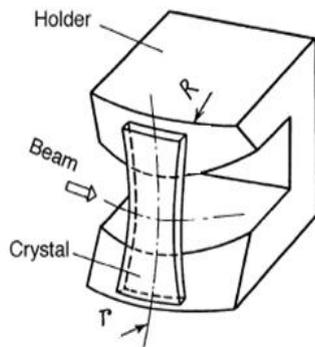


## ON THE WAY TO CRYSTAL COLLIMATION OF THE LHC BEAMS

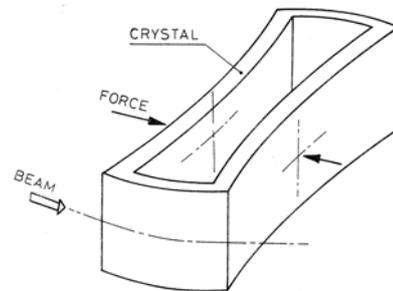
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### 1. Introduction

In the end of the 90-s, the IHEP and PNPI groups studied short bent silicon crystals with high-energy protons at U-70 and showed that exploiting the multi-pass (or multi-turn) mechanism (experimentally proven at the CERN SPS by H. Akbari *et al.*, 1993) one can extract from the accelerator a beam of the intensity up to  $6 \times 10^{11}$  protons per cycle, which is five orders of magnitude higher than that reached in previous experiments, the beam extraction efficiency exceeding 40 % (A.G. Afonin *et al.*, 1998). Two approaches to bend short crystals were developed in these studies and realized in strip and O-shaped crystals (Figs. 1 and 2). Improvements of the bent crystal quality in further experiments at IHEP with participation of the BNL, CERN, and INFN groups made possible to enhance the crystal extraction efficiency up to 85 % and to bring the intensity of the beam extracted from U-70 up to  $10^{12}$  protons per cycle (A.G. Afonin *et al.*, 2001). As a result, the bent crystals were applied to the main beam and to the halo particles. Thus, the extraction and collimation schemes with many crystals working simultaneously were developed [1].



**Fig. 1.** Strip crystal: the curvature across the strip (in the beam direction) is induced by bending along the strip (the so called anticlastic effect)



**Fig. 2.** O-shaped crystal: the curvature in the beam direction is induced by compressing the middle part of the crystal

Then, two crystal collimation experiments using the O-shaped crystals were performed at RHIC and Tevatron. At RHIC, the experimental set-up was mounted at a non-optimal location with high angular divergence of the beam that increased the background rate at the STAR detector (R.P. Fliller *et al.*, 2006). Later, the RHIC set-up was moved to FNAL, where an experiment at Tevatron in better conditions showed that replacing a standard 5-mm tungsten target (primary collimator) with a crystal results in reduction of the beam losses in the CDF experiment by a factor of two and in reduction of irradiation of the superconducting magnets by a factor of five. Also, it was shown that the secondary collimator could be placed further away from the beam, thus reducing the machine impedance (R.A. Carrigan *et al.*, 2007).

The promising results at IHEP and FNAL encouraged the H8-RD22 program at the CERN SPS, which later became the UA9 experiment and now led to the LUA9 project aiming to improve with crystals the efficiency of the LHC cleaning system. The realization of the project should reduce the background in the collider detectors and avoid quenching of superconducting magnets at the highest luminosities.

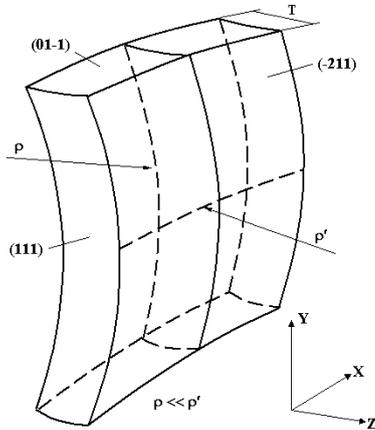
Below we describe our recent studies performed at PNPI, IHEP, and CERN with the aim to develop a crystal collimation system for the LHC.

### 2. Elastic quasi-mosaic effect in silicon and development of bent quasi-mosaic crystals for channeling

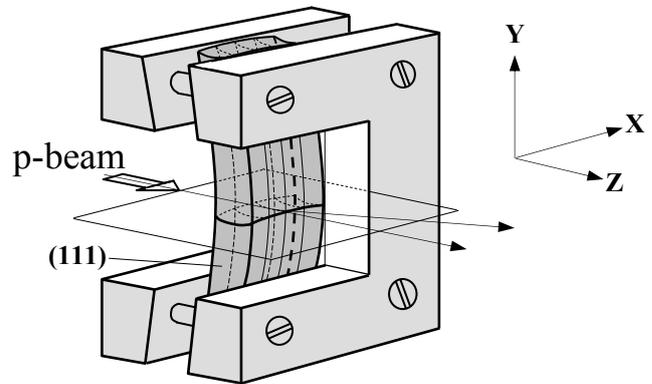
A significant advance was reached at PNPI with the development of a new method to produce bent silicon crystals for channeling using the elastic quasi-mosaic effect. This phenomenon was formerly discovered and well studied in quartz (O.I. Sumbaev, 1957 and 1968) and widely used in crystal-diffraction  $\gamma$ - and X-ray spectrometry. The effect arises from anisotropic properties of the crystal, which lead to curving

of normal cross sections of the specially cut single crystal quartz plates when they are being bent, thus resulting in broadening diffraction lines as if the single crystal has got a mosaic structure.

