

# Use of a bent crystal for beam extraction in a slow extraction mode\*

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## Abstract

A bent Si crystal placed before the first septum-magnet (SM-18) of the IHEP accelerator (A-70) available slow extraction scheme allowed one to extract, for physical experiments, a part of protons that used to be lost at the septum-magnet aperture boundaries in the non-resonant slow extraction mode. In this mode up to  $3 \cdot 10^8$  protons were extracted additionally. This is about 10–30% of intensity extracted towards channel  $N^{\circ}22$  without the bent crystal. Use of unbent crystal as an amorphous target results in a decrease of the extracted beam intensity.

## I. Introduction.

Nonresonant slow extraction (NRSE) of protons from the A-70 made it possible to carry on experiments with hadron beams for the experimental setups FODS-2, SWD and SPHINX [1–4] at extracted beam intensity of  $10^6 \div 10^9$  protons per cycle (ppc) and duration of extraction by 2s. But for experiments with electron beams for setups FODS-2 and SWD higher intensity is desirable.

It turned, number of extracted particles can be increased with the bent Si crystal placed upstream of the SM-18. In distinction to the direct beam extraction regime (see, for example,[5]), possibilities of this mode prove an existence of other methods of using bent crystals to extract beams from high energy accelerators for physical experiments. In the article the scheme of extraction as well as the obtained results are presented.

## II. The scheme of a beam jump over the septum.

The NRSE scheme is shown somewhere(see,for example,[2,3]). Necessary deflection of a circulating beam towards the septum-magnets is made by a local distortion (bump) of a closed orbit [6]. It is clear that part of a beam is lost on the septum of the SM-18 due to its finite thickness, while some of particles are lost on other septum-magnet aperture boundaries.It proved to be possible to diminish losses by means of a bent Si crystal of 3 cm long, 2 mm thick,bent by angle  $\sim 2.5$  mrad along the (110) axis and placed at a distance about 40 cm upstream of the septum. Disposition of the septum-magnet and the bent crystal in the SS-18 is shown in fig.1.

This scheme, if the input end (a face) of a crystal is perpendicular to the circulating beam, would allow for particles, to hit the septum but proved to be captured into channeling, to get displacement for one passage

$$\Delta R_{CR} = L \cdot \Theta_{CR} \approx 1mm, \quad (1)$$

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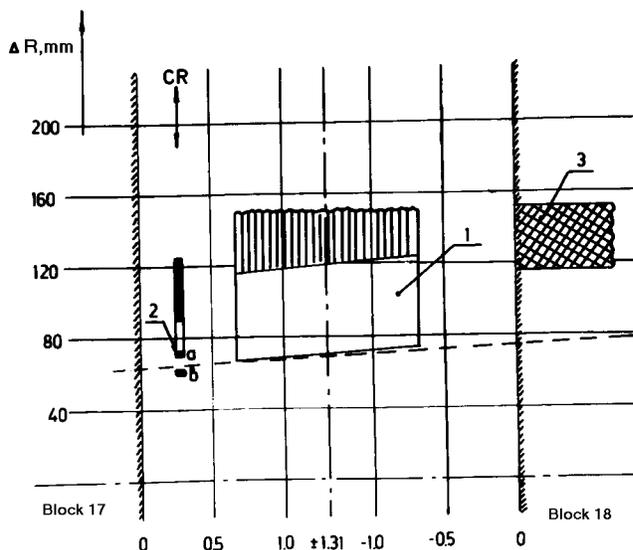


Figure. 1. Disposition of the septum-magnet and bent crystal. 1 is the SM-18 aperture, 2 is the crystal, 3 is nonlinear field zone of a magnetic block  $N^{\circ}18$ ; a and b mark the crystal position inside and outside of the septum, respectively. The vertical lines show the edges of magnetic blocks; a broken line is an injection beam envelope. A bender of a crystal is similar to that used in [5].

where  $L$  is a distance from crystal to septum-magnet along a closed orbit,  $\Theta_{CR}$  is a crystal bend angle.

At thickness of the septum  $\sim 0.5$  mm this displacement is enough for particles, going parallel to the septum and captured into a channeling mode, to jump into the SM-18 aperture. In our case the crystal was fixed with an angle to the central orbit  $\sim 4$  mrad and, according to geometry of the experiment, there were no particles to be captured into channeling from the input end of a crystal (so called “end-face capture mechanism”) and betatron amplitudes growth of which could become too large. The main mechanism to be responsible for capturing particles into channeling mode in our experiment was “a volume capture mechanism” opened in 1982 [7].

## III. Experimental results.

Fig.2 shows dependence of number of particles extracted towards channel  $N^{\circ}22$  [4] versus position of the bent crystal from the centre of the accelerator vacuum chamber.

