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THE OAK RIDGE 86-INCH CYCLOTRON

By

Robert S. Livingston
Alfred L. Boch

OAK RIDGE NATIONAL LABORATORY
OPERATED BY
CARBIDE AND CARBON CHEMICALS COMPANY
A DIVISION OF UNION CARBIDE AND CARBON CORPORATION
OAK RIDGE, TENNESSEE

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Electromagnetic Research Division

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Operated by
Carbide and Carbon Chemicals Company
A Division of Union Carbide and Carbon Corporation
Oak Ridge, Tennessee

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ABSTRACT

The design, construction, and development of the 86-inch fixed-frequency proton cyclotron are described. Unusual features of the machine are the vertical suspension of the dees in a horizontal magnetic field, the high proton beam energy obtained by the use of high rf potential on the dees, and an internal proton beam current exceeding one milliampere at 23 Mev. Major problems encountered were the control of "ion loading" in the resonant system, obtaining maximum energy, and the development of adequate targets. Design and construction began in August 1949. Within two years the proton beam power exceeded 30 kw.

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The need for a cyclotron in the Oak Ridge area was first discussed as early as 1946. The absence of high energy accelerators at the Oak Ridge National Laboratory or at nearby Southern universities emphasized the desirability of the Oak Ridge location. The availability of large magnetic and vacuum components from the Electromagnetic Plant simplified the planning of a cyclotron and facilitated its fabrication.

After evaluation of several possible systems, methods of assembly, and locations it was decided to construct a fixed-frequency cyclotron to produce 25 Mev protons and to install it in an existing building in the Y-12 area. Formal starting of the project dated from August 8, 1949.

The cyclotron is unique in many respects. The orientation of the magnetic field is at right angles to that in conventional machines, the median plane being vertical rather than harizontal. The U-shape of the magnet gives direct access to the top of the vacuum chamber and permits the use of an overhead crane for transferring the assembled dee system. High dee-to-dee potentials, 300-500kv, are achieved with a single-tube, grounded-grid, self-excited oscillator. Oscillator starting difficulties due to "ion loading" are voided by the use of insulated negatively-biased dees. Large capacitive coupling between the "shorting spider" and the liner is unnecessary due to system which provides for balancing the dees with high precision and thereby preventing the existence of large "unbalanced" currents to the liner. Intense induced radioactivity in the dees is avoided by lining them with thick graphite plates and covering the leading edges with graphite.

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Construction of the cyclotron required approximately one year; ground was broken for the magnet footings September 21, 1949, and the machine was ready for test operation the following September. The first proton beam was observed November 11, 1950; by the end of the year a beam of a few microamperes had been obtained at 20 Mev; and by September, 1951, currents above one milliampere at 20 Mev had been reliably recorded.

Continued cyclotron development has resulted in marked improvements in stability of operation and in larger proton currents. As this report goes to press, June 1952, steady performance has been obtained for 1.2 ma at 23 Mev, with peak performance at 1.8 ma at 23 Mev.

The cyclotron is now being used in the investigation of radiation effects on materials, for production of radioisotopes, and for experiments in basic physics. The future program calls for increasing the beam current until some basic limit is established, developing targets that can absorb the beam power, and further improving reliability of performance.

GENERAL DESCRIPTION

The 86-inch cyclotron was designed to produce a high proton current to an internal target at an unusually high energy for the fixed-frequency type of machine. An energy corresponding to a 2.6% relativistic increase in mass is achieved by the use of large rf potentials on the dees. Large ion currents are obtained from a newly developed ion source and are focused by an appropriately shaped magnetic field. An oscillator of high output, a dee system of large thermal capacity, and large water-cooled targets have been designed to accommodate proton beam power exceeding 30 kw. Proton energies up to 25 Mev and proton beam currents approaching two milliamperes at $\sim$23 Mev have been obtained.

The four magnet coils mounted in a U-shaped yoke are wound with 3" by 0.42" copper, 174 turns each, and oil cooled. The vertical arrangement permits the use of an overhead crane for handling the internal assemblies, Figure 1. The vacuum system consists of three 20-inch oil diffusion pumps, each equipped with an 8-inch booster pump, exhausting to a common header and backed by a 15-hp mechanical (Kinney) pump. The total pumping speed of the system is 15,000 liters per second at 0.03 microns.

The oscillator is of the grounded-grid, self-excited type using a single Federal 134 tube rated at 150 kw plate dissipation. Facilities are available for the use of a second tube if power requirements should make it desirable. A dee-bias system, in which a negative 1500 volt potential is applied to the insulated dees, is used to overcome the "ion loading" difficulties usually experienced with the self-excited oscillator. Very stable operation is achieved; the oscillator can be safely turned on at full power.

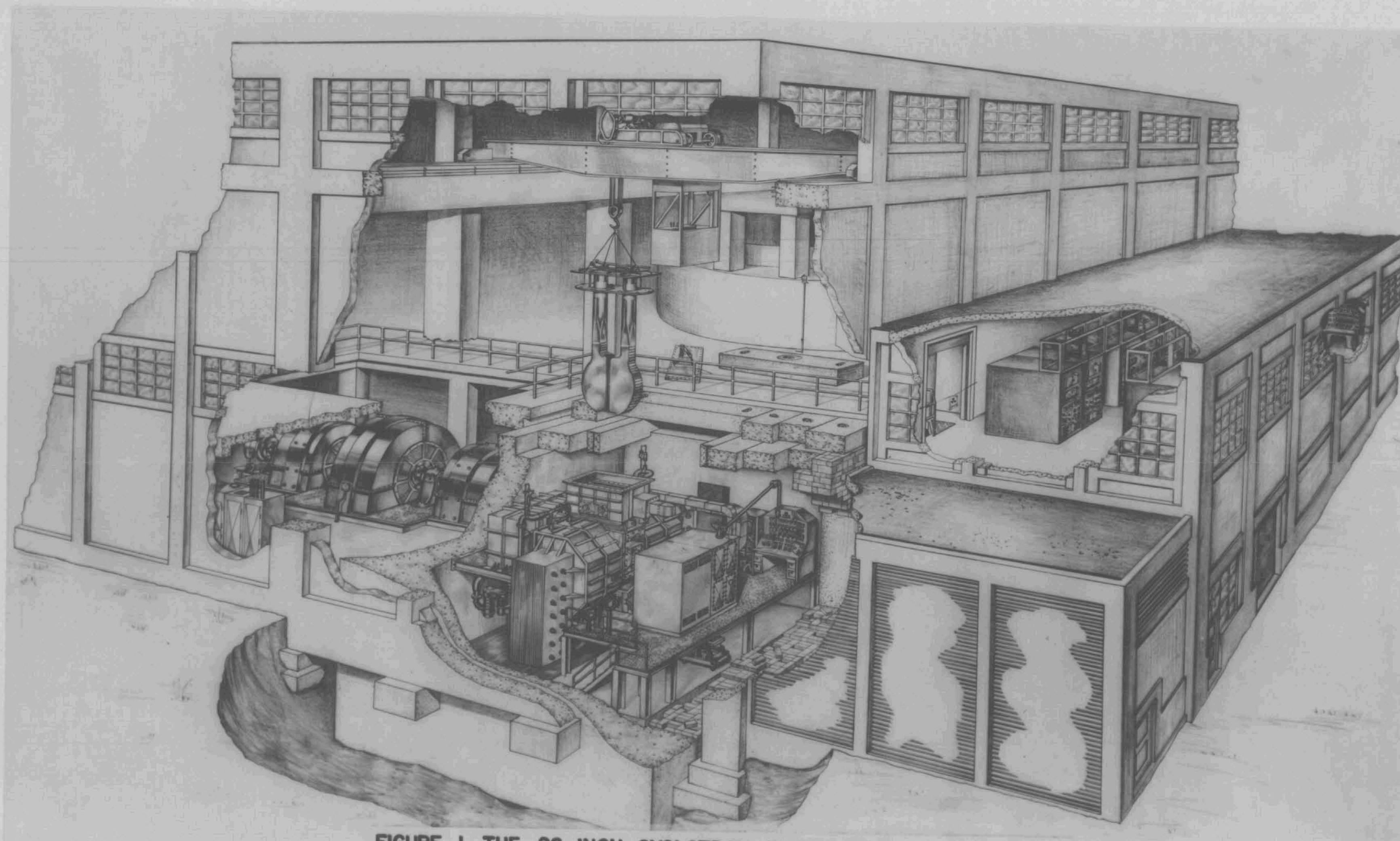


FIGURE I THE 86 INCH CYCLOTRON INSTALLATION

The dees are permanently attached to the quarter-wave dee stems and in turn attached to a copper-plated stainless-steel framework, Figure 2. This dee assembly rests upon four stand-off type insulators. A 750 $\mu\mu f$ capacitance inserted in the plate transmission line further insulates the dc biased system. Heavy silver-plated copper clamps joining the shorting spider to the dee stems successfully carry very large rf currents. The ion source is mounted on a long stem inserted through a vacuum lock in the cover of the vacuum chamber. Targets are inserted through a large vacuum lock at the bottom. The liner, dee assembly, ion source, and target are all supplied with water-cooling circuits.

Cyclotron Installation

A study of the buildings of the Electromagnetic Plant, Y-12, available for cyclotron use resulted in the selection of Alpha Process Building 9201-2. This building had been in "standby" condition since 1945. There was ample space for installation of the cyclotron magnet at the west end of the building and for associated equipment and work areas in other parts of the building, Figure 3. Facilities in standby which could be adapted to cyclotron use included cranes for handling heavy equipment, a motor-generator set for magnet power, a system for magnet cooling, numerous large dc power supplies, large vacuum pumps, de-ionized water supply, and the usual building lighting and power circuits, water supply, and heating and ventilation equipment.

The cyclotron magnet is located in a pit formed by digging through the ground floor to bed rock at the west end of the building. At this location it was possible to provide a 45' by 39' by 40' space for the cyclotron and its shielding without disturbing major installations in the building. The magnet was assembled from four magnet coils moved from a Beta process building

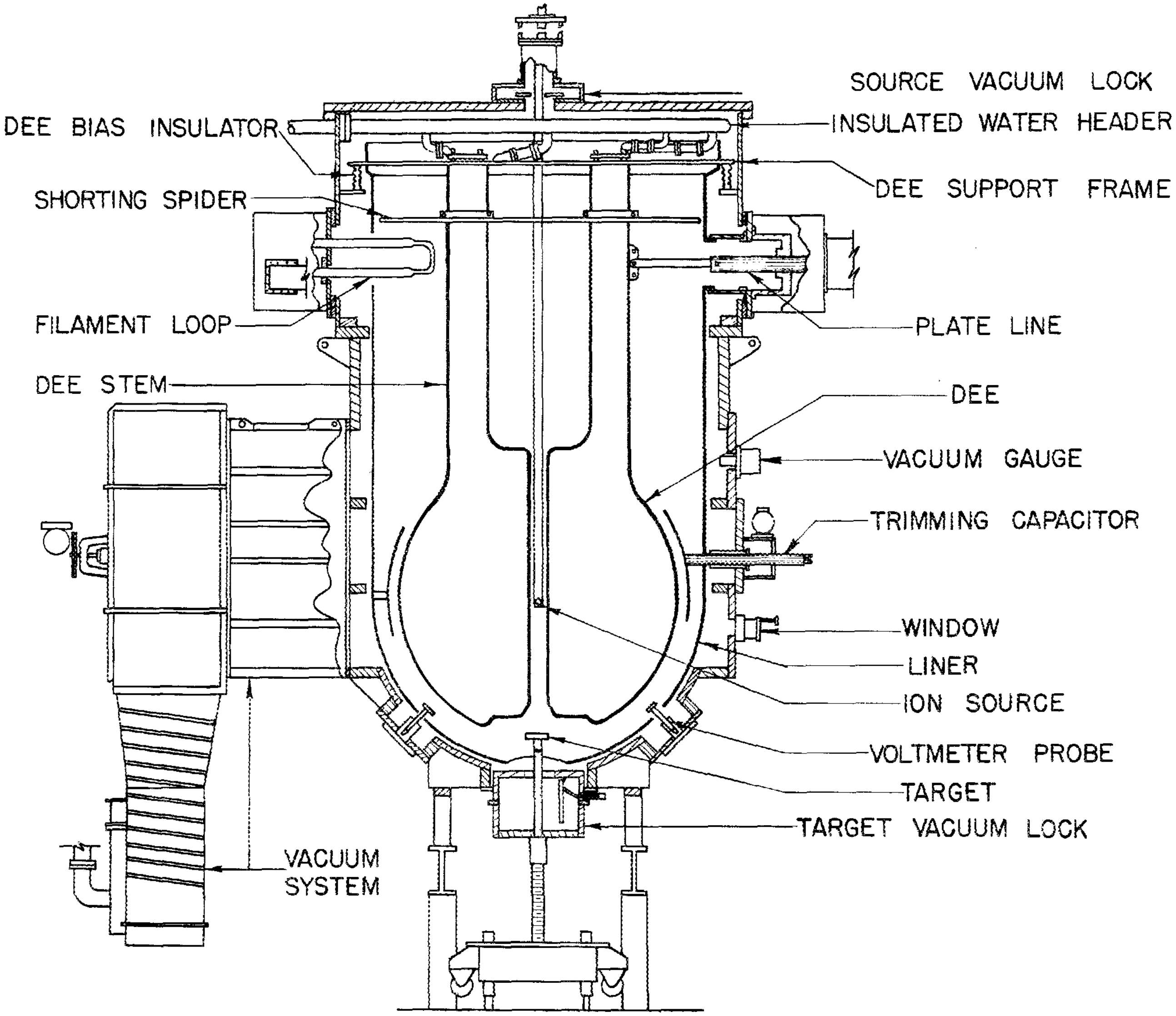
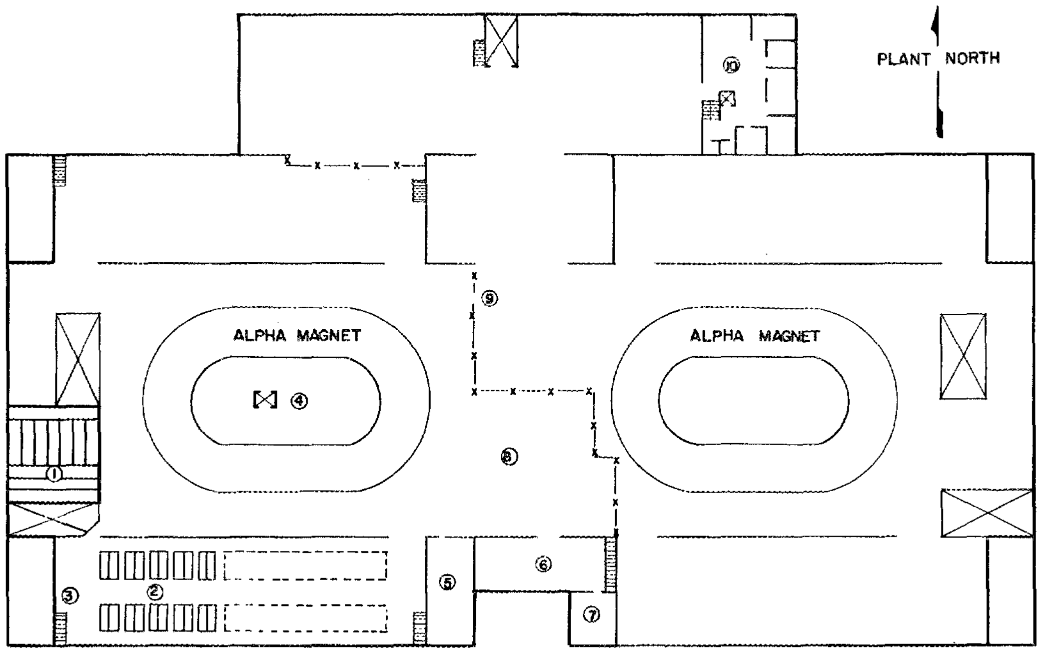
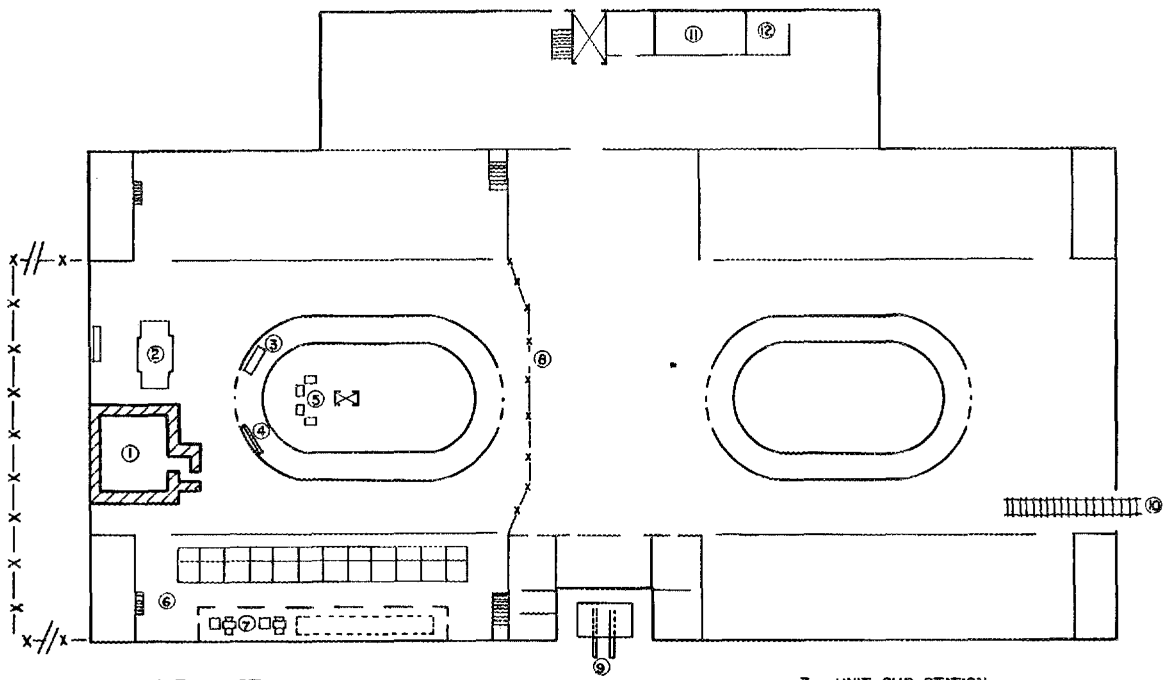


FIGURE 2. CROSS SECTION OF CYCLOTRON



1 ROOF OF CYCLOTRON PIT
2 POWER SUPPLIES
3 ELECTRONICS SHOP
4 DECONTAMINATION AREA
5 CREW OFFICES
6 SWITCHBOARD ROOM
7 MAIN CONTROL ROOM
8 MECHANICAL SERVICE AREA
9 ENTRANCE TO RESTRICTED AREA
10 OFFICES, ONE FLIGHT UP

BUILDING 9201-2, MAIN FLOOR



1 CYCLOTRON PIT
2 MOTOR-GENERATOR
3 REFRIGERATION UNIT
4 UTILITIES PANEL
5 KINNEY PUMPS
6 TARGET HANDLING AREA
7 UNIT SUB-STATION
8 ENTRANCE TO RESTRICTED AREA
9 MAIN TRANSFORMER
10 RAILROAD SPUR
11 CHEMISTRY LABORATORY
12 COUNTING ROOM

BUILDING 9201-2, GROUND FLOOR

FIGURE 3. BUILDING PLAN

and a 250 ton U-shaped yoke. The cyclotron pit is surrounded with concrete shielding walls and roof five feet thick. Roof blocks can be removed to permit moving the vertically suspended dees. Normal access to the pit is through an entrance maze on the east; the emergency exit is at the north.

A magnet motor-generator adjacent to the cyclotron area, complete with starting and regulating equipment, was readily adapted for use. The necessary vacuum, water, dry air, oil pumps, and cooling tower facilities were reactivated and modified as needed. Instruments for monitoring these utilities are mounted on a central panel adjacent to the cyclotron pit at the ground floor level.

The top of the shielding surrounding the cyclotron extends through the main floor level. Two bridge-type, overhead cranes, each having a 20 and a 5-ton hoist, are available for moving shielding blocks and other heavy equipment. In the central part of the building a servicing area and small machine shop is provided for the assembling and repairing of cyclotron parts. Special platforms and alignment jigs have been installed there for handling the cyclotron dees and liner. The overhead cranes have access to this area as well as to an opening for railroad cars at the east end of the building. Twenty Alpha power supplies in the southwest calutron control room have been paralleled to provide dc power to the cyclotron oscillator. An electronics shop has also been established in this area.

The main control room is in the south central part of the building, adjacent to the power switchboard; there is also a control station in the pit for testing purposes. Cyclotron crew offices are adjacent to the control room. Administrative and engineering offices are at the northeast corner of the building, one flight up from the main floor. A chemistry laboratory for handling target materials and a counting laboratory are in this same corner of the building, at ground floor level.

The west half of the building has been designated as a hazard area. Safety fences across both floors and outside around the west end of the building prevent unauthorized access to the cyclotron.

Design, fabrication, and installation of the cyclotron was accomplished by local personnel. Only the vacuum tank was fabricated by an outside contractor.

Specifications

The specifications of the Oak Ridge cyclotron were determined by the objective which was to obtain large proton currents at an energy above 20 Mev. It was believed desirable to operate at as low a frequency as possible because of the larger amount of engineering information available for oscillators in the region below 15 megacycles/sec.

A preliminary review of the problem of obtaining high rf voltage in a system using the available electromagnetic coils resulted in the following specifications:

Diameter of pole piece	86 inches
Maximum proton energy	25 Mev
Expected proton current	1 ma
Dee-to-dee potential	300 kv to 500 kv
Orbit radius at maximum energy	33 inches
Magnetic field (resonance)	8790 oersteds
Resonant frequency	13.4 mc/sec

Further study and model testing led to the selection of additional specifications:

Minimum magnet gap after shimming	17.5 inches
Radial decrease in field	2 % in 33 inches
Maximum azimuthal variation	0.2 percent
Radius of dees	35 inches
Thickness of dees	8 inches
Gap between dees	4 inches
Dee-to-liner clearance (on flat surfaces)	4 inches
Distance from peripheral surface of dees to liner	7 inches

Preliminary calculations on the design of the rf system provided the characteristics below:

Dee stems (balanced shielded line, 1/4 wave)	5.2 feet
Effective dee capacitance	176 μμf
Q of resonant system, unloaded	12,300
Q of resonant system, loaded	3,700
Maximum RMS current at shorting spider	5,600 amps
Plate line (resonant 1/2 wave)	21.1 feet
Filament line (resonant 1/2 wave)	28.3 feet
Resonant voltage amplification	16

Cost

The total cost of construction and preliminary testing of components of the 86-inch cyclotron was approximately one-half million dollars. The cost analysis is given in Appendix A. No costs were entered for equipment already available in Y-12, such as magnet coils and power supplies. The major costs incurred were for erection of the concrete shielding and of the magnet.

FIXED FREQUENCY CYCLOTRON THEORY

In the late 1930's the basic theory of the fixed frequency cyclotron was established in the papers of M. E. Rose[1] and R. R. Wilson.[2] In the next decade the theory of synchrotrons showed that the effects of phase grouping[3] at the center of the cyclotron had been overlooked and that this had led to erroneous conclusions on ion motion in the cyclotron. Recent work at ORNL has incorporated this phenomenon and has made use of terms of higher order. The subsequent paragraphs constitute a summary of a portion of the more recent treatment.[4]

Threshold Voltage. Due to the large distance an ion must travel in a cyclotron as it spirals out from the ion source only a small fraction of the starting ions would ever reach full radius were it not for certain focusing effects. In the course of the early part of the spiral motion from the source, components of electric field tend to shift ions in the direction perpendicular to the plane of the orbit. Two types of electric effects must be distinguished: (a) energy-change focusing due to the fact that ions spend less time in the defocusing region (where the lines of force curve away from the median plane) of the dee gap than in the focusing region, and (b) field-variation defocusing which is associated with the fact that the electric field changes during the transit of the gap. Ions in positive phase (those crossing the middle of the gap after the potential difference between the dees has reached its maximum)

1. Rose, M. E., Phys Rev 53, 392 (1938).
2. Wilson, R. R., Phys Rev 53, 410 (1938).
3. Bohm, D., and Foldy, L., Phys Rev 72, 649 (1949).
4. Cohen, B. L., Fixed Frequency Cyclotron Theory, Y-757, April 4, 1951. (Also AECD-3301).

are focused; those in negative phase are defocused. A detailed analysis of phase grouping and other phase shifting mechanisms indicates that the ion phase is unfortunately predominantly negative. Since field-variation defocusing dominates the energy-change focusing, some 90% of the initial supply of ions are lost to the dee surfaces. The loss may be reduced by increasing the dee voltage, thus reducing the number of turns an ion makes and keeping the total phase shift small.

In the latter part of the spiral motion, a focusing force associated with the curvature of the magnetic field lines (achieved by widening the gap between pole pieces), takes over to prevent further loss of ions to the dees. The radially decreasing magnetic field has the additional effect, however, of continually making the ion phase more positive. If the shift is too great, ions eventually arrive at the dee gap when the potential difference is low or even reversed and their acceleration in the cyclotron is stopped. The relativistic increase in mass as the ions gain velocity also tends to shift the phase in the positive sense. Again, the larger the dee voltage, the smaller is the total shift in phase. The cyclotron adjustments such as frequency setting, the magnetic field intensity, and field shape thus must involve compromises to keep the ions within necessary boundaries in space and in phase.

It is possible to calculate the various effects quantitatively and to predict the minimum dee-to-dee voltage required to obtain a given energy in a particular cyclotron. The minimum dee potential required for the 86-inch cyclotron to accelerate protons to various energies is given in Figure 4.

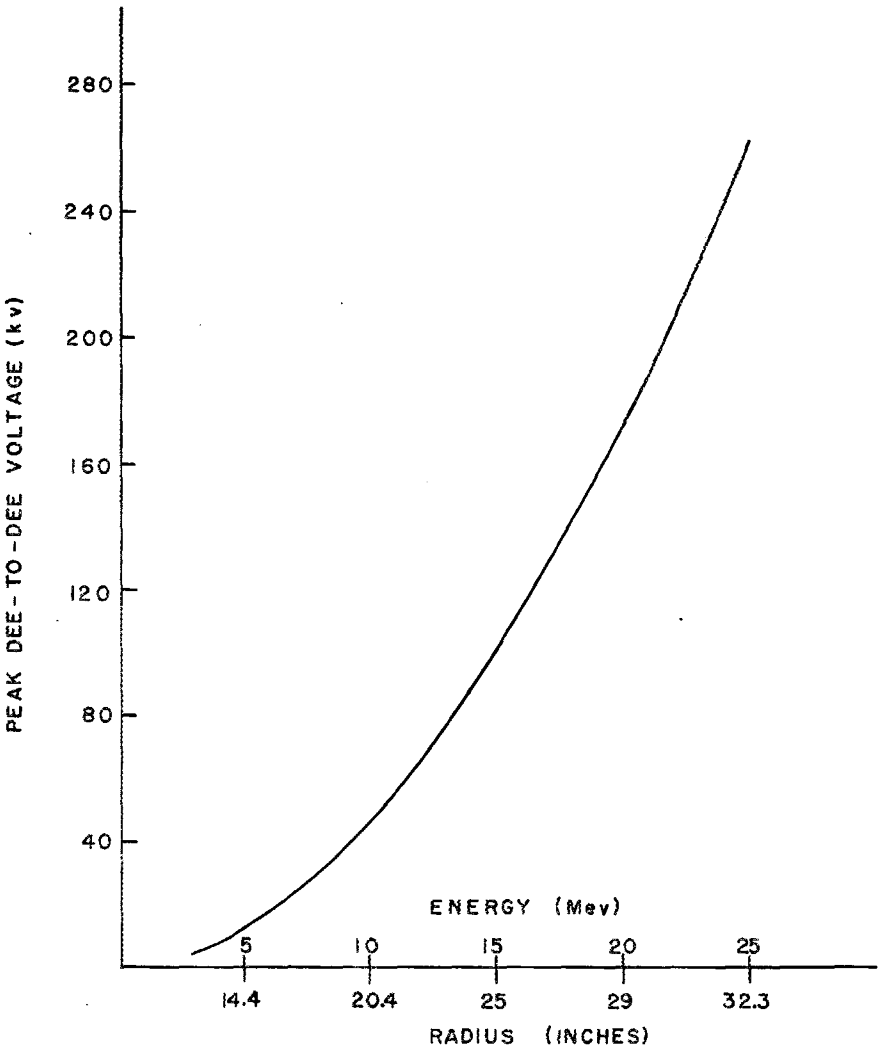


FIGURE 4. THRESHOLD VOLTAGE

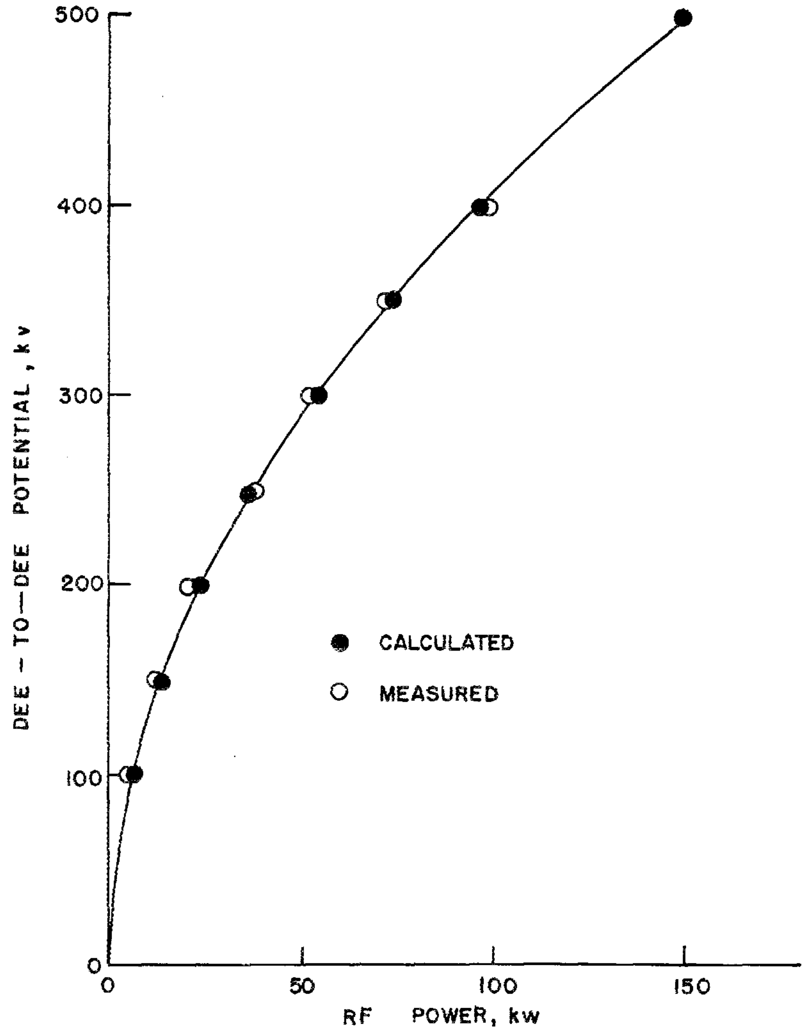


FIGURE 5. POWER FOR DEE EXCITATION

PERFORMANCE

During the last six months of 1951, over 300 bombardments totaling more than 1,000,000 microampere-hours were made for the following divisions of the Laboratory: Aircraft Nuclear Propulsion, Biology, Chemistry, Health Physics, Operations, Physics of Solids, and Electromagnetic Research; and for the Oak Ridge Institute of Nuclear Studies. While the 86-inch cyclotron has been operated at different times at calorimetered beam currents approaching two milliamperes, and at measured energies up to 25 Mev, and for continuous runs exceeding 100 hours, the performance of the machine is best demonstrated by describing the actual operating conditions for three types of runs. These runs are selected to demonstrate the sustained operation, isotope production, and high beam power obtainable. An analysis is then made of power distribution and cyclotron efficiency.

Sustained Operation

The cyclotron has been operated for long continuous periods with the beam on the target, "innage," a high percentage of time. Innage is defined as the percentage of available time in which a desired value of beam current is actually on the target. Innage during long runs has in some cases exceeded 97%. During the last five months of 1951, while the machine was being operated 168 hours per week, the overall innage averaged 60%. Much of the lost time, or "outage," has resulted from leaks in the vacuum system, electrical difficulties, mechanical problems, and interruptions for minor improvements, in that order. Routine operation outage is required for changing ion sources, changing targets, inspection of targets, refilling vapor traps, and initial operation adjustments following an interruption. A remote control mechanism has recently been installed which permits refilling vapor traps without interruption and without exposure of personnel. Total outage for changing an ion source averages about two hours.

Ion source filament life now averages 85 hours; some filaments have been used over 100 hours. If it were desirable to operate the cyclotron on a continuous basis the only essential outage would be for two ion source filament changes per week.

A recent cyclotron run illustrates the performances characteristics for sustained operation. For 58.6 hours the beam current averaged 620 μa and the target beam power 14.2 kw. Operating conditions for this run (A) are summarized in Table I. The steadiness of the beam during a run of this type is evident in the 8-hour segment of the chart from the beam recording meter, Figure 6.

