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Proton Extraction from the CERN SPS using a bent crystal

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Abstract

The extraction of high energy particles from a circular accelerator by means of channeling in bent crystals is an attractive alternative to classical extraction schemes, in particular for high energy proton colliders where a classical scheme becomes expensive and incompatible with normal operation. This paper reviews the ongoing extraction experiments at the CERN-SPS with bent silicon crystals. It describes the principles of beam extraction by means of a bent crystal and the different extraction schemes used: first- and multi-pass extraction and the methods to create diffusion. The limitations in tuning the accelerator to the desired impact parameters and crucial items concerning crystal preparation, bending and pre-alignment are discussed. The experimental procedures including an overview of the detection of circulating and extracted beam are given. Finally, the paper summarizes the results of these experiments together with ideas for future developments.

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1 Motivation and history

Existing high energy proton accelerators are frequently used for "fixed target" physics - the proton beam is extracted from the accelerator and transported to an external target, where secondary particle beams like pions, muons, electrons etc. are produced for subsequent use in experiments, or the protons are interacting in the specific experimental target followed by a complex arrangement of detectors to study nuclear or particle physics. In the following, circular proton accelerators of energies above some 10 GeV are considered.

The "classical" slow extraction scheme used today, up to the highest energy protons at Fermilab (800 GeV/c), is based on a resonant beam excitation which moves protons across an electrostatic septum. The small deflection angle (typically some 100 μrad) is sufficient to hit the field region of magnetic septa, which then provide the larger deflection angles (about 10 mrad) needed for extraction. Such a scheme can easily be 100 meters long, is very costly to build and complex to operate. Moreover, fixed target physics is not compatible with collider running (e.g. at the Tevatron at Fermilab) due to the resonant beam blow-up used for extraction, which contradicts the need for small beam spots during collider runs.

The situation becomes a lot worse if even higher energy accelerators like the LHC [1] (Large Hadron Collider, 7 TeV per proton beam), under construction at CERN, are considered. A classical slow extraction would seem almost impossible in the straight sections available there. Moreover, the LHC is conceived to be a proton-proton collider, and a classical extraction would not be compatible with such an operation. Nevertheless, the physics community both at the (late) SSC (20 TeV per beam) and the LHC came forward with proposals based on an extracted proton beam [2, 3]. In both cases, the idea was to send up to $2 \cdot 10^8$ protons per second onto a solid target in order to produce $B\bar{B}$ pairs and to measure CP violation in the B - meson decays.

In order to provide such an extracted proton beam, the idea was put forward to use planar channeling in a bent silicon crystal, placed in the halo of one of the colliding proton beams [4, 5, 6]. This would allow, in the case of the LHC, to extract 7 TeV protons and send them to a fixed target facility, without disturbing the collider experiments. In fact, after the cancellation of the SSC project, the B- physics proposal with an extracted beam at LHC was not encouraged: instead, it was suggested to use a dedicated collider detector to study the physics proposed. Nevertheless, it was felt that the option of a fixed target facility based on extraction with a bent crystal was an interesting one, and studies in this direction continue at Fermilab and at CERN. Moreover, accelerator scientists have realised that the directional properties of bent crystals might also be considered as one ingredient of the complex collimation scheme needed in order to protect the super conducting magnets of TeV hadron colliders [7]. Finally, the phase space of diffusing protons in accelerator physics experiments using e.g. non-linear excitation of the beam can be probed with such a bent crystal collimator/extractor.

Channeling and deflection of high energy proton beams in bent silicon crystals is well understood. If a parallel beam of e.g. 450 GeV protons is hitting the entrance face of such a crystal, deflection efficiencies of up to 50% can be achieved [8]. In the experiment, 50 mm long Si crystals cut parallel to the (111) plane and bent by 2 mrad were used. An overview of the deflection experiments and theory can be found in these proceedings [9, 10] and in [11].

The principle of proton extraction with a bent crystal was established by a group in Dubna in 1984, at energies below 10 GeV [12]. From 1989, efforts have continued in Protvino to serve additional users of fixed target experiments with 70 GeV protons extracted by means of a bent crystal [13, 14]. The deflection angle, given by geometrical constraints, is as large as 80 mrad in those applications, which is the main origin of the rather modest extraction efficiencies (below 1%) achieved. The group has shown, however, that an extraction system based on a bent crystal can be operated successfully and stable over many years.

The interest in the field of extraction with a bent crystal grew rapidly in the early 1990's when its potential for the future hadron colliders was fully realised (see above). Two groups, at CERN (SPS) [15] and Fermilab (Tevatron) [16], started more detailed tests in order to better understand the mechanisms leading to extraction with a bent crystal and to eventually increase the extraction efficiency. In the following, the different methods for extraction with a bent crystal are discussed. A detailed account of the CERN-SPS experiments with a 120 GeV coasting proton beam is given, together with results from our simulations.

2 Methods for extraction with a bent crystal

2.1 Halo formation and impact parameters

The future TeV colliders will be built with super conducting magnets. This, even more than in today's accelerators, will lead to imperfections, which in turn lead to a loss of protons from the circulating beams. Moreover, proton-proton collisions in the interaction points as well as collisions with molecules in the residual gas of the vacuum system also lead to losses. All together, such effects result in the creation of a "beam halo", into which protons diffuse. The outer limits of the halo are given by the collimators installed to protect the magnets.

The principle of a parasitic extraction of protons with a bent crystal is therefore very simple (Fig. 1): place a bent crystal on a goniometer in the halo of the circulating proton beam. Align the crystalline planes with the

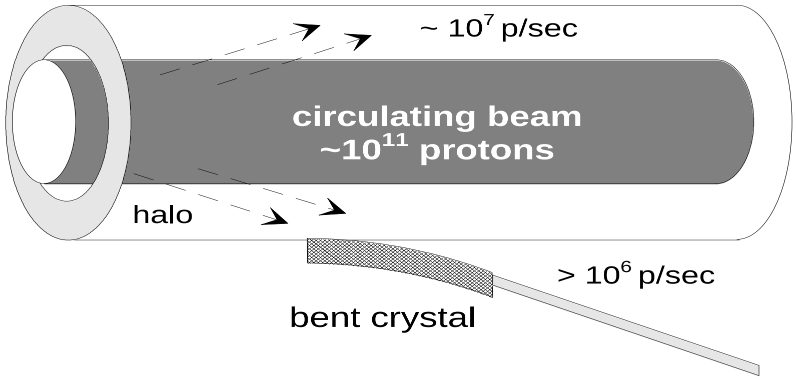

Figure 1: Principle of proton extraction from the halo of a circulating proton beam by means of a bent crystal

momentum of the protons in the halo, in order to allow channeling (and extraction). The main beam and thus the collider experiments would be undisturbed, and the protons used for extraction are only the ones which would otherwise be lost on the collimators.

At this point, a crucial parameter for such an extraction scheme has to be introduced (Fig. 2): the impact parameter b. Protons diffusing away from the main beam into the halo will eventually hit the crystal. The

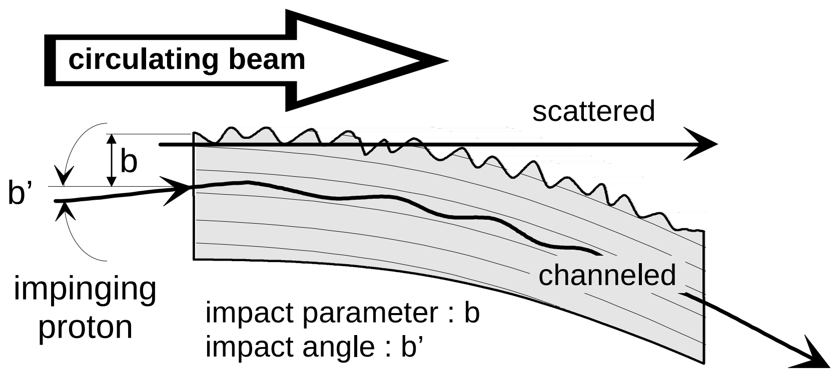

Figure 2: Protons hitting the bent crystal: definition of impact parameter (b) and impact angle (b'). Surface imperfections are schematically indicated at an enlarged scale.

depth from the crystal surface, at which this occurs, is referred to as impact parameter. (Note that this is in contrast to proton deflection with a bent crystal in an external beam [8]: there, the beam is usually steered onto the centre of the crystal face). Analogously, the impact angle b' is defined as the angle of incident protons with respect to the crystalline planes. Obviously, channeling and thus extraction is only possible if the protons hit the crystal with an impact parameter b large enough to overcome possible surface imperfections, and with an angle b' small enough to be within the critical angle for planar channeling. The latter is found to be 1.8 μrad for Si (110) planes and 7 TeV protons (i.e. LHC). This angle scales as $\frac{1}{\sqrt{p}}$ with momentum p and is 13.6 μrad for 120 GeV/c.

The problem in designing an extraction scheme with a bent crystal is strongly related to the impact parameters: it is very difficult to predict the impact parameter distributions which will prevail at the LHC, and it is certain that such a distribution will depend strongly on the running conditions of the collider. Furthermore, small imperfections of the crystal surface have to be expected. Therefore, it would be desirable to devise a scheme in which the initial impact parameters play a minor role (see below).

