Laboratory of Nuclear Studies
Cornell University
Ithaca, New York

THE 10 TO 20 GEV CORNELL ELECTRON SYNCHROTRON

Table of Contents

Laboratory of Nuclear Studies
Cornell University
Ithaca, New York

CS-33
R. R. Wilson
May 1, 1967

THE 10 TO 20 GEV CORNELL ELECTRON SYNCHROTRON

1. Introduction

The National Science Foundation awarded a contract to Cornell University on April 4, 1965 for the construction of a 10 Gev electron synchrotron. The synchrotron itself has now been built and preliminary tests have been made at low energy. Injection studies were initiated on March 1, and the first synchrotron acceleration was observed March 19. At present, May 1, an energy of over 1 Gev has been reached without trouble. We are limited at present because the Experimental Hall is not finished so that the magnet is powered by a flimsy temporary source. The building will be finished late this summer and as our permanent source of power becomes available we should be able to raise the energy toward its design value of 10 Gev. It is significant though that one Gev can be achieved easily - essentially without the use of any of the corrections or adjustments built into the machine. Our only difficulty so far has been with residual magnetism which was not automatically removed by the low-excitation a.c. field.

The present report is largely a revision and up-dating of CS DC-26 which was written two years ago when the construction of the synchrotron was authorized.

2. Tunnel and Buildings

The tunnel for the synchrotron magnet is located about 40 ft. under the Upper Alumni Athletic Playing Field at Cornell University, and is roughly 800 ft. in diameter. The bore of the tunnel is 10 ft. and the concrete floor is 7.5 ft. from the top of the bore - the walls consisting of gunite concrete that are about 5" thick. For the purpose of attaching things to the walls, there are vertical steel channels (Unistruts) embedded in the concrete at intervals of six feet. The plan of the tunnel is shown in Fig. 1a, and a typical view within the tunnel is shown in Fig. 1b.[1]

The building is located in Cascadilla Gorge and consists largely of an Experimental Hall which is 100' by 100' but which can be extended if necessary. The Experimental Hall is connected to the tunnel by means of the flares shown in Fig. 1a. The west flare is about 100' long and is shaped to allow beams to traverse the Experimental Hall at almost every point. The ancillary equipment for the synchrotron and the experiments are contained in the three story building that is wrapped around the experimental hall but which is shielded from it by a six foot thick wall.[2]

3. Magnet Design and Construction

The arrangement of the magnets is indicated in plan by Fig. 1a and a cross section of one of the magnets is shown by Fig. 2. The orbit radius is very close to 100 meters and there are six straight insertions, two of which are 40' long and four of which are 20' long. Around the rin-, there are 192 magnets each of which is about 11 1/2 ft. long - the separation between the iron of the magnets being 18.5 inches (for exact parameters see Sec. 21). The gap of the magnet follows the undulating size of the beam characteristic of strong focusing so that 96 of the magnets are vertically focusing (VF) having 1.5" gaps while the other 96 of the magnets are horizontally focusing (HF) having 1" gaps. Correspondingly, the coils in the VF magnets have 24 turns and in the HF magnets the coils have 16 turns. Fig. 2 illustrates a VF magnet in cross section. The

---

[1] The tunnel was designed by Jacobs Associates under sub-contract to Wm. M. Brobeck & Associates, and has been dug by Traylor Bros. It was started July 15, 1965 and was finished in July 1966.

[2] The building, designed by Ian MacKinlay for Wm. M. Brobeck & Associates is being constructed by Irwin & Leighton, Inc. The excavation was started March 15, 1966. We expect to occupy parts of the building as they are finished, but do not expect the completion of construction before the Fall of 1967. Thus part of the linac was installed in a temporary position in October in the adit of the tunnel and initial injection studies were begun. On December 1, the "Linac Stack" became available so the whole linac was installed in its final position. A temporary structure in the form of a wooden tunnel was then built through the Experimental Hall so that we could finish the magnet and start injection studies before completion of the building.

outside dimensions of the iron are 11 1/2" X 8" for both kinds of magnets. There is no conventional donut but rather a 1/32" thick stainless steel skin covers the outside of the magnet and serves as the vacuum wall.

Each magnet unit is firmly clamped to a base or strong-back made of steel "ship channel" that is about 11' long by 13" wide and 3" deep. Two of these bases with magnets are then supported on a 12" wide I-beam placed at those points which give minimal deflections of the channel due to the load - the average deflection being of the order of several mils. Other screws on the bases adjust and lock the radial and azimuthal positions of the magnets with respect to the I-beams. Although the I-beam deflects about 100 mils under its total load, the magnet units can each be adjusted so as to be level under this loaded condition; hence the vertical position of the magnet should not deviate from level by more than several mils at all positions along the I-beam. Each magnet and channel base weighs about 1.5 tons and the total weight of a completed I-beam together with its ancillary equipment such as chokes and condensers is about 5.5 tons.

After the magnet units are adjusted with respect to the I-beams, the I-beams themselves can be moved as a unit by the kinematically designed device shown in Fig. 3a. The jacks are motor-driven so that the position of the I-beams can be adjusted from the control room. One end of each I-beam rests on a ball joint fastened to its neighboring I-beam and can only follow the motion of the end of that I-beam: effectively, the I-beams are all hinged together. Electric transducers are attached to the I-beams so as to signal the relative radial and vertical positions of the magnets. These signals must be calibrated against a separate survey, but relative readings which can be made to about one mil can be used for automatic or manual positioning of the machine so as to give minimal beam displacements as determined by beam-position-sensing devices.

The magnet units are fabricated by first being assembled in halves by stacking punched iron laminations (14 mil thick Carlite coated Armco A-6 stamped by Hydro-Cam Engineering Company) on a stacking jig which has been machined to be level and straight. One of the prefabricated coils is then placed in position in the coil window, and, with appropriate dams at the ends, epoxy (Hysol R9-2039 with H2-3561 hardener) is poured so that it completely covers the coil. The coils are constructed of stranded cable which is made by twisting ten 1/8" O.D. Formex-insulated wires about a 5/16" O.D. copper tube through which cooling water can be passed. Half of the coils have been wound and epoxy-potted by Pacific Electric Motor Company and the other half were made by Everson Electric Company. A 1/8"-thick layer of lead, consisting of strips about 3/8" wide, is placed so as to cover the coil and thus shield it from scattered synchrotron radiation or from the degraded products of high energy electrons.

After two such magnet halves have been fabricated, they are then keyed and bonded together to make a whole magnet. This unit is slipped inside a 1/32" thick stainless steel box, and the cover and the end pieces are then welded in place so as to make the unit vacuum-tight. The coil leads come through the sides of the box through ceramic insulators. Vacuum flanges with 3 1/2" Conoseal joints are welded to the end pieces. Finally, the unit is completed by being firmly clamped to the ship-channel base as can be seen in Fig. 3b. These unit magnets have been assembled in our shop at the rate of about one per day.

The HF or narrow-gap magnets, in which there is more space because the coils are thinner, have correction coils made of two turns 1/4" O.D. copper tubing. These coils can be used for beam bumping or for correcting the magnetic field. The I-beam units were finished as completely as possible in our shop, i.e. assembled together with their condensers, chokes, and all the necessary bus bars and wiring: then these were moved over and installed in the tunnel.

4. a. Modified Magnets for Beam Extraction or Injection

Some of the magnets described in Section 3 have been modified as shown in Fig. 4 in order to provide an extension of the yoke to allow for extraction or injection of the beam. As can be seen, the ordinary magnet stampings have had a short length cut off either the outer or the inner return yoke. The magnet is then assembled in the usual manner except that when the two halves are brought together, an additional especially shaped stamping (Fig. 4) is placed between the shortened yokes. The stainless steel sheath must be modified to cover this extension and a 1.5" Conoseal coupling flange is welded to the stainless steel cover in order to attach a window or beam pipe.

In addition to the injection magnet which has the extension of the yoke on the inside, six magnets have been modified with an extension on the outside to allow for the extraction of photon beams. Five of these have been placed on the ring so as to give five beams in the Synchrotron Hall, and one has been placed just upstream from L-3 to give a photon beam in that area. We expect eventually to bring out an external electron beam through one of the modified magnets placed roughly in the vicinity of the 185th magnet so that the beam will traverse the center of the experimental hall.

4. b. The Quadrupoles

In each of the 40' long straight sections are located two quadrupole magnets, one focusing and one defocusing which are important parts of the magnet lattice. (See Section 5) The exciting coils of the quadrupoles, which consist of 32 turns of water-cooled 3/8" square copper tubing, are connected in series with the magnet. The dimensions are given in Section 20: they are roughly about 2' long with a 2' gap between them, and the gradient is about 5KG per inch at 15 GeV excitation. Fig.5 a,b shows the construction[3] which is similar to that of the synchrotron magnets in that the laminations and coil are potted inside a stainless steel sheath so that no donut is necessary. The return yokes are only at the top and bottom of the magnets which leave the sides relatively free for extraction of particles or for other experimental uses.

5. The Lattice

The lattice consists of 96 lenses, two magnets per lens, distributed in the roughly circular fashion indicated in Fig. 1a. The magnets are supported by 96 I-beams, i.e., 2 magnets per I-beam, and such that each end of an I-beam splits a lens. This arrangement permits changes to be made in the gradient parameter x_0 of a lens by simply moving the corresponding I-beam support in a radial direction. A half-lens appears at each end of the long straight sections in order to avoid having to make special I-beam bases at these positions. We have also chosen to reverse the sign of the gradient on opposite sides of the long straight sections. This makes the magnet anti-symmetric about the roughly North-South diameter and symmetric about the East-West diameter.

The gradient parameter, x_0, has been chosen to be 9.143" for a positive lens, and 9.121" for a negative lens at the isomagnetic line of the pole pieces, which implies 10-3/4 betatron oscillations per turn. This operating point is shown in the usual "necktie" pattern in Fig. 6. Avoiding possible "1/3" resonances at the positions of the dotted lines, as well as the more classical integer and half-integer resonances, demands that the deviation in x_0 be no more than $\pm 0.5\%$ from the specified values. With constant gradient pole pieces, the variation of the betatron frequency with radius due to a corresponding change in the

---

[3] D. A. Edwards, CS-35

momentum of the electrons is about 3.5% inch. If the full radial aperture of the magnet is to be utilized, then a linear change in x_0 with radius amounting to about 2%/inch is required. The pole face profiles have been designed to keep the betatron frequency constant with radius, with a maximum deviation of $\pm 0.5\%$ in x_0 from the required value.[4] The resulting shape of field as given by calculation and measurement is shown in Fig. 7a,b It can be seen that the horizontal aperture is about 2.5 inches in the HF magnets and narrows to about 2 inches in the VF magnets.

Straight sections have been accommodated by first calculating orbits as though the positive and negative lenses were distributed in a uniform lattice all around the ring and then by inserting the straight sections in a manner that does not perturb the orbits elsewhere. This has been done by inserting quadrupoles or by making other local changes. Off-momentum orbits are affected, however by the insertion of the straight sections.

In the case of the 20 ft. straight sections, it was found by Edwards[5] that the effects of making these insertions could be nullified by changing the value of x_0 in the two adjacent magnets to a value of 4.7" for 9 feet of the magnet. In the case of the 40 ft. straight sections, a quadrupole pair is placed near the center of the insertion; typically, each quadrupole has a length of about 25" and, at 10 BeV, a gradient of about 5000 gauss per inch at 10 GeV. The amplitude function β_z is shown in Fig. 8a. Figure 8b shows the displaced equilibrium orbit. The circumferential momentum compaction factor is 0.010, while the momentum compaction of the maximum radial excursion is .024.

---

[4] P. N. Bredesen and P. C. Stein, CSDS-24, October 11, 1965

[5] D. A. Edwards, CSDS-25, October 1, 1965

The isomagnetic line of a magnet is not the centerline of the pole piece but has been displaced toward larger radii in order to provide for maximum magnetic aperture. The outward shift is different for the two types of magnets, being 0.069" for VF lenses and 0.131" for HF lenses. In order to center the isomagnetic line on the principal orbit, the magnets have been moved radially inward by these same amounts.

Because the orbit is circular, and the magnets are straight, there is a deviation of the principal orbit from the isomagnetic line that amounts to 0.17" outward at the center of the magnet and to 0.35" inward at the ends of the magnet. At the outside edges of the vacuum flanges, which are 3.5" away from the magnet ends, the displacement from the extension of the isomagnetic lines amounts to 0.38. The flanges had been arbitrarily placed 1/4" inward from the centerline of the magnet, hence the principal orbit will pass almost exactly through the center of a flange of a VF magnet but will pass 0.06" inside the center of a flange of an HF magnet.

6. Magnet Excitation

The magnets have been designed to be excited to a peak magnetic field of 5KG which corresponds to an electron energy of 15 GeV. At this excitation the saturation is less than one percent and even at 6.6KG (20 GeV) the saturation is only 7.5%. The frequency is nominally to be 60 cycles per second, and the magnet is biased using the series-resonant circuit shown in Fig. 9. The actual values of the inductances, capacitances, resistances, etc. are given in the list of parameters of Section 21. The condensers and chokes are fastened directly to the I-beam bases under the corresponding magnet units.

At 10 GeV excitation the average loss per magnet unit will be 2KW making the total power to the magnet 400KW. In fact, a total of 800KW must be provided because of an additional loss of 77KW in the condensers, 240KW in the chokes, 50KW in the bus bars and 37KW in the exciting machinery. The water-cooled bus bars are located in the back groove of the I-beam bases as shown in Fig. 3. The peak voltage that appears above ground is less than 1,000 volts, even at 15 GeV excitation. The overall Q of the magnet system is about 60.

The AC supply will be located in the third floor hallway above the linac tunnel and will consist of a 500KW DC supply, the output of which is made into a square wave by four SCRs. This square wave is then applied to the magnet through a resonant filter which passes primarily only the 60 cycle component.

The DC supply for the magnets is split into six parts, each giving about 200 volts placed around the magnet ring in order to keep down the DC voltage. Each separate supply will be located at or near one of the straight sections. Five of the DC rectifier units, driven by a variable transformer and each rated at 145KW (enough for 15 GeV), are unregulated. The sixth supply is regulated so as to keep the DC current at the required level.

The magnets, chokes and condensers are all to be cooled by water which will be supplied at 65°F and come out at 80°F when the excitation is 10 GeV. This implies a total flow of 350 gal/min.

7. Flat-topping

Provision is being made for flat-topping the magnet current in order to provide a long pulse of high energy electrons of uniform energy. This can be done by means of conventional silicon-controlled rectifiers connected in the circuit of Fig. 10. Using one set of our magnets and chokes as a prototype, Wm. M. Brobeck & Associates have produced a flat-top current pulse of 7msec corresponding to a duty cycle of 40%. By running at 30 cycles per second the duty cycle could be extended to about 75%. We do not expect to install the flat-top circuit until after the synchrotron is running, but we are providing space and terminals for this later installation. Brobeck & Associates estimate that the cost of the flat-topping equipment will be about $200,000.

8. Magnetic Measurements

The shape of the pole tips was determined entirely by computation,[6] however, after a few hundred laminations were punched, the magnetic field was measured and found to correspond almost exactly to the calculated values, as shown in Fig. 7.[7] The experimental values of the field gradient index x_0 were 9.204 ±0.014 inches for the VF magnet and 9.045 ±0.014 inches for the HF magnet at the geometrical center of the pole pieces.

The position corresponding to the isomagnetic line is determined by measuring the effective length L_B which is defined as $\int B ds$. The measurement is made by the use of a flux coil consisting of two accurately spaced parallel wires that pass completely through the magnetic field from one end to the other - comparison being made against one of the magnets that has been used as a standard. Thus, even if errors creep into the manufacture of the magnets, for example, by a variance in the gap between the halves, the magnets can be placed so as to minimize those errors. The rms variance from the calculated position has been less than 10 mils and the worst magnet is off by 60 mils. The average effective length is 127.21" for VF magnets and 127.17" for HF magnets.

The integral gradient length $\int\left(\frac{\partial B}{\partial X}\, ds \Big/ \frac{\partial B}{\partial X}\right)_0$ is 126.0 inches for VF magnets and is 126.1 inches for HF magnets, accurate to about 40 mils. That the ends of the magnets have the peculiar cupped shape that is shown in Fig. 11 is due to the requirements that L_B and L_G vary in the proper manner across the pole piece.

The residual field is about 2.6 gauss for VF magnets and 4.3 gauss for HF magnets after excitation to 3.3KG. The shape of the residual field is close to that of the field which obtains at high excitation,

---

[6] P. N. Bredesen and P. C. Stein, CSDS-24, October 11, 1965

[7] R. Yamada and S. Mori, CS-31, April 27, 1966

the values of x_0 for the residual field being about 25% stronger than the usual value. Hence, at the injection field of 53 gauss, we can expect the gradient to be in error by about one percent. This implies that it will be necessary to correct the gradient at injection. We plan to do this by placing weak quadrupoles lenses in the straight sections.

9. Magnet Survey

Although in principle it should be possible to line up the machine from the beginning using only the beam, i.e., by leading the beam from one magnet to the next and then by adjusting magnet positions and correction currents so as to keep the beam within the aperture. In fact, we expect to put the magnets in place accurately enough using standard survey techniques so that the machine will work upon injection except for minor adjustments. We did exactly this with our 2 GeV Synchrotron and it should be possible to do the same thing with this machine.