Isotope Production

The conditions for isotope production runs vary greatly since the desired proton energy, beam current, and duration are determined by the nature of the target and the objective of the experiment. A recent gallium 67 production run illustrates this type of operation. A zinc target was bombarded with a 250 μa beam of protons at 23 Mev for two hours to yield 500 mc of gallium 67; the specific yield was 1000 mc/mah. With a zinc target it is necessary to reduce the beam power to avoid vaporizing the target surface. The proton current can be reduced by reducing the dee-to-dee potential, by adjusting the intensity of the arc in the ion source, or by tilting the ion source so that it is not fully aligned with the magnetic field. Operating conditions for this

TABLE I: SUMMARIES OF CYCLOTRON RUNS ILLUSTRATING:

A. Sustained Operation
B. Isotope Production
C. Beam Power Test

	A	B	C
Innage, actual hours	58.6	2	-
Radius, inches	30.5	30.5	30.5
Proton Energy, Mev	~ 23	~ 23	~ 23
Proton Beam			
Average metered current, μa	620	250	1813*
Integrated, μa-hrs	36,360	500	-
Metered power, kw	14.26	5.75	-
Calorimetered power, kw	14.2	5.7	41.7
Target			
Cooling water, gpm	28	9.4	26.6
Cooling water, ΔT in °C	1.9	2.3	5.9
Power dissipation, kw	14.2	5.7	41.7
Ion Source			
Arc potential, volts	132	130	150
Arc current, amps	1.6	1.2	1.4
Filament current, amps	400	400	400
Vacuum, 10^{-5} mm of Hg	1	2.5	2.5
Magnet			
Current, amps	1540	1550	1540
Field at center, oersteds	9067	9084	9067
Coil temperature, °F	160	161	160
Dees			
Dee-to-dee potential, kv	410	395	433
Dee bias potential, kv	1	1	1
Bias drain, less background, ma	7.5	7.5	15
Oscillator			
Frequency, Mc/s	13.53	13.55	13.53
Plate potential, dc, kv	18.4	17.0	19.2
Plate current, amps	13.0	13.0	17.3
Power input, kw	239	221	333
Gross Power Efficiency, % $\left(\frac{\text{Beam Power, kw}}{\text{Osc. dc Input, kw}} \times 100\right)$	5.9	2.6	12.5

* Calorimetered

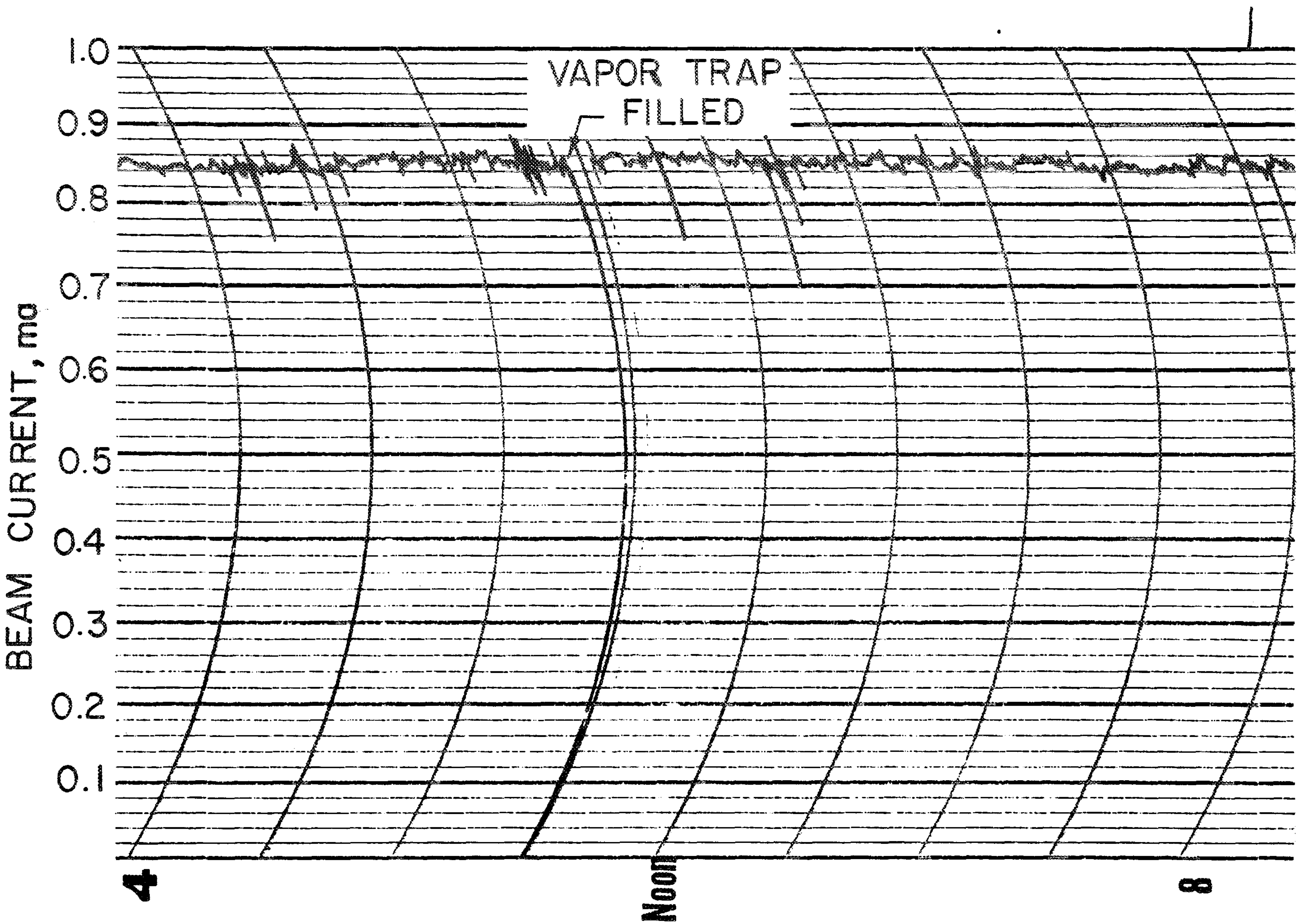


FIGURE 6. BEAM CURRENT CHART

run (B) are summarized in Table I. A comparison of this run with the preceeding one reveals the lowered efficiency obtained at reduced beam currents.

High Beam Power Tests

Test runs are made from time to time for the purpose of determining the adequacy and efficiency of cyclotron components at increasingly higher power levels. A run of this type was made May 22, 1952. The cyclotron had been operating steadily for some time with 500 μa of 23 Mev protons on a 6" by 10" water-cooled aluminum target of the grazing-incidence type. The beam current was increased in successive steps of about 500 μa by raising the dee potential and by optimizing the position of the ion source and the power input to it. Operation was sustained at each level long enough to record the various operating characteristics and to determine the power output to the target by calorimetric measurements. At the highest level obtained, momentary beam meter readings exceeded two milliamperes but operation at this level was very unsteady due to sparking; further increases were not attempted. The highest level at which operation was stabilized long enough to permit calorimetric determinations gave a beam power of 41.7 kw; at $\sim$ 23 Mev this corresponds to an average beam current of 1.8 ma. Operation characteristics for this high performance test (C) are summarized in Table I.

Cyclotron Efficiency

Tests of cyclotron operation efficiency have recently been made. As measured, efficiency tends to increase with dee-to-dee potential and with beam power.

<u>Power to Excite the Dees</u>. In an analysis of power efficiency it is helpful to know the rf power requirements for exciting the dees. The relationship is:

$$P = \frac{\pi f c}{Q} E^2$$

where f = the frequency of the dee system
c = the effective capacitance of the dee system
E = peak dee-to-dee potential
Q = the ratio of stored power to dissipated power in a half cycle.

When the rf system was designed, both Q and c were calculated and the power requirements ascertained, Figure 5. This curve indicates that 96 kw of rf power is required for exciting the dees to 400 kv. In an experimental test of this point on the curve, a steady run was interrupted, the tank was exposed to atmospheric pressure, the dee voltmeters calibrated at 18 kv dee-to-ground with a direct-reading rf voltmeter, the tank was again evacuated, and when operation was resumed the dc power input was measured for 400 kv dee-to-dee. The oscillator input was 162 kw. The oscillator efficiency, including plate line losses, has been measured at 60%. At this efficiency, approximately 97 kw of power was required to excite the dees. In a series of such measurements, good agreement was found between calculated and experimentally measured points, as shown in Figure 5, page 19.

<u>Efficiency Measurements</u>. From actual power measurements and known dee excitation requirements it is possible to calculate the ion loading and the efficiency of the cyclotron under various conditions, Table II. The dc power input to the oscillator, beam power, and the net ion current to the dees are readily measured. Dee excitation power requirements are obtained from Figure 5, as above. With the arc off, the total output of the oscillator is used to excite the dees to some desired rf voltage. When the arc is on, the oscillator

Conditions									
Beam Current, μa	0	500	0	0	800	0	0	1000	0
Dee-to-Dee, kv	365	365	365	380	380	380	400	400	400
Ion Source Arc	Off	On	On	Off	On	On	Off	On	On
Magnetic Resonance	-	On	Off	-	On	Off	-	On	Off
Measured									
Oscillator dc Input, kw	133	196	143	143	217	152	160	247	173
Beam-on-Target Power, kw	0	11.5	0	0	18.4	0	0	23.0	0
Dee Ion Loading, ma	0	11	11	0	10	10	0	12	12
Calculated									
Oscillator Output, including plate line losses, at 60% eff., kw	80	118	86	86	130	91	96	148	104
Dee rf Excitation, kw	80	80	80	86	86	86	96	96	96
Ion Loading Losses, kw	0	26.5	6.0	0	25.6	5.0	0	29.0	8.0
Average Energy of Ion Load, Mev	0	2.41	0.54	0	2.56	0.50	0	2.41	0.67
Gross Power Efficiency, % ($\frac{\text{Beam Power, kw}}{\text{Osc. dc Input, kw}}$ x 100)	-	5.86	-	-	8.47	-	-	9.31	-
Net Power Efficiency, % ($\frac{\text{Beam Power, kw}}{\text{Beam + Ion Load, kw}}$ x 100)	-	30.2	-	-	41.8	-	-	44.2	-

TABLE II: POWER DISTRIBUTION AND CYCLOTRON EFFICIENCY, at ~23 Mev output also includes the beam power, which is measured calorimetrically, and the power loss due to ion loading of the dees. Since the net dee ion loading current is already known, the average energy of the ion load is readily calculated for both on and off resonance conditions. The ion load results from ions becoming defocused and striking the dees. The ion transport efficiency, which depends upon both focusing and phasing, tends to improve at higher dee potentials. Apparently fairly large ion currents are circulating in the dees at the lower energies. This indicates that with improved ion focusing, much larger currents could be obtained on the target.

The gross power efficiency is defined here as the ratio of beam power to dc power input to the oscillator. Net power efficiency is the ratio of beam power to total power transmitted by all ions (beam power plus ion load power). In the experiment described in Table II both power efficiencies increased with beam power. While conditions were not all the same for the beam power test, (C) of Table I, the greater efficiency at 41.7 kw beam is consistent with the expected trend.

COMPONENTS OF THE CYCLOTRON

After the principal requirements for the cyclotron were established, it was possible to proceed with the design and fabrication of various components. Fabrication of the components was scheduled to permit orderly assembly of the machine; while the magnet was being assembled vacuum equipment was being prepared; by the time the vacuum tank was in place the oscillator had been tested with an electrical model and was ready for installation; in the meantime the dee assembly, power supplies, and utilities were being prepared. There were some modifications of designs as construction progressed and later, during the testing period, many additional changes proved desirable. In the following section the components are described in some detail in their present form. The modifications which were made in the original designs will be discussed elsewhere.

The components will be considered in the following order:

- Magnet
- Vacuum System
- Radio Frequency System
- Ion Source
- Targets
- Control Equipment
- Shielding
- Utilities

THE MAGNET

The availability of electromagnetic equipment in Y-12 contributed much to the speed and economy with which the cyclotron magnet was completed. It was found that the available coils could be used more conveniently in a magnet arranged with the planes of the pole faces vertical. Elimination of the conventional yoke across the top for reasons of access leaves only the lower yoke to complete the path for the magnetic field. The magnet yoke was assembled from two-inch steel plates. Four copper-wound magnet coils were transferred from a Beta magnet. The motor-generator set and oil-cooling facilities were already in place. The magnet was first energized on March 3, 1950, less than six months after excavation for the foundation was begun.

Yoke and Pole Cross Sections

In most magnets the cores, poles, and yoke usually have the same cross section. In contrast, the area of each 86-inch circular pole piece is 5770 square inches; the area of the roughly rectangular core of a Beta coil is 4500 square inches; and the yoke cross section is 3070 square inches. Larger coil currents and lower magnetic field requirements of this cyclotron permit the use of unconventional oversized poles and a smaller than normal yoke. Model magnet tests indicated that with 86-inch pole pieces, 10 inches thick and with vacuum tank walls four inches thick, a satisfactory magnetic field would be obtained. Model tests also indicated that only a very small gain in magnetic field would result if the yoke area were increased from 68% to 100% of the coil core area.

The Magnet Yoke

The steel yoke of the magnet is 22 feet and 5 inches long, 16 feet high and 4 feet by 5 1/2 feet in cross section, and weighs approximately 250 tons, Figure 7. It is set on reinforced concrete three feet thick and resting on solid rock. A two-inch plate, several inches longer and wider than the yoke, anchored to the concrete provided a relatively smooth surface upon which the yoke was assembled. The yoke is composed of hot-rolled steel plates, SAE 1010. Plates two inches thick were selected after consideration was given to factors such as flatness and uniformity of commercial plates. These plates were thin enough to be drawn into a rigid and magnetically satisfactory structure. The plates are four feet wide and of three lengths which permitted interlocking joints at the corners. The 32 layers of plates are held together by tack welds and 2 1/2" tie bolts.

Magnet Coils

Magnet coils for the cyclotron were obtained from Beta Magnet VI, Building 9204-3, Figure 8. The coils were replaced by an inexpensive structure with equivalent coil dimensions thereby permitting reassembly and operation of the other sections of the Beta magnet. The four standard Beta type magnet coils are capable of being energized in excess of 10^6 ampere-turns. Each coil has 174 turns of 3" by 0.420" copper conductor. With laminated steel core and steel case, each coil weighs approximately 35 tons. The coils are energized by currents up to 1700 amperes, or 62% more than for normal Beta magnet operation. The power per coil is 75 kw during normal cyclotron operation; in the Beta magnet they were operated at 35 kw.

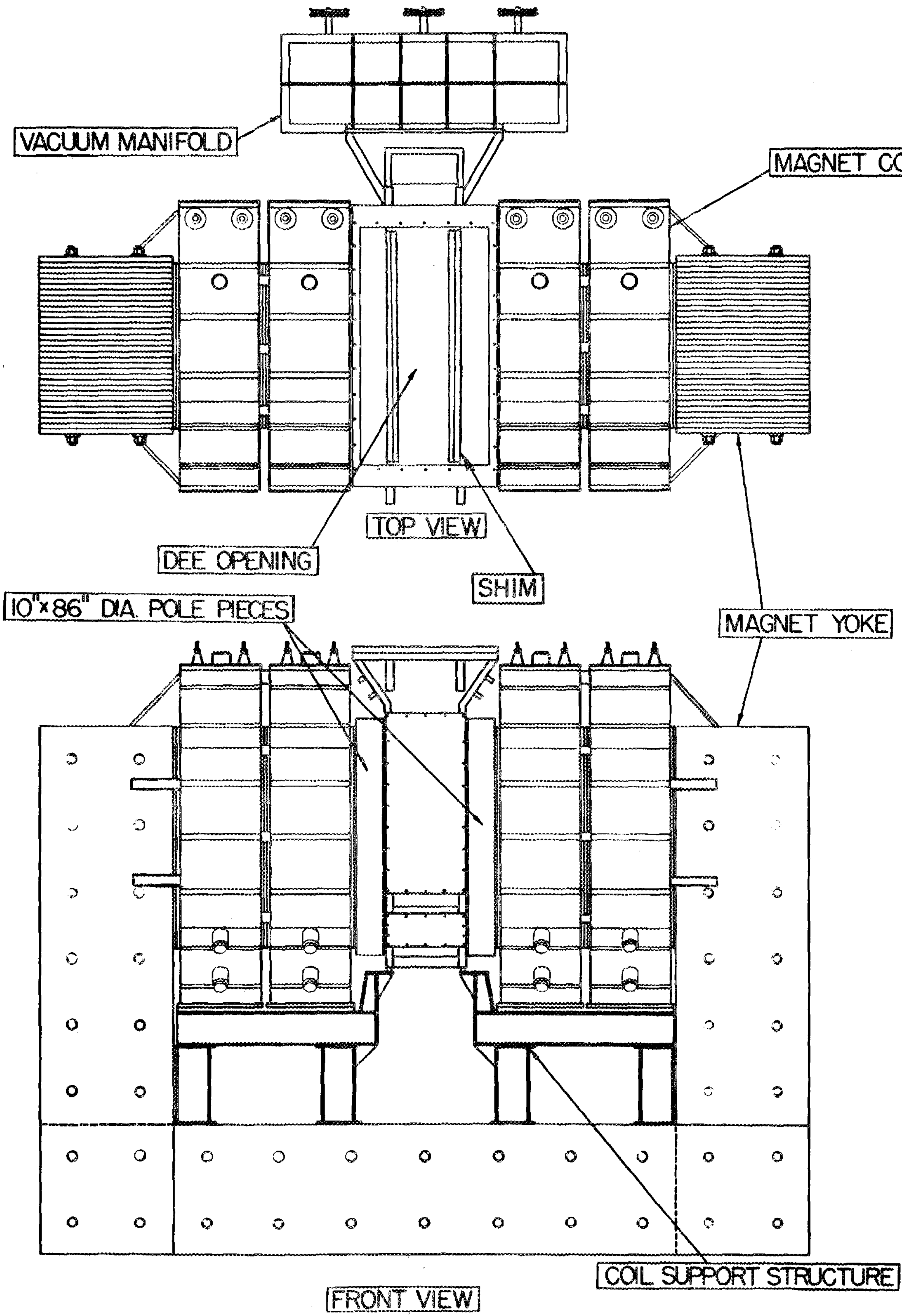


FIGURE 7. 86 INCH MAGNET, SKETCH

FIGURE 8. TRANSFERRING BETA COIL

FIGURE 9. MACHINING CONTOUR SHIMS

The magnet coils are supported entirely by the frame upon which they rest; the cores are not attached to the magnet yoke. Since the coil cases were slightly wider than the cores, one-inch steel spacers are used. During model magnet tests the large forces acting upon the coil cases were measured and suitable braces between cases and from cases to yoke were designed to hold the cases rigidly in place, Figure 7.

Cooling for the magnet coils was obtained by connecting to the magnet cooling system already in the building. The windings are cooled by passing more than 200 gpm of transformer oil, Transil Type C, through each coil. Automatic control of inlet oil pressure and thorough filtering of the oil is provided. Automatic alarms were installed to give warning in the event of loss of oil flow. The coils are equipped with flow meters, inlet and outlet pressure gauges, and voltmeters across each winding. The latter, at a known coil current, give an indication of coil temperature. A Brown recorder is also used to measure and record the temperature of the windings. An alarm warns the operator when the coil temperature has reached a predetermined value, usually 70° to 80°C. These precautions are necessary in order to insure the maximum life of the magnet coil insulation, which the manufacturer estimates will vary with temperature as follows:

Hot Spot Temperature (°C)	Average Temperature (°C)	Expected Life (years)
89	79	8 to 40
97	87	4 to 20
105	95	2 to 10
130 (maximum allowable)		short period

The coils can be operated for short periods at higher rates since one to three hours are required for the temperature to reach equilibrium.

Fire Protection

An automatically operated CO_2 system protects the cyclotron against fire. Detector heads near the magnet activate the system if they are subjected to a temperature rise of 20°C per minute. The system can also be activated by a manual "pull" switch at each exit from the pit. When the system is activated, alarms sound inside the cyclotron pit and in various parts of the building, including the control room. After a 40-second time delay, to allow personnel to get beyond the shielding wall, twenty-six 50-pound cylinders of CO_2 discharge into the cyclotron pit.

Pole Pieces

Unconventional oversized pole pieces are used to correct for the rectangular shape of the coil cores. These discs are SAE 1010 steel, 10 inches thick and 86 inches in diameter. In effect, additional pole piece thickness is provided by the 4" steel walls of the vacuum tank, and the 2" magnetic shims giving sixteen inches of steel between the dees and the coil cores.

The 10" steel discs are supported upon 3" steel pins anchored in the magnet cores. Each steel pin extends into the center of the disc approximately five inches; the disc is free to move on the pin. During assembly the pole pieces were moved back when the vacuum tank was inserted to provide maximum clearance. After the tank was in position upon its supports, wedges were inserted between the pole pieces and coil cores forcing the pole pieces to fit tightly against the tank wall. In this way the very large forces produced by the magnetic field are distributed uniformly on the tank.

Beam Control Coils

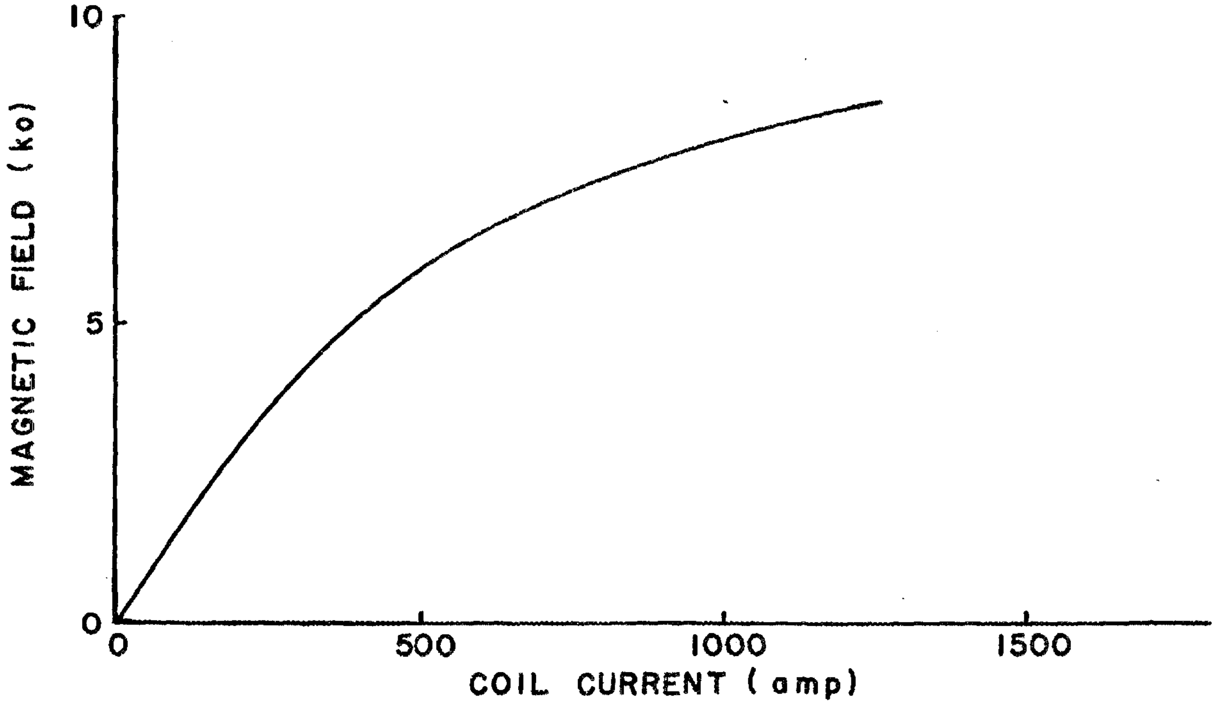
By means of auxiliary coils wound on the pole pieces it is possible to control the position of the beam with respect to the median plane of the tank. The coils consist of 65 turns of #6 wire wound on each 10" pole piece. A dc power supply provides up to 75 amperes. The direction and magnitude of the current is controlled to produce the desired effect on the proton beam.

Magnetic Shims

The magnetic shims are designed to further correct for azimuthal variations in the magnetic field due to the unusual shape of the magnet coil cores and to provide a focusing component that will keep the proton beam near the median plane. The shims were machined from 2 1/4" steel plate on a vertical boring mill, Figure 9. These shims reduce azimuthal variations to less than 0.2%. The radial decrease in field strength is at a rate of one percent in 13 inches out to a radius of 20 inches, Figure 10. The field then falls off less rapidly out to 26 inches, is nearly uniform to 31 inches, and decreases about 0.1% in the next two inches. At 33 inches the field is about 1.75% less than at the center. The magnitization curve taken at the center of the tank with the contour shims in place is also shown in Figure 10. Methods of magnetic field measurement are described in Appendix B.

Magnet Supply

The cyclotron magnet supply consists of a 3∅, 13.8 kv, 360 RPM, 8400 hp synchronous motor driving a 4286 ampere, 700 volt, 3000 kw generator. The motor had previously been used to drive two generators for energizing an Alpha magnet in the building. The brushes, field excitation, and other connections of the second generator have been removed. The cyclotron magnet is connected to the generator through three 1,000,000 CM lead-covered cables in parallel in a



MAGNETIZATION CURVE

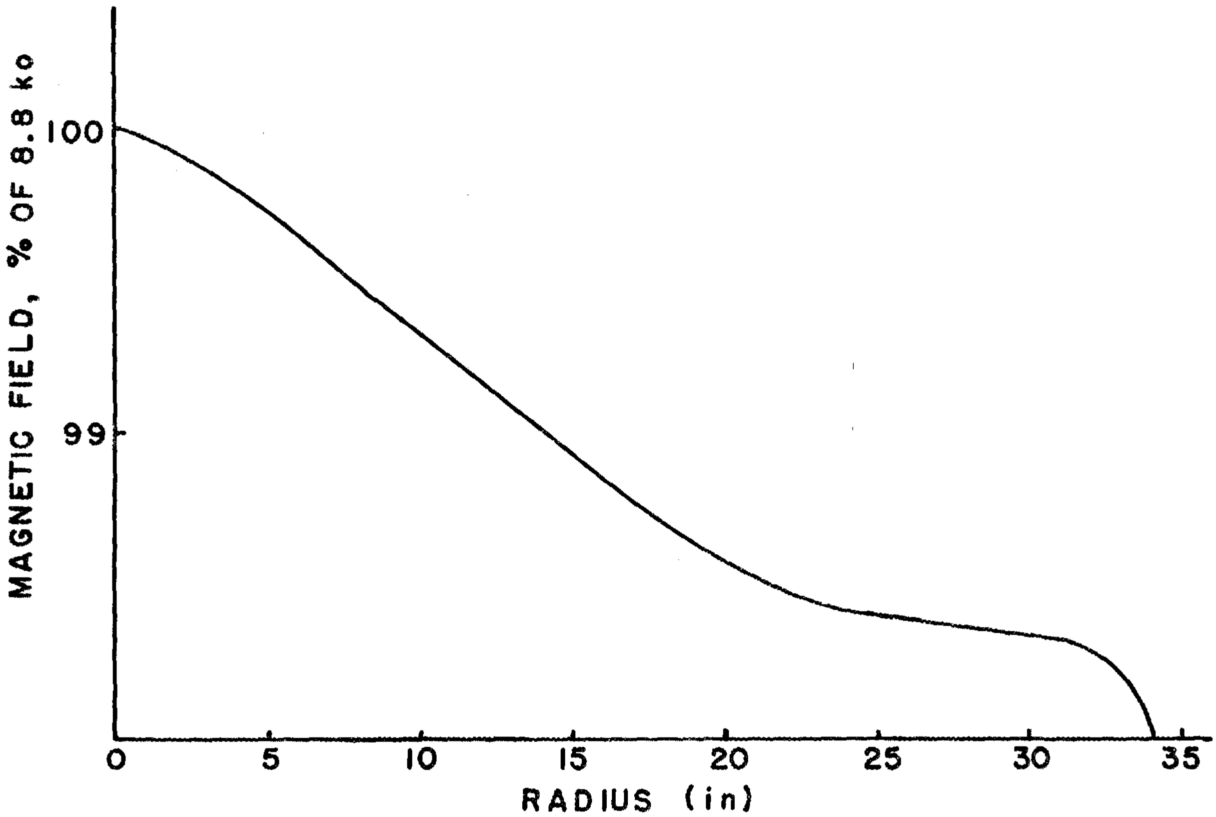


FIGURE 10. MAGNET CHARACTERISTICS

4 1/2" sealed conduit. The generator is operated at about 300 kw, supplying 1500 amperes at 200 volts to the cyclotron magnet.

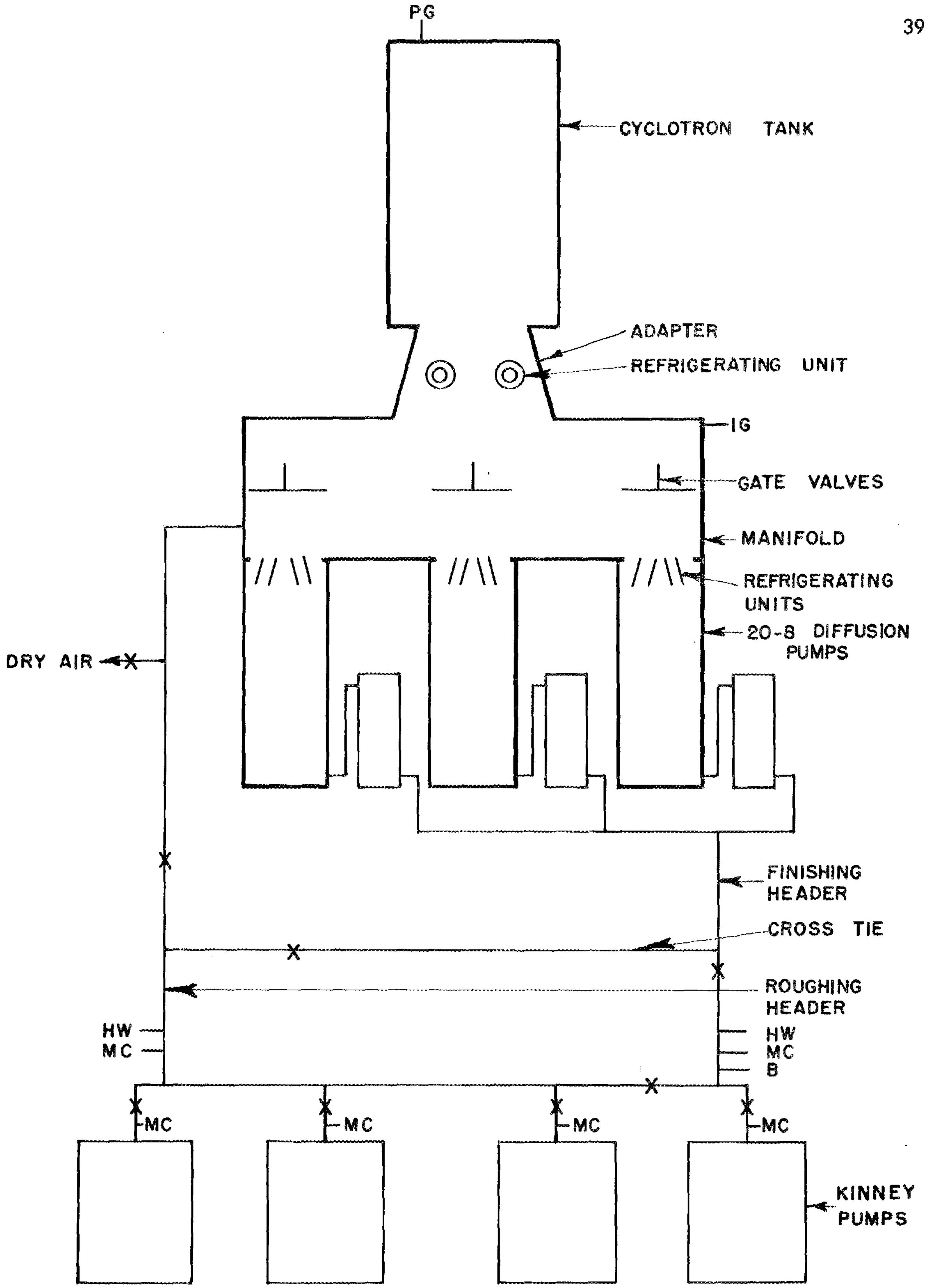
The existing current regulator was revised to operate over the new current and voltage range required for the cyclotron magnet. A limited current control of 100 amperes has been provided at the two control desks; decade controls on each console permit one and ten-ampere adjustments in magnet current. These current controls are used to adjust the magnet current, and in turn the magnetic field in the gap, for optimum operating conditions. One-ampere steps for an operating current of 1500 amperes cause very small changes in magnetic field due to saturation in the coil cores.

THE VACUUM SYSTEM

The use of a tank extension attached to the top of the vertical vacuum tank makes it possible to inclose the complete resonant dee system in the vacuum chamber. The tank is evacuated through a manifold leading to three sets of diffusion pumps, which are in turn backed by mechanical pumps, Figure 11. These latter pumps are located outside of the cyclotron pit some distance from the magnet. The arrangement of the vacuum pumping system resulted in part from the adaptation of existing equipment rather than from considerations of optimum engineering design. The very high pumping speed achieved has contributed substantially to the versatility and the high level performance of the cyclotron.

The Vacuum Chamber

The vacuum chamber, consisting of the tank, tank extension, adaptor, and vacuum manifold, has a total volume of approximately 450 cubic feet. It is positioned vertically between the two 10" pole pieces of the magnet. The tank is non-magnetic steel, type 304, except for two circular discs of mild steel, SAE 1010, 4" thick welded into the tank walls immediately opposite the pole pieces, Figure 12. The tank is designed to withstand the forces of the magnetic field as well as atmospheric pressure. The top of the vacuum tank is so shaped that the desired clearances for the dees is obtained. This required the forming of 2.5" stainless steel plates for framing the aperture. The overall height of the tank is 114"; the outside width at the pole pieces is 30"; and the inside width is 22". The total weight of the tank is 10.5 tons. The inside surfaces adjacent to the pole pieces are parallel within 0.030" and as flat as good machining practices permit. They are provided with a number of



IG — TRIODE ION GAUGE
HW — PIRANI GAUGE
X — VALVE
B — BOURDON GAUGE
PG — PHILIPS ION GAUGE
MC — McCLOUD GAUGE

FIGURE II. DIAGRAM OF VACUUM SYSTEM

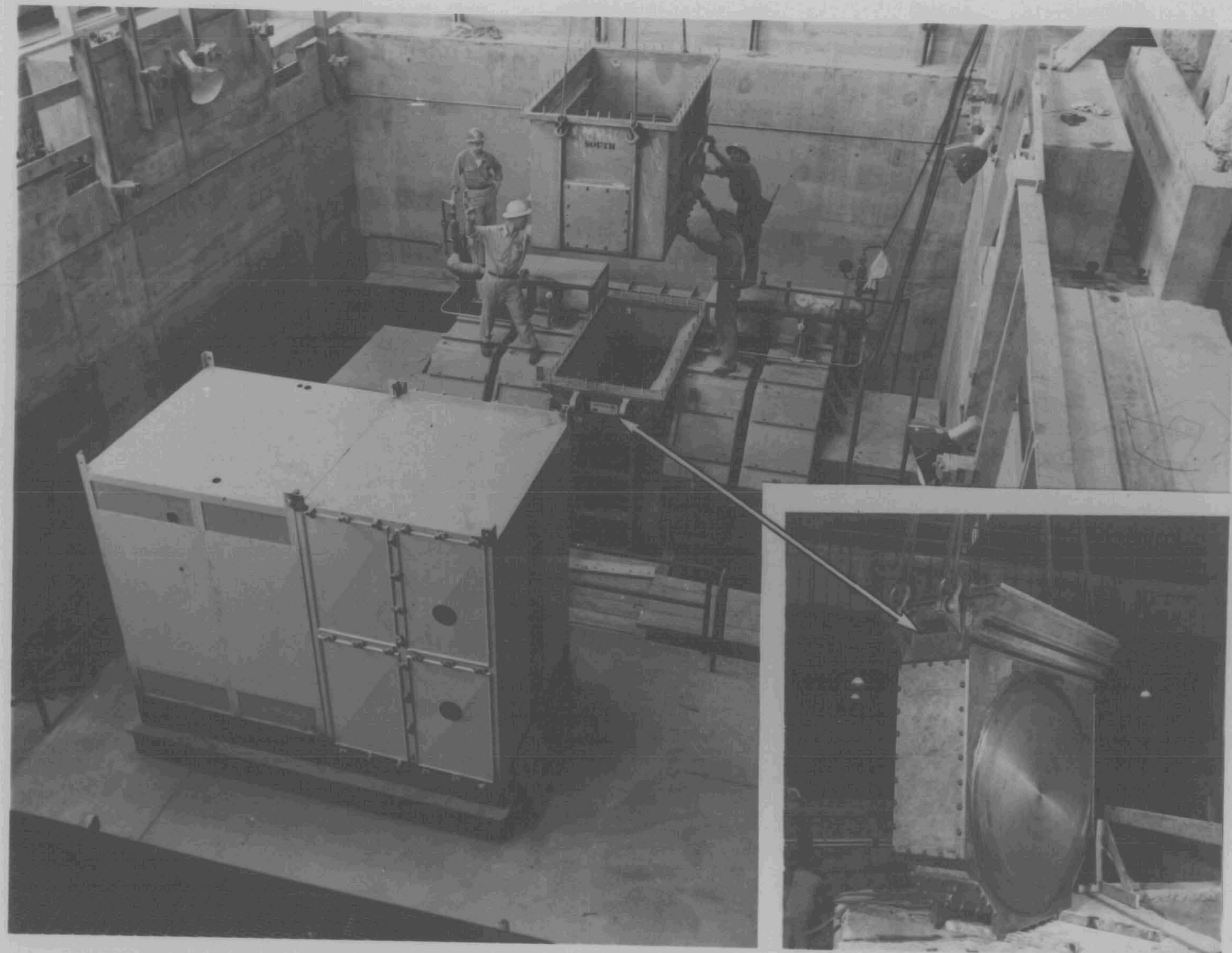


FIGURE 12. TANK AND EXTENSION BEING INSTALLED

tapped holes for the attachment of magnetic shims. The tank was designed at Y-12 and fabricated by Lukenweld Incorporated, Coatesville, Pennsylvania.

