TM-324
0510

SCATTERING EXTRACTION WITH THE WIRE SEPTUM

J. A. MacLachlan

October 14, 1971

Resonant extraction requires close control of the betatron tune ν_x, the guide field, and the sextupole field for the duration of the spill; a standard fast extraction requires a kicker with a rise time less than the beam revolution period. However, any method which will perturb the circulating beam so that it moves from a stable inside region to an unstable outside region may be used to extract the beam. If, as is true with a wire septum, the division between inner and outer regions is very narrow, the perturbation can be quite small.[1] It has been suggested that multiple scattering by the septum itself is an adequate extraction mechanism for early operation of the accelerator.[2] The effectiveness of this technique depends on the scattering efficiency of the septum and the angular distribution of the outscattered particles. If those particles scattered toward the inner stable region are within the machine acceptance they may be successfully extracted on a succeeding turn. In this note results for the angular distribution and scattering efficiency are presented and used to estimate the extraction efficiency.

The septum used in the calculations consists of 2 mil tungsten wires spaced 50 mils on centers. The beam is supposed to be swept very slowly onto the septum by a bump magnet with rise time $\gtrsim$10 msec. Because the phase ellipse is nearly upright at the septum and the sweep is very slow, the beam is shaved where the divergence is small and the use of a parallel beam in the calculation is a good approximation. The effect of the septum in x-x' phase space is sketched in Fig. 1.

The "whiskers" on the beam ellipse are produced by the scattering. As shown in the figure, half of each whisker is immediately extracted, and if earlier whiskers are short enough to survive they will eventually be extracted as well.

The outscattering of the septum at 200 GeV has been found from two different Monte Carlo calculations. As a first approximation, which one would expect to be quite good, the septum can be treated as a uniform density foil with

$$\rho = \rho_o \pi r^2/(2rd) = 19.3\pi/2x50 = .61$$

where ρ_o = 19.3 is the density of tungsten, r = .00254 cm is the wire radius, and d = .127 cm is the wire spacing. The scattering problem is then nearly completely treated by the Fortran subroutine MONACO used to calculate the outscattering of the main ring abort dump.[3]

The results of this approach are presented in Figures 2-6 for 4000 particles. The fraction of the beam undergoing nuclear interactions is 14%. Figure 2 gives the angular distribution in the horizontal projection. The divergence of the fractions scattered into and out of the accelerator are seen to be .24 mrad

FWHM. Fig. 3 shows the longitudinal distribution of the out-scattering. The obvious discontinuity in this plot reflects the large sampling distance (32 cm) appropriate to very low density. Fig. 4 gives the vertical angular distribution which has a FWHM of .4 mrad. Fig. 5 shows the vertical spread introduced by the scattering assuming a ribbon beam incident. Fig. 6 gives the longitudinal distribution of nuclear interactions.

The results above are encouraging, but one might hope for somewhat higher efficiency and less angular spread introduced into the beam. The structure of the septum should give slight improvements in both respects. Therefore, a calculation in which the wires were treated as discrete scatters was made. Because the wires are only ~.01 radiation length in diameter a thin foil correction of ~30% to the multiple scattering formula was used:[4]

$$\theta_{rms} = \frac{.015}{p}\sqrt{x/x_o}(1+\varepsilon)$$

$$\varepsilon = .14 + .06\ \log(x/x_o) \quad (x<.1x_o),$$

where θ_{rms} is the root mean square projected scattering angle, p is the momentum in GeV/c, x is the thickness of the scatter, and x_o is the radiation length.

Figures 7-11 present these results and correspond to Figures 2-6, respectively. The fraction of the beam interacting in the septum is 7% and the horizontal spread of inside and outside components is .16 mrad FWHM. The vertical angular spread is .24 mrad FWHM. Thus, in both important respects the wire septum is superior to a low density foil of the same Z.

The 93% outscattering efficiency of the septum represents an upper limit on the extraction efficiency because there remains the question of the efficiency of extracting the fraction of the beam scattered inward. Vertical scraping of the beam may be expected to be greatest where β_y is largest and the phase advance is an odd multiple of $\pi/2$. Without making any special assumptions about ν_y one can say that likely as not the phase will be approximately right for maximum loss at one of the points in the long straight where $\beta_y = 123$ m on every turn. At this point the vertical width will be

$$w_y = \sqrt{\beta_{ys}\beta_{max}}\, w_w = \sqrt{28 \times 96} \times 3 \times 10^{-4} = 1.56 \times 10^{-2} \text{ m}$$

where β_s and β_{max} are the vertical β's at the septum and the maximum point, respectively, and w_w is the angular half width of the whisker in radians. The whisker width was taken to include 90% of the scattered particles. The height of the beam at β_{max} is within the nominal aperture[5] but not with great margin of error. At the very least one must expect to lose the 10% of the beam outside of w_w or ~5% of the total beam.

Within the bump which extends from F46 to A17 the whisker points in the ±x direction at points A12 and A17 where the bumped beam is on the central orbit (see Fig. 12). For arbitrary ν_x one must expect the whisker to point approximately in the ±x direction at some point where β_x has its maximum value 123. The horizontal half width will then be

$$w_x = \sqrt{\beta_{xs}\beta_{max}}\, w_w = \sqrt{96\text{x}123} \cdot 2.8\text{x}10^{-4} = \pm.03 \text{ m}$$

where as in the vertical case w_w is the 90% angular half width of the whisker and β_{xs} is β_x at the septum. Again the 90% width just squeezes within the nominal aperture and ~10% of the inward scattered beam will be lost from horizontal phase space. Therefore, of the ~45% scattered in something like 10% is lost in both horizontal and vertical phase space. Thus the extraction efficiency η is something like

$$\eta \simeq .45 + .8 \text{ x } .45 = .8.$$

For that fraction which is scattered out it is necessary to know the acceptance of the extraction channel. The vertical half aperture of the vacuum pipe is not more than 7 mm. The scattered beam must pass through the doublet at F49 and then to about All before the vacuum chamber gets larger, a total run of 80 m. At this distance the whisker has rotated about $\pi/2$ and points in the -y direction; β_y is about 50 m. Thus the vertical extent of the beam is here

$$w_y = \sqrt{\beta_{ys}\beta_{A11}}\, w_w = \sqrt{26\text{x}50} \text{ x } - 3\text{x}10^{-4} = -1 \text{ cm}.$$

Reducing w_y to -7 mm excludes 15% of the extracted beam. Therefore, even with excellent vertical alignment one can expect to scrape 15% of the extracted beam vertically. Taking these figures together one gets η~.85[.45+.8x.45] = .7 as something like an upper limit for the efficiency of scattering extraction using the septum and a very slow bump. If the upstream guard septum with 150 mil spacing between wires is employed improvement can be expected as indicated by Maschke.[6] The addition of a guard septum is a trivial extension of the discrete wire calculation once the spacing and position are chosen.