The betatron oscillation wavelength in the 10 BeV machine is nearly 200 feet and displacements of the magnets that occur over distances comparable to this wavelength are the most important in causing large oscillations. In the tunnel, a single line of sight is some 150 feet long which, fortunately, is comparable to the betatron wavelength. A 10 mil r.m.s. displacement of the center of each magnet from the ideal orbit will produce a 2% chance that the actual orbit will be displaced more than 1 cm. from the ideal orbit. Similarly, an r.m.s. error of one milliradian in the radial level or twist of the magnets will produce the same chance of a displacement of one cm. It is worth mentioning here that an r.m.s. variation in H_0 of 10^{-3} from magnet to magnet will also produce this same effect. A radial displacement of just one of the I-beam support points by 10 mils will produce a maximum displacement of $\sim$20 mils in the orbit.

The basic grid for the survey around the ring will consist of 36 monuments most of which are to be mounted at regular intervals on the walls of the tunnel and some of which will be in the Synchrotron Hall. We have a first-order theodolite with which to measure angles and, together with measurements of lengths using steel and invar tapes, it should be feasible to locate points on the monuments to an accuracy of about ten mils. We call this the tunnel survey. More or less independently of this, the magnets are put in place by stretching wires between the index points that are mounted on them and then by measuring off-sets. The horizontal position of the machine is established to about 10 mils using a standard surveyors level. We call the latter survey the magnet survey. A comparison between the two indicates that an accuracy of placement of better than ±10 mils has in fact been achieved.

The magnet survey has been used to calibrate the electric transducers that are attached to the I-beams. It is expected that, after the first survey, the position of beam itself with respect to the magnet aperture will be used to determine further fine adjustments of the magnet positions and currents in the correction coils.

10. Vacuum System

At 10 GeV excitation and 150 MeV injection energy, electrons are lost from the orbit at injection time largely due to single scattering and the loss amounts to about 25% for a pressure of one micron Hg. There is an additional loss of electrons, constant throughout the cycle, due to hard bremsstrahlung collisions with the air. This amounts to several percent for a pressure of one micron. Accordingly, the average pressure around the machine must be better than one micron to avoid a beam loss of 30%. Conservativism suggests that the average pressure be held less than 10^{-4}mm Hg. The straight sections, where the RF accelerators will be located, are special and may require a vacuum of about 10^{-6}mm Hg in order to avoid discharges.

A 3" diffusion pump (NRC - HS2) is provided at every other short straight section, i.e. at the end of each I-beam, hence 102 pumps. The construction is such that pumps can be placed at any short straight section if the need should arise. In an experiment where the pumps were placed only at every fourth magnet, the pressure at the worst place was about four times the pressure indicated at the pumps. Figure 12 shows a typical pump and vacuum box. A 2" fore-vacuum line runs inside the I-beams just under the top flange. In fact, the pressure in the system comes down to below 5×10^{-6}mm Hg but goes up to about 10^{-5}mm Hg when the magnet is excited to the 15 GeV level.

The synchrotron is divided into 18 vacuum zones, one for each straight section and two for each 60° sector of the magnet ring. The zones are separated by pneumatically operated gate valves. At each long straight section there is a vacuum station consisting of a roughing pump (Stokes Model 148-HO) and three fore-pumps (Cenco Hypervac 45) for the three nearest zones. The only valves other than the isolation valves already referred to will be the manually-operated units on the roughing manifold.

The pressure is measured by PIG gauges (Consolidated No. GPH-001) located at each diffusion pump where the pressure reading is roughly 1/2 the average pressure in the magnet. The output current of each gauge is to be shown on a local meter and will be fed into the multiplex system so as to be available for display at the control room.

All flanges on the high vacuum system, except the standard flanges on the isolation valves, are Conoseal medium weight joints. They can be used with polyethelene gaskets or, in locations where the radiation level is high, with copper gaskets.

11. Injection

A Varian S-band 200 MeV Linac was chosen as the source of electrons to be injected into the synchrotron. The linac consists of three units, each fed by a separate klystron, and should give 200 MeV for small loads and 150 MeV when fully loaded, i.e. 2×10^{12} electrons per pulse of which 10^{12} are to be within 1/2% of the average energy. Thus, the initial tuneup can be made at 200 MeV with a very short pulse, while subsequent high intensity operation might occur at 150 MeV. The source can be modulated so as to inject electrons into every fourth cycle of the Linac RF. The Linac is located in a tunnel that is directly adjacent to the Synchrotron Hall so that the electrons enter the synchrotron at magnet No. 10.

The beam from the Linac is bent through about 25° by an achromatic system[8] consisting of two uniform wedge magnets W_1 and W_2 and a quadrupole Q as shown in Fig. 13a,b Magnet No. 10 has been modified to have an elongated return yoke to allow the electrons to enter. At the following straight section (s 11) the electrons are deflected again by a septum magnet S placed as close as possible to the circulating beam orbit. Then in one of the following straight sections, the injected beam intersects the central synchrotron orbit and is deflected by about 1° to make it tangent using the pulsed coil P. The long time for one traversal of the magnet, 2.5μ sec, relaxes the problem of producing the injection pulse in coil P.

It will also be possible to inject positrons from the Linac. The positrons are made by inserting a rotating tungsten converter in the electron beam from the first part of the Linac, for example, at the 50 MeV point. Then the phase in the remaining part of the Linac is

---

[8] K. Berkelman, <u>CSDS-20</u>, October 16, 1964

reversed so that the positrons made in the converter are accelerated and then injected into the synchrotron. We can expect in this way to obtain a high energy beam of roughly 10^7 positrons per second.

This intensity can be improved considerably by making a better match in phase space of the positrons from the converter to the characteristics of the Linac. This is done by using a magnetic lens system. For example, by adding a quadrupole lens system just before the radiator so as to make a smaller spot, a four-fold increase in the intensity should be produced. Then by following the radiator by a strong local solenoid lens and then subsequently by longer but weaker solenoidal lenses a further enhancement can be made so that roughly 10^{10} positrons per second might be accelerated by the synchrotron. It should even be possible to exceed this intensity by going to a more elaborate system.

12. RF System

The RF system consists of linac-like traveling wave accelerators which we call synacs that are placed in the four 20 ft. long straight sections.[9] A prototype synac was first developed and used successfully to accelerate electrons in our 2 Gev synchrotron.

The voltage in MeV required per turn (for fully biased 10 GeV operation) is given by

$$V = 4.4 \sin \omega t + 8.8 \sin^8 \frac{\omega t}{2}$$

which has a maximum of 9.4 MeV at about 7.5 m sec. Thus each of the four synacs must supply about 2.5 MeV per turn at the peak of the cycle.

---

[9] M. Tigner, CSDS-21, December 16, 1964

The synac units consist of a 714 MH_z disc loaded wave guide having a disc spacing of 1/3, i.e. 5.5 inches, and a diameter of about 13 inches, see Fig.14a. The frequency has been chosen to be the fourth subharmonic of the frequency of the injection linac (2855.96 MH_z) so that synchronization of the two systems will be possible. Each synac is made up of five subunits consisting of three pieces of wave guide about 4 ft. in length and two couplers that are bolted together to make an assembled unit about 16 ft. long as shown in Fig.14b. Some of the wave guide units have been fabricated for us by Litton Industries, others by Arco.

Each of the four synacs has an independent Klystron RF power supply; however, the high voltage and drive are common for reasons of economy and phase stability. The total peak power at 10 GeV, will be 425 kW and the average power will be 120kW. The average power going into the beam will be 24kW for a current of 7 ma (10^{11} electrons/pulse). Of this, 10 kW will go into the beam itself and 14 kW will be radiated by the electrons. For comparison, the total resistive loss in the copper will be about 96 kW. By reducing the beam so that the loss due to it is negligible compared to resistive losses, i.e., to about 10^{10} electrons per pulse, and by applying all the power that is available to the Klystrons ($\sim$700kW), we should be able to reach an energy of about 11.5 GeV.

The Klystron high voltage is supplied by an "inductrol" regulated transformer- a silicon-diode-rectifier combination with a capacitor bank of 140 mF. This power supply is capable of delivering an average power of 600 kW at an output voltage of 38 kV. An auxiliary supply is also provided to allow flexibility of operation and to serve as a stand-by for the main power supply. The auxiliary supply is capable of delivering 125 kW, enough to run one Klystron station at 43 kW average RF Power. Thus even under standby conditions, more than enough power is available to accelerate the full beam to 5 GeV.

The power amplifier Klystron for each synac is an Eimac 4 KMV 150 LH-1 which is located in the enlargement of the tunnel occurring at each of the 20 ft. straight sections. The Klystron is 66 inches high by 28 inches square. The power amplifiers and the D.C. supplies and modulators have been fabricated for us by Continental Electronics Company.

The electron source of the Linac is modulated so that only the properly phased pulse out of the four pulses available per synchrotron RF cycle will be filled with electrons. This will keep down beam loading in the linac and synchrotron, both of which must be synchronized, and should also reduce radiation damage in the magnet due to the electrons that otherwise would not be accepted at injection time.

13. Controls

Our basic conception of the synchrotron was that it be so simple and so inert that a small university group could build and then operate it. Our goal has been to simplify the controls to the point that one relatively untrained operator should be able to control and adjust essentially everything from the control room. We also wanted to minimize the cost and labor of installing the large number of wires and controls that are usually associated with a large synchrotron. To this end, a time-sharing multiplex system has been worked out by Littauer.

Generally speaking, there are between 50 and 100 values of any particular variable, such as beam positions, vacuum readings, magnet corrections, etc., and groups of these values corresponding to a particular variable can be presented as a histogram on an oscilloscope. It is also possible to present these data as typewritten lists and to

---

[10] R. Littauer, Multiplex Control and Monitoring of a Large Accelerator, (Particle Accelerator Conference, Washington, D. C., March 1965).

store them on punch cards or tape. The data can then be fed back into the system in order to reproduce previous conditions.

We hope to be able eventually to feed the data from the beam position indicators directly to a computer which will automatically calculate and set magnet positions and correction currents so as to optimize the beam of accelerated electrons. Although this may be overly ambitious, nevertheless, where possible controls and monitors have been designed so as to be consistent with this intriguing possibility.

14. Monitoring the Beam Intensity and Position.

Beam sensors are placed around the ring, each separated by about four magnets so that there are about 4 1/2 detectors per betatron oscillation. The detectors consist basically of a frame of ferrite through which the beam passes, see Fig. 15. Around each of the four pieces of ferrite that make the frame are wound a few turns of wire. The size of the signal induced in a particular coil depends on the position of the beam as well as the intensity. By taking an appropriate difference of the signals, the horizontal or vertical position can be determined. By adding signals, a total signal is given that is proportional to the intensity but not dependent on the position. The intensity and position signals are conveyed to the control room in digital form via the multiplex system.

15. Adjustments and Corrections.

Irregularities in the magnetic field fall into two general classifications: those which occur at the low field which exists at injection, and those which occur at high fields. The low field effects are due to residual magnetism, the earth's field, and eddy currents. These effects can be corrected by vertical and horizontal steering coils that are distributed around the ring at roughly the same intervals as are the detectors, namely, every four magnets. See Fig.16.

If one coil is actuated then a rather complicated betatron oscillation is excited. However, by actuating currents in three successive coils in a particular manner then the orbit is disturbed only in the immediate vicinity of these coils. Such a "beam bump" is made by programming the currents in three successive coils in the ratio of 2:-1:2 respectively. This allows for a simple adjustment of the correction currents inasmuch as one can dial a particular position detector on the multiplex system, then by exciting a beam bump at that location one can center the beam in the aperture. In this way one can center the beam in the aperture all around the ring. However, the number of betatron oscillations, easily determinable by the position detectors, or by exciting betatron oscillations by applying an oscillating field of the corresponding frequency to some deflection plates, may be wrong. A few quadrupole coils are distributed in each sector and can be excited so as to make the number of betatron oscillations per turn either the design (10 3/4) or the optimal value.

At high fields the magnetic field can be corrected by exciting currents in the correction coils that have been included in the narrow-gapped magnets. By programming these currents in successive magnets, a radial beam bump similar to that produced by the low-field correction coils can be produced. Vertical motions can be produced by making a vertical motion of the magnets by the use of the motor-driven levelling jacks. Thus either a simple vertical motion or a twist can be given to the magnets. By programming the motion of successive magnets, a localized vertical bump can be produced. In the same manner, horizontal corrections to the magnetic field or to the gradient can be made by making appropriate horizontal motions of the magnets by means of the horizontal jacks. All of these motions are produced at the central control room where one can dial a particular station corresponding to the position of a particular end of an I-beam, and then command changes in the vertical or horizontal positions by actuating the jack-motors - the actual positions being indicated by the transducer signals.

16. Radiation Damage

One of the first of our production magnets was exposed to various conditions of an intense beam of electrons from the first section of our injection Linac. The Linac could give about 300 ma of 20 - 30 MeV electrons in a 2 or 3 μsec pulse. In one series of runs, the beam was directed along the centerline of the magnet and then diffusing foils of increasing thicknesses were successively placed in the beam at the point of entry into the magnet so as to give a general radiation to the iron and the coil. With as much as 900 watts in the beam, i.e. about 300 ma in a 2 usec pulse at 60 pulses per sec, and with diffusers ranging from 16 to 130 units in thickness, a half dozen different runs of about six hours each showed no effects of radiation except for the failure of a rubber gasket at the downstream end of the magnet.

In a different series of runs a current was excited in the magnet so as to cause the beam to be deflected into the magnet yoke about half way down the magnet. In one set of runs, the beam intensity was increased gradually until it reached an average power of 360 watts, i.e., 300 ma for 2 usec at 30 cps. The total running time at this power was equivalent to about 24 hours. Throughout all the run, a transformer supplied 800 volts r.m.s. to one side of the coil: no breakdown was observed. Typically, the pressure in the magnet was observed to increase by a factor of two during the runs - depending on the current. Upon opening the magnet after the test, it was noticed that the epoxy in the area where the beam had struck was discolored and that in the same area the lead strips on the coil had melted due to absorption of scattered electrons. This caused a mess on the lower coil but did not cause a failure of the coil.

It appears that the magnets are quite radiation resistant - but that the very large currents can cause rather serious thermal effects. The expected injection currents should be one or two orders of magnitude smaller than those used in the tests. In order to protect the machine against an accidental exposure of an unduly large Linac current, the pressure in the machine will be monitored by a circuit which will turn off the Linac if a pressure increase occurs anywhere in the magnet.

The high energy electron and gamma ray beam can also be dangerous. Thus a beam of 10^{13} electrons per second at 10 GeV corresponds to an energy of 16 kW. This can cause severe thermal damage if it is absorbed inside the machine without care. We expect to insert thick metal "scrapers" at the end of each magnet in a position near the beam such that most of the radiation will be absorbed by them.

The spectrum of synchrotron radiation is characterized by being flat in radiated energy per unit photon energy up to a critical energy after which it falls off rapidly. For 10 GeV, this critical energy is 22 Kev and it varies with the cube of the electron energy. For our 2 GeV machine the critical energy is 3 Kev for comparison. The power that is radiated per unit photon energy in the flat part of the spectrum varies as E/R, hence for the 10 GeV machine the power radiated in low energy photons per electron is less than that for the 2 GeV Synchrotron by a factor of three. For some effects, such as the production of photo-electrons in the resonators, this is a consolation.

17. Ultimate Energy and Intensity

It appears now that it will be feasible ultimately to reach an energy of 20 GeV in the synchrotron. The magnet and the power supplies have been constructed to reach 15 GeV but it turns out,[11] by adding condensers and chokes, that the magnet can be excited to a field of 6.6KG corresponding to 20 GeV. About four times as much power must then be supplied - and dissipated - but the 3MW that will be necessary

---

[11] R.R.Wilson, CS-33, August 25, 1966

seems not to be excessive.

The radial size of the beam grows with energy because of anti-damping of the betatron oscillations due to synchrotron radiation. Thus the beam will be 1 cm wide at 10 GeV, 5 cm at 15 GeV, and larger than the aperture at 20 GeV. However, a special damping magnet has been developed by Robinson[12] at C.E.A. that will prevent this kind of growth of the beam, and it should be easy to adapt his design to our magnet.

At 10 GeV roughly 10 MeV per turn must be supplied to compensate for the energy radiated per turn. Since this varies as E^4, we must supply about 50 MeV/turn in order to reach 15 GeV, and 160 MeV/turn to reach 20 GeV. It turns out that powerful klystrons are available that are capable of producing a peak power of 7MW and an average power of 200KW. By using two of these tubes at the straight section L-3 where there is room enough to install two additional synac units, it should be possible to reach 15 GeV at 10 cycles per second. To reach 20 GeV, it would be necessary to install two more synacs in the long straight section in the Synchrotron Hall and to replace the klystrons in the four other straight sections. We have already identified some surplus power supplies that would be adequate and our rough estimate of the rest of the components necessary to reach 20 GeV is 2M$.

An alternative possibility for supplying the RF power is the superconducting Linac. A short section of this kind of Linac has already been successfully produced at Stanford[13] and we are watching their progress with great interest.

The intensity of the electron beam in the synchrotron depends in part on what the Linac can supply and then upon what kind of intensity limitations will occur during the process of acceleration. The Linac is hardly a limitation. Although the first section has already

---

[12] K. W. Robinson, <u>CEAL-TM-155</u>, December 10, 1965

[13] Perry Wilson Accelerator Conference, Washington, D.C. 1966

produced a current of 300 ma, we do not expect eventually to have more than 100 ma in the 1% energy acceptance of the magnet. If we can have the source modulated so that all this current comes in every fourth pulse, then it should all come at the proper phase to be accepted for acceleration by the synchrotron. In that case, close to 10^{14} electrons per second might be accelerated, but then we would be in terrible trouble with thermal and radiative effects.

