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First results on proton extraction from the CERN-SPS with a bent crystal

H. Akbari[2], X. Altuna[2], S. Bardin[2*], R. Bellazzini[6], V. Biryukov[2#], A. Brez[6], M.P. Bussa[8], L. Busso[8], A. Calcaterra[4], G. Carboni[6], F. Costantini[6], R. De Sangro[4], K. Elsener[2], F. Ferioli[2], A. Ferrari[2], G.P. Ferri[2], F. Ferroni[7], G. Fidecaro[2], A. Freund[3], R. Guinand[2], M. Gyr[2], W. Herr[2], A. Hilaire[2], B.N. Jensen[1], J. Klem[2], L. Lanceri[9], K. Maier[10], M. M. Massai[6], V. Mertens[2], S.P. Møller[1], S. Morganti[7], O. Palamara[5], S. Peraire[2], S. Petrera[5], M. Placidi[2], R. Santacesaria[7], W. Scandale[2], R. Schmidt[2], A.M. Taratin[2+], F. Tosello[8], E. Uggerhøj[1,2], B. Vettermann[2$], P.F. Vita[6], G. Vuagnin[9], E. Weisse[2] and S. Weisz[2]

Abstract

The feasibility of extracting protons from the halo of a high energy beam by means of a bent silicon crystal has been investigated. Protons diffusing from a 120 GeV beam circulating in the SPS at CERN have been extracted at an angle of 8.5 mrad. Efficiencies of about 10 percent, orders of magnitude higher than the values achieved previously, have been measured. The present results are promising in view of beam extraction from future multi-TeV proton accelerators.

1 ISA, University of Aarhus, Aarhus, Denmark
2 CERN, Geneva, Switzerland
3 ESRF, Grenoble, France
4 Laboratori Nazionali di Frascati, Frascati, Italy
5 Università di Lecce and INFN, Lecce, Italy
6 Università di Pisa and INFN, Pisa, Italy
7 Università 'La Sapienza' and INFN, Roma, Italy
8 Università di Torino and INFN, Torino, Italy
9 Università di Trieste and INFN, Trieste, Italy
10 MPI für Metallforschung, Stuttgart, Germany
* present address: LPAN, Paris, France
\# permanent address: IHEP, Protvino, Moscow Region, Russia
\+ permanent address: Polytechnical Institute, Tomsk, USSR
$ present address: Fachhochschule für Technik, Mannheim, Germany

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1. Introduction

The possibility of using a beam extracted from the future multi-TeV proton colliders LHC and SSC has been discussed for several years [1,2], particularly in connection with proposed experiments on CP violation in the decay of B mesons [3,4]. Exposing an external target to 10^8 extracted protons per second would yield about 10^{10} BB per year, allowing accurate measurements of CP violating parameters and rare decay modes in the B system. One way of extracting beam from the LHC and SSC is the use of a bent crystal: the space needed is minimal and the strong fields in the crystal allow deflection angles of the order of 1 mrad with good efficiency even at 20 TeV beam energy. Moreover, it has been proposed to place the crystal at a large distance from the centre of the beam and to extract only the halo of the circulating proton beam, allowing a parasitic extraction during collider operation.

Channeling of high energy protons and beam deflection in bent silicon crystals have been studied in detail in high energy beams [5,6]. Protons entering a crystal at small angles to one of the crystal planes are "trapped" in the strong fields coherently produced by the atoms in the planes. The critical angle ψ_p for channeling is proportional to $(Z_1Z_2d_p/pv)^{1/2}$, where Z_1 and Z_2 are the projectile charge and crystal atomic number, p and v the momentum and velocity of the beam, and d_p the distance between the planes in the crystal (for details see [7]). For example, in silicon for the (110) planes one finds $\psi_p \cong 5\ \mu\text{rad}/\sqrt{p[\text{TeV}/c]}$. Protons channeled in the crystal are guided by the planar potential even if the crystal is slightly bent, and will leave the crystal at an angle given by its bending angle. The theory of channeling is well established and the validity of the extrapolation of the underlying models up to relativistic energies has been proven by positron and electron channeling up to 280 GeV [8]. A recent experiment at CERN has shown that deflection efficiencies of up to 50% can be reached for a parallel beam of 450 GeV protons impinging on a bent silicon crystal [9]. The agreement found between the experiment and theoretical predictions is excellent. Extrapolating these results we conclude that very high beam deflection efficiencies can be achieved with a bent crystal for high energy protons under optimal conditions, even at TeV energies.

