Fermi National Accelerator Laboratory

FERMILAB-Conf-96/202-E
E853

First Results from Bent Crystal Extraction at the Fermilab Tevatron

C.T. Murphy et al.
The E853 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

July 1996

Proceedings of the *Workshop on Channeling and Other Coherent Crystal Effects at Relativistic Energies*, Aarhus, Denmark, July 10-14, 1996

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

FIRST RESULTS FROM BENT CRYSTAL EXTRACTION AT THE FERMILAB TEVATRON

C. T. Murphy*, R. Carrigan, D. Chen, G. Jackson, and N. Mokhov
Fermilab, Batavia, IL

H.-J. Shih
Superconducting Super Collider Laboratory, Dallas, TX

B. Cox, V. Golovatyuk, and A. McManus
The University of Virginia, Charlottesville, VA

A. Bogacz, D. Cline, S. Ramachandran, J. Rhoades,
and J. Rosenzweig
The University of California at Los Angeles, CA

B. Newberger
The University of Texas, Austin, TX

J. A. Ellison
The University of New Mexico, Albuquerque, NM

S. Baker
Argonne National Laboratory, Argonne, IL

C. R. Sun
State University of New York, Albany, NY

W. Gabella
Vanderbilt University, Nashville, TN

E. Tsyganov
Southwestern Medical Center, University of Texas at Dallas

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

A. Asseev and V. Biryukov,
Institute for High Energy Physics, Serpukhov, Russia

A. Khanzadeev, T. Prokofieva, V. Samsonov, and G. Solodov
Petersburg Nuclear Physics Institute, Gatchina, Russia

* Corresponding author, tel. +1 708 840 3150, fax +1 708 840 2950,
email thornton@fnal.fnal.gov

Submitted to the Proceedings of the Workshop on Channeling and Other Coherent Crystal Effects at Relativistic Energies, Århus, Denmark

Abstract

First results from Fermilab Experiment 853 are presented. E853 is an experiment to test the feasibility and efficiency of extracting a low-intensity beam from the halo of the Tevatron using channeling in a bent silicon crystal. The motivation of the experiment is to apply crystal extraction to trans-TeV accelerators like the LHC. Extensive simulation work has been carried out. Two accelerator operating modes have been developed for crystal studies, “kick” mode and diffusion mode. Results from the first successful extraction in kick mode are presented.

1.Introduction

Protons have already been extracted with bent crystals from the circulating beams at Dubna, Serpukhov, and the SPS at CERN. Experiment 853 extends these experiments by seeking to obtain significant parasitically extracted beam at 900 GeV in a superconducting accelerator. With 10^{12} protons circulating, the goals of E853 are to extract 10^6 protons/s and show that: 1) the luminosity lifetime is not seriously shortened; 2) the crystal can be aligned to the beam quickly; 3) no intolerable backgrounds are created at the collider experiments; 4) diffusion created by some kind of perturbation creates halo with an adequate step size, or jump, to clear the edge region of the crystal (called the "septum"), where it would be bent by only part of the total bend angle of the crystal.

E853 is also investigating the relative contributions of first-turn extraction and “multi-pass” extraction, the latter resulting from particles which encounter the crystal on the first turn but are not channeled, and then return to be channeled on some successive turn. The major goal of the experiment is to measure the extraction efficiency in the diffusion mode.

The original motivation for this experiment was to test a proposal that a beam of 10^8 protons/sec be extracted from the SSC for a fixed target B-physics experiment. The new equipment for this experiment was funded by the SSC. Despite the demise of the SSC, the experiment remains of interest as a step towards possible applications at both LHC and Fermilab.

2. Beamline

E853 is taking place in the C0 straight section of the Tevatron, the normal location of the proton abort line. The abort line consists of a magnetic dogleg that provides a 4 mrad horizontal kick so the abort line can clear the magnets at the downstream end of the long straight section. The middle bend in the dogleg consists of a series of Lambertson magnets. A series of four vertical kicker magnets are used to abort the beam into the field-free region of the Lambertsons. During collider runs, the abort line is not used at 900 GeV, so one of the kicker magnets was replaced by a bent crystal.

A sketch of the beamline geometry of the Tevatron Collider crystal extraction system is shown in Fig. 1. Protons in the halo of the beam distribution which intercept the bent crystal with the correct angle are deflected by 640 μrad upward into the field-free hole in the Lambertsons (see inset, Fig. 1). Protons in the field free region travel straight into the Tevatron abort line toward the extracted beam detectors.

The crystal is mounted at the upstream end of a 1 m beam pipe which ends with articulating bellows. Two precision motors (x,y) at each end of the pipe allow for the alignment of the crystal with four degrees of freedom. The most critical parameter is the alignment of the vertical angle of the crystal with the beam angle, which must be done to within 10 μrad to match the critical angle of the crystal with the beam angle. Therefore, motors were selected such that the least step in angle changes was 2.5 μrad.

Fig. 2 shows the core of the beam with respect to the crystal. Schematically, beam is “pumped” from the outer edge of the core of the beam into the horizontal halo by some mechanism, where it eventually intercepts the crystal on some turn following the appropriate number of betatron oscillations. We have planned two methods of pumping the outer edge of the beam onto the crystal. In the first method, called “kick mode”, a single proton bunch is given a single angular kick which gives a maximum deflection of 0.5 mm at the crystal. In “diffusion mode”, in which we will operate parasitically with p-$\overline{\text{p}}$ collider physics experiments, the principal source of pumping is expected to be elastic p-$\overline{\text{p}}$ collisions at the two collision points. To date, we have used only the kick mode.

3. Instrumentation

In the extracted particle line (see Fig. 1), there are two air gaps separated by 40 m in which there are six scintillators and four silicon strip planes to count the extracted beam and measure its trajectory precisely (in order to prove that it is channeled beam, not just scattered background). These detectors are removed from the beamline remotely when they are not in use.

