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RADIATION DAMAGE EFFECTS IN CHANNELING APPLICATIONS*

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ABSTRACT

Use of a bent single crystal to split off a small fraction of an incident high energy (400-800 GeV) particle beam has been demonstrated. The question which remains to be answered is will radiation damage effects deteriorate crystal performance in too short a time for practical application?

Single crystals exposed to 10^{17} high energy protons per cm^2 have been examined previously using low energy (1.5-3.0 MeV) helium ion backscattering. The amount of radiation damage indicated by this low penetration technique was very small. This paper reports verification that such an exposed crystal still channels high energy particles. Furthermore, results using helium ion backscattering following an irradiation to $10^{18}/cm^2$ predict no deterioration in channeling performance.

1. INTRODUCTION

Typical intensities of proton beams extracted from high energy (GeV) accelerators are 10^{12} to 10^{13} protons per acceleration cycle or pulse. Targets are usually long enough for the protons to interact in them. Typical counting rates for experiments which count individual particles are around 10^6 Hz. Thus, there are usually sufficient protons available to split the beam a number of times and deliver protons to several experiments simultaneously.

Normally electrostatic or magnetic fields are used to accomplish the splitting of particle beams. As the particle energy gets higher, the devices producing these fields get longer and more expensive. At energies above 100 GeV the length is many meters. Use of short (5 cm) relatively inexpensive single crystals to split off small fractions of high energy positively-charged particle beams has been demonstrated.[1,2] This paper reports on work done to determine that such crystals will have useful operating lifetimes.

2. EXPOSURE TO 10^{17} HIGH ENERGY PROTONS

Channeling of low energy (MeV) ^4He ions has been used to study radiation damage effects in single crystals. A single crystal of silicon was examined following irradiation to $10^{17}/cm^2$ by 400 GeV protons at Fermilab.[3] The 1.5-4 MeV ^4He ions from the dynamitron at the State

University of New York at Albany (SUNY-Albany) were allowed to strike the crystal face and backscattered ions were detected in a semiconductor detector. Channeling was observed, however the low energy backscatter technique only sampled a few microns into the crystal because of the short range of the ^{4}He ions.

High energy (GeV) particles traverse the length of the crystal, typically 10^4 times farther. Will the channeling performance be as good?

To answer this question we first used a single crystal of silicon to deflect 60 GeV particles in a low intensity beam (10^6/cm^2). Then we irradiated it with 400 GeV protons at an intensity per pulse of 5 x 10^{11}/cm^2 at Fermilab until we had accumulated 5 x 10^{16}/cm^2. Finally we remeasured the performance at 60 GeV.

3. CHANNELING VERIFICATION EXPERIMENT

The details of the channeling verification experiment just described are as follows:

A Dubna silicon crystal 9 mm high x 25 mm long x 1 mm thick was placed in a three-point bending jig (Fig. 1) made of a heat resistant plastic to reduce interference with experiments downstream of the irradiation point during the irradiation. It was bent 4 milliradians and mounted in a goniometer in the MB beam line at Fermilab. The line was tuned for 60 GeV positive particles (mostly pions). The Dubna crystal had a semiconductor detector built on its upstream end (Fig. 1). The signal from this detector was placed in coincidence with scintillators upstream and downstream and windows set on the Landau energy loss distributions for channeled and radon particles (Fig 2). The lower window corresponds to channeled particles which have lower energy loss.

The Dubna crystal was prepared with a (111) plane lying parallel to the crystal 9 mm x 25 mm face. Thus, when the crystal was oriented properly with respect to the incident beam, particles were channeled and followed the 4 mradian bend. Figure 3 shows the horizontal deflection seen by the downstream drift chambers when the events in the lower window (channeled particles) are displayed.

Since from previous irradiations, it was clear that the semiconductor detector built on the crystal would not survive, a new technique (Kim technique) was developed for finding the channel after irradiation. This technique consisted of placing a scintillator in front of the drift chambers just outside the position of the undeflected beam (Fig. 3). This scintillator detected bent particles.

By accident the crystal was broken during removal from the goniometer (Fig. 4a). Since the break occurred between the detector and the bending jig, only that portion in the bending jig was irradiated. The irradiation was made in the Fermilab PW line at 5×10^{11} protons/cm^2 per acceleration cycle (pulse). The crystal was irradiated with 400 GeV protons incident perpendicular to the face and the (111) plane.

