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DESIGN AND CONSTRUCTION OF THE BEVATRON QUARTER SCALE OPERATING MODEL

W. M. Brobeck

August 22, 1949

Berkeley, California

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DESIGN AND CONSTRUCTION OF THE BEVATRON QUARTER SCALE OPERATING MODEL

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Basis of Design

In July 1948 there were several basic questions regarding the design of the Bevatron on which information was lacking or on which the available information was not very encouraging. There was no doubt of the validity of the synchrotron principle which had been proved by the 37 and 184 inch cyclotrons and the synchrotron of the General Electric Company at Schenectady. However, the interrupted or "racetrack" type of magnetic field which had been used only in the electron synchrotron being completed at the University of Michigan had not yet been tested and the failure to find the beam on the Berkeley synchrotron threw much doubt on the calculations of the requirements of aperture and uniformity of the magnetic field. The state of the Bevatron design at the time provided for a maximum aperture of 4 by 14 feet with an attainable energy of 1.4 billion electron volts to be reduced if performance was satisfactory to an eventual 1 x 4 feet with which 6 Bev might be obtained. In addition the eventuality of having to close up the racetrack to form a complete circle was to be provided for. The cost of these changes in the full scale machine was obviously very great and it was realized that if a test of the design could be obtained quickly enough the cost of the test model might be more than repaid in avoiding a later conversion of the full size machine. On the other hand, if the most pessimistic indications proved true the saving would be considably greater.

The model was planned to have a rate of rise of magnetic field and magnet lamination thickness equal to those of the full size machine. Space was available for a machine of one quarter linear scale and the weight of iron of $1/64 \times 9000 = 140$ tons

was quite reasonable. The peak KVA required, however, would have been 1/64 x 100,000 = 1600 and the coil cooling for a reasonable repetition rate would have been a considerable problem if the full scale field were to have been obtained. It was agreed that all of the important questions could be answered if the beam were accelerated for only a few phase oscillation periods which are the order of a millisecond. Accordingly, the maximum field was taken as 1000 gauss which provides about 200 milliseconds acceleration after injection and made possible the use of an existing DC flywheel generator installed for cloud chamber magnet excitation. The model aperture was based on the 4 x 14 ft. full scale value to give the greatest flexibility. Provision was to be made for restricting the aperture after a beam was obtained.

In at least two respects the operation of the model was expected to be more difficult than that of the full scale machine. These concerned gas scattering and the small radial motion per turn at injection. Scattering calculations indicated a loss of about 96 percent of the beam at 10^{-5} mm. pressure compared to a negligible loss full scale for the 4 x 14 ft. aperture. To meet the scattering problem the injection energy was made somewhat higher than the value corresponding to the full scale magnetic field at injection. The vacuum pump capacity was made as large as possible and a liquid nitrogen cooled trap was provided for the full length of the vacuum tube. This, with the realization that the beam could be followed from immediately after injection and its decrease due to scattering allowed for, appeared to remove the scattering problem as a determining factor. The radial motion per turn with the accelerating voltage off in the model is 0.012 inches compared to 0.12 inches full scale. It was first thought that this might greatly reduce if not eliminate the beam that would clear the injecting electrode. Several schemes for moving the beam radially more rapidly than provided by the rising field were proposed, some of which might be practical but

this problem was made to appear much less important after Gluckstern calculated the fraction of the injected beam which should clear the injector taking into account the actual positions of the ions due to their radial and vertical oscillations as they passed the injector on successive turns. He estimated that approximately 5 percent of the injected beam should be accepted. The importance of these questions arose from the danger that lack of success with the model might discourage the construction of a larger machine in which these problems might not have arisen.

At the time of starting the design of the model an injector of the Van de Graaff type appeared most suitable for the full size machine due to its well focussed beam. To obtain this same advantage at lower energy an ion gun to accelerate 500 Kev protons was planned. The ion source and accelerating tube design of the Van de Graaff used with the linear accelerator was to be followed. The cyclotron had been considered for an injector since the start of the bevatron project but as far as was known no reasonably well focussed beam of useful size had ever been obtained from such a machine. Plans had been made for some time to build a cyclotron for test of focussing methods using an existing magnet and in November such tests were begun under the direction of Lofgren. By the end of the year results were so encouraging that it was decided to change from the d.c. injector to a small cyclotron capable of energies up to 1 Mev.

Specifications

The principal specifications of the model and those of the full size machine as planned when the model was being designed are listed in Table I.

Schedule and Dates

Decision was made to build the model on July 20, 1948. A primary requirement was that the model be completed and ready to test soon enough to avoid delay in the construction of the full size machine. The schedule for the latter, determined

mainly by the site preparation and building construction, permitted changes in design based on the model results up to July, 1949. To allow some time for testing, construction of the model was to be complete in ten months, i.e., by May 20, 1949. The construction schedule called for completion by April 1, 1949, to allow some margin for contingencies. A detailed schedule was laid out and progress reviewed weekly.

Principal dates of the project are the following:

Decision to build model	July 20, 1948
Building structure order placed	August 30, 1948
Building foundation order placed	September 23, 1948
Magnet erection started	November 12, 1948
Building completed	November 16, 1948
Coil winding started	November 22, 1948
First quadrant excited	December 20, 1948
Complete magnet excited	January 14, 1949
First half quadrant under vacuum	January 20, 1949
Complete system under vacuum	March 25, 1949
Decision to build injector cyclotron	January 7, 1949
First attempt to find cyclotron beam	April 1, 1949
Beam obtained from cyclotron	April 2, 1949
First attempt to find bevatron beam	April 26, 1949
Beam obtained from bevatron	April 30, 1949

The change in the plans for the injector was made when the assembly of the ion gun was practically completed in the shop. This change probably added a month to the completion time for construction but may have shortened the overall time to obtain a beam.

Magnet

As in the case of all the mechanical design of the model the design details

were merely scaled down from what had been planned for the full scale machine with no attempt to determine the most economical design for a smaller accelerator. Air cooling for the coils was shown to be adequate for the required average dissipation of 30 KW. Because of the low field, magnetic forces were negligible and only the bracing required to support the dead weight and ensure accuracy of location was necessary.

It was decided early in the job to build a twenty degree section of the magnet for test as soon as possible using the laboratory shop facilities. This magnet proved valuable as practice in mechanical construction and coil winding, as well as providing information on the magnetic field.

The magnet is built up of slabs consisting of 1/2 inch plates bolted together. Bolts, bolt insulation and washers designed for the full size machine were used without change. .020 inch cardboard was used for insulation between the plates and the slabs were assembled in two sets of fixtures designed for the purpose. There was considerable difficulty with short circuits between plates in the 20 degree section. This was largely eliminated by allowing the paper to protrude between the plates on the unfinished edges and by dipping each slab in varnish. It was necessary to check each slab for shorts just before dipping and several times later during assembly. Most of the shorts could be easily cleared but after completion about 20 shorts of less than 1 ohm remained in the approximately 5000 plates. These were not considered objectionable as they were randomly distributed.

The slabs were assembled into 72 trapezoidal sectors, the slope of the top and bottom yokes giving a value of n of 0.60 (incidentally a change from 0.73 at which the design was started). This is half as many sectors as planned for the full scale design. In order to improve the space factor which suffered by the proportionately thicker plates the yoke slabs were of two types in which the short plates, which were on the outside of the slabs, ended at different points and so

nested together when the two types were assembled alternately. The steel used was SAE 1010, hot rolled.

The edges of the plates forming the inside surfaces of the yokes and the ends of the legs were machined and the other edges were sheared. Many of the plates were bent when received from the shop and as a result all the plates were put through straightening rollers before assembly. The tapered surfaces of the leg plates gave the expected difficulty in machining but after the use of an inspection fixture built by the laboratory the accuracy obtained from the outside shop was almost as good as had been specified.

The magnet sectors are each supported on four jack screws to permit leveling. The jacks are welded to plates cast into the tops of the two concentric concrete foundation walls. The centers of the four quadrants are accurately located by brass plugs cast into the concrete floor and a tram rod used to measure radii from a center carried by a stand located over the quadrant center mark by a plumb bob. The bottom yoke slabs were first set in place and leveled using a height gage at each end to give the proper slope. The leg slabs were then set on the yokes using the tram rod to determine their radius and a gage to center then over the yokes. The yokes and legs were fastened together in each sector and between sectors by bolts passing through holes in two extended plates in each slab. These extended plates were also used for handling the slabs. Most of the alignment adjustments were made by turning screws or nuts and gave no difficulty.

The magnet coils were wound with 350,000 circular mil distribution cable which is expected to have 100 percent salvage value. The design followed that for the full size machine. The cable is supported on maple spacers with vertical bolts clamping the spacer stacks together. There are eight layers of four turns each in the coil and two conductors are connected in parallel to give sixteen effective series turns. The end windings follow the full scale design with vertical 90 degree bends where the coil leaves the quadrant followed by horizontal 90

degree bends into the radial run.

To facilitate assembly the coil spacers were marked with different colors to identify the various types. It was expected that the cable reels would be carried back and forth along the quadrant using the circular crane arrangement as the coils were wound. However, due to the small scale the cable reel was left in a fixed position above the center of the quadrant and any type of hoist arrangement would have been satisfactory. Most of the time in winding was spent on the 90 degree bends. These had a minimum radius of 3 1/8 inches to the centerline and required considerable skill to make. If the cable were first bent in the wrong place it was difficult to move the bend. The cable was tied to the separators with twine and the separators were clamped together using spacers on the bolts as the winding progressed. The supports for the end winding are made of wood to avoid magnetic or eddy current effects.

Cooling air enters every other space between leg slabs and exhausts through the alternate spaces. Sheet metal air ducts run around the outer and inner radii of the quadrant with connections to the spaces between the legs and to the end winding supports. Sixteen "radar" blowers rated at 550 CFM at 4 inches static pressure supply the air. These blowers are quite noisy but have been considerably improved by the use of felt linings to the inlet and exhaust pipes and use of a canvas section between the blowers and the ducts. Thermocouples are located at six points to measure the temperature of the surface of the cable insulation and of the copper. The highest copper temperature indicated reaches 23° C above the room air temperature at a repetition rate of 17 pulses per minute to a magnet current of 1750 amperes peak.

To provide for correcting the shape of the magnetic field both poles face windings and leg windings were provided. The pole face windings consisted of 12 No. 10 wires spaced on approximately 3 inch centers which ran at constant radii

along the faces of the core yoke slabs above and below the vacuum tube. The wires are contained in a "sandwich" consisting of an upper and lower layer of sheet fiber and radial spacing strips of plywood. The leg coils consist of ten turns each of No. 10 wire wound around each inner and outler leg slab. The radial variation of the field and the vertical position of the median plane can be varied by currents in the pole face windings. Currents in the leg windings can cause the field to vary in azimuth and so affect the radial position of the beam.

The flywheel generator powering the magnet is rated at 3000 amps at 180 volts pulsed. Ordinarily the current is limited to about 2000 amps maximum. Control is by means of a contactor in the magnet circuit which closes at the start of the pulse and field relays which (1) apply a high field voltage to build up the generator voltage in preparation for the pulse, (2) hold the field current at a set value just before the contactor closes, (3) apply a high reverse voltage to limit the maximum current after the acceleration period is over, (4) bring the generator voltage to as near zero as possible before the contactor opens. The contactor and field relays are controlled by adjustable electric time delay relays and the cycling rate is controlled by a mechanical timer. Repetition rates up to 20 pulses per minute are obtainable. The system was designed to make use of existing equipment and is not recommended for a permanent installation. A considerable amount of outage has been causedby defects in relay operation and for maintenance of the relays and contactors.

Magnetic Measurements

At the time of starting work on the model only d.c. model tests had been made on the design to be used so that a verification of the field shape and magnitude under pulsed conditions was desirable. This was the reason for construction of the 20 degree quarter size magnet model which was completed on September 21, 1948. This model consisted of four 5 degree sectors with an air cooled winding similar

to that of the operating model but with a larger number of turns. One end winding had the shape required for the operating model to make possible measurements of the stray field beyond the ends of the quadrant. Tests of this model verified the shape of the field predicted from the d.c. tests. The effect of eddy currents in the iron in decreasing the field in the center of the gap was observed but amounted to only about 3 gauss. The residual field was measured as 15 gauss and its shape determined. It was proved that the residual field could be reduced or reversed as expected. The magnetization curve was checked and the flux linkage measured to calculate the full circle inductance and to verify the generator voltage required. In some of the testing the field was determined by the use of an electronic circuit integrating the voltage induced in the pick up coils. This integrator required considerable development but operated very well in its final form.

