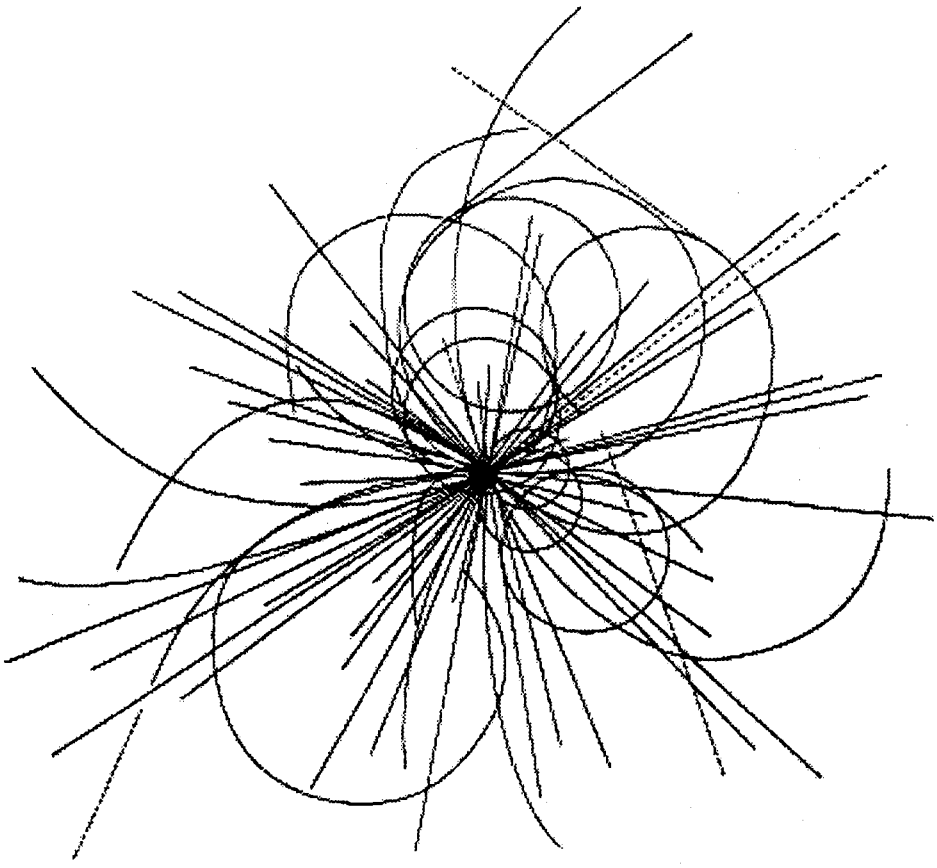
SSCL-Preprint-569

SSCL-Preprint-569
August 1994
Distribution Category: 400

E. Tsyganov
A. Taratin

Beam Halo Crystal Extraction from the Tevatron during Collider Runs



Superconducting Super Collider Laboratory

SSCL-Preprint-569

Beam Halo Crystal Extraction from the Tevatron during Collider Runs*

E. Tsyganov

Superconducting Super Collider Laboratory†
2550 Beckleymeade Ave.
Dallas, TX 75237, USA

A. Taratin

Joint Institute for Nuclear Research
Dubna, Russia

August 1994

*To be submitted to *Nuclear Instruments & Methods in Physics Research.*

†Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

Beam halo crystal extraction from the Tevatron during collider runs

E. Tsyganov
Superconducting Super Collider Laboratory, 2550 Beckleymeade Ave., Dallas, TX 75237

and

A. Taratin
Joint Institute for Nuclear Research, Dubna, Russia

We have shown by the computer simulation how to extract 1-TeV beam halo protons from the Tevatron using a bent crystal. More than 10^7 protons per second, now lost on scrapers and collimators, can be extracted in a "passive" mode, without interference with colliding beam experiments. This would reduce background in the colliding beam detectors. The problem of an existing imperfect layer at a bent crystal surface is solved by means of a thin crystal that is used as a crystal mirror for beam halo particles. The extraction efficiency can be as large as 99%. The availability of an extracted beam will enhance detector R&D studies at Fermilab and give an additional boost to the U.S. participation in the LHC experiments. As a second priority, small fixed target experiments could be carried out. Crystal scrapers-deflectors would also work well for the LHC where background radiation due to a beam halo loss could be reduced by the factor of 100.

1. Introduction

The Tevatron is the highest energy particle collider in the world today. Recent developments in the U.S. high energy physics program have enhanced the role of the Fermilab scientific program, despite the fact that a significant fraction of American physicists are oriented now towards Large Hadron Collider (LHC) experiments. Even in preparations for the LHC experiments, physicists are dependent upon the Fermilab experience gained with two running colliding beam experiments, CDF and D0. Therefore, Fermilab with its rich infrastructure and scientific traditions in particle physics would be the natural center of activity for domestic physicists in the preparation of elements of the LHC experimental detectors.

Besides the best expertise in colliding beam detectors, Fermilab could provide test beams of the highest energy, which are essential for a healthy R&D program in detectors, especially calorimetry. High energy particle beams should be considered as an essential contribution to the LHC program.

However, Fermilab colliding beam programs have an absolute priority, and therefore the fixed target mode of Tevatron operation is very strictly limited.

Bent crystals provide the possibility for Fermilab to combine extraction of some fraction of the proton beam with colliding experiments. Studies on steering high energy beams using bent crystals and applications of this phenomenon for beam extraction have demonstrated the feasibility of this technique.[1] Use of this technique can provide a double purpose mode of a collider operation, with extraction of a small fraction of the beam intensity. This extraction would be performed with no interference with the colliding beam experiments.

Although bent crystal extraction has been successfully demonstrated,[2] the mode of crystal extraction in parallel with colliding beam experiments is still under investigation. Several mechanisms of "pumping out" particles from the primary beam and delivering them to the crystal septum with no interference with beam emittance characteristics have been discussed [3] but not yet proved experimentally. Studies are in progress currently at Fermilab.[4]

One of the difficult problems in finding a good solution for a non-interfering beam extraction is the very small offset of a beam halo particle into the bulk of the crystal septum, when it is placed within the linear aperture of the collider. Even if the crystal edge could be polished and aligned to the circulating beam with precision better than one micrometer, this effective septum thickness still is much larger than the typical impact parameter for a particle which impinges the crystal during beam loss, and therefore the septum cannot be effective. A small average impact parameter for particles striking the crystal could also worsen crystal radiation damage. For the device to be practical at least several micrometers are required for the mean impact parameter. One way to provide this is to use rf manipulation of the circulating beam. However, when one tries to excite beam halo particles using some kind of beam rf gymnastics and send them to the bent crystal septum, there is no guarantee that the core of the beam is not disturbed.

Below we consider a "passive" mode of the crystal extraction from the Tevatron that requires no rf gymnastics to move particles into a crystal septum. Two processes that deliver particles to the crystal septum can be considered:

1. a natural emittance growth in the collider.

2. elastic and quasi-elastic scattering of primary protons by antiprotons in the interaction points, and proton interactions with the residual gas.

Although elastic processes could deliver particles to the crystal septum and provide a reasonable extraction rate (about 10^5 protons per second) with no interference with collider experiments, the most challenging task is to try to extract a beam halo, with a much higher extracted particle rate. Therefore, this work focuses exclusively on halo extraction.

To study the process quantitatively, we use a full simulation code that combines collider simulation with tracking particles in a crystal. The code is based on previous studies[5,6,7] and was adopted for the Tevatron lattice.

2. Beam halo extraction scheme and simulation results

2.1. General considerations

The dominant transverse emittance growth mechanisms predicted for the Tevatron colliding beams are intrabeam scattering and beam-beam interaction. The quality of the linear aperture generally defines long-term beam stability and formation of the beam halo. The head-on beam-beam effect is the major source of nonlinearities. The strongly nonlinear beam-beam force excites high order betatron resonances causing particles to diffuse into the tails of the transverse distributions and to be lost.

For the Tevatron in the colliding beam mode the measured value of the beam loss on scrapers placed at 10 σ from the beam is 0.4×10^7 protons per second for 10^{12} particles in the beam.[8] This corresponds to a beam lifetime of about 70 hours. According to other sources, a beam loss is several times less.[9] Further, we will use the measurements from reference [8]. The projected proton intensity for the Tevatron collider is 5.4×10^{12},[10] which implies proton loss of about 2×10^7 protons per second. As we will show, practically all these protons could be channeled in a bent crystal and delivered to the extraction line.

