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Colloquia: Channeling 2010

Modern success in channeling study and applications at the U-70 accelerator of IHEP

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Summary. — This paper presents an overview of the results obtained at the U-70 accelerator of IHEP to use bent crystals for beam control of high energy protons. Considerable attention is paid to practical application of crystals to create new modes of beam extraction from the accelerator to ensure experiments on high energy physics. It was shown that with the crystal deflectors the efficiency reached $\sim 90\%$ with intensity up to 10^{12} protons per cycle of U-70. The results of experiments on the use of crystals to enhance the effectiveness of the absorption of the unused beam, as well as the use of crystals for collimation of beam halo are presented. Perspectives to the use of bent crystals to extract low energy light ions from U-70 are also discussed.

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1. – Introduction

Ideas to use the particle channeling in bent crystals for steering the beams have been checked up and advanced in many experiments (see [1-3] and references herein). This method has found the widest practical application at the U-70 accelerator of IHEP, where crystals are used in regular runs for both beam extraction and forming [4, 5].

2. – Beam extraction from the U-70 ring by means of bent crystals

Different types of extraction schemes were realized by bent crystal. In the first case high efficiency of extraction up to 85% is reached applying short silicon crystals (Si 19, Si 22, Si 106 in fig. 1). Short crystals with lenth of 2 mm and about 1 mrad of bending take the role of first septum, while additional magnets provide deflection of a circulated beam out of the ring. Such high efficiency is based on a multi-turn process when particles,

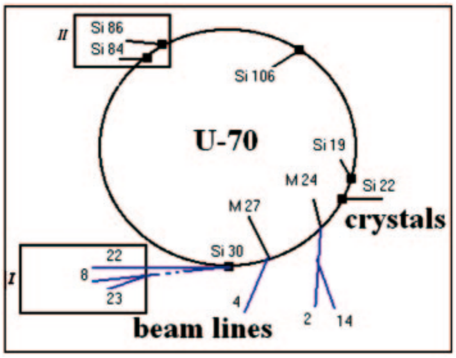

Fig. 1. – Crystal location at U-70 ring.

which are not captured into channeling mode on the first passage of the crystal, can be efficiently captured on next encounters with a crystal. Extraction efficiency of 70 GeV protons *versus* crystal length is presented in fig. 2 in comparison with the simulation results.

In fig. 3 the crystal extraction efficiency was measured as a function of proton energy. There is good agreement between the measured and calculated efficiencies of bent crystals. The efficiency reduction at the energy decrease is explained by the increase of multiple scattering angle and the decrease in dechanneling length. The obtained dependence also shows that by the use of the same crystal one can extract beams in a broad energy range of 40–70 GeV with an efficiency of more than 60%.

An important point is the crystal radiation hardness at accelerators. The limit of irradiation, at which a crystal survives, obtained in CERN and BNL experiments counts $\sim 2 \times 10^{20}$ proton per cm^2. Our experiments have confirmed these results. Crystals do not loose channeling properties during two runs of 1400 hours/each. As far as heat loads are concerned, our experience shows that crystal with efficiency 80–85% ensures

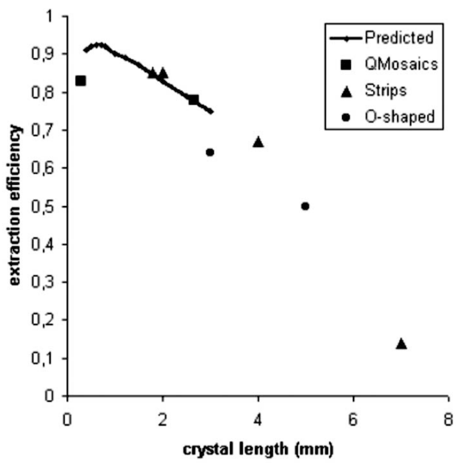

Fig. 2. – Extraction efficiency dependence *vs.* crystal length.