When the first sample vacuum tube sections were available two were tested in this model to determine the effects of eddy currents on the field shape. This effect was the order of one gauss. This showed that thicker sheet could have been used which would have greatly decreased the number of weld leaks. The liquid nitrogen trap tube was also in place during these tests.

Magnetization, radial and azimuthal uniformity, residual and stray field and median plane height measurements were made on the complete model magnet. The result of these tests are covered by magnet test group curves and will later be collected into a report. The azimuthal uniformity was measured around the complete ring at three radii. Along each radius the variation was within 3/4 percent except near the quadrant ends. The position of the magnetic median plane in one quadrant was determined to be within 1/4 inch of the centerline of the magnet gap by measuring the voltage picked up in a coil whose plane was vertical. Tests were also made to measure the time jitter between a peaking strip in the magnetic field and the pips from the peaking transformers on the magnet current leads

(described under instruments). This jitter was found to be less than 10 microseconds up to 150 gauss.

Vacuum System - Tanks

The vacuum system also followed designs which were being worked on for the full size machine. It was necessary to use a design for the tube on which construction could start immediately with good assurance of success without an extended development period. Calculations indicated that a stainless steel tube section using .031 thick sheet would have sufficiently low eddy current effects on the shape of the magnetic field, provided it were made in sections of about one foot each with insulated joints. A "gasket frame" was used between each pair of tanks. To support the atmospheric load a rather elaborate system was necessary. The .031 inch sheet is reinforced by "hat" sections of the same thickness spot welded to the outside surface. These sections are spaced about 8 inches radially and through each is run a 3/8 x 1 stainless steel bar acting as a beam. The ends of the bar rest on strips backing up the flanges of the stainless sheet and through which pass bolts clamping the tank flanges to the gasket frame. The gasket frame itself is of 1/2 x 1 1/4 stainless steel bar to which is welded 1/4 x 1 1/4 vertical bars called "skyhooks." The skyhooks pass out through the spaces between the magnet yoke slabs to "stools" which transmit the tension load of about 2200 lbs. per hook to the surfaces of the yokes. The radial component of the atmospheric load is taken by radial rods which hook under a projection at the outer lower corner of each gasket frame, pass between the leg slabs and through a hole in a plate attached to the lower yokes on either side of the slot between the sectors. A similar radial rod is provided on the inner radius to permit radial positioning of the tube section.

Two 1/8 x 3/16 gaskets are vulcanized to each face of the gasket frame. The inner gasket holds the vacuum while the outer gasket which is outside the bolt

holes balances the force on the inner gasket preventing rotation of the tank flanges and provides a seal for helium testing the space between the gaskets. This space is not vacuum tight due to leakage under the bolt heads and nuts but is adequate to confine the helium used in leak testing. Two small diameter tubes are carried alongside of one of the top skyhooks and communicate with this space between the gaskets. An isolating gasket between the openings to the tubes permits helium to be passed in one tube flowing entirely around the frame and out the other to check for leakage of the inner gasket at any point.

In order to provide some flexibility to permit compressing the gaskets and avoid excessively close tolerances for the stack of tube sections in the quadrant, an expansion joint is provided at each end of each section.

The tube through each quadrant is made up of eighteen tank sections of 5 degrees each with 19 gasket frames. Each tank section and each gasket frame is grounded through a wire which can be disconnected to check for the insulation resistance. Each gasket frame is provided with a strip spot welded to its inside edge to shield the beam from electrostatic charge that might accumulate on the rubber.

It was hoped that the full 12 inch vertical aperture corresponding to 4 ft. full scale could be obtained in the model but this was soon seen to be impractical. The pole face winding sandwich required 5/16 inch, the gasket frame bar 1 1/4 inches, the electrostatic shield had to be set 5/32 inch inside the bar and 1/8 inch was allowed for clearance. This reduced the 13 1/2 inch magnet aperture at the radius of the centerline of the quadrant by 1 27/32 inches on each side to 9 13/16 inches inside the vacuum tank corresponding to 3.3 ft. full scale. The radial aperture came out 38 5/8 inches corresponding to 12.9 ft. full scale.

The tank in each straight section is made of 1/2 inch mild steel with openings in the inner and outer face and in the top in addition to the openings in the

sides connected to the quadrant tubes. These "tangent" tanks are approximately 33 inches wide, 45 inches deep and 60 inches long in the radial direction.

A manifold supporting two Westinghouse 20 inch diffusion pumps is attached to the inner face of each tangent tank. Each manifold contains valves operated by air cylinders on top of the manifold for the inlet of each pump. Face plates of these tanks are provided with double gaskets and pump-outs.

Between the curved tube in each quadrant and each tangent tank is a straight tank section of sheet stainless steel construction similar to the "curve" tanks except that the two flanges nearest to the tangent tank are bolted up from inside and the flange next to the tangent tank is provided with a flat gasket. This construction while undesirable is necessary in order to permit assembly of the quadrant and tangent tanks after the coils are wound. These "transition" tanks each carry ports in the inner and outer walls intended for the insertion of probes. These ports are two inches wide by five inches high which is the largest opening that will clear the magnet coil end windings. Probe locks are designed to bolt on to these ports using a special molded double gasket similar to the RL standard pipe line gaskets.

The cyclotron tank is of non-magnetic manganese steel with integral mild steel top and bottom covers. Port openings are provided for the full length on all four sides. The vacuum load on each cover is taken by a single bolt screwed into a blind hole in the center of the cover and passing through the magnet core.

The inside surfaces of all the steel tanks were painted with Glyptal lacquer to prevent rusting. This coating was removed from the cyclotron tank as it was believed to be outgassing and increasing the difficulty in holding mf. voltage which occurred on first starting up. This trouble, however, was probably due to inadequate baffling of the pumps which was later corrected. No such difficulty has occurred on the bevatron system.

Vacuum Pumps

It was desired to do everything possible to increase pumping speed in order to reduce the gas scattering of the beam. Accordingly two 20 inch pumps are used at each tangent tank. Each pump has a baffle section cooled by Freon 12 from a common refrigeration compressor. A 3 Hp air cooled compressor was first provided but as this was unable to hold the suction pressure below 5 lbs. corresponding to -22° C evaporation temprature on hot days a 5 Hp water cooled compressor was installed. A good deal of trouble occurred with this system due to freezing up of the thermostatically controlled expansion valves at each of the eight baffles. The trouble was probably due to moisture remaining in the system after starting up. Thermometers are installed at the baffle outlets to check the operation of the expansion valves. These showed excessive hunting which was corrected by relocating the thermostat bulbs. Many of these thermometers which are the bimetal type ceased working apparently due to moisture condensing inside the bulb. They are to be replaced with mercury thermometers.

Each 20 inch pump is backed by an 8 inch booster which discharges into a manifold running completely around the magnet. A 2 inch isolating valve is used between each booster and the manifold. The roughing connection is made to the east tangent tank. A 300 CFM and a 105 CFM Kinney pump are provided, either or both of which can be used for roughing or backing. The 300 CFM pump will pump the tank down to 100 microns in about 40 minutes. The tank volume is 630 cubic feet. The 300 CFM pump is ordinarily shut down except during roughing and the first few hours after the diffusion pump gates are opened. A Model GM1 Hilco oil reclaimer is connected to the mechanical pump oil system to permit changing the oil in batches or circulating purified oil through the pumps under manual control. As designed the rate of flow is excessively slow in changing oil due to the small size of the pipes for the available gravity head.

The cyclotron injector has a pair of 6 inch pumps backed by a separate 105 CFM Kinney. It was expected that a considerable flow of hydrogen gas would have to be handled by the cyclotron pumps hence the large fore-pump capacity. Shortly after starting the cyclotron a refrigerated pump baffle connected to the Freon system was provided as one of several steps taken to reduce the cyclotron pressure. A common manually operated valve is used on the cyclotron diffusion pump manifold.

Each of the 20 inch diffusion pumps is provided with an oil level sight gage, a barrel water temperature cut off and a boiler temperature cut off. A "geissler" spark plug is installed in the main tank to close the pump gates and turn off the ion gages at pressures above 100 microns. This system has failed to protect against small leaks in the forevacuum system or failure of the refrigeration which has contaminated the ion gages so that a cut off operating when the ion gages go above full scale has recently been installed. Ion gages are located on each bevatron pump manifold and on the cyclotron tank. Western Electric gages are used but Distillation Products VG1A tubes are preferred when available as they seem to outgas more quickly.

A 1 1/4 inch stainless steel tube is provided along the outer radius inside each quadrant tube as a liquid nitrogen trap. One end of each trap tube enters the vacuum system through the probe ports in the transition sections on the East and West sides. Liquid nitrogen flows through an inner "squirt" tube to the far end of the trap. The liquid level is maintained by a carborundum resistor partly immersed in the liquid in the end of the trap tube outside the vacuum. The temperature of the resistor controls the air pressure which forces liquid nitrogen from a dewar through the internal squirt tube in the trap. Conventional bottle traps are provided in each tangent tank and in the cyclotron pump manifold. In operation these bottle traps have not been used. When the minimum pressure is required two of the four quadrant traps are kept cooled. The consumption of

each of the quadrant traps is 8 1/2 pounds of liquid nitrogen per hour.

Vacuum Testing

As is usual with complicated vacuum systems as many of the individual parts as possible were tested before trying to obtain a vacuum in the complete system. This was especially important in the case of the curve tank sections which had many leaks in welds due to the thinness of the sheet metal used. Helium leak detectors manufactured by the Consolidated Engineering Co. were used in all the testing and proved extremely valuable.

The tank sections were individually tested when received from the fabricator using a 6 inch diffusion pump system. The pump was permanently installed under a plate which formed one head of the tank section. A spacer was placed inside the tank and the top head attached. A hood flooded with helium was lowered over the tank while under vacuum to check final tightness. Leaks in the welds were repaired by hard soldering. As many as 100 leaks had to be repaired in a single tank section. The first of the tank sections were given an external pressure test at 1 1/2 atmospheres pressure difference to locate any mechanical defects such as poor spot welding. No such troubles were found and as the pressure test was distorting the tanks appreciabely this procedure was stopped when about one-eighth of the tanks had been tested.

After the individual tank sections were tested they were assembled a half quadrant at a time and tested with their gasket frames. In this test one of the tangent tanks with its two 20 inch pumps attached was used. A supporting frame was used inside the tube to prevent collapsing and to permit leak hunting all over the outside. After repairing leaks the half quadrants were covered with a flexible plastic sheet and the space under the sheet flooded with helium for an overall check. Finally the tube sections were again tested a quadrant at a time when installed in the magnet. For this test the top magnet yokes were left off

and special steel beams used in their place to support the top skyhooks to allow access to the top surface for leak hunting. The top and sides were reasonably accessible at this time but the bottom was not. At this stage some gasket frame leaks were stopped by blowing thin Glyptal through the helium testing space. When completed there were a few leaks sensitive to the helium leak detector. However, from the rate of pressure rise and the volume of the system the total leakage rate of the finished system was about 5 micron liters per second. With the pumping speed available this flow accounts for a pressure rise of about 3×10^{-7} mm Hg.

Pumping speed measurements made at various times during the assembly work showed a speed of 2200 liters per second for a single pump measured in the pump manifold. The speed measured at the outer end of a half quadrant with one pump in use was 900 liters per second with the support structure in place. In the final system the speed at the center of a quadrant would be more than twice this value.

In present operation (July 1949) the base pressure with the system cold and without liquid nitrogen in the traps is between 1 and 1.5×10^{-6} mm Hg. During the operation of the magnet the pressure rises to 2 to 4×10^{-6} without liquid nitrogen. Liquid nitrogen in two quadrant traps lowers the pressure 0.4×10^{-6} mm when the system is cold. With the pressure 1.5×10^{-6} closing off half the pumps approximately doubles the pressure. This indicates that most of the base pressure is due to gas coming from the tanks and tube from half to two-thirds of which is not condensable with liquid nitrogen.

