УДК 621.384.663; + 548: 539.12.04

BENT TUNGSTEN CRYSTAL AS DEFLECTOR FOR HIGH ENERGY PARTICLE BEAMS

A.D.Kovalenko, V.A.Mikhailov, A.M.Taratin, V.V.Boiko[1], S.I.Kozlov[1], E.N.Tsyganov[2]

The channeling properties of silicon and tungsten crystals are compared. The deflection of the beam of nuclei with energy 6 GeV per nucleon and their extraction from the Nuclotron, a new superconducting nuclear accelerator at the Laboratory of High Energies, JINR, with the bent silicon and tungsten crystals have been studied by computer simulation. It was shown that the use of tungsten crystals instead of ordinary silicon ones can increase more than ten times extraction efficiency.

The investigation has been performed at the Laboratory of High Energies, JINR.

Изогнутый кристалл вольфрама в качестве дефлектора для пучков частиц высоких энергий

А.Д.Коваленко и др.

Проведено сравнение свойств кремниевого и вольфрамового монокристаллов для каналирования частиц. Методом компьютерного моделирования исследовано отклонение пучка ядер с энергией 6 ГэВ на нуклон и их вывод из нуклотрона, нового сверхпроводящего ускорителя ядер Лаборатории высоких энергий ОИЯИ, с помощью изогнутых кристаллов кремния и вольфрама. Показано, что использование кристаллов вольфрама вместо обычных кремниевых дефлекторов может увеличить эффективность вывода пучка из нуклотрона более чем в десять раз.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

1. Introduction

The study of methods for steering high-energy particle trajectories by use of deflectors based on bent crystals began in the middle 70s. Nowadays, crystal optical elements have already found practical usage for extraction of beams from accelerators and for extracted beam spliting. The first beam extraction from a cyclic accelerator by means of a bent crystal was performed at the Dubna synchrophasotron [1]. The extraction efficiency was small enough, about 10^{-4}, because the system used for the beam guidance onto the crystal,

[1]Institute of Physical-Technical Problems, Dubna, Russia
[2]State University of New York at Albany

namely a fast decreasing the closed orbit radius, was not optimum. A successful extraction of 120 GeV proton beam from the SPS with a record efficiency of about 10% was fulfiled recently at CERN [2]. The injection of a white noise at the deflector plates of the feedback system was used to initiate the transverse diffusion of particles onto the bent crystal. The deflection efficiency up to 50% was observed for highly parallel beam of 450 GeV protons at the bending angle about 1 mrad [3].

Up to the present time only silicon single crystals have been used for the deflection and extraction of particle beams. However, higher deflection efficiences can be achieved by using crystals with larger atomic number due to increasing the critical channeling angle and electric field intensity of the crystal planes. As it was noticed [4], tungsten crystals may be optimum for the deflector production because they have small lattice atom vibrations, high melting point and low susceptibility to radiation damage.

Production of oriented single crystals of heavy metals with a purity of 99.99999% and a low discolation density is attainable at the present time. Experimental results obtained with the straight tungsten crystals have shown their high structure perfection [5]. It was shown that the crystal lattice damages which arose in the crystals oriented along [100] axis as a result of irradiation with 100 keV protons at temperature 77 K and the flux about 10^{17} p/cm^2 are connected with proton channeling and penetrate up to about 250 μm, tens times more than those observed before. The method of detection of relative variations of nonlinear surface resistance of the crystals at radio frequencies, or the so-called current states method, was used for the first time. The most important advantage of the method as compared to commonly known ones is a growth of sensitivity with increasing the crystal structure perfection.

The study of the characteristics of tungsten and molibdenum crystals as beam deflectors, and the development of methods for machining and bending the crystals without decreasing their structure perfection are the main goals of the investigations of the crystal optical systems planned at the Nuclotron, a new superconducting nuclear accelerator at the Laboratory of High Energies, JINR.

In this work the deflection of the nuclei beam with energy 6 GeV per nucleon and their extraction from the Nuclotron, with the bent silicon and tungsten crystals have been studied by computer simulation. It was shown that the use of tungsten crystals instead of ordinary silicon ones can increase more than ten times the extraction efficiency.

2. Channeling Properties of Si and W Crystals

Let us consider the properties which determine the efficiency of silicon and tungsten crystals as deflectors for high energy particle beams. The numerical values of the crystal characteristics are presented for (110) planar channels and for protons with energy 6 GeV.

