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Bent Single Crystals as Beam Elements

A properly aligned, bent single crystal is capable of deflecting a high energy beam of positively charged particles through a relatively large angle. In this process channeled particles traveling near a plane or axial channeling direction follow the gradually bending crystal. Such a crystal was tested in 1984 at Fermilab as a replacement element for an 8.9 mrad bend consisting of two magnets with a total length of 6m [1]. The crystal, with an active bending length of 19mm and a maximum radius of curvature of 161cm, was able to deflect 400 GeV primary protons. At Dubna, a bent crystal has been recently used to extract beam from the JINR Synchrophasotron [2].

Crystal septa have several limitations in acceptance. Only particles within the critical angle for channeling are accepted. The planer critical angle, ψ_p, is five microradians at 800 GeV for the (110) plane in silicon and is inversely proportional to the square root of the momentum at relativistic energies. Particle beams, on the other hand, tend to have angular divergences on the order of 200 microradians. Thus the angular acceptance in the direction of bend is typically 0.025. Likewise, the spatial acceptance in the direction of the bend is limited by the thickness of the crystal which is in turn set by the requirement that the crystal bend without breaking. Crystals up to 1mm thick have been used. This should be contrasted to beam spots which range from 3 to 10mm. Perpendicular to the bend the acceptance is good since the crystal can be quite wide and a substantial fraction of the particles captured in a plane will be bent. Microscopically the crystal does not accept all particles so that only about 0.5-0.65 of the particles incident within the critical angle are captured initially [3,4]. Finally, particles are dechanneled due to bending dechanneling as they enter the bent channels and by quasi-normal dechanneling after they are in the bend [5,6]. Taken together, these four factors lead to a beam attenuation of 10^3 to 10^4. (It should be noted that the portion of the beam that is not captured into channeling trajectories continues straight ahead.)

This small acceptance would appear to be a significant limitation on the application of crystals as deflecting elements or septa. Indeed this is the case. Surprisingly, there are a number of applications where this limitation turns out to be a benefit and the crystal can be used as a beam attenuator. In essence the crystal serves as a precision beam collimator producing a narrow beam with a very small angular distribution.

It is interesting to ask why there are situations where beam intensity needs to be reduced substantially. At the Fermilab Tevatron many experiments using charged particle beams now want to use the full primary proton beam energy. Lower energy secondary beams have been exploited quite well at both Fermilab and CERN. At the same time there is now considerable work on short-lived particle physics with an emphasis on slow vertex detectors such as emulsions and bubble chambers which require low intensity beams.

Alternate ways of reducing beam intensity such as pinhole collimators typically only reduce the beam by factors of 10 to 100. Such collimators are heavy and thus hard to control. Finally they tend to be a source of secondaries and result in beam halos. Alternatively some source of multiple scattering can be placed in a beam, but this degrades the beam angular dispersion and may also introduce unwanted beam contamination such as pions and kaons.

This article reports the successful application of a crystal as a beam septum and attenuator in the NE beam at Fermilab. The septum operated at 800 GeV, the highest energy at which channeling has been observed. In addition, an unsuccessful attempt to use a crystal in the MT beam at Fermilab is discussed.

In NE the crystal replaced a pair of dipoles downstream of E711, a high intensity (10^8 - 10^9 particles/spill) counter experiment, and upstream of a low intensity (10^4 - 10^5 particles/spill) emulsion spectrometer experiment, E653. By using the attenuation properties of the crystal it was possible to carry out certain activities in E653 while the high intensity experiment was in operation. In addition to replacing the bending magnets the crystal had to compensate a bend introduced by the E711 magnetic spectrometer. Figure 1 shows a distorted scale layout of the NE experimental area where the crystal was used.

In MT the crystal replaced a 1 mrad bend and was supposed to serve as a second beam attenuator after a pinhole collimator. The net beam reduction desired was 10^6 so that the Little European Bubble Chamber (LEBC) could operate in the beam.

Channeling Considerations

Prior to this work no channeling had been carried out above 400 GeV. Indeed the 400 GeV work had also been an application of a crystal as a beam element. The highest energy observations under controlled conditions have been at 250 GeV. The 800 GeV work required an extrapolation from detailed data of more than a factor of three. In such an extrapolation a number of points must be considered:

1) Mosaic structure. Mosaic structure in single crystals leads to misalignments between individual platelets. For some types of crystals this structure could far exceed the channeling critical angle at 800 GeV. So far, the high quality silicon crystals used for this work have never shown any effects that could be attributed to mosaic structure.

2) Crystal preparation. Crystals for bending must be prealigned so that a major crystal plane is parallel to the slab. For a crystal 1mm

thick and 50mm long a misalignment of 20 mrad would result in some particles leaving through the side of the crystal and thereby lead to only partial bending. A solid state detector is fabricated directly on the crystal to facilitate crystal plane alignment in the particle beam. Preparation of such crystals is exceedingly challenging.

3) Bending dechanneling. Dechanneling due to matching into the bent portion of the crystal must be minimized. Theoretical work by Ellison [7] and Kudo [8] agrees with the experimental work in the GeV energy regime [1,3,4]. Such dechanneling can be minimized by keeping the crystal radius of curvature large, that is by having an extended region of bend and therefore a longer crystal.

4) Normal dechanneling. Dechanneling due to scattering from electrons also occurs. This can be minimized by employing a shorter crystal. The dechanneling length should increase linearly with energy and be more than 45 centimeters at 800 GeV. For bent crystals, however, the potential well the particles are traveling in becomes shallower, narrower, and more densely populated with electrons. There is some experimental evidence that the ordinary dechanneling length for bent crystals can be shorter than for a straight crystal. This factor mandates against using a very long crystal.

For the NE application these factors give rise to the following performance expectations at 800 GeV:

1) Angular acceptance: In the direction of bend this should be about the size of the critical angle or 5 microradians for the (110) plane in silicon for a 50% acceptance contour. This results in a crystal phase space acceptance at the half height contour of

$$\phi^{x}_{crystal} = 2\sqrt{\frac{\ln 2}{\pi}}\ \psi_c\ t = 5.6 \text{ microradian-mm}$$

where ψ_c is the critical angle and t is the crystal thickness. The angular acceptance perpendicular to the bend is much larger than the beam angular divergence so that all angular directions in the beam are accepted.