Injector Ion Gun

The injector ion gun design was based on the pressure Van de Graaff in use with the linear accelerator. The vacuum tube uses the identical porcelain rings and the support structure uses herkolite tubes of the same cross section as those of the Van de Graaff. To hold the required 460 KV on the high voltage end (40 KV

is obtained from a focussing voltage supply) it was decided that the column should be 75 in. long and consist of 27 sections. The sparking distance from the high voltage shell to ground was made 44 inches. Thirteen rectangular hoops of 1 1/2 in. diameter aluminum tubing surround the structure.

The structure consists of four horizontal supporting tubes with two smaller diagonal tubes to take the vertical load. As no pressurized envelope is required much more space is available in the high voltage end than with the usual Van de Graaff. Taking advantage of this the electronic units are designed to slide into their supports as drawers into a filing cabinet.

Power for the ion source and equipment at the high voltage end is supplied by a 400 cps permanent magnet generator driven by a leather belt from the ground end. The ion source originally planned was identical to the Zinn source used with the Linear Accelerator. One departure from Van de Graaff practice is the use of 1/8 inch square gaskets in "metal to metal" type grooves between the sections of the accelerating tube. Bleeder resistances are used in place of a corona gap system of voltage distribution.

The ion gun has not yet been run as its place was taken by the 20 inch cyclotron. At the present time it is being modernized for use in tests of the 10 Mev linear accelerator to be used with the full scale machine. Modernization consists of changing to the PIG type ion source developed by Gow, installing the differential pumping system using a DPI Model MCF 275 diffusion pump backed by a Cenco Hypervac and making minor changes indicated from experience during assembly. A high frequency Cockroft-Walton generator is being developed which it is hoped will fit inside the ion gun support structure making the unit self contained.

The ion gun is provided with jack screws for vertical and horizontal adjustments and casters can be bolted to it for portability.

Injector Cyclotron

The injector cyclotron was designed following tests made on a similar cyclotron in an existing magnet. The design was based on producing the maximum possible beam current at an energy in the neighborhood of 1 Mev. The low magnetic field of 7 kilogauss was taken to give the maximum radius for the first turn to enable more beam to clear the ion source. The oscillator was designed for the highest possible voltage taking advantage of the duty cycle of 1 millisecond at a repetition rate of not over 1 per second.

The energy of 1 Mev at 7000 gauss requires a radius of 8 inches which can be obtained with a 20 inch pole diameter. The magnet core was designed as a C rather than the conventional H to improve access to the tank and avoid interference with the deflected beam. A strut was planned inside the vacuum tank to limit the deflection but as the latter amounted to only 7 mils at operating field the strut was omitted. The core was built of 1 inch steel plates interleaved and welded at the corners to resist the maximum bending moment that could exist without the strut in place.

The cyclotron was originally designed to be mounted with the pole faces vertical. However it was later decided to retain the conventional position as there was no great difference in the spread of the beam in vertical and horizontal directions. Trunnion blocks were left on the core, however, for use in case the vertical position is ever desired. The cyclotron is mounted on a stand provided with leveling and lateral motion screws. In addition the stand rests on skid and has eyes for the attachment of horizontal pullers for large horizontal motions. Eyebolts are provided in the building walls for attachment of the pullers. The complete cyclotron weighs 11 tons and the horizontal force required to pull it across the floor is 3 tons.

The magnet coils are air cooled by four Radar blowers rated at 4 inches

static pressure and 550 CFM each. The copper cross section is 1/8 by 1 inch wound in 14 layers, the conductor weight being 3350 lbs. Insulation is glass cloth and transite. The temperature rise of the conductor above the inlet air temperature in present use while dissipating 5 KW is 18 degrees C as indicated by a thermocouple wound in the coil.

The magnetic field shape, a linear decrease of 2 1/2 percent in 8 inches, is produced by removable shim plates fastened to the pole tips which are integral with the tank. The shim shape was arrived at by re-machining after measuring the shape of the resulting field. The gap at the center of the pole is 5 1/8 inches and at the outer diameter is 4 13/16 inches.

The vacuum tank and pumps have already been described under the vacuum system.

The dee system is conventional except that no cooling is used. Cooling tubes are provided inside the dee stems but have not been found necessary. Two dees are used, mounted on 3 3/4 inch inside diameter by 8 1/2 inch long zircon porcelain insulators. Three inch diameter by 46 long aluminum stems are attached to the insulators and the oscillator tube is mounted between the stems at their outer end to form the resonant circuit. An Eimac 3 x 2500A3 tube is used with its grid and filament connected across a special disc type series capacitor located in the line between the dee stems. The plate is connected to a tap on the grid stem at a point 16 inches from the tube end giving the desired coupling. The series capacitor is an array of 72 - 100 mmf condensers which surround the oscillator tube. The tube is cooled by forced air supplied at 1 1/2 lbs. pressure by a 46 CFM Roots blower. Filament leads pass through the center of the tubing used for the plate choke coil. This oscillator produces an estimated 100,000 volts between the dees, eight inch sparks to ground can be obtained from the insulator flanges.

The cyclotron tank is lined with sheet copper which makes contact with the aluminum face plate through a strip of spring fingers such as are used for radar shielding. Condensers between the dees and the face plate inside the tank proved unsuccessful due to electrical discharges and were replaced by vacuum condensers installed outside the tank. The purpose of these condensers was to increase the dee capacity and thus increase the stored energy in the dee circuit so that the ion load would have less effect. The nominal clearance between the dees and the liner is 1 inch and the clear opening inside the dees is 2 inches. The oscillator was designed and built by William Baker.

The cyclotron ion source is of the PIG type consisting of a 1/2 inch diameter tube at ground potential with an aluminum cap at each end. The caps are supported from the dee face plate on long rods and carry the tube between them on ceramic spacers. A small tube bringing the gas to the ion source tube also acts as a ground. A slot 1/8 inch wide by 1 inch high facing one dee is the ion outlet. This source has performed without trouble since a palladium leak was installed in the hydrogen supply system two months ago. It is a great improvement over the filament source which required frequent filament replacements. The arc normally runs at 5 to 8 amps and 750 volts pulsed for the same period as the oscillator.

The cyclotron arc voltage and oscillator plate voltage are supplied from pulse lines designed for a 1 millisecond flat topped voltage pulse. The pulse lines are discharged by spark gaps triggered by 5C 22 thyratrons. The arc pulse line is rated at 2 KV and 168 joules and the oscillator pulse line at 20 KV and 200 joules.

An electrostatic deflector of conventional design starting 60 degrees from the dee gap and extending 90 degrees is used. After leaving the deflector the beam passes through an iron tube which acts as a magnetic shield causing a more

sudden cut-off of the fringing field than would otherwise be the case. After leaving the shield the beam passes through a focussing magnet which focusses in both the vertical and horizontal directions. The aperture of this magnet is 2 inches by 12 inches inside the vacuum tube, and the length through the magnet is 9 3/8 inches from entering to leaving pole edges. The wedge angle is adjustable by rotating the end sections of the pole pieces and the entire magnet is mounted on a rotating table with vertical and horizontal adjusting screws.

After obtaining the cyclotron internal beam about two weeks was spent in bringing the beam out through the deflector channel and the focussing magnet and improving the focus. The sections of vacuum tubes required for the external beam were made up as these experiments progressed.

The beam emerging from the focussing magnet passes through an electrostatic deflector, now called the inflector, located in the north tangent tank of the bevatron. This device turns the beam through 90 degrees. Mechanical motions of translation at right angles to the entering beam, translation parallel to the entering beam and rotation about the entering beam as an axis are provided. The right angle motion was intended for use with the ion gun beam which was expected to be quite sharp. It has no effect with the cyclotron beam. The parallel motion permits placing the inflector exit at any point across the bevatron aperture. The tilt motion has a range of three degrees either direction from horizontal. In addition the last 22 degrees of the high voltage electrode can be connected to a separate power source to vary the angle at which the beam leaves the inflector. All the mechanical adjustments are made by screw drive and are furnished with cyclometer type counters.

The outer, ground, electrode is lined up by use of a radius rod turning in a bushing in the support plate. The high voltage electrode is set with respect to the ground electrode using adjusting screws for all motions. As originally installed the electrodes were four inches high with 1 1/4 inch gap. The exit

tip of the ground electrode is made of 1/32 inch sheet metal and reduced in height from 4 to 2 inches in the end 4 1/4 inches. These dimensions gave a satisfactory beam but operating reports should be referred to for the electrode geometries used in the various tests.

The inflector high voltage bushing is located in an extension of the north tangent tank and contains a separately insulated center conductor for connection to the 22 degree trimmer electrode. This center conductor was originally insulated with a mica spark plug but this was replaced after electrical breakdown with a porcelain insulator which now stands about 35 KV with respect to the bushing. The main electrode voltage runs around 60 KV. Connection between the bushing and the electrode is by cables wound on spring driven reels, as used in commercial x-ray machines.

The inflector mechanism is supported on a rigid frame which is located in the tangent tank by jack screws. This permits assembling and aligning the operating mechanisms and electrodes in the shop. Connections to the operating handles are made through universal jointed shafts.

Accelerating System and Frequency Control

The accelerating electrode is located in the south tangent tank supported from a single zircon insulator 8 inches inside diameter by 15 1/2 inches long. The length of the electrode is 23 inches and the gaps between the ends of the electrode and the tank liner are 4 inches making the distance between the centers of the gaps 27 inches. This is 2.4 percent of the full orbit length. The electrode and tank liner is made of copper sheet. The liner is punched with 7/8 dia. holes to remove about 43 percent of the sheet area to maintain pumping speed from the tube to the pump manifold. The aperture of the electrode is slightly larger than that of the tube and its capacity to the liner when installed is 260 mmf.

The electrode is powered by a single stage amplifier excited by an oscillator.

Both the amplifier and oscillator are tuned by saturable reactors using ferroxcube III cores. The required frequency range is 400 to 1200 KC and electrode voltage is 1200 volts.

The reactor saturating windings were originally connected in series and the current was controlled by an amplifier whose input was obtained from a shunt in the magnet circuit. After an initial period of operation, separate current control units were used for the oscillator and the radio frequency amplifier. Controls are available which are equivalent to a potentiometer across the shunt (the slope control) and an adjustable voltage in series with the shunt (the d.c. level control). In addition a discriminator circuit is available producing a voltage closely proportional to frequency. The output of this circuit can be fed back into the control amplifier input to improve the linearity of the frequency response to input voltage. The radio frequency power amplifier is keyed by changing the grid bias of the amplifier tube. However, a number of difficulties have occurred with this equipment, and most of the sources of difficulty have been established. The principal troubles were due to starting frequency jitter and lack of linearity in frequency tracking. The first was reduced by reducing all sources of 60 cycle hum, particularly that caused by differential ground voltages in units which had to be separated physically. The frequency tracking error was a droop inherent in the ferroxcube saturation characteristic. This is compensated by the addition of suitable non-linear elements in the amplification circuit.

The control amplifier input signal is shown on an oscilloscope together with a marker showing the cyclotron firing time to facilitate locating the proper setting to find the beam.

Instrumentation and Timing

The primary timing signal is obtained from one of two peaking transformers

responding to magnet current. These consist of spiral cores of about 120 turns 1 mil permalloy strip 1 cm wide wound with a toroidal winding of 1500 turns of No. 26 Formex covered wire. The magnet current conductor passes through a 1 1/2 inch diameter hole in the coil. The current in the winding is controlled by a regulator and adjusted by a Helipot potentiometer. When the field of the magnet conductor exactly equals that of the bias winding the magnetization of the permalloy core reverses producing a pip on the regulator voltage which is used as a timing trigger. This signal triggers the oscilloscopes and starts two time delay circuits one of which triggers the cyclotron arc and oscillator and the other turns on the accelerating voltage. A third timing circuit controls the duration of the acceleration. All the peaking transformers and time delays are adjustable from the operating position.

Provision is made for installation of probes at fourteen places in the bevatron tank and at a number of places in the cyclotron. Ordinarily probes are used only at the entrance and exit of the inflector for tuning up and at one point on the inside radius of the bevatron for observing the accelerated beam although any of the other probe positions may be used for experiments. All probe circuits, timing pulses and varying voltages are brought to co-ax outlets on an insulated patch panel in the control room. In addition all the connections to the oscilloscopes and to and from the various timing and control units are brought to the same panel. This makes possible setting up any type of control or oscilloscope display that might be obtainable with the equipment in a very short time without making "haywire" connections. Great care must be taken to avoid multiple grounds in these circuits.

