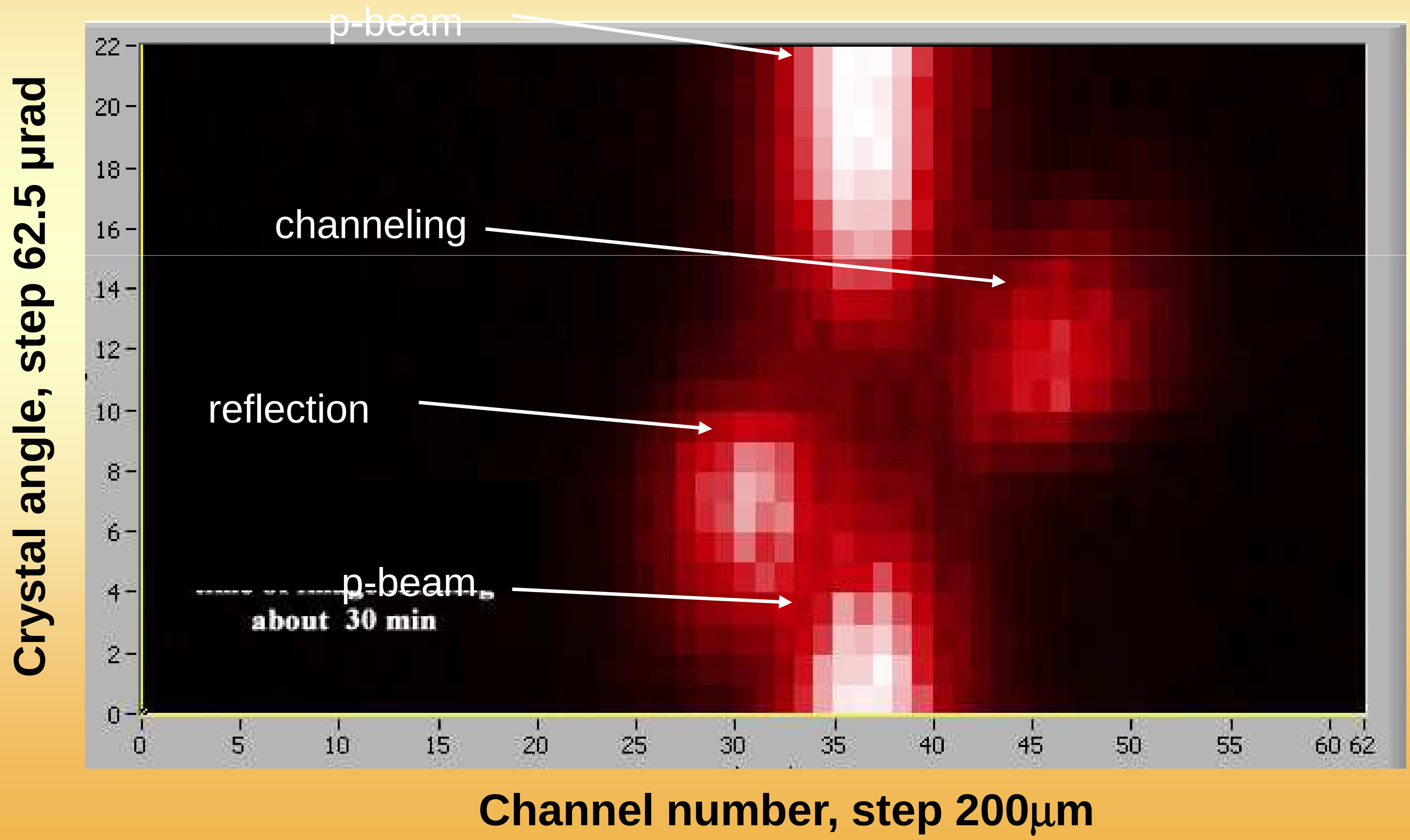


Volume Reflection of 1-GeV Protons by a Bent Silicon Crystal

Yu.M.Ivanov, N.F.Bondar, Yu.A.Gavrikov, A.S.Denisov, A.V.Zhelamkov, V.G.Ivochkin, L.P.Lapina, S.V.Kos'yanenko, A.A.Petrunin, V.V.Skorobogatov, V.M.Suvorov, A.I.Shchetkovsky (PNPI)
A.M.Taratin (JINR)
W.Scandale (CERN)

JETP Letters, 2006, Vol. 84, No. 7, pp. 372–376.

