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ON THE POSSIBILITY OF A CRYSTAL SEPTUM

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ABSTRACT

A crystal septum is considered for operation with a secondary beam such as M4. A 3 cm long curved crystal septum placed in the primary beam or M2 just beyond the present target box location would deflect the beam down into M4. The septum would make operation of the M4 beam possible at energies above 200 GeV and might permit use of the beam line during Tevatron operation.

INTRODUCTION

If a positively charged particle moves in a direction nearly parallel to the crystal planes in a single crystal it will be trapped in a channeled trajectory. In such a trajectory the particle oscillates between two adjacent crystal planes as it is repelled by the repulsive force of the nuclei. Roughly, the particle must be within the critical angle for channeling relative to the plane (16 microradians at 100 GeV for the (110) plane in silicon) to be captured[1-3].

If the crystal is bent the particle will follow the bend of the planes. At some minimum bending radius all of the particles will be lost, due to the centripetal acceleration exceeding the net inward centripetal force exerted by the planes. Tsyganov[4] was the first to estimate this radius. Later estimates by Ellison[5] and Kudo[6] with more comprehensive analyses have found somewhat larger minimum radii of curvature. Particles are also scattered out of channels (dechanneled) by electron scattering and the effect of dislocations. Even at 100 GeV such effects are non-negligible. Preliminary E660 running in M4 has shown sketchy agreement with the Ellison theory coupled with some ordinary dechanneling.

The present M4 beam at Fermilab was constructed under some very special constraints. It is at a relatively large angle to the incident beam, 8.25 milliradians, so that the beam flux is low and limited mostly to particles with energies below 200 GeV. In the Tevatron years there will probably be no way to feed this beam any flux at all unless some special measures are taken. One obvious idea is to try to snatch a little of the primary beam or the small angle flux from a target with a septum and feed it out to the existing M4 channel. An examination of the magnetic septa used for M1 and M6 shows that this would be difficult indeed with any conventional septum.

On the other hand it appears a silicon crystal several centimeters long placed in the forward direction can easily deflect a 400 GeV positive beam down 12 milliradians so it intercepts the M4 beam. In 1981 Aldo Menscione suggested that a crystal septum using this principle be installed just after the Meson target box in the M2 line approximately 55 feet from the target. Another bend about 100 feet later is needed to take out the four or so extra milliradian deflection introduced originally because the septum is downstream of the target box. Fortunately this can be done with the current M4 sweeper (centered at 192 feet) used for neutral beam operation. The details of the scheme are shown schematically in Figure 1, a vertical cross section of the first two hundred feet of the M2-M4 complex.

To understand the practicality of such a "crystal septum" it is necessary to estimate the transmission properties of the crystal. A typical crystal might be 1 mm thick and have an angular acceptance of ±8 microradians at 400 GeV/c. This leads to an angular admittance of 4×10^{-3} π mm mrad. This should be compared to the x emittance of the M-Center primary beam of 0.14 π mm-mrad or the approximate admittance of the M4 beam of .85 π

mm-mrad. The vertical admittance of the crystal is effectively infinite since any particle direction close to the plane will be bent and the height of the crystal perpendicular to the bend can be large enough to accommodate the beam. In addition to admittance considerations there will also be some loss of flux due to dechanneling, both as a result of the bending process and ordinary dechanneling.

As a result, the crystal septum will be able to transmit about one part in a thousand of either the primary beam or the typical flux in a forward secondary beam. A detailed evaluation of this transmission factor is given in Appendix I along with some discussion on phase space matching.

At 150 GeV this approach results in no net gain for the present M4 beam since the flux is on the order of one million particles/pulse at 3 x 10^{12} protons on M-Center. As shown in Figure 2, the production distribution falls very rapidly so that by 250 GeV there could be a substantial gain with a crystal septum.

The current M4 sweeper at 192 feet can handle the necessary differential deflection for beams up to 375 GeV. The M4 bends could handle beam momenta up to 1200 GeV. (This number is large because the beam dispersion is very low in M4.) The first two quadrupoles in M4 are the limiting magnetic elements. (At 200 GeV the present configuration requires 5.34 kG/in. Toohig[7] quotes the quadrupole design value as 4.8 kG/in.)

One special aspect of the crystal septum offers some relief from this difficulty. The angular emittance of the crystal in the bend direction is just the critical angle. For all practical purposes this is an extremely parallel beam. Thus it should be possible to use the quadrupoles to focus in the direction perpendicular to the bend and meanwhile let the beam blow up in the bend direction. If this is done one only requires a gradient of 1.25 kG/in in the first set of quadrupoles and 0.78 kG/in in the second set to focus in the x direction if the pairs of quadrupoles are ganged. The y direction (this is the bend direction) will blow up and be ±.189 inches, with a divergence of .032 milliradians at the 700 foot collimators and ±1.44 in with a divergence of ±.151 millirad in the M4 pit. While this could be used for some purposes a better strategy might be to let the beam blow up in y in the first section then go from point to parallel with the object being the first quadrupole set for the second section of the beam. This can be done up to about 300 GeV/c. For that case the y spot size at M4 would be about ±.35 inches. Ray traces for these cases are shown in Figure 3.

Ultimately 400 GeV could be reached by increasing the spacing between the quadrupoles in the second set. As noted by D. Green[8] this can be done by shuffling elements in the existing pit.

For these approaches it is important to preserve beam quality in the y direction by minimizing multiple scattering. At 400 GeV multiple scattering equivalent to the critical angle emittance would be introduced by 13 meters of air or 1.3 cm of mylar.