In our studies of bent crystals with X-rays, the quasi-mosaic effect was observed in silicon [2]. A plate proper cut in respect to the silicon lattice and a bending device with a plate for channeling are shown in Figs. 3 and 4. The measured bending angles of the (111) atomic planes in silicon were found to be in agreement with theoretical estimations and within a range optimal for crystal collimation of high energy charged particle beams (from zero to several hundred  $\mu\text{rad}$ ).



**Fig. 3.** Elastic quasi-mosaic effect in a bent silicon plate: bending of the plate to a cylinder of a radius  $\rho$  results in quasi-mosaic curving of the (111) crystallographic planes along the thickness  $T$ . The radius  $\rho'$  characterizes the curvature induced by anticlastic forces



**Fig. 4.** Quasi-mosaic silicon plate in a bending device. The channeling Si (111) plane coincides with the vertical narrow face of the plate

### 3. Extraction of a high intensity 70 GeV proton beam with quasi-mosaic silicon crystals at IHEP

The evident advantages of quasi-mosaic crystals are better heat dissipation from the interaction area and a smaller crystal size in the beam direction in respect to the strip and O-shaped crystals. These features were used in the IHEP-PNPI experiment on crystal extraction of a very intensive 70 GeV proton beam at IHEP.

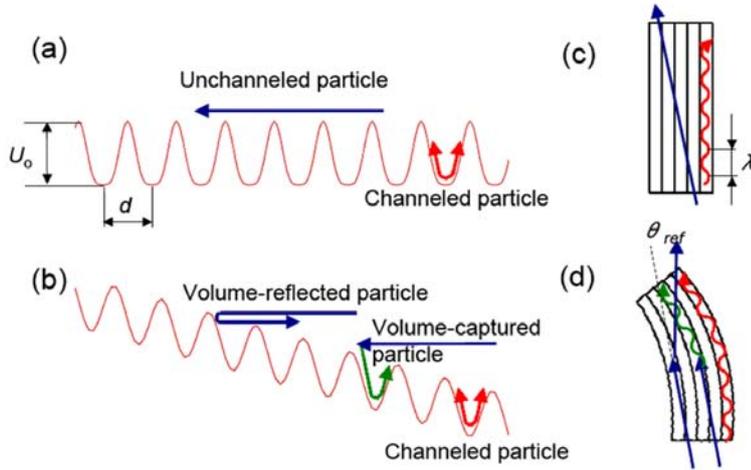
For this experiment, a silicon plate of  $2.65(Z) \times 30(X) \times 60(Y)$  mm<sup>3</sup> size was prepared and bent to the radius of 1.9 m providing a quasi-mosaic bending of the (111) planes approximately 400  $\mu\text{rad}$  along the plate thickness that was measured with X-rays before installation into the accelerator ring. The device was similar to that shown in Fig. 4.

In the proton extraction experiment, the intensity of the extracted beam reached  $4 \times 10^{12}$  protons per cycle and exceeded by a factor of 4 the best previous results. The beam intensity in the ring was equal to  $5.5 \times 10^{12}$  protons per cycle, so the efficiency of the multi-turn crystal extraction with the quasi-mosaic crystal was  $\sim 73$  %. The duration of the extracted beam was  $\sim 1$  second. The heating of the crystal was measured with a thermocouple, and the crystal temperature was found to be  $\sim 50$  °C. So, this experiment has demonstrated a feasibility of extraction of very intense beams from accelerators with crystals and has shown a significant potential to increase the extracted intensity.

### 4. Observation of the volume reflection effect with quasi-mosaic silicon crystals at IHEP

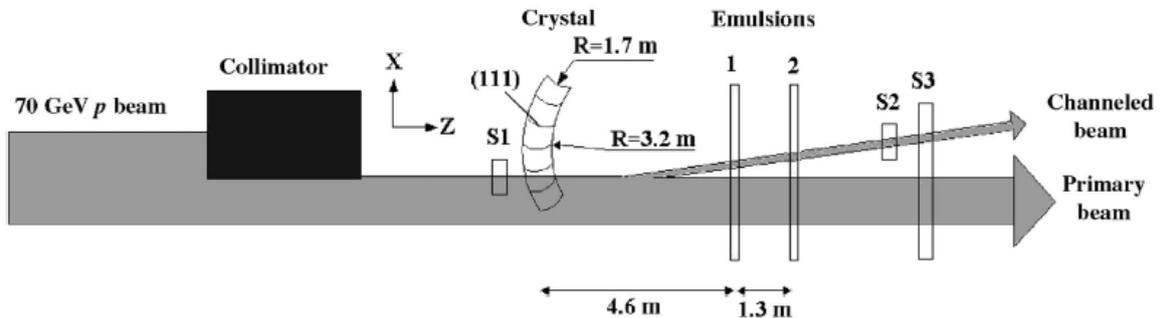
Details of channeling in quasi-mosaic silicon crystals were studied with the external and internal 70 GeV proton beams at IHEP. For these studies, samples with sub-millimeter thickness were prepared according to simulations, which indicated the advantage of very short (along the beam) crystals. In crystals of small thickness, the multiple Coulomb scattering becomes negligible, and this feature turned out crucial to observe for the first time the volume reflection effect predicted earlier (A.M. Taratin and S.A. Vorobiev, 1987). This effect arises from reflection of protons by a bent atomic plane at the tangency point and results in angular deflection of the reflected particle opposite to the atomic plane bending (Fig. 5a – d). The process

competes with the volume capture effect discovered at PNPI earlier (O.I. Sumbaev and V.M. Samsonov, 1982).