Another scintillator is placed near the crystal outside the circulating beam vacuum tube at 90^{o}. It is referred to as the “interaction counter”, for it monitors inelastic nuclear collisions in the crystal, and its signal is proportional to the beam incident on the crystal.

The beam is also monitored with a CCD camera imaging a fluorescent flag in the first air gap. The camera signal is digitized and stored by a computer as well as broadcast in realtime over the Fermilab video distribution system. A standard Tevatron segmented wire ionization chamber (SWIC) also monitors the x and y distribution in the second air gap.

4. Crystal and bender

We use the (111) planes of a silicon mono-crystal of dimensions 40mm x 3mm x 10mm. The half angle for channeling at 900 GeV is 5 μrad compared to a vertical divergence of the unperturbed beam in the accelerator at the crystal of $\sigma = 11.5$ μrad. Details about the crystal quality and characterization measurement are given in Ref. [1], which also contains further details about the experimental setup not repeated here.

An important quality of the crystal is the flatness of the edge facing the circulating beam (see Fig. 2), for particles intercepting this surface with small impact parameters will be bent upward by only part of the total bend angle if they leave the crystal after a partial bend because of the non-flatness of this surface. Interferometric studies of this surface indicate that it is flat to within 0.3 μm. This flatness is fully adequate for kick mode, in which the “step size” into the crystal is distributed between zero and 500 μm. In diffusion mode, in which initial step sizes of fractions of a micron are expected, the relevant comparison is with the increase in the betatron amplitude of a particle which has been multiple scattered by, for example, 10% of the length of the crystal. This increase in amplitude is distributed between zero and roughly 10 μm, large compared to the 0.3 μm flatness.

The bending jig is a four-point bender, adjusted by a spring-loaded screw. The bend angle was set by adjusting the screw while measuring the bend angle using conventional optical techniques. The angle of reflection of light reflected from the two flat ends of the crystal which extend beyond the bending jig was measured; the difference is the bend angle. This technique was accurate to about 30 μrad. A subsequent measurement of the bend angle by an interferometric technique gave a bend angle of 642 ± 5 μrad.

The radius of curvature of the central region of the crystal is 3125 cm, so that P/R is 0.3 GeV/cm. Using the standard plot of centripetal dechanneling loss vs. P/R [2], we expect a bending dechanneling loss of 12%.

5. Extraction Observations in Kick Mode

During the four-hour run in which we first observed extraction, the Tevatron operated at 900 Gev with six equally spaced bunches of protons (there were no antiprotons), each with an initial intensity 10^{11}. The normalized emittanace (1σ) of the circulating proton beam was 3.33 π/P mm-mrad. This results in a beam at the crystal with σ_x = 0.6 mm, σ_y = 0.32 mm, $\sigma_{x'}$ = 6.2 μrad, and $\sigma_{y'}$ = 11.5 μrad, where x and y refer to horizontal and vertical, respectively. The horizontal and vertical tunes of the machine were 20.585 and 20.574, respectively.

In kick mode, we give one of the six proton bunches an angular kick using a Tevatron injection kicker with a pulse length of 3 μsec (1/6 of a turn). This kick gives a maximum deflection of 0.5 mm at the crystal. The purpose of this mode is to move a fraction of the beam deep into the crystal, well past the (possibly misaligned) imperfect edge of the crystal facing the beam. In this mode, there should be substantial channeling on the first turn in which the kicked beam encounters the crystal.

Because of the accelerator phase advance between the kicker magnet and the crystal, on the first turn following the kick, the beam has moved away from the crystal (as illustracted in Fig. 3). On turn 2, and again on turn 7, the beam is at maximum amplitude towards the crystal. To first order, we expect to see sizeable extraction on turn 2, and extraction on later turns only to the extent that beam that was not channeled in turn 2, but multiple scattered to a different vertical angle, returns to encounter the crystal with the correct angle.

In our first successful observation of crystal-extracted beam, the crystal edge was placed 4.5 mm from the beam centerline, equivalent to 8 standard deviations of the unperturbed horizontal beam size. The beam density is so rare at this distance that no beam was observed to interact with the crystal on the first few kicks. However, after a few hundred turns following each kick, the beam had grown, as nonlinearities in the machine gradually spread the beam to fill most of the phase space mapped out by the betatron oscillation shown in Fig. 3. After about 12 kicks, the beam had grown by a factor of 3 in the horizontal plane (and a factor 2.5 in the vertical plane, owing to the strong vertical/horizontal coupling in the Tevatron), in both size and divergence. Thereafter, an equilibrium state persisted in which the crystal edge defined the beam size, and about 2.4×10^9 protons/kick (~3% of the total bunch intensity) were lost from the machine on each kick.

In this equilibrium state situation, the vertical angle of the crystal was varied in 10 μrad steps to try to bring the crystal planes into alignment with the beam angle. The pulse heights of various counters in the two air gaps, whose voltages had been decreased several hundred volts so that they were operating in a “calorimeter mode”, were recorded during a 100 nsec gate matching the second turn of the selected bunch. A plot of pulse height of a counter in air gap 2 vs. crystal angle is shown in Fig. 4. A clear peak with a width (σ) of 35 μrad is seen. This width should be a convolution of the half angle for channeling (5 μrad) and the beam angular divergence (29 μrad, after the growth noted above). The agreement is good.