The control room is equipped with six type 512 Tektronix d.c. oscilloscopes with long persistence (P7) screens for observing the time varying phenomena on which the results of practically all tests appear. The meters are ordinarily

used only for tuning up and occupy a very secondary position. These oscilloscopes are each provided with a calibrated sweep speed control extending to three seconds and with a voltage calibrating circuit for the vertical deflection. They have proved excellent in use. What difficulties have occurred have been mainly due to minor bugs explainable by the fact that these were the first six produced on a production line by the manufacturer or to obvious faults in their application.

A typical use of the six oscilloscopes is the following: (1) Probe current with bevatron r.f. envelope as a marker. (2) Magnet current or voltage showing complete cycle. (3) Frequency control amplifier input with peaking transformer as a marker. (4) Cyclotron arc voltage and r.f. envelope as selected. (5) Cyclotron beam when probe at inflector entrance is inserted. (6) Available for miscellaneous testing. These conditions are of course frequently changed.

The controls are located in a room built inside the bevatron building. Two walls of the room are formed by the relay racks. The room is darkened by closing the doors and dimming the lights by Variac control during almost all the operation to improve the visibility of the oscilloscope displays.

Building

The bevatron model is installed in the south end of a building 50 ft. wide by 100 ft. long. The building construction is a light pressed steel framework covered by corrugated aluminum sheet. About half the floor area is required by the bevatron magnet. Of the remainder, approximately 220 square feet are taken by the control room, 125 square feet by the inflector power supply, 150 square feet by the cyclotron and its accessories, 100 square feet by a tool crib and the remainder is used for mechanical and electrical service facilities. No machine tools other than a band saw, drill press, grinder and sander are installed in the building.

Trenches 44 inches deep by 24 inches wide are located on the north-south

and east-west diameters of the magnet running to the walls except at the north. The north trench connects to a trench running to the east wall outside the magnet which communicates with the control room relay racks.

A one ton electric monorail hoist is installed in the building. A radial rail supported from a column at the center of the magnet and from a circular rail above the magnet ring carries the hoist when working above the magnet. This radial rail also connects with a fixed spur track running to the north door of the building. This system was installed to take advantage of clearance between the frames of the building above the magnet and to avoid interference with the high voltage power supply of the ion gun. However, with the cyclotron injector it is probable that a conventional monorail crane covering the entire building would have been more suitable and no more expensive.

There is no space corresponding to laboratory space in the building and no provision for shielding as the bevatron model is considered as a temporary installation and there is no expectation of using it for nuclear research.

Costs

The total cost of the bevatron model as completed and in condition for its initial operation was $348,224. The analysis of this cost is given in Table II.

Acknowledgments

The following are the persons responsible for the various phases of the work.

Cyclotron oscillator design and construction	W. Baker
Mechanical design of magnet core	J. Bell
Electronics engineering	G. Farly
Mechanical design of magnet coil and ion gun	H. Gordon
Electrical power engineering	C. Grauer
Electrical installation supervision	C. Harris

Mechanical design of cyclotron and general design consultation	E. Lofgren
Mechanical design of vacuum system	R. Peters
Supervision of magnetic measurements	D. Sewell
Particle dynamics and theoretical physics problems	L. Smith, R. Gluckstern
Mechanical installation and vacuum testing supervision	W. Twitchell

The contributions which most of these persons have made to this report is gratefully acknowledged.

The work described in this paper was performed under the auspices of the Atomic Energy Commission.

INFORMATION DIVISION
scb/10-13-49

TABLE I

SPECIFICATIONS OF MODEL COMPARED WITH FULL SCALE MACHINE

		1/4 Scale Model	Initial* Stage	Later Stage
Nominal aperture inside vacuum tube	Ft.	1 x 3 1/2	4 x 14	1 x 4
Radius to center of tube	Ft.	11 1/2	46	50
Length of straight sections	Ft.	5	20	20
Length of orbit	Ft.	92.4	369	394
Maximum magnetic field	gauss	1000	5300	16,000
Maximum proton energy	Bev	.0059	1.48	6.44
Magnet gap	inches	13 1/2	54	14
Injection energy	Mev	0.625	4	4
Injection radio frequency	mc/sec	0.39	0.260	0.230
Maximum radio frequency	mc/sec	1.19	2.4	2.46
Frequency ratio		3.4	10.0	11.3
Injection field	gauss	326	206	190
Useful width of field at injection ($1/2 < n < 1$)	inches	36	144(est.)	48
Relative radial width	% of radius	26	26	8
Relative height of aperture	% of radius	7.1	8 1/2	2
Acceleration time	secs	0.3	1.5	1.85
Initial rate of rise of field	KG/sec	4.45	4.45	9.60
Final rate of rise of field	KG/sec		2.44	5.90
Magnetic field exponent "n"		0.60	0.60	0.60
Initial energy gain per turn	ev	43.5	700	1750
Final energy gain per turn	ev		385	1075
Injection time (time for beam to cross half width of useful field)	microsec	3900	2415	318
Turns during injection time		1530	627	74

*As planned at time model was designed

TABLE I

SPECIFICATIONS OF MODEL COMPARED WITH FULL SCALE MACHINE

(continued)

		1/4 Scale Model	Initial Stage	Later Stage
Radial motion per turn during injection (r.f. off)	inches	0.012	0.12	0.32
Scattering loss at 10^{-5} mm air pressure	percent	96	12	57
Distance between accelerating gaps	ft.	2 1/4	10	10
Electrical angle between accelerating gaps	degrees	8.8	9.8	9.0
Peak accelerating electrode voltage		.570	8200	22,300
Repetition rate at full energy	pulses/min.	20	10	10
Stored energy in magnetic field (approx.)	megajoules	.040	80	80
Peak magnet current	amps	1780	8333	8333
Number of series turns on magnet		16	88	88
Peak ampere turns		28,500	732,000	732,000
Initial voltage on magnet	volts	250	18,000	18,000
Voltage at maximum current	volts		12,000	12,000
Peak instantaneous power	megawatts		100	100
Allowable time average dissipation in magnet	KW	30	3500	3500
Conductor weight	tons	5	360	351
Conductor cross section	sq. in.	0.273	1.31	1.31
Number of conductors in parallel		2	2	2
Conductor length	ft.	6360	139,800	136,800
Coil resistance at 65 C - 98% conductivity	ohms	.053*	0.268	0.262

*At 50 C

TABLE I

SPECIFICATIONS OF MODEL COMPARED WITH FULL SCALE MACHINE

(continued)

		1/4 Scale Model	Initial Stage	Later Stage
Initial inductance	henrys	.026	3.6	
IR drop at maximum current	volts	94	2230	
R.F. cycles per phase oscillation	At injection	280	167	105
	At maximum energy	---	2010	2140
R.F. cycles per betatron oscillation	Vertical	1.14	1.14	1.15
	Horizontal	1.69	1.69	1.69

TABLE II.

CONSTRUCTION COST OF 1/4 SCALE BEVATRON

	Direct Labor			Total Direct Labor	Stores Issues & Small Purchases	Contract & Equipment Purchases
	Mechanical Shops	Electronic Shops	Building Trades			
Building and Site	$ 1,990	$ 114	$6,797	$ 8,901	$10,168	$17,404
Magnet	12,225	993	8,984	22,202	12,275	45,100
Vacuum System	29,766	854	8,539	39,159	18,491	31,953
Injector - Ion Gun	10,348	857	50	11,255	5,168	6,044
Injector - Cyclotron	10,128	2,494	1,817	14,439	8,341	1,834
Accelerating System	1,234	1,312	56	2,602	1,152	606
Miscellaneous	1,625	1,715	692	4,032	6,087	10,008
TOTAL	$67,316	$8,339	$26,935	$102,590	$61,682	$112,949

	Overhead				Total Overhead	Total Cost
	Mechanical Engr.	Electrical Engr.	Adm. & Service	Research Personnel		
Building and Site	$ 36	$ 566	$307	$ 52	$ 961	$ 37,434
Magnet	7,994	6,466	46	6,553	21,059	100,636
Vacuum System	14,004	364	-	231	14,599	104,202
Injector - Ion Gun	13,234	2,102	-	185	15,521	37,988
Injector - Cyclotron	6,090	1,808	-	1,285	9,183	33,797
Accelerating System	1,186	4,795	-	-	5,981	10,341
Miscellaneous	1,333	1,313	-	1,053	3,699	23,826
TOTAL	$43,877	$17,414	$353	$9,359	$71,003	$348,224

NOTE: Building and Site includes electric power and water service, magnet foundation, and cranes.
The building proper is estimated at $24,000.

