BENT SINGLE CRYSTALS TO FORM HIGH ENERGY PARTICLE BEAMS

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1. INTRODUCTION

The idea of deflecting high energy particles with the help of bent single crystals (Tsyganov E.N., 1976) has widely been applied at the IHEP complex for the beam forming. In what follows we present the results of our work with the crystals used in the extracted beams [1-5].

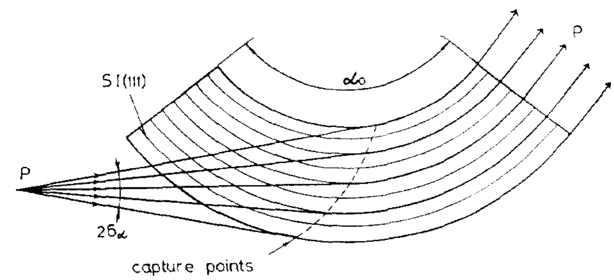
2. EFFICIENCY OF HIGH ENERGY PARTICLE DEFLECTION WITH A BENT SINGLE CRUSTAL AT THE END-FACE AND VOLUME CAPTURE IN THE CHANNELING MODE

Two mechanisms of capturing particles into the channeling mode are known: the one, when the particle trajectory coincides with the tangentials to the crystallographic planes at the end-face (the co-called end-face capture) and the other one - in the depth of the crystal (the so-called volume capture). In the first case the number of the particles with a fixed momentum P, captured into the channeling mode, depends on the ratio of the critical channeling angle to the incident beam divergence Φ/σ; in the second case it is determined by the capture probability W(R), which depends only on the crystal curvature radius. As a result, the beam deflection efficiency decrease because of the dechanneling processes, which are determined by the length and radius of the crystal curvature.

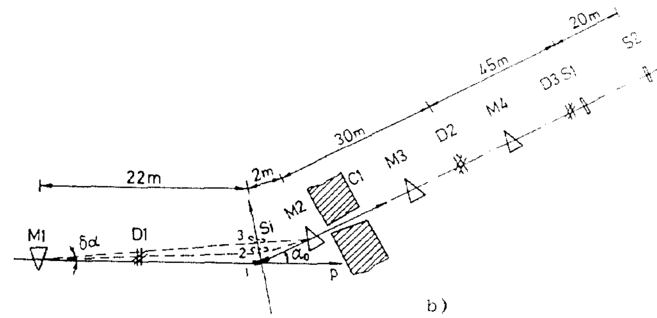
The experiment [1] on studying the end-face and volume capture of the 70 GeV particles into the channeling mode with the help of a bent Si single crystal of (111) orientation was carried out on beam line N21 of the IHEP accelerator (fig.1). Magnet M1 steered the proton beam onto the oriented bent single crystal. The crystal was rotated with 0.03 mrad step w.r.t. the proton beam direction, and it transversed the beam with a 100 μm step. The particle beam, deflected by the single crystal, was then guided by the correcting magnet M2 through the aperture of the 6-m steel collimator C1, and two magnets M3 and M4 purified the beam from the background. Two scintillation counters S1 and S2 with the sizes 100x100 mm^2, operate in the coincidence mode and determined the intensity of the deflected particles. The proportional chambers D1, D2 and D3 (their aperture of 100x100 mm^2 and a 5 mm step), worked in an analog mode and monitored the position of the incident and deflected beams.

The goal of the experiment was to find out the dependence of the deflected particle number on the crystal rotation angle w.r.t. the incident beam. The end-face capture takes place, if the orientation of the crystal is optimal. When the crystal is rotated, following the direction of its curvature, by the angle ψ, larger than the incident beam divergence, there arise conditions for the beam to become tangential to the bent planes in the depth of the crystal, i.e. the volume capture occurs. To study the dependence of the volume capture probability on the crystal curvature radius, we bent it with a variable curvature radius from $R=\infty$ at the one end up to $R=L_0/2\alpha_0$ at the other end, here $L_0=100$ mm is the crystal length and $\alpha_0=21$ mrad is the angle of bending.

The dependence mentioned above was measured two times. First, the beam hits the crystal on the side with large R so that with the crystal rotation towards the bend at the point the particle trajectory becomes tangential to the planes the curvature radius decreases. Then the crystal was overturned by 180° and the particles hit the crystal at the end with small R. The



a)



b)

Fig.1a,b. The layout of the experimental equipment. M1-M4 - bending magnets; Si - a bent single crystal; C1 - steel collimator; D1, D2 and D3 - analog proportional chambers; S1, S2 - scintillation counters (b). Volume capture conditions (a).

curvature radius at the point of the volume capture increased with the variation of the rotation angle ψ. Fig. 2 presents the plots for the dependence of the deflected particle number (in the units relative to maximum) on the crystal rotation angle for both cases. Sharp peaks correspond to the end-face capture mode. 6x10^5 protons per cycle hit the crystal cross section at the beam divergence $\sigma \simeq 0.1$ mrad. The maximum number of the particle deflected by the crystal was 2.5x10^4/cycle. The measured dechanneling length was L_D (80±10) mm. The number of the volume captured particle w.r.t. the peak maximum achieved $\simeq 6\%$.

