Highly Efficient Deflection of the Divergent Beam by Bent Single Crystal

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Abstract

We have investigated the proton beam deflection in the geometry where the first crystal formed a divergent beam and the second crystal shaped this beam into parallel one. In spite of the aberration influence a high bending efficiency was obtained.

I.

Nowadays the bent single crystals of silicon are applied for bending low-divergent (as compared to channeling angle $\theta_L \sim 0.02 \div 0.002$ mrad at 100 GeV – 10 TeV) high-energy particle beams [1]. The CERN experiment [2] has demonstrated that efficiency of bending proton beam of energy 450 GeV and divergence less than 3 μrad is up to $\sim 50\%$. In Ref. [3] a method was proposed for focusing a beam with a bent monocrystal in the plane of bending. The focusing (parallel to point) was due to the difference of the bending angles of crystal, the end face of which had a special shape. Another important application of a focusing crystal may be related to the reverse motion of particles – transformation of the beam diverging from a point-like source into a parallel. To do this, the crystal entry face must have a special shape. The problem of the focusing a divergent beam is typical for steering of the secondary particle beams, and in particular for their extraction from colliders.

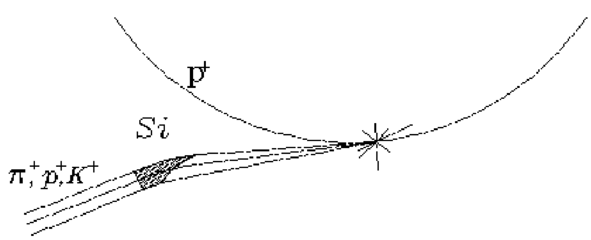

Figure. 1. The scheme of extraction of the secondary-particle beam from accelerator by the focusing crystal

To extract most of the secondary particles produced in the target situated in the vacuum chamber of accelerator (at the crystal focal point, see Fig. 1), certain conditions must be fulfilled. It is known that most of the produced secondaries exit in the angular range

$$\pm\theta \;=\; \frac{0.4\ \mathrm{GeV/c}}{P} \tag{1}$$

where P is momentum. The acceptance of the focusing crystal is

$$\pm\varphi \;=\; \frac{H}{2F} \tag{2}$$

where H is the crystal thickness, F focus distance, should be about $\pm\theta$.

High efficiency of particle trapping into channeling mode may be obtained, if the target size Δx in the bending plane is

$$\Delta x \;\leq\; 2\theta_L F \tag{3}$$

Then the particles entering the crystal are aligned w.r.t. the crystal planes within θ_L, and the trapping efficiency η may be close to the theoretical limit $\sim 70\%$. In the realistic experiment the defects of the focusing device may lower η essentially.

The above conditions for the efficient extraction of secondary particles can be easily met at TeV energies. The estimates for LHC collider (energy of protons is 7 TeV) show that in this way one can extract the secondary particles with intensity of up to $\sim 10^8$/s.

The experimental investigation of the efficiency of capture and deflection of the beam diverging from a point-like source was made at the extracted 70 GeV proton beam of IHEP accelerator. The experimental scheme is in Fig. 2.

The crystal Si_1 (with usual flat faces) bent by 60 mrad was exposed to the 70 GeV proton beam of $10^{11}/s$ intensity, and bent the beam with moderate intensity $\sim 10^7/s$ toward the magnet-optics system $MQ - M$ where two other crystals were placed. The beam formed with the forward part of the magnet system was brought onto the crystal Si_2 which had the focusing end face. This crystal was 2 mm thick 15 mm high 70 mm long and 18 mrad bent. The crystal focused the beam at the distance of 0.5 m into a narrow vertical strip with the width $\simeq 80\mu$m FWHM at the crossover and divergence ± 2 mrad. The beam formed in this way was used as a source of protons. In order to focus and deflect this divergent beam, the crystal Si_3 with focus distance 2.5 m was used. It had size $2 \times 20 \times 30$ mm^3 and was bent by 6 mrad. (The first and second crystals had orientation (111), the third was cut along the (110) planes.) This crystal had the acceptance of $\varphi = \pm 0.4$ mrad. According to preliminary measurements, it gave for the parallel-to-point focusing the crossover size $\sim 200\mu$m FWHM (ideal value is $\Delta x = 2\theta_L F = 125\mu$m). The crystals were aligned to the beam successively. Each of them had an independent goniometer.

