BROOKHAVEN NATIONAL LABORATORY
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Internal Report

MQB-6
January 16, 1963

STUDIES OF THE RAPID BEAM EJECTOR AT THE COSMOTRON*

by

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For an experiment to measure the magnetic moment of the Λ hyperon, it was necessary to extract the external beam of the Cosmotron with maximum efficiency and with minimum time duration. To accomplish this end, the standard external beam[(1)] of the machine was supplemented with the Rapid Beam Ejector (RBE)[(2)]. It was found that, unfortunately, the ejection efficiency of the beam was less than normal when the RBE was used. Measurements of the ejection efficiency were made by irradiating polyethylene foils at the second focus of Beam 1 with 3 BeV protons. The external beam was tuned up and optimized in a standard manner. It was found that the ratio of the number of protons ejected with the RBE to the number ejected without the RBE was 0.3 in one run and 0.22 in another try. It was also observed that the RBE did not shift the position of the external proton beam focus to within $\pm$ 1/8 in.

It was considered possible that because the RBE pulse was so short, the particles were not all able to arrive at appropriate horizontal and vertical betatron oscillation phases to strike the target during the short interval of large orbit perturbation. To alleviate this difficulty the RBE was reconstructed with four turn coils in each half instead of one turn coils, the top and bottom halves connected in parallel as before and used with the same condenser bank and other circuitry. The inductance of this

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* Work performed under the auspices of the U.S. Atomic Energy Commission
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new RBE was about 16μH which with the 0.15μF capacitance should result in a rise time of about 25μsec. This time scale is now much longer than the betatron oscillation periods but still short enough for the experiment. Observations of the timing of the ejected beam were made by using the integrated signal from a scintillation counter. When the RBE was properly tuned, there was a signal pulse of about 40μsec. The timing of the RBE was set somewhere between the turning off of the radio frequency system and the appearance of the normally ejected beam. Specifically, with rf turnoff at 1075 msec the beam would coast towards the target so that the beam would start targeting at about 1079 msec. The RBE would under these circumstances be fixed at about 1078.5 msec with the exact timing and voltage trimmed to minimize the amount of beam not contained in the fast RBE spike. The beam not contained in the fast spike was checked with a gated counter setup and was found to be as small as 2% with careful tuneup and as bad as 8% when the adjustments were not so well done. Measurements of the ejection efficiency were now made again. All external beam parameters were optimized both with and without the RBE. The ejection efficiency was found to be 27% without the RBE and 16% with the RBE. Thus the ejection efficiency is 0.6 as great with the RBE.

During the program of optimizing the RBE parameters, the distribution of beam inside the machine at the entrance to the ejection magnet (M_1) of the external beam system was measured. Rows of 1/8" x 1/8" polyethylene foils were placed on the jump target holder and the residual activity measured in a deep well counter system. Unfortunately, the measurements without the RBE were not consistent from day to day. Two runs without RBE are shown in Fig. 1 and 2. Figure 1 also shows a vertical distribution. Figure 1 compares favorably with previous studies of the external beam[(1)]. Figure 2 does not look consistent with a good tuneup for the external beam. Anyway, Fig. 3 shows a distribution taken with the RBE on. Since the data without RBE are not consistent, it is difficult to conclude anything from these data. The beam with RBE seems to be within the M_1 aperture but not as narrow as the well tuned case without RBE.

Shortly after the experimental use of the RBE was completed, some computer studies were initiated to improve the understanding of the

RBE. The method consisted generally of solving the equation of motion for the radial betatron oscillation with a time increasing highly localized perturbation in one straight section. For this computation we let θ be the angle of rotation of the particle measured from the RBE straight section (East), x the amplitude of oscillation and $x' = \frac{dx}{d\theta}$ the slope of the particle trajectory. Then $x = x_o \cos\nu\theta + \frac{x_o'}{\nu} \sin\nu\theta$

$$x' = -\nu x_o \sin\nu\theta + x_o' \cos\nu\theta$$

so that the coordinates of the particle are projected around a quadrant by the matrix multiplication

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cos\frac{1}{2}\nu\pi & \frac{1}{\nu}\sin\frac{1}{2}\nu\pi \\ -\nu\sin\frac{1}{2}\nu\pi & \cos\frac{1}{2}\nu\pi \end{pmatrix} \begin{pmatrix} x_o \\ x_o' \end{pmatrix} .$$

The matrix multiplication was done on the IBM 610 computer and x and x' printed out at each straight section. At each traversal of the RBE straight section, the x' is decreased corresponding to the bending in the RBE field. Results for an initial $x_o = x_o' = 0$ and $\nu = 1.1\sqrt{1 - 0.7} = 0.602$ are shown in Fig. 4. These results are in agreement with the answers obtained by assuming the adiabatic growth of zeroth and first harmonics in the Cosmotron field corresponding to the RBE. The next calculation which was done on the NYU 704 computer consisted of repetition of the above calculations for numerous particles with various initial conditions corresponding to a collection of particles of various amplitudes and phases of betatron oscillation. Some typical results are shown in Fig. 5. These indicate that the entire distribution of particles is moved similar to the motion of a single particle in the first calculation while the shape of the distribution remains unchanged.

