УДК 539.1.076+621.384.6

NEW RESULTS ON SIMULATION OF THE NUCLOTRON BEAM EXTRACTION WITH A BENT CRYSTAL

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Extraction of relativistic deuteron beam from the Nuclotron with bent tungsten and silicon crystals was studied by simulation with taking into account ionization energy losses of particles and real accelerator acceptance. The dependence of extraction efficiency on the crystal radius, thickness, and orientation is discussed. The possibility of increasing the extraction efficiency with the crystal thickness increase is analyzed. It was shown that particle scattering in the holder material does not reduce significantly the extraction efficiency.

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

Новые результаты по моделированию вывода пучка нуклотрона изогнутым кристаллом

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Вывод пучка релятивистских дейтронов из нуклотрона изогнутыми кристаллами кремния и вольфрама исследован моделированием с учетом ионизационных потерь энергии частиц в кристалле и реального аксептанса ускорителя. Получена зависимость эффективности вывода пучка нуклотрона от толщины, радиуса изгиба и ориентации кристалла. Анализируется возможность увеличения эффективности вывода с увеличением толщины кристалла. Показано, что рассеяние наводимых на дефлектор частиц в материале кристаллодержателя не приводит к существенному уменьшению эффективности вывода.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

1. INTRODUCTION

Investigations of new tungsten deflectors using a circulating nuclear beam of the Nuclotron are planned at the Laboratory of High Energies. The experimental set-up produced for this purpose and named «Crystal-W» including an original goniometer for a crystal alignment relative to the Nuclotron beam and its first successful test were described in [1]. Tungsten crystals possess a stronger internal electric field than silicon crystals due to higher Z and can be more efficient for the accelerator beam steering.

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The technology developed for the crystal growing [2] gives a hope to produce the tungsten deflectors with a dislocation density and mosaic spread which are low enough for the Nuclotron energies. The crystal deflectors for the Nuclotron beam extraction have to be thin enough with thickness of about 100 microns to be bend with an optimum radius [3]. However, during the manufacture of thin tungsten plates their widths have decreased, too, up to 7–8 mm. The bending devices, which were usually used before for silicon crystals, leave free of matter the central part of the crystals to decrease the accelerator beam losses. The bending force was applied at the crystal sides.

For narrow and thin tungsten plates this method of the deflector manufacture is not appropriate. Therefore, a special bending device has been made to glue the crystal plate on the cylindrical surface of the holder. The best substance for the holder in this case is the same as the crystal.

In this work the influence of the holder substance on the Nuclotron beam extraction efficiency was studied by simulation for deuterons with the energy of 6 GeV/u. Besides, the extraction efficiency dependence on the crystal thickness, bending radius, and orientation were studied.

2. SIMULATION PROGRAM

The real position of a bent crystal in the goniometer, which is placed behind the defocusing magnet at the beginning of the warm straight section of the Nuclotron, was considered in our simulation. The crystal bent along the (110) planes in the horizontal plane with a bending angle of 100 mrad was placed at the distance $X_{bc} = 1$ cm from the outside of the closed orbit.

It was supposed, that circulating beam particles begin to hit the crystal in consequence of a slow transverse diffusion. The diffusion can be realized due to the noise injection on the inflector plates of the Nuclotron [4]. The distribution shapes in X, X' for particles first hit the crystal in the transverse diffusion case were studied by simulation in [5]. The distribution of impact parameters $b = X - X_{bc}$ is exponential $P(b) = \exp(-b/b^*)$. The corresponding distribution in impact angles $P(X')$ was reproduced in this work with using $X_{bm} = X_{bc} + nb^*$ as the maximum value of the betatron oscillation amplitude.

The surface region of all crystal deflectors cannot efficiently deflect particles due to different defects of the crystal lattice appeared during the deflector production. The surface itself can be mirror for usually used silicon crystals, that is, the surface roughness is much smaller than $1\,\mu$m. However, there are the experimental data [6], which show that the inefficient surface layer can be much thicker because of lattice defects generated in the crystal volume during its cutting. The experiments on the accelerator beam extraction with a bent crystal [5] have shown that the first pass of particles through the deflector is unsuccessful in most cases.

