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THE PROTON SYNCHROTRON

E. J. Lofgren

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I. In 1910 and 1911 Geiger and Marsden performed a series of experiments designed to reveal something of the structure of the atom. They directed a collimated beam of alpha particles through a thin gold foil and observed the distribution in direction of the emerging particles. While most of the particles were scattered through small angles they found that some suffered very large deflections, indeed 0.01 percent of them were deflected through angles greater than 90°. This was completely inconsistent with any kind of continuous structure of the atom, as for example a homogenous distribution of positive charge with imbedded electrons. Rutherford proposed a very different model in which the positive charge and most of the mass was concentrated in a central sphere 1/10,000 the radius of the whole atom. Occasional close collisions of the impinging alpha particles with this central nucleus would result in large deflections and it was possible to explain quantitatively the experiments of Geiger and Marsden. This was the beginning of our modern theories of atomic and nuclear structure. Since that time and especially since 1930, a large part of nuclear physics has consisted of further probing of the nucleus with beams of various particles to reveal its structure and properties. To give even an outline of the developing ideas of nuclear physics is not consistent with the purpose of this article. We are concerned with the means of providing the probing particles.

Naturally occurring high energy particles (except for cosmic rays) are limited to the α and β particles of radioactive substances whose energies are a few million electron volts. As nuclear experiments continued, increasing energies and a greater variety of particles were needed. In addition the control over natural particles as to direction, intensity, and energy is limited. These limitations were relaxed in a series of developments and inventions of particle accelerators which is outlined in Table I. The development of the first three was carried to the point of successful application to nuclear physics in the early 1930's. The betatron dates from 1940. The next three became useful machines in 1946, 1947, and 1948. All of these machines are still being developed and with their varying energy ranges, intensities, suitability to different particles, and degrees of control, each one supplements rather than replaces its predecessors.

Cosmic rays have provided, as increasing efforts have been made to understand their nature, a rich source of particles which could be used as tools of nuclear investigation. These observations have already yielded the positive electron, a growing family of mesons, and have provided the experimental background to a number of advances in electrodynamic theory. Cosmic ray particles may have energies up to 10^{16} electron volts, assuming that extensive Auger showers are initiated by a single primary particle. They strike the earth's atmosphere at a rate of about 0.9 per cm^2 per second, and consist chiefly of protons, although it has recently been shown that a few percent of them are nuclei of various atoms up to at least the middle of the table of elements in mass with the possibility that all nuclear species are present. As the particles pass through the atmosphere they interact with atmospheric nuclei and create or share their energy with a number of other particles. Cosmic radiation below the top of the atmosphere is therefore an exceedingly complicated mixture of inter-related particles and quanta. This extreme complexity makes it desirable, in the energy range where it can be done, to supplement cosmic rays with laboratory produced radiation so that conditions can be controlled and simplified. Of course, the artificial source can also have much greater local intensity. It is here that the proton synchrotron which we shall describe fits into the scheme of things. Projected machines are in the range 1 to 6 Bev. The average energy of primary cosmic ray particles is 10 Bev, so while the lower range of cosmic ray energies is nicely covered the upper range to 10^{16} electron volts is a million times higher.

II. The limitation to cyclotron energies is imposed by the relativistic increase of mass of the particles as they are accelerated. This can be readily seen as follows. An ion in a uniform constant magnetic field of B gauss describes a circular path of r cm radius such that

$$Br = \frac{v}{e/m}$$

where $\frac{e}{m}$ is the charge to mass ratio of the ions and v is the velocity. From this we can write for the time per revolution,

$$t = \frac{2\pi}{e/m\ B}$$

This is essentially a constant in the non-relativistic range hence a radio frequency field of frequency 1/t applied to a diametral accelerating gap will give an incremental acceleration each revolution to ions starting in the proper phase. However, the mass changes with the velocity according to the relationship $m = \frac{m_o}{\sqrt{1-\beta^2}}$, where m_o is the mass of the ion at rest and β is the ratio of the velocity of the particle to that of light. If then the particle is accelerated until its velocity is 1/2 the velocity of light (the energy of a proton with this velocity would be 150 Mev), the mass is 15 percent greater than the rest mass and the time t is 15 percent greater than for the first turn. Under these conditions the ions get out of phase with the radio frequency and are not accelerated.

