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OFFICE OF NAVAL RESEARCH

NYO-780

DESIGN AND CONSTRUCTION OF SYNCHRO-CYCLOTRON FINAL REPORT ON JOINT ONR-AEC PROJECT FEBRUARY 1, 1947 TO SEPTEMBER 1, 1950

By
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September 1, 1950

Carnegie Institute of Technology

Technical Information Service, Oak Ridge, Tennessee

PHYSICS

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SECTION I - INTRODUCTION

This report might better be termed a status report than a final report since the construction of the cyclotron is not yet completed. However, it is a final summary of the work under joint ONR-AEC program during the period February 1, 1947 to September 1, 1950 for, after this time, the major support for the CIT cyclotron program has come directly from the AEC.

Since this is a status report, some of the discussions cannot lead to definite conclusions at the present time. On the other hand, definite conclusions which have been reached are summarized.

Since a large part of this material has been described in progress and in technical reports, brevity is used wherever possible.

SECTION II - MAGNET AND COIL DESIGN

The first model magnet was made with 6-inch diameter pole pieces. To expedite the rough tests which were made to orient ourselves in this work, steel available in the laboratory was used. This was far inferior to the steel ultimately selected for the cyclotron. Phenomena studied included the effect on the field at the center of the magnet of a single current-carrying turn of various radii placed at different positions on the poles and also on the yoke. This work was done to evaluate the benefit to be gained by special shaping of the coil. The effect of the distance between the top of the coil and the pole face on the field produced was examined. The variation of the field at the center due to variations in coil geometry, separation of horizontal yoke members, gap thickness, yoke thickness, and addition of extra steel at the base of the pole to increase its diameter locally was studied.

A series of studies were made on a model magnet with poles 2 inches in diameter.[1/] This could be changed quickly and cheaply to give rough data over a wide range of parameters. The efficiency, defined as the ratio of magnetic potential drop in the gap to that in the entire magnetic circuit, was measured for various coil heights and magnetic fields. Quantitites held constant in this series of experiments were the distance from the top of the coil to the pole face, the gap thickness, and the yoke cross-section. From this

1/ "Half Magnet for Design Studies", M. Foss, J. G. Fox, R. B. Sutton, E. Creutz; to be published.

data, combined costs of power and steel were determined as a function of the coil height. The coil height giving the minimum cost was found for a field of 20,000 gauss. In the final design a slightly longer pole was chosen for convenience. Since the cost curve had a flat minimum this resulted in little increase in cost.

Various pole shapes were measured to obtain the efficiency of poles with various tapers and the effect of a shim on the efficiency.

Using approximately the best pole shape and holding the gap fixed and the distance between the top of the coil and pole face fixed, the following quantity was determined: the efficiency of the yoke for various ratios of cross-sectional area of yoke to cross-sectional area of pole. The minimum cost of power, steel, and copper is a function of this ratio.

The next magnet we made had poles 9 inches in diameter and used coils made of copper sheets lying in horizontal planes. Measurements were made on the flux density in the gap, the pole base, and the yoke. This pole was designed for use at 16,000 gauss in the gap. Improvements in oscillator design made it apparent that 18,000 to 20,000 gauss could be used. This pole was unsatisfactory for these higher fields due to its excessive length. Tests were, however, made replacing the steel at the edge of the pole face with Hiperco. These held the field up to appreciably greater radii.

A new 9-inch magnet was made with poles having the optimum length as determined by experience with the 2-inch model. However, the poles were cylindrical instead of having the optimum taper. Again the coil consisted of horizontal sheets of copper. The flux density was measured in the pole at various heights and in various parts of the yoke. The Hiperco tests were repeated but dropped when this material was found to be dimensionally unstable. The 2-inch model tests had indicated that it should be possible to work at 20,000 gauss in the gap provided that shimming could be done. Experiments with this model showed that it is possible to shim at 20,000 gauss.

A new model with pole faces 8.667 inches in diameter was made having the optimum size and shape of the pole, yoke, and coil as determined from earlier experience. The copper density in the coil was 80 percent of that of solid copper. A preliminary shim design based on calculations and previous experience was tested. A method of measuring the relative field in the gap at points along a radius to .1 percent was developed and used on later detailed shim studies on this magnet. Shim studies showed it would be very difficult to hold up the field out to a radius greater than 90 percent of the pole face radius. This was due to the pole cross-section being too small just below the pole face. New improved poles indicated it might be possible to hold up the field to 95 percent of the pole face radius. Experiments with this model showed the effect of moving the vertical yokes out to increase the working space. The deflection of the poles under the magnetic load was found to average .002 to .004 inches for the model.

A number of shims were tested and a pole face contour finally obtained which, with 20,000 gauss at the center, produced a field of 96.7

percent of this value at 96.5 percent of the total radius (corresponding to the magnetic index n = .2)[2], with an approximately linear decrease in field from center to edge. A final pair of model poles was machined out of the steel forgings actually used for the full-scale magnet poles. The results were satisfactory, and the design was frozen. The shim is described in detail in a progress report.[3]

[2] $n = -\frac{r}{H} \frac{\partial H}{\partial r}$

[3] "Synchro Cyclotron Progress Report", October 1, 1948 (Navy Contract N7onr-303, Task Order 1) Carnegie Institute of Technology

SECTION III - ENGINEERING DESIGN

The synchro-cyclotron magnet steel is shown in Fig. 1. Using the results of the theoretical and experimental program described in Section I, the magnet was designed weighing 1500 tons, using 130 tons of copper, and dissipating 320 kilowatts. It was found possible to shim this magnet with a field at the center of 20,000 to 21,000 gauss to produce a useful Hρ of 3.35 to 3.45 x 10^6 gauss-cm., corresponding to theoretical proton orbits of 437 to 459 Mev.

The machining of the pole tip was held to ∓ .0025 inches on almost all dimensions.

The magnet coil was designed by CIT staff and was wound at the Brooklyn Naval Shipyard. It is shown schematically in Fig. 2.

Each of the two coils is in a case of inner radius 82" and outer radius 118.8" with a height of 25.7". The base plate is magnetic steel while the inner and outer shells and cover plate are stainless steel. There are about 23-15/16 electrical turns separated from each other and from the steel shells by pressboard and fishpaper and separated from the base and cover plates by formica plates.

The base plate is 3.9" thick and is suitably drilled and tapped for oil inlets and support bolts. The inner shell is 3/8" thick and the outer shell is 3/4" thick. The cover plate is 1-1/4" thick.

Each electrical turn consists of sixteen bars of copper in parallel,

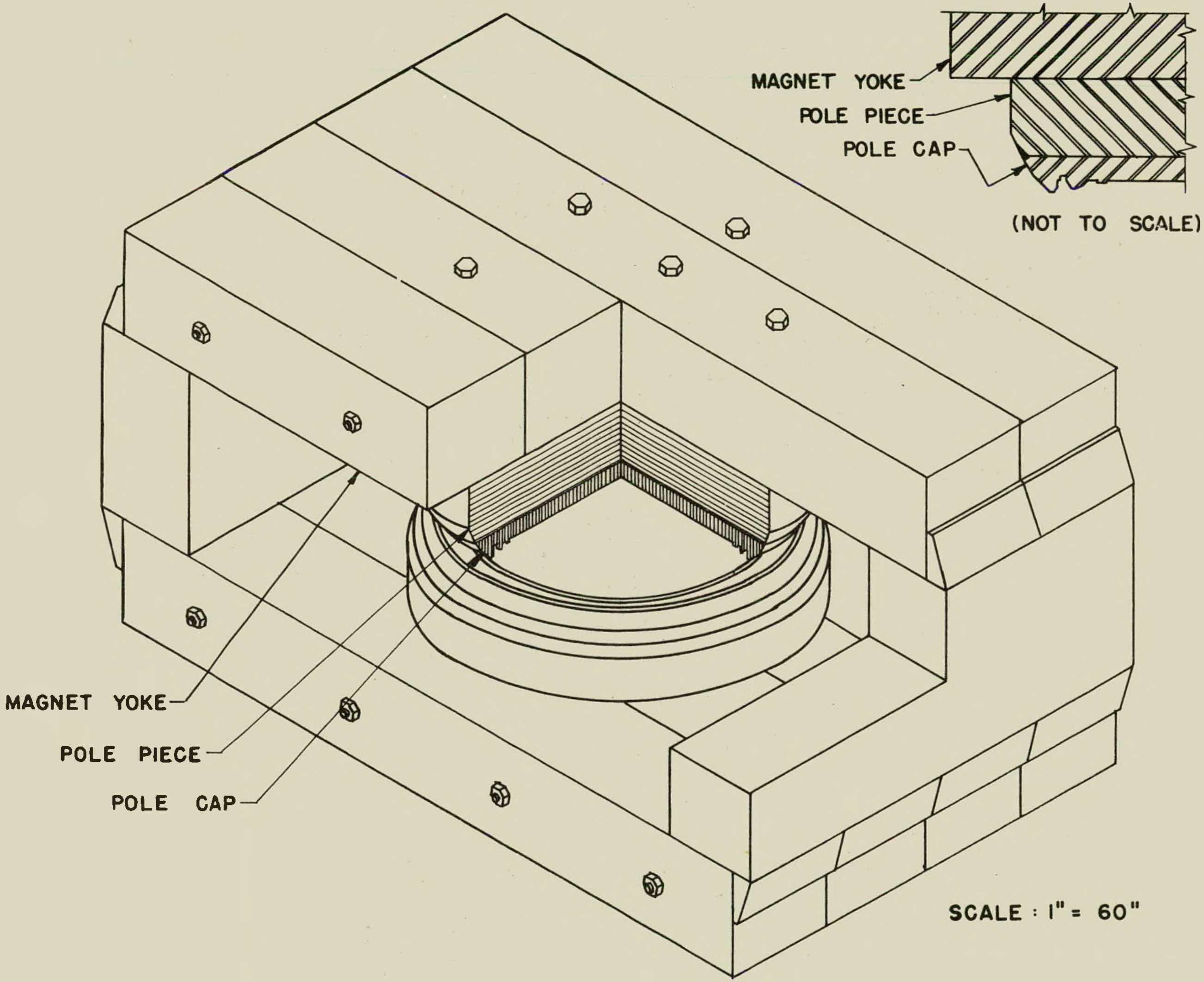

Fig. 1—Isometric view of the magnet. Small view shows schematically the shim contour.

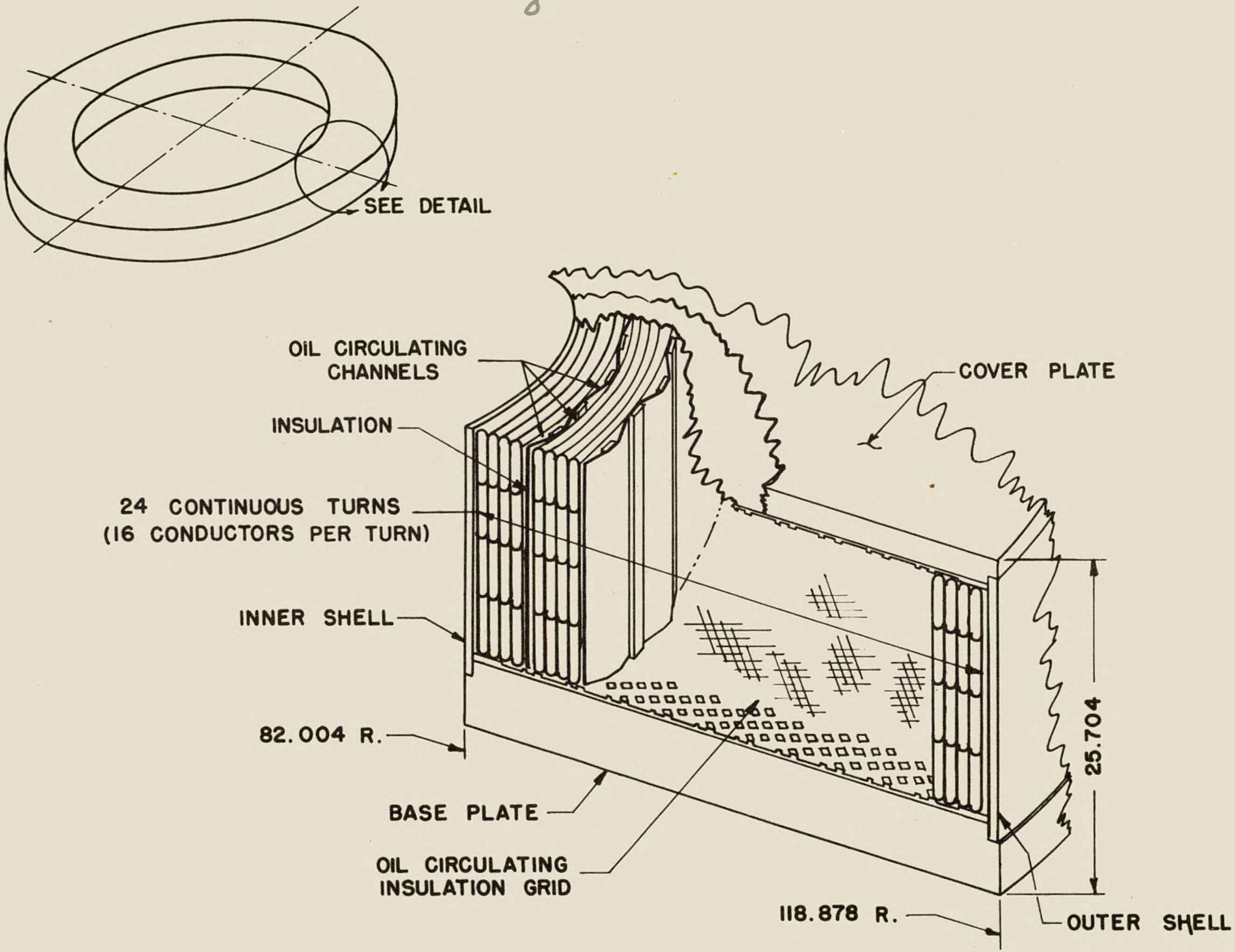

Fig. 2 —Schematic view of the coil. The sixteen copper bars and the insulation making up each turn are shown as in the formica insulating grid which serves to distribute the cooling oil.

stacked four high by four wide. Each bar is .339" wide and 4.930" high and approximately 15,000" long, made up of 35' lengths brazed together. The total weight of copper per coil is about 65 tons.

A band of 52S-1/2 hard aluminum 1/16" thick and 19-1/2" wide is used to bind the copper after winding. The ends of the band are wrapped around aluminum bars pulled together by bolts to produce a tension of 16,000 pounds.

The coil insulation consists of the horizontal formica plates and the vertical insulation between turns of the coil and between the coil and the can. The formica plates are 3/16" thick with 1/2" squares raised an additional 3/16". There are 24 15° sectors making up each base. These insulating grids serve to distribute the cooling oil uniformly over the coil.

The vertical insulation between the turns of copper is fabricated of sheets of fishpaper 47-1/2" long, 19-3/4" wide and .034" thick, butted together to form a continuous strip 15,000" long. The joints are made by glueing 2" wide by .030" thick strips of pressboard on each side. There are also strips of pressboard 1/2" wide by .060" thick glued on alternate sides of the fishpaper on 2" centers to form triangular cooling ducts through which oil flows vertically.

The insulation between the copper and the inner coil can is the same as that between the copper and the outer aluminum band. This consists of two layers of .093" press board with .093" x 1" x 1" angles at the top and bottom corners. Glass tape is inserted along all metal seams to prevent weld-flash from entering the can.

The cross-sectional area of a single turn of copper is 26.5 square inches. The average resistivity of the conductor is 1.69×10^{-6} ohm centimeters at 20° C. In the summer the coil may run as hot as 45° C at which temperature its resistance will be 417×10^{-6} ohms per coil. To obtain 480,000 ampere turns per coil, 20,080 amperes are needed. This requires 8.38 volts across the terminals and a dissipation of 168 kilowatts per coil. The voltage drop in the leads does not exceed one volt.

