BNL-101801-2014-TECH

AD/RHIC/RD/19;BNL-101801-2013-IR

Populating 114 or 171 RHIC rf Buckets through Beam Manipulation at Injection

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May 1990

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U.S. Department of Energy

USDOE Office of Science (SC)

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RHIC PROJECT

Brookhaven National Laboratory

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In the beginning RHIC will fill only 57 of the 342 electrical buckets produced by the RHIC rf system. This is accomplished by transferring beam bunches from the AGS to RHIC with the same bunch to bunch spacing as that in the AGS populating one in six of the available electrical buckets. The usefulness of RHIC would be enhanced, if some of the remaining empty bucket could be filled.

Filling 114 of the RHIC buckets may be possible by transferring beam bunches from the AGS to RHIC one bunch at a time and between beam transfers advancing the phase of the AGS rf systems the appropriate amount so as to deposit the next beam bunch in the next third electrical bucket. In this way 1/3rd of the available buckets can be filled.

But for this approach to work a very fast injection kicker is required since the spacing between beam populations in RHIC is only 95 nsec. In this time the kicker amplitude must rise from 1% to 99% of its required value (assuming a kick amplitude error of 1% can be accepted). This implies a 1/e time for the fast part of the kick rise of 30 to 40 nsec. since time must be allowed for the switch tube to ionize and for the wave shape to settle on the top. Assuming the kicker is as described on page 230 of the RHIC Conceptual Design Report, BNL 52195, a pulsed voltage greater than 130 kilovolts is required to produce this kick rise rate (kicker inductance is computed to be 8.22 microhenries). Such a kicker is not impossible to built but its design and development presses the state of the art and will require a large development and testing effort.

Amplitude errors in this injection kicker can NOT be made negligible and are certain to excite bunch to bunch betatron motion. For this reason this total system must include a bunch to bunch coherent damper. Also there is no chance that this process can be extended to allow the population of 171 RHIC buckets because of the extreme kicker speeds required.

In an effort to avoid these kicker difficulties I have been studying a process of manipulating the RHIC rf voltage to cause the beam constraining buckets to slide forward in position moving from one bucket position to another, a process first described in RHIC Technical Note 39 (AD/RHIC-39). To use this process beam is transferred to RHIC with the original AGS spacing and moved to its final location later. The referenced note describes the additional wide band pulsed rf component required and presents a set of computer generated transient voltage waveforms produced by this system. The reader was expected to visualize the beam constraining buckets created by these voltages and their accompanying "adiabatic" motion. This note expands on that work developing these bucket shape and sizes and focusing on the time required for the beam bunch sliding manipulation.

The fundamental problem with this approach to increasing the beam population in RHIC is the long time required for the bunch sliding manipulation which must be carried out at injection energy. As I will show later a time of 4.8 min. is required to fill RHIC with 114 populated buckets and 8.9 min. to fill 171 buckets using this process. George Parzens tells me that due to intrabeam scattering the longitudinal beam doubling growth time for gold at injection is about 5 min. which will become even shorter, if intensity improvements occur. After consultations with S.Y. Lee and Sandro Ruggiero I understand that this growth time can be lengthened by introducing additional energy spread in the beam but that this will require a larger gamma-T jump at transition reducing the jump margins now planned. For lighter elements this problem does not exist since their growth time due to intrabeam scattering is much longer.

In spite of this difficulty I have proceeded to write this note making a record of this analysis in the hope that by the time we start constructing hardware to fill 114 or more buckets in RHIC we will have a better understand of these processes and maybe we can find a way around this problem. Perhaps a reader can suggest a solution.

Figure 1 through 8 show the electrical buckets produced by the transient rf voltages generated by the switching and phase shifting of the added wide band rf system described previously in RHIC Technical Note No. 39, (see that note for illustrations of these waveforms). The "resultant angle" label on these figures is the angular relation of the equilibrium (after the turn-on switching transient is complete) rf sum vector (wide band voltage plus static high Q cavity voltage) to that of the stationary high Q rf cavity voltage. This vector moves through 360 degrees relative to the stationary voltage and is the voltage that advances the beam populations in phase, if moved at an "adiabatic" rate. The bucket area relative to that of the stationary bucket is indicated below each bucket shape in these figures. The relative area label of the moving bucket (shaded) is the fourth label in figures 1 through 5 but becomes the third label in the following figures as this bucket moves forward. The computer program that generated these bucket shapes does not bring the fifth bucket into view as the second and third unpopulated buckets merge and the fourth bucket is moved into the location previously occupied by the third bucket. Nevertheless, these waveforms are continuous and a fifth bucket does exist. This graphic limitation is only a limitation in the computer code which I have not bothered to rectify. The relative area of this moving bucket is reduced during this process, see figure 9, but return to unity at the end. If this area reduction is undesirable, the rf voltage amplitudes in both generators can be raised appropriately to keep the bucket area constant during the phase moving process.

The process illustrated in figures 1 through 8 moves a populated bucket (shaded) which starts as the third buckets after the stationary first bucket and advances it a total of one bucket spacing during the process. This procedure is the end process that would fill 171 of RHIC's buckets since every second bucket is now filled. The process that fills 114 buckets is not illustrated because its shape and area change are so small as to be uninteresting.

The minimum time required for this bucket sliding action depend on two parameters, namely the acceleration of phase advance ($d^2\Theta/dt^2$) and the degree to which the bucket is populated. If the bucket is filled to the limit, it cannot be moved without beam spillage. On the other hand, if only the central core of the electrical bucket is filled, it can be move rapidly. Electrically we can slide the rf phase at a fixed phase velocity starting and stopping abruptly, but this aggravates beam spillage. The work described here will move the rf phase with a sine wave acceleration (ie. $d^2\Theta/dt^2 = A \cdot \text{SIN}\ kt$ where A and k are adjusted to accomplish the desired phase motion in the desired time). I am not sure that this is the optimum phase advancing procedure, but it was the best of those procedures tried. Figure 10 illustrates the phase-time function generated by this process and compares it to that generated by a square phase acceleration function. There is little difference and I believe either could be used.

The procedure used in this analysis consists of the following steps.

1. Chose a population 1/2 width, degrees.

2. Start a particle with the correct energy but displaced in phase relative to the bucket center by the 1/2 width value chosen in step 1. Select a number of point on this particle trajectory to be used as seed in the following steps.

3. Select a total phase motion desire and a total elapse time for the phase slide. All values of time are measured in units of $1/W_{syn}$ where W_{syn} is the small amplitude synchrotron radial frequency, rad/sec.

4. Adjust the constants in the phase acceleration sine function to meet the parameters chosen in step 3.

5. Start a particle at each of the "seed" location chosen in step 2 and follow its motion as the electrical bucket is move as described.

6. With the phase motion complete and with the electrical bucket now stationary the trajectory of the displaced particle from step 5 is traced.

7. The phase space area enclosed by the trajectory found in step 6 is compared to that of the starting particle, step 2. Note- some particles may no longer be enclosed in the stationary bucket and will be counted as lost.

8. The fraction of starting particles retained and the average area growth enclosed by their trajectories relative to that of the starting seed particle can be computed.

The results of this work is presented in figures 11 through 14. Figures 11 and 12 give results for a total phase motion of 360 degrees as would be required for the RHIC bucket sliding process described. The 180 degree total phase shift results, figures 13 and 14, represents the process that would be required in the AGS, if single bunch transfer is utilized followed by a half bucket space slide.

In RHIC the time required to slide 360 degrees must be greater than 30 units of $1/W_{syn}$, see figure 11 and 12. For this slide time the population density (area increase) is essentially unchanged, see figure 12, and all seed particles are retained unless the beam population exceeds a 1/2 width of 135 degrees, a highly filled bucket. The $1/W_{syn}$ value for RHIC with an rf crest amplitude of 5 kv is 0.053 sec. Thus it will take 1.59 sec. for each phase slide. To move all 12 AGS bunches into their final position to fill 114 RHIC buckets 36 slides are required for a total elapse time of 57.2 sec. Since 10 AGS loads are required to provide 114 bunches a total time of 572 sec. or 9.54 min. is needed. This time could be reduced to 4.8 min., if a 20 kv rf system is installed (ie. using 4 of the ferrite cavities described in RHIC note 39). The corresponding time required to fill 171 RHIC buckets is 1.59 sec./slide, 48 slides/(AGS cycle) times 14 AGS cycles for a total time of 1069 sec. or 17.8 min. This could also be reduced to 8.9 min. with 20 kv rf system.