The situation when the first hit of particles in the crystal is not successful was considered in our simulation. The computer experiments were performed in the assumption that the imperfect layer thickness equals $1\,\mu$m. The values of $b^* = 0.3\ \mu$m and $n = 3$ were used for the exponential distribution of the impact parameters of particles first hit the crystal. Thus, all first hits of particles are in the imperfect surface region of the crystal.

The particle trajectories in the crystal were calculated using the model [7] with taking into account ionization energy losses of particles [8]. Full turn transfer matrix for transverse and longitudinal co-ordinates was used to transport particles around the accelerator ring.

Particles can pass through the all length of the crystal in the channeling states. These particles are deflected at the angles near the crystal bending angle and considered as extracted. Some part of particles will be lost in inelastic nuclear interactions with crystal atoms. Other particles are elastically scattered in the crystal that changes their betatron oscillation amplitudes. Besides, the energy losses of particles in inelastic interactions with the crystal electrons lead to the particle trajectory shift from the closed orbit. The average energy losses of particles equal 3.87 MeV and 22.14 MeV for silicon and tungsten crystals with the length of 1 cm. The corresponding maximum shifts of particle trajectories in F magnets are 0.78 mm and 4.4 mm. The particles remain in the circulating beam if the acceptance conditions are fulfilled

$$\epsilon_x < \epsilon_{xm}, \quad \epsilon_y < \epsilon_{ym},$$

$$\epsilon_{xm} = (x_m - |\delta|\eta_m)^2/\beta_{xm}, \quad \epsilon_{ym} = y_m^2/\beta_{ym},$$

where ϵ_x, ϵ_y are the single particle horizontal and vertical emittances, ϵ_{xm}, ϵ_{ym} are the corresponding values of the accelerator acceptance, η_m, β_{xm}, β_{ym} are the dispersion and beta functions for F and D magnets, x_m, y_m are the half-sizes of the accelerator pipe, $\delta = \Delta p/p$ is a relative deviation of a particle momentum.

3. SIMULATION RESULTS

The first passage of circulating particles through the crystal is unsuccessful because they hit the imperfect surface layer. However, the particles get the increase of betatron oscillation amplitudes due to scattering in the crystal.

Figure 1 shows the particle distributions in impact parameters for the second, third and fourth hits in the crystal. For the silicon crystal, the distribution maximum is successively removed from the crystal surface after each passage through the crystal. For the tungsten crystal, the impact parameters of particles are stretched over full thickness already in the third hit because the particle scattering in the crystal is much stronger.

The corresponding particle distributions in impact angles are shown in Fig. 2. It is clearly seen a faster broadening of the angular distributions for the tungsten crystal. The dashed parts in the histograms show the angular regions where particles can be captured into channeling states. The capture regions are shown for the case when the crystal plane direction is perfectly adjusted with the beam envelop slope angle $\theta_b = -(\alpha/\beta)X_{bc}$. The width of the capture region, which equals two critical channeling angles θ_c, is about three times bigger for the tungsten crystal.

Particles can be extracted when they hit the crystal outside the imperfect surface layer. Besides, their directions have to be in the capture region. Therefore, the crystal plane orientation relative to the beam slope θ_b is important. The distributions in the number of passages through the crystal for extracted particles are shown in Fig. 3 for different crystal orientations. Many particles are extracted already in the second hit in the crystal for a perfect alignment when the crystal plane direction coincides with θ_b. In the opposite case, when the crystal orientation is far from θ_b, the circulating particles have to be scattered in few passages through the crystal to come in the capture region [9]. In this case, it is needed 10–15 passages in average for the silicon crystal and 3–4 passages for the tungsten crystal.