As already mentioned, there is serious difficulty with delivering the beam loss to the extraction septum. If we suppose that the halo particle moves away from the beam center at a typical rate of about 0.1 mm per hour, we get a one turn step size of less than the size of an atom.[9] Of course, an accelerator

is not a such precise machine. Nonlinear effects due to multipole magnetic components produce turn-to-turn variations of a particle trajectory. Vibrations of quadrupoles, dipole power supply ripple and other noise sources produce a beam position jitter. These effects, according to our estimations, are of a fraction of a micrometer. Therefore, one can expect that a typical impact parameter in a crystalline target would be about this much. A simple crystal extraction scheme would not be effective under these conditions because of the large ratio of septum thickness to mean impact parameter. Radiation damage to the crystal, which usually does not present a problem,[11] in this case could be worsened because of the very high spatial density of radiation, and would reduce the channeling transparency of the crystal.

Placing a crystal at a radial distance of 16–20 beam σ could solve both the spatial and radiation problems, because at this distance particles have stable trajectories for only several turns and are well scattered in space. However, this is not really feasible because scrapers must be placed at about 10 beam σ to control the beam loss.

One could overcome the difficulty of delivering halo beam particles well into the crystal septum by using a crystalline scatterer. This idea and its application to the SSC were examined in 1991.[7] Instead of impinging directly on the bent crystal, a particle first hits a thin crystalline scatterer placed at the proper radial distance. To scatter a particle in the horizontal direction, crystalline planes are placed vertically.

The crystal which thickness equals a quarter of oscillation wavelength of particles in the planar channel is a real scatterer. It broadens the angular distribution of incident beam particles. However, a large part of incident particles gets small angular deflections, much smaller than critical channeling angle. They will form a maximum at the edge of the crystal deflector when such a scatterer is used to throw circulating particles over the imperfect layer at the bent crystal surface.

Developing further the idea of a crystalline scatterer placed perpendicular to the beam,[7] we propose to align a scatterer along the beam with an angular offset of about 1/2 of a critical angle, which makes the scatterer a "crystal mirror." Planar channeling in this "mirror" gives particles a kick, in a proper direction, about of a critical angle of channeling, 17 μrad for a tungsten (110) plane. The optimal thickness of the crystal mirror is one-half of a channeling wavelength because, in the first approximation, this thickness images a parallel beam into a parallel beam. For the tungsten (110) plane this thickness is about 24 μm,

and about 42 μm in the case of silicon. In the case of a small divergence beam, as is in our case, more that half of the incident particles are reflected in one pass, and this probability rises due to multipass mode.

When a crystal is used as a mirror to throw halo particles of a circulating beam over the crystal surface edge, the maximum of the impact parameter distribution will be far enough from the crystal edge. Therefore, a particle loss on the imperfect layer becomes smaller than with amorphous scatterer or with ultra thin crystal scatterer of 1/4 wavelength. [7] The thin tungsten crystalline mirror increases the mean impact parameter at the bent crystal to about 200 μm. This reduces the effective septum thickness presented by the bent crystal by more than a factor of 10^3 in comparison with the case when no scatterer is used. If desirable, one can increase a mean impact parameter even more using several crystal mirrors placed in sequence ("crystal fan").

An amorphous scatterer is less effective than the crystalline scatterer because of the much larger thickness required. Besides, it always gives a maximum of an impact parameter distribution at the edge of the crystal.

At a thickness of 24 μm, edge effects of the order of a fraction of a micrometer (angular miscut, nonflatness, etc.) on the crystalline scatterer do not present serious problems. However, to reduce the problem one can use a very thin amorphous target-prescatterer. A 20-μm thick amorphous tungsten prescatterer is a proper choice for the Tevatron, providing about 1 μrad angular kicks for particles in both planes due to multiple scattering. It gives a mean impact parameter at the crystalline scatterer of 1 μm. Naturally, the amorphous target has no edge problems similar to the crystalline one. If a particle did not pass through the full thickness of the prescatterer at the first strike, initial multiple scatter angular disturbance will be increasing with the subsequent passes until, finally, a particle will go into the bulk of a prescatterer material and undergo a full multiple scattering.

During fixed target runs, the electrostatic septum placed in D0 straight section provides a 50-μrad kick and drives 900-GeV protons to the extraction Lambertson magnets in A0. Therefore, a 100-μrad bend in a crystal septum would be enough to extract beam halo particles. Placed at radial distance of 10 beam σ, a crystal septum gives a particle an angular kick of about 10 rms beam divergence, therefore providing a necessary separation of its trajectory from the main circulating proton beam. Although all our calculations

have been made for the C0 section, results on the bending efficiency are generally applicable to most of the azimuthal positions in the Tevatron.

The most effective bent silicon crystalline septum for Tevatron would have the following parameters:

- bending angle equal to 100 μrad
- 5 mm along the beam, 1 mm in height, 0.3–1.0 mm thick
- cutting precision better than 0.1 mrad
- flatness and crystalline defects on surface less than 0.5 μm

All three elements of the crystal extraction system should be placed in properly optimized radial and azimuthal positions, according to the Tevatron lattice and scraper settings. To simplify the analysis, we place all the elements on the same azimuthal position. Therefore, our results probably could be improved if one could make further optimization.

Although we consider a 100-μrad bend as the most efficient, we also performed calculations for the 600-μrad and 3000-μrad bends.

In determining extraction efficiency, the following sources of particle loss in bent crystals considered:

- normal dechanneling, due to multiple scattering in a channel
- centrifugal acceptance, due to the distortion of a plane potential in a bent crystal
- "surface acceptance" area
- angular acceptance, limited by the critical angle of channeling
- septum wall thickness, i.e. surface nonflatness, crystalline imperfectness and miscut
- nuclear interactions

Beam dynamics in the accelerator enhance performance of the bent crystal as an extraction device. Due to very slow transverse diffusion, beam halo particles that encounter the crystal extraction system have a very narrow angular spread (quasi-parallel beam), therefore providing a very high channeling efficiency. In addition, due to the small scattering angles involved, a scattered particle will make multiple passes through the bent crystal, increasing the probability of channeling. These two circumstances drive up the extraction efficiency significantly.

2.2 Simulation

We made a full Monte Carlo simulation of the Tevatron beam halo extraction. As was already mentioned, the location of the bent crystal was chosen at the C0 straight section at the azimuth of E-853 experiment.[4]

The scheme of the extraction is presented in fig. 1. The extraction system could be placed either in the horizontal or in the vertical plane. The extraction device consists of an amorphous prescatterer, SC1, a crystal scatterer, SC2, and a bent crystal septum BC. Although the most efficient azimuthal positions for all three extraction elements would be different for each element, the same azimuthal position for all of them was used in our present studies to simplify the calculations and present a more practical case. In the simulation, the crystal scatterer was placed immediately behind the bent crystal in the beam direction, and the amorphous prescatterer was placed immediately behind it. The radial position of the SC1 was chosen to be 6 mm, i.e. 10 beam σ. Typically, a 20-μm thick tungsten prescatterer SC1 was used with an rms multiple scattering angle of 1 μrad. The inner edges of the crystal scatterer SC2 and the bent crystal BC would be additionally shifted from the beam orbit. The radial positions of SC2 and BC were varied to obtain an optimum for the extraction. The results are typically obtained for the case with the bent crystal radial offset of d = 15 μm relative to the SC2, that is close to optimal with respect to the loss in an imperfect surface layer. We used a geometry in which particles were deflected in the horizontal plane.

We calculated the particle orbits for the two-dimensional (X-S) case. If the halo formation is going independent in the X- and in the Y-plane, only half a halo will be extracted by one crystal and another half will be scraped by the Y scraper. In this case one should place a similar extraction system in the Y-plane to extract all the halo particles. We believe, however, that the halo particles of large amplitude oscillations in the X-plane have large amplitudes also in the Y-plane, and vice versa. In this case a bent crystal extraction in one plane will work as an efficient drain for all the halo particles.

To simulate beam halo, initial values X, X' of particles were generated at the bent crystal position using a flat distribution for X_{max} from 6 mm to 6.0001 mm, and with a uniform phase distribution. Typically, 1000 particles were generated for each version of initial conditions. After the first collision with the amorphous scatterer SC1, which gave a particle an angular rms kick of 1 mrad, a particle traveled

typically many turns before it hits the crystal scatterer SC2, placed at a radial position of 6.001 mm, i.e., outward from SC1 by 1 μm. A full turn transfer matrice for the X-plane was used to transport particles through the accelerator ring. Figure 2 demonstrates the impact parameter distributions at SC2. We have to remark that in a case of failure to be channeled in SC2 a particle remains trapped in the Tevatron ring, and returns for another pass. Eventually, almost every particle will succeed in channeling in SC2 due to the multipass process, with minimal nuclear interaction loss. Scattering of particles by the atomic planes of the crystal scatterer increases considerably the particle amplitudes, and they begin to hit the bent crystal.