In order to investigate proton beam extraction with a bent crystal, we are performing an experiment with a 120 GeV circulating proton beam at the CERN-SPS [10]. The experiment aims at an understanding of the extraction process, in particular its efficiency, when a crystal is used to extract protons from the halo of a circulating beam. For an extraction experiment, the crystal has to be held and bent in a mechanical device which does not obstruct the beam. Moreover, since halo protons are slowly diffusing onto the crystal and therefore have small penetration depth (impact parameter), the quality of the crystal surface is expected to play a crucial role - in contrast to proton deflection with crystals in external beams. In a circular machine, protons not extracted after a first crystal traversal will undergo multiple scattering and might either be lost or channeled and extracted in a later turn. Such "multi-pass extraction" has been theoretically described and its effect on the extraction efficiency has been predicted [11,12]. In this paper, first experimental results on the efficiencies obtained in proton beam extraction from the SPS with a bent crystal are reported.

2. Experiment

A schematic view of the experimental arrangement is shown in Fig. 1. Two silicon crystals, 18 mm high, 1.5 mm thick and 30 mm long in beam direction, are bent in "Serpukhov-type" bending devices [13]. The central 10 mm of the crystal height are not obscured by the material of the bending device. The bend angles are adjusted with a differential screw and are set to be 8.5 mrad. The crystals are cut parallel to the (110) planes with an accuracy better than 200 μrad, then polished and chemically etched to remove the damage from the cutting. Finally, the crystals were mechano-chemically polished (Syton technique) to obtain an optically flat surface needed for the laser measurements mentioned below. Bragg reflection of 8.9 keV X-rays with a penetration depth of a few micrometers was used to verify that the surface is a perfect crystal lattice. The crystals, which can be used alternatively, are mounted in a vacuum tank on remotely controlled goniometers. The goniometers are used to adjust the angles of the crystals with respect to the beam axis with a stepsize of 4 μrad and to place them at different distances from the closed orbit (i.e. centre of the beam). After installation, the crystals were pre-aligned with respect to the theoretical beam axis using a laser beam reflected from the crystal surface. The same laser system also allows continuous monitoring of the crystal orientation.

The protons are extracted horizontally towards the centre of the SPS and detected 20 m downstream of the crystal (cf. Fig. 1). A scintillating screen (CsI) equipped with a CCD camera is used to get a two dimensional view of the extracted beam on a video screen in the SPS control room. A scintillator hodoscope with 32 horizontal and 32 vertical strips (1 mm wide) is used for continuous monitoring of the beam profiles. Two sets of horizontal and vertical microstrip gas chambers (MSGC) with a pitch of 200 μm, placed 1 m apart, are used to measure the divergence and the profiles of the extracted beam. Three scintillation counters (S1, S2 and S3) are used in coincidence as a trigger for these detectors. These counters show clean peaks in pulse height for minimum ionizing particles. This allows background from multiparticle events produced by interactions in the crystal to be vetoed, while rejecting only 10% of the single particle events.

