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June 9, 1954

Berkeley, California

# A 90-INCH CYCLOTRON WITH AN ADJUSTABLE-ENERGY EXTERNAL BEAM*

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## ABSTRACT

The 90-inch cyclotron under construction at Livermore, California, is intended to produce a large external beam which may be tuned through the following ranges:

| | |
|---|---|
| protons | 4 to 15 Mev |
| deuterons | 4 to 12.5 Mev |
| tritons | 7.5 to 8.5 Mev. |

The report is a survey of the design of the dee and resonator, magnet, electronic equipment, and plant layout.

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* This work was done under the auspices of the Atomic Energy Commission.

# A 90-INCH CYCLOTRON WITH AN ADJUSTABLE-ENERGY EXTERNAL BEAM

Bob H. Smith

## Introduction

The 90-inch cyclotron now under construction at Livermore, California, is intended primarily for the acceleration of protons, deuterons, and tritons. It differs from other fixed-frequency cyclotrons in that the external beam may be tuned through a wide range of energies—from 4- to 15-Mev protons, 4- to 12.5-Mev deuterons, and 7.5- to 8.5-Mev tritons. The energy ranges are obtained by tuning the frequency from 4 Mc to 9.5 Mc and the magnetic field from 2,000 to 9,000 gauss.

The cyclotron is located in a pit 18 feet deep. In order to reduce background radiation, the external beam is directed to the center of a cubic experimental pit which is 40 feet on a side. The machine is intended to produce as stable an external beam as possible. Accordingly, the design of this machine differs from that of the conventional cyclotron in many respects.

The pole pieces are cam-shaped (Fig. 1), so that the external beam crosses the fringing field at normal incidence to minimize spreading of the beam. The last turn is peeled well out on the cam by a deflector that is made in two sections and occupies almost 180°. In order to provide sufficient space for the deflector only a single dee is used (Fig. 1). The threshold dee voltage is held to a reasonable value by the choice of the 1% magnetic field fall-off. The operating dee voltage is twice the theoretical threshold and is shown in Fig. 2.

The machine has two frequency ranges through which it may be tuned--4 to 6.2 Mc, and 6.2 to 9.5 Mc. For the low range the entire dee stem is used; for the high range only part of it is used. Within each range the frequency is varied continuously by adjustment of the dee-to-liner spacing. The liners are mounted on ball bearings which are located out of the rf field and are suitably protected from rf currents. The liners are moved by electric motors controlled from the console.

The worst sparking condition occurs for 15-Mev protons where the operating dee voltage is 180 kv and, fortunately, the dee-to-liner spacing is maximum, 3 inches. This is somewhat higher voltage than is ordinarily held