These somewhat pessimistic results apply directly only for a bump rate as slow as one septum width per turn. If the bump rate is faster, they apply only to that part of the beam which hits the septum; presumably the rest is extracted perfectly. The present bump magnets can kick the beam width of 1 cm in 10-20 turns. Then only about 10% of the beam hits the septum and the efficiency figure is

$$\eta \approx .9 + .7(.1) = 97\%.$$

In a very careful calculation one might wish to include the effect of beam divergence in the several slices that the septum takes in x-x' space.[7] To some approximation the result is to broaden the angular distributions by the beam divergence. Because the divergence is small the net effect on η is inconsequential for the beam output if not for the irradiation of accelerator components.

ACKNOWLEDGEMENT

I would like to thank Lee C. Teng and Donald A. Edwards for helpful discussion.

REFERENCES

1. L.C. Teng, private communication.
2. A.W. Maschke, private communication.
3. J. MacLachlan, T. Borak, M. Awschalom, TM-244.
4. J. Ranft, CERN/MPS/Int. MU/Ep 66-8.
5. Nominal aperture is taken as being set by a partial aperture abort system (L.C. Teng, TM-294) and therefore is a minimum value.
6. A.W. Maschke, FN-100.
7. W. Lee and J. MacLachlan, TM-256; and J. MacLachlan, T. Borak, L. Teng, F. Shoemarker, IEEE Trans. on Nucl. Sci., Vol. NS-18, No. 3 (1971) p. 981.

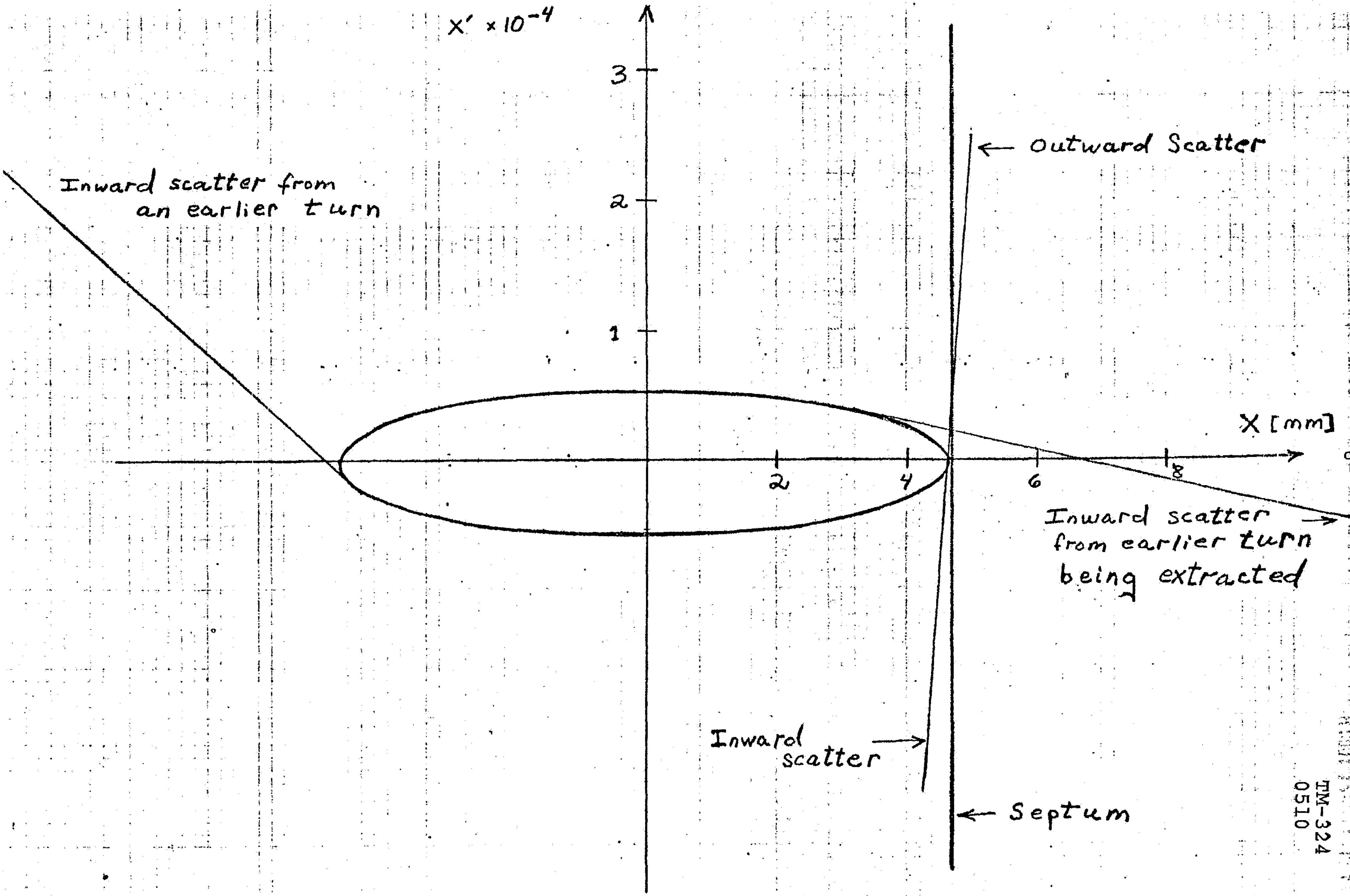
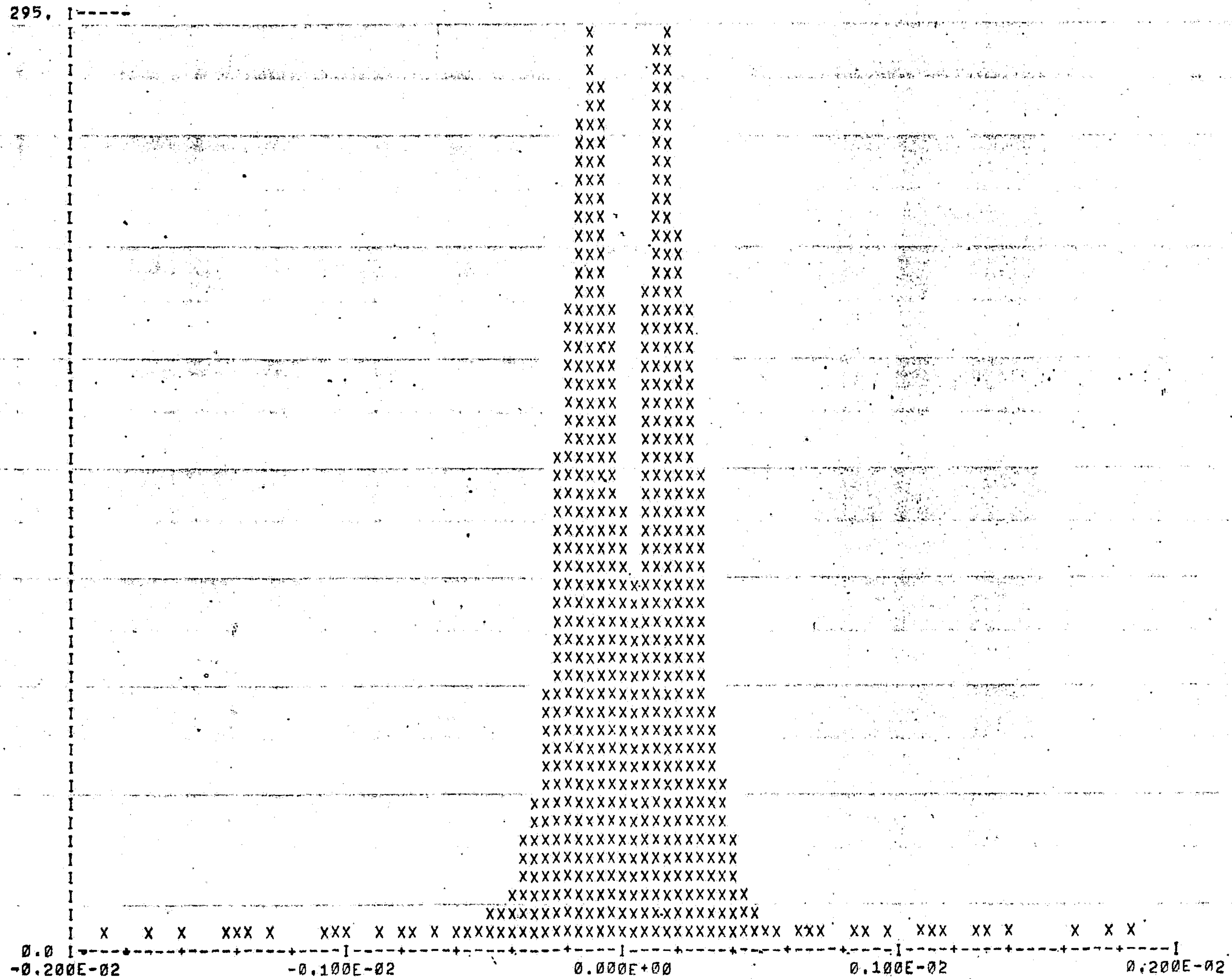