1. The potential depth of planar channels for the static crystal lattice as it follows from Lindhard's potential for a single atomic plane

$$U_0 \approx 2\pi Z_1 Z_2 e^2 N d_p C a \sim Z_2 a \sim Z_2^{2/3}, \qquad (1)$$

where Z_1, Z_2 are the projectile and crystal atomic numbers, N is the atomic density, d_p is the channel width, $C=\sqrt{3}$, a is a screening length. For the periodic planar potential with thermal vibrations of the crystal atoms included at room temperature in the Moliere approximation we have

$$U_0\text{: } 22.7 \text{ eV (Si)} \Rightarrow 131.9 \text{ eV (W)}.$$

2. The critical channeling angle, $\vartheta_c=(2U_0/pv)^{1/2} \sim Z_2^{1/3}$, determines the angular acceptance of the straight channels and for the realistic potential depths presented above equals

$$\vartheta_c: \ 87.7 \ \mu\text{rad (Si)} \Rightarrow 196.8 \ \mu\text{rad (W)}.$$

3.The space acceptance of planar channels depends on the critical distance r_c of particle approach to the channel wall for sustaining the stable trajectories of channeled particles

$$A_s = 1 - \frac{2r_c}{d_p}, \quad r_c = a + ku_1, \tag{2}$$

where u_1 is the rms apmlitude of thermal vibrations of the crystal atoms. The value of k depends on the particle energy and the considered crystal thickness. The values of u_1 and a are smaller for tungsten crystals, whereas the channel width is bigger

$$u_1, a, d_p: \ 0.075, 0.194, 1.92 \text{ Å (Si)} \Rightarrow 0.05, 0.112, 2.238 \text{ Å (W)}.$$

So, the space acceptance of tungsten planar channels is bigger than for silicon ones, that is, their channels are more «open».

4. The dechanneling length value can be estimated from

$$S_d \simeq E_{xc}/A, \quad A = \langle \frac{\Delta \bar{E}_x}{\Delta s} \rangle, \tag{3}$$

where E_{xc} is the critical transverse energy of channeled particles, its value is correlated with r_c, and A is the average rate of transverse energy change with penetration depth, or the friction coefficient. For well-channeled particles the friction coefficient is determined mainly by the electron scattering, which is proportional to the local electron density in the channel

$$\frac{\Delta \bar{E}_x}{\Delta s}(x) \sim \rho(x).$$

The electron densities in the considered planar channels of tungsten and silicon crystals calculated in the Moliere approximation are shown in Fig.1. The most difference of the density values is at the plane position, but in the middle of the channel the electron density for tungsten crystal remains still bigger two times than for silicon one. The rate of increase

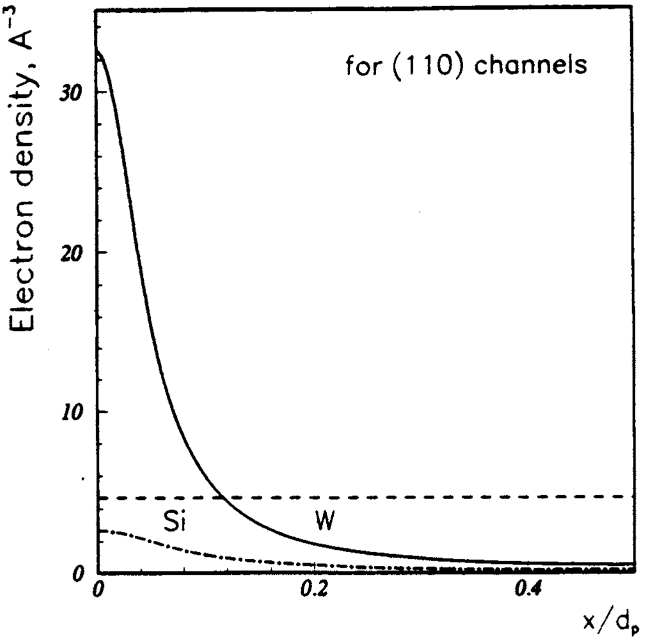

Fig.1. The averaged electron density in (110) planar channels of silicon and tungsten crystals at the room temperature in the Moliere approximation as a function of the distance from the atomic plane