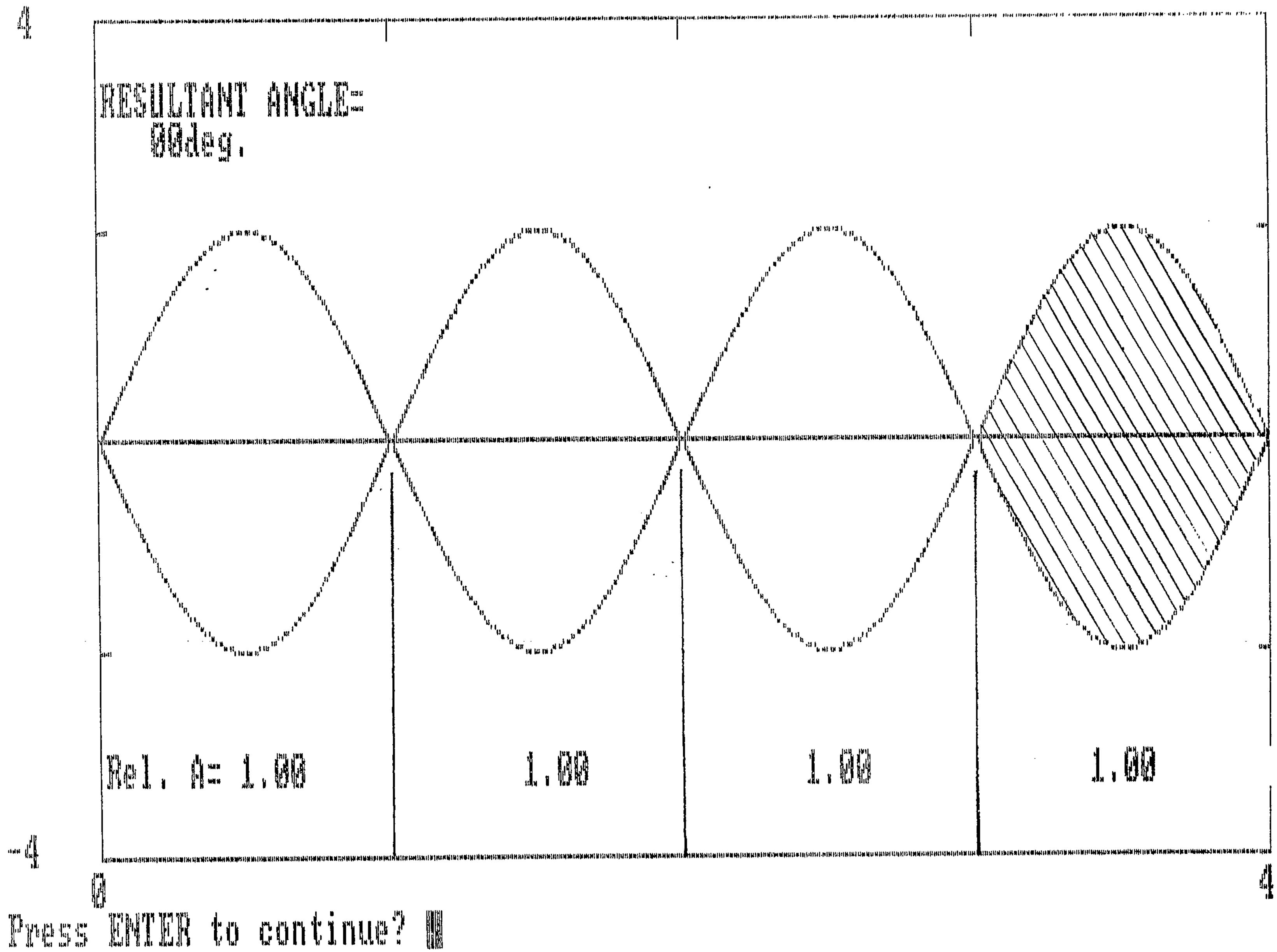

4
RESULTANT ANGLE=
00deg.
Rel. A= 1.00
1.00
1.00
1.00
-4
0
4
Press ENTER to continue?

FIGURE 1

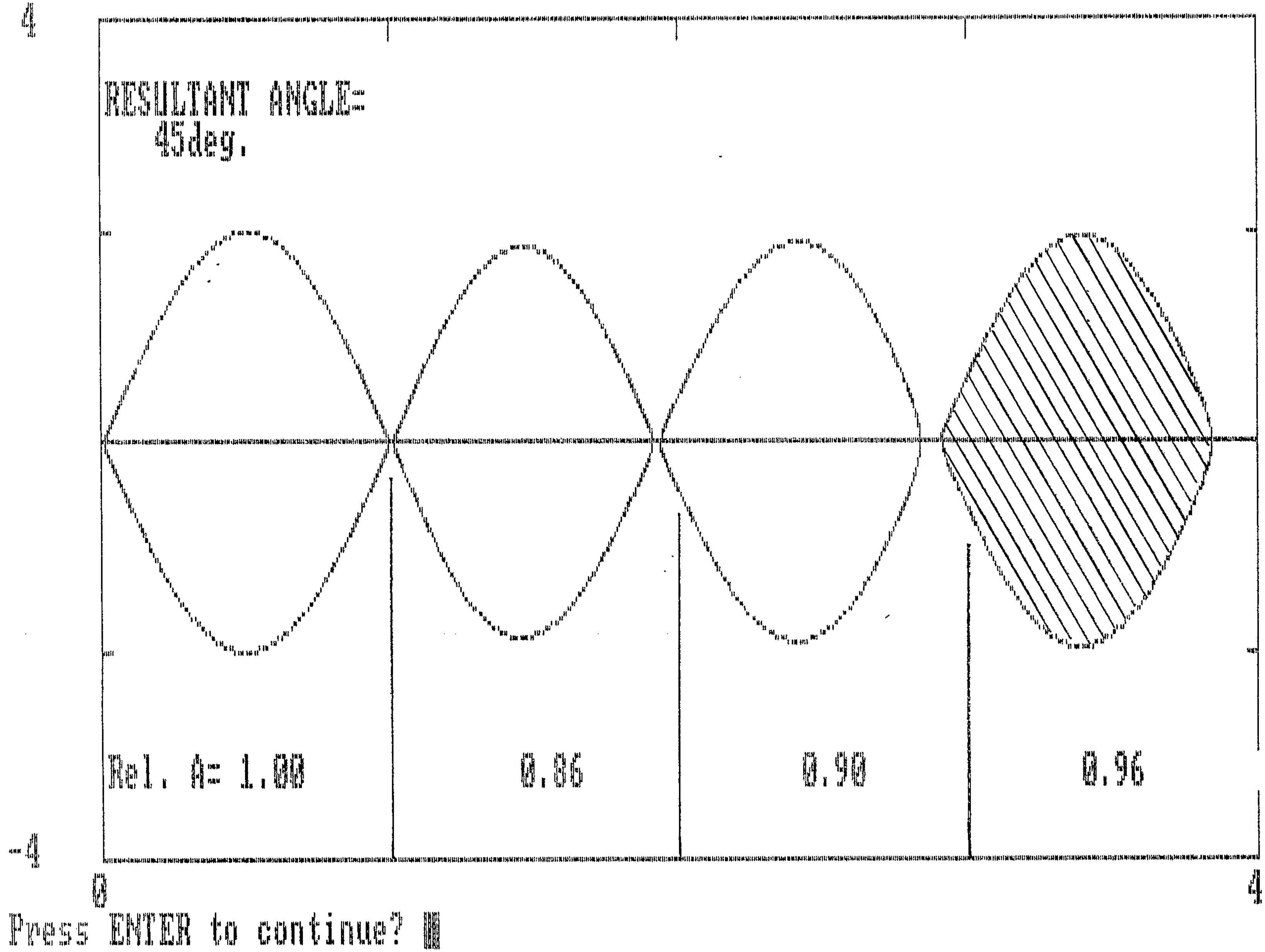

4
RESULTANT ANGLE=
45deg.
Rel. A= 1.00
0.86
0.90
0.96
-4
0
4
Press ENTER to continue?

FIGURE 2

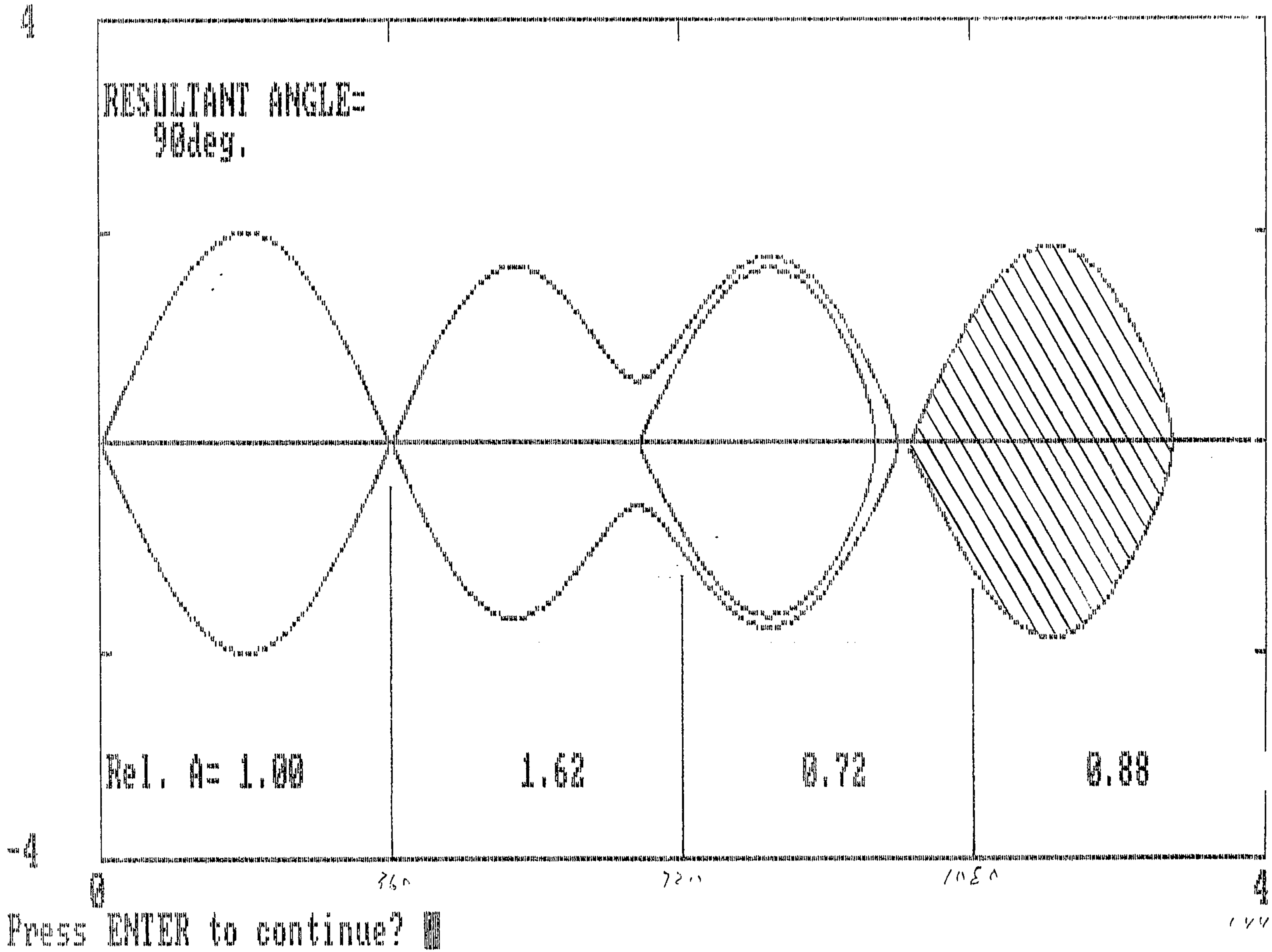

RESULTANT ANGLE=
90deg.
Rel. A= 1.00
1.62
0.72
0.88
4
-4
0
360
720
1080
4
Press ENTER to continue?

