Novel applications in accelerator science based on bent single crystals.

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Abstract.
Ideas of use the particle channeling in bent crystals for steer the beams have been checked up and advanced in many experiments. However, until now, this method of beam formation has limitations in application, since the channeling process involves beam particles with low angular divergence, limited by the angle of Lindhard. Here we test at the U-70 accelerator two crystal devices, the focusing crystal and multistrip crystal, which expand the boundaries of application of bent crystals at accelerators.

Keywords: crystal channeling, particle beams, muon collider

1. Introduction.
Ideas of use the particle channeling in bent crystals for steer the beams have been checked up and advanced in many experiments (see [1] and references). Recently, a curved single crystal was tested at the LHC for the task of the beam collimation [2]. This method is also widely used in U-70 accelerator of IHEP, where crystals are used in regular runs for beam extraction and forming [3]. However, until now, this method of beam formation has limitations in application, since the channeling process involves beam particles with low angular divergence, limited by the angle of Lindhard $\theta_L (\theta_L \sim (1/E)^{1/2} = 0.02–0.002$ mrad for protons with energies of $E = 100–10000$ GeV, respectively). Here we describe two crystal devices, the focusing crystals and multistrip crystals, which expand the boundaries of application of bent crystals at accelerators.

2. Possibility of production of extracted secondary particle beams at large hadron colliders with focusing crystal device.
If the energy of the accelerated proton beam is $E > 1$ TeV, as at large colliders (such as the LHC and larger), the energy of secondary particles becomes as high as hundreds of GeVs. The divergence angle of such particles from the target in the laboratory reference frame $\theta[\text{mrad}] = 400/P[\text{GeV}/c]$ ($P$ is the momentum of a particle) is about 1 mrad or less. This property allows a surprisingly simple method based on a crystal focusing device to obtain particle beams [4]. The proposed scheme is shown in Fig. 1a. Secondary particles ($\pi$ and $K$ mesons) are generated on a miniature internal target placed in the ring of a large proton accelerator with an energy of about 1 TeV and higher (e.g., LHC or FCC). The target can be a gas or liquid metal jet target. A crystal device is placed at a distance of several (no more than ten) meters. It is noteworthy that great progress in the fabrication of different variants of such devices was achieved in several years [5–11].
As an example, Fig. 1b shows a silicon focusing device developed at the IHEP [9]. An oriented silicon plate with a trapezoidal cross section is prepared. The plate is bent in the vertical direction by a metallic holder. The anisotropy of the crystal lattice induces the uniform horizontal bending of the trapezoid, where a focusing effect occurs on the canted side. A high quality of the device was tested at the focusing of protons with energies of 50 GeV [9] and 400 GeV [10]. The crystal device not only focuses but also deflects a particle beam, providing the output beam parallel within the Lindhard angle, which is about 10 µrad at energies $E \sim 400$ GeV.

To extract the beam from the ring accelerator without collision with magnets, the deflection angle in the crystal less than one degree is sufficient. It was shown in [12–14] that crystals under such conditions can form focused pion and kaon beams with a high efficiency. Fig. 2a shows the calculated spectrum of pions that are produced on the target and reach the focusing edge of the crystal by the Malensek formula [15]. The angles of horizontal and vertical captures of the focusing crystal are assumed to be 2 mrad, which is achievable with existing technologies.

To obtain a particle beam with a narrow momentum distribution, as in the magneto-optical channel, one can use the extraction scheme, where a magnet placed between the target and crystal deflects particles in the plane perpendicular to the plane of deflection of the crystal. The width of the momentum distribution will be equal to the ratio of the transverse size of the crystal to the magnet-induced linear dispersion. We also note that one of the standard dipoles of the accelerator can be used as the magnet by placing the target in front of it (see Fig.2b).
Fig. 2 a – Normalized spectrum of the production of π mesons in the target per nuclear interaction event into the angular range covering the crystal. b – Schematics of the formation of a secondary beam with a narrow momentum distribution planned to be implemented at the U-70.