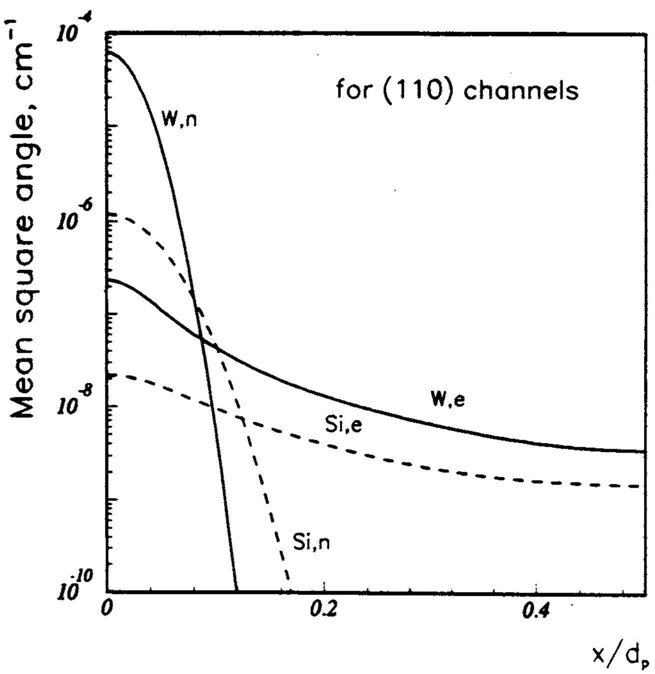

Fig.2. The rate of increase of the mean square angular deviation of 6 GeV protons due to multiple scattering by the crystal electrons (e) and nuclei (n) in (110) channels of Si and W crystals as a function of the distance from the atomic plane

of the mean square angular deviation of the 6 GeV proton beam due to multiple scattering by the crystal electrons and nuclei in (110) channels of Si and W crystals are presented in Fig.2. The total rate is bigger for tungsten crystals almost everywhere in the channel. However, as it will be shown below the dechanneling length is still bigger for tunsten crystals.

5. The maximum electric field intensity in the planar channels

$$E_m: \ 6 \text{ GV/cm (Si)} \Rightarrow 42.52 \text{ GV/cm (W)}.$$

6. The critical radius of the planar channel curvature for existence of the channeling states of particles in the bent crystals, $R_c = pv/eE_m$, decreases for the tungsten crystal

$$R_c: \ 1.16 \text{ cm (Si)} \Rightarrow 0.16 \text{ cm (W)}.$$

That is, the tungsten crystals can be stronger bent, and we can get bigger deflection at the same crystal length.

7. One of the serious problems which arise at the usage of the silicon crystals as the beam deflectors is their fragility. The silicon crystals can be elastically bent up to the definite limit after which they will be broken. This radius is proportional to the thickness of the crystal plate. In the first experiment there was discovered the beam deflection by a bent crystal, which was fulfiled in Dubna [6], it was shown that for the silicon crystal bent along (111) planes $R_{br}(\text{cm}) \approx 76 \times t(\text{mm})$. The tungsten has the limit of elastic deformations also, but it is a plastic substance and can be bent to a smaller radius if dislocations are introduced. These dislocations which separate the elastically bent parts have not to be a catastrophic obstacle for high energy channeled particles. So, the tungsten deflectors could probably have bigger thickness than the silicon ones at the same curvature.

3. Beam Deflection Efficiency

The crystal bending decreases the depth of the effective planar potential and leads to the shift of the particle trajectories to the outer channel wall. In a harmonic approximation the depth of the effective potential for bent channels decreases as

$$U_b(R) = U_0\left(1 - \frac{R_c}{R}\right)^2.$$

The decrease of the dechanneling length with the crystal bending occurs mainly due to this lowering of the potential barrier. However, for the crystal bent with a large curvature a considerable decrease of dechanneling lengths occurs also due to stronger multiple scattering of channeled particles by the crystal electrons and nuclei because of the trajectory shift.