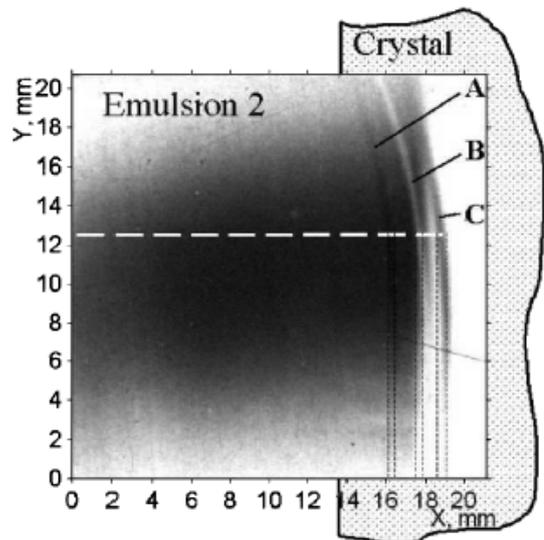
**Fig. 5.** (a) Periodic planar potential in a straight crystal for positively charged particles. The arrows show a channeled particle with the oscillatory motion in the potential well and a non-channeled particle, whose transverse energy is larger than the depth of the potential well  $U_0$ . (c) Schematic representation of the particle trajectories in a straight crystal. (b) Periodic planar potential in a bent crystal for positively charged particles. The arrows show the volume-reflected, volume-captured, and channeled particles. (d) Schematic representation of the particle trajectories in a bent crystal

A scheme of the experiment at IHEP is shown in Fig. 6 [3]. The crystal was mounted on a rotary table providing a 4 mm overlapping in the X-direction with a wide parallel beam of 70 GeV protons. The beam had an intensity of  $10^5 \text{ s}^{-1}$  and a divergence of  $15 \mu\text{rad}$ . The multiple scattering in the crystal was  $13 \mu\text{rad}$ , so both the divergence of the incident beam and the beam scattering in the crystal were small as compared to the critical angle for channeling  $\theta_c$  equal to  $24 \mu\text{rad}$ . A silicon plate of  $20(X) \times 60(Y) \times 0.72(Z) \text{ mm}^3$  size was bent to a radius of 0.48 m that induced a quasi-mosaic bending of the (111) planes with a radius of 1.7 m for an angle of  $420 \mu\text{rad}$ . The anticlastic (saddle) radius in the XZ-plane was found to be 3.2 m in the middle of the plate, and it was larger near the clamped areas.



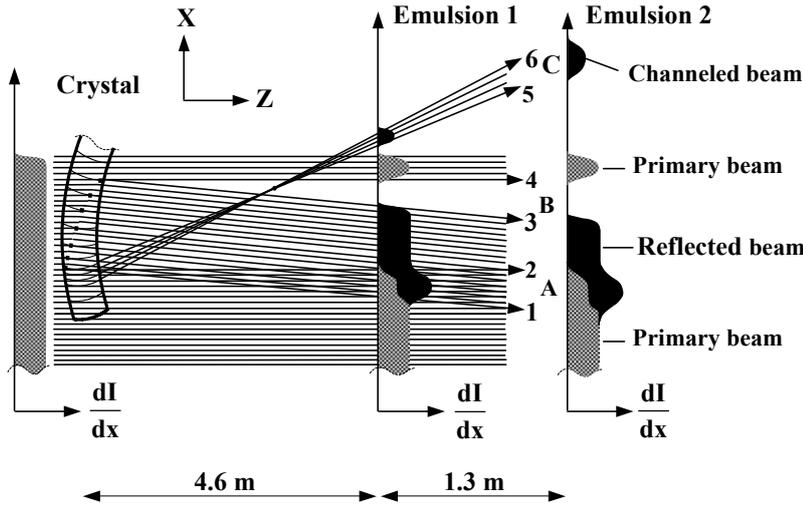
**Fig. 6.** Layout of the experiment at IHEP. S1, S2, and S3 – scintillation counters

**Fig. 7.** Image of the proton beam on emulsion 2 (beam goes to the observer). The white dashed line indicates a trace of microscopic measurement. The black dashed lines show X-readings corresponding to the borders of lines A, B, and C



Images of the beam transmitted through the oriented crystal were measured with emulsions. They displayed three distinct curved lines A, B, and C (Fig. 7). The lines were well visible near the sharp edge of the primary beam formed by a single jaw collimator in front of the crystal. For both emulsions, the positions and widths of the observed lines were measured with a microscope.