2.2 Creation of diffusion for tests at existing accelerators

In order to test the principles and investigate the mechanisms of proton extraction with bent crystals at existing accelerators, different schemes have been developed to simulate the formation of a beam halo, i.e. to induce a beam growth artificially. Once again, the question of crystal surface imperfections is of importance: in order to be sure that the beam will hit the crystal inside some surface layer, the so-called "kick-mode" is being used (Fig. 3). In this mode, the full beam is kicked with a fast kicker magnet (risetime $\approx$ 100 ns) by a large amount

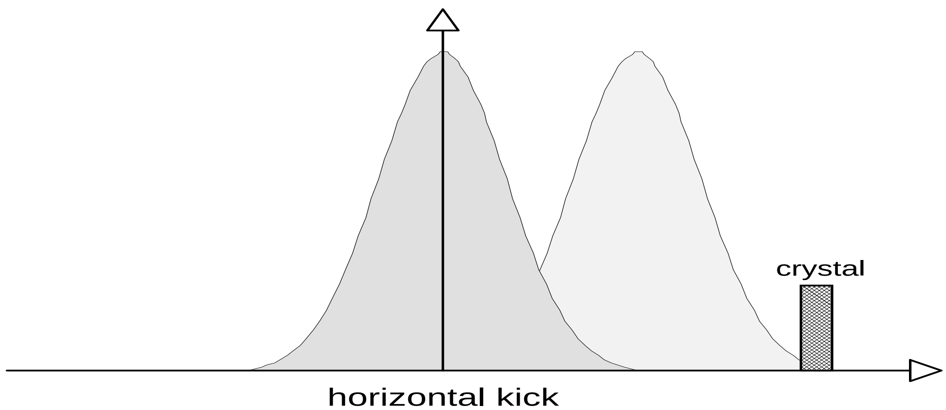

Figure 3: Schematic illustration of the kick mode: instantaneous displacement of the whole beam towards the crystal

(e.g. 0.1 mm or more, up to 5 mm) towards the crystal. This leads to the obvious advantage of large impact parameters, however, it has also several drawbacks:

- high instantaneous rates extracted leading to problems with the detection due to saturation of the counters
- unclear how much beam is lost on the crystal, thus difficult to determine the extraction efficiency
- the mode is clearly not parasitic, thus not relevant for future applications

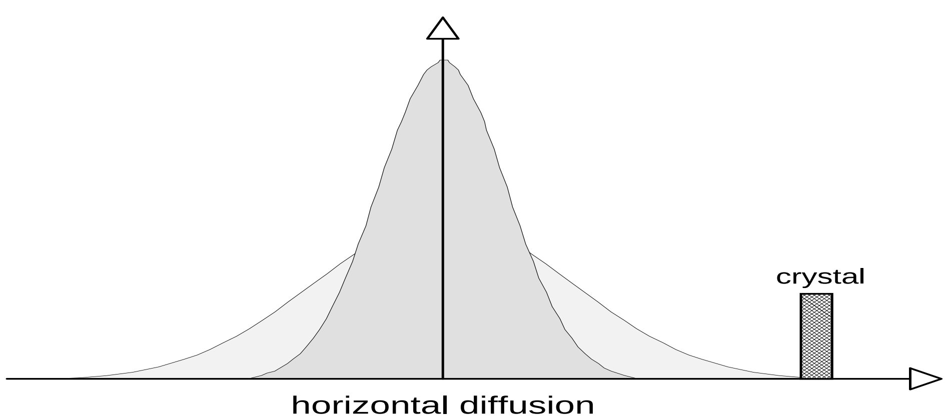

Figure 4: Schematic illustration of the diffusion mode: slow beam growth due to small random kicks from electrostatic plates

Alternatively, different schemes are used to impose some slow diffusion (Fig. 4) onto a circulating proton beam. The one generally used at the SPS takes advantage of existing electrostatic plates (normally used as "dampers" in the transverse feedback system), where small randomly generated kicks are produced by band limited white noise voltage on the plates [22]. This has the advantage that the diffusion speed is tuneable, the process is slow and steady, and the instantaneous rates are reasonable. The disadvantage, however, is that the impact parameters are generally found to be small, i.e. below 1 μm.

Slow and controllable diffusion may also be produced by white noise on the radio frequency system in the accelerator [17]. The momentum spread thus produced is transformed into a position spread at locations with large dispersion. Finally, artificial non-linearities and tune-ripple is used to create diffusion, too [18, 19]. This method leads to rapidly increasing diffusion speeds and therefore larger impact parameters at larger distances from the beam centre, but the b and b' distributions are hard to predict or simulate.

2.3 First- and multi-pass extraction

If a high energy proton hits the front face of a bent crystal within the critical angle for channeling, there is a high probability for this particle to be channeled and, assuming a rather small bend angle of the crystal and a smooth curvature, to be deflected by this angle. This has been shown experimentally in detail, e.g. in beam deflection experiments with 450 GeV protons [8]. First-pass extraction corresponds exactly to this situation (Fig. 2): protons hitting the crystal with impact parameters large enough to be well inside the imperfections of the surface layer, and with a small angle, will be channeled and extracted.

Contrary to the situation in an external beam [8], protons which are not channeled at their first encounter with the crystal have "another chance" in a circular accelerator: they are scattered in the material of the crystal, usually by a very small angle, and will be transported around the accelerator. After one or several turns, they will hit the crystal again, sometimes with a large enough impact parameter and a small enough angle, and will eventually be channeled. This is referred to as "multi-pass extraction" and has a big importance for the projection to future accelerators: in this case, the initial impact parameter distribution is only determining the scattering of the protons in the crystal , and is therefore of little importance. Extraction is governed by the later passes, when the impact parameters are larger. The importance of multi-pass extraction has been shown both in simulations [20, 21, 22, 23, 24, 25] and in dedicated experiments with a thick amorphous layer on the crystal [26].

3 Experimental arrangement at the SPS

The principle of the experiments at the CERN-SPS is schematically shown in Fig. 5. A 120 GeV coasting beam

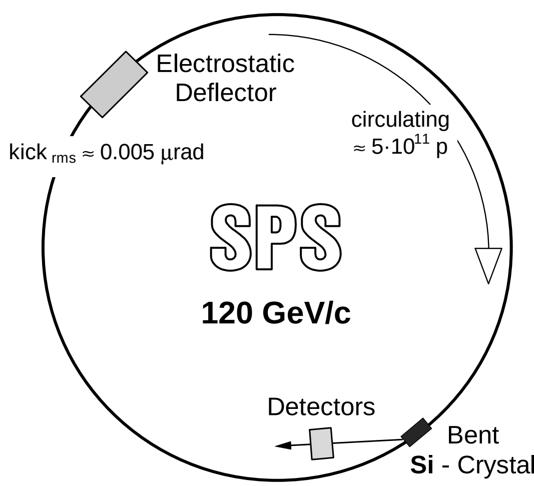

Figure 5: The principle of the SPS extraction experiments with a bent crystal

with an intensity of about $5 \cdot 10^{11}$ protons is used. At this energy the behaviour of the SPS is very linear and the lifetime of the beam without external interference can be several hundred hours. Extraction takes place in the horizontal plane. The crystal is placed typically at a horizontal distance of 10 mm from the closed orbit, some 10 times the transverse beam size, where only a few halo particles are found initially. The beam is then excited horizontally with band limited white noise induced on a pair of condenser plates ("dampers") [22]. Once the beam has diffused onto the crystal, angular scans are performed with the goniometer in order to determine the optimal alignment of the crystalline planes with the protons in the halo. The protons extracted by the bent crystal are measured in an arrangement of detectors placed about 20 meters downstream of the crystal, as shown in Fig. 6. Details of the equipment used and the experimental procedure are given in the following

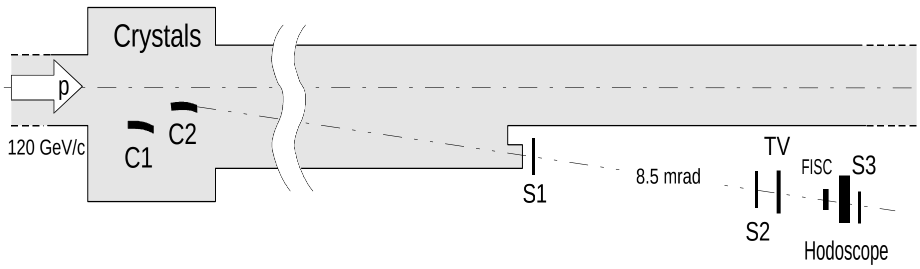

Figure 6: Schematic view of the crystal and detector arrangement to measure the extracted proton beam at the SPS

sections.

3.1 The bent crystals

For high energy channeling experiments, the intrinsic quality of the crystals used is of paramount importance. Industry provides the necessary material - both silicon and germanium crystals are available with mosaic spread of less than 1 μrad. The mechanical properties are somewhat better for silicon, which is also more easily available and cheaper. For extraction experiments, the quality of the cutting and the surface roughness are crucial parameters, too (cf. the above discussion on small impact parameters and Fig. 2). The crystals have thus to be cut as parallel as possible to the plane used for channeling and extraction, and the polishing should be done to the perfection available today. However, a small angle with respect to the crystal plane (miscut) cannot always be avoided. Such a miscut can have positive or negative angles with respect to the planes (Fig. 7) where the latter is very undesirable, because channeled particles can leave the crystal without passing the full length and therefore experience a smaller bending angle.

