ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

PROGRESS REPORT

THE UNIVERSITY OF MICHIGAN
RACETRACK SYNCHROTRON

FEBRUARY 1, 1950

REPORT PREPARED

BY

H. R. CRANE IN COLLABORATION WITH THE SYNCHROTRON STAFF

PRINCIPAL CONTRIBUTORS TO THE RESEARCH

T. H. BERLIN
R. W. BOGLE
H. R. CRANE
I. E. DOUGHERTY
D. M. DENNISON
G. M. EDICT
G. M. GROVER
O. E. HAAS
J. S. MALIK
P. B. McKOWEN
W. A. NIERENBERG
W. C. PARKINSON
R. W. PIDD
H. A. WESTRICK

Project M604-4

U. S. NAVY DEPARTMENT, BUREAU OF ORDNANCE
TASK UMH CONTRACT NO. NOrd 7924

ABSTRACT

The 300 Mev University of Michigan synchrotron differs in a number of important respects from the conventional circular synchrotrons, such as the one constructed by Professor McMillan at Berkeley. The novel features of its design will permit greater versatility in its operation and eliminate some of the difficult problems associated with the circular synchrotrons. Many of these features have been adopted in the design of the billion volt proton accelerators and consequently, the studies undertaken for the Michigan machine will be of wide interest and value. The innovations bring with them certain problems, however. The present progress report contains a technical description of the machine, of its special problems, and of the methods which have been developed for solving them.

The more essential of the changes that have been introduced are four in number.

(a) The magnetic field is concentrated into four circular quadrants separated by regions which are relatively field free. The equilibrium orbit of the electrons thus consists of four circular quadrant arcs with a radius of curvature of 100 cm separated by four straight sections, each with a length of 76 cm. The advantages of the straight, field-free sections are obvious since they permit easy access to the injector, radio frequency accelerator, and targets. The progress of the electron beam can be studied by introducing defining slits at one straight section and observing the position of the beam in subsequent straight sections. Auxiliary fields, either static or oscillating may be produced in any of the straight sections for the purpose of moving the beam or of influencing the oscillations of the electrons about their equilibrium orbit. The theory of the synchrotron with field-free straight sections - the racetrack synchrotron - has been studied in detail. There exist certain conditions upon the magnetic field fall-off which must be met to insure successful operation. These are, however, not difficult to comply with experimentally.

(b) The electrons are injected with an initial energy of around 500,000 e.v. This is approximately ten times the injection energy in the more conventional machines. The great advantage of this method is that the magnetic field at injection is relatively high and does not exhibit the local fluctuations which constituted one of the serious problems of the

other synchrotrons. The whole injection apparatus, moreover, is removed from the donut and consequently, is easier to service and adjust.

(c) The acceleration of the electrons in the donut is accomplished from the start by means of the radio frequency accelerator and not through the use of the double method of betatron acceleration and radio frequency acceleration as is usual. This eliminates the careful adjustment of the flux bars but it does mean that the radio frequency must be modulated in a prescribed manner. The possibility of radio frequency modulation can be used to shift the position of the equilibrium orbit in order that the electrons in subsequent cycles after injection can avoid hitting the injector box. At the time of maximum magnetic field, when the electrons have their highest energy, the frequency modulation can be employed to cause the beam to impinge on a target. The problem of frequency modulation, which must also be used in the billion volt proton synchrotrons, presents some difficulties but there appear to have been satisfactorily solved in the Michigan machine.

(d) The aperture (cross sectioned area of the donut divided by the square of the radius of curvature) of the Michigan synchrotron is somewhat smaller than that of other machines. The advantage of this is that the volume of magnetic field and indeed the size and cost of the synchrotron can be reduced. In other words, for a given cost, a machine with small aperture will yield a higher final energy for the electron beam. It is important to investigate the properties of a synchrotron with a small aperture in order to design economically the large billion volt machines. As far as can be foreseen at the present time, the smaller aperture does not involve any serious difficulties but it does demand a more careful adjustment of the magnetic field. It should be emphasized that the Michigan aperture is only slightly less than that of the other synchrotrons and thus, while it will give data on the desirability of this trend, it does not constitute a major departure from current designs.

FOREWORD

Authorization for the design and construction of a 300 Mev "racetrack" synchrotron at the University of Michigan was given by the U. S. Navy, Bureau of Ordnance in February, 1946. Since that time the work on the project has been reported to the Bureau of Ordnance in the form of brief monthly progress reports, plus a number of more detailed reports on special phases of the design. Until now no comprehensive report has been written. The reason for doing so at this time is threefold. First, in spite of the fact that a beam of high-energy electrons has not yet been produced by the machine, enough testing has been done and enough information gained so that it is believed that a report will be of value to others working in the same field. Second, the attempts to produce a beam in the machine as it was originally constructed have been halted temporarily and attention has been turned to the re-design of certain parts, on the basis of the experience gained. Third, a partial change in personnel is taking place, because of the fact that the three men* who have been largely responsible for the construction and testing have just completed their requirements for the Ph D, and have turned over their part in the work to a new crew of graduate students.

The plan in writing this report is not to explain the principles of the synchrotron or to give detailed descriptions of the "standard" features of the synchrotron, but to concentrate the attention upon the problems which are peculiar to the racetrack type of synchrotron and upon which some new knowledge or experience can be contributed. In short, this is a report addressed to physicists who are familiar with the general field.

---

*J. E. Dougherty, G. M. Grover and J. S. Malik.

TABLE OF CONTENTS

Page

FOREWORD

BRIEF HISTORY OF THE PROJECT

TECHNICAL DISCUSSION OF THE DESIGN

CONSTRUCTION AND PERFORMANCE DATA ON THE MAJOR COMPONENTS

EXPERIMENTAL RESULTS

PROGRAM FOR MODIFICATION

TABLE OF PLATES

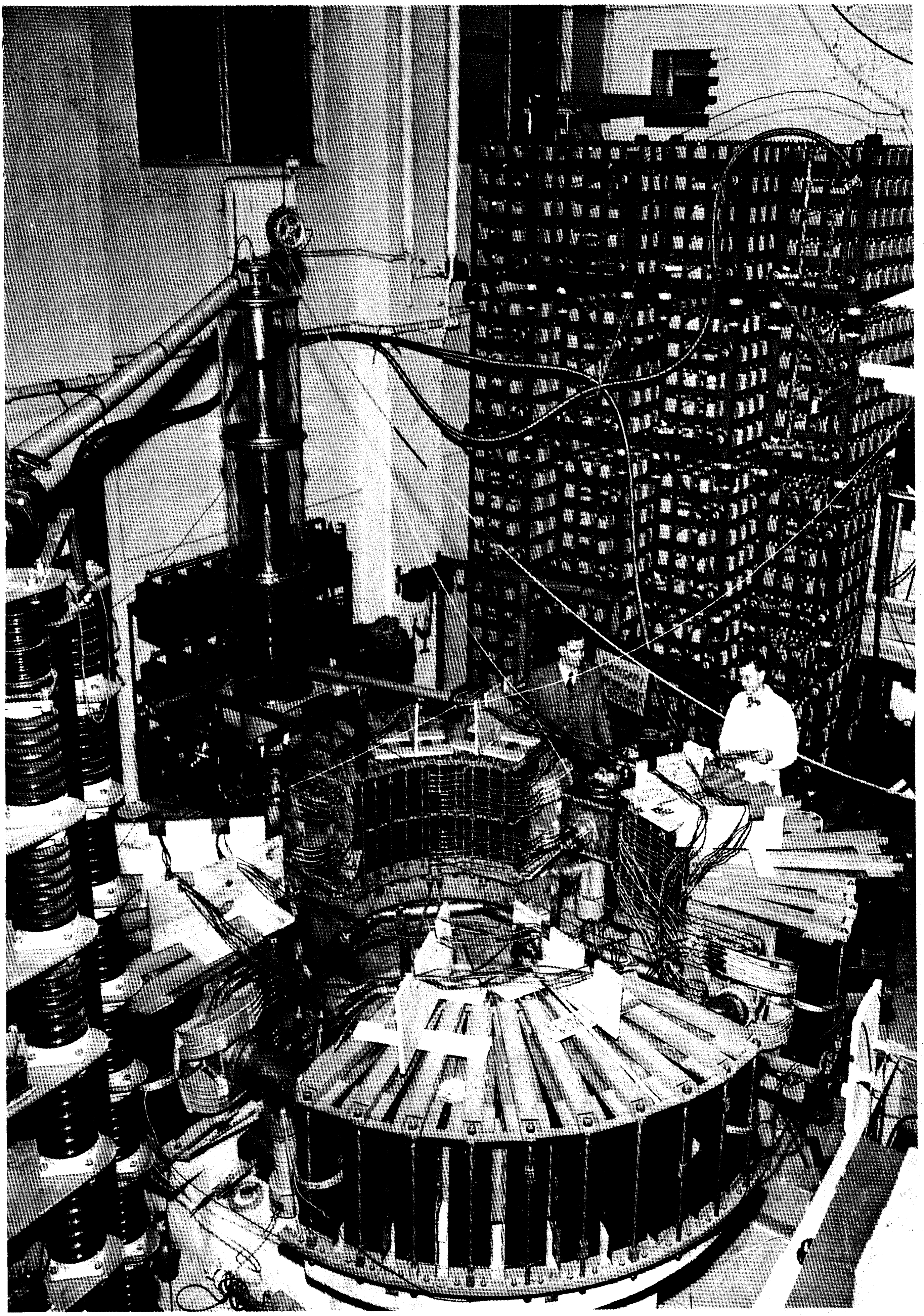


PLATE I

GENERAL VIEW OF THE SYNCHROTRON AT THE TIME OF THE FIRST OVER-ALL TEST.

RACETRACK SYNCHROTRON

BRIEF HISTORY OF THE PROJECT

As the late war approached its end in 1945, many physicists turned their thoughts to the problem of building accelerators for the production of energies much higher than those which had been available before the war. During this period E. M. McMillan[1] in this country and V. Veksler[2] in Russia discovered the principle of the synchrotron, quite independently of each other. Almost immediately the University of California announced its intention of building a synchrotron of 300 Mev, and several other institutions followed suit. All of the synchrotrons which were started or planned in this initial period were fashioned, in large degree, after the 100 Mev betatron which was then in successful operation at the General Electric Research Laboratories. Following the existing experience in this manner had many immediate advantages in reducing the risk of failure or decay. But such design also carried limitations that would make themselves felt in the event that energies much higher than 300 Mev were to be attempted; namely, (1) the style of magnet did not represent the most effective use of a given amount of iron and (2) the continuous annular guide field did not permit the insertion of very high voltage RF

---

[1] E. M. McMillan, Physical Review, 68 143 (1945).

[2] V. Veksler, Journal of Physics, (U.S.S.R.) 9 153 (1945).

accelerating electrodes, which would be necessary to compensate for the radiative losses[1] of the electron beam at high energies.

At the time the Michigan group became interested in high energy synchrotrons, it was clear that there was a need for experimentation with some rather basic changes in design if it were to be possible later to extend the work into the billion volt energy range. The broad objective adopted for the Michigan program was therefore to try to work out a design which would be capable of extension to much higher energies than contemplated with the machines then under construction.[2] Three main characteristics were settled upon as necessary to such an end.

(1) Accessibility of the orbit tube, in the form of open sections, in order to allow wider possibilities in regard to the kinds of RF acceleration and injector which could be used. The fact that extremely high RF voltages would be necessary to compensate the radiative losses in electron machines and that this would entail the use of large resonant cavities became a strong argument in favor of the open section. This was not, however, one of the points upon which the original decision to experiment with open sections was made, since the problem of radiative losses did not appear upon the scene until somewhat later. The decision to experiment with open sections was, of course predicated upon

---

[1] Julian Schwinger, Physical Review, 70 789 (1946).

[2] H. R. Crane, Physical Review, 69 542 (1946); 70 800 (1946).

theoretical proof that the orbit would be stable.[1,2,3]

(2) A compact magnet, economical in terms of both steel and stored energy. This meant using a rather small aperture as well as working out a new design for the iron core.

(3) High voltage injection, in order to minimize the scattering and make a small aperture feasible. The use of frequency modulation starting instead of betatron starting followed as a logical consequence of the choice of high voltage injection.[4]

So many radical departures in design naturally raised a multitude of problems and, needless to say, many of them have not yet been solved. The Michigan machine is not yet in operation. Meanwhile, however, several events have occurred which have been highly gratifying in indicating that the design which we originated has proved to be of value in the extreme energy range. The two giant proton synchrotrons (Berkeley and Brookhaven) which are now under construction, and the electron synchrotron which is planned at Cal. Tech. follow in considerable detail this design. The 1/4 scale model of the Berkeley machine (which is more than twice as large as our full scale machine) has operated successfully, dispelling any doubts as to the practicability of the racetrack design.

---

[1] D. M. Dennison and T. H. Berlin, Physical Review, <u>69</u> 542 (1946); <u>70</u> 434 (1946).

[2] R. Serber, Physical Review, <u>70</u> 434 (1946).

[3] A later treatment of the dynamics of particles in the racetrack has been published by N. M. Blackman and E. C. Courant, Review of Scientific Instrument, <u>20</u> 596 (1949). Also see J. S. Malik, Thesis, University of Michigan (1949).

[4] The question of the stability of orbits in an electron synchrotron with frequency modulation has been investigated by D. M. Dennison and T. H. Berlin and published in the Physical Review, <u>70</u> 58 (1946).

In the sections immediately following, the reasons will be given for the choice of the various points of design as they were originally worked out or as they were worked out in the course of building the machine.

TECHNICAL DISCUSSION OF THE DESIGN

Magnet Design.

The choice of a ring shaped (cylindrically symmetrical) magnet instead of the cyclotron style magnet is made principally for two reasons. (1) It is the most economical of iron, since it gives the shortest possible return path from every part of the magnet gap. (2) All return paths are of the same length. The latter is of importance in minimizing the azimuthal iron hysteresis and eddy currents. The part due to hysteresis is, in a given return path, proportional to the hysteresis power loss, consequently, it is proportional to the quantity of iron in the return path (provided, of course, that the flux density is constant throughout). Paths of various lengths will, therefore, give rise to an azimuthal variation in phase.[1] The same can be said of the losses which are due to eddy currents, both those which are confined within the individual laminae and the more uncertain ones which pass through the contacts between laminae. The only important contribution to phase shift which is not proportional to the quantity of iron in the return path is that due to eddy currents in

---

[1] The importance of phase variations due to varying length of return path was first remarked upon by E. M. McMillan (private communication). He found it to be a large effect in his magnet, which is of the cyclotron style.

the copper of the windings. This can be expected to be quite constant in azimuth, except at the ends of the quadrants where the effect may be considerable.

Assuming that a ring of cylindrically symmetrical magnet is to be used, there remains the choice between a C and an H-window cross section. Whether all of the return flux is sent around one side or Whether it is divided and sent around both sides, of course, makes no difference in principle, but there are several practical points to consider. In circular machines it is imperative to use a C cross section since it provides the only means of access to the donut, but in the racetrack this is not a crucial point, inasmuch as the access is provided by the straight sections. If the gap is to be short circuited flux bars for betatron starting, the C cross section possesses the advantage or providing space for and access to, the flux bars. The C must, in that case, be faced inward, to give the correct sign for the betatron acceleration.[1] In the racetrack, we may avail ourselves of the advantages of the H-window cross section since, as mentioned, the question of access is not crucial. The specific reasons why we chose the H-window shown below instead of a C are briefly:

Circular machines with C cross section (C facing inward) and short ci cuiting bars for betatron starting are by far the most numerous, and far the most successful in the energy range in which they are used; namely, up to about 330 Mev.

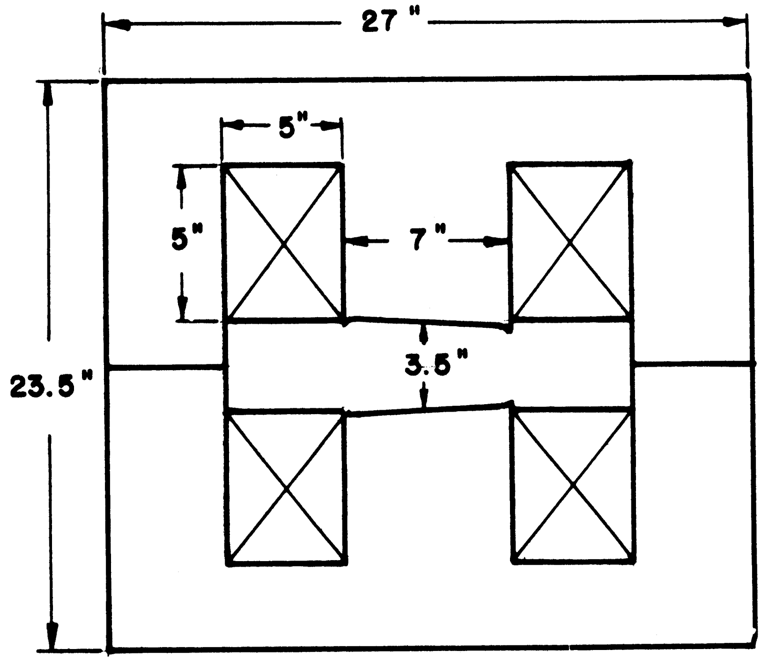


FIGURE 1. Cross Section of the Iron Core

(1) By the insertion of shims the fall-off exponent can be changed without even disassembling the machine. Since one of the peculiarities of the racetrack is that certain values of the fall-off must be avoided because of resonance, a convenient way of changing the fall-off was considered to be of prime importance. (2) The mechanical assembly is easier, since the problem of counteracting the tendency for the C to "bite" under magnetic forces largely disappears. (3) The coils are clamped in place more securely and easily in the H-window. This might not be true of air cooled coils, but the solid windings in our case can be compressed by the iron and need no further support. (4) Some iron is saved in the H-window over the C, but this is perhaps the least important of the reasons for the choice.

The dimensions of the magnet cross section were arrived at after a number of d.c. models had been made and studied. The details of the measurements are given in a separate publication.[1] The ratio of height to width of the winding spaces which was adopted was not the most favorable one from the standpoint of economy of condenser energy and iron alone, for the following reason: The distance to which the winding projects beyond the end of the quadrant (into the straight section) is equal to the width of the winding. Therefore, there was an advantage in keeping the width of the winding small. The width chosen, relative to the height, was therefore somewhat smaller than that which would have given the maximum efficiency.

Water Cooled Vs. Air Cooled Windings.

One of our prime objectives in the design was to try to make a compact magnet, using a much smaller amount of iron for a given electron energy than is used in the more conventional machines. Making the winding compact and thereby reducing the length of the iron return path was obviously the way to reduce the weight of iron needed. But at the same time it was desired to use CW operation rather than intermittent cycling, in order to have the advantage of large electron output. These two requirements meant that the coils would have to handle a high average power and yet occupy a small space. A winding consisting of current-carrying pancakes alternated with pancakes of copper tubing carrying water for cooling was chosen as the answer to these requirements.

---

[1] W. C. Parkinson, G. M. Grover, and H. R. Crane, Review of Scientific Instruments, 18 734 (1947).

Choice of Magnet Frequency.

There is one strong argument in favor of using low frequency in a racetrack, which does not apply to circular machines. The presence of some out-of-phase magnetic field in the straight sections is unavoidable. The contributors to this are: (1) eddy currents induced in the metal boxes (injector box, accelerator box, etc.); (2) eddy currents in the mass of copper, which is immediately above and below the donut at the quadrant ends; and, (3) eddy currents induced in the last few iron laminae by the fringing flux which emerges from the face of the quadrant. Since the out-of-phase field in the straight section is due predominantly to eddy currents of one sort or another, its strength at the instant of injection is proportional to the magnet frequency. The second argument in favor of low magnet frequency is connected with our desire, already mentioned, to use water cooling in the winding. In making pancakes of copper tubing it is of advantage to use tubing not less than 1/4 inch diameter. The use of 1/4 inch tubing will permit frequencies up to approximately 20 cycles per second, without excessive loss due to eddy currents in the tubing. The third argument in favor of low frequency has to do with RF voltage required for acceleration. As mentioned earlier, one of our initial objectives was to develop a frequency modulated, high-energy injection system. At 500 Kev injection energy the electron velocity is .86C; therefore, the required frequency modulation is .86 to 1. The energy gain per revolution for the electron immediately after injection (during the frequency modulated phase of operation) is the following, for our machine and for 300 Mev final energy.