Radiation damage will affect the crystal septum. Earlier studies suggest difficulties may occur at exposures of 10^{17} - 10^{18} particles/cm^2. The E660 group carried out an exposure in 1981 that suggested, with some ambiguity, that unbent silicon crystals would have substantial degradation of channeling properties at this level. Further studies with bent and unbent crystals now underway in P-West have shown little damage at 10^{17}/cm^2. In any case 10^{17} particles/cm^2 corresponds to crystal lifetimes on the order of one week in the M-Center primary beam and many weeks if slightly off to the side of the primary beam.

Crystal heating will, of course, have to be considered. The P-West exposures at beam levels similar to those in M-Center have not noticeably disturbed the crystal structure for bent or unbent crystals. Some heating may even help to anneal out undesirable dislocations.

A crystal septum in a primary beam or in M2/M3 would, of course, have some impact on M2/M3 operations. A 3 cm silicon crystal (with an atomic number 1 above aluminum) corresponds to ten percent of a collision length and thirty percent of a radiation length. The holder surrounding the crystal would present the same or less material to the beam. (The low z material Torlon made by Polymer Corporation is extremely radiation resistant and has worked well in the damage studies.) This amount of material so close to a primary target should constitute no significant detriment to the performance of the principle beam from any standpoint including emittance, flux or halo.

Implementation of a Crystal Septum

A crystal septum for M4 requires the following:

1) A single crystal with a fixed bend arranged so the aspect angle and position relative to the primary beam or the M2-M3 beam can be varied.
2) A refurbished beam pipe in the principal beam such as M2 allowing the deflected beam to leave the pipe through a thin window.
3) A refurbished beam pipe just spstream of the M4 sweeper centered at 192 feet.
4) Possible provision to temporarily block the existing M4 aperture with about four feet of steel just after the target box.

Single Crystal: A silicon single crystal 3.7 cm long and 1.6 mm wide with the (110) plane in the major face of the crystal should be able to deflect the beam the necessary 12 milliradians or so. It is not necessary that the crystal have an intrinsic detector implanted on it. Going to a germanium crystal would increase the angular acceptance by about 25%. The present E660 silicon crystals could be used for the septum although a slightly thicker crystal would be preferable.

For the septum the crystal deflection would be fixed. The tolerance for how accurately the bend has to be established is moderated by two factors - the angular acceptance of the M4 sweeper and the angular width of the primary beam and the secondary production cone. The beam divergence is several hundred microradians. The acceptance of the M4 sweeper is ±2 inches while the center of the acceptance is about 20 inches from the beam line. This leads to an acceptance of ±1.25 milliradians. In effect the angle of deflection must be set prior to installation to about 10%. The best way to do this would be by using the E660 apparatus in M4. Laser surveying has also been used and should be able to produce the required precision. Some care must be taken that the bend is all in the y direction. Twisting the bend by a tenth of a <u>radian</u> would cause it to miss the sweeper horizontal aperture.

The aspect angle and vertical position of the septum should be adjustable so that the initial capture angle direction of the crystal can be optimized. Note that the crystal aspect angle does <u>not</u> have to be set to the tolerance of the critical angle but to the beam angular divergence. Provision should be incorporated to remotely remove the whole septum from the principal beam such as M2. This could be done by making the extent of the vertical travel below the beam large enough so that the septum could be moved well below the beam. Figure 4 shows a schematic representation of a possible crystal holder.

A precision goniometer element belonging to the State University of New York (Albany) is available for the angle control. Some care would need to be taken to keep the stepping motor well out of the radiation field, probably by mounting the crystal on the end of a rod several feet long.

Principal Beam Vacuum Pipe Modification: The modification required on the principal beam pipe is straight-forward. Fifteen to twenty feet of new pipe would be built with an escape window for the downward deflected beam. Note that in M2 this portion of the pipe also serves M1 and that the pumping port is close to the 55 foot location. The new pipe would have to be installed in a rather hot area. On a typical Thursday afternoon the level is down to the point where two workers using their week's radiation allotment could install it. Downsteam of the modification about 60 feet of new pipe would be installed. A few unistrut clamps might have to be repositioned. This should be relatively straight-forward since access is not bad.

M4 Vacuum Pipe Modification: This region is somewhat more difficult mechanically but not as hot. About twenty feet of new enlarged vacuum pipe would be needed upsteam of the sweeper. This would have to be slipped in as a series of short pipes to join a 4 inch sleeve fitting at the sweeper and another coupling upstream. The existing pipe would not be removed but laid to the side several inches away.

The biggest clearance difficulties in the present arrangement is the stand of the M2 vertical vernier at 150 feet which clears the existing tube by about 1/2 inch and the first M2 quadrupole stand which clears by 2 inches. Some modification would definitely have to be made on the stands. Note that the vernier is next to the downstream end of the M2 fixed collimator, a hot a hot object. Again it appears possible for several people to make the modification with about a week's badge exposure. No vacuum pipe would be installed in this region which would result in some beam divergence degradation by multiple scattering.

Temporary M4 Beam Stop: Iron brick could be rapidly positioned on a ready built table in the trench just after the target box. No surveying would be necessary and the job could be done quickly. In particular the bricks could be removed very quickly. Again this is a hot area.

Such a stop is not absolutely necessary, particularly if the beam is operated above 200 GeV/c. For the test it guarantees that most of the beam is coming from the crystal. On the other hand the sweeper also has somewhat the same effect. We know from sad experience that the sweeper can kill the M4 beam.

CRYSTAL SEPTUM RUN-IN

With the M4 beam properly set on a particular momentum there will be three parameters associated with the crystal septum that can be varied: the septum aspect angle, the septum vertical position, and the current in the M4 sweeping magnet. It would be desirable to provide some sort of front-end monitor on the septum, possibly a charge loss monitor similar to the arrangement used on the production target. The crystal would probably be moved to a point about a half inch below the primary beam using such a monitor. The crystal aspect angle and the sweeper current would then be scanned in a two dimension grid roughly corresponding to

100 microradian steps. A single beam pulse would be sufficient for each point. Such a scan might take an hour. Introduction of some sort of flux monitor just before or after the sweeper could reduce this to a one dimensional scan. Once the crystal direction was established it would not have to be changed for different beam energies. The sweeper current would change but in a calculable way.