For the measurements, a 120 GeV coasting beam with an intensity of about $5*10^{11}$ protons was used. The SPS shows hardly any non-linear effects at this energy and little natural diffusion, resulting in a beam lifetime of more than hundred hours. The normalised beam emittances (2σ values) are 6-8 mm*mrad horizontally and vertically for an unperturbed beam. The crystal was placed at a distance of 10 mm from the closed orbit, corresponding to 6 - 10 times the r.m.s. transverse beam size, where only a few halo particles are found when no noise is applied. The beam is excited horizontally with band limited white noise induced on a pair of condenser plates. Random kicks producing a typical deflection of about 0.001 μrad (r.m.s.) are applied. The horizontal beam size slowly increases and protons diffuse towards the crystal. The horizontal emittance is typically 60 mm*mrad when the crystal is reached by the particles with large amplitudes, while the vertical emittance remains unchanged (<10 mm*mrad). The statistical nature of this process allows reliable calculations and a simulation of the diffusion process. Mean impact parameters of the protons on the crystal are estimated to be in the micrometer range.

For protons to be channeled in the crystal, they must have an angle with respect to the crystalline planes smaller than the critical angle for channeling, i.e. ±14 μrad at 120 GeV. Therefore, for extraction from a parallel beam, the crystal has to be aligned with the beam envelope with an angular precision better than 28 μrad. The horizontal width of the extracted beam is expected to be determined by the impact parameters of the incident protons and the product of the critical angle and the distance to the detectors, which results in a width of 0.7 mm (FWHM) at the hodoscope. The vertical profile of the extracted beam should be mainly determined by the vertical beam size and vertical divergence of the beam hitting the crystal (about 20 µrad r.m.s.), and by multiple scattering in the crystal resulting in 2.5 mm (FWHM).. The multiple scattering due to the material in the extracted beam accounts for about 0.7 mm (FWHM). If a substantial fraction of the extracted beam comes from multi-pass extraction, the horizontal and vertical beam profiles can be much broader and are limited only by the transverse dimensions of the crystal (1.5 and 18 mm, respectively).

3. Results

Fig. 2 shows the intensity measured in the coincidence of the scintillation counters S1*S2*S3 as a function of the crystal orientation angle. The extracted beam intensity shows a clear peak as a function of the angle. The FWHM of the angular scans is typically 200 µrad. This distribution is much wider than expected from considerations of beam divergence and planar critical channeling angle alone.

The horizontal and vertical profiles of the extracted beam measured with the hodoscope for a crystal orientation angle far away from the maximum of the angular distribution are shown in Fig. 3a. An unexpected structure indicating two peaks is visible both in the horizontal and vertical profiles. The profiles at the maximum of the angular scan are shown in Fig. 3b. Here, only one narrow peak is visible with FWHM of 2 mm for horizontal and 3.5 mm for vertical profiles. The horizontal width corresponds to a divergence of 87 µrad, much larger than expected. Fig. 3c shows the horizontal and vertical beam divergence as measured with the MSGC telescope, where sharply peaked distributions with little background are seen. The angular width is dominated by the resolution of the MSGC and multiple scattering.

The unexpectedly large width of the angular scan (Fig. 2) and the structure of the beam profiles observed for different crystal orientation (Fig. 3a,3b) can be qualitatively explained. The mounting of the crystals in the present bending device produces an unwanted curvature of the crystal in the vertical plane, i.e. transverse to the plane of beam extraction. Moreover, the direction of the (110) planes at both ends of the crystal varies as a function of the vertical position. The crystal is fixed to the bending device at four points on its sides which leads to straight sections at both ends. These well known effects (anticlastic bending [14]) have been measured with reflected laser light (see Fig. 1). Furthermore, protons hitting the crystal after several passages may lead to a vertically extended beam due to multiple scattering in the silicon. These effects together provide an explanation for the experimental observations: for example, a vertical beam size of 2 mm can explain the width of the angular scan of 200 μrad (Fig. 1). The result of a simulation containing the approximate crystal geometry and multi-pass effects is shown in Fig. 4 [15]. The beam profiles simulated with a crystal misaligned by 200 μrad with respect to the maximum of the angular scan have the same characteristics as the measured ones and a sharp profile is reproduced for an aligned crystal. As reported previously [16], experimental evidence for anticlastic bending has also been obtained from measurements with a vertically displaced beam at the crystal location.