60 cycle/sec operation, 3600 e.v. per turn

20 cycle/sec operation, 1200 e.v. per turn

10 cycle/sec operation, 600 e.v. per turn

To permit phase oscillations, the peak RF voltage should be about twice the above figures. The RF system under consideration at the time the decision on magnet frequency had to be made was a conventional broad band power amplifier driving a large Klystron-type cavity for acceleration. Calculation indicated that for 14% modulation, 2000 volts RF (suitable for 20 cycle operation) could be produced with an amplifier under 10 Kw, but that higher values would be difficult.

As a result of the arguments presented, 20 c.p.s. was chosen as the frequency of operation.

Magnet Driving System.

To drive a low frequency magnet the 60 c.p.s. power must be converted to the lower frequency either by a motor and alternator or by some electronic means. The method chosen for the Michigan machine was to let the magnet and condenser bank constitute the tank circuit of a self-excited oscillator, using a large water-cooled triode. The disadvantage of this type of frequency conversion is that the maximum over-all efficiency one can hope for is about 75%, as against 90% or more for rotating machinery. On the other hand, there are several advantages over rotating machinery which, in our particular case, out-weighed the sacrifice in efficiency. (1) Rotating machinery would have required an irrevocable decision upon the magnet frequency, which we were reluctant to make, in view of the experimental nature of the whole problem. The triode oscillator system is completely flexible as the frequency. (2) Rotating machinery would have required a special room, and rooms were at premium. (3) The equipment for the rectifier and oscillator was more readily available than was rotating at the time. (4) The problem of starting the magnet was simpler with triode driving. Also, the problem of keeping the resonant frequency of the magnet matched to the frequency of the driver is nonexistent in the self oscillator.

Choice of Method of Producing 1/2 Mev Electrons for Injection.

The methods available for the production of the beam of electrons for injection were (1) a high voltage accelerator tube powered by a Cockroft-Walton d.c. voltage generator, a.c. transformer, pulsed transformer, or Van der Graff generator, or (2) a pulsed RF cavity-type accelerator. The first decision was whether to attempt to go to at least 2 Mev ($\beta = .98$) where frequency modulation of the synchrotron would be unnecessary, or to use a more moderate energy with frequency modulation. It was believed at the time that the development of a frequency modulated oscillator for the synchrotron would involve fewer problems than the development of a 2 Mev injector gun. Further, the use of an accelerator tube in the range of 1/2 Mev was a "previously solved problem" at Michigan[1] and the equipment left over from earlier days was available. It was decided to use a Cockroft-Walton type d.c. voltage generator of 600 Kv maximum voltage, coupled with a four-section glass accelerator tube with a grid-controlled electron source at the top. In practice it turned out that this was as straightforward as it was hoped it would be, and no trouble was experienced with it.

---

[1] H. R. Crane, Physical Review, <u>52</u> 11 (1937).

Z Vs. R. Injection.

Because of the fact that the high voltage gun was so large, it was not practical to use it in any position except the vertical. That meant the Z injection would require only one deflection, 90° in the vertical plane. R injection, on the other hand, would require in addition a deflection of about 30 degrees in the horizontal plane. Orbits of the electrons immediately after injection were computed by D. M. Dennison[1] and it was shown to be possible to satisfy the conditions for efficient capture by Z injection, provided the injector nozzle was displaced from the center of the donut in radius. The position is shown in the sketch below.

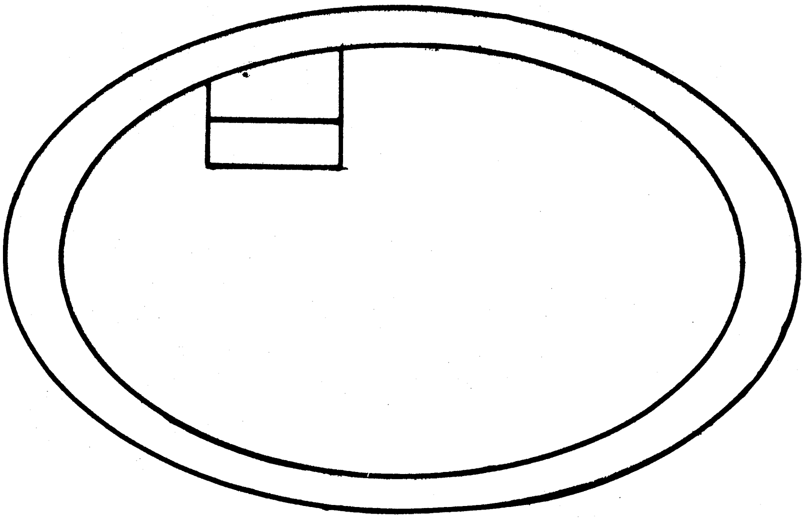


FIGURE 2

The injection problem in a racetrack is more complicated than it is in a circular machine, for the reason that immediately after injection the amplitude of the "betatron oscillation" becomes greater than that which is indicated simply by the distance of the nozzle from the equilibrium orbit. This is due to the existence of the straight sections, and the

---

[1] D. M. Dennison, Article contained in the Seventh Annual Report, University of Michigan, Bureau of Ordnance, U. S. N. Contract NORD 7924 task UMH4.

percentage increase in amplitude is a function of the ratio of the length of the straight section to the length of the curved section. Therefore, neither injection from R without Z amplitude nor injection from A amplitude is possible, unless the equilibrium orbit is moved away from the nozzle at an extremely high rate. It is essential, therefore, when injecting from R to take advantage of Z oscillations, or when injecting from Z to take advantage of R oscillations, so that the beam may swing beyond the nozzle and yet miss it for many turns by passing to one side or the other of it. The original choice of injector position was the one shown in Figure 2.

CONSTRUCTION AND PERFORMANCE DATA ON THE MAJOR COMPONENTS

Magnet.[1]

A cross section drawing of the magnet was shown on an earlier page, and the several photographs of the machine show how the magnet is assembled. The important electrical and mechanical quantities are given below:

Weight of iron 12.5 tons

Windings: Each pancake consists of 29 turns of solid, 1/8 inch x 3/8 inch double cotton covered conductor. 8 pancakes above the gap and 8 below in each quadrant.

Cooling: Pancake made of 1/4 inch O.D., .035 inch wall, double cotton covered copper tubing. 4 pancakes above the gap and 4 below in each quadrant. One side of each current pancake is adjacent to a cooling pancake.

---

[1] The iron core was built by the Allis Chalmers Company. The windings were built in the laboratory.

All cooling pancakes are in parallel for water, and fed through plastic tubing for electrical isolation.

Circuit: The transposition circuit for the four quadrants is shown in Figure 3, where each horizontal line indicates two of the 29 - turn pancakes in series.

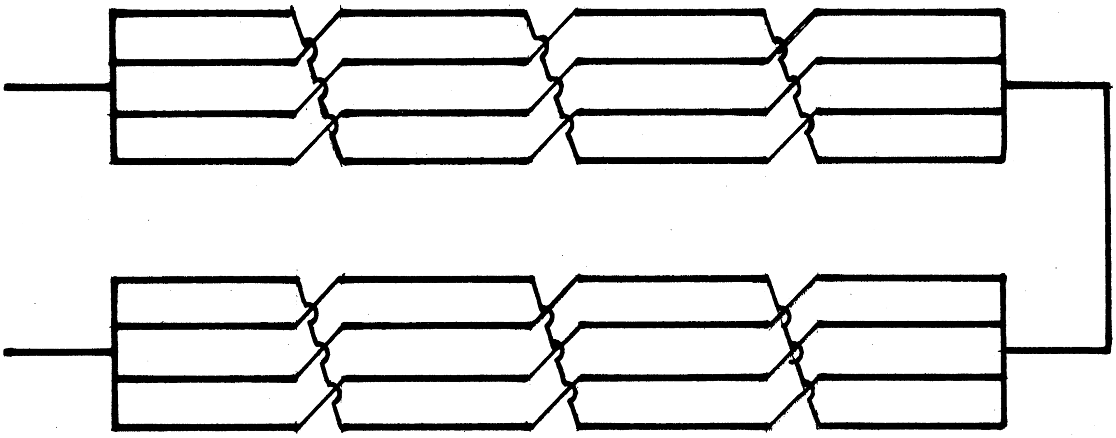


FIGURE 3

The series circuit shown has been used for the tests at low field. For full field the upper and lower sets of windings will be operated in parallel. The electrical data given below refer to the series connection. They are given for 1000 gauss peak field, since that is the approximate field at which they were measured.

Inductance: 0.3 henries

Voltage: At 20 c.p.s. and 1000 peak gauss the peak voltage is 3000

Energy: At 1000 gauss, 630 joules

Kva at 1000 gauss, 20 c.p.s. 75

Kw loss at 1000 gauss, 20 c.p.s. 2.5

Q: 30

Field Measurements.

During the time of the assembly of the magnet quadrants and also after completion tests were made to check both the radial fall-off index and the azimuthal uniformity of the field. Although the magnetic measurements were carried through on all the quadrants, their results were never found to differ significantly from the values indicated by the geometrical slope and separation of the pole faces. Two methods were used for measuring peak magnetic field: one was to excite the magnet with d.c. and explore the field with a flip coil and ballistic galvanometer; the other was to excite the magnet with a.c. and measure the a.c. voltage generated in a search coil. The two methods were found to agree within the limits of error. The a.c. method was used to obtain the results presented here. By means of peaking strips and a synchroscope it was possible to obtain the phase of the field at all points, and consequently to compute the field at all points at the instant of injection (30 gauss). It was not feasible to obtain in a similar way a map of the instantaneous value of the fall-off index, because of the way in which the computation of the fall-off magnifies errors in the field values. The separation of the pole faces and their slope is adjustable in each magnet block after final assembly, merely by changing the thickness of the fibre shims. It was therefore found to be of advantage to have a search coil mounted on a small car which could travel inside the donut, so that the field could be checked and adjusted after final assembly. Such a car is shown in the photograph which follows. Since the donut is elliptical in cross section,it is possible to keep the car centered and roughly oriented parallel to the major

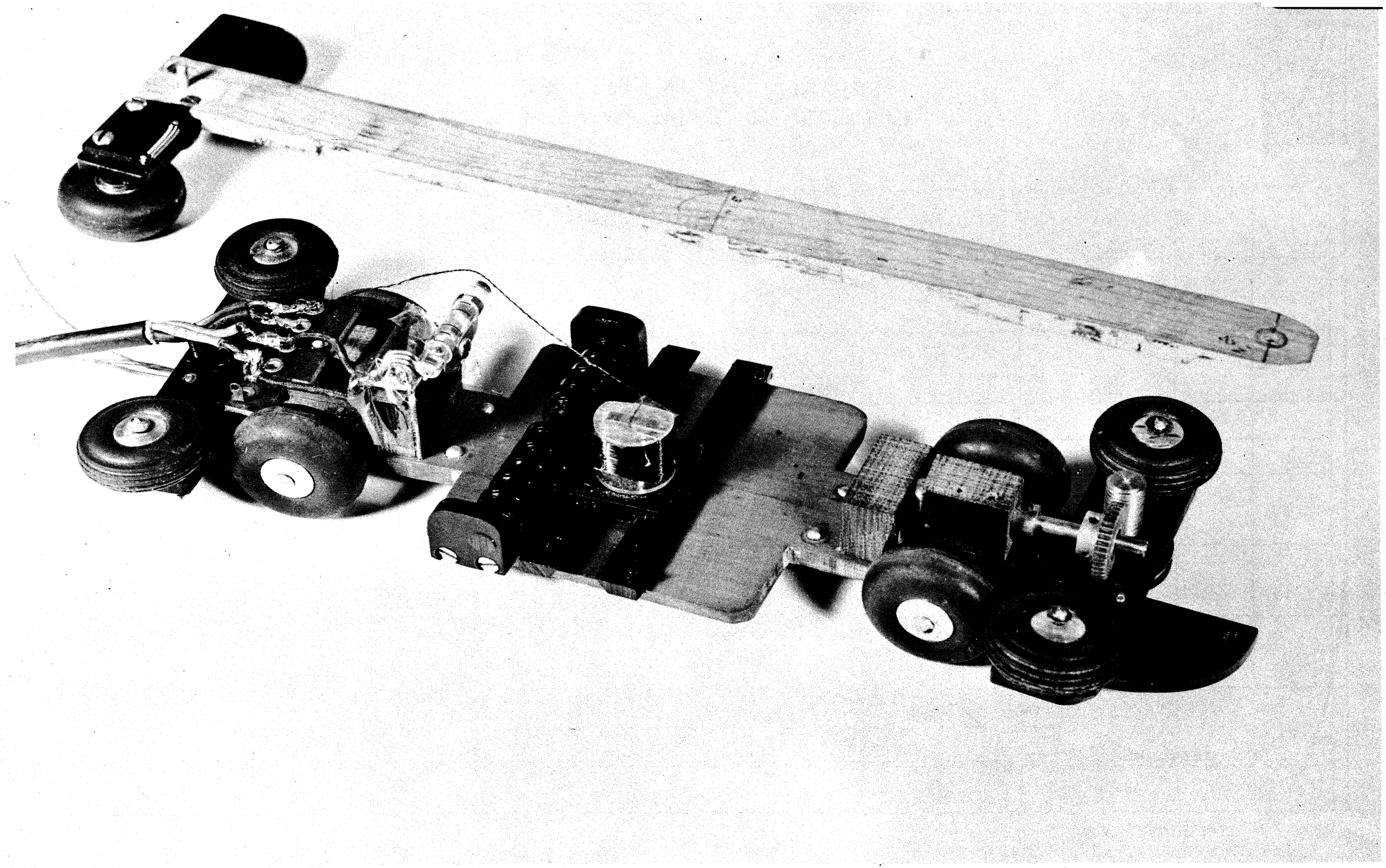


PLATE II

CAR FOR MAGNETIC MEASUREMENTS INSIDE DONUT

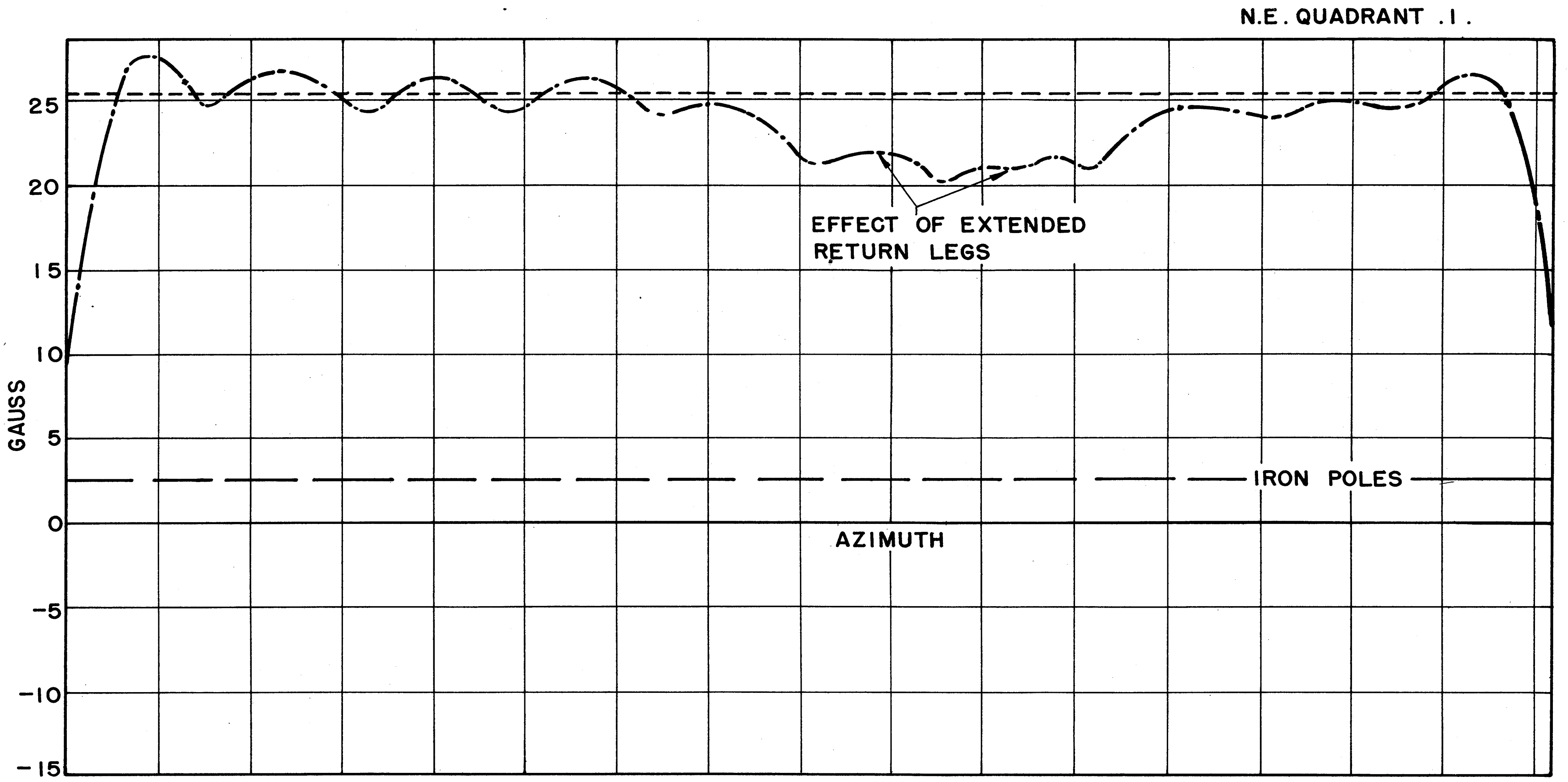


FIG. 4

PLOT OF FIELD AT INJECTION
AS FUNCTION OF AZIMUTH

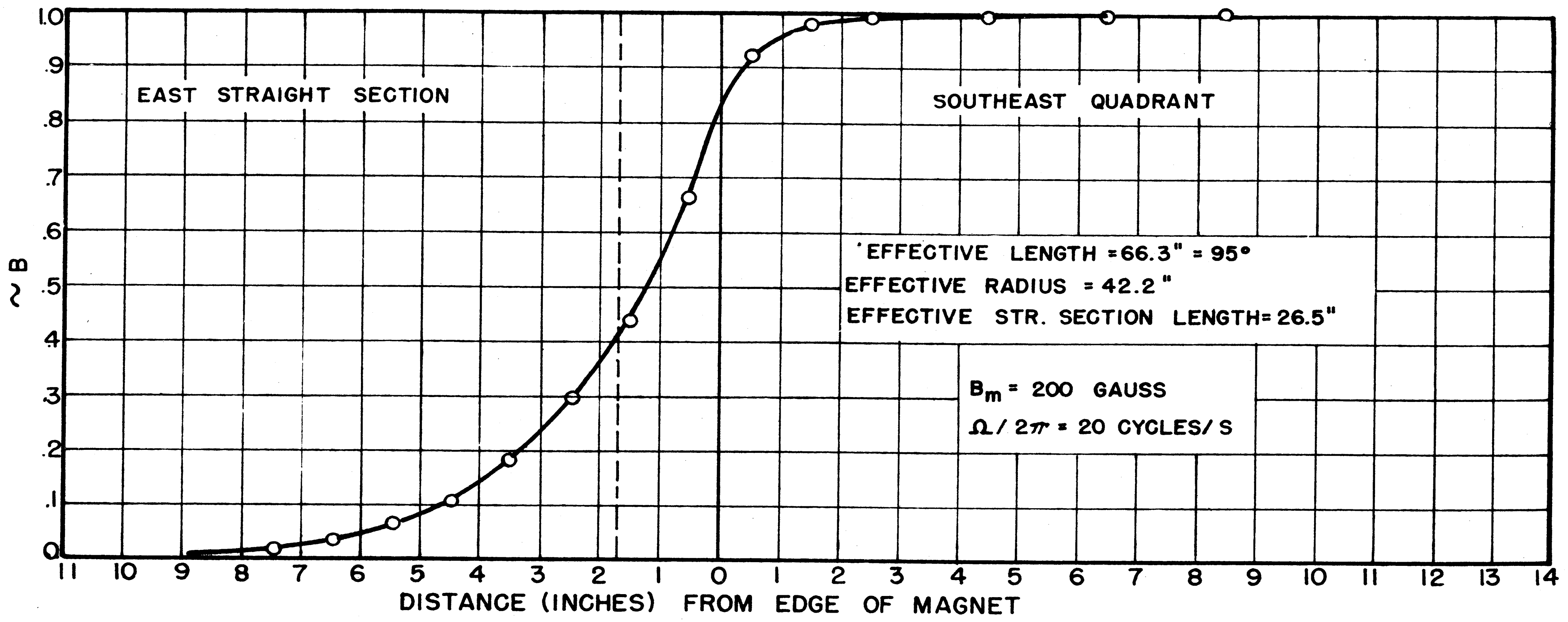

1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
~B
EAST STRAIGHT SECTION
SOUTHEAST QUADRANT
'EFFECTIVE LENGTH = 66.3" = 95°
EFFECTIVE RADIUS = 42.2"
EFFECTIVE STR. SECTION LENGTH = 26.5"
B_m = 200 GAUSS
Ω / 2π = 20 CYCLES/S
11 10 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
DISTANCE (INCHES) FROM EDGE OF MAGNET