The bottom line in crystal septum performance will be particle flux. The flux would have to be measured at several different energies. One strategy would be to tune the beam at +175 GeV/c and measure its yield just before a Thursday shutdown. After the septum was installed the system would be retuned with the M4 target box aperture blocked. The optics would be readjusted at that momentum to the unfocussed Y mode. The beam momentum would then be scaled up to 300 GeV/c. Such tests could be done in a day or so. It should be recognized that there could be plenty of surprises so that the possibility of initial failure is well understood.

It would be useful to leave the crystal in place and repeat the tests several times in the following weeks to see if any radiation damage problems developed.

ACKNOWLEDGEMENTS

The author would like to thank A. Jonckheere, D. Green, and R. Dixon for much helpful information on the Meson Area beams. The original idea of the crystal septum is due to Aldo Menscione and John Elias. Members of E660 including C.R. Sun, W. Gibson, and S. Baker have discussed the septum idea at some length.

APPENDIX I - TRANSMISSION OF CRYSTAL

The transmission of a crystal can be estimated by the following formula:

$$E = E_c E_b f_s f_\theta f_d f_v$$

where

E is the fractional transmission of the crystal.

E_c is the initial capture efficiency of particles incident within channeling phase space. (This should be 1, but present preliminary data from E660 suggests less than 2/3)

E_b is the bending transmission in channeled planes ($1-F(\Gamma)$ in the notation of Ellison[5]). Very preliminary data from E660 shows that the transmissions are less than or equal to the $X_c = 1 - 2/D$ curves in Ellison. This is deduced by deflection curves such as Figure 5 which show the outgoing distribution of particles after the crystal. The intermediate points are due in part to ordinary dechanneling. Figure 6 compares the bending dechanneling to Ellison's theory.

f_s is the fractional spatial acceptance in the direction of the bend in either a primary or secondary beam. If the beam width is $2x_b$ and wider than the crystal this is $t/2x_b$ where t is the crystal thickness.

f_θ is the fractional angular acceptance in the direction of the bend. If the beam half width is θ_b and is larger than the critical angle then $f_\theta = \psi_c/\theta_c$.

f_d is the fractional transmission resulting from ordinary dechanneling. For some bend length L with unbent ends u and a dechanneling length λ_o at a momentum p_o this can be estimated as

$$f_d = \exp\left\{\frac{-(L+u)}{\lambda_o}\ \frac{(p_o)}{p}\right\}$$

since it is expected that the dechanneling length will increase linearly with momentum. Results from E660 are not yet clear. Here λ_o is taken as 4 cm at 100 GeV/c.

f_v is the fractional spatial acceptance perpendicular to the bend. For silicon it is easy to make this 1.

Now $\pi\theta_b\ x_b = \phi$, the beam phase space. Thus the transmisson is

$$E = \frac{\pi}{2}\ E_c\ E_b\ \frac{(t\psi_{co})}{\phi}\sqrt{\frac{p_o}{p}}\ \exp\left\{\frac{-(L+u)}{\lambda_o}\ \frac{p_o}{p}\right\}$$

where ψ_{co} is the critical angle at the momentum p_o.

At this point it is useful to consider the phase space for both the primary beam in M-Center and a typical secondary beam and then to compare them to the acceptance of the crystal.

Figure 7 shows schematic representations of the emittance of the M-Center primary beam[10] at the target (a) and 55 feet downstream (b), the acceptance of the crystal (c), and the emittance of a typical secondary beam as set by magnet apertures (d,e). Note that since the acceptance of the crystal is so small it would take a very long drift to rotate phase space enough to begin to cut off corners of the crystal acceptance. The crystal might be better matched if it was placed after a quadrupole which forced the beam parallel.

The transmission has been calculated for a secondary beam as a function of momentum for a particular case. A silicon crystal 1.6 mm thick (equivalent to the present meson target thickness) should be able to be bent to a minimum radius of 120 cm. To be conservative a bending radius of 240 cm is used. The crystal length is taken as 3.7 cm corresponding to a bend of 13.3 mrad (slightly larger than the actual bend that is needed.) The transmission is

p (GeV/c)	E
50	$.48 \times 10^{-3}$
100	$.80 \times 10^{-3}$
200	$.78 \times 10^{-3}$
400	$.44 \times 10^{-3}$

These numbers suggest that it might be possible to get fluxes of up to 10^5 particles/pulse down the M4 beam line at high momentum.

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11. Alterton et. al., CERN 80-07 (1980).

Figure 1 - Vertical schematic of the M2/M3 and M4 beams. Notice the crystal septum at 54 feet deflecting down to the M4 sweeper with an 11.9 mrad deflection. The most difficult beam clearance point is on the vertical vernier stand in M2.

Figure 2 - Positive yield per unit momentum as a function of the M4 beam at 400 GeV/c. The solid curve is based on a model to CERN 300 GeV/c data in CERN 80-07[11] at 1.75 mrad. The dotted curve is the same function plotted for 8.25 mrad corresponding to M4. Both are corrected for decay. The dashed curve is the yield observed in E660 in M4 multiplied by 1/p to correct for momentum acceptance considerations. Notice that by 200 GeV/c the two production distributions are expected to differ by four orders of magnitude. The experimental M4 points do not agree at low momentum but are falling rapidly at high momentum.

Figure 3 - Typical rays for M4 equipped with a crystal septum. The beam in the direction of the bend is allowed to blow up so that image grows to ±1.5 inches in the M4 pit.