After exposure to 5×10^{16} protons/cm^2 the crystal fragments were lined back up (Fig. 4b) using a laser and remounted in the MB line goniometer. The detector was used to get the crystal oriented close to the proper channeling direction. Then the Kim technique was used to find the (111) plane (Fig. 5). The bend was increased to 5 mradians and the spectrum shown in Figure 6 was obtained. Thus, the crystal channeled high energy particles properly after exposure to 5×10^{16} high energy protons per square centimeter.

4. EXPOSURE TO 10^{18} HIGH ENERGY PROTONS

Since the low energy backscattering and high energy bending results agreed, a more intense exposure was made and examined using the faster low energy backscattering technique. A high resistivity (100 Ω cm) zone refined silicon crystal[3] was exposed to 10^{18}/cm^2 high energy (28 GeV) protons in the U Line at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL). The single crystal was irradiated at an intensity of approximately 2×10^{13} protons per pulse and one pulse every two seconds. The irradiation continued for 34 hours. During that time the temperature exceeded 80°C causing the plastic holder to soften. The initial bend placed on the crystal relaxed.

The short-lived residual radioactivity was allowed to decay. Then the crystal was examined using the low energy ^4He ion backscattering technique at SUNY-Albany. No radiation damage effects were detected (Fig. 7).

5. DISCUSSION

The radiation damage caused by a high energy particle incident on the crystal in a random direction comes from ionization and nuclear interactions. The particles are essentially minimum ioizing at GeV energies. The crystals used are about 10% of a nuclear collison length. Thus, the potential for radiation damage by an individual particle is small. After about $10^{13}/cm^2$ incident high energy particles there is evidence for deterioration in the performance of the semiconductor detector built on the crystal. This is an electronic effect. The mechanisms for charge collection are very sensitive to defects which produce metastable states (traps). The energy scale for producing these traps is electron volts - the scale of the binding energy of electrons - and the cross section is greater than 10^{-18} cm^2. These traps do not affect channeling performance.

Channeling is affected by displacement of nuclei in the lattice, e.g., interstitials. The nuclear interactions occurring upon irradiation have a much higher energy scale - MeV, the scale of the binding energy of nucleons in the nucleus. The cross section for nuclear interactions is less than 10^{-24} cm^2.

Comparing the energy scales, one would predict a deterioration in channeling performance at greater than $10^{19}/cm^2$ based on the electronic deterioration observed. Thus, good channeling performance at $10^{17}/cm^2$ should not be surprising.

6. CONCLUSIONS

Very high (MeV) potentials are seen by the channeled particles as they approach the nuclei in a row of atoms forming the channel in a single crystal. The positively-charged particles are deflected back toward the center of the channel. Thus, the particles tend to follow the channel in a bent crystal. Milliradian bends have been achieved in very short (centimeter) lengths of crystal. This makes these devices capable of splitting off a small fraction of an incident positively-charged beam of particles for a different application.

The irradiation damage results reported in this paper predict useful performance of silicon single crystals for beam splitting. No alteration in channeling capabilities has been seen after an exposure to 10^{18} high energy protons at a repetition rate of 10^{13}/sec.

7. ACKNOWLEDGEMENTS

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2. S. I. Baker <u>et al</u>., "Deflection of an 800 GeV Particle Beam Using Channeling," Proceedings of this Relativistic Channeling Workshop.

3. G. H. Wang <u>et al</u>., Nucl. Instrum. Methods <u>218</u> (1983) 669.

Figure 1. Plan view of the silicon crystal with three point-bending device (bending jig) shown schematically.

Figure 2. Energy-loss spectrum in silicon for 60 GeV particles entering the end of the crystal in Figure 1. The crystal is oriented to permit channeling of particles. Those channeled appear in the lower window. Because the beam divergence is much larger than the critical angle for channeling, most of the events fall within the higher energy-loss peak.

Figure 3. Apparatus for finding the deflected particles using the Kim Technique. Particles are detected by scintillation counters C1, C2, C3, and K in coincidence with the semiconductor detector on the silicon crystal X. The scintillation counter A with a hole in it just in front of the crystal eliminates events passing through the top and bottom of the crystal where charge collection is poor. Counter K is displaced to detect only deflected particles. The ratio with and without scintillation counter K is recorded and is a maximum when particles are channeled and deflected. The drift chambers D1, D2, and D3 are used to analyze the channeled events.