A picture of the CCD camera image of the fluorescent screen at the peak of the above distribution is shown in Fig. 5. In the central bright spot, the CCD is heavily saturated, so the apparent beam size is much bigger than the true beam σ. The most interesting feature of this image is the narrow “comet tail” descending downward from the central spot. This corresponds to protons which were not bent through the full 640 μrad of the full crystal. This tail could be the result of some combination of several effects. Particles which enter the crystal with a small impact parameter can exit the face of the crystal facing the beam (mentioned above) either because their horizontal angles are directed toward that face or because they are within the “septum width” (irregular region) of that face. Centrifugal dechanneling can occur anywhere in the bent part of the crystal, and dechanneling resulting from the multiple scattering can occur anywhere in the crystal. In fact, the tail extends further downward, but it is cut off by the V-shaped aperture of the field-free hole in the Lambertsons (see Fig. 1). At this time we do not have a quantitative model of the tail.

The CCD camera is not saturated in the tail, so its width represents the true horizontal width of the channeled beam. We were able to measure both the horizontal and vertical widths of the beam by using CCD camera images taken low in the shoulders of the curve of Fig. 4, where the CCD camera was not saturated. We found σ_x = 1.3 mm and σ_y = 0.5 mm, to be compared with values of 1.5 and 0.35 mm, respectively, expected from beam optics. The agreement is quite good, considering the coarseness of the projections of the CCD camera image on the two axes.

6. Multi-pass extraction

It was mentioned above that contributions to extraction would be observed on turns following turn 2, resulting from multiple scattering of beam not channeled in turn 2. Fig. 6 shows what we actually observed on later turns following one particular kick. There are ~10% fluctuations from kick to kick. In Fig. 6 we also compare the observations with an elementary Monte Carlo simulation.

Our elementary Monte Carlo simulation [3] takes into account the following effects. An ensemble of particles with Gaussian distributions of positions and angles consistent with the measured rms’s is generated and given a kick. On the second turn, protons in the outer 0.5 mm encounter the crystal. Those protons within the critical angle are counted as channeled. The protons outside the critical angle are given a multiple scattering angle change in accordance with a Gaussian distribution with a width of the rms multiple scattering angle for a particle remaining inside the crystal for the full crystal length (11 μrad). This scattering can be seen in the upper right hand box of Fig. 7. These multiple scattered protons are assumed to remain within the aperture of the Tevatron, for the rms scattering angle is within the acceptance of the Tevatron. They are propagated through another turn using the linear transfer functions for the Tevatron and tested again for acceptance within the critical angle. The process is repeated for particles not within the critical angle. Any proton incident on the crystal is given a 9% chance on each turn to have an inelastic nuclear interaction in the crystal and is considered lost on some aperture.

The qualitative agreement between the observations and the simulation on the first 7 turns is thus understood. The minor peaks at turn 4 and 5 are the result of the tail of the protons multiple scattered on turn 2 arriving at the crystal with an angle within the critical angle, even though the unscattered beam is not close to the crystal. On turn 7, the beam again comes very close to the crystal (see Fig. 3) so that all of the protons multiple scattered on turn 2 encounter the crystal again, leading to a large amount of extraction.

There is qualitative, but not quantitative, agreement between the predictions and observations in Fig. 6, in two senses. First, most of the turns predicted to have only a small extraction rate (11,16,22,23) are observed to have a factor two or more of the predicted rate. Second, at ~20 turns the simulation indicates that the maximum extraction rate should be ~50% of that of turn 2, while the data shows extraction on turns with large extraction rates still equal to that on turn 2. The difference is even more pronounced after ~80 turns (not shown), when the observed extraction rate is still ~50% of turn 2, but the simulation rate is ~2%. These disagreements are not surprising, given the simplistic nature of the simulation.

It is possible that the continuing large extraction rate after 20 turns is a result of non-linearities (not included in the simulation) and fluctuations in the orbit at the micron level. Fermilab has not investigated fluctuations at that level. Other effects not included in the simulation are dechanneling effects, the possibility that a particle incident on the crystal leaves the crystal through the face which faces the beam, and the vertical-horizonal coupling.

7. Long-term effects

The CCD camera was videotaped continuously during the study session. At the peak of the angular scan the bright flash on the screen (see Fig. 5) persisted for ~30 msec. Following that, there were occasional weak flashes on the screen occuring at random time intervals and at the same spatial position as the major portion of the extracted beam. These weak extractions occured as late as 20 secs after the beam had been kicked. The cause for beam to be moved onto the crystal so long after the kick is not understood.

Although we know how much beam was lost from the Tevatron following each kick (2.4×10^9 protons), we do not yet know what fraction of that number was channeled and extracted. Standard intensity monitors, such as toroids, do not work well in this range, and it has not yet been possible to calibrate either the counter pulse heights nor the CCD images. Further efforts to measure this number will be made in the fall of 1995.

8. Impact on collider experiments

At a very early stage of this experiment, we used RF noise to drive beam onto a straight crystal at 10 times the rate which we intended to use for extraction. The proton loss rate at one of the collider experiments (CDF) was observed to be slightly below the threshold which this experiment regards as unacceptable background [4]. This observation will be reconfirmed when we run in diffusion mode later in 1995 (see below).

9. Future goals

When we resume study sessions in the fall of 1995, we plan to measure the extraction efficiency in kick mode. We will align the surface of the crystal facing the beam to the horizontal angle of the beam by minimizing the intensity of the “comet tail” as the horizontal angle is varied.

The most important studies relevant to future applications are in diffusion mode, i.e., continuous extraction. First we will measure the extraction rate and extraction efficiency with whatever natural diffusion exists in a proton-only fill of the Tevatron, when there is no halo being generated by antiproton-proton collisions. The same measurements will be made during collisions.

However, the biggest challenge of this technique is that there is inadequate halo at the Tevatron, under either of the above operating conditions, to obtain extracted intensities high enough to be interesting for experiments. Therefore, halo must be generated by perturbations of either the transverse or longitudinal phase space, and in a manner which does not appreciably decrease the luminosity for the collider experiments.