From the analysis of curves 1, 2 (fig.2) we calculated the value for the volume capture probability at different crystal curvature radii. The W(R) is close to the linear one, in this $W_{|R=2M} \simeq 0.3\%$, $W_{|R=10M} \simeq 1\%$. Whereof it follows, that the bent single crystal may be used in the volume capture mode to form proton beams of an essentially lower (by 6-7 orders of magnitude) intensity.

The advantages of the volume capture as compared with end-face one are as follows. No precise orientation of the crystal is required in this case, the deflection effect is less sensitive to the beam instabilities, and the changes in the crystal bend angle, that may appear because of heating by the beam, are of no danger. The volume capture may be more efficient, than the end-face one when the deflected beam has large angular divergence. In this case one gets an opportunity to use the bent single crystal to form the secondary beams.

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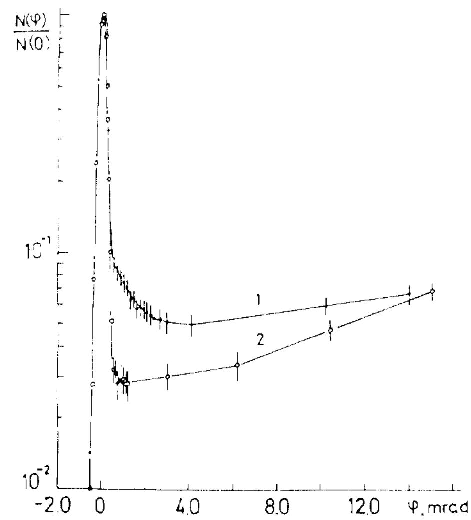


Fig. 2. Plotts for the dependence of the number of deflected particles versus the crystal rotation angle w.r.t. the direction of the incident beam.

3. RADIATION, HEAT AND MECHANICAL RESISTANCE OF THE CRYSTALS

In order to clarify the possibilities to form high intensity beams we introduced an oriented bent single crystal Si(111) (35x0.5x40 mm^3) with the bend angle of 13 mrad into the densed part of the extracted proton beam. Both slow and fast extracted beams were used (extraction time - 0.5 and 5 μs, respectively, repetition rate - 9 s). Under these conditions, extreme for the crystal, we carried out a number of measurements of the deflected beam intensity versus exposure time. The measurement results obtained for the case of slow extraction are presented in fig.3. The dashed-broken line shows the variations of the crystal temperature being heated by the beam. The solid lines were used to fit the measured values (black and white points) of the number of deflected particles as the primary beam intensity of $6x10^{12}$ and $4.5x10^{12}$)/cycle (beam emittance - 2 π·mm·mrad). The dashed lines illustrate the calculated dependences of the deflection efficiency versus temperature. As is seen, being heated almost up to $\delta T \simeq 100°C$ the crystal changes its channeling properties insignificantly.

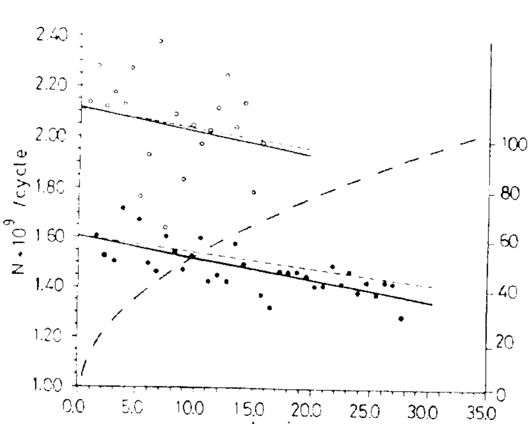


Fig. 3. The measurement results for the dependence of the crystal deflected beam intensity versus time.

In the fast extracted beam (intensity of $\simeq 1.5 \times 10^{13}$/cycle), the crystal undergoes not only temperature influence, but also dynamic loadings at the instant, when the beam passes through, and it with stands all these loadings. The primary beam emittance was equal to $\varepsilon = 1.5\pi$·mm·mrad) and the beam density at the point of the crystal location was $>10^{14}/cm^2$ per cycle. The intensity of the deflected beam was almost record, $\simeq 10^{10}$ per cycle, no noticeable dependence of the deflected particle number on time and crystal heating was observed. The crystal channeling properties did not deteriorate even after $\geqslant 10^{18}$ particles/cm^2 passed through the crystal.