FIG. 5

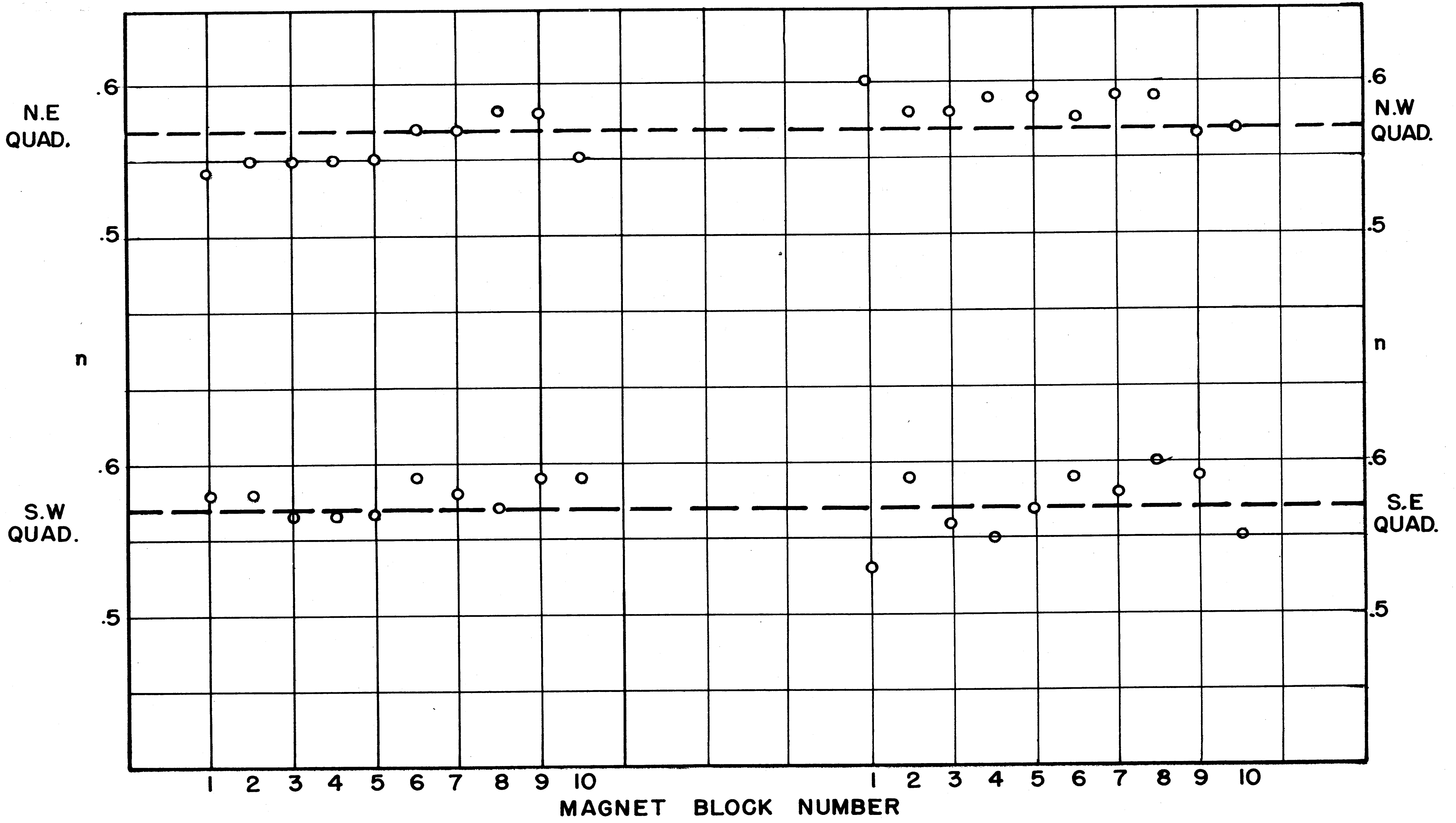

N.E
QUAD.
S.W
QUAD.
N.W
QUAD.
S.E
QUAD.
n
.6
.5
1
2
3
4
5
6
7
8
9
10
MAGNET BLOCK NUMBER

FIG . 6

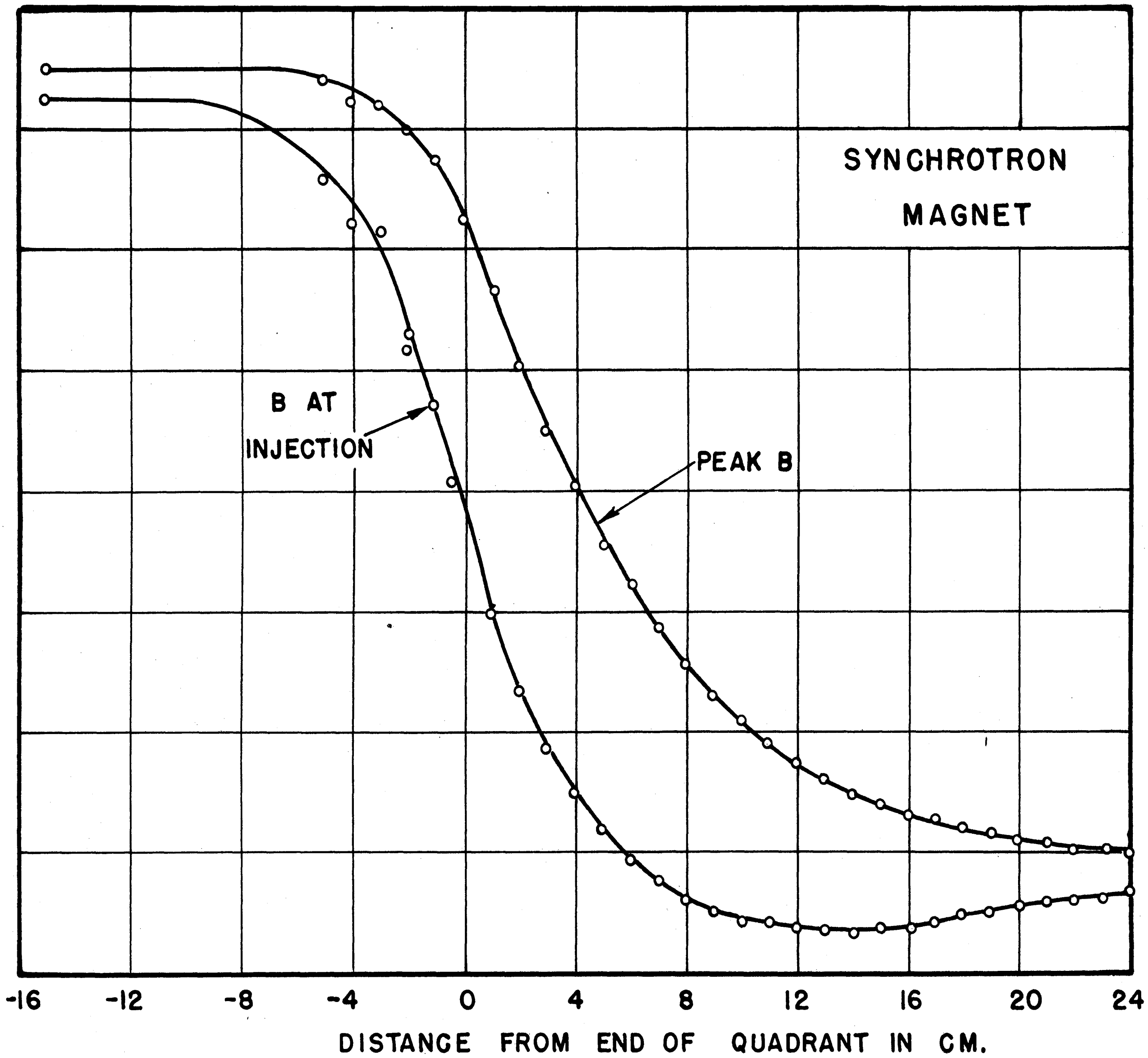


FIGURE 7

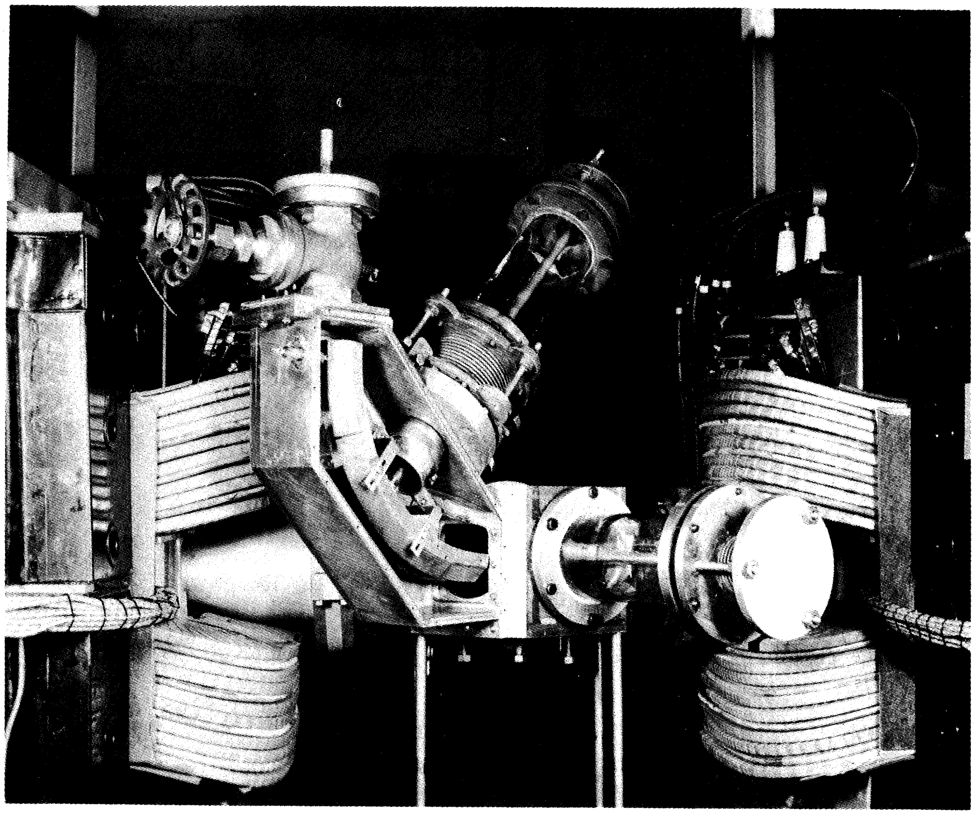
FIELD AT THE INSTANT OF INJECTION, COMPARED WITH THE PEAK FIELD, IN THE NEIGHBORHOOD OF THE END OF THE QUADRANT. THE MEASUREMENT WAS MADE AT 20 C.P.S. AND 1800 GAUSS PEAK FIELD.

axis by using eight wheels. A more positive control through which the car is kept horizontal is obtained, however, through the stick with which it is pushed along in the donut. This is articulated only in one plane. For fall-off measurements, the search coil can be moved transversely on the car by means of the bakelite lead screw, operated by strings. The car is also well adapted to carrying a peaking strip for phase measurements.

Several graphs follow which show the results of the field measurements. It will be seen that the field is remarkably good in some respects and bad in others. The phase variation in azimuth is quite small, and results in a variation in instantaneous field at injection of only about 8%. This may be contrasted with a variation of about 100%, which has been typical of other synchrotrons before correction. The smallness of the variation may be attributed to two things: the uniformity in length of the magnetic circuit, and the rather high field at injection (30 gauss as against about 8 gauss for other synchrotrons).

The phase change in the transition region between quadrant and straight section is quite large. It has been corrected successfully by means of coils wound around the back legs of the end blocks of iron in the quadrants.

These can be seen in Plate III. Power for the coils is tapped off the condenser bank, passed through a step-down transfer and finally through a set of four Variacs, one for the coils in each straight section. The loss in this circuit is sufficient to shift the phase nearly 90 degrees with no further addition of resistance. The



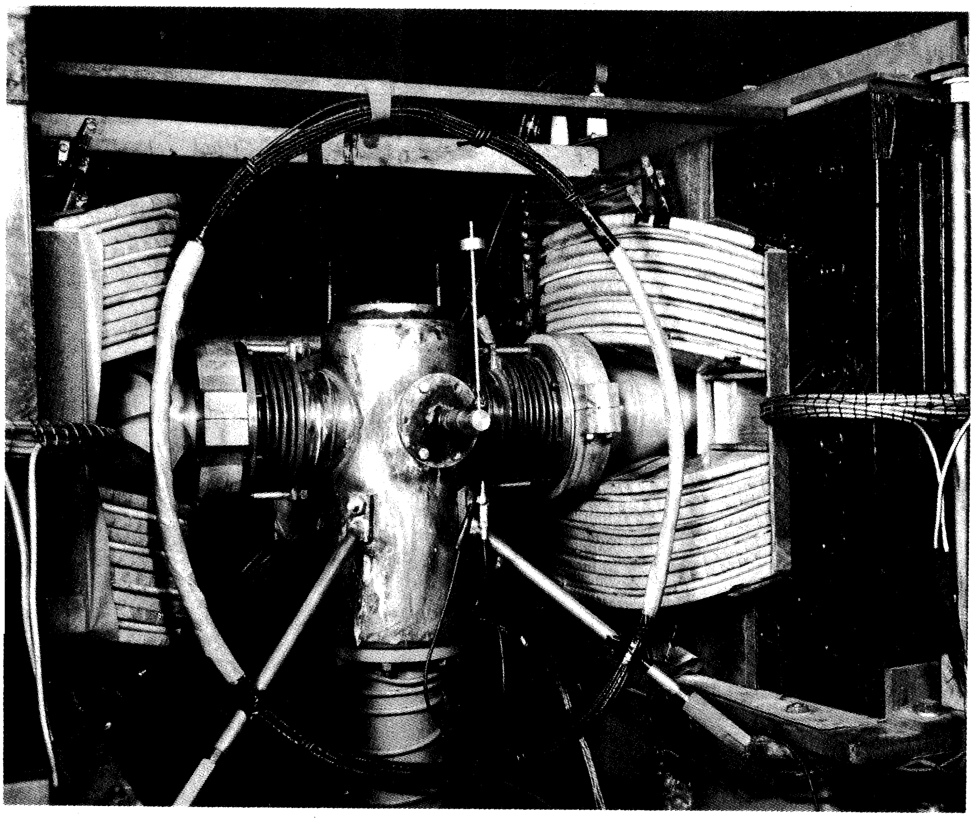


PLATE III

UPPER: EAST STRAIGHT SECTION SHOWING NEW BOX FOR HORIZONTAL INJECTION, PARTLY ASSEMBLED.

LOWER: WEST STRAIGHT SECTION, SHOWING CORRECTING COILS AND DETECTION BOX.

location of the correcting field is somewhat displaced from the region of maximum phase shift, so the electrons follow a slight double curve. That the correction can be made successfully is demonstrated by the fact that electrons can be made to circulate for several revolutions around the synchrotron, and that this can be done only by adjusting the current in the correcting coils.

The fall-off index reverses sign in the straight section and causes the effective fall-off for the whole machine to be somewhat smaller than that measured within a quadrant. The effect is shown in Figure 8. The curve shown is, of course, based upon peak field measurement. The difficulty of mapping the fall-off index for the instant of injection has already been remarked upon. It might eventually prove necessary to attack the problem of such a measurement, however, because of its importance. Fortunately, there is an independent kind of evidence indicating that the effective fall-off at injection during a.c. operation is not different, within the error of measurement, from that found by either d.c. or peak a.c. field measurements. The trajectory of the electron beam for several revolutions determined by means of probes and was found to be the same with a.c. and d.c. operation of the magnet. In this measurement the peak field was only 1800 gauss, so any deviation of fall-off at injection time would be expected to be reduced by more than a factor 5, from what it would be at 10,000 gauss. Measurements of fall-off by means of electron trajectories are not reliable to better than 5%, so altogether it can be said only within rather wide limits that the effective fall-off remains constant over the cycle.

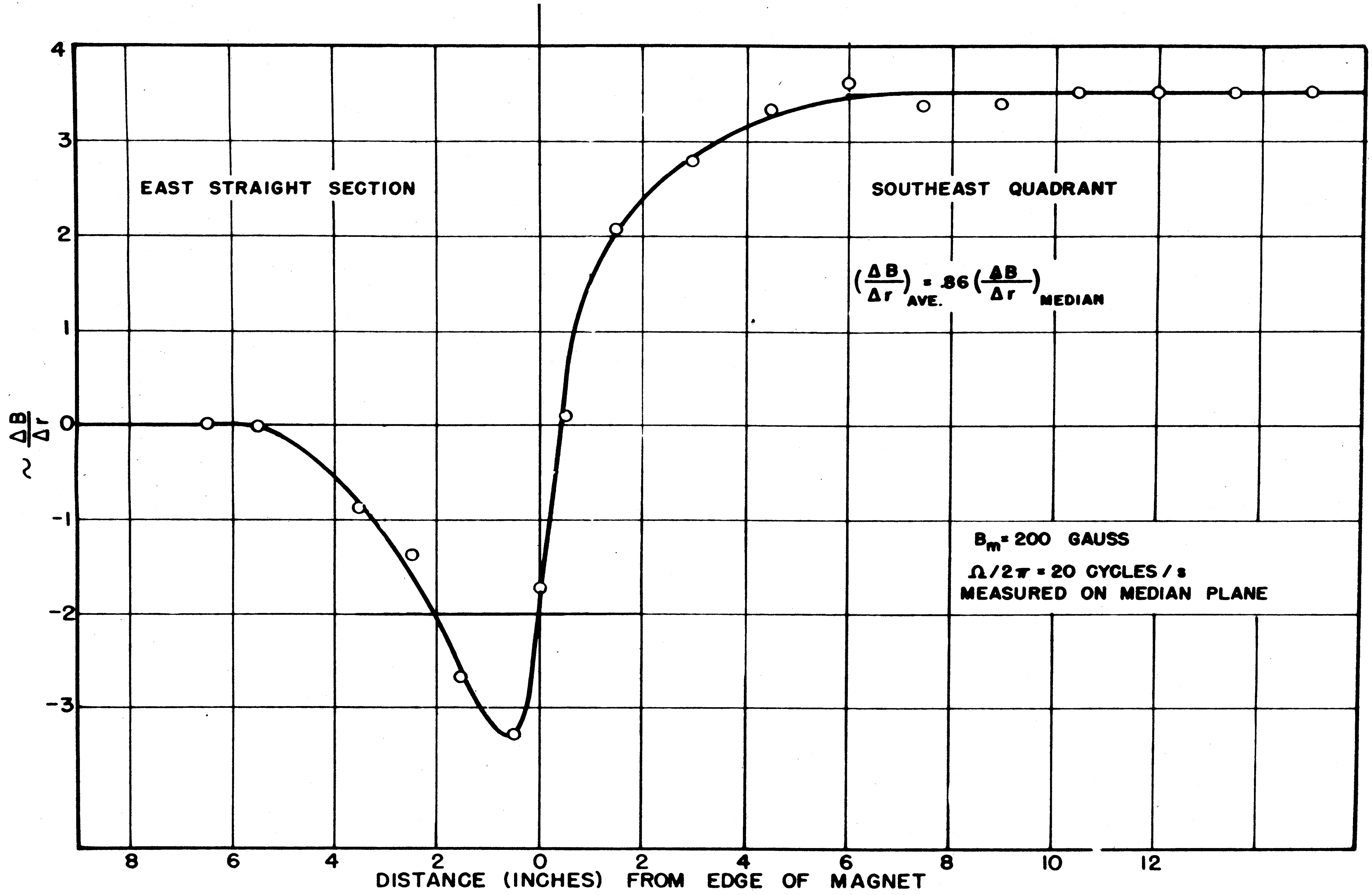

4
3
2
1
0
-1
-2
-3
$\sim \frac{\Delta B}{\Delta r}$
EAST STRAIGHT SECTION
SOUTHEAST QUADRANT
$\left(\frac{\Delta B}{\Delta r}\right)_{AVE.} = .86 \left(\frac{\Delta B}{\Delta r}\right)_{MEDIAN}$
$B_m = 200$ GAUSS
$\Omega/2\pi = 20$ CYCLES / s
MEASURED ON MEDIAN PLANE
8
6
4
2
0
2
4
6
8
10
12
DISTANCE (INCHES) FROM EDGE OF MAGNET

FIG. 8

It is evident from the data presented that the magnetic field has two major faults: (1) The phase lag near the quadrant ends is large, requiring the application of a correcting field which is in itself so large that it is critical of adjustment and inconvenient to produce. (2) The effective length of the quadrant is too great (95 degrees). This requires the radius of the donut to be made about 5% greater than that of the quadrant in order not to lose donut aperture, and results in a compromise orbit which does not follow the radial center of the magnet gap. The latter causes some loss of effective aperture.