Figure 4. Elevation view of the broken silicon crystal used to verify channeling after irradiation to $5 \times 10^{16}/cm^2$ using 400 GeV protons.

a) Orientation for measurement of channeling properties before break, showing where crystal broke after the measurement
b) Orientation for measurement of channeling properties after irradiation of portion of crystal inside bending jig.

Figure 5. Goniometer angular scan using the Kim Technique. Small peak corresponds to angle for planar (111) channeling in silicon.

Figure 6. Drift chamber D3 horizontal coordinate spectrum following 400 GeV proton irradiation to $5 \times 10^{16}/cm^2$ (no selection of channeled particles or angles).

Figure 7. Backscattering of 2 MeV ^{4}He ions from silicon irradiated to $10^{18}/cm^2$ using 28 GeV protons.

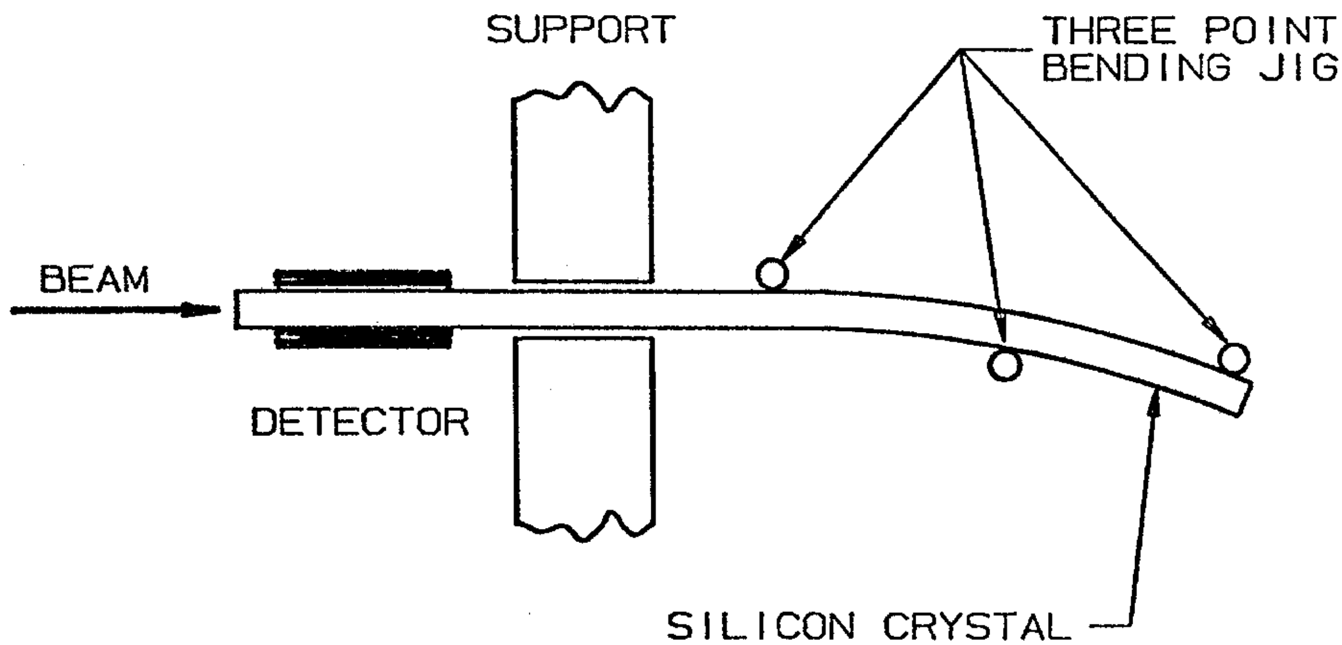

Figure 1

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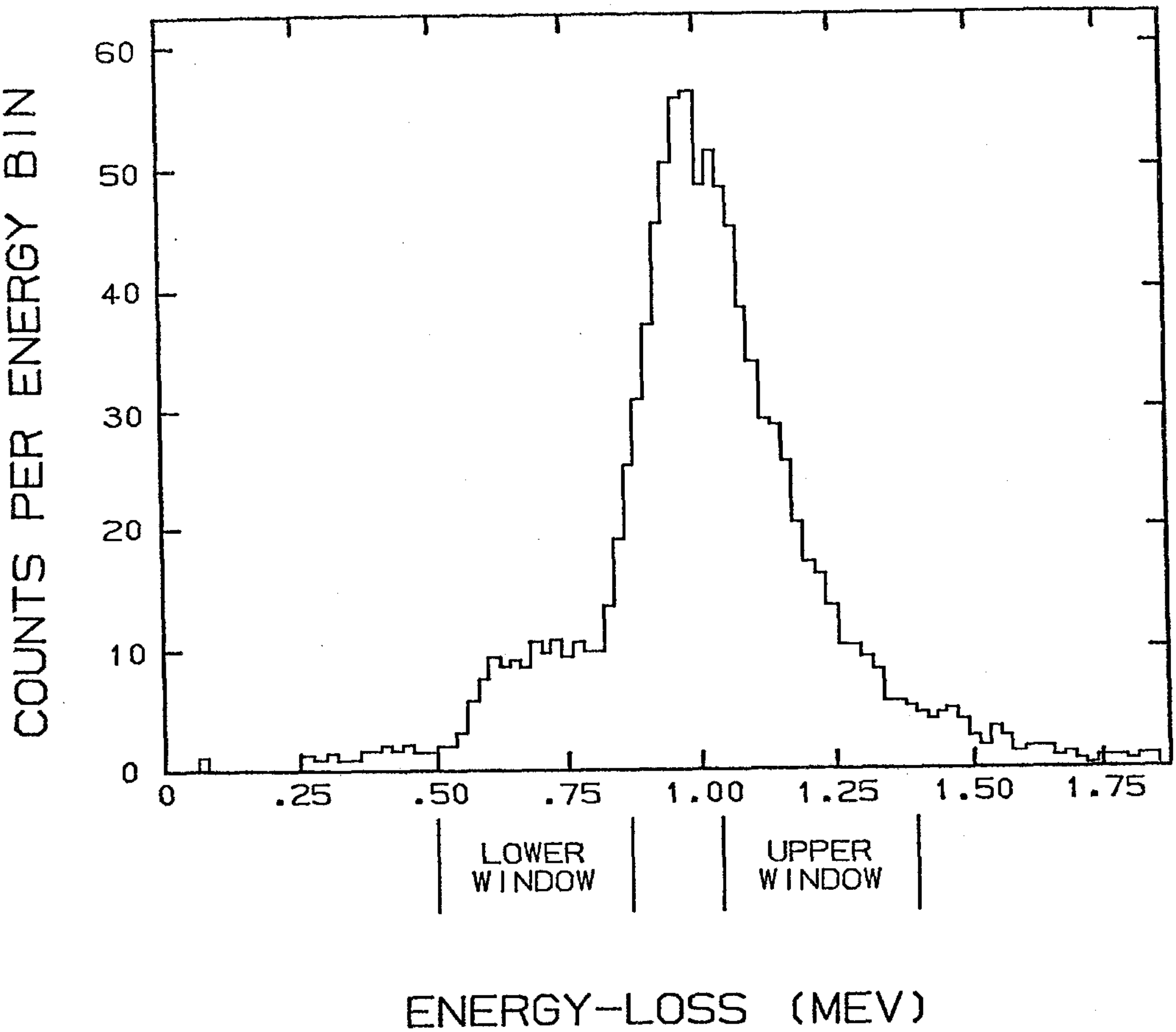

60
50
40
30
20
10
0
COUNTS PER ENERGY BIN
0
.25
.50
.75
1.00
1.25
1.50
1.75
LOWER WINDOW
UPPER WINDOW
ENERGY-LOSS (MEV)