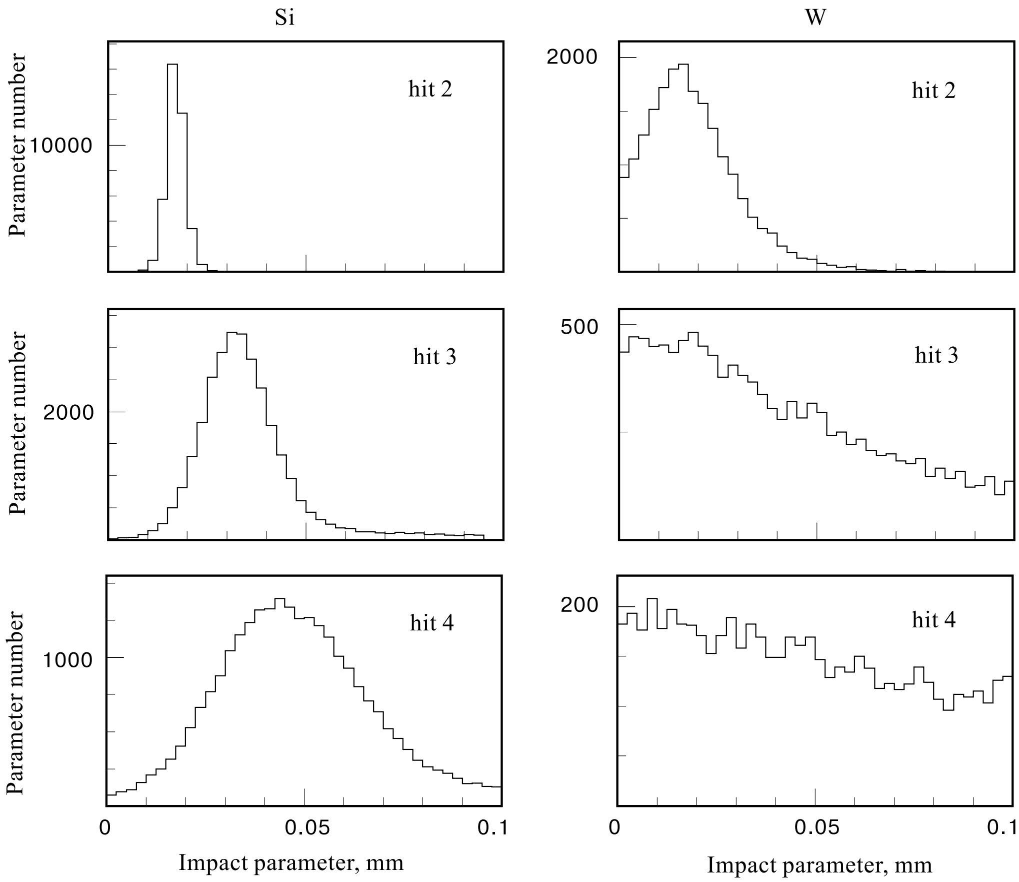

Fig. 1. The distributions in impact parameters of deuterons with the energy of 6 GeV/u of the Nuclotron circulating beam for the second, third and fourth hits in the silicon and tungsten crystals

The dependence of the extraction efficiency of circulating deuterons from the Nuclotron on the orientation angle for the silicon and tungsten crystals are shown in Fig. 4. The dependence is asymmetric and the asymmetry is different for the silicon and tungsten crystals.

There is a volume reflection of particles by bent planes in the crystal for negative angles of the crystal tilt, $\theta = X' - \theta_b$. For the silicon crystal, multiple scattering of particles is not very strong. Therefore, additional deflection of particles due to the volume reflection reduces significantly the number of passages through the crystal, which are necessary for particles to come into the capture region. This increases the extraction efficiency for negative tilt angles [9].

For the tungsten crystal, the multiple scattering is much stronger. Therefore, addition of the volume reflection leads to a very big increase of the betatron oscillation amplitudes for negative tilt angles. As a result, the particles, which hit the crystal, have a big angular spread that decreases the probability of the particle capture into the channeling states. Therefore, with a tungsten crystal the positive tilt angles are preferable to get higher extraction efficiency.