The first interesting results appeared when the RBE field was made a function of radius as well as time. A calculation was done with an RBE field chosen as $C\,n\,(1 - 0.0222x^2)$ where C is a constant, n the revolution number which puts in the linear time dependence and, of course, x is the same amplitude defined before. It was found that after a number of revolutions the (x, x') distribution of particles was modified as well as the mean position. The program was then modified to approximate more accurately the spatial dependence of the RBE field. The RBE coils are 4.19 inches above and below the orbital plane and the inner and outer coils are separated by 7.5 inches. It can then be shown that the field on the orbital plane is given by

$$H = H_o\, 4.215 \left\{ \frac{x + 3.75}{(x + 3.75)^2 + (4.19)^2} - \frac{x - 3.75}{(x - 3.75)^2 + (4.19)^2} \right\}$$

where x = o is assumed to correspond to the center of the RBE system and H_o is H at x = o. The orbits of 21 particles subjected to this RBE field were computed for about 80 revolutions (20μsec) and the results shown in Fig. 6. This calculation was not completely realistic in that in practice the particles are not known to be initially centered in the RBE coils and the time dependence may not have been appropriate. The field distribution may also be inaccurate due to end effects and eddy currents in the vacuum chamber. It is also known that the n value of the Cosmotron is not constant over a very large radius so that the linear matrix method is not too good. Anyway, the results show an effect which may be modified quantitatively but not removed by more sophisticated analysis. After many revolutions, the particles are greatly spread out in betatron oscillation phase space. This is not a violation of Liouville's Theorem but a drastic distortion of the boundary of the occupied portion of phase space.

From these results, it was conjectured that the betatron oscillations have been made essentially larger requiring more traversals of the jump target lip for beam extraction and thus, through multiple scattering, increasing the emittance of the beam and impairing its match of the successive optics. It is known from some other work that the beam efficiency is decreased by excessive betatron oscillations. With this model in mind, the proposal was therefore made to increase the spacing of the turns in the RBE thus making the field more uniform and preventing this distortion of the betatron oscillation distribution. Experimental work on the RBE was interrupted by the long shutdown for installation of new straight sections. Recently a new RBE was installed having two turn top and bottom coils with a radial separation of 22 inches instead of the 7.5 inches used in the old configuration. With the same energy available in the pulsing condensers, one expects a lower field in the RBE but no difficulty has been experienced in targeting the entire beam at full Cosmotron energy. It has also been shown that the ejection efficiency of external beam I is the same with and without the RBE. In Table I are shown some data taken using the new Beryllium foil monitor[3] for the external beam intensity.

TABLE I

Cosmotron Energy Bev	RBE	No. of Pulses	External Beam	Internal Beam	Ratio
2.2	Off	15	2695	580	4.65
2.2	On	10	1605	393	4.08
2.9	Off	10	1675	546	3.07
2.9	On	10	1848	551	3.35

For these data, beam I operating at better than 30% ejection efficiency was used. In RBE cases, the beam not contained in the fast spike was estimated less than 10%. Intensity measurements here are in arbitrary units.

These results indicate that the solution of this problem is complete. It should be pointed out, however, that with the new straight sections in the Cosmotron, the general magnetic properties of the machine have been much improved and the new RBE design may not be the sole reason for its improved performance.

It is believed at the time of this writing that the RBE ejects the beam with good efficiency and no further work or study of this problem is contemplated.

The authors acknowledge the assistance of many members of the Cosmotron staff for assistance in this work. Particular thanks go to Mr. Kurt Minati for mechanical design work, to Mr. I. Livant for his work with the pulsing circuitry and to the operating engineers for their help with the experiments. The counting equipment of the Brookhaven National Laboratory Radio Chemistry group was invaluable in the early experiments. Programming for the 704 calculations was done by Mrs. Mary Lou Buchanan.

(1) The External Beam of the Cosmotron. BNL Internal Report, Physics Dept. R.L. Cool, et.al. March 1958.

(2) David C. Rahm, Rev. Sci. Instr. 32,1116 (1961)

(3) Clifford E. Swartz and Paul Feldman, Rev. Sci. Instr. 33, 565 (1962)

FIGURE CAPTIONS

Figure 1. This figure shows the radial and vertical distributions of particles at the entrance to the ejection magnet M_1.

Figure 2. This figure shows a repetition of the data of Fig. 1 but the results are not in agreement.

Figure 3. This figure shows the radial distribution of particles at M_1 with the RBE.

Figure 4. The trajectory of a particle with no initial betatron oscillation is shown for twelve revolutions subject to an RBE field linear in time and uniform in radius. The time dependence of the RBE was scaled unrealistically large but the problem is linear so that the correction to the results is a trivial scale factor.