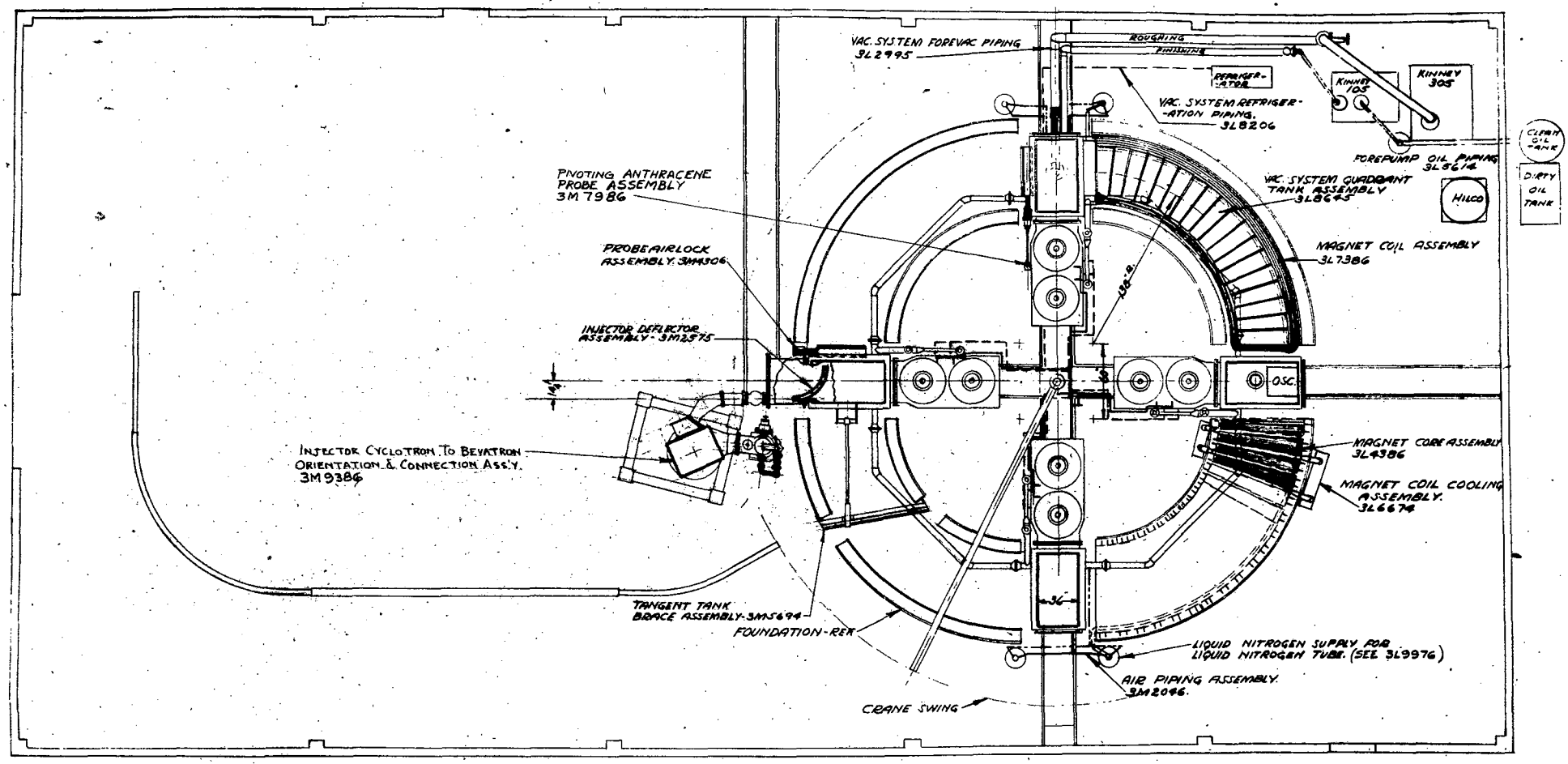
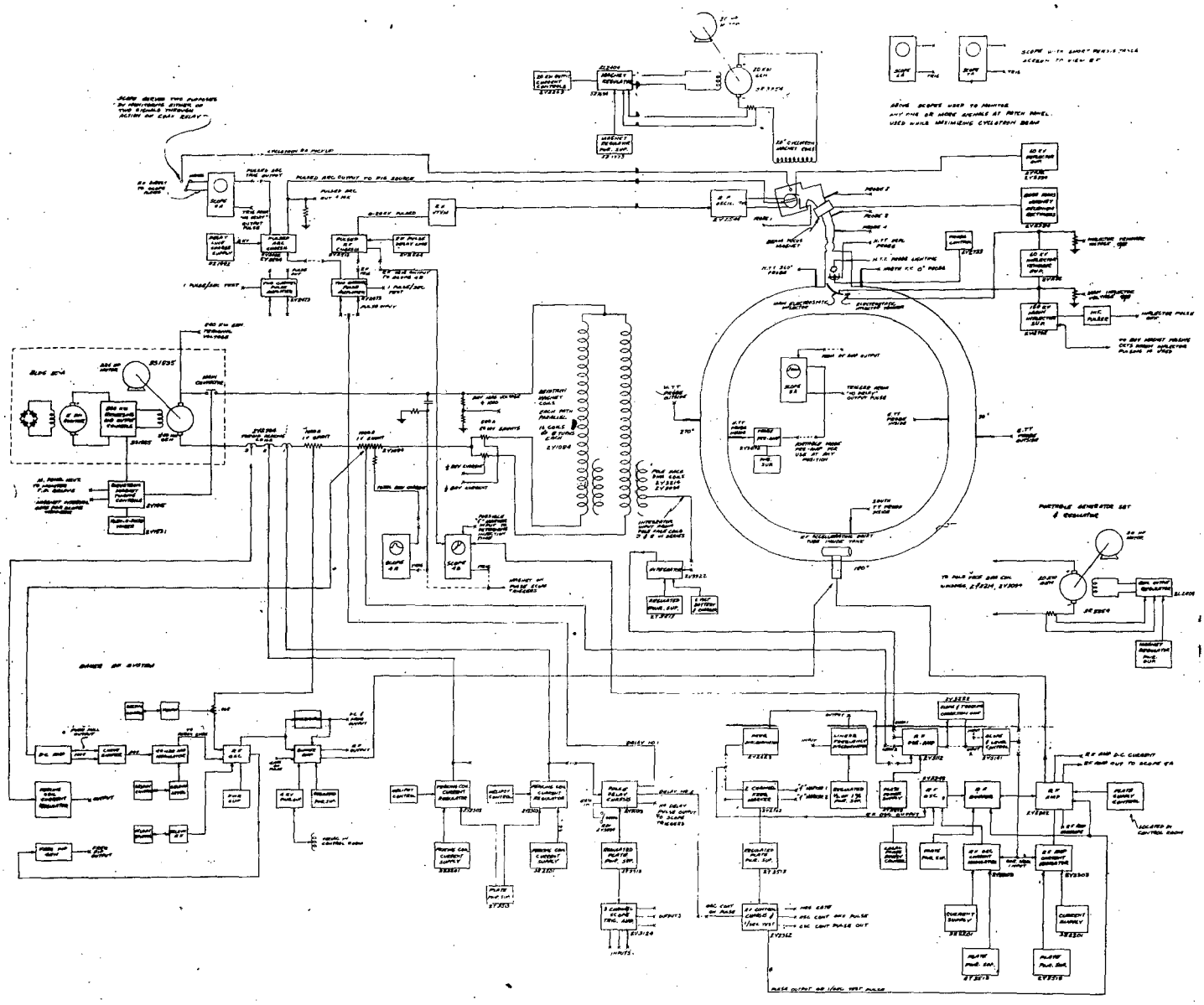


FIG. 1

GENERAL ASSEMBLY



MARK	REFERENCE POINTS
EY 1815	MAGNET PULSING CIRCUIT
EY 2775	EARLY RF BLOCK SCHEMATIC
EY 3234	BRIEF RF BLOCK SCHEMATIC
EY 3004	TEKTRONIX SCOPES PATCHING SCHEMATIC
EY 2534	CYCLOTRON PULSED ARC CIRCUIT
EY 2548	CYCLOTRON PULSED RF CIRCUIT

NOTES:

"X" DENOTES PATCH PANEL CONNECTION

— — DENOTES RG-58/U PATCH CABLE AT PANEL

THE OSCILLOSCOPE CONNECTIONS SHOWN ARE FOR MONITORING THESE PARTICULAR OPERATIONS ONLY. PATCH PANEL CHANGES MAY BE MADE READILY TO VIEW OTHER SIGNALS.

FIG. 2

BLOCK DIAGRAM OF ELECTRICAL SYSTEM

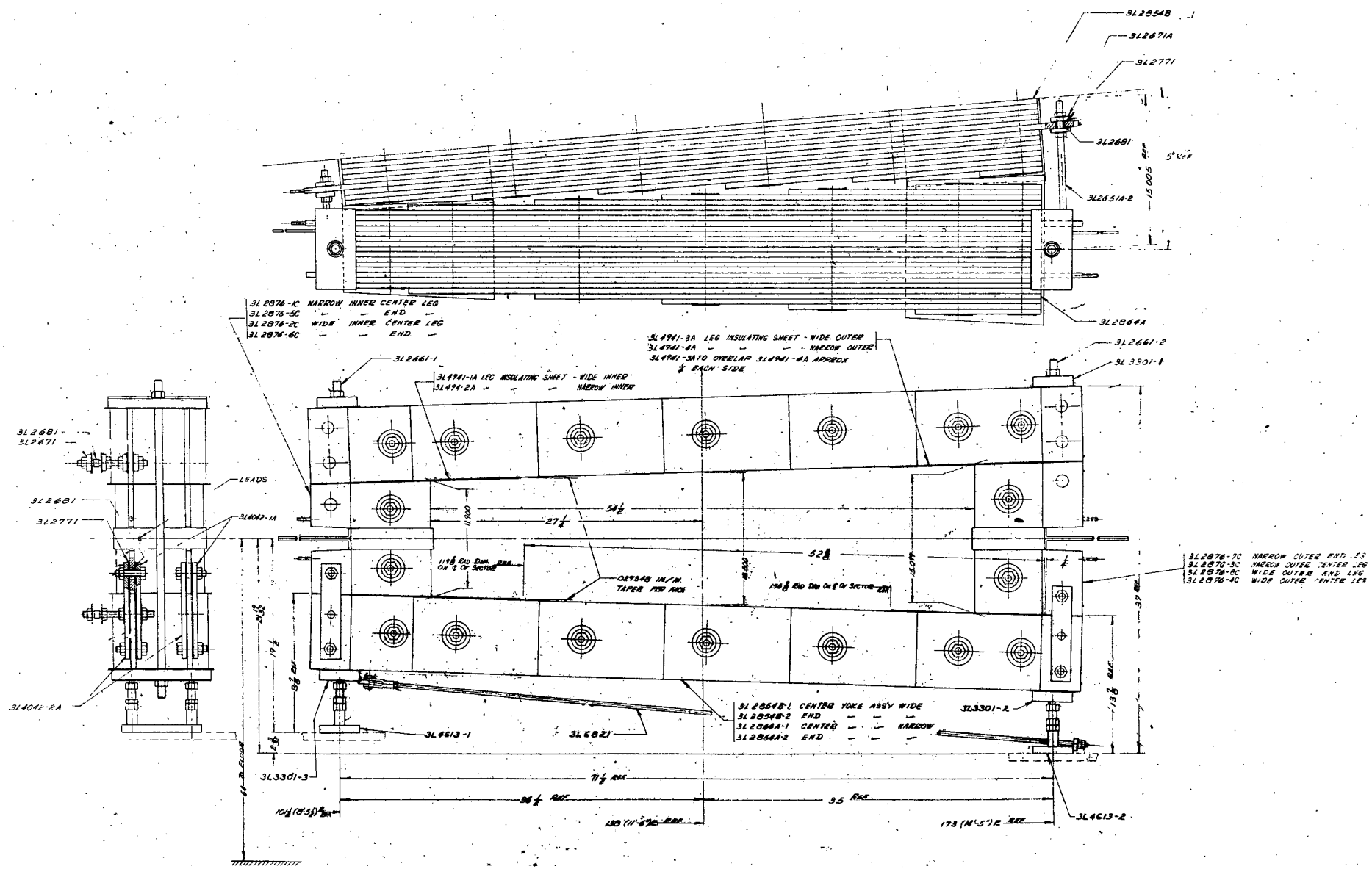


FIG. 3
MAGNET SECTOR

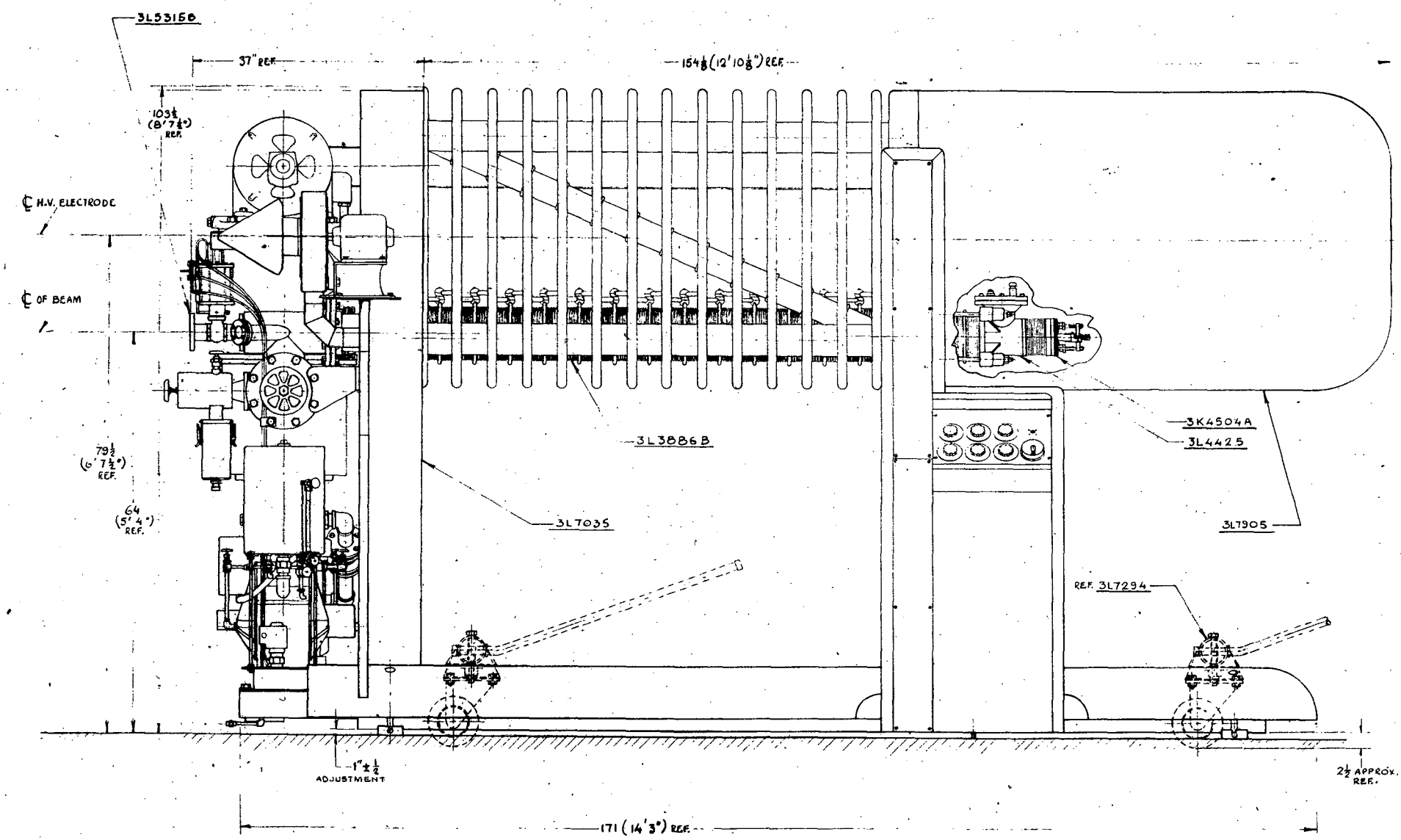

3L53150
37" REF.
154⅛ (12' 10⅛") REF.
103¼ (8' 7¼") REF.
℄ H.V. ELECTRODE
℄ OF BEAM
79½ (6' 7½") REF.
64 (5' 4") REF.
3L3886B
3L7035
3K4504A
3L4425
3L7905
REF. 3L7294
1" ± ½ ADJUSTMENT
2½ APPROX. REF.
171 (14' 3") REF.