Figure 1: Scattering by the septum

TM-324
0510

THETA-X VALUES FOR PARTICLES SCATTERED OUT

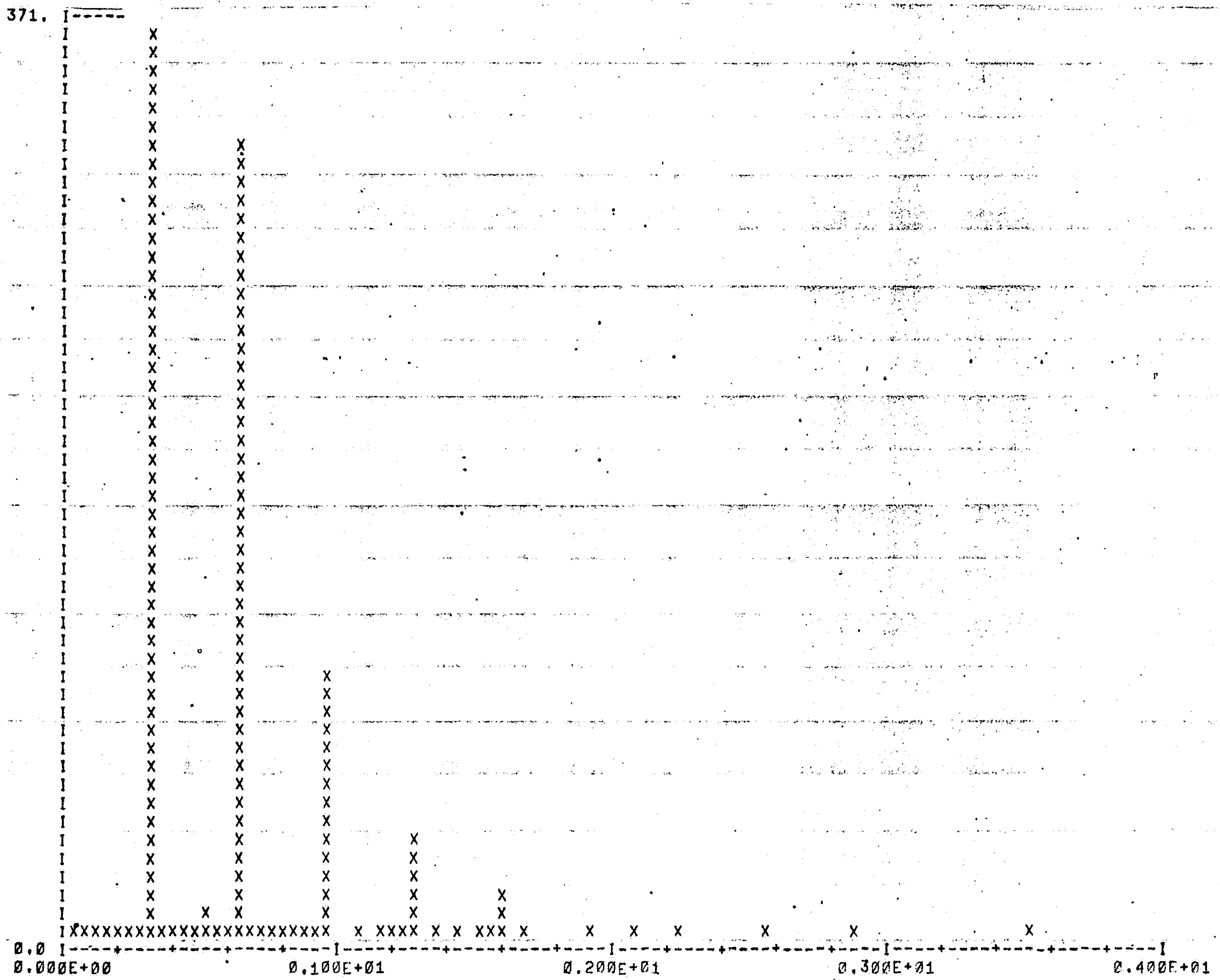
GRAPH 1



BIN SIZE IS 0.400E-04

POSITION ALONG BEAM OF OUT SCATTERING (M)