The measured powers are as follows:

Field in Center of Magnet	Power
20,000 gauss	323 kw
20,500 gauss	376 kw
21,000 gauss	436 kw

The vacuum chamber and pumping ducts were designed by CIT and made of welded aluminum at the Brooklyn Navy Shipyard. The chamber parts into two halves in a vertical plane through the center of the magnet, permitting the removal of the chamber without disturbing the magnet pole tips. (See Fig. 3.)

The dee is made of an aluminum frame covered with copper skins to which copper tubing is brazed. It is supported on insulating columns, making it possible to provide a DC bias. (See Fig. 4.) Fig. 4a shows the tuning line inner conductor which connects the dee to the rotary condenser.

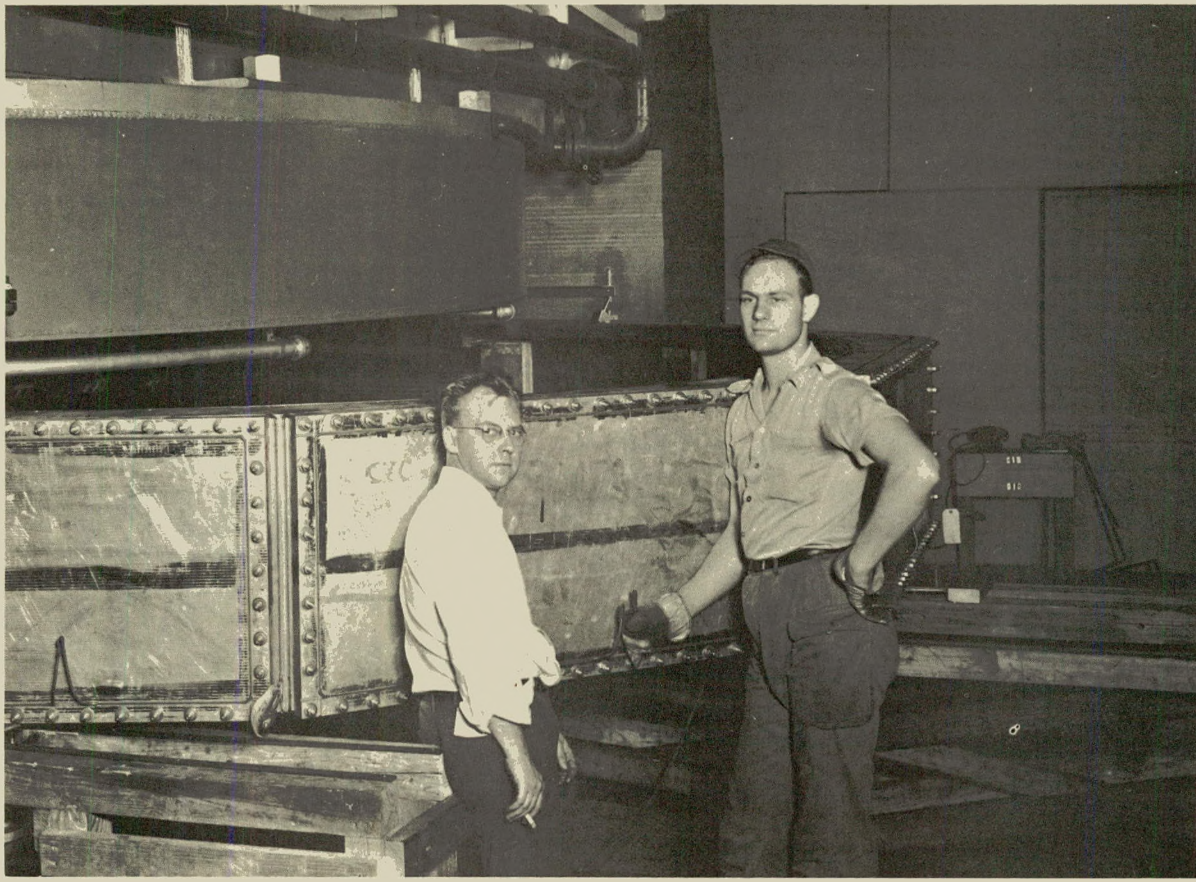

Fig. 3--One-half of the vacuum chamber about to be moved into place against the pole by Mr. Witt and Mr. Prasnikar.

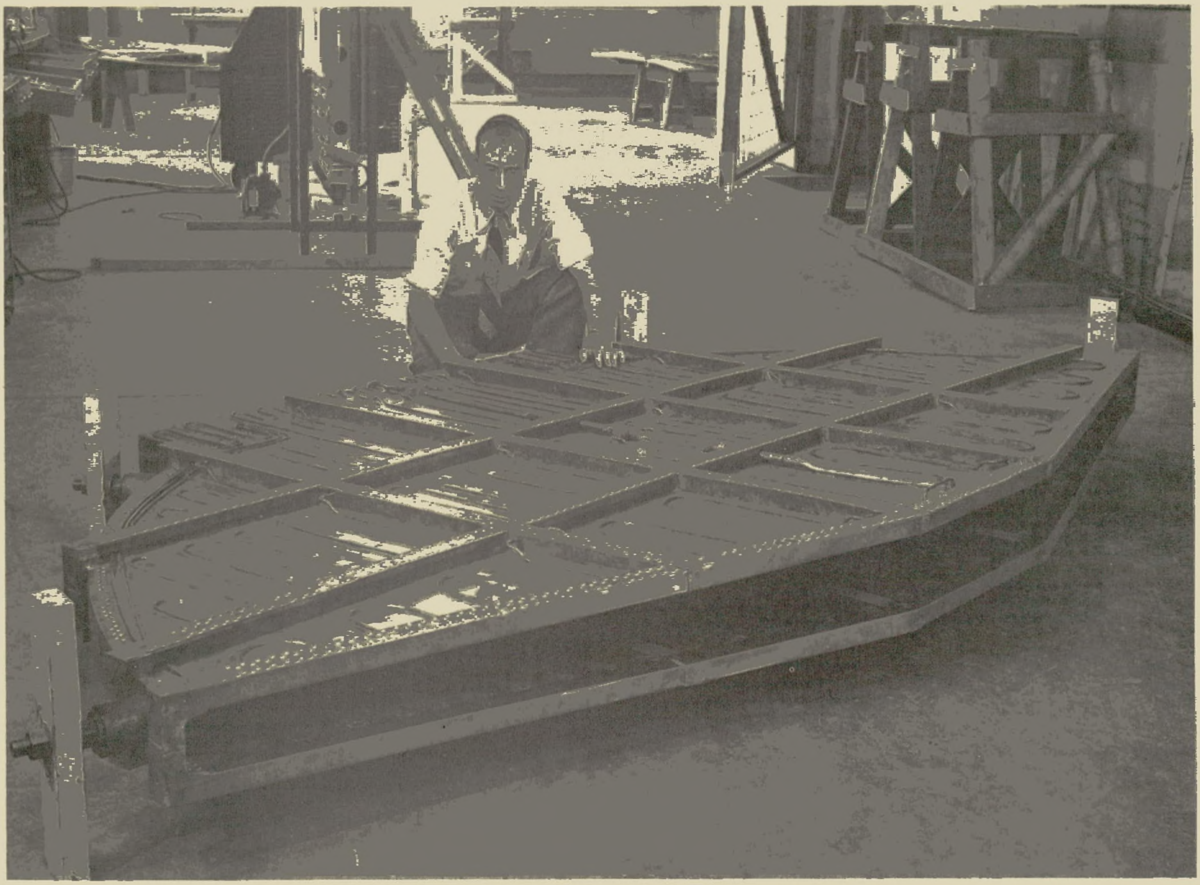

Fig. 4--Mr. Kearns inspects the dee.

Fig. 4a--Mr. Kearns leak testing the water cooling tubes on the tuning line inner conductor.

The pole tip liner consists of copper sheets to which copper tubing is brazed. Numerous holes are drilled in them to facilitate vacuum pumping.

An ion source and current measuring probe have been designed and constructed.

SECTION IV - VACUUM SYSTEM

The vacuum system for the cyclotron was originally designed and reported in an ONR report.[4/] Schematic layouts are shown in Figs. 5 and 6.

The various pieces comprising the 8 inch connecting lines between the 32 inch, 20 inch, and 8 inch diffusion pumps were made in our shop. Each assembly was leak-tested with a helium mass spectrograph after manufacture. The mechanical pumps were mounted in the fore-pump pit under the cyclotron. The vacuum chamber and ducts were thoroughly cleaned after arrival and were mounted in place.

With the chamber and ducts in place it was possible to mount the 32 inch diffusion pumps in their final position. The pump lines were aligned and the booster pumps and 4 inch fore-lines were then installed. Part of the plumbing is shown in Fig. 7.

A freon compressor for the freon cooled baffles was mounted in the fore-pump pit and connected to the 32 inch pump baffles.

After mounting the 15 HP roughing pump and the associated 8 inch roughing line to the chamber, the vacuum system was ready for testing. These tests revealed the following facts:

1) The chamber was tight and satisfactory for cyclotron use.

[4/] "Design of Cyclotron Vacuum System", D. Rose, Technical Report No. 4 (Navy Contract N7onr-303, Task Order 1) Carnegie Institute of Technology.

VACUUM CHAMBER IN CROSS-SECTION

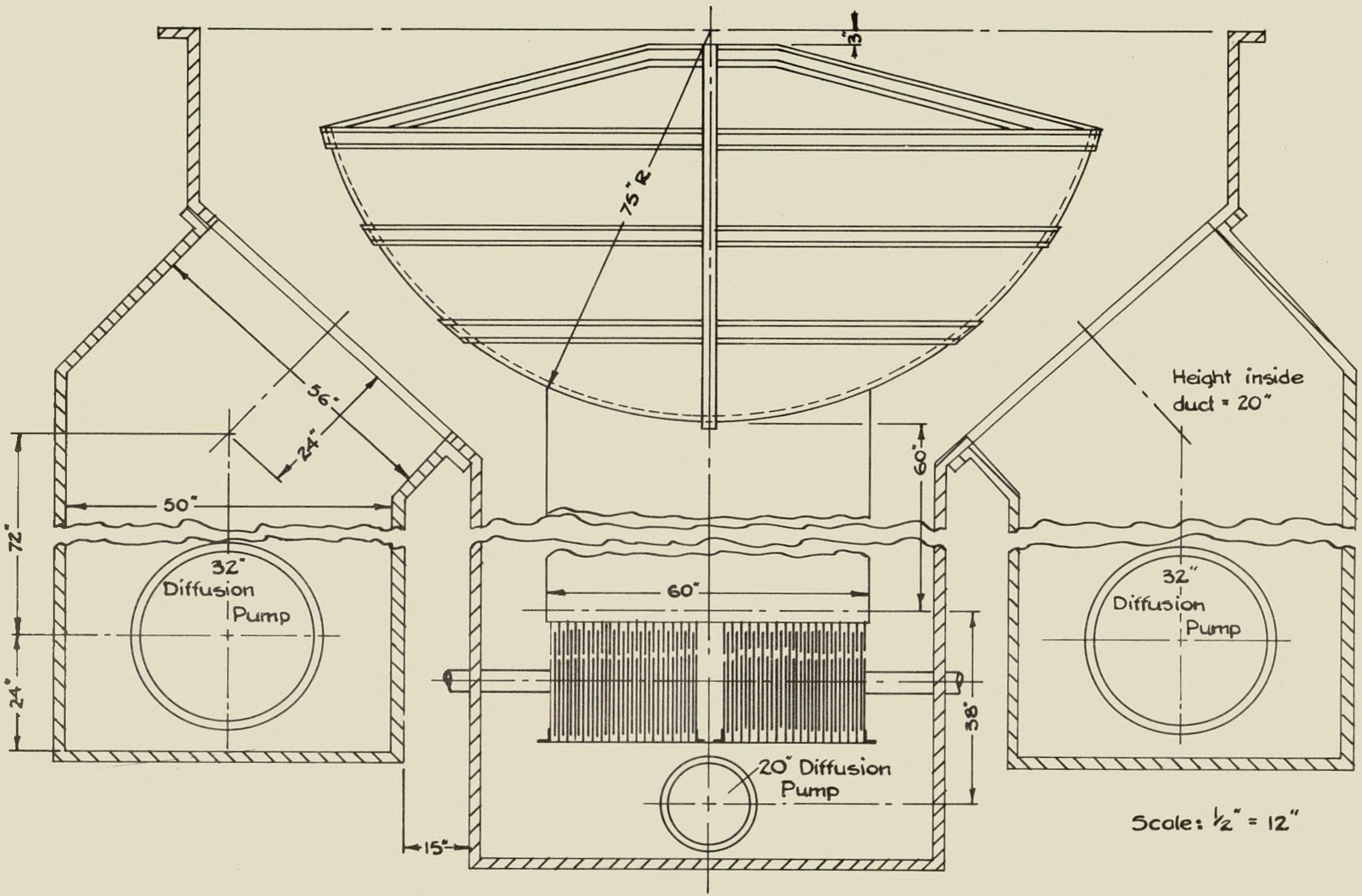

Fig. 5—Schematic diagram of the pumping system showing only that half of the vacuum chamber which contains the dee. The pumping ducts, diffusion pumps and rotary condenser are shown.

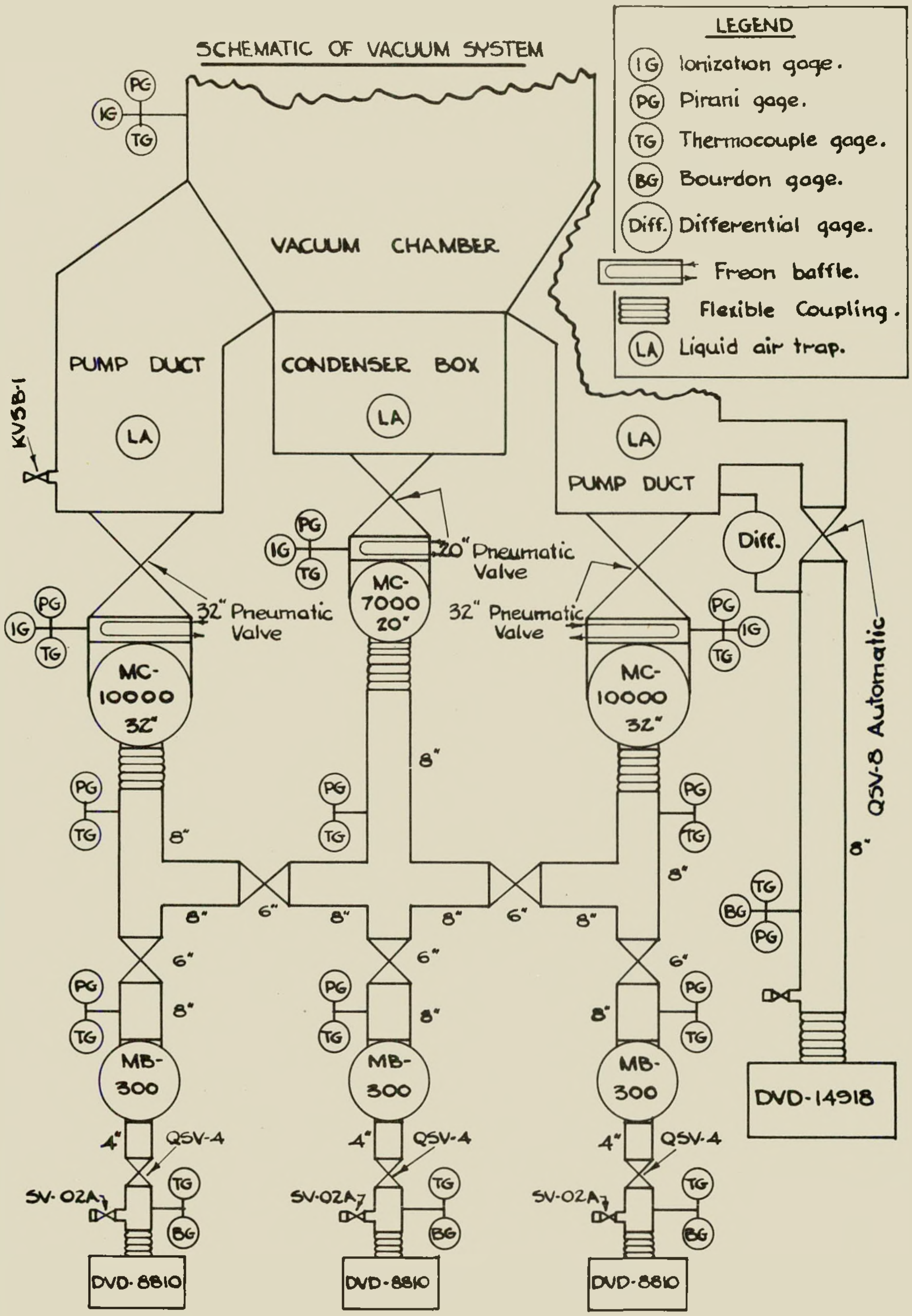

Fig. 6—Schematic layout of vacuum pump system. Dimensions in inches refer to diameter of lines.