The correct estimations of the dechanneling lengths demand the calculations with the realistic potential and electron density of the crystals and with taking into account the concrete conditions. So, the average rate of transverse energy change with penetration depth due to multiple scattering by the crystal electrons and nuclei in bent crystal $A(R)$ was calculated here by averaging over initial distribution, $P(E_{x0})$, of the incident particles in transverse energy

$$A(R) = \int_0^{E_{xc}(R)} A(E_{x0}, R) P(E_{x0}, R) dE_{x0}, \tag{4}$$

where $A(E_{x0}, R)$ is the rate average over the trajectory for the particle with initial transverse energy E_{x0}. Figure 3 shows the dependence of the dechanneling lengths on the bend radius calculated in the Moliere approximation for silicon and tungsten crystals when the incident beam is parallel. The dechanneling length for W crystals is bigger than for silicon ones whereas the local friction coefficient is bigger everywhere in the planar channels of the tungsten crystals, Fig.2. It occurs due to considerably higher critical transverse energy for channeling in tungsten crystals.

The knowledge of the capture efficiency of incident particles into the channeling rigime

$$P_c(R) = \int_0^{E_{xc}(R)} P(E_{x0}, R) dE_{x0}, \tag{5}$$

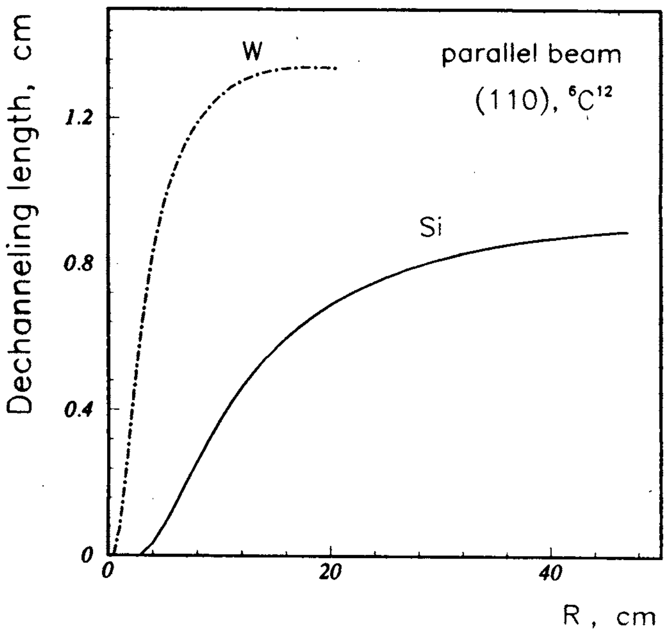

Fig.3. The dependence of dechanneling length on the bend radius of (110) channels for Si and W crystals, the incident beam is parallel

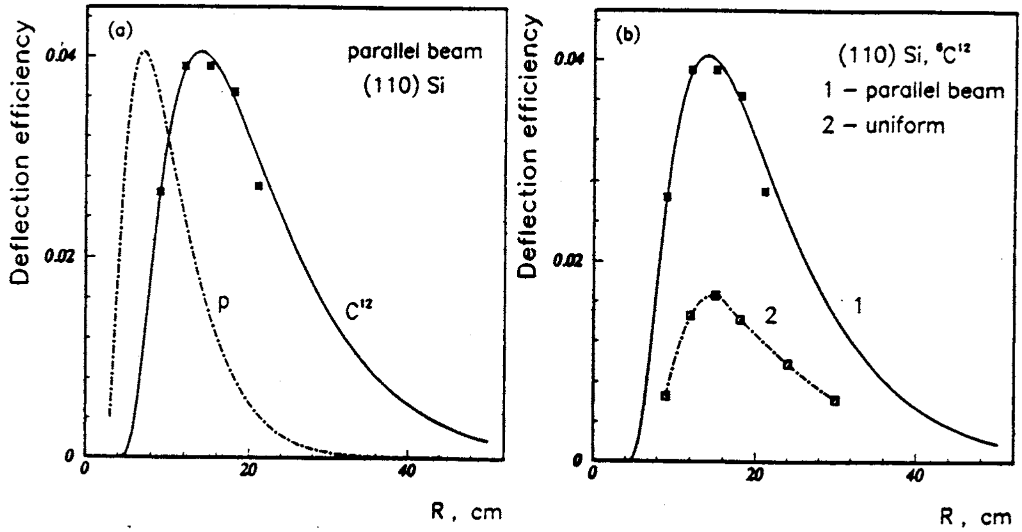

Fig.4. The deflection efficiency of nuclei with energy 6 GeV/u by the (110) Si crystal as a function of the crystal bend radius (a) for parallel beam, 1 — protons, 2 — nuclei of ${}^{6}C^{12}$; (b) for nuclei of ${}^{6}C^{12}$, 1 — parallel beam, 2 — the beam with uniform angular density in the interval $(-\vartheta_c, \vartheta_c)$