In order to determine how to correct the two faults mentioned, a full scale model of the end (16 inches) of a quadrant was set up (Plate IV). The only differences between this and the synchrotron magnet are that the return path on the model has smaller cross section and that only four copper pancakes are used, above and below. To test the effect of the copper upon the phase lag in front of the quadrant, the windings in the model can be made flush with the pole faces or moved away until they are as shown in the photograph. The iron laminae which form the pole pieces can be slit so as to form a throat of any desired taper. The one shown in the photograph is 3 inches in radius. All experiments were run at 60 c.p.s. while 20 c.p.s. performance can be predicted with only fair precision from the 60 c.p.s. measurements. The use of 60 c.p.s. has the advantage of showing phase lags more sensitively, besides being more convenient. For peak field measurements a search coil with vacuum tube voltmeter was used, and for phase

PLATE IV

FULL SCALE AC MODEL OF A QUADRANT END.

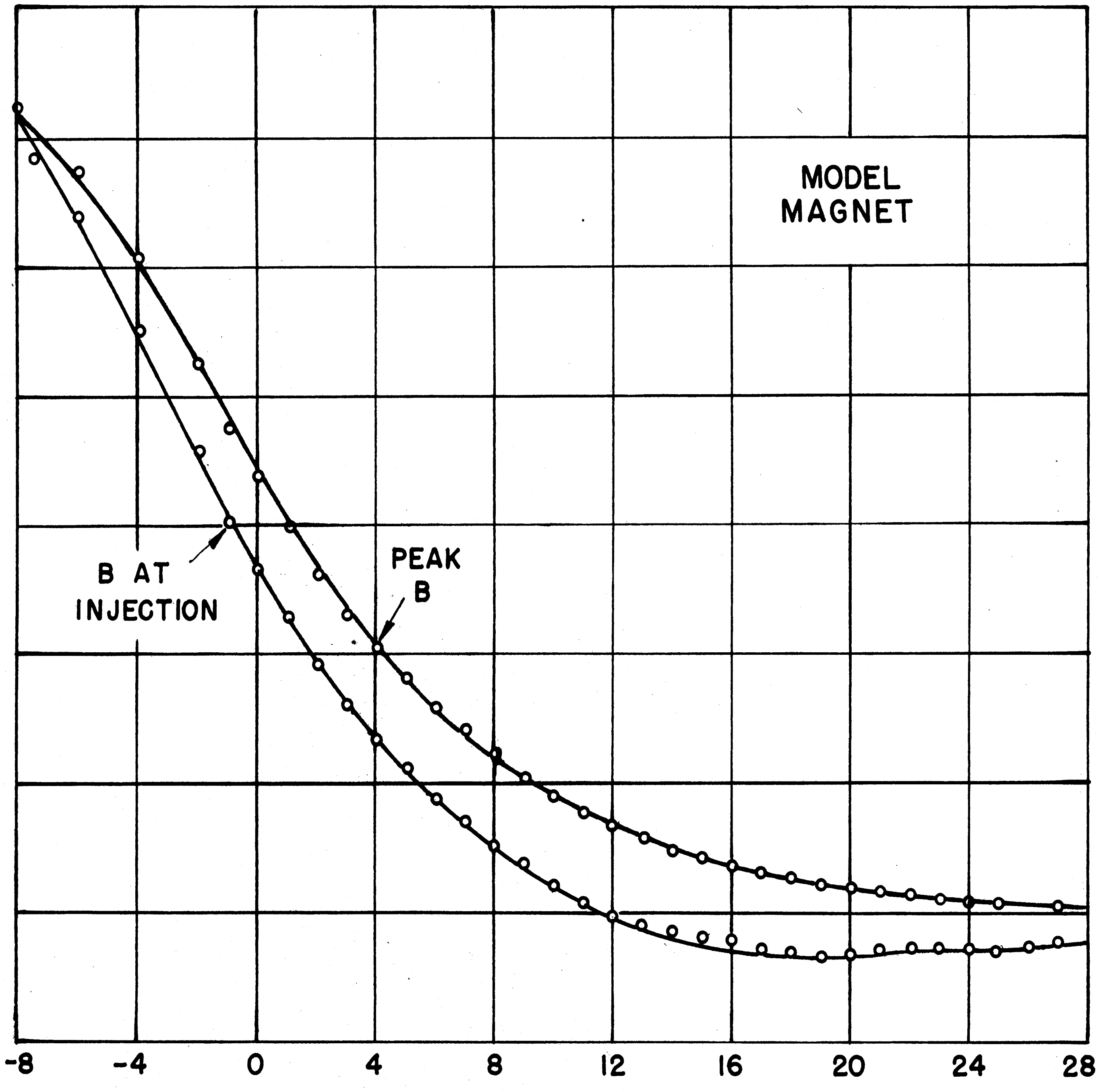


FIG. 9

FIELD AT INJECTION (30 GAUSS) COMPARED WITH THE PEAK FIELD, FOR A THROAT HAVING A 3 INCH RADII. THE MEASUREMENT WAS MADE AT 60 C.P.S AND 1150 GAUSS PEAK.

measurements a pair of peaking strips of .002 inch diameter molybdenum permaloy wire were used with a Tektronix synchroscope.

Results showed that the phase change in the fringe field caused by moving the copper between the two positions previously described was hardly perceptible. Practically all of the phase lag therefore,must be attributed to the flux which enters the laminae normally at the face of the quadrant. This is verified by experiments in which the iron was tapered at the throat. Figure 9 shows plots of the peak field and injection field, for a 3 inch radius at the throat. These curves should be compared with those in Figure 7, keeping in mind that the phase lag in the tapered one would be roughly two times as small as shown if it were reduced to 20 c.p.s. A great improvement is therefore obtained. At the same time, needless to say, an accurate measurement of the required correction to the total length of the quadrant was made in order to have its effective length equal 90 degrees. The length of the quadrant was determined on the basis of the peak B curve, since it is assumed that in operation of the injection B curve will be brought up to that by means of phase correcting coils. The reduction in effective length brought about by the flaring of the throat alone was not as much as one might have guessed: only 1.5 cm at each end. It was necessary to shorten the quadrant an additional 2.5 cm at each end in order to make it effectively 90 degrees. Replacement blocks which will contain the improvements worked out with the model are being ordered for the ends of all the quadrants. (This means replacing 20% of iron in the magnet.)

Electron Gun and Injection System.

The high voltage for injection is produced by a 600 Kv Cockroft-Walton-type condenser-rectifier multiplier of 8 stages (see Plates V and VI). A 60 c.p.s. X-ray transformer is used for the input. The rectifier tubes are Heintz and Kaufmann 953E, rated at 150 Kv peak inverse. The condensers are Plasticon 6000 V, 2 Microfarad, 13 units per section. The filaments of the diodes are heated by means of belt driven automobile generators. To maintain a uniform voltage distribution along the stack, a bleeder resistor is connected across each of the 6000 volt condenser units, and spark gaps are provided, to protect the diodes and condensers against surges. It should be remarked that whenever a gas discharge strikes in the electron gun, the voltage of one side of the Cockroft-Walton tower is abruptly lowered, and if it were not for the protection of the spark gaps, a breakdown would occur through the diodes. The voltage is measured and regulated by means of a single high resistance from the top of the stack to ground. This is built of a large number of metalized resistors shielded by a bakelite tube. Regulation is accomplished in a standard manner: a voltage sample (about 1000 volts) from the high resistance is compared with that from a battery, the difference is amplified and used to control a power tetrode which constitutes the load on a transformer, the primary of which is in series with the primary of the X-ray transformer which supplies the Cockroft-Walton stack.

The electron gun is a 4-stage linear accelerator, shown in Plate VI. Electrons are supplied by a tungsten filament and are focused by the lens system shown in Figure 10. The middle plate,

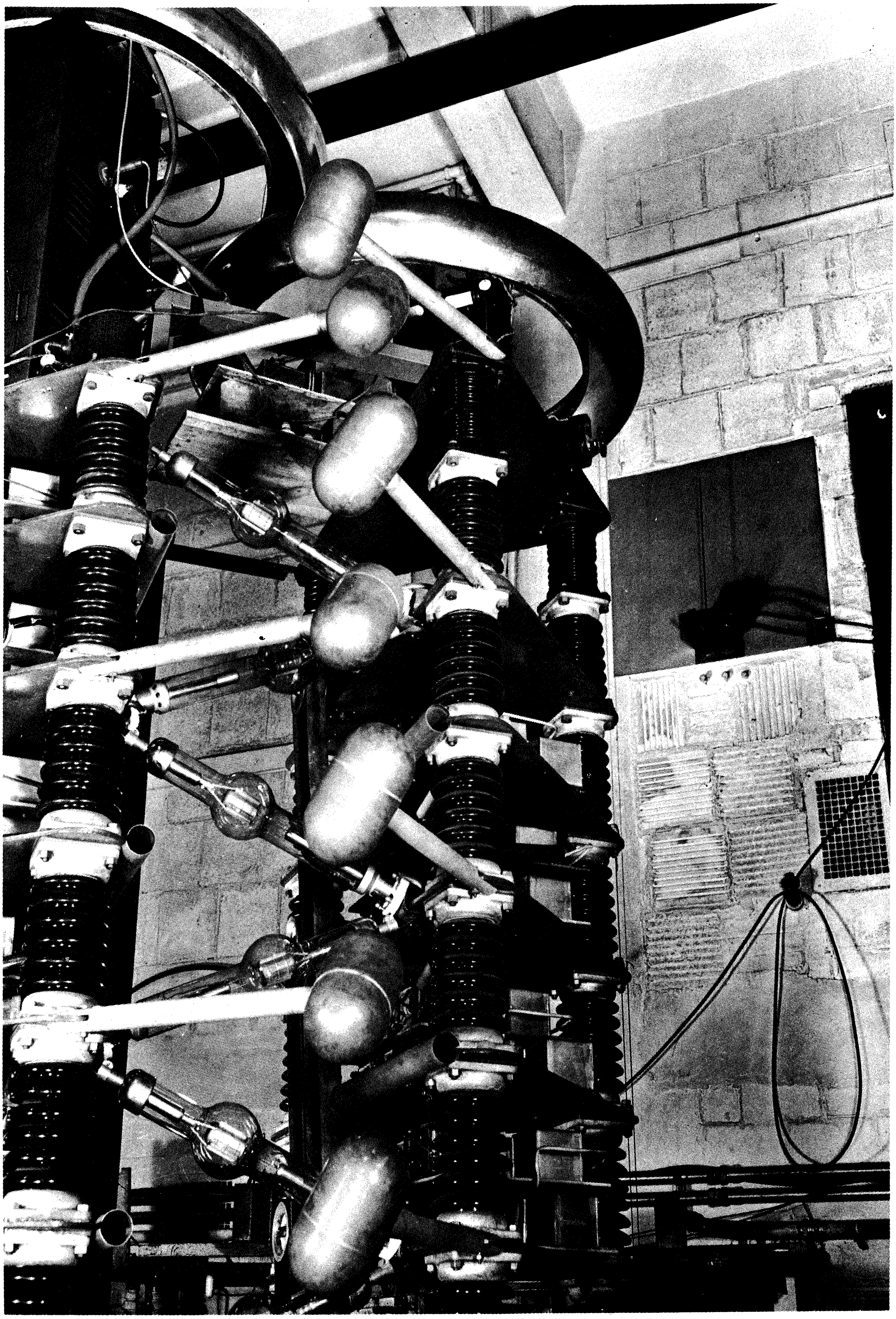


PLATE V

COCKROFT - WALTON SET

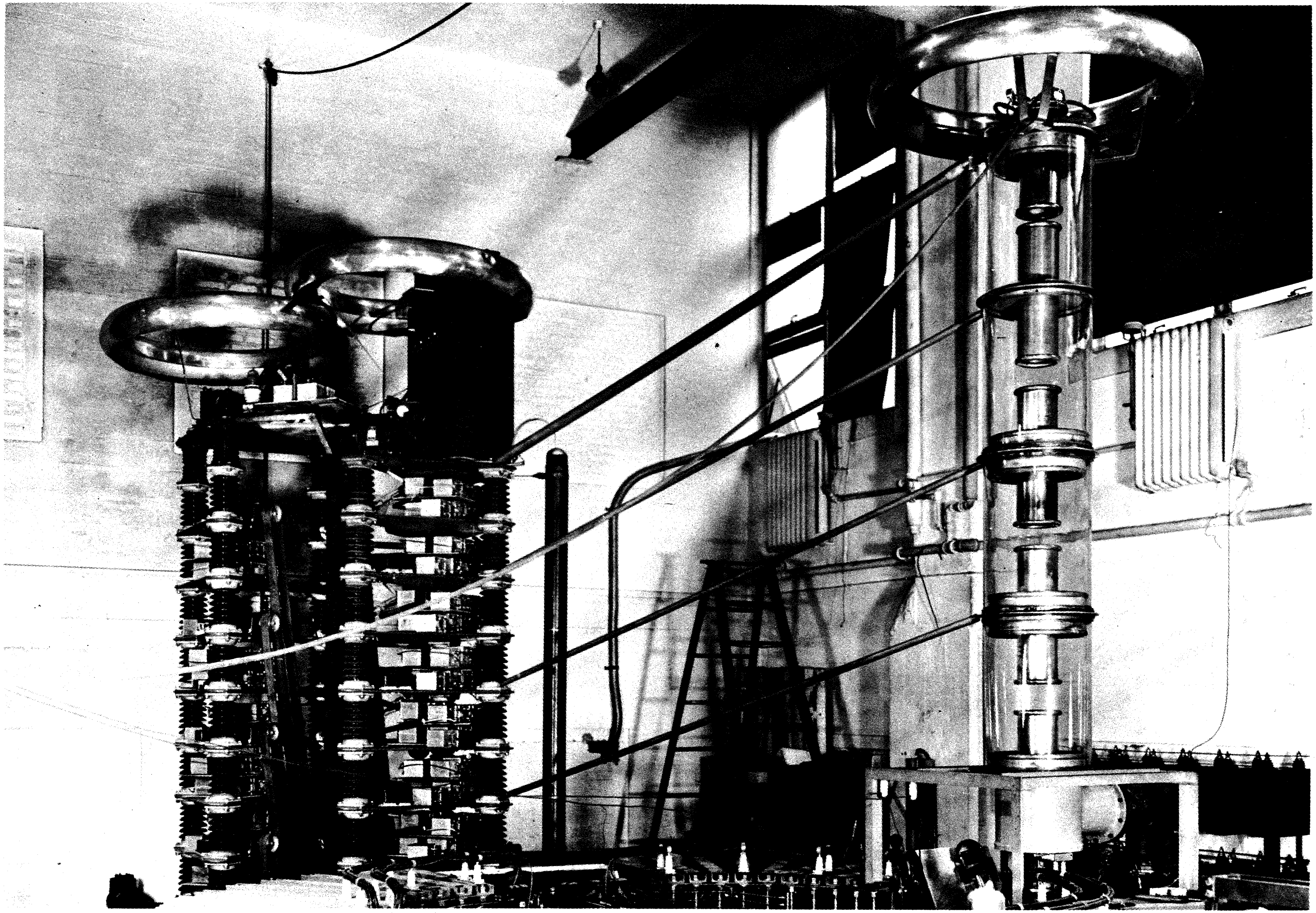


PLATE VI

ELECTRON GUN

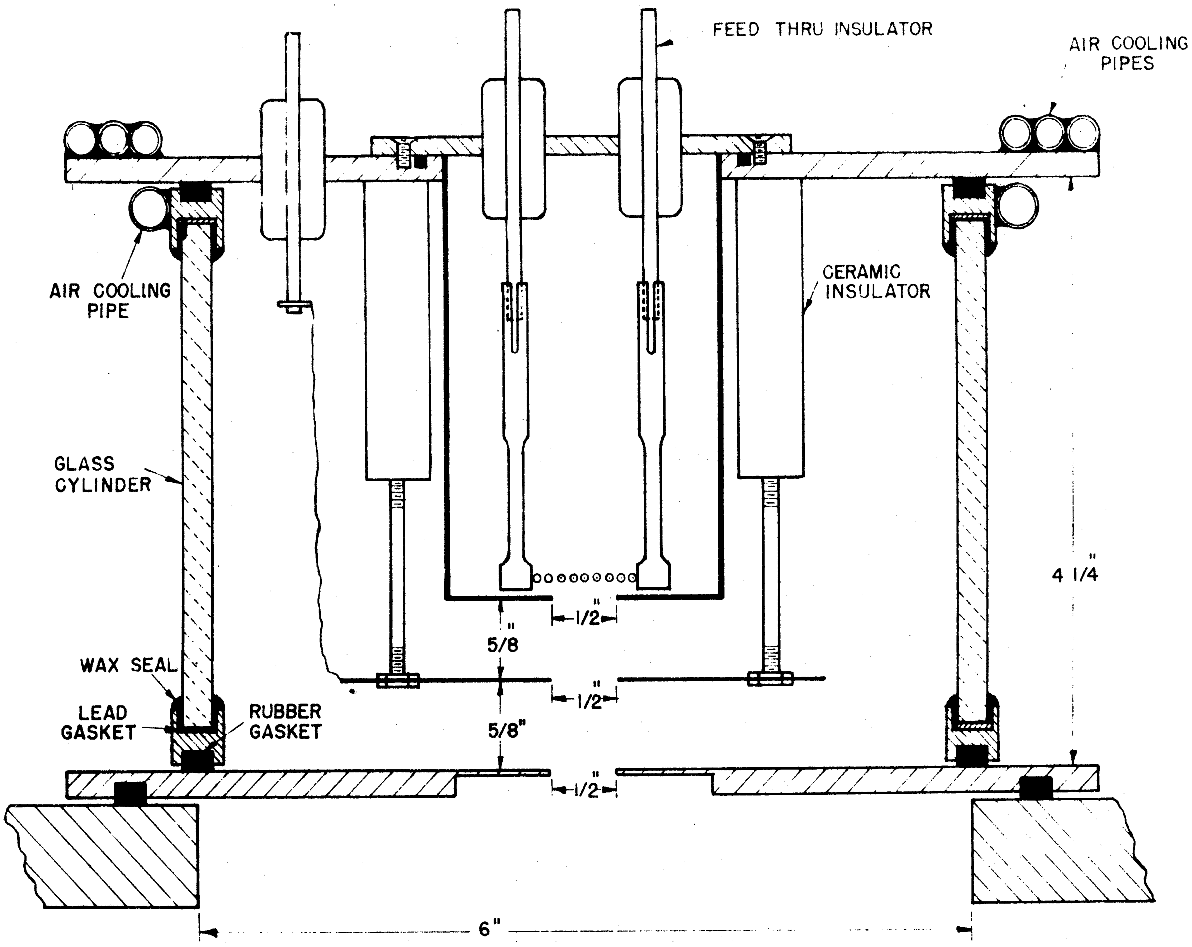


FIGURE 10

which acts as a control grid, is pulsed at 20 Kv by a pulser located on the top of the Cockroft-Walton stack. The pulser is powered by a belt driven 110 V, 60 c.p.s. generator and is triggered by a radio link. The pulse is about 10 microseconds in length. The focused spot at the bottom of the accelerating tube has a width at half maximum of approximately 2 cm, and an intensity of about 40 milliamperes per square cm.