The tank is little more than a framework supporting the two heavy side plates; there are openings in all four sides and the two lower corners of the periphery. A tank extension is attached at the top, the vacuum adaptor at the back, the target faceplate at the bottom, faceplates for mounting voltmeter probes at the two lower corners, and a plate with window, variable trimmer, and a vacuum gauge at the front. The faces of these openings are machined flat to accommodate the vacuum seals which consist of continuous square rubber gaskets located in grooves in the faceplates of sufficient cross section to accommodate the entire gasket under pressure. The resulting metal-to-metal contact between tank and faceplates assures proper alignment and the vacuum seal has proved very satisfactory.

The tank extension, constructed as a housing for the dee stems, is attached to the top of the vacuum tank, Figure 12. The extension, 57" by 107" and 52" high, was fabricated of 0.5" stainless steel with suitable reinforcements. The combined volume of the tank and extension is 280 cubic feet. The liner and dee assembly are inserted through a 101" by 51.5" aperture at the top. Brackets welded to the inner walls of the extension provide for positioning and support of these assemblies. The rf coupling circuits enter the extension through bushing-type insulators in the front and back. Openings on the sides provide for access to the dee stems for adjustment of the line coupling. A recent revision of the water header system inside the tank extension has required a 6" addition to the extension to provide additional space and electrical clearance. An aluminum plate, upon which the ion source assembly is mounted, covers the top opening of the tank extension and completes the vacuum chamber.

The Pumping System

The vacuum tank is attached to a vacuum manifold and thence to the pumping system through an adapter, Figure 13. An opening is provided through the top of the adapter for the insertion of a refrigerated unit to trap moisture and to prevent diffusion pump oil from reaching the cyclotron dees. The vacuum manifold contains three 20-inch disc valves remotely controlled from the utilities control panel. Three Westinghouse oil diffusion pumps are attached to the bottom of the vacuum manifold. The diffusion pump arrangement consists of a primary and a booster pump in series. The barrel of the primary pump is 20" in diameter, flaring near the top to allow higher conductance past the pump-head baffle. The booster pump is 8" in diameter and discharges through a 4" pipe. The overall height of the unit is approximately 62 inches. The original Westinghouse jet assemblies have been replaced with DPI MC-7000 jet assemblies which have increased the pumping speed approximately 25%. To prevent oil vapor from diffusing into the vacuum tank an evaporation unit is mounted in the top of each of the three diffusion pumps, just below the gate valve. Each of these units is composed of three concentric truncated copper cones 6" high, the largest being 20" in diameter. Evaporation of Freon 22 in coils attached to these cones maintains a temperature below -40°F. The pumps and condensers of the system are placed outside the cyclotron pit, near the pumping area, Figure 3.

Three different types of diffusion pump oil have been used. Myvane oil (D.P. 20) and Litton-C have given satisfactory results; each oil has a high resistance to oxidation and an ultimate vacuum of approximately 0.002 microns. Octoil S, now used, has even better ultimate vacuum characteristics (0.0002 microns) but its poor resistance to oxidation requires great care in manipulation of the vacuum system.

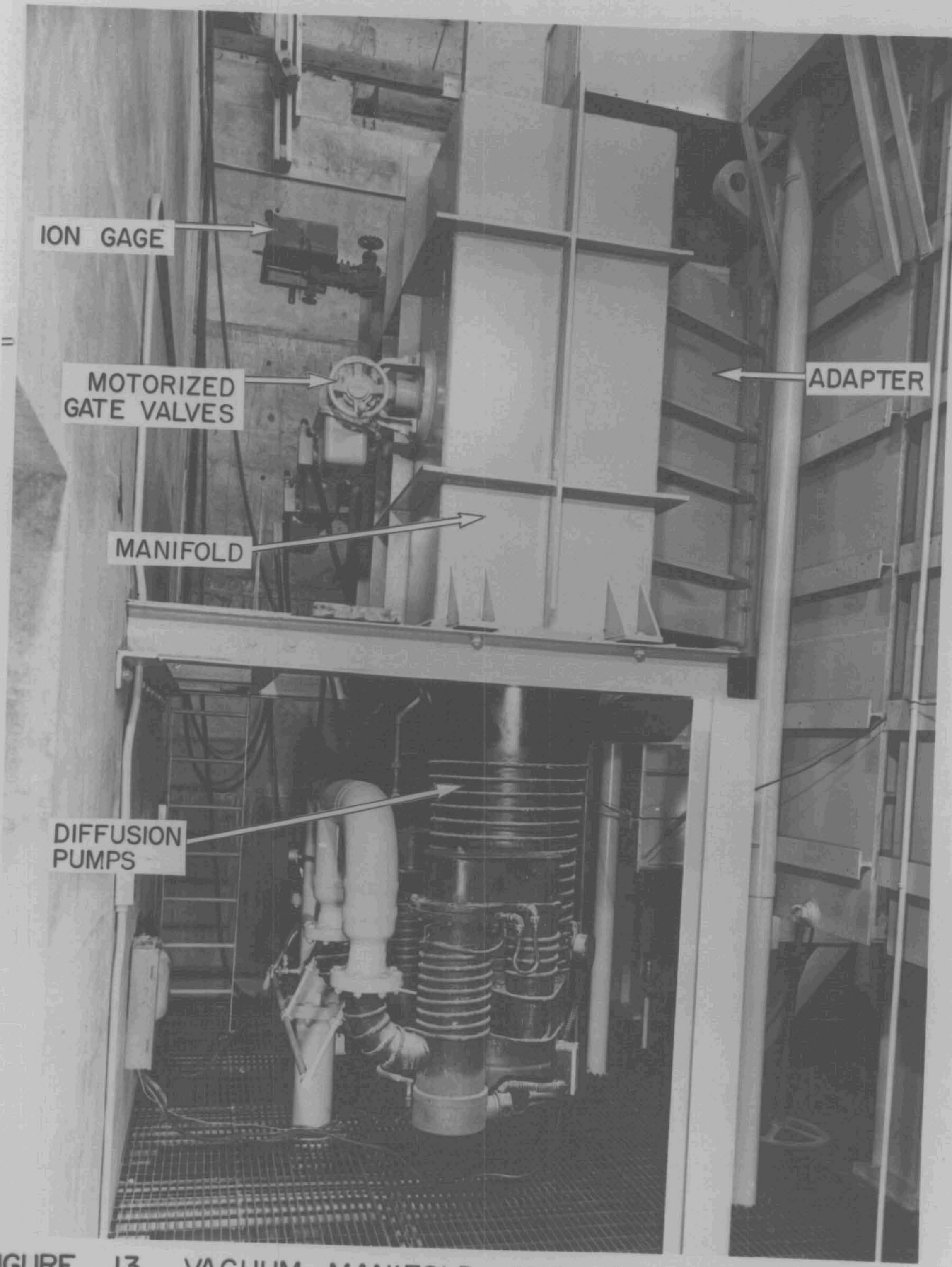


FIGURE 13 VACUUM MANIFOLD AND DIFFUSION PUMPS

In the original Alpha building installation a group of four mechanical vacuum pumps were located to the east of the cyclotron pit. These Kinney pumps, Model DVD 14916, have a theoretical displacement of 300 cfm at the normal speed, 450 rpm; each requires a 15-hp, three-phase, 460-volt motor. In order to use these pumps in their original location, two 10" vacuum lines approximately 100 feet long were run from the north side of the cyclotron through the east shielding wall and under the ground floor to the vacuum pump area, Figure 11. Three of the Kinney pumps are tied together with a common 10" header, each pump being tied to the header through a 6" Chapman angle valve. One of the vacuum lines connects directly to this header at one end and through a 6" Chapman valve to the vacuum manifold at the other end. This line forms the roughing header for the cyclotron. The second vacuum line connects the fourth mechanical pump to the three diffusion pumps and thereby forms the finishing header, or fore vacuum, for the diffusion pumps. Appropriate cross-ties installed at each end of the lines make it possible to parallel the two vacuum lines during the pumping down operation if increased conductance of the vacuum system is desired.

Previous experience with Kinney pumps had shown that a steady stream of dry air injected into the outlet side of the pump cylinder could eliminate the need for a refrigerated vapor trap in the inlet line. Since this system had proved satisfactory and convenient, it was adopted on the cyclotron. The dry air is obtained from the Lectrodryer unit that also supplies the dry air when the tank is exposed to atmospheric pressure; dry air is used in the tank in order to minimize the amount of moisture entering the tank and thereby to reduce the time required for the next pumpdown.

Vacuum Instrumentation

Several vacuum gauges are used to provide essential operational data, for the location of leaks, and to protect the equipment. Each Kinney pump is equipped with a Stokes-type McLeod gauge between the pump and its header valve. This is necessary in order that the performance of each pump may be ascertained before it is connected to the vacuum header. A similar McLeod gauge is connected to the finishing header and another to the roughing header. In addition, an Allis-Chalmers type Pirani gauge is connected to each header. On the finishing header, the Pirani gauge has a contacting device built into the meter which will operate a relay and in turn sound an alarm if the pressure exceeds a predetermined value. The alarms are located in the remote control room and on the utility panel. Duplicate sets of meters for the finishing header Pirani gauge are located at the local control desk and on the utility panel. A Bourdon type vacuum gauge attached to the finishing header in the Kinney pump area gives a convenient indication of header condition.

On the high vacuum side, two types of vacuum gauges are used: a triode ionization gauge and the Philips ion gauge. The triode ionization gauge tube is an Eimac 35T modified by a 1/2" diameter glass tube fused to the side and connected to the tank vacuum through a rubber compression type seal. Since no provisions are made for a vapor trap ahead of the ion gauge, the pressure read by this gauge is total tank pressure. No tube damage has been apparent thus far, perhaps because the ion gauge is not turned on until the tank pressure is less than 0.5 microns. The ion gauge assembly is located on the vacuum manifold directly above the gate valve assembly. In this position the conductance from the diffusion pumps around the gate valves to the ion gauge has been estimated to be approximately the same as the conductance from the diffusion pumps to the tank proper. Also, in this position the steel wall of the manifold provides the tube filament with some protection from the magnetic field. The local and the main control panels each have a separate ion gauge power supply and meter.

In addition to the ionization gauge, a Philips gauge is installed at the front of the tank near the variable trimmer assembly. This type of gauge is far more rugged than the triode ion gauge and more sensitive to small changes in pressure, but it is probably not as accurate in reading absolute pressure. The Philips gauge has a cathode made up of two parallel metal plates 1 1/2" square with 1/2" separation and a one-inch wire ring anode spaced between and parallel to the two cathode plates. In the tank the assembly is mounted normal to the direction of the magnetic field. Meters and controls are provided on both control panels. These gauges serve two functions: first, to determine when the tank pressure is low enough to permit operation of the ionization gauge, and second, for observing increase in tank pressure with increase in hydrogen flow as a secondary check on the hydrogen flowmeter.

Typical Performance

Base pressure with roughing pumps	10 microns
Pump-down time (atmosphere to 50 microns)	9 minutes
Base pressure with diffusion pumps	0.006 microns
Rate of rise on tank assembly	0.00015 microns/sec
Time to return to atmospheric pressure	8 minutes
Diffusion pump operating temperatures	
20-inch pumps	240-245 °C
8 -inch pumps	240-265 °C
Pumping speed (at tank face)	
Pump No. 1	5100 L/sec
2	4900 L/sec
3	4900 L/sec

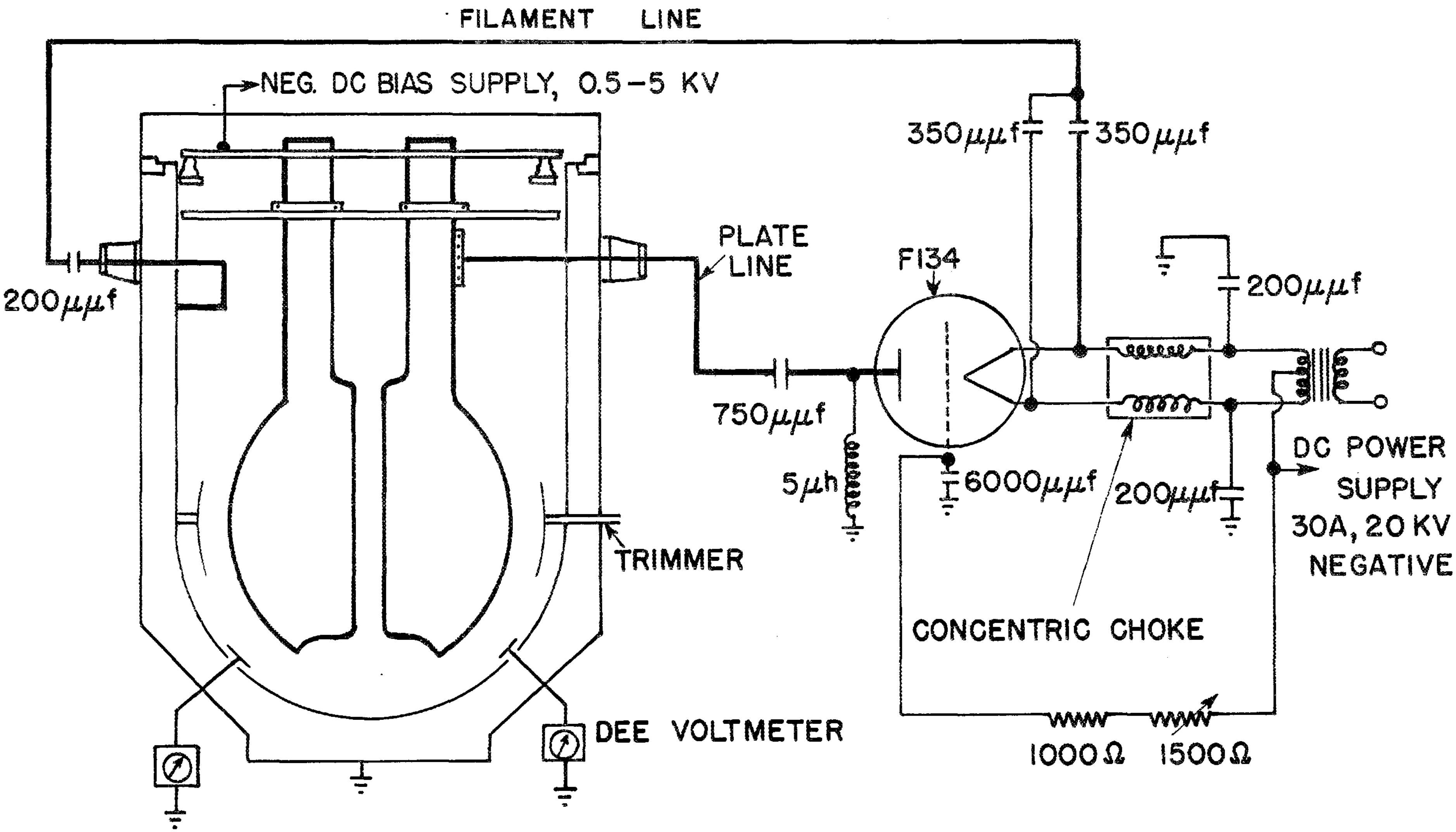
THE RADIO-FREQUENCY SYSTEM

The radio-frequency system consists of the resonant dee system with its quarter-wave transmission line (dee stems), the half-wave filament and plate coupling lines, and the oscillator with its dc power supply. The details of electrical design specifications and circuit characteristics are given in Appendix C. A description of the physical units is given below. Except for standard commercial components all parts of the rf system were designed and fabricated locally. The entire system is shown schematically in Figure 14.

The Resonant Dee System

The resonant dee system is completely inclosed in the vacuum chamber, Figure 2. The insulated dee assembly and the grounded liner are suspended from supporting structures near the top of the tank extension. This arrangement simplifies the installation of the dees and gives the entire assembly mechanical rigidity and stability.

The dee assembly consists of the two dees suspended by their stems from the dee support frame, Figure 15. The resonant frequency is determined by the position of an adjustable shorting spider along the quarter-wave transmission line. The whole assembly is insulated by and rests upon four ceramic insulators, Alsimag 222 (American Lava Company). The dee assembly is maintained at a negative potential to reduce the effect of "ion loading." A modified Alpha I "G" dc power supply is used for this purpose. The bias potential is controlled by a motor-driven induction regulator in the supply; the limit switches are set for a range of 300 to 5000 volts. The control is interlocked so that it can be operated only when the oscillator is operable.



FEDERAL 134 RATED AT:
400 KW INPUT
150 KW DISSIPATION

PLATE LINE 21.1 FT.
FILAMENT LINE 28.3 FT.

FIGURE 14. RADIO FREQUENCY SYSTEM

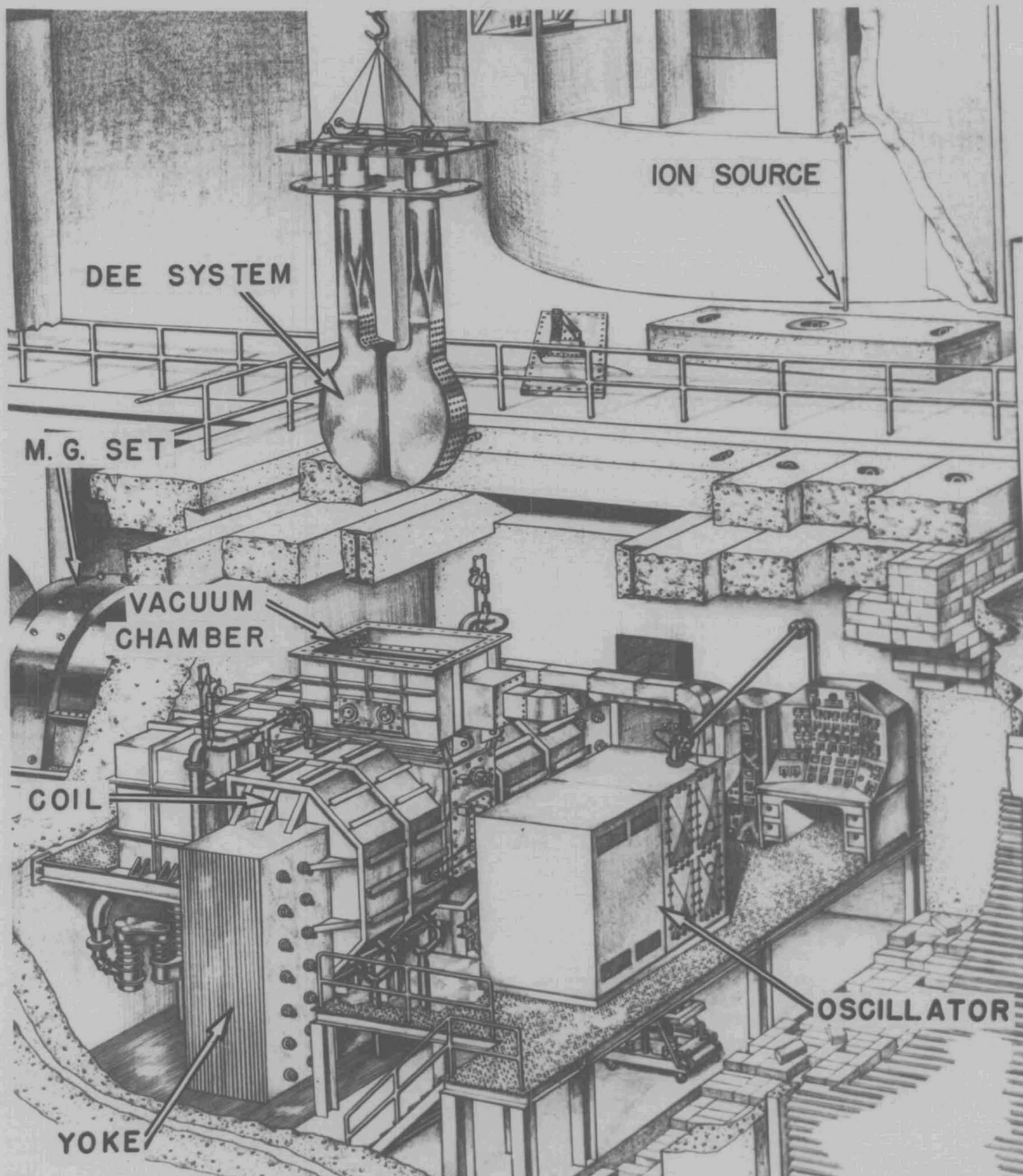
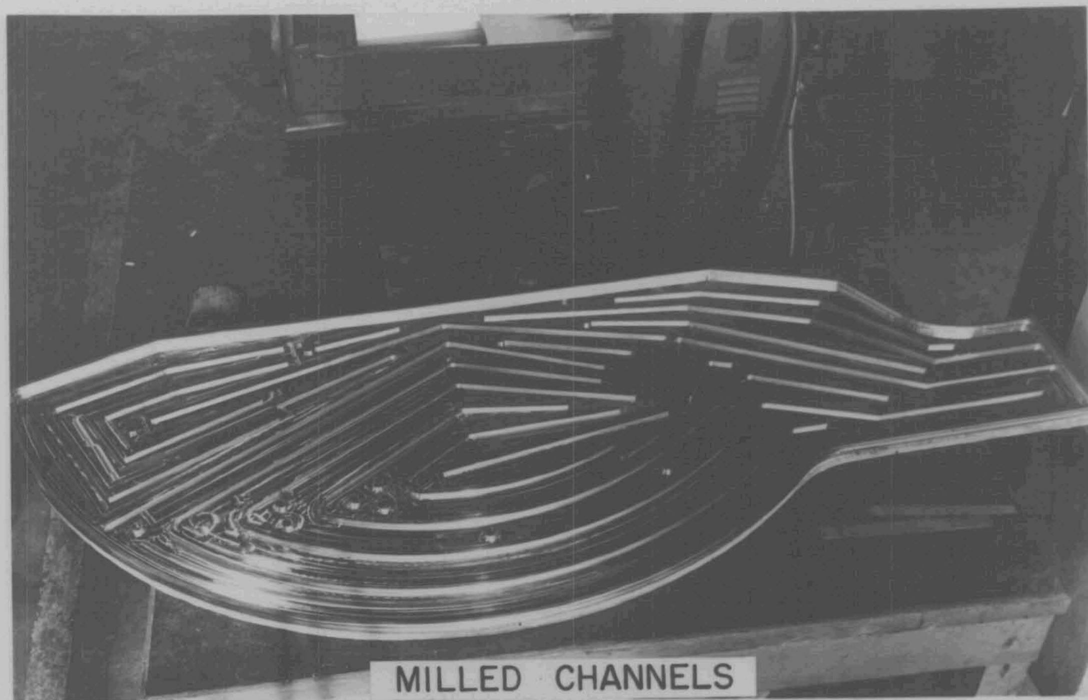


FIGURE 15. CYCLOTRON COMPONENTS

The Dees. The two sets of dees now in use differ chiefly in the way water cooling is obtained, Figure 16. Preliminary estimates of cooling requirements indicated that a water flow of approximately 350 gpm would be desirable. The first set of dees was fabricated with water channels in the thick sides of the dees. The sides were made from 7/8" copper plate in which a pattern of water channels was machined; a 1/8" copper plate was then furnace-brazed over the surface. The pattern of water channels was designed to direct a maximum amount of water along the leading edge of the dee and to concentrate the flow at the mid-point of this edge where calculations indicate the maximum heating occurs. The sides of the second set of dees are 1/8" copper with five loops of 7/8" copper tubing flattened and furnace brazed to the inner surface. The tubes extend through the dee stems and are joined in parallel at the top. Both designs have proved satisfactory but the latter is much easier and less expensive to fabricate.

The peripheral walls of the dees are perforated to permit high pumping speed. Graphite plates are attached to the inside of the dees and along the entering edges to protect the copper from the stray proton beam. The lower corners of the dees are cut away to provide clearance for large targets. On the second set of dees the corners are cut back farther to permit the use of very large grazing-incidence targets. Provisions are made on the south dee for mounting an accelerating electrode.

In order to reduce the long-lived neutron-induced activity, future cyclotron dees and dee stems will be fabricated from copper which is very low in undesired impurities, and silver solder will be avoided. Calculations have been made for the maximum amount of various impurities that can be allowed in order that saturation bombardment with 5 ma of protons on an average target



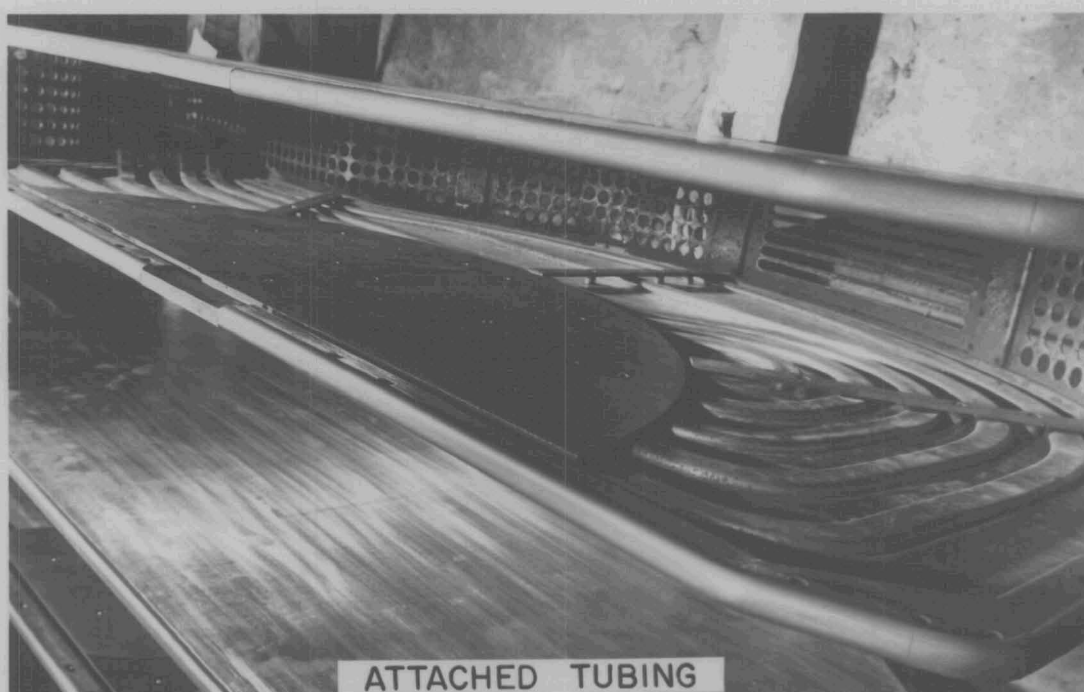


FIGURE 16. WATER COOLING OF DEES

will result in a neutron-induced activity radiation level of less than 500 mr/hr near the dees. In these calculations thermal neutron capture cross sections were used. Copper meeting these specifications, listed below, is commercially available.

Impurity	Half Life of Activity	Maximum Amount (ppm)
Ag	270 days	170
Au	2.7 days	30
As	1.0 days	1200
Sb	60 days	400
Se	127 days	600
Te	60 days	2,000
Fe	45 days	20,000
Zn	250 days	2,000
Co	5 years	6
Ta	117 days	20

Dee Stems. The dee stems were fabricated from 12" copper tubing. They are mechanically attached to the dees, the joint being copper-sprayed and polished to give good electrical contact. The dee stems are cooled by means of 7/8" copper tubing silver-soldered to the inner wall.

Dee Support Frame. The dee support frame is accurately positioned on insulators in the tank extension. This water-cooled rectangular frame is composed of 1" by 3" copper-plated stainless steel bars and is 86.25" long and 38.5" wide. The dee stems are attached to this frame in such a way that they can each be tilted in any direction, moved horizontally in any direction, and rotated about their vertical axes. This flexibility makes it possible to achieve various dee-to-dee gaps and simplifies centering the dees with respect to the magnetic field. The dee support frame also serves as the dee handling fixture and is designed so that the dees may be transferred into the vacuum chamber after being pre-set in an alignment rack. All water circuits in the dees, dee stems, and spider connect to 3" inlet and outlet headers mounted upon the dee support frame, inside the vacuum chamber.

Spider. The shorting connection between the two dee stems, the "spider", is adjustable over a 16" range to provide a means of tuning the dee circuit. The spider is oval in shape, 83 1/2" long by 43" wide and fabricated from 3/16" copper plate. The dee stems are clamped rigidly to the spider by means of two 12" split silver-plated water-cooled copper rings which can be clamped securely around the stems; the rings are attached solidly to the spider plate, Figure 17. The dee stems are also silver plated over the adjustment range. The spider adjustment is made by means of four one-inch threaded copper posts mounted firmly to the top of the spider and extending up through the dee support plate at which point the adjustments are made. Cooling is provided by 7/8" copper tubing flattened and silver soldered to the upper side of the spider plate. The water jumpers from the stationary water header to the movable spider are flexible metal hose and are connected with rubber compression-type fittings.

Variable Trimmer. A variable capacitance for tuning the dees is obtained by means of a trimmer which is mounted adjacent to the south dee. The trimmer plate is a 1/8" copper sheet strengthened by a 5/8" copper rod slotted to fit around its perimeter. It is 6" wide, has a projected length of 26", and is curved on a 38.5" radius. It is water cooled through 7/8" flattened copper tubing silver soldered to the back. To maintain balance the variable trimmer is matched by a fixed plate of the same design attached to the liner adjacent to the north dee. The variable trimmer is mounted on an aluminum faceplate on the south side of the tank, along with a window and a vacuum gauge, and is operated by a reversible ac motor with a v-belt drive. A lead screw drives a keyed shaft through a sliding vacuum seal over the 7" range in $\sim$1.5 minutes. Controls for the trimmer motor and a position indicator are provided at both the local and the main control desks.

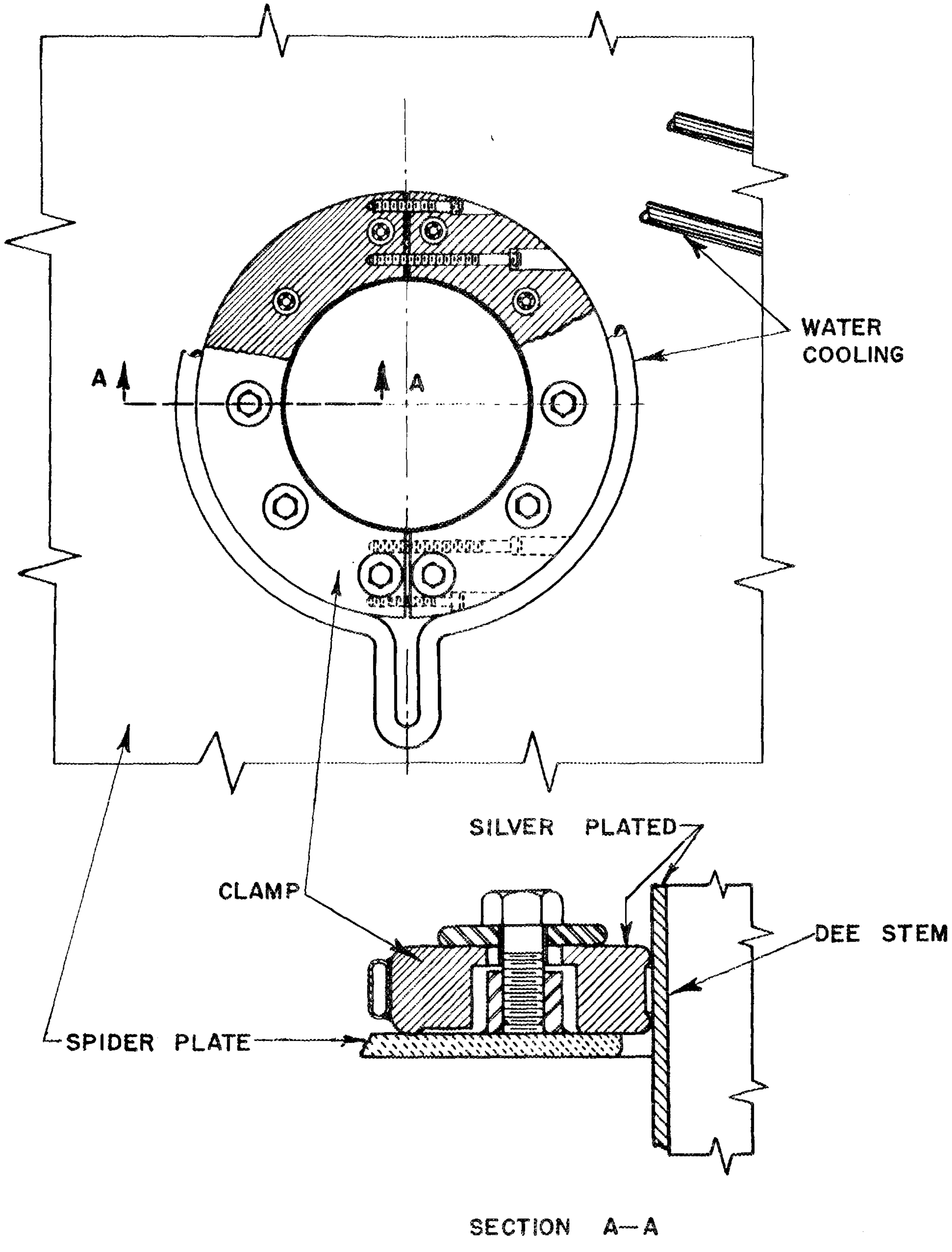


FIGURE 17. RF JOINT AT SPIDER

Liner. The inside of the tank and tank extension is lined with a water cooled sheet of 3/32" oxygen-free high-conductivity copper. This liner encloses the dees and dee stems on the four sides and on the bottom. The structure is braced with 2 1/2" stainless steel channels to make it self-supporting and rigid. It is water cooled by means of 7/8" flattened copper tubing silver soldered to the outer surface. Access openings are provided for the two oscillator coupling lines, two dee voltmeter probes, target assembly, and the variable trimmer. The top of the liner is opened to provide access to the spider and dee adjustments and for the removal of the dees. The periphery of the liner is perforated to permit high pumping speed. The liner is supported and positioned at the top on rails welded to the sides of the tank extension. The lower end of the liner is positioned by means of lugs on the tank walls which engage other stainless steel lugs welded to the bottom of the liner, in a tongue and groove fashion. Figure 18 shows the liner being installed for vacuum testing during the construction period.

Water-Cooled Headers. There are two main water-cooling circuits in the tank. Headers for the inlet supply and the outlet for the liner are at ground and pass directly through the north wall of the tank extension. The second header system, supplying all parts of the dee assembly, is attached to the dee support frame. Since the dees are insulated to operate at a dc bias, sections of two-inch rubber hose about seven feet long are used to insulate the dees and to connect to the inlet and outlet headers at the extension wall.