As was mentioned before, we use a crystal SC2 as a crystalline mirror with a tilt angle of about 1/2 of the critical channeling angle. The remarkable peculiarity of such a scatterer is the small thickness needed to give the particle a large angular deflection, because scattering of particles occurs when the contributions of crystal atoms are added coherently. It is important because the particle loss due to inelastic interactions with scatterer atoms will be considerably smaller in this case. To provide a 17 μrad scattering angle, a 0.4-cm thick amorphous tungsten scatterer would be required. The rate of nuclear interactions in such a scatterer would amount to about 7%, which would preclude to use a such a scatterer in a multipass mode. Besides, a crystalline scatterer provides an angular deflection in only one plane, perpendicular to the crystallographic planes. Figure 3 demonstrates an ability of a tungsten crystal to work as a crystal mirror. It shows angular distributions of outgoing particles for the cases when the crystal planes (110) were tilted by 8.5 μrad and 12.75 μrad relative to the direction of incident 900 GeV-protons.

Particle trajectories both in the crystalline prescatterer SC2 and in the bent crystal, BC, were calculated by a numerical solution of the equations of motion in the potential of bent atomic planes. After a step size of $\Delta S = 2$ μm, which is much smaller than the wavelength of a particle oscillation in the channel, the change of transverse velocity due to multiple scattering was computed. More details of these simulations can be found in references.[5, 6] The model describes well all the existing experimental results on channeling with bent crystals.

Silicon and tungsten crystals were used as SC2, and 40 to 200 μm mean impact parameters were obtained at BC. Figure 4 shows typical impact parameter distributions at the bent crystal position for tungsten and silicon scatterers SC2. The scatterer SC2 clearly works as a crystal mirror.

Most of the particles that hit the bent crystal, BC, can be captured into channeling regime by the bent planar channels. These particles are deflected at a bending angle α if they are not dechanneled due to multiple scattering by crystal electrons and nuclei. Another part of particles will experience multiple scattering in the crystal (which is rather small) or could be lost due to inelastic nuclear interactions. After multiple scattering in the bent crystal, particles continue to travel around the accelerator and strike the bent crystal again. We assume that a particle is extracted if it exits from the crystal at the crystal bending angle, within the critical angle of channeling. It was also assumed that the imperfect layer of 0.5 μm thickness at the crystal surface is 100% inefficient. These imperfections can include short planar channels due to a crystal miscut or surface planar channels with shorter dechanneling length than in the body of the crystal. These give particles large angular deflections, but do not allow them to be extracted. It is probably a stricter limitation than in reality.

We continue the calculations until all the particles end the process being extracted, or experience a nuclear interaction, or being lost in the imperfect surface layer, or dechanneled and lost in the accelerator.

Results of simulations for the bending angle of 100 μrad and a 5-mm long silicon crystal presented on figs. 5–8. Figure 5 presents the data when a silicon crystal was used as a crystal mirror and the thickness of the bent crystal was 0.3 mm. Extraction efficiency is 0.981 for this case. Cooling the bent crystal allows one to reduce thermal displacements of atoms in crystal planes, that reduces the particle losses due to inelastic interactions with the crystal. Figure 6 presents the case when the crystal was cooled to 4 K. Extraction efficiency is 0.988. This is the highest extraction efficiency found for the case of a 100-μrad bend.

Also shown in fig. 6 is the particle distribution versus the number of turns between a first prescatterer hit and the extraction. Its structure is stipulated by successive hits of particles in an interval near the amplitude value of X_{SC1}, during the betatron oscillations. About 300 turns are necessary for a particle again to hit the prescatterer SC1 if it missed SC2 at the first attempt. The distribution of a number of passages through the bent crystal is also presented.

Figure 7 presents the data when a tungsten crystal was used as a crystal mirror. The thickness of the silicon bent crystal is 0.3 mm. The bent crystal offset was 5 μm for this case. Extraction efficiency is

0.977. Figure 8 presents the case of a tungsten crystalline prescatterer, the bent crystal is 1 mm-thick. Extraction efficiency is 0.982. The bent crystal offset is 15 μm.

Figure 9 presents the data for a 600-μrad bend. The bent crystal length is 5 mm, its thickness is 1.0 mm. The crystal is cooled to 4 K. Extraction efficiency is 0.981. For comparison, at a temperature of 293 K the corresponding efficiency is 0.967.

Figure 10 presents the data for a 3-mrad bend. The bent crystal length is 25 mm, its thickness is 1.0 mm, the crystal is cooled to 4 K. Extraction efficiency reaches 0.840. For comparison, at a temperature of 293 K the corresponding efficiency is 0.783.

As we mentioned earlier, all results were obtained with a particle trajectory simulation only in the X-plane, to save the computer time. Figure 11 presents the X-Y case for the 100-μrad bend. In the Y-plane we supposed the particle emittance is equal to one in the X-plane. The vertical size of the all three elements is 1 mm. Although statistics are poor for the case, results confirmed that due to a difference in the X- and Y- tunes the extraction process is going as usual, except for the slower rate.

3. Conclusions

We have presented here a stationary passive device for the beam halo crystal extraction. It would extract the natural proton beam loss, the beam halo, which for the Tevatron is about 2 x 10^7 protons per second. The process does not interfere with colliding beam experiments. Thus, the device is suitable for cleaning up the proton beam halo (a clean crystal scraper), or for useful extraction of the proton beam halo particles with a 99% efficiency. When it is used as a clean scraper, it could work as an efficient clean radiation drain preventing radiation due to a proton beam loss that now is spreading around the Tevatron.

The device is suitable to be used at the LHC collider for both circulating proton beams. It could reduce the background radiation due to a beam halo loss by a factor of about 100.

If one desires a higher intensity beam for fixed target experiments or tests, the system could be programmed for slow motion in the radial direction toward the circulating beam, therefore providing the necessary extraction rate. Of course, a slow local distortion of closed orbit could work as well.

Thermal limitations probably present some problem for straightforward use of a crystal extraction system at rates more than 10^{12} protons per second.

If there is a significant beam orbit vibration, a time duty factor of the extracted beam will be about 50%. It probably could be improved by introducing a compensative vibration of the SC1.

In conclusion, we propose to build a "passive" crystal extraction for the Tevatron that will work parasitically during collider runs. Normal beam halo loss mechanisms could provide extraction of up to 2×10^7 protons per second.

To make a practical approach to a clean crystal scraper design, we propose to place such a device at A0 near the present abort kicker. A 3-mrad bent crystal kicker will direct the proton beam halo into the existing beam dump. Orientation and adjustment of the system would be done without interference with colliding beam experiments, using radiation measurements near the proton beam dump setup. A 2.5-cm long silicon crystal could be used as a scraper. The extraction efficiency for this case is 0.84.

Acknowledgments

The authors wish to thanks Drs. S. Baker, R. Carrigan, G. Jackson, R. Meinke, N. Mokhov, T. Murphy, J. Peoples, N. Slavin, and T. Toohig for their valuable discussions and help.

References

[1] E. Tsyganov, Some Aspects of the Mechanism of a Charge Particle Penetration Through a Monocrystal, Fermilab TM-682, Batavia (1976); A. F. Elishev et al., Steering of Charged Particle Trajectories by a Bent Crystal, Phys. Lett. v. 88B (1979) 387; and R. A. Carrigan et al., Possible Applications of the Steering of Charged Particles by Bent Single Crystal, Nucl. Instrum. Methods 194 (1982) 205.

[2] V. V. Avdeichikov et al., Accelerated Beam Extraction by Means of a Bent Single Crystal at the JINR Synchrophasotron, JINR Communications 1-84, p.1, Dubna, January 1984, English translation FERMILAB-FN-429, February 1986; A. A. Asseev et al., On Using Bent Single Crystals for Proton Extraction from IHEP Accelerator, Proceedings of 1991 Particle Accelerator Conference, p. 189, May 1991, San Francisco, CA; A. A. Asseev et al., IHEP Preprint 89-57, Serpukhov, 1989; and H. Akbari et al., First Results on Proton Extraction from the CERN-SPS with a Bent Crystal, Phys. Lett. B313 (1993) 491.

[3] B. S. Newberger et al., Super Slow Extraction at the SSC using channeling in a Bent Crystal, Nucl. Instrum. Methods A325 (1993) 9; W. Gabella et al., RF Voltage Modulation at Discrete Frequencies with Applications to Crystal Channeling Extraction, in Proceedings of the 1993 Particle Accelerator Conference p. 233, Washington, 1993; and E. Tsyganov et al, Resonance Excitation of the SSC Beam Halo by RF Voltage Pulses, SSCL-609, December 1992.