Figure 4 - Schematic of a possible crystal septum holder. The crystal bend is rigidly fixed. The height and aspect angle to the beam can be varied. Beam monitors attached to the crystal holder help to position the septum.

Figure 5 - Preliminary data from E660 for the angular distribution out of a crystal bent through a total of 9.6

milliradians. The beam momentum is +120 GeV/c. Some of the incident beam feeds through because the angular cut on the incident beam is not prefectly confined to the critical angle. There is some beam spill at about 5 milliradians because the three point suspension has a high curvature at the midpoint. In between there is some loss due to ordinary dechanneling.

Figure 6 - Bending transmission predicted by the more conservative form of Ellison theory. The point shows the actual transmission found from Figure 5.

Figure 7 - Phase space for the M-Center primary beam and M4 at the target and 55 feet downstream. (c) shows the admittance of the crystal septum.

VERTICAL SCHEMATIC OF M2/M3 AND M4

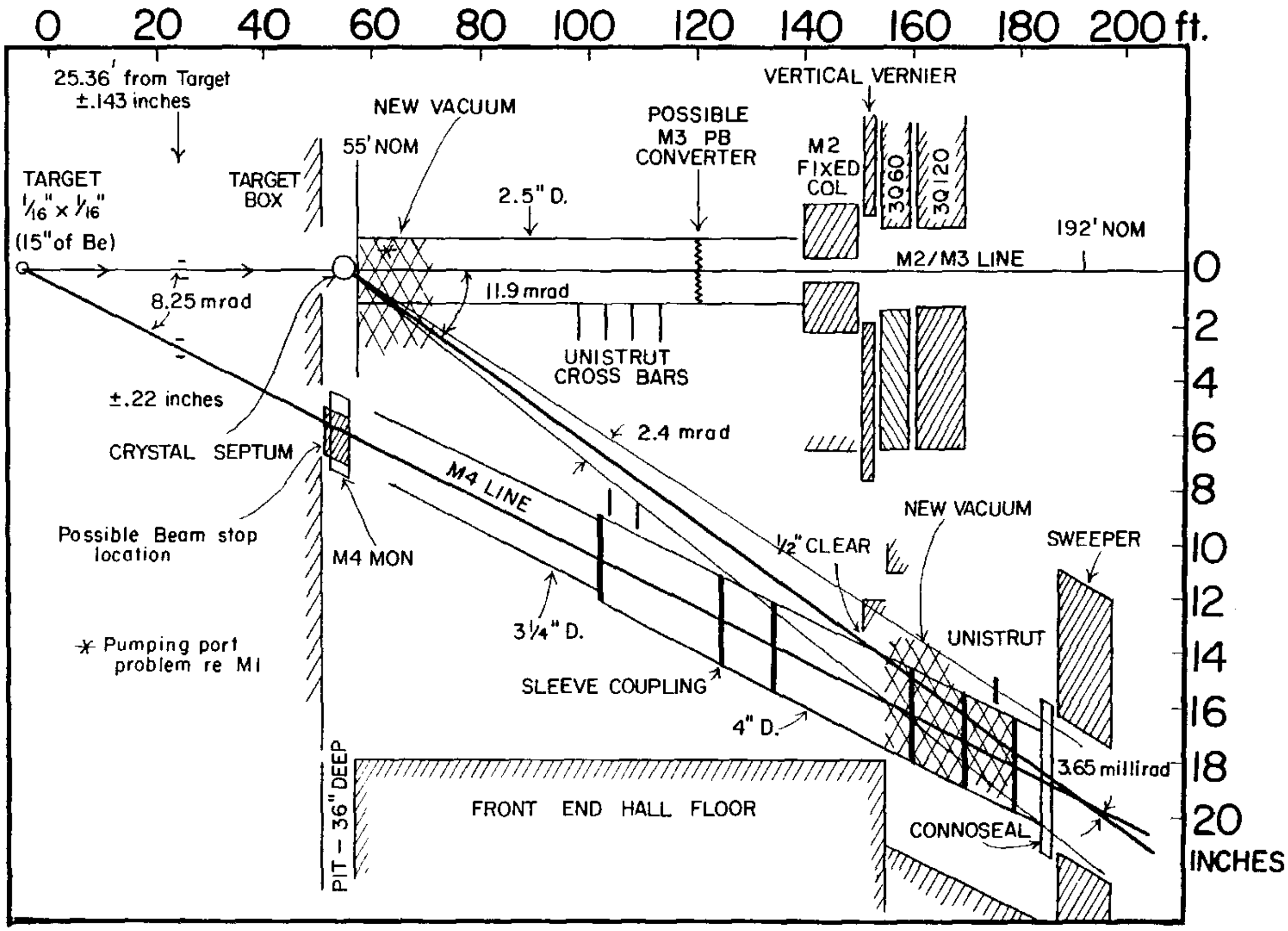


Fig. 1

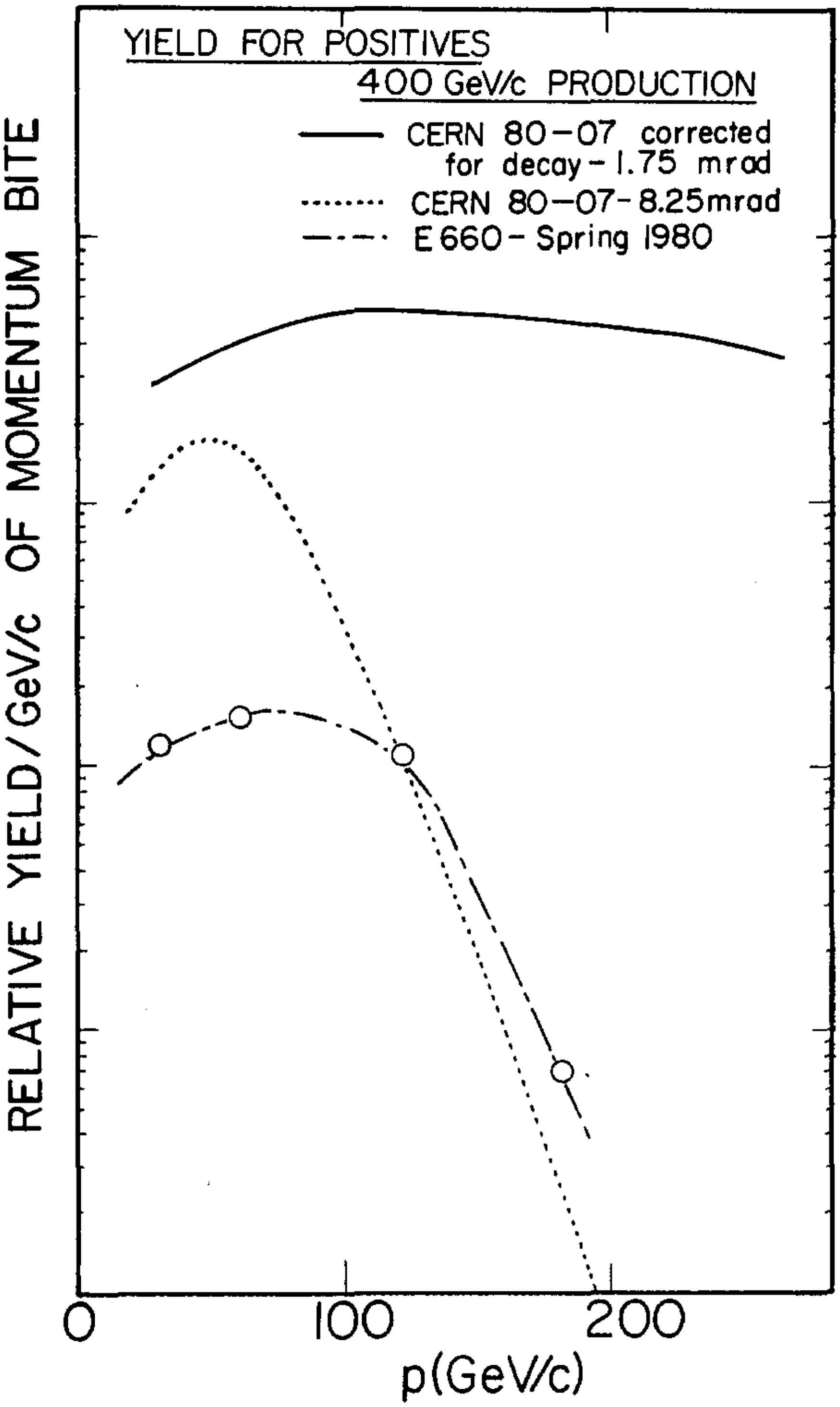
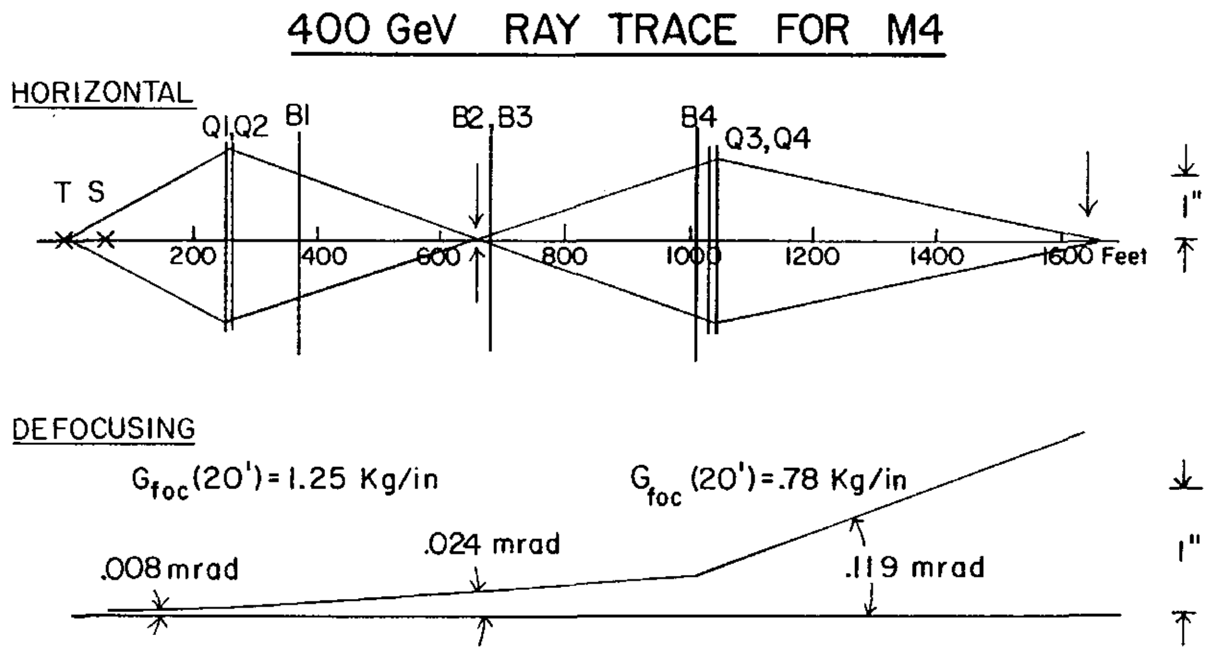

YIELD FOR POSITIVES
400 GeV/c PRODUCTION
CERN 80-07 corrected for decay - 1.75 mrad
CERN 80-07 - 8.25 mrad
E660 - Spring 1980
RELATIVE YIELD / GeV/c OF MOMENTUM BITE
0
100
200
p(GeV/c)