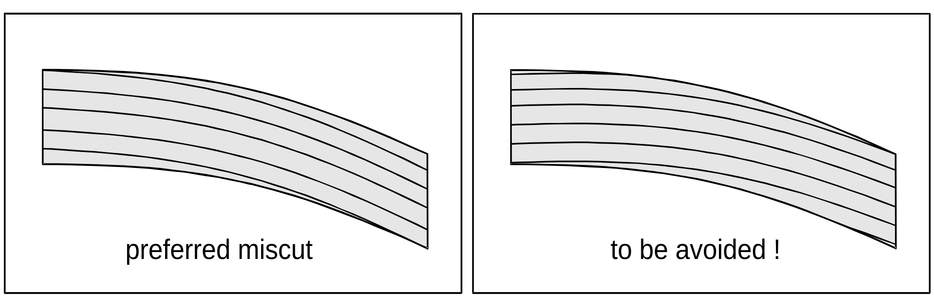

Figure 7: Crystal planes indicating preferred and unwanted miscut

To avoid this undesirable effect, a (small) positive miscut was introduced deliberately for some of the crystals used in the experiment. These miscut angles were generally in the order of 250 μrad and were measured with a precision of about 100 μrad. Its precise value is not important as long as it is small enough and positive.

All extraction experiments performed at the SPS use planar channeling in (110) Silicon crystals. The first series of crystals were cut and polished at the Max Planck Institut für Metallforschung in Stuttgart, Germany. In order to avoid focusing effects [27], the crystal edges have to be sharp.

The crystals were bent in a classical bending device inspired by the ones used in Serpukhov (Fig. 8). A

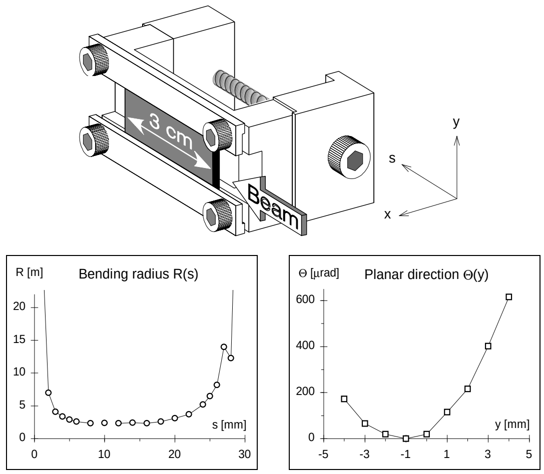

Figure 8: bending device for the first crystals used at the SPS (top) and results of laser measurements illustrating the horizontal curvature along the crystal as well as the anticlastic bending in the vertical plane (bottom)

30·18·1.5 mm^3 silicon crystal is clamped on the stainless steel device, and a differential screw is used to bend the entire device to the desired 8.5 mrad. Experience shows that this technique of bending a crystal, although bearing the advantage of simplicity, has an inherent disadvantage: an unwanted curvature is observed in the vertical direction, perpendicular to the plane of deflection. This is referred to as "anticlastic" bending. The results of laser reflection measurements on the surface of such a crystal are also shown in Fig. 8. The most serious effect is the change of direction of the (110) planes at the crystal entrance face as a function of vertical position: this implies that there is a different optimal alignment depending on the exact vertical position of the beam on the crystal, as observed experimentally (see 5.1).

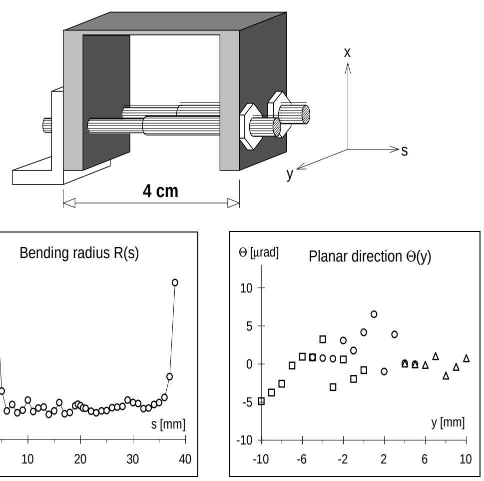

Figure 9: Schematic drawing of the U-shaped crystal (top), together with results from laser measurements (bottom)

In order to avoid such "anticlastic" effects, a new type of crystals (Fig. 9) was cut and polished at ESRF in Grenoble, France. Miscut angles of less than 100 μrad are achieved, however the sign of this miscut is unknown. The surface roughness is estimated to be about 50 Å. Here, the crystal and parts of the bending device are cut out of a single piece of silicon crystal. Still, the (110) planes are parallel to the 20·40 mm^2 surface used for extraction, but the legs of this "U-shaped" crystal are used as support for two differential screws, which in turn bend the crystal. Laser measurements for this type of crystal give very satisfactory results, as shown in Fig. 9. The anticlastic effect is clearly much smaller, note the difference in the vertical scale between Fig. 8 and Fig. 9.

3.2 Crystal installation and alignment

The bent crystals are installed on goniometers in a vacuum tank located in the straight section LSS5 at the SPS accelerator for extraction in the horizontal plane. A schematic drawing is shown in Fig. 10. Due to the

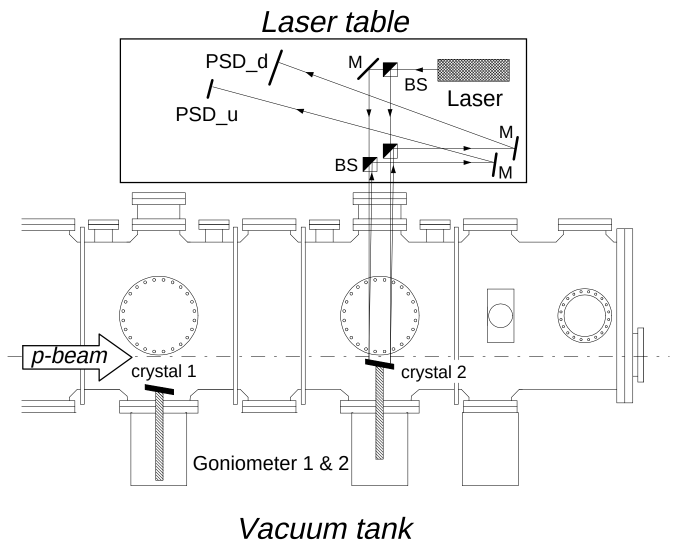

Figure 10: Top view of the crystal location in the SPS vacuum tank, together with the laser table. In the arrangement shown, crystal No.2 is used close to the circulating beam, while crystal No.1 is retracted. Beam-splitters (BS) and mirrors (M) on the laser table are used to bring two parallel laser beams onto the crystal and the reflected beams to the Position Sensitive light Detectors (PSD_u for the upstream, PSD_d for the downstream beam).

difficult accessibility of the location (the SPS has only two scheduled shutdowns per year), it was felt necessary to have two goniometers with bent crystals installed which can be used alternatively. The goniometers have two degrees of freedom. First, a horizontal translation can move the crystal towards or away from the beam with a range of 90 mm and a precision of 0.05 mm. Secondly, the horizontal angular alignment can be performed with a step size of 2 μrad.

A laser system is installed adjacent to the vacuum tank in order to pre-align the crystals with respect to the beam axis. The principle of this laser set-up is shown in Figs. 10 and 11. The laser beam is split into

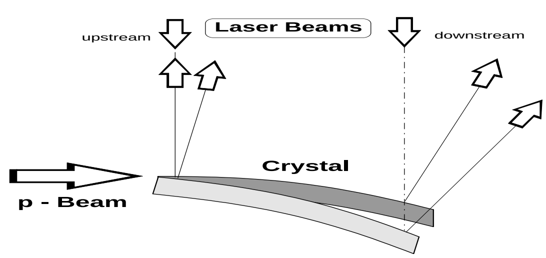

Figure 11: Principle of the laser reflection pre-alignment and monitoring system.

two parallel beams, hitting the entrance and exit ends of the crystal. The former is used for pre-alignment by autocollimating the laser beam with the beam direction as well as to monitor this alignment, the latter can be used to monitor the bend angle. Position sensitive detectors measure the laser beams reflected from the surface of the crystal with a precision of a few μm. On a commercial laser table light travels some meters, and an angular resolution of a few μrad is thus achieved. A typical measurement series with the recording of the two laser light detectors for different goniometer settings is shown in Fig. 12. The agreement with the expectation

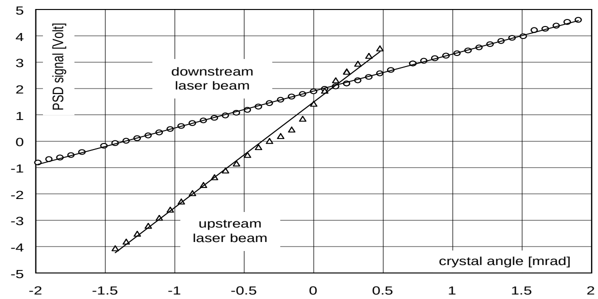

Figure 12: Results from laser light detection during an angular scan. Reflected laser light is measured with a position sensitive detector (PSD). Solid lines are the expected curves.

is excellent. The difference in slope reflects the fact that the range of the "downstream" detector is three times larger - its resolution, however, is a factor of three worse.

3.3 Detection of extracted particles

A set of detectors is placed in the path of the extracted protons downstream of the bent crystals (Fig. 6). First is a scintillating CsI disc viewed by a CCD camera. Its display is available on-line on a TV screen in the SPS control-room, but the information is also digitized and can be stored for off-line analysis. This instrument has proven most valuable when tuning the crystal angles, setting up the SPS and "hunting" for instabilities created by inappropriate settings of some accelerator parameters.

Three scintillation counters are used in coincidence to determine the integral flux of protons plus background at 8.5 $\pm$ 1.1 mrad. These detectors are of diameter 50 mm (S1) and a size of 100$\cdot$100 mm^2 (S2) and 50$\cdot$50 mm^2 (S3), respectively.