It is seen that, on moving the crystal towards the chamber centre, intensity of an extracted beam grows reaching a certain maximum. The intensity increase under this maximum reaches

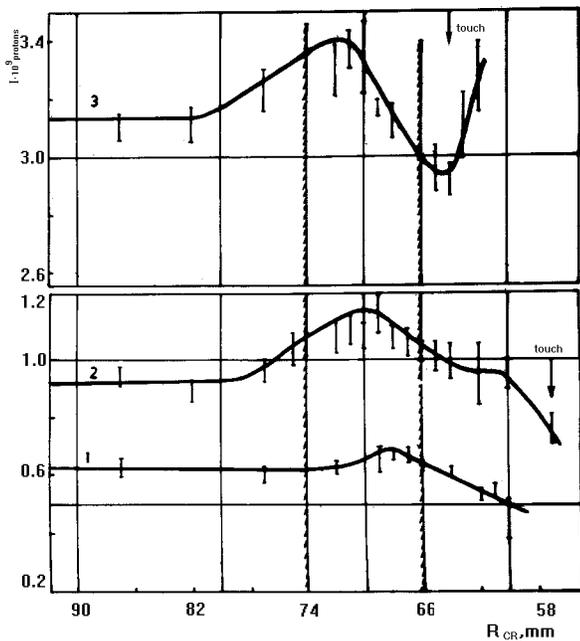


Figure. 2. Dependence of intensity, extracted into channel  $N^{\circ}22$  versus the bent crystal coordinate. The curves 1,2,3 correspond to the different levels of extracted intensity. Coordinates of the input and output ends of the SM-18 septum are shown with the vertical dashed lines.

$\sim 3 \cdot 10^8$  protons that consists of  $\sim 30\%$  at extraction of  $\sim 9 \cdot 10^8$  ppc or  $\sim 10\%$  at extracted beam intensity  $\sim 3 \cdot 10^9$  ppc, respectively.

In order to make sure that the result obtained is due to the channeling effect and not a simple scattering of particles by the crystal as an amorphous target, analogous dependencies were taken for the unbent crystal placed on the same azimuth of the accelerator.

The essential difference of the crystal influence was seen. In the case of the bent crystal use, increase of intensity is seen already at coordinates  $\sim 80 - 82$  mm that is  $\sim 14 - 16$  mm from the septum inside the aperture. The unbent crystal does not give any intensity increase, providing only losses of particles interacting with it inside of the SM-18 aperture. The losses are increased when the crystal is being moved towards the input end of the septum. Further moving the crystal across the septum into the accelerator chamber results in additional losses of particles on external (oriented to the circulating beam) side of the septum with some intensity increase after touching by the crystal a denser part of a beam not to be scattered yet by targets. In this case a significant (by 1.5-2 times) shortening the spill of secondary particle beams extracted in parallel for other experiments was fixed.

## IV. Discussion of results.

### A. Beam extraction mechanism.

Two mechanisms of particles capturing into the channeling mode are known [8]: the end-face and volume ones, i.e. when particle trajectories are tangential to the crystallographic planes

at the face end or into the depth of a crystal, respectively. In the first case, number of particles of a certain energy to be captured into a channeling mode depends on the ratio of the critical channeling angle to the divergence of an incident beam  $\psi_c/\Theta$ ; while in the second case it depends on capture probability  $W(R)$  that is the function of a crystal bend radius.

Phenomenon of proton capture into the channeling mode in the depth of a bent crystal was shown experimentally in the 1 GeV region by the authors of the work [7]. Later this effect was proved in [9] at the proton energy 8.4 GeV. Existence of a volume capture at 70 GeV was experimentally proved in the work [10] where the data of a proton capture probability into the channeling mode versus a crystal bent radius are obtained. We will use data from [10] to explain the results of our experiment.

Though the internal target moving mechanism used does not allow to optimize a crystal orientation, the results of the experiment prove one more possibility of using bent crystals for extraction of particles from accelerators.

One can understand dependencies of fig.2 with help of fig.3 where the phase pictures (portraits) of the circulating unperturbed beam (1) and beam jumped into the SM-18 aperture (region 2) are shown. The regions of possible losses of the particles having various angles on the septum (3), of a crystal influence (4), a calculated acceptance of the extracting channel including the septum-magnets for our regime (5), a phase region (6) for particles underwent scattering in targets without septum-magnets are shown as well.

Increase of an extracted beam intensity that starts at the crystal coordinate  $\sim 80$  mm (see fig.2) is due to transmission of particles by the crystal into region (5) of the extraction channel acceptance. Maximum of intensity reached at the crystal coordinates  $\sim 70 \div 72$  mm is due to deflection of a part of a beam, additionally jumped into SM-18 aperture, from a wall of the septum.