Fig. 7--View from below the diffusion pumps.

2) Only two leaks were detected, and these were in the gasket seals. They were believed to be due to non-uniform thickness of gasket material.

3) The vacuum reached was 3×10^{-6} mm of mercury.

4) Starting with cool pumps and the system at atmospheric pressure, the pump-down times were as follows:

   1 hour, 45 minutes to reach 10^{-5} mm mercury

   2 hours, 30 minutes, to reach 3×10^{-6} mm mercury

Other activities of the vacuum group were:

1) Finding and testing suitable gasket material for the cyclotron.

2) Repairing and maintaining a helium mass spectrometer.

3) Conducting vacuum tests on the seal for the rotary condenser.

4) Examining high voltage and vacuum characteristics for material used in the rotary condenser.

5) Building test vacuum systems.

6) Establishing vacuum measuring methods for the cyclotron.

SECTION V - ELECTRONICS SHOP

The Electronics Shop was set up at Saxonburg and has carried out the following construction:

Power Supplies

General laboratory - 300 v	6
Geiger counters	6
General laboratory - 5 kv	2
General laboratory - 10 kv	1
General laboratory - 4 kv stabilized	1
High current supplies for generator fields	2
Current regulator for magnet	1

Sealing Circuits

Scale of 1024 with H.V. supply	6
Scale of 64 with H.V. supply	1
Scale of 2 plug-in units	50

Cyclotron Operation and Instrumentation

Ion source arc modulator with associated power supplies	1
Delay trigger for arc	1
Current stabilizer for manual control of cyclotron field	1

Current stabilizer for motor field in cyclotron field supply	1
Thirty megacycle frequency discriminator	1
Ion gauge control circuits	5
Pirani gauge control circuits	1
Thermocouple gauge control circuits	5
H.V. supply for multiple cold cathode ion gauges	1
<u>General Purpose Portable Pulsers</u>	3
<u>Ionization Gauge Control Units</u>	7
<u>Flux Measuring Equipment</u>	
Flux metering	1
0-2 kv regulated magnet current supply	1
Ultra-stable audio oscillator	1
<u>Laboratory Synchroscopes</u>	
High speed synchroscope-sweep .01 μsec/in with distributed type pre-amp and deflection amplifiers and sweep	1
Synchroscope-sweep .1 μsec/in with amplifiers and sweep	1
<u>Pulse Attenuators</u>	3

<u>Special Test Equipment</u>	
Pulse voltmeter	1
Pulse amplitude discriminator	1
Scale-of-two test circuit	2
Pulse amplifiers with discriminator	1
Pulse pre-amplifiers	4
<u>D.C. Amplifiers with Electrometer Tubes</u>	3
<u>Dual Pulse Height Selectors</u>	2
<u>Six Channel Coincidence Circuit</u>	1
<u>Counting Rate Meters</u>	2
<u>Pulse Amplifier with Probe</u>	1
<u>Coincidence Circuits</u>	2
<u>Three Channel Variable Delayed Pulse Generator</u>	1
<u>General Laboratory Equipment</u>	
Intercom-amplifiers	20
Public address amplifier	1

The Electronics Shop has maintained and repaired the above equipment in addition to the commercial equipment in use at the laboratory.

SECTION VI - OSCILLATOR

This report covers the period from February 1, 1947 to September 1, 1950. At the beginning of this period, work was proceeding on a model which had - due to a recent boost in magnet size - shrunk from full scale to approximately three-fourths scale. Four 304-TH tubes were used, a pair coupled into each of two long shorted coaxial lines extending radially from the dee structure, 90° apart, with a rectangular open-circuited line extending back between these coupling lines, to which the variable capacity was attached. This arrangement and subsequent modifications of it failed to give the frequency coverage desired; at this time it was hoped that the frequency bands required for both protons and deuterons could be covered with a simple adjustment of tuned traps, which would suppress the undesired band of frequencies. The configuration described above, however, was so susceptible to parasitic modes of oscillation that it would not have been satisfactory even for the acceleration of a single kind of particle. A major change was then made, involving moving the coaxial lines mentioned above so that they joined the structure at the open-circuit end of the rectangular tuning line. This arrangement, after solution of many theoretically insignificant yet troublesome problems concerning parasitic modes, wiring capacity, lead reactance, and tube coupling location, appeared quite promising. It had been decided by this time that relatively major changes would be required to shift from the deuteron band to the proton band and back. Up to this time, February 1949, only 304-TH and 304-TL tubes had been used, and the variable capacitance employed was a simple affair sometimes made up of a large stationary plate and a large swinging plate, sometimes numbers of war-surplus vacuum condensers, and sometimes an array of several transmitting type variable air condensers. Of these methods the first proved most satisfactory. No rotary condenser had been designed in time for a model to be constructed and used.

In February 1949 we moved, and arranged that at the new location we would install a new model which would be full-scale, using a rotating condenser - which was to be an inexpensive model of the prototype condenser planned at that time - and using type 880 tubes, as planned on the prototype. Procurement and modification of the various components, arrangements for filament power, water and air cooling, and sundry details delayed initial operation of the full-scale model for several months. It was soon found, however, that data from the three-fourths scale model could serve as little more than a guide to what one might expect from the larger model. For example, results now indicate that four 880's will suffice, while the data from the three-fourths scale model had indicated that six would be necessary. This does not indicate a failure of the principles of dimensional analysis, but rather is attributable to differences in physical details, such as dee capacitance, proportions of the structure, and tube parameters.

Once again the "de-bugging" process was drawn-out. Parasitic modes at higher frequencies than desired for proton acceleration were successfully eliminated with light-bulb loads inductively coupled to the tube lines, and the lower mode (the principal mode, which, it had been hoped, would serve for deuterons, but fell in the wrong range) was avoided by means of a series resonant circuit from dee to vacuum chamber. Extensive experimentation with tuning line and tube line length, and with tube coupling position, led to an arrangement which covered the desired band for protons (19 to 32 mc) but which skipped a narrow range of frequencies around 25 mc. These holes disappeared when the rotating toothed model condenser was replaced with one of the swinging-plate type. Further investigation and analysis indicated that a sidewise resonance was occurring, in which the convolutions of the teeth of the rotating condenser acted as a lossy resonant line at the frequencies where the hole in the band occurred. With these ideas in mind, Dr. Martyn Foss supervised the redesign of the rotating condenser so as to avoid these difficulties and still obtain the range of capacitance necessary to cover the frequency range.

A schematic circuit of the oscillator is shown in Fig. 8 and a schematic section in Fig. 8a. A plot of rotary condenser capacity as a function of oscillator frequency observed on the model is shown in Fig. 9. Fig. 10 shows the variation of dee lip voltage with frequency (with 1200 volts on the 880 plates) with the value of grid resistance (four oscillator tubes) set to give best results. Other curves show in Fig. 9 how

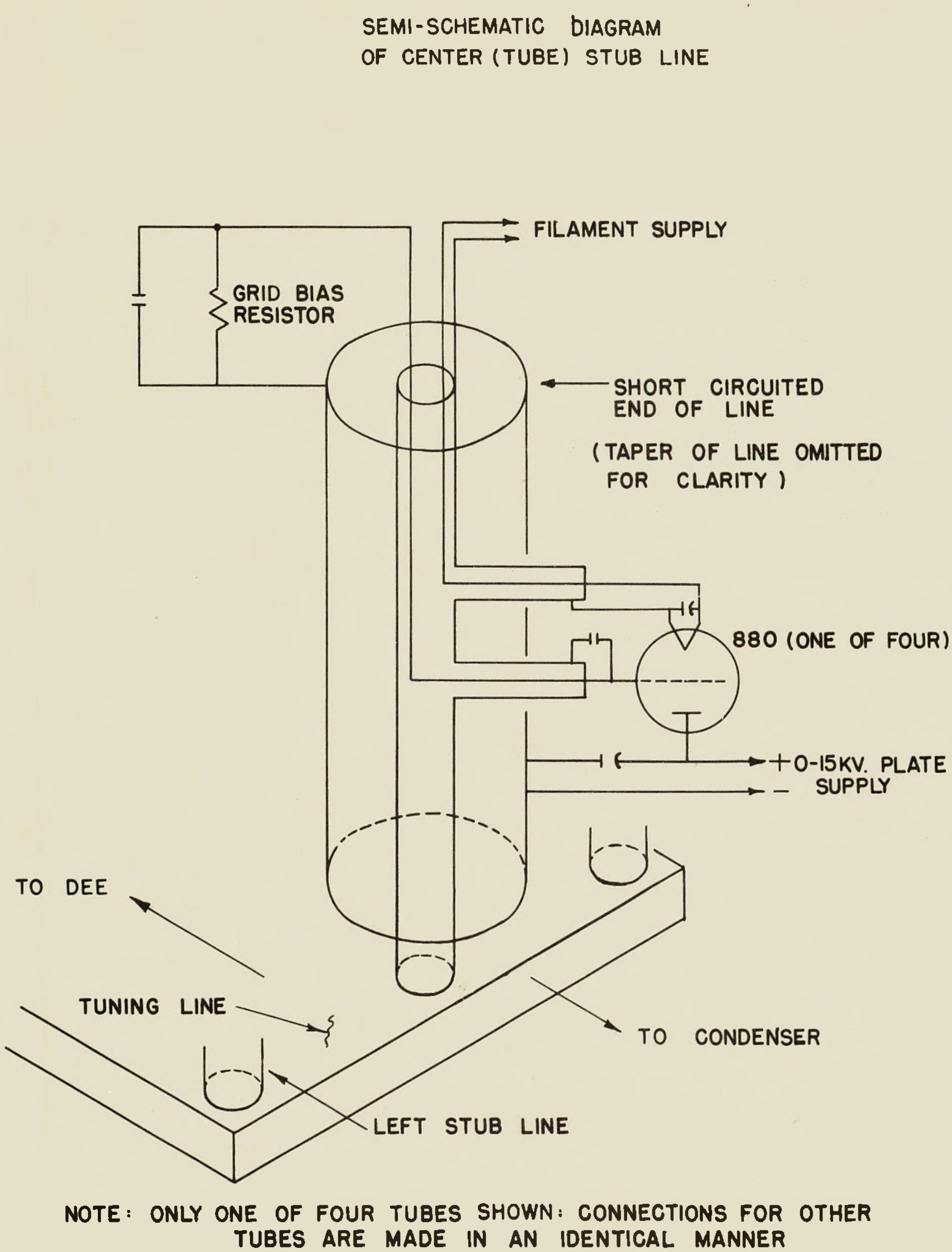

Fig. 8—Schematic circuit of the oscillator showing electrical connections.

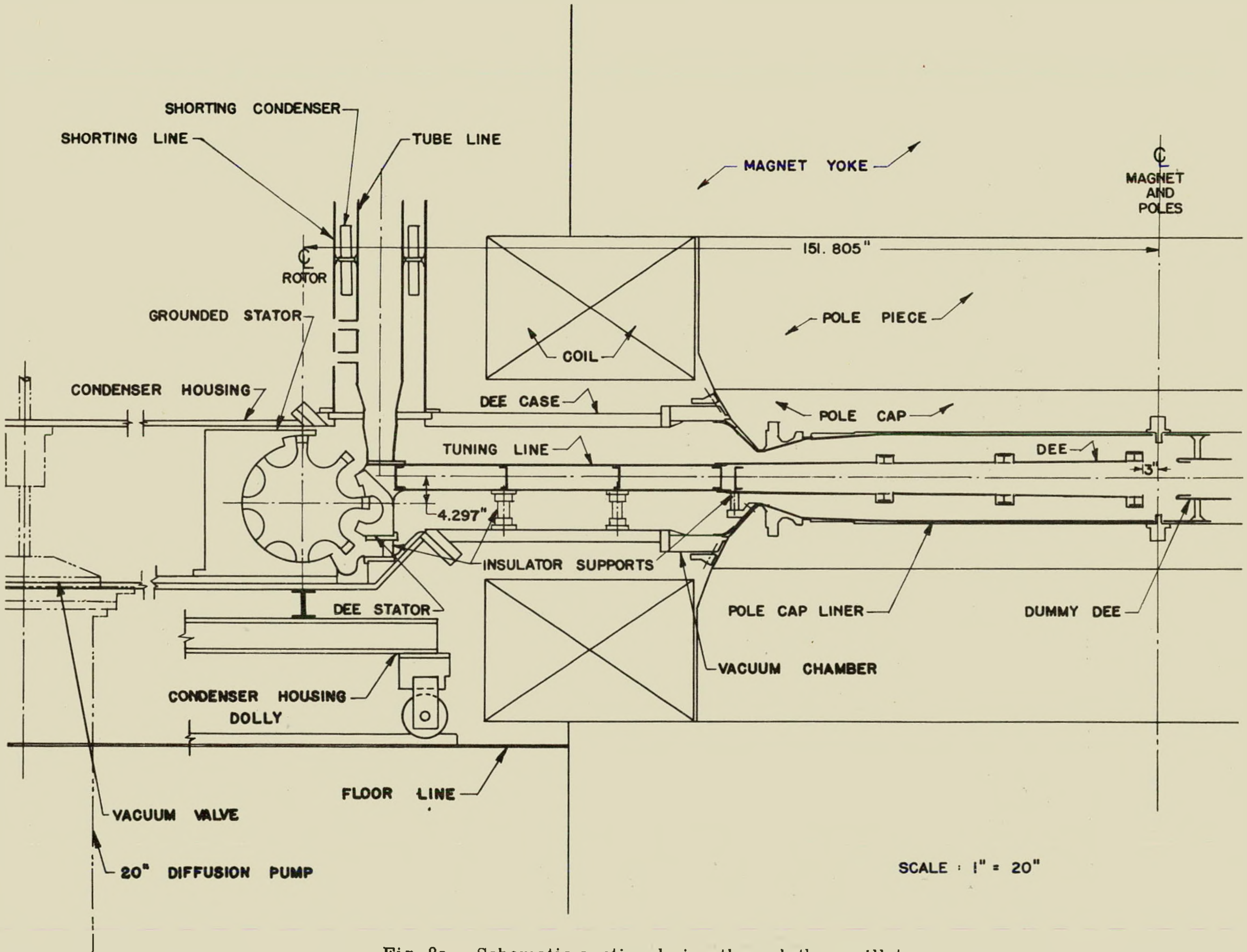

Fig. 8a—Schematic sectional view through the oscillator.