Early simulation work on perturbations used RF amplitude noise generated in a band width below the synchrotron frequency [5-6]. The RF noise, which increases the momentum spread near the edge of the longitudinal phase space, converts to a spatial growth if the crystal is placed at a position of high dispersion. This technique has the attraction that it does not disturb the core of the phase space, thus having minimal impact on the luminosity for collisions. At the SSC, the preferred location for the crystal had a quite large dispersion. However, at the Tevatron, the only feasible location for the crystal has a dispersion which is too small for this technique to be effective. Therefore, we will perturb the transverse phase space with noise on a horizontal damper, as has been done at the CERN SPS [7]. This will pump beam into the halo, but it will be depleting the core as well as the edge of phase space.

In this configuration, we will measure the extraction efficiency and rate as a function of a number of variables: the noise amplitude, the horizontal angle of the crystal, the distance of the crystal from the beam, and maybe even the crystal length. We define the efficiency to be the ratio of the number of protons extracted into the abort line to the total number lost from the machine. At the CERN SPS, this efficiency has been measured to be ~10% at 120 GeV [7]. The most detailed simulation of the Tevatron experiment by Biryukov [8] predicts an efficiency of about 36%. This simulation also predicts that the efficiency could be improved to 70% if the crystal were shortened to 1 cm in length.

10. Future applications

While no applications of this technique of extraction are firmly planned, several are under discussion. It is hoped that beam might be extracted from the LHC, where the halo generated by the collisions will be large enough that creating additional halo will not be necessary. At Fermilab, there is a possibility of using the technique to produce a low-intensity test beam at 900 GeV. A suggestion has been made that if the technique could extract 10^7 protons/sec, which may be possible after the increased intensities resulting from the Main Injector, this would be an adequate beam for a charm experiment with ten times the statistics of the current world data[9].

Conclusions

Protons have been channeled and extracted from an accelerator at an energy of 900 GeV, the highest energy achieved with this technique. Plans are set to measure the extraction efficiency in diffusion mode, which may be as high as 37%, according to simulations.

Acknowledgements

We would like to acknowledge the support of the SSC Laboratory for the equipment for this experiment, and the generous support of the Fermilab Accelerator Division in operating the experiment and the installation work. This work was supported in part by the US Department of Energy under contracts DE-AC35-89-ER-40486 and DE-AC02-76CH0300.

References

[1] R. Carrigan et. al., Nucl. Instr. and Meth. B 90 (1994) 128.

[2] R. Carrigan, in Relativistic Channeling, R. Carrigan and J. Ellison, eds. (Plenum Press, New York, 1987) 347.

[3] S. A. Bogacz, D. B. Cline, and S. Ramachandran, Nucl. Instr. and Meth. B 111 (1996) 244.

[4] G. Jackson, "Results from Beam Diffusion and Collimation Measurements in Preparation for Fermilab Tevatron Crystal Extraction", Proc. 1993 Part. Acc. Conf., Washington D.C. (1993).

[5] B. S. Newberger, H.-J. Shih, and J. A. Ellison, Nucl. Instr. and Meth. A 235 (1993) 9. B. S. Newberger, H.-J. Shih, and J. A. Ellison, Phys. Rev. Lett. 71 (1993) 356.

[6] W. Gabella, J. Rosenzweig, R. Kick, and S. Peggs, Particle Accelerators 42 (1993) 235.

[7] H. Akbari et. al., Phys. Lett. B 313 (1993) 491.

[8] V. Biryukov, Phys. Rev. E 52 (1995) 6818.

[9] D. Christian, in Heavy Quark at Fixed Target, B. Cox, ed. (Frascati Physics Series, 1994) 421.

Figure captions

Fig. 1. Schematic of the beam line around the Tevatron C0 region. The crystal bends up out of the page into the field-free region of the Lambertson magnet chain (see inset).

Fig. 2. View of the circulating beam looking upstream at the bent crystal. The ellipse represents the halo of the beam schematically. The crystal is bent upwards 640 μrad and is on the outside of the ring. The parallel lines represent the crystal planes.

Fig. 3. Horizontal beam position and angle on successive turns after a kick. The size of these quantities depends on the magnitude of the kick. Most of the extraction occurs on turns when the beam is near the crystal face, as in turn 2 and 7. The units are arbitrary.

Fig. 4. Pulse height in an air gap 2 counter vs. vertical angle of the crystal with respect to an arbitrary angle. The dotted line shows the pedestal in the ADC unit for no kick.

Fig. 5. CCD camera of fluorescent screen in the first air gap. The width of the tail (see text) is 3 mm.

Fig. 6. Extraction rate as a function of the turn number from the computer simulation and from the pulse height in a scintillator following a particular kick, renormalized to the simulation result for turn 2. Pulse heights of less than 30 units are indistinguishable from the noise. There are 10% fluctuations in the relative pulse heights from kick to kick. Agreement between the observations and the simulation is good in the early turns, but extraction persists during later turns longer than the simulation predicts.

Fig. 7. Horizontal phase space distributions as a function of turn number after a kick The first pass through the crystal multiple scatters the protons which were not within the half-angle for channeling (see spread in upper right corner). These multiple-scattered protons come back in later turns with different angles, and some of them are extracted. The hole in the distribution results from suppressing the core of the beam, which will never intercept the crystal, from the tracking.