Fig. 2



400 GeV RAY TRACE FOR M4

HORIZONTAL

DEFOCUSING

Fig. 3

GONIOMETER SYSTEM FOR CRYSTAL SEPTUM

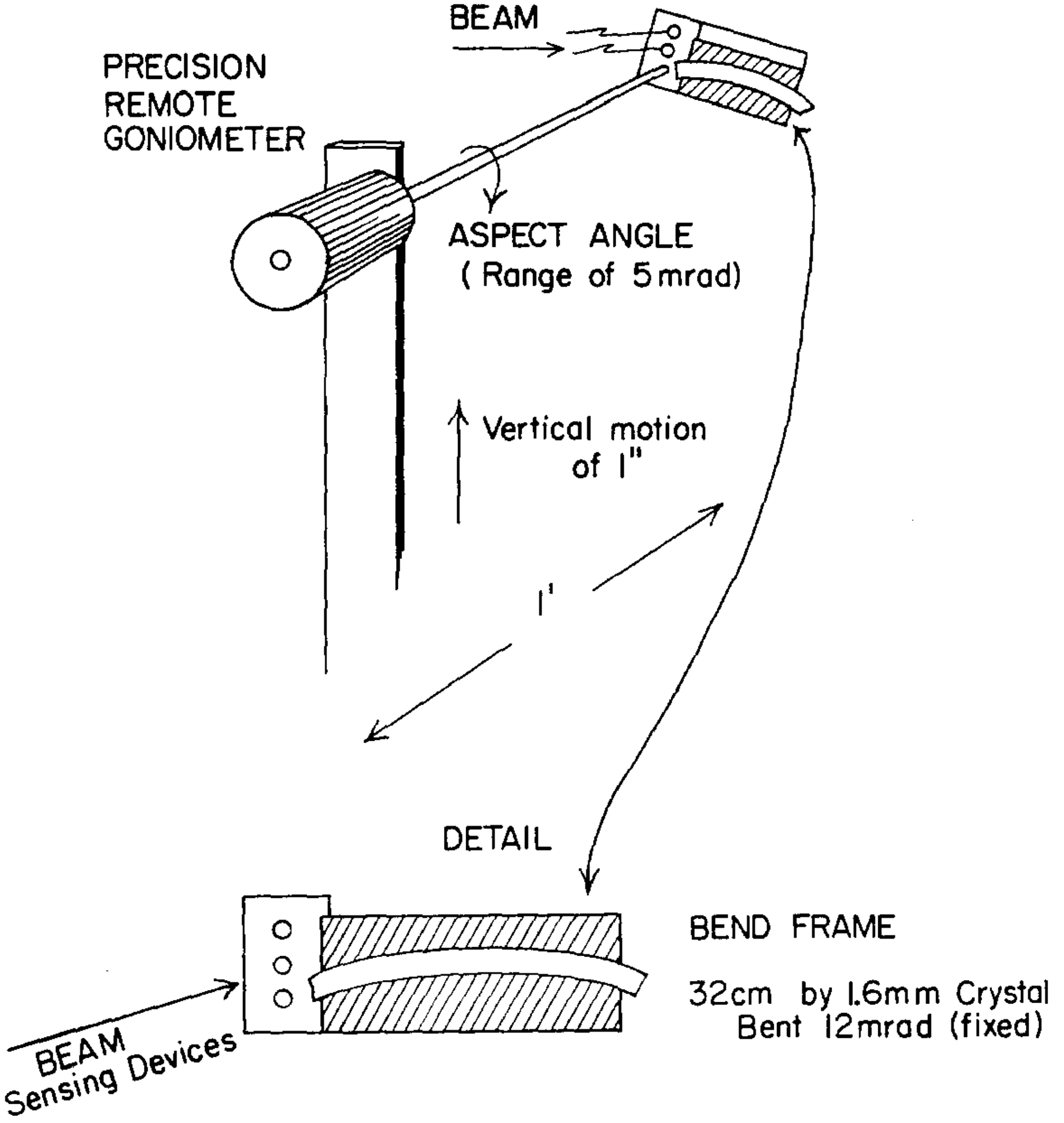


Fig. 4

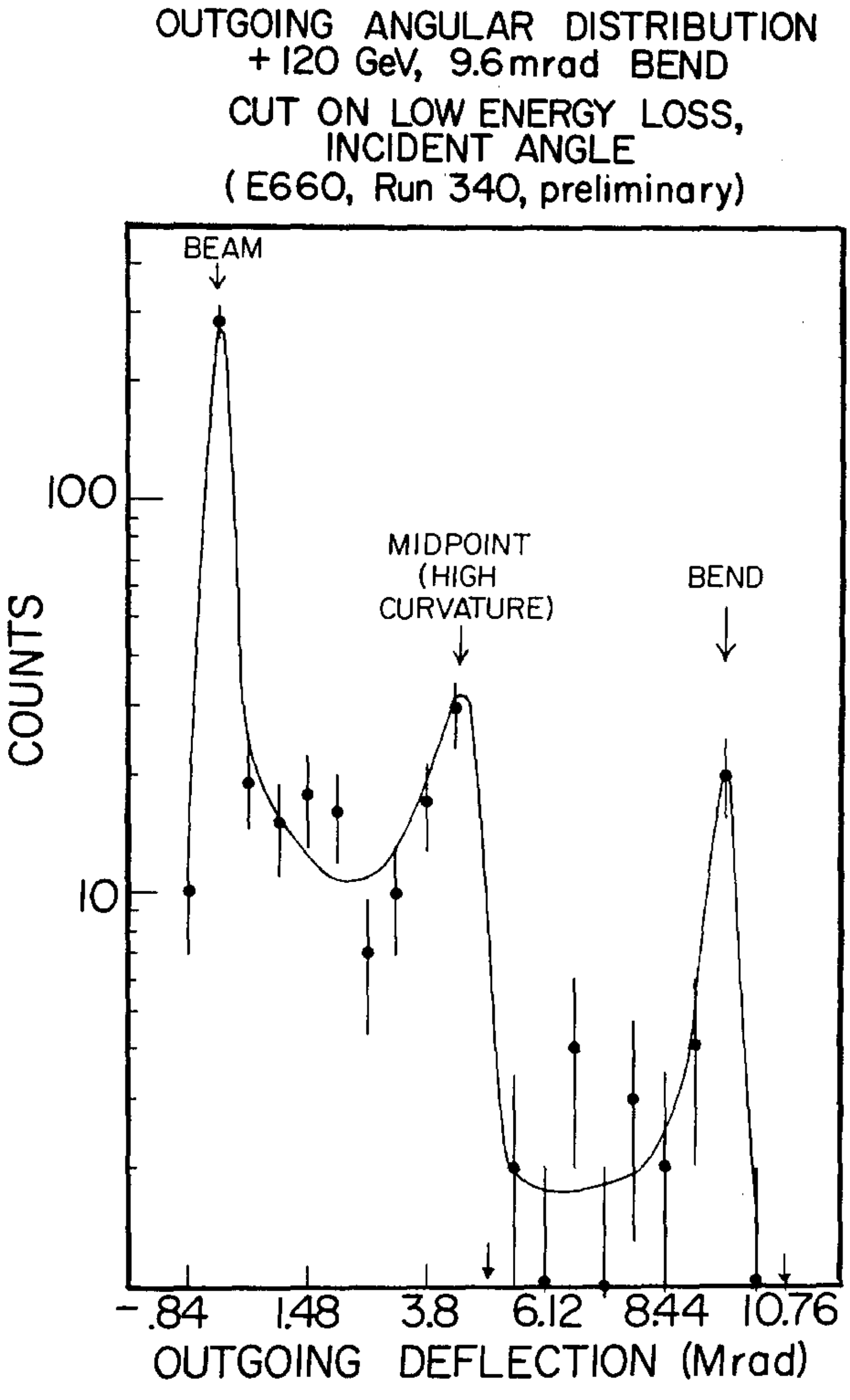

OUTGOING ANGULAR DISTRIBUTION
+120 GeV, 9.6 mrad BEND
CUT ON LOW ENERGY LOSS,
INCIDENT ANGLE
(E660, Run 340, preliminary)
BEAM
100
10
COUNTS
MIDPOINT
(HIGH
CURVATURE)
BEND
-.84
1.48
3.8
6.12
8.44
10.76
OUTGOING DEFLECTION (Mrad)