Coupling Lines. The lengths of the plate and filament coupling lines were calculated and then verified by full scale electrical model tests, as described in the Appendix B. In making the actual installation, a "hump" was provided in each line so that at some future date the lines could be shortened

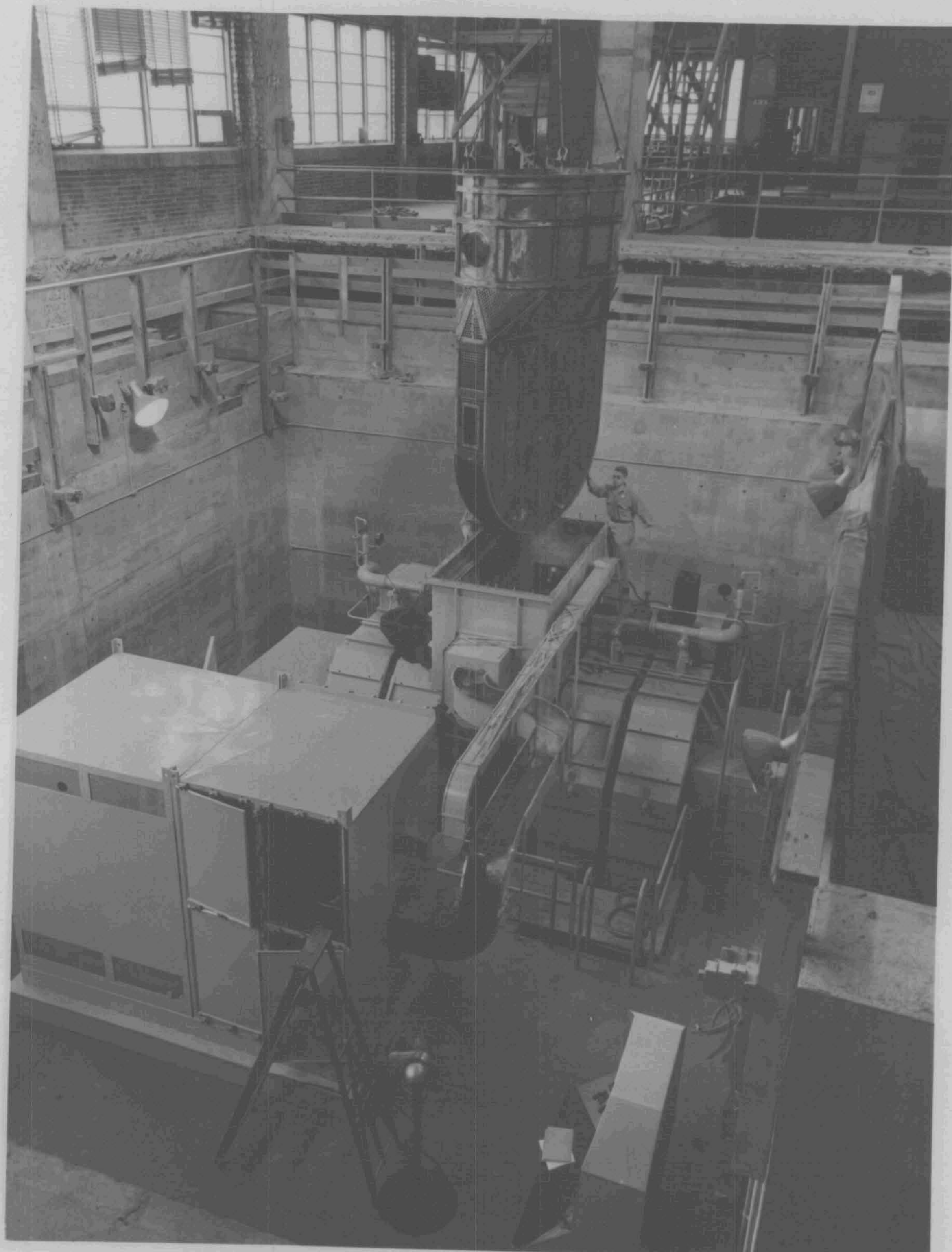


FIGURE 18. INSTALLING LINER

without moving the oscillator cabinet. The hump also accommodates the greater length of the filament line, Figure 19.

The plate line is a 3 3/4" OD water-cooled copper tube centered in a 12" square ground shield. The filament line is 2 1/2" OD air-cooled tube with a 6" shield. The outer ground shields for both coupling lines were fabricated from 1/16" thick copper sheets and in short sections for ease of handling and assembly. Each section has one-inch flanges with a stainless steel backing strip at either end for joining the sections. Also, one side of each section is removable to provide access to the inner conductor which is centered in the shield by means of plastic (Teflon or D-29) spacers.

Since power loss calculations indicated the necessity for water cooling the plate line, concentric piping was used. The outer pipe of the plate line is 3 3/4" OD copper with 0.109" wall thickness. The inner pipe is 2 3/4" OD brass with 1/8" wall; this keeps the water near the wall of the outer tube where cooling is needed. To keep the quantity of water in the plate line assembly to a minimum necessary for the cooling, a third tube, 5/8" copper, was placed inside the brass tube as a return line. Water is obtained from the distilled water supply used for tube cooling in the oscillator cabinet.

The plate transmission line enters the cyclotron tank through a zircon bushing 8 1/8" in diameter sealed with a 1/8" rubber gasket. To provide for replacing the bushing, it was necessary to sectionalize the transmission line. A 9" section is removable from the line and a mechanical split clamp serves to make the connection. The water circuit is brought out of either end of this section by means of a 5/8" copper tube linked by Tygon tubing. The plate coupling line is joined to the south dee stem by means of a 2 1/4" by 3/8" by 12" silver-plated copper terminal block permanently welded to the stem. An adjustable jumper connecting this terminal block to the coupling line permits approximately 11" of adjustment along the dee stem.

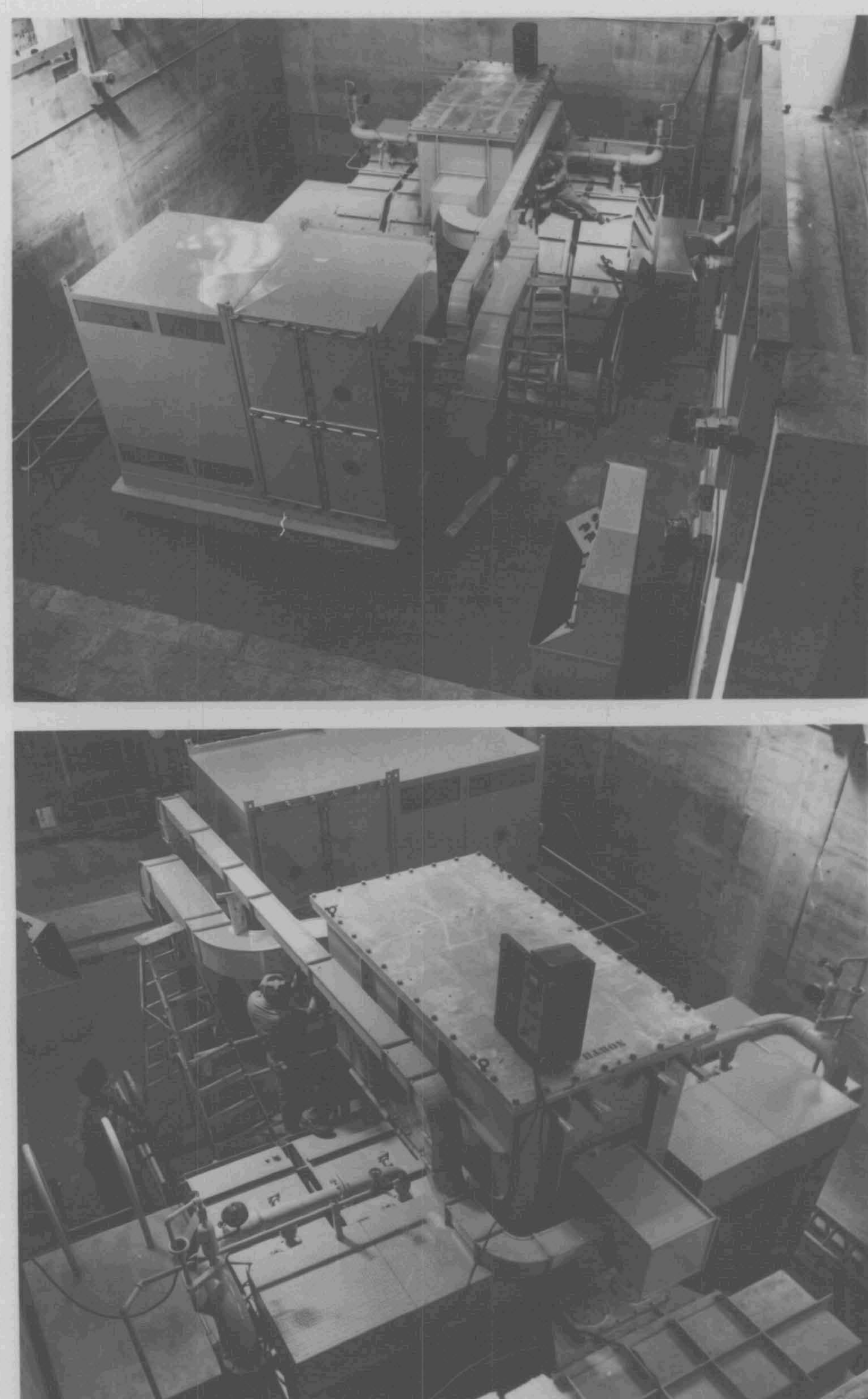


FIGURE 19. INSTALLING COUPLING LINES

The filament line is inductively coupled to the north dee stem by an adjustable loop in series with a variable capacitor. The loop of 1 1/2" ID copper pipe is 7" across and can be moved over the range 4" to 18" from the dee stem. The electrical connection is from the line to the capacitor through the insulator to the loop. The grounded end of the loop passes through a sliding vacuum seal in the tank extension wall. The filament line, including the coupling loop, is air cooled.

The Oscillator

The oscillator cabinet is on a steel platform in the cyclotron pit, at the ground floor level, Figure 15. The location was determined by the required length of coupling lines and by the magnet field distribution. A position of suitably low field intensity, < 60 oersteds, was located by mapping the stray field about the magnet. The double cabinet for housing the oscillator and associated equipment is 6 feet by 11 feet by 7 1/2 feet high. Rf losses are reduced to a minimum by the use of copper for lining the cabinet and for as many components as possible, Figure 20.

The oscillator is of the self-excited, radio-frequency grounded-grid type. It was designed for the use of two F-134 tubes. During test operation only one tube was used and present performance is still being obtained with one tube. When more power is required the second tube can be added. Vacuum type capacitors, both fixed and variable, are used throughout with the exception of the ceramic capacitors for grounding the grid. The rf chokes in the filament supply circuit consist of coils of solid copper bar, one inch square. The ceramic "Lapp" coils originally used for introducing cooling water to the tube and the plate line failed whenever the oscillator voltage was increased to give 200 kv dee-to-dee. They have since been replaced with choke coils

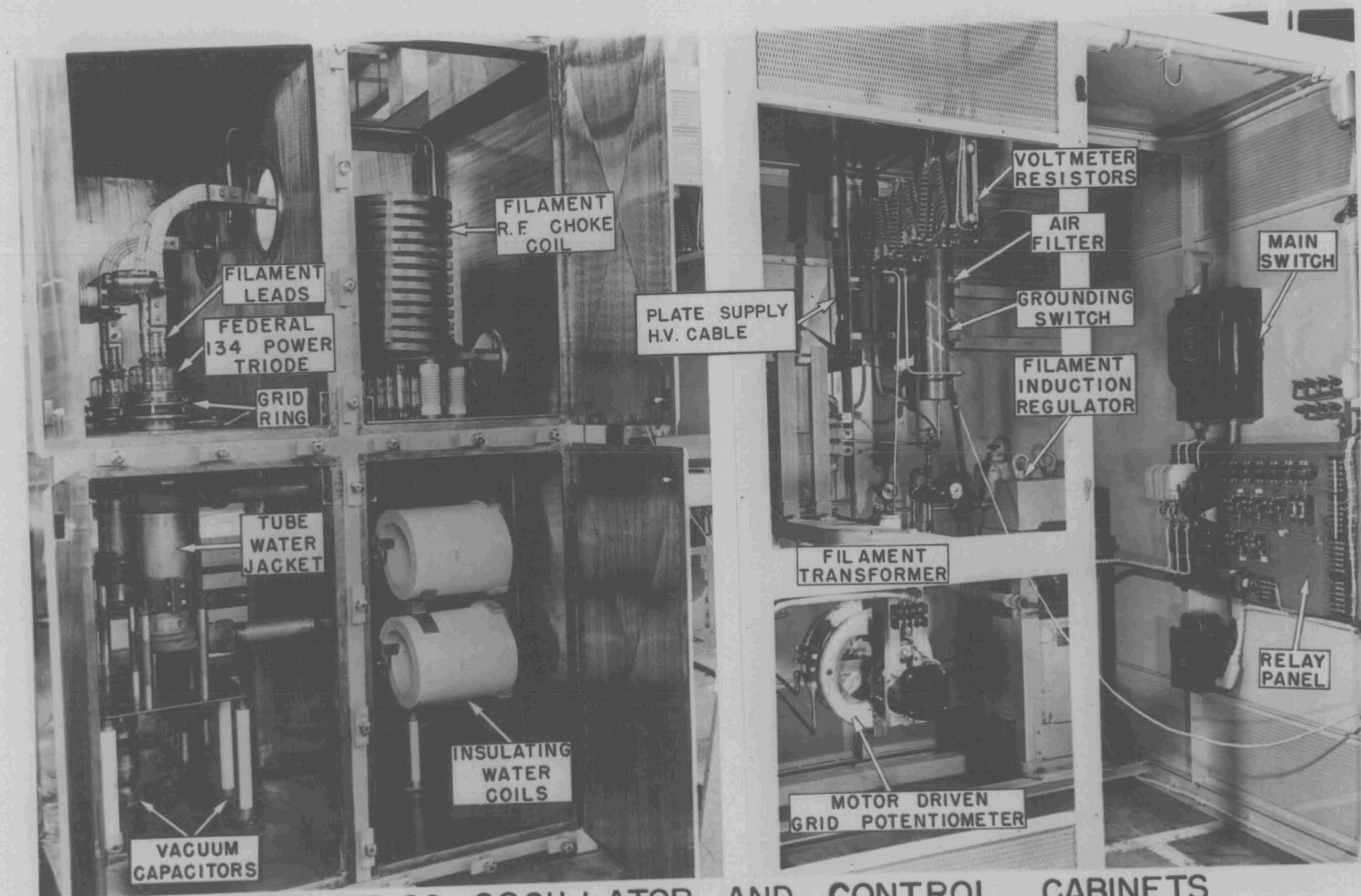


FIGURE 20. OSCILLATOR AND CONTROL CABINETS

wound from copper tubing to provide rf insulation. The control cabinet, adjacent to the oscillator cabinet, houses the filament transformers, filament induction regulator, fixed and variable grid bias resistors, voltmeter resistors, and control and interlock equipment. Interlocks on all doors of the cabinets provide protection from high voltage equipment.

Oscillator Plate Supply

Twenty Alpha I high voltage supplies have been modified so that each supply can deliver 1.5 amps at 20 kv, positive at ground. The supplies are connected in parallel; a fused disconnect switch in the output of each supply permits the operator to remove a faulty unit from service without disturbing the remainder. The negative output potential can be varied from 2 to 20 kv by means of induction regulators in the primaries of the supplies. With this arrangement it is possible to trim each individual supply or to vary the total plate voltage by changing all supplies at once. The appropriate overload relays are used for the protection of the oscillator tube and supplies.

THE ION SOURCE ASSEMBLY

The ion source is mounted on a long stem extending down through the top of the vacuum tank, through the dee support frame and spider, and between the dee stems to the center of the dees, Figures 2 and 21. The stem is a 2" copper tube about 14 feet long. It is guided by positioning brackets attached to the liner. By means of adjustments at the top of the tank the ion source can be moved up or down and rotated about a vertical axis to secure the desired alignment. When repair or replacement of the ion source is necessary the whole assembly can be removed through a vacuum lock. Stepped plugs properly located in the roof shield are removed to permit changing the ion source with a minimum of lost time.

Hydrogen Feed System

The rate of flow of hydrogen into the ion source is governed by a pneumatic valve which is remotely controlled from either control station. The cylinder from which the hydrogen is supplied is housed outside of the cyclotron building. At each station a pressure gauge in the line controlling the penumatic valve has been calibrated to read hydrogen flow in cubic centimeters per minute. The rate of flow required during operation is from 2 to 3 cc/min. In order to conveniently obtain a periodic re-calibration of the gauge, a flow meter (Fisher-Porter Rotometer) is permanently installed between the supply and the pneumatic valve. Since both the flow meter and the pneumatic control depend upon constant gas pressure to make the rate of flow meaningful, a specially designed Taylor differential pressure transmitter is installed ahead of the flow meter.

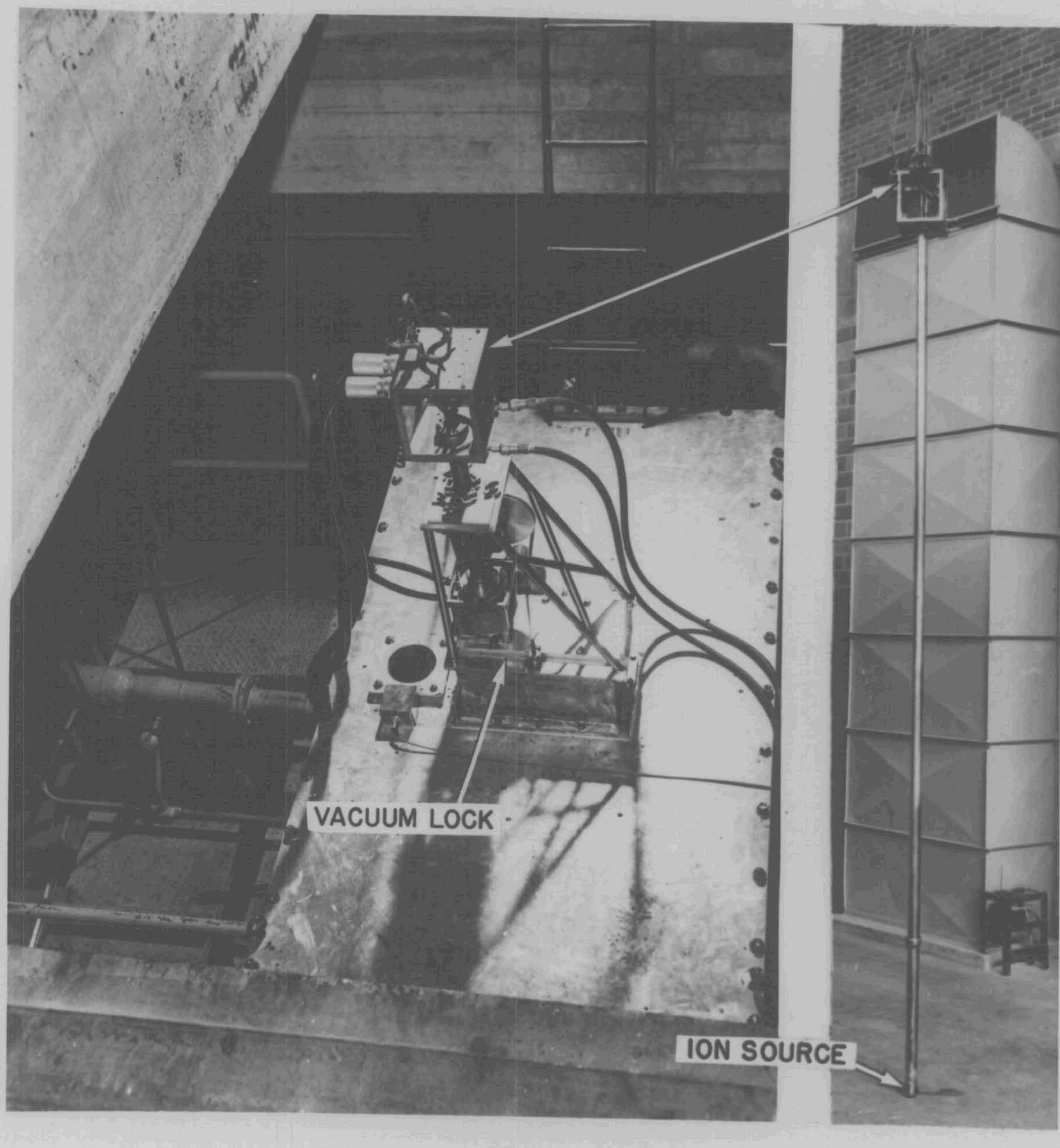


FIGURE 21. ION SOURCE ASSEMBLY.

The Ion Source

A hot-cathode ion source is used and the usual "feelers" on the dee are replaced by a slotted graphite accelerating electrode, Figure 22. The ionization, or arc, chamber is a graphite tube 0.563" OD, 0.375" ID, and 10.7" long, enlarged at one end to fit over the cathode, and closed at the free end with an insulated anode. The cathode is inclosed in a copper support block attached to the end of the source stem through which hydrogen is fed into the arc chamber. A 0.170" tantalum filament drawing 300 to 450 amperes serves as the hot cathode. Electrons are accelerated from the filament into the arc chamber by a 100 to 300 volt potential, the normal arc current being 0.5 to 1.5 amperes. Protons escape from the ionization chamber through a lateral slit. This arc slit is usually 0.062" by 2.5" but smaller apertures are used when small proton beam currents are required. A defining slot between the filament chamber and the arc chamber determines the shape and position of the arc. The filament is aligned to completely cover this circular defining slot. The front edge of the defining slot is placed tangent to the external plane of the arc slit.

The floating anode is a graphite plug insulated from the arc chamber by a piece of quartz tubing. This anode is held in place with adhesive cement (Sauereisen Insa-Lute), which is also used in making the cathode chamber gas-tight.

A slotted graphite accelerating electrode is mounted on the dee facing the arc slit. The offset of this accelerating slit with respect to the arc slit is adjustable, as is the spacing between them. The alignment of the ion source with the magnetic field and with the accelerating slits is critical and is carefully adjusted to obtain best performance. There are two water-cooling circuits, one for the filament leads and the other for the chamber

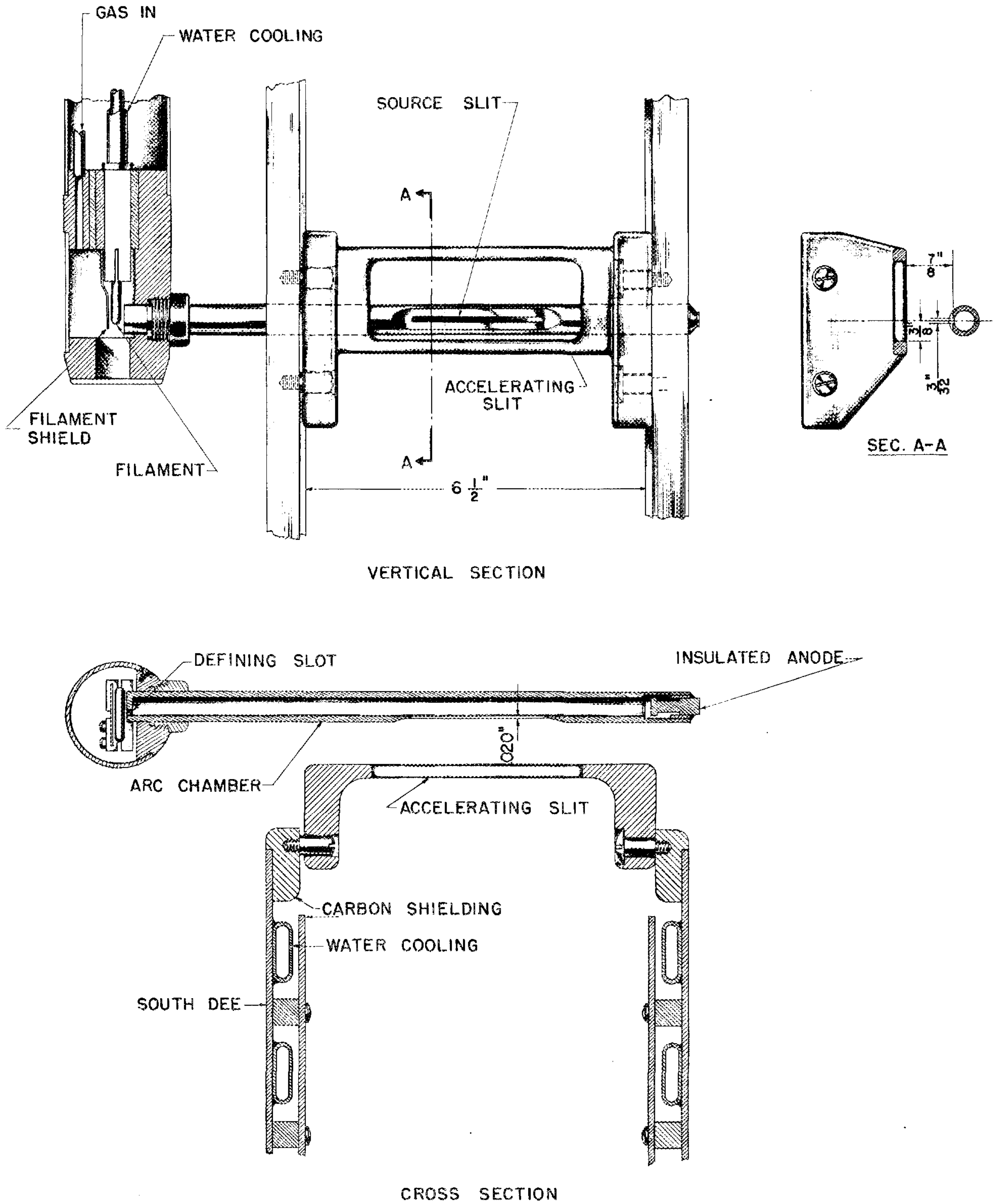


FIGURE 22. ION SOURCE

support block, the total water flow being about two gallons per minute.

Ion Source Power Supplies and Controls

The power supply and control circuits for the filament and arc are shown schematically in Figure 23.

Filament Supply. To supply dc power to the ion source filament, two Alpha I filament supplies are connected in parallel. Each supply, consisting of a 400:12 step-down transformer and a copper oxide rectifier, is rated at 300 amperes at 3 to 6 volts. The output of these supplies is controlled by saturable reactors in series and operated through one G. E. Reactrol unit, which evenly divides the load on the two rectifiers.

Arc Supply. The potential between the filament and the ionization chamber of the ion source is provided by a dc power supply rated at 10 amperes at 75 to 400 volts. This supply is made up of a bank of three 2 kva, 460/230 volt transformers, connected ΔY, and a three-phase full-wave rectifier using FG-32 mercury vapor tubes.

Arc Controls. Arc voltage and arc current can each be varied independently. A saturable reactor in the primary of the arc supply is controlled by a Reactrol control unit which receives its signal from a potentiometer across the dc output. A motorized control on the potentiometer makes it possible for the operator to select the desired arc voltage, which then remains constant regardless of arc current.

The arc current flows through a rheostat from which a signal goes to a Reactrol unit which controls the dc current in the saturable reactors in the primary of the filament supply. This regulates the filament temperature and thus the arc current. A motor drive on the rheostat is used by the operator in selecting the desired arc current, which is then held constant regardless of arc voltage.

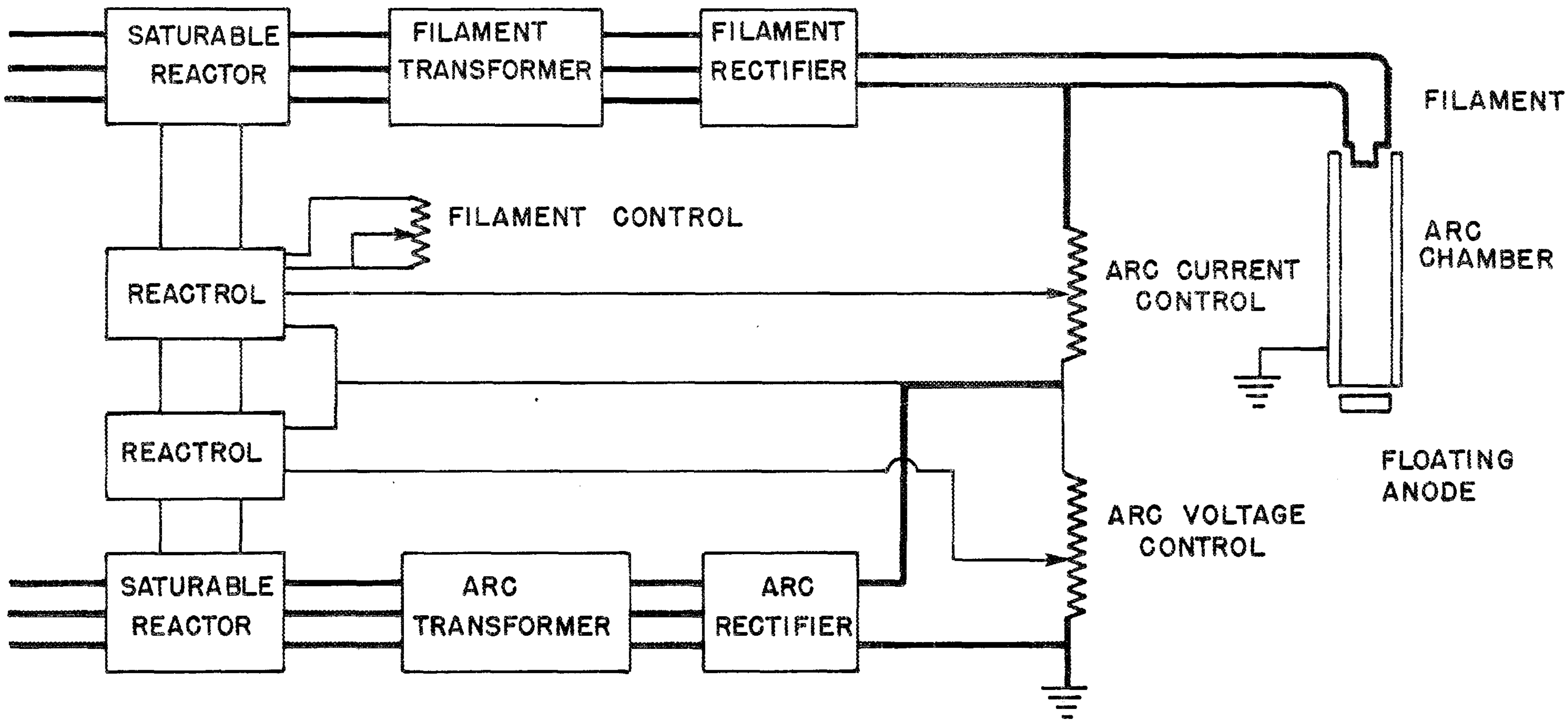


FIGURE 23. ION SOURCE SUPPLY AND CONTROL CIRCUITS

CYCLOTRON TARGETS

Various types of targets can be attached to a target head and in turn mounted on the shaft of a target dolly which can be rolled into position between the magnet coils, Figure 24. Hydraulic pistons on the target dolly lift the target vacuum lock into position against the bottom of the vacuum tank. The target is then raised from the vacuum lock to operating position, or lowered, by worm gears driven by an electric motor which may be remotely controlled.

The target shaft consists of two concentric stainless steel tubes, which provide an inlet and return for the target coolant as well as providing support for the target, Figure 25. At the top of the outer tube, a quick-change locking mechanism is welded in place. This mechanism provides a means of attaching the target head to the target shaft in a manner permitting remote operation and thereby reducing exposure of personnel when a bombarded target is being removed. The device forces the outer tube against a gasket in the target head by means of a wedge which provides full effectiveness when rotated 90°.

The Target Head

The target head is a non-expendable part of the target assembly which distributes the water from the central tube to the target. It is machined from copper or brass. A copper block which fits onto the shaft has an accurately machined hole to receive the inner tube so that by-passing of the water circuit will be negligible. The target is attached to the head by either a compression seal which was used on early targets, or by means of cap screws, Figure 26.

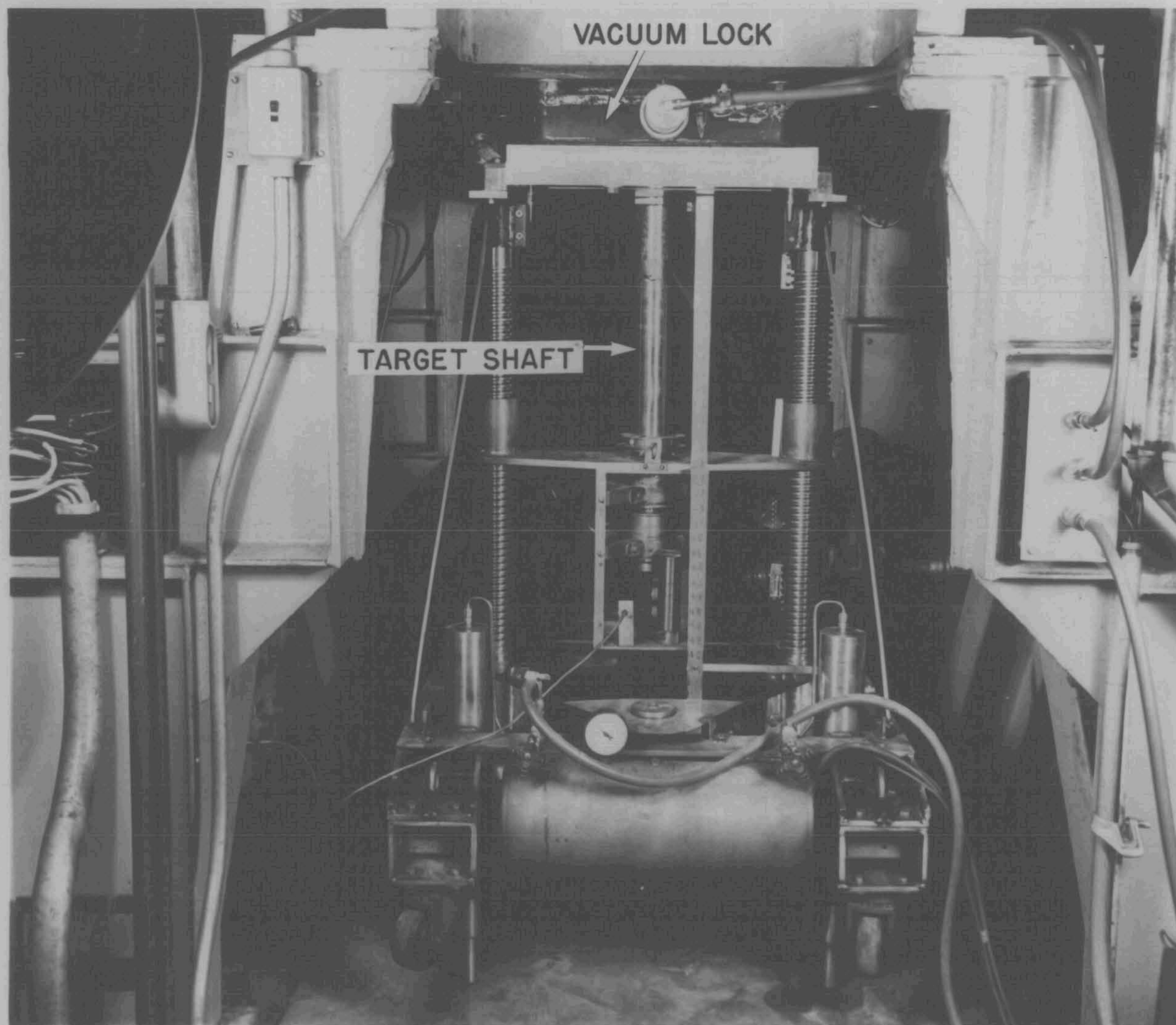


FIGURE 24. TARGET DOLLY

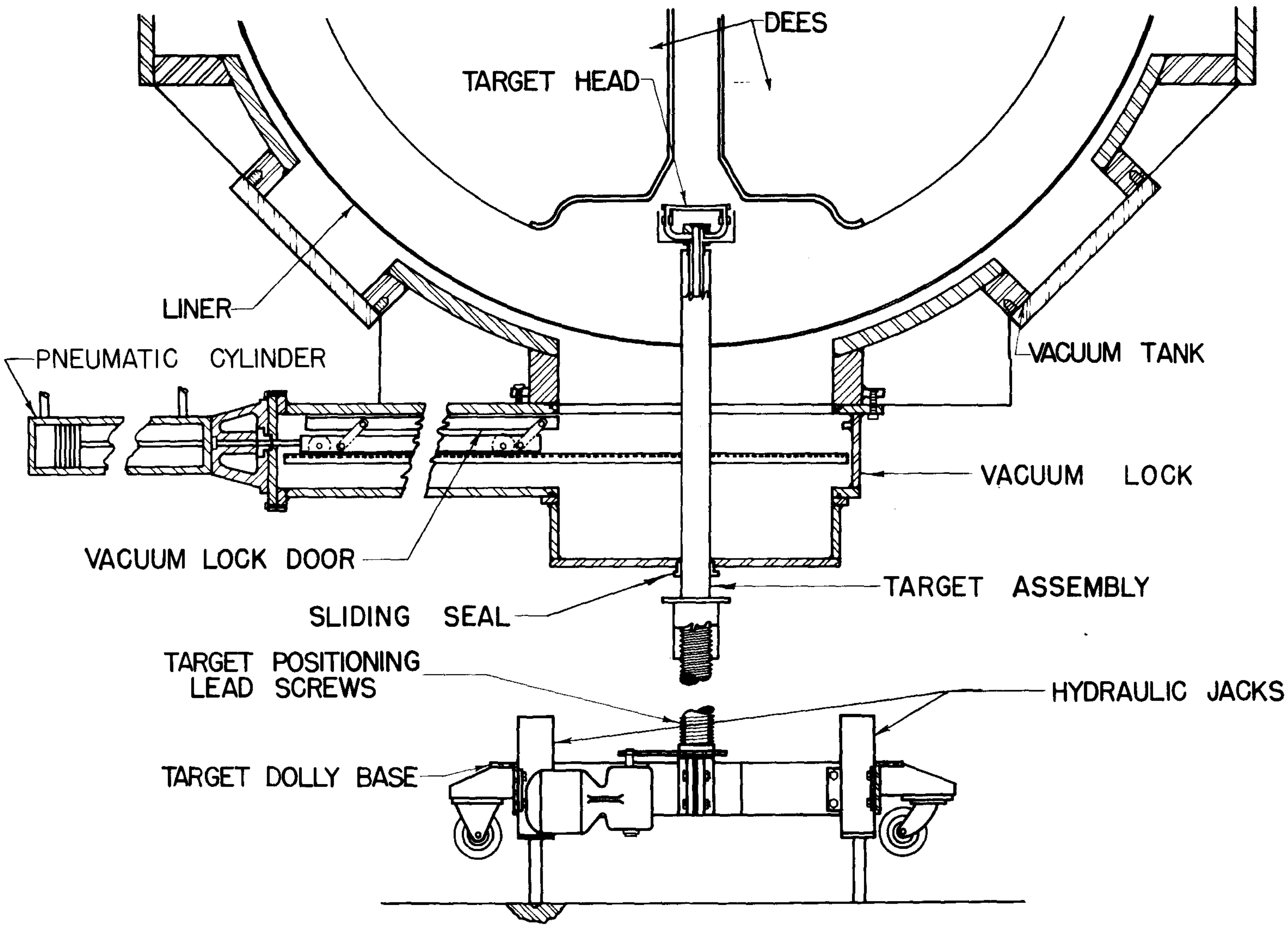
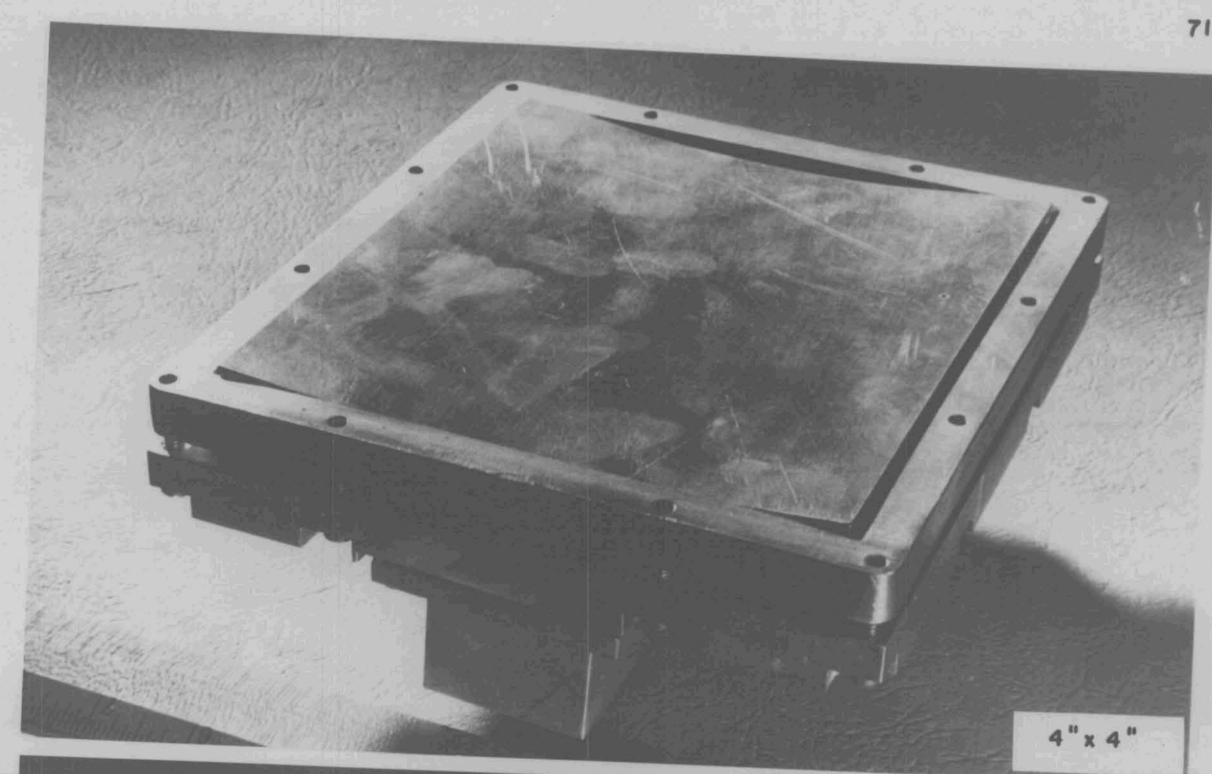