The amount of RF power that we have provided will initially limit us to some 10^{13} electrons per second. The phenomenon of beam flutter can be expected to manifest itself at roughly this intensity, but this kind of beam blow-up can be controlled by inserting octupole lenses around the magnet. Thus it appears that the practical limitation of our intensity will be our ability to live with the problem of counting rates, of induced radioactivity, and of thermal and radiation damage - but we can expect to obtain and to handle roughly 10^{13} electrons per second.

It has been previously noted that positrons can also be produced by the Linac and that eventually we can expect a beam of about 10^{10} positrons per second, or better, from the Synchrotron.

18. Conversion to a 20 BeV Colliding Beam Facility.

Once a synchrotron works to give an intense beam, the question arises as to whether it can be used as a colliding beam facility for in that case exceedingly high energy phenomena can be studied. A large ring diameter is advantageous in that the radiation by the electrons is decreased but the large radius is disadvantageous because the frequency of revolution is less and hence the number of collisions also becomes less - the two effects apparently just cancel each other.

To use our synchrotron as a colliding beam facility, it will be necessary to inject electrons in the normal direction and positrons in the opposite direction. The magnetic field would be cycled between the injection energy and a sufficiently high energy to cause the beam oscillation to damp out so that electrons or positrons could be injected on successive cycles until the magnet has been filled. Then the magnetic field would be held at a constant value while the electrons and positrons could circulate through an interaction region in opposite directions. The filling time might take from one to ten seconds and the interaction time might take about 100 seconds after which the beam could be replenished in a cyclical manner. Alternatively, the synchrotron might be run in a flat-top mode at about 20 cycles per second so as to give roughly a 90% duty cycle and such that the beam could be constantly replenished.

There is not much point in allowing the electron beam to circulate freely for much longer times than indicated above inasmuch as an electron will radiate an amount of energy equal to its kinetic energy in a short time, i.e. in $2.5/E^3$ Bev seconds which is about 20 ms for 5 Bev electrons and is about 2 ms for 10 Bev electrons. This is important for the use of our synchrotron because it implies that the vacuum that is presently obtainable in our magnet is probably good enough. In fact, the vacuum could be improved to be 10^{-6} torr simply by doubling the number of diffusion pumps, and it might be improved by another order of magnitude by the use of cold spots. The loss of electrons from the beam by the gas is due to bremsstrahling collisions which cause energy changes greater than can be accepted by the synchrotron. The acceptance energy is about one percent of the electron energy, and this implies that the lifetime of the beam in seconds would be about $10^{-4}/p$, torr i.e. it would be about 100 sec at a pressure of 10^{-6} torr.

Of course, in the vicinity of the interaction region, where the experiments would be made, it would be necessary to have a very good vacuum, of the order 10^{-9} torr, to reduce experimental background effects due to interaction with the gas. It should be quite possible to produce such vacua at the experimental region by the use of differential pumping.

The changes in the synchrotron need not be major. The Linac would have to be augmented so as to give positrons as well as electrons. One possibility would be to use the present Linac and injection system without change for injecting electrons into the magnet. The Linac beam could then be occasionally diverted so as to strike a conversion target in order to make positrons and then these could be bent through about 180° and accelerated in another Linac placed along the back wall of the beam room. The high energy positrons might then be injected into the ring somewhere in the East flare. About one million dollars worth of Linac would be required at present prices.

In order to overcome the anti-dampening that exists because of our particular choice of magnet lattice, a Robinson-type dampening magnet or magnets could be added. It would also be wise to place special magnets near or in one of the 40' straight sections in order to improve the luminosity in the interaction region.

19. Construction Schedule and Costs.

At the present writing, May 1, 1967, the magnet has been fabricated and has been installed in the tunnel. Although the construction of the building has been delayed so that it will not be finished until the Fall of 1967, we are already occupying the part of the building in which the Linac is to be housed, and we have built a temporary tunnel-like structure through the Experimental Hall which is still under construction. This structure isolates us from the construction workers and has allowed us to finish the synchrotron and to test it at low energy using a temporary power source. As soon as the building services and power supplies become available, which may be some time this summer, we hope to reach 10 GeV. If we do not run into serious problems, we can expect to initiate an experimental program this year.

Nearly all of the components of the synchrotron have been purchased or firm construction contracts have been awarded. The costs have been close to our initial estimates, except for the building whose dimensions are somewhat larger than had been originally planned. The tunnel cost 1.2M$; the building, 4.2M$; the Linac, 1.0M$; the magnet and power supplies, 1.5M$; the Vacuum System, 0.3M$; the RF System, 0.9M$; Labor and Overhead, 1.5M$; and miscellaneous other costs, 0.9M$: This brings the total cost to about 11.5M$ which appears to be comfortably less than the 12M$ that has been made available to us by the National Science Foundation. Included in these items are expanded experimental areas and some components that will allow us eventually to reach much higher energy.

20. The Synchrotroneers.

It is a complex task to try to identify the people who are constructing the synchrotron because some are deeply involved while others are only peripherally concerned. For those on the academic staff it is an activity that must compete with their other University duties such as teaching, research, or committee work. Our system is a loose one in which about a half dozen key people do what is necessary to be done by recognizing problems, acting on them themselves, and then by keeping others informed by conversations in the halls of the Laboratory. Once a week, about a dozen people meet to discuss plans and progress, Fig.17.

The Deputy Director, Prof. Boyce McDaniel and the Associate Director for Operations Mr. Robert Matyas have been crucial in their contributions to the work. They have both carried major responsibilities at every level: Prof. McDaniel tending toward scientific and technical problems while Mr. Matyas was more concerned with problems of management and construction. Prof. McDaniel became completely responsible for the completion of the synchrotron in the Spring of 1967 when the author became Director of the 200 GeV synchrotron. Much of the most critical work has had to do with the design and construction of the tunnel and the buildings: Prof. John DeWire has been responsible for this tremendously complicated operation which has interacted with the basic synchrotron design at every stage. That the timing of building construction has been synchronized with the progress of the accelerator has also been due to his efforts. Prof. Raphael Littauer has been in charge of those elements of the synchrotron that are mainly electrical, such as the power supplies, the magnet coils, the chokes and condensers, as well as the multiplex system for controlling and monitoring the synchrotron. Without his brilliant and sophisticated solutions of these problems, the Synchrotron would be a different and a much more awkward instrument. Mr. C. Kellers has assisted him with the design and construction of the magnet power supplies. Prof. D. Edwards has made the calculations of orbit theory that led to the final choice of the parameters of the synchrotron. His contribution has been diversified, though, and in addition to an early administrative interaction, he has also designed and supervised the constructing of the quadrupole lenses. Prof. DeWire has been in charge of the vacuum system, the original design of which was due to Littauer. The survey has been the responsibility of Prof. W. Woodward who mastered the cabalistic rites of another profession; and the magnets have been positioned by Prof. R. Talman assisted by Dr. D. Rust. The profile of the pole tips of the magnet was computed by Prof. P. Stein. Dr. R. Yamada made exhaustive measurements on the magnetic field that was actually obtained. The radio frequency system that has evolved has been completely due to Dr. M. Tigner. Prof. A. Silverman was involved in the early planning of the machine and is now concerned with considerations of the experiments to be made with the machine. Prof. K. Berkelman has designed the injection system. The Linac has been the responsibility of Mr. E. von Borstel. Dr. Helen Edwards took charge of the injection studies; she also devised and installed the beam-position detectors that were used by her in bringing the synchrotron into operation

We have been exceptionally lucky in the excellence of our technical staff. Mr. K. Loveless, the shop foreman has been ingenious not only in helping with the mechanical design but also in devising methods used in the construction. Mr. J. Fuller of the shop was deeply involved at a creative level in the development of the magnets. He constructed a series of proto-types and then led the group of about six men who constructed the 200 or so magnet units at the very fast rate of one-a-day. Mr. R. Bower has been in charge of the assembly of the I-beams and then of connecting them together in the tunnel. He has been responsible for the design and installation of a tremendous amount of the equipment that makes a synchrotron function. In the installation, he has been aided by Mr. C. Chaffey who has been in charge of the crew doing the work. Mr. J. Sanford has supervised the wiring installations and Mr. D. Miller has been in charge of drafting. Mr. H. Doney has expedited the vast amount of material ordered from industry. Angela Gonzales, the "emminence gris" of the Laboratory, has been much concerned with our esthetic environment not only in her choice of dramatic colors but by being intolerant of those impure lines and unbalanced volumes that tend to creep into the design of the synchrotron.

There are many people who contribute in a vital way to the synchrotron construction even though they are not members of the Laboratory of Nuclear Studies. Dr. Jerome Fregeau of the National Science Foundation is typical. By understanding every facet of the synchrotron construction, sometimes better than we do, he has been able to keep the lines of fiscal authorization open, contributing to the speed of the work, and his over-all view of the project has been constructively useful to us. Mr. John Burton, Vice President for Business at Cornell, is responsible for the construction of the tunnel and the buildings: his decisions on such matters have often been of crucial importance to us. Representing the University on the site is Mr. Frank DelleCave whose knowledge of the minute details of the building construction and his sympathetic but aggressive coordination of our interests with regard to the contractor have kept the work going apace. Mr. Norris Raneer, who was in charge of tunneling for Traylor Bros., did a magnificant job for us; and Mr. A. Wissing of Irwin & Leighton is getting us into the right parts of the building at the right times in spite of great difficulties. We are lucky, too, that Mr. Ian MacKinlay, our architect realized that "form follows function" - especially when a synchrotron is being built - but he has also insisted that the forms be nice too. All of these men have been mentioned here because they have had the kind of transcendental involvement that people get in contributing to a scientific project.

21. Parameters of 10 GeV Synchrotron

General

Nominal electron energy	10 GeV
Nominal electron intensity	10^{13} electrons per second
Possible electron energy	20 GeV
Nominal repetition rate	60 cycles per second
Nominal positron intensity	10^{10} positrons per second
Major diameter of tunnel	811.5 ft.
Orbit circumference	757 meters (2500 ft.) .47m
Orbit period	2.53 usec.
Height of beam	54 inches
Height of tunnel	7-3/4 ft.
Width of tunnel	10 ft.
Straight sections	2 of 40' length 4 of 20' length 186 of 17" lengths

Magnets

Length of magnet unit (overall)	134.98"
Effective length of magnet L_B	323 cm.
Number of magnet units	192
Chord length of I-beam supports	24.160'
Length of small straight sections	43 cm.
Length of "20 ft." straight section	628 cm.
Length of "40 ft." straight section	1238 cm.
Clear length between magnet units	10"
Magnetic field at 10 GeV	3.3 Kg
Injection field at 200 MeV	66 gauss
Magnetic field for 1.5% saturation	5 Kg.
Residual field after 3.3 Kg excitation	∿2 gauss
Gradient length of pole profile, x_0^-	9.045 ± 0.014
Gradient length of pole profile, x_0^+	9.204 ± 0.014
Gradient length near 20' straight section, x_1^-	4.731
Gradient length near 20' straight section, x_1^+	4.738

Magnets (Continued)

Gap height, positive (vertical focusing) lenses	1.501"
Gap height, negative lenses	1.022"
Weight of iron per magnet unit:	
wide gap	1890 lb.
narrow gap	1954 lb.
Weight of copper per magnet unit:	
wide gap	315 lb.
narrow gap	210 lb.

Magnet Excitation

Current at 10 GeV	424 A peak
Inductance of magnet unit (series):	
wide gap	8.7 mH
narrow gap	5.8 mH
Capacitance per magnet unit at 60 cycles	1.94 mF → 6@ 313μ + [illegible]
Resistance of magnet unit:	
wide gap	31 mΩ → N=24
narrow gap	21 mΩ N=16
Inductance of choke coil	7.25 mH
Resistance of choke coil	15 mΩ
A.C. voltage (1.5" magnet) at 10 GeV	500 V rms
Total energy dissipation at 10 GeV	770 kW
D.C. i^2R losses at full bias	360 kW
A.C. i^2R losses	180 kW
Core and eddy losses	115 kW
Capacitor loss	80 kW
Busbar losses	35 kW

Magnet Lattice

Basic period	FFDD
Number of basic periods	46
Length of basic period	580"
Phase shift per basic period	75.4°

Number of betatron oscillations per turn	10-3/4
Maximum orbit excursion for 1% energy variation	1.12" (.63)
Minimum orbit excursion for 1% energy variation	0.10" (.37)
Bending magnet length ℓ_B	127.2"
Effective gradient length ℓ_G	126.0"
Maximum radial compaction factor	0.024
Circumferential compaction factor	0.010
β_{max}	72'
Maximum orbit excursion for 1 mr angle variation between similar magnets	0.86"
Maximum orbit excursion for 1 mr angle variation between lenses	0.66"

Injection

Energy of linac: loaded to 10^{12} p.p.	150 MeV
unloaded	200 MeV
Linac frequency	2855.76 Mc
Duration of linac pulse	2.5 μsec
Momentum width, 50% of beam	$\leq$ 1%
Intensity within $\Delta p/p$ = 1%	$\geq$ 1.5x10^{12} electrons /pulse
Beam divergence	2x10^{-4} radians
Number of linac sections	6

RF System

Frequency	713.94 Mc
Harmonic order	1800
Number of 16' linac sections for 10 GeV	4
Peak voltage required at 10 GeV	10.5 MeV/turn
Average RF power demand at 10 Gev	120 kW
Peak RF power demand at 10 GeV	425 kW
Average power rating of each klystron	50 kW

Vacuum System

Base pressure required for 25% loss	10^{-3} torr
Actual pressure in magnets	5×10^{-6} torr
Pressure at linac sections	10^{-6} torr
Number of diffusion pumps	96

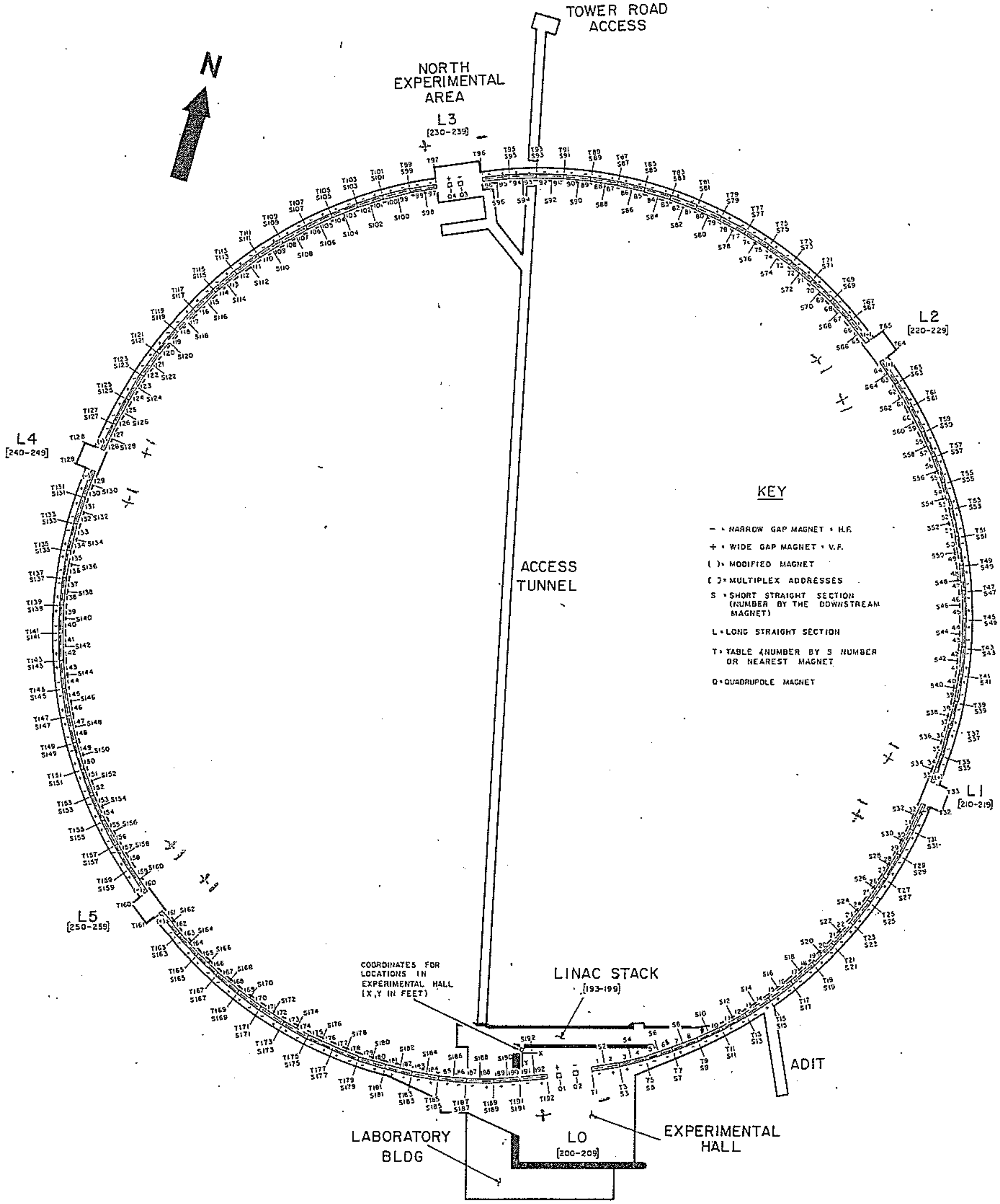
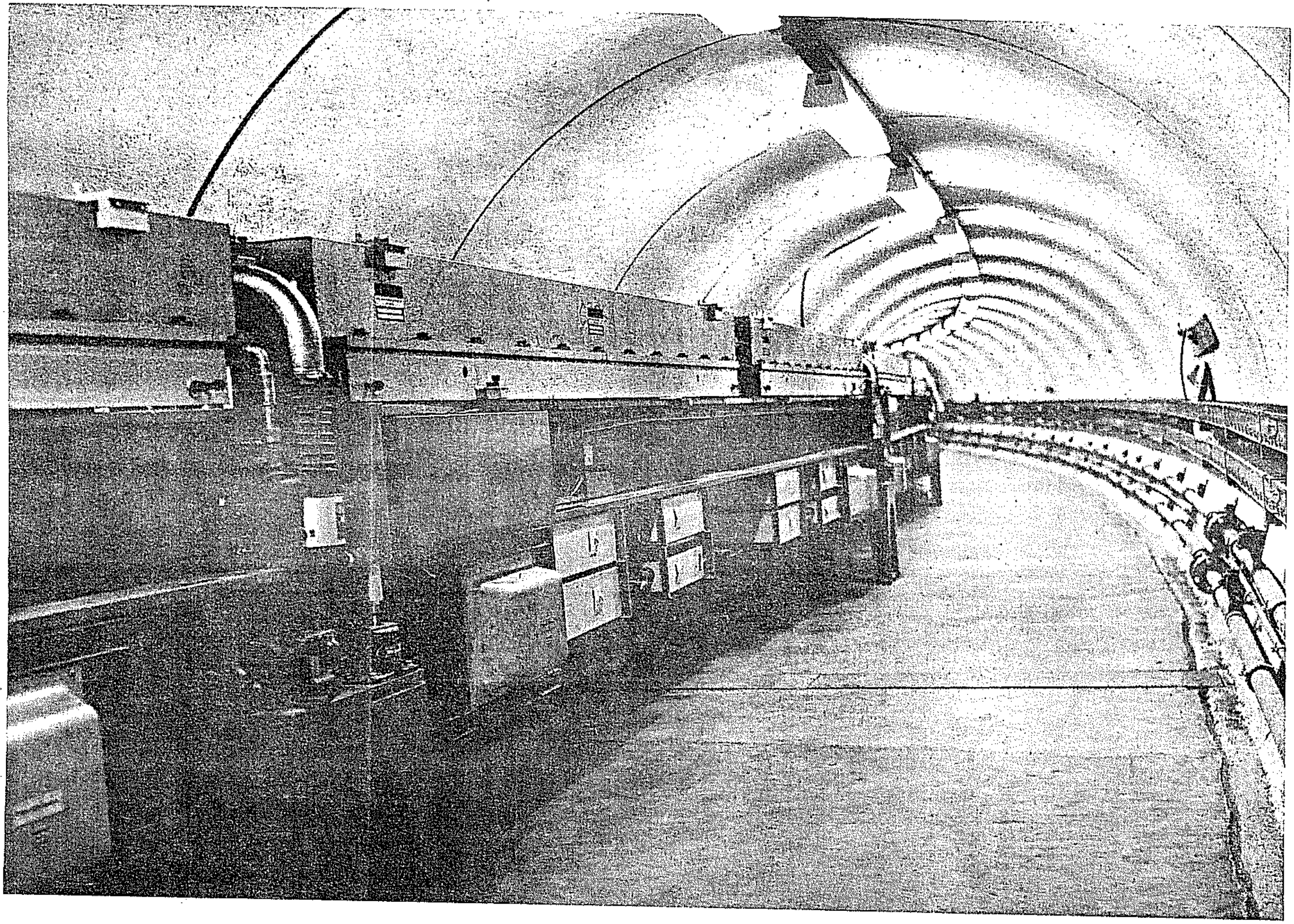