Fig. 5

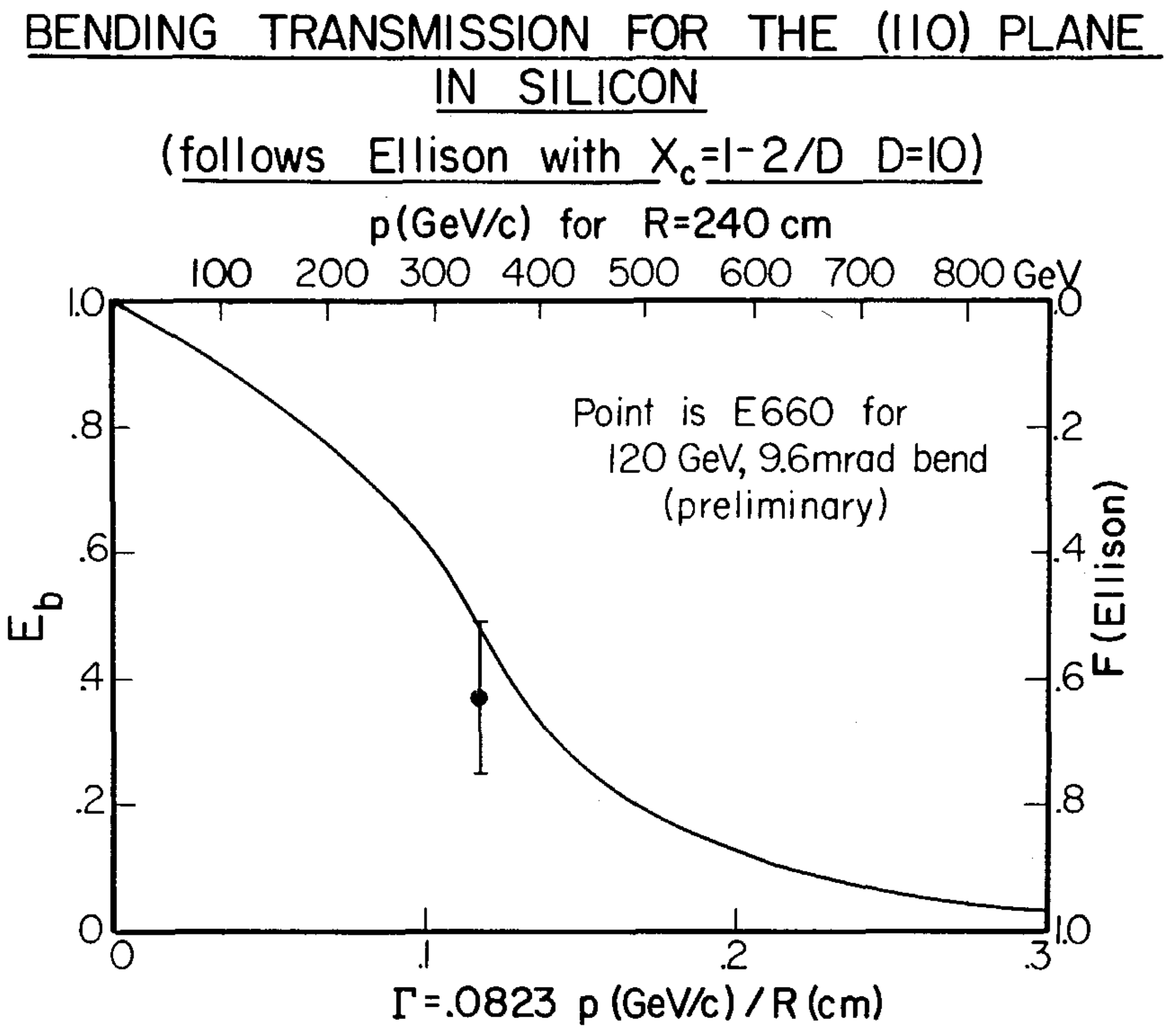

BENDING TRANSMISSION FOR THE (110) PLANE IN SILICON
(follows Ellison with X_c=1-2/D D=10)
p(GeV/c) for R=240 cm
100
200
300
400
500
600
700
800 GeV
1.0
.8
.6
.4
.2
0
E_b
.0
.2
.4
.6
.8
1.0
F (Ellison)
Point is E660 for
120 GeV, 9.6mrad bend
(preliminary)