4. BEAM SPLITTING WITH CRYSTAL. SIMULTANEOUS OPERATION OF THREE BEAM CHANNELS AT U-70

Two Si bent crystals were used to provide a simultaneous operation of beam lines NN21, 22, 23 [2,3]. One of them was placed in the N30 straight section of the machine in the slow extraction section to beam line N8, the other was installed in beam line (see fig.4). The first crystal with the sizes 20x0.5x30 mm^2 (LxHxV) deflected the fraction of the proton beam captured into the channeling mode to beam line N22. The deflection angle was 8.1 mrad, the intensity of the incident beam was $\simeq 5x10^{11}$/cycle, the intensity of the captured fraction was $\simeq 10^8$ particles per cycle. The second crystal with the sizes 60x0.5x15 mm^3 deflected the fraction of the proton beam with intensity $\simeq 10^7$ per cycle to beam line N21, the deflection angle being 60 mrad. The main part of the proton beam was steered onto the target of beam line N23. The particle losses on both crystal splitters were not more than $\simeq 10^9$/cycle, i.e., 0.2% of the primary beam intensity. The beam intensities obtained in beam lines N21 and N22 were sufficient to carry out a number of experiments. The simultaneous operational mode for beam lines N21, N22 and N23 realised with the scheme described here, was tested during one run. The scheme proves to be working quite successfully.

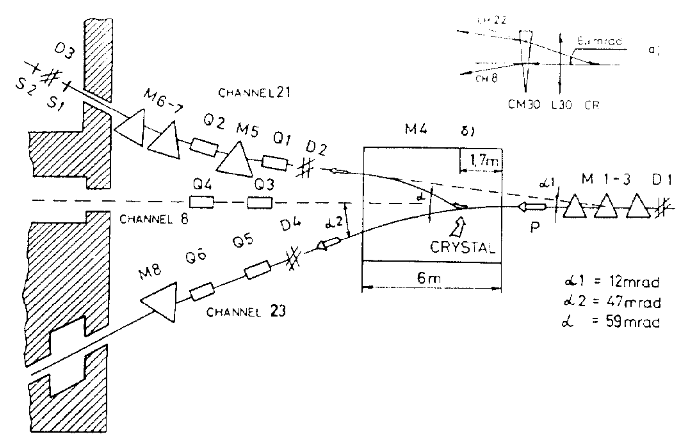


Fig. 4. Location of bent crystals in the proton beam extraction line(a) and in beam line N8 (b) to provide simultaneous operation of beam lines N21, N22, N23.

5. PROTON BEAM DIAGNOSTICS WITH THE HELP OF CRYSTALS

The properties of the bent single crystal to affect the beam within a small phase space $\varepsilon = 2\Phi t$ (Φ being the critical channeling angle, is equal to 0.02--0.002 mrad for 100 GeV - 10 TeV particles in the Si crystal with plane orientation (111), $t \leqslant 1$ mm - the crystal thinckness) may be used in obtaining total information on the characteristics of incident beam (emittance, profile, galo, momentum spread) [4].

The measurement scheme is presented in fig.5. The part of the beam captured into the channeling mode, was deflected by 13 mrad and then directed to the axis of the extended magnetic optical system (lenses Q1, Q2 and magnet M). At the end of the system the beam was detected by an analog ionization chamber D and scintillation counters S1 and S2 in coincidence mode. The optical scheme was realized in beam line N21 of the IHEP machine. The crystal was installed in beam line N8, along which the 70 GeV high intensity proton beam was transported. The results on measuring the beam emittance, profile and galo as well as the momentum spread, are shown ing.6. This measurement technique may widely be used at future machines for precise measurement of high intensity beams, where the counter technique cannot be used for particle detection purposes.

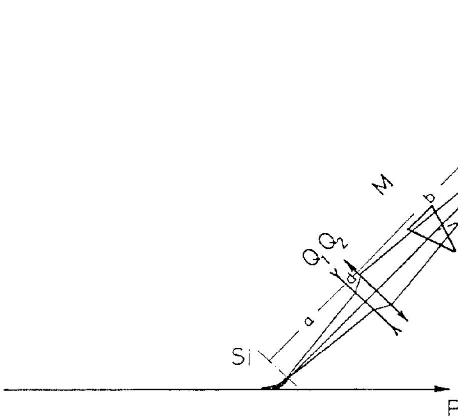


Fig. 5. Beam characteristics measurement scheme Si-bent crystal, D - analog ionization chamber, S1, S2 - scintillation counters, Q1, Q2 - quadrupole lens doublet, M - deflecting magnet (solid lines - the rays - in the horizontal plane, broken line - dispersion).