The effect of focusing the beam from the divergent to parallel was detected by measuring the intensity of the beam deflected by the third crystal during when the latter was rotated around the vertical axis crossing its entry face. The intensity obtained in this angular scanning is shown in Fig. 3. The scan FWHM approaches to $2\theta_L$ ($\simeq 4\theta_L$ at the base), which attests a good qual-

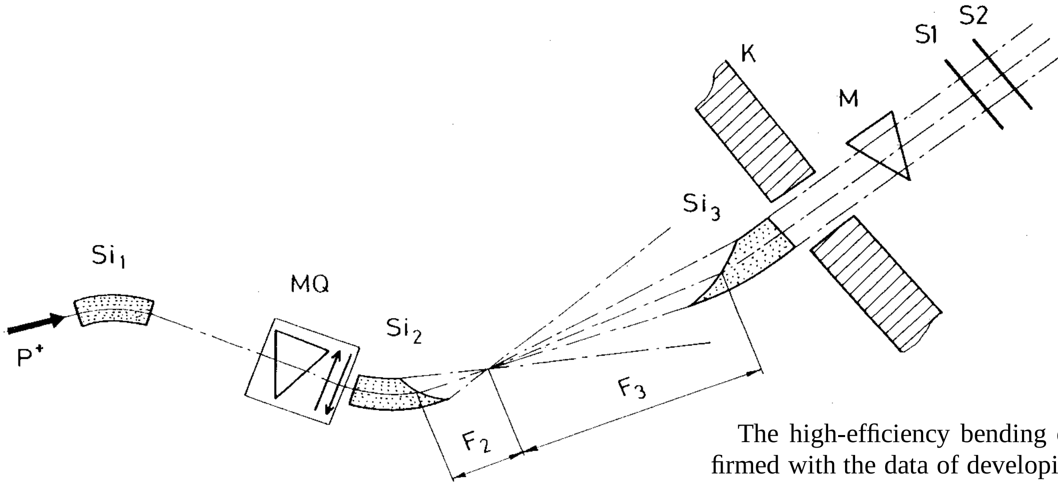

Figure. 2. The scheme of experiment

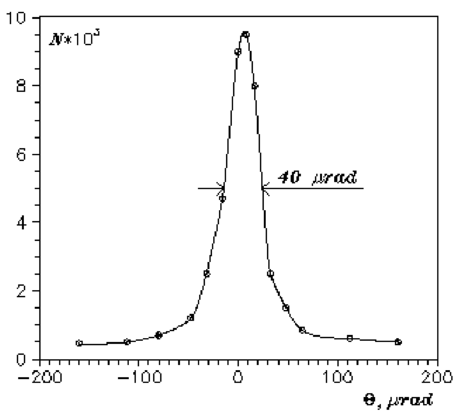

Figure. 3. Angular scan of intensity for the beam bent with the third crystal

ity of focusing. According to measurements with the remoted scintillation counters S1 and S2, crystal Si_3 at the best angle deflected $(15 \pm 2)\%$ of the protons incident on its face, which is factor of ~ 2 lower than the calculation for the ideal focusing.

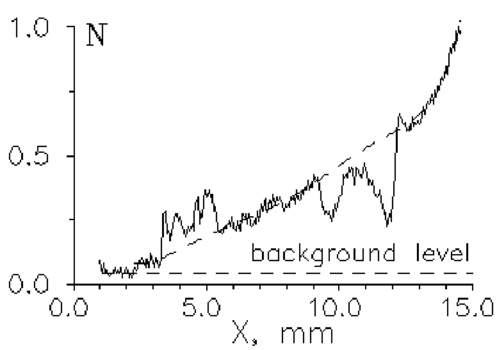

Figure. 4. Beam profile on the nuclear emulsion downstream the third crystal

The high-efficiency bending of the divergent beam is confirmed with the data of developing the beam profile on the nuclear emulsion, which was placed downstream the crystal Si_3 at its optimal alignment. This profile is shown in Fig. 4. The wide beam (excess over the background) corresponds to the divergent beam formed by crystal Si_2. The dip at the right is the shadow of the crystal Si_3, due to the capture of beam fraction in channeling mode. From the ratio of areas one can find that $\sim 30\%$ particles are trapped in channeling mode. On the left of the figure the contribution of particles bent by Si_3 is seen, superimposed on the broad profile of the beam divergent from the crystal Si_2. The bent-beam fraction, according to the figure, is 14% of incident particles. This well agrees with the measurements by scintillation counters. Reduction of the number of bent particles by the factor of 2.2, as compared to the particles trapped in the channeling mode, is explained by dechanneling. It is also seen from the figure, that efficiency of particle bending is not uniform over the crystal thickness (at the edges it is higher than in the middle). Apparently, this is due to defects of crystal Si_3. For focusing the beam with this crystal from parallel to point, there was observed a characteristic split of the beam profile some distance downstream the crossover, similar to the profiles of Fig. 4. Above $\sim$ 500 GeV and for the same crystal size, the fraction of the bent particles will be close to 30%, as in this case the particle losses in the process of deflection are insignificant because of the dechanneling length growth. The obtained efficiency is high despite the defects of both Si_2 (the source) and Si_3. In further studies we suppose to use microstrip detectors to measure precisely the characteristics of the incident and bent beams. We hope with this detailed information to improve the quality of focusing crystals and to bring the bending efficiency closer to the theoretical value.

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