The theory of the synchrotron, electron or proton, and the synchro-cyclotron which circumvented this difficulty was worked out independently by V. Veksler[1], E. McMillan[2] and M. L. Oliphant[3] and depends upon the phase stability of an ion in a magnetic field under certain conditions. Suppose we have an ion in the extreme relativistic energy range pursuing a circular path of radius r in a uniform magnetic field and that we apply a radio frequency voltage of the proper frequency as before but suppose it to be of such phase that the voltage goes through zero as the ion crosses the accelerating gap and that an earlier crossing of gap will result in acceleration. In the relativistic range the radius is approximately proportional to the energy.

$$r = (E^2 - E_r^2)^{1/2} / 300 B,$$

where E is the total energy = $E_k + E_r$, E_r is the rest energy = 935 Mev for proton, E_k is the kinetic energy. The expression may then be rewritten in the form

$$r = (E_k^2 + 2 E_k E_r)^{1/2} / 300 B .$$

If E_k is large compared to E_r as it is in the relativistic range

$$r = E_k / 300 B, \text{ approximately.}$$

The velocity approaches the constant velocity of light. Earlier arrival at the gap results then in greater energy and a longer circular path but little change in velocity hence the particle will next time cross the accelerating gap later. Conversely if it were to arrive too late it would be decelerated, pursue a shorter path and catch up in time. The particle if disturbed in phase then oscillates about the stable phase where it gains no energy in crossing the gap. These arguments for stability of phase are not valid at low energy but the same kind of stability can be achieved by having the magnetic field decrease radially. This is desirable anyway to keep the ions in the median plane of the magnetic field. If the magnetic field or the frequency or both are slowly changed in the proper direction the energy of the particle will increase and the stability will hold for the phase such that just enough energy is gained during each revolution to keep step with the changing field or frequency. In addition to the phase oscillation which is slow compared to the rotational frequency there are also radial and vertical oscillations in position which are comparable with the rotational frequency. They are known as the betatron oscillations.

Several different accelerators have been devised on the basis of the principle of phase stability. The distinction between them depends upon which parameters are varied. In the acceleration of electrons no change of frequency is required if the particles are started by other means with 2 Mev or a little over because they then have 98 percent of their limiting velocity. The magnetic field is increased with time to hold the orbit radius constant. The vacuum tank is toroidal and the magnetic field fills an annular space. This machine is a synchrotron. There are two possibilities in the case of heavy ion acceleration. In the first the magnetic field is constant and has the same configuration as for a cyclotron. The ion source at the center and the accelerating dee is also the same but the frequency of the accelerating voltage decreases as the mass of the ions increase and their period of revolution increases. The orbit radius increases so that the total path is a close pitched spiral. This machine is a synchro-cyclotron. As accelerators of this type are made larger an economic limit is approached at 500 to 1000 Mev due chiefly to the very large magnet structure required. The remaining possibility is that the magnetic field as well as the frequency should vary. The orbit radius can then be held constant requiring only an annular magnet which is very much cheaper than the corresponding cyclotron type of magnet. Three of these proton synchrotrons are being built at present. One at the University of Birmingham, England, is designed for 1.3 Bev. Another is under construction at the Brookhaven National Laboratory which will accelerate protons to about 3 Bev and is called a cosmotron. A third is building at Berkeley which will initially operate at 3 1/2 Bev but which can be modified to produce protons of about 6 Mev. This machine has been given the name bevatron. The only physical limit to the energy of this class of accelerator is that imposed by the electromagnetic radiation from a charged particle moving in a circular path. For protons this limit is so high that the cost, which is one to two million dollars per Bev*, is the governing limitation. The theory of the proton synchrotron is given in detail in references (4) and (5) and proposals for their construction are outlined in (3) and (6).

III. The basic design of the Berkeley bevatron stems from the proposals of W. M. Brobeck[(6)]. The magnet will consist of four spaced, 90° annular segments so that the ion orbits are quarter circles connected by straight sections. That magnet arrangement was first proposed by H. R. Crane[(7)] for a synchrotron which he is now building. The straight sections of the vacuum tank between the magnet segments provide places to evacuate the tank, to inject the beam, to place the accelerating electrode, and to do experiments with the beam. Magnet power will be provided by a motor generator with a large flywheel. During build up of the magnetic field, energy will be drawn from the flywheel and stored in the magnet. As the field is reduced the generator acts as a motor and returns energy to the flywheel. The motor makes up only the losses which for each pulse amount to 40 percent of the stored energy. It is intended that the protons will be injected at 10 Mev from a linear accelerator. Some of the interesting dimensions as finally settled are given in the first column of Table II.

