THE EFFICIENCY ANALYSIS OF THE PROTON BEAM EXTRACTION FROM THE IHEP ACCELERATOR BY A BENT CRYSTAL.*

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ABSTRACT

The work is devoted to the analysis of an efficiency of accelerated beam extraction from the 70 GeV IHEP accelerator (A-70) by a bent Si crystal. Comparison of the theoretical and experimental results is made. The satisfactory agreement is found.

1 INTRODUCTION

Particles dynamics in the channel of a crystal is investigated by the phase plane method. The efficiency of particles capture into the crystal channels is calculated for the case when the emittance of an accelerated beam is lager than the acceptance of a crystal. It is typical for the A-70. It is shown that maximum number of particles hitting crystal channels depends on asimuthal layout of a crystal in the accelerator. A numerical analysis of a transverse motion of particles in the accelerator with an account of their interaction with a crystal was realized.

2 MOTION OF PARTICLES IN THE PLANE CHANNEL

Equation of a particle motion in the channel of a bent crystal was taken as (see, for example [1]):

$$\begin{cases} dx/ds = y \\ dy/ds = -(1/pv)V'(x) + k, \end{cases} \qquad (1)$$

where the transverse coordinate of a particle x is taken from the channel axis perpendicularly to the big facet of a crystal and a lateral coordinate s - along the channel axis; p and v are, respectively, a momentum and a speed of a particle; $V(x)$ is a continuous electrical potential of the space between planes; k is a curvature of a crystal.

Let x_c signifys the maximum value of the transverse coordinate x in a channel at which, if $x \geq x_c$, scattering of particles on the crystal atoms takes place. It results in leaving the channel by scattered particles. We will consider dechanneled particles as lost thus determining the lower limit of the channeling particles number at calculations.

We assume further $x_c = d/2 - 2.5\rho(T)$, where d is a distance between the atomic planes forming a channel * and the parameter ρ considers the termal oscillations of atoms into a crystal. In particular, for the (110) plane of the Si crystal ρ equals 0.075 Å at the room temperature (see, for example, [2]).

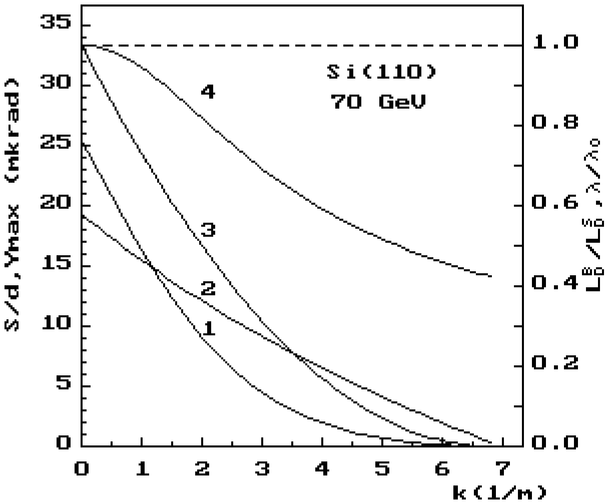

Figure 1: The dynamic characteristics of the Si crystal versus its curvature.

Some dynamic characteristics of the Si crystal oriented in along the crystallographic plane (110) in dependence of its curvature k are presented in fig.1. The phase volume S normalized to the distance between the planes d (curve 1) is proportional in fact to the maximum number of particles that can pass through the channel of the given curvature. The maximum anglular semi-spread of the channeled particles y_{max} (curve 2), the bent crystal dechanneling length L_D^B normalized by the dechanneling length of the straight crystal L_D^S (curve 3) as well as the wave-length λ of the linear oscillation of particles normalized by the wave-length λ_0 in the unbent crystal (curve 4) are presented in fig.1 also.

As a potential V(x), the Molier potential was taken at calculation of curves of fig.1:

$$V = A\sum_{i=1}^{3} (a_i/b_i G)\exp(-b_i G)[ch(b_i G X) - 1], \qquad (2)$$

where: $X=2x/d$; $G=d/a_T$ (a_T =0.195 Å is a distance of Thomas-Fermi screening); a_i=0.2, 1.1, 0.7; b_i=3.0, 0.6, 0.15; $A=Z_1 Z_2 e^2 nd$ (Z_1, Z_2 are the atomic numbers of the channeling particles and material of the crystal, respectively; e is the electron charge; n is the surface density of atoms for the channeling planes of a crystal).

For numerical calculations the program was made on the base of the "macroparticles" method. The crystal was

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presented on the phase space (x, x') as a rectangle limited by the straight lines $|x - x_0| = (\Delta x)_{CR}$ and $|x' - x'_0| = \varphi_c$, where $(\Delta x)_{CR}$ is a thickness of a crystal, φ_c is the crystal channeling angle and (x_0, x'_0) are the coordinates of the centre of gravity of the presented crystal.