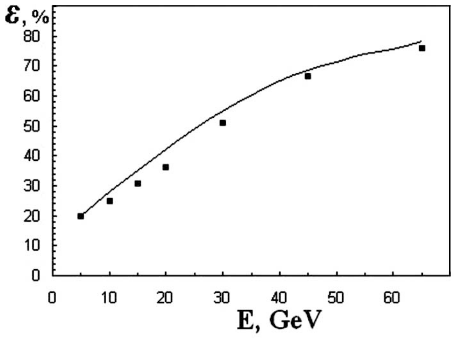

Fig. 3. – Crystal extraction efficiency *vs.* proton energy.

beam extraction at the intensity of up to 10^{12} particle/cycle and duration 1–2 s/cycle, suiting the requirements of the most experiments at the IHEP accelerator. The created extraction method has been working at IHEP since the end of 1999 in every accelerator run. Detailed consideration of all the systems of this extraction is given in [5].

Another option of extraction using long crystals (a few cm in length, several tens mrad bend) was investigated. The efficiency of extraction drops with the deflection angle increase (fig. 4), but these moderate intensity beams are also promising for providing the physical program with protons and ions in a few IHEP beamlines [6].

3. – Crystal channeling use for beam collimation improvement at U-70

The classic two-stage collimation system for loss localization in accelerators typically uses a small scattering target as a primary element and a bulk absorber as a secondary element. The role of the primary element is to give a substantial angular kick to the incoming particles in order to increase the impact parameter on the secondary element, which is generally placed in the optimum position to intercept transverse or longitudinal beam halos. An amorphous primary target scatters the impinging particles in all possible

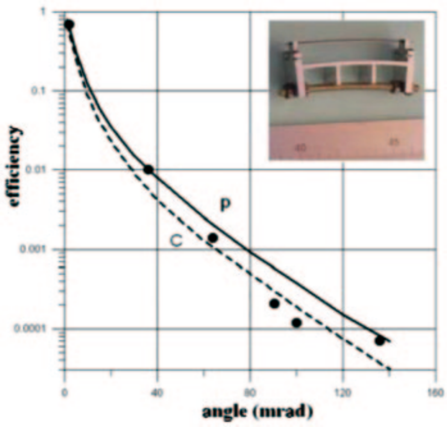

Fig. 4. – Extraction efficiency dependence *vs.* crystal bend angle.

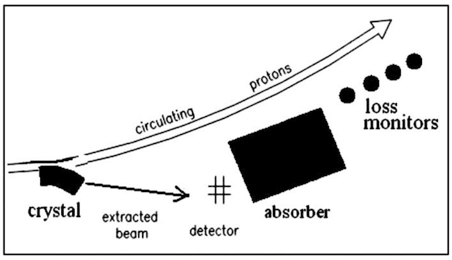

Fig. 5. – The scheme of the experiment on beam collimation by crystals.

directions. Ideally, one would prefer to use a "smart target" which kicks all particles in only one direction: for instance, only in the radial direction, only outward, and only into the preferred angular range corresponding to the center of the absorber (to exclude escapes). A bent crystal is the practical implementation for such a smart target: it traps particles and conveys them into the desired direction. Here, the random scattering process on single atoms of an amorphous target becomes the selective and coherent scattering on atomic planes of an aligned monocrystal.

In the U-70 experiment [7] different crystals in high-vacuum goniometers were serially entered in a circulating accelerated beam as shown in fig. 5. This angle of bending is sufficient to separate the circulating and deflected (by the crystal) beams in space. The beam deflection effect due to channeling was measured by secondary emission detector (SEM) located in the vacuum chamber of an accelerator near to the circulating beam. Parameters of the accelerator and experimental details are described in [5].

Measurements have been carried out at a proton energy of 50 GeV. Figure 6 illustrates the beneficial effect of crystals when used as a primary element of the system concerning a beam (the beam was brought to a crystal with the help of a slowly increasing bump). It shows beam profiles in the radial direction of 23 m downstream of the crystal as measured on the entry face of the absorber. Two cases are reported. First, the end face of the amorphous absorber is used as a primary target while the crystal is kept outside of the beam envelope. As expected, the beam profile is peaked at the absorber edge. The second case corresponds to the aligned crystal: in this case the crystal channels most of the incoming particles (about 90%) into the depth of the absorber.