Figure 5. This figure illustrates a typical result showing that the shape of the distribution of particles in betatron oscillation phase space is preserved. The RBE field was one half as strong as Fig. 4. but still about twice as large as the actual RBE case. Again, however, the problem is linear

and can be scaled at will. The qualitative results are valid for all straight sections (actually the North is plotted here) and all revolutions.

Figure 6. (in two parts). Here the same distribution of particles as in Fig. 5 is followed through an RBE with the correct radial dependence. The problem is no longer linear so the rate of rise in time of the RBE field was scaled to a realistic value.

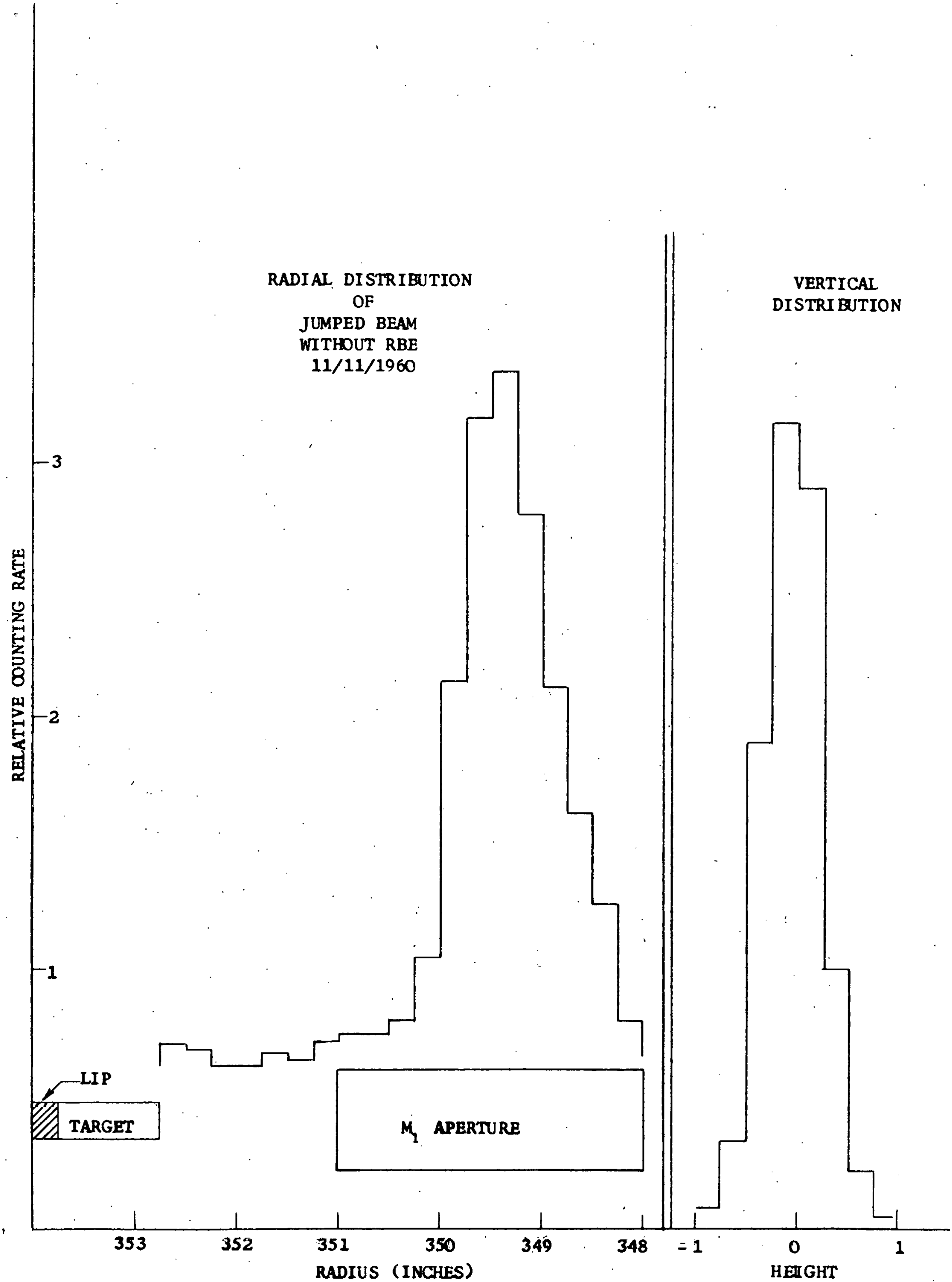

RADIAL DISTRIBUTION
OF
JUMPED BEAM
WITHOUT RBE
11/11/1960
VERTICAL
DISTRIBUTION
RELATIVE COUNTING RATE
3
2
1
LIP
TARGET
M_1 APERTURE
353
352
351
350
349
348
-1
0
1
RADIUS (INCHES)
HEIGHT