[4] R. A. Carrigan et al., Proposal for a Test of Low Intensity Extraction From the Tevatron Using Channeling in a Bent Crystal, FNAL, May 22, 1991; G. Jackson, Extraction from the Fermilab Tevatron using Channeling with a Bent Crystal, Proceedings of the 1993 Particle Accelerator Conference, p. 1366, Washington, May 1993; and R. A. Carrigan, Jr., et al., Extraction from TeV-Range Accelerators Using Bent Crystal Channeling, Nucl. Instrum. Methods B 90 (1994) 128.

[5] A. M. Taratin et al., Planar Dechanneling and Volume Capture of High-Energy Protons in a Bent Crystals, Nucl. Instrum. Methods, B47 (1990) 247.

[6] H.-J. Shih et al., Bent Crystal Extraction of the SSC Beam with RF Noise Induced Diffusion, SSCL-389, March 1991.

[7] A. Taratin et al., Ultrathin Crystal Scatterer for the SSC Beam Extraction System, SSCL-545, December 1991.

[8] N. Mokhov, Scrapers, private communication.

[9] G. Jackson, Results from Beam Diffusion and Collimation Measurements in Preparation for Fermilab Tevatron Crystal Extraction, in Proceedings of the 1993 Particle Accelerator Conference, p. 402, Washington, 1993.

[10] D. A. Finley, Fermilab Collider Upgrade: Recent Results and Plans, Proceedings of the 1993 Particle Accelerator Conference, p. 3721, Washington, May 1993.

[11] S. I. Baker, Radiation Damage Effects in Channeling Applications, in *Relativistic Channeling*, edited by R. Carrigan, Jr., and J. Ellison, Plenum Press, New York and London, 1987, p. 391; Yu. A. Chesnokov et al., Proc. 15th Int. Conf. on High Energy Accelerators, 1992, Int. J. Mod. Phys. A (Proc. Suppl.) 2 (1993) 173; and S. I. Baker et al., Effects on Channeling of Radiation Damage Due to 28 GeV protons, Nucl. Instrum. Methods B 90 (1994) 119.

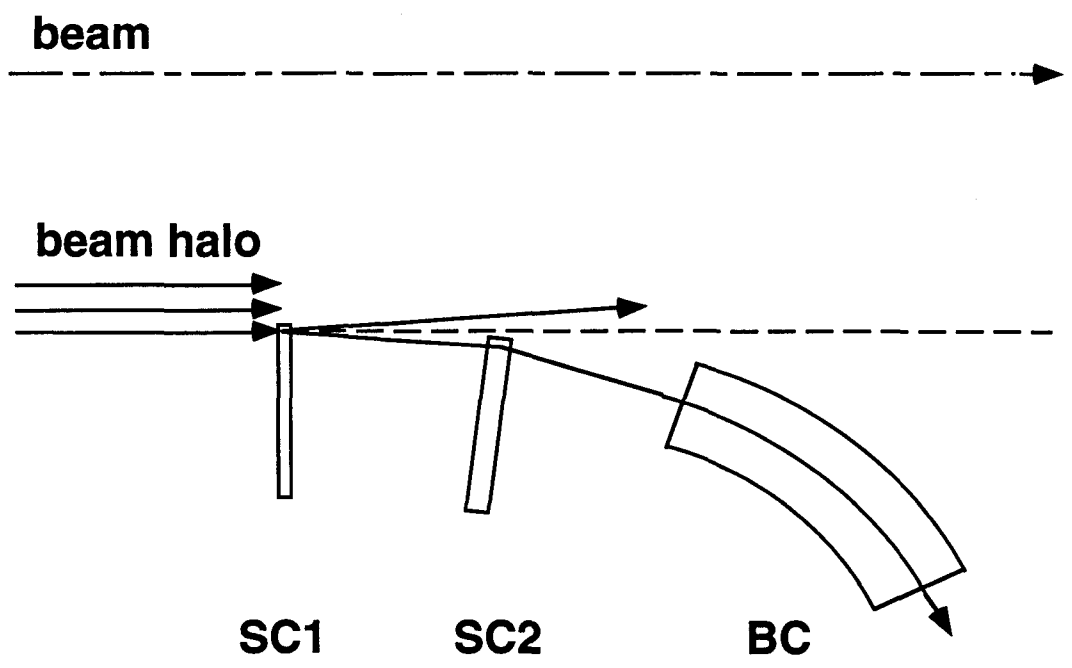


Fig.1. The diagram of crystal extraction. SC1 -- amorphous scatterer, SC2 -- crystalline scatterer, BC -- bent crystal.

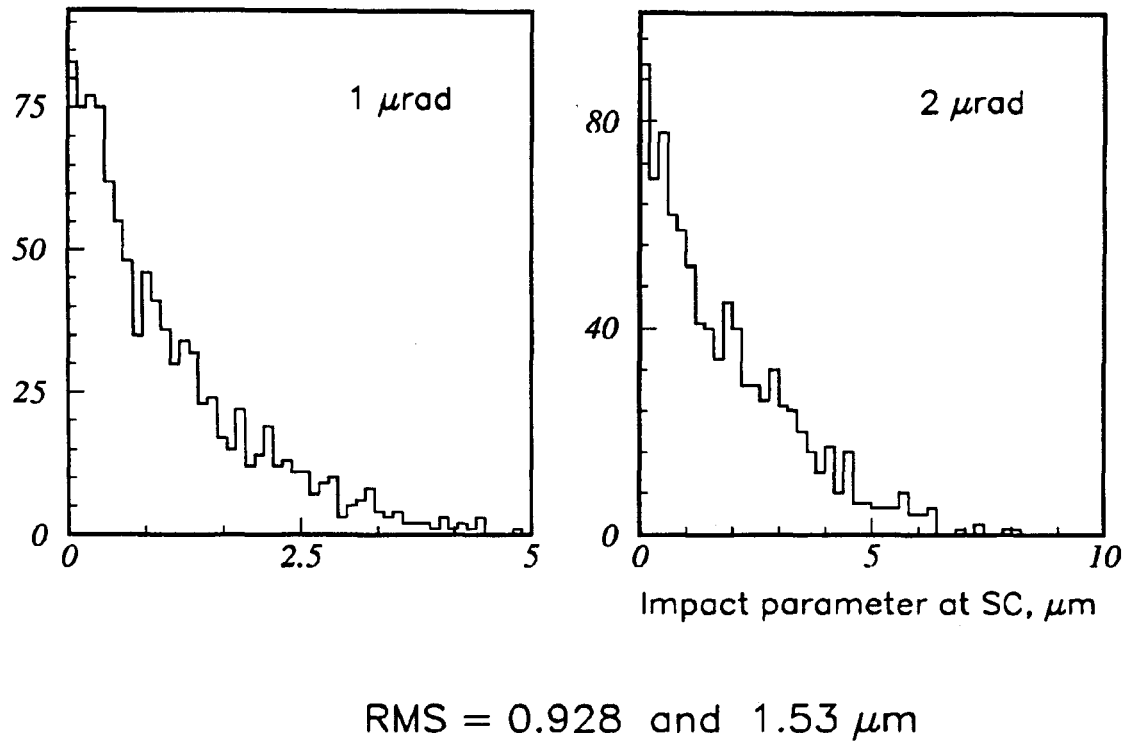


Fig. 2. Impact parameter distribution at the crystalline scatterer for two different amorphous scatterers.