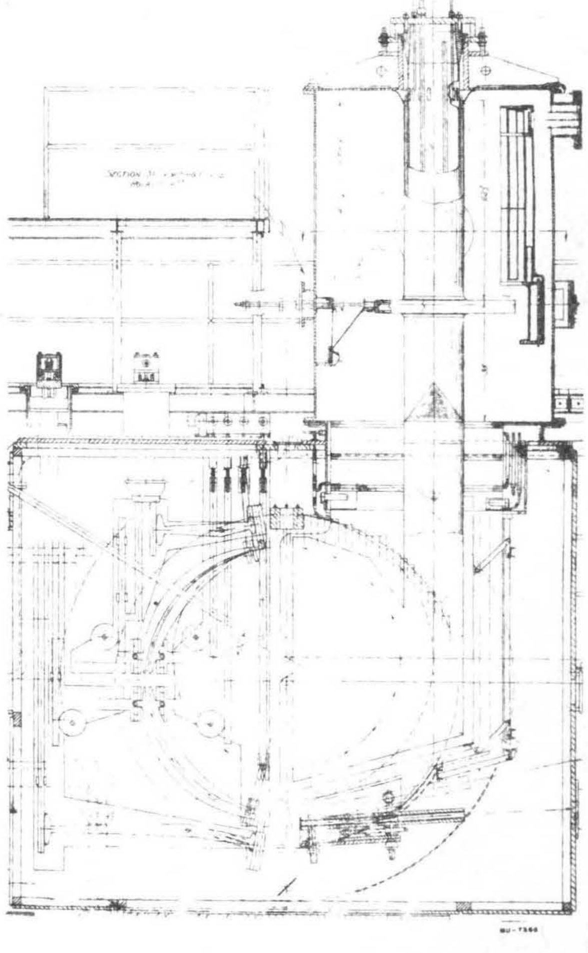
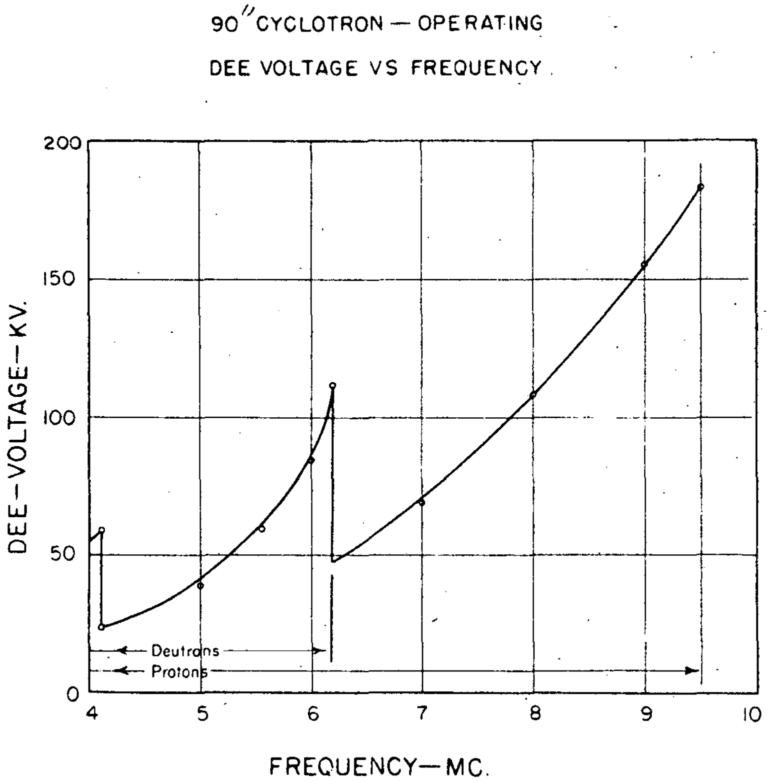


Fig. 1.


90″ CYCLOTRON — OPERATING
DEE VOLTAGE VS FREQUENCY
200
150
100
50
0
DEE-VOLTAGE—KV.
4
5
6
7
8
9
10
FREQUENCY—MC.
Deutrons
Protons

MU-7434

Fig. 2.

in cyclotrons with this gap, but experience indicates that the greater cleanliness of the vacuum system maintained by mercury (rather than oil) diffusion pumps will allow this high dee voltage.

The rf skin losses were computed to be 167 kw, but measured 180 kw on the full-scale rf model. The rf equipment was designed to deliver 300 kw, leaving 120 kw for stray ion and beam losses. Assuming that the beam power will be about 40 percent of the total ion power, the internal beam should be about 3.2 milliamperes.

The rf system is of the driven type rather than the self-excited type, the frequency being determined by a crystal oscillator. Temperature variations are prevented from detuning the resonator by means of a servo system. Essentially, the phase angle across the final amplifier is detected and supplies a signal to a servo amplifier which actuates the resonator trimmer. This method has been used on several machines in Berkeley and it has been found that the phase angle across the final amplifier can be kept within 1°, thus keeping the resonator in almost perfect tune. Servo systems of this type are referred to as "efficiency servo systems", because they hold the final amplifier at maximum efficiency, the plate voltage always being at minimum as the pulse of plate current occurs.

