CRYSTAL OPTICS OF HIGH ENERGY BEAMS

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INTRODUCTION

Experimental observation of the effect of charged beam deflection by bent single crystal [1] opened perspective for crystal optics systems [2-6]. Crystal deflectors are successfully used for U-70 extracted beam deflection, and crystal septum was used for beam slow extraction out of accelerator.

Figure 1 shows scheme of first experiment on U-70 beam deflection to SPHINX set up [5]. Beam with 10^{11} protons/cycle intensity was adjusted to deflector by magnet system at channel head. Efficiency was equal to 10^{-4}, which allows simultaneous work of SPHINX set up during experiment on the main beam. Set of experiments requires proton beam with varied intensity in a range 10^6–10^{10} protons per cycle and stable enough time structure. Slow extraction of such low intensity could not enable this structure; crystal deflector use allows simple solution of this problem. In 1989 there was extracted part of beam circulating in U-70 by bent crystal onto PROZA set up [6] (fig.2). About $4\cdot10^6$ protons were slowly extracted during 0.8 sec per each cycle.

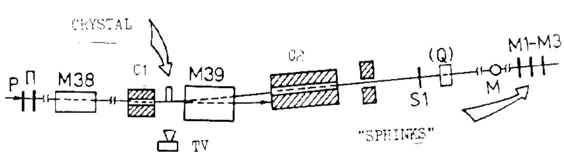

Fig. 1. Beam deflection onto SPHINX.

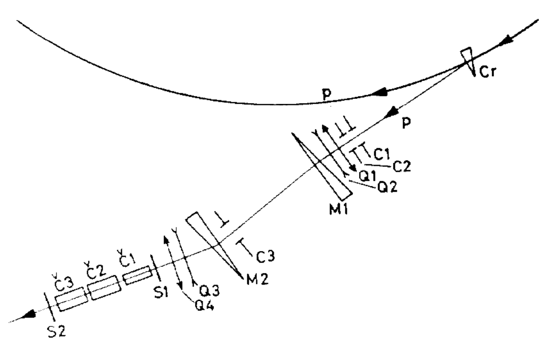

Fig. 2. Beam extraction onto PROZA.

CRYSTAL DEFLECTOR EFFICIENCY ESTIMATES

For crystal optics efficiency investigation we developed a complex of computer codes, taking into account beam dynamics in accelerator and multiple passes of particles through deflector. Figure 3 shows 70 GeV beam deflection efficiency for 10 mrad deflection. For beam extraction one can use existing system of slow extraction; in this case one should to deflect beam on 1 mrad to put it into gap of first septum magnet of extraction system. We modeled such extraction numerically [7]. Efficiency achieves 93%. Contribution of multiple passes into efficiency achieves 60% for strong

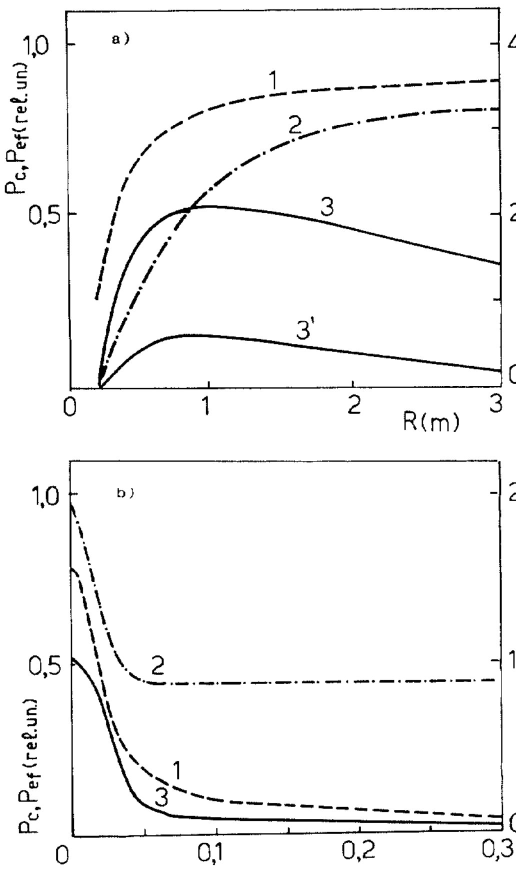

Fig. 3. 10 mrad deflection efficiency as function of a) radius, b) divergence.