After the electron beam has been accelerated by the linear acceleration tube, it is bent 90 degrees in the electrostatic field of a pair of "inflector" plates of 8-inch radius. In the design of the inflector plates, one can proceed along two different lines, both of which we have tried. (1) A simple pair of plates can be used without a grounded shield. In this case a dipole electric moment is produced in the donut, which is capable of perturbing the orbits of the electrons on succeeding revolutions. To minimize this dipole moment the spacing between the plates must be made as small as possible. The width of the inflector must also be made small, because the electric field which is destructive to the orbits extends beyond the physical edges of the plates. Thus, if an unshielded inflector is used, its plates must be made narrow and closely spaced, which of course can only be done at the expense of beam intensity. In the operation of the model bevatron at the University of California, it was found that pulsing the high voltage off the inflector immediately after injection allowed more of the particles to survive. In this case protons were being accelerated, and the low frequency made it feasible to remove the voltage within a few revolutions of the particles. It would be more difficult in our case, where the frequency of revolution for the electrons is about 20 times as great.

(2) A shielded inflector may be used, in which the grounded plate is made in the shape of a trough or box which surrounds the positively charged plate. While the arrangement is physically larger, it is not to be concluded that it effectively occupies more space in the donut. It was remarked that with the unshielded inflector there is

a region at either side which is not available for electron orbits because of the strong electric fringe field. Therefore, whether or not the effective size of the inflector is greater or less when a shield is used cannot be answered a priori, and no experimental determination has yet been made.

In the cause of early experiments a pair of unshielded plates 1/2 inch wide and separated 1/4 inch was used. Later a shield was used, which increased the physical width to 1 inch. While in both cases an electron beam was easily introduced into the donut and made to circulate for several revolutions, an accelerated beam was not obtained in either case, so it is not possible to give an experimental comparison of the two inflectors.

Within the past two months some preliminary tests have been made with the aim of reducing the physical size, particularly the width of a shielded inflector without the usual severe sacrifice in beam intensity. In the simple pair of plates the width must be at least twice the distance apart, in order to have any appreciable region in which the electric field is uniform. The effective width then becomes at least four times the spacing, when either the shield or the external fringe field is taken into account. The section of an inflector shown in Plate VII represents an attempt to circumvent the conditions on the height to width ratio by providing a graded potential at the side walls. A resistance (outside the injection box) acts as a potential divider which graduates the potential on the metal fins which form the side walls. Clearly, the height to width ratio can be increased over that in a single pair of plates, by a factor equal to the number of intermediate fins plus one. The sample shown is 1 cm in width. In tests

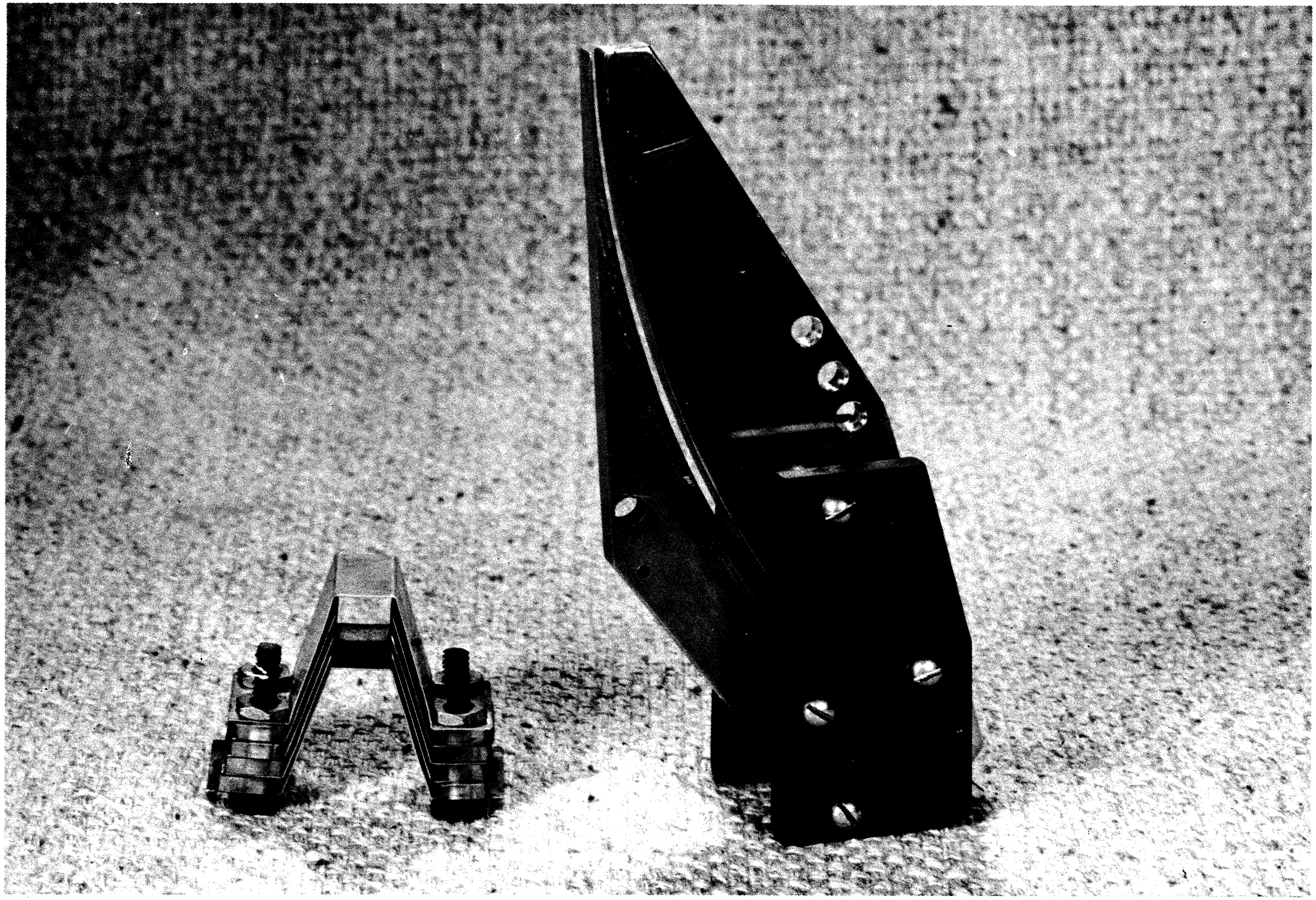


PLATE VII

TWO EXPERIMENTAL MODELS OF INFLECTORS.

under vacuum, sparks occurred between the fins at about 7500 volts (total). Since 15000 volts would have been necessary to deflect the electrons on a 16-inch radius (the maximum radius we could have allowed), the experiment was temporarily discontinued.

The second object in Plate VI is an unshielded pair of plate 1/4 inch in width, which is soon to be tried. These are narrower than any so far used, and the problem will lie in obtaining sufficient intensity of beam.

At this point a few general remarks may be appropriate as to why it is essential to have a narrow inflector in the racetrack-type of synchrotron. It was pointed out earlier that the amplitude of the "betatron oscillation" in both R and Z periodically increases and decreases due to the straight section. If a particle happens to be approaching the equilibrium orbit as it passes through a straight section, its amplitude will be decreased; if it happens to be going out from the equilibrium orbit, its amplitude will be increased. Thus the alternate growth and decay of the amplitude of the betatron oscillation occurs on at a frequency which is a beat between the betatron oscillation frequency and the frequency of going through straight sections. For the synchrotron under discussion (effective n = .445 length of the straight sections 30 inches, radius 40 inches), the maximum to minimum amplitude for these beat oscillations is 1.27 in Z and 1.22 in R. One cycle of growth and decay is completed after approximately three cycles of the betatron oscillation or after passing through about 13 straight sections. It would be very fine if the particle could be injected under such conditions that it would initially be at the maximum of this growth and decay. It would then clear the inflector plates for several revolutions and never return beyond the lip of the inflector. This situation has been achieved and turned to good use recently by J. L. Lawson in operating the non-ferromagnetic synchrotron at the General Electric Research Laboratories (soon to appear in the Physical Review). This synchrotron has no straight sections, but he effectively introduces two of them temporarily by means of coils which modify the fall-off index locally. Conditions are made such that the betatron oscillation begins its contracting phase at the time of injection. After it has had time to reach its minimum, the "straight sections" are removed and the amplitude is left at its low value. It is possible to achieve this in a circular synchrotron because the "straight sections" can be introduced at any desired azimuth with respect to the point of injection. With the racetrack it turns out, unfortunately, that with the point of injection necessarily located at a straight section, the particles begin almost exactly at a minimum in the growth and decay of the betatron oscillation. Changing the fall-off index within reasonable limits helps this situation but little; it is quite insensitive to n. The problem of getting the beam to miss the inflector plates therefore contains one more element of difficulty in the racetrack than it does in the circular machine.

If the beam, when injected into the racetrack from R, has some Z betatron amplitude, it can miss the inflector for many revolutions by passing it at one side or the other (in Z) even though its R oscillation amplitude grows immediately after injection. This can allow enough time for the R equilibrium orbit to be moved away from the inflector or for the R amplitude to be damped by other means. This is the principle upon which racetrack injection has to depend, and it is clear why a narrow inflector is essential.[1] An artificial method of damping the betatron oscillation, but one which is hardly fast enough to keep ahead of the growth process just mentioned, will be described in the paragraphs following.

Betatron Oscillation Damper.

As already pointed out, it is necessary, immediately after injection either to move the equilibrium orbit away from the inflector plates or to damp the betatron oscillation, otherwise the electrons will strike the inflector plates within a few (the order of 10) revolutions. Perhaps the most direct way of accomplishing this is to delay the beginning of the accelerating RF for a fraction of a microsecond after the injection "cross-over." This allows the equilibrium orbit to contract, due to the increasing magnetic field. This scheme is most applicable when the electrons are injected from radius. In the Michigan machine, when operating at 10,000-gauss peak, the rate of rise of the magnetic field at injection is such that a 1% contraction in radius will occur in about 7 revolutions of the electrons. This rate appears to be completely adequate. However, there are strong reasons why it is desirable to use a much lower peak magnetic field when first attempting to get a beam in the machine; namely, that the initial difficulties due

---

[1] An illustration of the behavior we are discussing was obtained from the operation of the model bevatron at Berkeley. When obstructing plates were fastened to the sides of the inflector the captured beam disappeared completely.

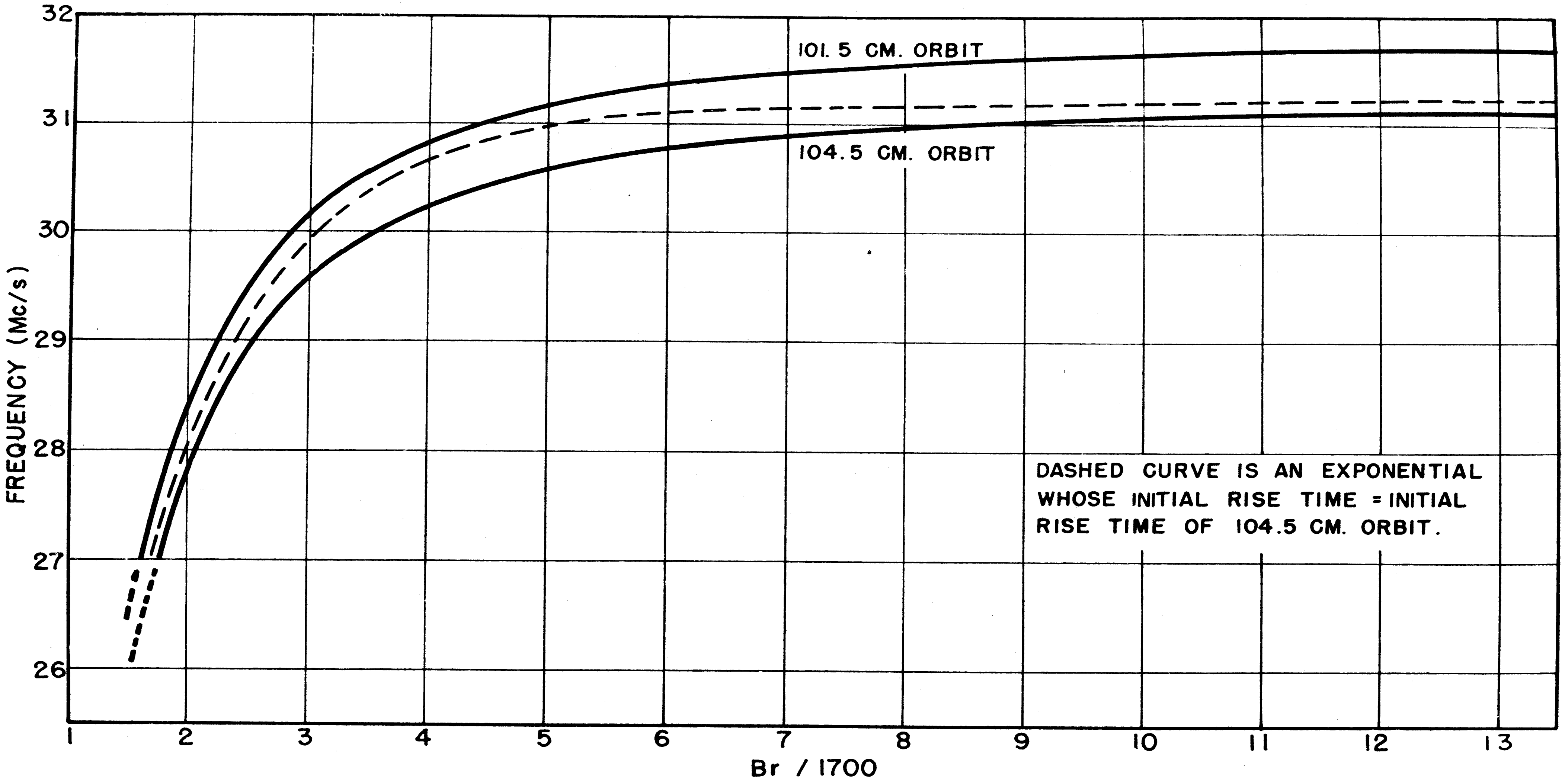
to the out of phase components in the field are much more severe than at low peak field. If one lowers the peak field to 100 gauss it requires 70 revolutions for a 1% contraction of the equilibrium radius, which greatly reduces the effectiveness of that process as a means of saving the beam from striking the inflector plates.

As an attempt to make possible the use of a very small peak magnetic field, we have devised another scheme for making the electrons miss the inflector plates. The apparatus is set up for Z injection, but it is equally applicable to R injection. A pair or rectangular metal plates is mounted in one of the straight sections (in the vacuum) so that a vertical electric field can be applied to the beam, over a length of about 10 cm. An oscillator produces about 600 volts RF between the plates at a frequency which is equal to that of the Z betatron oscillation. The RF voltage is sufficient to damp the Z oscillation to zero in about 10 revolutions. The useful part of the injection pulse extends over several RF cycles, so only half the electrons injected will pass through the damping field in such a phase that their Z oscillations will be damped; the other half will have their amplitude increased and will be lost. The damping RF is turned on well in advance of the injection pulse, is allowed to continue for about 10 cycles after the "picking" or "cross-over" time, and then is clamped off. The clamping is done by means of a power tetrode across the oscillator tank circuit. The RF voltage is effectively killed within three cycles.

An incidental use of the device described lies in the experimental determination of the betatron oscillation frequency. This has been tried successfully on the model bevatron at Berkeley (private communication). A small RF voltage of tunable frequency was applied and when its frequency matched the betatron frequency at some time during the acceleration, the beam was disturbed sufficiently so that it was lost. It is useful to be able to determine the betatron frequency, and therefore, the effective fall-off index, in this way in a racetrack, because the effective fall-off differs considerably from that measured in the quadrants, and because it may also vary over the magnetic cycle.

RF Accelerator.

Plans for the RF acelerator have undergone major changes since the beginning of the project. The difficulty in the problem lies in the combination of the high RF voltage (about 2000) and large modulation (14%) which must be produced. During the first year of the construction of the synchrotron a rather straight forward type of system was built. A pair of 10,000 Mc (723 A/B) Klystrons was used to produce a beat frequency of the appropriate value for accelerating the electrons in the synchrotron. Modulation of one of the Klystrons through the repeller voltage produced the necessary 14% modulation of the beat frequency. The repeller voltage on the other Klystron was used for stabilization against drift in the average frequency. The modulation pulse which was put onto the repeller was produced by passing a square wave through an R-C combination. The desired time vs. frequency curve is only slightly different from a simple exponential curve, as Figure 11 will show. A combination of three R-C



DASHED CURVE IS AN EXPONENTIAL
WHOSE INITIAL RISE TIME = INITIAL
RISE TIME OF 104.5 CM. ORBIT.

FIGURE 11

COMPARISON OF A SIMPLE EXPONENTIAL CURVE (DASHED) WITH THE IDEAL FREQUENCY VS TIME CURVES FOR ORBIT RADII 3 CM. APART.

circuits in series was used to give a somewhat better fit than the simple exponential shown in the figure.

The beat signal, amounting about .1 volt was amplified by a succession of broad band stages using double tuned coupling. The final stage, a 4 x 500, fed a cavity resonator 8 feet in diameter, which was the accelerator for the electrons. The cavity and the power section of the amplifier are shown in Plate VIII.

The apparatus described worked in excellent fashion and produced 1000 volts RF in the cavity. For operation of the synchrotron at full energy (300 Mev), one further power amplifier stage would have been necessary, since the electron has to gain approximately 1000 volts per turn, and a factor 2 excess is desirable to allow for phase oscillation. The final stage was never built, however, because some exploratory experiments which we were making at the time along other directions showed promise of a simpler method of doing the job. Three other lines of attack were tried, and a brief description of each will be given, although only one was finally adopted.

1. Reactance tube. Since the frequency is constant for most of the time and has to be appreciably changed for only about 100 microseconds in each repetition period of 12000 microseconds, the idea of changing the resonant frequency of the accelerating cavity by means of a pulsed reactance tube seemed to be an attractive possibility. The scheme would be to operate the cavity as a high Q, self-excited oscillator, for which only a few hundred watts would be required to produce the necessary 2000 RF. A high power, normally non-conducting, reactance tube would be connected across the cavity.