FIG. 1

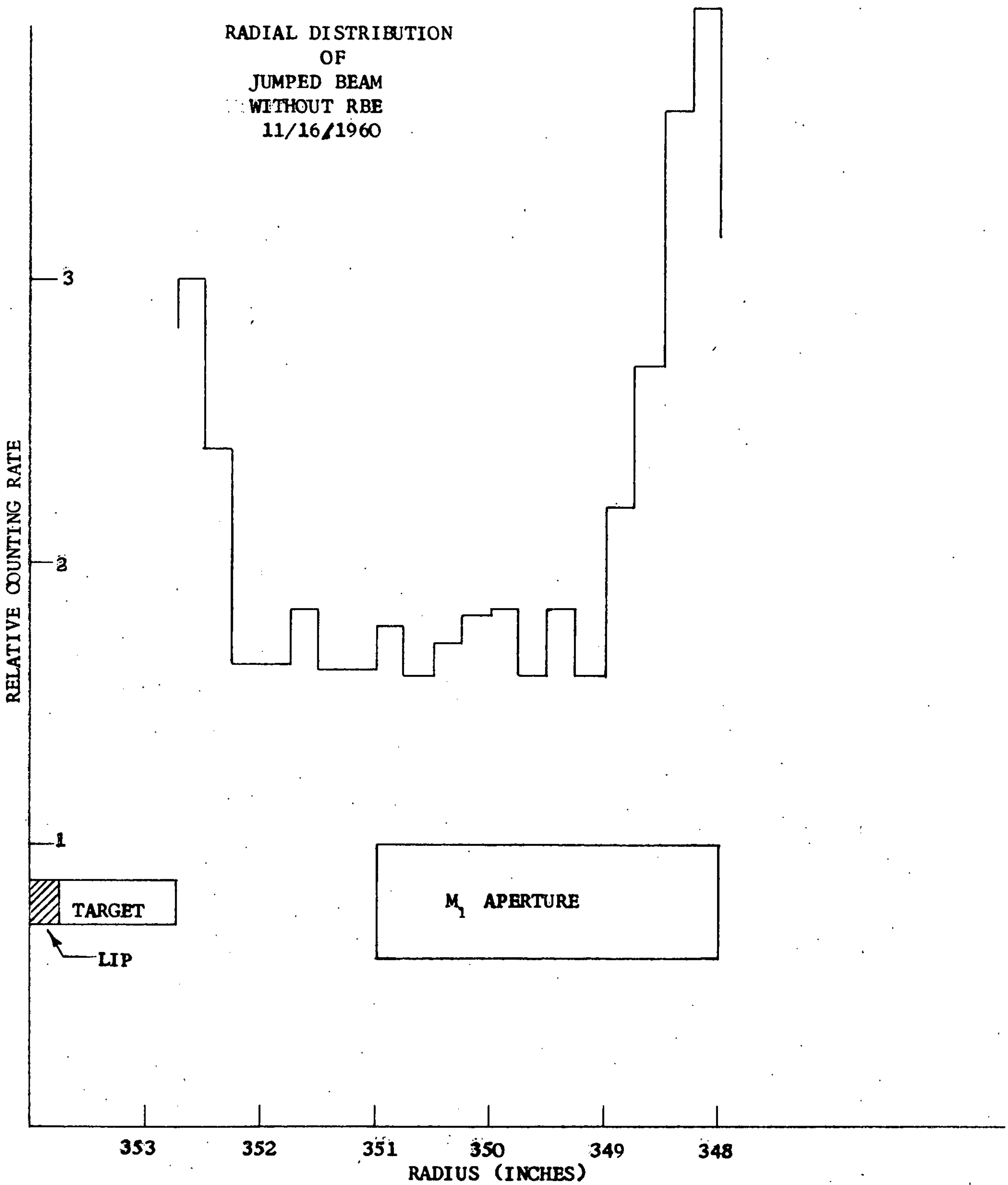

RADIAL DISTRIBUTION
OF
JUMPED BEAM
WITHOUT RBE
11/16/1960
RELATIVE COUNTING RATE
3
2
1
TARGET
LIP
M1 APERTURE
353
352
351
350
349
348
RADIUS (INCHES)