FIGURE 3

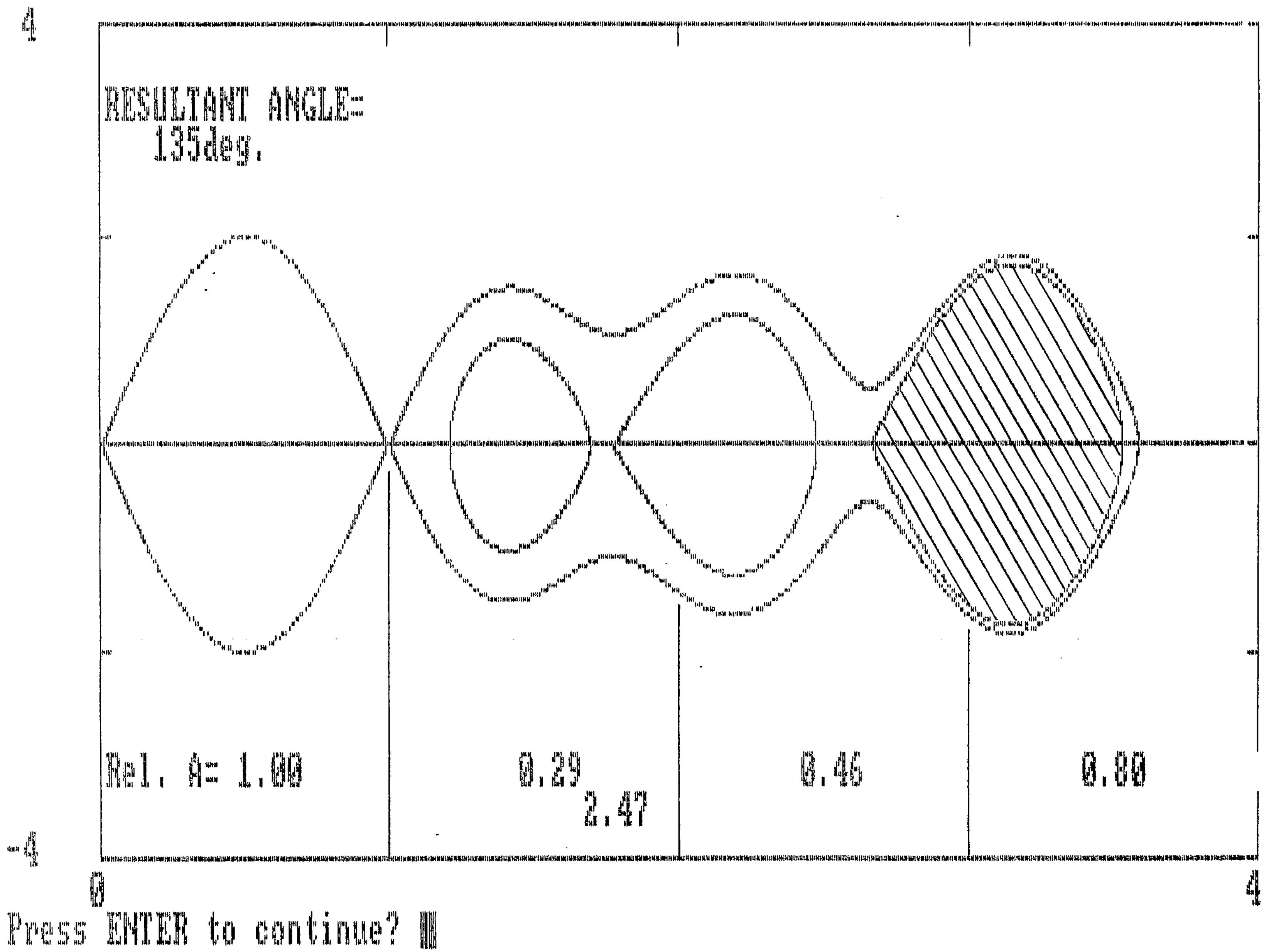

4
RESULTANT ANGLE:
135deg.
Rel. A= 1.00
0.29
2.47
0.46
0.00
-4
0
4
Press ENTER to continue?

