New Aspects of Using Bent Crystals for Slow Particle Beam Extraction from Colliders

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Abstract

The analytical and computation calculations of the efficiency of circulating beam extraction with the help of a bent crystal are presented. The most probable intensity of the extracted beam is determined in terms of heating the crystal. Two beam extraction techniques differing by various orientations of the nuclear planes with respect to the beam and using the channelling effect are considered.

1 INTRODUCTION

Beam extraction bent crystals have widely been applied over recent years in modern accelerators FNAL,CERN, U-70 [1,2]. The main problem related to this extraction technique is the exact angle alignment and raising the thermal and radiation resistivity of the crystal. The range of angle alignment and crystal heating depends on the beam parameters and target design.

In our numeric simulations we have considered two positions of the crystal with respect to the beam. With the first position (fig.1(1)), the particles are stepsized normal to the nuclear planes and with the second one (fig.1(2)), they are stepsized parallel to them.

Computer simulations have shown that the efficiency of beam extraction from the UNK using the channelling effect may reach 95% with the first position and 90% with the second one when the alignment accuracy is 10 μrad for the 600 GeV machine and 5 μrad for the 3 TeV accelerator. In the case of an efficient heat removal from the lateral sides of the crystal its heating will not exceed 500^{0}C during 20-sec extraction of the total intensity, I=6 $\cdot$ 10^{14}p.

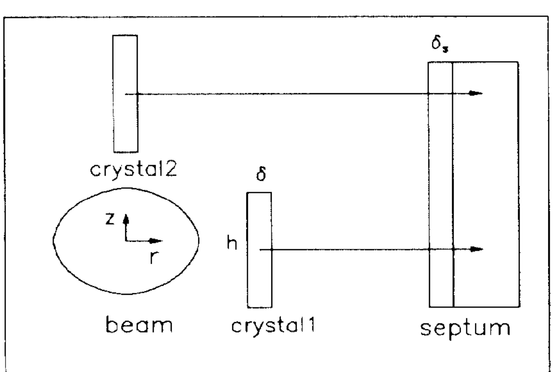

Figure 1: Two positions of the crystal.

2 BEAM EXTRACTION USING THE CHANNELING EFFECT

In this case we intend to use a short crystal bent to a small angle needed to increase the amplitude of betatron oscillations and sufficient for their stepsize into the septum. The beam is guided slowly to the crystal by distorting the closed orbit with bump-magnets. The calculations for some specific systems of the UNK have shown that for direct stepsize of particles behind the septum knife the required deflection angle is $\alpha \sim 500\mu$rad, whereas for the one in a few turns after the interaction it is sufficient to deflect the particles at an angle of $\alpha \sim 100\mu$rad. The particle trajectories in the crystal were found from the numeric solution of the equations of motion in the field of bent nuclear planes /1/ with account of multiple Coulomb, elastic and diffractive scattering and electromagnetic radiation.

2.1 The first position of the crystal

With this position of the crystal the extraction efficiency depends primarily on the angle alignment of the crystal with respect to the circulating beam. Figure 3 shows the intensity of the extracted beam and the average number of particle crossings through the crystal deflector versus the angle alignment.

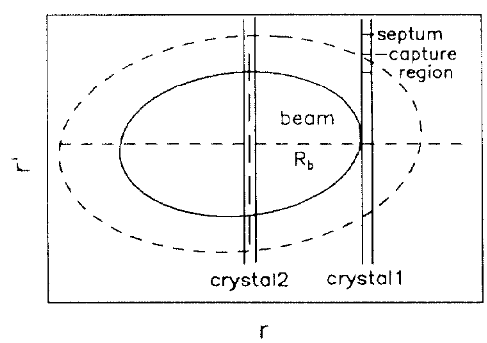

Figure 2: Extraction phase plane.

Figure 2 shows the particle motion on the phase plane during extraction. The particles missing the capture region in the channelling regime scatter on the target, thus increasing the amplitude of betatron oscillations (the dashed curve). After several crossings through the target they can hit the capture region or get lost due to nuclear interactions in the crystal body or in the accelerator equipment.

The efficiency of particle extraction due to nuclear losses on a short target with $l_c \ll L_n$ long may be estimated as

$$\xi = \frac{1}{I}\sum_{i=1}^{n} e^{-N_i l_c/L_n} \approx e^{-\bar{N} l_c/L_n}. \qquad (1)$$