Figure 2

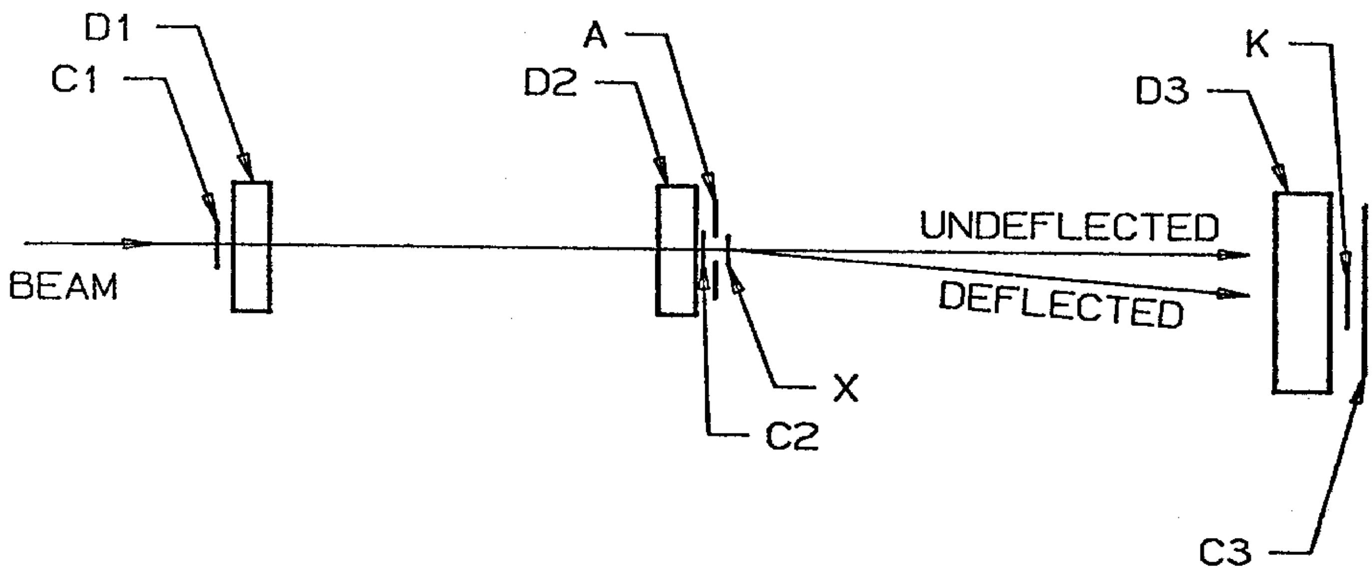
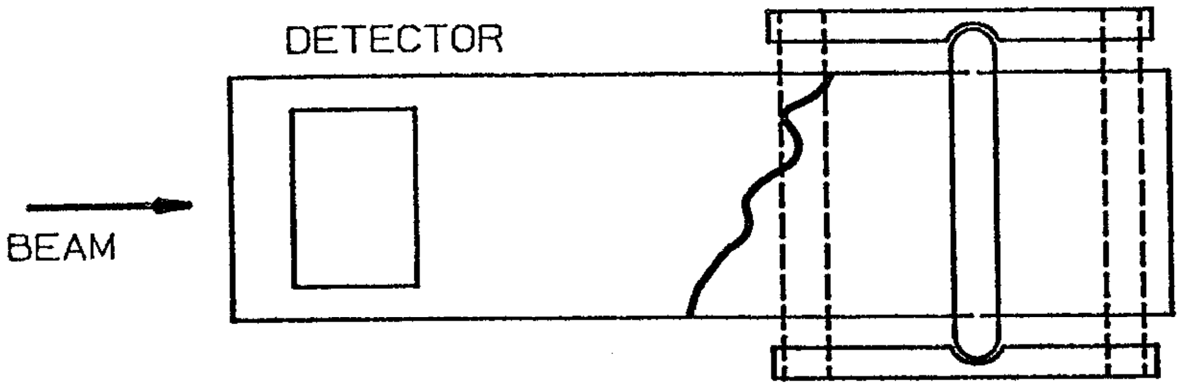


Figure 3

(a)



(b)