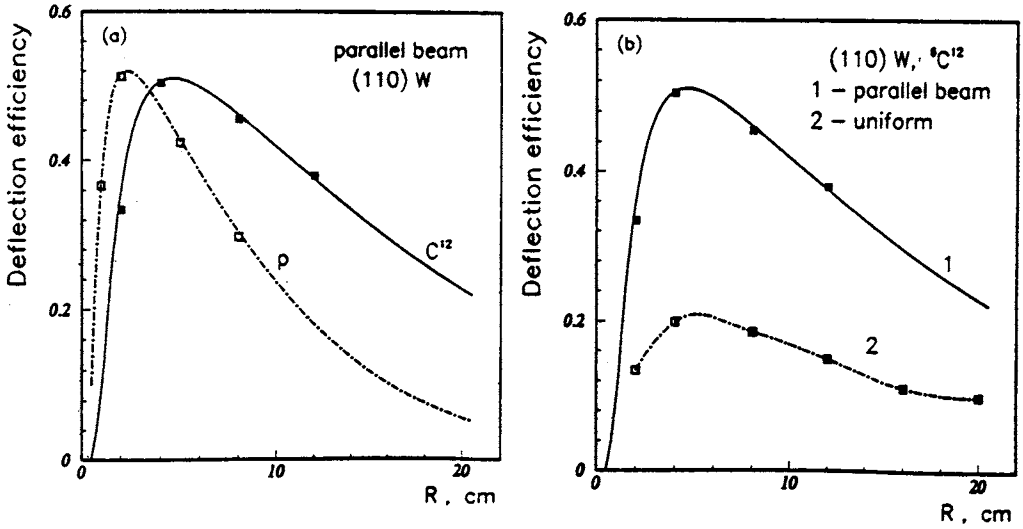

Fig.5. The same as fig.4 for the tungsten crystal

and the dechanneling length S_d allows one to estimate the efficiency of the beam deflection at the angle α by the bent crystal

$$P_d(\alpha, R) = P_c(R)\exp(\alpha R/S_d(R)). \qquad (6)$$

As it was noticed earlier [7], these estimations depend on the selection of the critical approach r_C of particles to the atomic planes of the crystal. Computer simulation of the particle trajectories in the crystals does not contain this parameter. Therefore, the comparison of the deflection efficiency of the Nuclotron beam with the tungsten and silicon crystals was produced by computer simulation of the beam passage through the crystals according to the model [7].

Figure 4 shows the deflection efficiency of nuclei with energy 6 GeV/u by the silicon crystal bent along (110) planes as a function of the crystal bend radius for the parallel beam and the beam with uniform distribution in the range of the angles $(-\vartheta_c, \vartheta_c)$, the bending angle $\alpha = 100$ mrad. The same dependences for the tungsten crystal are presented in Fig.5. Here the symbols are the results of the computer experiments, and the curves are the analytical estimations according to (3-6) with the values of r_c for best fitting these results. For the parallel beam the maximum deflection efficiency with the tungsten crystal is about 50%. This is higher ten times than with silicon one. For the uniform beam when its width is larger than 2 ϑ_c^W this differrence increases $\vartheta_c^W / \vartheta_c^{Si}$ times in addition. The optimum bend radius and the corresponding crystal length, $S_{cr} = \alpha R$, reduce few times for the tungsten crystals. Therefore, the tungsten deflectors can be considerably shorter than the silicon ones.

4. Multiturn Beam Extraction from Nuclotron

A necessary angle for raising the Nuclotron beam to the experimental hall exceeds 90 mrad. The circulating beam guidance onto the crystal can be produced by means of the closed orbit bump or by increasing the vertical betatron oscillations of the beam particles. It is optimum to locate the crystal deflector at the azimuth, where the beam divergence is minimum that is near a focusing quadrupole. However, the deflector location near the center of the focusing quadrupole leads to large troubles with the crystal alignment while it is possible. When it is located outside the quadrupole the growing orbit bump takes away fast the beam from the angular region of channeling of the oriented crystal. On the other hand, as a result of the excitation of particle betatron oscillations the beam divergence at the crystal location increases. Therefore, it will be more optimum to decrease the distance between the beam and the crystal at the begining by means of the bump up to the touching at $3\sigma_{y0}$, that is about 7 mm for the Nuclotron, and only then to throw the beam particles onto the crystal due to the transverse diffusion or the resonance excitation. The possible scheme for the Nuclotron beam extraction is presented in the work [10] and consists of the correcting magnets for creating the orbit bump and the inflector for the excitation of the vertical betatron oscillations of the circulating particles.