FIG. 4

ION GUN

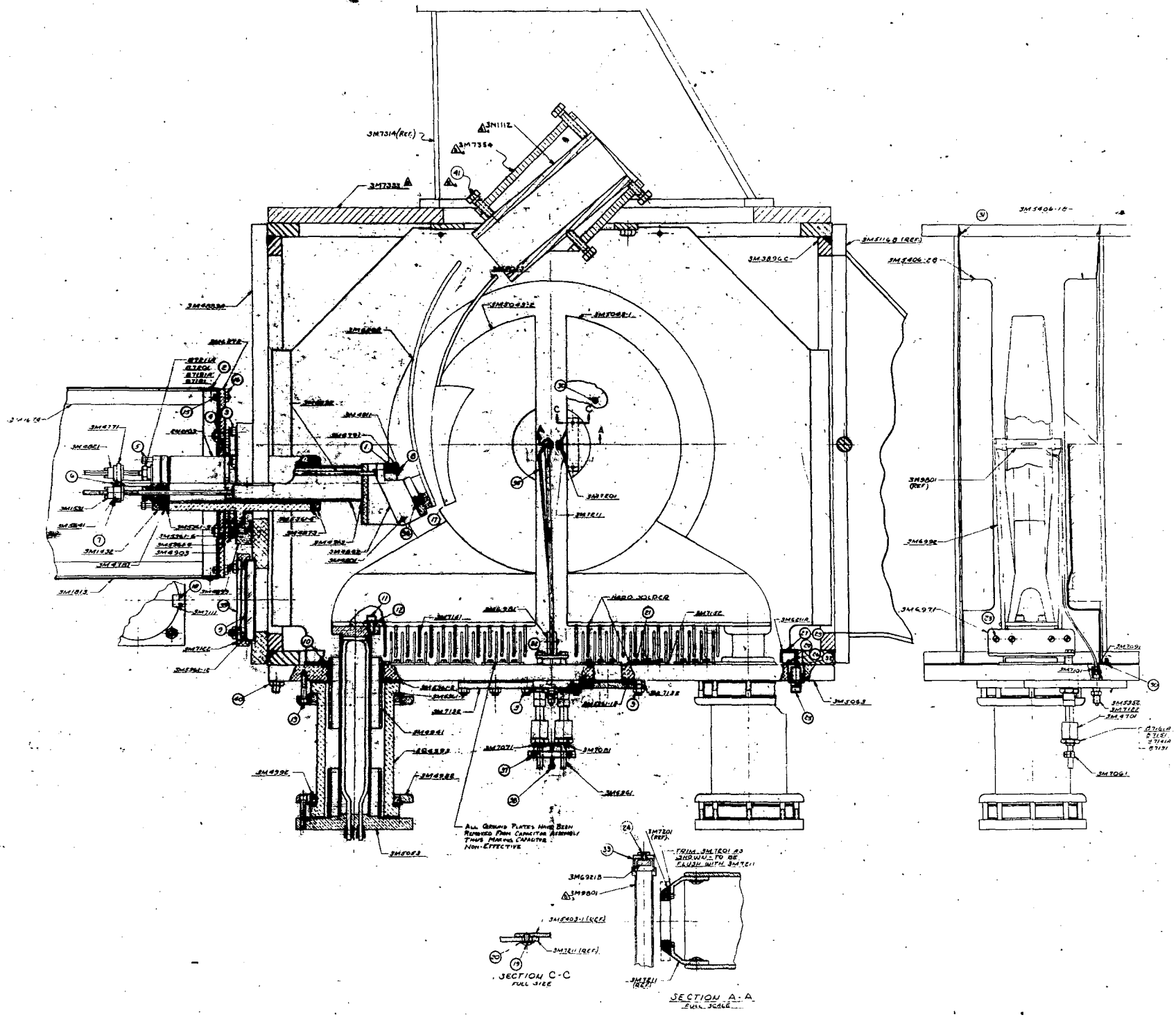


FIG. 5
INJECTOR CYCLOTRON

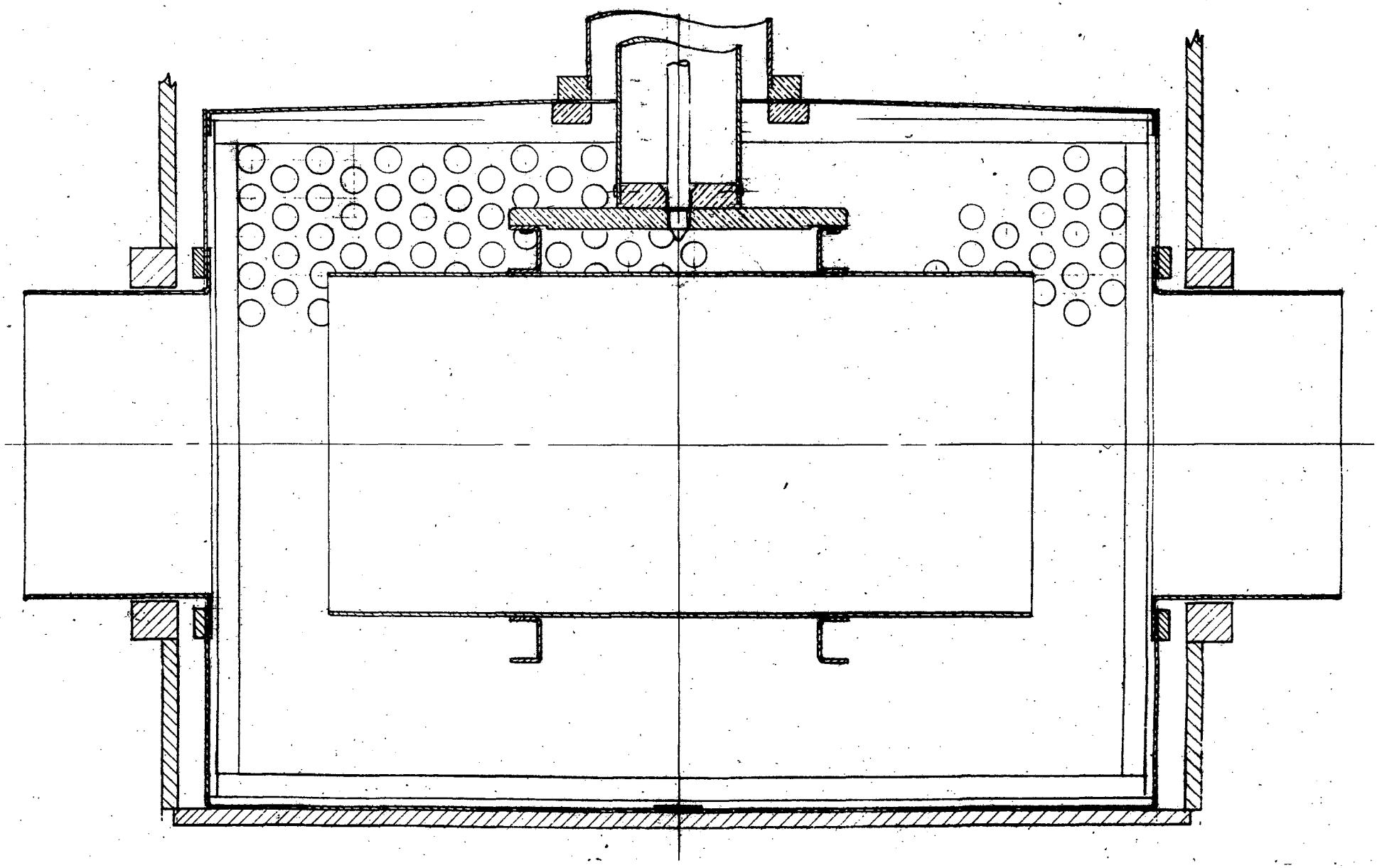


FIG. 6

ACCELERATING ELECTRODE

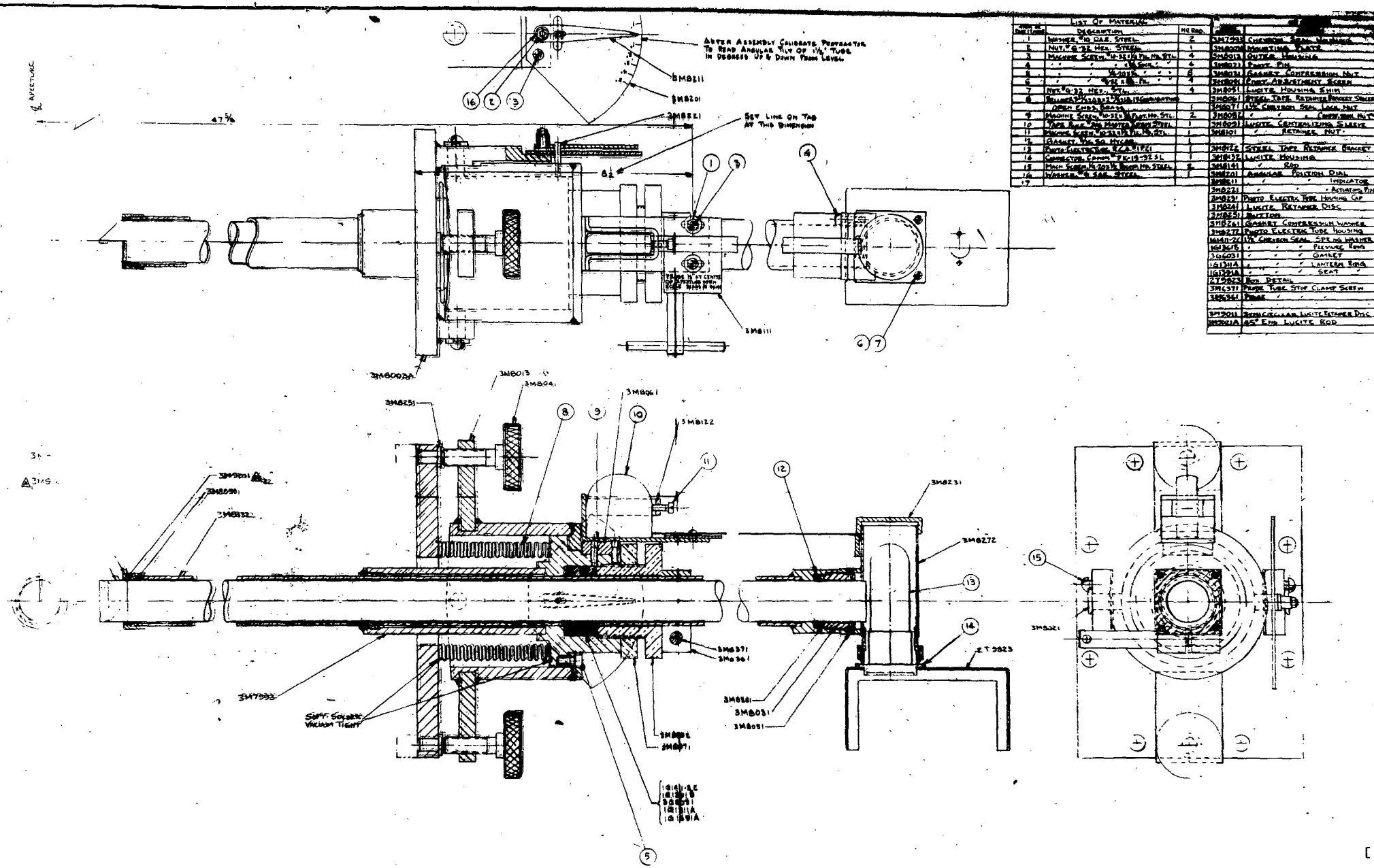
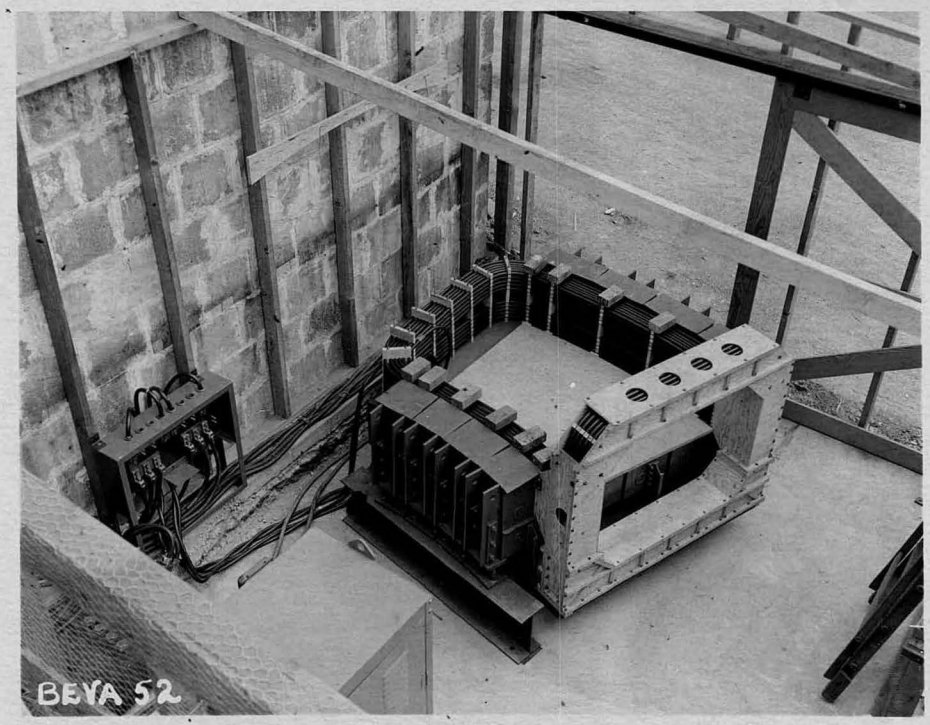