Observation of Volume Reflection with 1GeV protons at PNPI using Quasi-Mosaic Crystal of 30 μm Thickness



Results

Deflection angle of reflected protons:

$$2\theta_R \sim 240\ \mu\text{rad} = 1.4 \cdot \theta_c$$

Probability of the volume reflection:

$$P_R \sim 0.7$$

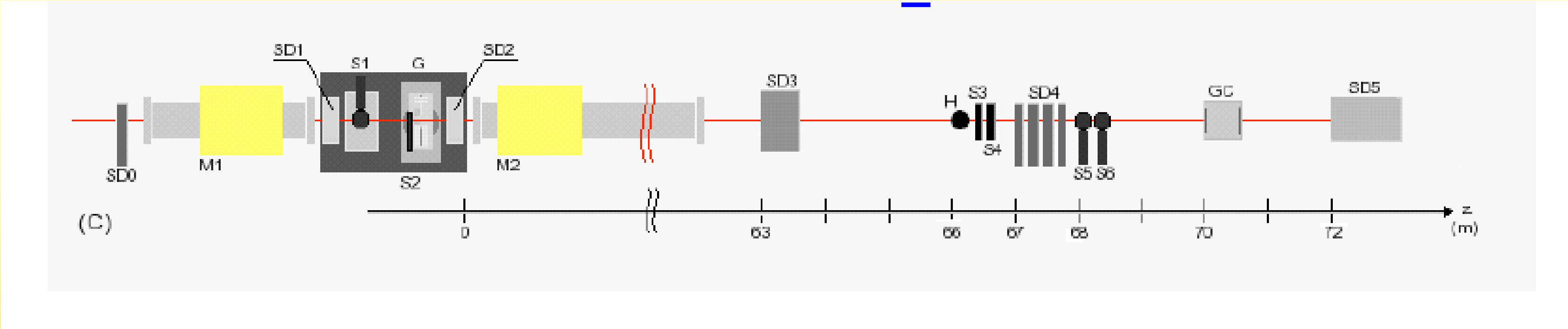
Probability of the volume capture:

$$P_{VC} \sim 0.3$$

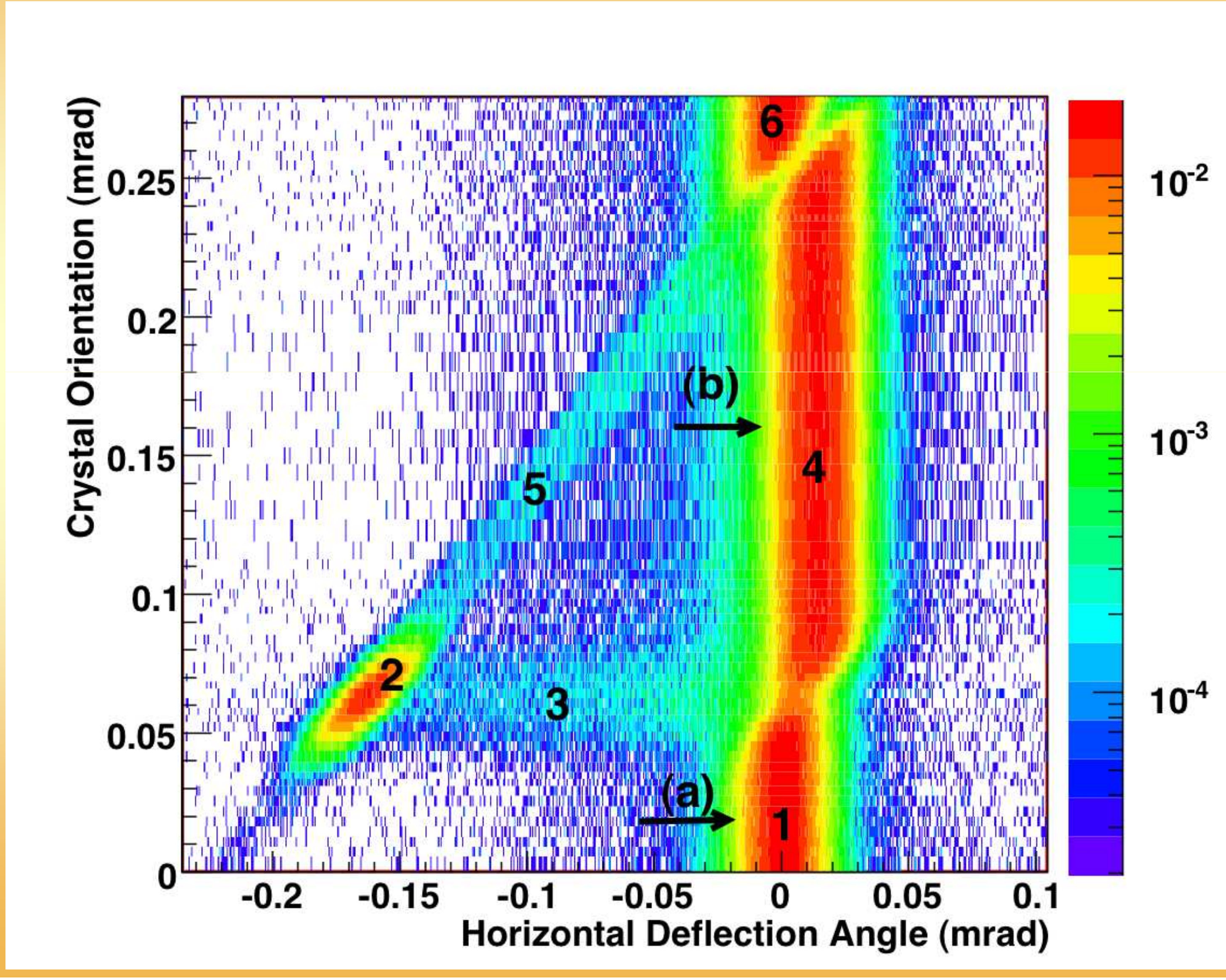
Channeling experiment with 400 GeV protons at SPS CERN (H8-RD22 Collaboration, 2006)