2) Bending dechanneling: For a radius of curvature of 880cm Ellison [5] predicts the fraction of particles accepted into the bend to be $f_b > 0.6$.

3) Normal dechanneling: For the 45mm crystal and a 450mm dechanneling length at 800 GeV, 90% of the incident beam inside the critical angle should remain channeled. This dechanneling length is extrapolated from data presented in Wijayawardana's thesis [4] extending to 200 GeV.

4) Surface acceptance: All the particles within the critical angle are not accepted into channeling trajectories. Particles near the nuclear centers will be multiply scattered out by the high charge density. Studies [3,4] show that the fraction accepted, f_s, is approximately 0.5 to 0.65.

The last three factors give a transmission for particles inside the channeling critical angle of 0.27.

The phase space of the NE beam can be estimated by using two segmented wire ionization chambers in the beam, one located at the E711 target and the second 30m downstream. Based on the measurements, the beam width is t_B = 1.9mm FWHM at the E711 target and the angular divergence is θ_B = 311 microradians FWHM. The beam phase space is $\phi_{beam} = \pi/4\ t_b\theta_b$ = 464 microrad·mm. The solid ellipses in

Figure 2 illustrate this phase space at the E711 target and at the crystal. The corresponding crystal acceptance is also shown.

The overall beam transmission is then predicted to be

$$f_T = \frac{\phi \text{ crystal}}{\phi \text{ beam}} \times f_b \times f_d \times f_a$$

$$= 3.2 \times 10^{-3}$$

The observed beam transmission based on counter and ion chamber readings is $f_T^o = 0.54 \times 10^{-3}$. The lower yield could have been due to a number of factors including non-optimum positioning horizontally and vertically in the incident beam, possibly underestimating the dechanneling effects, and the possible loss of some particles out the side of the crystal.

Practical Experience

In the course of trying these two applications, a number of design factors were addressed.

Beam design: In the NE beam the crystal replaced a normal 3.14 mrad east bend. This bend consisted of two 20-ft bending magnets operating at 6.9 kg. For safety purposes these magnets were interlocked during the high intensity upstream operation so they could bend no more than 1.25 mrad east. An additional west bend was introduced into the beam by the analysis magnets of the upstream experiment. These magnets had a magnetic field-path length of 39.6 KG•m giving rise to a west bend of 1.5 milliradians at 800 GeV and a net deflection at the crystal of 26mm. The net deflection required to compensate the additional west bend, the horizontal deflection at the crystal, and the original bend was 4.9 mrad.

In fact the total net bend required was not clearly established when the crystal bend was originally set in a test beam. For example, it was not clear just how the upstream analysis magnets would operate. The crystal angle was set to 3.67±0.17 milliradians and the original bend was used to supply the remaining deflection.

As shown in Figure 1 there are several quadrupoles between the crystal and the downstream experiment. Under normal circumstances these acted to focus the beam on the E653 target. A quadrupole can steer a beam if the beam is off center in the quadrupole resulting in a net angular deflection. No special effort was made to develop a quadrupole tune for the crystal, although this might have been used to good effect. This could have been done, for example, by imaging the crystal on the E653 target. Wijayawardana has considered such tunes in his thesis [4].

The beam in MT was even more straightforward. The crystal replaced a 0.88 mrad west bend centered 12m after the pinhole collimator. There were no quadrupoles in the beam before the first beam detectors.

Tuning: Since it is necessary to align the crystal plane with the beam direction there must be a detector downstream that is sensitive to the deflected beam but not saturated by the undeflected beam. A counter telescope is useful provided it does not see the direct beam, the non-beam background is low, and there is a large enough angular acceptance to permit some mis-steering. Segmented wire ionization chambers (SWICs) are helpful in visualizing the actual bend, provided they are sensitive enough. However, a SWIC is not a convenient count monitor for a short time segment of a spill. This is a necessary requirement to move the crystal goniometer several times in the 23 second Tevatron spill during the alignment process.

The beam monitor for the NE alignment consisted of portions of the E653 beam counter telescope 90m downstream of the crystal. The effective diameter of the telescope was 7cm so that the angular acceptance was 0.79 milliradians (total). There was also a very sensitive segmented wire ionization chamber located near the E653 target. The chamber had a 1mm wire spacing and was 48 wires wide, giving rise to an effective aperture of 0.54 milliradians. This was particularly useful in establishing the actual bend. Figure 3 shows the beam profile as it appeared on the SWIC when the crystal plane was centered on the beam for the first time. At the same time the plane was detected by the counters, it was immediately visible in the SWIC. Several points are worth noting. The actual deflection due to the beam system, including the bend by the crystal, was such that the spot was 16mm to the east, indicating an excess deflection of 0.18 milliradians. This excess could have come from a number of causes such as quadrupole steering. An important point is that the beam was near the edge of the SWIC and the counter hodoscope so there was little margin of safety. A slightly larger misalignment of this sort could have given rise to the inability to get a crystal to work in MT.

With the SWIC it was possible to easily center the beam at the E653 target using the original bending magnet pair as a trim element. Figure 4 shows the beam after it was centered and optimized. Most of the background probably arose from the fact that no special provision was made to dump the beam beyond the existing dump about 20m downstream of the crystal. Although the crystal deflection is large the E653 target is still only 0.4m perpendicular to the undeflected beam. Some sort of thick reentrant beam dump would probably be desirable. Parenthetically, it was found that most of the background was not due to muons.

Several sets of beam counters were used in the MT tests. All of them followed a long superconducting bend that removed direct beam. The closest monitor to the crystal was a single counter 60m downstream which had a large background, possibly due to secondaries produced in the pinhole collimator upstream of the crystal and the lack of a coincidence. There was a coincidence monitor telescope 190m downstream whose angular acceptance was 0.1 milliradians. This turned out to be a challengingly tight tolerance. A second problem was positioning the 1mm crystal on a line 12m downstream of the pinhole. Such positioning is done regularly by good surveyors but it was not easy to verify this independently. An attempt was made to scan the pinhole collimator across the crystal detector, but it met with only limited success since the crystal detector saturated in the intense beam and indicated a width roughly three times the pinhole width.

When no septum beam was observed after considerable scanning, the crystal was taken back to the test beam and the bending angle was checked. It was found to be 0.75-0.85 milliradians rather than the originally measured 0.95-1.0 milliradians which was enough to have misdirected the beam on its way to the second monitor telescope.