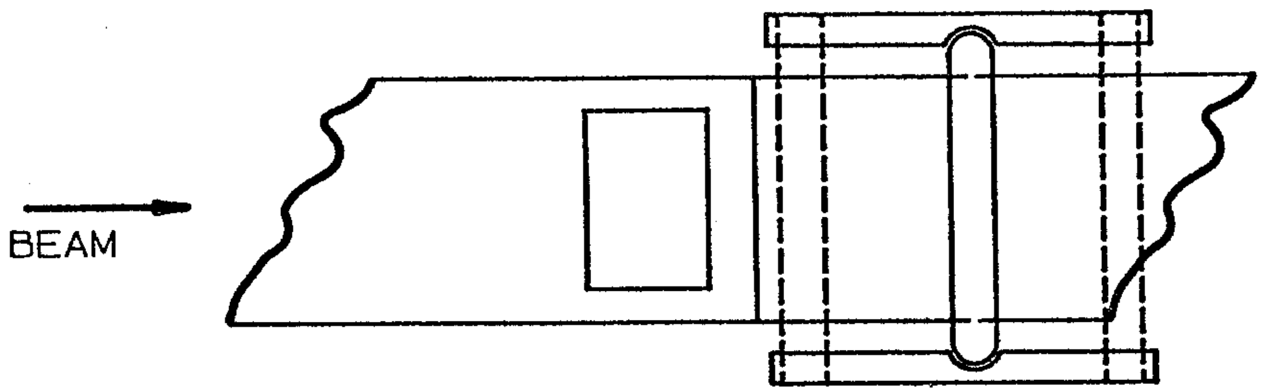
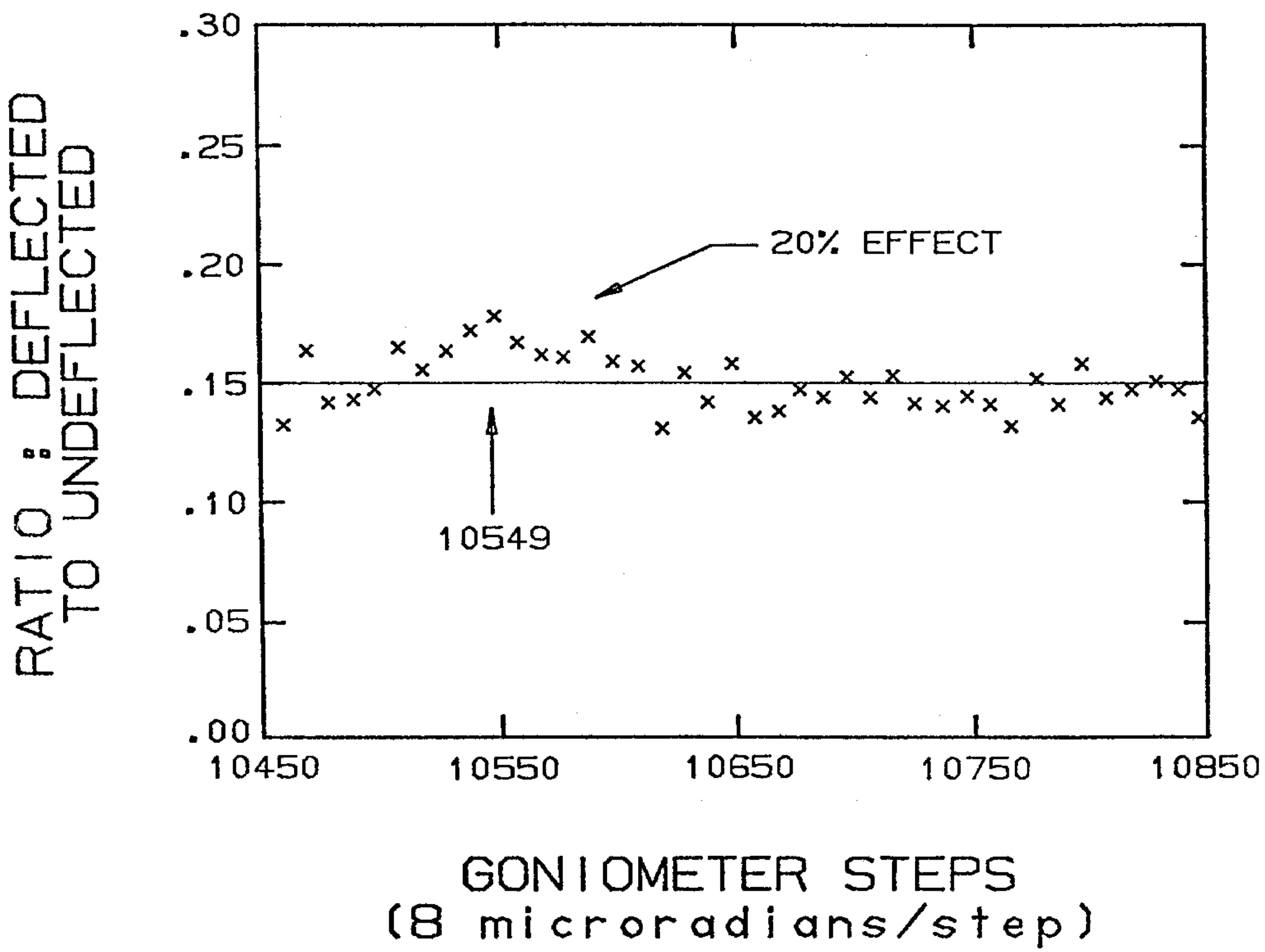