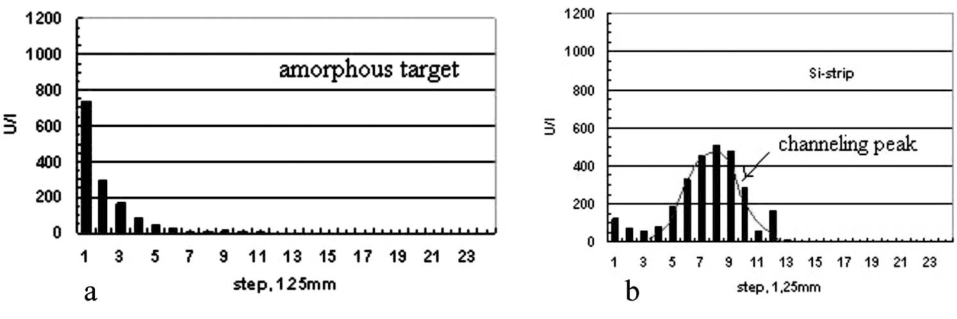

Fig. 6. – Beam profiles on the entry face of the absorber in different cases.

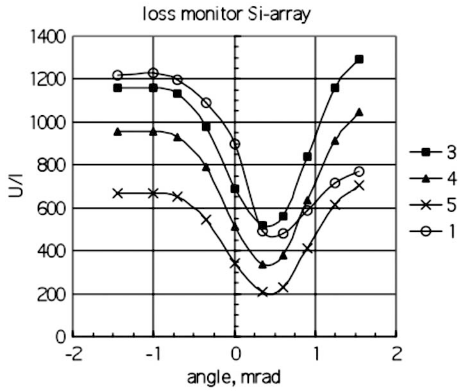

Fig. 7. – Dependences of loss monitors *vs.* orientation of the crystal with respect to the beam.

The deep flow of particles improves collimation, or can be used for extraction of circulating particles from the accelerator. In fig. 7 are shown orientation curves of particle losses, measured by the signals on the 5 ionization chambers located in the vicinity of the absorber.

Particle losses at the optimum alignment of crystals decrease by 2-3 times in comparison with disoriented crystals that corresponds to the calculation. Approximately in as much time intensity of muon torch behind an absorber far from the accelerator should decrease, that is an important factor in the achievement of high intensity of circulating proton beam in the accelerator. In fig. 8 the effects of reduction of beam losses behind an absorber are shown at application of the crystal in comparison with the usual one-stage scheme of beam collimation by a steel absorber.

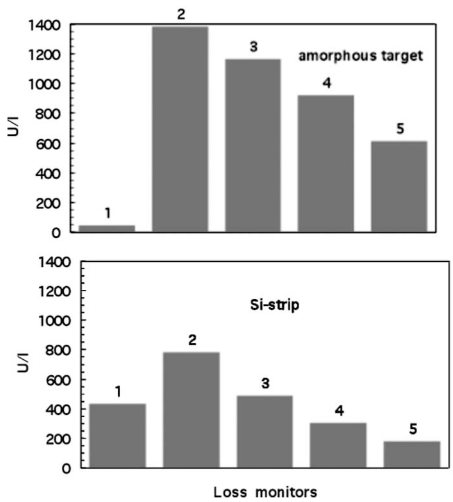

Fig. 8. – Losses at usual collimation by the edge of the absorber (top), application of a strip-type crystal (bottom).

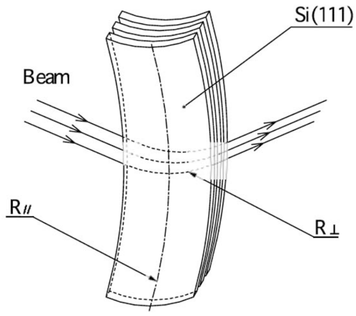

Fig. 9. – The array of bent silicon strips for beam deflection due to channeling.

4. – Extraction by a crystal at low energy

The phenomenon of deflection of a charged particle beam in a bent crystal is well investigated and successfully applied for beam extraction for high-energy accelerators at energies of about 10 GeV and higher. However, the task of bending and extraction of charged particles with energies below 1 GeV presents a big practical interest, *e.g.*, for example, for the production of ultrastable beams of low emittance for medical and biological applications. There exists a big experimental problem in steering such energy beams, which is connected with the small size of the bent crystal samples. The efficiency of particles deflection is determined by the ratio of the critical channeling angle θ_c to the beam divergence φ and drops exponentially with the crystal length L: Eff $\sim (\theta_c/\varphi) \times \exp[-L/L_d]$, where the characteristic parameter L_d, called dechanneling length, is relatively small for low energy. For example, at $E = 500\,\text{MeV}$ we have $\theta_c = 0.24\,\text{mrad}$ and $L_d = 0.4\,\text{mm}$. With usual channeling bent crystals (about 1 mm in length) only 10% efficiency was achieved for the deflection of sub-GeV energy particles in beam line.