Before the design entered the final stage there was some uncertainty as to whether the theory could be trusted in detail. In particular no machine

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* Bev = 10^{9} electron volts

had yet run with straight sections as proposed by Crane, and it was possible than an unforeseen perturbation would introduce ion oscillations large enough to drive the beam into the tank walls. There was also the very important question as to just what would be a reasonable cross section for the useful magnetic field. Obviously there are conflicting factors. With a given investment in magnet and excitation equipment one can have a small aperture with high field resulting in high energy particles but imposing a severe limitation on deviations from ideal ion orbits. On the other hand, choosing a large aperture would lower the final energy. To turn the injected ions into their orbit some kind of electrodes are needed which extend into the tank and many of the ions on subsequent turns will be intercepted by this structure. We were not sure what fraction could be made to escape this fate.

To answer questions such as these and to provide general operational experience it was decided to build a working model on 1/4 linear scale. Since nearly all of the things which might go wrong would occur soon after injection, it was sufficient to accelerate only up to about 6 Mev. This, of course, made the model very much cheaper in terms of magnet and excitation equipment. The second column of Table II gives the essential dimensions of the model.

The general structure is shown in Fig. 1. The functions of the indicated parts are given in following paragraphs. The magnet structure is made of 1/2 inch plates separated by paper insulation to decrease eddy current effects and for the same reason the vacuum tank is made of 1/32 inch stainless steel in sections about 1 foot long, each section sealed to but insulated from the others by rubber gaskets. The atmospheric load on the tank is transmitted by attachment bars to the magnet yoke. Fig. 2 is an over-all view with the injector cyclotron in the foreground.

The protons are accelerated to 0.7 Mev in a cyclotron which operates for one millisecond and is triggered by the bevatron magnet current as it reaches the proper value. The ions pass through a focussing magnet and then as they enter the bevatron magnet they are turned by the electric field of the inflector electrodes so that they are tangent to their bevatron orbit. As the magnetic field increases but with no energy added to the ions they oscillate about circular paths of decreasing radius. Before they all reach the inner tank wall the accelerating electrode is excited with a frequency equal to the rotational frequency. This electrode is in the straight tank section opposite the inflector and is an open ended copper tube placed so that the ions go through it. The energy given to the protons is equal to the change in voltage on the electrode during the traversal since the electric fields at the two ends are opposite in sign. In the model bevatron the protons are given about 40 electron volts per turn to keep step with a magnetic field increasing at 4000 gauss per second. Since the ions are well out of the relativistic range the velocity and hence the rotational frequency is proportional to the momentum of the particles. The momentum of a particle at constant radius is proportional to the magnetic field, hence the applied radio frequency must vary as the magnetic field. This variation in frequency is accomplished by passing a portion of the magnet current around the ferromagnetic core of the inductance in the radio frequency circuit. The increasing saturation of the core as the magnet current increases lowers the inductance and increases the frequency of the circuit. The required frequency range is from 0.4 to 1.2 megacycles per second. In about one quarter of a second the magnetic field has nearly reached its limiting value of 1000 gauss and the protons an energy of about 6 1/2 Mev. The radio frequency is cut off and a further small increase of magnetic field decreases the orbit radius and the ions are intercepted on a probe introduced through the inside wall of the annular tank. The oscilloscope trace, Fig. 3, shows the history of a single pulse, in this case the acceleration lasts for only 10 milliseconds so that the entire pattern can be shown. Ions of the wrong energy or direction hit the probe on the first turn. Of the surviving ions those which cross the accelerating electrode in the right phase are accelerated. Those in the wrong phase are driven into the probe immediately after the r.f. is turned on.

IV. Due to the long path of the ions in the bevatron they suffer many collisions with the residual air molecules in the tank. Note from Table II that the ions in the bevatron and the model are accelerated for 1.75 seconds and 0.25 seconds, respectively, while for comparison, in the 184-inch synchro-cyclotron they are accelerated for only 0.002 seconds. The combined effect of many such collisions during this long acceleration, particularly just after injection when the energy is low, causes a substantial loss of beam. We found that an increase of pressure of 1.7×10^{-6} mm Hg resulted in a decrease of the beam by a factor of 1/e. This agreed with the expected loss within the accuracy of the theory and the measurements. The usual operating pressure was 2×10^{-6} mm. The decreasing loss of beam at greater energies is shown in Fig. 4. Here the final energy is adjusted by changing the duration of the accelerating radio frequency pulse and recording the integrated beam picked up on a probe with a constant injected pulse. Most of the loss occurs at energies less than 3 Mev.

Using the adjustable aperture diaphragms provided in two of the straight tank sections, these data were taken for three cross sections. The middle curve most nearly corresponds in relative size to the 24-inch high by 72-inch wide aperture selected for the full size bevatron.