FIG. 2

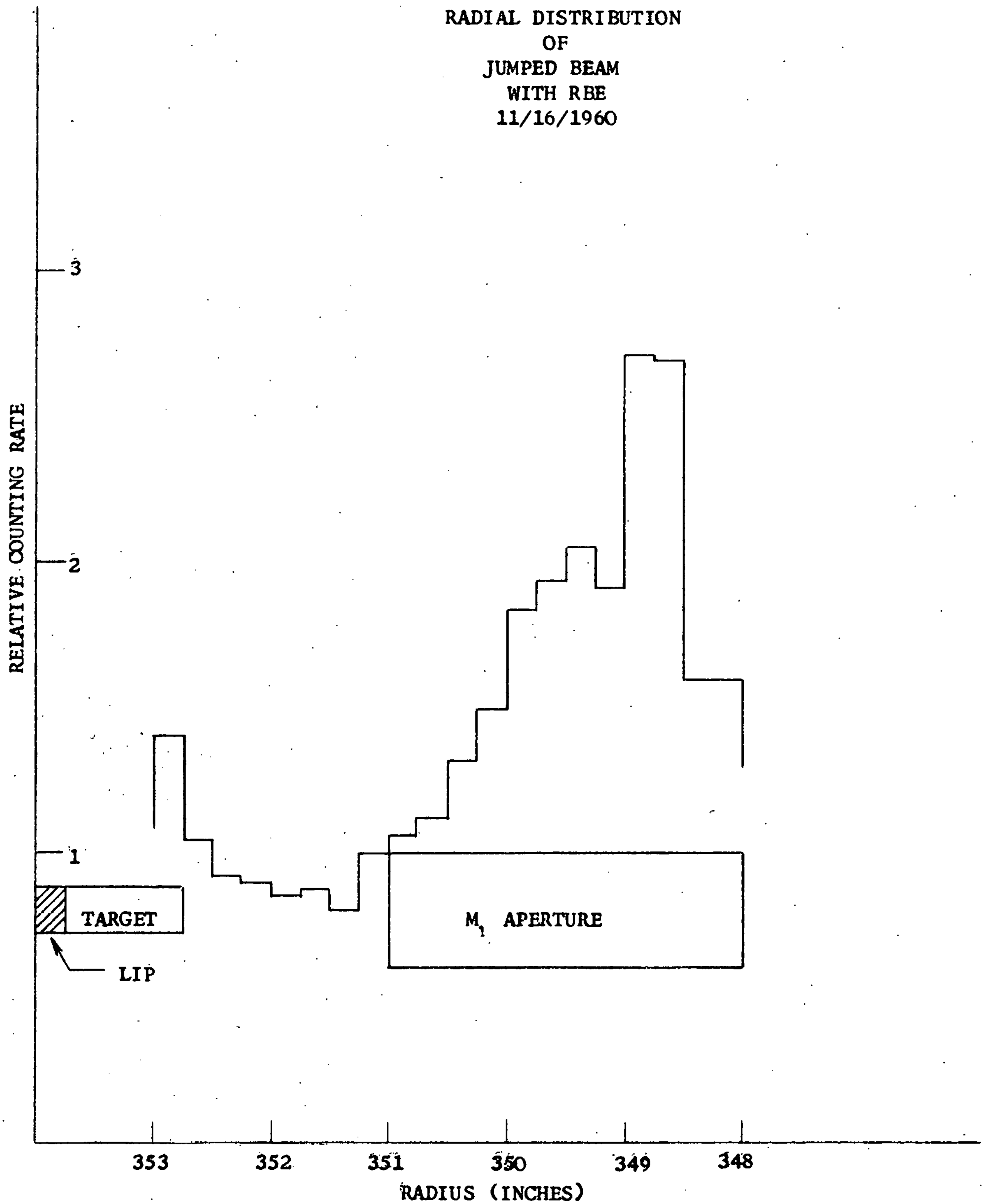
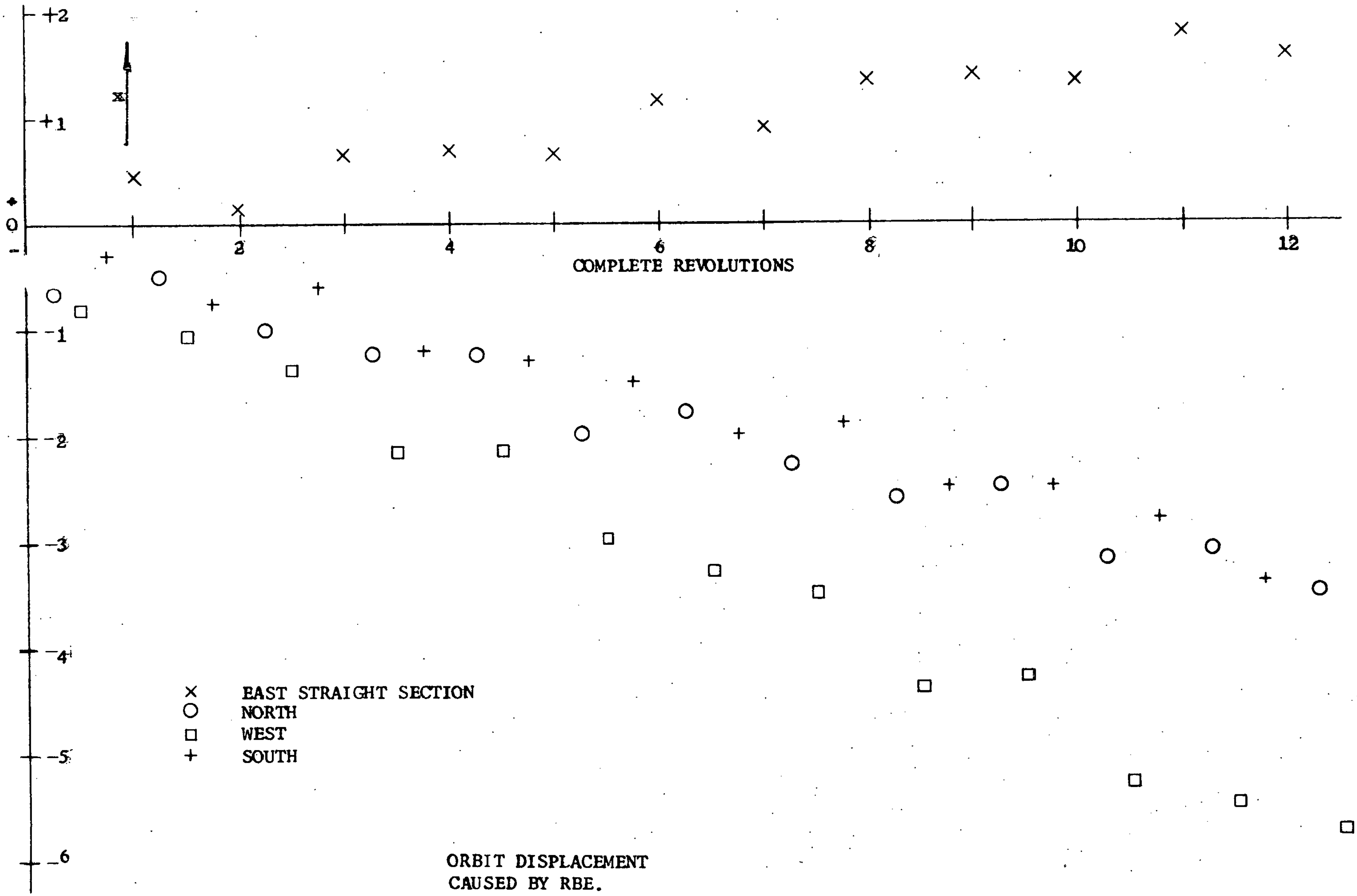