FERMILAB E853
CRYSTAL EXTRACTION
C0 LONG STRAIGHT SECTION

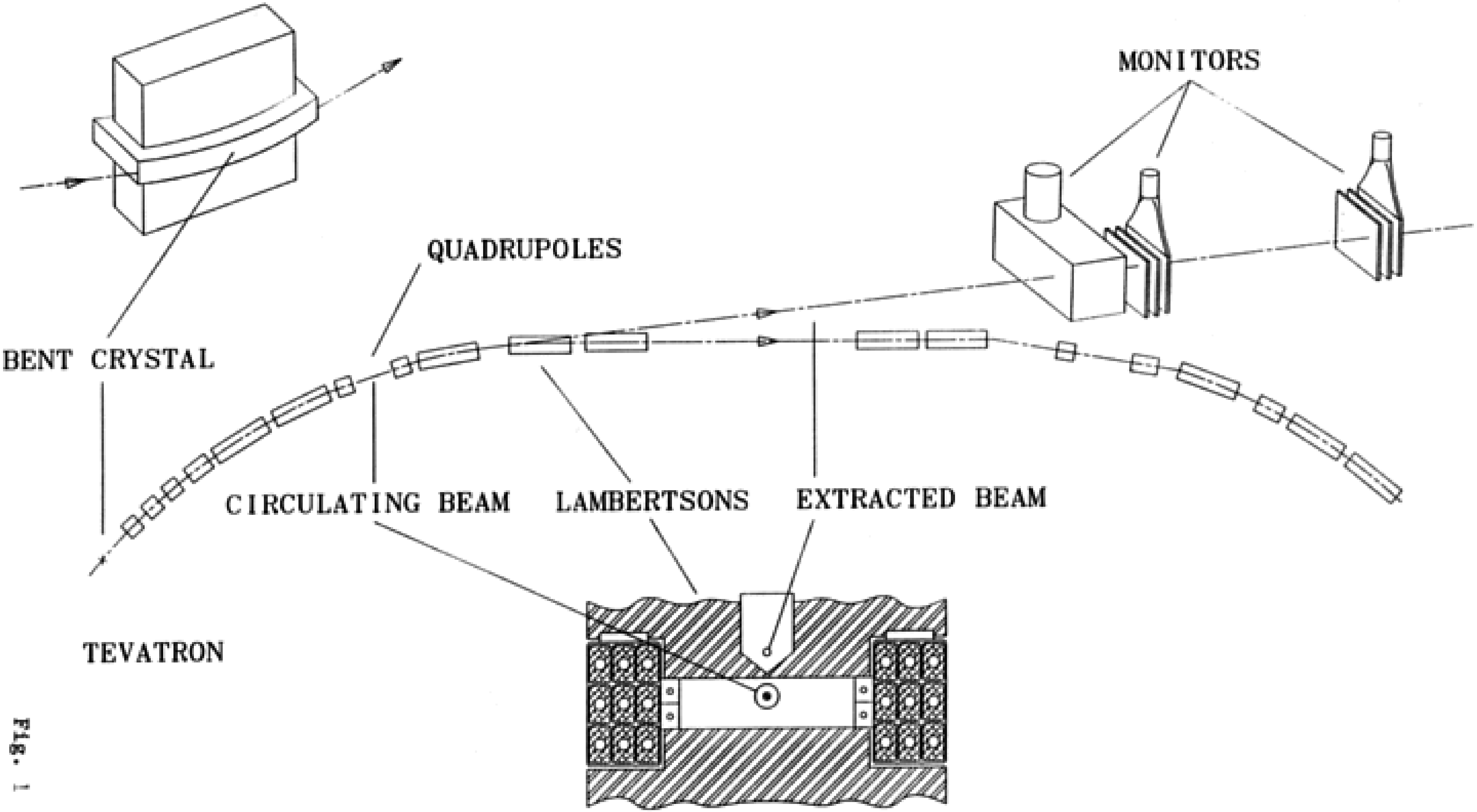
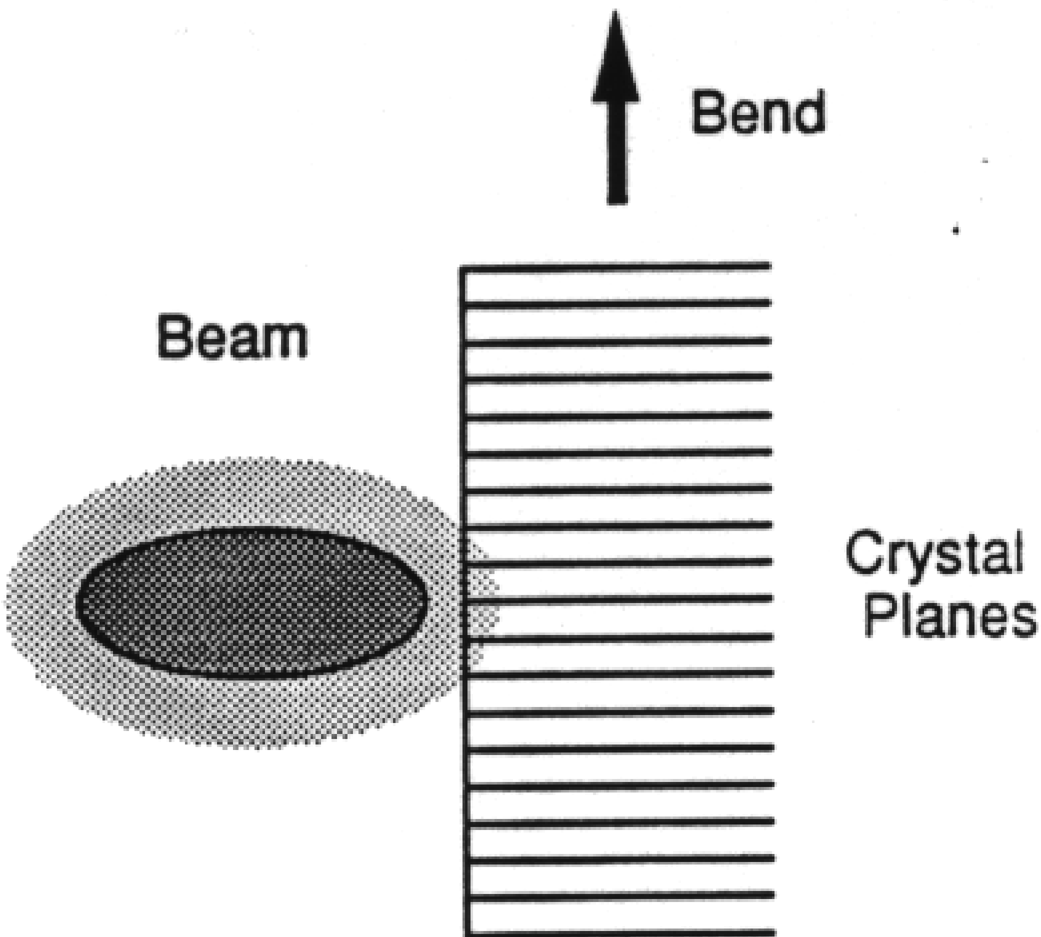