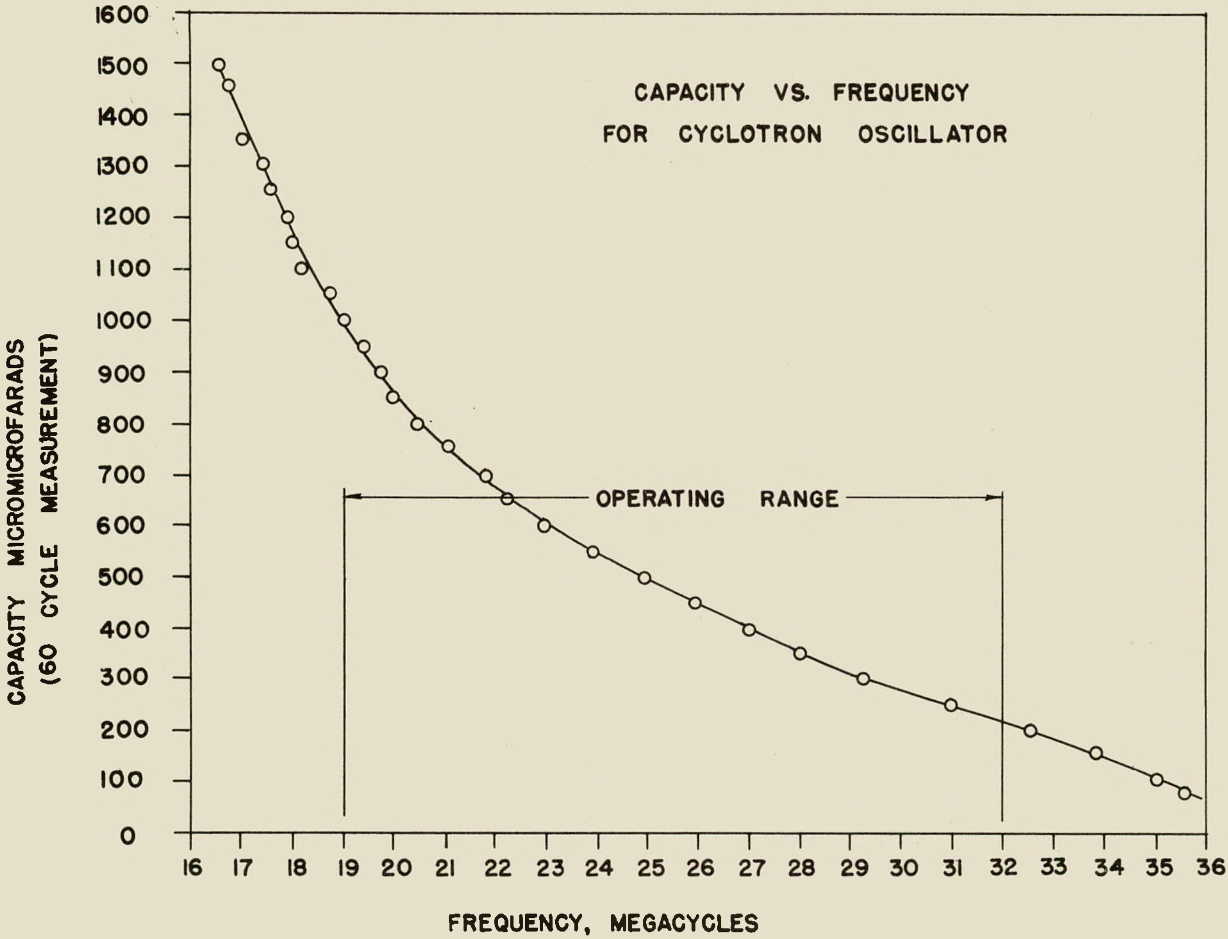

Fig. 9—Capacity necessary in rotary condenser to produce various frequencies in model oscillator.

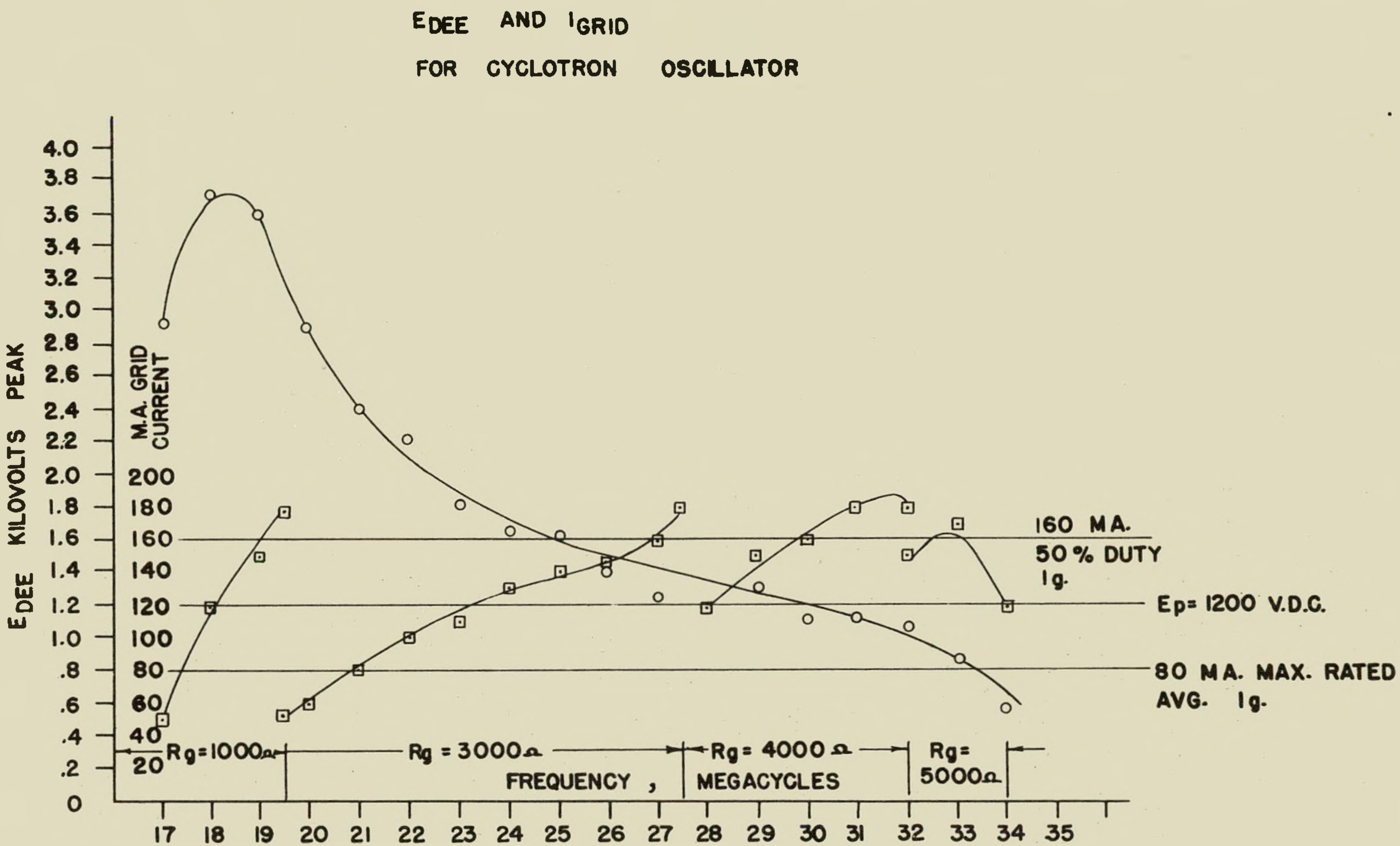

Fig. 10 — Measured voltage on the dee lip of the model oscillator with 1200 volts on the plates of the four 880's. Grid current and optimum grid resistor are also shown.

oscillator tube grid current varies over the FM cycle; average grid current for the FM cycle is somewhat less than 160 ma.; thus with the oscillator working on a .5 duty ratio, average grid current will fall under 80 ma., which is inside the manufacturer's ratings. After much discussion and reworking, the order for the condenser was finally placed.

In February 1950 another move was necessary, this time to the cyclotron site. The model was taken apart, transported to Saxonburg, and reassembled in the equipment room, where the plate and filament power supplies for the prototype were already located. Here the model was operated with these prototype components, and a few final measurements involving the practicability of sealing off the vacuum chamber at the base of the tube lines were made. The results of the work to that date were forwarded to Mr. Berman, who carried forth the mechanical design for the prototype.

The capacitors for the pulse-forming network which connects the Westinghouse 15 kv constant current power supply to the oscillator have been installed, and the reactor which is to be used with them has been ordered. Spare 880 tubes have been purchased, and their mountings and magnetic shields have been designed. Design of equipment for turning the oscillator on and off, and for measuring various RF voltages around the structure is proceeding. The same is true of negotiation on the matter of the capacitive terminations for the tube lines, this being necessitated by the desirability of being able to bias the dee with a DC voltage of up to 2 kv. The matter of plate by-pass condensers is at present under consideration.

At a later date, further investigations may be undertaken concerning the possibility of covering the deuteron range.

SECTION VII - ROTARY CONDENSER

One of the most difficult problems of the synchro-cyclotron design was that of the rotary condenser. It was of course necessary to carry out this design concurrently with the experimental work on the oscillator. Changes in this program made it impossible to freeze the condenser design until early in 1950.

The rotary condenser modulates the frequency of the oscillator over the required band, about 32 to about 19.5 megacycles per second. The rate of modulation influences the phase of the accelerated ions. The condenser is designed to accelerate the ions at constant phase according to data taken on the 3/4 scale oscillator. Since the final oscillator will not have the same "D" voltage vs. frequency it is fortunate that this relation is not critical.

The time spent by the condenser to return to low capacity (high frequency) is wasted so far as the cyclotron is concerned. Since the power available can operate the oscillator on a 50 percent duty cycle maximum, the condenser is designed to return to low capacity in the same time that it takes to get from low to high capacity.

A condenser of this type acts as a capacity loaded transmission line in the direction of the axis of the shaft. If the wave velocity parallel to the shaft is such that the shaft is a whole number of full waves in length then the average voltage on the D stator is zero, thus reducing the grid excitation to zero. This behavior is commonly encountered in 300 megacycle work; the large size of this equipment brings it into the 25 megacycle band.

The difficulty is eliminated by keeping the wave velocity along the axis high. In order to accomplish this the axial inductance is kept as low as possible and about half the capacity to ground is located in concentric ring condensers near the ends of the shaft which propagate a signal with the velocity of light. The ring condensers fit closely around the cylindrical section of each end of the rotor. The rotor is made of aluminum alloy 14S which has been heat treated to obtain better strength.

The first critical speed is at about 10,500 rpm. and the expected maximum operating speed is about 3500 rpm. At 3000 rpm. the rate of frequency modulation is 400 cycles/sec. At 3500 rpm. the bearings should have a life-time of approximately 10 years. The bearings are S.K.F. spherical seat roller bearings, mounted in a special bearing housing assembly, which was designed for this particular purpose in order to incorporate both the function as a bearing housing and seats for the rotating vacuum seals, used to bring the 3.5" diameter shaft through the vacuum wall of the condenser housing. This entire assembly is simultaneously cooled, lubricated, and sealed with Myvane oil, which is pumped through and cooled in an outside heat-exchanger, and it is mounted on low dielectric-loss insulators to the condenser housing since this is at ground potential whereas both the bearing and vacuum seals are at 2000-3000 volts rf. potential.

The grounded stator is made from a solid steel forging which was copper-plated after finish-machining. It provides a magnetic shield for the rotor, thus reducing the eddy current losses during operation. The dee stator is made from a solid copper forging.

The housing is made from 1-1/4" low carbon steel plate, vacuum-tight welded all around. A rotating water-seal is mounted at the end of the rotor shaft in order to lead cooling water into and out from the rotor. Six V-belts are used for the drive. The entire condenser will be mounted on a cart running on four flanged wheels in order to facilitate easy assembly and disassembly of the condenser from the rest of the cyclotron. A sketch of the condenser layout is shown in Figs. 11, 11a, and 11b.

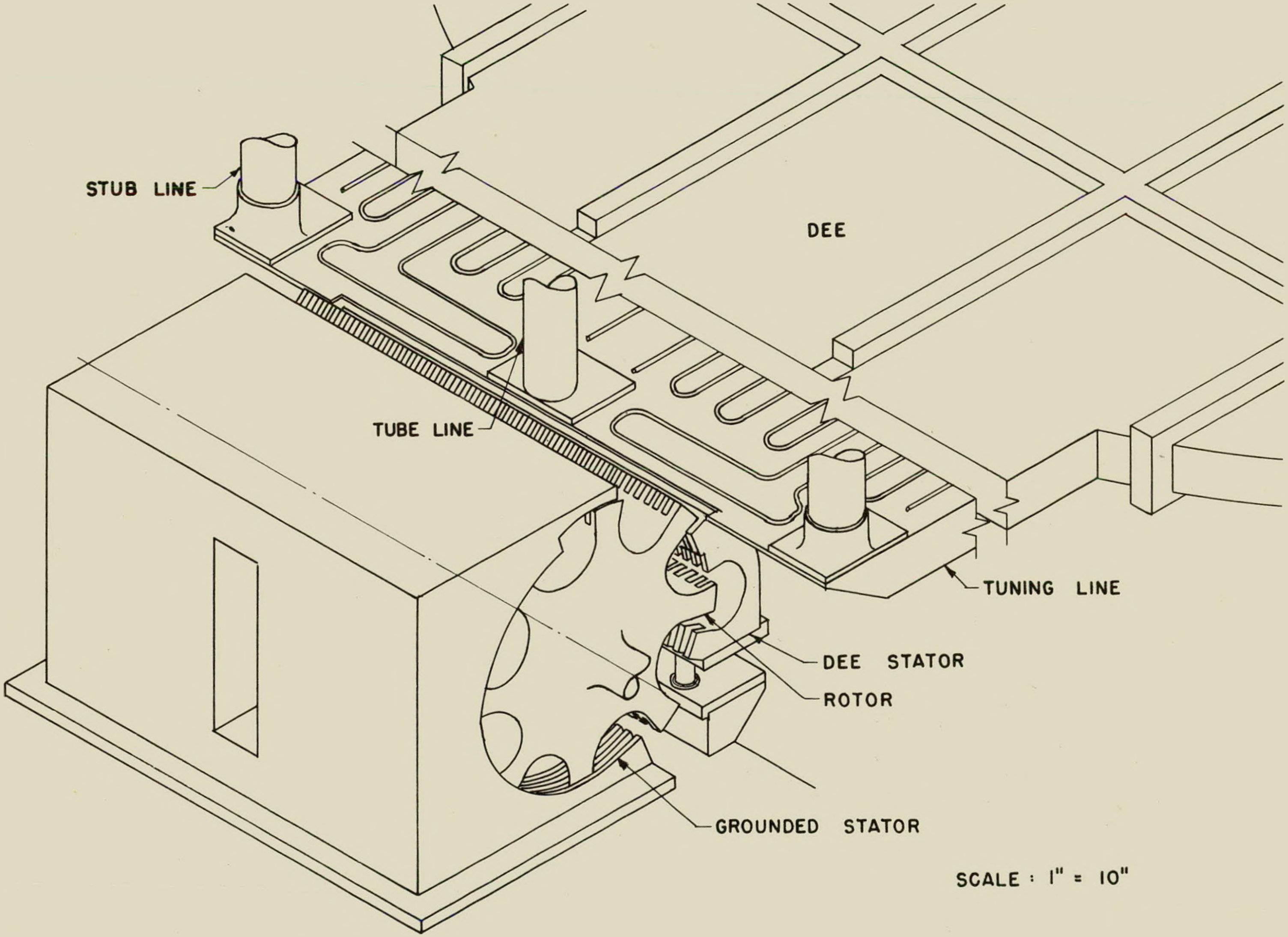

Fig. 11 — Rotary condenser. Notice the break between the tuning line and the dee in this drawing.