RADIAL DISTRIBUTION
OF
JUMPED BEAM
WITH RBE
11/16/1960
RELATIVE COUNTING RATE
3
2
1
TARGET
LIP
M$_1$ APERTURE
353
352
351
350
349
348
RADIUS (INCHES)

FIG. 3



ORBIT DISPLACEMENT
CAUSED BY RBE.

FIG. 4

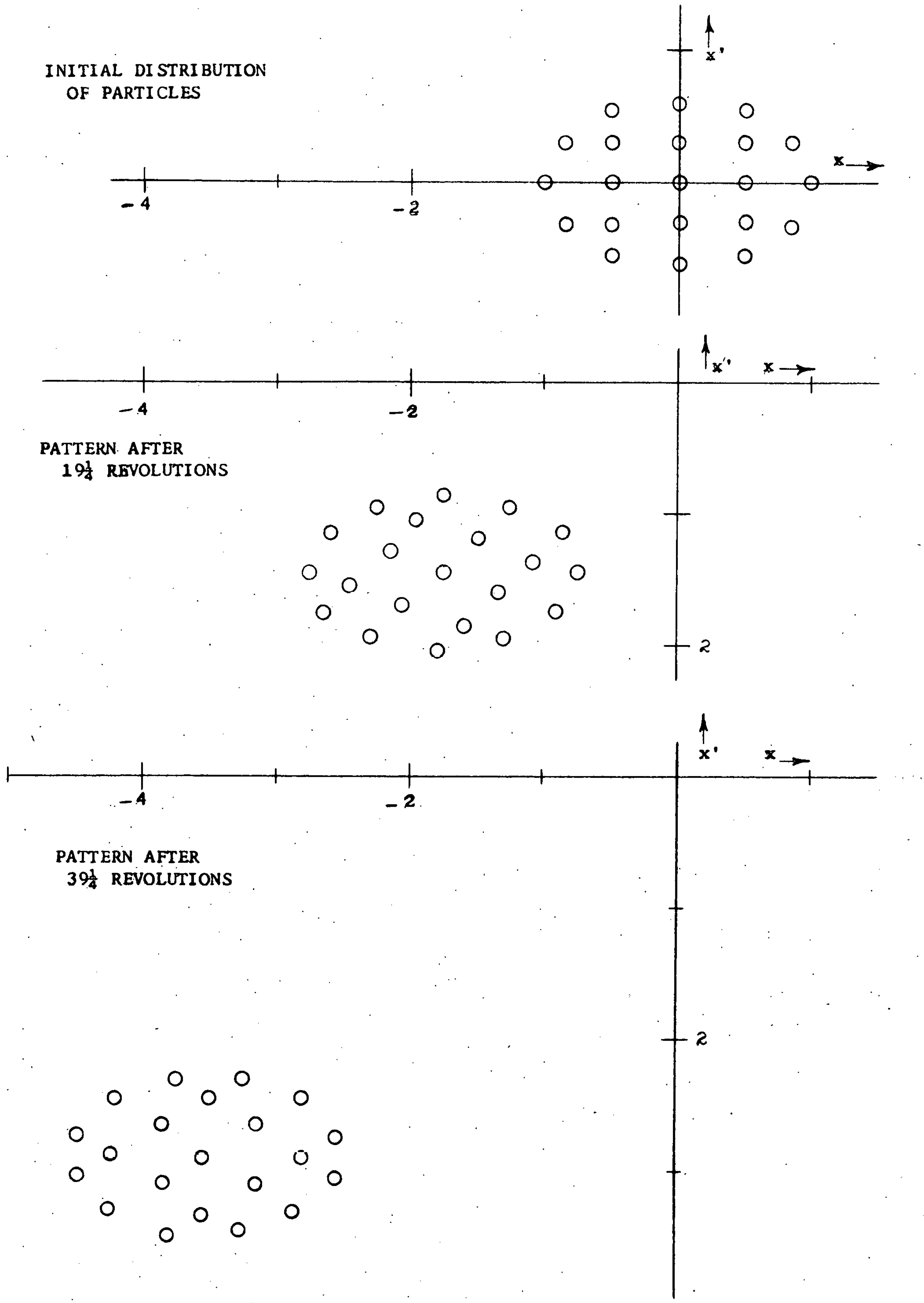

INITIAL DISTRIBUTION
OF PARTICLES
x'
x
-4
-2
x'
x
-4
-2
PATTERN AFTER
19¼ REVOLUTIONS
2
x'
x
-4
-2
PATTERN AFTER
39¼ REVOLUTIONS
2