FIGURE 4

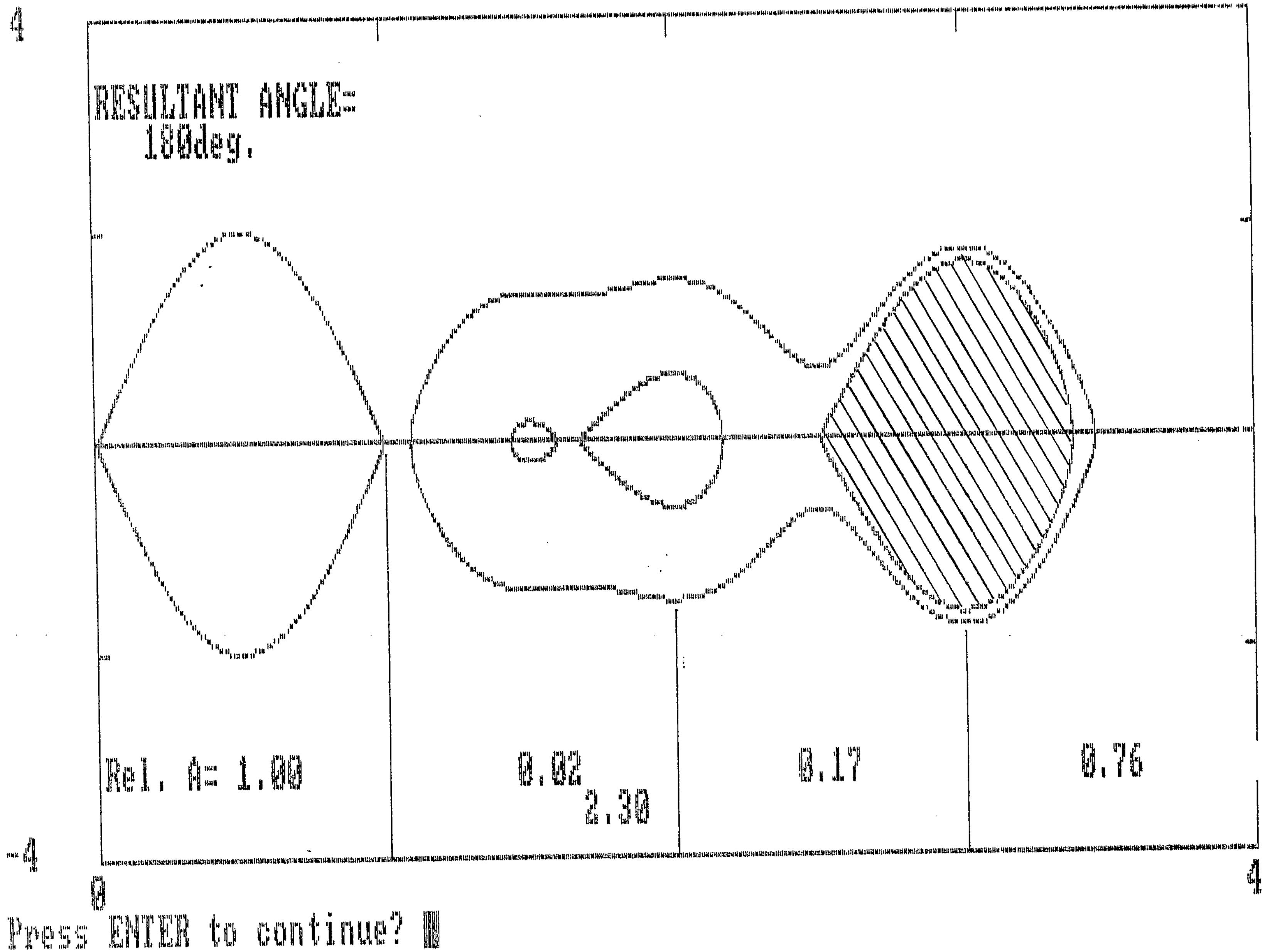
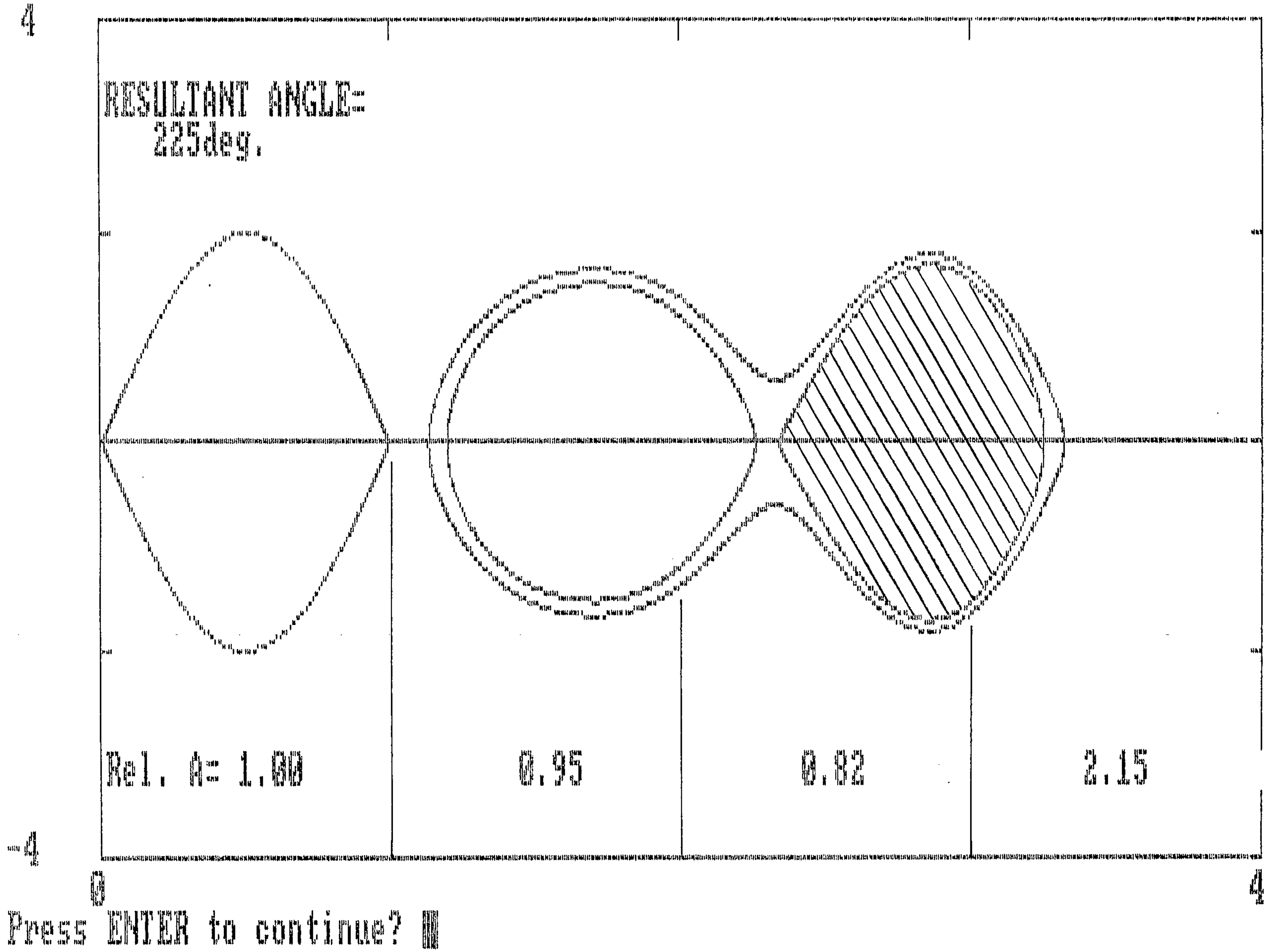
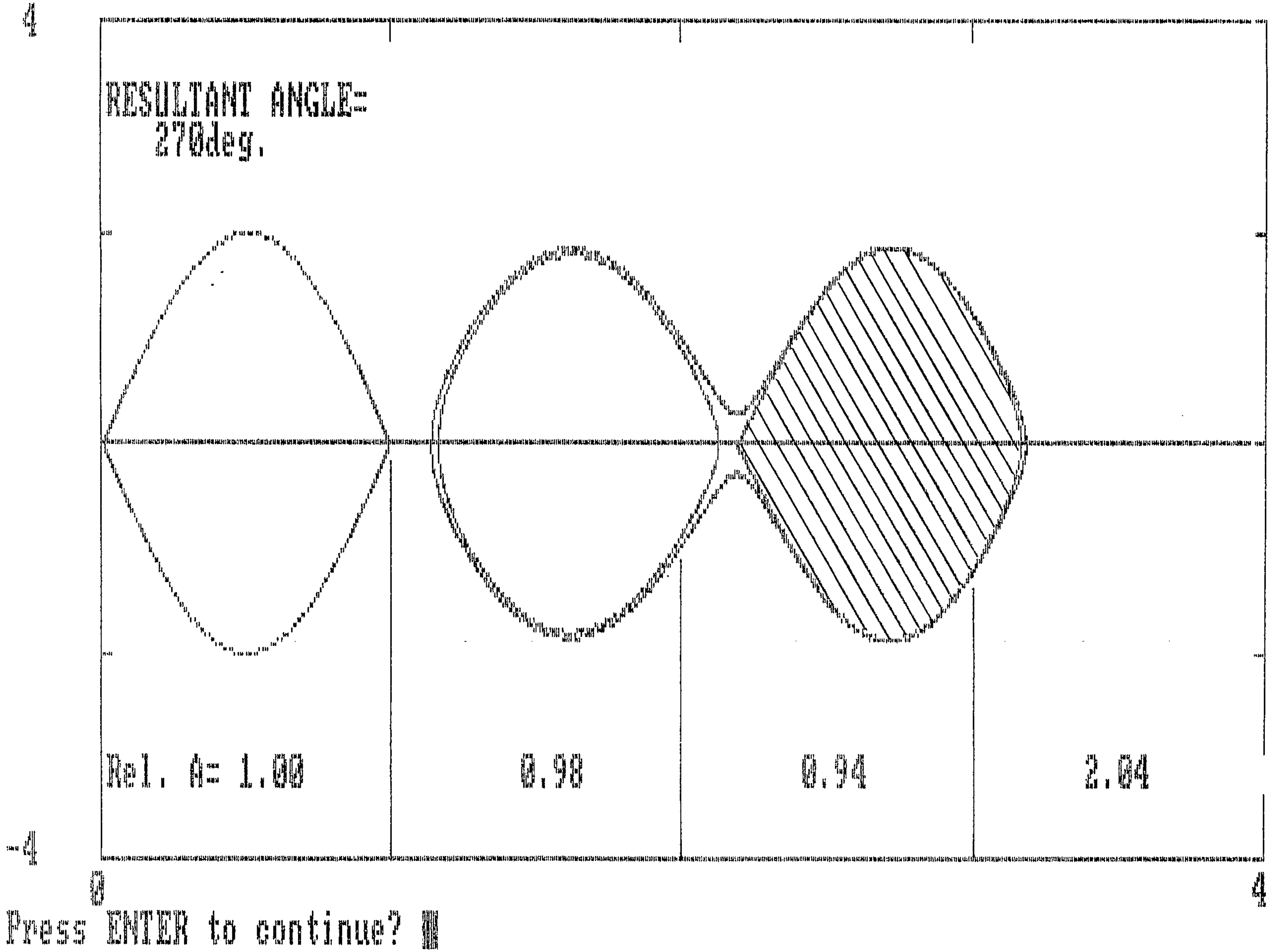