Still the main problems arise in the task of extraction of a circulating beam from the ring accelerator as in addition significant cross-section sizes of a crystal exceeding its length here are required. Thus the bend angle of a crystal should be more than 1 mrad so that the deflected beam was well separated from the circulating one. Potentially suitable tools in this case can be the bent quasimosaic crystals such as in [8] or thin straight crystals [9, 10], but in both these cases it is necessary to increase the deflection angle of particles in few times. For low energy we propose a novel crystal technique, which can effectively work in a wide energy range and is especially attractive for low energy below 1 GeV.

The first option is based on the use of an array of shot bent channeling crystals (fig. 9) with sub-millimeter length (special thin silicon wafers of about 100 micron thickness were used for the production of such samples). Thus the bend of the array also occurs, as a bend of the single well-investigated silicon strip [11].

The second option is based on the reflection of particles on very thin straight crystal plates with thickness, which is equal to an odd number of half-lengths of channeling oscillation waves $L = \lambda(2n + 1)/2$, where $\lambda = \pi d/\theta_c$, $d = 2.3\,\text{Å}$—interplanar distance in silicon. It means for example that the optimum length of a crystal should be $10\,\mu\text{m}$ for particles with energy of 50 GeV. The reflection angle in one silicon plate should be

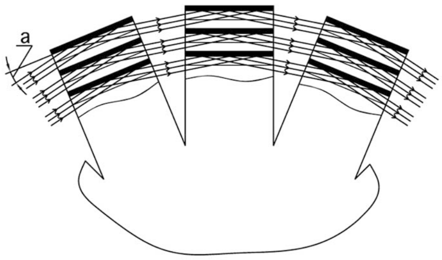

Fig. 10. – Veer-type reflector for bending of particle beam with use of thin straight crystals. Reflection of trajectories of particles from nuclear planes is schematically shown.

equal to twice the critical angle $\theta_c = (2U_0/pv)^{1/2}$, where: $U_0 \sim 22\,\text{eV}$ is the value of the potential of planar channel in silicon; p, v the momentum and the speed of the incident particle. For the enhancement of the deflection angle, the few aligned plates placed like a veer are foreseen (fig. 10).

Recently crystal extraction/collimation experiments in U-70 are started at a low energy of 1.3 GeV with a new crystal technique [7]. The first result, a channeling peak of about 20%, has shown an array from seven thin strip crystals. The big loss of efficiency is explained by non-optimal tuning of circulating beam towards the crystal by bump-magnet. At low energy because of sizable beam, about 50 mm, there is a drift of the incident angle about a half milliradian that should be removed at prompting a beam by high-frequency noise (this work is planned). In fig. 11 the profile of a 1.3 GeV beam is shown deflected by a silicon array. The fraction of channeling peak is allocated by a thick line (channeling peak is well separated from a circulating beam and approximately corresponds to the efficiency of a possible beam extraction from the accelerator).

5. – Perspectives of beam collimation on the basis of reflections in axially-oriented crystals

Recently IHEP group together with employees of several Russian and foreign centers of science have explained the new physical phenomenon—reflection of high energy protons from the bent atomic planes of a silicon crystal ([3] and references herein). Volume reflection is caused by interaction of the incident particle with the potential of the bent

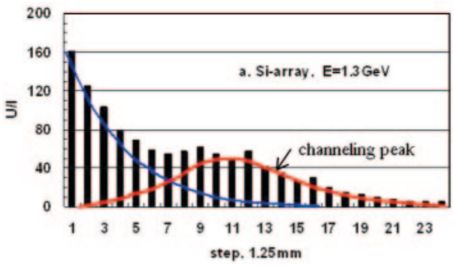

Fig. 11. – The 1.3 GeV proton beam profile at the absorber entry deflected by array of silicon strips.