In order to measure the extraction efficiency for the optimum crystal alignment, the beam has to reach a "steady state" diffusion mode, i.e. when the extracted beam intensity does not vary with time. The efficiency is determined as the ratio of protons extracted to protons lost in the SPS for a given time interval. The number of protons in the circulating beam and the proton flux onto the crystal is obtained from intensity monitors and beam lifetime measurements. The systematic error of these measurements is estimated to be less than 10%. The rate of protons extracted is determined by integrating the beam profiles measured by the hodoscope after subtracting the background. The combined efficiency for the hodoscope and the trigger after removing multiparticle events is found to be (78±12)%, where the error given stems from residual systematic uncertainties. Typically, $6*10^5$ protons have been extracted per second and the extraction efficiency is found to be about 10% (see Table 1). The present results are orders of magnitude higher than the values obtained in the pioneering crystal extraction experiments performed at Serpukhov with a pulsed 70 GeV beam [13].

4. Conclusions

The extraction of 120 GeV protons from the halo of a beam coasting in the SPS by means of a bent crystal has been successful. When the crystals are pre-aligned with the laser system, the extracted beam is easily observed on the TV screen and the optimum crystal alignment can be found in about one hour. The reproducibility of the beam extraction (both the angular setting and the measured efficiency) with a bent crystal is remarkable. Efficiencies of about 10% have been measured at impact parameters of the order of 1 μm. Under these conditions, the extraction can be maintained for many hours. This suggests that beam extraction with a bent crystal is feasible at the future proton colliders and that the intensity of extracted protons required for a CP experiment in the B system could be reached provided that about 10^9 protons per second hit the crystal. Further studies will give additional insight to this new technique: new crystals and bending devices are being prepared where the anticlastic bending is minimised and systematic studies with varying machine parameters are being performed. The present experimental results, the first simulations and the experience with beam deflection using a crystal in external beams encourage us to hope for a further increase of the extraction efficiency in future experiments at the SPS and for the possibility of extracting beam with a crystal at the LHC and SSC.

Acknowledgements

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Table 1: Measured extraction efficiencies, as obtained from the analysis of the hodoscope profiles, for two independent measurements with different crystals. Errors given are systematic uncertainties of the different measure-ments, statistical errors are negligible.

	crystal 1	**crystal 2**
intensity of circulating beam	$(7.0\pm0.1)*10^{11}$	$(3.7\pm0.1)*10^{11}$
beam lifetime (hours)	29±2	12±1
protons lost per second	$(6.7\pm0.5)*10^{6}$	$(8.9\pm0.7)*10^{6}$
protons detected per second	$5.6*10^{5}$	$6.6*10^{5}$
background (%)	5	2
detection efficiency after cuts (%)	78±12	78±12
extraction efficiency (%)	**10.2±1.7**	**9.3±1.6**

Figure captions

Figure 1: Schematic drawing of the experimental arrangement. The scintillation counters S1, S2 and S3 are used as a trigger for the scintillating CsI screen with a CCD camera. Also shown is one of the crystals mounted on its bending device as well as the crystal curvature R along the beam (s) and the angle of the (110) planes with respect to the beam direction for different vertical positions (y) at the crystal entrance.

Figure 2: Result of an angular scan: the extracted beam intensity obtained from the coincidence between scintillation counters S1*S2*S3 is shown as a function of the angular setting of the goniometer (1 step = 4 μrad).

Figure 3: (a) Beam profiles of the extracted 120 GeV proton beam, measured with angular scan. Double peaks attributed to crystal distortions are seen.

(b) Beam profiles measured at the peak value of the angular scan.

(c) Horizontal and vertical beam divergence as measured with the MSGC, at the peak of the angular scan.