4
RESULTANT ANGLE=
180deg.
Rel. A= 1.00
0.02
2.30
0.17
0.76
-4
0
4
Press ENTER to continue?

FIGURE 5



4
RESULTANT ANGLE=
225deg.
Rel. A= 1.00
0.95
0.82
2.15
-4
0
4
Press ENTER to continue?

FIGURE 6



4
RESULTANT ANGLE=
270deg.
Rel. A= 1.00
0.98
0.94
2.04
-4
0
4
Press ENTER to continue?

FIGURE 7

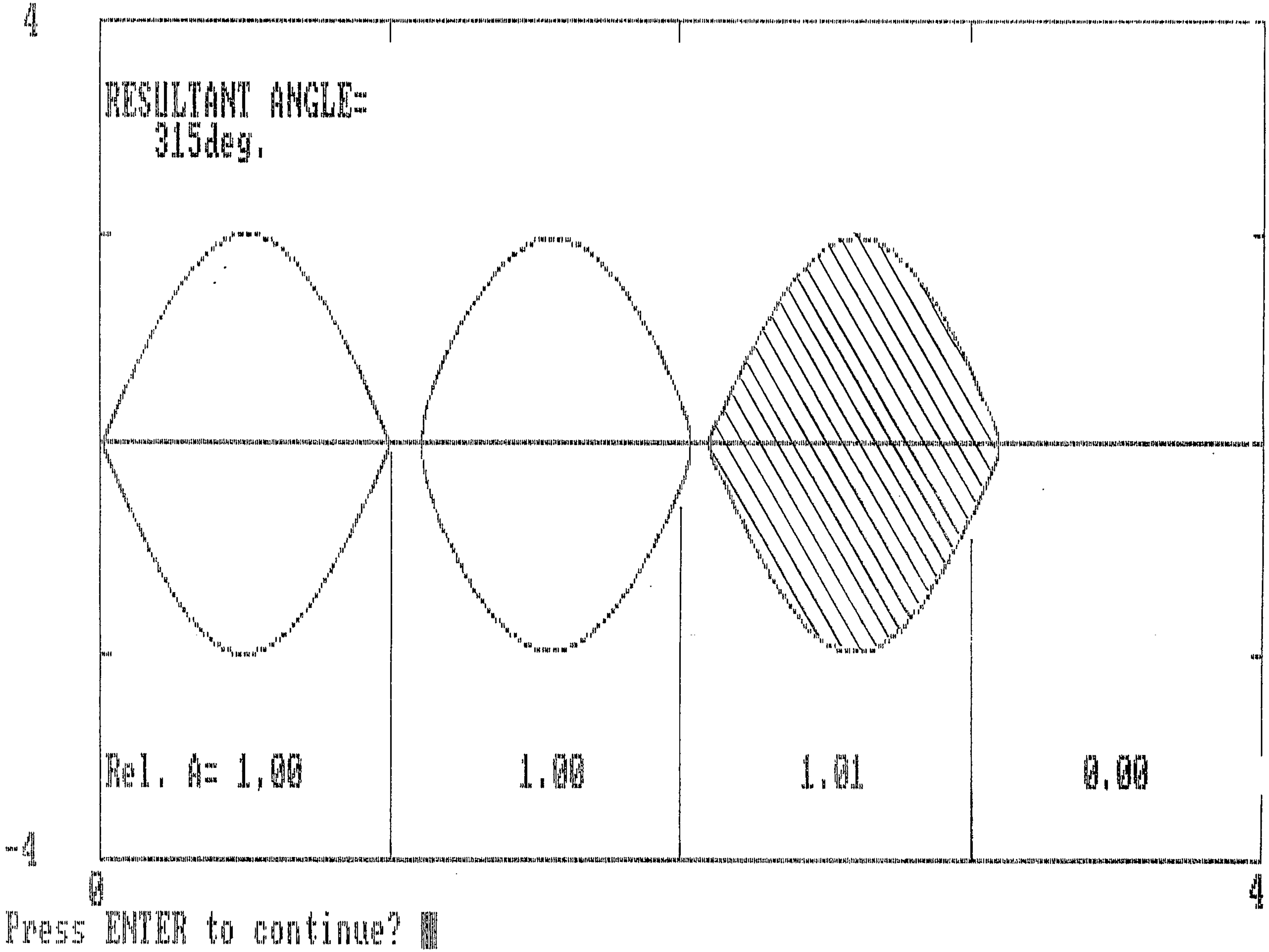

4
RESULTANT ANGLE=
315deg.
Rel. A= 1,00
1.00
1.01
0.00
-4
0
4