The betatron oscillations of the ions in the radial and axial directions are approximately given by

$$^{*}f_r = \sqrt{1 - n} \quad f_o$$

$$f_a = \sqrt{n} \quad f_o$$

where n expresses the radial decrease of the magnetic field $n = \frac{r}{B}\frac{dB}{dr}$ and where f_o is the rotational frequency. The constant, n, equals 0.6, hence both the frequencies are near to the rotational frequency. It is very important that there be no simple harmonic relation between these frequencies. If there were, the amplitude of one of the oscillations might build up until the ions were lost to the tank walls. These frequencies were measured by an experiment suggested by H. R. Crane in which a radio frequency field is established in a radial or axial direction across the vacuum tank. At the proper frequency it will increase the oscillations and destroy the beam. The calculated frequencies were verified to about 1 percent.

Some things of interest were learned which are not yet quantitatively explained. Two of these effects apply to the critical period of injection. It was found that if the accelerating r.f. voltage was applied as shown in Fig. 5 rather than with a linear rise or an abrupt step the beam was increased by 75 percent. There was also an increase of about 100 percent if the voltage on the inflector electrode was removed immediately after injection.

The largest beam with the bevatron aperture set at 6 in. x 18 in. was 3.5×10^{-11} coulombs per pulse (or about 2×10^{8} protons per pulse). The injected beam measured at the end of the inflector electrodes was 10^{-8} coulombs. The over-all particle efficiency of the machine then was about 1/3 percent. In the full scale bevatron the losses due to gas scattering should be negligible because

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*The accurate expressions are complicated by the effect of the straight sections of which these expressions take no account.

of the higher injection energy. In addition, while the tank height is scaled up by a factor of four the size of the inflector electrodes need not go up at all, so that ions will have a greater chance of missing the inflector after injection. It is therefore reasonable to expect a particle efficiency of at least several percent in the full scale bevatron.

The bevatron development at the Radiation Laboratory is sponsored by the Atomic Energy Commission. It is under the direction of Professor E. O. Lawrence and involves the work of many people. W. M. Brobeck is responsible for the basic design. Major responsibilities are also carried by those listed as authors in references 8 to 11. In addition Professor R. S. Shankland of the Case Institute and Professor F. H. Schmidt of the University of Washington carried out some of the experimental measurements.

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TABLE I

Name	Particle	Highest Energy of Presently Operating Equipment in Mev	Highest Energy of Equipment Under Construction in Mev	Remarks
Electrostatic Accelerator	Any charged particle	5	12	Capable of precise energy control and collimation. Limited to the lower energy range because voltage is applied in one step.
Rectifiers or Transformers	Any charged particle	2		Similar to the electrostatic accelerator.
Cyclotron	p d α	10 20 40	 30 	A reliable and economical accelerator in the medium energy range. Limited to energies of a few 10's of Mev by the relativistic mass increase.
Betatron	e	100	300	For electrons only. A simple machine in the medium energy range but limited by radiation loss to several hundred Mev.
Synchro-cyclotron	p d α	350 190 380	450	This machine overcomes the energy limitation of cyclotron but becomes uneconomical above 500 Mev. Beam intensity is lower.
Linear Accelerator	p e	32 30	66 1,000	The energy is unlimited, it has the advantage over magnetic machines that the beam emerges in a well collimated bundle with a small energy spread.
Synchrotron	e	300	1,000	Raises the energy limitation of the betatron.
Proton Synchrotron	p	6 1/2	3,500	The energy limit is the economic one but it is higher than that of the synchro-cyclotron

p, proton or hydrogen nucleus
d, deuteron or heavy hydrogen nucleus
α, alpha particle or helium nucleus
e, electron
Mev, 10^6 electron volts

Most of these figures were taken from Particle Accelerators, Brookhaven National Laboratory.

TABLE II

	Bevatron now being constructed	1/4 scale model now completed
Proton Energy	3 2/3 Bev	6 1/2 Mev
Number of protons per pulse	10^{10} or more	$2 \cdot 10^{8}$
Pulse rate	10 per minute	18 per minute
Orbit radius	48 1/2 feet	11 1/2 feet
Length of straight sections	20 feet	5 feet
Cross sectional aperture of useful magnetic field.........vertical	24 inches	9.5 inches
radial	72 inches	36 inches
Number of revolutions during acceleration	$3.8 \cdot 10^{6}$	$0.9 \cdot 10^{6}$
Distance traveled during acceleration	270,000 miles	15,000 miles
Acceleration time	1.75 sec	0.25 sec
Maximum magnetic field	9,800 gauss	1,000 gauss
Magnet weight	10,000 tons	150 tons
Energy stored in magnet	$8.3 \cdot 10^{7}$ joules	$4 \cdot 10^{4}$ joules
Magnet operating power	6,000 kilowatts	30 kilowatts
Acceleration radio frequency	.37 to 2.5 mc	0.4 to 1.2 mc
Injection energy	10 Mev	0.7 Mev

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(10) E. J. Lofgren, W. M. Brobeck, E. O. Lawrence, D. C. Sewell, Ibid.