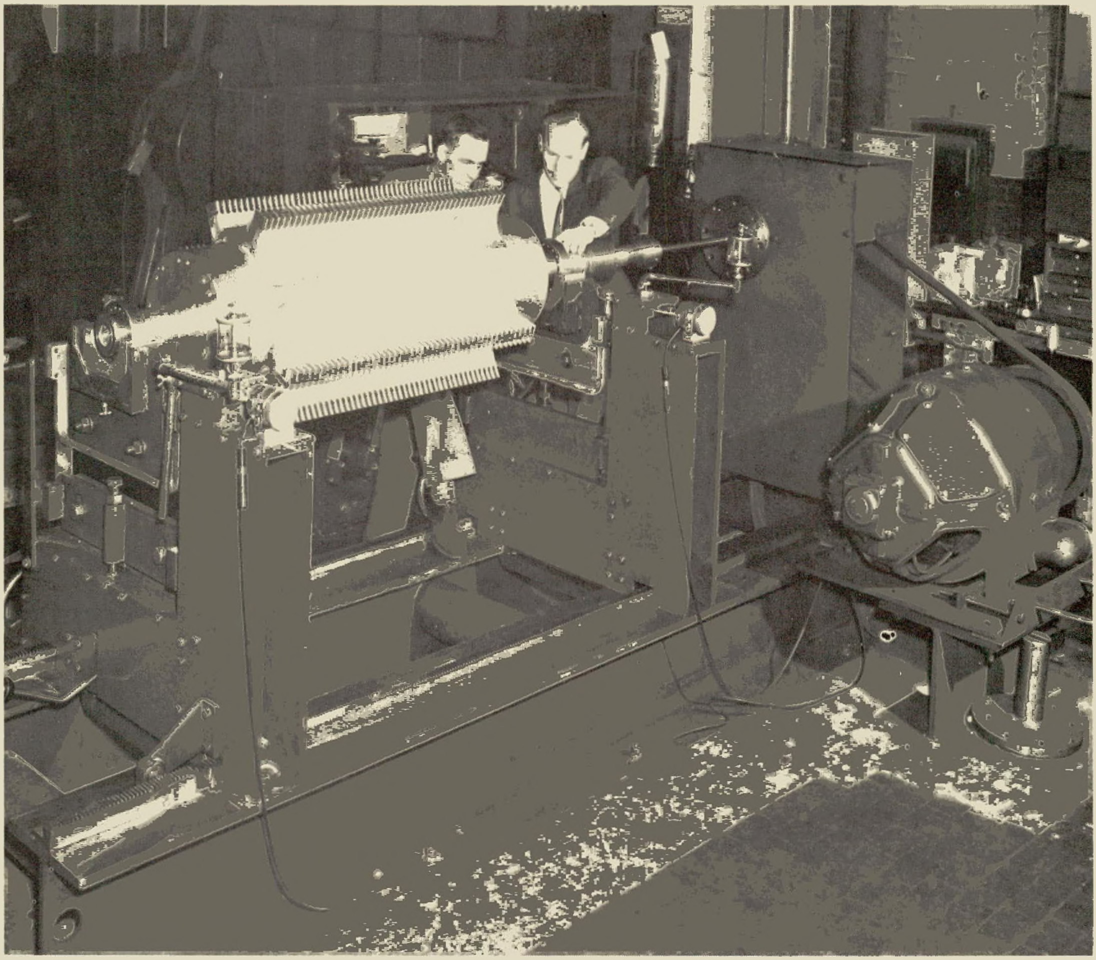

Fig. 11a — The condenser rotor being balanced by Mr. Ankersen and Mr. Sattelmeyer.

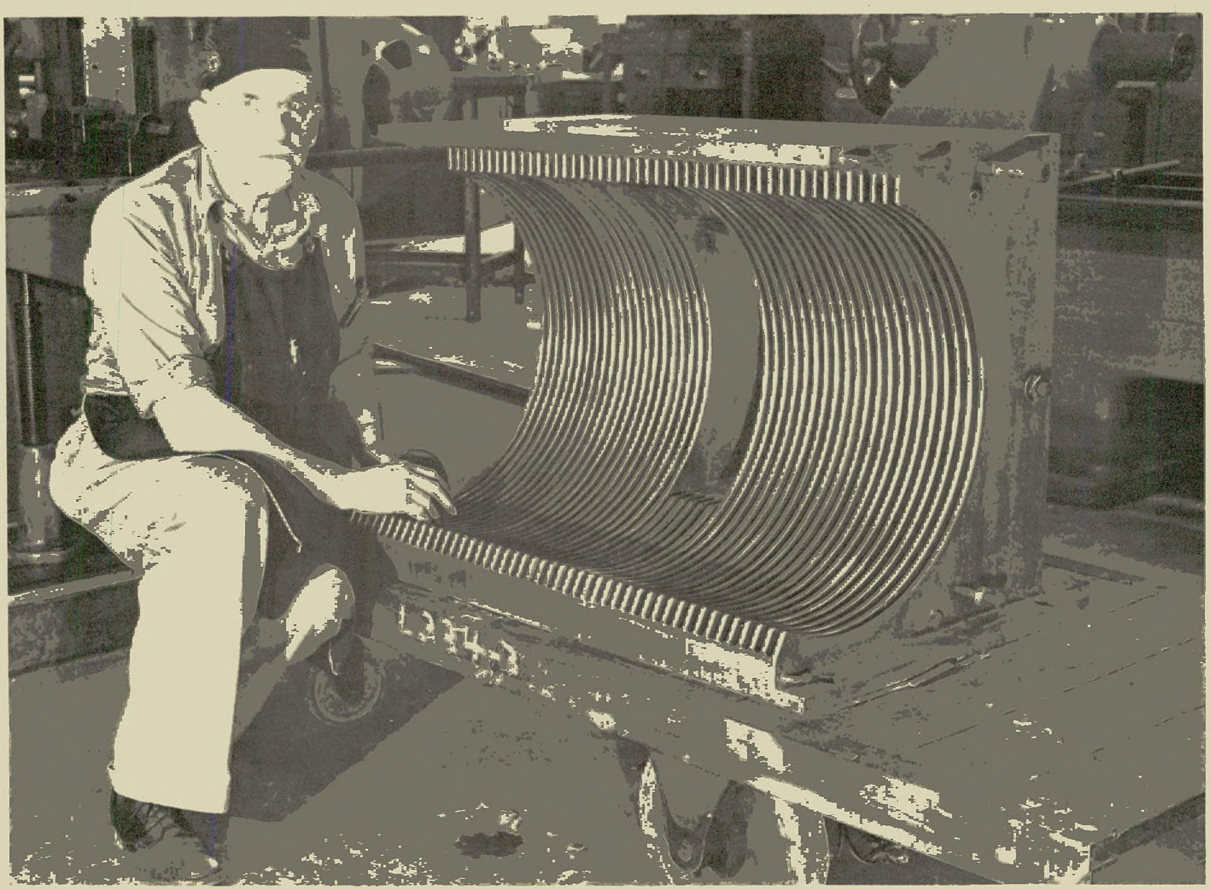

Fig. 11b--The grounded stator of the condenser being checked by Mr. Cooper.

SECTION VIII - SHIELDING

In order to save space in the cyclotron room a dense material was sought for the radiation shielding. The material chosen was magnetite concrete[5/] consisting entirely of commercial magnetite, Portland cement, and water. Extensive studies were made to determine the optimum proportions of these ingredients to give suitable strength with high water content and high density. A density of 200 pounds per cubic foot was obtained with a 28 day crushing strength of 3,000 pounds per square inch and a water content of 10 percent. The diffusivity of moisture from this concrete was measured and found not to contribute seriously to the deterioration of the shielding properties during a ten-year period.

One wall, that which separates the control room from the cyclotron, was prepared with a mixture of this magnetite concrete and surplus one-pound projectiles. Three hundred twenty tons of these projectiles were supplied by the Navy and it was found possible to mix 200 pounds of these and 100 pounds of the magnetite concrete in each cubic foot.

All removable shielding blocks were stacked in two vertical layers to that no straight-through cracks remained. The total thickness

5/ "Magnetite Concrete for Radiation Shielding", E. Creutz and K. Downes, Journal of Applied Physics, Vol. 20, No. 12, pp. 1236-1240, December 1949 of the wall shielding is eight feet with space available to increase it by at least another six feet if necessary. Ceiling beams of reinforced concrete provide five feet of shielding overhead. A 45-ton crane is available for moving the shield blocks. Views of the ceiling shield are shown in Figs. 12 and 13.

Two 80-ton doors are provided. These are elevated into the closed position by means of three hydraulic cylinders under each. Safety devices are provided so that these doors cannot be moved from the open position when any appreciable weight such as the weight of a man is added to them. Also, they cannot be opened without turning off the cyclotron oscillator or reducing the magnetic field from its resonance value. A partly open door is shown in Fig. 14.

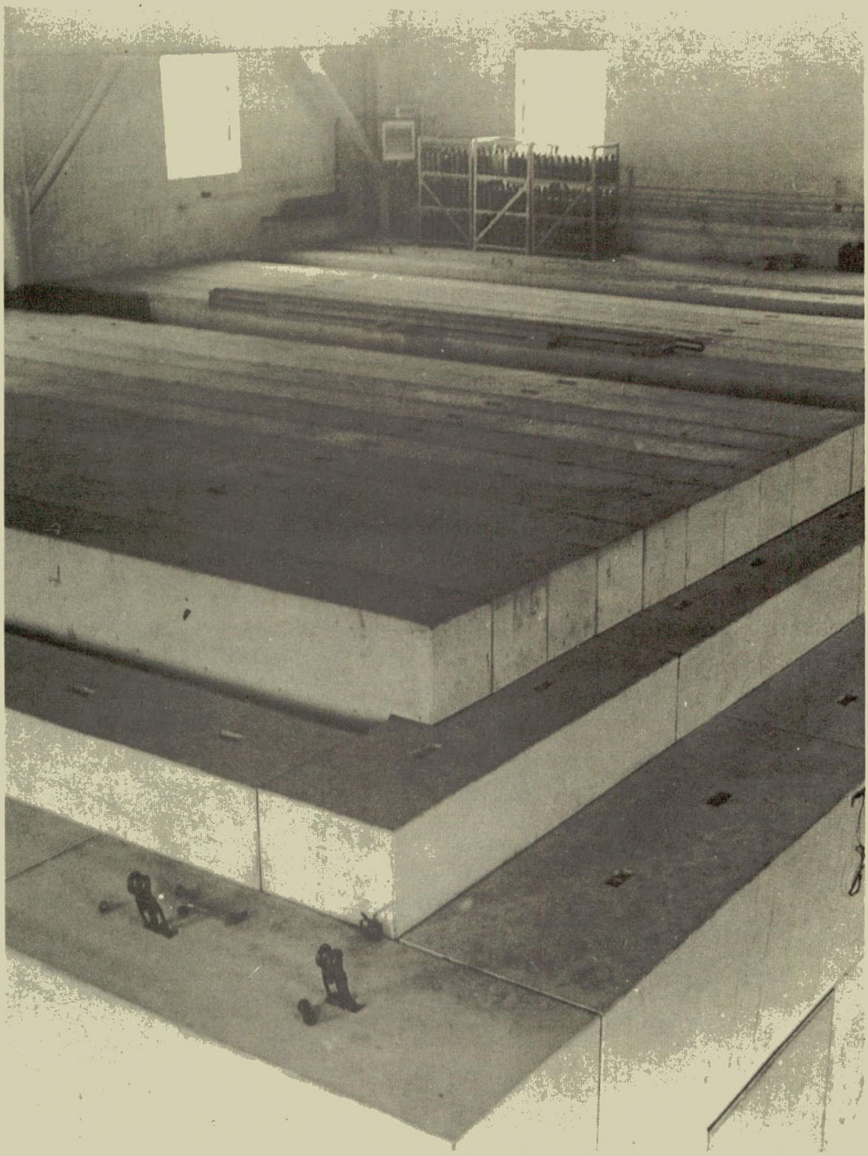

Fig. 12--View of the shielding from above.

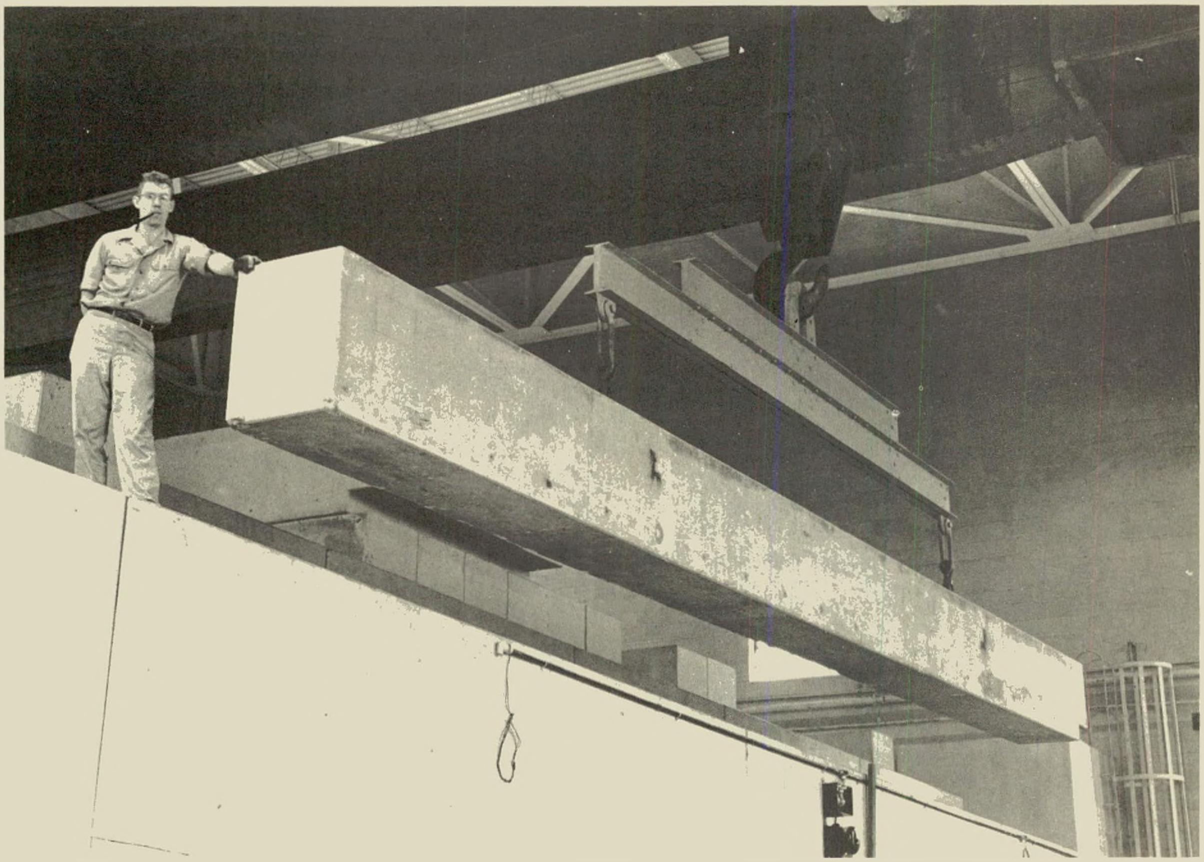

Fig. 13--One of the ceiling shielding blocks being put in place. This is being supervised by Mr. Downes.