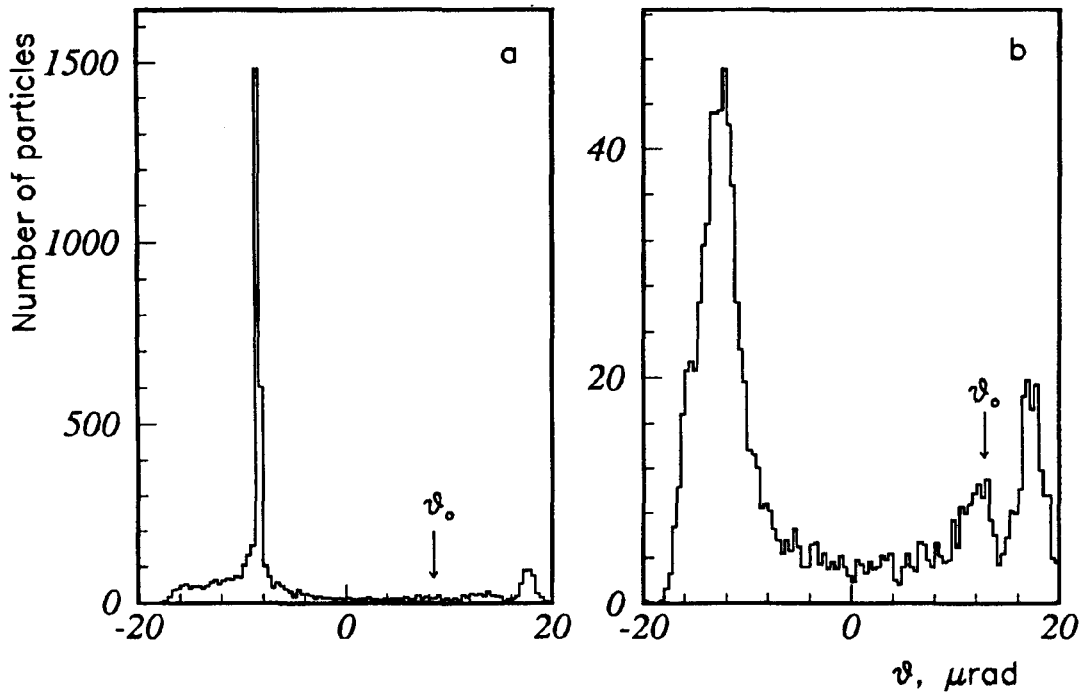


Fig. 3. Angular distributions of outgoing particles for the cases when the tungsten crystal planes (110) are tilted (a) by 8.5 μrad and (b) by 12.75 μrad relative to the direction of an incident 900 GeV-protons.

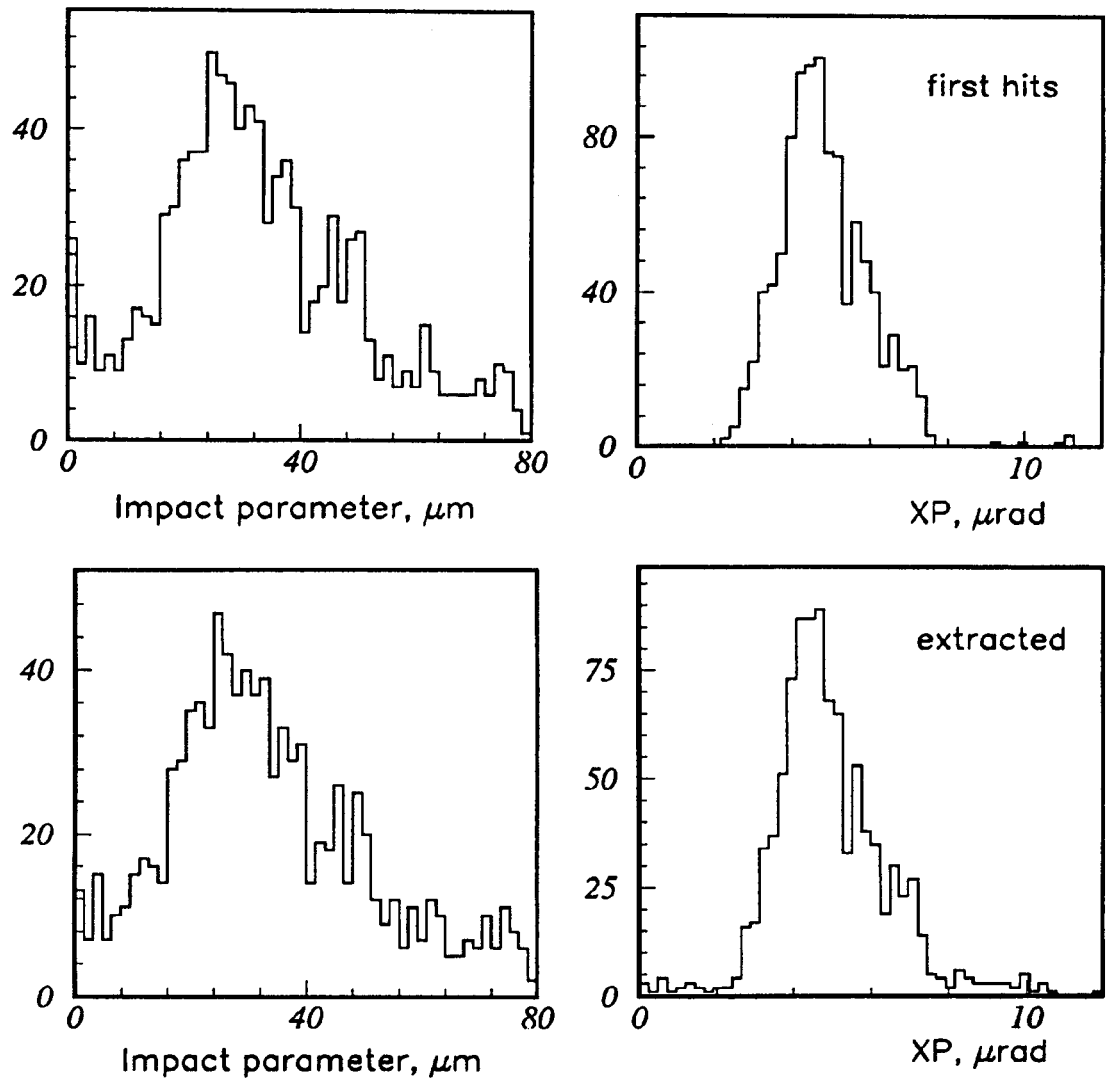


Fig. 5. Impact parameter and angular distributions for the case of silicon crystal scatterer. The bending angle is 100 μrad, the crystal length is 5 mm. Extraction efficiency is 0.981.

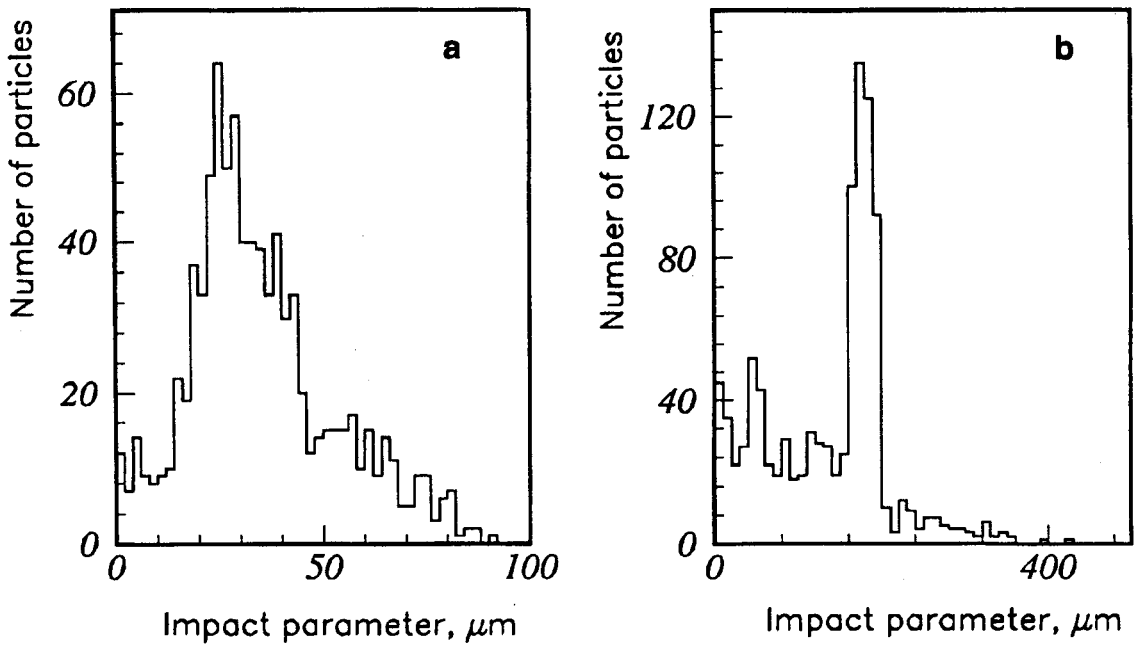


Fig. 4. Impact parameter for different crystal mirrors SC2: a - silicon, b - tungsten.