bend. Nonchanneled particles can experience volume reflection [8]. As simulation shows, this reflection leads to cooling of beam fraction. Figure 4 shows this process schematically. Cooled fraction gets to capture region at deflector entry (fig.5) and is extracted.

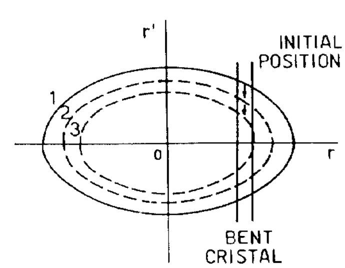

Fig. 4. Beam fraction cooling by volume reflection.

CRYSTAL DEFLECTOR USE AT COLLIDERS

Crystal optics efficiency at designed superconducted colliders (UNK, SSC) should be higher due to better ratio of crystal acceptance to beam emittance. At UNK

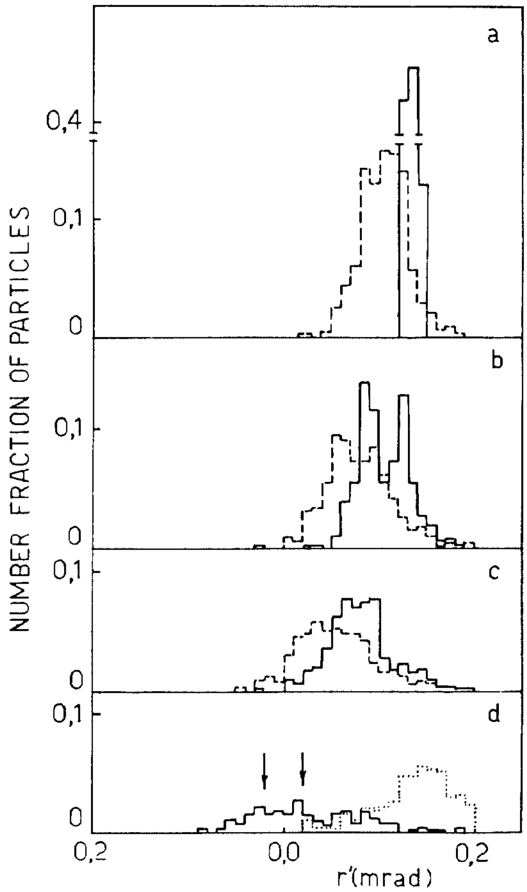

Fig. 5. Beam fraction distribution before and after deflector passage: after 0 (a); 10 (b); 20 (c), 70 (d) turns.

crystals are proposed to be used in system of loss location and emittance formation for lower irradiation accelerator equipment [6]. Figure 6 shows simulated distribution of particles at internal absorber for 1st injection stage of UNK. Crystal use for beam halo extraction during collider work is perspective [6].

Figure 7 shows scheme of beam extraction out of 2-nd stage of UNK. Efficiency of 3 TeV beam deflection on 0.3 mrad by silicon crystal could acheive 90%. For beam life 24 hour, assuming 1.5% accelerated protons to be halo extracted by deflector, proposed system allows slow extraction up to 10^7 protons per second.

The calculations for SSC, analytical ones [9], as well as computer simulation [10], give high (93%) efficiency of multiturn extraction. The analytical dependence (for beam angular divergence much smaller than channeling angle) is given by

$$f = \frac{q}{q(1-\lambda)+\lambda}, \qquad (1)$$

where q is one-turn deflection efficiency, $\lambda=1-\exp(L/L_N)$ is a probability of inelastic interaction of nonchanneled proton with crystal nuclei. Figure 8 shows the extraction efficiency; the curve represents fig.1 of ref. [9] (deflection on 90 μrad), the points represent fig. 14 of ref. [10] (100 μrad deflection), in good agreement.