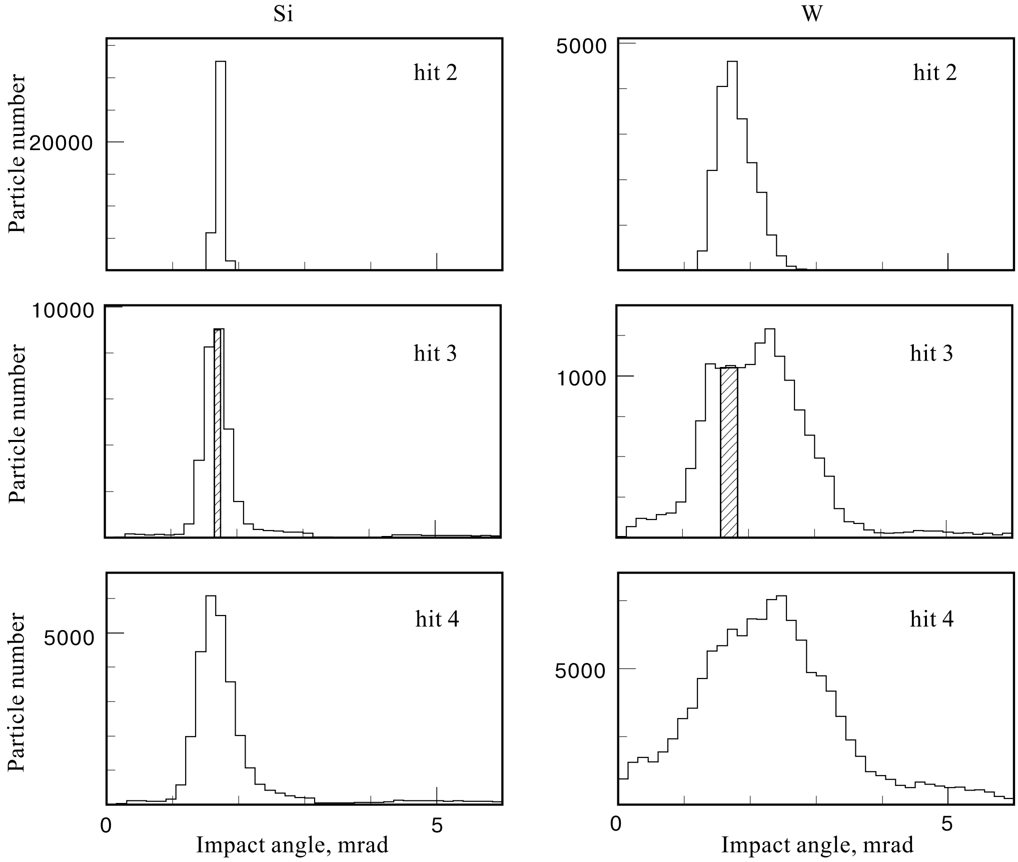

Fig. 2. The distributions in impact angles of deuterons with the crystals. The conditions are the same as for Fig. 1. The dashed parts of the histograms show the angular regions where particles can be captured into channeling states

Figure 5 shows the dependence of the extraction efficiency on the crystal thickness t. For the silicon crystal, the efficiency increase is about 60% when the crystal thickness is increased four times. For the tungsten crystal, there is the efficiency increase of about 20% for $t = 100$ μm in comparison with $t = 50$ μm. However, the efficiency does not practically grow with further thickness increase. The experiment on the SPS beam extraction with a bent silicon crystal didn't show any difference of the extraction efficiency for two crystal thicknesses of 1.5 mm and 3.5 mm [10].

Let us determine conditions when the crystal thickness increase can give the extraction efficiency growth. It is obvious, that the efficiency dependence on the crystal thickness can appear when the extraction of circulating particles occurs due to multiple passes of them through the crystal. Besides scattering in the crystal, the number of possible passes of circulating particles through the crystal is limited by inelastic interactions with the crystal atoms — $N_{\rm in} = L_{\rm in}/L$, where $L_{\rm in}$ is the inelastic interaction length; L, the crystal length.