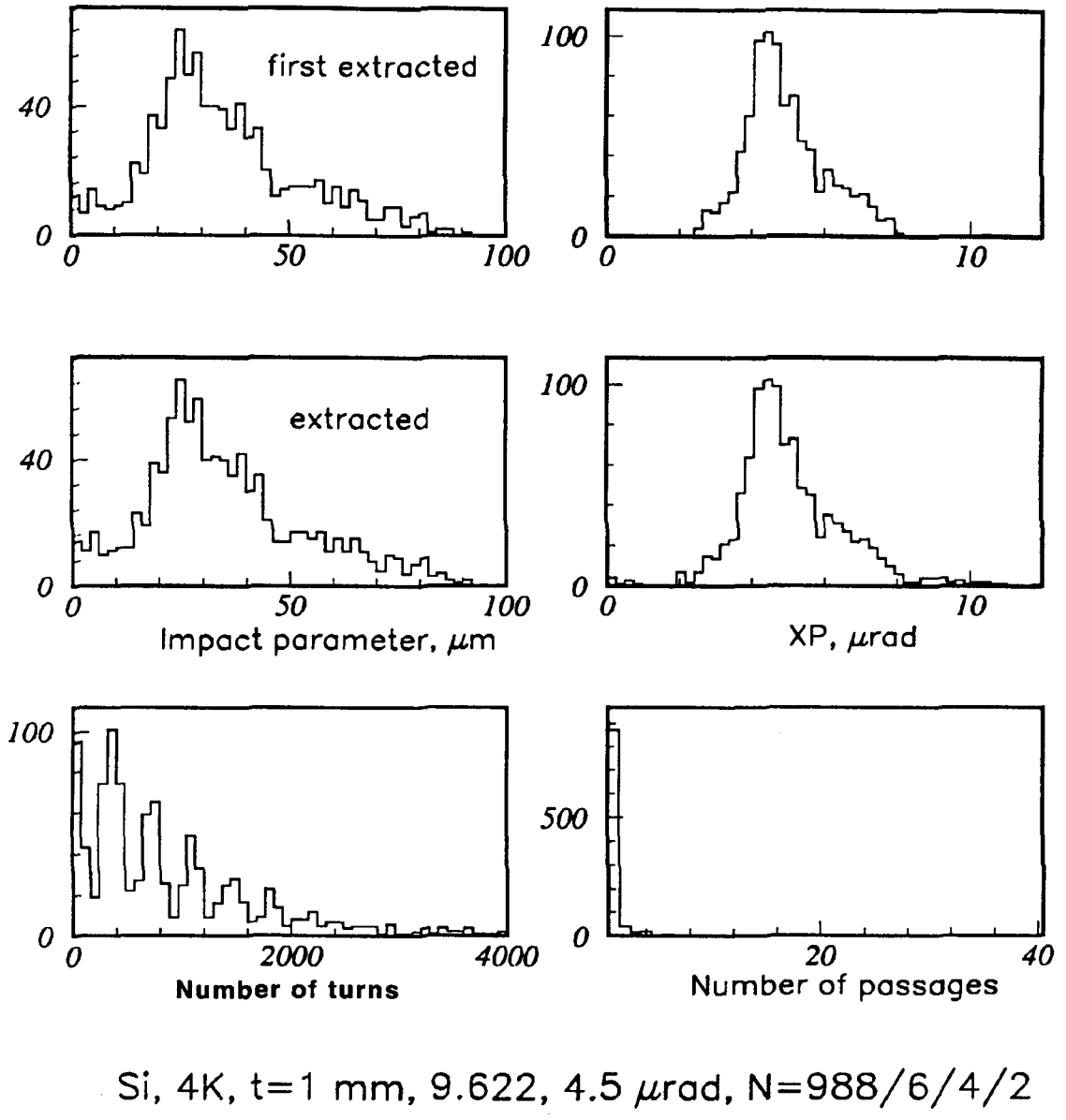


Fig. 6. Impact parameter and angular distributions for the case of silicon crystal scatterer. The bending angle is 100 μrad, the crystal length is 5 mm. The bent crystal thickness is 1 mm, and the crystal is cooled to 4 K. Extraction efficiency is 0.988. Also shown is a time structure of the extracted beam, and the distribution of a number of passages through the bent crystal.

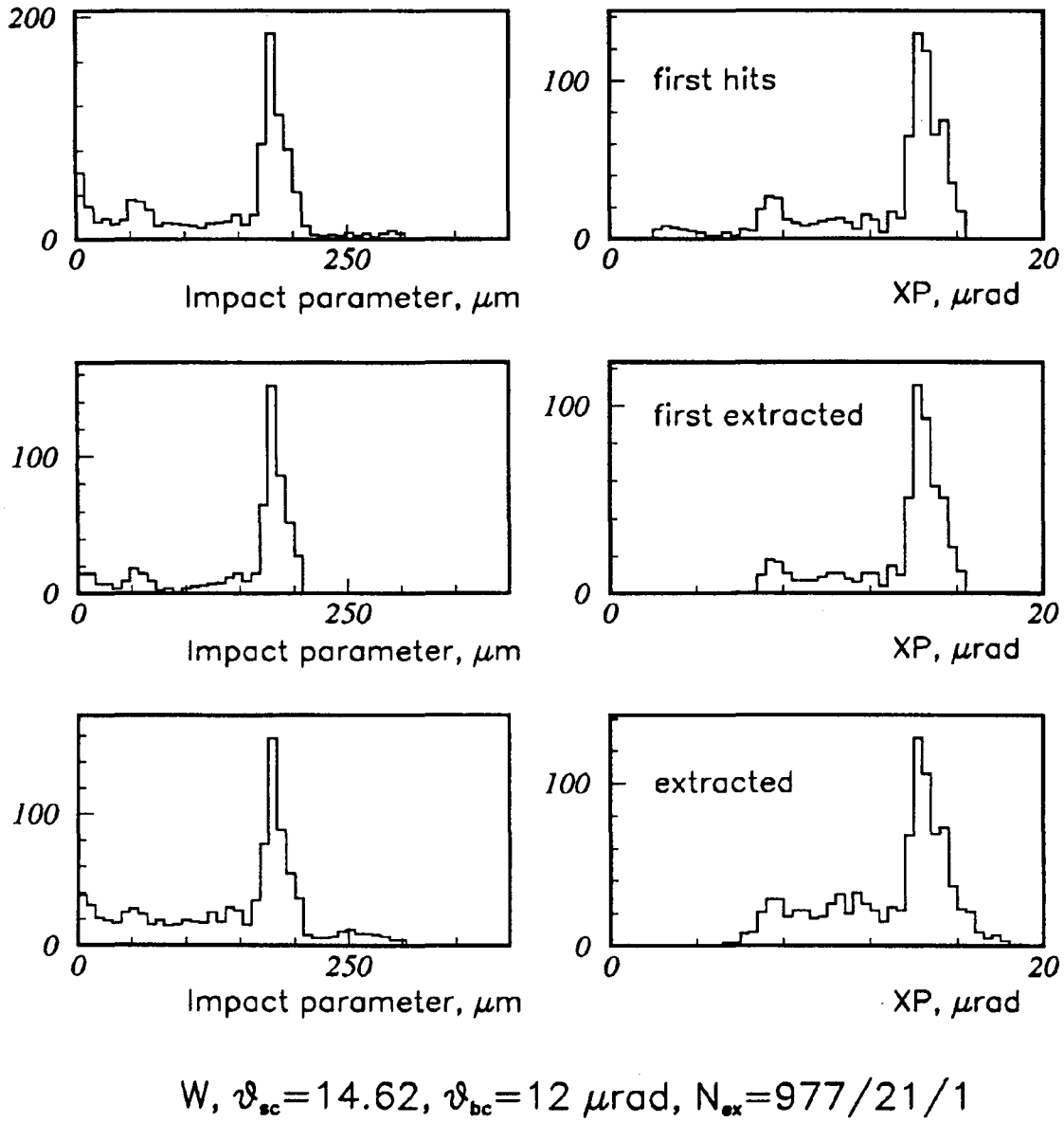


Fig. 7. Impact parameter and angular distributions for the case of a tungsten scatterer. The bending angle is 100 μrad, the crystal length is 5 mm, the crystal thickness is 0.3 mm. Extraction efficiency is 0.977. The bent crystal offset is 5 μm.