FIGURE 25 CYCLOTRON TARGET INSTALLATION



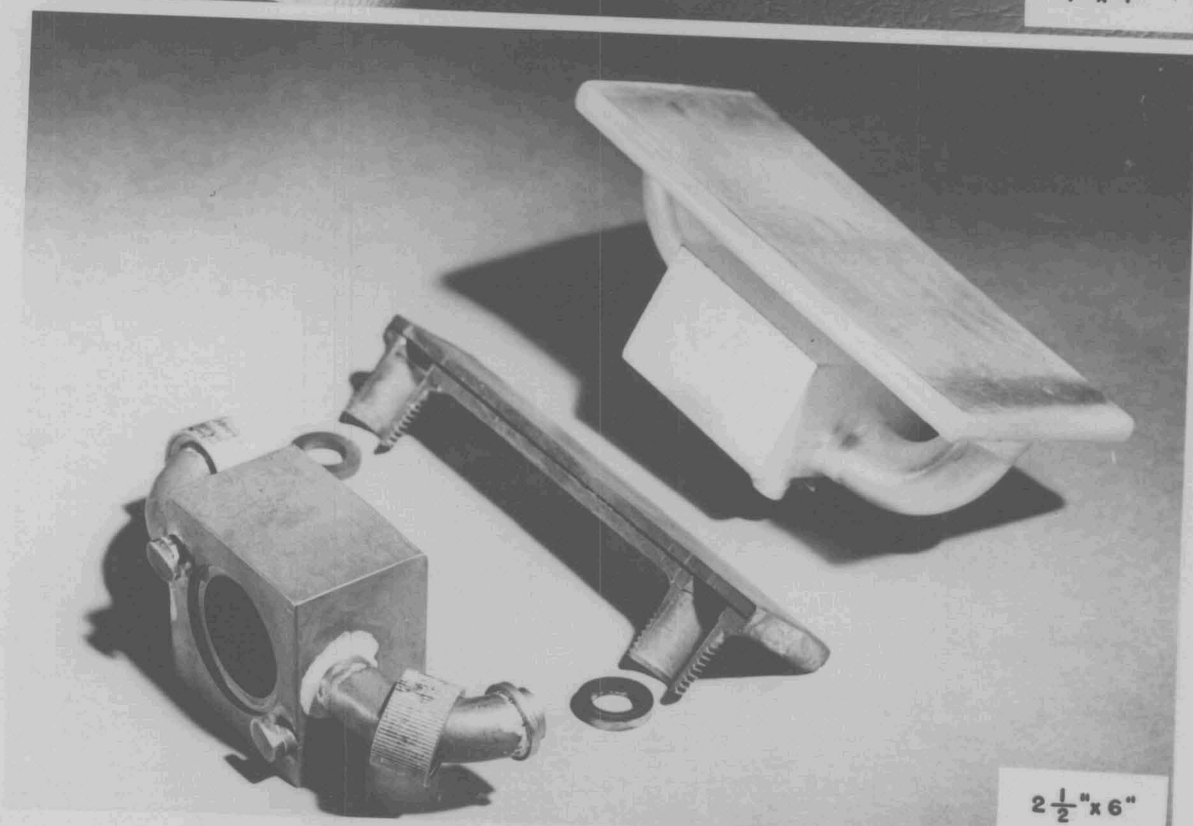


FIGURE 26. FIRST GRAZING INCIDENCE TARGETS

The Target

The target is usually constructed from either copper or aluminum since both of these materials have superior heat transfer properties. The aluminum targets have an added advantage in that if pure aluminum is used, only short-lived gamma activity is produced by the protons, thereby allowing the targets to cool rapidly (radioactively). The target shaft upon which the target and head are mounted is electrically insulated and serves as the lead for monitoring the target current.

Of the various types of experimental targets, two are shown in Figure 27. With the first, the beam passes through a 0.015" aluminum window and into the target directly behind the window. Cooling water circulates in contact with the target which is held in place by a spring clip. This is a convenient system for irradiating metallic targets where only a few microampere-hours are needed. Beams above 100 μa have been used without damage to the aluminum windows. In the second type, layered target foils are exposed directly to low-current beams.

For larger beam currents a grazing incidence target is used which makes use of the increased area exposed when the beam strikes the target at a small angle, 2 to 5°, Figure 28. With the beam spread over a large surface the heat transfer requirements are reduced and larger currents may be handled without melting the target. Over 40 kw of beam power has been measured on an aluminum target of the type shown. These targets are made from plates of copper or aluminum in which small water passages are milled to provide high water velocity immediately behind the surface bombarded. If another material is to be bombarded it is deposited in a milled-out section of the target surface. The target is then bent to the proper curvature to fit the beam and attached to its mountings to give the desired angle of incidence.

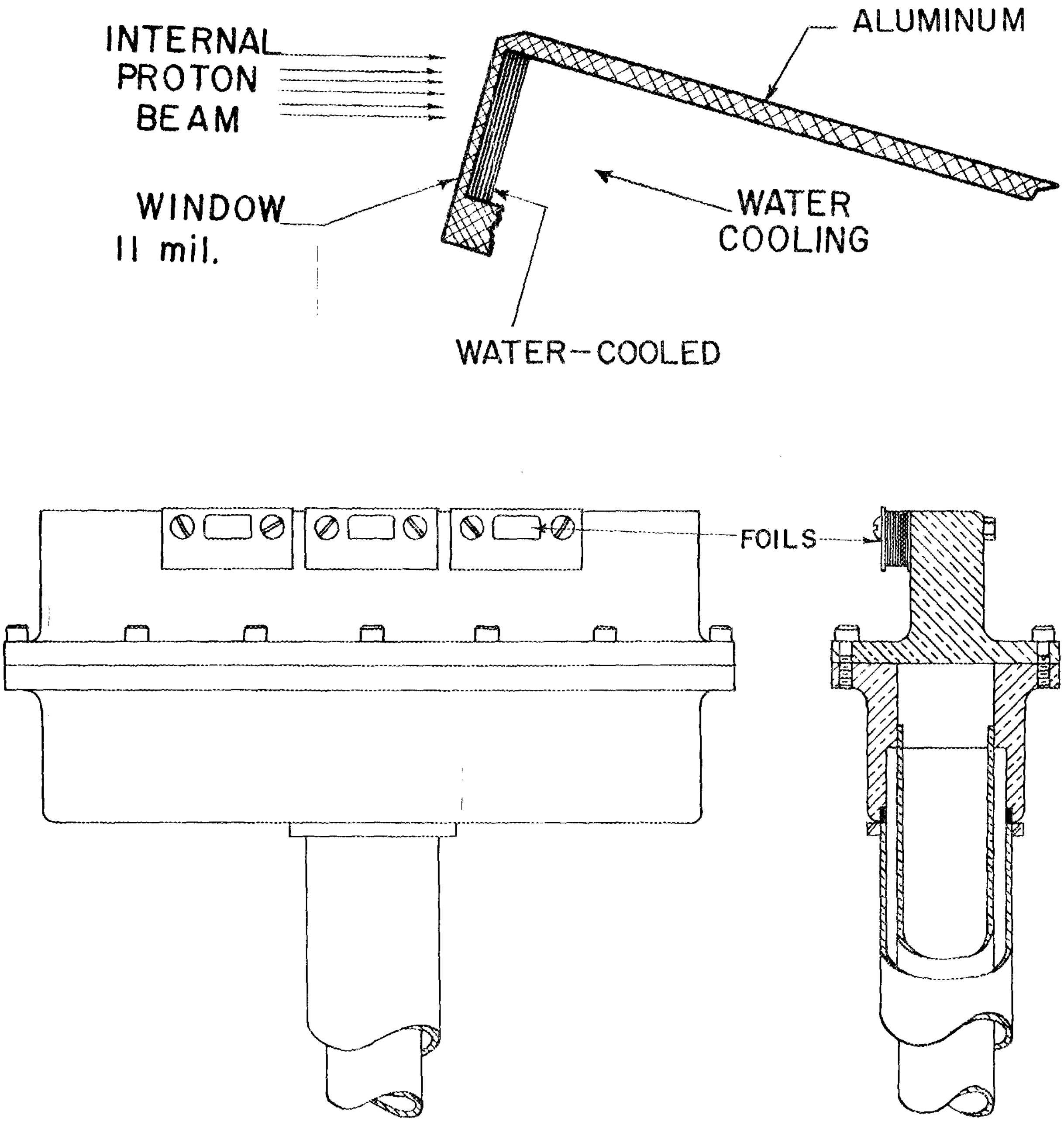


FIGURE 27. EXPERIMENTAL TARGETS

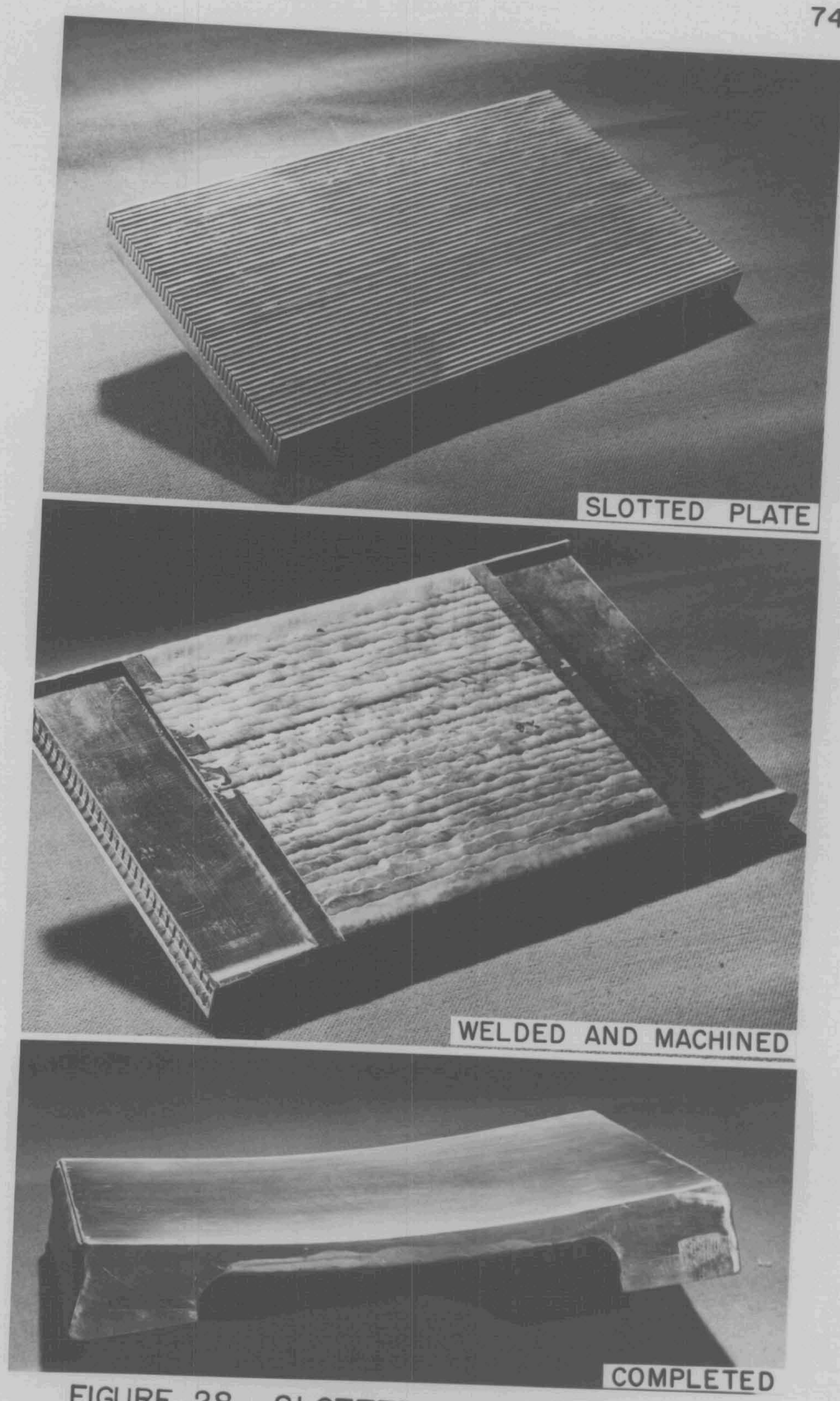


FIGURE 28. SLOTTED-PLATE TARGET, 6"x 10"

CONTROL EQUIPMENT

Two control stations have been provided. A local control station inside the cyclotron pit is used for preliminary adjustments and testing. When the machine is ready to operate at hazardous radiation levels, control is shifted to the main control room which is located 400 feet from the cyclotron pit. The two sets of controls have proved very convenient and well worth the duplication required. With exceptions as noted, all of the following items are available at both control stations.

1. Individual voltage control for each of the 20 rectifier units of the oscillator power supply.
2. Individual ammeters for the 20 rectifier units.
3. Master On-Off control of the 20 rectifier units.
4. Master voltage control of the 20 rectifier units.
5. Total current meter for the 20 rectifier units, or oscillator tube plate current ammeter.
6. Voltmeter for the plate voltage of the oscillator tube.
7. Individual dee-to-ground peak-reading rf voltmeters.
8. Dee-to-dee peak-reading rf voltmeter.
9. Dee support plate rf voltmeter, remote console only.
10. Beam current milliammeter.
11. Beam current integrator, remote console only.
12. Beam current recording meter, remote console only.
13. On-Off control of the ion source filament current.
14. Manual current control of the filament supply.
15. On-Off control of the ion source arc supply.
16. Current control of the arc supply.

17. Voltage control of the arc supply.

18. Filament current meter.

19. Arc current meter.

20. Arc voltage meter.

21. Oscillator tube filament On-Off control.

22. Oscillator tube filament voltage meter.

23. Dee trimmer drive control.

24. Dee trimmer position indicator.

25. Magnet energizing current, coarse and fine adjustment.

26. Magnet energizing current meter, remote console only.

27. Ion source stem rotational alignment control, remote console only.

28. Oscillator tube grid current meter.

29. On-Off control for dee bias supply.

30. Voltage control for dee bias supply.

31. Dee bias voltage meter.

32. Dee bias current meter.

33. Dee-to-dee phase relationship oscilloscope.

34. Master overload relay for oscillator tube plate current.

35. Pirani gauge for vacuum finishing header, pit console only.

36. Ionization gauge, 35-T type, controls and meter.

37. Philips ionization gauge controls and meter.

38. Vacuum gate valve push-button controls.

39. Ion source hydrogen gas flow indicator and control.

40. Radiation instrumentation for gamma-neutron recording and for neutron measurements, remote console only.

41. Individual magnet coil voltmeters.

42. Recording potentiometer for magnet winding temperature, remote console only.

43. Auxiliary magnet field On-Off control, remote console only.

44. Auxiliary magnet field raise-lower control, remote console only.

45. Auxiliary magnet field current meter, remote console only.

46. Target calorimetric heat balance recorder, remote console only.

47. Recording wattmeter and controls for calibrating the target balance recorder, remote console only.

48. Indicator lights for the following:

    a. Control station in use - local or remote
    b. Oscillator cage door closed
    c. Oscillator permissive switch closed
    d. Oscillator control power on
    e. Oscillator tube filaments on

49. Red indicator light, alarm bell, and silence button for the following:

    a. Insufficient oscillator tube cooling air
    b. Insufficient oscillator tube cooling water
    c. Oscillator cabinet water overflow
    d. Insufficient dee water
    e. Insufficient ion source water
    f. Insufficient probe water
    g. Insufficient liner water
    h. High level of radiation outside shielding
    i. Vacuum pressure too high
    j. Magnet coils hot
    k. Insufficient oil flow
    l. Fire fog system in pit activated
    m. Rotating target in operation

Control Stations

The local control station is in the cyclotron pit at the ground floor level. Instruments are mounted on a console type desk and on an auxiliary 62" by 19" relay cabinet, Figure 29. For the console desk, 1/8" sheet steel panels were attached to a five-foot steel office table.

FIGURE 29. LOCAL CONTROL STATION

A small room adjacent to the building switchboard room, Figure 3, was adapted for use as the main control room. Located on the main floor in the south central section of the building, this remote control station is approximately 400 feet from the cyclotron. Controls and instruments are mounted on a console desk, similar to but larger than the local console, and on four auxiliary, 62" by 19", relay cabinets, Figure 30.

Power to operate the control circuits is supplied through two 110 volt ac buses. All Off relays are supplied through a common bus and can be operated from either station at any time. The bus for On and Raise-Lower circuits are on a divided bus, that is, there is a separate section at each control station. Only one section of this bus can be energized at a time through a selector switch at the local control station. An operator inside the cyclotron pit can thus prevent operation from the remote control panel.

Control Circuits

The various controls, indicators, and alarm circuits at the control stations are briefly described below. The numbers used refer to the items listed above.

1. Since the power supply is made up of 20 individual rectifiers which were available in the building, it is necessary to control each rectifier separately in order to balance the load distribution. There is a motor-driven induction voltage regulator in the primary circuit of each rectifier.

2. To meter the current output individually the ground side of each rectifier is connected through a 0-3 ampere ammeter at the console to a common ground. Each meter is protected by an inductor-capacitor network. A film gap is connected from the high potential side to ground to protect the meter from high voltage in case a lead opens.

FIGURE 30. REMOTE CONTROL CONSOLE

3. For the master On-Off control of the rectifiers, two relays were mounted at each rectifier. The On relays for all rectifiers are energized simultaneously from the divided control bus. The Off relays on all rectifiers are energized simultaneously from the common control bus. Thus, the plate voltage of the oscillator can be turned off from either console at any time, but can be turned on from only the console in use. The power that actually turns on each rectifier comes from its own unit, so unless a rectifier control is turned on, the rectifier is not energized. Because of this, only those rectifiers which are in standby service and switched into the line are energized. The Off switch is interlocked with the overload relays, the oscillator control power, and the reverse current relay from each rectifier, so that any one of them will turn off all rectifiers.

4. The master voltage control is used to change the output voltage of all rectifiers simultaneously. A master relay contact parallels each of the individual Raise-Lower switch contacts. When the proper relays are energized through the master Raise-Lower switch at either console the induction voltage regulators at all rectifiers are run simultaneously. The supply to these motors is interlocked so that if the master control is in use none of the individual controls will work. This is necessary to prevent an operator from trying to run a regulator in both directions at the same time.

5. To meter the total current at each console, the leads from the ground side of the meters for the individual rectifiers are connected together through a shunt to ground and the potential drop metered at both consoles.

6. A 0-2 milliampere meter with a 0-25 kv scale is used at each console to meter the plate voltage to the oscillator tube. In the oscillator cabinet a 12.5 megohm multiplier resistor is connected from the plate supply bus to

ground. The indicating meters at the consoles are connected in series with the ground end of the multiplier resistor.

7 & 8. The peak-reading dee voltmeter circuits register both dee-to-ground and dee-to-dee rf potentials. An oscilloscope across the dees permits a continuous check of the phase relationship of the potentials on the dees. Current from each voltmeter probe located approximately six inches from each dee is rectified, filtered, and measured by a one-milliampere meter. Similar meters on the two consoles are in series. They are calibrated and provided with the proper shunts for two scales, 0-150 kv and 0-300 kv dee-to-ground, and 0-300 kv and 0-600 kv dee-to-dee.

9. The rf potential on the dee support frame, which is proportional to the unbalanced dee-to-liner current, is metered from a probe in a manner similar to the dee-to-dee potential. In operation the position of the trimmer capacitor is adjusted to minimize the rf potential on the dee support frame. This type of control is also extremely useful in matching the frequency of the dee system to the magnetic field for peak resonance conditions.

10. The current to the target is filtered and then indicated on an ammeter with ranges of 0-.1-1-2 milliamperes. Jacks are provided at both consoles for connecting other meters of any desired range.

11. A modified watt-hour meter is used to record integrated beam current. It consists of an ordinary low range watt-hour meter, the current coil of which is supplied from a regulated 60-cycle square wave by a synchronous vibrator driven in phase with the voltage applied to the current coils of the meter. After chopping, the target current is filtered, amplified, and then applied across the potential coil of the wattmeter. Thus the rate at which the disc turns is proportional to the target current. Tests have shown that it maintains excellent calibration (± 2.5%) over the specified ranges. The various

ranges, 10-50 μa, 50-200 μa, 200-1000 μa, are necessary to prevent distortion in the amplifier which energizes the potential coil.

12. The beam current is also recorded on an Esterline-Angus recording milliammeter reading one milliampere full scale.

13. The ion source filament On-Off switch is interlocked with the source cooling water and the filament rectifier fans.

14. The filament current can be set to any desired maximum value by a control which actuates a rheostat located in the input signal circuit to the filament reactrol.

15-17. For arc control circuits see the section on ion source power supply, page 66.

18. Filament current is indicated by a 0-500 ampere meter across a 500 ampere, 50 mv shunt in the filament lead.

19. The arc current is indicated by a 0-10 ampere dc meter.

20. The arc voltage is indicated by a 0-400 volt dc meter.

21. The On switch of the oscillator tube filaments is interlocked with air cooling and water cooling for the tubes.

22. The oscillator tube filament voltage is metered by a 0-700 volt meter in the primary of the filament transformer.

23. The trimmer is driven by a 1/4 hp motor through a gear reduction unit and a belt drive.

24. The trimmer position is indicated by a 100 microampere dc meter. A regulated dc supply, with 105 volt output, applies a constant voltage across a potentiometer which is turned an amount proportional to the travel of the trimmer.

25. To adjust the magnet current over a limited range (110 amps) a dc source is provided at each console. Two decade resistors are in series with a 1.5 volt dry cell and with the current regulating shunt of the magnet regulator. The current is adjusted so that the drop across one step of the coarse decade corresponds to 10 amperes and the drop across one step of the fine control decade corresponds to one ampere on the magnet current measurement shunt. The decade resistors buck out part of the signal from the shunt to the regulator and causes the regulator to change the magnet current in ten- and one-ampere steps.

26. The magnet current meter on the remote console has a suppressed zero so that its scale is from 1,000 to 2,000 amps. It is energized by a 2,500 amp, 50 mv shunt.

27. A Selsyn motor system operating through reduction gears is made to control the rotation of the ion source stem a maximum of three degrees. This makes possible the alignment of the source for maximum ion output.

28. The grid current of the oscillator tube passes through a 3 amp, 50 mv shunt. X-ray cable is used in connecting this shunt with meters in both consoles.

29-32. See the section describing the bias potential on the dees, page 47.

33. A two-inch oscilloscope installed on each console receives its signal from the dee voltmeter probes. Signals from the north and south dees are placed on the vertical and horizontal plates respectively.

34. The overload relays for the oscillator plate current are connected to the ground side of the total current shunt at each console. The local console relay can be adjusted to trip at any desired amount from 4 to 16 amps dc. The relay at the remote console can be set for 10 to 40 amps. The ground connection can be switched from one relay to the other by a switch on the local console.

35. The hot wire of the Pirani gauge is located in the discharge of the diffusion pumps (in the finishing header).

36. An ionization gauge of the type using a modified Eimac 35-T tube is mounted on an auxiliary panel at each control station. There are two 35-T tubes mounted in the vacuum manifold with a selector switch in a junction box located outside the shielding wall for convenience in case a tube burns out during a run.

37. Conventional Philips ionization gauges are used. Two chambers are provided in the vacuum tank and either can be switched to either control station. See page 46.

38. Motor-driven gate valves are mounted between the tank and the diffusion pumps. Push-button controls and indicating lights for these valves are located at the remote control station, the utilities panel, and at the gate valves.

39. The hydrogen gas flow indicator and control is mounted on an auxiliary panel at each console. This control is operated by compressed air, see page 62.

40. Radiation instruments are discussed in a separate section, see Appendix E.

41. The voltage drop across each magnet coil is important since the coils are carrying approximately 40% more current than they were originally designed for. With the voltage drop and current known, the coil temperature is readily determined from a family of curves.

42. The average temperature of the magnet coils is recorded by an installation which takes a signal from the current measurement shunt and compares it with a signal from the magnet voltage. As the coil temperature

increases the ratio of voltage to current increases. A contactor in the recorder can be set to sound an alarm when the temperature reaches a set value. The present limit is set at 77°C.

43-45. The controls for the auxiliary field windings consist of an On-Off push-button and a potentiometer which controls the input to the field of a 15 kw amplidyne generator which in turn determines the dc output supplied to the windings. A 0-30 amp meter is used to indicate the current output of the generator.

46. A recording potentiometer which reads directly the temperature difference between the incoming and outgoing target water to within 0.1°C is also available. The power dissipated on the target is reliably determined from a heat balance obtained from the flow rate and the temperature rise of the coolant. A wobble-plate rate meter is used to measure the water flow. The power input can be determined by applying the formula:

$$\text{Power (kw)} = 0.266 \times \text{Flow Rate (gpm)} \times \Delta T\ (^\circ C)$$

In general, the power input obtained from meter reading and the calorimetry method check within 5%.

47. The recording wattmeter and controls for a system which is used for calibrating the recorder described in (46) above have been installed at the remote control panel. This system is as follows: Three 460 volt, three-phase heaters have been installed in the target water inlet circuit located below the cyclotron. These heaters, rated at 27 kw, are energized from an induction regulator which is controlled from the remote console. A recording wattmeter is used to measure the amount of power being dissipated in the water. By energizing the calibrating heater to any power desired, up to 27 kw, and observing the change in probe water temperature on the heat balance recorder,

very accurate check points can be obtained on the ΔT expected from dissipating any value of beam power up to 27 kw under actual operating conditions.

48. These lights and the trouble lights, bells, and silence buttons (below) are all on an auxiliary control panel.

49. A red light comes on and a bell rings at the remote control station if any one of a number of things go wrong. A push button under each light can be used to silence the bell, but the light stays on until the trouble is cleared. The push button has a momentary contact; the alarm circuit is so relayed that if the trouble clears and then reappears the bell rings again.

SHIELDING

The shielding wall surrounding the cyclotron is designed to reduce the neutron flux to less than 200 neutrons/cm^2-sec, the permissible exposure for 100 kev neutrons. Theoretical calculations indicate that a one-milliampere beam of 25 Mev protons on most targets produces neutrons at a rate of about 10^{14} per second. For a maximum beam of five milliamperes, this gives a flux of about 10^8 neutrons/cm^2-sec, 20 feet from the target. After filtering through several feet of concrete, the neutrons are reduced in energy to at least the inelastic scattering threshold of materials in concrete, 10 to 100 kv. Most neutrons may be expected to have energies considerably less than this, and a considerable fraction are thermalized. The shield wall must be thick enough to produce an attenuation of 10^5 or about 12 attenuation lengths. The attenuation length of fission neutrons in concrete is about 4.5 inches,* while for lower energy neutrons it is considerably less. For this length a wall thickness of 54 inches is indicated. To allow for a factor of safety, a five foot shield wall of ordinary concrete was specified.

The cyclotron shielding consists of five feet of concrete on the four sides and the top, Figure 31. Three walls are solid reinforced concrete but the south wall is built of prefabricated concrete blocks, 4" by 8" by 16", which can be removed in case of a major redesign requiring more space in the cyclotron pit. The east and west walls provide support for the roof. Two roof girders made of 36" I-beams, cast into concrete, rest on these walls. Openings through the shielding wall provide for a main entrance at the ground floor level, an emergency exit from the lower level of the pit, and openings

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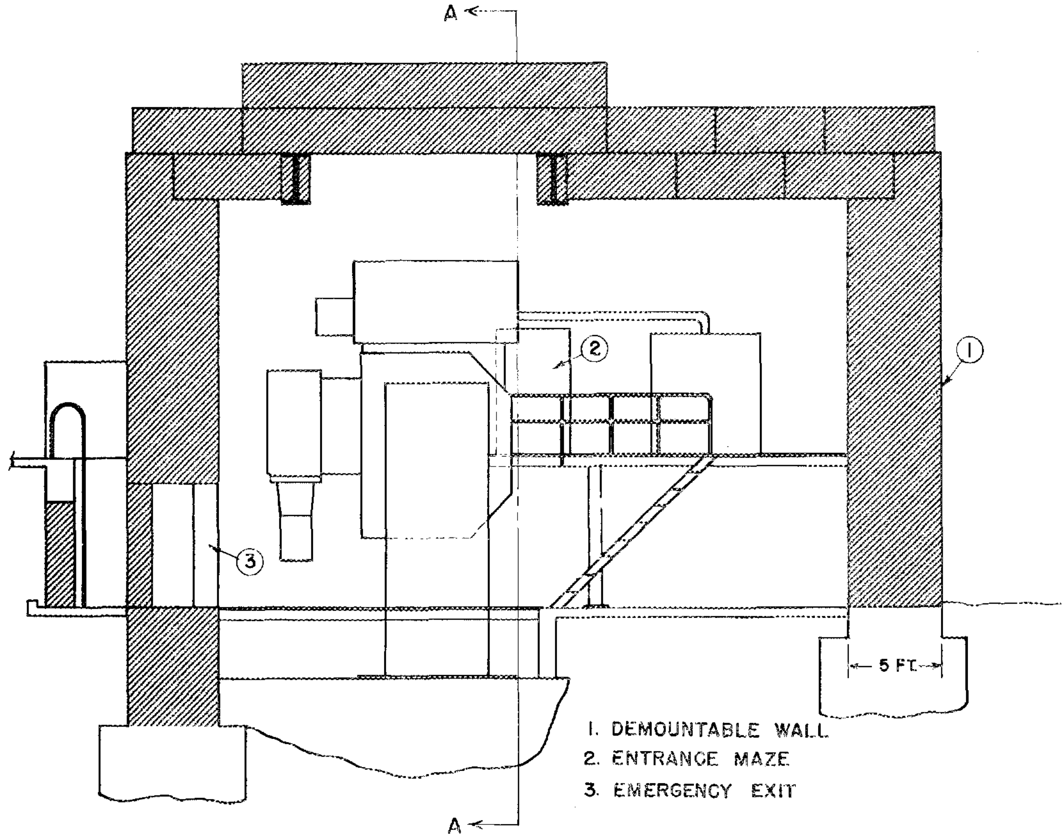
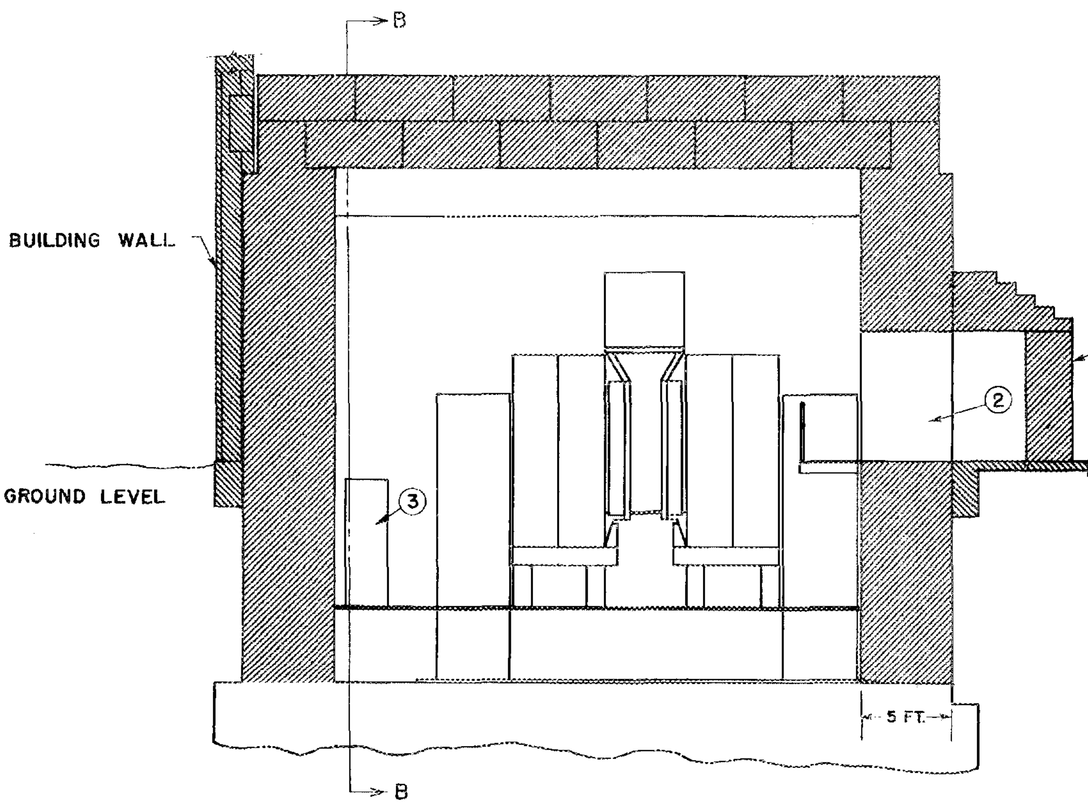
* Sleeper, H. P., Jr., ORNL-436.