0
.1
.2
.3
Γ=.0823 p (GeV/c) / R (cm)

Fig. 6

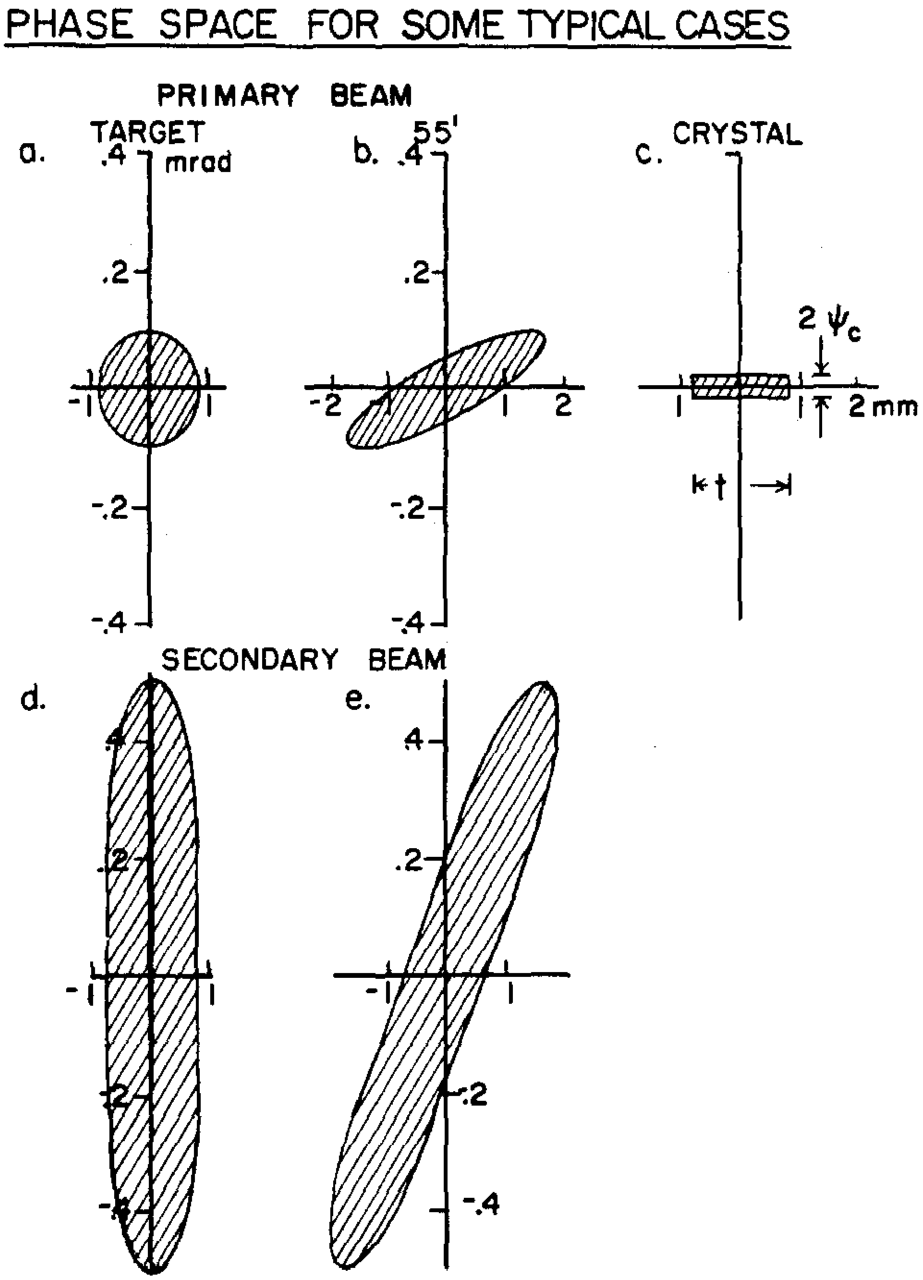

PHASE SPACE FOR SOME TYPICAL CASES
PRIMARY BEAM
a.
TARGET
mrad
.4
.2
-.2
-.4
-1
1
b.
55'
.4
.2
-.2
-.4
-2
-1
1
2
c.
CRYSTAL
$2\psi_c$
1
1
2 mm
t
SECONDARY BEAM
d.
.4
.2
-.2
-.4
-1
1
e.
.4
.2
-.2
-.4
-1
1

Fig. 7