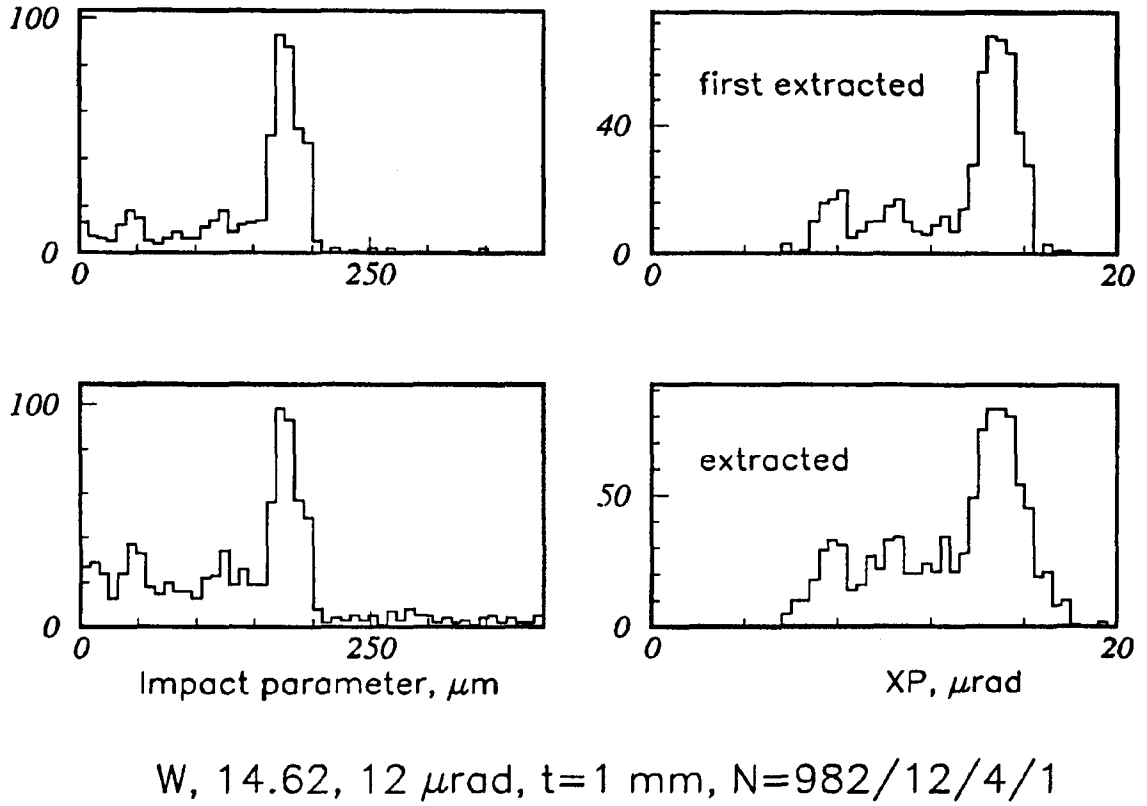


Fig. 8. The same as on fig. 7, but for the case of 1 mm bent crystal thickness. Extraction efficiency is 0.982. The bent crystal offset is 15 μm.

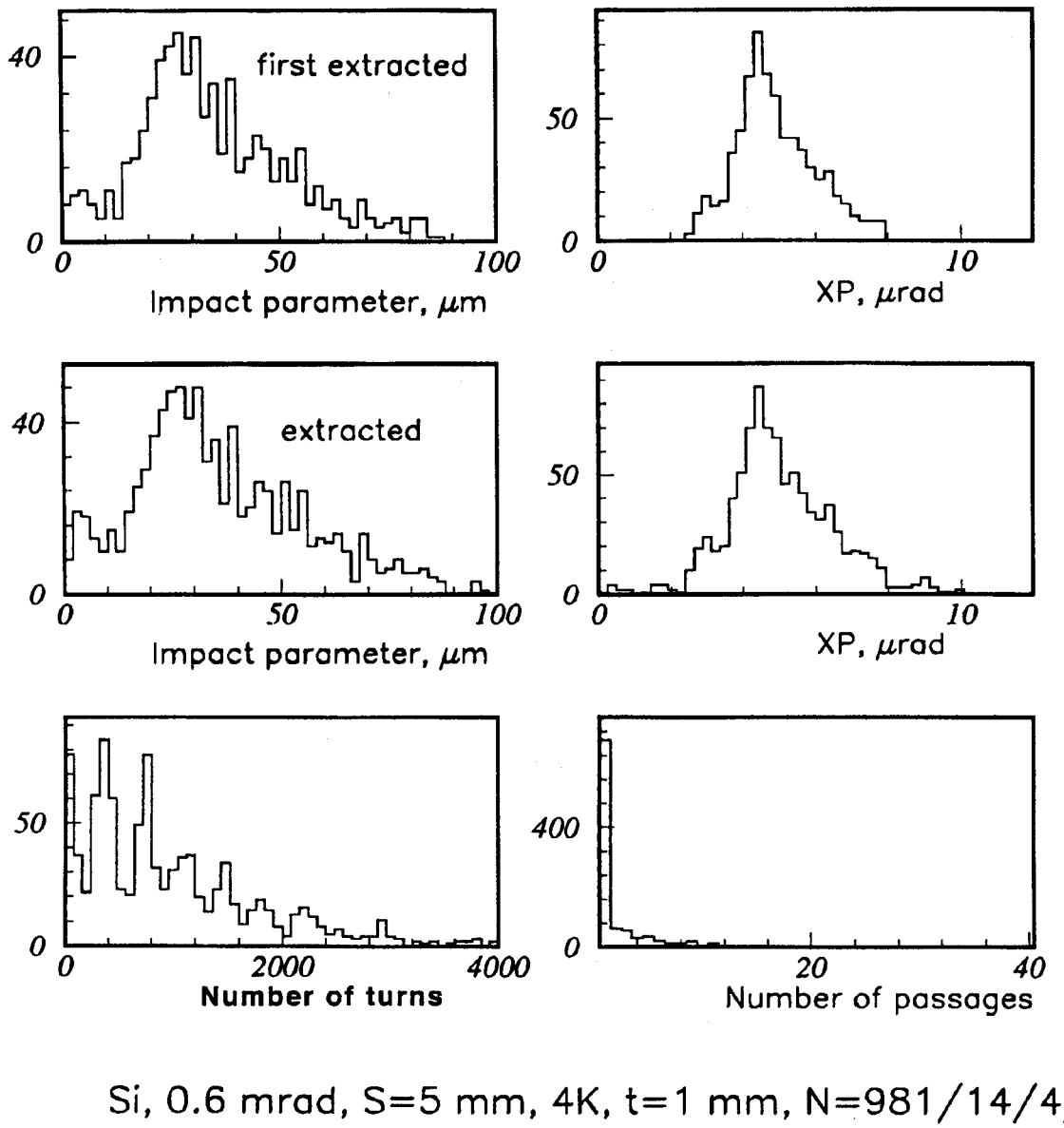


Fig. 9. Impact parameter and angular distributions for the case of silicon bent crystal with the length of 5 mm and the bending angle of 600 μrad. The bent crystal thickness is 1 mm, the crystal is cooled to 4 K. Extraction efficiency is 0.981, from 1000 particles simulated.