(11) Lloyd Smith, A. A. Garren, L. R. Henrich, Ibid.

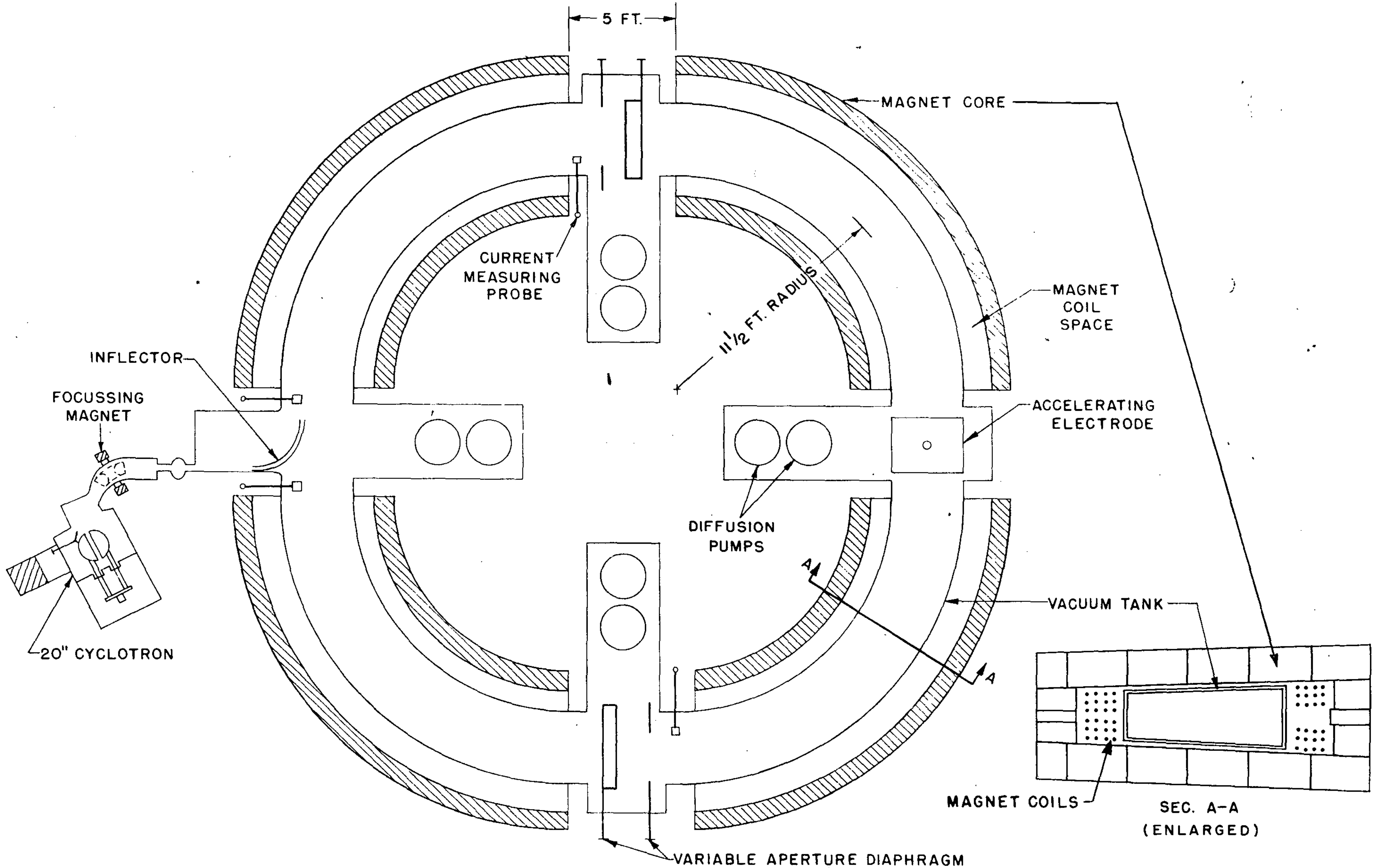


DIAGRAM OF THE 1/4 SCALE OPERATING MODEL BEVATRON.