At the beginning the coordinates were taken as: $x_0 = x_m, |x'_0| \leq x'_m$ (x'_m is the maximum value of the radial angular spread of particles in a beam for the certain asimuth of the accelerator). The angular orientation of the crystal x'_0 was fixed during calculations and the position of the crystal centre x_0 was changed gradually. Particles were considered as lost if they did not reach the crystal acceptance.

The channeling efficiency was calculated according to the formula:

$$\varepsilon = \varepsilon_{CR} \cdot \varepsilon_B, \qquad (3)$$

where: ε_{CR} is a coefficient of the channeling efficiency decrease due to physics processes inside a crystal; ε_B equals numerically to the sum "weight" of the particles hit into the crystal acceptance. ε_{CR} is expressed by:

$$\varepsilon_{cr} = (S / 2d\varphi)\exp(-L / L_D^B), \qquad (4)$$

where L is the length of a crystal.

We used the value of the dechanneling length from the ref. [3]: L_D^S =5.4 cm for the crystal oriented along the (111) plane and L_D^S =4.4 cm for the crystal orientation along the (110) plane.

As calculations show, at slow passage of a crystal through the beam the channeling efficiency ε depends on the angular orientation x'_0 of a crystal.

If we put the crystal in a straight section of A-70 (β=27 m, α=1.7, x_m =7.35 mm) and take into account the radial emittance of 2π mm·mrad and ε_{CR} is $2.27\cdot10^{-2}$, we will see that the maximum channeling efficiency equals 0.36% and is reached at $x'_0 \approx 0.35x'_m$.The channeling efficiency in this case does not depend of the momentum spread of the beam.

The variants of placing the crystal at the asimuths where β-functions are extremal and phase ellipses are oriented in the main axis were investigated also. It was found out that practically all of the beam particles can hit the crystal acceptance if x'_0=0 that corresponds to the maximum efficiency of channeling ε_{max}~2%. However the allowed range of the crystal angular orientations is turned to be very narrow. Because of that this angle range can be considered equals ~2φ_c.

In the most of experiments on particle extraction from A-70 by a bent crystal only small part (~5-10 %) of the accelerated proton beam hit the crystal. In this case the important point is a consideration of the momentum spread of the beam particles. The results of the calculation are presented in fig.2.

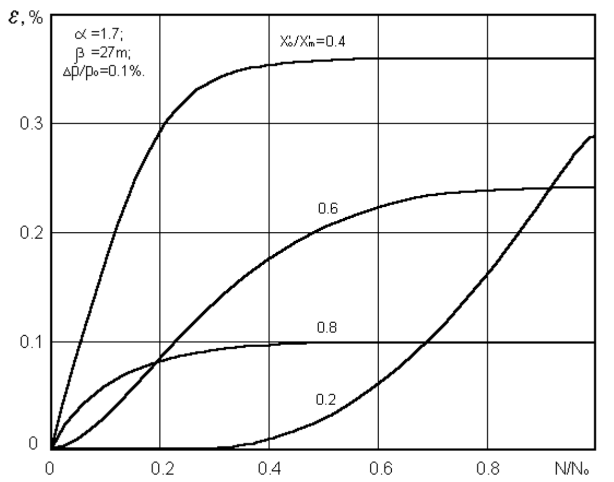

Figure 2: Dependence of the channeling efficiency versus number of particles hitting the crystal during extraction for different angular orientations of a crystal.

The relative momentum spread of a beam $\Delta p/p_0$=0.1% was taken at calculations and the crystal was placed in a straight section of A-70. It is seen that the channeling efficiency depends significantly from the angular orientation of the crystal x'_0. So, for example, at N/N_0=0.1 the channeling efficiency value may change from zero to 0.18%.

3 COMPARISON WITH EXPERIMENTAL DATA

It is interesting to compare the calculated data with experimental results on extraction of particles from A-70 by the bent Si crystal (see, for example, [4,5]).

3.1 Extraction by crystal without a target

It was shown above (see fig.2) that the channeling efficiency is changed broadly if the angular orientation of a crystal x'_0 changes. For comparing the calculated and experimental data it is necessary to have the concrete dependence of $x'_0(t)$ which is determined by the closed orbit on the asimuth of a crystal. The analysis of the closed orbit dynamics at the asimuth of a crystal shows that the value x'_0 is being changed during extraction in a broad range (~1 mrad). It exceeds the maximum value of the radial angular spread of a beam x'_m about 2 times. This effect leads to a significant decrease of the channeling efficiency in comparing to the case of keeping unchanged the angular orientation x'_0 of a crystal.