2.1. **Experiment on the formation of a secondary particle beam by means of a crystal.**

As mentioned above, focusing crystals were often tested on proton beams. Here, we report the results of the experiment demonstrating the formation of pion and kaon beams by a crystal in the 4a beamline of the IHEP accelerator. Figure 3a shows the layout of the experiment. The focusing crystal was adjusted to the channeling regime on a proton beam, as in [9]. A point source of a 50-GeV divergent proton beam was created on the basis of an active thin-plate target (150 µm in thickness, 20 mm in length, and 10 mm in height) made of heavy CsI scintillator.

![Diagram](image)

Fig. 3 a – Layout of the experiment: (T) CsI target, (Cr) crystal in the goniometer, (S) miniature scintillator, (Vm) vertical magnet, and (H) scintillation hodoscope; b – Orientational dependences of the number of particles deflected by the crystal: (top) experiment for protons, (bottom) experiment for the secondary particles, $\theta_{al}$ is the crystal alignment angle.

The focusing (111) Si crystal had a width of 2 mm, a height of 20 mm, and a length of 25 mm. The bending angle was 3.4 mrad and a focal length was 1.5 m. We collected events of coincidence of the CsI scintillator target, miniature detector $S$ whose size is comparable with the cross section of the crystal, and hodoscope $H$ far from the crystal. The beam channeled in the crystal and deflected by it enters the hodoscope cell and initiates a signal peak in it. Fig. 3b shows the dependence of the number of particles (efficiency) deflected by the total crystal bend angle on the alignment angle $\theta_{al}$ of the crystal in the goniometer. About (14 ± 3)% of protons were deflected by a total angle of 3.4 mrad corresponding to the bending of the crystal. The FWHM of the angular dependence in Fig. 3b is 105 µrad. This narrow angular range, where the deflected beam is
observed, corresponds to the geometrical parameters of the experiment, where the rotating crystal is directed to the target. The reached parameters are in agreement with the Monte Carlo computer simulation of the experiment using the algorithm proposed in [12], where the geometry of the arrangement of the target and crystal, capture of particles into the channeling regime, and dechanneling inside the crystal are taken into account. According to the calculations, 16% of particles should be deflected to the total angle.

The second stage of the experiment was performed with the switched-on vertical magnet $V_m$ (see Fig. 3a) and with the crystal already tuned to the channeling regime using the proton beam. At the switching-on of the vertical magnet between the crystal and detector, we adjusted to secondary particles, primarily $\pi$ mesons, in the momentum range of $(18 \pm 3)$ GeV/$c$. Under the same conditions, we measured the same orientational curve (when the crystal “sees” the target) on the hodoscope but for secondary particles (bottom curve in Fig. 3b) and determined the yield of particles. It appeared that the crystal deflected the beam with an intensity of 0.001% per proton incident on the target, which corresponds to the calculation in [12]. This value is an order of magnitude lower than that in the magneto-optical channels of the U-70 accelerator. This is explained by the nonoptimal crystal optics for a relatively low energy of 50 GeV of the primary proton beam, when the crystal is too small for a noticeable part of secondary particles divergent by tens of mrad from the target to be captured into the channeling regime. The situation is fundamentally different for TeV energies, where the electrostatic field of the crystal, which is equivalent to a magnetic field of 1000 T for deflection of particles, becomes of primary importance.

3. Muon Collider operating by means of the focusing crystals.

Recently in [16] the new method of producing neutrino beams at accelerators was proposed, similar to the method of producing pion and kaon beams described in the previous paragraph. The difference is that it is necessary to focus the beam of pions and kaons with two crystals – in the horizontal and vertical planes, and instead of the near experimental setup it is necessary to provide a decay tunnel several kilometers long, where neutrinos are obtained from decays $\pi, K \rightarrow \mu \nu_\mu$. We note that the neutrino beam obtained with the help of the crystal is accompanied by muons of very high energies. These muons can be used to create a new type of muon Collider.

The idea of a muon Collider has been developed since the 70s [17]. Currently, various energy projects ranging from 120 GeV [18], for the study of the Higgs boson, to 3 TeV in the beam [19], are being considered as an alternative to the projects of electron linear colliders. Modern muon Collider projects are very expensive and complex and require the construction of a chain of new superconducting accelerators to solve problems with a short lifetime and reduce the emittance.
Fig. 4. Crystal muon collider: $T_{1,2}$ – internal targets in the LHC, $FC_{1,2}$ – focusing crystals, $DT_{1,2}$ – decay tunnels, $BL_{1,2}$ – beam lines.