NORTH - SOUTH SECTION, B-B



EAST - WEST SECTION, A-A

FIGURE 31. CYCLOTRON SHIELDING

for utility lines entering the pit. In these latter openings, spaces around the pipes are tamped solidly with Bensonite iron ore. Several two-foot square openings for possible future use are temporarily closed with concrete blocks.

The entire roof of the pit is composed of removable concrete blocks in two layers. Eight 40-ton blocks rest upon the east and west walls. Thirteen 20-ton blocks rest upon the roof girders. These smaller blocks are so arranged that by removing three of them, a sufficiently large opening is formed in the roof to pass the dee assembly and liner. They can be handled by a single overhead crane; the larger blocks require the use of two 20-ton overhead cranes. When it is necessary to change the ion source in the cyclotron a small stepped plug through the roof blocks immediately over the cyclotron may be removed, making it unnecessary to remove the three 20-ton blocks. All blocks are so placed that there are no cracks penetrating the entire thickness of the shield.

The main entrance and the emergency exit are provided with mazes built of 4" by 8" by 16" concrete blocks. The main entrance leading directly to the oscillator platform is designed so that equipment can be quickly and easily moved in and out of the cyclotron area. The maze at this entrance is a passageway four feet wide consisting of three short corridors at right angles to each other. The walls of the maze range in thickness from 32" on the south side to 48" on the east side, opposite the opening in the main shielding wall. The roof, supported by steel beams, is 36" thick. The emergency exit from the floor of the cyclotron pit through a maze in the north wall is only 20" wide. The ladder at the outside of the maze leads to the ground floor of the building.

Measurements indicated the presence of an excessive neutron flux just outside of the entrance maze. A shield door of two inches of wood and eight inches of encased paraffin, designed to reduce the neutron flux, has now been installed and neutron measurements indicate an attenuation factor of 200 through the door. There is still some leakage around the edges. The neutron flux, normalized to a one milliampere proton beam on tantalum at 25 Mev, is tabulated below in units of permissible exposure (200 n/cm^2-sec for a 40-hour week).

	Units
Waist height, center of door	0.1
Waist height, edge of door	6
Waist height, 4 feet in any direction	0.2
On floor, center of door	0.5
10 feet above floor, center of door	60

UTILITIES

The various utility services required for cyclotron operation were provided by conversion of established utility installations formerly used for calutron operation. A pumphouse and cooling tower are adjacent to the building in which the cyclotron is located. Two 2800 gpm centrifugal pumps, each driven by a 250 hp motor, circulate distilled water through heat exchangers and to an 8000 gallon storage tank on the roof. Also, two 6000 gpm pumps driven by 300 hp motors circulate the cooling tower water with the tower basin as a reservoir; the usual bank of fans is available for tower draft. A system for circulating oil through the calutron magnets and the cooling tower is capable of pumping over 5000 gpm. Water lines and oil lines were available within a few feet of the cyclotron location. Of course the capacity of these systems far exceeds the cyclotron requirements; they were adapted with a minimum of modification.

Distilled Water System

The water used in the system is demineralized steam condensate with a resistivity of around 25,000 ohms per cubic centimeter. Should it be desirable to increase the resistivity of the water, a de-aerator of the steam ejector type can readily be activated. The estimated cyclotron water requirements in gallons per minute are:

	Rated	Present
Dee assembly	300	175
Liner	50	15
Variable trimmer	10	3
Source	10	3
Target	75	50
Oscillator and transmission lines	70	50
Diffusion pumps	30	30

The original system furnishes water at 160 psi to a pressure regulating valve, which reduces the pressure to 70 psi. The components of the cyclotron, with the exception of the target, have been designed to provide adequate flow at this pressure. In order to prevent the pressure from rising above this value a relief valve was installed on the low pressure side of the regulator valve which dumps into the storage tank on the roof. Three replaceable filters in parallel are used in the 4" line from the pressure regulating valve to the cyclotron. For the target circuit, where the dolly makes excessive impedance, a separate regulator has been added to provide a pressure of 140 lbs/in^2.

Originally, the existing system had a 20 psi back pressure due to the location of the storage tank on the roof. To make the 70 psi head pressure more useful, a 5000 gallon tank was installed near and on the same level as the cyclotron. All water circuits in the cyclotron empty into this tank through a 6" header, thus reducing the back pressure to about 4 psi. Water is separately pumped from this tank back to the storage tank on the roof.

Magnet Oil System

Magnet cooling oil at 100 psi was available in a 10" header within a few feet of the cyclotron. The oil has a specific gravity of 0.895 and a viscosity of 9.8 centipoises at 100°F. Since no provisions had been made for filtering the oil, eight cylindrical filters were installed in parallel, each presenting about 10 square feet of single layer flannel. A pressure reducing valve is arranged so that if controlling air pressure fails the regulating valve will close, thus protecting the magnet coils from excessive pressure. The return section of the system has an 18 psi back pressure and provisions have been made for the installation of a booster pump should this high back pressure be trouble some.

Oil connections to the four magnet coils are in parallel. Each coil requires around 225 gpm at a maximum allowable pressure of 35 psi. Even with the small heat load of the magnet, the cooling tower and draft fans must be operated during the course of a long run in order to secure an appropriate drop in oil temperature and to insure that the coil temperature remains below the limit of 170°F.

Compressed Air System

A centrally located air compressor serves the entire Y-12 area; two auxiliary compressors are available in the cyclotron building. Compressed air is used for pneumatic controllers, pistons, and air wrenches. Since the plant compressed air supply contained too much oil to be satisfactory for cooling oscillator tubes, a Nash water-seal centrifugal compressor was installed near the cyclotron with 4" pipe duct. The oscillator tube requires 300 cfm of air at 10 psi.

Dry air is required as a drying agent for the Kinney pumps as well as for exposing the vacuum chamber to atmospheric pressure. A set of Hoffman centrifugal blowers, Type EBA, and Lectrodryers, Type BWC, were installed to provide dry air at 3 psi.

Ventilating and Heating

The cyclotron pit is kept under a slightly negative pressure by means of a centrifugal blower. The pit air is filtered by CWS filters and then exhausted above the roof of the building. This blower motor is interlocked with the fire alarm system so that the air draft is cut off in the event of fire.

Utility Control and Instrumentation

Thorough instrumentation and centralized control of the utility services are provided at a 7 foot by 20 foot utilities panel, Figure 32. The utilities panel is supplied by a 1 KVA, 460/115 volt transformer connected to the 460 volt building supply. This installation is located outside the shielding wall and about 20 feet east of the pit. During construction of the cyclotron, thermocouple wells, orifice flanges, and guage nipples were installed at those points in the lines where information was desired. These were then connected to the utilities panel. A smaller panel with only the most essential indicators and alarms is located in the main control room. The utilities panel presents the following data:

Magnet Oil System

1. Records supply and regulated pressure.
2. Indicates supply and return temperature.
3. Indicates average voltage drop as a function of coil temperature, through each of the four coils, and provides an alarm should this voltage drop indicate a coil temperature in excess of 170°F.

Distilled Water System

1. Records supply and regulated pressure.
2. Indicates supply and return temperatures.
3. Records discharge water temperature of the six vital flow circuits: liner, dees, oscillator, source, target, and variable trimmer.
4. Records flow through each of these six circuits and provides an alarm should any fall below a minimum.

Miscellaneous Indications, Controls, and Alarms

1. Vacuum, Pirani gauges on roughing and finishing headers, alarms on high pressure.
2. Diffusion pumps, heater power control.
3. Gate valves, control for motor drives
4. Ventilation inside shielding wall
5. Liquid level of distilled water storage tank.
6. Nash air compressor.
7. Lectrodryer.
8. Fire alarm and CO_2 system.
9. Radiation monitors and alarms.
10. High voltage interlock system.

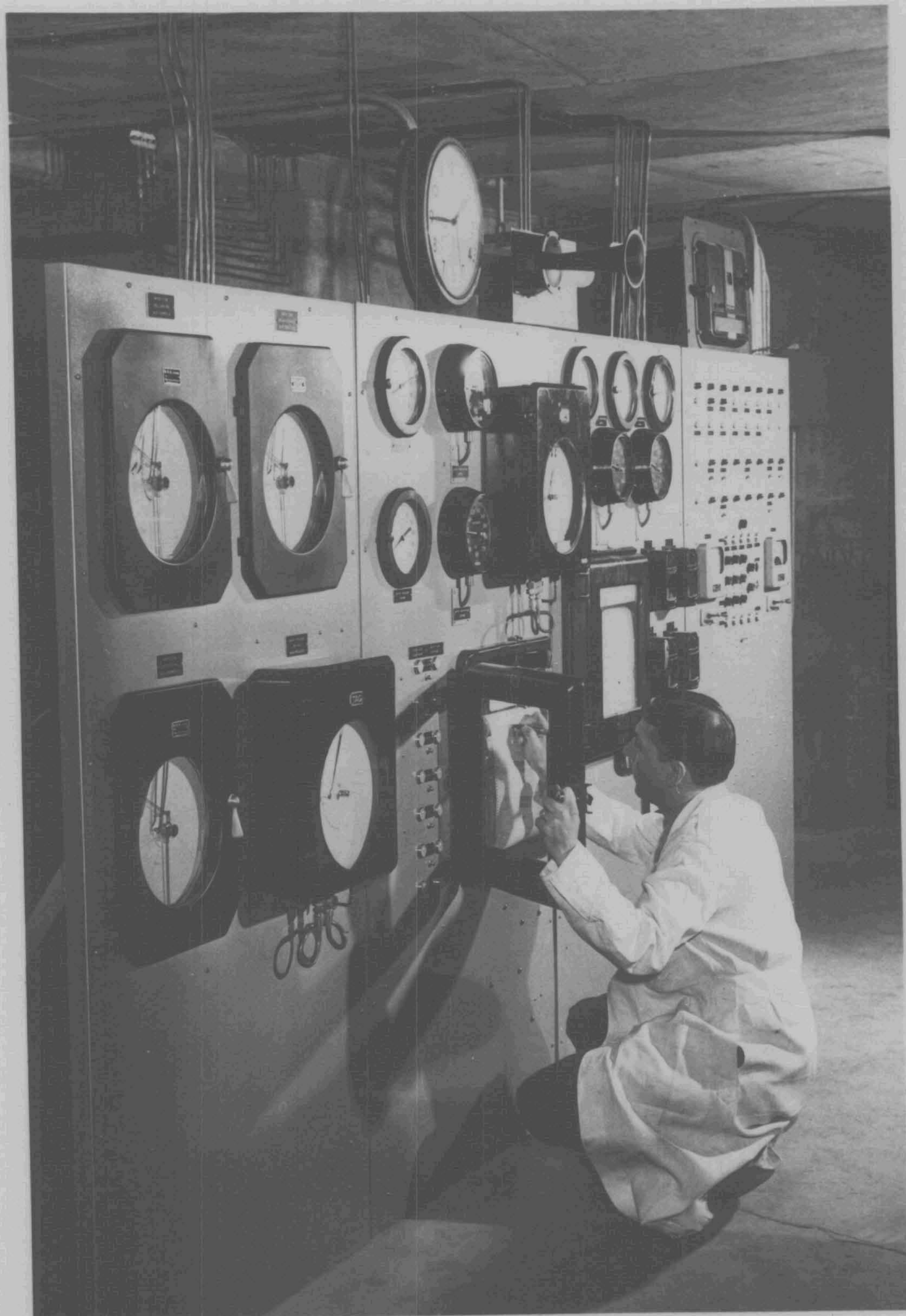


FIGURE 32. UTILITIES PANEL

CYCLOTRON DEVELOPMENT

A period of eight months elapsed after the first beam was obtained on the cyclotron in November 1950 before reliable performance at high beam currents was achieved. In this period a considerable amount of experimental testing and equipment revision was necessary. During two shutdowns (March and July, 1951), modifications were made which resulted in control of ion loading, correction of the median plane of the magnetic field, and in increased continuity of operation. The machine was then operated for six months without any major interruptions. A scheduled shutdown was made in January 1952 to permit changes which resulted in a significant increase in beam energy. The target vacuum lock was also enlarged to admit larger targets, and better facilities for safe handling of targets with high-gamma activity were provided.

Ion Loading

When the cyclotron was originally assembled oscillations were readily obtained at atmospheric pressure, but when the machine was placed under vacuum it was virtually impossible to start the oscillator. It is a characteristic of the grounded-grid self-excited oscillator, such as used on the cyclotron, that, due to oscillating electrons, or ions, a condition is set up at low rf voltage which prevents the dees from charging up to full voltage and therefore opposes the initiation of rf oscillations. This condition is referred to as "ion loading."

Test Grids. In the first successful effort to overcome this difficulty vertical grid structures composed of #12 copper wire were mounted near the liner walls, opposite the dees. The grids were supported on insulators attached to the liner and were shunted to ground through ceramic capacitors.

When a negative bias of 1500 volts was applied to this grid structure, rf oscillations could readily be obtained on the dees in vacuum, but continued operation was impossible due to excessive rf heating and insulator failure.

Water-Cooled Grids. The grid wires were replaced by grid structures of 3/8" copper tubing suspended vertically between the dees and the liner and supported by insulators at the top and at the bottom. This grid system, with a negative bias of 1 to 3 kv, permitted reasonably satisfactory cyclotron operation except for an occasional insulator failure. As higher beams were obtained the rate of failure of the lower insulators became excessive and they were removed, allowing the grids to swing freely between the dees and the liner, occasionally shorting to ground. The arrangement was further improved by water cooling the grid structure. Operation was fairly steady up to 200 kv, dee-to-dee. Severe sparking occurred frequently, especially at the higher beam currents.

Approximately 30 successful runs were made with the water-cooled grids. The best performance during this period is summarized:

Beam Meter Reading (μa)	Energy, at $H\rho$ (Mev)	Dee-to-Dee Potential (kv)
5000	3	50
1000	15	210
100	20	240
10	22	280
2	24	300

Biased Dees. It had become apparent that the water-cooled grids were a principal factor in limiting the dee-to-dee voltage. In order to improve operation, a time consuming and questionable program of grid design and development would have been necessary. As an alternative method for controlling ion loading, without the use of grids, the dees were insulated so that a dc bias potential could be applied to them. A temporary installation involving relatively simple changes was made first. A 750 $\mu\mu$f capacitance was inserted in series with the plate coupling line at the tube end to prevent the shorting out of the dc bias without interfering with the transmission of the rf power. The dee support plate was insulated from ground by means of 1/8" of Teflon, which has excellent rf insulation characteristics. An insulating hose was inserted in the water header. The liner clamps were removed from the spider and the liner-to-spider clearance was increased to 1/2" at all points. This effectively isolated the dees from ground. After the above changes, cyclotron performance improved markedly, as shown by data taken in June, 1951.

Beam Meter Reading (μa)	Energy, at H_ρ (Mev)	Dee-to-Dee Potential (kv)
1010	15	300
790	20	330
500	22	380
200	24	380

New Dee System. Although periods of excellent operation were obtained with the original insulated dee system, operation was uncertain because of Teflon insulation failures and local heating effects. In July, 1951, a second set of dees with improved water circuits and other features was installed. In the new system the dees rest upon four Alsimag 222 insulators mounted from the inner walls of the tank. The plate-line dee-stem terminal is brazed to the dee stem, eliminating the doughnut-shaped clamp and insuring good contact and cooling at all times. The connecting dee-stem clamp and the dee support plate are water cooled. A 3/8" gap is maintained between the tank and the dee support plate so that the entire system is insulated from ground. A negative bias potential is then applied to the assembly in the usual manner. Since this system was installed ion loading has ceased to be a problem.

RF Balancing. In the insulated dee system no direct electrical connection exists from the spider to the liner (ground). This means that all the ground current due to dee-to-dee-to-ground unbalance must flow by capacitor action from the spider through vacuum to ground or from the dee support plate through vacuum to ground. Of the two paths, the dee support plate to ground probably offers the least impedance to the rf current due to the capacitor area involved. This current results in undesirable heating of the tank walls. A method of minimizing this ground current by balancing the dees has been developed. It consists of changing the dee-to-ground capacitance of the south dee by means of a trimmer capacitor until a minimum dee support plate rf voltage is reached. This balance must be made at frequent intervals during operation because the slightest movement of any dee system component results in a change of dee-to-ground capacitance, with resultant unbalance. Controls for performing this operation, along with an rf voltmeter, have been installed at the remote control desk.

Magnetic Field Corrections

Preliminary magnet shims were designed to correct for azimuthal variations in magnetic field and to provide beam focusing. A displacement of the median plane of the magnetic field was corrected by the addition of auxiliary coils on the pole pieces. The preliminary shims were later replaced by one-piece machined shims.

Magnet Shims. Measurement of magnetic field distribution on the 1/16 scale model magnet and later on the actual installation had shown some irregularities which were the result of converting the rectangular field of the calutron to a circular field for the cyclotron. The 10" pole pieces and 4" tank walls had left some weak areas that were to be corrected. Magnet shims were designed to correct for these variations in the field and also to introduce the desired radial distribution of the field required for beam focusing. Preliminary shims were made from flat 86" discs of steel, 2" thick with layers of 0.016" steel shim stock attached to the discs to obtain the desired effects. At some points as many as ten layers were required. The desired field pattern was achieved through repeated field plotting and rearrangement of shim pieces, as described in Appendix B. These patchwork shims were used during the early weeks of test operation of the cyclotron. The chief disadvantage of the layered shims was the problem of outgassing them each time the tank was evacuated. From the pattern obtained with the preliminary shims, solid shims were designed. The desired contour was machined into the surface of a 2 1/4" steel plate with a vertical boring mill, see Figure 9.

Auxiliary Magnetic Coils. When it was observed that the beam currents were sharply diminished beyond the 30" radius, a series of tests was made to determine the beam pattern and the position of the beam as a function of radius. A target head was designed to contain five copper targets which could be injected sequentially into the path of the beam at various radii during a single continuous period of operation; no vacuum lock was available at this time. The shape and position of the beam was determined by radioautographs of the exposed targets. It was found that the beam remained near the median plane at radii from 5" to 23" but that from 23" to 30" it was deflected away from the median plane at an angle of approximately 20° (to the west). At 30" almost all of the beam was striking the dees. To correct this condition an auxiliary coil of 65 turns of #6 wire was wound on the 10" thick pole piece at each side of the tank. With $\sim$10 amperes dc in the coils, directed in such a way as to increase the field on one side (west) and to diminish it on the other, the beam is focused close to the median plane at all radii.

Increasing Continuity of Operation

Early operation was somewhat sporadic with the machine frequently shut down for adjustments, modifications, repairs, vacuum troubles, or perhaps just to permit some component to cool off. Continuity of operation improved markedly when difficulties associated with ion loading were brought under control. Lost time due to poor vacuum was reduced by a redesign of the ion source and target assemblies. A more rigid ion source stem reduced the incidence of filament breakage.

In preliminary operation the ion source and the target had both been mounted on the same faceplate and inserted through the bottom of the vacuum chamber. Since no vacuum lock was provided, frequent changes of these units resulted in much waiting for satisfactory vacuum conditions. During the July shutdown, separate ion-source and target assemblies were installed, each with vacuum lock. These assemblies have been described in a previous section, pages 62 and 68. The increase in innage time for the period June through September 1951 is shown in the distribution of cyclotron time given below:

Cause of Outage	Percent of Scheduled Time			
	June	July	August	September
Leaks and high pressure	20	23	4	4
Arc and filament trouble	13	3	2	1
Electrical trouble	12	5	2	4
Rf heating of tank	10	-	-	-
Dee changes	7	37	-	-
Dee balancing	1	-	-	-
Source changes	-	2	3	4
Target handling	2	7	4	2
Refrigerant care	-	-	2	2
For experiments	-	-	18	7
Miscellaneous	23	2	10	6
Total Outage	88	79	45	30
Total Innage	12	21	55	70
	100	100	100	100

Target Development

When an internal target is used with the face of the target at 90° to the beam path the total energy of the beam is concentrated on a surface not more than 4" by 1/4". The pattern of a cross section of the beam is determined from radioautographs of target surfaces. With water as a coolant it is possible to transfer only about 1 kw/in^2 while maintaining a surface temperature below 150°C. At higher temperatures a surface boiling condition would permit a more rapid transfer of heat but the melting of many of the materials used for bombardment limits the use of this principle. The cyclotron beam has a maximum cross sectional area of less than one square inch which, with a perfectly uniform beam, limits the proton beam power on a 90° target to one kilowatt. This means that at 20 Mev the cyclotron could be operated safely at a current of not more than 50 μa, which is far below the maximum current obtainable.

In order to absorb more power on an internal target the effective area can be increased by rotating the target, or by inclining the surface so that the beam strikes at a small angle of incidence; a combination of both could be used. Rotating targets have been investigated but none have been used yet. The grazing incidence principle has been used in spreading the beam over large target surfaces.

Grazing Incidence Targets. The first water-cooled target mount, Figure 33, was particularly convenient since the grazing angle could be varied from run to run by simply rotating the target tube in the mechanical seals. The flexibility of this design allowed various sizes of bombarded areas, as well as different grazing angles, to be tested in the early exploratory runs. The targets were made from aluminum or copper tubing, flattened in the region

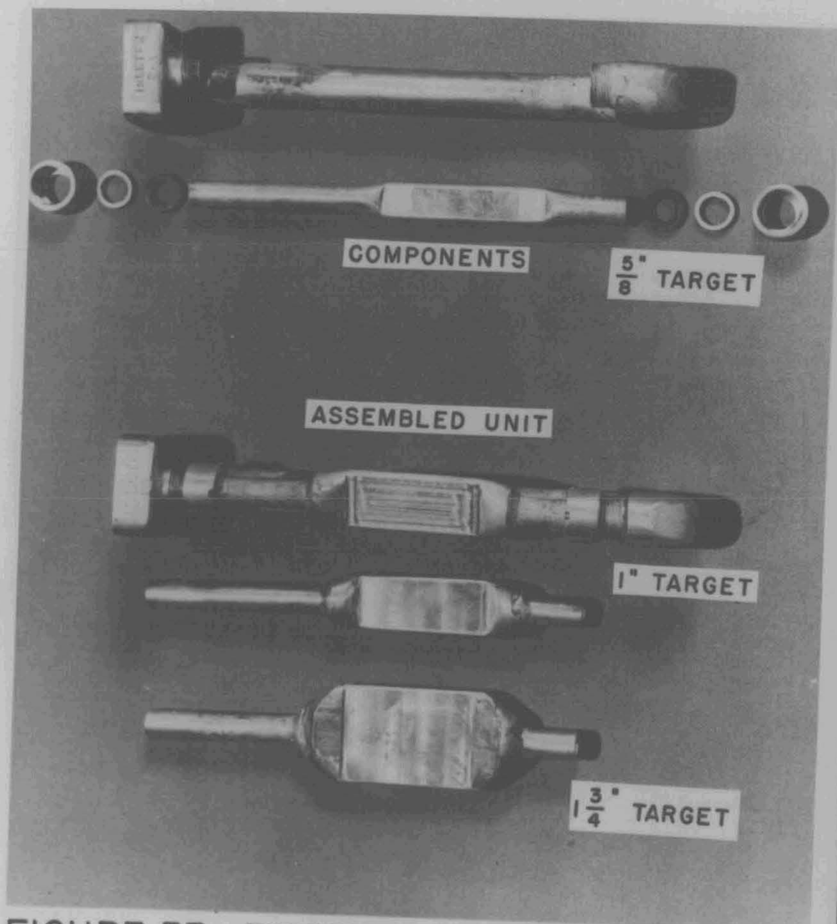


FIGURE 33. FIRST WATER-COOLING TARGET

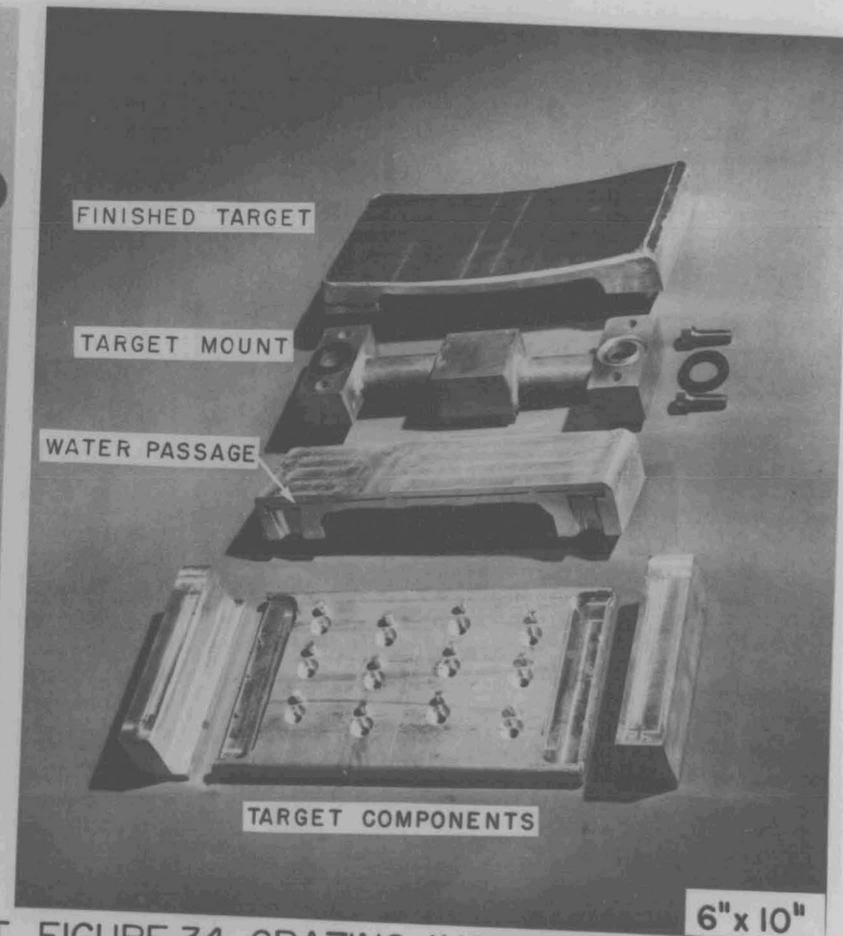


FIGURE 34. GRAZING INCIDENCE TARGET

of bombardment to form a 1/16" water passage which, with sufficient water pressure, gave water velocity of 20-30 ft/sec. This velocity serves to keep the temperature drop at the water-to-metal film at a minimum required for handling large heat fluxes or for bombarding materials with low melting points.

As the cyclotron beam was increased from 20 μa to 500 μa it became necessary to develop targets having more area in order to dissipate the larger power input. Targets of 6" by 2 1/2" were made with the long dimension in the direction of the beam path, Figure 26. When the new biased dees were installed it was found that the beam dimension parallel to the magnetic field was 4 inches compared with 2 1/2" in the first set of dees. With improved operation the beam current available rose to above 1000 μa. Consequently, a still larger grazing incidence target, 6" by 10", was made; steps in fabrication of this target are shown in Figure 34. The starting material for these targets is tubing 4" in diameter and with 1/4" walls. The tubing is annealed and then flattened in a hydraulic press against a 1/16" mandrel at about 50,000 psi. The flattened tubing is machined on the ends for attachment of the water header. To provide needed rigidity twelve holes are drilled through the target and pins fitted snugly into the holes. The pins and the header are Heli-arc welded, the desired target material is applied to the surface, the target is bent to the proper curvature, and the mounting is machined for the desired angle of incidence, usually $\sim 2°$.

Recently an improved method of construction of the 6" by 10" targets has been developed which produces a more rigid target surface and better thermal characteristics, see page 72 and Figure 28.

Increasing Proton Energy

Early experiments indicated that the beam energy was somewhat below the energy calculated from $H\rho$. For methods of measuring the energy of the internal beam, see Appendix D. Where the calculated energy was approximately 22 Mev, activation studies indicated $\sim$19 Mev. In order to locate the cause of this lower energy a harmonic analysis of the magnetic field was made, the rf voltage distribution on the dees was measured, and the effect of ion source position on beam energy was investigated.

Locating the Center of Rotation. Apparently the center of beam rotation was misplaced from the magnetic center in such a way as to reduce the actual radius. Since grazing incidence targets are designed to operate at rather small angles, $\sim 2°$, it is necessary to know the center of beam rotation; the target must be very accurately aligned with respect to the beam path. The orbital path, and hence the center of rotation, was determined with a "burnout" target. Seven lead foils, 0.002", were attached at widely spaced intervals to a long target base and placed across the beam path. The foils melted cleanly, permitting the beam to be measured accurately. From this data the center of rotation appeared to be 1.5" below and 2.5" south of the magnetic center. Beam energy calculated from this center agreed with the energy as measured from target activation.

Harmonic Analysis of the Magnetic Field. Since the first harmonic in the magnetic field can cause precession of orbit centers a harmonic analysis of the magnetic field measurements was made, see Appendix B. Where the field is expressed as:

$$H = H_{av}(1 + A \sin \theta + B \cos \theta)$$

the coefficients A and B can be determined, Figure 35. Calculations based upon this analysis indicate that no appreciable orbital precession can result.

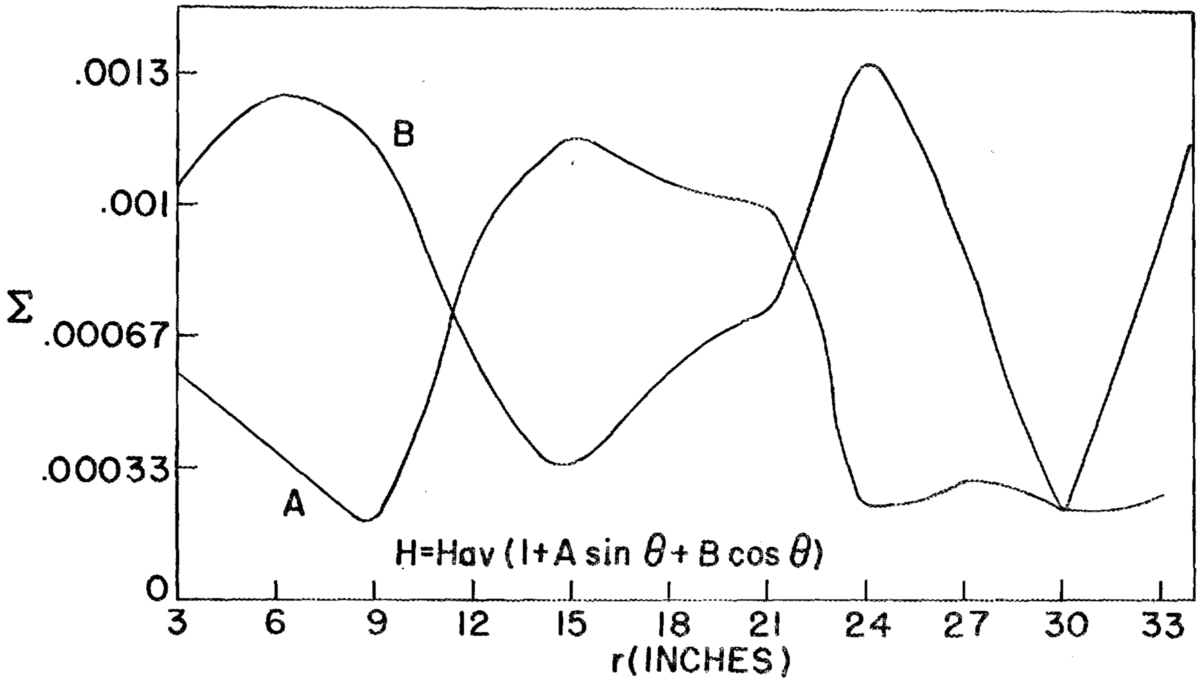


FIGURE 35. HARMONIC ANALYSIS OF MAGNETIC FIELD

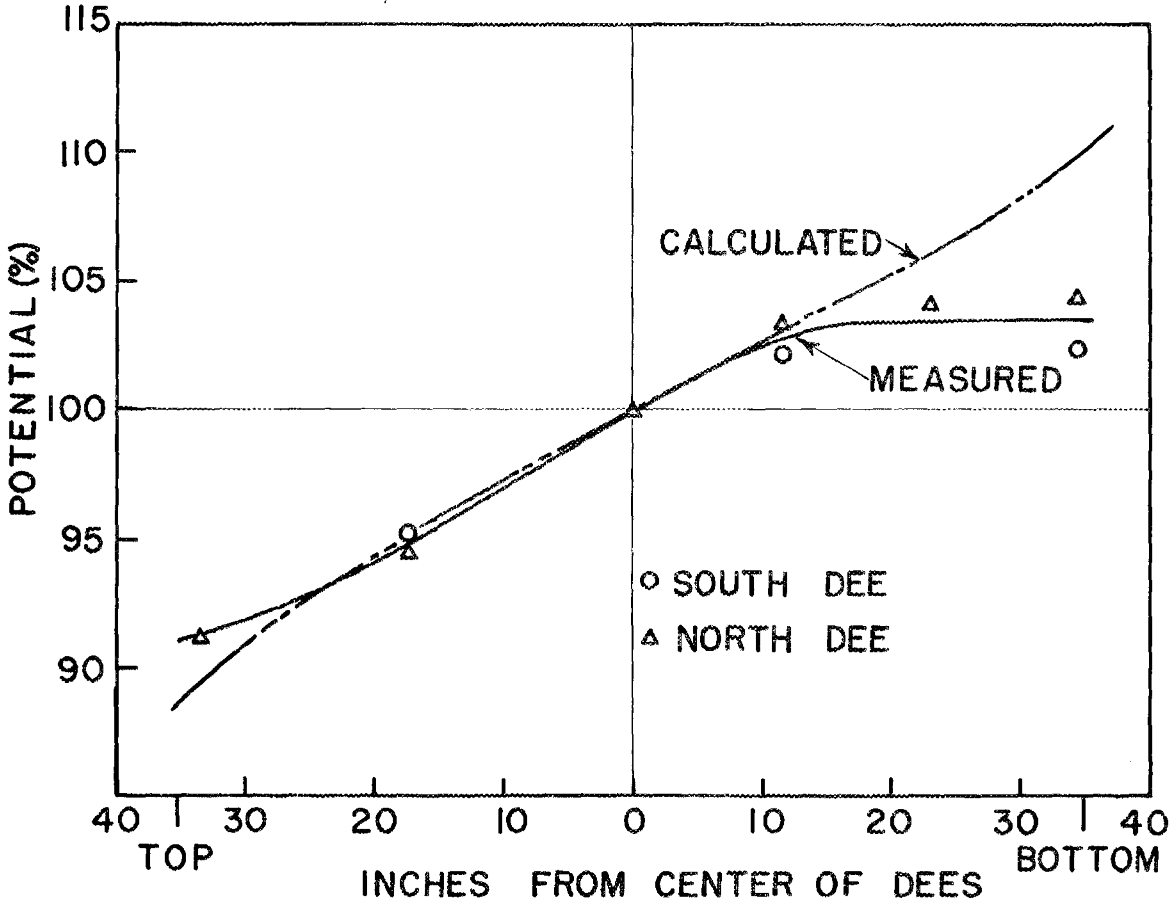


FIGURE 36. POTENTIAL DISTRIBUTION ON DEES

RF Voltage Distribution on the Dees. The distribution of rf voltage on the dees was measured on the full scale electrical model, Figure 40, which had been used in the original design work. The measured and calculated voltage distributions were then compared, Figure 36. The measured values fall within the experimental errors for the calculated values except for the lower fourth of the dees. The voltage distribution was not changed significantly by shifting the trimmers full range and the distribution was essentially unchanged when the dees were "loaded" with a 100,000 ohm resistor. When the effect of the distribution was analyzed it was not found possible to account for the measured eccentricity of the beam orbits.