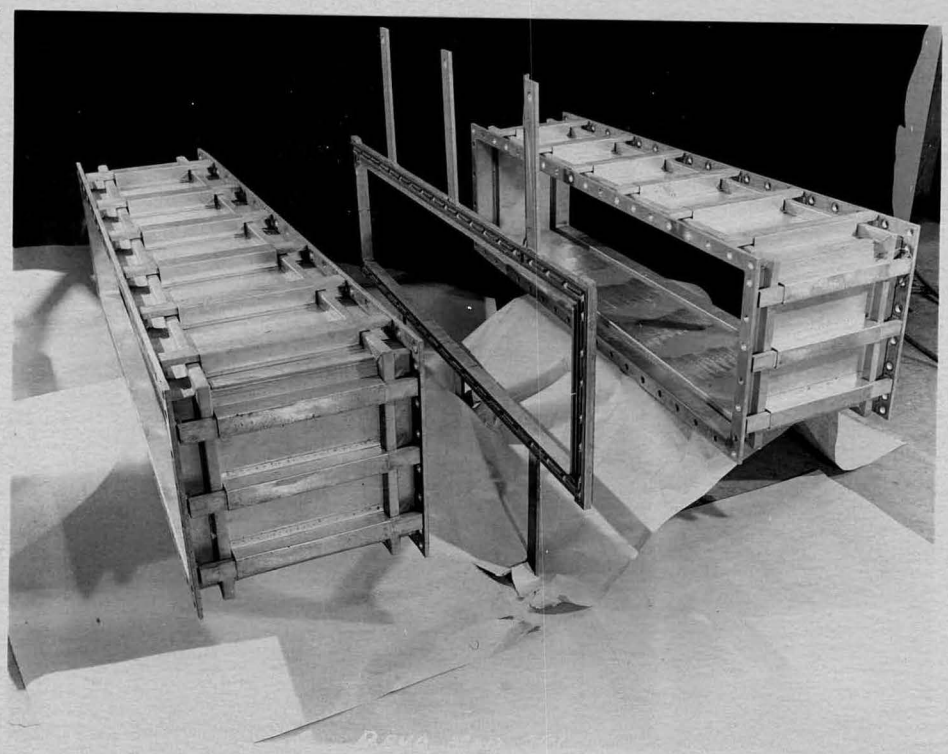
FIG. 7.

SCINTILLATION PROBE

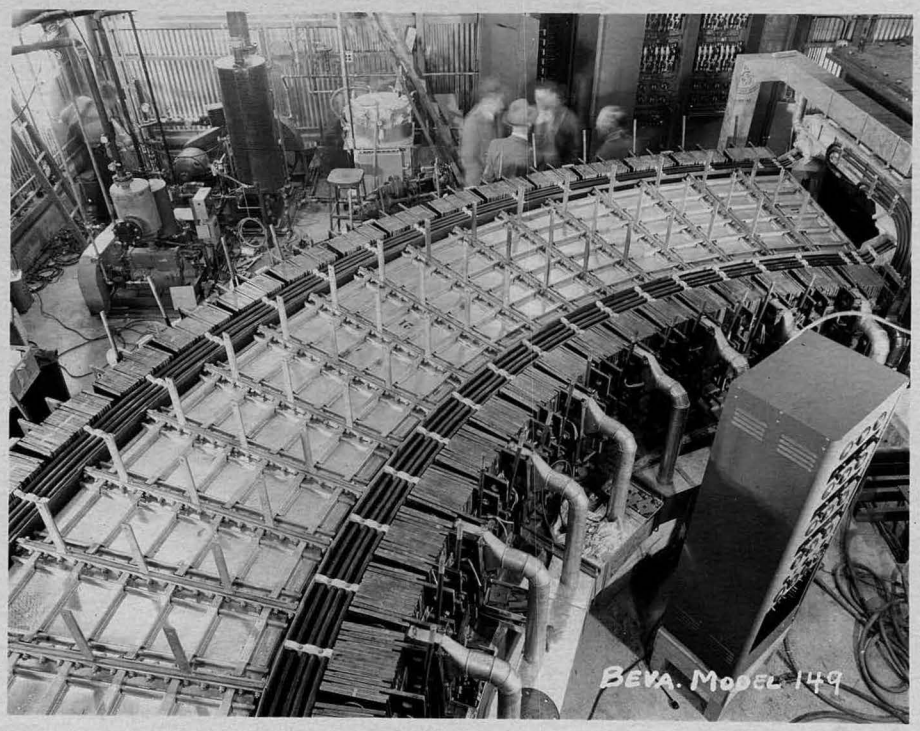


20 DEGREE MAGNET TEST SECTION

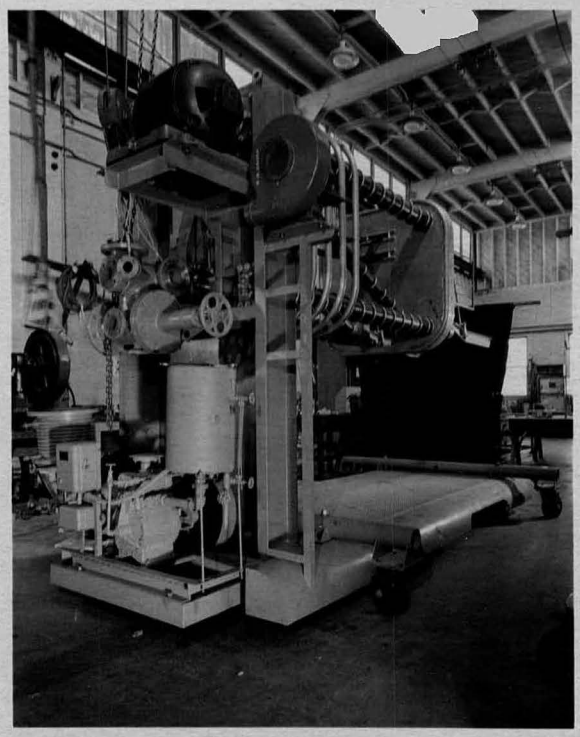
MAGNET BEING ASSEMBLED. "SKYHOOKS", POLE FACE WINDING "SANDWICH" AND GROUND WIRES FOR TANK SECTIONS SHOULD BE NOTED.



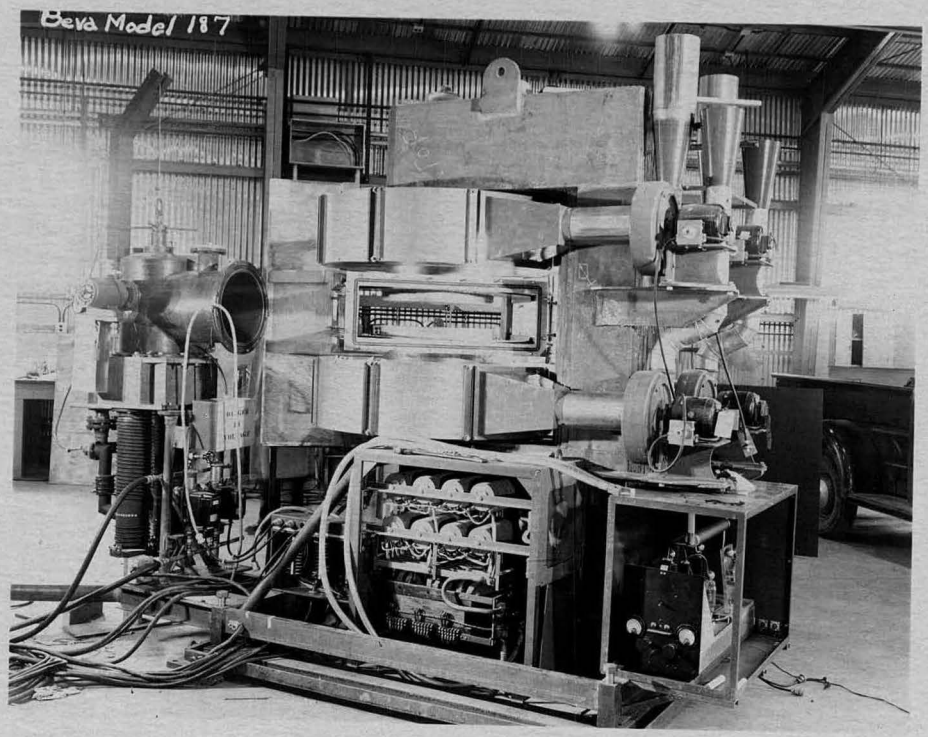
STAINLESS STEEL TANK SECTION WITH GASKET FRAME



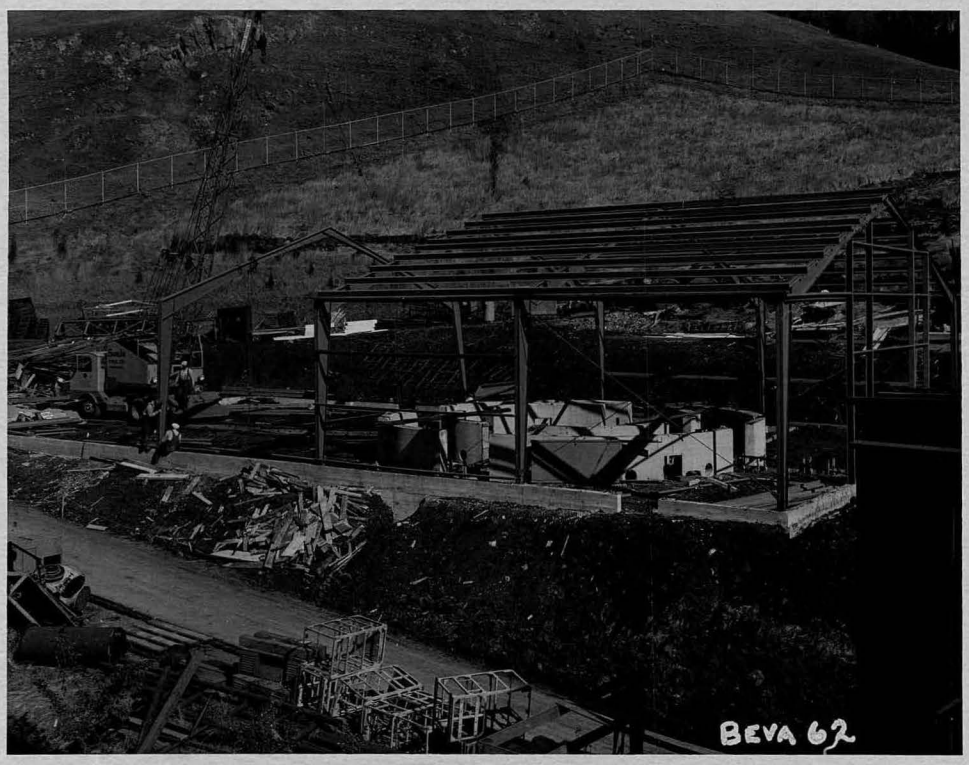
QUADRANT VACUUM TANK IN PLACE IN MAGNET SHOWING "SKYHOOKS."