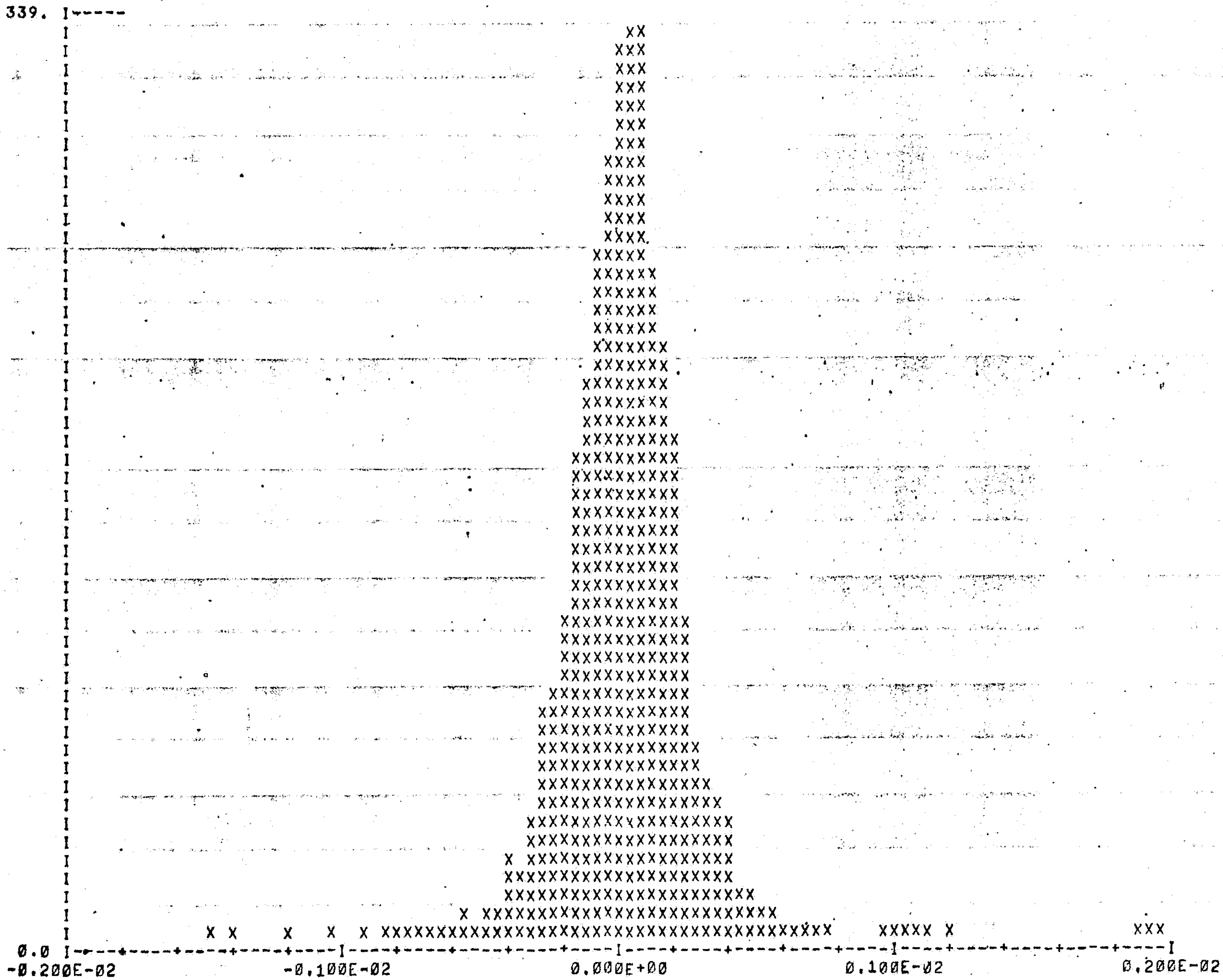
GRAPH 2



BIN SIZE IS 0.400E-01

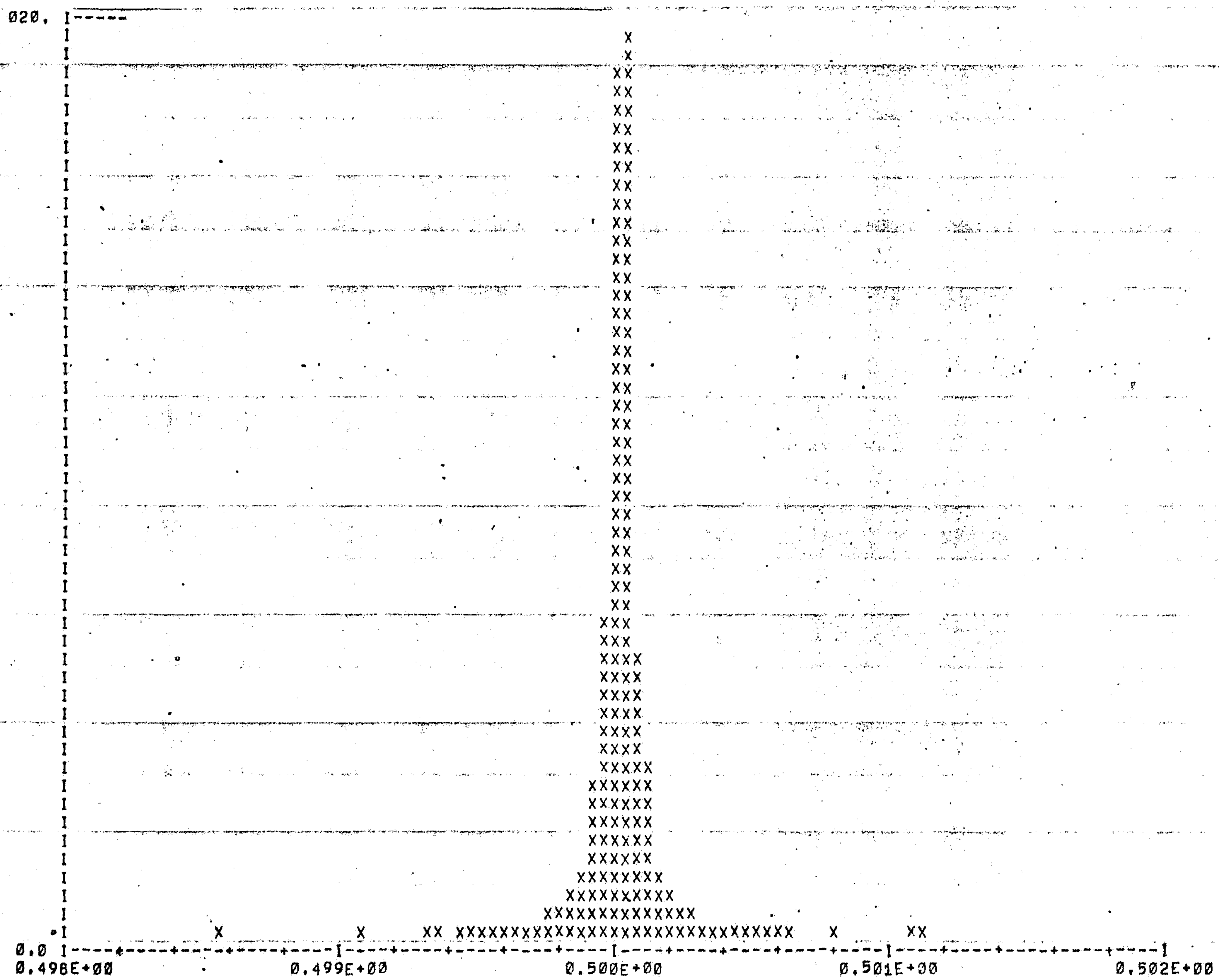
VERTICAL ANGLES (THY) OF OUT SCATTERED PARTICLES

GRAPH 3



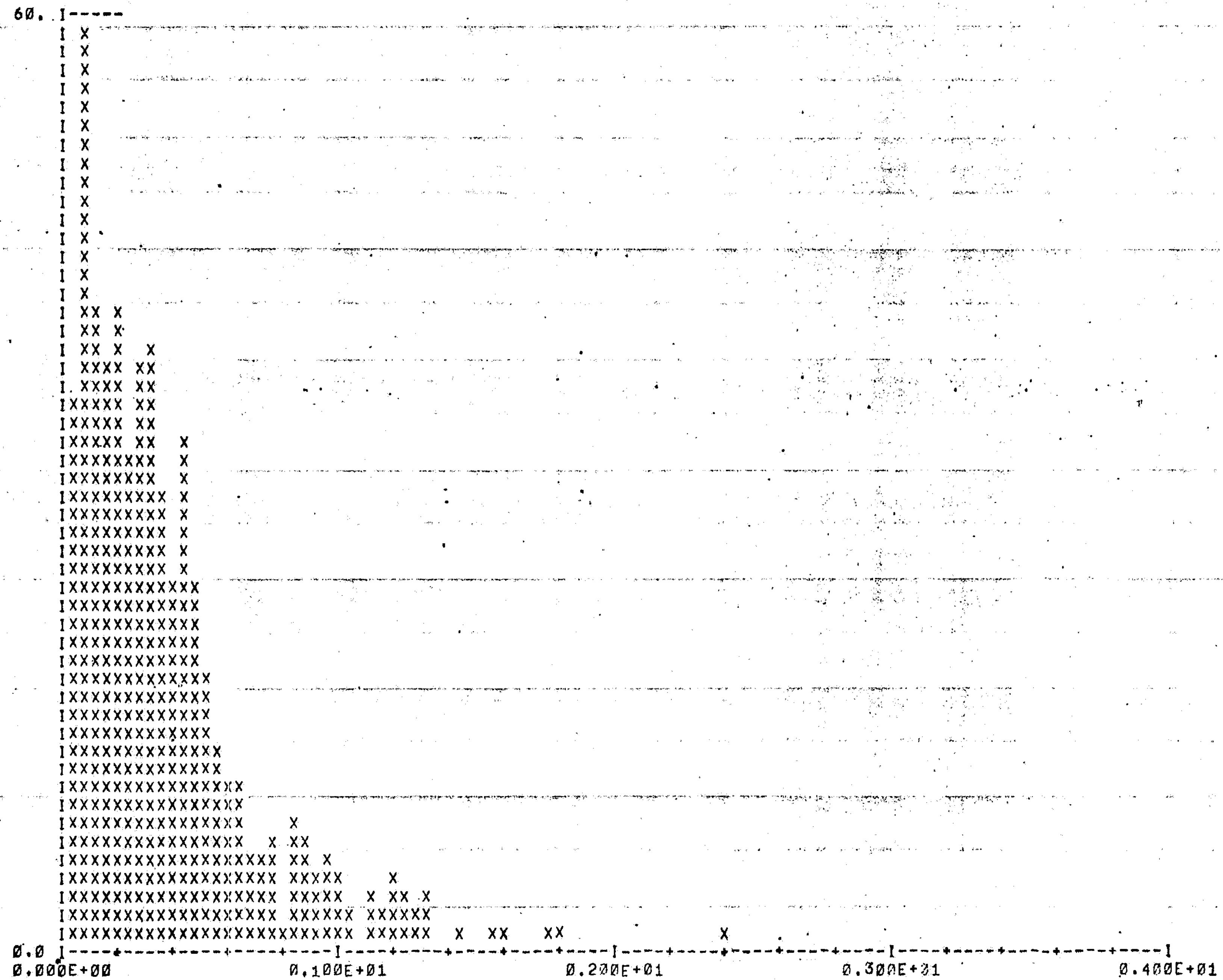
BIN SIZE IS 0.400E-04