A second attempt was made to align the beam in MT. This time the crystal was centered along a remotely controlled "gunsight" consisting of two scintillators with holes for the beam to pass through on either side of the crystal. It was hoped that the beam would go through the holes and not count when the scintillators (and the crystal) were properly aligned with the beam. In the test beam this worked as planned so that when the system was dismounted and then repositioned the crystal angle returned to within 150 microradians. Unfortunately, the ambient background in MT was so high that it was impossible to identify the beam. The system was abandoned after a short test due to running time pressures. An alternate method of reducing the beam intensity using approximately 1m of beryllium was successful.

Orientation of the crystal plane in the beam: For the two septa discussed here and the original M-bottom septum [4] the crystal was first installed in a test beam where it was prealigned and the bend angle set. The test beam permitted relatively relaxed operation at intensities below 10^5/sec and the ability to make accesses to manually adjust the bend angle. The low intensity permitted counting of individual particles and accurate measurement of angles and positioning using drift chambers.

The crystal septa used so far have characteristically had three or four degrees of freedom. The crystal is bent using a four pin bending jig in which two inner pins are coupled to a differential screw and press against the crystal with displacements much less than a tenth of a millimeter. The jig hangs on the crystal but must rest on the goniometer holder that supports the upstream end of the crystal. On the NE goniometer this made it difficult to cancel the torque that resulted from turning the screw. The NE crystal and jig is shown in Fig. 5.

The remotely controlled and automated goniometer varies the angle of the crystal relative to the beam. These goniometers are controlled through the normal Fermilab EPICS beamline control system and control system software. The Ardel goniometers and controllers that have been used have a minimum step of five microradians and have proven to be quite reproducible and relatively free of hysteresis. Typically, a crystal plane can be positioned within 100 microradians of the last setting. Remotely controlled x and y motions have also been provided to position the crystals in the beam.

The amplified signal from the semiconductor detector on the crystal provides a convenient method of aligning the crystal at low beam intensities since channeled particles have a substantially lower energy loss than randomly directed particles. This can be seen in Fig. 6 which shows a typical energy loss distribution for a detector in the test beam when the plane is aligned. The crystal detector can also be used to position the crystal within the beam provided the rates are not too high. Figure 7 shows how this technique was used to position the crystal in the NE beam and measure the beam width.

Semiconductor detectors suffer from radiation damage and the resolution may deteriorate after fluences of 10^{11}-10^{13} particles per cm^2 [9]. No controlled information has been gathered for these crystals but there has been evidence of deterioration. This can be monitored by observing the width of a low-level alpha source mounted near the detector and also by observing the low energy side of the Landau peak. The crystal used in NE had a noisy detector which made it difficult to align in the test beam.

No evidence has been found of deterioration of the crystal lattice. Earlier tests of fluences of up to 10^{17} particles/cm^2 have shown no degradation of beam transmission [10]. Although solid state considerations suggest some problems may occur at fluences not much greater than 10^{17} particles/cm^2, annealing should remove these defects [11].

Ideally with prealignment it should be possible to place the crystal in the beam so that the planes are aligned with the beam. However, there is a limit to the ability to survey the crystal into its new location and there can be problems in knowing what the true beam direction is.

Some feeling for the survey problem can be gained from considering a typical goniometer mount which is about 15cm long. The mount can be oriented parallel to the beam to within 0.1-0.2mm, corresponding to an angular precision of approximately a milliradian. A supplementary technique that has been used is to position a laser with an autocollimator perpendicular to the beam and reflect the laser from a mirror on the goniometer. In the cramped environs of a tunnel this gives about the same precision.

Since it is not possible to position the crystal exactly in the beam, it is necessary to plan on scanning the goniometer over a region of five to ten milliradians in steps less than one third the beam divergence over the face of the crystal. As can be seen from Fig. 2, the beam angular divergence over the crystal may be much smaller than the overall beam angular divergence. A five milliradian scan requires 200 steps of 25 microradians each. At four steps per spill this would take an hour on the Fermilab Tevatron.

In the initial scan in NE the plane was found after 40 minutes of scanning and 130 steps. The scan was started well to one side of the beam in order to scan only in one direction. The actual location was 0.26 milliradians west of the survey position when the E711 west bend was taken into account. (For the original MB septum the plane was within 0.5 milliradians of its expected location [4].) Figure 8 shows a scan over the plane in NE with small steps. The peak to background is much better than the original scan, possibly due to the coarse interval of the first scan never giving a location fully centered on the beam.

Use Of A Bent Crystal As A Phase Space Monitor

A novel application of channeling was identified in the course of these studies. This was the possibility of using the crystal as a probe of the beam phase space. Since the critical angle for channeling is much smaller than the beam angular divergence the crystal provides a delicate angular probe.

The angular divergence over the NE crystal is about 50 microradians FWHM. The full beam angular divergence was 300 microradians FWHM as can be seen in Figure 2. The crystal provides direct information on the tilting and distortion of the phase space ellipse. Figure 2 shows several scans at different positions on the beam spot (the vertical lines) corresponding to different magnet currents on the magnet pair the crystal replaced. There is some evidence that the beam moved across the crystal and the angular position moved accordingly. Thus the crystal provides an interesting probe of the details of beam phase space, something that is difficult to obtain in other ways.

Summary and Future Possibilities

This article summarizes two attempts to install crystal septa in 800 GeV proton beams for use as beam attenuators. One was successful with the crystal operating according to expectations and with little complication. Eight hundred GeV is the highest energy at which channeling has been observed. The beam was used later for silicon wafer tests in conjunction with the E653 experiment [12]. The other attempt failed, in part because it was difficult to determine the crystal position in the beam and possibly because the beam and beam tuning elements did not provide sufficient latitude for angular deflection misalignments. Both cases demonstrate that reasonably accommodating monitor instrumentation is needed.

With this caveat there appear to be no overwhelming problems in applying crystals as beam elements in applications where beam attenuations of a thousand to ten thousand can be tolerated or are desired. In addition a bent crystal may be an interesting diagnostic tool for the detailed analysis of beam phase space.

Some possibilities for future applications of crystals have been considered. At Fermilab there has been some consideration of the possibility of using a crystal as a temporary upstream element in the polarized proton beam that is under construction. The current design concept employs a more conventional magnetic Lambertson septum operating as a switch. Crystals have also been discussed as potential extraction elements for future high energy hadron machines intended primarily as colliders [13], such as the SSC and the LHC for CERN. Based upon the above results there is good reason to take this possibility quite seriously.