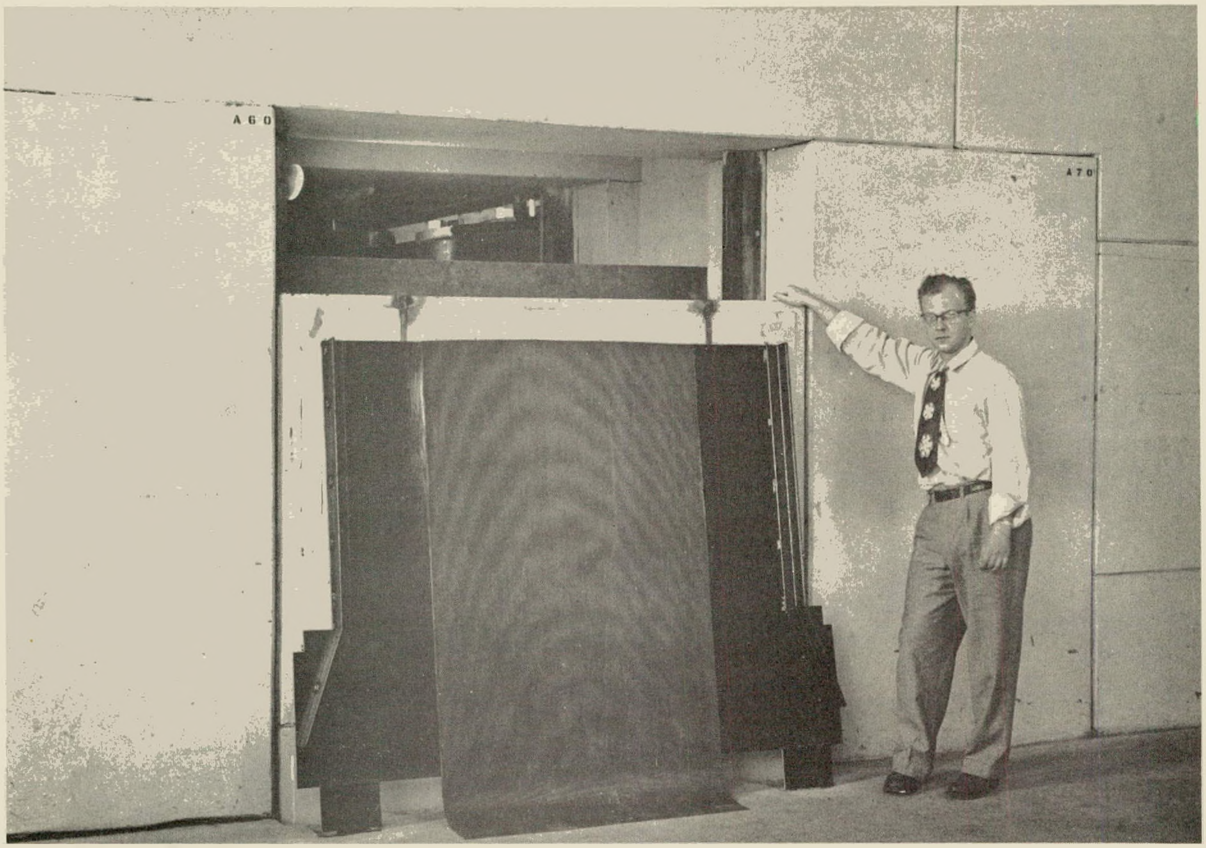

Fig. 14--One of the two hydraulically operated doors being raised into the closed position. The black painted steel panel in the foreground is a safety door which lies horizontally when the concrete block is in its lowered position. As the block rises, this steel panel lifts and removes any obstructions.

SECTION IX - COOLING SYSTEM

The design and construction of the synchro-cyclotron incorporated two primary and one secondary cooling systems as follows:

A. Primary

1. Oil Cooling System - removes heat from copper coils which provide the magnetic field.
2. Recirculating Water Cooling System - removes heat from various apparatus and surfaces such as homopolar generator, rotary condenser, oscillator, vacuum tubes, dee, dummy dee, pole tip liner, etc.

B. Secondary

1. Cooling Tower System - removes heat from the media in the two primary systems and dissipates it through a cooling tower.

Oil Cooling System

The oil cooling system must function in a satisfactory manner to remove heat from the copper coils at the rate of 300 or more kilowatts and dissipate this heat to water in the cooling tower system at a similar rate by means of a suitable exchanger. In addition, the oil being in direct contact with the copper must not experience too high a temperature rise and also must be inhibited against the catalytic oxidation effect of copper on oil. Because the oil passages in the copper coils are exceedingly narrow, with a right triangular cross-section .060" x 2" it is imperative that oxidation products do not easily form, that foreign matter, particularly metal and moisture be kept from the system, that every effort be made to maintain the oil in or close to its original condition.

The manner in which the coils are actually cooled by the oil is intimately related to actual coil development and design which has been discussed in detail elsewhere.[6] It is upon the final design that the above specifications for the oil cooling system depend. The design stipulates that the quantity of oil required would have to be in excess of that dictated by the heat capacity of the oil. The rate of oil flow therefore required to dissipate 300 kw. must exceed 525 gpm. The rate of flow selected for design purposes was 600 gpm. with a 10° F temperature rise in the bulk of the oil. This would allow for a larger temperature rise in the boundary layers. To accomplish this a distribution and piping system was designed to allow a maximum rate of 800 gpm. oil flow rate. The additional capacity provides a suitable safety factor and allows for some decrease in heat transfer rates over a long period of time. The power is supplied by a 25 hp. 800 gpm. Ingersoll Rand, Cameron centrifugal pump.

In order to insure uniform temperature over the entire coil the distribution system is arranged wo that each coil is supplied by four

[6] "Synchro Cyclotron Progress Report", July 1, 1948 (Navy Contract N7onr-303, Task Order 1) Carnegie Institute of Technology

symmetrical inlet and four symmetrical discharge manifolds with means of adjusting slight differences in the flow rates.

The heat exchanger, designed by the Griscom-Russell Company, is a two pass shell-tube type with oil on the shell side and water from the cooling tower system in the tubes. Its capacity provides for a 10° F drop in oil temperature and a 9.3° F rise in the cooling water. The design values throughout the oil cooling system have been substantially verified in actual operation. In fact, a total of 356 kw. have been removed without exceeding maximum design limits.

The oil used is a special purpose oil produced by Gulf Oil Corporation known as Cyclotron Oil. It is fortified by an inhibitor against catalytic oxidation on copper. Further protection and oil maintenance are provided by frequent centrifuging using a De Laval separator and periodic examination of oil samples for increases in neutralization-number and moisture content.

Further precautions were employed to prevent initial presence of foreign matter in the oil by completely descaling the interior of all steel pipe and parts and the inclusion of strainers just prior to the oil inlet manifold to the coils.

The magnet oil cooling system has operated approximately 395 hours to date producing results that indicate fully satisfactory operation.

Recirculating Water Cooling System

The cooling load for the various apparatus which the recirculating water cooling system is designed to serve has been estimated as follows:

Oscillator - 4 to 6 880 vacuum tubes		125 kw.
Homopolar generator		30 kw.
Filaments		10 kw.
Rotary condenser		18 kw.
Cloud chamber		100 kw.
Bus bar, Ion source, Deflector, Vacuum chamber walls		5 kw.
	Total	288 kw.

Knowing the total load and allowing a 10° F rise in the cooling water it becomes apparent that the quantity of water must be in the range of 175 to 200 gpm. Using this as a basis an Ingersoll Rand, Cameron centrifugal pump was selected to produce a head of 141 psi. at the rated flow of 200 gpm. Copper tubing and brass fittings are employed throughout the distribution system. A Griscom-Russell designed heat exchanger transmits the heat from the recirculating water to water in the cooling tower system, the recirculated water passing through the shell and the cooling tower water through the tubes. Both heat exchangers are shown in Fig. 15. Automatic control maintains a pressure of 50 psi. through the distribution system.

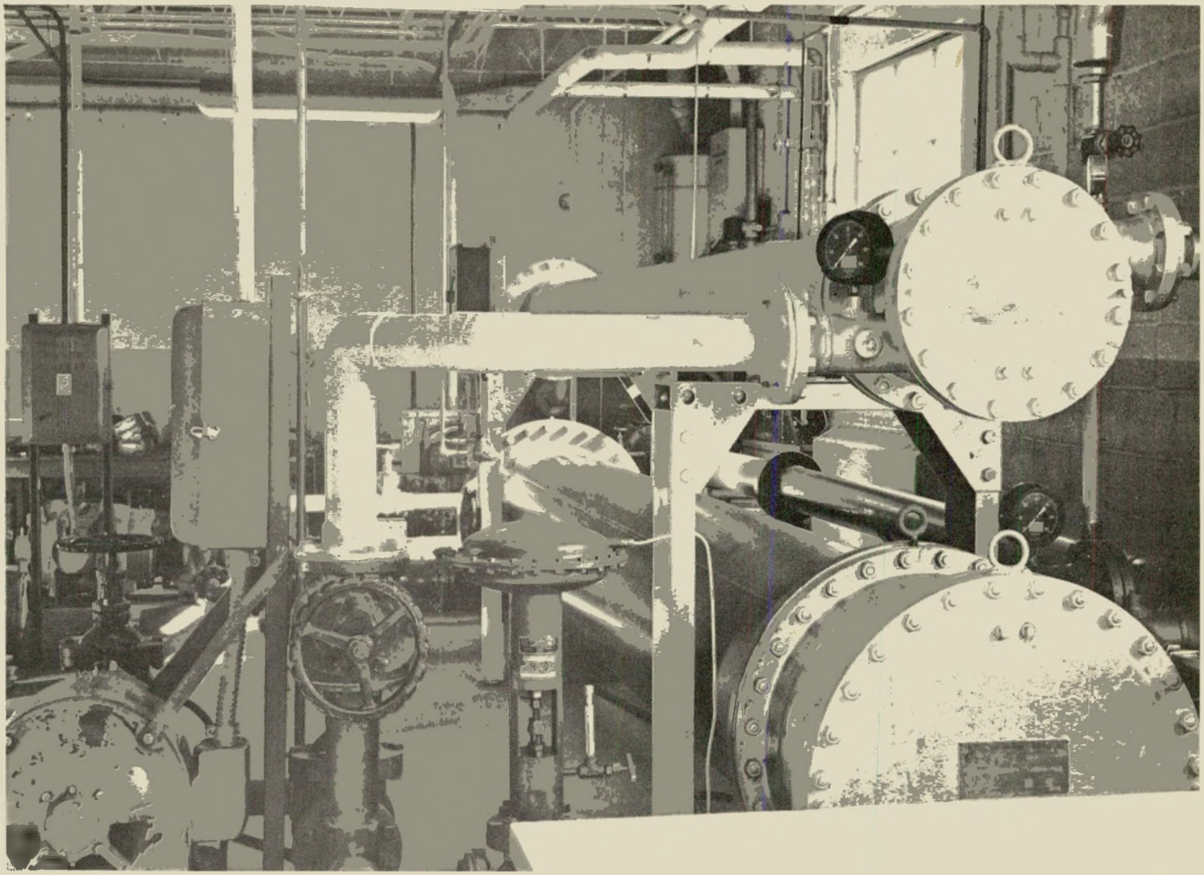

Fig. 15--The circulating water system heat exchanger above and the oil heat exchanger below. The oil centrifuge may be seen just beyond the far end of the lower exchanger.

Five manifolds are available adjacent to the cyclotron for convenient connection with cooling ducts in individual equipment. An automatic make-up and expansion tank keeps the water supply constant in the system. The use of steel and aluminum equipment requires the addition of an inhibitor to reduce attack on the aluminum and steel provoked by the presence of minute quantities of copper in the water. The use of 1/8 ounce per gallon of sodium chromate is planned.

The system is only partially used and has operated satisfactorily on this basis for over nine months.

Cooling Tower System

This system employs a Fluor Corporation induced draft counter flow cooling tower of standard design to dissipate the 300 kw. from the oil cooling system and the 288 kw. from the recirculated water cooling system, a total of 588 kw. The tower is designed to produce a 10° drop in the water temperature with a 3° approach to the wet bulb temperature. Normal flow of 425 gpm. will dissipate 607 kw. With a maximum flow of 500 gpm. dissipation of 715 kw. is possible. The tower is shown in Fig. 16.

The system includes an Ingersoll Rand, Cameron centrifugal pump capable of 500 gpm. discharge at 62 psi. Automatic temperature control in the oil system operates a pressure controlled valve to the oil heat exchanger. Make-up water is automatically supplied to the cooling tower pump by a level control. The fan used to force air up through the tower is dual speed, allowing a change for summer or winter operating conditions.

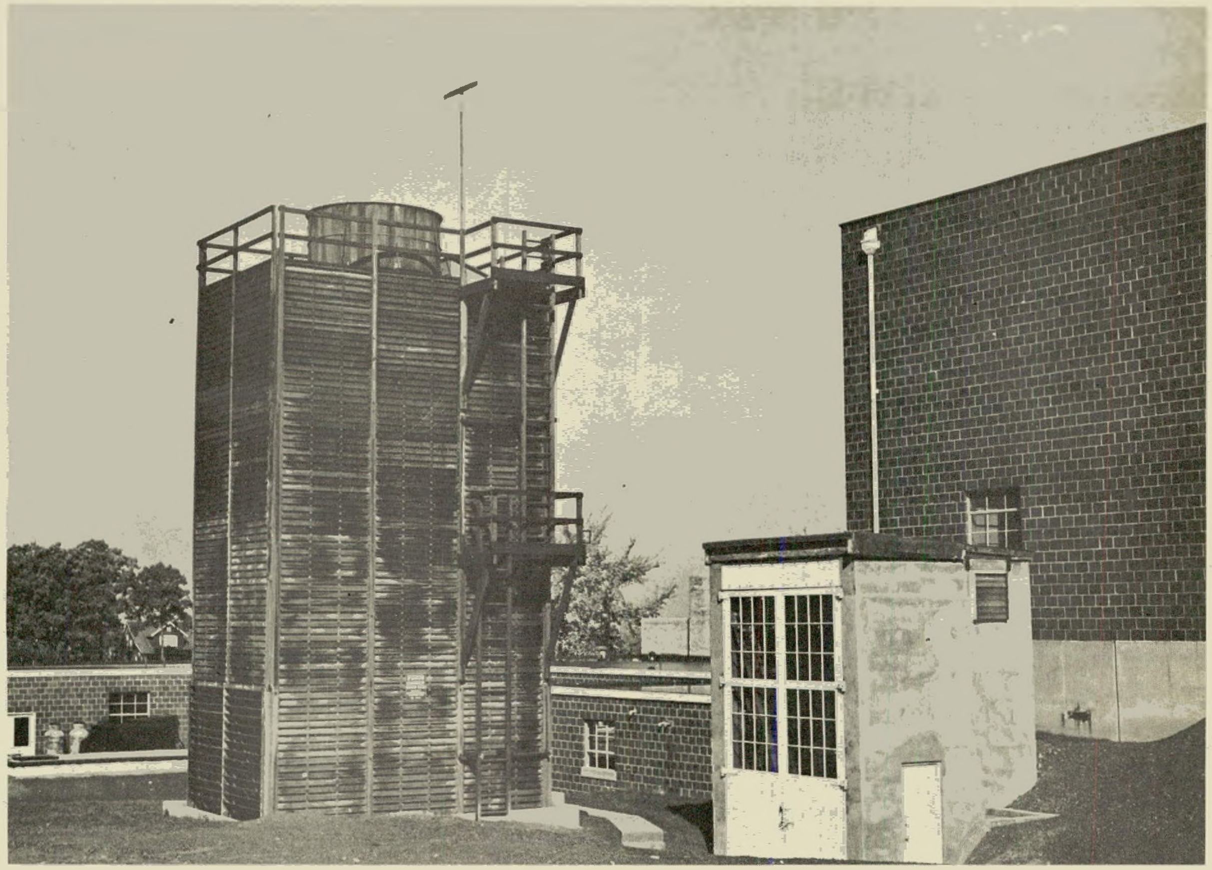

Fig. 16--The cooling tower. The small concrete building at the right houses the homo-polar generator.

The water is treated to prevent scaling and chlorinated to prevent slime formation on heat exchanger tubes. Also frequent blow downs prevent the accumulation of salts from the evaporation of the water.