Increased Energy. During the shutdown early in 1952 the ion source and accelerating slit positions were raised 1.5", to a point 1" below the magnetic center, and the dees were tilted from the support frame so that the dee center was shifted southward 0.5". Since these changes the energy measured on targets at a radius of 30.5" agree with $H\rho$ calculations. Preliminary tests indicate, however, that the center of rotation is still 1.75" south of the magnetic center.

Presence of Large Circulating Currents

Measurement of maximum beam power has been handicapped by the limited thermal capacity of targets. If ion source and dee-to-dee potentials are repeatedly adjusted for increased beam current the targets overheat and fail before the limit of output is reached. When the cyclotron is adjusted to off-resonance conditions the beam is lost to the walls of the dees instead of striking the targets. The ion output as measured by the current in the dee bias circuit can then be greatly increased. The dee bias current is corrected for leakage and the results obtained are believed accurate to better than 10%.

As a measure of available circulating currents, a 500 μa beam was obtained with the dee-to-dee potential at 320 kv and the dee bias 1 kv; the magnetic field was then raised slightly off-resonance and the ion output was maximized by readjusting the ion source conditions. The average energy of the ions for both cases was estimated from oscillator loading corrected for efficiency, see pages 26-27.

Conditions	Dee Bias Drain (ma)	Dee Bias Leakage (ma)	Ion Loading Current (ma)	Ion Loading Power (kw)	Avg. Ion Energy (Mev)
500 μa beam, on resonance	18.6	8.6	10.0	17.0	1.7
4 μa beam, above resonance	59.9	8.6	50.4	37.4	0.74

With the beam on resonance and the cyclotron operating with 500 μa on the target, the above experiment shows that 10 ma of beam is circulating for the first few revolutions with an average energy of 1.7 Mev. With the "off-resonance" condition in which almost all of the beam strikes the dees, an ion current of 50 ma at an average energy of 0.7 Mev was reached. This suggests that much larger beams may be obtained at the full energy as the cyclotron technology improves.

ACKNOWLEDGEMENTS

Completion of the 86-inch cyclotron required the cooperative efforts of personnel from the Engineering and Maintenance Divisions of Y-12 and the Electromagnetic Research Division of ORNL. The whole program was closely supervised by R. S. Livingston and A. L. Boch.

Preliminary designs of the rf system were prepared by C. Becker and E. Vincens. Other electrical circuits were designed and modified by M. B. Marshall, J. C. Ezell, and H. K. Bailey. The magnet was designed by E. D. Hudson and F. S. McGuiness, the former making many tests and measurements of magnetic field distribution. While the magnet was being built, H. C. Hoy and A. L. Boch were building and testing the radio frequency system. At the same time, M. B. Hilton, G. F. Leichsenring, F. H. Neill, and B. W. Stockbridge were designing the mechanical features of the machine, their work being supervised by E. Zurcher. Special targets were designed and fabricated by J. H. Cupp, F. H. Neill, N. Stetson, and J. A. Martin.

Various fabrication problems involved in the design features were investigated by J. E. Harding, J. S. Luce, C. W. Mason, O. D. Matlock, and R. G. Reinhardt, with the counsel of W. R. Chambers. Special design problems associated with the utilization of existing facilities were attended to by H. B. Bainbridge, R. S. Lord, A. W. Riikola, and M. Wallis. R. Harmatz, with the advice of E. P. Blizzard, established the shielding specifications. Fabrication, modification, and installation of electrical and mechanical equipment was done under the supervision of J. C. Bowles, J. M. Case, A. A. Groppe, C. B. Hopkins, G. W. Mitchel, W. L. Morgan, and C. B. Newman.

Measurements of beam energy and distribution and of radiation effects have been made by R. A. Charpie, B. L. Cohen, and J. L. Fowler. The cyclotron is being operated under the immediate supervision of A. L. Boch.

The staff responsible for operation and development of the 86-inch cyclotron, as of June 1, 1952, is as follows:

Engineer in Charge	A. L. Boch
Staff Engineers	R. S. Lord M. B. Marshall
Operations Supervisor	A. W. Riikola
Operations Crew Chiefs	H. L. Dickerson C. L. Viar E. G. Richardson, Jr. C. P. Shelton

Others who assist on a part-time basis are:

Electrical Engineer	E. L. Olson
Mechanical Engineers	J. S. Luce F. H. Neill
Physicists	R. A. Charpie B. L. Cohen
Health Physicists	L. C. Emerson E. G. Struxness R. O. Wollan

APPENDIX A: COST ANALYSIS

The following figures are for construction and preliminary testing of the cyclotron components. The cost of equipment which existed in the building is not included, but costs of modifying this equipment are included.

Item	Cost	Total Cost
1. Building Modifications		
Preparation of cyclotron site including offices, laboratories, and service area	$18,092.02	$18,092.02
2. Magnet		
a. Magnet yoke	46,494.40	
b. Coil supports	5,876.95	
*c. Moving coils from a Beta magnet and replacing them with support structures	3,735.58	
d. Magnet wiring	1,080.68	
e. Magnetic shims	5,751.78	
f. Field measuring equipment	7,000.00	69,939.39
3. Power Equipment		
Preparation of existing motor-generator set and associated power equipment; reinstallation of building transformer, switch gear and control wiring	11,940.28	11,940.28
4. Vacuum System (Installed)		
a. Vacuum tank	21,664.01	
b. Vacuum manifold	8,395.31	
c. Tank extension	13,077.92	
d. Modifications to existing vacuum pumps and piping	11,312.89	
e. Vacuum testing	7,000.00	61,450.13
5. Models		
a. Electrical model	6,000.00	
b. Other models	565.92	6,565.92

* Coils used are from a Beta magnet; no revisions were necessary.

	Item	Cost	Total Cost
6.	Oscillator Power Supply		
	Revisions of 20 calutron supplies, associated switchgear and transformers to give a 600 kw dc power supply	$ 24,621.43	$ 24,621.43
7.	Control Consoles		
	Construction and wiring	11,218.63	11,218.63
8.	Utilities		
	Water, lights, magnet oil, heat, and necessary revisions to existing pumphouse	45,068.80	45,068.80
9.	Oscillator		
	Including plate and filament transmission lines	40,429.64	40,429.64
10.	Resonant System		
	a. Dees	30,073.11	
	b. Liner	14,767.11	
	c. Spider	2,507.63	
	d. Trimming capacitors	5,376.19	
	e. Miscellaneous	2,000.00	54,724.04
11.	Shielding		
	a. South wall	17,315.19	
	b. Other walls	67,275.00	
	c. Roof blocks	32,153.00	116,743.19
12.	Ion Source		
	Including power supplies and hydrogen system	9,500.00	9,500.00
13.	Target	3,565.92	3,565.92
14.	Handling Equipment, and platforms	14,423.85	14,423.85
15.	Radiation Instruments	8,000.00	8,000.00
	TOTAL		$496,283.24

APPENDIX B: MAGNETIC FIELD MEASUREMENTS

When the magnetic shims were being shaped to provide the desired field configuration, extensive measurements were required for the entire field after each shim correction. Semi-automatic equipment, developed to facilitate magnet field plotting, greatly reduced the time required. A search coil arm capable of moving the search coil to any portion of the tank was mounted from one of the poles. The motor, clutch assembly, and a gear train providing a slow speed for rotating the arm 360 degrees in 30 seconds, or a fast speed for moving the coil radially 1/2" per second, are shown in Figure 37. Two cams, driven from the gear train, close microswitches which energize markers at each side of the meter record chart (G. E. fluxmeter, Type 8CE) and thus provide an exact index of search coil position.

A flip coil with an effective area of 114.9 cm^2 and rotated 180 degrees, a Hibbert Standard having 1.920×10^6 line turns, and a ballistic galvanometer with a period of 26 seconds were used in taking magnetization data shown in Figure 10.

The search coil is counter-balanced and rotates at a reasonably uniform speed which is changed very little when the magnet is energized. Rotational speed of the arm is reduced about 50%, however, by motor loading arising from eddy currents in the gears and drive shaft. Most of the data was taken from circular runs; the radial runs, except for the reference runs, were used to provide check data. A control box with switches for reversing the motor, and for making the proper circuit changes when shifting to and from radial and circular runs, is mounted on a platform at the top of the tank.

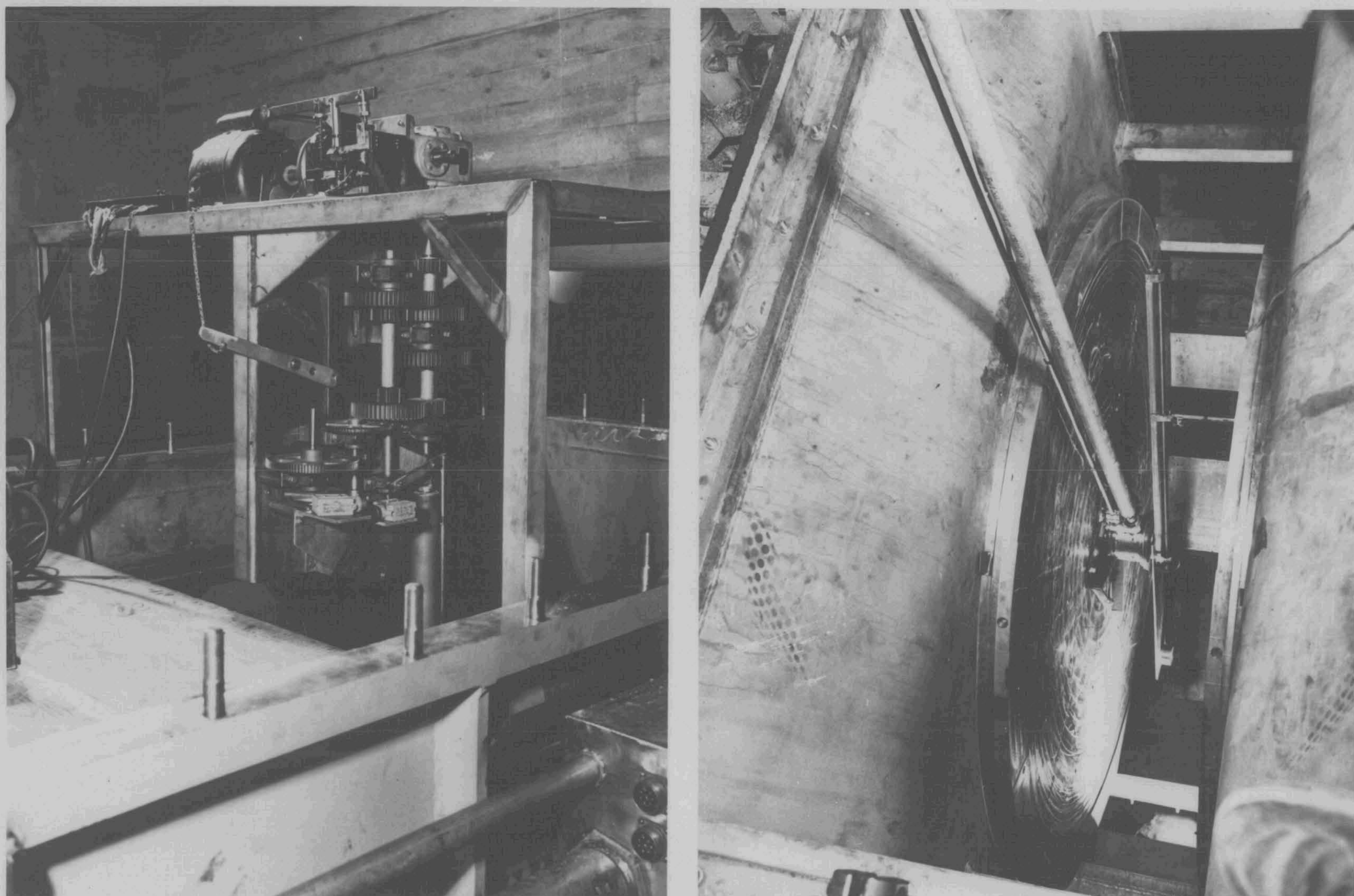


FIGURE 37. MAGNETIC FIELD MEASURING EQUIPMENT

The fluxmeter, Hibbert Standard, and recording meter were installed more than 100 feet from the cyclotron magnet where the stray field from the magnet, although very small, was still sufficient to require adjustment of the fluxmeter. The fluxmeter is subject to fairly large drift and requires continuous attention to obtain satisfactory flux measurements over one-minute intervals. The search coils have an area of 17,455 cm^2 and a resistance of 2400 ohms. For two of these coils the maximum sensitivity is about 0.1% per small division on the chart. The resistance of the search coils is much larger than recommended for use with the fluxmeter; the use of fine wire to reduce the volume of the coils results in the greater resistance.

A complete set of field measurements includes circular runs every four inches out to 36 inches in both clockwise and counter-clockwise directions and also radial runs every 30 degrees, starting at the center and going to 36 inches and back to the center; this requires about an hour. It is possible then to make minor changes in the shims and to take a complete set of field measurements in a few hours. The close agreement of measurements made by forward and reverse runs is shown in the matched charts, Figure 38.

After the contour shims were installed, field measurements indicated that the flux in an area of 3 to 4 square feet was about 0.2% higher than in the rest of the tank at corresponding radii. Approximately 0.020" of material from each pole over the area opposite the high field region was removed in about two hours with a portable grinder. While tests indicate that azimuthal uniformity to greater than 0.2% can be obtained by careful testing and grinding, this has not been done because there is no apparent justification for interrupting present cyclotron operation.

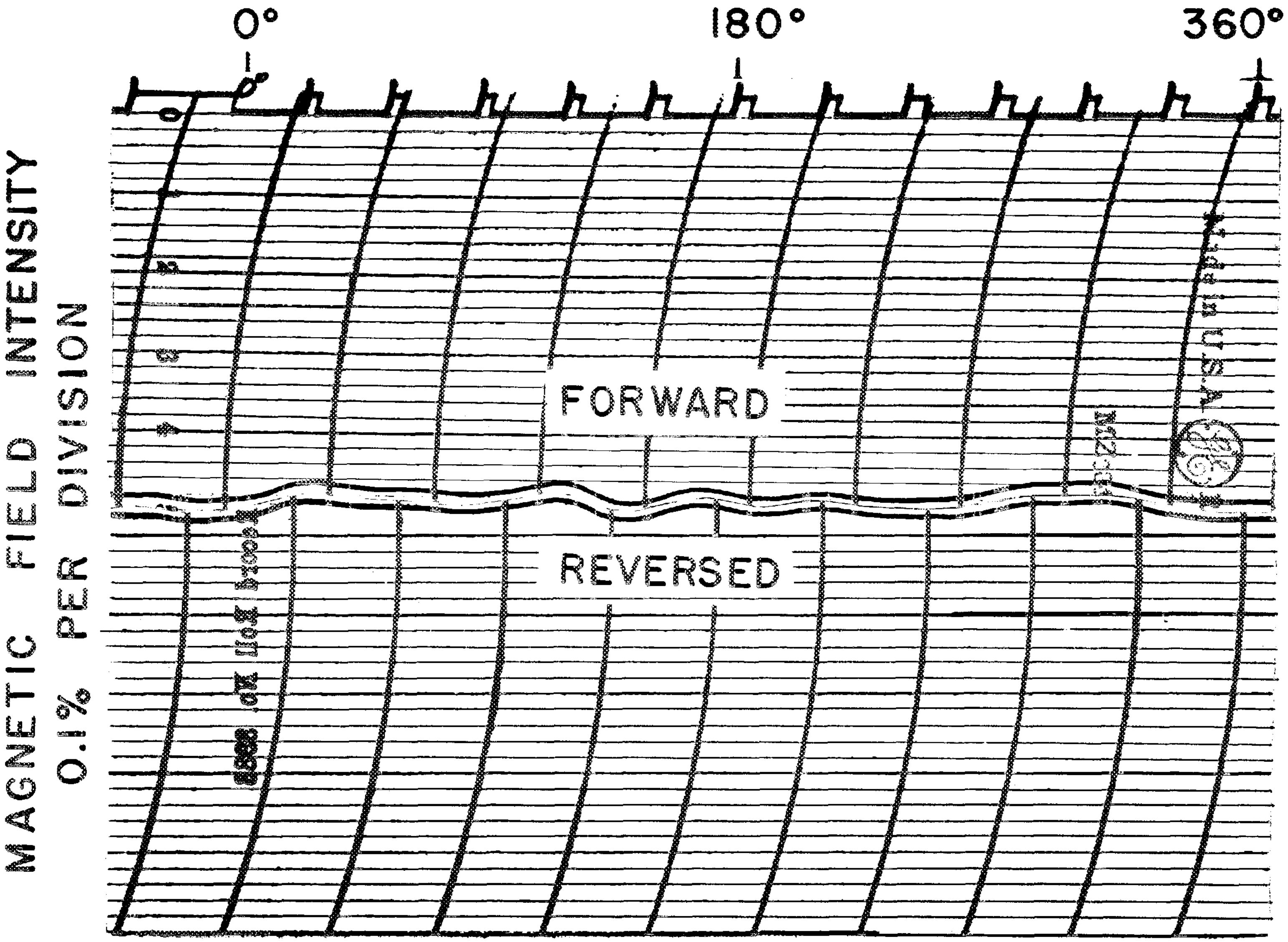


FIGURE 38. AZIMUTHAL FIELD VARATIONS

APPENDIX C: DESIGN OF THE RADIO-FREQUENCY SYSTEM

In designing the radio-frequency system emphasis was placed on the primary requirement of obtaining large proton beam currents at the desired energy. This implies the need for very high accelerating voltages between deés to reduce the number of revolutions and thus reduce the phase lag due to relativistic mass increase during the accelerations. Every attempt was made to keep the power required to maintain these voltages to a minimum by proper choice of design and geometry. Since exact calculation of all constants of such a system was not possible the calculated results were used in building a full scale model of the radio-frequency system from which the final information for the construction of the actual machine was secured, page 15.

The three major components of the radio-frequency system are: the resonant dee system which is composed of the cyclotron dees, the dee stems, and the liner; the oscillator; and the coupling lines between the oscillator and the dee system. The cylindrical dee stems within an oval liner constitute a balanced quarter-wave transmission line which is tuned by shifting the ground plane by means of a movable shorting spider across the dee stems.

With the exception of the biased dee change previously described, the oscillator and associated resonant system in use at the present time differs very little from the original as described by the section to follow. The oscillator was designed and constructed for two-tube operation; only one tube has been used, however, see Figures 14 and 39.

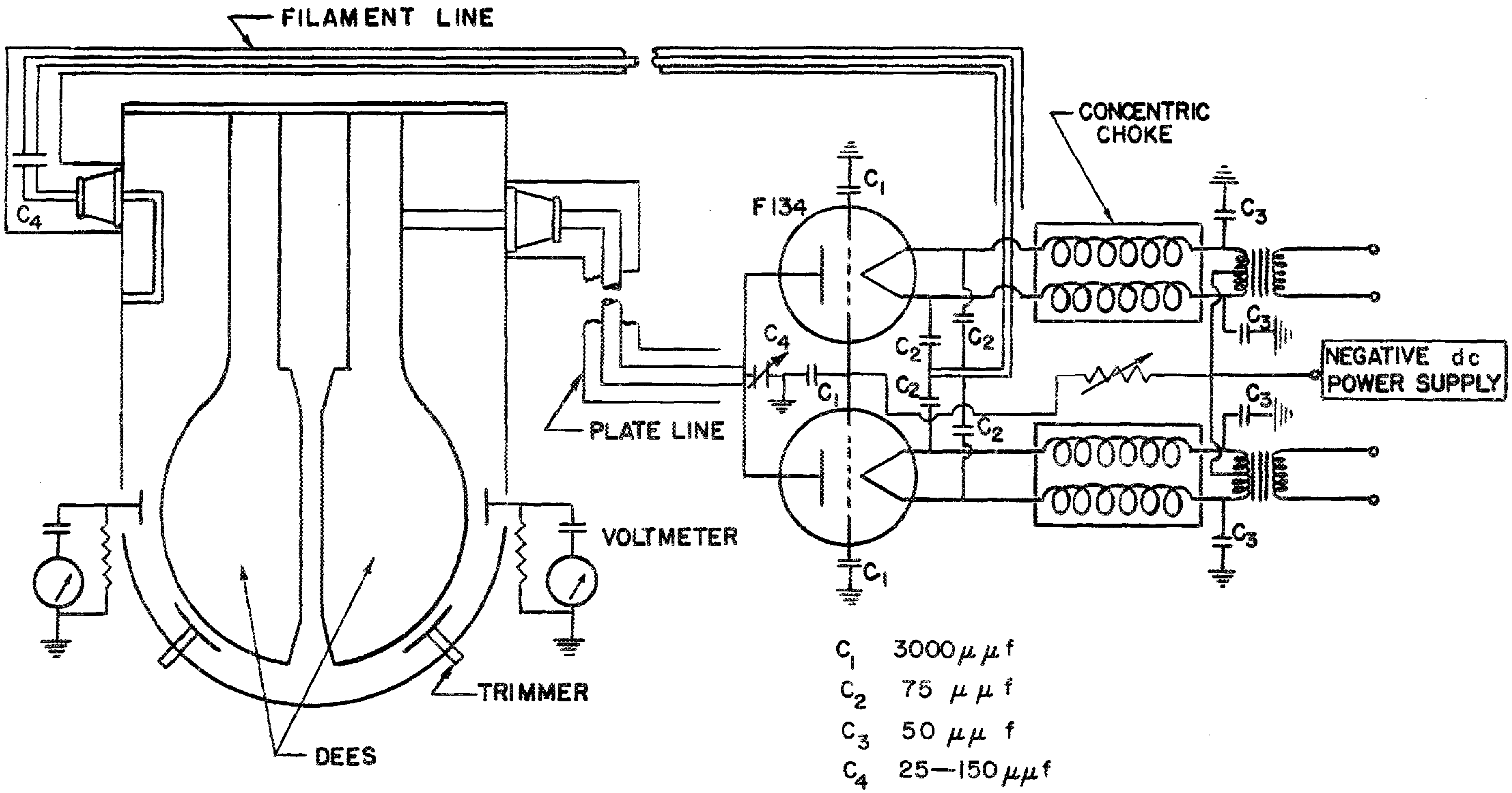


FIGURE 39. RF SYSTEM, ORIGINAL INSTALLATION

The Resonant Dee System

The desired maximum dee-to-dee potential of 500 kv is produced most efficiently by means of resonant systems with distributed circuit constants. The frequency of oscillation must satisfy the resonance requirements of the protons, in this case 13.4 megacycles per second. The constants of the resonant transmission line terminating with the dees must be calculated to obtain this frequency. A balanced quarter-wave transmission line consisting of the two cylindrical dee stems enclosed in a single oval shield, which is an integral part of the grounded liner of the vacuum chamber, was used because such an arrangement provides for lower resistance and more nearly uniform current densities than is obtained with rectangular structures. A line of this construction possesses 10 to 12% lower resistance than a balanced line with circular shields and equal cross-sectional area. The rf attenuation for the transmission line must be small in order to obtain the high Q required for the high dee voltage. Where d is the distance between centers of dee stems, a the radius of the stems and s the radius of the flattened oval of the shield, the conditions for minimum attenuation are:*

$$d/(2s + d) = 0.46$$

$$s/a = 3.7$$

The practical cross-section dimensions used in construction are:

$$d = 3.27 \text{ ft}$$
$$a = 0.5 \text{ ft}$$
$$s = 1.85 \text{ ft}$$

* Green, E. I., Leibe, F. A., and Curtis, H. E., "The Proportioning of Shielded Circuits for Minimum High-Frequency Attenuation," Bell System Technical Journal Vol 15, April, 1936, pages 248-283.

The length of the line (dee stems) is determined by its termination as represented by the capacitance and inductance of the dees. The next step was then to estimate the constants of the dees. To provide adequate clearance for a maximum beam radius of 33 inches the dees were made 35 inches in diameter. Other dee dimensions depended upon available vacuum tank space, electric gap requirements, mechanical strength of structures, and acceptable electrostatic focusing. The following dimensions were specified for the dee structure:

Radius of dees	35 inches
Thickness of dees	8 inches
Distance between dees	4 inches
Distance from plane surface of dees to ground	4 inches
Distance from peripheral surface to ground	7 inches

A first approximation of the dee capacitance is obtained from

$$C_{gD} = 1.11 \sum_{1}^{n} K_n \frac{F_n}{4\pi d_n} \ \mu\mu f$$

where K is a constant allowing for fringing effects, F is the surface being considered and d the distance to ground. The value thus obtained for one dee is approximately 260 μμf, including allowances for probes, etc. To this figure must be added twice the dee-to-dee capacitance. From a field plot this was estimated to be 30 μμf, so that C_D = 320 μμf. Since the dees have large proportions and represent a considerable length, compared with the wave length of the oscillations, they behave like a transmission line. The figure C_D must therefore be modified to allow for this characteristic. The "effective" capacitance of this dee-line is given by:

$$C_{eD} = \left(\frac{1}{2\pi f}\right) \left(\frac{1}{Z_{OD} \cot\left(\frac{2\pi \ell_D}{\lambda}\right)}\right)$$

where Z_{OD} = characteristic impendance of one dee
λ = wave length
ℓ_D = diameter of dee

It can be shown that the geometric capacitance is equal to:

$$C_{gD} = \frac{\ell_D}{Z_{OD}\ v}$$

where v is the velocity of wave propagation. The value of C_{gD} is previously estimated. Thus an estimate of the magnitude of C_{eD} may be obtained from the ratio:

$$\frac{C_{eD}}{C_{gD}} = \frac{\tan \frac{2\pi \ell_D}{\lambda}}{\frac{2\pi \ell_D}{\lambda}} = 1.10$$

This means the effective capacitance is approximately 10% larger than the geometric capacitance. Thus $C_{eD} = 1.10 \times 320 = 352$ μμf, or, reduced to dee-to-dee geometry, $C_{eD} = 176$ μμf.

The length of the balanced transmission line for resonance with C_{eD} may now be determined from:

$$Z_c = Z_o \tan \beta \ell$$

where $Z_c = \frac{1}{2\pi f C_{eD}}$

Z_o = characteristic impedance of shielded line

$\beta = \frac{2\pi}{\lambda}$ radians per unit length

ℓ = length of balanced line

The value for Z_o of the balanced shielded line was estimated at about 145 ohms by assuming a rectangular shield and making allowances for the rounded corners. The formula for the rectangular shield is available in handbooks. Then:

$$\ell = \left(\frac{\lambda}{2\pi}\right) \arctan \left(\frac{1}{2\pi f\ C_{eD}\ Z_o}\right)$$

and the length, ℓ, is approximately 156 cm or 5.2 ft.

The Oscillator

The nature of the cyclotron load imposes severe operation conditions upon the oscillator. Of the two oscillator systems commonly in use, the self-excited oscillator and the master-oscillator-power-amplifier type, the former was selected. Both have certain advantages and the choice is one of simplicity versus complexity of equipment and circuits. Experience has shown that the grounded-grid type of oscillator is well adapted for cyclotron work. Its circuit is extremely simple, apparently free of undesirable parasitic oscillations, and does not require neutralizing capacitors. In spite of its load dependence, it performs stably with proper design and adjustment.

The characteristics of the oscillator must be of such magnitude as to permit the desired push-pull mode of oscillation for maximum dee-to-dee voltage with best efficiency and stability. The conditions for oscillation are:

1. Voltage from cathode to ground and plate to ground must be in phase.

2. The feed-back voltage must be of sufficient magnitude to provide the required energy for maintaining oscillation at the desired dee frequency.

3. The overall system phase shift, from plate through coupling lines to cathode, must be close to 360 degrees.

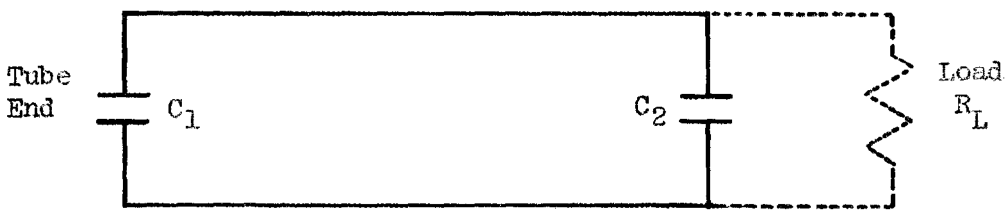
A schematic diagram of the oscillator coupled with the resonant dee system is shown in Figure 39. Characteristics of the Federal 134 oscillator tube used are tabulated below:

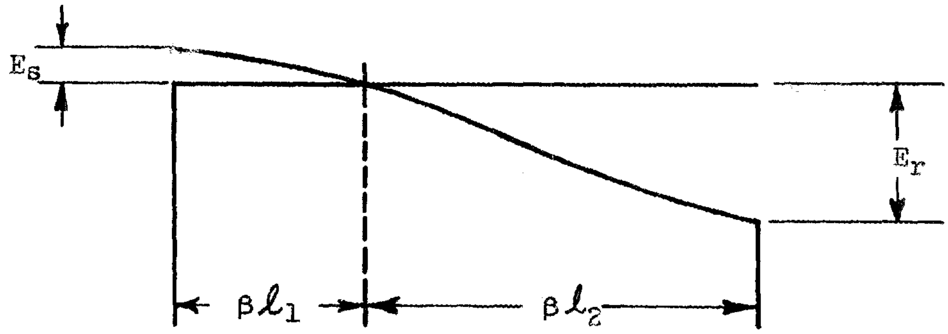
Characteristic	Maximum Rating	Operation Data
DC plate voltage	20,000 volts	18,000 volts
DC grid voltage	-4,000 volts	-2,000 volts
DC plate current	20 amperes	14.5 amperes
DC grid current	2.0 amperes	1.04 amperes
Plate input	400 kilowatts	260 kilowatts
Plate dissipation	150 kilowatts	60 kilowatts
Power output		200 kilowatts
Plate-to-ground, rf peak voltage		15,700 volts

Coupling Lines

Conditions for the required phase shift in the system are best assured through the use of half-wave resonant transmission lines for both the plate and filament (feed back). The general equipment location determines to some extent the physical length of the lines. The plate line is directly connected to one dee stem and the filament line to the other stem through a coupling loop.

The Plate Line. The plate line is a 3 3/4" copper tube enclosed in a shield 12" square. With the approximate physical length determined by equipment location, the problem remains to fix the line termination so that the voltages at each end of the line correspond to plate rf peak voltage, E_s, and the required load voltage, E_r, respectively. The line terminations and voltage distribution on the half-wave resonant line are shown below.





With resonant conditions, and no losses, ℓ_1 and ℓ_2 can be obtained from:

$$Z_1 = \frac{1}{2\pi f C_1} = Z_o \tan \beta \ell_1$$

$$Z_2 = \frac{1}{2\pi f C_2} = Z_o \tan \beta \ell_2$$

The end effect C_2 is estimated at 13.3 $\mu\mu$f. The resistive load imposed by the dee system is neglected since the slight detuning effect will be compensated by the variable part of the terminating capacitor C_1. This capacitor includes a variable section as well as all other plate-to-ground capacitance present, the latter being approximately 450 $\mu\mu$f. The characteristic impedance, Z_o = 70 ohms, is chosen to give smallest possible losses and to permit a value of C_1 so that the line may be readily tuned within a desired frequency range. The length ℓ_2 is then evaluated at 17.44 feet, and ℓ_2 is computed from the relationship of voltage distribution on the line, which can be shown to be:

$$\frac{E_s}{E_r} = \frac{\sin \beta \ell_1}{\sin \beta \ell_2} = \frac{\sin \arctan \frac{Z_1}{Z_o}}{\sin \arctan \frac{Z_2}{Z_o}} = \frac{1}{A}$$

where A is the voltage amplification factor and $\beta = 2\pi/\lambda$ radians per unit length. From the two equations for ℓ_1 and ℓ_2 an evaluation of C_1 is obtained:

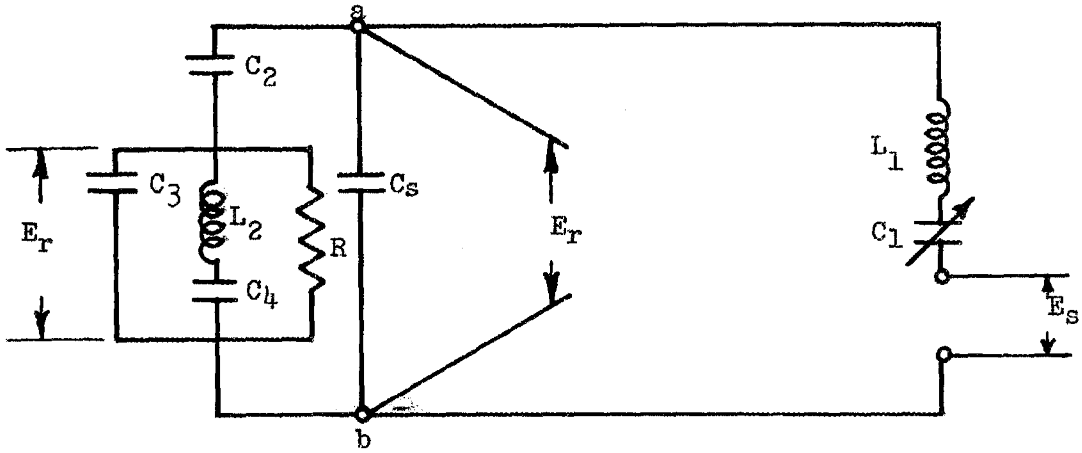
$$C_1 = C_2 \frac{\tan \beta \ell_2}{\tan \beta \ell_1}$$

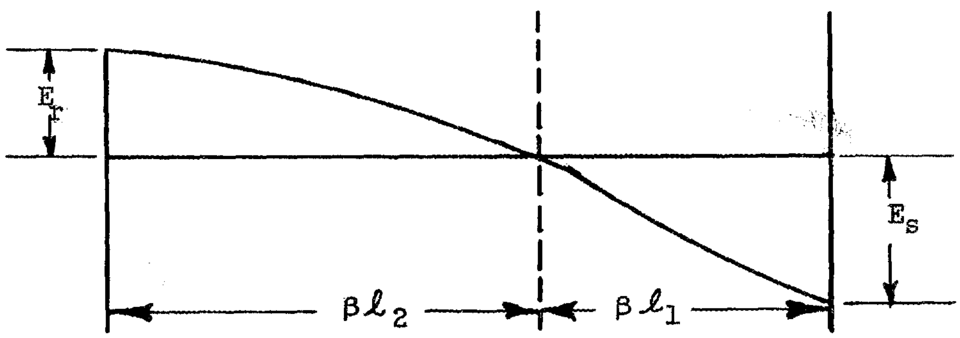
The numerical values for the model plate line, so determined for resonant condition at 13.4 megacycles are tabulated below:

C_1 line termination capacitance, tube end	515 $\mu\mu$f
C_2 line termination capacitance, load end	13.3 $\mu\mu$f
ℓ_1 at 18.21°	3.71 feet
ℓ_2 at 85.5°	17.44 feet
ℓ at 103.7°	21.15 feet
E_s sending voltage	15,700 volts
E_r receiving voltage	50,000 volts
Amplification factor	3.19

The magnitude of receiving end voltage was set at 50,000 volts for several reasons. By keeping the voltage high, within bushing limitations, the rf current is kept low, and consequently the power losses and cooling water requirements are minimized.