Press ENTER to continue?

FIGURE 8

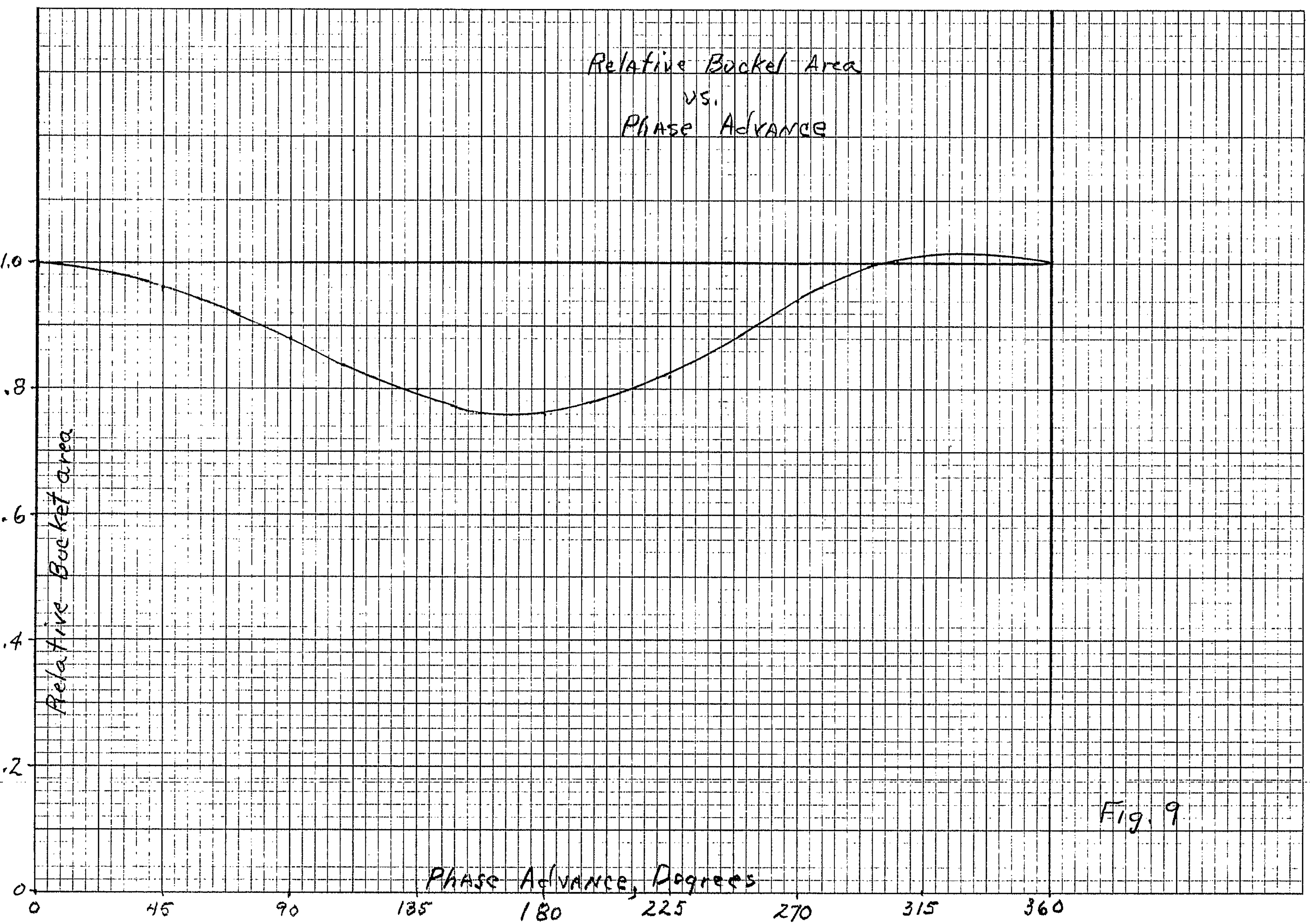

Relative Bucket Area
vs.
Phase Advance
Relative Bucket area
1.0
.8
.6
.4
.2
0
Phase Advance, Degrees
0
45
90
135
180
225
270
315
360

Fig. 9

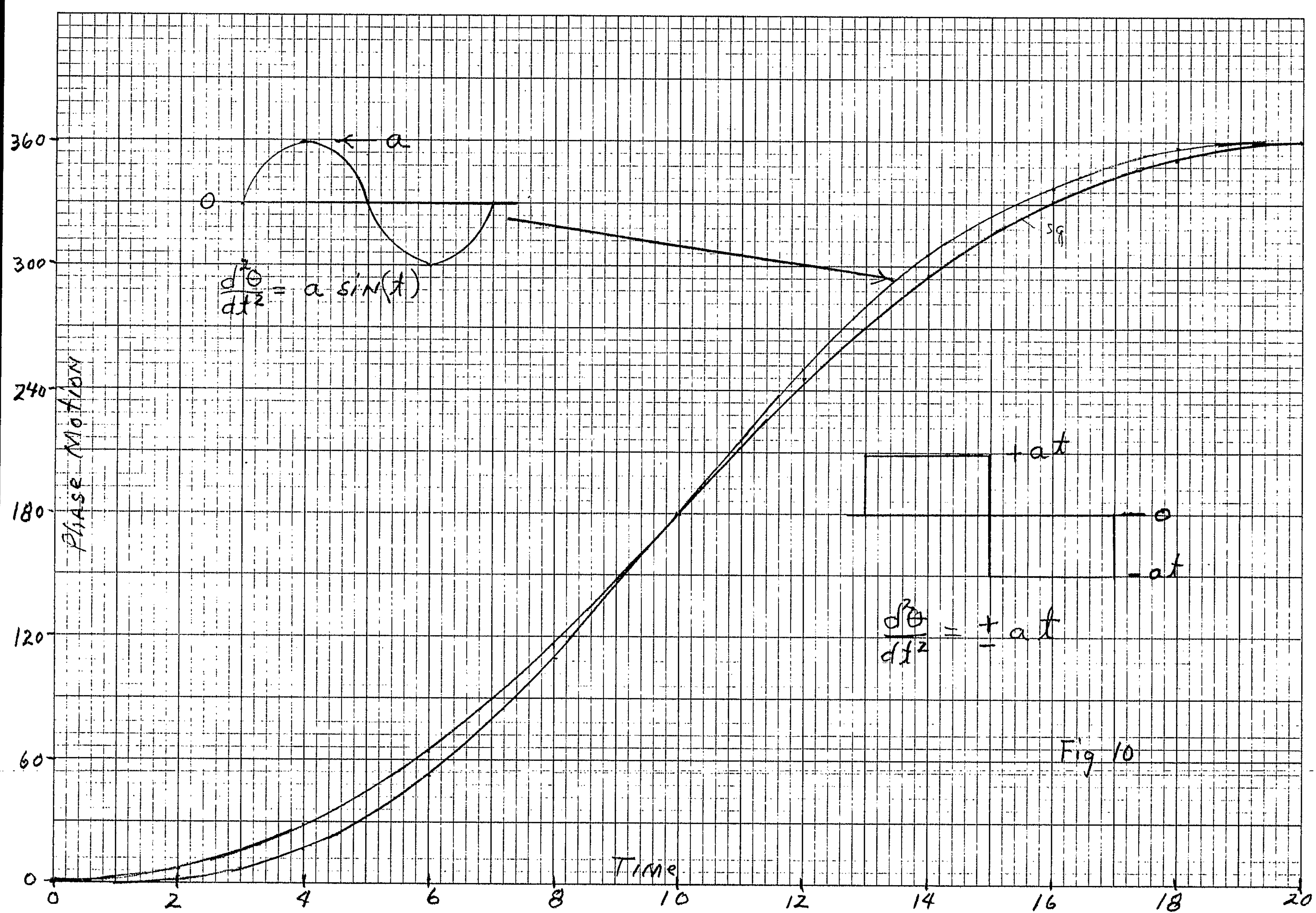

360
300
240
180
120
60
0
Phase Motion
Time
0
2
4
6
8
10
12
14
16
18
20
a
0
$\frac{d^2\theta}{dt^2} = a\sin(t)$
+at
0
-at
$\frac{d^2\theta}{dt^2} = \pm at$