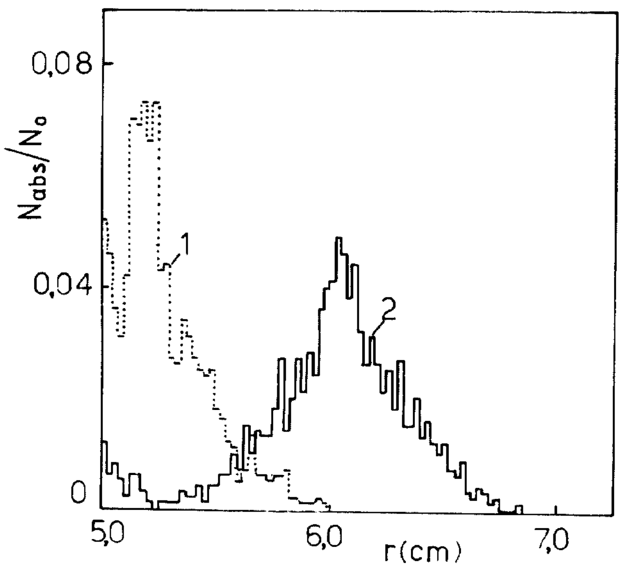

Fig. 6. Beam distribution at absorber.

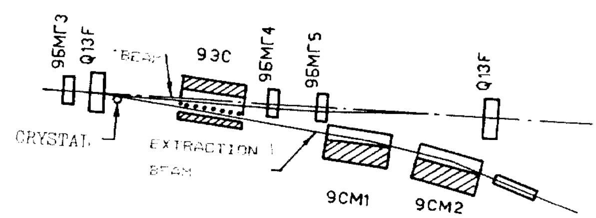

Fig. 7. Beam extraction from UNK halo.

ROLE OF BETATRON OSCILLATIONS

One of problems in halo extraction is very small impact parameters of protons hitting the deflector; the deflector has an ineffective "skin layer" due to imperfections of preparation and orientation. It is shown in ref. [11] that betatron oscillations in this situation:

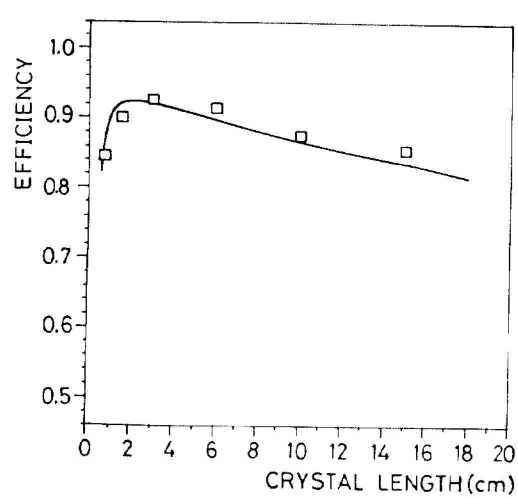

Fig. 8. SSC extraction efficiency. Curve of Ref. [9] vs. points of ref. [10].

a) effectively transfer the protons from quasi-amorphous skin layer onto a good portion of crystal, working in the multiturn mode; this greatly reduces demands on a deflector quality;

b) focuse the protons scattered after a pass through the skin layer, reducing scattered beam angular divergence by factor of 0.5 order; this is important for LHC case especially, where the scattering angle is near to channeling one;

c) displace ("reflect") the angular distribution of scattered beam for its secondary hit onto deflector; the angle of displacement is about 1/2 of the scattering angle.

These effects are clearly seen on the phase diagram (fig.9), where phase coordinates of protons exiting the crystal after the 1st pass (marked by O), and their entry coordinates for the 2nd pass through the crystal (after one or more turns in the ring; marked by *), are shown.