The triple coincidence is also used to open a gate for the scintillator hodoscope counters. The hodoscope,

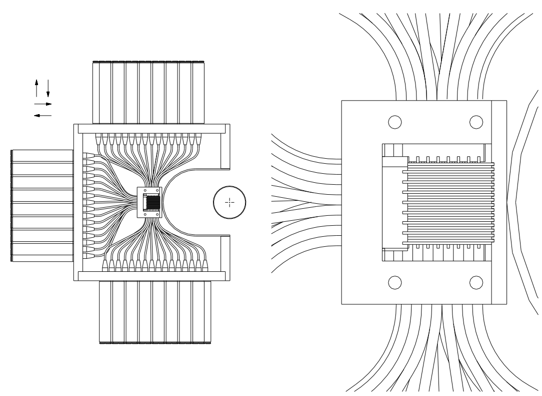

Figure 13: Schematic drawing of the scintillation counter hodoscope installed close to the SPS vacuum tube to measure the profiles of the extracted proton beam. The drawing on the left gives the full set-up showing the light guides and photomultipliers. The right drawing zooms into the centre of the hodoscope, showing the arrangement of the 32 scintillators.

shown in Fig. 13, consists of 32 scintillator strips of 1 mm width both in the horizontal and the vertical plane. These are read out into scalers. Data is taken in cycles of 5 s every 14.4 s (SPS cycle time), thus allowing for goniometer steps to be performed in between data taking. In the control-room, an on-line display (Fig. 14) shows the profiles every cycle and the evolution of the extracted intensity over 200 cycles.

Upstream of the hodoscope, a thin motorised FISC counter (FInger SCintillator) is installed. Its width being 1 mm originally, it allowed to cross check the calibration of the 32 hodoscope counters used for the horizontal beam profiles. Recently, the scintillator has been changed to 0.2 mm width, and the step size been made

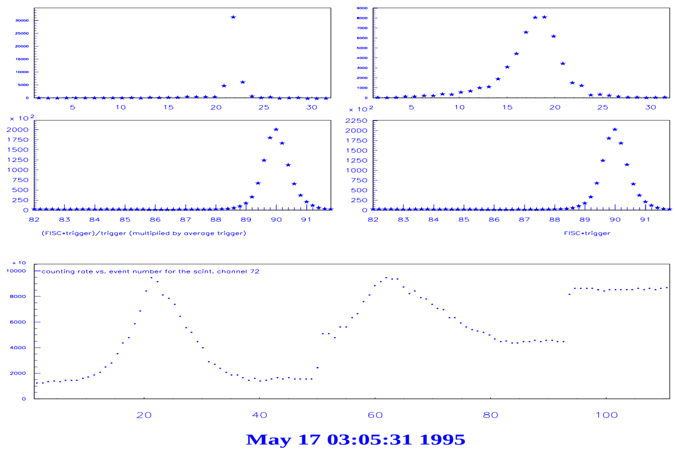

Figure 14: On-line display as available in the SPS control room during the proton extraction experiments. The horizontal and vertical profiles as measured with the hodoscope are shown in the top row. Two horizontal profiles measured with higher resolution with the 0.2 mm FISC counter and different trigger conditions are shown in the center. Below, the extracted beam intensity as a function of time is shown: in this example two angular scans with different step size were performed. Then, the crystal was set to the optimal alignment for a measurement of the extraction efficiency.

variable, such that a horizontal profile with improved resolution can be recorded with the FISC (Fig. 14). In the first extraction experiments [34] microstrip gas chambers with a resolution of 0.1 mm were used in place of the new FISC counters.

Extracted beam profiles measured with these detectors for different crystal/beam conditions are shown in chapter 5.

3.4 Beam excitation and lifetimes

The SPS experiments are performed during dedicated machine development sessions a few times per year. During the preparation of the SPS for the experiment the coupling between the horizontal and vertical planes is minimized, the closed orbit is corrected, and tune and chromaticity are checked. Beam is injected from the CERN Proton Synchrotron (CPS) at 14 GeV, accelerated to 120 GeV and stored. Finally the radio frequency (RF) is switched off to obtain a debunched beam. The coasting beam obtained in this way with some 10^{12} protons circulating has to be scraped (usually vertically) in order to obtain the required intensity of a few 10^{11} protons. At this point, the beam emittances at 120 GeV ($\epsilon = \frac{\sigma^2}{\beta}$) are found to be typically $2.0 \cdot 10^{-8}$ m horizontally and $1.0 \cdot 10^{-8}$ m vertically.

One of the two crystals is moved to a distance of 10 mm from the theoretical centre of the beam (i.e. about 10 times the sigma of the beam size). Random horizontal kicks provoked by a pair of electrostatic plates generate a growth of the beam size and diffusion of protons towards the crystal. A noise generator coupled to the power amplifier of the damper plates is used. The output from the noise generator has been investigated [28] and the resulting kick strength for different noise power has been deduced. In the case the kicks are uncorrelated, the expected average emittance growth per second as a function of the kick strength k should be [22]

$$\frac{< \Delta\epsilon >}{sec} = \frac{1}{2} \cdot \beta \cdot \nu_{rev} \cdot < k^2 > \tag{1}$$

where β is the value of the β-function at the location of the crystal (about 90 m) and ν_{rev} is the revolution frequency of the protons in the SPS (43375 Hz). The diffusion process is restricted to the horizontal plane only, the vertical plane is not affected.

To test the model, the emittance growth of the beam can be measured with wire scanners during the diffusion process. The result of such a measurement is shown in Fig. 15. The agreement of the expected growth rate with the kick strength is excellent at the largest noise power amplitudes used. At lower values, the measurement with beam indicates a slightly larger kick strength, presumably due to other noise sources in the SPS.

The intensity of the circulating proton beam is measured every 14.4 seconds (SPS cycle time) with beam current transformers. This information is recorded and a beam lifetime is calculated from the decreasing

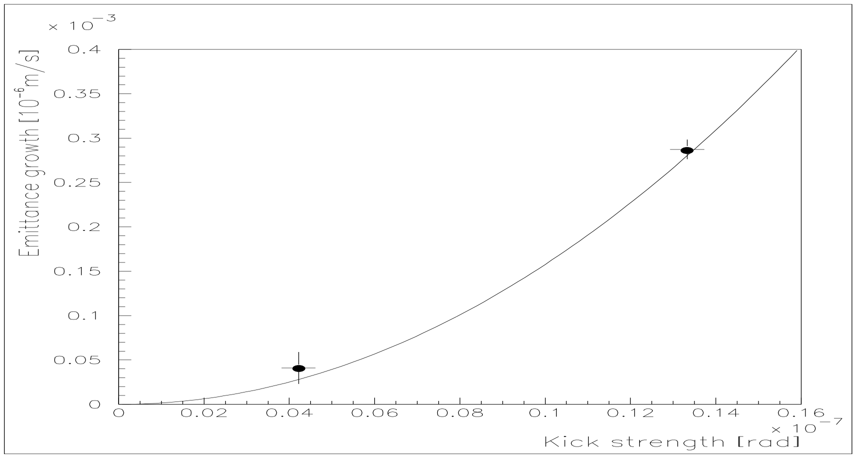

Figure 15: Emittance growth measured for different kick strength provided to the beam by the damper system. The solid line is the prediction (eq. (1))

intensity observed, assuming an exponential decay of the intensity. An example of the "lifetime monitor" is shown in Fig. 16. The precision of the monitors and thus the lifetime measurement is somewhat limited: at

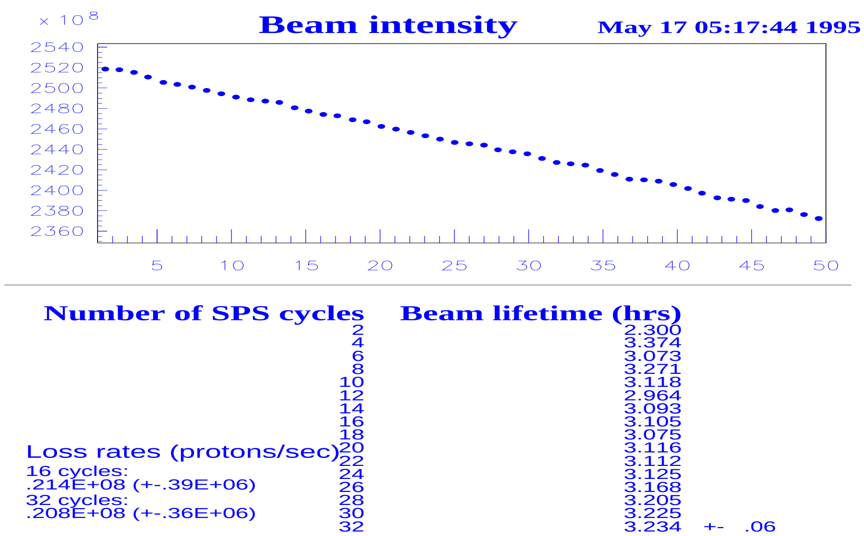

Figure 16: Example of a lifetime measurement during the extraction as seen on the on-line display in the control room. Beam intensity and lifetime are calculated and displayed every 14.4 seconds.

intensities of 10^{11} protons and lifetimes of 20 hours, an uncertainty of 10% has to be taken into account.

3.5 Extraction efficiency

One of the most important quantities to investigate is the efficiency obtained in proton extraction with a bent crystal. The calculation of

$$\epsilon = \frac{I_{extracted}/sec}{I_{lost}/sec} \quad (2)$$

requires the determination of the number of protons extracted and number of protons lost due to the presence of the crystal. $I_{extracted}$ is usually obtained from the integration of the beam profiles measured with the hodoscope after background subtraction - note that two independent numbers can be extracted from both the vertical and horizontal profiles, allowing for a consistency test.