VERTICAL DISPLACEMENTS (FROM .5) OF OUT SCATTERED GRAPH 4



BIN SIZE IS 0.400E-04

DISTRIBUTION ALONG BEAM OF STARS

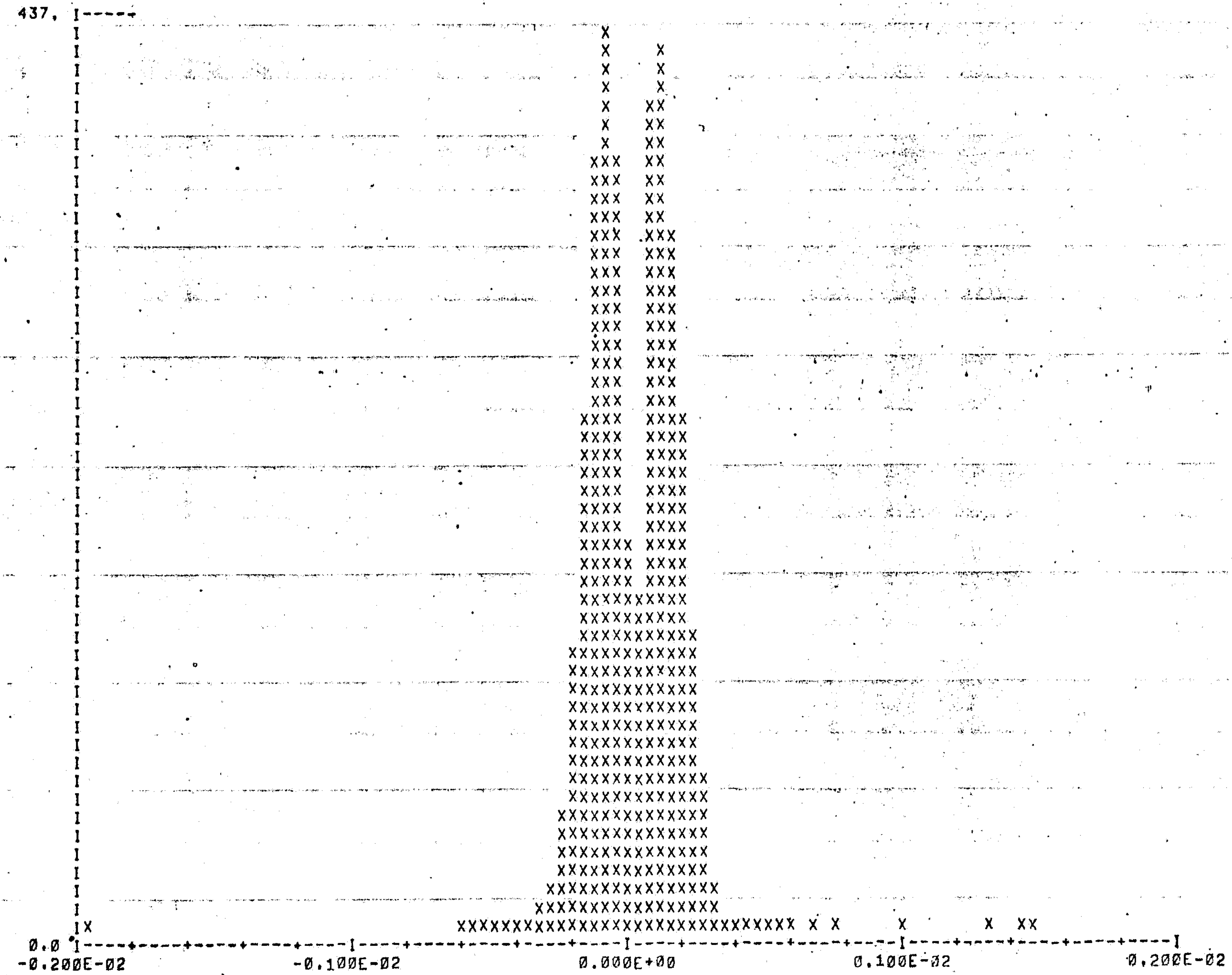


BIN SIZE IS 0.400E-01

UNSCATTERED= 0 SCATTERED= 3445 STARS= 555