H8 beam line

CRYSTAL area **FAR_DETECTOR area**

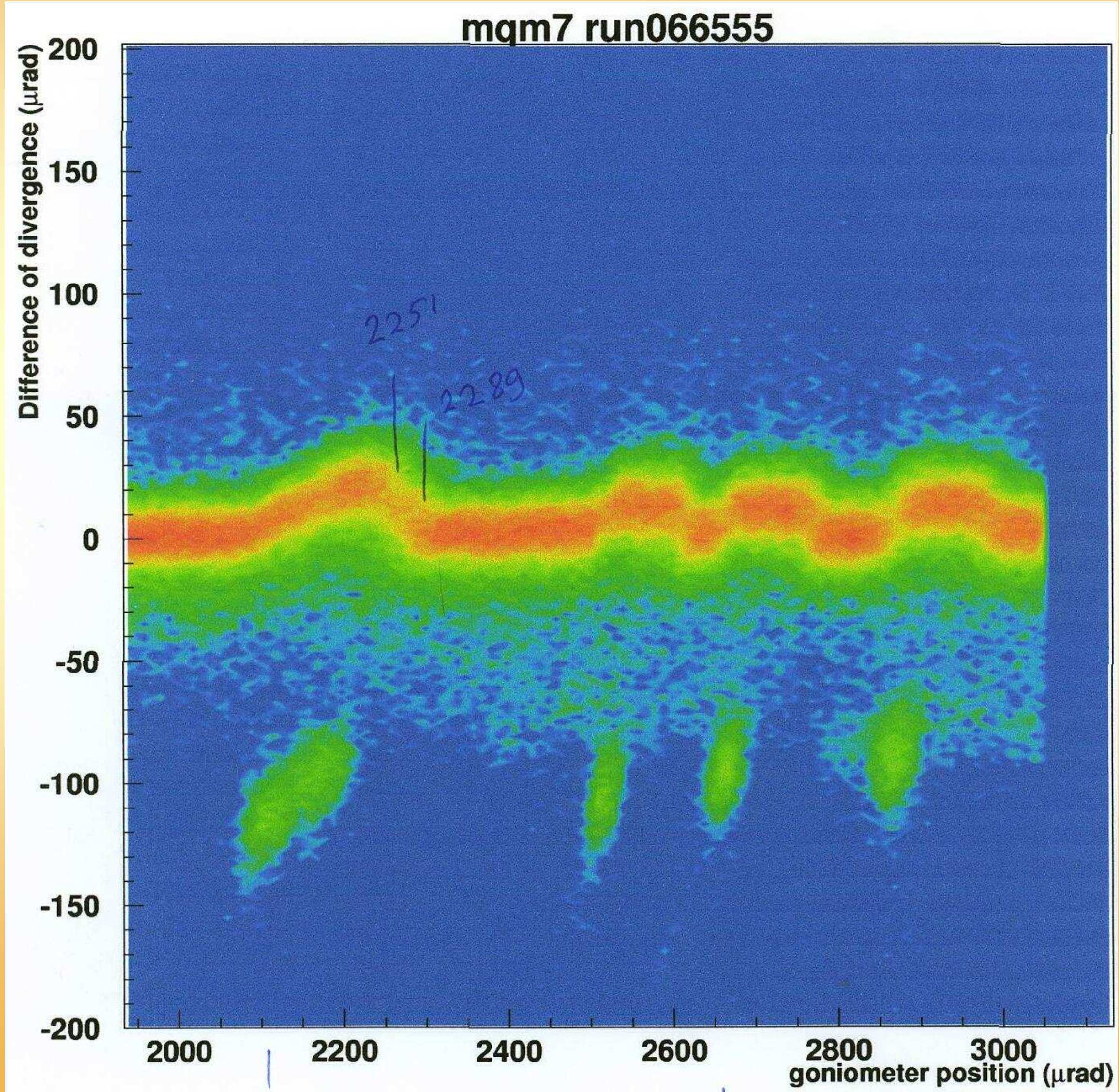


Result of typical angular scan with one of the crystals

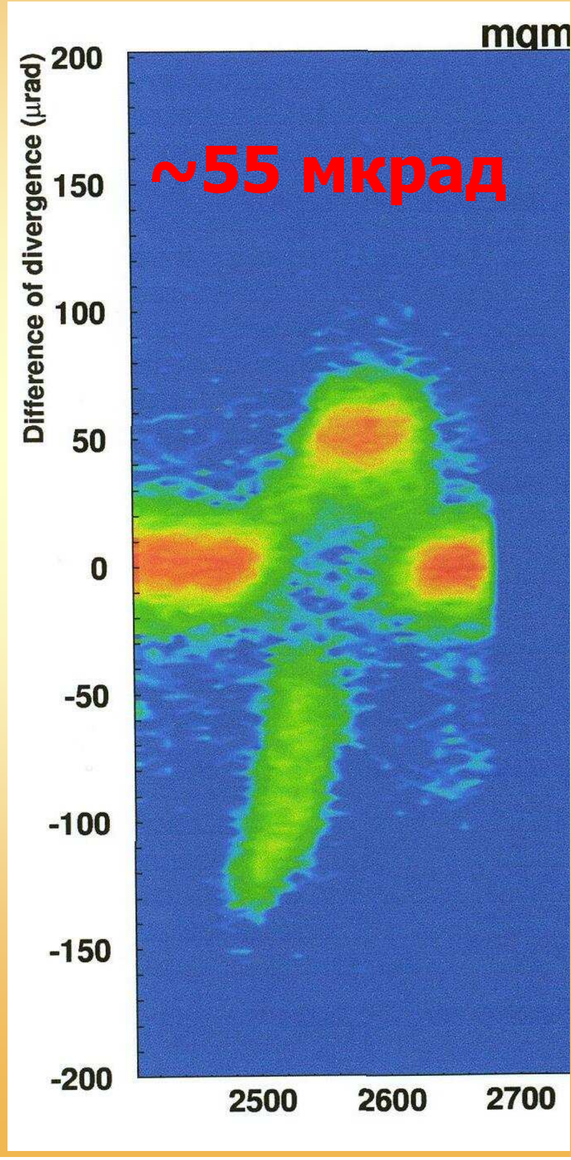


Observation of volume reflection effect from 5 quasi-mosaic crystals

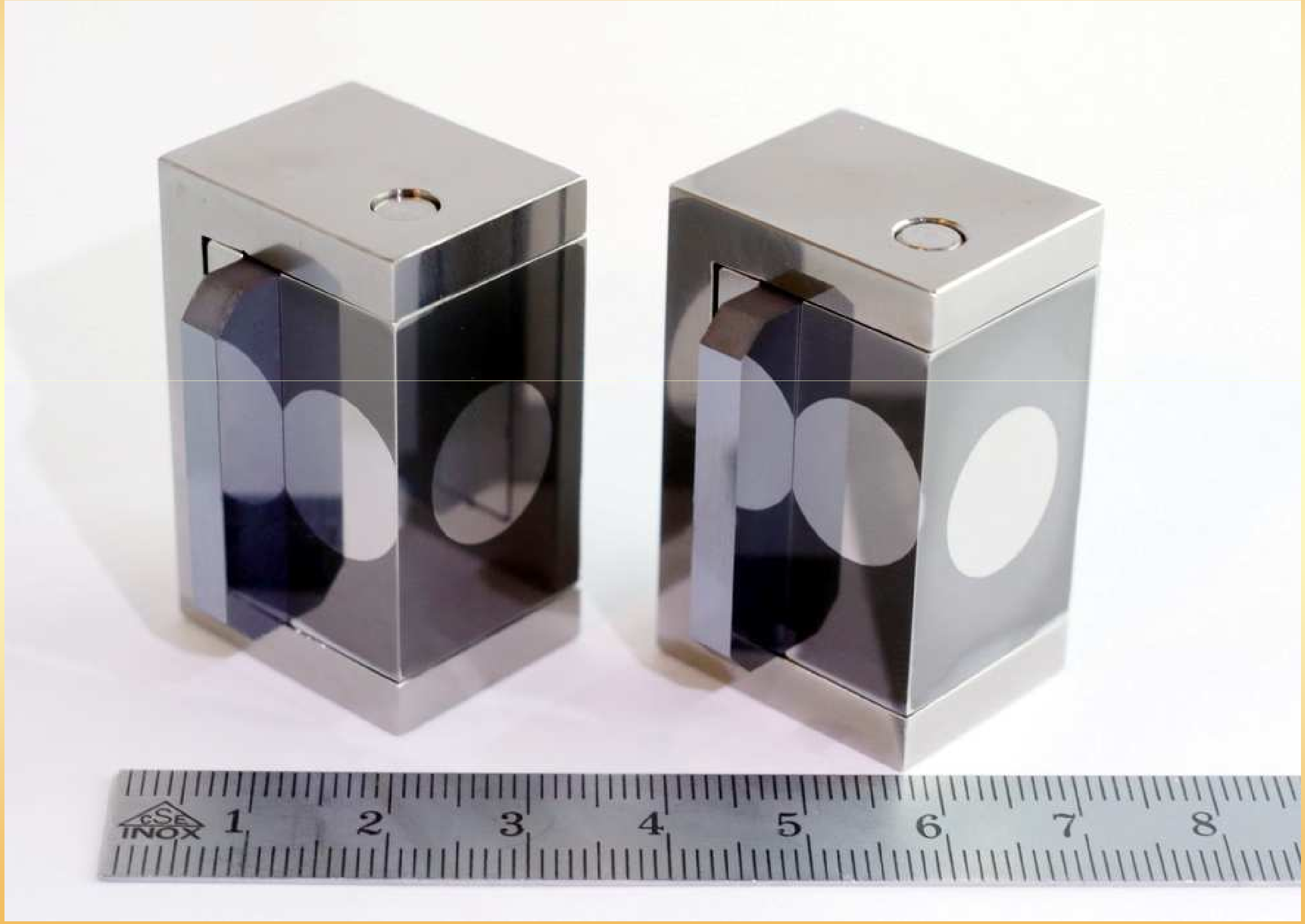
Not aligned 5 crystals



Aligned crystals



Deflectors QM33 and QM34 for LHC



Materials

Holder - alloy VT6 (Russian analog of Titanium grade 5)

Spring - alloy BRB2 (Russian analog of Alloy 25)

Coating on the mirrors - alloy Ni-Mo (Mo-10%), non-magnetic, 2500Å

Crystalline plate - high pure silicon ingot used for QM1-29

Technologies

Bending device	**-**	**lab mechanical workshop**
Metal polishing	**-**	**lab optical workshop**
Coating on the mirrors	**-**	**lab magnetron sputtering**
Crystalline plate	**-**	**lab optical workshop and X-ray setup**

Crystal parameters

Sample	QM33	QM34
Channeling planes	(111)	(111)
Length along beam (mm)	4.0	4.0
Miscut (μrad)	~ 20	~ 20
Surface layer (nm)	~ 200	~ 200
Bending angle (μrad)	44 ± 3	47 ± 3
Torsion in center (μrad/mm)	≤ 1	≤ 1
Saddle curvature (μrad/mm)	~ 6	~ 6

Future plans

To study installed crystals at SPS and LHC (in the ring and with external beams)