The amount of protons lost per second due to the presence of the crystal, I_{lost}, is deduced from the lifetime measurements. Note that the lifetime with the crystal retracted is at least a factor 10 longer than with the crystal present, such that the loss can to a good approximation be assumed to stem from interactions with the crystal only. The stability of the diffusion created by small random electrostatic kicks is such that a reliable measurement of the extraction efficiency can typically be obtained in about 10 to 20 minutes. Results of such measurements are reported in chapter 5.

4 Computer simulations

4.1 Diffusion and impact parameter distribution

In order to get a better understanding of the measurement conditions in the extraction experiments with bent crystals, simulations are indispensable. In addition to an appropriate treatment of the crystal properties (cf. the deflection experiments in external beams [8, 9]), the behaviour of the protons in the circulating beam and thus the interplay between accelerator and crystal has to be correctly treated. The mode best suited for this purpose is the diffusion mode. In the following, we will concentrate on the situation relevant for the CERN SPS experiments with a 120 GeV coasting proton beam. The maximum average kick strength that can be provided by the "damper" plates at the SPS is $<| k |> =$ 0.100 μrad - however, this leads to large diffusion speeds of order 1 mm/sec and thus very short beam lifetimes. In practice, kicks between 0.0001 and 0.01 μrad are used.

The diffusion created by these kicks is a stochastic process, and statistical parameters (e.g. mean values) can be calculated analytically. However, single particle properties like impact parameters and angles can only be assessed by tracking simulations. These are described in more detail in [22, 23, 24]. A beam of typically 10'000 protons was followed through the SPS accelerator, with parameters close to the ones found in the experiment. Emittance growth due to induced voltage (white noise) on the damper plates was simulated, and the impact parameter and impact angle distribution resulting at the crystal position were recorded. An example is shown in Fig. 17 for a kick strength of 0.01 μrad. Note that while this is the strongest kick applied in the experiment,

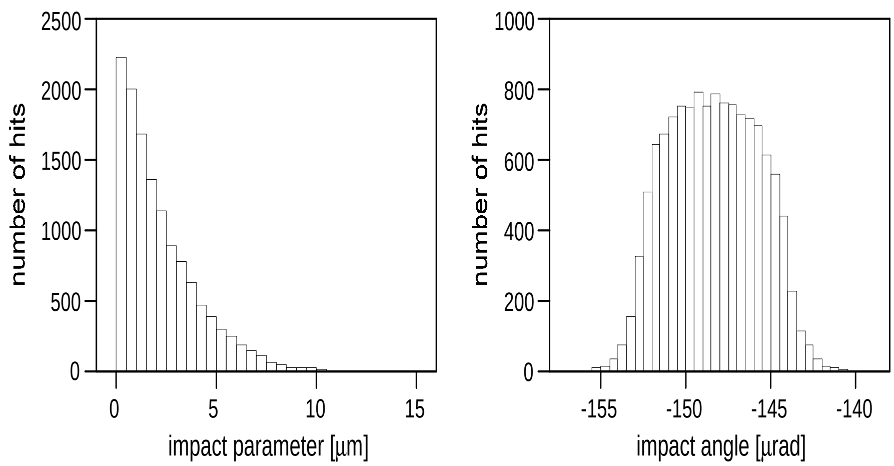

Figure 17: Result of the computer simulation: impact parameter and angle distribution for first hit on the crystal (kick strength 0.01 μrad)

it is one of the weakest to be used in the simulations: tracking for this kick strength already required several days of computer time on a powerful workstation. However, it was shown [22] for larger kick strength that the simulated emittance growth follows nicely the expected law (equation (1) and Fig. 15).

Moreover, as was shown earlier [22], the mean impact parameter rises approximately linearly with the kick strength (for not too large kick strengths) and scaling of the impact parameter distribution found in the simulation is thus permitted. The important result at this stage is that the mean impact parameter (of an approximately exponential distribution) for realistic kick strength in the SPS experiment is estimated to be of order 50 nm to 1 μm.

4.2 Multiple scattering and proton losses

If the impact parameter is too small or the impact angle too large, the proton hitting the crystal will not be channeled but will undergo multiple scattering or other interactions. A realistic model of the crystal has been used in the simulations, as shown in Fig. 18. The effective length traversed by each individual proton hitting

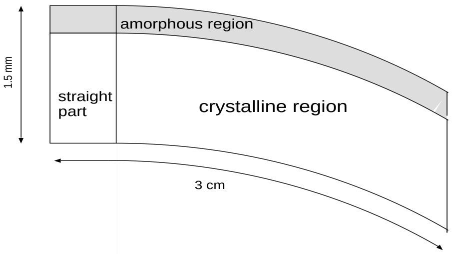

Figure 18: Schematic model of the crystal as used in the computer simulations

the crystal [24] with impact parameter b and angle b' was used to calculate the r.m.s. multiple scattering angle according to the standard formula [29]. This angle was then applied to the particles in the simulation program and the tracking of the protons pursued through the SPS. In this way, impact parameter distributions for the first and later hits on the crystal were obtained as shown in Fig. 19. The simulation was done for a very small

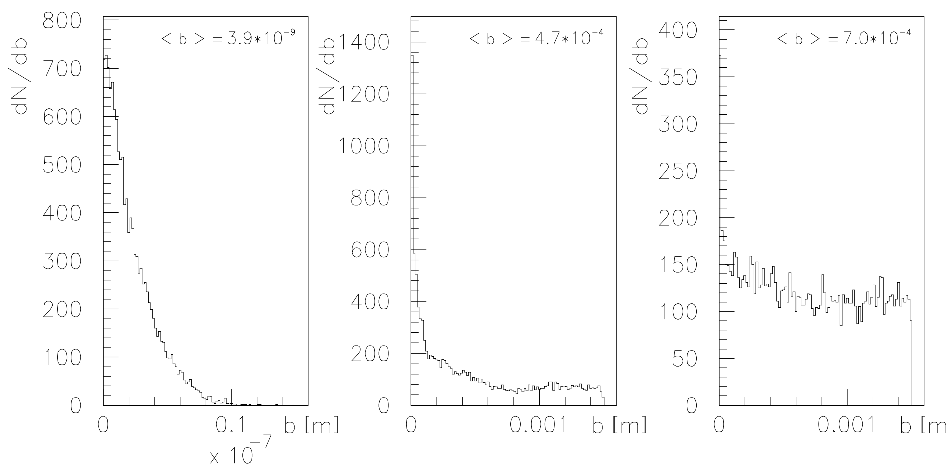

Figure 19: Impact parameter distributions for the first, third and fifth hit of protons on the crystal (from left to right). The figure for the first hit corresponds to the initial impact parameter distribution. Note the change of scale from the first to the later hits

average kick strength, i.e. the mean impact parameters were very small for the initial encounter with the crystal. It can be seen that the mean impact increases rapidly with the number of hits on the crystal independent of the initial distribution which therefore becomes irrelevant.

Protons might be lost with a certain probability due to nuclear interactions or due to an excessive energy loss after several traversals of the crystal. These effects were taken into account in the simulation, together with the obvious cut-off parameters like maximum number of revolutions and maximum amplitude larger than the vacuum chamber.

4.3 Channeling, dechanneling and extraction

Protons can be channeled and extracted if they hit the crystal with a large enough impact parameter and a small enough angle. In the case of the SPS, this critical angle for Si (110) amounts to 13.6 μrad at 120 GeV. While the details of channeling and dechanneling can be treated in great detail with sophisticated simulation programs, as shown e.g. in [11, 30, 31], this was not felt to be crucial here. Instead, the phenomenologically deduced parameters confirmed in beam-line experiments with bent crystals [32] were used for 120 GeV protons and Si (110). The parameters taken into account were:

- surface transmission

- straight crystal dechanneling length
- bending dechanneling fraction
- modified dechanneling length (bent crystal)

A particle cannot be channeled if it hits the crystal too close to the region of thermal vibration of a nucleus in the lattice, and it is more easily channeled if it penetrates into the crystal just in the middle of the channel (i.e. between the lattice planes). This probability to be channeled depends on the position of its hit with respect to the lattice planes. Integrated over the thickness of the crystal, this is called *surface transmission*. The calculation of this quantity for a trajectory perpendicular to the inner surface [32] gives a value of about 80% which is used in the simulation.

To be successfully extracted a particle must remain channeled, but interactions with electrons inside the crystal or with the nuclei in the lattice, can lead to dechanneling of initially channeled particles. These dechanneling processes can be approximated by an exponential decrease of the number of channeled particles:

$$n = n_0 e^{-l/l_0}$$

where l_0, called *normal dechanneling length*, is equal to 10.8 cm for (110) silicon planes and 120 GeV/c protons.

We must add the fraction of particles dechanneled due to the curvature. There are two mechanisms, one is a centrifugal effect which for our experimental conditions (using the minimum curvature radius of the crystal), is estimated to give a fraction F of dechanneled particles in the order of 24% [32]. The other is the increase of probability for the proton to interact with electrons or nuclei in the crystal. To take this into account the dechanneling length must be modified as $l_b = l_0(1 - F)^2$.

4.4 Results of the simulation

With the parameters as described above, complete simulations of the extraction process were performed assuming a crystal with an (unrealistically large) imperfection of 5 μm and a damper kick strength of 0.0001 μrad. This work was done in the context of experiments trying to prove the importance of multi-pass extraction. Detailed results from the simulation can be found in [24].