The authors would like to acknowledge the help of H. White and G. Koizumi in some of the planning leading up to these tests. W. Gibson, I.-J. Kim, C. R. Sun - SUNY-Albany, I. Mitchell - Chalk River, and J. R. Ellison - New Mexico have all contributed many ideas and much information on the possibilities of crystals as beam elements. The original idea of a crystal septum was developed by E. Tsyganov of Dubna while visiting Fermilab [14]. H. Haggerty first suggested the use of a crystal in MT. The NE crystal was fabricated at Chalk River while the MT crystal was kindly supplied by a Dubna/Leningrad team.

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Figure 1 - Plan view of the NE beam. Note that the scale is distorted. E711, the high intensity experiment is upstream of the crystal, E653, the low intensity experiment, is downstream. The crystal 30m downstream of the E711 target replaced forty feet of bending magnet. Note the beam dump 20m downstream of the crystal.

Figure 2 - Phase space ellipse in the NE beam. Half maximum curves are shown. The first panel shows the ellipse near the E711 target, the second at the crystal 30m downstream. The width at the E711 experiment was measured using a SWIC profile monitor. The width at the crystal was measured using the crystal. The overall angular divergence was inferred from the combination. The vertical lines in the second panel show crystal angular scans. The crystal angular acceptance is shown in the second panel.

Figure 3 - Beam profile at E653 when the crystal was first aligned. The lower trace is the horizontal profile. Each bin is 1mm wide. The beam center is 16mm east of the nominal beam line center.

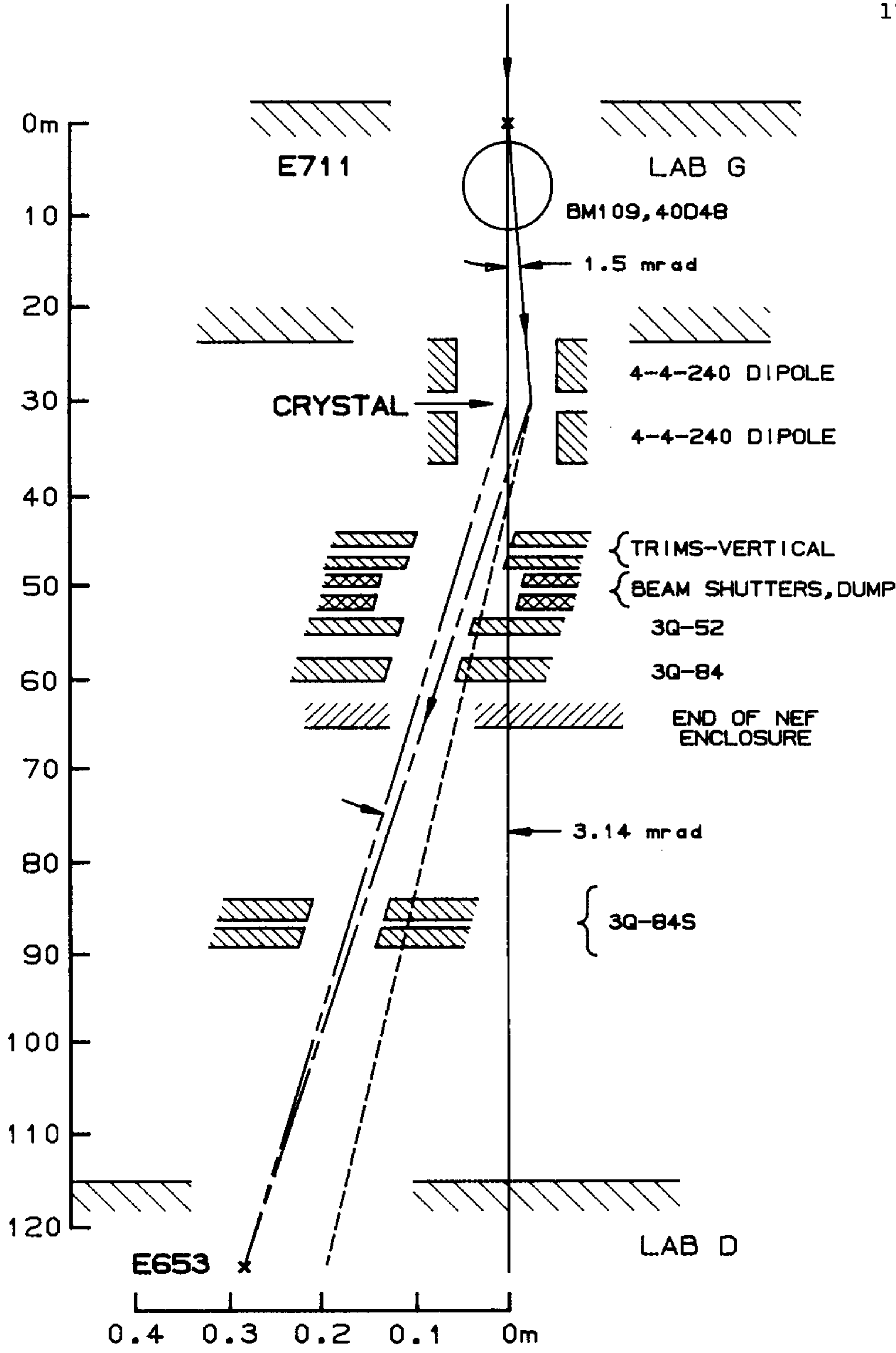
Figure 4 - Beam profile at E653 with the beam line trimmed to bring the spot closer to the nominal center. Note that the beam is less than 2mm wide horizontally.

Figure 5 - NE crystal installed in the bending jig.

Figure 6 - Typical energy loss spectrum near a silicon (110) plane. The dotted line is the energy for particles within the critical angle while the solid line shows the energy loss over the entire angular divergence of the beam. The vertical scale is arbitrary.

Figure 7 - NE horizontal beam distribution measured with the crystal semiconductor detector by moving the crystal across the beam. The full width at half maximum of the beam was 9mm. The different symbols are scans taken at different times.

Figure 8 - Goniometer scan over the plane in the NE beam. One goniometer step is 5 microradians. The width is 46 microradians FWHM.