To date this sytem has not had to meet the full load demand required of it during full operation, so that no complete check has been possible. In addition exceptionally cool summer conditions prevented the extreme design values from being approached. It has succeeded in removing the heat demand placed upon it to date with considerable capacity to spare.

SECTION X - MISCELLANEOUS

Homo-Polar Generator

To produce the large currents required in the low impedance coil for the magnet a homo-polar generator was designed and manufactured by the Electric Products Company in Cleveland. The design characteristic was 21,000 amperes at 18.7 volts. Certain features of the design, particularly the magnetic shielding for the bearing, were worked out jointly with Carnegie Institute of Technology personnel. The generator is shown in Fig. 17.

Bus Bars

To carry the current of approximately 21,000 amperes at 18.7 volts from the generator to the cyclotron magnet coils about fifty feet away, copper bus bars were designed and built. The material used was approximately 15,000 pounds of copper scrap with a cross-section of 4.93" x .342", left over from the winding of the coils.

Twenty-one of these straps were used in parallel for each of the two leads, and special adapters were made for both ends to facilitate connections to both the generator and the coil terminals. All the adapters on the coil terminals are water cooled and supplied with thermal switches to protect the coil terminals from overheating. To increase the active cooling surface of the 21 copper straps, these are mounted in three bundles each consisting of seven straps with a 1/2" air space between. This arrangement provides sufficient cooling to allow the bus bars to be run at full load maintaining a stationary temperature of approximately 60° C.

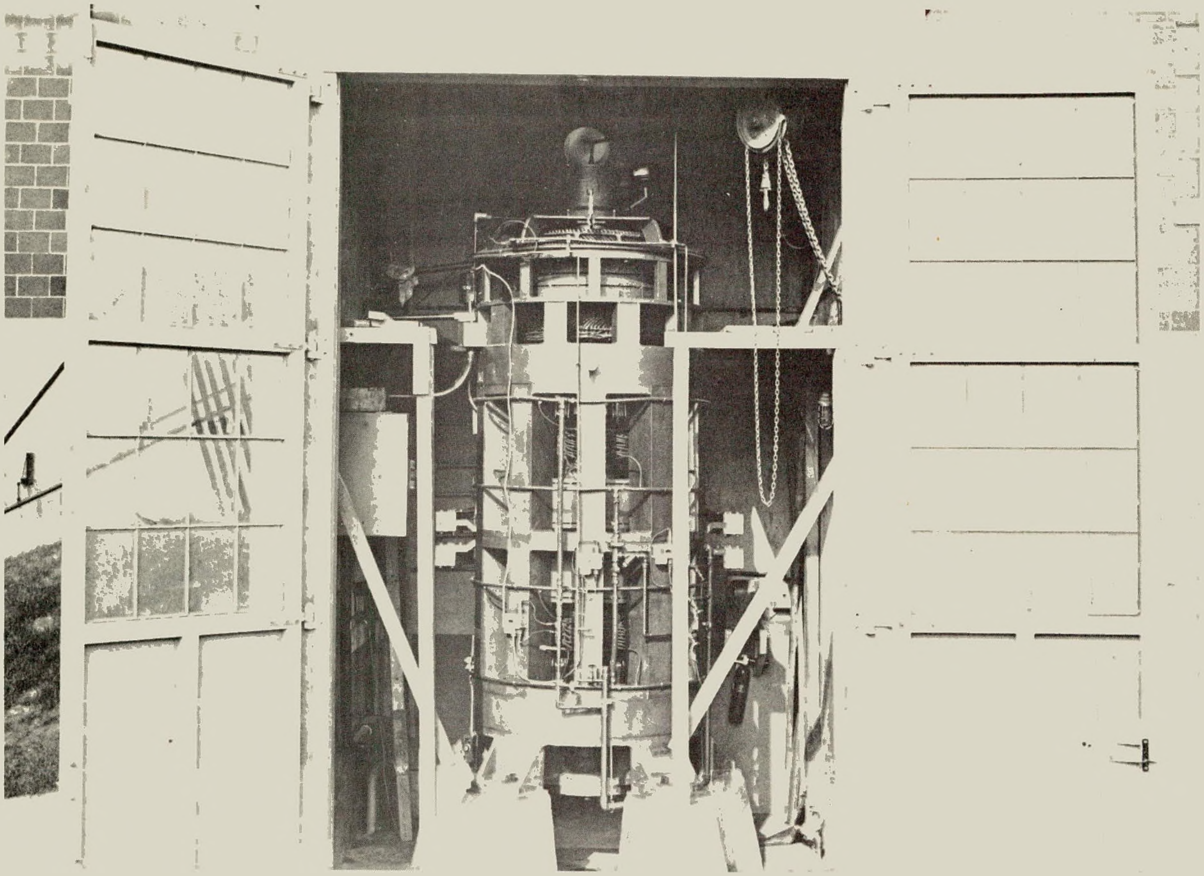

Fig. 17--The homo-polar generator. Its outside diameter is about five feet.

Vacuum Valves

In order to be able to open and close the throat of the two 32" and one 20" diffusion pumps providing the high vacuum in the vacuum chamber, three vacuum valves were designed and built. The valves are automatically operated by compressed air cyclinders and are controlled by vacuum gauges so that they will close when a leak occurs which the pump is not able to handle. One valve will close if a leak occurs in the pump line, in order to allow the two remaining pumps to maintain the vacuum in the chamber. To start out, the valves are closed and the roughing pumps pump down the system until the diffusion pumps warm up. The valves will close from a full open position in a fraction of a second, using 50 pounds air pressure.

SECTION XI - RESEARCH EQUIPMENT

Short Time Measurements

The technique of measuring very short time intervals of the order of one one-billionth of a second is being developed. As a check on the equipment, the half life before capture of positrons in solids is to be measured. This equipment will then be used for studying mesons. Equipment based on this technique can be used as an indicator to discriminate mesons from other ionizing particles such as electrons and protons. With a detector thus specific for mesons, various properties of these particles and their interaction with matter can be investigated.

Nuclear Emulsion Program

The technique, now rather standard, of observing the history of ionizing particles by the tracks they leave in special emulsions is being developed. It was in emulsions of this kind that the heavy or π meson was discovered in England.

Proton-proton Scattering

One of the basic interactions in the nucleus is the force between two protons. This can be examined experimentally by studying the distribution in intensity and angle of moving protons scattered from stationary protons.

Proton-neutron Scattering

This interaction is also basic to nuclear structure. Equipment is being designed to carry out these experiments at 400 Mev.

Low Temperature Laboratory

A Collins helium cryostat has been obtained jointly with ONR and CIT funds. One wing of the laboratory is set-up for low temperature experiments using this equipment. Although this work is not part of the nuclear research program as such it is mentioned here because of its proximity and possible future cooperative use in nuclear experiments.

Beta-ray Spectrograph - G. Hinman

Design work is in progress on a large beta-ray spectrograph for use in the measurement of internal conversion coefficients of gamma-rays. Although it has been shown that the distortion in the shape of the beta and gamma spectra by the finite resolving power of the instrument does not effect measurements of the conversion coefficients, a spectrograph of high resolution is desirable in order to distinguish gamma produced peaks from accompanying continuous beta-spectra. The problem of intensity will be quite troublesome because of the small size of many of the conversion coefficients and hence an effort is being made to obtain the best luminosity-resolution characteristics. If one is limited by the total amount of a radioactive material available, it is desirable to build the instrument with the best Ω (solid angle of acceptance) to R (resolution) ratio. If the limit is the specific activity of the material and thickness of the source, the instrument with the largest $\Sigma\,\Omega$ (source area times solid angle) product is preferable. Below are listed the performances, in some cases very rough, of several instruments in these two cases.

The $\underline{r}$ in the table below is a measure of the instrument size. Its meaning can be made more clear by considering the perturbation method of finding the trajectories of particles. In this method one chooses a particular "central orbit" and considers orbits close to this one using perturbation theory. The $\underline{r}$ in the table below is the maximum distance of this central orbit from the axis of symmetry of the spectrograph. One might better choose the greatest distance of any orbit from the axis (a quantity depending on Σ and Ω), but because the perturbations are usually of about the same kind for different instruments, and because they are small compared to $\underline{r}$, results obtained using this quantity rather than $\underline{r}$ will not differ appreciably from those given below.

Type	Resolution vs solid angle (T = Transmission in percent) (R = Resolution in percent)	Resolution vs (source area - solid angle product) in steradians in same units as r^2
180° (no shim)	$T = 1.11\ R^{1/2}$	$\Sigma\ \Omega = 8.9 \times 10^{-5} R^{5/2} r^2$
180° (shim)	$T = 2.22\ R^{1/2}$	$\Sigma\ \Omega = 18 \times 10^{-5} R^{5/2} r^2$
Solenoid (ring focus)	$T = 4.47\ R^{1/2}$	$\Sigma\ \Omega = 70 \times 10^{-5} R^{5/2} r^2$
Siegbahn-Svartholm	$T = .6\ R$	$\Sigma\ \Omega = 92 \times 10^{-5} R^{5/2} r^2$
Solenoid (no ring focus)	$T - R/2$	$\Sigma\ \Omega = 7.9 \times 10^{-5} R^3 r^2$
Magnetic Lenses	Performance less by a factor of two or three than for corresponding solenoid type.	

These results for the 180° types, the solenoid (no ring focus), and the magnetic lenses are rough estimates based chiefly on the report by Frankel and Nelson[7/], but they are sufficient to show that these are not the best designs on the basis of performance alone. The results for the other two types have been considered more carefully. In each case the effectiveness of small areas of the source has been considered for mono-energetic radiation.

The results given are for the best relative sizes of instrument parameters, and the resultant dependence on instrument size of the results is explicitly included.

From the table it is seen that the highest T to R ratio is given by the solenoid (ring focus) instrument. Methods for producing the uniform magnetic field required have been considered. It could of course be produced by a long solenoid. However, since the size of the source in this type of instrument is very small compared to the r, a large instrument is desirable. The length of solenoids with sufficiently uniform fields then becomes prohibitively great and other methods seem more economical. For example, a set of four coils was designed which could produce the required field. The diameter of the larger pair of these was about twice $2r$. The field could also be produced by a coil wound on a sphere with the projection

7/ "Preliminary Report on Beta-Spectrometer Design Investigations", Stanley F. Frankel and Eldred C. Nelson, June 1948 (unpublished) of the turns per unit length along an axis a constant. It was found that spun aluminum or copper spheres of sufficient accuracy could be purchased and that the cost was not excessive.

However, because it was felt that the most frequent limitation on luminosity was specific activity of the source and not total source strength available, it was decided to construct a Siegbahn-Svartholm double-focusing instrument. Design of the magnet for spectrograph is now in progress, and it is at present planned to make $\underline{r} = 50$ cm. No great difficulties with the design are foreseen. The use of the instrument near the cyclotron may require some shielding from stray fields, but it is felt that satisfactory operation in this respect can be achieved. It is planned to make this instrument capable of focusing mesons although it is by no means certain that a sufficient source of them will be available from the cyclotron or that a useful number will travel from source to detector before decaying. The power required to focus 20 Mev mesons is expected to be about 10 KW.

Cloud Chamber - R. Winter

A Wilson cloud chamber, having an inside diameter of 38 cm, a depth of 8 cm, and a range of pressure from 0 to 15 atmospheres has been constructed. An air-core solenoid has been designed to provide a pulsed field in the chamber of at least 14,000 gauss uniform to one percent.

The chamber, piston, and base are made of stainless steel, chosen because of its high strength, low magnetic permeability, and high electrical resistance, desirable in pulsed-field chambers. A rough calculation shows that if the piston of this chamber were made of aluminum, the eddy-current forces acting on the piston along its axis would reach 50 kilograms when the field is building up, but only three kilograms for a stainless steel piston.

The design of the magnetic field coils is complete. The coils will contain 6.08 tons of copper and produce a field $H = 19.5\sqrt{P}$ where P is the power in watts and H is the field in gauss[8/]. The coils should produce 14,000 gauss with a 540 kilowatt pulsed generator obtained through the Office of Naval Research. (By cutting down the repetition rate and by putting a fly-wheel on the generator shaft, up to 19,500 gauss may be obtainable with the same equipment.)

Illumination is provided by Type GLZ "Amglo" flashtubes. The tubes and associated circuits are in operation.

8/ "Design of Cloud Chamber Coils, Martyn H. Foss, Technical Report No. 2, (navy Contract N7onr-303, Task Order 1) Carnegie Institute of Technology

SECTION XII - SITE

A gift of the former KDKA transmitter building and fifty acres of land near Saxonburg, Pennsylvania provided the site for a large part of the nuclear research program. The remainder of the program is carried out on the campus at CIT, and in cooperation with the University of Pittsburgh at their cyclotron laboratories. At Saxonburg additional connecting buildings were constructed to a total of 20,000 square feet of floor area. A versatile shop of 2300 square feet, laboratories and a library of several hundred volumes donated by Mr. George Aderhold of Saxonburg provide a working unit where advanced graduate students live and study. A remodeled farmhouse on the property provides housing. In the fall of 1950 the school moved two Quonset huts to the site, providing housing for four families, and started construction of a twenty-man dormitory with kitchen and cafeteria facilities. A general plan of the area is shown in Fig. 18.

A hot lab designed for work with one curie of radiation is being constructed by the Chemistry Department. It will be used in cooperation with the physicists for preparing sources, as well as for fundamental radiochemistry research.

Fig. 18--General view of the cyclotron site, showing from left to right the former KDKA transmitter building now used for offices and laboratories, the new low temperature laboratory wing, the stack for the hot laboratory, the high-ceilinged cyclotron room, and the cooling tower.

SECTION XIII - PERSONNEL

A list of personnel working full- or part- time on the cyclotron project as of September 1, 1950 is given below:

I. Research Division

Staff

J. Ashkin
E. Baldwin
A. Clark
E. Creutz
H. Corben
S. DeBenedetti
M. Foss
J. Fox
S. Raboy
L. Smith
R. Sutton
E. Williams

Graduate Students

F. Crane
R. Grandey
G. Hinman
S. Kao
P. Levy
G. Minton
C. Mundo
B. Neumeyer
H. Richings
D. Rose
R. Sugarman
R. Winter

II. Engineering Division - M. Foss, J. Thompson

Group A. Mechanical Engineering

Section 1 - Design

R. Ankersen
H. Berman
R. Bluestone
K. Downes
H. Emmett
J. Eustis
W. Geist
H. Martin
M. Trimble

Section 2 - Installation and Testing

W. Kearns
H. Graham
C. Pearce
F. Witt

Group B. Electrical Engineering - D. Brower

Section 1 - Electronics

F. Davis
R. Findley
L. Johnson
E. Kikta
G. Lang

Section 2 - Controls and Power Systems (DC, AC, RF)

D. Anderson
H. Colborn
H. Collins
C. Grace
D. Grace
J. Jackson
J. Mates
K. Ming Shen
F. Pittman
J. Ramaley
P. Thompson
T. Vuchinich

Group C. Engineering Operations - W. Cleary

R. Flatt
A. Lauer
J. Solonika

III. Business and Services Division - J. H. Coleman

Group A.

I. Beck
N. Ludwig
J. Muchow
E. Eisemann

Group B. Shops

Section 1 - Nuclear Research Center Shops - R. Orr

A. Caldwell
F. Cooper
M. Johnston
S. Nowakowski
F. Sherman
J. Szlachetka

Section 2 - Campus Shops - A. Feiglstok

A. Adams
H. Lefke
E. Lloyd
R. Rhule

Group C. Cyclotron Room - J. McDivitt

W. Call

Group D - Special Services - C. Love

J. Bouch
G. Burtner
R. Byers
C. Cox
J. DaPra
D. Geisler
W. Hay
A. Lesseski
R. Parker
K. Rubinosky
K. Wonderline

Group E - Transportation

L. Renfrew
C. Smith

SECTION XIV - REPORTS AND PUBLICATIONS

The following is a list of reports written during the duration of this contract. (February 1, 1947 to September 1, 1950.)