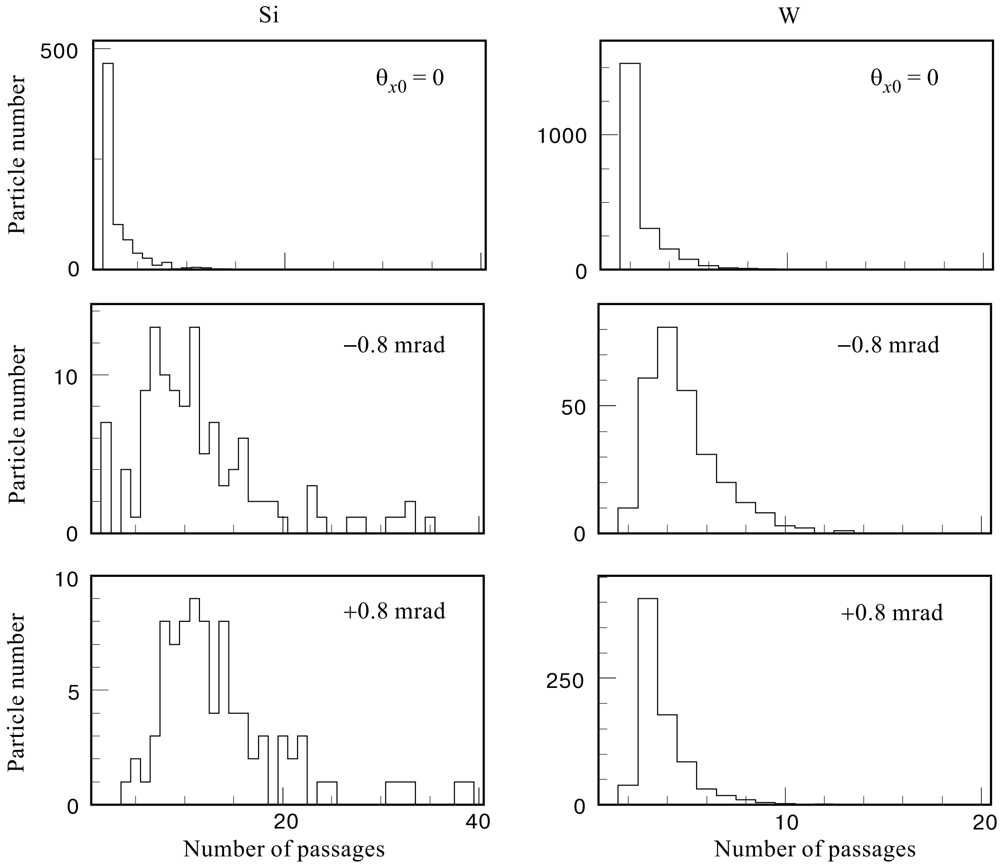

Fig. 3. The distributions of extracted particles in the number of passages through the crystal for different angles of the crystal relative to the beam envelope slope

Let us consider first, to simplify the picture, that the crystal is placed in the middle of the quadrupole magnet, where the beam envelope slope does not change during the beam broadening (the function $\alpha = 0$). Let the crystal face closest to the circulating beam is at the distance X_{bc} and the crystal thickness increase occurs due to addition of layers to its opposite face.

In the assumption that the beam density in the $X - X'$ phase space is constant, the extraction efficiency is proportional to the relation $R^* = (A_{\rm ch} \cdot A_{\rm cr})/A_{\rm cr}$, where $A_{\rm ch}$ and $A_{\rm cr}$ are the areas of the capture region and the region of overlap between the beam and the crystal (Fig. 6). The extraction efficiency does not change with increasing the crystal thickness if

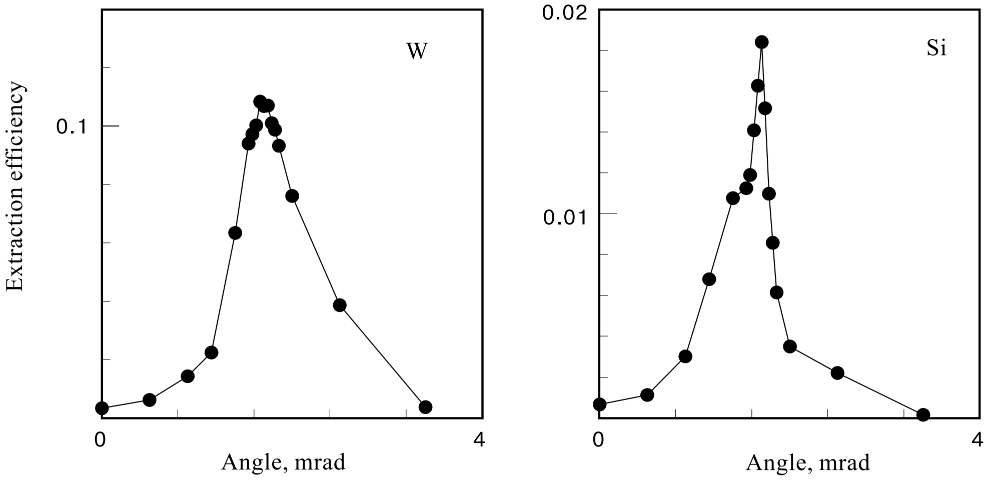

Fig. 4. The dependence of the extraction efficiency of circulating deuterons from the Nuclotron on the orientation angle of the silicon and tungsten crystals. The crystal bending radius, length and thickness are 10cm, 1 cm and 100 μm, respectively

the increase of betatron oscillation amplitudes due to particle scattering in the crystal Δx_m is much bigger than a crystal thickness. In fact, the relation R^* is approximately the same for different crystal thicknesses in the case of a wide beam (Fig. 6*a*).