Fig 10

BATAR.001

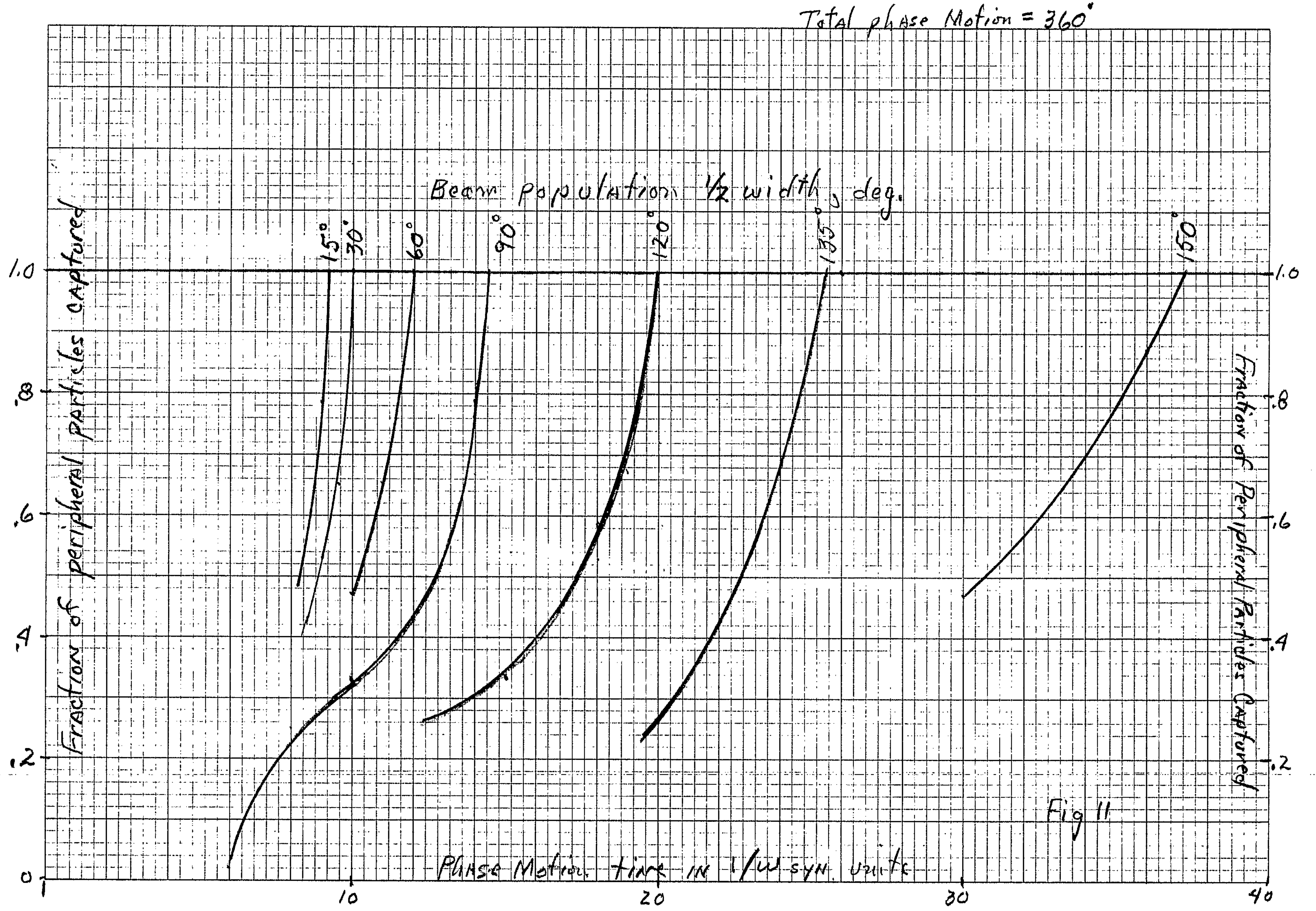
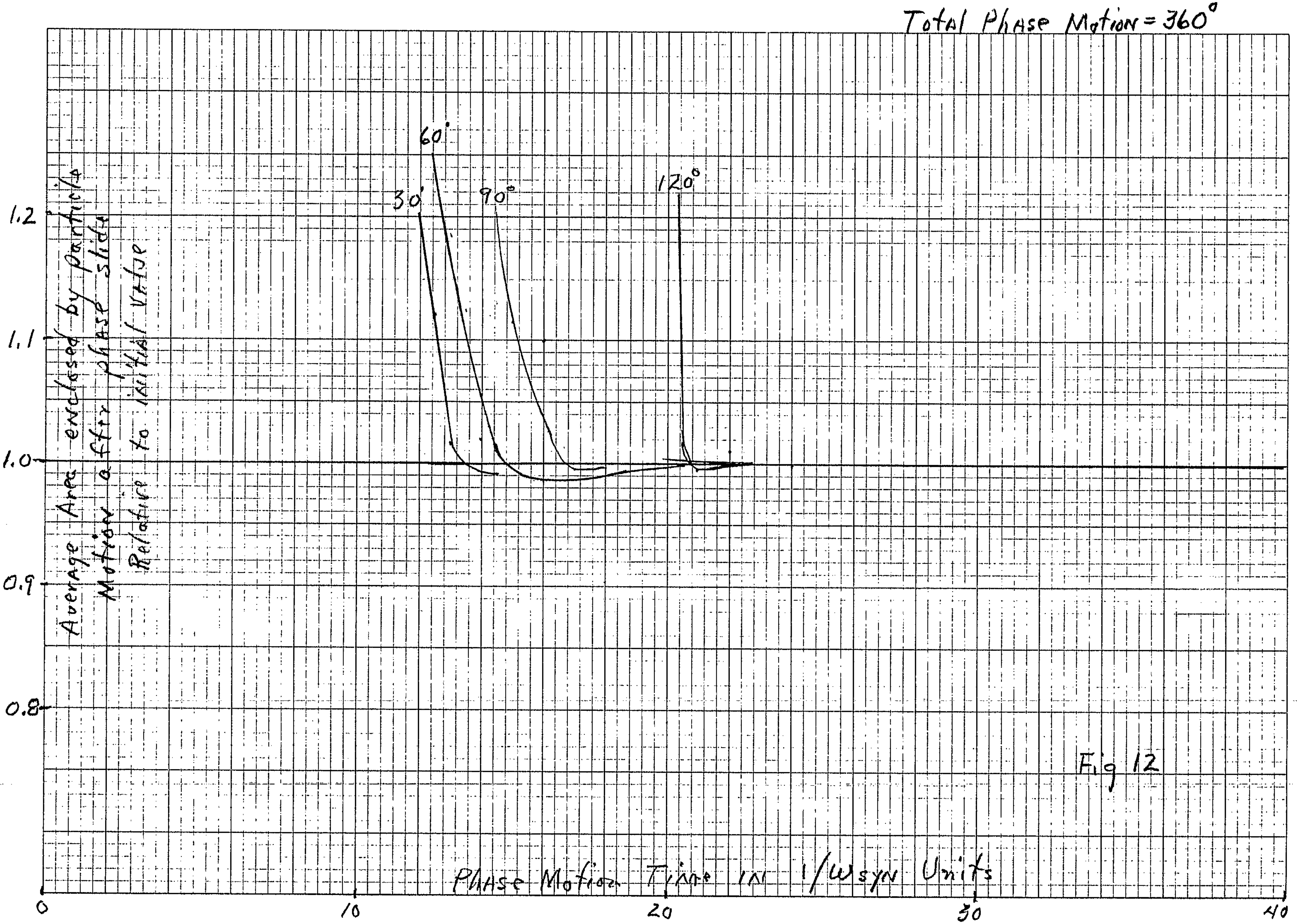


Fig 11

30



Total Phase Motion = 360°
60°
30°
90°
120°
1.2
1.1
1.0
0.9
0.8
Average Area enclosed by particle
Motion after phase slide
Relative to initial value
Phase Motion Time in 1/Wsyn Units
0
10
20
30
40