FIG. 1

OZ 779

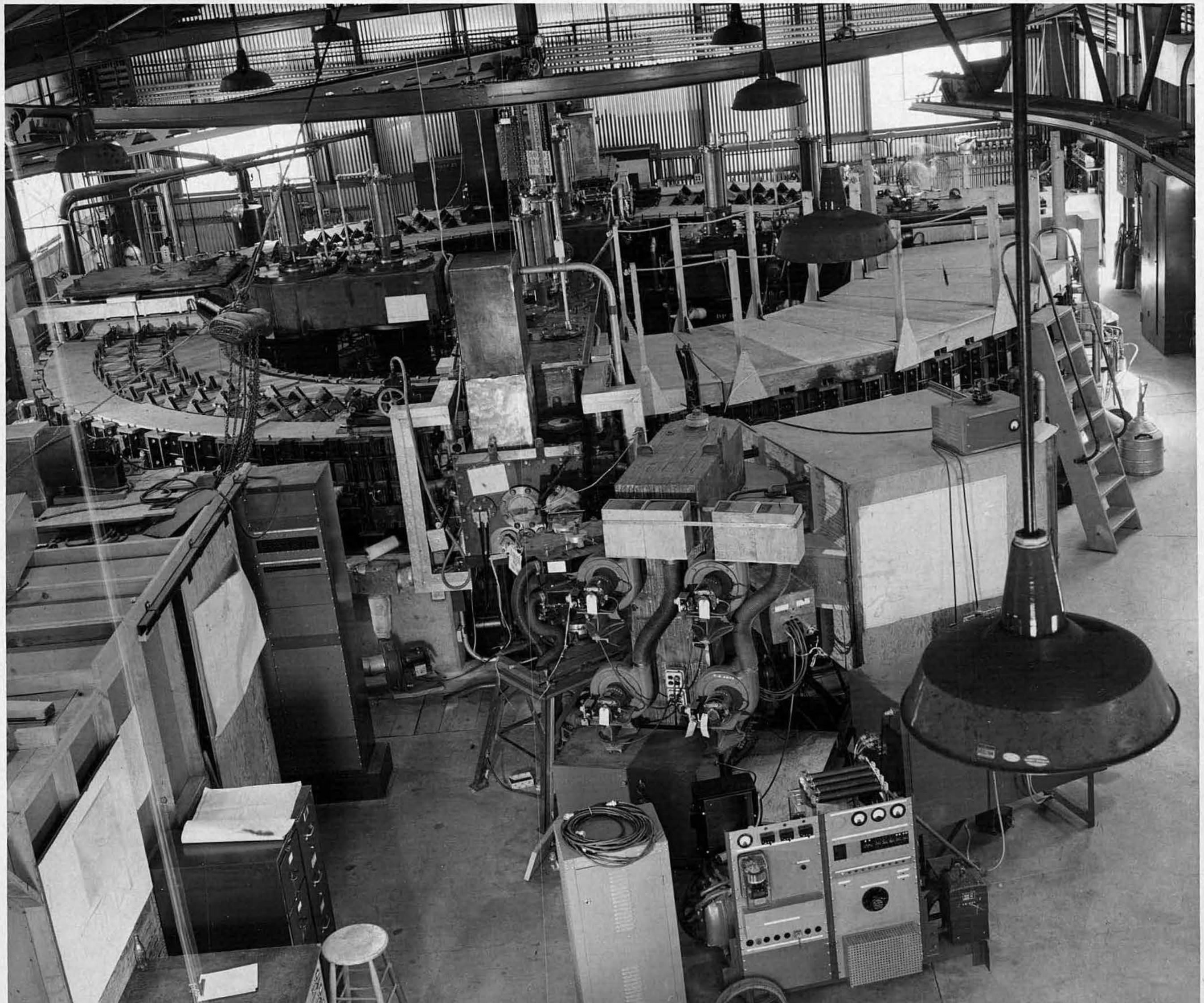