At the usage of bent crystal for beam extraction from cyclic accelerator there is possibility for multiple passages of circulating particles through the crystal deflector. Therefore, the extraction efficiency P_{ex} can be higher than the deflection efficiency of the same beam at its single passage through the crystal [8,9].

For estimation of real space and angular distributions of particles which hit the crystal and contribution of multiple passages of circulating particles through the crystal the computer simulation of the Nuclotron beam extraction was fulfiled by the similar way as it was made earlier [10]. Two points in the accelerator lattice were considered. The inflector is located in the first point, and the bent crystal in the second one near the defocusing quadrupole through the superperiod from the inflector at the distance of 3 cm above the closed orbit to be not the obstacle for the beam particles at the injection stage. The sinusoidal voltage with the resonance frequency

$$f_{res} = frac(q_v)f_0 \text{ or } f_{res} = (1 - frac(q_v))f_0, \tag{7}$$

where $q_v = 6.85$ is a vertical betatron tune, $frac(q_v)$ is a fractional part of q_v, f_0 is a rotation frequency, begins to be served at the inflector plates when the beam approaches the crystal at the distance of $3\sigma_y \simeq 7$ mm as a result of the orbit bump. Figure 6 shows the calculated distributions of particles in the impact parameters and angles with the crystal when the amplitude of the angular deflection in the inflector was 1 μrad that corresponds the voltage amplitude about 400 V for nuclei with energy 6 GeV/u and $Z/A = 1/2$.The angular distribution is approximately uniform with width about 300 μrad.

The density of the particles depends on the angle, which they have after the crystal passage [10]. Besides, some particles which hit the crystal can be lost due to inelastic nuclear interactions. The mean free path of protons between the nuclear interactions S_n equals 45.5 cm and 9.58 cm in the silicon and tungsten, accordingly. For nuclei S_n is proportional to $A^{-0.71}$, where A is their atomic weight. So, with increasing the nucleus weight the possible contribution of their multiple passages through the crystal deflector in the extraction efficiency decreases.

The optimum crystal lengths were used in our computer experiments that is 1.5 cm for the silicon crystal and 4 mm for the tungsten one. The calculated values of the extraction efficiency for nuclei of $^6C^{12}$ are 27% and 2% with the tungsten and silicon deflectors,

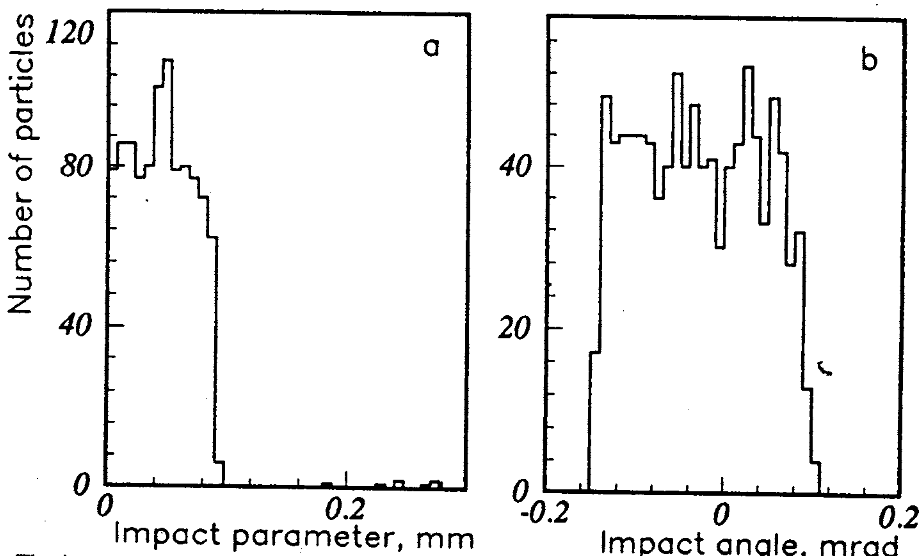

Fig.6. The impact parameter (a) and angle (b) distributions of particles with the bent crystal when the amplitude of the angular deflection in the inflector is 1 μrad

