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Possibility of high efficient beam extraction from the CERN SPS with a bent crystal. Simulation results

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ABSTRACT

The extraction of the SPS beam of 270 GeV/c protons assisted by a bent crystal was studied by simulation. Two methods for delivering the SPS beam onto a crystal were considered: transverse diffusion and orbit bump of the beam. It was shown that the main condition for high efficient beam extraction with a bent crystal, which is a small divergence of the incident beam, can be fulfilled. Extraction efficiency up to 99% can be reached for both methods of the beam delivering. The irradiation of the electrostatic septum wires during the beam extraction can be considerably reduced.

1. Introduction

High energy positive particles can be captured in channeling regime in a crystal if their incident angles relative to the crystal planes are smaller than the critical one $\theta_c=(2U_o/pv)^{1/2}$, where p, v are the particle momentum and velocity, respectively, and U_o is the well depth of the crystal potential averaged along the planes [1]. Channeled particles move in a crystal oscillating between two neighbouring planes.

Channeling is also possible in a bent crystal if its radius is larger than the critical one, $R > R_c=pv/eE_m$ [2], where E_m is the maximum strength of the electric field in the planar channel. Channeled particles are deflected by a bent crystal. The deflection by a small angle with short crystals can be efficient (about 80%) if the incident beam has a divergence considerably smaller than θ_c [3]. This is the first main condition for high efficient beam deflection by a bent crystal. The second condition requires the precise angular alignment of a crystal. The angular step of the goniometer should be considerably smaller than θ_c.

Particles of the diffusive halo surrounding the circulating beam have a very small angular spread in collisions with a primary collimator. Therefore, the usage of a bent crystal as a primary collimator should be efficient if the necessary precision of the angular alignment of the crystal can be realized. The critical angle for 6.5 TeV protons of the LHC collider θ_c=2.6 μrad for the (110) planar channels of a silicon crystal. High precision goniometers with the step value of 0.1 μrad were produced for the studies of crystal assisted collimation of the LHC beam. Recently the first successful tests of the crystal deflectors were fulfilled for the LHC beam halo collimation [4]. The contribution of multiple passages through the crystal increases the channeling efficiency up to 95% according to our simulation results. The channeling efficiency is determined by the beam fraction passed through the whole crystal length in channeling regime. The collimation efficiency increases additionally also due to dechanneled particles with large deflection angles.

Possibility to have a time for the optimal crystal alignment is required for the successful usage of the crystal deflector. The LHC beam lifetime in collider mode is of many hours therefore such possibility exists.

Radiation resistance of the crystals is also very important. The integral doses for silicon crystals without significant changes of their channeling properties can be larger 10^{20} proton/cm^2 according to the existed data [5]. However, for the beam halo collimation a thin surface range of the crystal works mainly. The radiation and thermal resistances of silicon crystals for such conditions require special studies.

A short bent crystal with a small bend angle can be also used for the efficient beam extraction from the accelerators. In this case a crystal deflects particles directing them over the wire of the electrostatic septum or septum magnet of the slow extraction system. Such beam extraction assisted by a bent crystal is wide used in IHEP Protvino [6]. A local orbit bump is used to deliver the accelerated beam onto the

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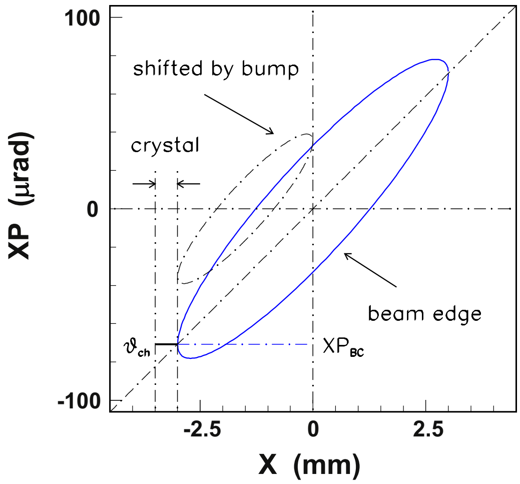

Fig. 1. (color online). Schematic picture. A particle trajectory of the beam edge (solid line) touches the crystal, which is aligned with the beam envelope, $\theta_{ch} = X'_{BC}$. A particle trajectory of the beam core shifted by the orbit bump is shown by dot-dashed line. Its envelope direction is far from θ_{ch}.

crystal. The extraction efficiency from U-70 with a bent crystal reaches 85%. However, the growing orbit bump changes the envelope inclination at the crystal (see Fig. 1). This effect decreases the deflection probability of particles by the crystal. The shift of the crystal towards the orbit is an alternative to the growing orbit bump.