TOWER ROAD ACCESS
N
NORTH EXPERIMENTAL AREA
L3 [230-239]
L2 [220-229]
L1 [210-219]
L4 [240-249]
L5 [250-259]
ACCESS TUNNEL
KEY
— = NARROW GAP MAGNET + H.F.
+ = WIDE GAP MAGNET + V.F.
( ) = MODIFIED MAGNET
[ ] = MULTIPLEX ADDRESSES
S = SHORT STRAIGHT SECTION (NUMBER BY THE DOWNSTREAM MAGNET)
L = LONG STRAIGHT SECTION
T = TABLE (NUMBER BY S NUMBER OR NEAREST MAGNET
Q = QUADRUPOLE MAGNET
COORDINATES FOR LOCATIONS IN EXPERIMENTAL HALL (X,Y IN FEET)
LINAC STACK [193-199]
ADIT
LABORATORY BLDG
LO [200-209]
EXPERIMENTAL HALL
Q1
Q2
Q3
Q4

Fig. 1a



View of installed magnet modules in east half of 10 GeV synchrotron tunnel.

Fig. 1b

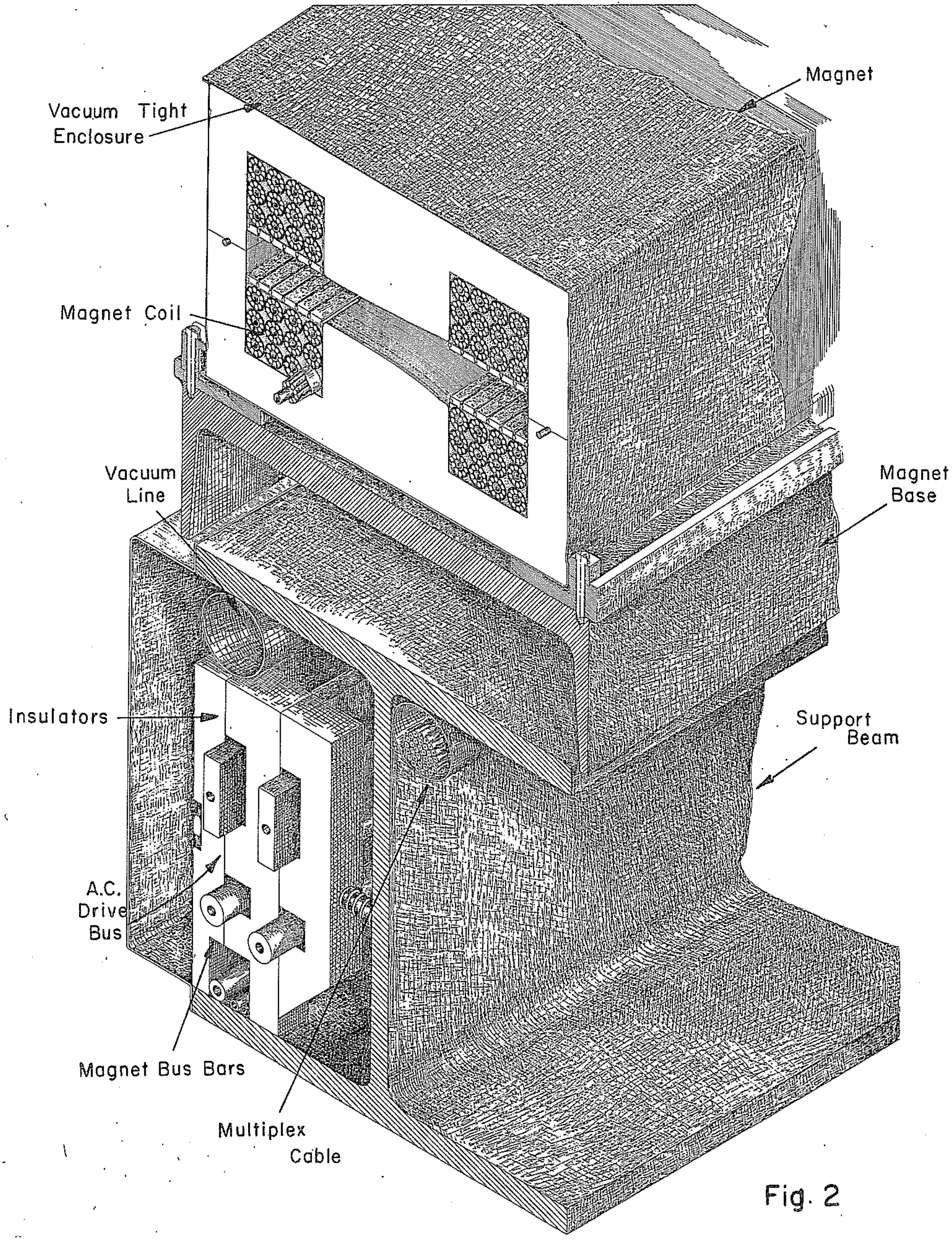


Fig. 2

Cross-Section of a Synchrotron Magnet Unit

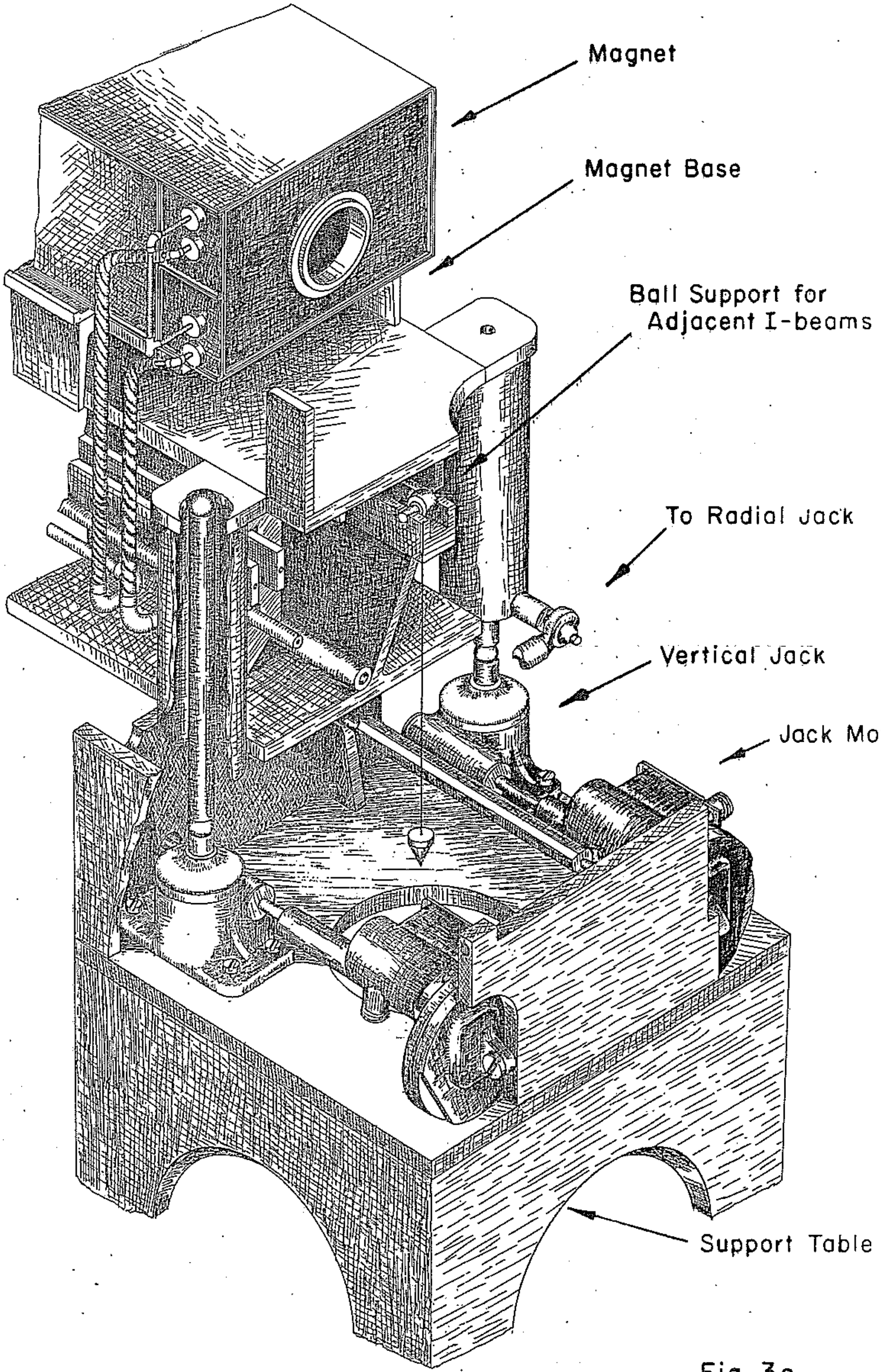

Magnet
Magnet Base
Ball Support for Adjacent I-beams
To Radial Jack
Vertical Jack
Jack Motor
Support Table