INJECTOR ION GUN - REPLACED BY CYCLOTRON

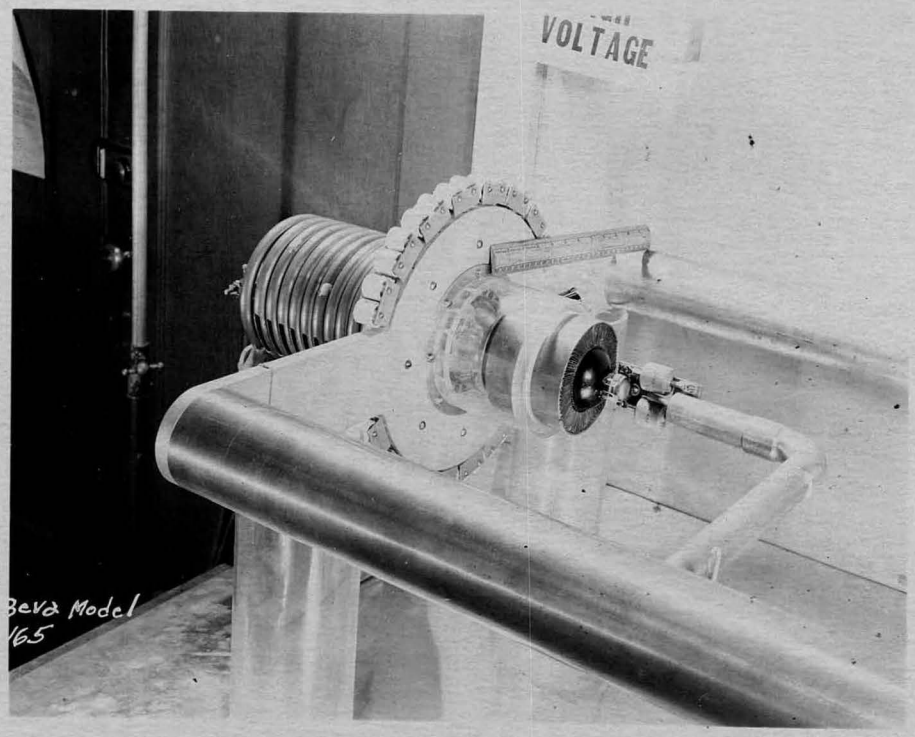


INJECTOR CYCLOTRON PARTIALLY ASSEMBLED

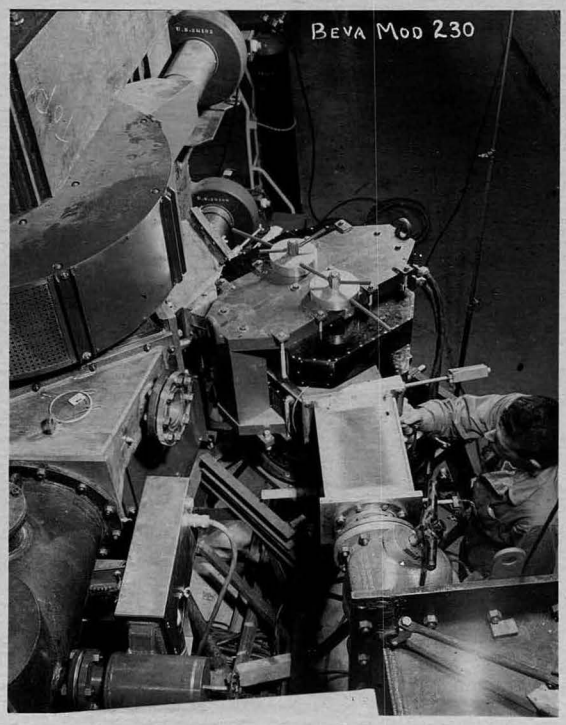


BUILDING UNDER CONSTRUCTION NOVEMBER 10, 1948

GENERAL VIEW OF OPERATING MODEL

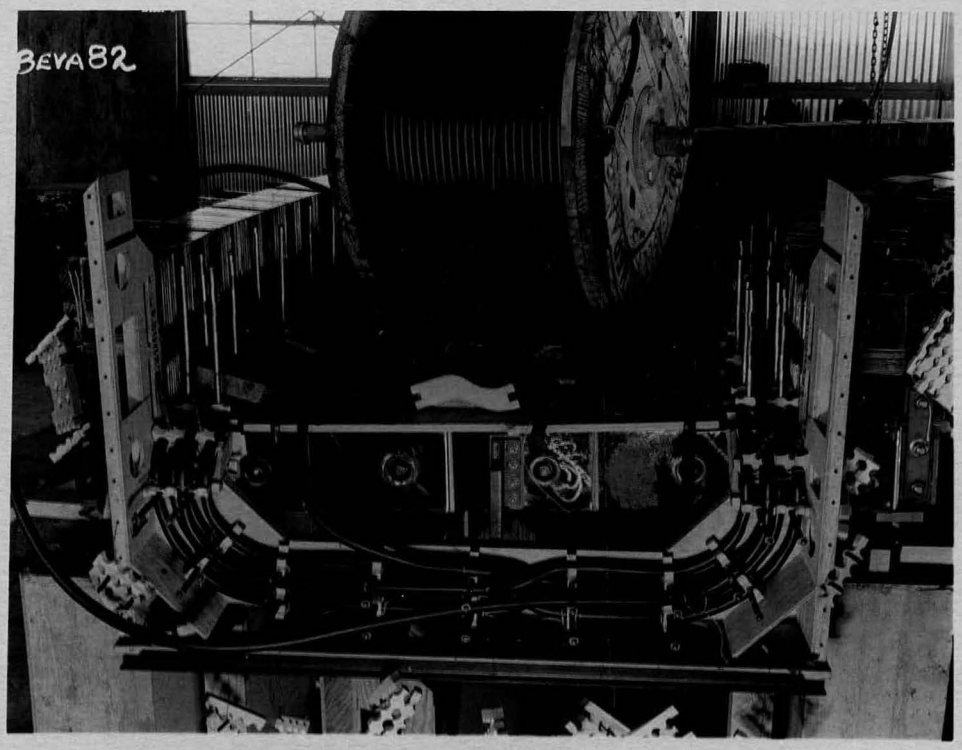


CYCLOTRON OSCILLATOR



CYCLOTRON CONNECTION TO BEVATRON
SHOWING FOCUSSING MAGNET

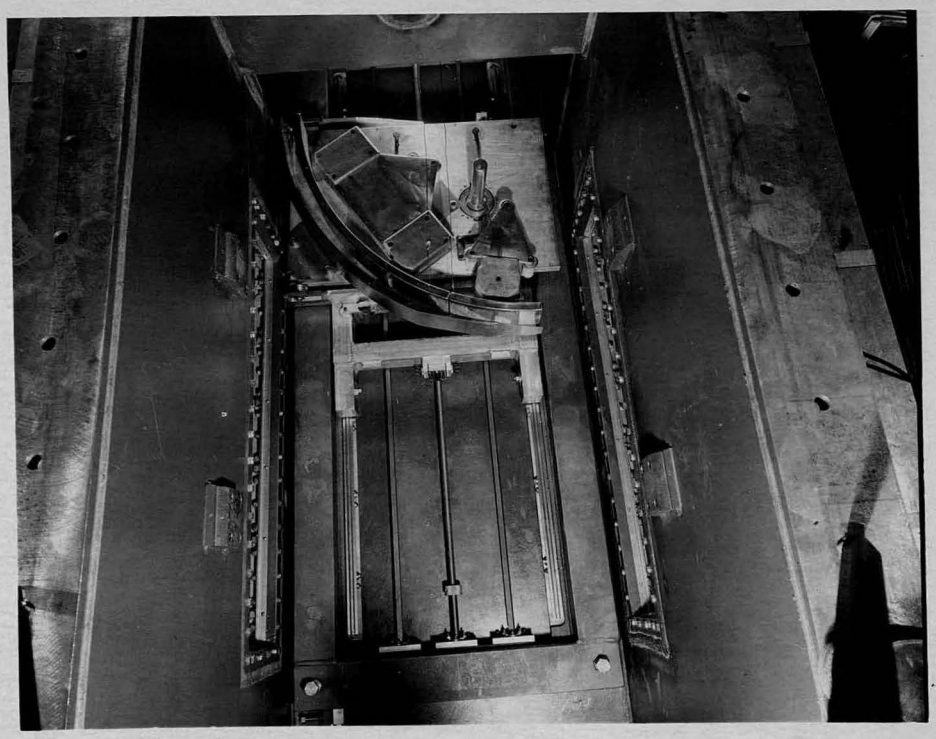
OZ 630



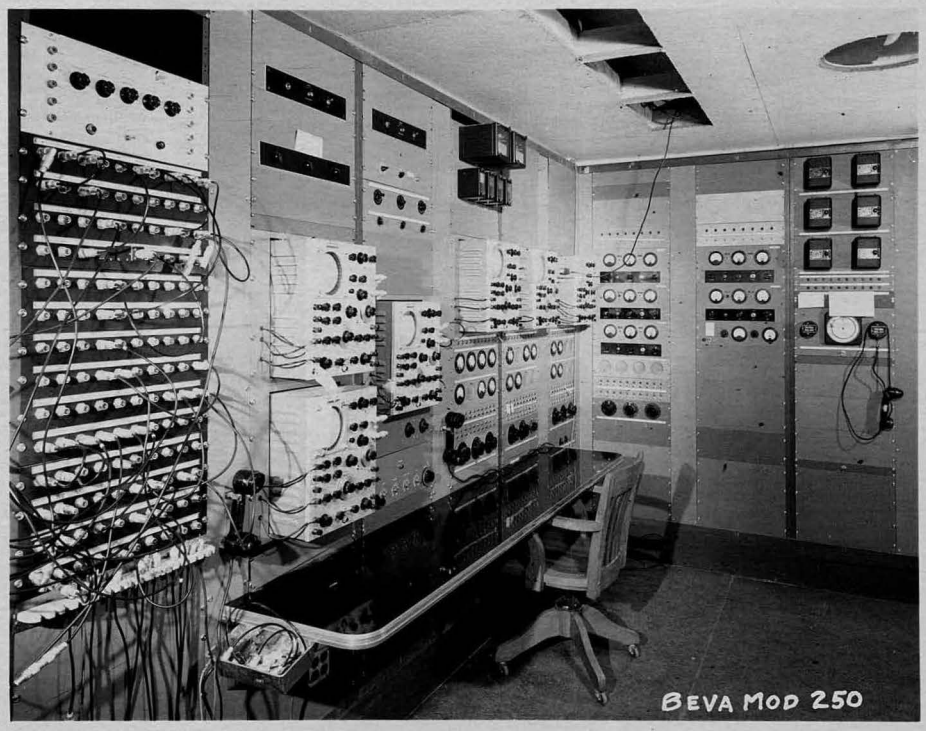
MAGNET COIL WINDING

MAGNET WITH COILS PARTIALLY WOUND

OZ 626



"INFLECTOR" IN POSITION IN TANK



CONTROL ROOM. PATCH PANEL IS IN LEFT FOREGROUND. OSCILLOSCOPES IN CENTER AND MAGNET TIMING CONTROLS AT RIGHT. OSCILLATOR FREQUENCY AND TIMING CONTROLS ARE IN THIRD PANEL FROM LEFT.

OZ 631