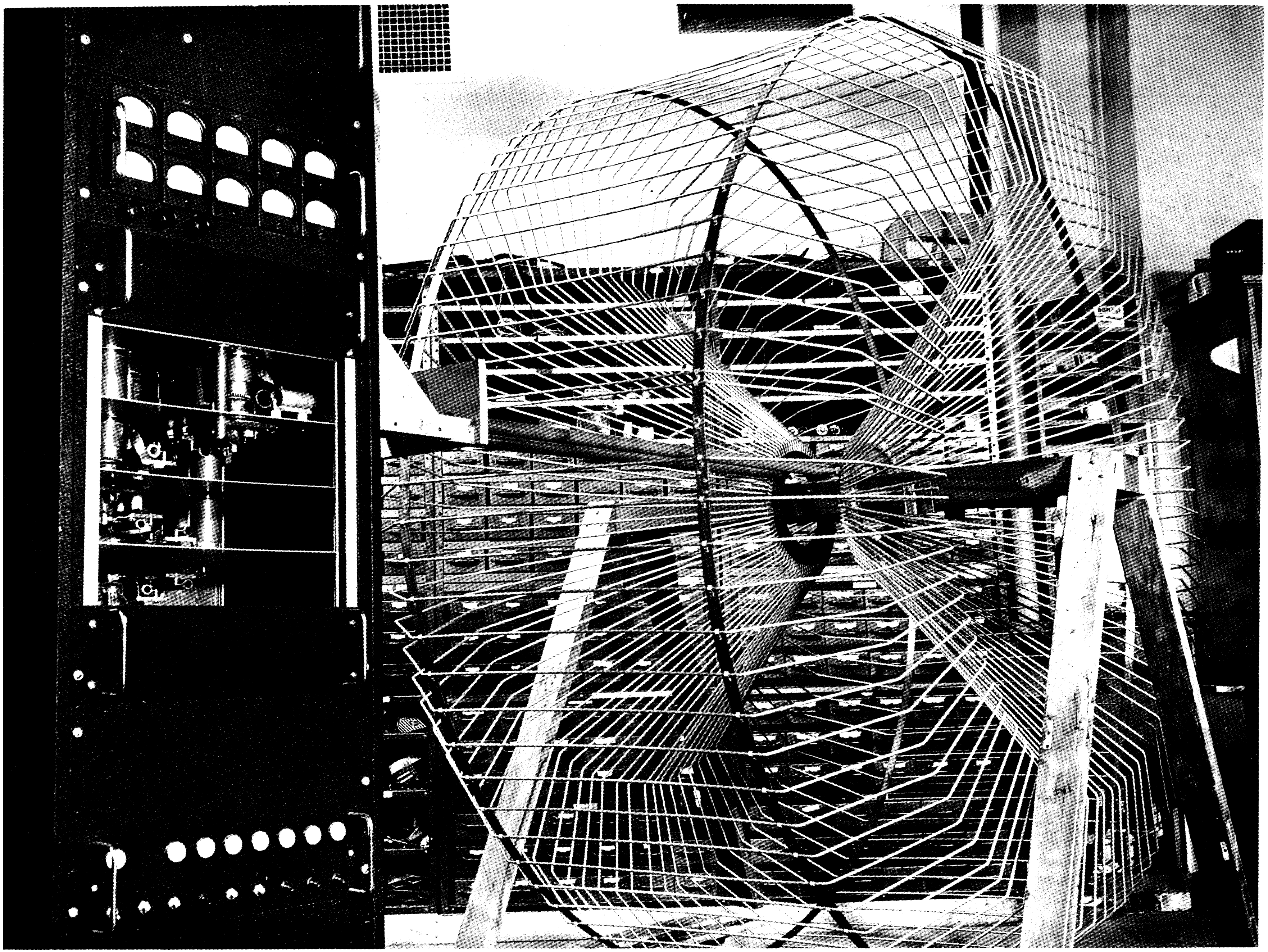


PLATE VIII

At injection time the reactance tube would be pulsed with a shaped modulation pulse. At 2000 volts peak, the circulating current in the cavity was found by experiment to be about 20 amperes. In order to produce a 14% change in frequency the a.c. current through the reactance tube would therefore have to be about 6 amperes. Preliminary experiments were made with such a circuit, and a rather serious difficulty was found. It was concerned with the fact that the current through the reactance tube was very large compared to that through the driving oscillator. Therefore, any slight deviation from quadrature phase in the reactance tube introduced a real component which overwhelmed that of the driving oscillator and either killed the oscillation or greatly increased its amplitude. In a reactance tube circuit the frequency change depends as much upon the amplitude in the cavity as upon the quadrature current in the reactance tube, so a change of amplitude resulting from the pulsing of the reactance tube becomes an extremely confusing factor. As indicated by Figure 11, the frequency vs. time relation must be controlled to within 2 or 3 percent. After experimenting with the reactance tube, it was concluded that, while the principle was attractively simple, the difficulty of control was such as to make it impractical without a great deal of further research.

2. Variation of capacitance by means of ferro-electric materials. Since a cavity may be tuned over a wide range by variation of the capacitance, a method of electrically controlling the capacitance would be a desirable way to produce the modulation. The ceramic bodies formed by barium and strontium titanate possess the property of extremely high dielectric constant (5000 for 71% Ba and 29% Sr), which has a

strong dependence upon electric polarization.[1] A number of these bodies were made in our laboratory, and some were found which combined a Q of order 500 with a frequency change of 40%. However, the dielectric constant was found to have such a high temperature coefficient that stabilization was difficult, in spite of the high Q. It was necessary to have an RF current of about 20 amperes through the ceramic condensers in order to produce the necessary frequency change in the cavity, and even when series - parallel combinations were used, the temperature control presented a problem. The conclusion was that the method was entirely feasible, but it was put aside in favor of the saturable reactor method, which will be described next.

3. Saturable reactor. The method adopted makes use of a resonant circuit consisting of a drift tube and a saturable core inductance. The drift tube, which is a piece of 4-inch diameter pipe 12 inches long, accelerates the electrons, and replaces the cavity used previously. The drift tube (as capacitance) and the saturable core inductance form the tank of a Hartley oscillator. For the core material a number of the newly developed ferrites, including ferroxcube were tried, and while some gave very large frequency changes, all had too great a loss at 30 megacycles. The material which gave the best Q, with sufficient frequency change was the "A" powder of Lenkurt Electric Co., San Carlos, California. With this material the Q of the tank is 150 and the maximum frequency change 30% (see Figure 12).

---

[1] NDRC Report VII, August, 1944, 14-300.

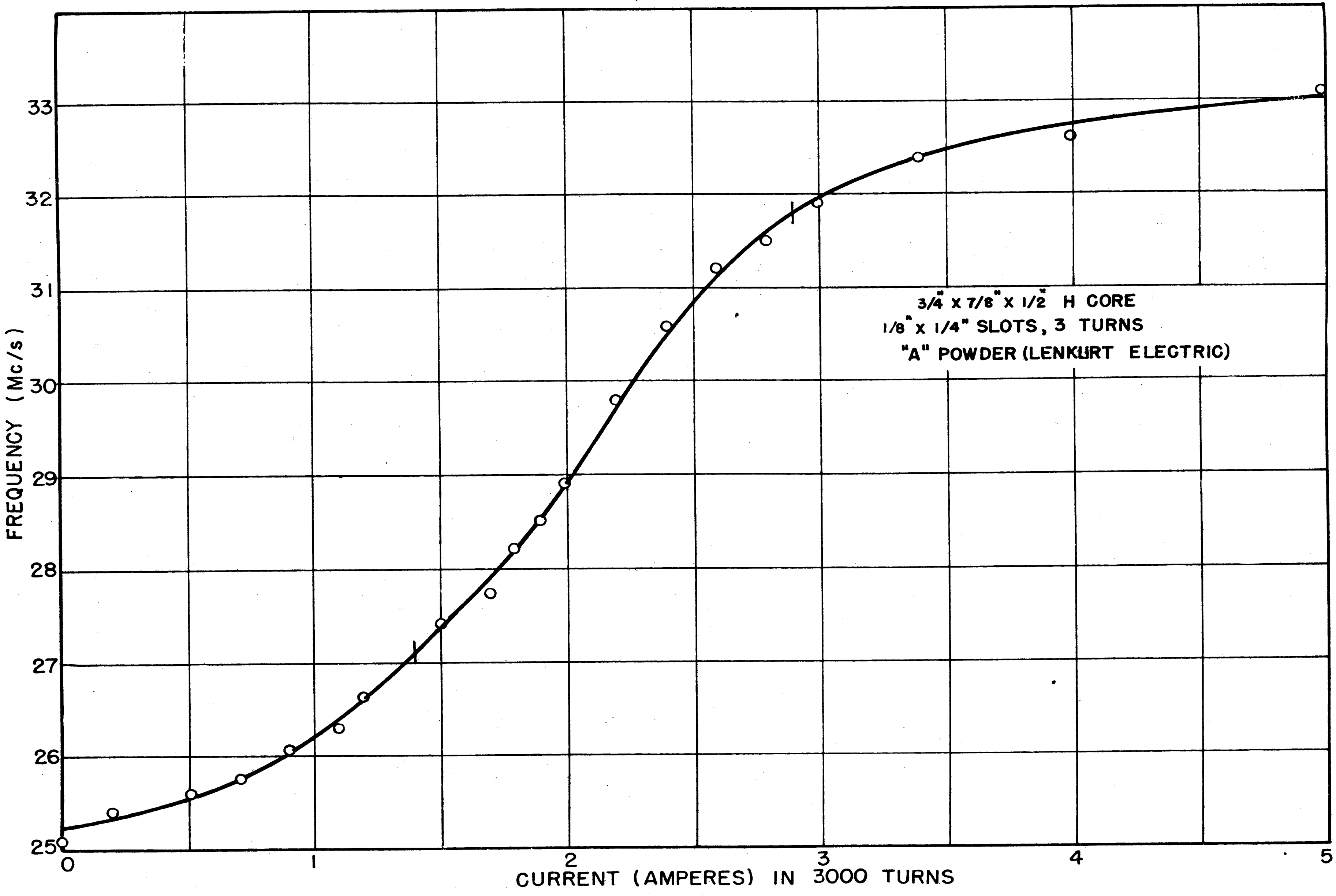


FIGURE 12

FREQUENCY CURVE OF THE OSCILLATOR AS A FUNCTION OF CURRENT IN THE BIAS MAGNET. FLUX DENSITY AT TOP FREQUENCY IS ABOUT 9000 GAUSS; THE CHANGE NECESSARY TO PRODUCE 14% MODULATION IS ABOUT 1500 GAUSS.

It is clear from Figure 12 that it is necessary to operate with a bias field. In order to be able to change the field through the powdered iron rapidly (with at least 100 Kc components) and yet maintain a bias field independently, the following scheme is used. The two halves of a .002 inch hypersil core 7/8 inch x 7/8 inch cross section are mounted between the poles of a d.c. magnet as shown in Figure 13. The flux from the d.c. magnet normally divides equally between the two pieces of powdered iron - the one used as the core for the inductance and the dummy. The modulation pulse merely transfers flux from the oscillator core to the dummy, leaving the total flux unchanged. It is necessary to make the pulse circuit magnetically independent of the bias field circuit because of the rapid change required in the pulse circuit. The internal construction and external appearance of the apparatus is shown in Plates IX, X and XI.

The direction of the current in the pulse windings is such that when it flows it lowers the RF frequency. The pulsing circuit is shown in Figure 14. The tube is normally non-conducting. A positive square wave is impressed upon the grid before injection. Injection concides with the end of the conduction period of the tube. The current through the inductance then decays according to a simple exponential, which is independent of the tube characteristics, since the tube during that time is non-conducting. The voltage supplied to the tube is 10 Kv and the maximum current during the pulse is 9 amperes. The length of the square wave is approximately 100 microseconds. Figure 15 shows an accurate reproduction of the