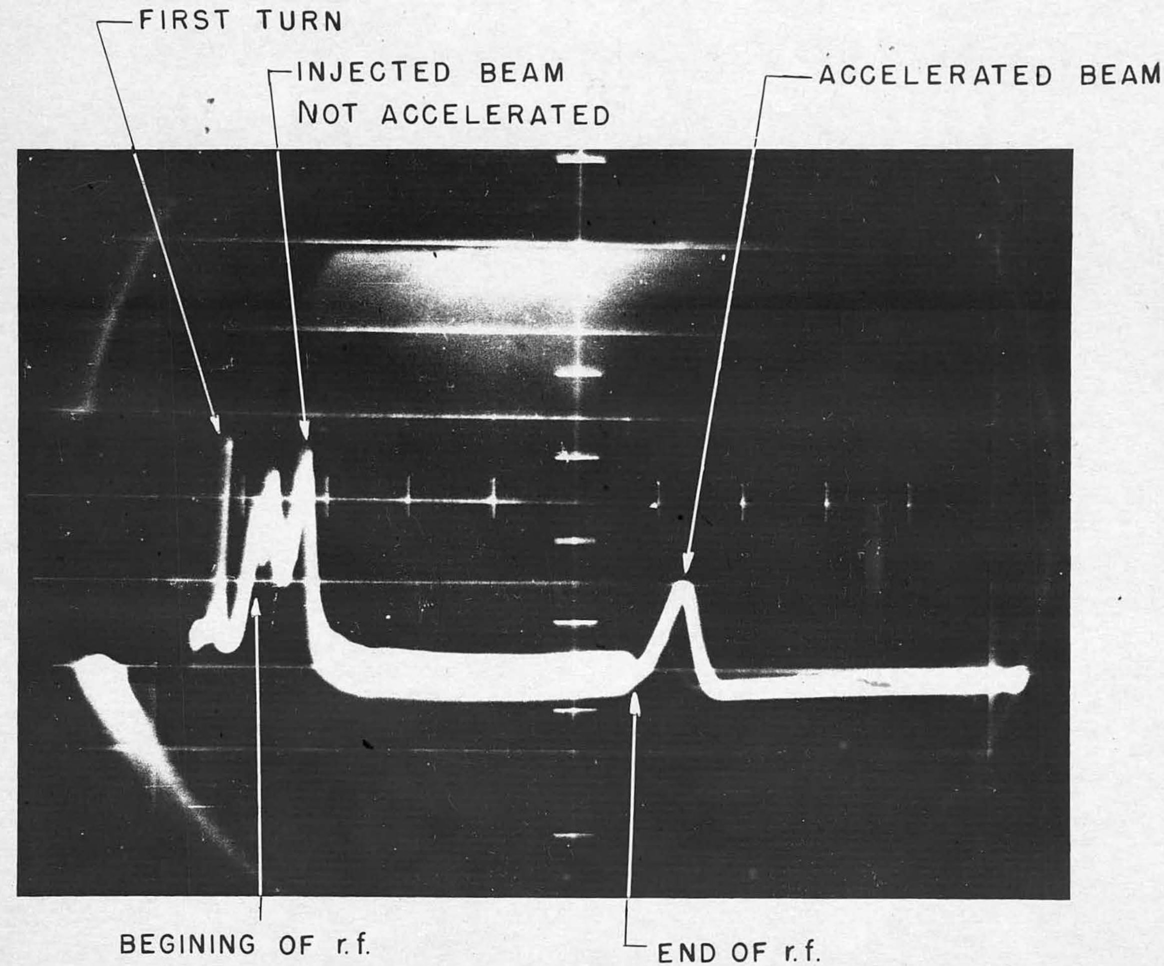