There are several reasons for departing from the more standard self-excited rf system for this cyclotron. First, the stability of the frequency of the dee voltage is as important as the stability of the magnetic field. The high beam currents anticipated for this machine would cause an uncontrolled self-excited oscillator to drift about 1.0 percent. This could be reduced to about one part in 20,000 by means of sufficient control equipment, but stability within a few parts per million is easily obtained with a driven system. A second reason is that a machine which requires high rf power over a wide range of frequencies is associated, inherently, with severe mode problems. The driven system, with only one transmission line connected to the resonator, presents a less severe mode problem than the self-excited system.

## Plant Layout

The floor plan is shown in Fig. 3. That the machine was tailored to an existing building influenced the location of the generator room, rectifier room, and power transformers, and the pit depths. The location of the electronic equipment was chosen outside the shielding and near the console for ease of maintenance and for safety. This location has the further advantage

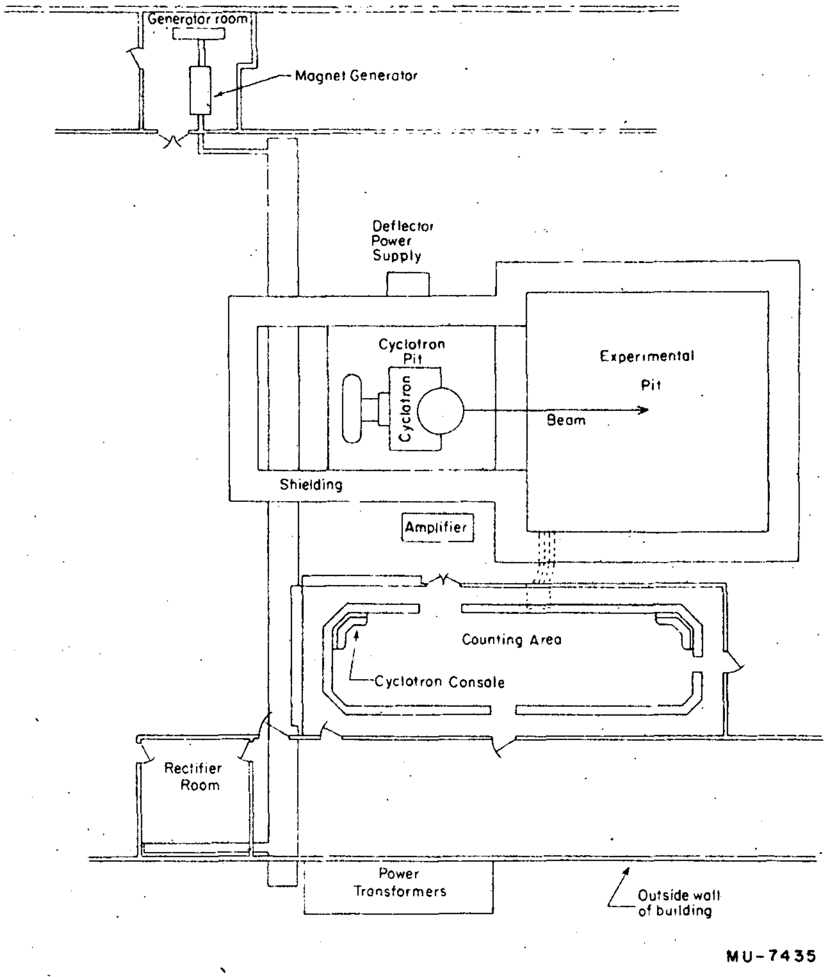

Generator room
Magnet Generator
Deflector Power Supply
Cyclotron Pit
Cyclotron
Experimental Pit
Beam
Shielding
Amplifier
Counting Area
Cyclotron Console
Rectifier Room
Power Transformers
Outside wall of building
MU-7435

Fig. 3.

that the stray magnetic field is lower than in the cyclotron pit.

The counting area is air-conditioned in order to better fit the needs of the sensitive counting equipment, and it proved convenient to place the console and crystal oscillator here.