Fig. 3a

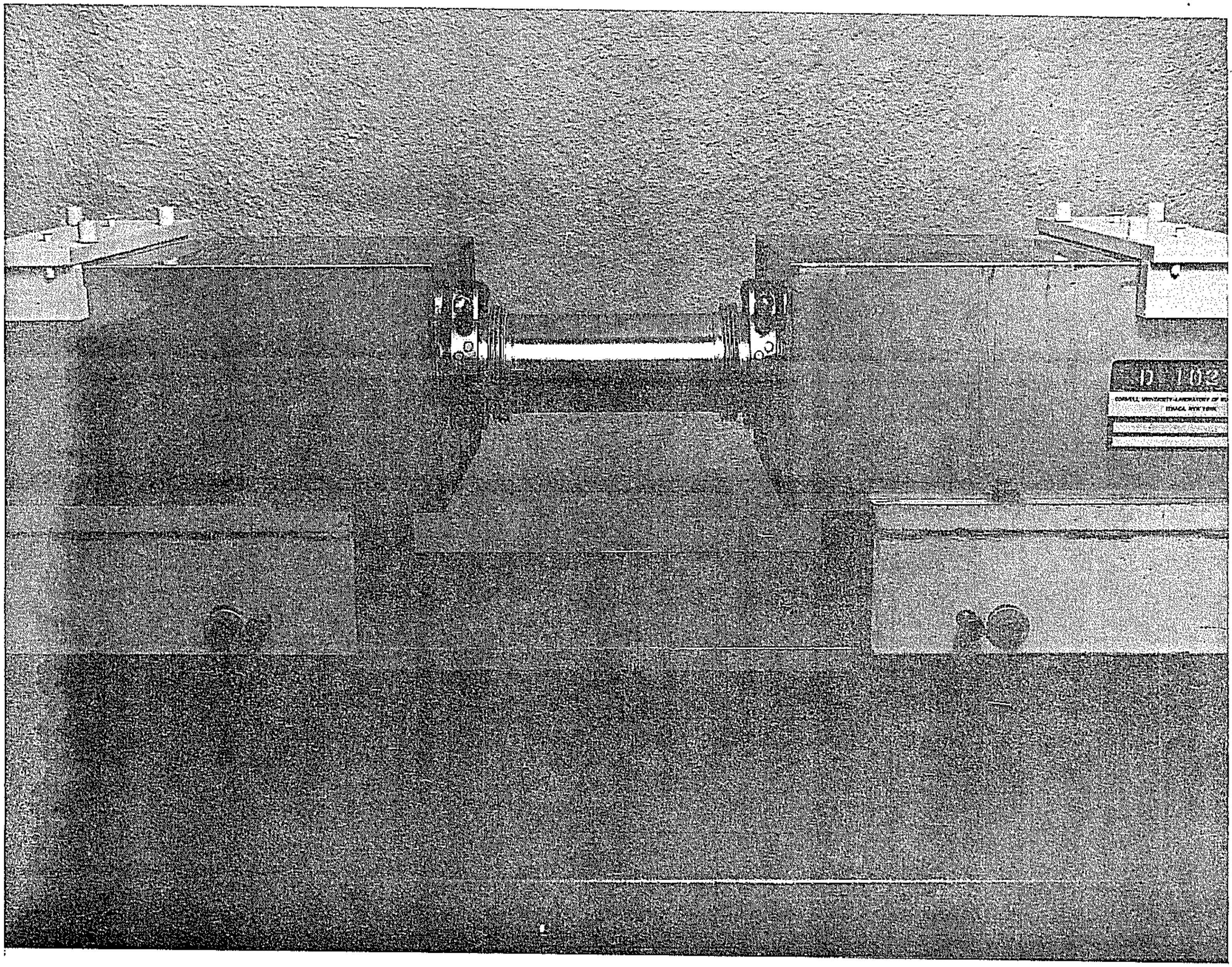


Fig. 3b

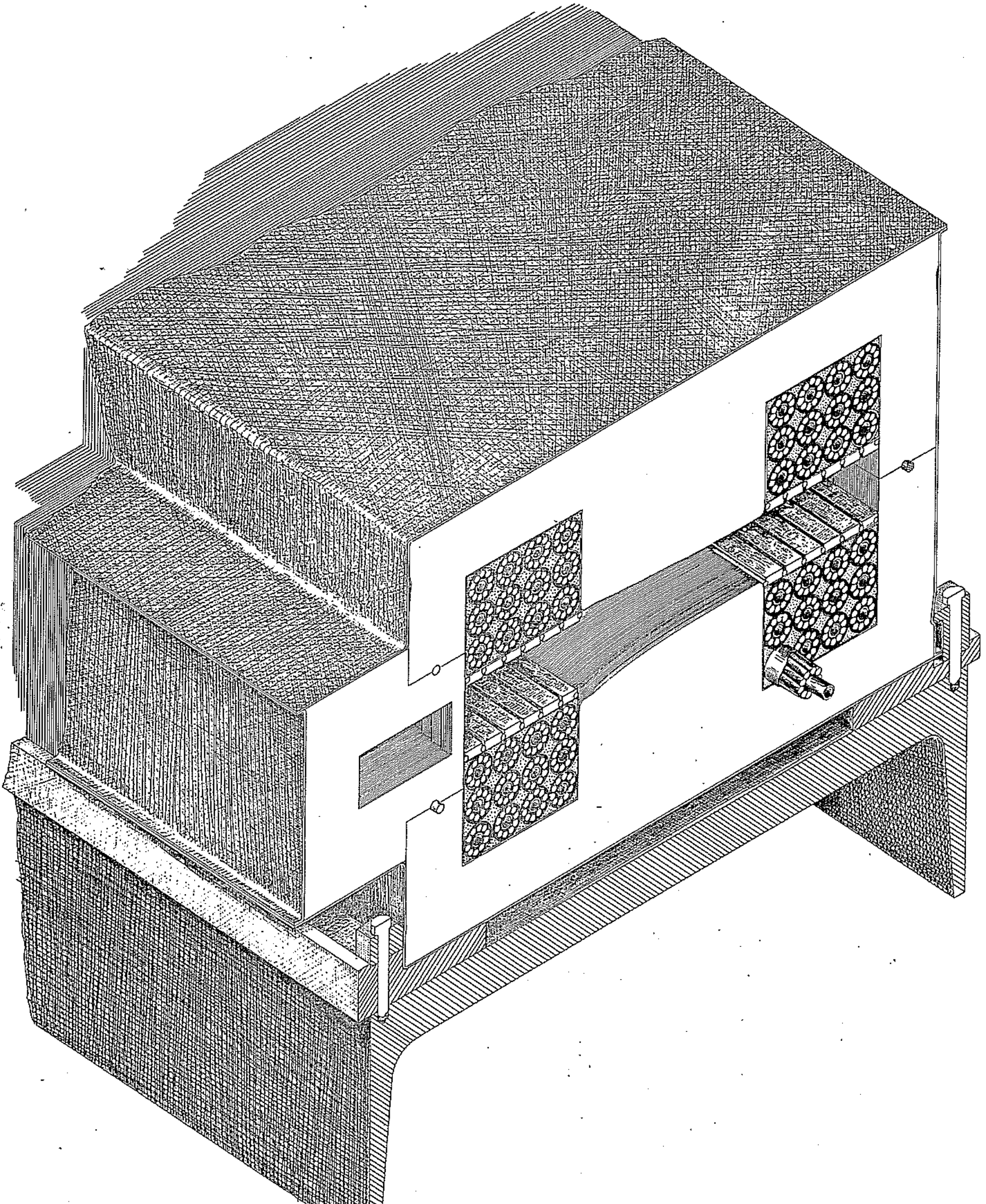


Fig. 4

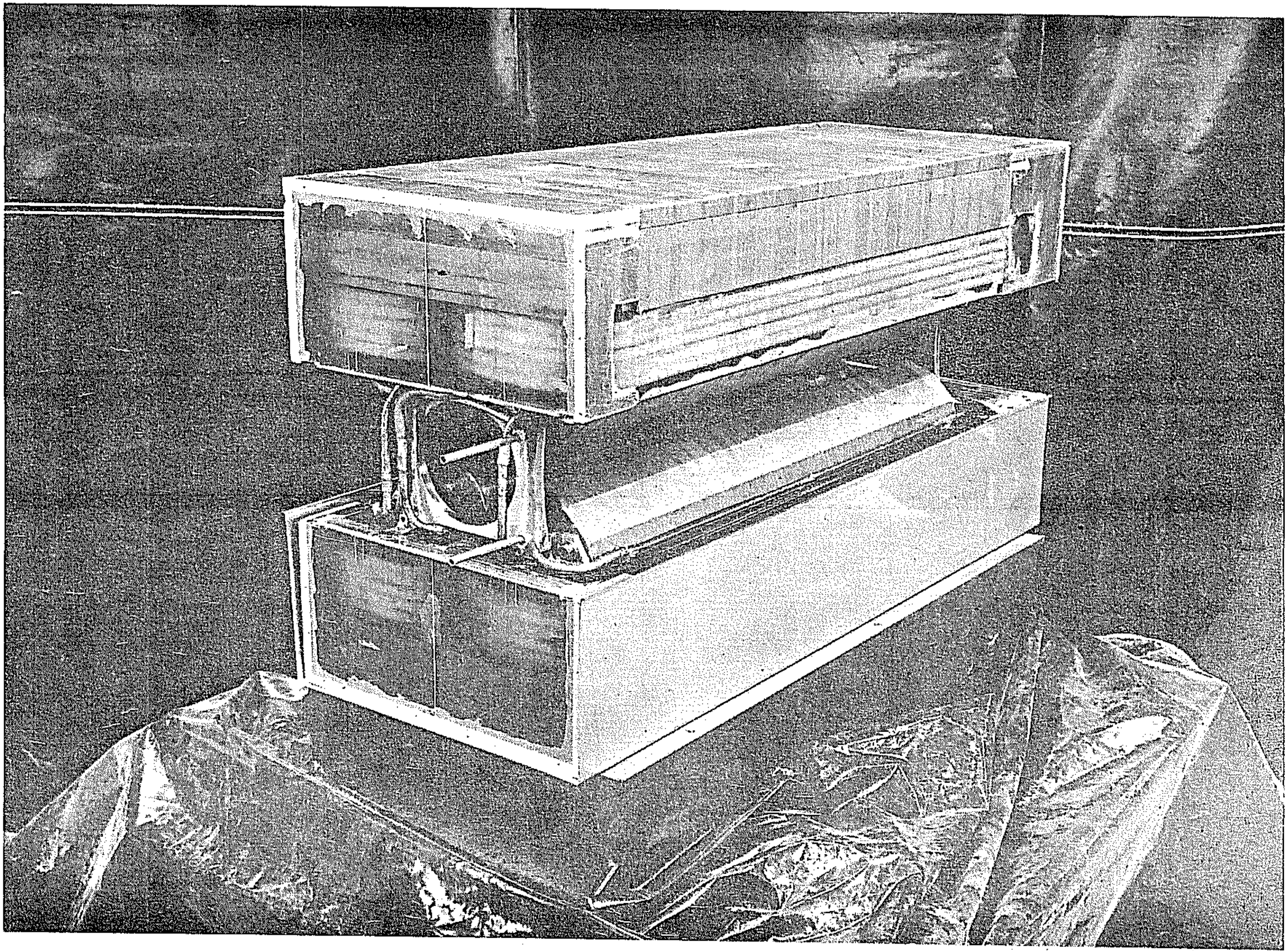


Fig. 5a

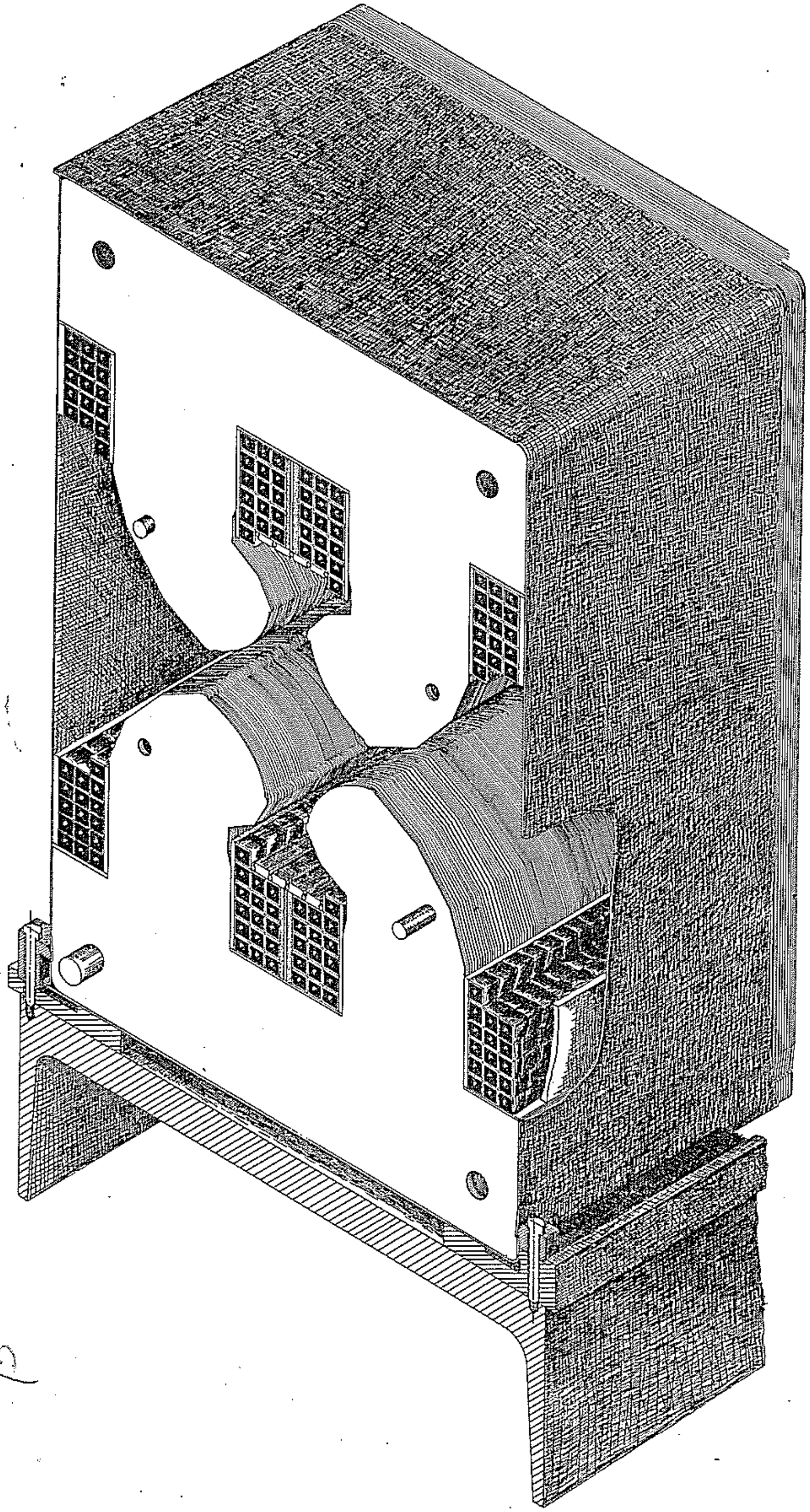


Fig. 5b

Resonance Lines Near
$\nu = 10^3/4$

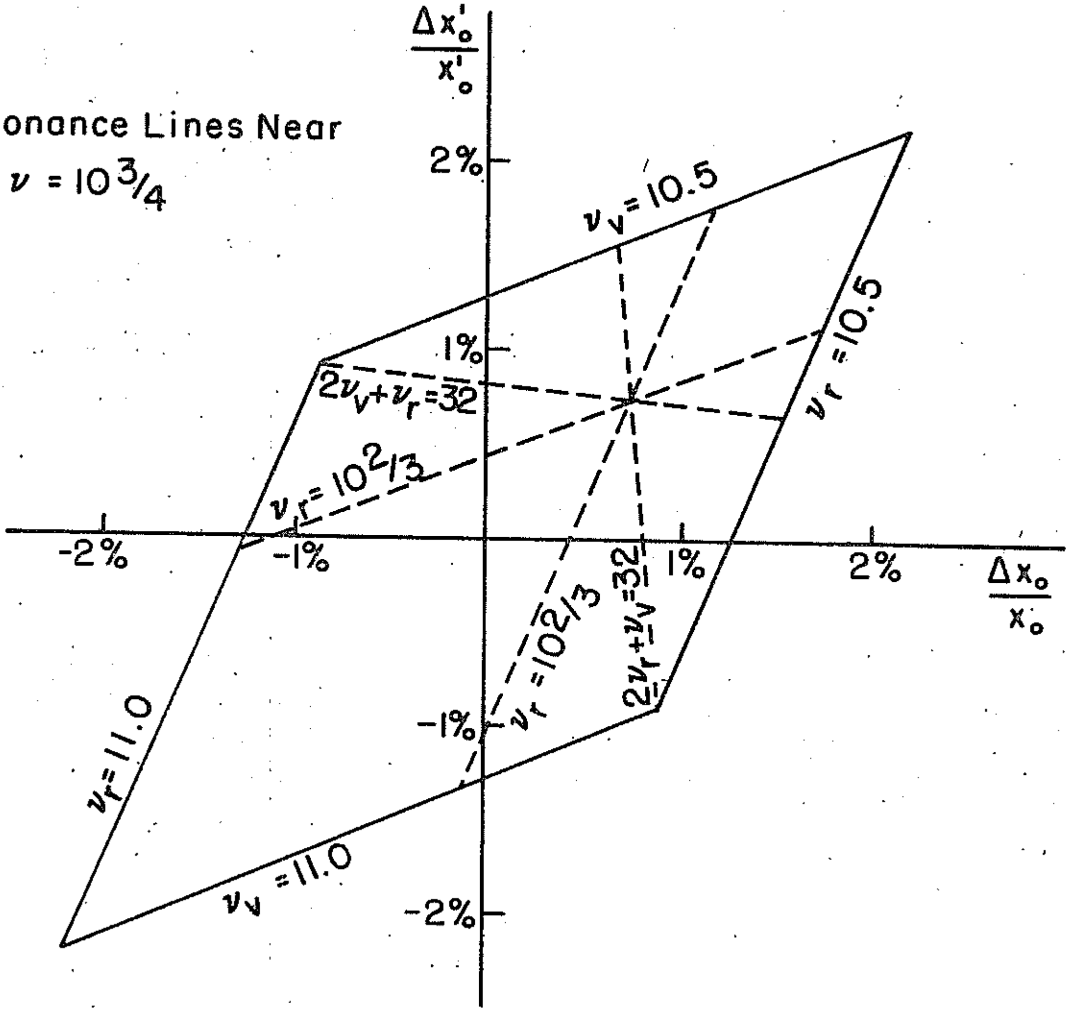


Fig. 6

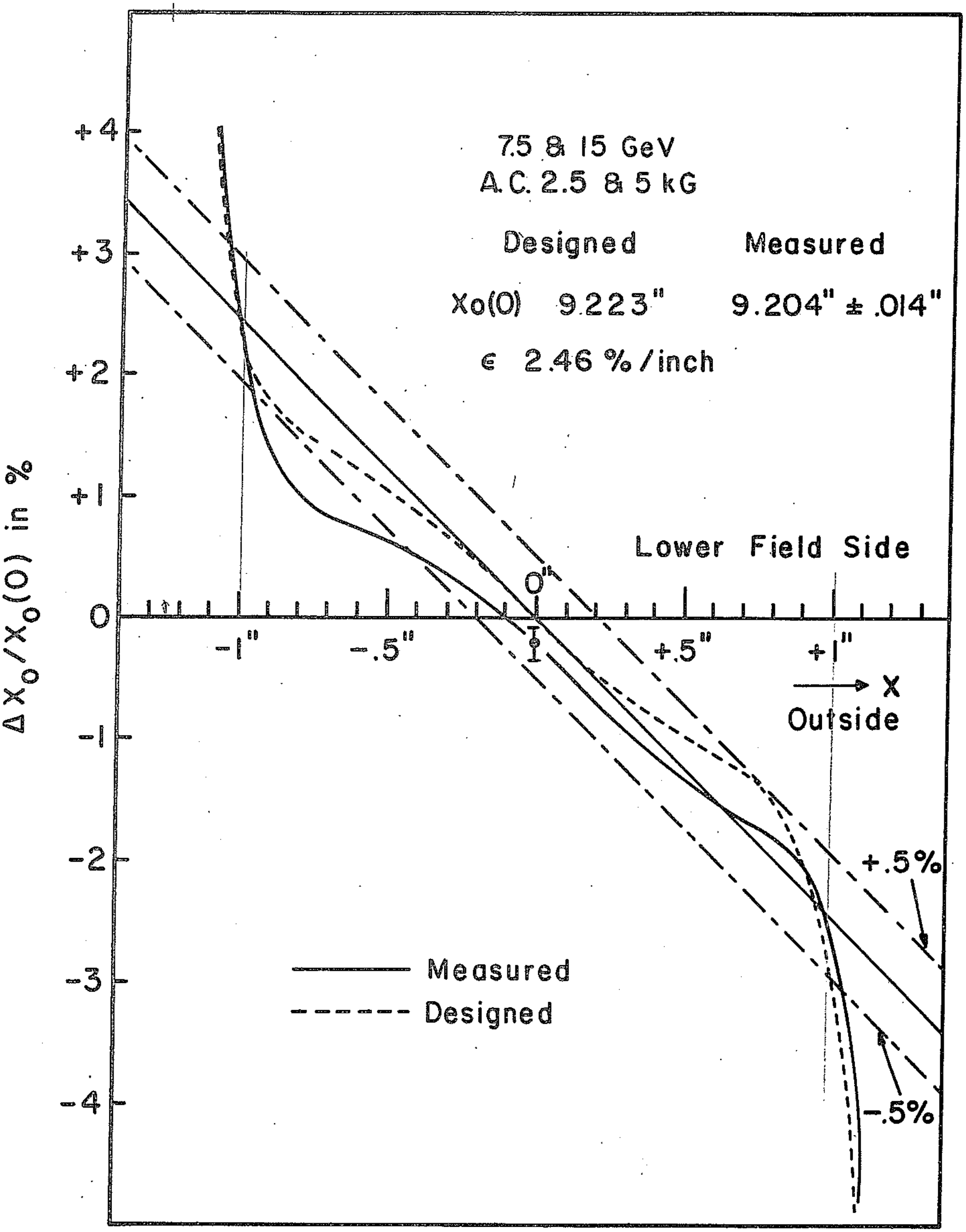


Fig. 7a. $X_0(X)$ Distribution of Wide Gap Magnet

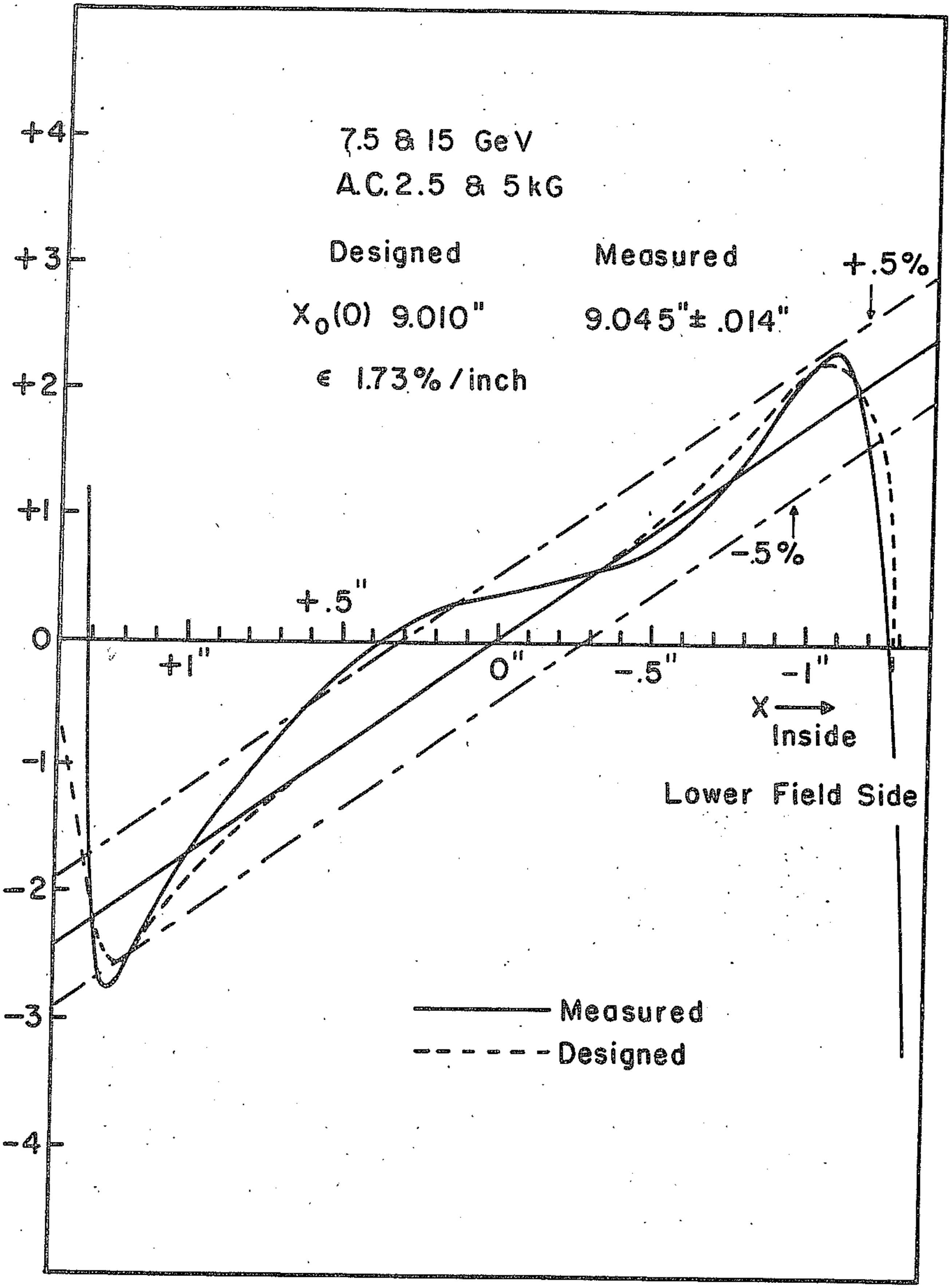