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30
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E711
LAB G
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4-4-240 DIPOLE
CRYSTAL
4-4-240 DIPOLE
TRIMS-VERTICAL
BEAM SHUTTERS,DUMP
3Q-52
3Q-84
END OF NEF
ENCLOSURE
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3Q-84S
LAB D
E653
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0.3
0.2
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Figure 1

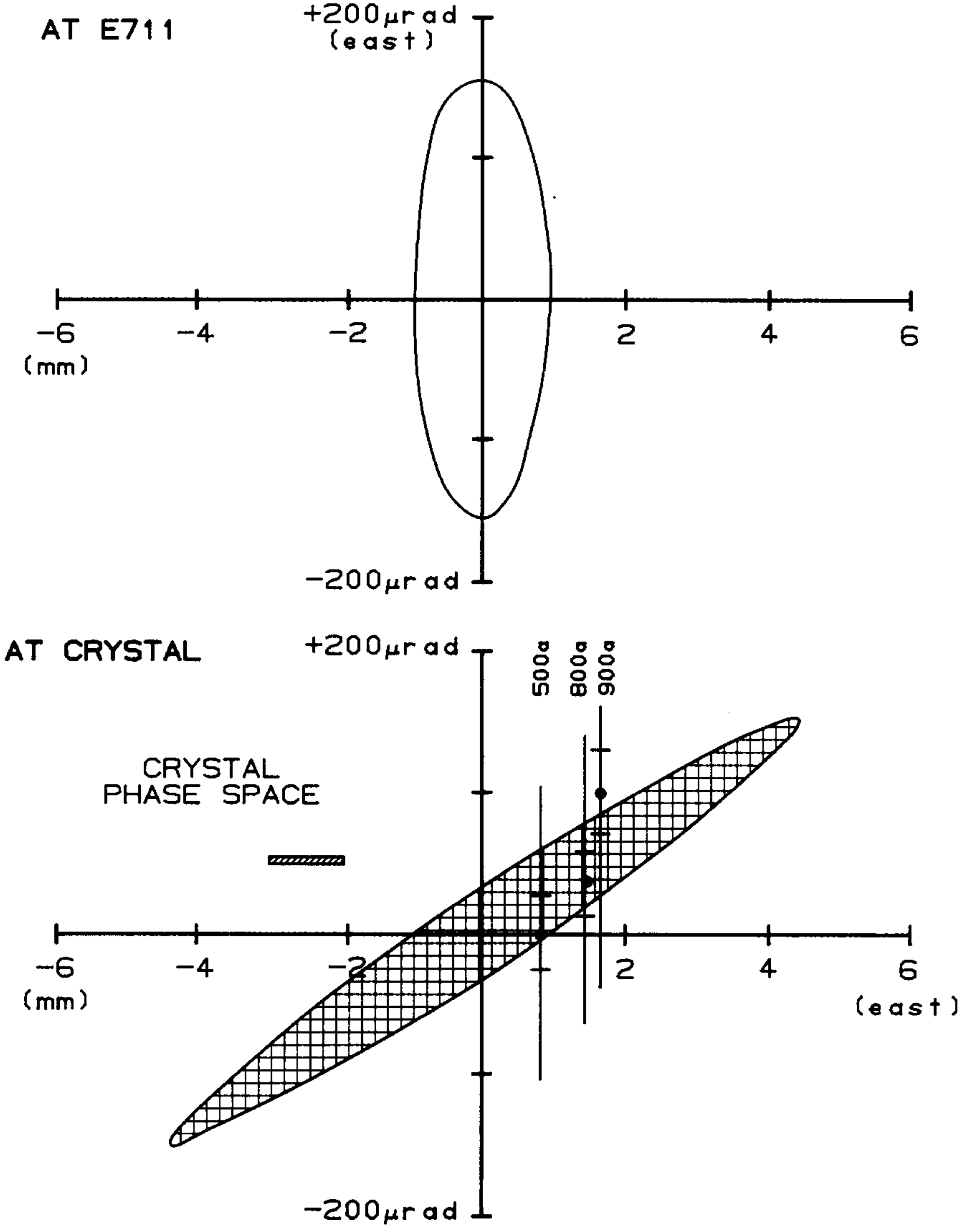
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Figure 2