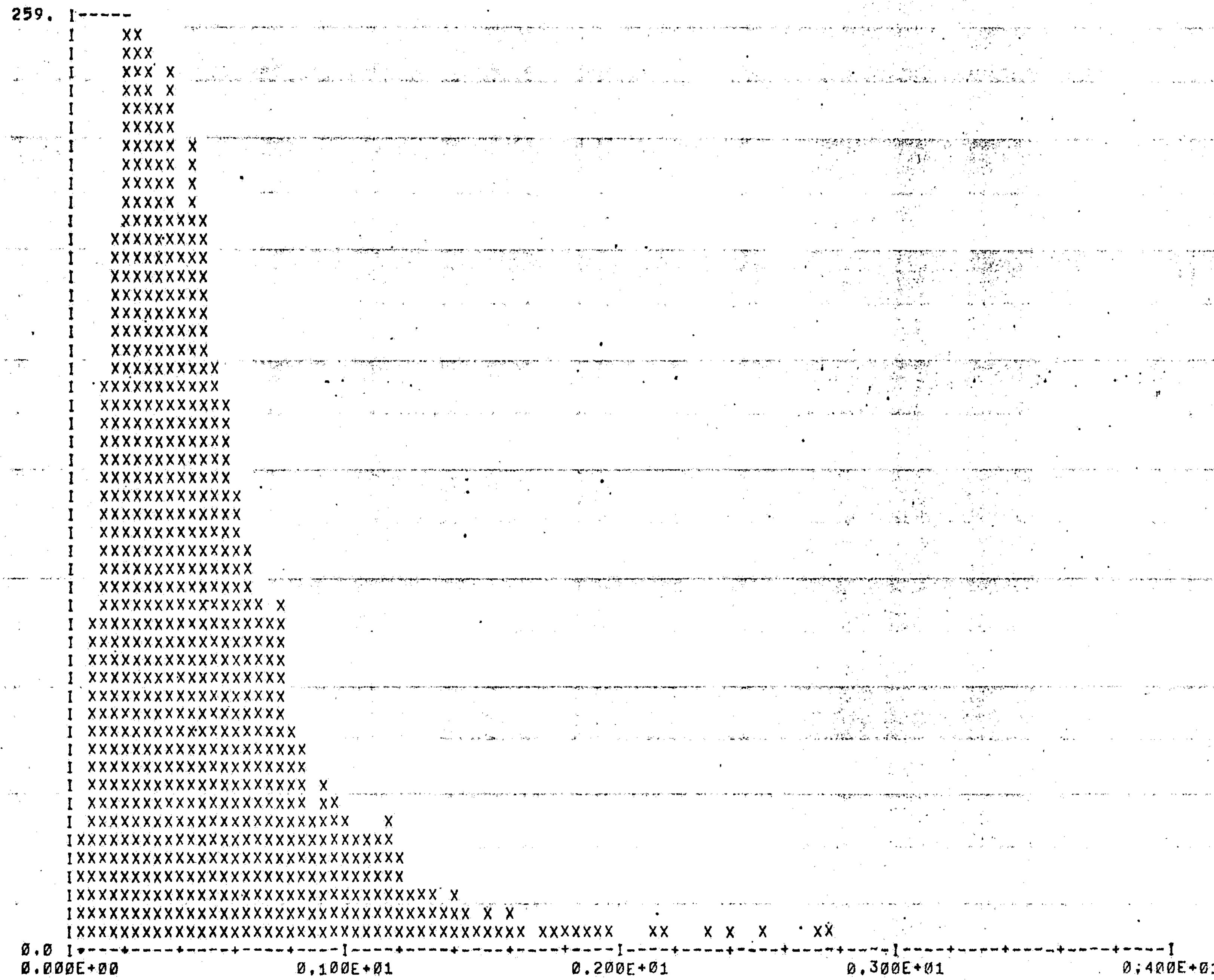
THETA-X VALUES FOR PARTICLES SCATTERED OUT

GRAPH 1



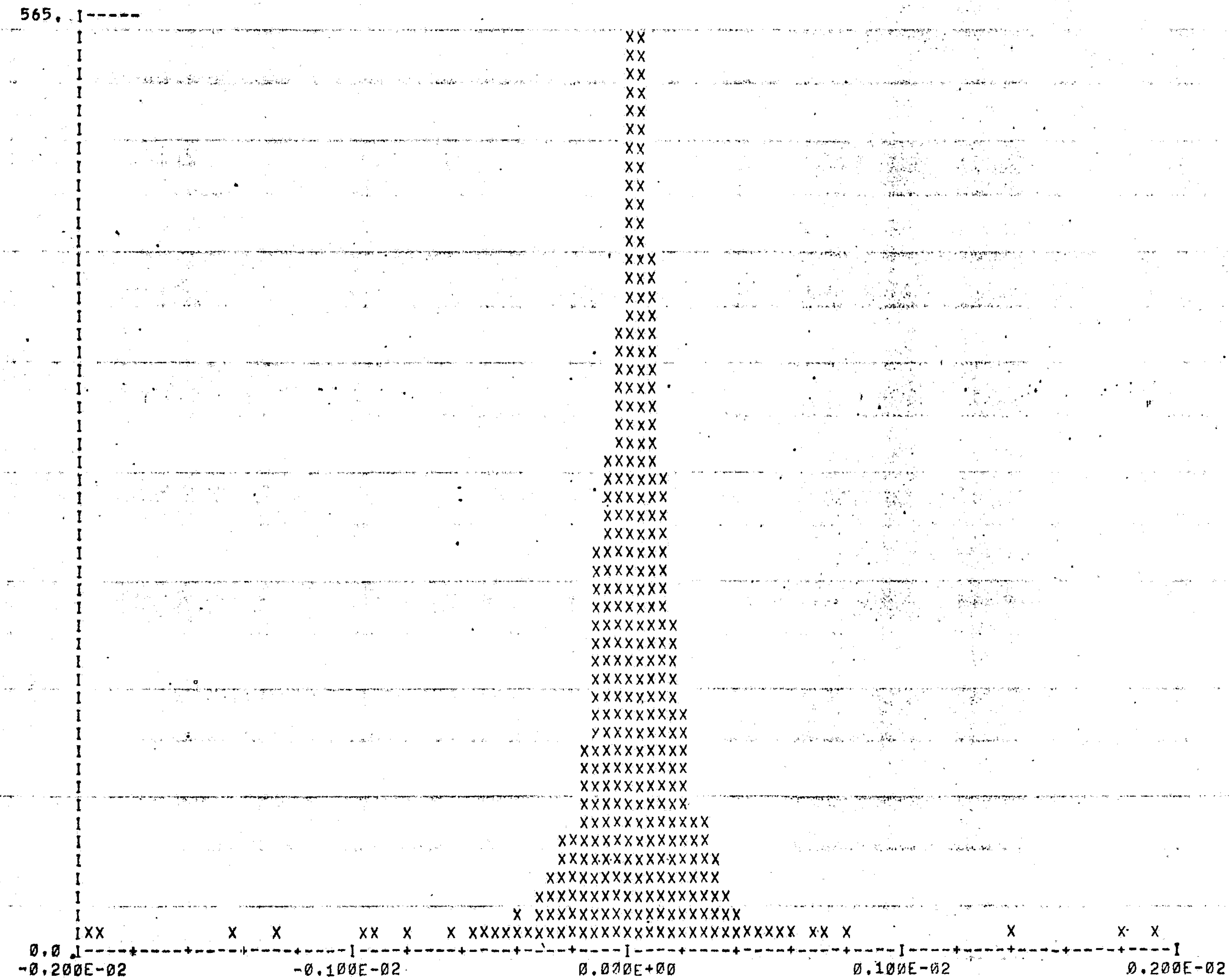
BIN SIZE IS 0.400E-04

POSITION ALONG BEAM OF OUT SCATTERING (M) GRAPH 2



BIN SIZE IS 0.400E-01