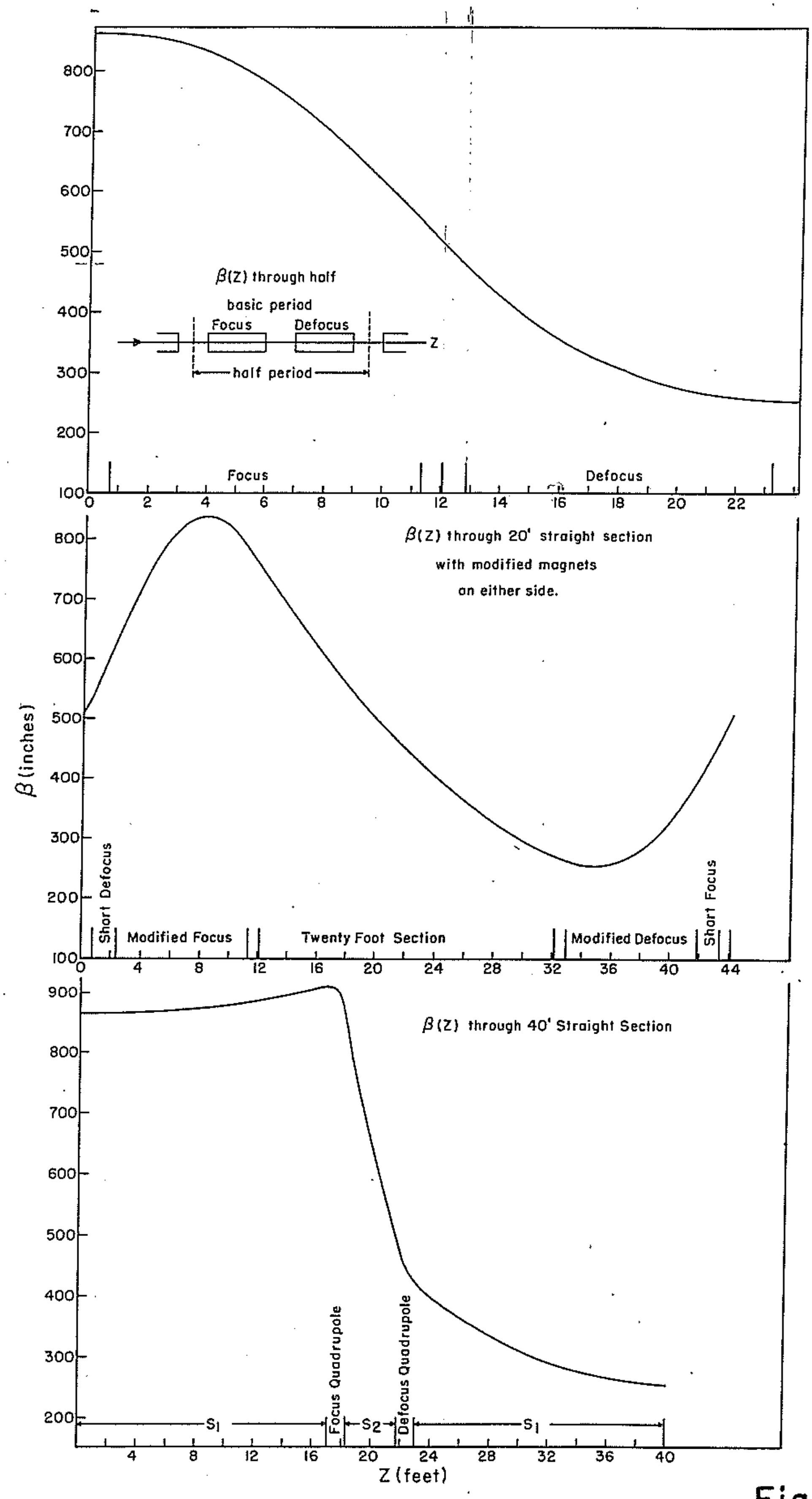
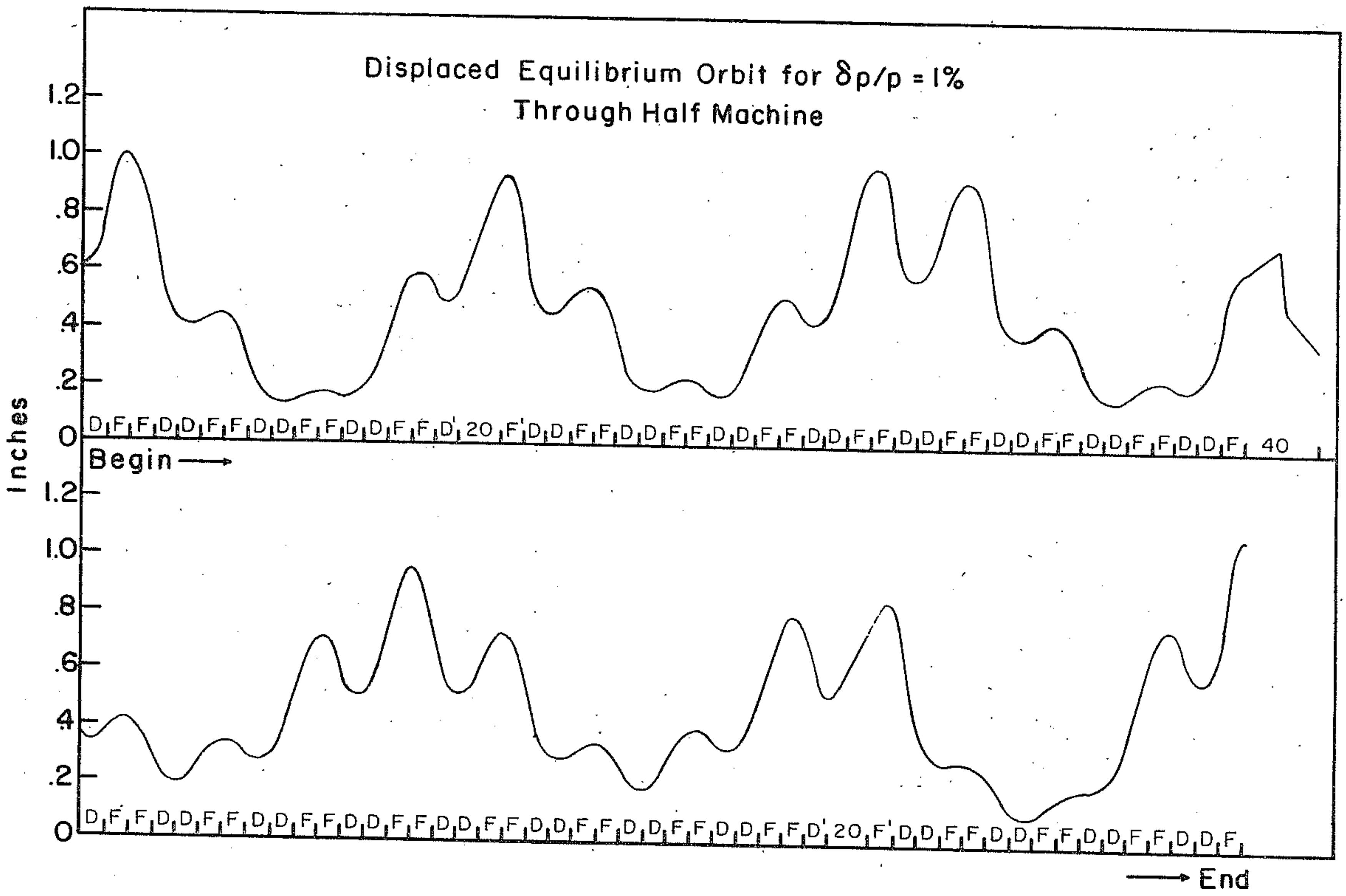


Fig. 7b. X (X) Distribution of Narrow Gap Magnet



$\frac{d\beta}{dz} \simeq \frac{875}{16' \times 12''} =$

Fig. 8a



Displaced Equilibrium Orbit for $\delta p/p = 1\%$
Through Half Machine

Fig. 8b

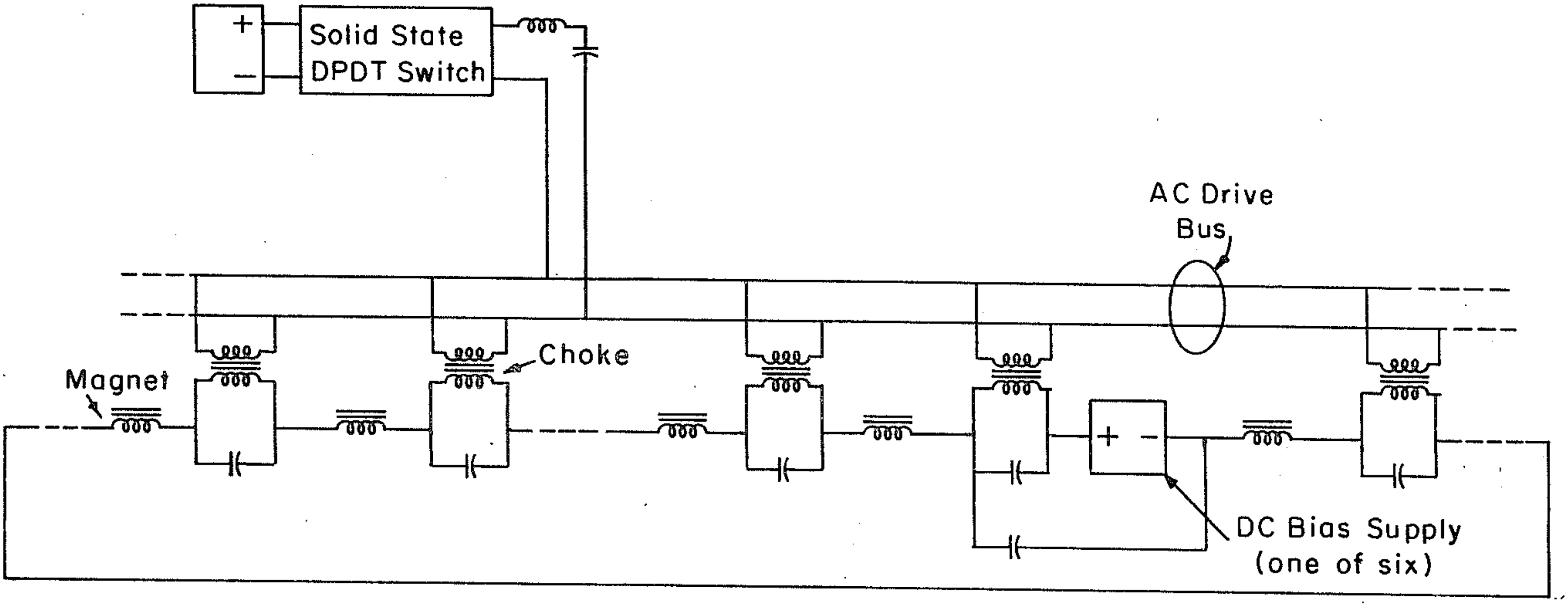

+
−
Solid State
DPDT Switch
AC Drive
Bus
Choke
Magnet
+ −
DC Bias Supply
(one of six)