An explanation of the experimental results is given in Fig. 8. Due to anticlastic forces, the (111) planes change their orientation along the X-direction. On the entry face in the area where incident protons are tangent to the (111) planes, the main part of protons is captured by channeling (rays between 5 and 6), producing a spot C. For protons tangent to the atomic (111) planes somewhere inside the crystal, a volume reflection takes place (rays in between 1 and 3). Out of the X-ranges for the channeling and volume reflection, the incident protons pass through the crystal and experience only multiple scattering (rays above ray 4 and below 2). In this case, there is an area depleted of protons in between the reflected and primary beams, denoted by B, and another area where primary and reflected protons mix, denoted by A. Above and below the mid-plane shown in Fig. 7, the picture is similar except for the shift of the projected spots due to a change of the anticlastic curvature in the vertical direction. As a result, the joint pattern on the emulsions comprises three lines (two black lines A and C and one light line B) of slightly curved shape.



**Fig. 8.** Channeling and volume reflection in oriented quasi-mosaic crystal: interpretation of beam images on the emulsions (top view, protons go from left to right). The incident beam is shown as parallel and uniform. The dots within the crystal indicate tangency points of proton trajectories with the (111) atomic planes where the volume reflection takes place

The deflection angle of the channeled protons is estimated from the ratio of the distance between lines A and C to the distance between the crystal and the corresponding emulsion. Averaging the results over two emulsions, we find a value of the deflection angle  $(435 \pm 6) \mu\text{rad}$  that agrees with the bending angle of the (111) planes measured with X-rays.

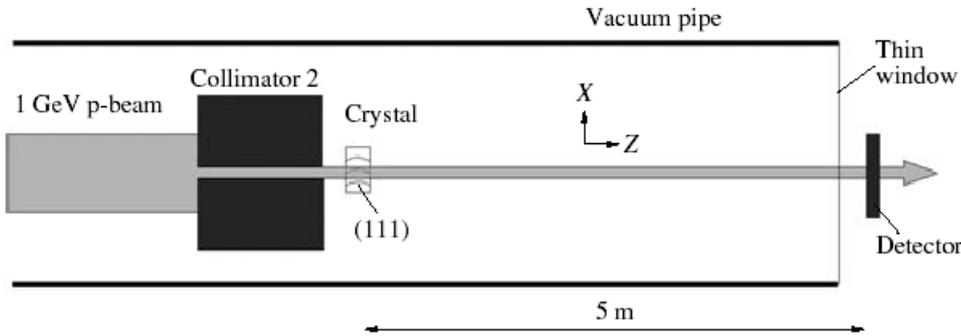
The deflection angle  $2\theta_R$  of the reflected protons is estimated from the angular width of lines A and B as the ratio of the line width to the distance from the crystal to each emulsion. Averaging the widths of A and B, we find the deflection angle  $2\theta_R$  equal to  $(39.5 \pm 2.0) \mu\text{rad}$ , or  $(1.65 \pm 0.08) \theta_c$  in terms of the critical angle for channeling. The width of the volume reflected beam shows that the angular acceptance for volume reflection is determined by the bending angle of the atomic planes essentially exceeding the acceptance for channeling ( $\approx \theta_c$ ).

The dark colour of line A demonstrates that the volume reflection is more intense than the channeling, so the volume reflection should play an important role in any application of bent crystals to beam manipulations. In fact, the observation of the volume reflection effect at IHEP resulted in an essential re-interpretation of the crystal collimation experiments at RHIC and Tevatron.

## 5. Study of the volume reflection effect in quasi-mosaic silicon crystals at PNPI

In the next experiment at PNPI, a bent quasi-mosaic silicon crystal was investigated with a narrow external parallel beam of 1 GeV protons (at IHEP a wide beam was used). This made possible to observe the channeling and volume reflection effects in the measured beam profiles separately, and thus to reveal the volume reflection effect in an evident manner [4].

The experimental layout is shown in Fig. 9. The beam was formed with two collimators distanced by  $\sim 31$  m and with a deflecting magnet between them. In the horizontal plane, the width and divergence of the beam incident on the crystal were  $\sim 80 \mu\text{m}$  and  $\sim 160 \mu\text{rad}$ , respectively. The vertical size of the beam on the crystal was  $\sim 1$  mm, and the beam intensity was  $\sim 2 \times 10^4$  protons per second.



**Fig. 9.** Layout of the experiment on the observation of volume reflection with the 1 GeV proton beam at PNPI

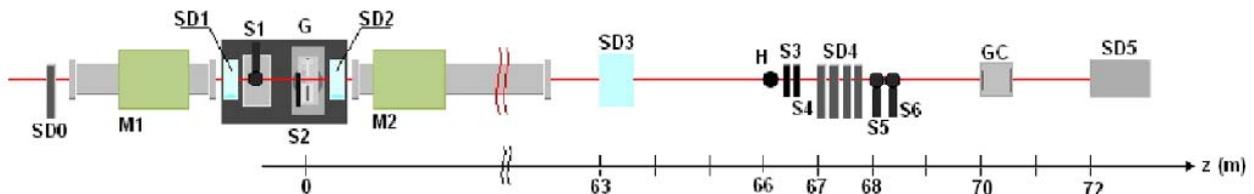
The silicon plate thickness was  $30\ \mu\text{m}$  giving the multiple scattering angle of  $105\ \mu\text{rad}$ , which is smaller than the critical angle for channeling equal to  $170\ \mu\text{rad}$  for the (111) silicon planes in the case of 1 GeV protons. The plate was bent with a radius of 22 mm in the vertical plane by means of clamping in cylindrical mirrors with a hole of 3 mm in diameter at the centre for passing the proton beam. The quasi-mosaic bending of the (111) planes measured with X-rays was found to be  $\sim 380\ \mu\text{rad}$ . The bent crystal was mounted on a rotary table attached to the exit of the second collimator. Position-sensitive detectors were placed at a distance of 5 m from the crystal outside the vacuum pipe.