The essence of our proposal is shown in Fig. 4. Internal targets $T_{1,2}$ are installed in two different rings of one of the large hadron colliders (TeV class). Two focusing crystals $FC_{1,2}$ form beams of secondary pions and kaons as described in the previous paragraph. Muon beams are produced in decay tunnels about a kilometer long. If the energy of the primary proton beam is 6.5 TeV, as in the LHC, one can count on the formation of muon beams of about hundreds of GeV. The production angles of muons at such energies are of the order of tens of microrad. In this case beamlines $BL_{1,2}$ with a final lens with a high gradient can capture and focus muon beams in a large momentum range of several percent.

Below we give a very rough estimate of the luminosity of such a muon Collider. The well-known formula for luminosity is $L = f \times \frac{N^2}{4\pi\sigma^2}$, where $f$ is the frequency of collisions, $N$ is the number of particles in a bunch, $\sigma$ is the beam size. For example, for the LHC, where about 3000 bunches with a frequency of circulation of about 10000 per second (that is, $f = 3 \times 10^7 \text{s}^{-1}$), the intensity of $10^{11}$ particles per bunch and a beam size of several dozen microns, this gives $10^{34} \text{cm}^{-2}\text{s}^{-1}$. Bunches of $10^{-4} \times 10^{11} = 10^7$ pions will form in thin internal targets of 10 $mg/cm^2$ long. Taking into account the selected momentum range of 10% and the size of the focused beams of the order of 1 mm at the muon intersection point, we obtain the luminosity value $L_\mu \sim 10^7 \times 10^{12} \times 10^2 = 10^{21} \text{cm}^{-2}\text{s}^{-1}$.

This is not enough for full-scale muon experiments, but it can be used at least as a test bench for future experiments. The undeniable positive quality of this proposal lies in its simplicity. No need
to build a new accelerator. The project can be implemented in the existing LHC and Tevatron, or under construction FCC and preserved Russian project UNK.

4. Implementation of multistrip crystals to protect the septum magnets

A new accelerator problem – the radiation protection of the electrostatic septum began to be solved with the help of a strip crystal at CERN [20]. On the accelerator U-70 we have a similar task – the protection of the magnetic septum, but its current partition is much thicker, about 2 mm [21]. In our case, it is more optimal to use the reflection on the crystal chain. Volume reflection is more efficient than channeling, but requires amplification of the deflection angle by applying multistrip crystals as shown in Fig. 5a. It should note, at first time different constructions of such type multi - crystal structures were developed and tested in UA9 experiment (see [1]).

According to our measurements in a beam line deflection angle of the beam by crystal device in Fig.6a is equal to 0.16 mrad. At next step a station with this crystal was installed in a block 22 of the U70 accelerator to protect the SM24 septum in a block 24 as shown in Fig. 5b.

![Fig5. a – Multistrip crystal device for the beam deflection: (top) the schematic of operation and (bottom) the appearance and arrangement with respect to the beam. b – The scheme of SM24 septum shadowing in the U-70 ring.](image)

In the first tests we just threw a beam on the septum with a fast kicker magnet. In the Fig. 6a we see how the loss of particles on the septum decreases with the optimal orientation of the crystal. The measured shadowing factor is 60%. This is confirmed by Monte Carlo calculations. Fig. 6b shows the calculated shadow of the crystal in the particle distribution in the septum region.
Fig. 6 a – the dependence of particle loss on the septum of the crystal orientation based on the data of BLM monitor; b – particle distribution in the section where the septum magnet is located. The dip on the left is due to the shadowing of the septum from the oriented crystal device.

These results are even more optimistic than those obtained in CERN at the SPS accelerator (shadowing factor 40%), where a single curved crystal strip was used instead of a multistrip structure [20]. In the future, it is planned to use the multi-crystal to shadow the septum not in the experimental mode, but in the intensive slow resonant extracted beam of $10^{13}$ particles per spill from the U-70.

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