Here I is the number of particles to be extracted, $\bar{N}$ is the average number of proton crossings through the crystal before they are captured into the channelling mode and extracted, and L_n is the nuclear length of the target matter. Then the value of particle losses in the crystal is defined as $\eta \approx \bar{N} l_c/L_n$. If the inlet angle of the particle is $\vartheta < -\vartheta_c$, then the process of its variation during subsequent crossings through the crystal looks like accidental particle roving in a medium with absorbing boundaries. The average number of intersections of protons with the target before they hit the capture region is $\bar{N} \simeq (|\vartheta| - |\vartheta_c|)^2/\sigma^2 + N_0$, where σ^2 is the scattering dispersion. If particles cross the input nuclear planes at an angle smaller than the critical one, $|\vartheta| > \vartheta_c$ then passing through it as if it were an amorphous substance they experience multiple Coulomb and potential scattering at the crystal input, i.e. in this case $\sigma^2 = \sigma_\vartheta^2 + \sigma_a^2$. The value of r.m.s. scattering of particles on the potential of input nuclear planes, $\sigma_\vartheta = 0.7 \times \vartheta_c^2/\vartheta$ is inessential for large input angles and therefore the dispersion is determined mainly the scattering of protons on the amorphous target of a length equal to that of the crystal: $\sigma_a^2 \approx \frac{200 \cdot l_c}{L_r \cdot \gamma^2}$.

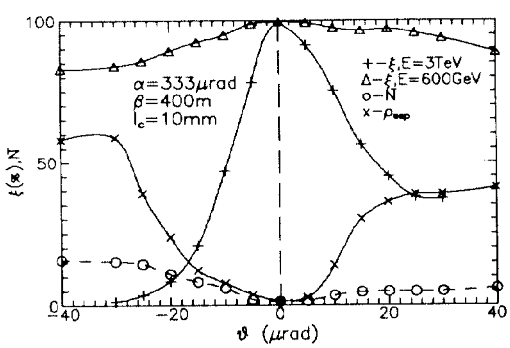

Figure 3: Efficiency and losses of the extracted beam for the first position of the Si (110) crystal.

The angular deviation for which the extraction efficiency falls e times is determined by the expression $\vartheta_e = \frac{14.1}{\gamma} \cdot \sqrt{L_n/L_r}$ and is independent from the crystal length may serve like an estimate for crystal alignment.

The volume reflection[3] is added when $\vartheta > \vartheta_c$ and the dispersion becomes $\sigma_v^2 = \sigma_\vartheta^2 + \sigma_a^2 + \sigma_v^2$, where in our case $\sigma_\vartheta^2 \simeq 2\vartheta_c^2$. This explains the asymmetry of the extraction efficiency curve. The dashed line in figure 3 shows the number of particle with E=600GeV crossings through the crystal versus the angle alignment. If the target is positioned exactly the line has a pronounced minimum. Using losses monitors determining the intensity of the particles escaping the target or wire detectors one may find precisely the optimal alignment of the crystal with the help of a goniometer or by changing the local distortion orbit.

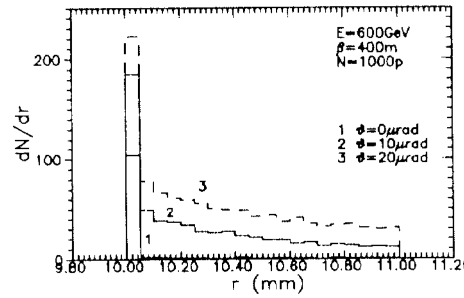

Figure 4: The distribution of particle density hitting the crystal front surface.

In addition the extraction efficiency falls due to particles hitting the septum knife . Figure 3(x) shows losses of the particles with the energy E=600GeV on the knife with thickness δ_s=0.2mm.

Figure 4 shows the distribution of the density of particles hitting the crystal front surface. When guided slowly on the target, all particles hit the inner edge of the crystal, having a thickness of a few microns. The particles left uncaptured into the channelling mode distribute across the crystal cross section actually uniformly.

2.2 *Crystal heating*

The value of the energy released into the crystal during slow extraction can be estimated as $\Delta E = dE/ds \times I_c l_c$, where I_c is the number of protons hitting the front surface, dE/ds is the density of energy release in the matter (for Si dE/ds=5.7MeV). If there is no heat removal the crystal heating is $\Delta T = dE/ds \times \bar{N} I/\rho C p S$, where ρ and Cp are the density and heat capacity of the target substance, S is its area. For the optimal alignment of the S=20 mm^2 crystal $\bar{N} \approx 2$ and if the total intensity beam is dumped on it $I = 6 \cdot 10^{14}$p its heating is $\Delta T \approx 3000^0$C that is more than the melting temperature, Si (Tmel=1410^{0}C).

With an efficient heat removal from the side edges a stationary heat exchange process is established and the temperature distribution function may be found in the form

$$T(x) = \frac{1}{\lambda \delta l_c}\iint_o^{h/2} P(x) dx dx + T_o, \qquad (2)$$

where P(x) is the density of energy release from coordinate x, λ is the specific heat conductivity of the target, h is the crystal height, δ is its thickness. If the integral is taken from center of the front crystal surface that is the symmetry point of heat distribution then

$$\Delta T = \frac{\Delta E \cdot (h - z)}{4t\lambda l_c \delta}, \qquad (3)$$

where z is the halfsize of the beam.