FIG. 5

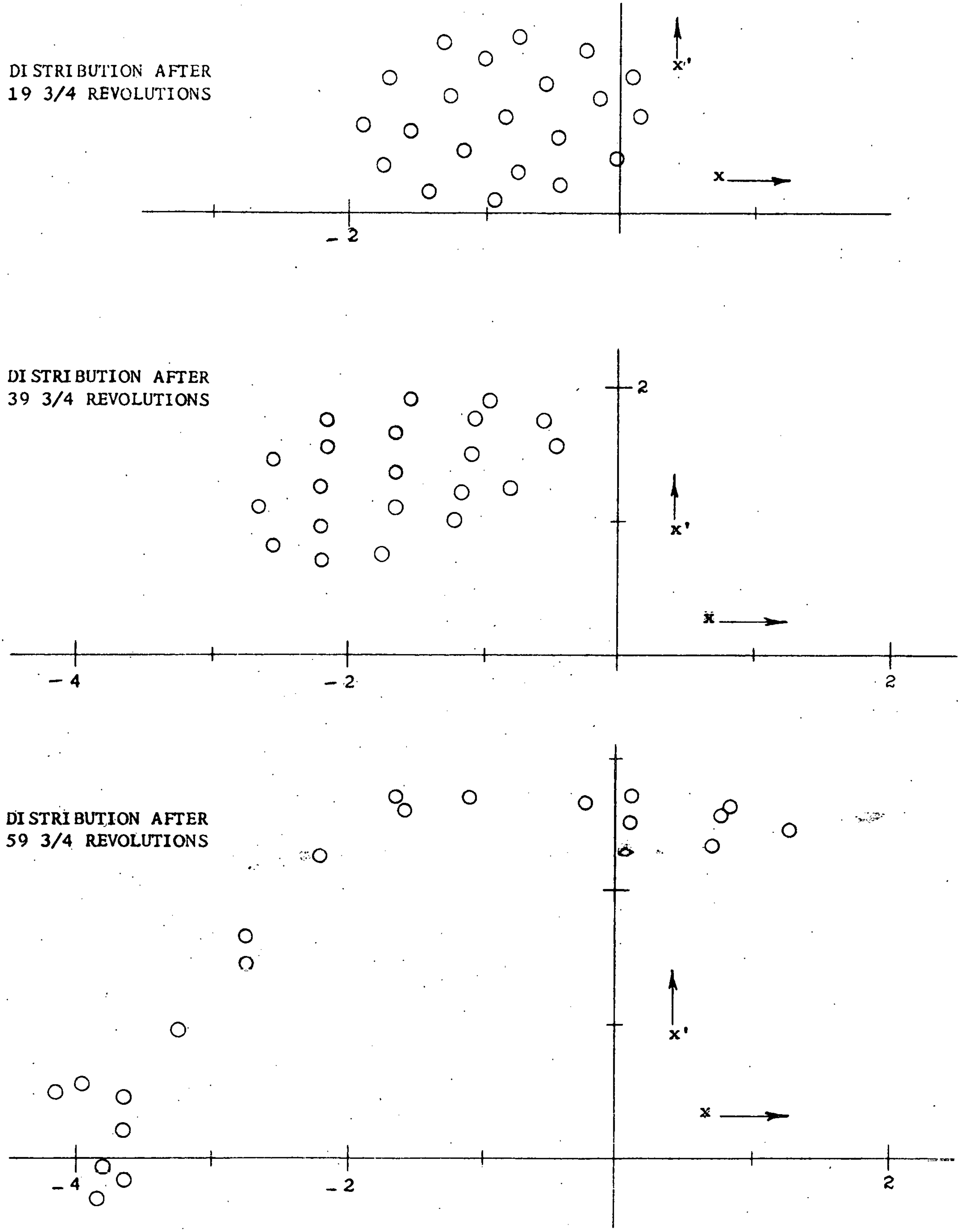

DISTRIBUTION AFTER
19 3/4 REVOLUTIONS
x'
x
-2
DISTRIBUTION AFTER
39 3/4 REVOLUTIONS
2
x'
x
-4
-2
2