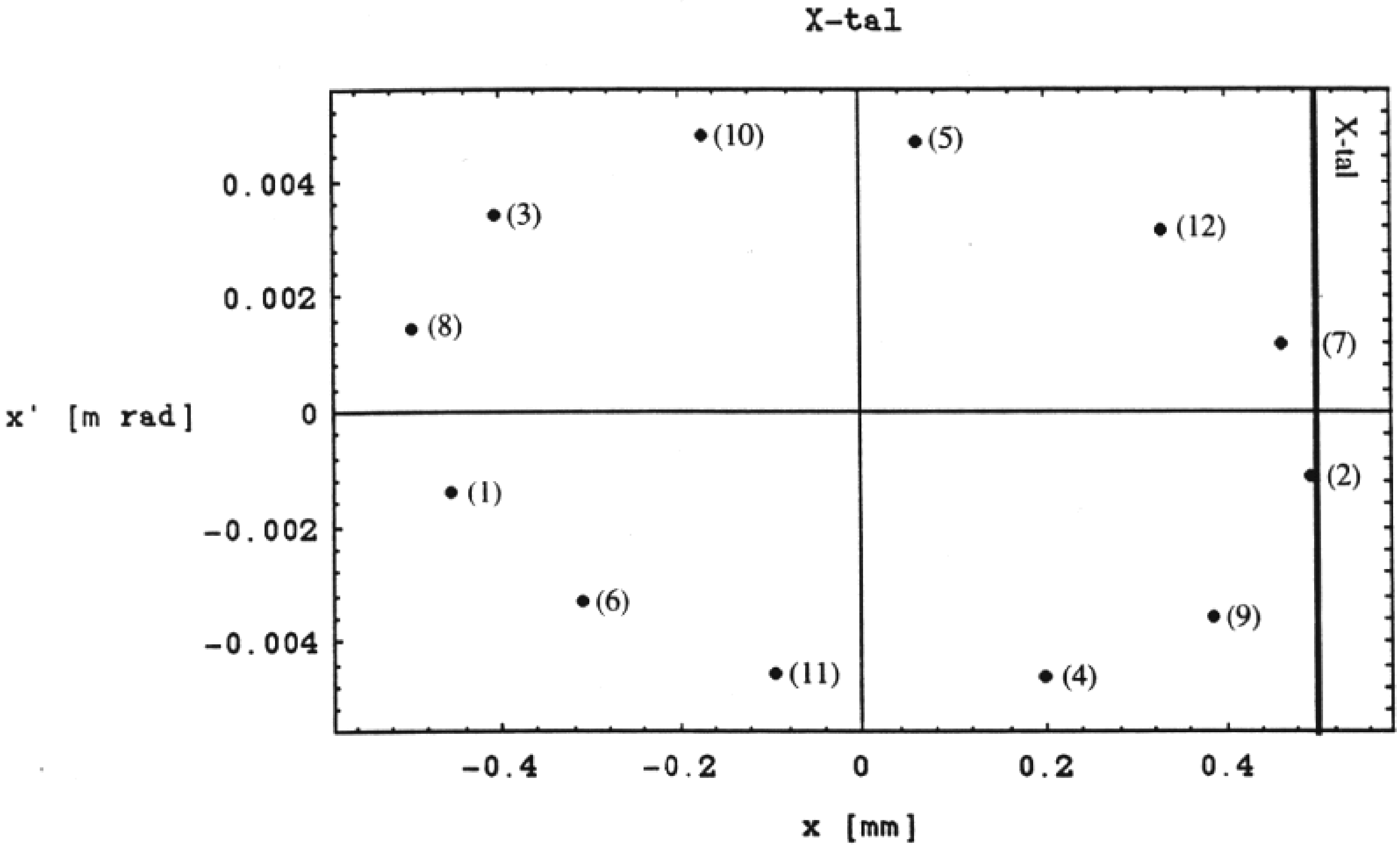
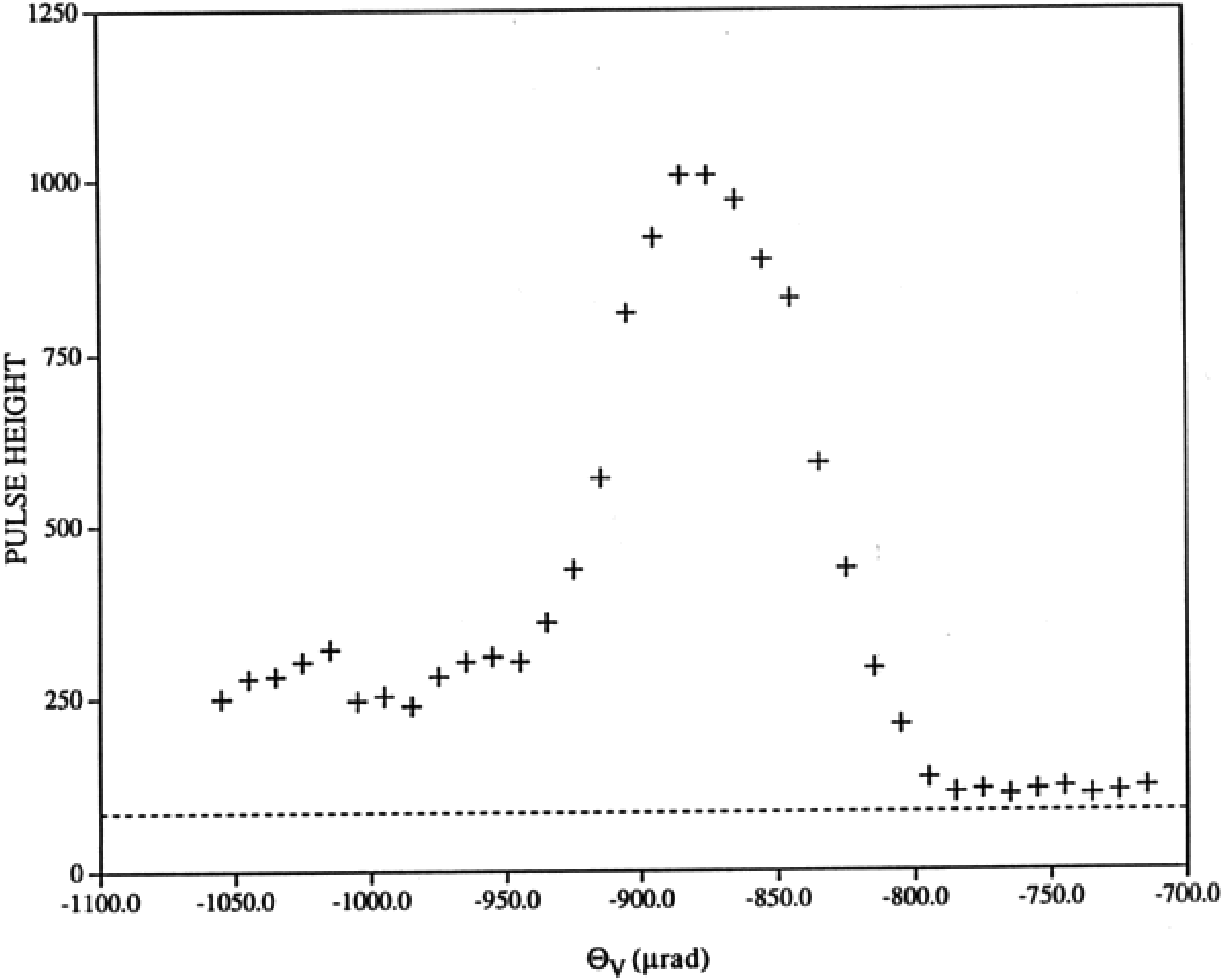