If particle scattering in the crystal is small, that is, $\Delta x_m < t$, the particles of a slow broadening beam find themselves in the capture region at once when they begin to hit the additional external layers of the crystal. The relation R^* in the external layers for these particles is big that gives the growth of the extraction efficiency (Fig. 6*b*). In this case the amplitude increase Δx_m and the number of possible passes through the crystal $N_{\rm in}$ determine the maximum impact parameter of particles $b_{\rm in} = N_{\rm in}\Delta x_m$. Therefore, when $t > b_{\rm in}$ the further increase of the crystal thickness is senseless.

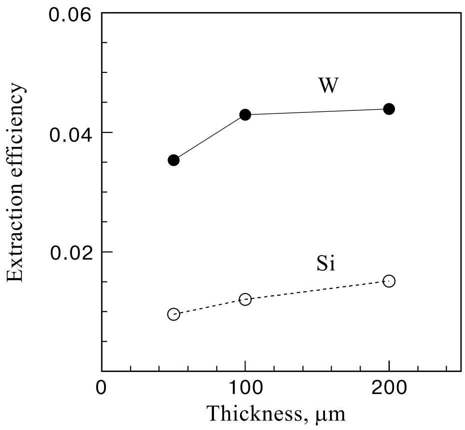

Fig. 5. The dependence of the extraction efficiency of deuterons from the Nuclotron on the crystal thickness. The crystal bending radius and length are 20cm and 2 cm

For the real position of the crystal outside the magnet elements of the accelerator, where $\alpha \neq 0$, the envelope slope of the broadening beam changes. This change equals $\Delta\theta_b = (\alpha/\beta)t$ along the crystal thickness [11]. When $\Delta\theta_b > \theta_c$, the particles of a broadening beam do not hit the capture region in the external crystal layers at once (Fig. 7*a*). Therefore, the capture probability of particles in these layers does not grow. So, there is another limitation on the crystal thickness — $t_\alpha = (\theta_c/\alpha)\beta$. When $t < t_\alpha$, the

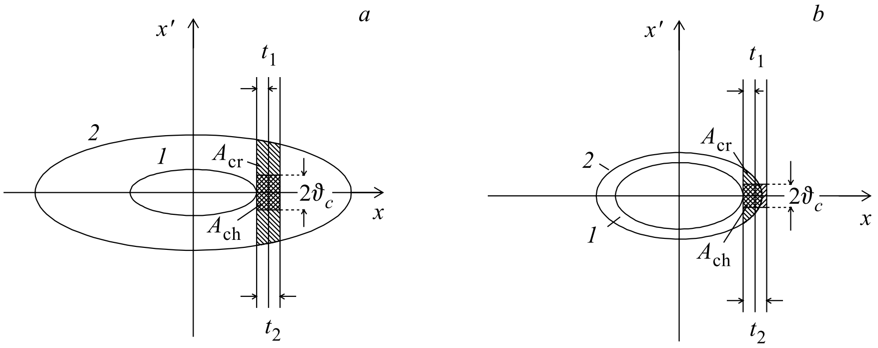

Fig. 6. The beam envelopes in $X - X'$ space for the initial state of a slow broadening beam (1) and for the beam after one or a few passages through the crystal (2). Two different crystal thicknesses are marked in as t_1 and t_2. $A_{\rm ch}$ is the region where particles can be captured into channeling states in the crystal, θ_c is a critical channeling angle. $A_{\rm cr}$ is the region of overlap between the beam and the crystal. (a) A big increase of betatron oscillation amplitudes of particles $\Delta x_m > t$ due to scattering in the crystal; (b) A small increase $\Delta x_m < t$. The crystal is placed at the accelerator azimuth where the alpha function $\alpha = 0$