Figure 4: Expected beam profiles obtained in a simulation, showing the double peaks due to the anticlastic bending, when the crystal is turned 200 μrad away from the best alignment (4a) and for the optimal angle (Fig. 4b).

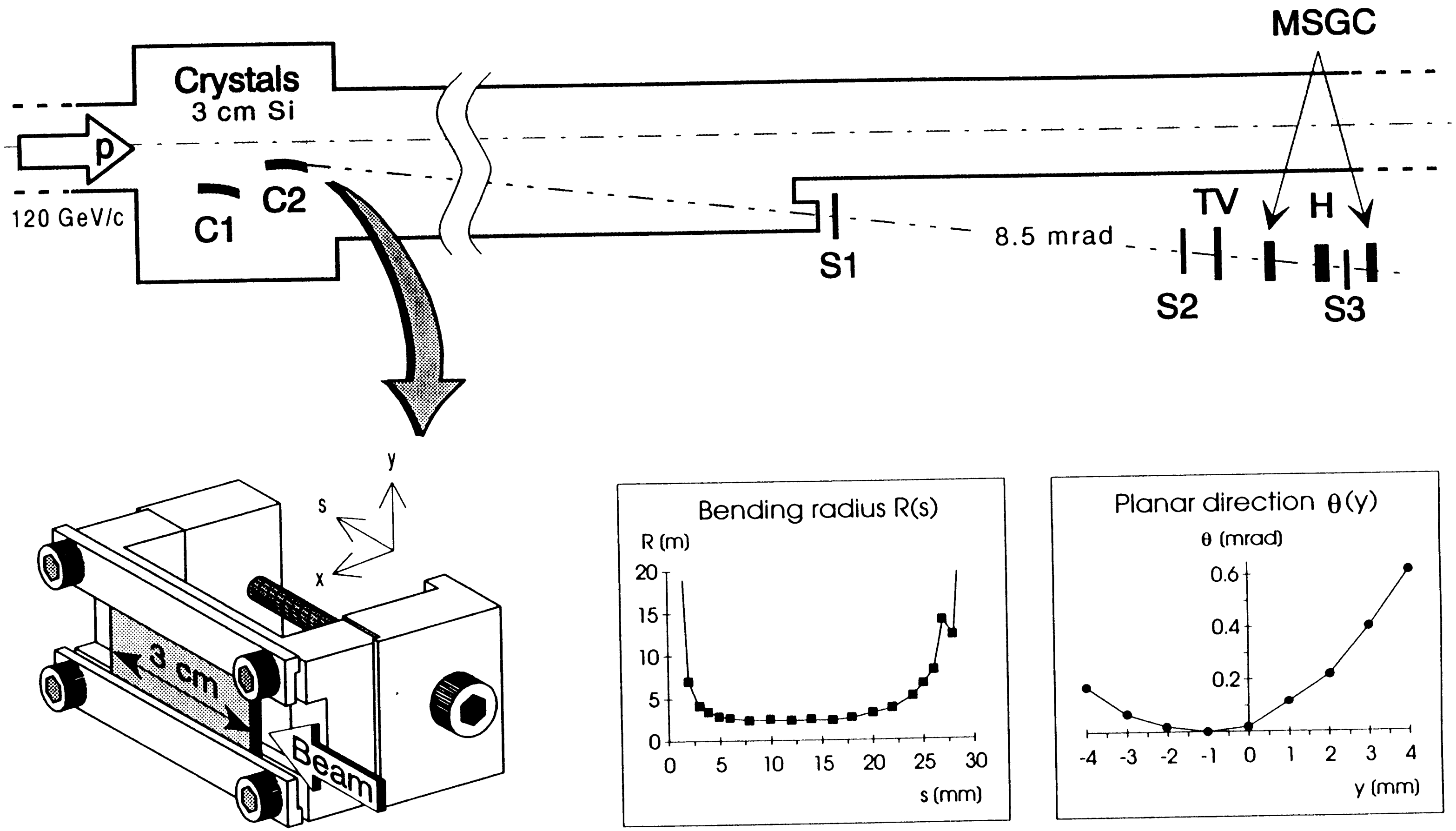
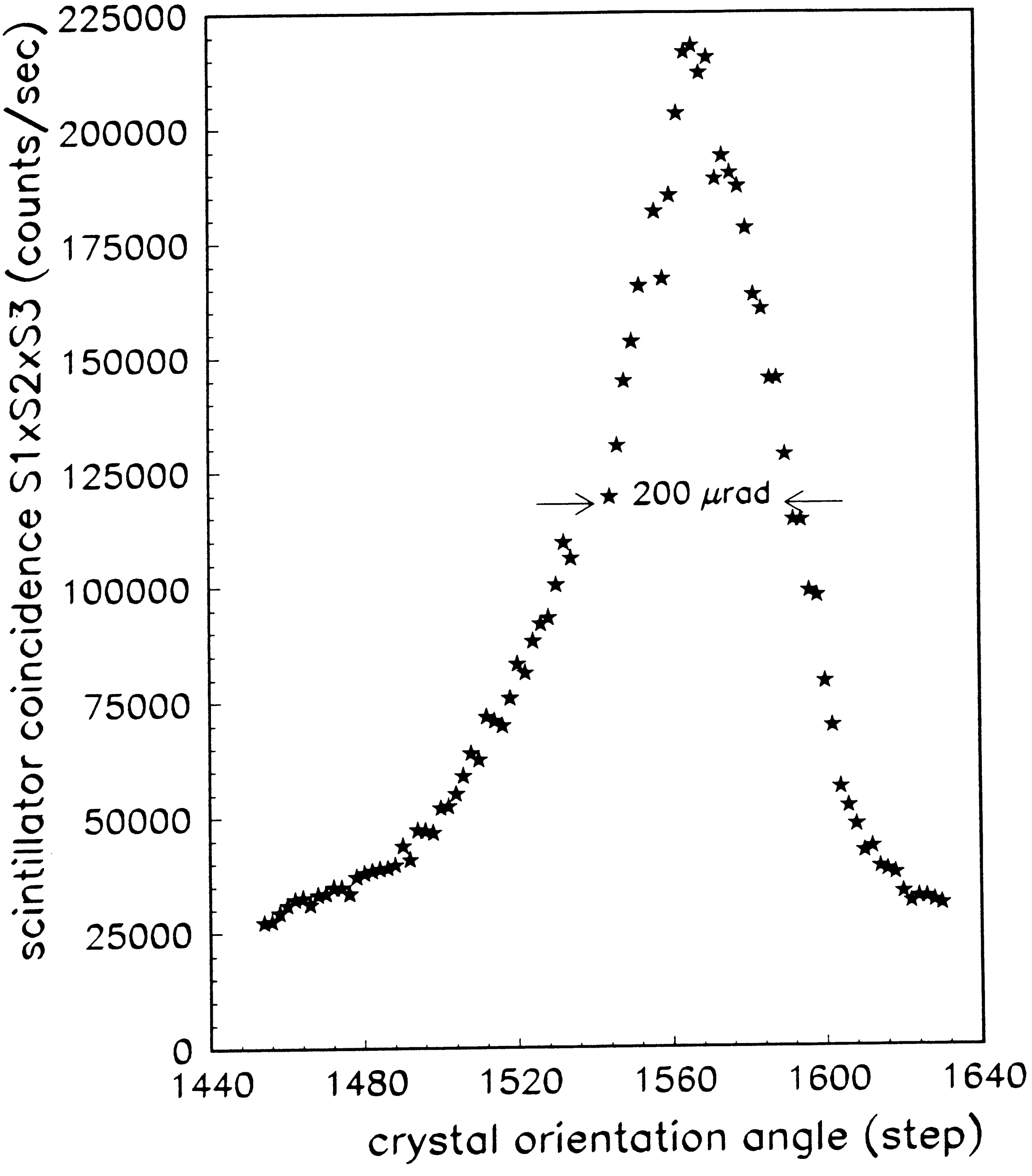