The direct extraction when the beam deflected by a bent crystal exits the accelerator pipe had been studied at the CERN SPS [7]. This requires a large deflection therefore the bend crystal angle was 8.5 mrad. Transverse diffusion of the circulating beam due to the injection of noise pulses into the transverse damper plates was used to deliver the beam particles onto the crystal. The angular spread of particles at the first hits with the crystal determined by the noise amplitude can be made smaller than the critical channeling angle. The whole beam passes through the crystal at the fixed crystal position relative to the beam orbit. The extraction efficiency can be very high if one uses a short crystal with a small bend angle to deflect the beam particles into the electrostatic septum of the slow extraction system.

Possibility of a high efficiency of the SPS beam extraction assisted by a bent crystal using the transverse diffusion or the orbit bump is considered in this paper. The whole accelerated beam is delivered onto the crystal. The beam fraction passed through the whole crystal length in channeling regime and a small dechanneled fraction with deflection angles sufficient to jump over the septum wire are extracted from the accelerator. The extraction losses are small, 0.5–0.6%, and determined by the inelastic nuclear interactions of protons in the crystal and in the septum wires.

2. Simulation of the SPS beam extraction with a bent crystal

The SPS beam extraction by a bent crystal was studied by simulation of particle trajectories in the crystal and accelerator as it was described in Ref. [8]. The simulations were performed for the SPS beam of 270 GeV/c protons for which the critical channeling angle of the (110) silicon channels θ_c=13 μrad and the critical radius of the crystal bend R_c=0.46 m.

Four azimuths in the SPS ring were considered, which correspond to the equipment positions of the UA9 crystal collimation experiment. The initial beam which is Gaussian in the six dimensional phase space was given at the azimuth of the crystal 1 (C1). The so-called TAL absorber was at the second azimuth. One can imagine the electrostatic septum for the beam extraction in this position. The third azimuth corresponds to the RF accelerating system position. The forth azimuth was at the position of the transverse damper plates. The positions of

Table 1
Relevant accelerator parameters.

Parameter	C1	TAL
β_x(m)	90.945	87.660
σ_x (mm)	0.9047	0.888
$\Delta\mu_x$from C1 (2π)	0	0.2405
X^* (mm)	3	6

* Here X is the initial distance from the orbit bump

Table 2
Parameters of crystal C1.

Length (mm)	Bend angle α (μrad)	Bend radius R (m)	Miscat angle θ_m (μrad)
1.87	165	11.33	10

the crystal and the TAL absorber are with large values of the horizontal beta function. The horizontal betatron phase advance between them is close to 90 degrees. The relevant accelerator parameters at these two azimuths are listed in Table 1. The parameters for the crystal 1 are presented in Table 2.

The SPS beam collimation studies with a bent crystal showed [9] that the collimation leakage (both in the crystal and absorber) is minimal with the optimal absorber offset (2–3 mm) relative to the crystal. The absorber offset of 3 mm was selected for our simulation. Almost the whole accelerated beam with Gaussian distribution is in the range of $\pm 3\sigma_x$. The RMS horizontal beam size at the azimuths of the crystal and absorber is close to 1 mm. Therefore, the crystal distance from the orbit was selected to be X_{BC}=3 mm. Thus, the absorber (septum) distance from the orbit with the selected offset value is X_{tal}=6 mm.

It was assumed that at the beginning of the extraction process, the crystal orientation for channeling θ_{ch} is always aligned with the beam envelope direction at its position $X'_{BC} = (-\alpha_x/\beta_x)X_{BC}$, where α_x and β_x are the horizontal betatron functions, to have maximum probability for particles to be captured into the channeling regime.

2.1. Transverse diffusion

At every turn the circulating particles acquire some angular kick when they pass the damper azimuth. The kick is randomly selected from the Gaussian distribution with the RMS value σ_d. The maximum value of σ_d for 270 GeV/c protons, which can be realized in the damper is about 0.04 μrad according to [7]. Let consider the situation realized for this regime with the maximum value of σ_d.

Fig. 2 shows the angular distribution of particles at their first hits with the crystal. The distribution maximum is near the beam envelope direction. The distribution width at its half height is 5.8 μrad. The half width is considerably smaller than θ_c therefore the channeling efficiency is high, about 95%. Fig. 3 shows the impact parameter distribution of particles with the absorber (septum). Assuming a septum wire diameter of 0.2 mm, the particles which hit the septum (0.2 mm from its edge) are about N_w=0.4%. Inelastic nuclear interactions in the crystal were occurred for N_{cr}=0.2% of the beam particles. The total beam losses of the extraction process in the crystal N_{cr} and in the septum wire N_w are about 0.6%. Thus, the beam extraction efficiency from the SPS with the bent crystal can be larger than 99%.

The distribution of the number of turns performed by particles before the extraction is shown in Fig. 4. The distribution for the considered case with the RMS kick σ_d=0.04 μrad (1) is non-uniform with a long tail. About 3×10^6 turns are necessary for the beam extraction. That is the extraction time is about 70 s. This time can be reduced by a factor of 4 using the noise with the RMS kick value