Decrease of an intensity growth determined by the channeling effect under moving the crystal towards the input end of the SM-18 can be explained as a miss of an extraction channel acceptance by deflected particles and loss of them on the septum at their multiple Coulomb scattering into the crystal.

If the crystal deepens into a beam outside the septum, protons that captured into a channeling mode can jump into the septum-magnet aperture only after having got a noticeable growth of a betatron amplitude and at the favourable phase on the following turns. On the "high" level of extracted intensity (curve 3 of fig.2) some growth of it is seen after touching a denser part of a beam by the crystal (marked with an arrow). Under this conditions a crystal, to be as an additional target, perturbs a beam scattering regime that results in shortening of a spill of extraction by 30-50%.

On the "low" level of intensity (curves 1,2 of fig.2) when the denser part of a beam was moved from the septum by decrease of a bump strength, a crystal touches the beam on a larger distance from the septum (marked with an arrow on curve 2). Decrease of intensity before the septum in this case may be explained with particles loss into a crystal, to be as a target, during their multiple interaction. Growth of amplitudes of the particles, even to be captured into channeling mode, in this case

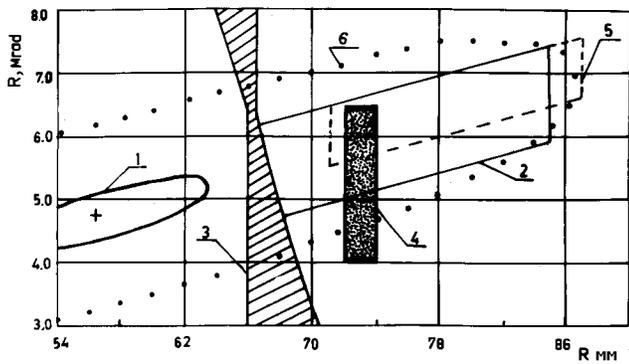


Figure. 3. Illustration of a regime of a beam extraction by the bent crystal on the phase plane.

turns out not to be enough; such particles practically don't jump into an acceptance of the extraction channel.

In the case of an unbent crystal use the change of extracted intensity can be easily understood in a frame of consideration of a beam dynamics under its interaction with an ordinary target. Scattering a beam in a target has no influence, due to small scattering angles, on extraction intensity till a target comes into zone of the septum coordinates. There are some losses increase here because of hitting the septum by scattered particles that results in decreasing an extracted intensity. Only some intensity growth appears again when the crystal is nearer to the circulating beam than the septum and a denser part of the beam is being touched with it. But since the secondaries spill is being shortened in this case by 1.5–2 times, this regime does not valid for use.

#### B. Numerical estimations.

Estimations of intensity which one can extract using, in our scheme, a bent crystal placed before the first septum-magnet will be made for beam intensity onto an ordinary target  $10^{12}$  ppc. It is known (see, for example, [1]) that 70–75% of particles make inelastic nuclear interactions with internal targets or to be lost on the accelerator chamber walls. The rest particles being underwent a multiple Coulomb scattering, ionization energy loss and nuclear elastic scattering continue their movement into accelerator gaining a noticeable growth of betatron amplitudes. Finally, one get the radial distribution of this particles at the point of a crystal placing that analogous to one shown in [3]. Evaluation show that at intensity  $3 \cdot 10^{11}$  of particles under this curve about  $1.2 \cdot 10^{10}$  of protons hit the crystal. Probability of a volume capture for our case calculated according to [10] equals about 1%.

So, in our scheme one can extract with help of a bent crystal additionally about  $1.2 \cdot 10^8$  of particles at  $10^{12}$  of protons interacting with a target. To obtain a sum of additionally extracted protons, that is well agreed with the experiment, one has to take into account that from 3 to 5 targets work simultaneously interacting with primary beam of total intensity up to  $2.5 \cdot 10^{12}$  protons every accelerator cycle [1].

## V. Conclusion.

A bent crystal placed before the first septum-magnet of the A-70 slow extraction system made it possible to extract additionally up to  $3 \cdot 10^8$  protons, used to be lost on septa, towards channel  $N^{\circ}22$  in parallel to the work of a few internal targets generating secondaries for other experiments. A relative growth of extracted proton beam intensity depending on an extraction regime was 10–30%. Capturing of particles into the crystal channeling mode was due to the volume capture mechanism.

The main advantage [10] of the volume capture in comparison with the end-face one is that no precise alignment of the crystal is necessary (one can do without a goniometer). Besides, the volume capture may be more effective for the beam of a large divergence [8].

The regime of extraction obtained may be used when planning experiments for channels  $N^{\circ}22,23$ . The effect of increasing an extracted beam intensity when using a bent crystal in this scheme, apparently, to be magnified by introducing a goniometer to make an optimal angle relations between the crystal, the beam and septum-magnet.

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