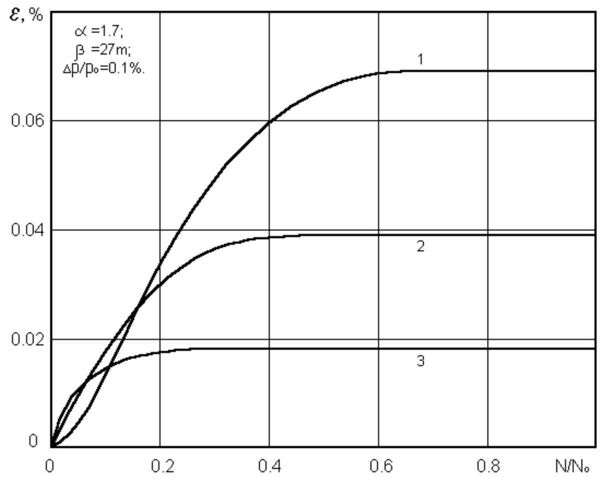

Figure 3: Dependence of the channeling efficiency is the number of particles hitting the crystal for various parameters X'_θ: 1 - $X'_\theta(0)$=0; 2 - $X'_\theta(0)$=0.2 mrad; 3 - $X'_\theta(0)$=0.4 mrad.

Dependence of the channeling efficiency ε versus the number of particles N hitting the crystal is given in fig.3. It corresponds to the case when the angular orientation of the crystal is changed during a beam extraction from the initial value of $X'_\theta(0)$ to $X'_\theta(0)+\Delta X'_\theta$, where $\Delta X'_\theta$=1 mrad. Curves 1,2,3 correspond to the values of X'_θ equal 0; 0.2 and 0.4 mrad. The parameters of the beam and the crystal as well as its asimuthal position are the same as for the data presented by fig.2. Fig.3 shows that the channeling efficiency decreases significantly with the growth of the parameter X'_θ when the crystal interacts with full intensity of the beam. From the other side, it is seen also that at hitting the crystal by a small part of a beam intensity the channeling efficiency grows faster with increasing the initial value of the angle X'_θ.

Since the initial orientation of a crystal was for the conditions of obtaining the maximum channeling efficiency at hitting the crystal by ~10% of the initial beam intencity, the realized at IHEP variant is obviously close to the presented by curve 3 of fig.3, the maximum calculated channeling efficiency of which is ~$1.9\cdot10^{-4}$. It is close to the value of the efficiency obtained at experiments on A-70 by this method, ~$1.5\cdot10^{-4}$ [4].

3.2 Extraction at scattering the beam by a thin target

The much higher efficiency of particles extraction as compared with the case considered above can be obtained if preliminary swinging the betatron oscillations of particles by thin target of a carbonic cloth [5] is used. At this method the particle amplitudes at the crystal asimuth keep constant during the extraction and, as a consequence of it, the angular orientation of a crystal X'_θ keeps optimal.

One can see here the analogy with a variant of placing the crystal at asimuths where beta-functions are extremal. The maximum channeling efficiency reachs the value ε_{max} and, as at that case, equals ~2%.

It appeared to be very close to the actual value of the efficiency of particles extraction from A-70 for the given regime. We may comment what has been said by the next way: the figure ~0.7%, which was obtained in [5] to get the order of magnitude of the extraction efficiency by a bent crystal, was lowered. The reason is in the next. At simultaneous work of a few internal targets and duration of the beam interaction with them $\Delta t\geq1$ s about 70% of primary protons make inelastic nuclear interactions in targets [6]. The rest particles having undergo elastic nuclear, multiple Coulomb scatterings and ionization losses of energy increase amplitudes of their oscillations till the losses occur on the vacuum chamber wall.

Those particles namely, the intensity of which is about 30% of the initial one, have to be considered at evalution of the efficiency of a beam extraction by bent crystal in this case. So, returning to the work [5] we have to take the particles density on the crystal ~$5\cdot10^{8}$ but not $1.5\cdot10^{9}$, i.e. three times less. The value of the extracting efficiency will be, respectively, ~2.1%. It agrees well with the value of a predicted efficiency of extraction obtained above for the case of preliminary scattering the beam by a thin target.

4 CONCLUSION

The program to describe the dynamics of a proton captured in the channeling mode inside a bent crystal proved to be effective. The efficiency of the 70 GeV proton beam extraction obtained for various regimes used at the IHEP accelerator by mathematical simulations is in a good agreement with the experimental data. The final value of the efficiency at extraction of protons by a bent crystal towards the experimental setup PROZA under scattering the beam by a thin target have been defined more exactly. It turned to be ~2%. We assume that the value of a few percents is the maximum efficiency of extraction for the case when the beam emittance is much larger that the acceptance of a bent crystal. That corresponds to the A-70 case.

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