Fig. 9

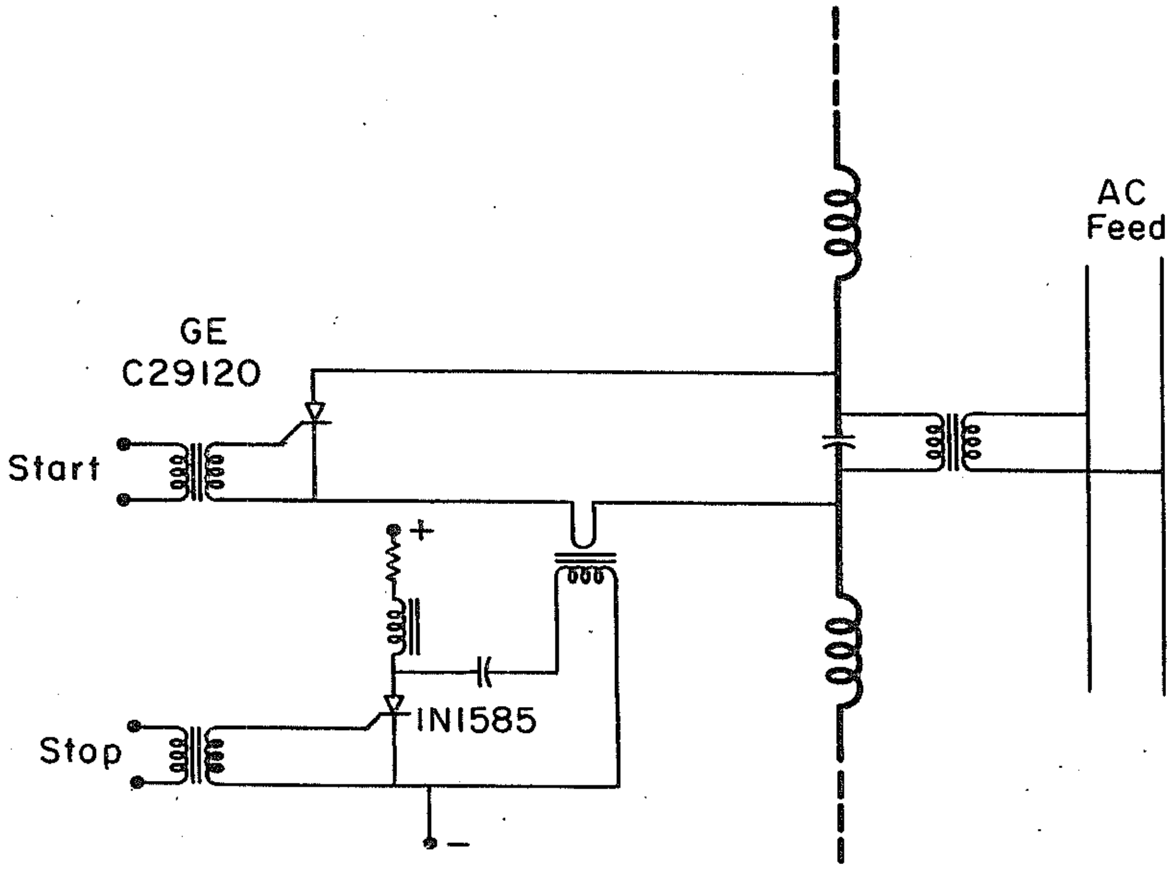
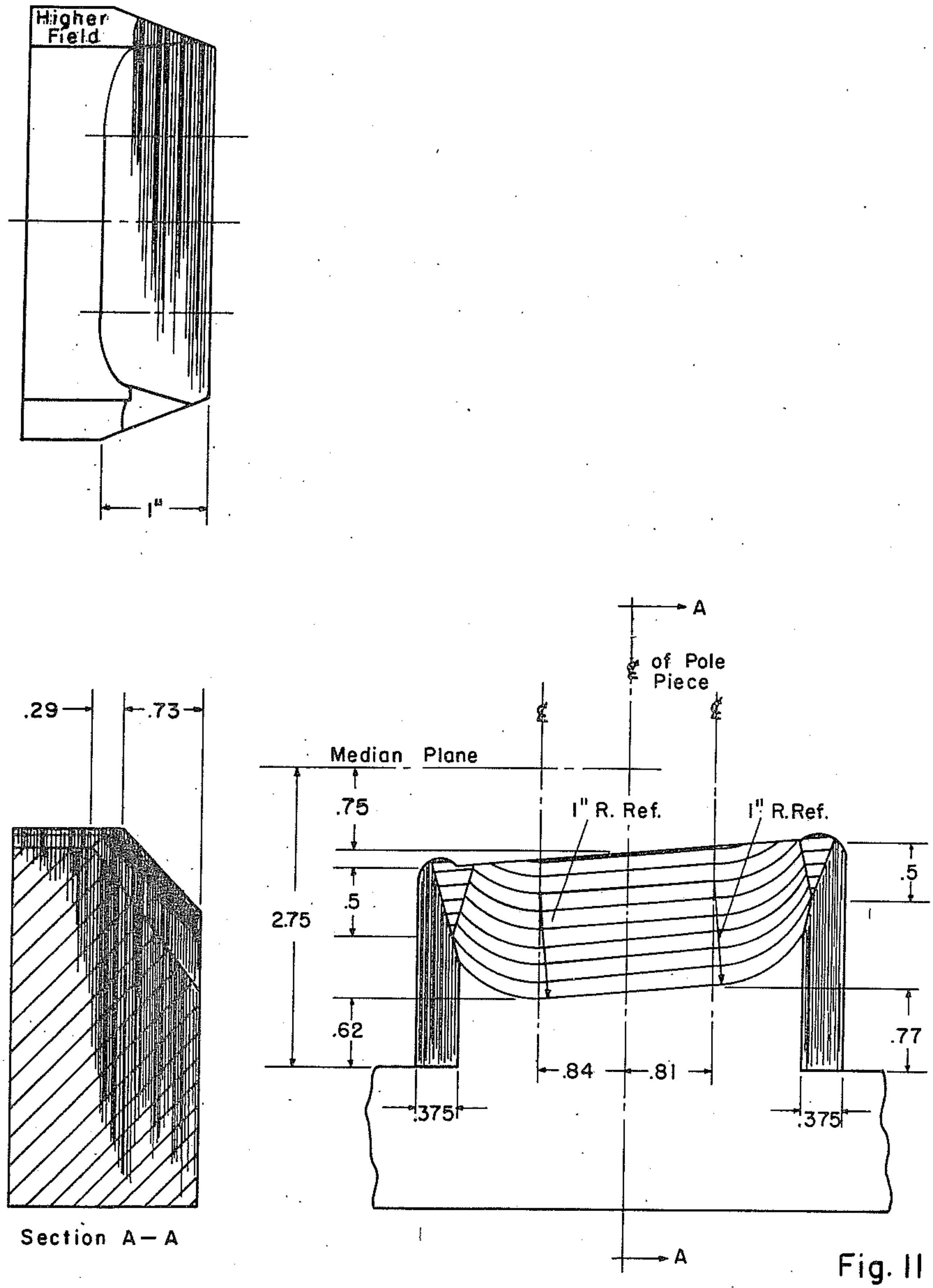


Fig. 10



Section A—A

Fig. 11

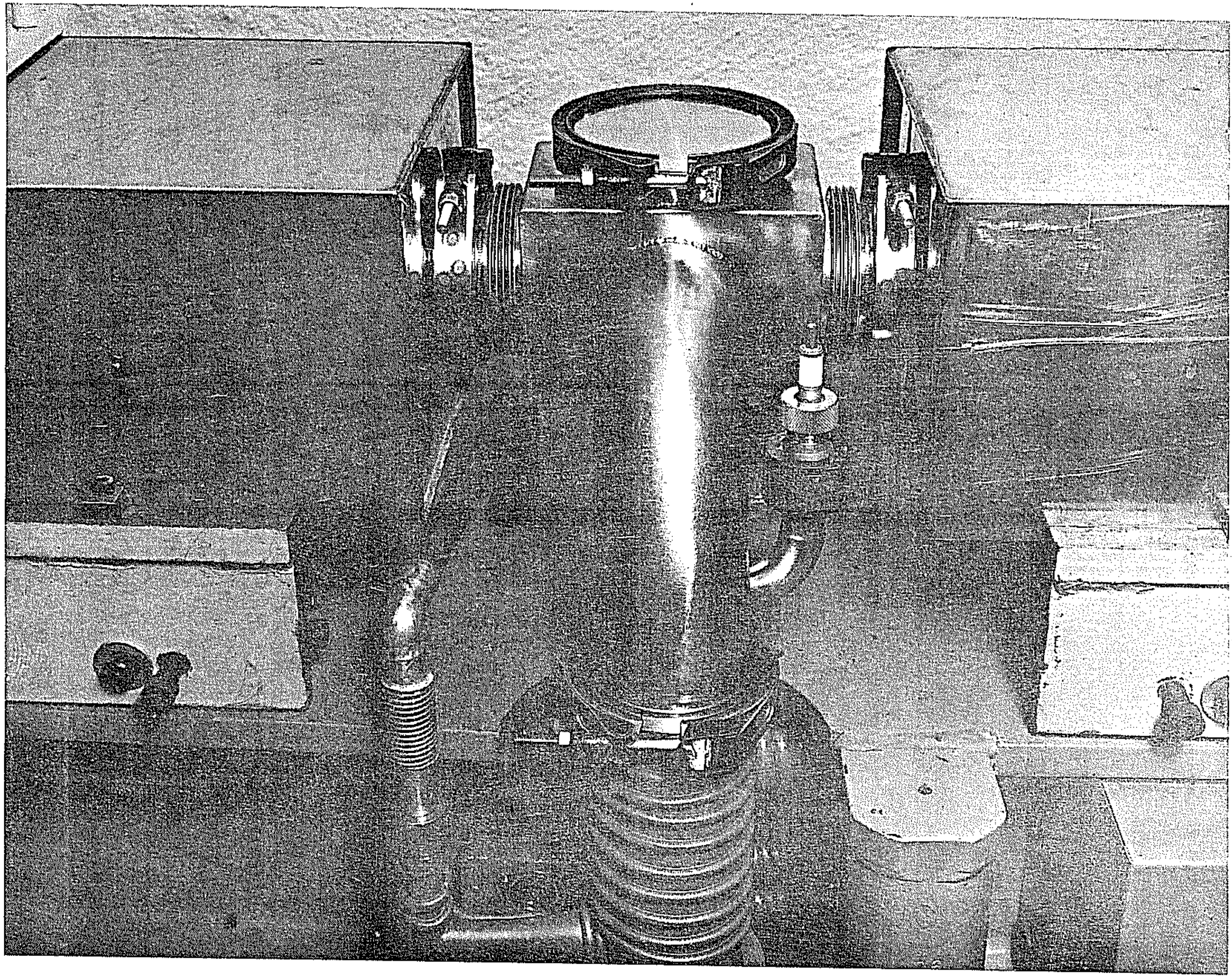


Fig. 12

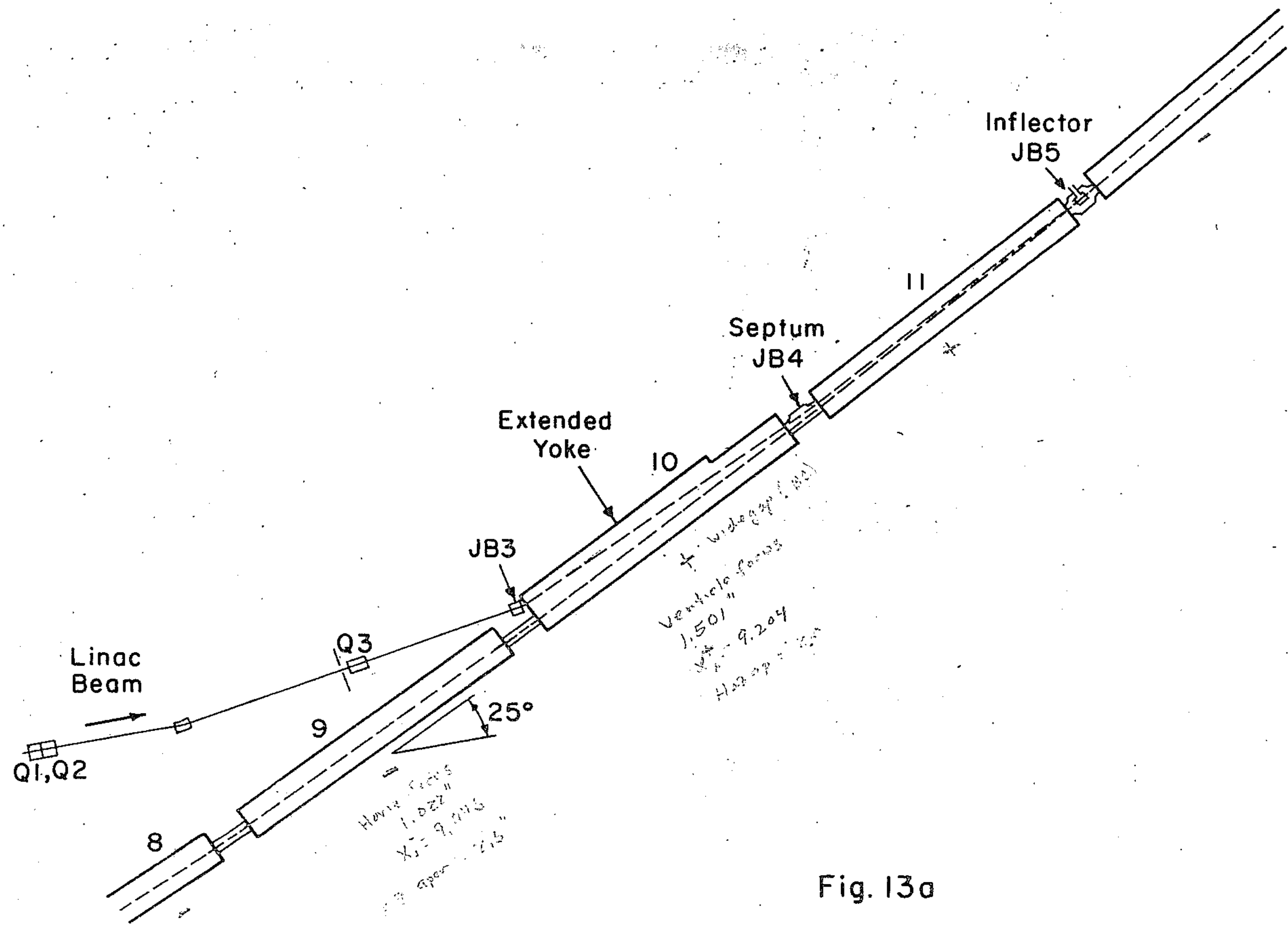

Inflector
JB5
11
Septum
JB4
Extended
Yoke
10
JB3
Q3
Linac
Beam
Q1,Q2
9
8
25°
+ widegap (.85)
Vertical focus
1.501"
9.204
Horiz focus
1.022"
X = 9.
ap
.75"