Fitting experimental peaks, we found the probabilities of the volume reflection and channeling effects to be  $(0.71 \pm 0.03)$  and  $(0.63 \pm 0.03)$ , respectively. The mean deflection angle of the protons volume reflected in the crystal was found to be  $(236 \pm 7)\ \mu\text{rad}$ . These results confirmed in a clear and evident way the existence of the volume reflection effect in bent crystals.

## 6. Study of the volume reflection effect in bent silicon crystals with a 400 GeV proton beam at CERN

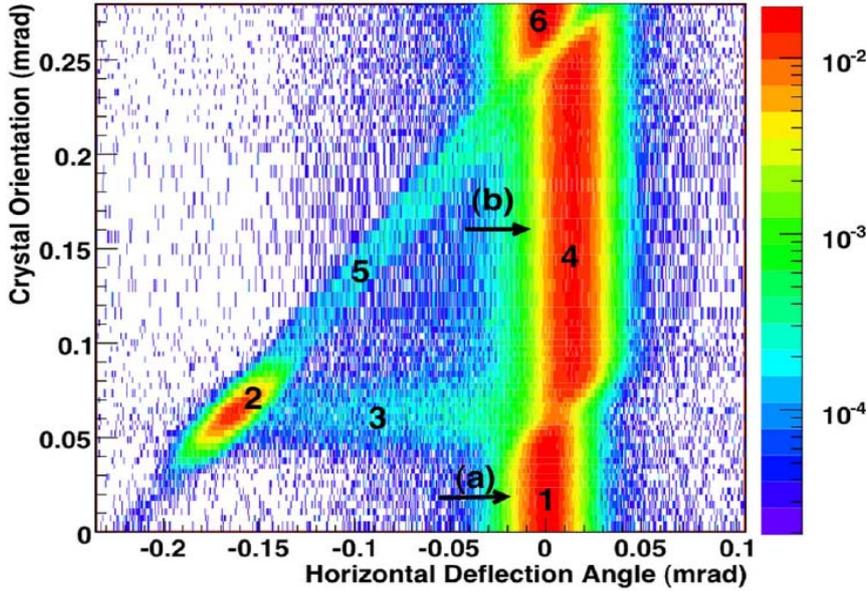
In 2006–2009, detailed studies of beam-crystal interactions were carried out at the CERN SPS in frames of the H8-RD22 Collaboration. The first experiments in these studies were devoted to measurements of the volume reflection effect with 400 GeV protons [5, 6].

The experimental layout shown in Fig. 10 consisted of a high precision goniometer (G) with crystals and various detectors to track particles [7]. The goniometer consisted of three high precision motion units, two linear and one angular. With the linear motions, the crystals were positioned with respect to the beam centre with an accuracy of several  $\mu\text{m}$ . With angular scans, the crystals were aligned with respect to the beam axis with an accuracy of  $1.5\ \mu\text{rad}$ . Scintillator counters were used to determine the beam transverse offset with respect to the crystal (S1 and S2), to provide the basic trigger signal for silicon detectors (S3 and S4), and to measure the beam divergence and the beam profile (S5 and S6). High statistics data were taken with a set of silicon micro-strip detectors (SD $n$ ) with the spatial resolution in the range 10–30  $\mu\text{m}$ .



**Fig. 10.** H8-RD22 experimental set-up in 2006. M1 and M2 are two bending magnets – a part of the H8 beam transport line with no specific function for this experiment. See the text for more details

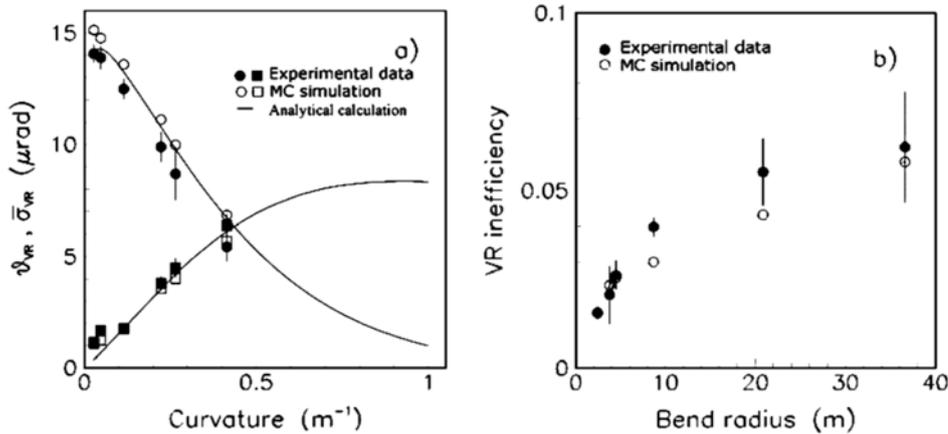
For the experiment, several quasi-mosaic and strip silicon crystals were prepared. In fact, the results of the measurements with all these crystals turned out to be very similar. A plot of an angular scan made with one of the strip crystals is presented in Fig. 11. This crystal had the (110) channeling planes bent due to anticlastic effect at an angle of  $162\ \mu\text{rad}$  along its 3 mm length in the beam direction. The multiple scattering angle of 400 GeV protons in this crystal was equal to  $5.3\ \mu\text{rad}$ , which is smaller than the critical angle equal to  $10.6\ \mu\text{rad}$ . The proton beam had a divergence of  $(8 \pm 1)\ \mu\text{rad}$  and a spot size of about 1 mm.