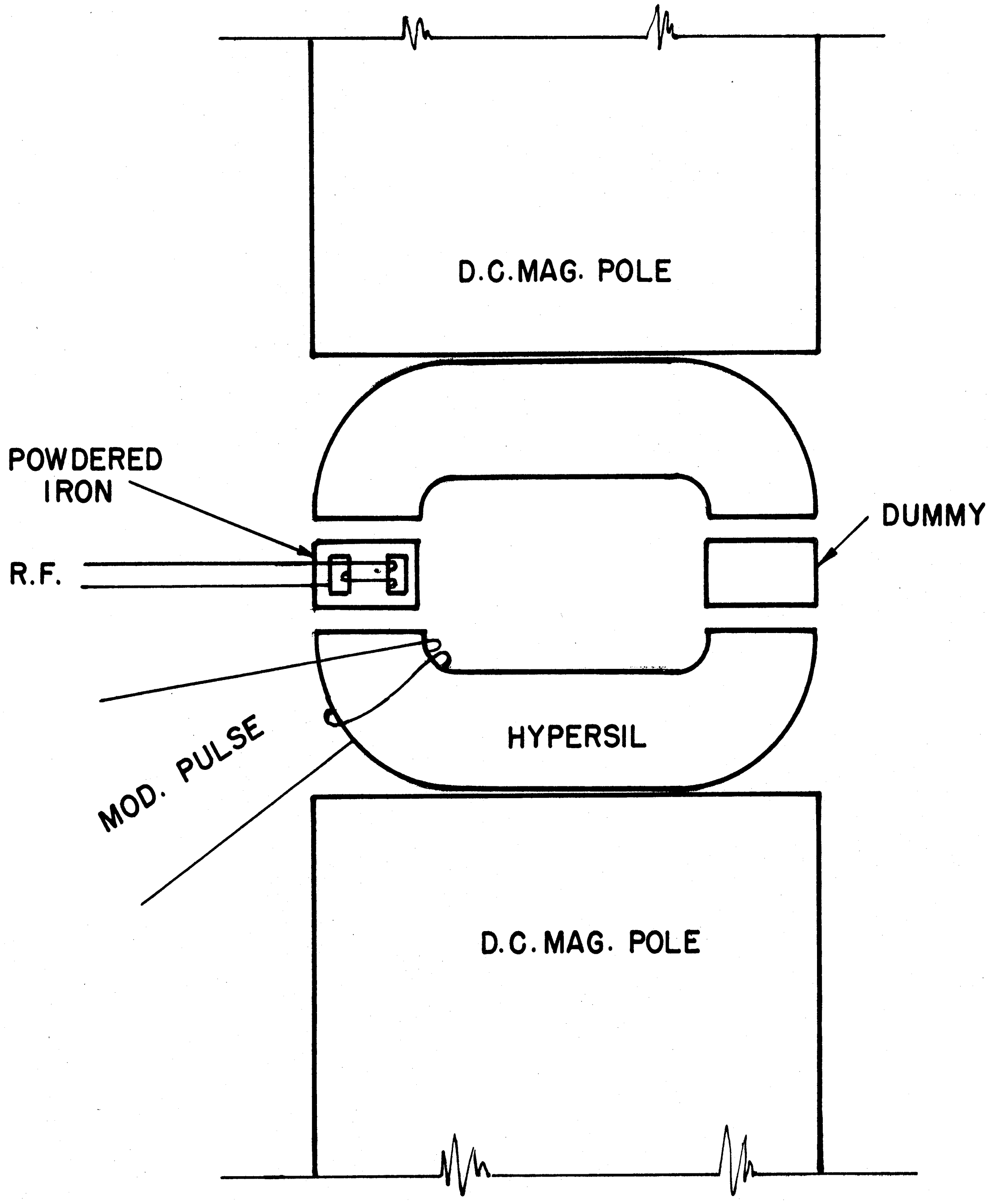

D.C. MAG. POLE
POWDERED IRON
R.F.
DUMMY
MOD. PULSE
HYPERSIL
D.C. MAG. POLE

FIGURE 13

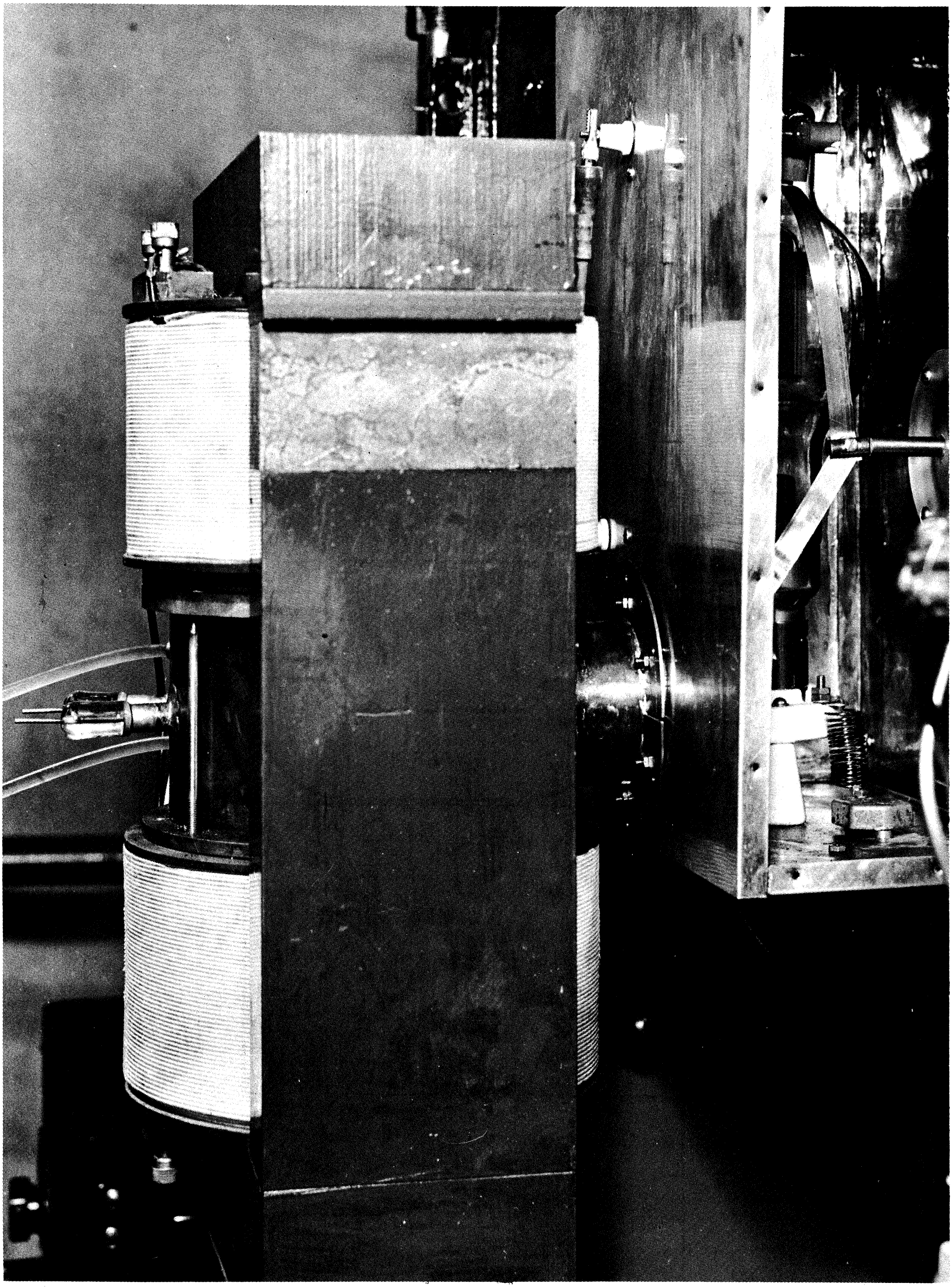


PLATE IX

BIAS MAGNET, OIL BOX, AND OSCILLATOR TUBE

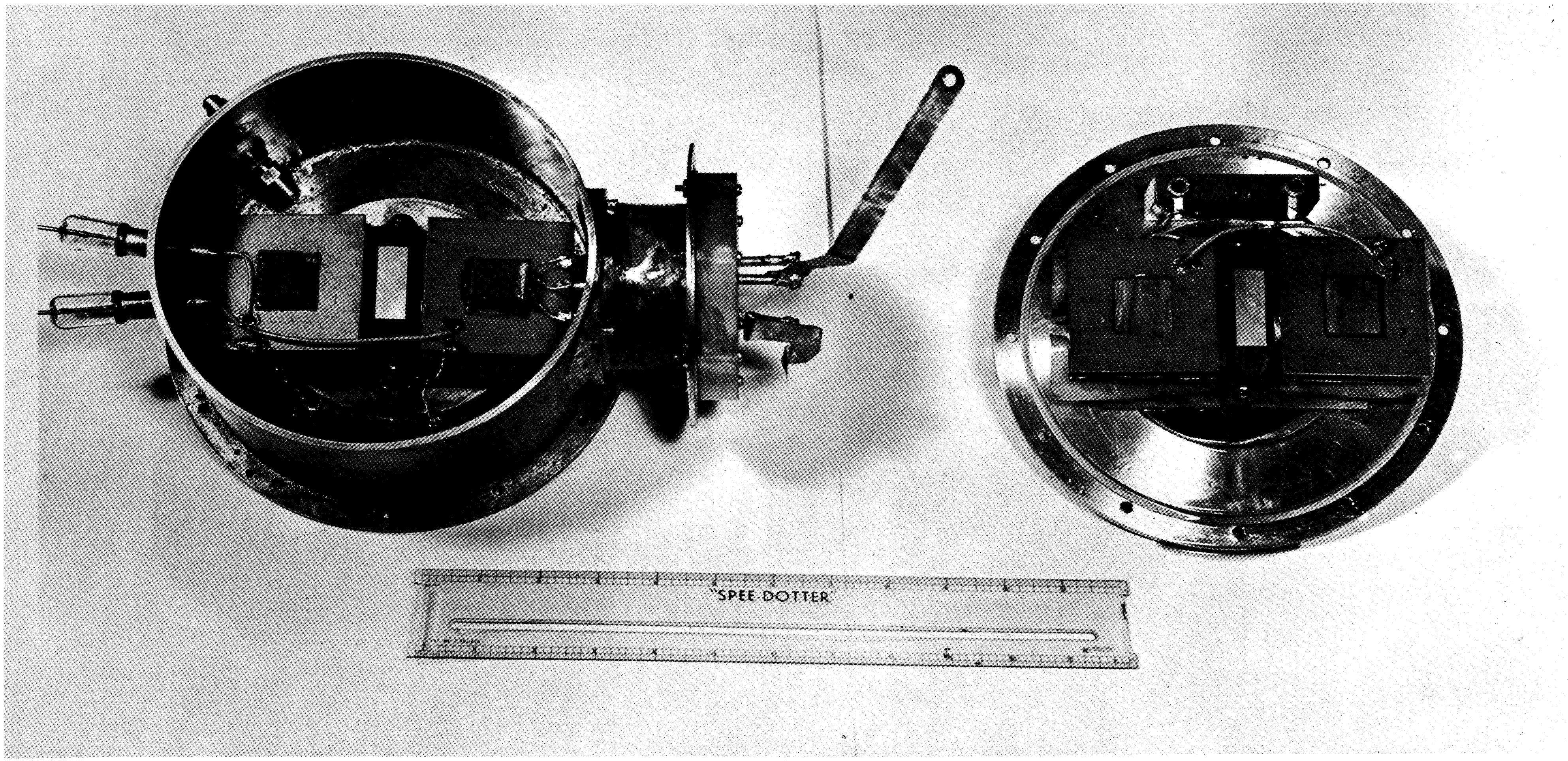


PLATE X

PULSE COILS, HYPERSIL AND POWDERED IRON CORES IN OIL BOX

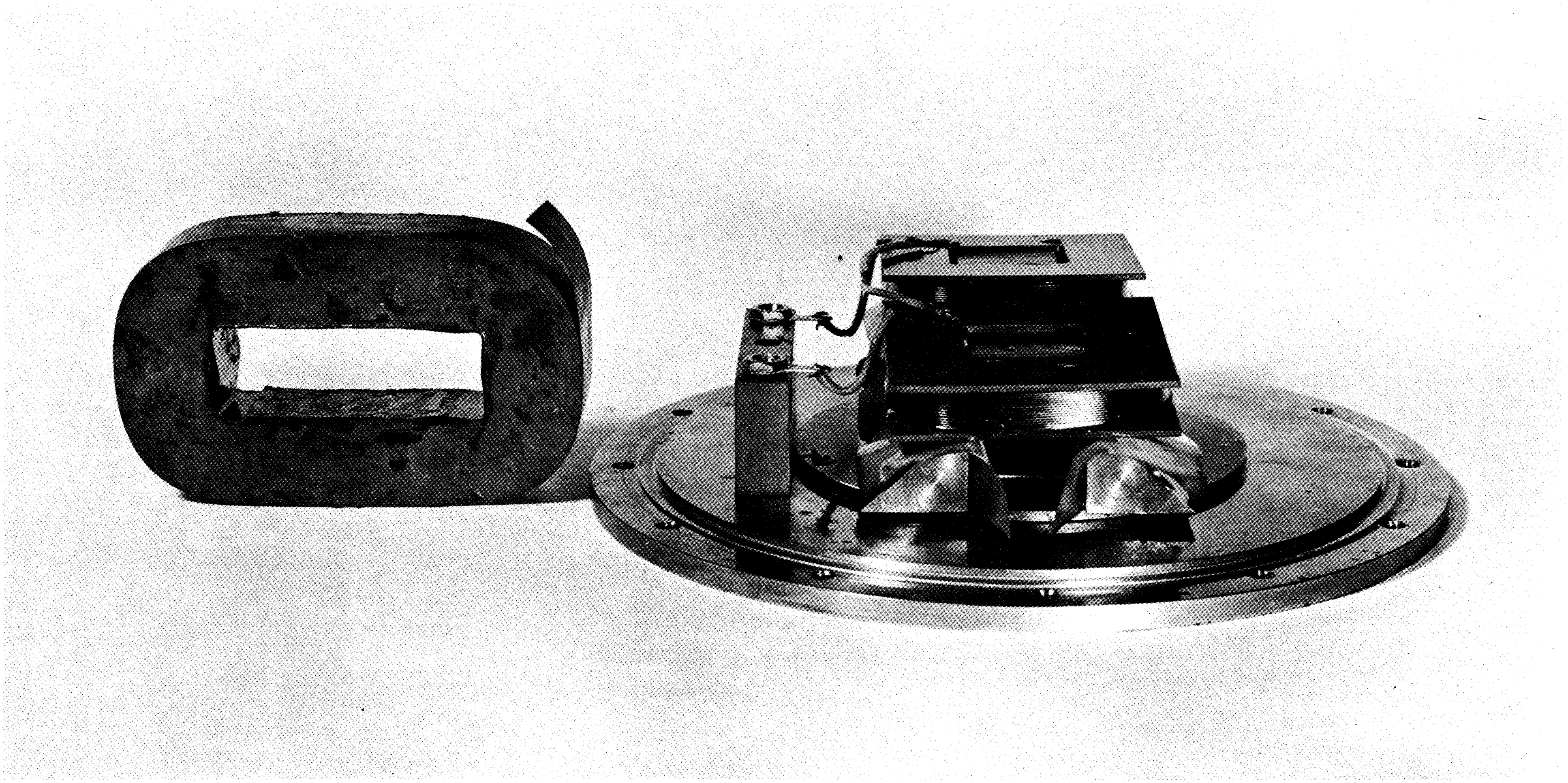


PLATE XI

A HYPERSIL CORE BEFORE BEING CUT; PULSE WINDINGS ON HALF OF THE HYPERSIL CORE.

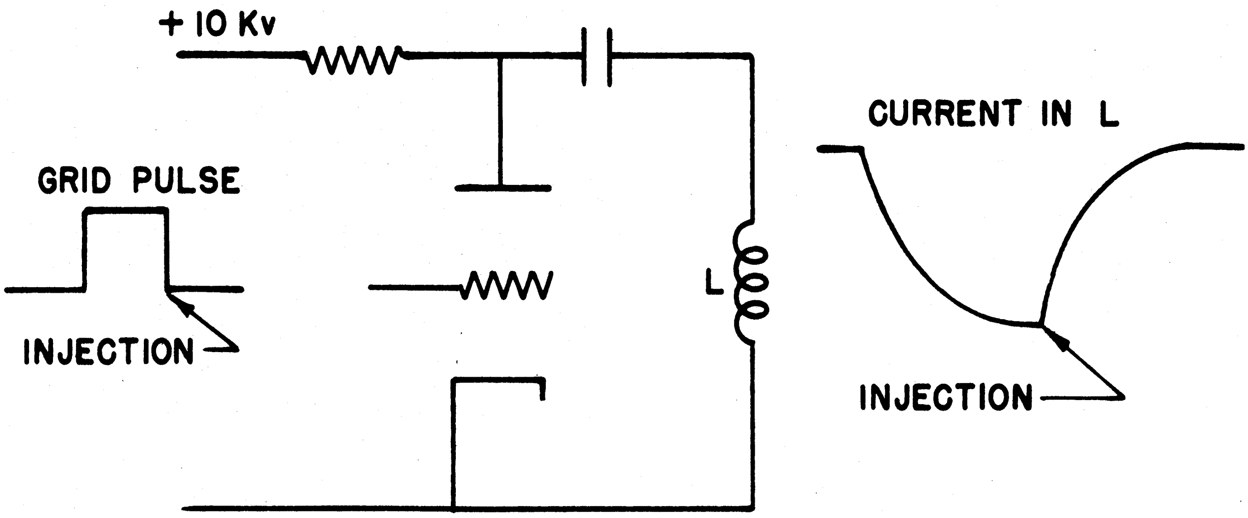
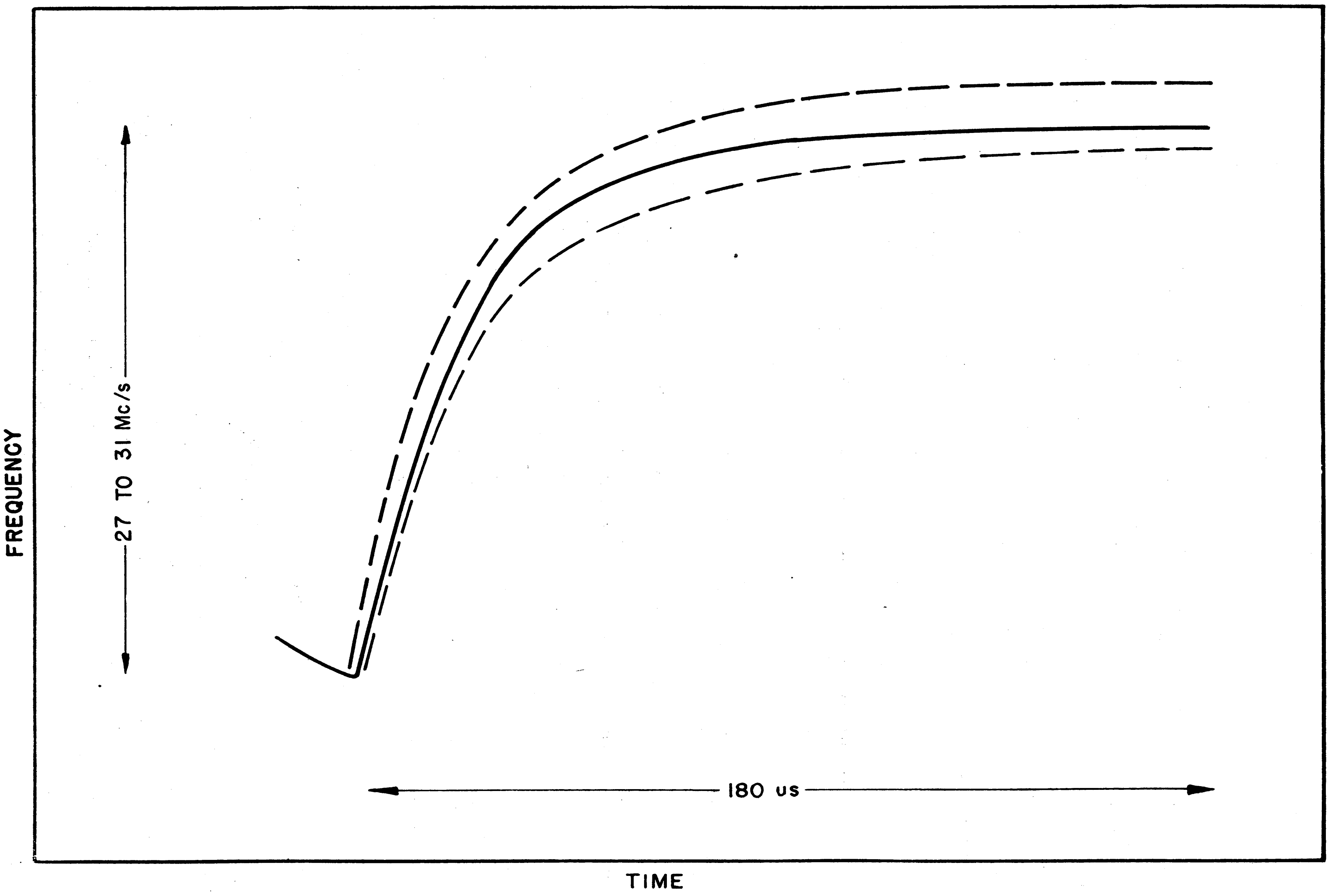


FIGURE 14

synchroscope trace of the frequency vs. time curve obtained, compared with the ideal curves for two orbit radii 3 cm apart. This indicates what the error in "tracking" is, without any correction to the simple exponential. Corrections can be introduced either by using multiple RC-circuits in series or by using biased diodes which start conducting at various places along the rise curve.

The windings on the powdered iron core are resonated with the capacity of the drift tube to form the tank circuit of the Hartley oscillator. The length of the drift tube is such that the maximum energy which an electron can gain in passing through it is one fifth of the peak RF voltage on the drift tube. Since the electrons must gain 1000 volts per revolution, and since a factor 2 excess is desired to allow for phase oscillations, the peak RF voltage required on the drift tube


FREQUENCY
27 TO 31 Mc/s
180 us
TIME

is 10 Kv. At this voltage the circulating current in the winding of the powdered iron inductance is 100 amperes, and the power loss in the tank circuit is 3 Kw. A 6C21 tube is used for the oscillator, and because of the large power dissipation, particularly in the powdered iron inductance, the apparatus is operated only for the first 1000 microseconds after injection. During the remaining 11,000 microseconds of the acceleration cycle, the acceleration will be done by a second drift tube, located diametrically opposite to the first, and operated as a constant frequency, high Q, low power oscillator. Phase can be preserved in the change-over, since the second drift tube can be pre-excited by feeding a small signal to it from the first drift tube. The alternatives are to use two drift tubes or to make the powdered iron reactor and its pulse equipment much larger. The performance of the RF equipment described has been satisfactory. The second drift tube oscillator has not been built, in view of the fact that electrons have not yet been accelerated through the range of the first one.

Detector.

Three kinds of detector have been built and used: direct pickup probe with amplifier, proportional counter, and scintillation counter. The direct pickup is used for locating and measuring the beam after it has gone through 1, 2, 3, or 4 quadrants, or even several times around, but not for detecting the accelerated beam. Rods 1/16 inch in diameter are bent in the shape of cranks and mounted on conical vacuum seals which can be rotated. With one of these cranks mounted on a horizontal axis of rotation the vertical distribution of the beam can be explored, and similarly with one on a vertical axis the horizontal distribution can be explored. The current which is picked up and amplified appears as a pip on a synchroscope which is synchronized with the magnet by means of a peaking strip. The height of the pip is large compared to the background, and the beam can be detected even after it has gone around the synchrotron three or more times. Usually, two probes are used at a time, and they can be inserted in any of the four straight sections. They are turned by means of selsyn motors from the control desk.

For use in detecting the accelerated beam,a small proportional counter was made and mounted on the end of a movable probe. The active part of the counter was in the shape of a pill box 1 inch in diameter and 3/8 inch thick, with the collecting wire in the shape of a hoop. The plane of the pill box was vertical and tangent to the electron orbit. The signal was amplified by means of an amplifier of .1 megacycle band width and displayed on the synchroscope which was synchronized with the magnet. Such a detector gives, of course, the ultimate in sensitivity because it detects individual electrons. However, the major problem is this, as in other methods, is the speed of recovery after the paralyzing effect of the injection pulse. Although the counter is shielded with a thick enough foil to prevent the injected electrons from entering, a large signal is nevertheless produced, because the 500 Kv electrons make X-rays with high efficiency which in turn produce secondary electrons in the counter. The large signal from the injection blocks the amplifier, and it is this which limits the speed of recovery of the system, rather than the clearing of the ionization in the counter. The situation can be improved but not cured by modifications in the amplifier, using so-called anti-blocking circuits, or by gating the signal. Both were tried but the recovery could not be shortened to less than 10 microseconds.

Scintillation counters have given the best results; mainly, we believe, because the electron multiplier tube, which amplifies the signal to one volt or more, is by its nature not subject to blocking. All of the phosphors tried, however, showed some long-time constant phosphorescence, in addition to the "prompt" light emission.

Zinc oxide-zinc has its energy peak in the ultra-violet and has a time constant of about 10^{-7} seconds (information from R.C.A.). It was found to have, as reputed, a strong prompt radiation, but this was followed by a lower intensity of radiation of time constant the order of 10 to 100 microseconds. Stilbene and naphthalene were found to give about the same results: prompt radiation followed by a lower intensity of radiation tailing out to several hundred microseconds. Time permitting, it would be interesting to make quantitative comparisons of the decay of various phosphors. If the phosphor is placed at 180 or 270 degrees from the injector, the synchrotron affords a convenient mean of delivering an intense bombardment of .5 Mev electrons to the phosphor for a fraction of a microsecond.

The electron multiplier tube, which is used in the scintillation detector, provides an excellent opportunity for gating the signal, in such a way that the amplifier can be protected from the injection signal. The voltage on one of the dynodes of the multiplier can be removed, to interrupt the multiplication chain. If this is a dynode which is several stages removed from the output dynode, very little signal is introduced into the output by the gating pulse. Thus, the major difficulty in gating amplifiers; namely, the disturbance produced by the gating pulse is circumvented. Such an apparatus is now under construction.

EXPERIMENTAL RESULTS

The completed synchrotron was operated for approximately six months before the program of modifications, to be described later, was embarked upon. During that time much information was obtained experimentally, in spite of the fact that it was not found to be possible to accelerate electrons. The information obtained, which served as the basis for the program of alteration, will now be summarized.

Dynamic Measurement of Fall-off Index.[1]

The effective fall-off index, n, is quite different from that measured inside the quadrants, because of the effect of the fringe field in the straight sections. The effect of the straight sections may of course be taken into account by making a map of n all the way around the machine under either static or a.c. excitation. It is much more difficult, however, to make a map of n as of the instant of injection. It is well known that a substantial variation in n over the magnetic cycle can occur in betatron and synchrotrons, due to phase shifts which have radial dependence. The simple a.c. or d.c. measurement of n will not detect this, and to obtain phase measurements of sufficient accuracy to give it reliably is quite difficult, because n itself is already a second order property of the field. The effective fall-off can, however, be inferred

---

[1] A more detailed account is given by J. S. Malik, Thesis, University of Michigan, 1949.

unequivocally from the trajectory which the electrons follow in the first few revolutions. This is the experiment we have done.

By means of the pickup probes which could be moved across the donut by remote control, the position of the beam with respect to the median plane was determined at each straight section. Moreover, the coordinate at which it passed through a given straight section on the first three revolutions was determined. That several maxima in the current distribution across the donut really represented several revolutions of the electrons around the machine was easily verified in the following way. A shutter was arranged in the donut beyond the point of measurement. When it was closed, one of the maxima was unaffected, but all others disappeared. A phenomenon which seemed surprising at first was the sharpness of the maxima, particularly the fact that the maximum for the third revolution was as sharp as that for the first. The explanation was found to lie in the fact that at each extreme of the betatron oscillation one side or the other of the beam was trimmed off by the donut wall. This process reduces the intensity as the beam goes around, but does not allow it to spread.