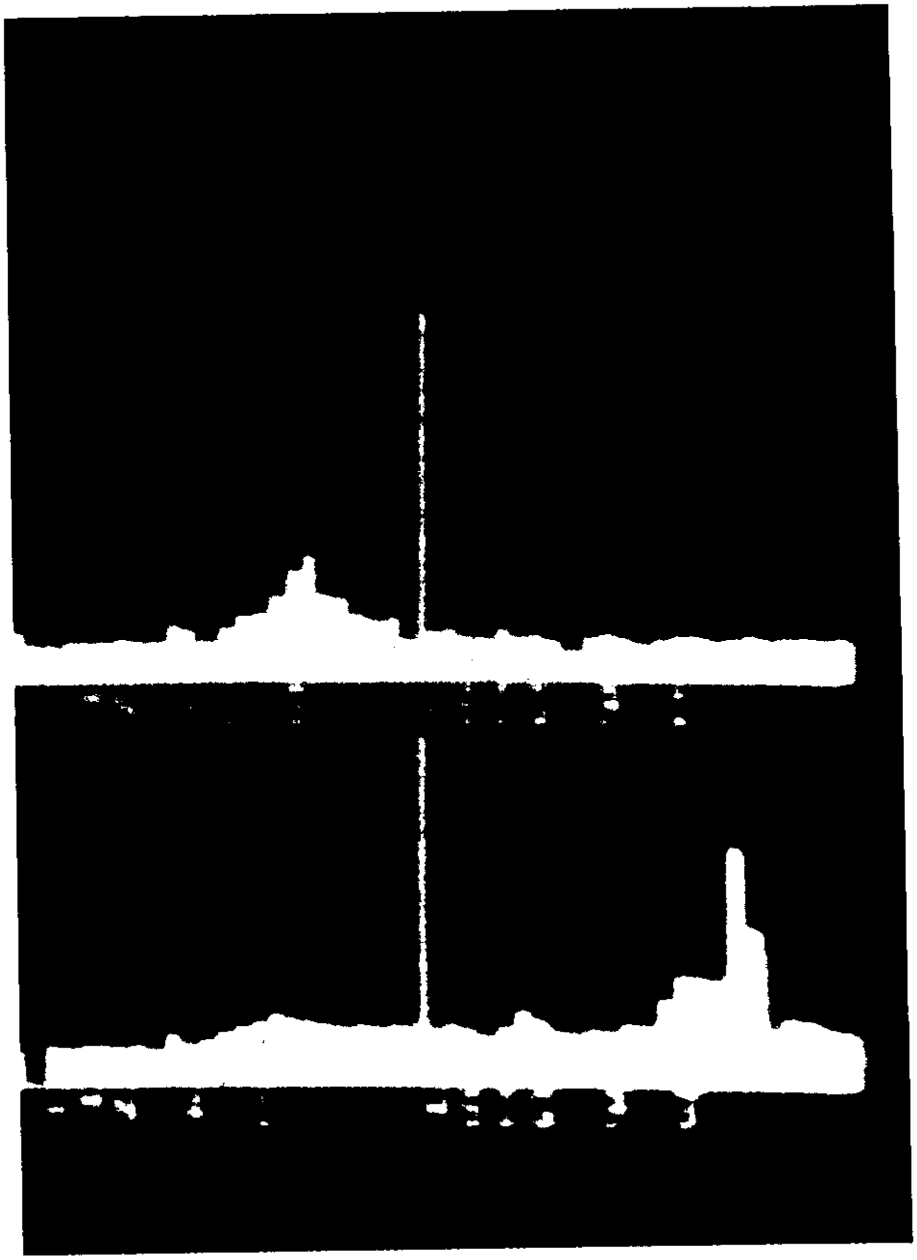


Figure 3

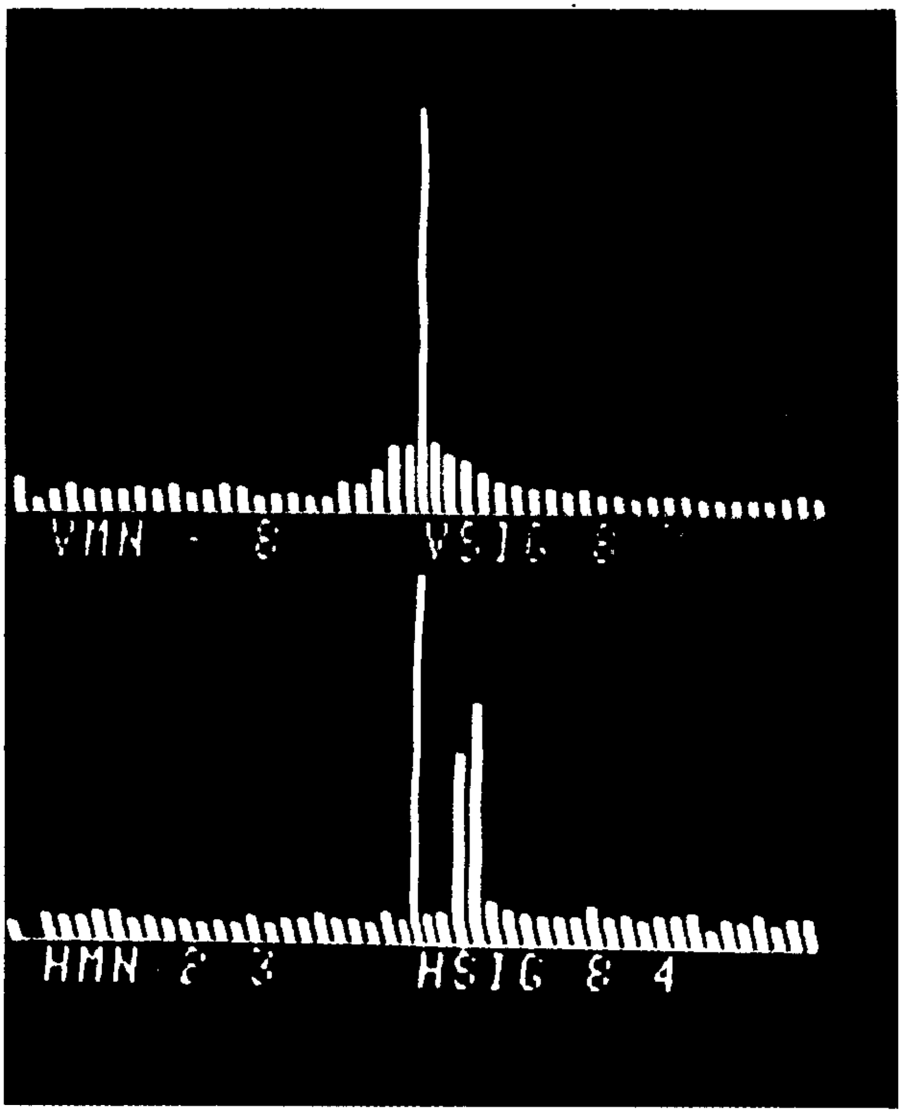
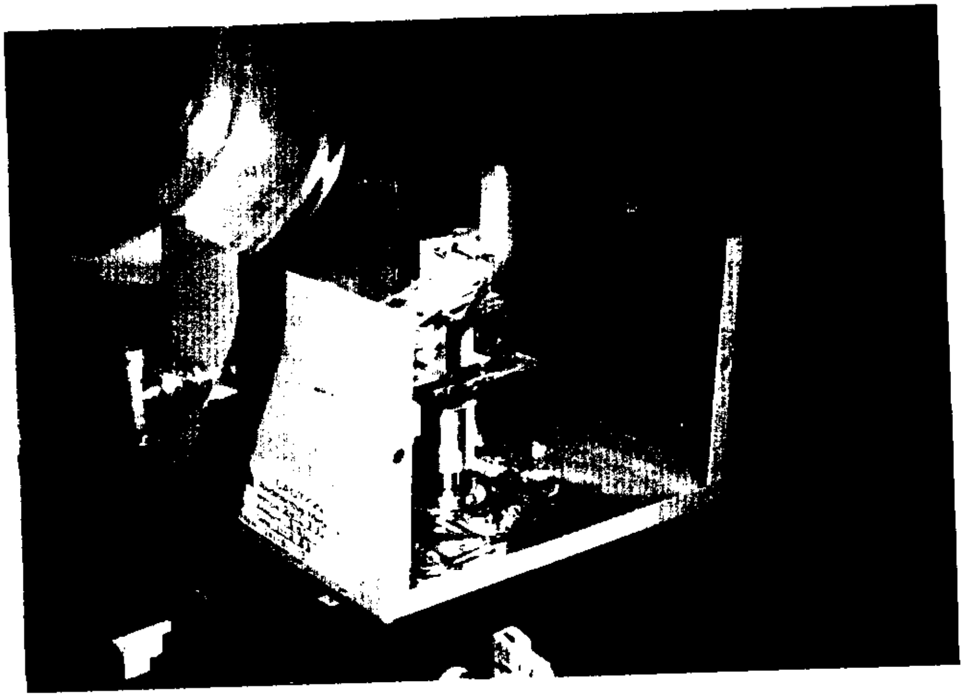