With a precise alignment of the $h \times \delta = 20 \times 1mm^2$ Si crystal $\Delta T = 250^0$ C for the 20 second beam extraction

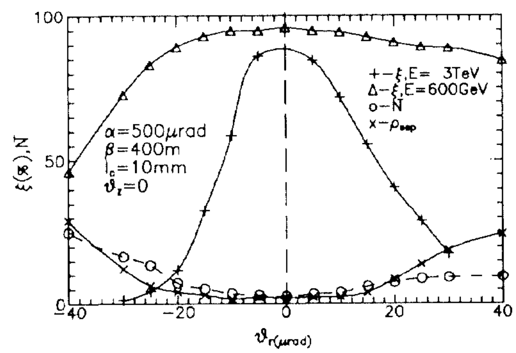

Figure 5: Efficiency and losses of the extracted beam for the second position versus alignment in r plane.

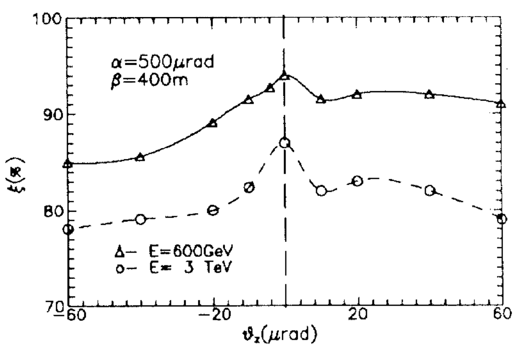

Figure 6: Efficiency of the extracted beam versus alignment in z plane.

from UNK. For a poor alignment of the target the number of crossings through the crystal may increase essentially and result in destruction of the target. A denser particle distribution close to the inner crystal edge increases its heating by some tens of degrees.

As seen from equation 3, to decrease the crystal heating it is necessary to chose a thicker and narrower crystal, $\delta \uparrow$ and h$\downarrow$, not much narrower than the relevant beam transverse size.

The duration of extracting a high-intensity beam as it is expected at the UNK must sufficiently long, t>10sec. This implies that the intensity of the extracted beam, at which the chosen crystal may function normally is $I \sim 6 \cdot 10^{13}$p/s, depending weakly on the particle energy. When we scrape the halo of a collider beam [4] the extracted efficiency becomes low, $I = 10^8 \div 10^9 p/s$, making the crystal heating inessential.

To prevent heat- and radiation-induced destruction of the target one may use a beam scraper system that would localize particles having large amplitudes which have a low probability to be captured into channelling mode.

In our case the septum is the part closest to the beam and limiting the machine aperture, thus defining the region of the crystal angle alignment as $\vartheta_s = \pm\frac{1}{\beta}\sqrt{R_s^2 - R_b^2}$ (see fig.2). When we have a large displacement of the input angle from the beam axis for $\vartheta > \vartheta_s$ the beam is extracted both with an amorphous target and for $\vartheta < \vartheta_s$ it is extracted by volume reflection.

2.3 *The second position of the crystal*

With the position of the crystal as shown in fig. 2(2) in addition to crystal alignment in the output plane r is the alignment of the angular position ϑ_z in plane z normal to the extraction plane. For the UNK 10% decrease of the extraction efficiency corresponds to an alignment of $\vartheta_z \sim$ 0.1rad for the 1st and 2nd stages.

If the crystal thickness is less than the beam size then, due to a higher density of particles on the crystal edge, the local heating is higher than for the first position of the crystal. With heat removed from the external lateral surface of the crystal, the maximal temperature rise is observed on the front edge that can be found from formula 2: $\Delta T = \frac{\Delta E \cdot (h-\Delta)}{2t\lambda l_c \delta}$, where Δ is the impact parameter. In this case the terms for choosing the crystal are the same as in the case of the 1st position of the crystal, i.e. $\eta \downarrow$ and $\delta \uparrow$. The crystal height should be larger than the impact parameter.

The extraction processes were simulated numerically with account of the inaccuracy of the angular alignment of the crystal, $\vartheta = \pm 10(5)\mu$rad, and orbit pulsations $\Delta r' = \pm 10(5)\mu$rad for the 1st and 2nd stages of the accelerator, respectively.

3 CONCLUSION

A high design efficiency of the system, that was 95% for the 1st and about 90% for the 2nd positions of the target is provided by the possibility of multiple crossings through the target. As a result, the share of the particles left uncaptured into the channelling mode or scattered on the target becomes captured again and is extracted. The losses on the septum knife δ_s=0.2mm thick will be less than 1%. Other losses are determined by nuclear interaction of protons with the crystal substance.

With a precise alignment of the Si crystal it will be possible to extract beam of the total intensity from UNK for the 20 second and more.

4 REFERENCES

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