The main results are that the simulated angular scans show a width of about 50 μrad, and the expected extraction efficiency is 32%. This result confirms qualitatively, that a sizeable extraction efficiency can be expected even when the impact parameters are small compared to the surface imperfections if the multipass extraction process is important.

5 Experimental results with the first crystals

5.1 Results for a crystal with a "perfect" surface

The first series of experiments took place in 1992, employing crystals on a "bridge" type bending device as shown in Fig. 8. First results performed in the "kick-mode" (see 2.2) are reported in [33]. Signals from extraction were immediately recorded, indicating that there was no particular problem to align the crystal. Therefore, all the following experiments used the "diffusion mode", employing a variety of kick strengths which led to lifetimes between 0.5 and 50 hours, approximately.

Angular scans were performed with these crystals, an example of which is shown in Fig. 20. A full width half maximum of about 200 μrad was found, much larger than initially expected. For pure first pass channeling one would expect a width of about twice the critical angle, i.e. $\approx$ 30 μrad. Moreover, the beam profiles showed double peaks, visible as two beams also on the TV screen, when the crystal was not optimally aligned (Fig. 21). On the peak of the alignment scan, the extracted beam showed narrow profiles in the hodoscope, with about 10% background due to interactions, as shown in Fig. 21.

The extraction efficiencies obtained under different running conditions with the first two crystals are given in Tab. 1 [34]. Efficiencies of about 10% were found, which are about 100 times higher than obtained in the earlier experiments at Serpukhov [13]. Note, however, that comparing to the results obtained for proton beam deflection in an external beam, as much as 35% efficiency could be expected [32], if surface imperfections could be neglected.

The width of the angular scans and the observed double peaks were interpreted as a result of the anticlastic bending of the crystals (Fig. 8), as confirmed in simulations (see e.g. [34]). In fact, this unwanted curvature of the crystal was also measured with the proton beam: the circulating beam was collimated to about 1 mm vertical spot size, and the collimators remained in position in order to stop protons scattered in the crystal and

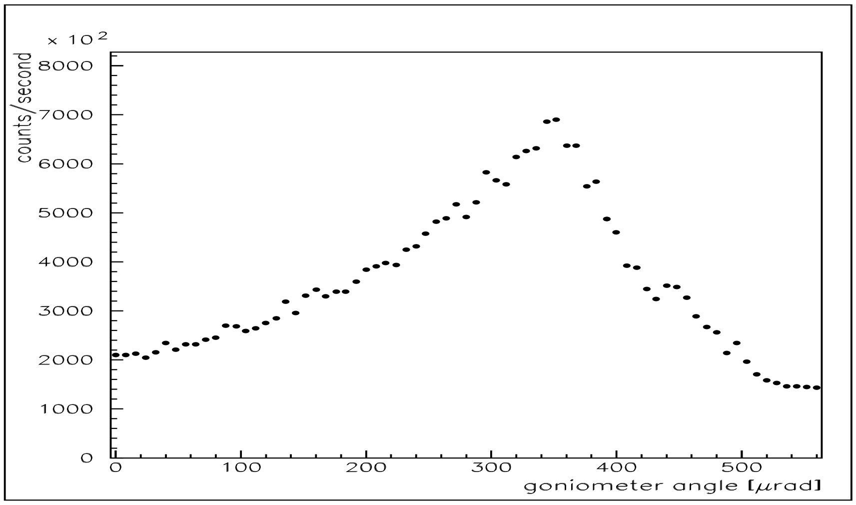

Figure 20: Typical angular scan measured with the first crystals (Fig. 8)

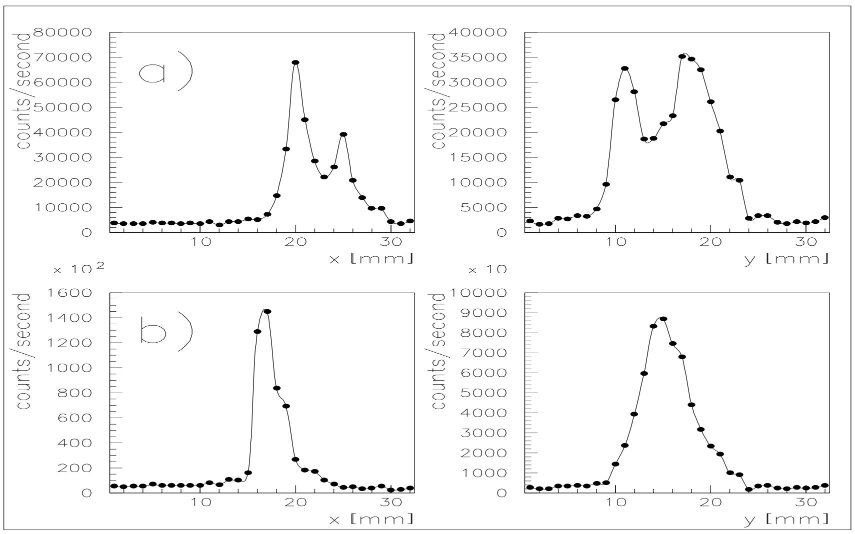

Figure 21: Horizontal and vertical beam profiles as measured with the hodoscope off the peak of the angular scan (a) and on the peak (b). For details see text.

thus to "freeze" the vertical beam size. Angular scans were then performed for different vertical beam positions on the crystal. For that experiment the beam was locally displaced with orbit correction magnets. The results are given in Fig. 22, showing the "parabolic" dependence of the optimum alignment on the vertical position. This is in agreement with the observations with the laser light reflections from the surface (Fig. 8).

5.2 Results with an amorphous layer

It can be speculated that the unexpected large width of the angular scans indicate a substantial contribution from multi-pass extraction. It is experimentally difficult to separate the contributions from first and multi-pass extraction and no unambiguous observation of first-pass extraction has been made in our experiment. In order to investigate the importance of the multi-pass process, a series of measurements were performed with a crystal used previously in the extraction experiment (Fig. 8), but now covered with an amorphous layer of 30 μm of SiO. This layer prevents, even for the strongest kicks applied with the damper plates, any first-pass extraction since channeling cannot occur in the amorphous layer and the impact parameters are much smaller than the width of the layer. In this way a clean sample of particles only extracted with the multi-pass mechanism is obtained. Results obtained with this crystal are shown in Fig. 23 and in Tab. 2. Clearly, a substantial

Table 1: Results obtained during the first measurements using crystals a shown in Fig. 8

	Crystal 1	Crystal 2
beam intensity (protons)	$(7.0 \pm 0.1) \cdot 10^{11}$	$(3.7 \pm 0.1) \cdot 10^{11}$
beam lifetime (hrs)	20 ± 2	12 ± 1
protons lost per second	$(6.7 \pm 0.6) \cdot 10^{6}$	$(8.9 \pm 0.7) \cdot 10^{6}$
protons detected per second	$5.6 \cdot 10^{5}$	$6.6 \cdot 10^{5}$
background (%)	5	2
detection efficiency (%)	78 ± 12	78 ± 12
extraction efficiency (%)	**10.2 ± 1.7**	**9.3 ± 1.6**

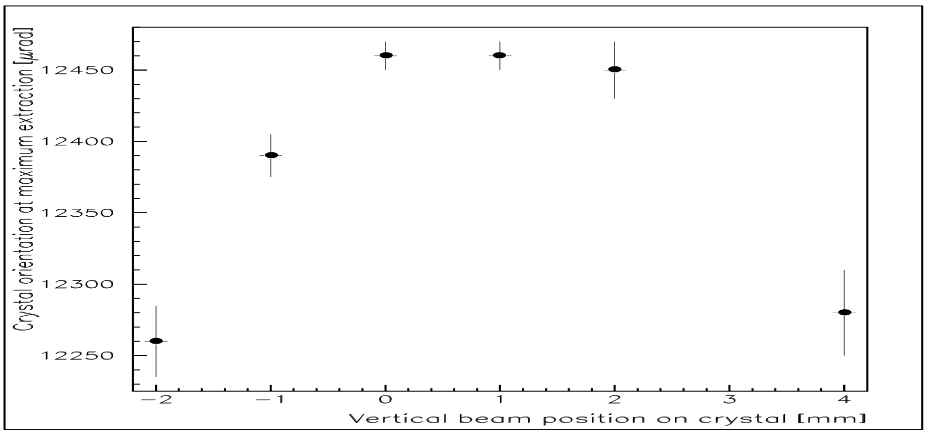

Figure 22: "Anticlastic" bending as measured by displacing the beam vertically: the maximum of the angular scan is shown for different beam positions.

extraction efficiency remains, indicating that multi-pass extraction is a dominant process in our extraction with bent crystals [26]. Note that the chosen thickness of 30 μm might, in addition to prevent first-pass, introduce excessive multiple scattering and thus suppression of some multi-pass extraction at later turns.

6 Results with the U-shaped crystal

The second generation of SPS extraction experiments uses the so-called "U-shaped" crystal (Fig. 9), which does not show the unwanted curvature (anticlastic bending). A typical angular scan obtained with this crystal is shown in Fig. 24. The angular scan is clearly narrower than the ones observed with the "anticlastic bending" crystals. However, although this crystal should have a surface cut and polished to the state of the art, the width of 70 to 100 μrad is still much above the one expected for first-pass extraction (i.e. 28 μrad). The extracted profiles do not show any double peaks, neither on nor off the maximum of the alignment scan (Fig. 25). Nevertheless, the vertical profile shows an interesting behaviour (Fig. 26): its width is changing, becoming more narrow the higher the extracted beam intensity (i.e. the better the alignment of the crystal). It may be speculated that this is due to a reduction in the number of passes which protons have to perform through the crystal before they are finally channeled and extracted. More passes implies more scattering (in both planes) and can possibly explain a larger vertical beam width. Extraction efficiencies observed with this crystal vary slightly with the kick strength of the damper, i.e. with beam lifetimes, as shown in Tab. 3. The significance is however very weak. Also shown in Tab. 3 is the background measured under the profiles in the hodoscope.