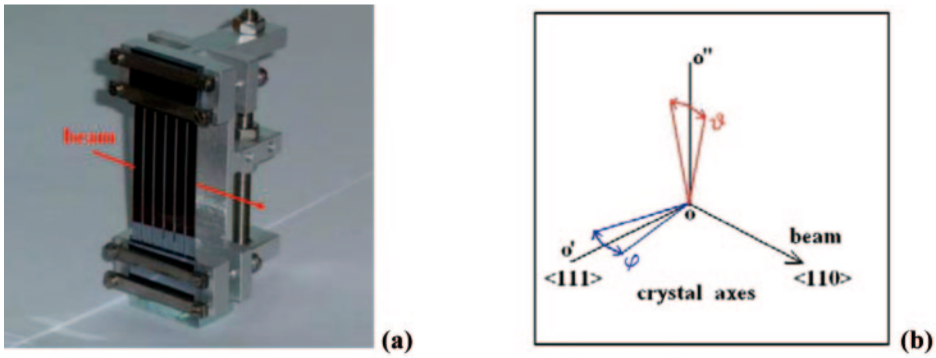

Fig. 12. – Crystal multistrip structure and scheme of its rotation in two-axes goniometer.

atomic lattice and occurs on a small length in the vicinity of a tangent to the bent atomic plane, leading to the deflection of the particle aside, opposite to the bend. The phenomenon of reflection occurs in a wide area of angles and is more effective than usual channeling. Therefore there are real prospects to use of volume reflection for extraction and collimation of beams in the big accelerators [12].

For real application the increase in the angle of reflection by few times is required. Two ways were proposed for this purpose:

– Reflection on a chain of crystals (multiple volume reflection—MVR in a sequence of crystals [13]).

– Reflection near to an axis in total potential of several skew planes (MVR in one crystal [14, 15]).

The first testing of multi-reflection structures with planar alignment for a U-70 circulating beam shows promising results [16]. This technique was also successfully tested at Tevatron [17].

Now in [18] we tested amplification of reflection angle due to both effects (multi-crystals and axial enhancement) for improvement of beam collimation scheme in U-70 synchrotron at 50 GeV. A multicrystal structure, 6 silicon bent strips (fig. 12a), was prepared by our technology described in [16]. This structure was installed in a two-axes goniometer in U-70 circulating beam (fig. 12b) like a first stage of a collimation system. Reduction of particle losses in accelerator was observed during planar crystal rotation, which was increased by vertical rotation as shown in fig. 13. This effect is fully explained by Monte Carlo simulations presented in fig. 14 where planar reflections and axial enhancement in crystal are shown.

Thus the new method of beam steering was demonstrated, based on reflections of particles in multi-crystal enhanced by axial effect, which is very promising also for negative particles.

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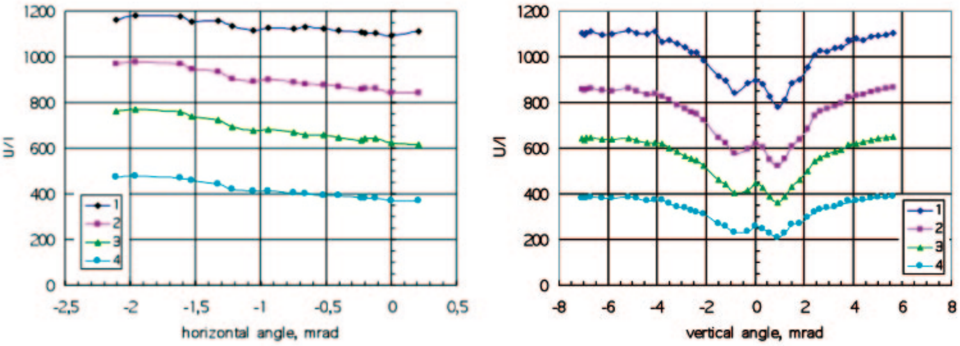

Fig. 13. – Reduction of particle losses of circulating beam in four places downstream collimator *vs.* horizontal and vertical crystal rotation.

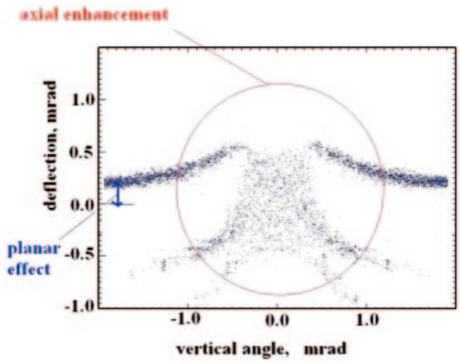

Fig. 14. – The dependence of 50 GeV proton deflection *vs.* vertical crystal angle at one passage in crystal multistructure initially aligned in mode of planar reflections.

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