VERTICAL ANGLES (THY) OF OUT SCATTERED PARTICLES GRAPH 3

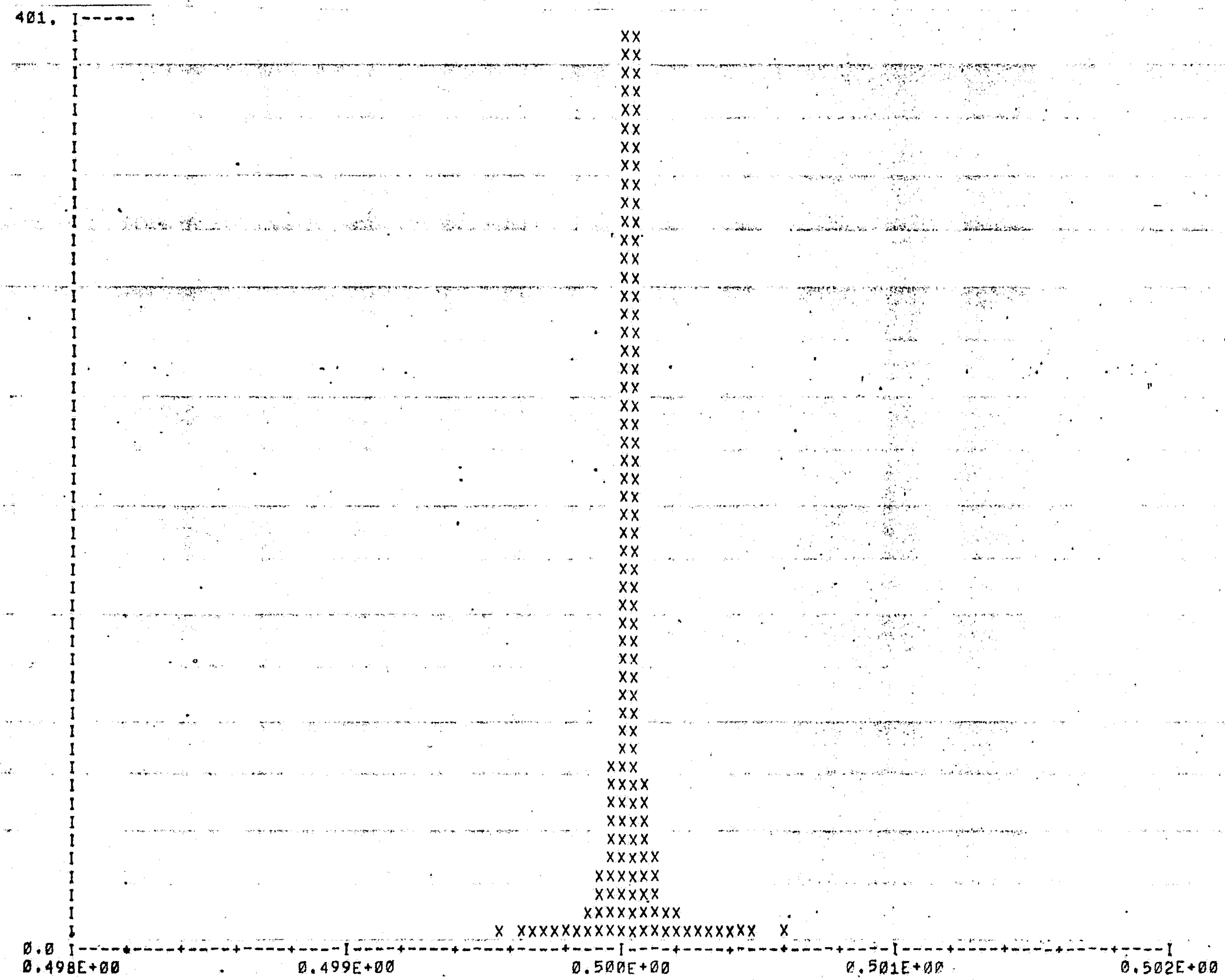


BIN SIZE IS 0.400E-04

TM-324
0510

VERTICAL DISPLACEMENTS (FROM .5) OF OUT SCATTERED

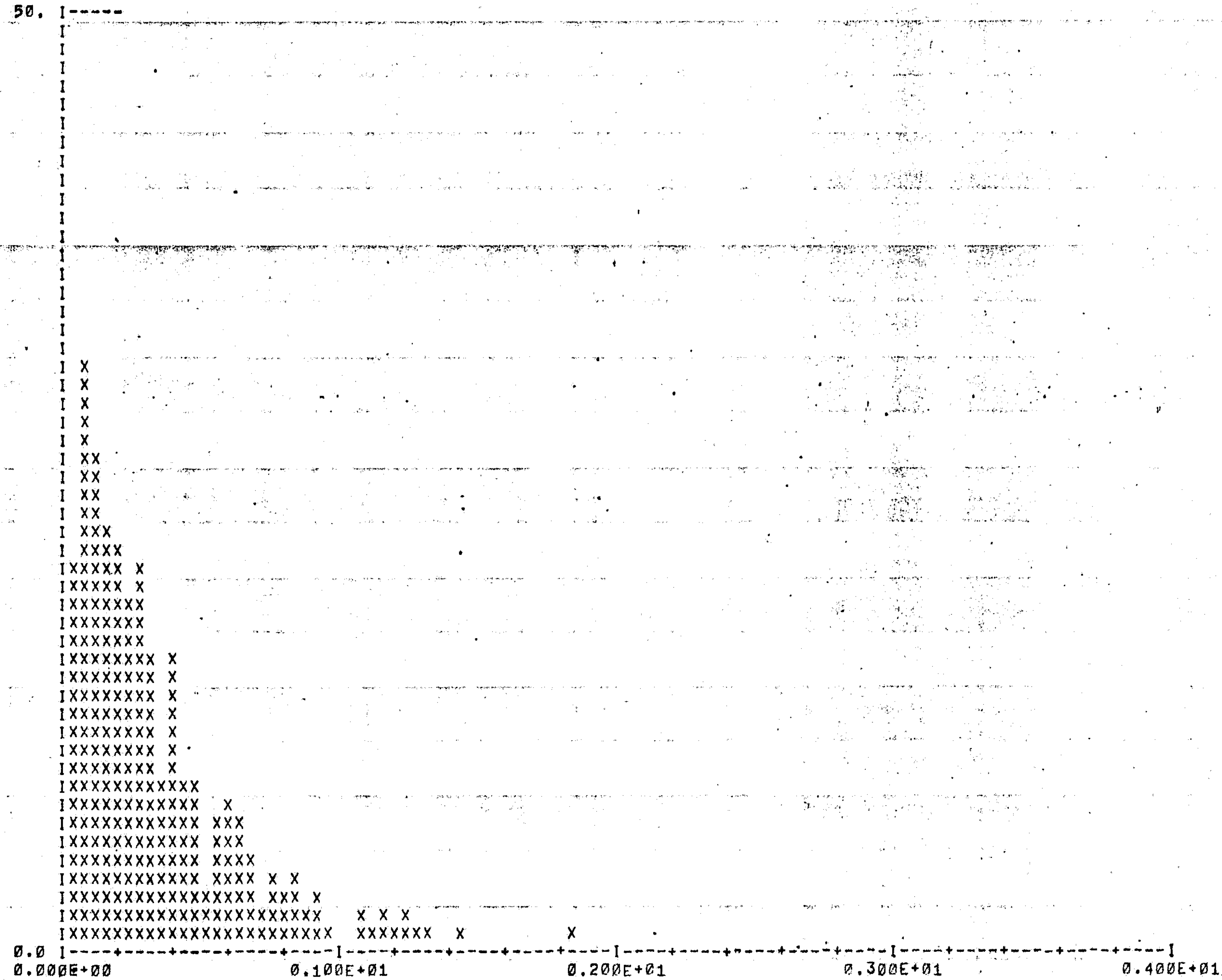