**Fig. 11.** Beam intensity recorded by the silicon micro-strip detectors as a function of the horizontal deflection angle ( $X$ -axis) and the crystal orientation ( $Y$ -axis). Six regions can be distinguished: 1 and 6 – non-channeling mode; 2 – channeling; 3 – dechanneling; 4 – volume reflection; 5 – volume capture. A wider angular acceptance of the volume reflection as compared to that of channeling is clearly seen

The deflection angle of the channeled beam and the channeling efficiency were found to be  $(165 \pm 2) \mu\text{rad}$  (in agreement with the value of the bending angle of the crystal) and  $\sim 55\%$ , respectively. The deflection angle of the volume reflected beam and the volume reflection efficiency were found to be  $(13.9 \pm 0.2_{\text{stat}} \pm 1.5_{\text{syst}}) \mu\text{rad}$  and  $\sim 98\%$ , respectively. The latter value is significantly larger than the maximal theoretical single-pass efficiency for channeling.

The trend of the volume reflection parameters (the deflection angle and efficiency) in a bent silicon crystal were investigated as a function of the crystal curvature [8]. The measurements were performed at six different curvatures, the experimental results and simulations are presented in Fig. 12a, b. The agreement between the experimental data, the analytical approach and the MC simulation is fairly good.



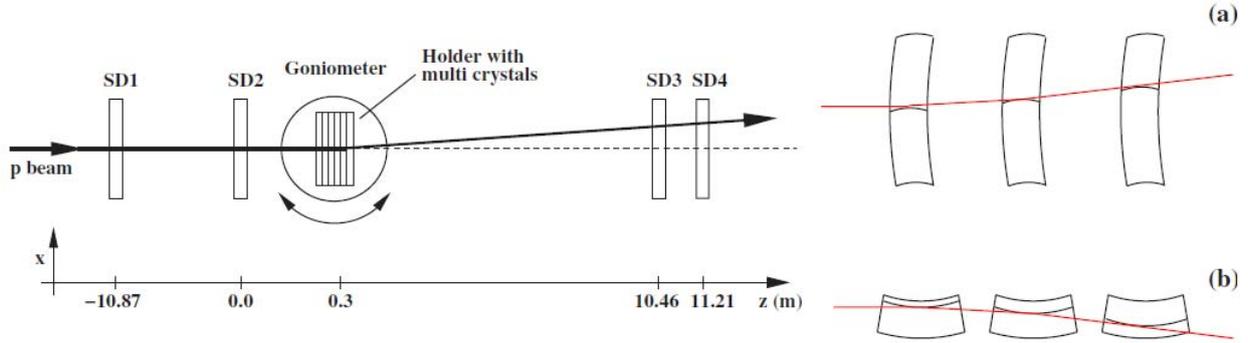
**Fig. 12.** Dependencies of the volume reflection parameters on the crystal curvature and the bending radius  $R$ : a – the deflection angle (dots) and its rms deviation due to potential scattering (squares) versus the crystal curvature; b – the volume reflection inefficiency versus the bending radius

Taking into account the observed dependences of the Volume Reflection (VR) parameters on  $R$ , the optimal bending radius for a short silicon crystal for beam deflection due to VR is found to be about  $10R_c$ .

The strong potential scattering of particles for  $R$  close to  $R_c$  shows that such a crystal can be used as an effective scatterer. The thickness of the crystal scatterer can be reduced down to the wavelength of the particle oscillations in the planar channel ( $60 \mu\text{m}$  for 400 GeV protons and  $250 \mu\text{m}$  for 7 TeV protons). In this way, the inelastic losses of particles in the scatterer can be minimized.

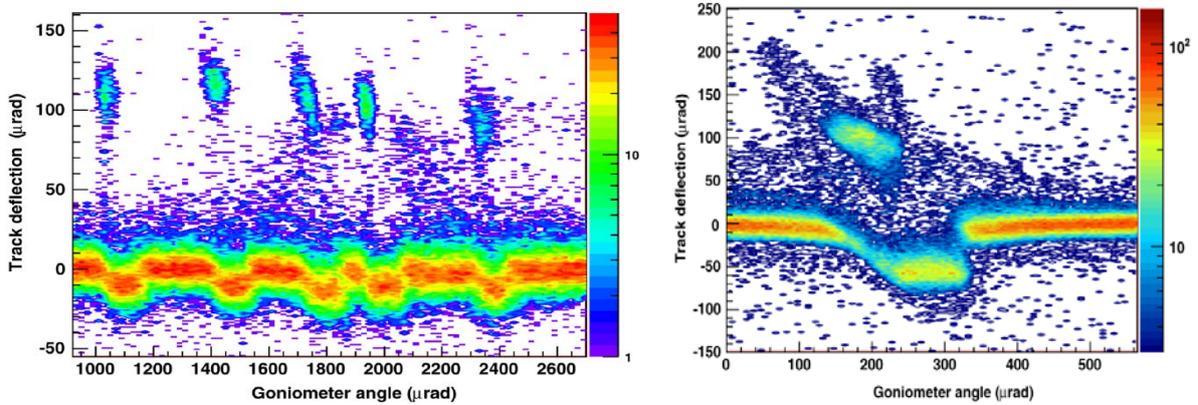
## 7. Study of multiple volume reflection in bent crystals with a 400 GeV proton beam at CERN

Very high efficiency of volume reflection makes possible to use several crystals to increase the deflection angle of the volume reflected particles. The first experiment was performed with two aligned quasi-mosaic crystals [9]. Then, the multiple volume reflection of the proton beam was studied in detail with a five-crystal deflector [10]. A scheme of this experiment is shown in Fig. 13a, b.