Fig. 13a

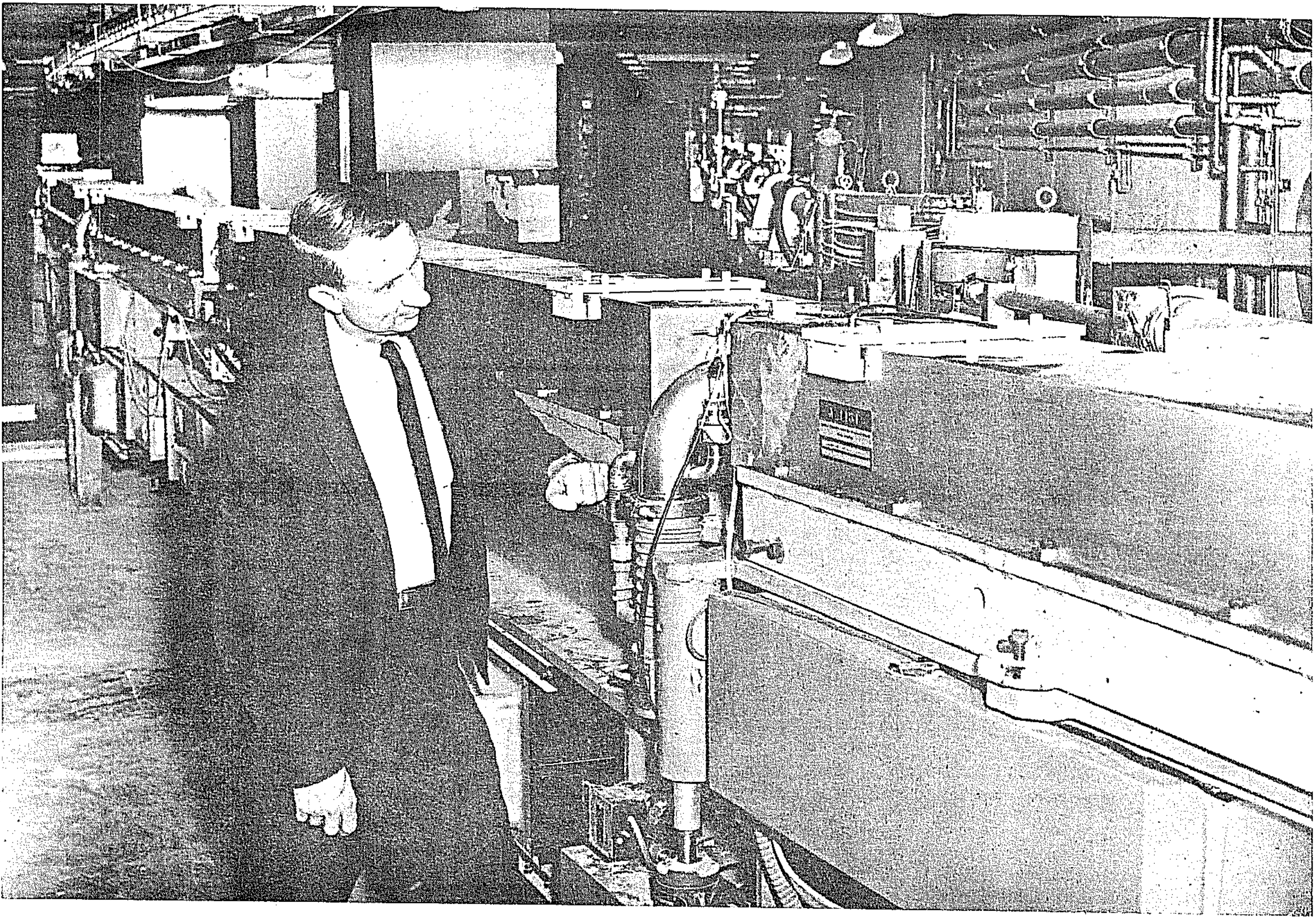


Fig. 13b

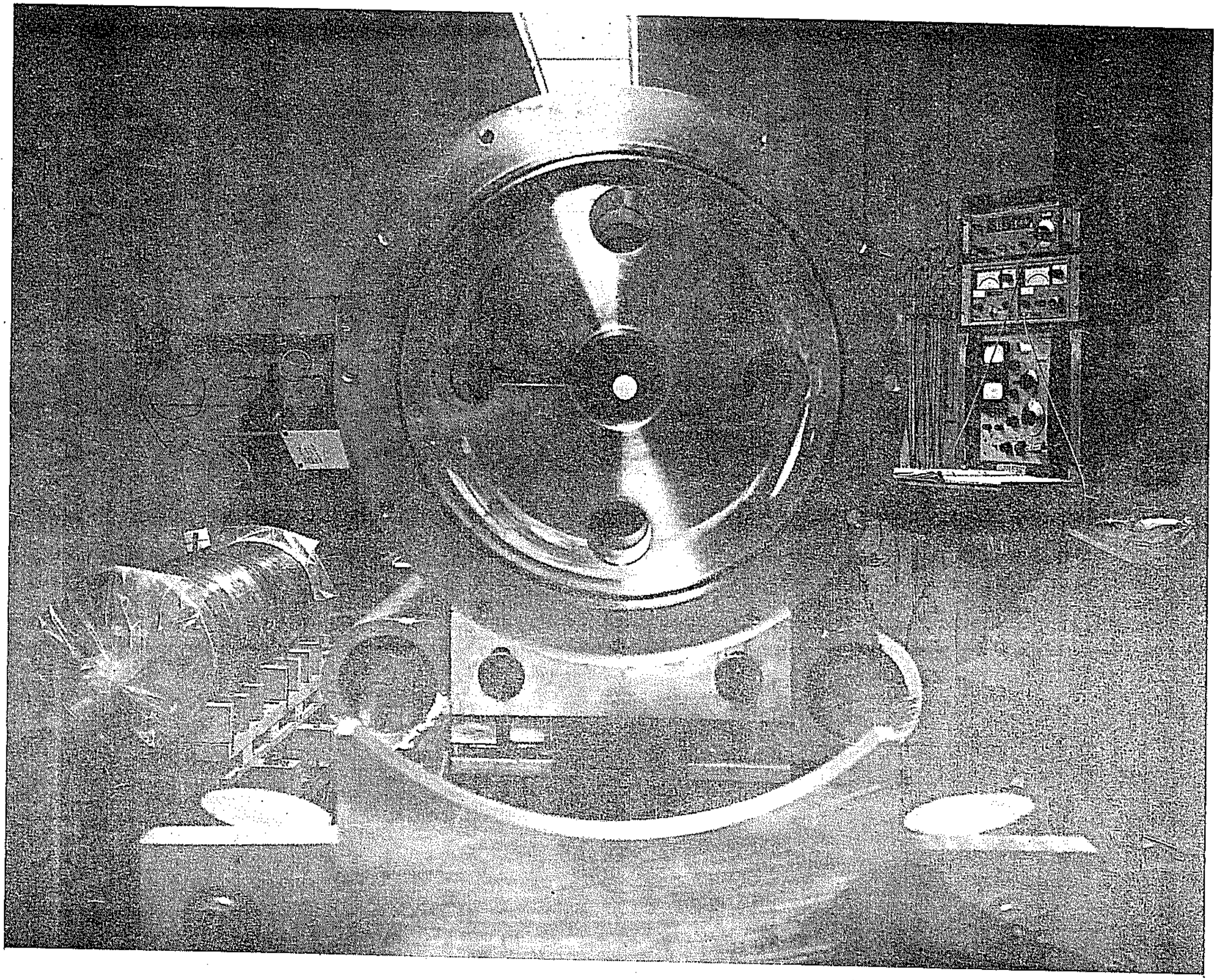


Fig. 14a

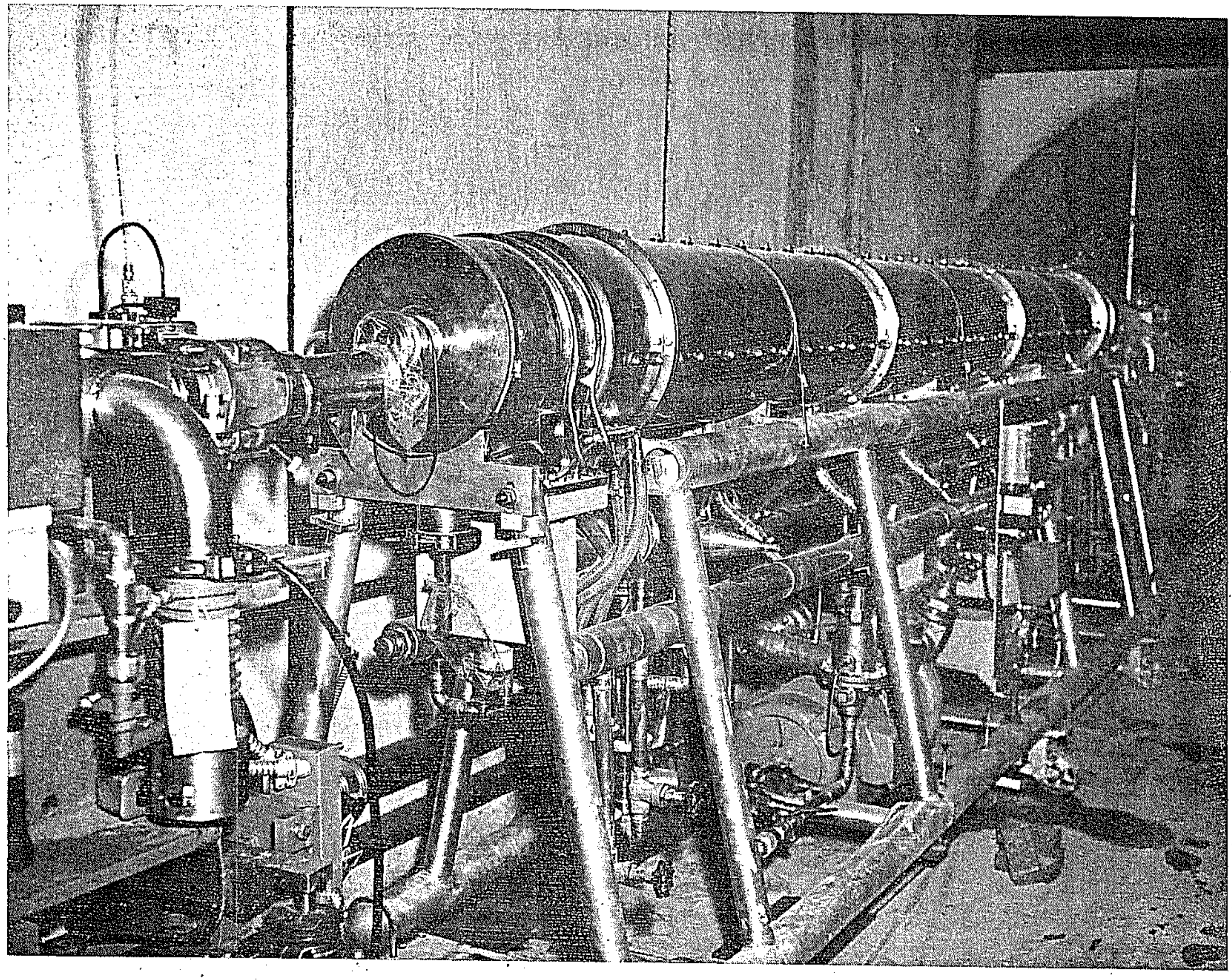


Fig. 14b

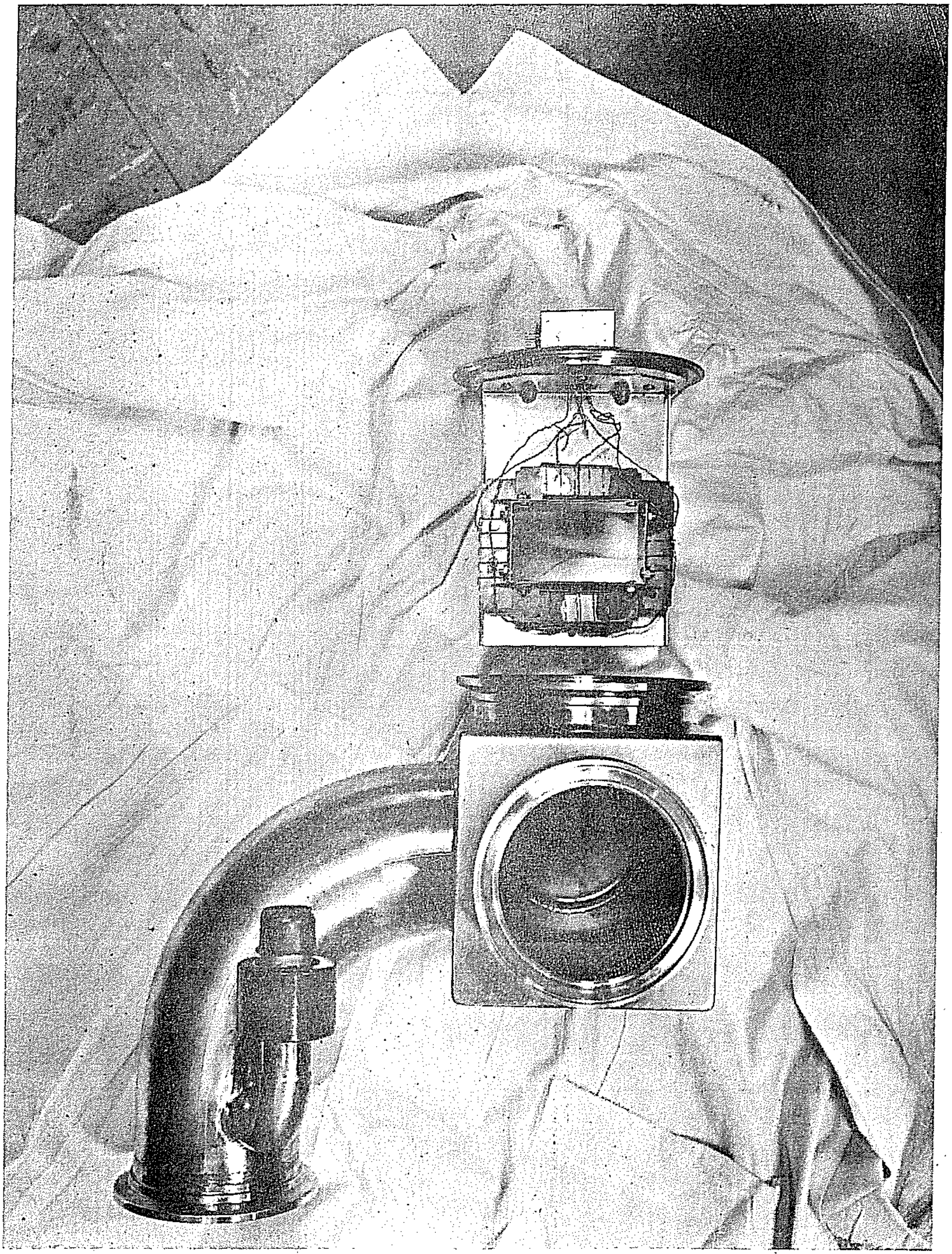


Fig. 15

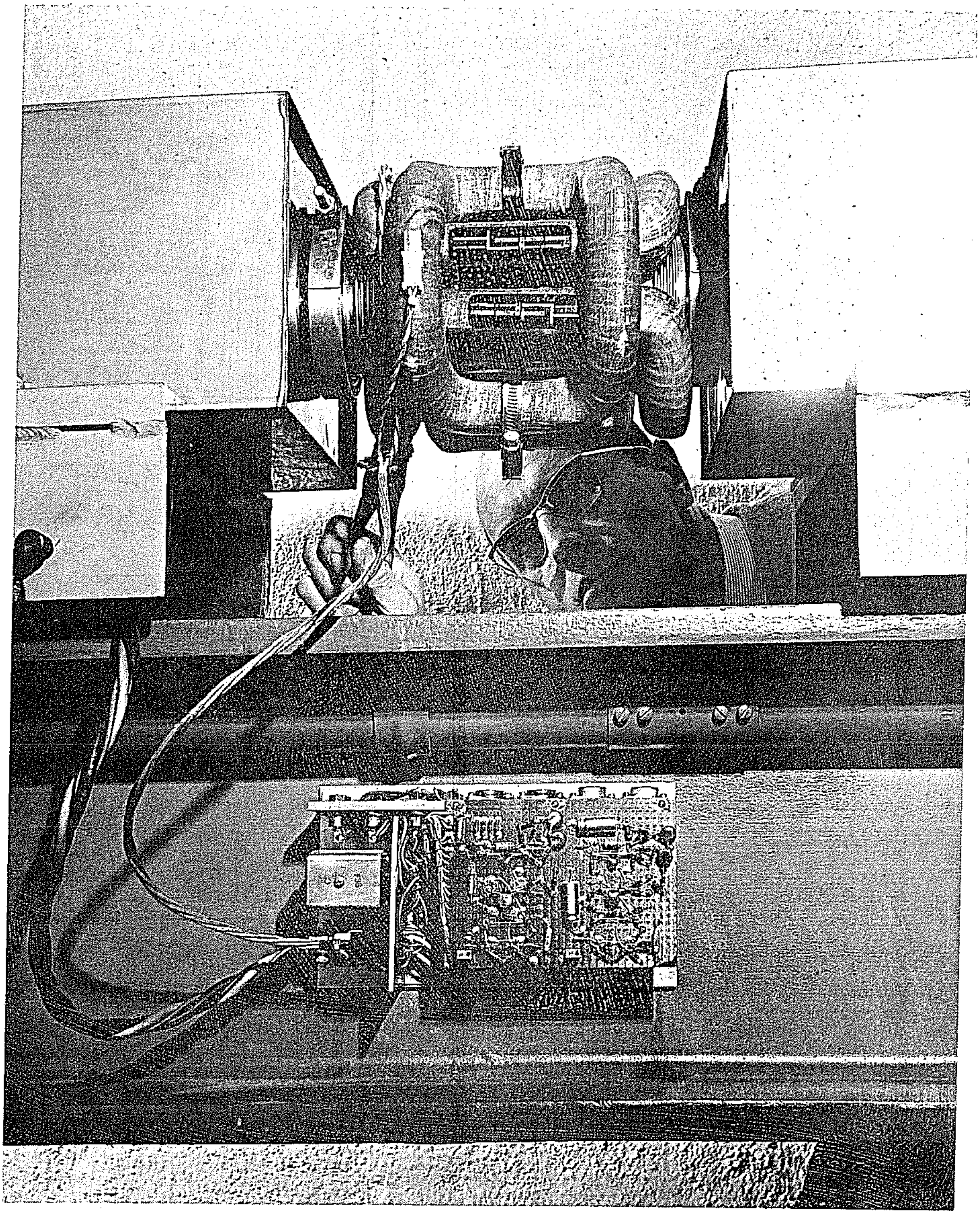


Fig. 16

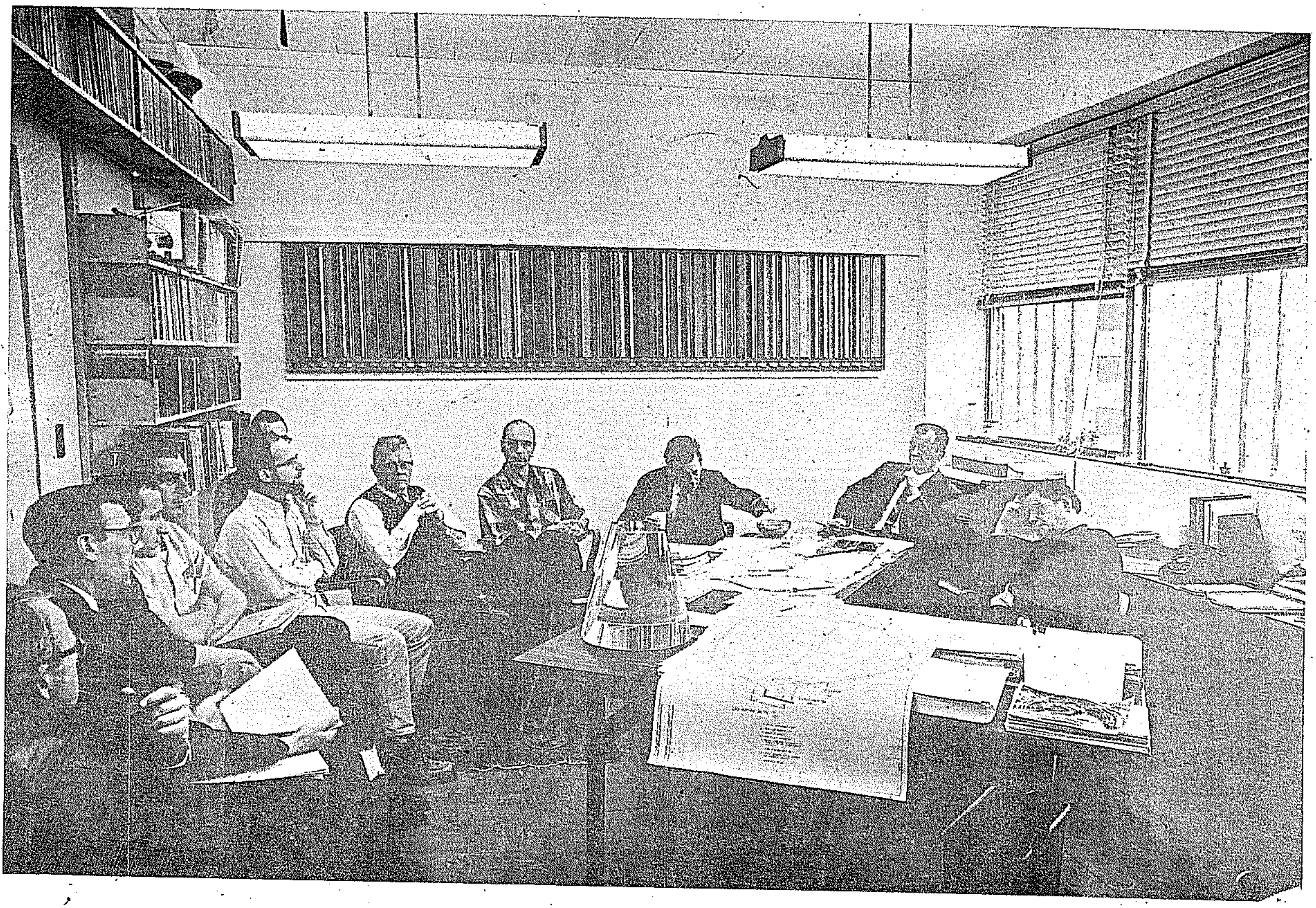


Fig.17 From left are shown D. Edwards, R. Bower, E. von Borstel, K. Loveless, D. Rust, C. Kellers, J. DeWire, R. Littauer, W. Woodward, R. Matyas, R. Wilson.