Figure 4



RATIO : DEFLECTED TO UNDEFLECTED
.30
.25
.20
.15
.10
.05
.00
20% EFFECT
10549
10450
10550
10650
10750
10850
GONIOMETER STEPS
(8 microradians/step)

Figure 5

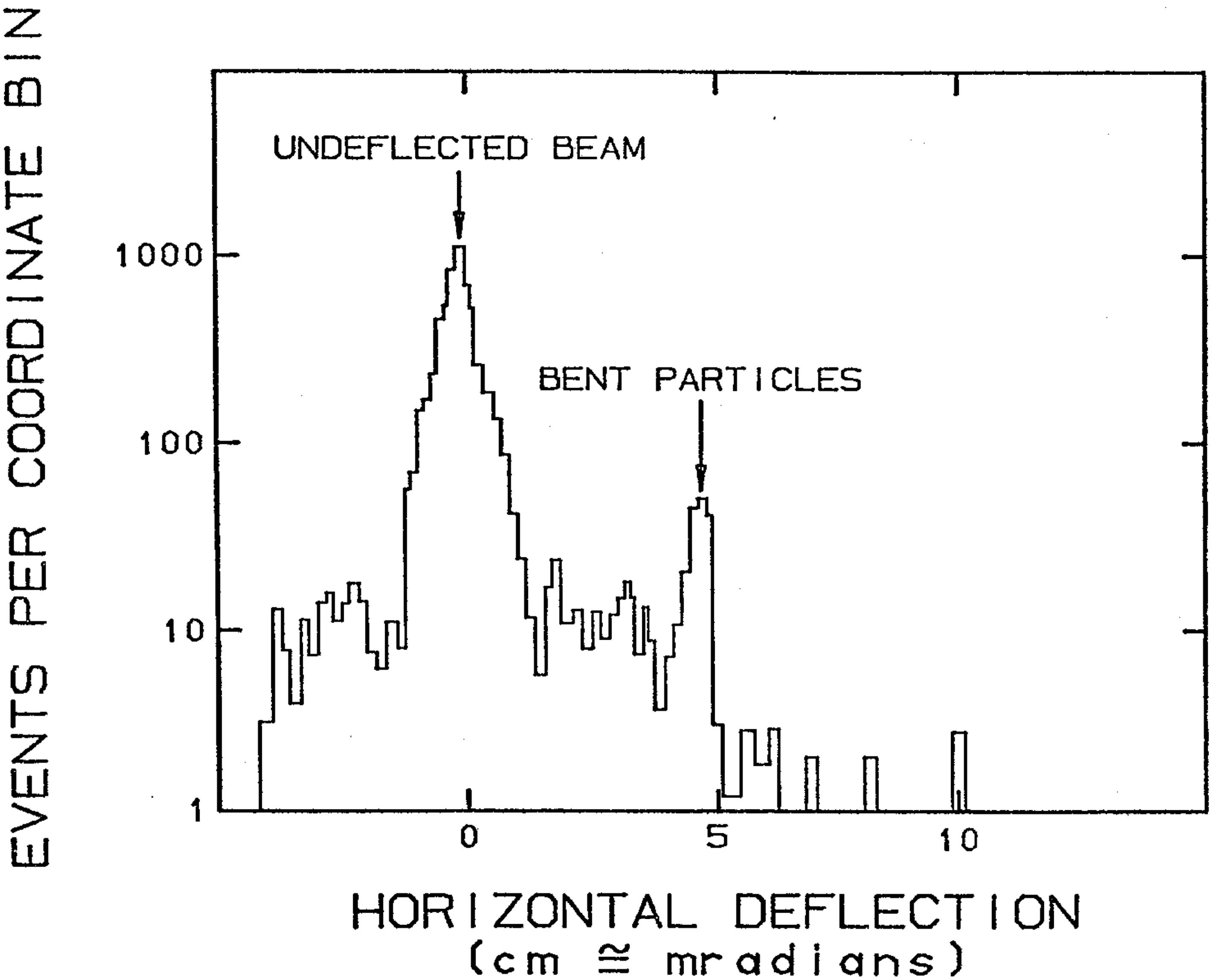

EVENTS PER COORDINATE BIN
UNDEFLECTED BEAM
BENT PARTICLES
1000
100
10
1
0
5
10
HORIZONTAL DEFLECTION
(cm ≅ mradians)