**Fig. 13.** Schematic layout of the experimental set-up used to study multiple volume reflection at the H8 beam line of the CERN SPS. The trajectory of a particle undergoing a sequence of volume reflections in a series of aligned crystals is schematically represented on the right for quasi-mosaic (a) and strip (b) crystals

In the aligned positions of five bent quasi-mosaic crystals (Figs. 13, 14), the deflection angle was determined to be  $(52.96 \pm 0.14) \mu\text{rad}$  and the efficiency was found higher than 80 % for the angular acceptance at the deflector entrance of  $70 \mu\text{rad}$ , the maximal efficiency value being  $(90 \pm 1 \pm 3) \%$ .



**Fig. 14.** Beam intensity distributions observed in the angular scans performed before (left) and after (right) the relative alignment of the five crystals. The beam intensity is reported as a function of the track deflection angle (vertical axis) in different goniometer angular positions (horizontal axis)

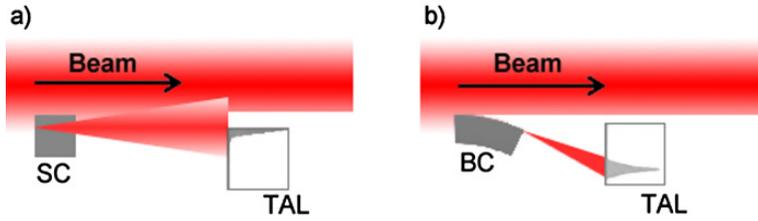
The experiments demonstrated that the mean deflection angle grows proportionally to the number of reflections, but the deflection efficiency is decreasing with the number of reflections due to volume capture of protons in each of the crystals. The volume-captured beam fraction was typically about  $\epsilon \approx 1.9 \%$  per reflection.

In the following experiments, we found that under a certain alignment the deflection efficiency can reach 88 % for eleven crystals [11]. Multiple volume reflection in single crystals was also observed [12].

In the whole, the studies of multiple-volume reflections in bent crystals resulted in the development of beam deflectors which have an efficiency exceeding the channeling efficiency and provide a much wider angular acceptance and the deflection angles sufficient for beam collimation.

## 8. Study of crystal collimation with proton and heavy ion beams at the SPS: the experiment UA9

The idea of crystal collimation in comparison with the traditional one is shown in Fig. 15a, b, where it is easy to see that the crystal deflects halo particles onto the absorber far from the absorber edge, thus decreasing scattering of halo particles back to the main beam.



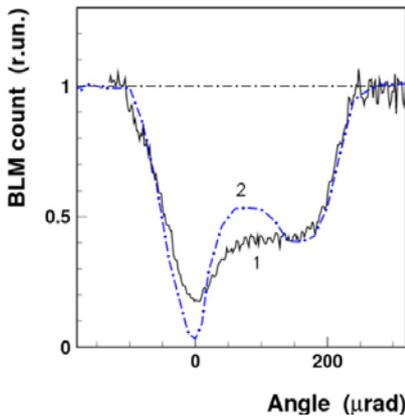
**Fig. 15.** (a) Collimation scheme using a solid state primary collimator scatterer (SC). (b) Collimation scheme with a bent crystal (BC) as a primary collimator. Halo particles are deflected and directed onto the absorber (TAL – Target Aperture Limitation) far from its edge

After extensive investigations of the beam-crystal interaction at the SPS H8 and H4 external beam lines in frames of the H8-RD22 Collaboration, the UA9 crystal collimation experiment in the SPS ring was proposed. It was approved in September 2008 and started its operation in 2009 [13].

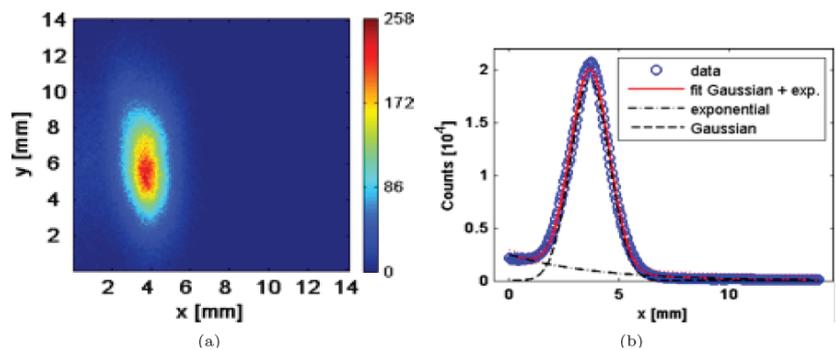
The UA9 set-up consists of two stations [14]. The first station contains four goniometers with crystals of different types, which can be used alternately as a primary collimator. The second station contains a 60-cm-long tungsten absorber used as a secondary collimator. Between the two stations, there are: a Medipix pixel detector to observe the spatial distribution of the deflected particles and a two-sided LHC collimator to align the UA9 elements relative to the beam orbit and to scan the beam halo.