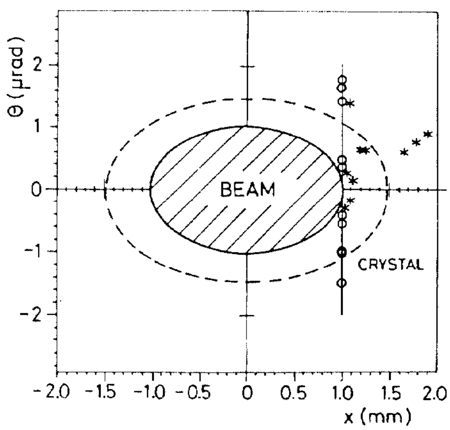

Fig. 9. Phase diagram of halo extraction (see text for details).

Due to these effects orientational dependence of efficiency can have, in general case, a few maxima, corresponding to the directions of a primary beam and disturbed one. The choice, which maximum to use, depends on the skin layer thickness and other parameters.

The calculations of one of variants of the LHC beam halo extraction (0.7 mrad deflection) show that the efficiency weakly depends on the skin layer thickness, decreasing from 70% (for ideal surface) to 50% (0.1 mm skin layer).

TAGGED HADRON BEAMS FORMATION

With energy increase more possibilities for crystal use in beam optics and particle physics are opening. E.g., in ref. 2 an extraction of secondary hadrons from Interaction Region of SSC by tungsten crystals is proposed. In refs. 11,13 a possibility to tag a secondary beam is shown, due to radiation of channeled beam in crystal deflector, on the examples of UNK and SSC.

The number of radiated photons is defined practically by soft, synchrotron, part of spectrum only. For this reason one photon emission length is equal to

$$L_1 = 95\,\frac{mc^2}{E/R}. \qquad (2)$$

which amounts for pion in silicon, germanium and tangsten with crytical bend 2.2 cm, 1.1 cm and 0.27 cm respectively.

At high energies radiation energy loss becomes high, so, one of methods of particle identification can be the measurement of channeling particle energy loss in the crystal and calculation of increase $dE/dz \sim \sim 1/m^4$ because of radiation, if all photons are absorber. More obvious methods of particle identification are (a) emitted photons number measurement ($\sim 1/m$), (b) photons energies measurement ($\sim 1/m^3$), (c) use of different absorbtion lenghts of photons with different energies.

Two schemes for hadron beams tagging were proposed [13]. In simplest one tagging is performed by detection of photons emitted forward and not scattered in the crystal. The photons characteristic energy of 10 MeV order and high directivity of radiation, spaced between deflected and undeflected hadron beams, simplify the detection substantially. The number of detected photons is restricted by scattering of photons in the crystal. According to calculation the pion identification efficiency is near to 90% at 10-15 TeV energy.

The second scheme uses the idea to displace the spectrum (by appropriate curvature choice) to the frequency, where Compton scattering dominates. In this case photons are scattered on angles of one radian order; their exit probability is defined by the crystal thickness (about 1 mm), not length. The problems arised here are analysed in [13].

DEFLECTORS WITH VARIED CURVATURE

With energy increase the set of effects, available to crystal optics, widens. Partly this is due to increase of curvature influence versus multiple scattering effects. In crystals with varied curvature some new effects become possible. One of them is a gradient nechanism of volume capture [14]. A formula for its efficiency was derived in ref. [15]:

$$q = \frac{R'\lambda\langle x\rangle}{2\cdot R\cdot d/2}, \qquad (3)$$

where R is a bending radius, R' its derivative, λ oscillation period, and $\langle x\rangle$ is averaged over oscillation transverse distance (relatively to atomic plane). A gradient effect in volume capture was experimentally observed [16], in agreement with (3).

Another effect - suppression of dechanneling in crystal with varied curvature [11] - can be used for reducing of heat and radiation load on the equipment, when crystal deflector is used.

A volume capture in crystal with decreasing curvature allows to form a channeled beam, monochromatic on transverse energy (with accuracy 1-2 eV) [11], which could be a unique tool in investigation of many processes related with channeling.

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