The Filament Line. A similar approach was used in approximating the length and terminations of the filament line. The line is 2 1/2" copper tubing, with a shield six inches square. The schematic circuit with voltage distribution is shown below:





L_2 represents the inductance of one filament choke coil, and R the resistance to the driving current. C_2 is a coupling capacitance to isolate the rf line from dc potential. The termination between a-b at the tube end of the line can be represented by an equivalent resistance in series with an equivalent capacitance of the following magnitudes: $C_e = \sim 147$ μμf and $R_e = \sim 2.7$ ohms.

For all practical purposes R_e can be neglected. Then the effective termination is that of a pure capacitance, and since its value is very nearly that of $(C_2 + C_3)$ in series, we may assume the voltage E_r to be approximately twice the required driving voltage, $E'_r = 3040$ volts peak. The error introduced in computing the length of the line by this simplification is very small, within design limitations. Again for resonance condition, with $X_{c1} = X_{\ell 1}$, values are obtained for $\beta\ell = 90°$ and $\beta\ell_2 = \arctan 1\ 2\pi f C_e Z_o = \sim 48°$. The Z_o value of 52 ohms is chosen for reasons similar to those stated for the plate line. The required voltage at the coupling loop is given by $E_s = E_r/\sin\beta\ell_2 = \sim 8200$ volts peak. The coupling loop at the dee stem must be positioned to give this voltage. The numerical values for the line are tabulated below:

C_1	phase correcting capacitance	variable
C_2	coupling capacitance	300 μμf
C_3	filament-to-ground capacitance	300 μμf
C_4	capacitance of a filament choke by-pass	400 μμf
C_s	stray capacitance	50 μμf
C_e	effective capacitance at tube end	147 μμf
R	resistance to driving current	625 ohms
L_1	inductance of coupling loop	variable
L_2	inductance of a filament choke	21 μh
Z_o	characteristic impedance	52 ohms
ℓ_1	at 90°	18.55 feet
ℓ_2	at 48°	9.9 feet
ℓ	at 138°	28.25 feet
E_s	sending voltage, peak	8200 volts
E'_r	driving voltage, peak	3020 volts
E_r	receiving voltage, peak	6080 volts
Amplification factor		0.74

The phase relationship of the overall system can be checked best by a vector diagram. As previously mentioned, this shift must be close to 360°. For a loss-less line the voltage and current at any point of the line may be expressed as the vector sum of incident and reflected waves. From the termination values, length of lines, and standing wave ratios, the vector diagrams for the two lines are determined. For this particular case the total shift so measured is from one to two degrees within 360°.

Model Tests

A full scale electrical model of the 86-inch cyclotron complete with dees, liner, trimmers, spiders, and transmission lines was constructed of wood covered with thin copper sheet so as to simulate the electrical characteristics of the real machine. The model with liner side removed is shown in Figure 40. Due to time limitations no exhaustive tests were made but the major dimensions of components were verified. Resonance tests on the model indicated that a frequency of 13.4 mc/sec required a line length of 99 inches from spider to the horizontal center line of the dees. A change of one inch in spider position is equivalent to a change in frequency of $\sim$ 0.1 mc/sec.

Two modes of oscillation of the system were studied: the desired resonant frequency where the dees are oscillating at 180° out of phase, or in push-pull operation; and the anti-resonant frequency which is the in-phase or push-push mode of oscillation. It is desirable to have a frequency spread between these two modes of at least 0.4 mc/sec to make it difficult for the mode of oscillation to shift from the resonant to the anti-resonant. It is also essential for the resonant mode to have the higher Q. When the resonant frequency was set at 13.4 by adjusting the spider the system would not oscillate in the push-push mode unless the dees were deliberately shorted together.

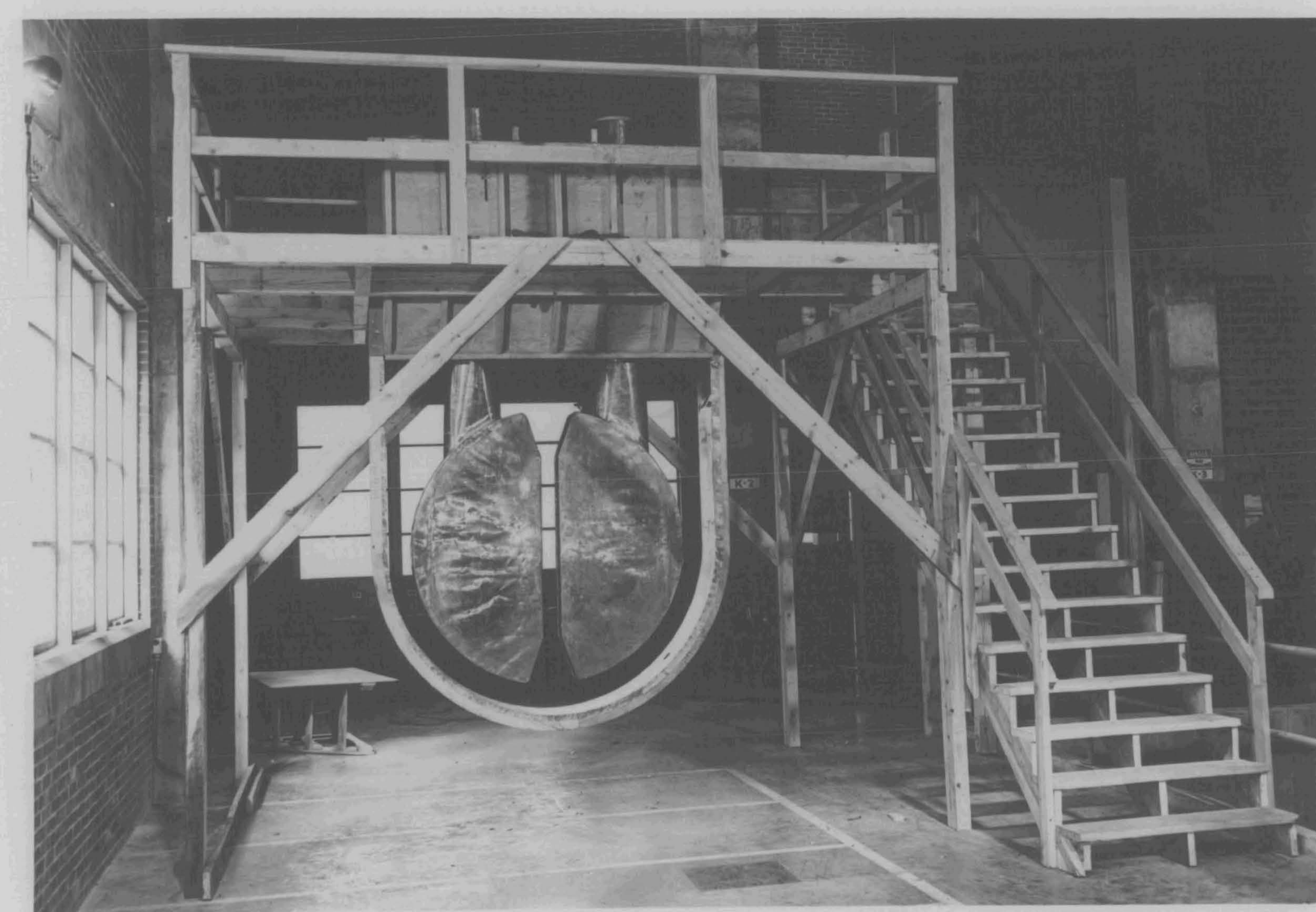


FIGURE 40. ELECTRICAL MODEL

The overall amplification of the plate transmission line and the dee stem, as measured by means of voltmeter pickup probes, was found to be 15. Following extensive experimental measurements on the plate line, filament line, and loop, the dimensions arrived at for the final design were:

Plate Line

Frequency	11.8 to 14.8 mc/sec
Length range	15 ft, 5 in to 21 ft, 6 in
Initial length	21 ft, 1 in (for 13.4 mc/sec)
Outer conductor	12 in sq copper duct
Inner conductor	3 3/4 in OD copper pipe
Cooling (water)	9 gpm
Z_o	70 ohms

Filament Line

Length range	24 ft, 6 in to 32 ft, 6 in
Initial length	28 ft, 3 1/2 in (for 13.4 mc/sec)
Outer conductor	6 in sq copper pipe
Inner conductor	2 1/2 in OD copper pipe
Cooling	Forced air
Z_o	52 ohms

Voltages of approximately 80 kv dee-to-dee could be obtained on the model before the air breakdown point was reached. The approximate power required to excite the dees is given by the relationship:

$$P_1 = P_2 \left(\frac{E_1}{E_2}\right)^2$$

A voltage (E_2) of 80 kv was obtained for a power input (P_2) of 3.2 kw. Then, with an oscillator efficiency of 50%, a power input (P_1) of 125 kw would give a voltage (E_1) of 500 kv. This figure of 125 kw required to excite the dees to 500 kv compares favorably with the calculated value of 150 kw.

APPENDIX D: PROTON ENERGY MEASUREMENTS

The energy of the internal proton beam has been measured by three different methods: activation of foils, a "photo-plate" method, and by calculations based upon the measured curvature of the outer orbit of the beam. These methods all give reasonably comparable results.

Foil Activation

Stacks of foils are exposed to the beam in a special target mounting, Figure 27, so that the depth of activity can be traced for a particular reaction. The best results by this method have been obtained with copper foils. The reactions used were Cu 63(p,n)Zn 63 and Cu 63(p,2n)Zn 62 having extrapolated activation thresholds of 4.3 and 14.5 Mev respectively. This method is illustrated in Figure 41. Some work has also been done with carbon foils; activation was traced as a function of depth for the reaction C 12(p,pn)C 11, which has an extrapolated threshold of 18.7 Mev. Unfortunately this threshold was so close to the beam energy as to make it experimentally difficult to obtain high accuracy.

The "Photo-Plate" Method

In the photo-plate method the beam is allowed to impinge upon a photographic plate after passing through an aluminum absorber. The absorber has graduated thicknesses which are equal to the proton range for a number of energies between 15 and 23 Mev. The blackening of the film behind each section of different thickness depends upon the energy, the thickness of the absorber, and the intensity of the beam on the absorber. In the range of thicknesses where all the beam passes through the absorber the film exhibits different densities. The degree of blackening depends upon the energy incident on the film both because of the variation of specific ionization with energy and because of the finite thickness of the emulsion. This means that the range in the emulsion must be taken into account.

In practice the raw data is also corrected for effects such as variation in beam intensity. To determine the energy, theoretical curves are obtained for various energies until the "best fit" is obtained with the corrected data. From the dissimilarity in shapes of the final curves an estimate of the energy spread is obtained.

Calculation from Beam Curvature

A "burnout" target upon which several widely-spaced lead foils, 0.002", are placed across the beam can be used to determine the path of the proton orbits at the radius of the target. This type of target was used for determining the center of beam rotation, page 106. The curvature of the burnout pattern produced by the circulating beam and the known magnetic field intensity may be combined with the ratio e/m for the proton to give a maximum value of the energy. The accuracy of the measurements depends upon the uniformity with which the tops of the foils are fused and thus is difficult to estimate. It is not as accurate as with the photo-plate or the foil activation methods.

Measured Energy

Energy measurements were made by these three methods at a radius of 30.2" late in 1951. The energies with estimated accuracies were:

Copper Foil Method	19.2 ± 0.3 Mev
Photo-Plate Method	19.0 ± 0.5 Mev (width 0.2 Mev)
From Beam Curvature	19.2 Mev

From the radius and e/m of the proton, the calculated energy was 22 Mev. This discrepancy has been discussed on page 106. Since the readjustment of the ion source in the spring of 1952 and with a slight increase in rf frequency, the energy at 30.5" is approximately 23 Mev.

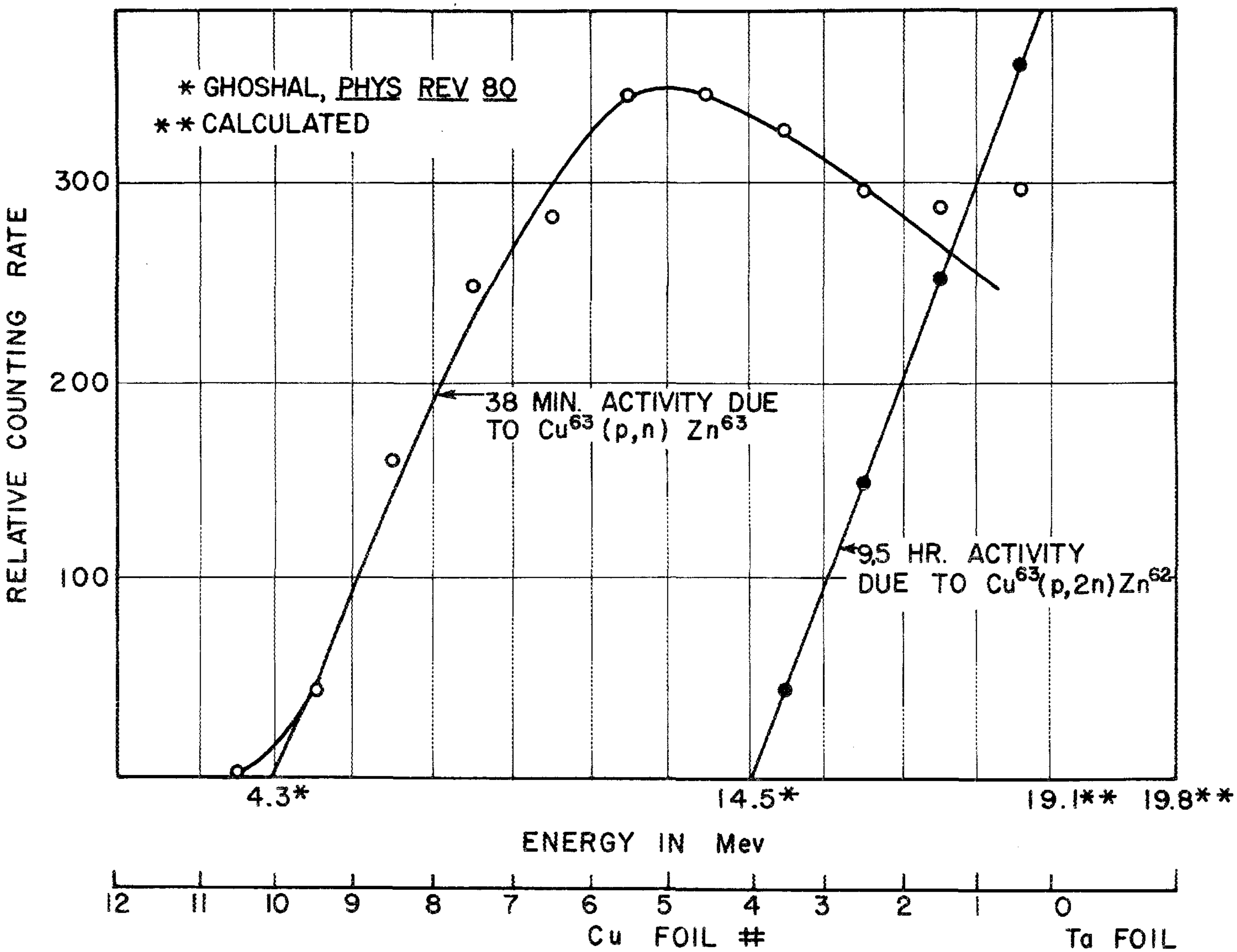


FIGURE 41. ENERGY MEASUREMENT FROM COPPER FOILS

APPENDIX E: RADIATION INSTRUMENTS

Several types of radiation detection instruments are used for protecting operating personnel against excessive radiation and for monitoring cyclotron operation. Both stationary ac-operated instruments and portable battery-operated survey meters are used.

Stationary AC-Operated Instruments

Neutron Detection. A neutron proportional counter has been designed and constructed which consists of a paraffin-encased enriched boron-trifluoride counter tube, a one-tube cathode-follower pre-amplifier, and a scaler instrument containing an amplifier and high voltage supply. The instrument is located at the utility panel and the counter tube is just outside the main entrance to the pit. A rate meter gives an immediate indication of the neutron flux density and activates an alarm at any predetermined level. When more accurate determination is necessary the scaler may be used. The instrument is adjusted to operate in the proportional region of the counter tube at a position where only neutrons are counted, independent of gamma radiation. The calibration chart is based on data obtained with a polonium-beryllium neutron source.

A neutron monitor has been designed and constructed to make a continuous record of the neutron flux density at the cyclotron. This instrument consists of a paraffin-encased boron-lined ionization chamber, pre-amplifier, and a Brown recording potentiometer. The chamber is of aluminum, 3 3/8" in diameter, 10 3/4" long, and surrounded by an aluminum shield. The center electrode is insulated from the chamber with Fluorothene. A metal box containing the pre-amplifier range switch, input resistors, and a 45-volt battery is attached to the ionization chamber. The ceramic range switch was specially treated to make its leakage resistance of the order of 10^{15} ohms and also to reduce the effect of humidity on it. It is essential that all components in the pre-amplifier have very little leakage. Special low leakage (Fast) polystyrene condensers were used. A cathode follower pre-amplifier with a CK 571 AX electrometer tube is used to feed the signal to the recording potentiometer. The network and power supply for the pre-amplifier were constructed in a metal box and placed inside the potentiometer cabinet.

Several changes were made in the Brown recording potentiometer in adapting it as a part of this neutron monitor. A separate dc amplifier is unnecessary since the amplifier in the potentiometer is used to amplify the small current developed in the ionization chamber, in addition to its function as a part of the potentiometer. A zero adjustment was added to correct for any slight drift during the warm-up period and to compensate for any change in battery voltage over long periods of time. There are two ranges with the full scale sensitivities of 300 and 3000 neutrons/cm^2-second. The chambers are also sensitive to gamma radiation so it is necessary to compensate for the gamma radiation in determining the neutron flux density. A cam and microswitch arrangement have been added to the potentiometer so that an alarm may be made to operate at any position on the scale.

Two of these instruments have been constructed and installed. One of the ionization chambers is located outside the shielding wall of the cyclotron with its associated instrument on a rack at the utilities panel. The other chamber is in the cyclotron pit with its associated instrument at the remote control station. This instrument has been used to help monitor the cyclotron beam. As improved performance of the cyclotron has increased the amount of radiation, it has been necessary to change the sensitivity of this instrument several times.

The speed of response of these instruments is 2 1/2 seconds from zero to full scale deflection.

A long counter neutron detector* having approximately uniform sensitivity from a few kev to a few Mev neutron energy has been constructed and installed at the cyclotron. The long, enriched, boron-trifluoride proportional chamber is surrounded by a paraffin cylinder 10 1/2" long and 8" in diameter. This cylinder is shielded except on one end, by a boron shield and another paraffin cylinder so as to make it directional and less sensitive to neutrons which have been scattered about the building. The counter tube with its paraffin cylinder is suspended approximately four feet off of the floor outside the shield wall of the cyclotron near the entrance to the maze. A negative potential, 1800 volts, is applied to the outer shell of the counter tube. The center electrode of the counter tube is connected to the grid of the 1-A-1 pre-amplifier and the signal is further amplified with an A-1 linear amplifier. The pulses are counted with a 1024 scaler. The tube characteristics have been obtained and the instrument calibrated with a polonium-beryllium source.

Beta and Gamma Detection Instruments. A gamma monitor has been designed and constructed for continuously recording the gamma radiation present outside the shield walls of the cyclotron. It is similar to the neutron monitor described previously with the paraffin cylinder and the boron-lined chamber being replaced by an aluminum ionization chamber. An alarm has been added to this instrument and may be set to operate at any level of gamma radiation. There are two ranges on this instrument with the full scale sensitivity of 15 mr/hr and 150 mr/hr. Very little zero drift is noted after the instrument has had

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* Hanson, A. D., and McKibben, J. J., A Neutron Detector Having Uniform Sensitivity From 10 kev to 3 Mev, MDDC 972.

a 15-minute warm-up period. The speed of response is 2 1/2 seconds from zero to full scale on both ranges.

An ORNL Model 1010 gamma Monitron has been installed at the entrance to the pit to indicate the level of gamma radiation to the personnel entering this area. This instrument is a rate meter with two ranges and a warning light indicating excessive radiation levels.

A gamma detector using a thin wall GM tube in a probe is located in the cyclotron pit. The instrument has been placed in the weakest part of the magnetic field to minimize the effect on the meter. The probe is attached to approximately 40 feet of cable so that gamma radiation may be measured in areas adjacent to the cyclotron where there is a strong magnetic field. There are two ranges on this instrument with a full scale sensitivity of 15 mr/hr and 150 mr/hr.

Portable Survey Meters

Neutron Detection. A fission-chamber neutron detector is used in making a survey of neutron intensity at various locations outside the shield walls. This instrument consists of an enriched-uranium-lined proportional chamber, a two-tube amplifier with discriminator, and a multi-vibrator which feeds a count rate meter. There are three ranges on this instrument with full-range responses from 10 n/cm^2-sec to 10,000 n/cm^2-sec. The rate meter has a long time constant which makes it necessary to wait a few minutes before taking a reading. The instrument is not sensitive to beta or gamma radiation. It is calibrated with a polonium-beryllium neutron source.

Beta and Gamma Detection. Three commercially built beta-gamma survey instruments include the Precision Radiation Instruments, Model No. 101; the Victoreen Instrument Company, Model 263; and the Nuclear Instrument and

Chemical Corporation, Model 2610. These light weight instruments each consists of a count-rate meter with a thin wall glass GM tube mounted in a probe. A metal shield on the probe is provided to differentiate between beta and gamma radiation. Intensities of 0 to 20 mr/hr may be measured over the three ranges.

A Sylvania Electric Products, Model RB316 (Cutie Pie) portable survey meter is used to measure the activity of the targets after they have been removed from the cyclotron. It is a beta-gamma discriminating air ionization rate meter. The chamber, which is 3 inches in diameter and 6 inches long, is made of a paper base material coated with Aquadag. The center electrode of the chamber is coupled to a balanced bridge circuit utilizing an electrometer triode tube as one arm of the bridge. Radiation in the chamber causes this arm to unbalance the bridge and thus produce a current in the meter. There are three ranges on this instrument with a response up to 5,000 mr/hr. It may be set at zero in the presence of radiation.

A General Electric long-probe scintillation gamma survey meter has been obtained to measure the radiation on various targets. With the light weight 6-foot probe, the operator can remain behind protective shields while measuring radiation from the targets. It responds to gamma radiation up to 3,000 R/hr over five ranges. The instrument consists of a fluorescent screen, photomultiplier tube, a relaxation oscillator, high voltage supply, and a count rate meter. The instrument may be zeroed in a radiation field.

APPENDIX F: LIST OF DRAWINGS FOR THE 86-INCH CYCLOTRON

Pit, Building Utilities, Magnet Yoke and Coils

BSK-13613a	Yoke Tie-Bar
CSK-13818	Cyclotron Coil Leads Enclosure
CSK-13946	Operating Floor - GR 921.02 Section and Details
C2e-14222	Magnet Yoke Lamination Shackles
C2e-14228	Pipe Floor Opening, Bldg. 9201-2
C2e-14248	Floor Support Column
D2e-14728	Foundation and Anchorage Details, Bldg. 9201-2
D2e-14752	Coil and Tank Support Structure, Bldg. 9201-2
D2e-14808	Exhaust Floor Openings
D2e-14892	East Maze Excavation Plan
DSK-13635	Yoke Details
DSK-13642a	Yoke Assembly
DSK-13690	Oil System
DSK-13785	Installation of Coil Braces
DSK-13867	Vacuum Manifold Support Columns
DSK-13896	Manifold Support Installation
DSK-14123	North Maze - Steel Details
DSK-17296	Oscillator Platform Addition
E2e-12879	Shield Walls - Foundation Plan, Bldg. 9201-2
E2e-12880	Shield Walls - Sect's and Det's S. H. #1, Bldg. 9201-2
E2e-12881	Shield Walls - Sect's and Details S. H. #2
E2e-12900	Shield Walls - Sect's and Details S. H. #3, Bldg. 9201-2
E2e-12901	Shield Walls - Sect's and Details S. H. #4, Bldg. 9201-2
E2e-12923	Roof Details
E2e-13086	East Maze Supports, Bldg. 9201-2
E2e-15322	Alignment Dock Doors
ESK-13747a	Cyclotron Layout View from West End of Pit
ESK-13748b	Plan View of H-C Cyclotron
ESK-13749b	Horizontal Section Through Cyclotron showing major piping
ESK-13932	CO_2 System Piping
ESK-13933	Oscillator Platform GR 929-0, Sect's and Det's
ESK-13935	Oscillator Cabinet Support Stand
ESK-13947	Cyclotron Operating Floor GR 921.02
ESK-14124	North Maze Sections
ESK-14125	North Maze - Plan View
ESK-14203	Fire Door Installation
ESK-13964	Cooling Oil System (Reference Dwg.)

Cyclotron Manifold, Tank, Pole Pieces, Tank Extension, and Shims

BSK-13697	Pole Piece
BSK-13795	Tank Studs
CSK-13757	Support Structure
CSK-14488	Distances Between Pole Pieces
D4b-12921	714 Trap Assembly
DSK-13896	Vacuum Manifold and Support Installation
DSK-13902	Tank Extension End Face Plate
ESK-13698b	Tank
ESK-13705a	Contour Shim Plate
ESK-13714a	Vacuum Header
ESK-13729a	Vacuum Manifold
ESK-13800	Tank Extension Side Face Plate
ESK-13801	Tank Extension Top Face Plate
ESK-13966	Tank Extension Water Connections
ESK-13986a	Contour Shim Blank
ESK-14772	6" Tank Extension
FSK-13798c	Tank Extension
FSK-13990	West Shim Contour Plan
FSK-14141	East Shim Contour Plan

Cyclotron Liner

CSK-14032	Liner Water Flange
DSK-13811a	Liner Water Tubing
DSK-13812a	Liner Flange Detail
DSK-13819	Trimming Capacitor Bearing Plate and Side Cover for Liner
DSK-14055	Redesign of Liner Water Tubing
DSK-13868	Liner Guides and Opening for Target and Source
ESK-13810b	Liner (See ESK-17078)

Transmission Lines: Filament Loop Assembly and Spider

CSK-13936	Filament Line Outer Transmission Line
CSK-13961	Filament Line Clamp
CSK-13959	Filament Loop Bushing
CSK-13963	Loop Detail
CSK-13976	Plateline Connection
CSK-13977	Plateline Termination
CSK-14231	Inner Plateline Connections
CSK-14753	Reworked Plateline Connections
CSK-14752	Revised Plateline Clamp
CSK-14778	Water Header Hose Fitting Flange
CSK-14779	Water Header Hose Fitting Nipple

Transmission Lines: Filament Loop Assembly and Spider (Cont.)

D4b-10970	M-2-M Bushing
DSK-13861a	Spider Water Tubing
DSK-13927	Plateline Outer Transmission Line
DSK-13928	Plateline Cover Box
DSK-13953	Inner Plateline - Connections
DSK-13970	Plateline - Assembly
DSK-13965	Plateline Collar Clamp
DSK-13987	Filament Line
DSK-14707	Spider Condenser Ground Plate
ESK-13860b	Spider
ESK-13951	Filament Line Face Plate
ESK-13952	Filament Line Cover Box
ESK-13955	Plateline Face Plate
ESK-13956	Filament Line Connector
ESK-13957	Filament Loop Capacitor Holder and Clamp
ESK-13960	Filament Loop Details

Cyclotron Trimmers and Faceplate Assembly

A4b-16698	1/2" Wilson Seal Body
CSK-17206	Philips Gauge Base Plate
C4b-11988	Philips Gauge Assembly
C4b-13124	Tank Window Flange and Pumpout Tube
CSK-17207	Philips Gauge Shield
D8b-14575	M. Tank Window Assembly
DSK-13819	Trimming Capacitor Bearing Plate and Side Cover for Liner
DSK-13929	P. I. G. Housing
ESK-13860	Stationary Trimming Capacitor
ESK-13884	Adjustable Trimming Capacitor
ESK-13885	Faceplate
ESK-13886	Shaft and Plate

New Source Assembly

ASK-14323	Vacuum Lock - Door Control Arm
ASK-14324	Vacuum Lock - Door - Mech. Bearing Block
ASK-14325	Vacuum Lock - Wilson Seal Body
ASK-14326	Vacuum Lock - Swivel Joint
ASK-14327	Vacuum Lock - Door Mech. Bell Crank
ASK-14328	Vacuum Lock Push Rod
ASK-14329	Vacuum Lock - Door Pivot Pin
ASK-14369	Vacuum Lock Door
ASK-14370	Vacuum Lock Door Lug
CSK-14371	Stanchion Socket
CSK-14372	Vacuum Lock Cover
CSK-14373	Rework Top Plate
CSK-14374	Stanchion for Source Tube

New Source Assembly (Cont.)

DSK-17113	Source Grounding Contacts
ESK-14330	Vacuum Lock Chamber
ESK-14375a	Source Details
ESK-14376	Vacuum Lock Seal Details

Cyclotron: Tank Grid System and Dee Bias

CSK-14780	Dee Bias Insulators
CSK-14816	Dee Support Plate Insulated Positioning Assembly
DSK-14733	Insulated Dees Standoff Insulator Fittings

New Target Dolly and Vacuum Lock

BSK-14967	Vacuum Lock #2 Wheels and Screws
CSK-14977	Vacuum Lock #2 Conversion Wedge
CSK-14976	Vacuum Lock #2 Conversion Tank Support Blocks
DSK-14907a	Vacuum Lock Face Plate #2
DSK-14912	Vacuum Lock #2 Cylinder Base and Support
DSK-14916a	Vacuum Lock #2 Small Parts
DSK-14924	Vacuum Lock #2 Yoke
DSK-14926	Vacuum Air Cylinder and Toggle
DSK-14938	Vacuum Lock #2 Door
DSK-14954	Vacuum Lock #2 Target Faceplate Guides
DSK-14974	Vacuum Lock #2 Stud Strips
ESK-14867a	Sliding Door Vacuum Lock #2
CSK-14505a	Dolly Extension Block
CSK-14767b	Squirt-Tube Assembly
CSK-14810	Quick Change Target Index Pin and Spacer
CSK-14053	Dolly Jack Extension
CSK-17097	Target Water Quick Change Hose Connection Assembly
DSK-14445a	Target Dolly Detail
DSK-14446a	Target Dolly Parts 1 & 2
DSK-14447a	Target Dolly Jacks
DSK-14704a	Target Locking Device Quick Change
DSK-14721b	Wilson Seal Details
DSK-14734d	Bearing and Pulley Details
DSK-14751b	Shield Tube, Gear, and Seal
DSK-14776a	Support Plate Details
DSK-14790	Target Face Plate Rollers
DSK-17094	Target Water Quick Change Hose Connection Details
ESK-14448b	Dolly Base Frame
ESK-14480	Target and Dolly

New Dee Assembly

BSK-14792	Hose Nipple
BSK-17259	Dee Carbon Shields Type 2
CSK-14595	Dee Water Header
CSK-14693	Dee Adjustment Plate
CSK-14816	Dee Support Plate Insulated Positioning Assembly
CSK-17104	Dee - Tantalum Shields
DSK-14461b	Dee Water Header
DSK-14467b	Dee Carbon Shields
DSK-14636a	Dee Stem Collar
DSK-14637b	Dee Stem Details
DSK-14795	Dee Water Header Flanges (Insulated Assembly)
DSK-14798	Dee Water Header Bushing Fittings (Insulated Assembly)
DSK-14840	Carbon Shields
ESK-14456c	Dee Details
ESK-14470b	Dee Stem Assembly
ESK-14839	Dee Carbon Shields
FSK-14469c	Dee Wall Details
FSK-14468c	Dee Assembly

New Target Assembly

BSK-14359a	Seal Assembly
BSK-14360	Target Pulley
BSK-14547	Outer Shield Water Header
BSK-14561a	Water Header Support
CSK-14361a	Target Shield Tube
CSK-14362a	Wilson Seal Details
CSK-14572	Stationary Target Tube Assembly
CSK-14573a	Stationary Target
CSK-14754a	Target Head A5
CSK-14755	Head Adaptor A5 Clamping Frame
CSK-14773	Head Adaptor A5 Insertion
CSK-14861	Beam Scanning Target
CSK-14875	Grazing Incidence Target
CSK-14881	Quick Change Target High Flow Header
CSK-14923	Grazing Target Blank
CSK-17183	Target Head Physics Program Plan
CSK-17184	Target Base Physics Program Plan
DSK-14363	Junction Box Frame
DSK-14364a	Wilson Seal Details
DSK-14365a	Wilson Seal Details
DSK-14366a	Tube Assembly and Detail

New Target Assembly (Cont.)

DSK-14546	Outer Shield Water Header
DSK-14547	Outer Shield Water Header
DSK-14560a	Outer Shield Assembly
DSK-14702a	Target Support Plate
DSK-14704a	Quick Change Target Locking Device
DSK-14756a	Head Adaptor A5
DSK-14877	Grazing Incidence Target Model A
DSK-14893	Energy Target
DSK-14895	Beam Scanning Target #2
DSK-14896	Beam Scanning Target #2
DSK-14902	Grazing Target Model B
DSK-14956	High Intensity Target Model B
ESK-14542	Target General Assembly
ESK-14884a	High Intensity Target

Magnetic Field Scanning Probe

ASK-13841	Field Scanning Probe Adaptor Stud
BSK-14148	Shafts
BSK-14149	Indexing Cam.
CSK-13742	Hub Assembly
CSK-13763	Probe Details
CSK-13765	Probe Details
CSK-13767	Probe Details
CSK-13834	Rework of Hub Stem I
CSK-13837	Dummy Tank Bearing Adaptor
CSK-14147	Drive Shaft
DSK-13762a	Details of Hub Stem I
DSK-13764a	Details
DSK-13766b	Details
DSK-13767	Details
DSK-13839	Drive Support Platform
DSK-14129	Shifting Plate
DSK-14130	Motor Drive Details
ESK-13741b	General Assembly
ESK-13821	Details
ESK-14131	Drive Support Frame
ESK-14132	Drive Support Plates
FSK-13769	Drive Assembly

Electrical Circuits and Oscillator Cabinet

CSK-14187	Filament Control Circuit
DSK-13728	F-134 Tube Connector
D5e-14824	Circuit Breaker Panel for M. G. Set-C
ESK-13727	Tube Support Detail
ESK-13725	Filament Choke Base and Details

Miscellaneous

ESK-14396	Outline Assembly
CSK-14053	G Slit and Support Assembly
CSK-14054	Details of G Slit and Support
C Dwg. No.	Magnetic Contour Lines at the 930 Elevation
ESK-14395	Magnetic Contour Lines at the 930 Elevation
DSK-14378	Diffusion Pump Cooling Baffles
DSK-14695	Refrigerated Baffle for Diffusion Pump
DSK-14696	Refrigeration System Diffusion Pump Spacer
DSK-14700	Refrigeration System Tank Baffle
DSK-14706	Schematic Diagram Refrigeration System
DSK-14821	Defrost Tray
CSK-14771	Radiation Window
DSK-14638	Target Hook
DSK-14765	Ball Joint
ESK-17263	Wall Socket
ESK-17271	Window Tank
ESK-17272	Window Flange
CSK-17279	Window
DSK-17273	Pit Section
DSK-17274	Pit Plan Section
E3f-14355	Air Flow Filter
E3f-14314	Kinney Pump Exhaust