GRAPH 4



BIN SIZE IS 0.400E-04

DISTRIBUTION ALONG BEAM OF STARS

GRAPH 5



BIN SIZE IS 0.400E-01

UNSCATTERED= 0 SCATTERED= 3715 STARS= 285

TM-324
0510

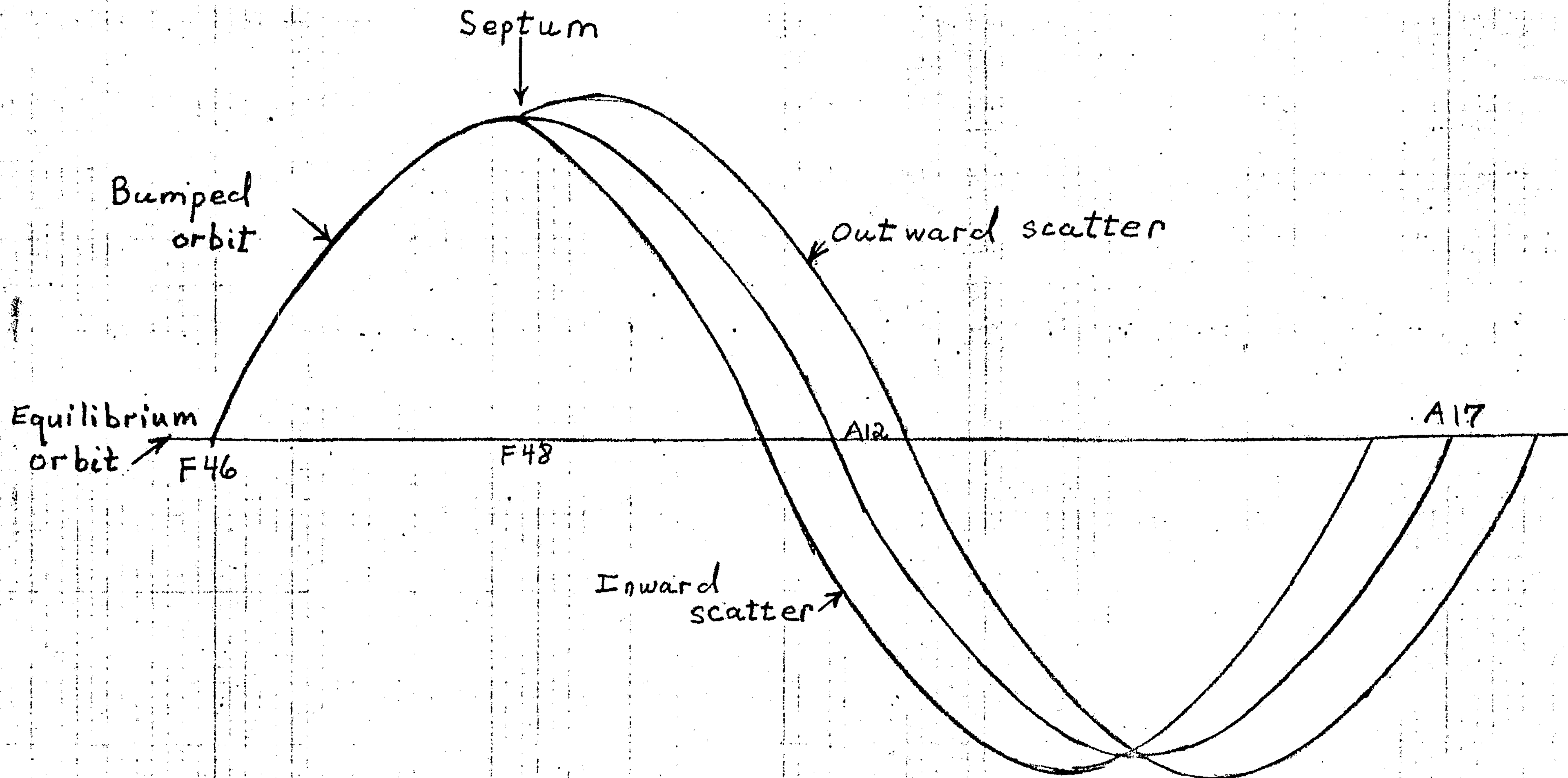


Figure 12: Scattered particle orbits