Fig. 1


Bend
Beam
Crystal
Planes


X-tal
X-tal
x' [m rad]
x [mm]
0.004
0.002
0
-0.002
-0.004
-0.4
-0.2
0
0.2
0.4
(1)
(2)
(3)
(4)
(5)
(6)
(7)
(8)
(9)
(10)
(11)
(12)



PULSE HEIGHT
1250
1000
750
500
250
0
-1100.0
-1050.0
-1000.0
-950.0
-900.0
-850.0
-800.0
-750.0
-700.0
Θ_V (μrad)

Fig. 4

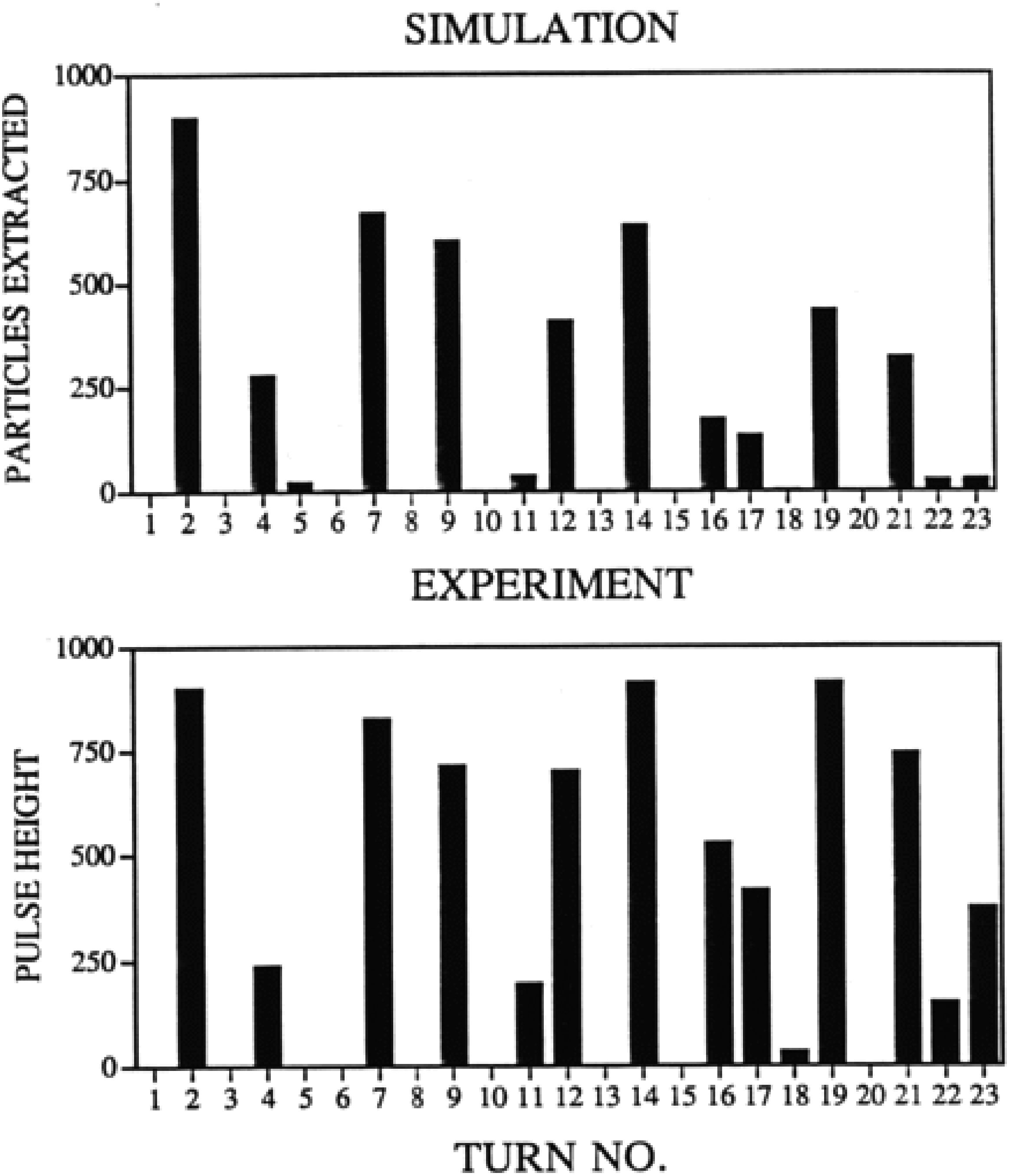

SIMULATION
PARTICLES EXTRACTED
1000
750
500
250
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
EXPERIMENT
PULSE HEIGHT
1000
750
500
250
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
TURN NO.

Fig. 6

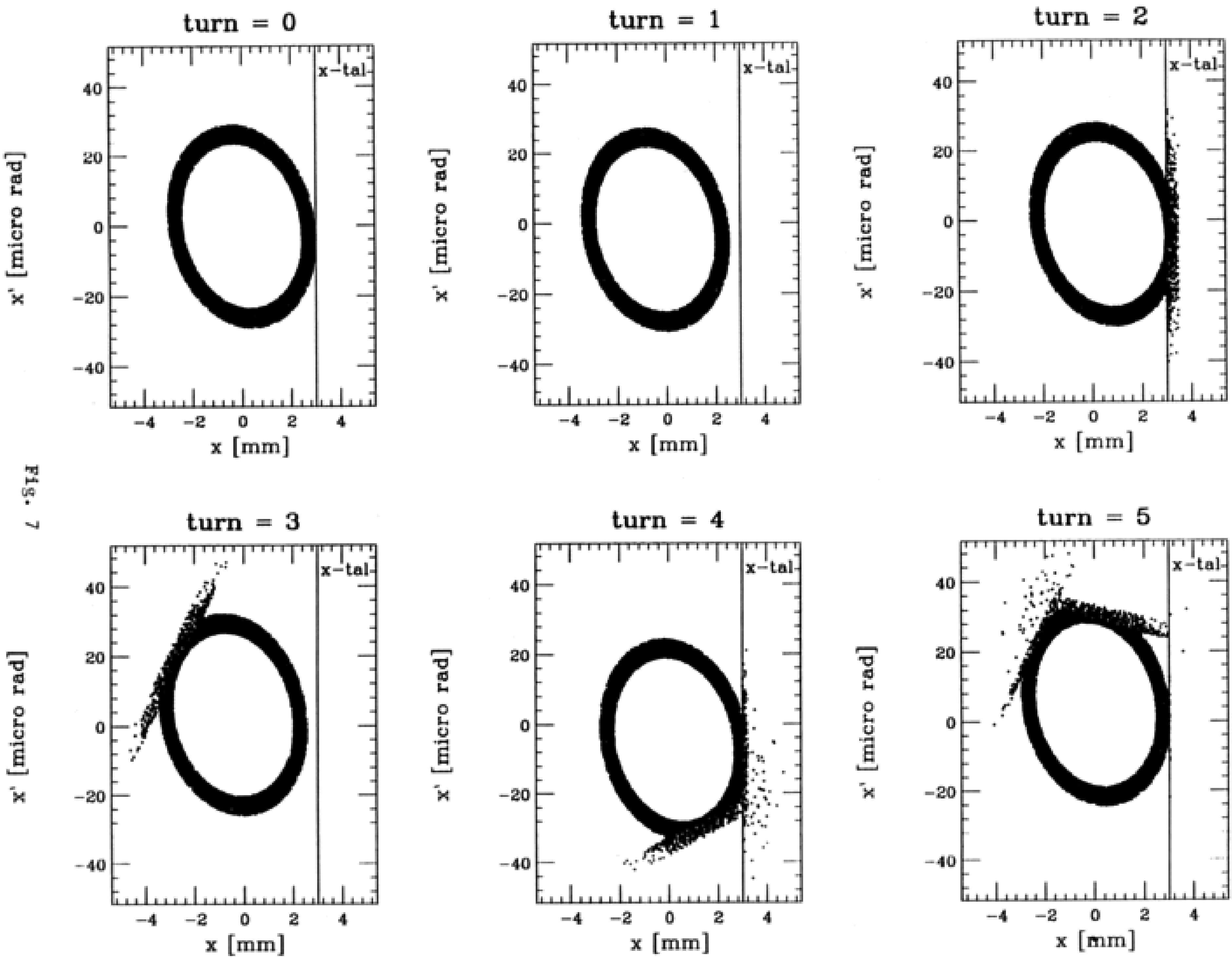

turn = 0
turn = 1
turn = 2
turn = 3
turn = 4
turn = 5
x' [micro rad]
x [mm]
x-tal
40
20
0
-20
-40
-4
-2
0
2
4

Fig. 7