Figure 4



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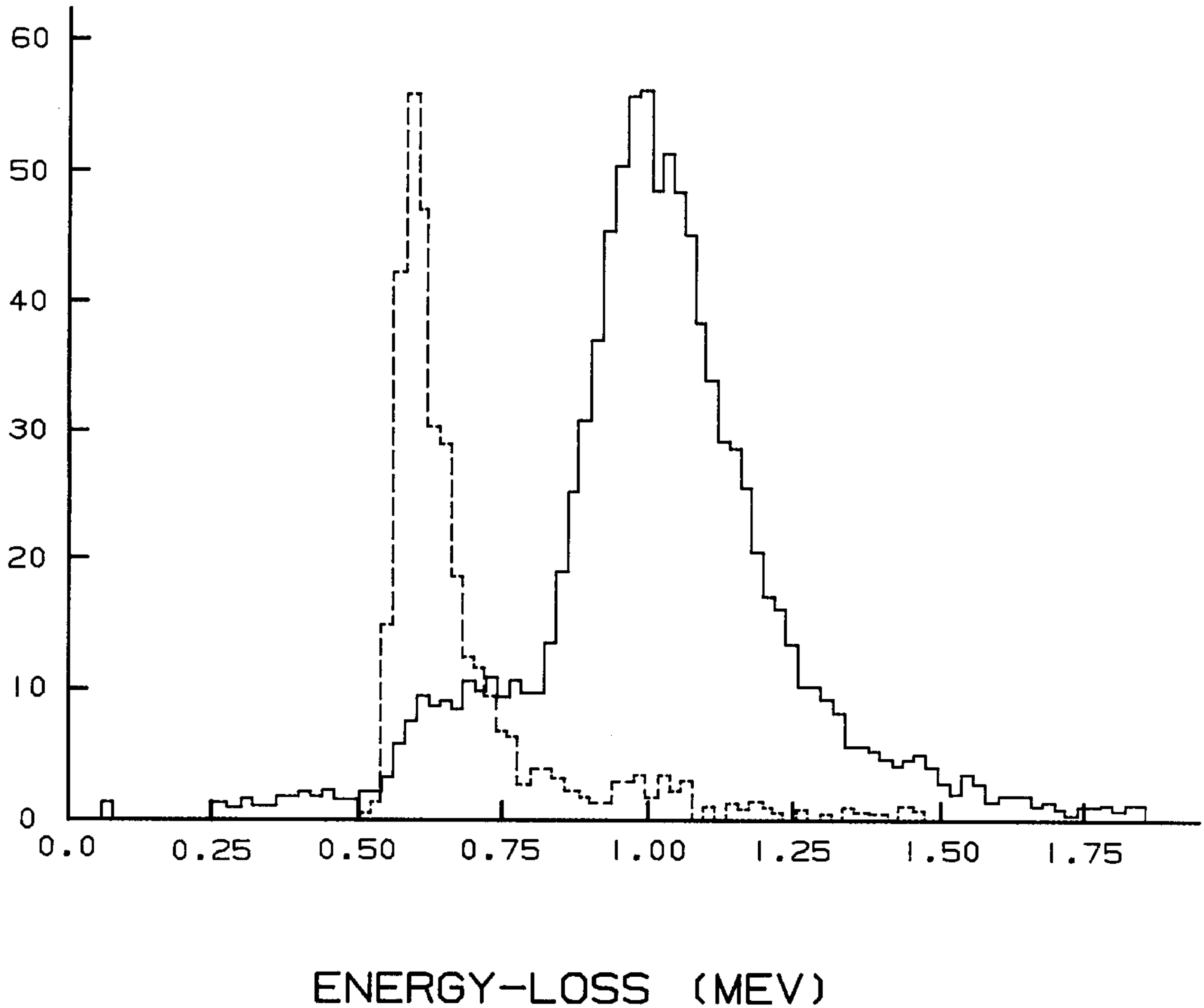
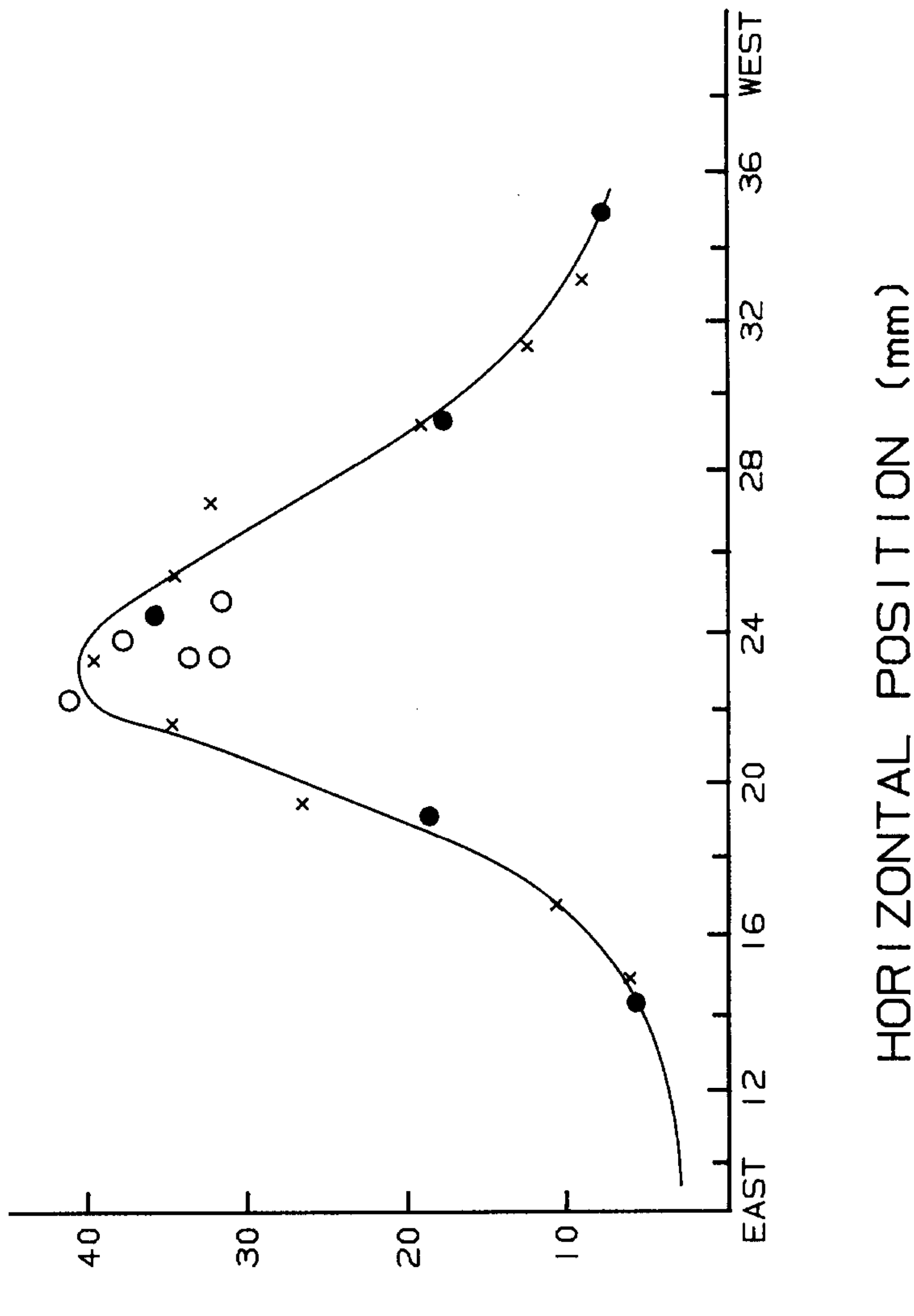