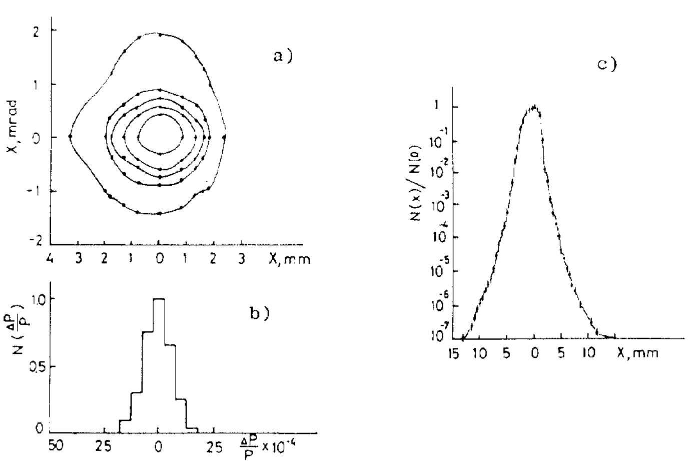


Fig. 6. Measurement results of the incident-on-the crystal proton beam: emittance. Five closed equipotential lines, starting from the centre, the phase space of the beam at the level 0.75, 0.5, 0.25, 0.1, 0.01 of the maximum density. The following values for the emittance correspond to these figures: (0.26, 0.68, 1.2, 1.6, 4.2)π xmmxmrad. b) particle spread over momenta; c) beam profile.

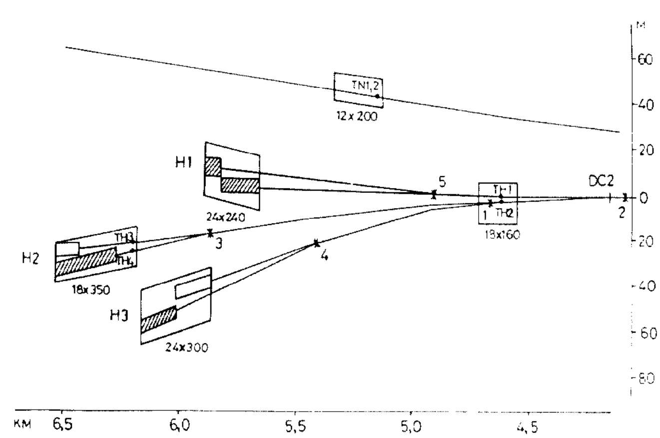
6. ON POSSIBILITY TO CONSTRUCT CRYSTAL BEAM LINES FOR PARTICLE TRANSPORT (MULTIPLE CHANNELING)

The efficiency of deflecting particles with the crystals is, as a rule, not very high $\eta \simeq 10^{-3}$-10^{-4} since the emittance of the extracted beams at the accelerators is higher than the acceptance of the crystal $2\varphi t$ (the ratio $2\varphi t/\varepsilon \simeq 10^{-2}$). However the beams, bent with the single crystal, are well formed. The high manufacturing quality, bending and alignment of the crystals make their emittance close to $2\varphi t$. Therefore one may expect a considerable increase of the beam deflection efficiency with one more bending by the crystal. This was tested in one of the IHEP beam lines, where instead of two bending magnets we installed bent single crystals, at a distance of 70 m between them. The first one was installed in the beam of 5×10^{12}/cycle intensity and deflected 7×10^{8} protons at 13 mrad. The second crystal with the bent angle of 13 mrad, deflected 2×10^{7} protons per cycle, which makes up 3%. Hence it has been shown, that crystal beam line for particle beam transport can be constructed in reality. These beam lines may become a cheap way to construct testing areas at the accelerators— colliders of new generation, where no standard electromagnetc beam lines are foreseen.

6. PLANS TO USE BENT SINGLE CRYSTALS IN THE UNK EXPERIMENTAL AREA

The experimental studies, carried out at IHEP, experiments at FNAL on deflecting 800 GeV beams together with favourable theoretical predictions allow one to hope that in the future crystal deflectors will be used in the IHEP experimental base (3 TeV protons).

The bent crystals are planned to be used in the UNK beam lines (fig.7) first of all to form proton beams of moderate intensity [5].



REFERENCES

[1] N.A.Galyaev et al. IHEP Preprint 90-147, Protvino, 1990.

[2] M.D.Bavizhev et al. IHEP Preprint 89-77, Protvino, 1989.

[3] A.A.Arkhipenko et al. IHEP Preprint 90-91, Protvino, 1990.

[4] Yu.A.Chesnokov et al. IHEP Preprint 90-169, Protvino, 1990.

[5] N.A.Galyaev et al. IHEP Preprint 89-191, Serpukhov, 1989.