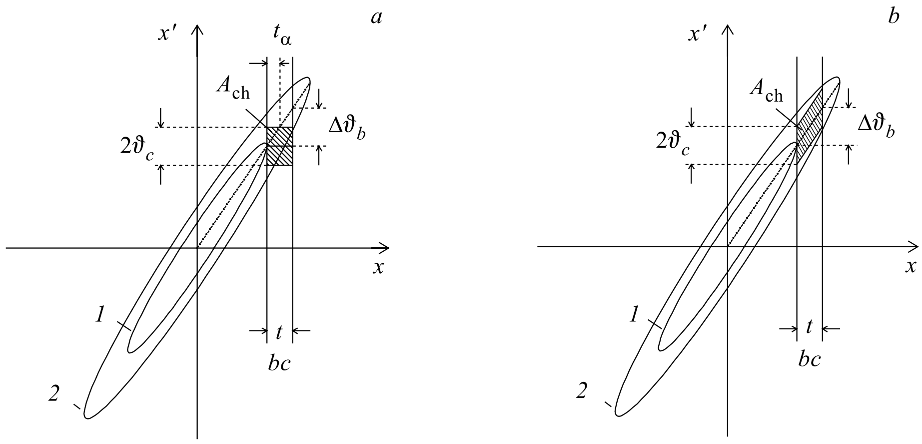

Fig. 7. The same as Fig. 6 when the crystal is placed at the accelerator azimuth with $\alpha \neq 0$. Here $\Delta\theta_b = (\alpha/\beta)t$ is the change of the beam envelope slope along the crystal thickness t. The thickness t_α corresponds to $\Delta\theta_b = \theta_c$. (a) The angular position of the capture region $A_{\rm ch}$ is the same along the crystal thickness. (b) The angular position of $A_{\rm ch}$ changes along the crystal thickness according to the beam envelope slope due to the special shape of the entrance face of the crystal

gain of the extraction efficiency can be achieved with increasing the crystal thickness. This is possible in the opposite case of $t > t_\alpha$, too, if the entrance part of the crystal is bent. For this purpose the entrance face of the crystal has to be specially machined to place the capture region along the beam envelope (Fig. 7*b*). The slope angle of the entrance crystal face to the radial direction has to be $\theta_{\rm sl} = (\alpha/\beta)R$.

The extraction efficiency dependence on the crystal radius is shown in Fig. 8. For the beam deflection in a single pass through the crystal the optimum radii are about 5 cm and 15 cm for silicon and tungsten crystals correspondingly [3]. For the beam extraction from the accelerator, the optimum radius of the crystal (and its length) is smaller because a shorter crystal increases possibility of multiple passages of particles through the crystal.

All presented data were received with using assumption that the crystal is glued on the holder. That is there is not an empty space under the crystal in the central part of the holder. The holder substance was the same as the crystal (Si or W, correspondingly). The maximum losses of the extraction efficiency, which were observed for big tilt angles of the crystal relative to the beam slope, were smaller than 10%. The losses are small because the particles with big amplitudes of betatron oscillations, which can hit the holder, have small probability of capture into the channeling states because of a big angular spread when they hit the crystal.

So, when the accelerator beam extraction can be realized with a short crystal, which does not give a significant broadening of the beam, an additional increase of the extraction efficiency can be achieved with increasing the crystal thickness. Besides, our simulation shows that an additional scattering of circulating particles on the holder substance does not decrease significantly the extraction efficiency. That is the crystal deflector can be successfully produced by gluing the crystal on the holder with a given curvature. However, this deflector construction has to be avoided in the case of a fast extraction of the intensive beam ($\sim 10^{13}$ protons per second) because of a possible destruction of the crystal [12].

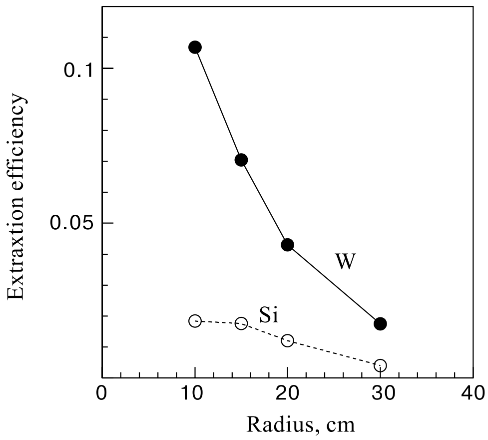

Fig. 8. The extraction efficiency as a function of the bending radius of the crystal. The crystal thickness is 100 μm

Acknowledgements

This work was partly supported by Grant No. 437 from International Science and Technology Centre and by Grant No. 99-02-17324 from Russian Foundation for Basic Research.

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Received on April 3, 2000