Fig 12

Total Phase Motion = 180°

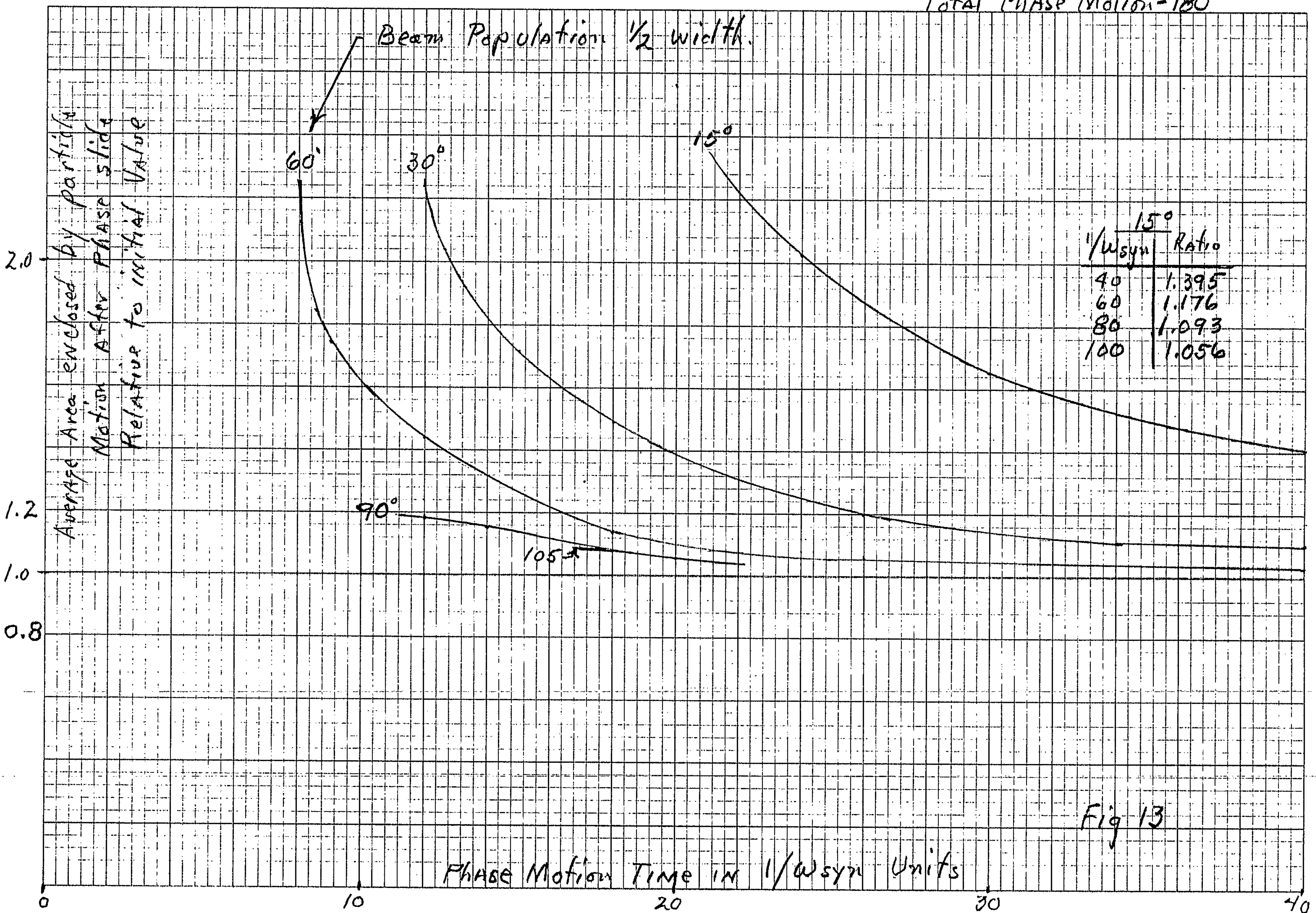
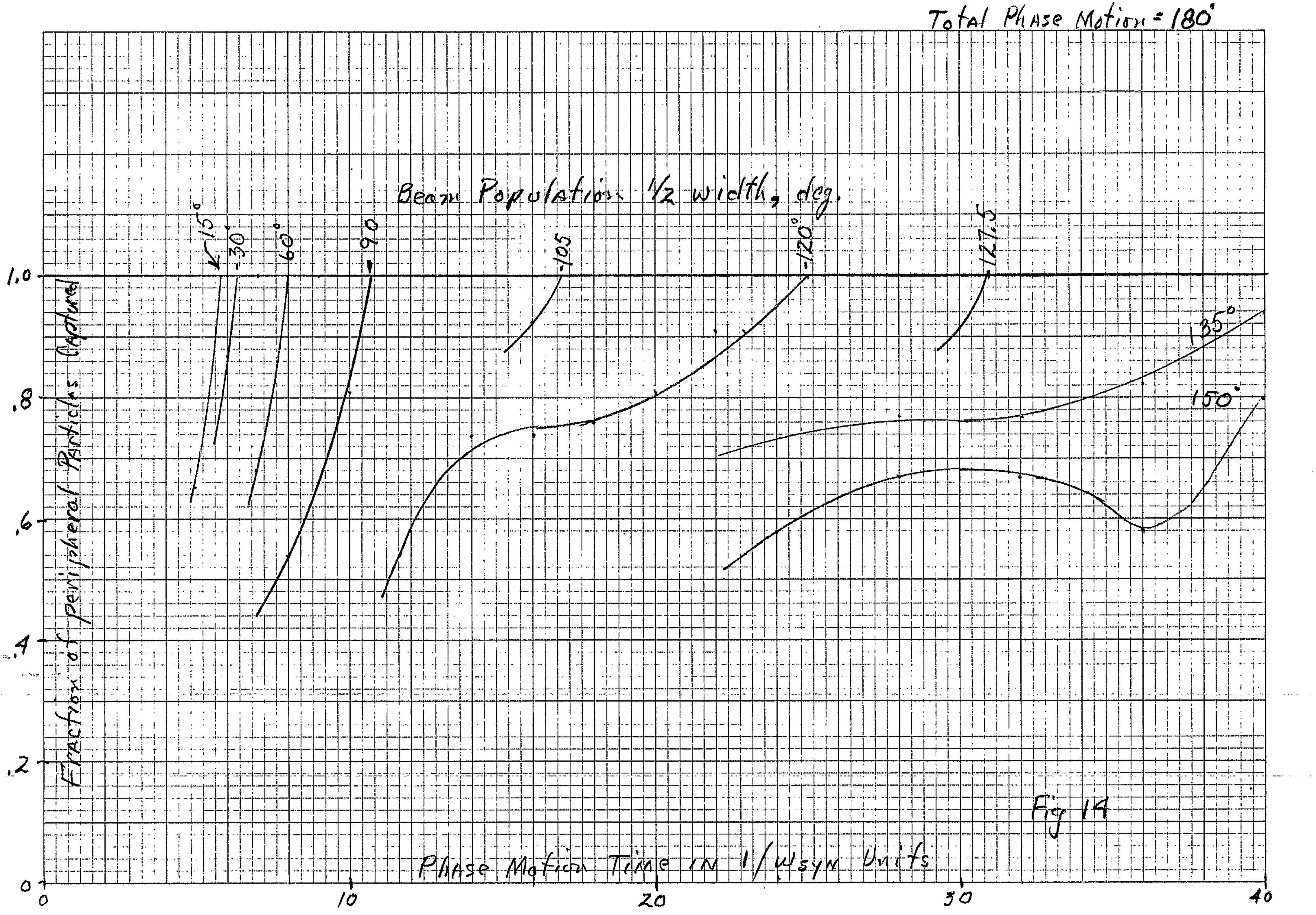


Fig 13


Total Phase Motion = 180°
Beam Population 1/2 width, deg.
15°
30°
60°
90
105
120°
127.5
135°
150°
1.0
.8
.6
.4
.2
0
Fraction of peripheral Particles Captured
Phase Motion Time in 1/wsyn Units
0
10
20
30
40
Fig 14