DISTRIBUTION AFTER
59 3/4 REVOLUTIONS
x'
x
-4
-2
2

FIG. 6a

DISTRIBUTION AFTER
79 3/4 REVOLUTIONS

NOTE
SCALE ½ = 1

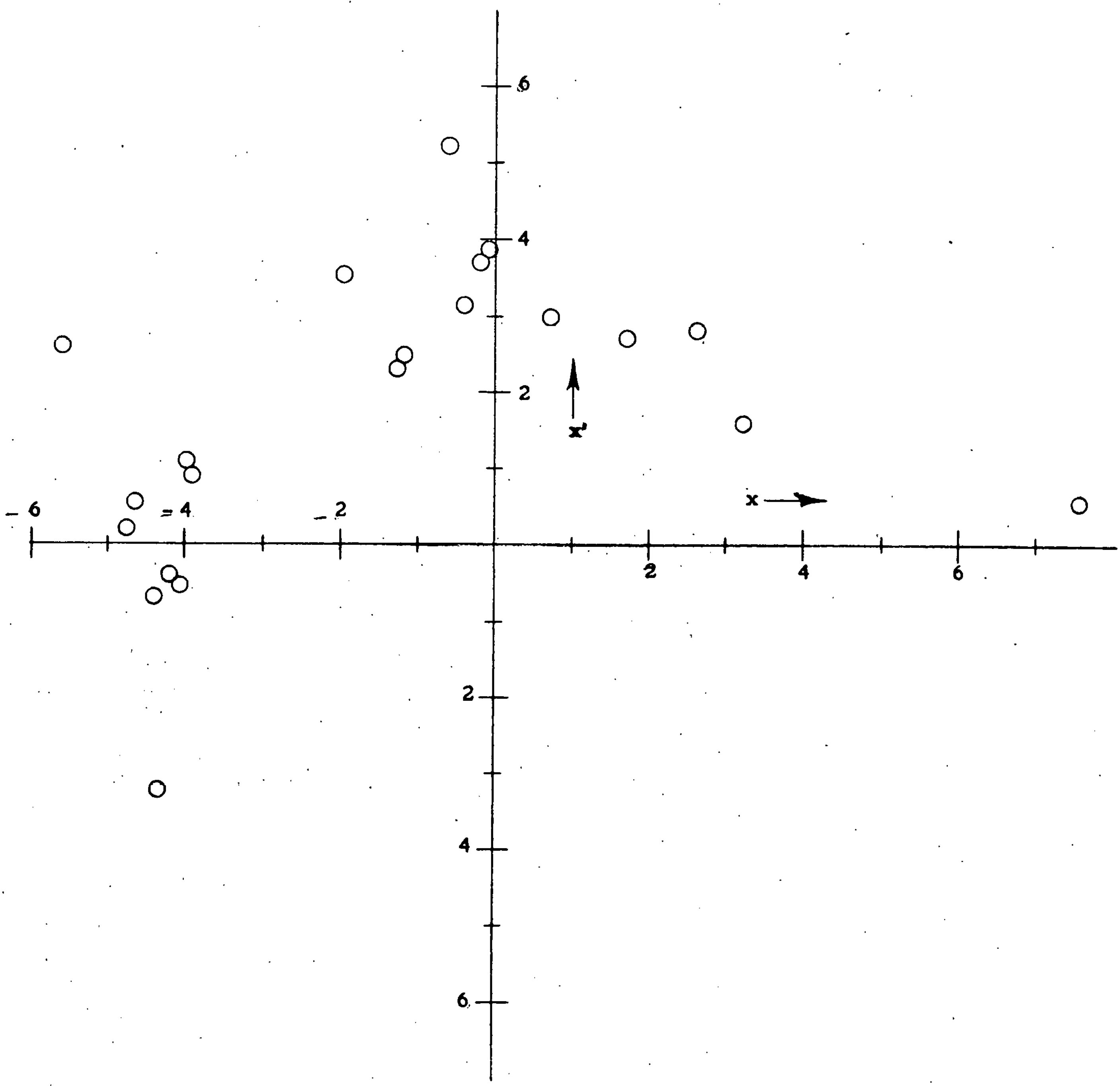


FIG. 6b