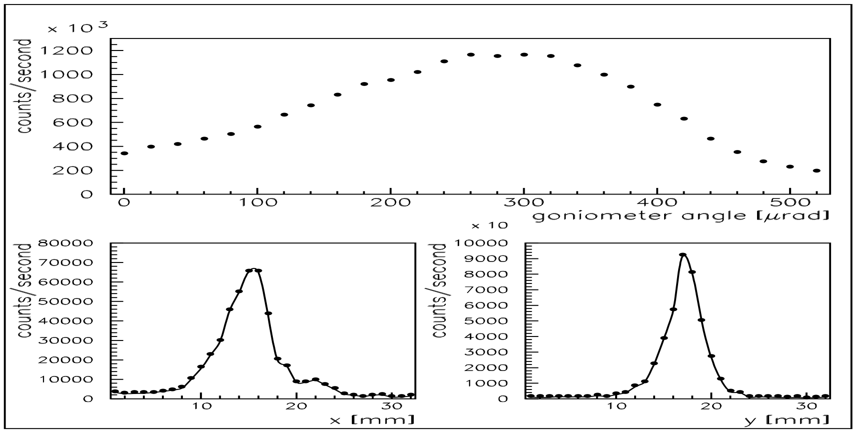

Figure 23: Angular scan and beam profiles at the maximum of extraction for the crystal (Fig. 8) with an amorphous layer.

Table 2: Extraction efficiencies measured for a crystal covered with an amorphous layer of 30 μm thickness. The crystal and bending is of the type shown in Fig. 8

intensity (10^{11} p)	lifetime (hours)	extracted rate (10^5 p/s)	background (%)	extr. efficiency (%)
5.9	33 $\pm$ 2	2.07 $\pm$ 0.02	13.9	3.6 $\pm$ 0.2
5.8	43 $\pm$ 10	1.54 $\pm$ 0.05	15.2	3.7 $\pm$ 0.8
4.4	28 $\pm$ 2	2.38 $\pm$ 0.03	13.0	4.8 $\pm$ 0.3
1.9	5.1 $\pm$ 0.2	8.78 $\pm$ 0.04	13.8	7.6 $\pm$ 0.3
0.6	1.8 $\pm$ 2	7.27 $\pm$ 0.05	13.3	7.4 $\pm$ 0.4

When compared to Tab. 2, it is evident that the U-shaped crystal provides higher intensity and less background than the crystal with an amorphous layer. Once again, this may be related to the number of passes: for every pass through the crystal (or the amorphous layer), there is a certain probability that the protons interact. More passes would therefore give a higher background from such interactions. The bending device is different for the two crystals, too (Fig. 8 and Fig. 9): assuming that some protons can have large vertical amplitudes after a number of passes through the crystal, one can imagine that the U-shaped crystal, showing less steel outside the crystal surface, would give less background. (Note that these mechanical parts contain a lot of material, thus even few protons hitting the steel may give considerable contribution to the background). In order to assess the dependence of the extraction efficiency from the mean impact parameter, a series of measurements was performed at different crystal distances x from the closed orbit and different damper noise values. The results are given in Tab. 4 and Fig. 27. The measured beam lifetime can be used to deduce the kick strength, and the extraction efficiency is deduced in the usual way from the beam lost per second and the extracted protons detected per second in the hodoscope. As is shown in Fig. 27, initially there is an increase and then saturation for larger kicks - however, when repeating a measurement at -10 mm (open symbol) with large kick strength (and therefore lower beam lifetime), the efficiency value found is lower. Note that this last measurement was made with only $1.2 \cdot 10^{10}$ protons circulating in the SPS, which is the lower limit for a reliable lifetime measurement. Finally, the results shown here might be influenced by the increase of the beam size in the vertical plane due to multiple scattering in the crystal (multi-pass effect).

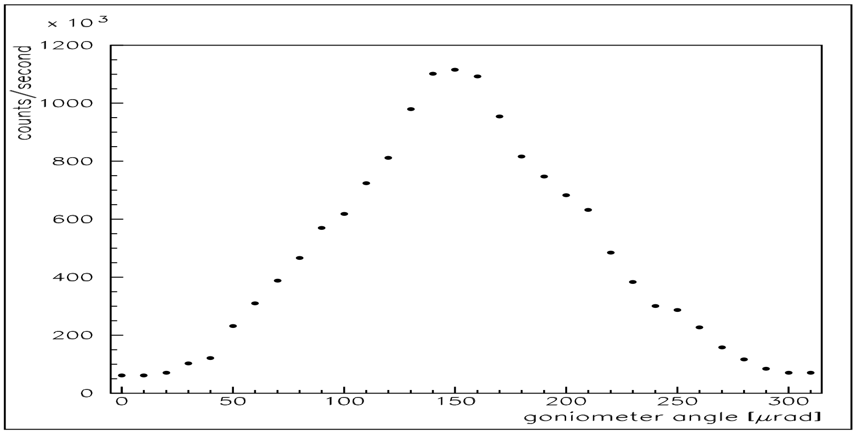

Figure 24: As Fig. 20, but for the "U-shaped" crystal with a perfect surface

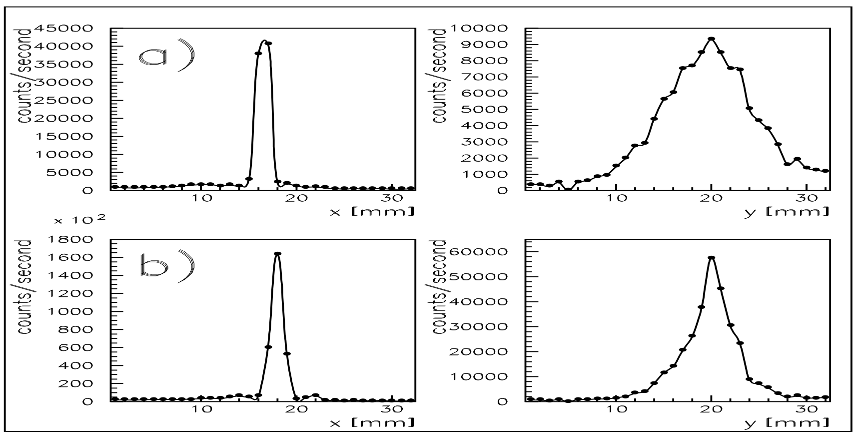

Figure 25: As Fig. 21, but for the U-shaped crystal (Fig. 8)

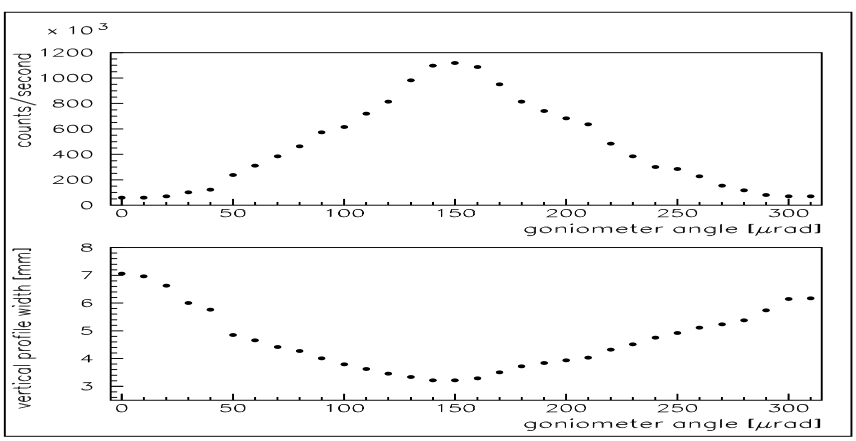

Figure 26: Angular scan and change of width of vertical profile of the extracted proton beam, measured with the U-shaped crystal (Fig. 9)

Table 3: Extraction efficiencies measured with the 1.5 mm thick U-shaped crystal (Fig. 9)

intensity (10^{11} p)	lifetime (hours)	extracted rate (10^5 p/s)	background (%)	extr. efficiency (%)
4.9	44 ± 8	3.45 ± 0.06	3.2	10.6 ± 2.6
0.13	0.7 ± 0.1	7.88 ± 0.07	4.0	15.4 ± 2.2
0.07	0.9 ± 0.1	2.67 ± 0.04	3.2	12.4 ± 1.4
0.16	0.6 ± 0.1	9.48 ± 0.06	3.1	13.0 ± 2.2

Table 4: Measurements with the U-shaped crystal (Fig. 9) at different distances X from the closed orbit. The damper noise values were adjusted to achieve comparable extracted proton rates - the kick strength therefore increased with increasing distance

distance X (mm)	lifetime (hours)	protons lost (10^6 p/s)	extr. protons (10^5 p/s)	extr. efficiency (%)
-10	3.5 ± 0.30	11.6	3.1	4.1 ± 0.8
-15	4.4 ± 0.40	6.0	3.2	8.3 ± 1.0
-20	3.0 ± 0.30	8.9	5.1	8.9 ± 1.0
-25	2.4 ± 0.30	8.9	5.7	10.0 ± 1.5
-10	0.6 ± 0.05	6.0	2.5	6.5 ± 0.7

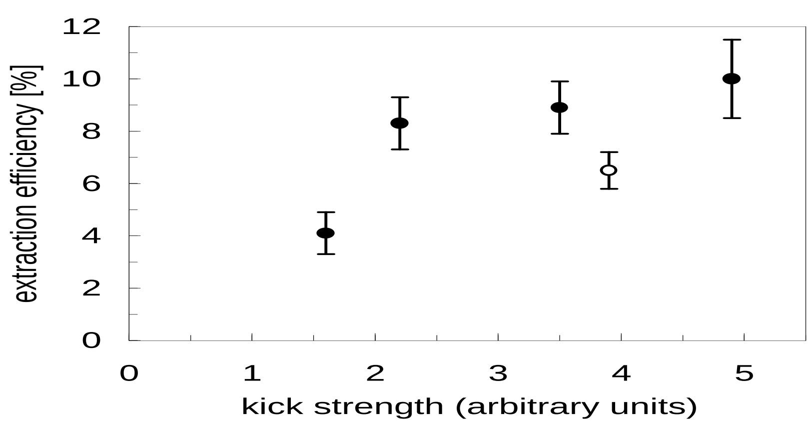

Figure 27: Extraction efficiencies measured for different kick strengths of the damper, with the U-shaped crystal placed at different distances from the closed orbit (Tab. 4). The open symbol denotes a repeated measurement at x = -10 mm.