Figure 6


HORIZONTAL POSITION (mm)
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28
32
36
10
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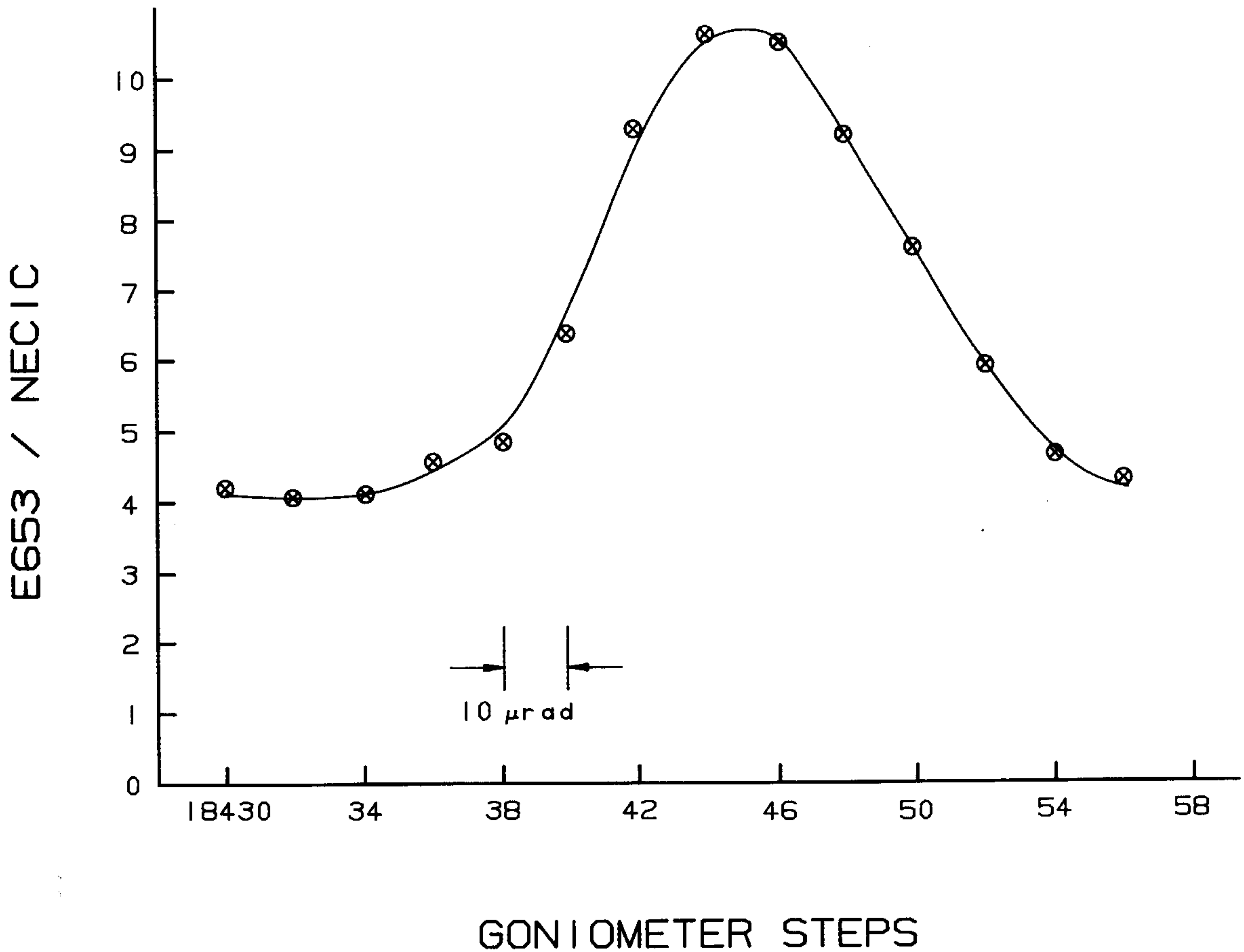
Figure 7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9
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50
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58
GONIOMETER STEPS

Figure 8

Abstract

Two attempts have been made recently at Fermilab to use channeling in bent crystals to provide beam attenuation and deflection of 800 GeV protons. One attempt was quite successful, attenuating a high intensity beam by a factor of 2000 to provide a useful beam at an emulsion experiment. This represents the highest energy where channeling has been observed. The other attempt failed but led to useful insights on how to improve the technique. The possibility of bent crystals as phase space monitors is discussed.