Progress Reports to the ONR

July 1947; November 1947

January 1948; April 1948; July 1948; October 1948

January 1949; April 1949; July 1949; October 1949

January 1950; April 1950; July 1950

Technical Reports to the ONR

No. 1 - Design of Cyclotron Magnets by M. Foss, June 27, 1948

No. 2 - Design of Cloud Chamber Coils by M. Foss

No. 3 - High Magnetic Fields by M. Foss

No. 4 - Design of Cyclotron Vacuum System by D. Rose, June 1949

No. 5 - Rotating Condenser for Synchro-Cyclotron by M. Foss, August 30, 1949

No. 6 - Three-Quarter Scale Model Oscillator by E. M. Williams, L. W. Johnson, H. M. Collins, August 1, 1950

Publications

Magnetite Concrete for Radiation Shielding by E. Creutz and K. Downes, JOURNAL OF APPLIED PHYSICS, Vol. 20, No. 12, December 1949

Booklet published by Carnegie Institute of Technology describing the Nuclear Research Center, June 1949

The Half-Life of Positrons in Metals by S. DeBenedetti and H. Richings, Abstract presented at the Chicago meeting of the American Physical Society, November 24-25, 1950

Wide-Deviation Frequency-Modulated Oscillators" by E. M. Williams and Lucio Vallese, PROC. IRE, Vol. 36, No. 10, October 1948

Oscillator Design for 130-inch Frequency-Modulated Cyclotron by E. M. Williams and H. E. DeBolt, 1948 IRE National Convention

The Exponential-Line Pulse Transformer by E. R. Schatz and E. M. Williams, 1950 IRE National Convention

Pulse Transients in Exponential Transmission Lines by E. R. Schatz and E. M. Williams, to appear in October 1950 PROC. IRE

Design of Exponential-Line Section Pulse Transformers by E. M. Williams and E. R. Schatz, to appear in forthcoming issue of PROC. IRE

Other papers are in preparation, based in whole or in part on the following doctorate theses:

The Commutation Interval in Electronic Switching Circuits by James B. Woodford, Jr. (fundamental theory for hydrogen thyration pulse deflector system)

Current Distribution and Losses Near Discontinuities in Transmission Lines by H. E. DeBolt (analysis of losses in an analogue of dee-transmission line structure)

Two additional papers are planned by the oscillator group. The first of these will be based on the final oscillator design and its performance in tests on the completed cyclotron. The second will describe the cascade pulser system which has been designed for the deflector, and the results of experimental tests on models in the Electrical Engineering Department laboratories.

Other papers in preparation are Permeability Measurements with a Standard Solonoid and Half-Magnet for Design Studies.

SECTION XV - SUMMARY OF CYCLOTRON DESIGN CHARACTERISTICS

CIT SYNCHRO-CYCLOTRON (Data for Proton Acceleration)

Useful Radius	∽ 68.4	Inches
Proton Energy	∽ 420	Mev
Beta for Protons	∽ $.7 = \beta = (\frac{v}{c})$	
Acceleration Time	1250	μ sec
Repetition Rate	400	pps
Initial Rate of Change Frequency	6400	mc/sec^2
End Rate of Change of Frequency	12800	mc/sec^2
Average Energy Gain per Revolution	15	Kev
Number of Revolutions During Acceleration	28000	
Distance Traveled During Acceleration	132	Miles
Starting Frequency at 20000 Gauss	30.4	mc/sec
Acceptance Time at 60 pps	100	μ sec
Beam Pulse Length	100	μ sec

MAGNET

Pole Gap (Nominal)	15.615	Inches
Pole Gap (at Edge)	10	Inches
Pole Diameter (at Tip)	141.67	Inches
Pole Diameter (Useful)	136.8	Inches
Mangetic Field (Center)	20500	Gauss
Magnetic Field (at r = 68.4")	19700	Gauss
Steel Weight	1459	Tons
Copper Weight	130	Tons
Coil Resistance (28° C) (Both coils in series)	.0008	Ohms
Coil Current	21000	Amps
Coil Voltage	17	Volts
Coil Power	360	Kw
Coil Ampere Turns	1.08×10^6	
Copper Cross-Section (per turn consisting of 16 conductors in parallel)	1.36 x 19.75	Inches^2
Copper Cross-Sectional Area	26.75	Inches^2
Space and Insulation Between Turns	.090	Inches
Bus to Generator	28.42	Inches^2
Oil Capacity of Coils	300	Gallons
Oil Temperature Rise	10	$^{\circ}$ F
Oil Flow Rate	600 - 800	Gal/min

Coil Weight (total for two coils)	184	Tons

Time Constant of Exciter Generator - Te = 0.64 - 0.94 sec

Time constant of Homopolar Generator - Tg = 2.7 - 5.3 sec

Time constant of Magnetic Field - Tm = 20 - 35 sec

MAGNET COOLING SYSTEM

Magnet Coils

Oil Used: Gulf Cyclotron Oil (Inhibited against corrosion of copper)

Thermal Conductivity (at 100° F)	0.075 BTU/hr ft° F	3.1×10^{-4} cal/sec cm° C
Specific Heat (at 100° F)	0.456 BTU/lb° F	.456 cal/gr° C
Density (at 100° F)	55.6 lbs/ft^3	.89 gr/cm^3
Viscosity (at 100° F)	10.45	Centipoises
Oil (Quantity)	1400	Gallons
Oil Flow Rate	600 - 800	Gal/min
Oil Temperature Rise	10	° F

Heat Exchangers - Double Pass - Shell and Tube

Type with water in tubes. Manufactured by Griscom-Russell Company

Oil Pressure In	32 - 40	psi
Oil Pressure Out	27 - 28	psi

Cooling Tower

12' x 18' Base x 31' High induced draft counter flow cooling tower. Manufactured by Fluor Corporation

Cooling tower capacity 500 gallons per minute. Water circulated by Ingersoll-Rand Cameron centrifugal pumps. Tower produces 10° F drop in water temperature with 3° F approach to the wet bulb temperature. Normal flow 425 gallons per minute.

OSCILLATOR

Frequency Range	18 - 32	mc
Tubes	880 (4 in parallel)	
Cooling Air (per tube)	100	CFM
Oscillator Input (Average)	125	Kw
Plate Voltage	15	Kv
Plate Current	10	Amps (maximum)
Dee Bias Voltage	1000 - 2000	Volts DC
Dee R.F. Voltage (Peak)	15	Kv

ION SOURCE

Filament Length	4-5/8	Inches
Filament Diameter	.120	Inches
Filament Material	Tungsten	
Power Supply Frequency	20	KC
Power Input	1.8	Kw
Power Available	3	Kw
Arc Voltage	500	Volts
Arc Current (Maximum)	10	Amps
Arc Pulse Length (Range)	1 - 200	μ sec

OSCILLATOR HIGH VOLTAGE POWER SUPPLY

Input Transformer	150	KVA
Primary	2300	Volts
Secondary	240	Volts

Induction Regulator		
Voltage Input	240	Volts
Voltage Output (Range)	40 - 432	Volts
Current (Maximum)	186	Amps
Rectifier Transformer (Westinghouse Type ASL Power)	165	KVA
Input Voltage	40 - 432	Volts
Output Voltage (Maximum)	9740	Volts
Rectifier Tubes	Type WL857B	
Recitifier Output Voltage (Maximum)	12500	Kv
Rectifier Power (Maximum)	125	Kw
Pulse Network Voltage	15	Kv
Pulse Network Current (Maximum)	20	Amps
Pulse Network Duty Cycle	50	%
Filament Supply Transformer (single phase)	30	KVA
Primary Voltage	208	Volts
Secondary Voltage	12.5	Volts
Secondary Current (320 amp/tube)	1280	Amps total

ROTARY CONDENSER

Nominal Gap		
Dee Stator to Rotor	.131	Inches
Ground Stator to Rotor	.080	Inches
Ring Condensers to Rotor Shaft	.030	Inches

Actual Minimum Gap		
Dee Stator to Rotor	.115	Inches
Ground Stator to Rotor	.064	Inches
Ring Condensers to Rotor Shaft	.025	Inches
Number of Rows of Teeth	8	Rows
Number of Teeth per Row	46	Teeth
Rotor Material	Aluminum Alloy	14S-T41
Rotor Weight	1200	Pounds
Dee Stator Material	Copper	
Copper Plating Thickness (On Steel Ground Stator)	.0025 - .0035	Inches
Available Capacity Range	1000	μμf
Rotor Speed (Maximum)	3000	rpm
Total Weight (With Case)	7.5	Tons
DC Motor	20	HP
DC Motor Voltage (Maximum)	230	Volts
DC Motor Current	75	Amps

<u>WATER COOLING SYSTEM</u> (Rates based on 10° F temperature rise)

	Nominal	Maximum
Capacity of Heat Exchanger	135 gal/min	200 gal/min
Homopolar Generator		
Shaft	4 - 6 gal/min	7.5 gal/min
Brushes	3 gal/min	5 gal/min

		Nominal	Maximum
Top Bearing (Heat Exchanger for Oil Cooling)		2 gal/min	3 gal/min
Bottom Bearing (Heat Exchanger for Oil Cooling)		1 gal/min	3 gal/min
Bus Bar Terminals		1 gal/min	1.5 gal/min
Rotary Condenser			
Rotor		+10 gal/min	
Dee Stator		+ 4 gal/min	
Ground Stator		+ 6 gal/min	
Ring Condensers		+ 1 gal/min	
Baffles and Bearing Seal		1 gal/min	2 gal/min
Bearing Oil Exchanger		3 gal/min	
Oscillator			
Dee			
Top Pole Skin			
Bottom Pole Skin	Total	+60 gal/min	80 gal/min
Dummy Dee			
880 Tubes			
Ion Source		3 gal/min	
Cloud Chamber Coil		14 gal/min	

+Estimated Values

VACUUM SYSTEM

Vacuum Chamber		
Material	Aluminum (61ST6)	
Plate Thickness	2	Inches

Volume	15000	Liters
Dimensions	May be approximated by circular tank of 85" radius x 28" high	
Operating Pressure	$2 \times 10^{-6} - 2 \times 10^{-5}$ mm	
Pump Down Time From Cold Pumps to 10^{-5} mm	1.75	Hours
Pump Down Time From Cold Pumps to 10^{-6} mm	2.5	Hours
Mechanical Pumps		
Roughing Pump - DVD 14918 (one)		
Free Air Capacity	146	l/sec
Pumping Speed at 100 Microns	92	l/sec
Ultimate Pressure	5	Microns
Shaft Speed	360	rpm
Motor	15	HP
Cooling Water	30	gal/hr
Oil . . .	Socony D.T.E. Heavy - Medium	
Fore Pumps - DVD 8810 (three)		
Free Air Capacity	52	l/sec
Pumping Speed at 100 Microns	33	l/sec
Ultimate Pressure	5	Microns
Shaft Speed	450	rpm
Motor	5	HP
Cooling Water	20	gal/hr
Oil	Socony D.T.E. Heavy - Medium	

Oil Diffusion Pumps

Type M.C. 15000 - 32" ID DPI (two)

Pumping Speed at 4×10^{-4} mm	15000	l/sec
With Refrigerated Baffle at 4×10^{-4} mm	8000	l/sec
With Refrigerated Baffle at 2×10^{-6} mm	5000	l/sec
Heater Power	6	Kw
Heater Voltage	208	3 Ø
Cooling Water	45	gal/hr
Ultimate Pressure	2×10^{-6}	mm
Oil	Myvane	
Oil Capacity	4	gallons

Type M.C. 7000 - 22" ID DPI (one)

Pumping Speed at 5×10^{-4} mm	7000	l/sec
With Refrigerated Baffle at 2×10^{-5} mm	3500	l/sec
With Refrigerated Baffle at 2×10^{-6} mm	1000	l/sec
Heater Power	4	Kw
Heater Voltage	208	3 Ø
Cooling Water	15	gal/hr
Ultimate Pressure	2×10^{-6}	mm
Oil	Myvane	
Oil Capacity	2	gallons

Type MB300 - 8" ID (Boosters) (three)

Pumping Speed at 10^{-2} mm	300	l/sec
Heater Power	3	Kw
Heater Voltage	208	3 Ø
Cooling Water	15	gal/hr
Ultimate Pressure	5×10^{-5}	mm
Oil	Myvane	
Oil Capacity	3	quarts

Freon Compressor (Baffle Refrigeration)

Motor	1	HP
Speed	1300	rpm
Baffle Temperature	+20	°F

HOMOPOLAR GENERATOR

Motor (Syn 3 Ø:60 cy.)	600	HP
Motor Voltage	2300	Volts
Motor Speed	1200	rpm
Motor Field Current	20	amps
Motor Field Voltage	100	Volts
Generator Voltage	18.7	Volts
Generator Current	21000	amps
Exciter Voltage	35	Volts
Exciter Current (Maximum)	171	amps

SHIELDING

Inside Dimensions	37-1/4 x 44 x 10-2/3 Feet	
Wall Thickness		
East Wall (Magnetite Concrete)	8 feet	ρ = 200 lbs/ft^3
North Wall (Magnetite Concrete)	8 feet	ρ = 200 lbs/ft^3
West Wall		
Concrete	3.66 feet	ρ = 200 lbs/ft^3
Magnetite Concrete with Steel Projectiles added	4.34 feet	ρ = 300 lbs/ft^3
South Wall		
Concrete	2.2 feet	ρ = 150 lbs/ft^3
Earth Fill (Outside)	$>$10 feet	
Ceiling Thickness		
Concrete over Magnet	2.5 feet	ρ = 150 lbs/ft^3
Remainder of Ceiling	5 feet	ρ = 150 lbs/ft^3
Total Weight of Magnetite Concrete	1125	Tons
Total Weight of Ordinary Concrete	1050	Tons
Total Weight of Doors (Magnetite Concrete)	48	Tons Each
Opening Speed	7.2	Feet/min
Opening Time	1.1	Minutes
Closing Speed	2.2	Feet/min
Closing Time	3.6	Minutes

CLOUD CHAMBER MOTOR GENERATOR SET

Three Phase Motor	125	HP
Motor Voltage	2300	Volts
Motor Current	31.3	Amps
Generator Armature Voltage	180	Volts
Generator Armature Current	3000	Amps
Generator Field Voltage	230	Volts
Generator Field Current	29	Amps
Generator Field Control Resistor	4.94	Ohms
Rated Duty Cycle (On)	5.5	Sec
Rated Duty Cycle (Off)	9.5	Sec
Operational Duty Cycle (On)	4	Sec
Operational Duty Cycle (Off)	56	Sec
Pulsed Current (Maximum)	3980	Amps
Fly Wheel Weight	8000	Lbs
Fly Wheel Moment of Inertia	25000	Lb ft^2

CLOUD CHAMBER COILS

Estimated Total Weight (With Supports)	8	Tons
Diameter (Inside)	21.76	Inches
Diameter (Outside)	50.37	Inches
Height (Each Coil with Base)	15.4	Inches
Coil Weight (Copper)	6.08	Tons (Both)
Coil Weight (Total)	7	Tons (Both)
Coil Resistance at 50° C (Both in Series)	.0627	Ohms

Core	Air	
Coil Air Gap	4.59	Inches
Magnetic Field at Center of Gap	$19.57\sqrt{P\ (\text{Watts})}$	Gauss
Homogeneity	Within .5	%
Coil Turns (Total for Two Coils)	536	Turns
Coil Conductor		
Trapezoid Bases (Before Winding)	.842 and .822	Inches
Height (Before Winding)	.822	Inches
Coil Cooling Hole (Diameter)	.3	Inches
Cooling Water Flow	14	Gal/min
Cooling Water Pressure	50 - 75	psi
Cooling Water Temperature (In)	30 - 35	° C
Cooling Water Temperature (Out)	58 - 63	° C

END OF DOCUMENT