## Resonator and Dee

The shape of the dee was chosen experimentally to reduce the voltage taper along the dee edge. Two tests were made on the quarter-scale rf model, and they gave values of 0.5 percent and 2.5 percent voltage taper respectively. This difference is within the accuracy of the measuring equipment.

Each dee liner is suspended by means of two phosphor bronze ball-bearings that carry the vertical load, and is driven perpendicularly to the dee by four lead screws mounted on similar ball bearings. The ball bearings are mounted behind the liners outside the rf fields, but as a precautionary measure spring fingers make contact across the bearings to carry any rf current that might occur. The four lead screws are connected together by means of a chain that is driven by a dc motor. The liner can be moved from a maximum spacing of three inches to contact with the dee. Ordinarily the minimum spacing used will be 0.75 inch.

The frequency spectrum is covered in two ranges, which are determined by the positions of the four shorting fingers in the resonator. (See Fig. 1.) Often shorting fingers located in the vacuum system have been a source of difficulty. Each set of fingers is 32 inches in length and the individual fingers are 1/8 inch wide. The maximum total current is 9,280 amperes, which results in a current density at the fingers of 72.5 amps per linear inch. Experience indicates that fingers of this type will carry about 300 amps per inch safely.

On the low-frequency range, a larger amount of drive loop area is required than for the high-frequency range. This requirement is met in a somewhat novel way. The transmission line has a characteristic impedance of 50 ohms. The low-frequency drive loop consists of a section of 50-ohm parallel-plane transmission line. On the low-frequency range, high fields exist in the region of the parallel-plane line and couple strongly to it. When the high-frequency range is employed, negligible fields exist in the region near the parallel-plane line; hence, it is not coupled to the resonator. In this case the parallel-plane line behaves only as a transmission line and not as a drive loop. By proper choice of the geometry, appropriate loop areas were obtained for each range.

The trimmer is shown in Fig. 1, located at the rear of the dee. It is mounted on ball bearings, which are protected in the same way as those of the liners. The rf currents are carried off the trimmer by means of flexible straps all along its length.

The transmission line is made of 50-ohm and 10-ohm sections so arranged as to provide approximately the desired dee voltage vs frequency for a fixed plate voltage swing of the final amplifier. The determination of the geometry of this line was greatly simplified by means of a special transmission-line calculator suggested by Dr. Kenneth MacKenzie. The calculator is useful for problems of the type "Given the sending and receiving end voltages as a function of frequency, find the combination of lines that will best meet these conditions." More detailed information about this calculator will be furnished by the author upon request.

## Final Amplifier

The final amplifier contains an RCA type A-2332 shield grid triode. The measured interelectrode capacitances, and the operating conditions as determined from the constant-current characteristics, are:

| | | |
|---|---|---|
| Input capacitance | 1050 | μμf |
| Output capacitance | 250 | μμf |
| Grid-plate capacitance | 16 | μμf |
| Plate voltage | 20 | kv dc |
| Plate current | 25 | amp dc |
| Grid current | 0.5 | amp dc |
| Transconductance | 87,000 | μmho |
| Grid resistor | 1400 | Ω |
| Grid driving power | 1500 | watts |
| Efficiency | 79 | % |
| Rf power output | 380 | kw |

The type A-2332 is capable of considerably more power than is indicated above. In the use here described the power is limited by the 500-kw power supply. There is no rating of plate dissipation at this time, but as much as 750 kw has been dissipated in the plate for periods sufficiently long to reach steady-state conditions. The high power sensitivity and low grid-plate capacitance suit the tube well to the present application.

Even though the grid-plate capacitance is small compared with the input capacitance, neutralization is required because of the high transconductance.

A modified form of grid neutralization that is insensitive to frequency is employed, and does not require adjustment over the range of frequencies through which the cyclotron tunes--i. e., 4 to 9.5 Mc.