A typical series of measurements of the beam heights with respect to the median plane is given below. The heights are in units in which 1 is the height of the injector above the median plane (Z injection was being used). The measurements were made with the magnet operating at approximately 1500 gauss-peak, and 20 c.p.s. The values obtained for n should be compared with the value .33 obtained by measuring n statically, around the machine, and integrating to find the effective value. The value of n inside the quadrants was .47. The results show that at the field used (1500 g) the radial dependence of the phase lag is not

Revolutions	0	1/2	1	1-1/2	n
	1	-.75	- .85	.85	.335
	1	-.70	- .35	.80	.33
	1	-.60	- .85	.90	.34
	1	-.30	- .75	1.05	.325
	1	-.10	-1.1	1.25	.36
	1	-.50	- .60	-1.00	.325
	1	-.90	- .60	.80	.325
	1	-.64	- .17	.87	.33

great enough to produce a change in the effective n of more than 5% at injection time. Similar measurements were made when the magnet was set for a fall-off of .47 effective (.57 in the quadrants) and good agreement was found with the statically measured values. The present setting of the magnet is for n = .47 effective.

Phase Correction in the Fringe Field.

It has been pointed out that the phase lag of the field in the straight sections is such as to cause an actual reversal of the field at the time of injection. A field sufficient to correct this is easily produced by means of a coil carrying quadrature current, but because of space limitations it is difficult to apply it at the right location. It was found to be much easier to shift the phase of the first block of iron in the quadrant than to shift the phase immediately in front of the first block. This was done by winding a few turns (16) around the back legs of the magnet blocks. Since with this arrangement the position of the correcting field does not exactly coincide with that of the lagging field, the electrons suffer two successive deflections in opposite directions, the sum of which is zero. One of the first experiments was therefore to determine the current required in the correction coils. Electrons were first made to circulate 2-1/2 times around the machine using a d.c. field, then this beam was reproduced using a.c. (1500 gauss peak) on the magnet with the aid of the correction coils. The coils facing each straight section were controlled by a separate Variac. The setting for the current was not hard to determine, but it was found that Vernier Variacs made the adjustment easier.

Attempts to Circulate the Beam in a Constant Magnetic Field.

Because of the type of injection used, there appeared to be a good possibility that the beam could be captured in a static field and allowed to circulate for a hundred microseconds, or at least long enough to allow its detection by a time difference. This would have the advantage of eliminating all difficulties arising from the phase shifts in the a.c. magnetic field. Injection was from above (Z injection) and the Z oscillation damper (already described) was used as a means of making the electrons miss the inflector plates. To disturb the electrons and make them collide with the scintillation detector probe, the RF accelerator was turned on at a given time (50 or 100 microseconds) after injection and at a frequency slightly lower than the resonant frequency. For a time it was believed that electrons were being observed up to 300 microseconds after injection. This turned out, however, to be a rather complicated artifact. The RF which was turned on to eject the beam, acted as a carrier in the scintillation detector amplifier, increasing its sensitivity. This made the small dark current from the injector gun observable, where it was not observable otherwise. The effect was, of course, coincident with the pulsing of the RF oscillator, and it appeared that a circulating beam was being ejected from the orbit. That the electrons did circulate in the constant field for at least five revolutions, and probably more, was evidenced by the fact that many maxima could be found in the current distribution across the donut, when careful adjustments were made.

Attempts to Accelerate Electrons.

After carefully adjusting the phase connection coils, inflector plate voltage, and gun voltage so that there were a number of maxima in the current distribution across the donut, indicating that the electrons were making a number of revolutions, attempts were made to capture and accelerate the beam. The additional variables were then: the interval between injection and time of turning on RF, the RF frequency vs. time curve, fine adjustment of phase correction coils. To make the beam strike the scintillation detector in this experiment, the RF was turned off after about 100 microseconds. The beam was then expected to spiral inward and strike the detector, which was located at the inner side of the donut. Two different peak magnetic fields were used in the experiments, 1500 gauss and 200 gauss. The reason for working at low field was to minimize the phase lag difficulties. Z injection was used throughout, and to make the electrons clear the injector the Z oscillation damper was used.

The type of experiment described above was run for approximately two months, and no accelerated beam was found.

PROGRAM FOR MODIFICATION

1. Magnet.

Experiments in shaping the magnet poles were described earlier in this report, and it was shown that a very great reduction in the out-of-phase field components in the fringe field could be made. The order has been placed for new end blocks for the quadrants, which will incorporate this improvement. At the same time the length of the quadrant will be adjusted so that its magnetic length will be exactly 90 degrees (in the present magnet the physical length is 90 degrees and the magnetic length is nearly 95 degrees). The coil windows in the iron will be flared at the ends so that when the copper crosses the donut it will be further from the beam. This will allow more working space and will improve the field in the straight section.

2. Aperture.

The present donut is made in quadrants, of pyrex. Each quadrant is made of castings about 14 inches long, which are sealed together, (see Plate XII). Due to the fact that such a donut is neither uniform in cross section nor constant in radius, extremely poor use is made of the available space between the poles of the magnet. By changing to a ceramic donut in which the outside faces which are next to the magnet poles are flat, a significant increase in aperture in both R and Z can be achieved. Such a donut is now being manufactured. A comparison between the old and new cross sections is shown in Figure 16. The contrast is actually greater than indicated by the figure because of the non-uniformity of the old donut.

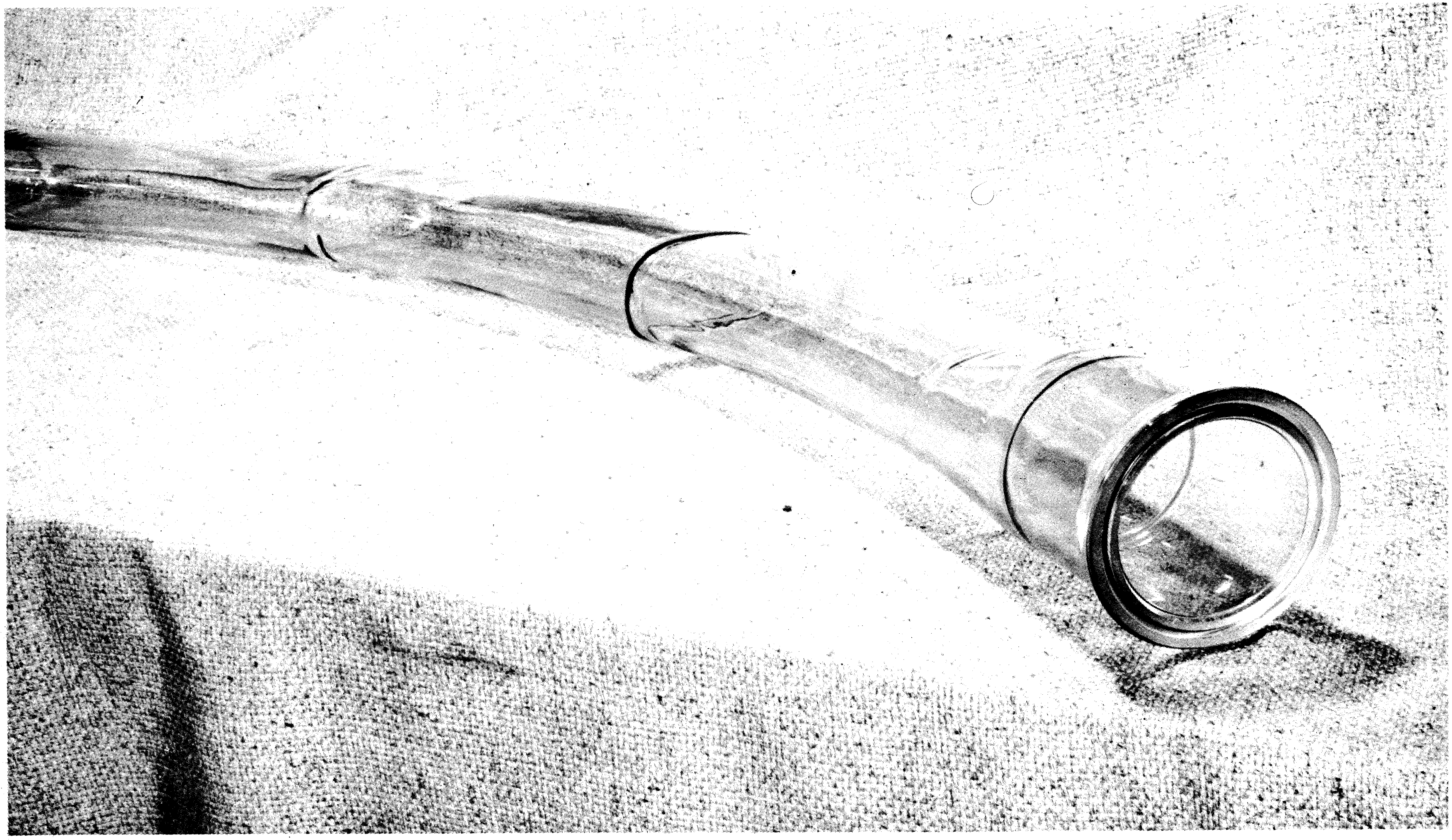


PLATE XII

THE PYREX DONUT

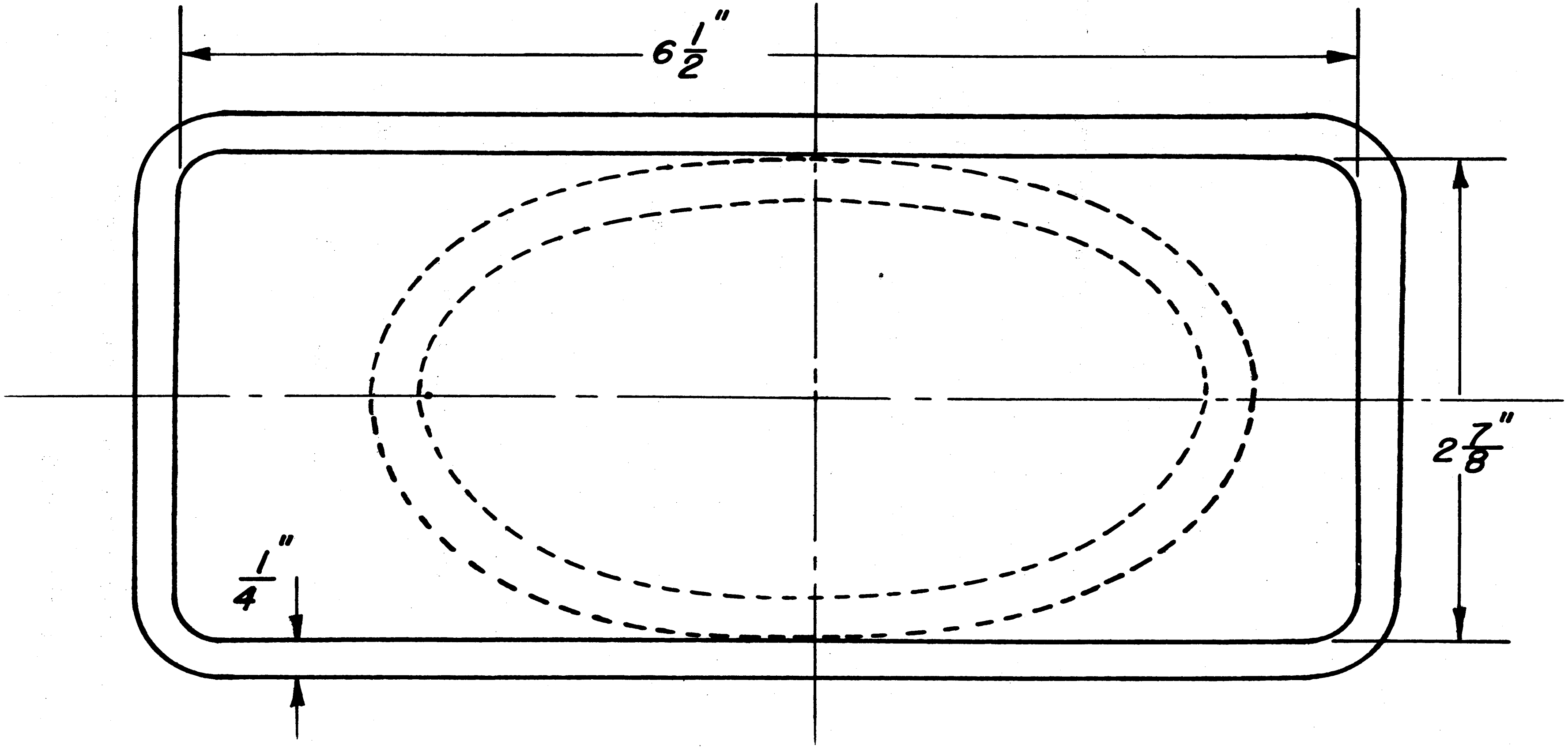


FIGURE 16

RIGHT: CROSS SECTION OF THE CERAMIC DONUT. SMALLER (DOTTED) OVAL IS THE CROSS SECTION OF THE PRESENT GLASS DONUT.

3. Injection.

In all the experiments so far the injection has been from above the donut (Z injection). The plan was to inject from above but rather far to the outside of center, so that the contraction in equilibrium radius immediately after injection would allow the beam to clear the plates. In practice it was found that, due to geometrical limitations and the size of the inflector plates, the point of injection could not be placed as far from center as desired. Because of this, the scheme of placing the point of injection as high as possible and near center, and of using the Z oscillation damper to make the beam clear the inflector was adopted. The modification program includes two changes: (a) R injection, rather than Z, has been installed; (b) the physical size of the inflector **is** reduced by a factor of five. The width of the portion inside the donut is now 0.5 cm. Recent tests indicate that the useful injected beam is now about five times less than before, a negligible loss if the probability of the beam missing the injector has been improved.

4. Pole Face Windings.

In other synchrotrons it has been found useful to have a few conductors parallel to the orbit above and below the donut. By means of these, time variations in n can be made, and also the median plane can be shifted upward or downward. Such windings will be installed as part of the modification.

5. Detector.

A new scintillation detector, incorporating the scheme of gating the signal by pulsing a dynode in the multiplier tube, is under construction. The principle was described in an earlier part of this report. A similar type of circuit has been developed to gate the proportional counter.

6. Refrigeration.

In the present machine there is a 4-inch diffusion pump at each straight section and one on the gun. All have water-cooled baffles. The vacuum, measured at a straight section, ranges from 3×10^{-6} to 10^{-5} mm. No measurement has been made in the donut between straight sections, but a somewhat higher pressure is certainly to be expected. Recent synchrotron experience both at Berkeley and at Schenectady indicates that a vacuum at least as good as 10^{-5} is essential. In order to have some margin of safety, we are installing a freon system which will refrigerate the baffles to at least 30 degrees below zero centigrade.

7. Boxes in the Straight Sections.

The vacuum chambers in the straight sections which contain the inflector, drift tube, detector, etc., are of various shapes and thickness of brass. Stray magnetic fields from the magnet ends therefore induce eddy currents in the boxes which are not the same, and in compensating for stray field effects, it would be desirable to have the boxes as nearly alike as possible. In addition to this consideration of uniformity, a suitable choice of the box material such as magnetic iron has been shown to have an important magnetic shielding effect. That this is so should not be considered to be obvious. In fact, if the iron boxes come too close to the magnet ends, the straight section fields become much worse. However, an iron box of optimum size and shape has been found which reduces the out-of-phase straight section fields to one-half the value observed for the brass boxes. These iron boxes are under construction.

8. 20-Cycle Oscillator.

During all the initial experiments, peak magnetic fields ranging downward from 1500 gauss were used. While the high voltage transformers and other heavy equipment for full power have been installed, the oscillator tubes necessary for high fields have never been installed. This is being made a part of the modification program. An oscillator which delivers 100 Kw power is under construction. The magnetic field at this power level will be 8000 gauss.

TIME SCALE FOR THE MODIFICATIONS

Two periods of major overhaul are contemplated at present. (The new radial injector is already in place and has undergone satisfactory test.) The new iron straight sections, pole face windings, and resilvered pyrex donut will be installed by March 31. The refrigerated diffusion pump baffles will also be installed by this time.

A second overhaul will take place June 1, at which time the new magnet ends and the ceramic donut will be delivered and installed. It should be mentioned that the modifications program does not imply a serious curtailment of the operating program on the synchrotron. The modification will involve a loss of only a few weeks' running time.

The key items in the modification are the new magnet blocks and the new donut. Delivery on the transformer blocks and on the donut is promised for June 15.

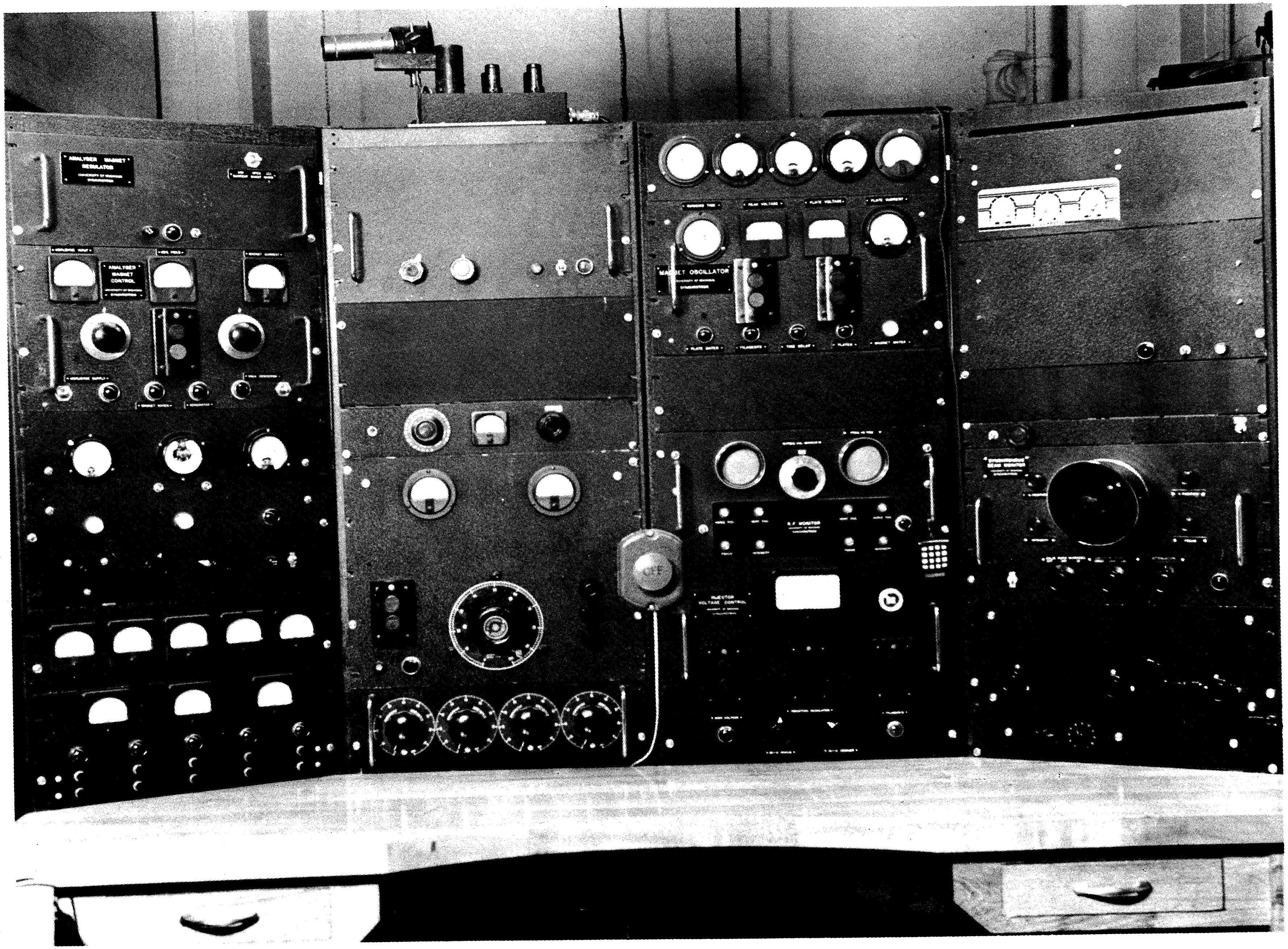


PLATE XIII

THE CONSOLE