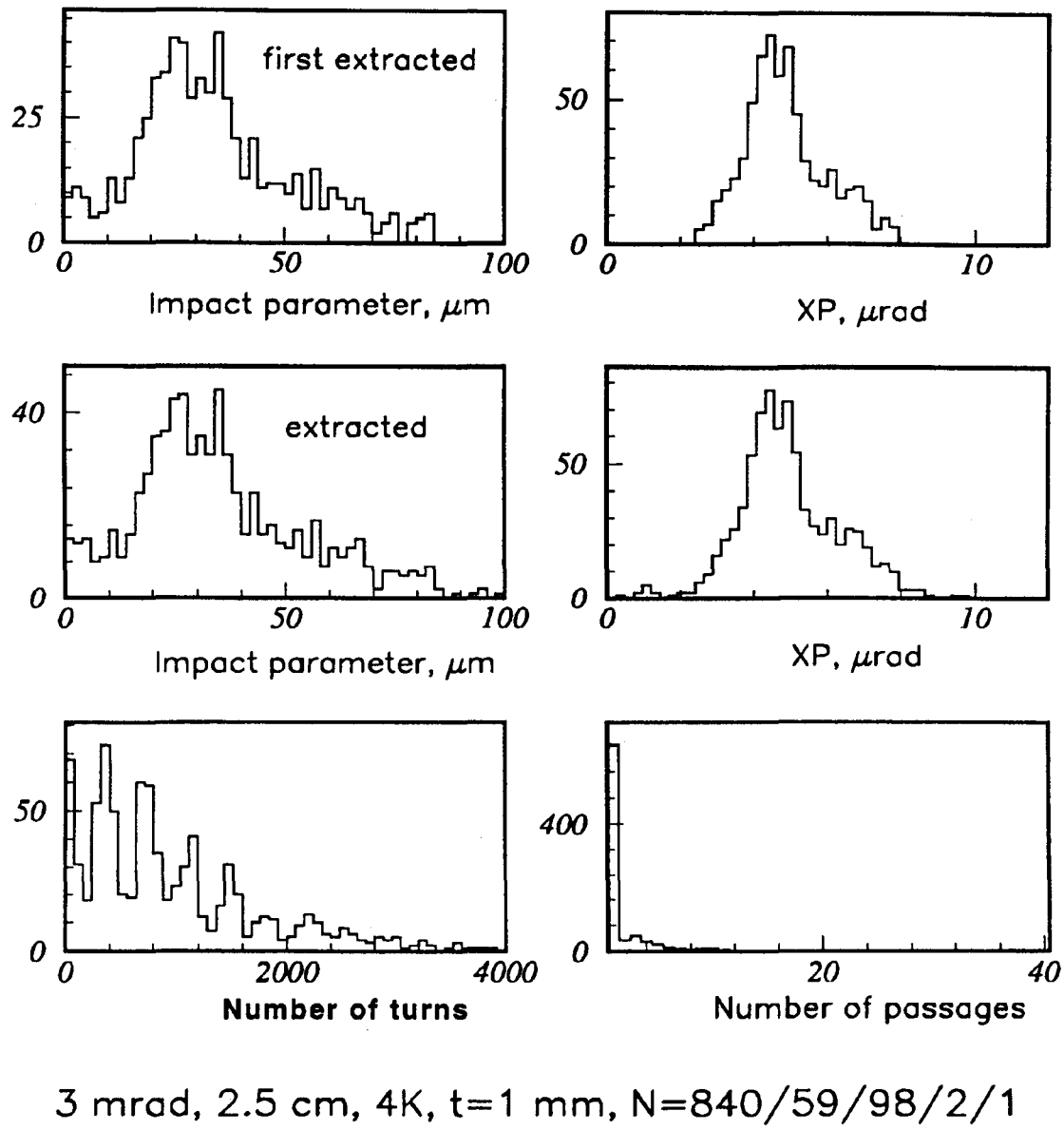


Fig. 10. Impact parameter and angular distributions for the case of silicon bent crystal with the length of 25 mm and the bending angle of 3 mrad. The crystal is cooled to 4 K. Extraction efficiency is 0.840, 1000 particles simulated.

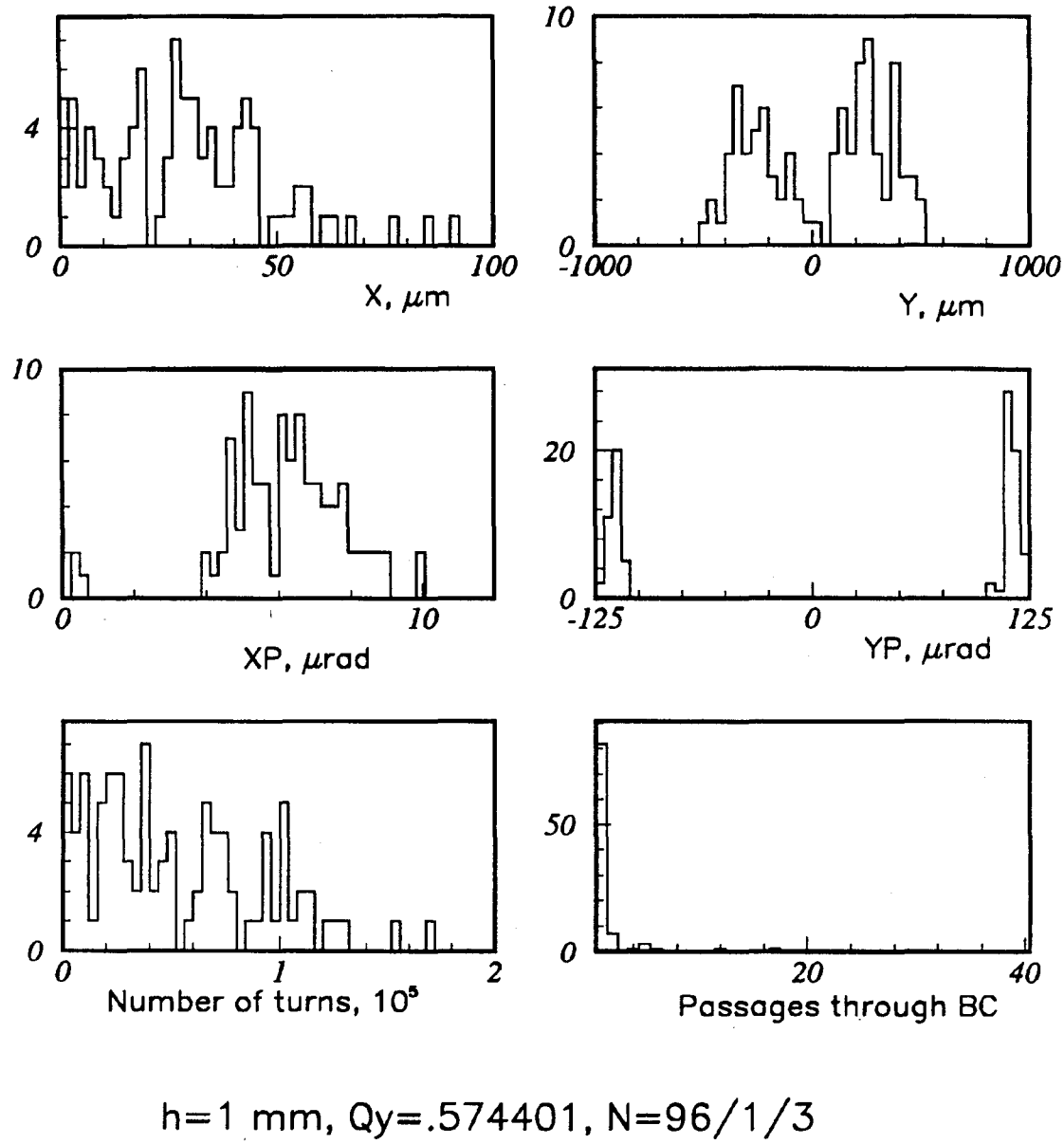


Fig. 11. Results of the simulations in the X-Y case. A bend is 100 μrad, the crystal length is 5 mm, the crystal thickness is 0.3 mm.. The vertical sizes of all the elements are 1 mm. The Y-tune was changed slightly to avoid a repetition of trajectories. One hundred particles are simulated.

Figure captions

Fig. 1. The diagram of crystal extraction. SC1 -- amorphous scatterer, SC2 -- crystalline scatterer, BC -- bent crystal.

Fig. 2. Impact parameter distribution at the crystalline scatterer for two different amorphous scatterers.

Fig. 3. Angular distributions of outgoing particles for the cases when the tungsten crystal planes (110) are tilted (a) by 8.5 μrad and (b) by 12.75 μrad relative to the direction of an incident 900 GeV-protons.

Fig. 4. Impact parameter for different crystal mirrors SC2: a - silicon, b - tungsten.

Fig. 5. Impact parameter and angular distributions for the case of silicon crystal scatterer. The bending angle is 100 μrad, the crystal length is 5 mm. Extraction efficiency is 0.981.

Fig. 6. Impact parameter and angular distributions for the case of silicon crystal scatterer. The bending angle is 100 μrad, the crystal length is 5 mm. The bent crystal thickness is 1 mm, and the crystal is cooled to 4 K. Extraction efficiency is 0.988. Also shown is a time structure of the extracted beam, and the distribution of a number of passages through the bent crystal.

Fig. 7. Impact parameter and angular distributions for the case of a tungsten scatterer. The bending angle is 100 μrad, the crystal length is 5 mm, the crystal thickness is 0.3 mm. Extraction efficiency is 0.977. The bent crystal offset is 5 μm.

Fig. 8. The same as on fig. 7, but for the case of 1 mm bent crystal thickness. Extraction efficiency is 0.982. The bent crystal offset is 15 μm.

Fig. 9. Impact parameter and angular distributions for the case of silicon bent crystal with the length of 5 mm and the bending angle of 600 μrad. The bent crystal thickness is 1 mm, the crystal is cooled to 4 K. Extraction efficiency is 0.981, from 1000 particles simulated.

Fig. 10. Impact parameter and angular distributions for the case of silicon bent crystal with the length of 25 mm and the bending angle of 3 mrad. The crystal is cooled to 4 K. Extraction efficiency is 0.840, 1000 particles simulated.

Fig. 11. Results of the simulations in the X-Y case. A bend is 100 μrad, the crystal length is 5 mm, the crystal thickness is 0.3 mm. The vertical sizes of all the elements are 1 mm. The Y-tune was changed slightly to avoid a repetition of trajectories. One hundred particles are simulated.