FIG. 2

PHOTOGRAPH OF THE MODEL BEVATRON SHOWING THE INJECTOR CYCLOTRON IN THE FOREGROUND.

0Z 785



OSCILLOSCOPE TRACE OF BEVATRON BEAM. HORIZONTAL DIVISIONS ARE 2 MILLISECONDS. VERTICAL DIVISIONS ARE 0.8×10^{-7} AMPERES

FIG. 3

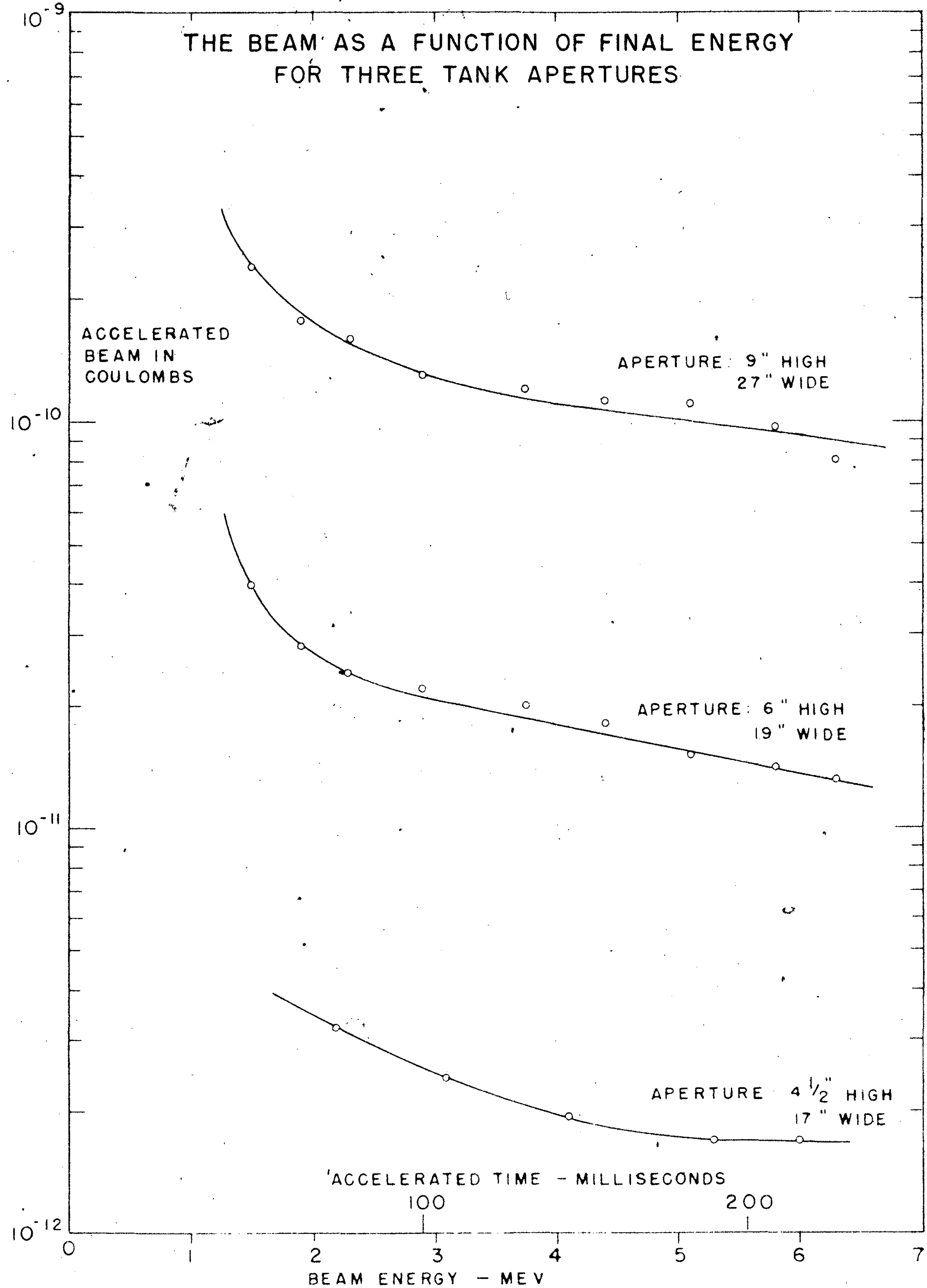
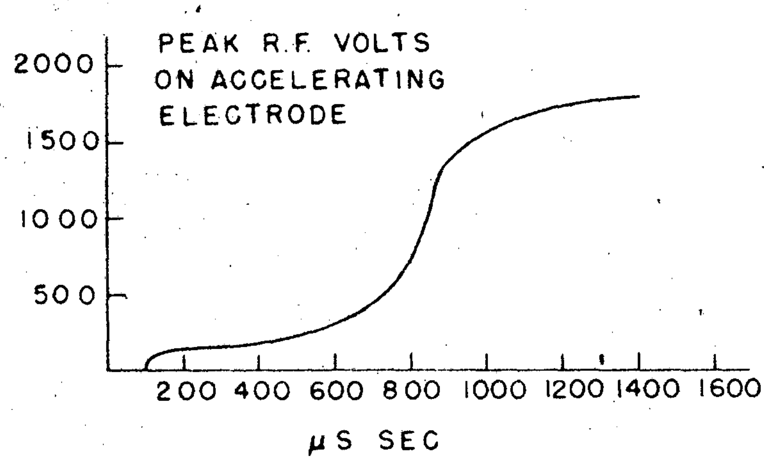

THE BEAM AS A FUNCTION OF FINAL ENERGY
FOR THREE TANK APERTURES
ACCELERATED
BEAM IN
COULOMBS
APERTURE: 9" HIGH
27" WIDE
APERTURE: 6" HIGH
19" WIDE
APERTURE 4 1/2" HIGH
17" WIDE
ACCELERATED TIME - MILLISECONDS
100
200
10^-9
10^-10
10^-11
10^-12
0
1
2
3
4
5
6
7
BEAM ENERGY - MEV

FIG. 4

14385 - I



OPTIMUM SHAPE OF RADIO FREQUENCY
RISE TIME CURVE.

FIG. 5