MSGC
Crystals
3 cm Si
p
120 GeV/c
C1
C2
S1
8.5 mrad
TV
H
S2
S3
y
s
x
3 cm
Beam
Bending radius R(s)
R (m)
20
15
10
5
0
0
5
10
15
20
25
30
s (mm)
Planar direction θ(y)
θ (mrad)
0.6
0.4
0.2
-4
-3
-2
-1
0
1
2
3
4
y (mm)

Figure 1



scintillator coincidence S1xS2xS3 (counts/sec)
225000
200000
175000
150000
125000
100000
75000
50000
25000
0
1440
1480
1520
1560
1600
1640
crystal orientation angle (step)
200 μrad

Figure 2

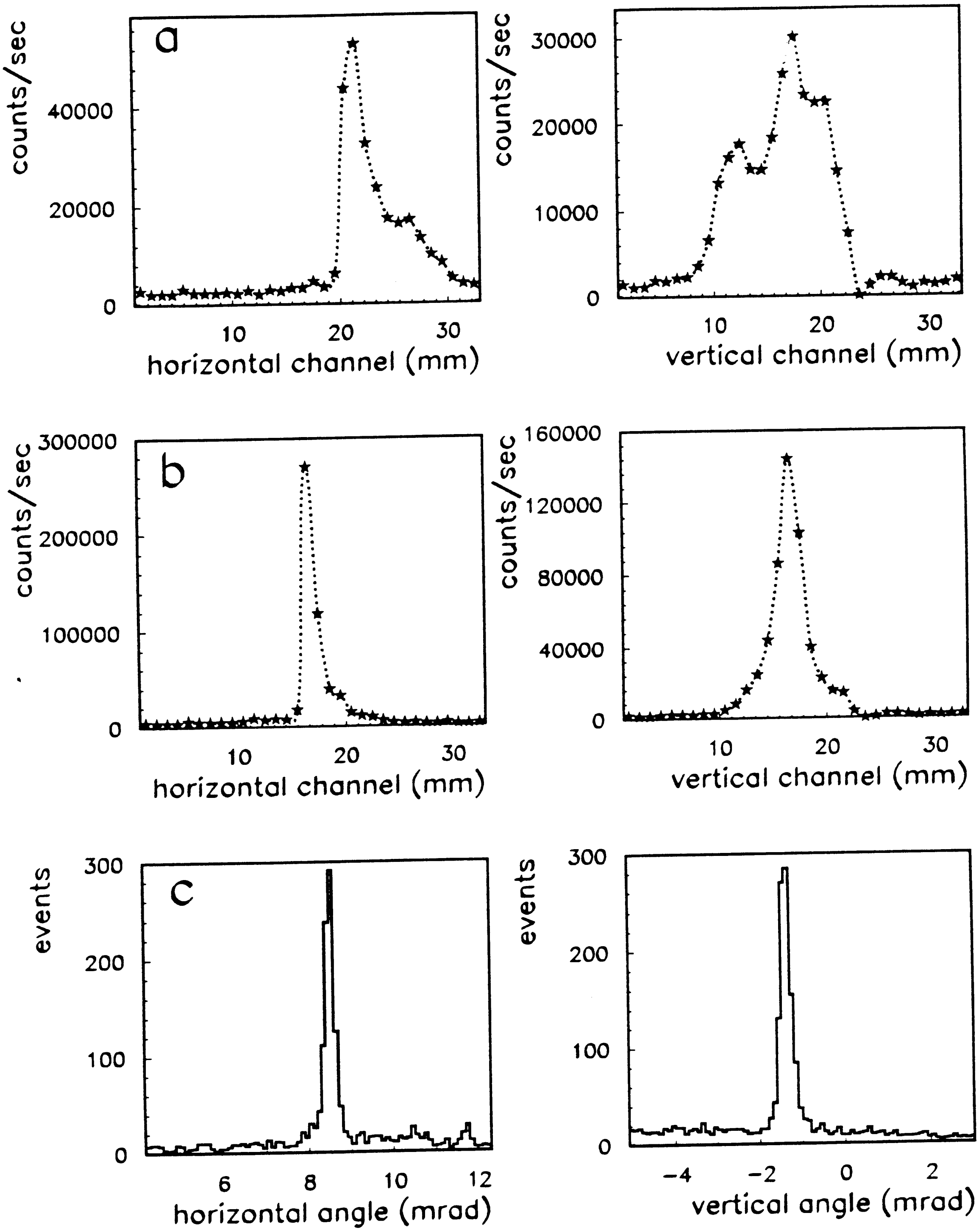

a
counts/sec
40000