Figure 6

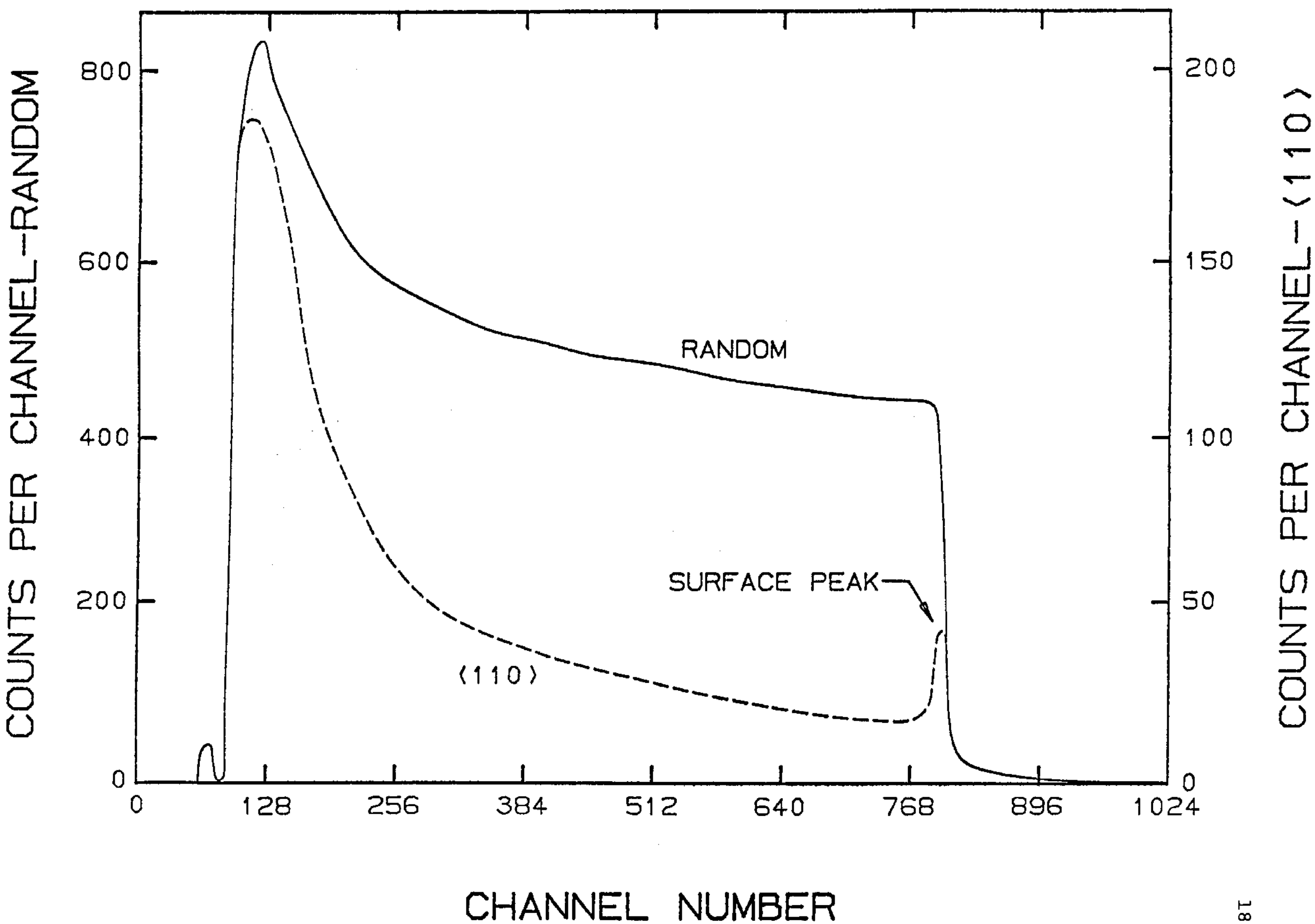


Figure 7

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