In the first dispersive area downstream the absorber, a TAL station with targets limiting the accelerator aperture is installed to detect the off-momentum halo fraction. Such particles, which have lost some momentum in the crystal or in the absorber, may escape from the collimation area. At the high dispersion area, they undergo an additional displacement from the orbit and may be detected.

The test beam was formed with 120 GeV or 270 GeV protons, typically in a single bunch with  $10^9$ – $10^{12}$  particles. Lead ion beams were used in the same range of energy per nucleon and with ten times less particles. In the storage mode, the beam lifetime ranged from a few minutes to 10 hours. The number of particles hitting the crystal was in the range of  $10$ – $10^3$  protons per bunch with the duration of a few ns. To increase the total intensity and the loss rate, four, eight or 52 bunches were used.



**Fig. 16.** 1 – dependence of the detector counts on the angular position of the crystal; 2 – the dependence of the number of protons inelastically scattered in the crystal on its orientation angle, as was obtained by simulation

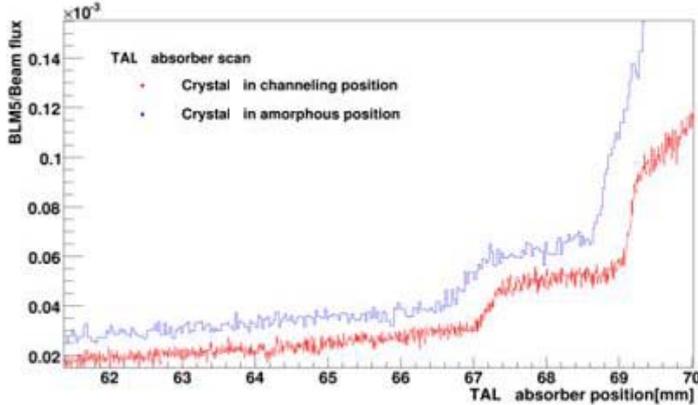


**Fig. 17.** Image of the beam deflected with the crystal (a) and its horizontal projection (b) obtained with the Medipix detector

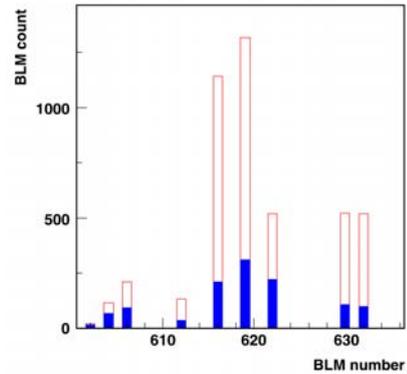
A typical response of the beam loss counters to the angular scan of the crystal is shown in Fig. 16 [13, 15]. In the minimum of the loss count, the fraction of the beam halo channeled by the crystal is maximal. With the best crystals, the reduction of beam losses in the channeling state reached a factor of  $\sim 25$ .

A wide angular range of decreased beam losses to the right of the minimum is due to volume reflection of halo particles in the crystal.

Images of the deflected beam obtained with the Medipix detector [13] are shown in Fig. 17a, b. The channeling parameters of the crystals in the collimation position were studied by means of collimator scans. For two tested silicon crystals, the channeling efficiencies were found to be  $(75 \pm 4)\%$  and  $(85 \pm 5)\%$  [13].



**Fig. 18.** Off-momentum collimation leakage for the crystal in channeling (red) and in amorphous (blue) positions. See the explanation in the text



**Fig. 19.** Beam loss map in the SPS for the amorphous (red) and channeling (blue) orientations of the crystal

The fraction of beam halo particles escaping from the collimation devices was estimated by using the target of the TAL station [16]. Fig. 18 shows the dependence of the loss count (BLM) on the horizontal position of the target (absorber). The off-momentum collimation leakage for the crystal in the channeling mode was found to be reduced by a factor of about 5.

The stored multi-bunched beam was used to measure beam losses in regions of the SPS ring far from the crystal. Fig. 19 shows the beam losses detected 1 km downstream of the crystal [16]. It is seen that the losses for the channeling orientation are few times smaller than those for the amorphous one.

Summarizing, we can conclude that the UA9 results provide a solid demonstration of the potential advantage of the crystal-assisted collimation in colliders.

## 9. Study of crystal collimation with a 7 TeV proton beam at the CERN LHC: the LUA9 project

In 2011, to extend crystal collimation technology at the LHC, the LUA9 project was proposed [17]. In the project, it is supposed to install crystals close to the existing LHC primary collimators to provide a usage of the secondary collimators as halo absorbers. Beam crystal collimation is planned to test for all degrees of freedom: horizontal, vertical, skew and longitudinal. The crystal orientations are planned to control with an accuracy better than  $1 \mu\text{rad}$ . The optimal channeling angle for the LHC is estimated to be  $\sim 50 \mu\text{rad}$ , the optimal crystal length along the beam being  $\sim 4 \text{ mm}$ . It is proposed to carry out all necessary R&Ds during 2012–2014, to install first crystals at the LHC in 2014, and to start experimental studies in 2015.

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