20000
0
10
20
30
horizontal channel (mm)
counts/sec
30000
20000
10000
0
10
20
30
vertical channel (mm)
b
counts/sec
300000
200000
100000
0
10
20
30
horizontal channel (mm)
counts/sec
160000
120000
80000
40000
0
10
20
30
vertical channel (mm)
c
events
300
200
100
0
6
8
10
12
horizontal angle (mrad)
events
300
200
100
0
−4
−2
0
2
vertical angle (mrad)

Figure 3

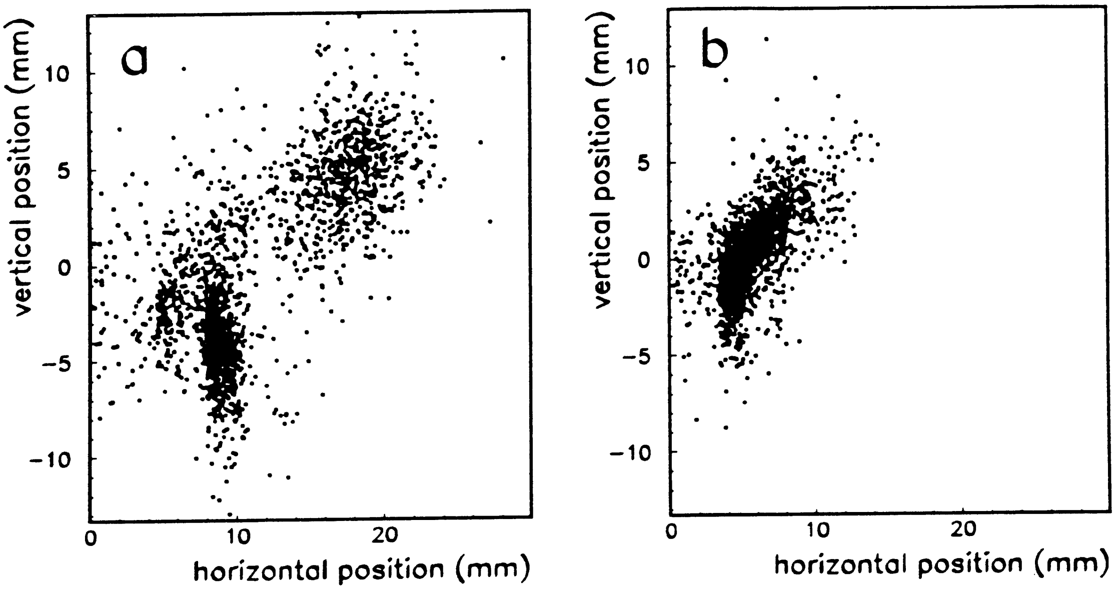

a
b
vertical position (mm)
horizontal position (mm)
10
5
0
-5
-10
0
10
20

Figure 4