7 Possible improvements and outlook

In the near future, the SPS extraction experiments with bent crystals will be continued only with U-shaped crystals. In order to investigate the importance of large impact parameters (it can be seen from Fig. 19 that impact parameters can reach values of several mm due to multi-pass effects), there are presently two U-shaped crystals installed: the crystal with an effective thickness of 1.5 mm and an exact copy of it but with a thickness of 3.5 mm. In the present design (Fig. 9), this is the maximum thickness possible for mechanical reasons. Measurements with different kick strengths are planned to compare the extracted beam profiles and extraction efficiencies for these two crystals.

The encouraging results of experiments in Serpukhov [13, 14], but also the computer simulations referring to the Fermilab experiment [25] indicate that a possible gain in extraction efficiency might be obtained in the multi-pass extraction mode by adding a thin scatterer prior to the crystal. This would create small angle scattering and thus larger impact parameters at the crystal location, if the scatterer is placed at the appropriate phase advance. Simulations for the specific situation at the SPS are under way, and experiments are planned for 1996.

Given the available kick strength and reasonable beam lifetimes in the SPS, the diffusion mode using the dampers will not allow us to reach significantly larger impact parameters. Other ways of increasing the beam size and producing a halo, in particular using non-linearities created by sextupoles combined with a tune ripple [18, 19], will be tested together with bent crystal extraction. This method provides potentially much larger impact parameters and might allow us to test the scheme of a pure first pass extraction. (Note that no unambiguous observation of first-pass extraction has been made in our experiment, in spite of the state-of-the art surface of the U-shaped crystal). While the first-pass mode might be a disadvantage for proton extraction from LHC, it is the crucial mode if the extraction of heavy ions (from Nuclotron, RHIC or LHC) should be envisaged [36, 37] - the large nuclear reaction and electromagnetic dissociation cross sections prohibit a multi-pass scheme for ions. In the multi-pass extraction mode for protons, a strong dependence on the beam optics has been found in simulations [23]. This work will have to be pursued in a scheme with an external scatterer, both in simulation and eventually in an experiment. Some simulations also predict a larger extraction efficiency for a shorter crystal [11]. Although this is mechanically non-trivial for a deflection angle of 8.5 mrad as required at the SPS, a shorter crystal will eventually have to be tested. Finally, in view of a bent crystal extraction scheme for LHC, the interplay between crystal and collimation scheme will have to be investigated - this could be to the benefit of the collimation system, too, as indicated in the early simulations for the SSC scraper system [7].

8 Summary

Following the pioneering experiments in Dubna and Serpukhov, substantial progress has been achieved at the CERN SPS in the understanding of the mechanisms leading to extraction of high energy protons with a bent silicon crystal. The importance of the crystal bending technique, which is determining its shape, has been established. Crystal installation and pre-alignment techniques with laser light reflection from the surface have been refined. The important multi-pass contributions to the proton beam extraction allows to decouple the crystal from the accelerator to the extent that the initial impact parameter distribution is no longer critical. With the U-shaped crystal at 120 GeV, an extraction efficiency of up to 15% has been obtained, and there are prospects for improvement. The extracted beam has been found to be very stable in intensity and position over periods of hours, which is important for fixed target precision experiments. Setting up the extraction with a bent crystal at the SPS including the alignment is an easy and reproducible procedure. This work will continue and there is hope that it will eventually find its application at the future high energy hadron colliders.

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References

[1] LHC Study Group, *The LHC Pink Book*, CERN Report 91-03 (Geneva, 1991)

[2] SFT Collaboration, An expression of interest in a super fixed target beauty facility at the SSC, *Report EOI-14* (May 1990)

[3] LHB (Large Hadron Beauty Factory), Letter of Intent, CERN/LHCC/93-45, LHCC/I5 (CERN, Geneva, 1993)

[4] R.A. Carrigan, T.E. Toohig and E.N. Tsyganov, *Nucl. Instr. Meth.* **B48** (1990) 167.

[5] B. Cox et al., *Proceedings of Summer Study on High Energy Physics in the 1990's*, Snowmass, CO, 1988, p.56.

[6] W. Scandale, *Proceedings of European Committee for Future Accelerators: Large Hadron Collider Workshop*, (Aachen, 1990), CERN Report 90-20 (Geneva, 1990) Vol. 3, p. 760.

[7] M. Maslov, N. Mokhov and I. Yazynin, SSCL Report 484 (1991).

[8] S.P. Møller et al, *Nucl. Instr. Meth.* **B84** (1994) 434.

[9] S.P. Møller et al., *these proceedings*

[10] A.M. Taratin, *these proceedings*

[11] V. Biryukov, V.I. Kotov and Yu A. Chesnokov, *Physics-Uspekhi* **37** (1994) 937.

[12] V.V. Avdeichikov et al., *JINR Communications 1-84*, Dubna (1984) English translation: Fermilab report 80/45, unpublished

[13] A.A. Asseev, M.D. Bavizhev, E.A. Ludmirsky, V.A. Maisheev and E.A. Myae, in: eds. V. Suller and Ch. Petit-Jean-Genaz, *Proc, Fourth Europ. Part. Acc. Conf.*, (London 1993), World Scientific 1994 p. 2388.

[14] A.A. Asseev, E.A. Myae, S.V. Sokolov and Yu.S. Fedotov, *Nucl. Instr. Meth.* **A324** (1993) 31.

[15] B.N. Jensen et al., A proposal to test beam beam extraction by crystal channeling at the SPS: a first step towards a LHC extracted beam, CERN/DRDC/P29 (1991)

[16] R.A. Carrigan et al., Proposal for a test of low intensity extraction from the Tevatron using channeling in a bent crystal, FNAL Proposal P853, Fermilab National Accelerator Laboratory, Batavia, IL, 1991, and R.A. Carrigan et al., these proceedings

[17] H.J. Shih and A. Taratin, Bent crystal extraction of the SSC beam with RF noise induced diffusion SSCL Report 389 (1991).

[18] W.E. Gabella, J. Rosenzweig, R. Kick and S. Peggs, *Proceedings 1993 IEEE Part. Acc. Conf.*, Washington (1993), p. 233.

[19] W. Fischer, An experimental study on the long-term stability of particle motion in hadron storage rings, Ph.D. thesis, University of Hamburg, Germany (1995), and to be published in Phys. Rev. E.

[20] V. Biryukov, *Nucl. Instr. Meth.* **B58** (1991) 202.

[21] A. Taratin, S.A. Vorobiev, M.D. Bavizhev and I.A. Yazynin, *Nucl. Instr. Meth.* **B58** (1991) 103.

[22] W. Herr, Diffusion of particles induced by transverse noise and its application to crystal extraction experiments CERN/SL/92-53 (AP).

[23] S. Bardin, Etude de l'extraction multipassage par un cristal courbé des faisceaux de haute énergie CERN/SL/Note 92-52 (AP)

[24] G. Vuagnin, Simulation of the crystal extraction experiment at the SPS, CERN/SL/Note 95-24 (AP)

[25] A.M. Taratin and E. Tsyganov, *Nucl Instr. Meth.* **A363** (1995) 511.

[26] X. Altuna et al., High efficiency multi-pass proton beam extraction with a bent crystal at the SPS, Accepted for publication in *Phys. Lett.* **B357** (1995) 671.

[27] A.S. Denisov et al., *Nucl Instr. Meth.* **B69** (1992) 382.

[28] M. Gyr et al., SL MD-Note 176 (1995).

[29] Particle Data Group, *Phys. Rev.* **D50**, Part I (1994)

[30] A.M. Taratin, *Nucl. Instr. Meth.* **B95** (1995) 243.

[31] V. Biryukov, submitted to Nucl. Instr. Meth. B

[32] S.P. Møller, *Nucl Instr. Meth.* **A361** (1995) 403.

[33] S. Weisz and the RD22 collaboration, *Proceedings 1993 IEEE Part. Acc. Conf.*, Washington (1993), p. 20.

[34] H. Akbari et al., *Phys. Lett.* **B313** (1993) 31.

[35] A. M .Taratin et al, SSCL Report 545, 1991.

[36] A.D. Kovalenko, A. Taratin and E.N. Tsyganov, *JINR preprint E11-92-8* (1992).

[37] V.V. Borko et al., *Investigation of Channeling of High Energy Protons and other Charged Particles in Bent Single Crystals of Heavy Metals and Development of High Efficiency Particle Extraction from Accelerators"* Project Proposal, Dubna (1995) unpublished.