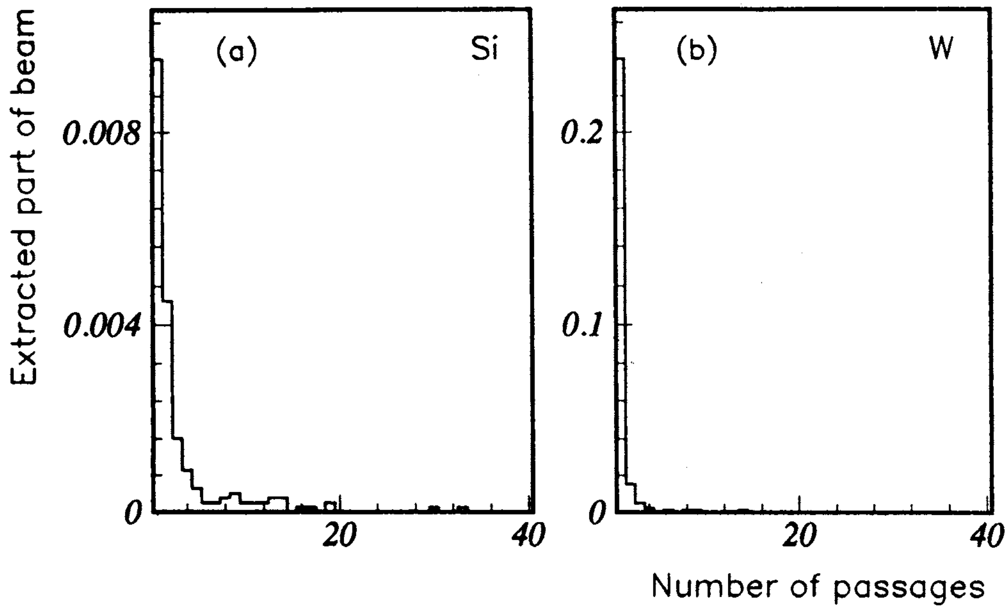

Fig.7. The distributions of the extracted particles in the number of passages through the bent crystal, (a) for Si crystal, (b) for W crystal. The beam particles are nuclei of $^6C^{12}$ with energy 6 GeV per nucleon

accordingly. Figure 7 shows the distributions of the extracted particles in the number of passages through the crystal deflector. The extraction efficiency due to multiple passages is about 3% for the tungsten crystal and about 1% for the silicon one. Although the losses of unchanneled fraction due to nuclear interactions at the beam passage through the crystal are larger, the crystal length $S_{cr} = 0.033\ S_n$ for Si and $0.042\ S_n$ for W, and the beam broadening due to multiple scattering is stronger, $\vartheta_{ms} = 0.42$ mrad for Si and 1.2 mrad for W.

So, our computer experiments have shown that the efficiency of crystal optical systems for high energy particle beams can be increased about an order of magnitude with using the high-purity tungsten crystals instead of ordinary silicon ones.

References

1. Avdeichikov V.V. et al. — JINR Rapid Communications No.1-84, Dubna, 1984.
2. Akbari H. et al. — Phys. Letters, 1993, B313, p.491.
3. Moller S.P. et al. — Nucl. Instr. & Meth., 1994, B84, p.434.
4. Carrigan R.A., Jr. et al. —Nucl. Instr. & Meth., 1982, 194, p.205.
5. Boiko V.V., Kozlov S.I. — Zh. Eksp. Teor. Fiz. (to be published).
6. Elishev A.F. et al. — Phys. Lett., 1979, B888, p.387.
7. Taratin A.M., Vorobiev S.A. — Nucl. Instr. & Meth., 1990, B47, p.247.
8. Taratin A.M. et al. — Nucl. Instr. & Meth., 1991, B58, p.103.
9. Biruykov V.M. — Nucl. Instr. & Meth., 1991, B53, p.202.
10. Kovalenko A.D. et al. — JINR Rapid Communications No.6[63]-93, Dubna, 1993.

Received on July 25, 1995.