The grid inductance consists of a foreshortened parallel conductor line. The grid circuit is tuned by a shorting plane, which is mounted on motor-driven lead screws located within the conductors of the line.

## The Efficiency Servo System

The efficiency servo system consists of three chassis: (1) the frequency converter, which is installed in the final amplifier cabinet; (2) the phase detector, in the control room; (3) the servo amplifier, located with the other power equipment.

The frequency converter was developed for this application and employs diodes in such a way that the output signal is exactly equal in amplitude to the smaller of the two input signals. The local oscillator signal, the amplitude of which is independent of cyclotron operation, is made the smaller of the two signals. Thus, no adjustment of the phase-control equipment is required as the operating conditions of the cyclotron are varied. The output frequency of the frequency converter is 55 kc, which is suitable for transmission to the phase detector in the control room.

The phase detector produces a dc output signal which controls the servo amplifier. The servo amplifier is of standard form and controls the dc motor that actuates the cyclotron trimming capacitor.

## The Driver

The driver consists of three tubes--a 2E26, a 4-400, and a 6166 which drives the grid of the A-2332. The tuned circuits in the driver chassis are ganged together mechanically and are operated by a small servo amplifier which receives its signal from a potentiometer on the shaft of the crystal switch in the master oscillator. Thus, tuning the master oscillator automatically tunes the driver amplifier.

## The Master and Local Oscillators

The heart of this chassis is a crystal switch that has 102 positions. This allows a frequency difference between crystals of 55 kc, which is suitable for the intermediate frequency of the efficiency servo system. The crystal switch contacts two adjacent crystals simultaneously--one for the master oscillator and the other for the local oscillator.

## Tune-Up Equipment

In order to break through the multipactoring region, dee voltage is built up quickly. The space is swept free of electrons before the discharge can grow to the point where it overloads the final amplifier. This is accomplished by first applying all voltages in the amplifier chain except the screen voltage of the 4-400. The screen voltage is then suddenly applied.

In order to establish dee voltage, however, the resonator must first be tuned to the signal frequency. This is accomplished by connecting a small variable-frequency oscillator directly to the transmission line through a motor-driven switch. The oscillator provides only a few volts on the dee, which is not sufficient to cause a discharge but may be measured by means of a sensitive volt-meter. Thus, the resonant frequency is measured and adjusted to that of the master oscillator. The tune-up oscillator is disengaged, and normal voltages are applied to the amplifier chain, exciting the dee.

## Amplifier Power Supplies

Usually a "soft" plate-power supply is used for cyclotrons so that excessive current will not flow when the dee sparks. Such a supply allows the plate voltage and hence the dee voltage to vary with change in ion loading.

In order to provide high dee-voltage stability a "stiff" power supply is employed. The final amplifier is protected from excessive current during sparking by two "crowbars". The term "crowbar" as employed here refers to a device that short-circuits the power supply quickly, usually within microseconds, when a fault occurs. The power supply is protected by opening the primary of the plate transformer within a few milliseconds.

Consider first the excitation crowbar. Suppose that a spark occurs at the dee, which reduces the dee voltage to less than the multipactoring level. In this case the final amplifier is presented with a load impedance approaching, a short circuit, and hence draws considerably more than normal plate current. The overcurrent is detected and actuates the excitation crowbar, which grounds the screen of the 6166, removing excitation from the final amplifier. After a suitable time delay (about 2 seconds) to allow the vacuum pumps to remove the gas formed by the spark, the rf system is recycled, re-establishing dee voltage automatically.

The second crowbar consists of an ignitron which short-circuits the plate supply of the A-2332. It is intended that this crowbar be actuated only in the extreme case of a power arc within the A-2332. A power arc draws hundreds of amperes, so the plate crowbar is normally set to operate at several times normal current (at about 50 to 75 amperes). The plate crowbar fires within 5 microseconds after the power arc is detected. Within 5 milliseconds a second signal opens the electronic contactor, which deenergizes the plate supply. During the 495-microsecond interim period the power-supply current is held within safe limits by the filter inductance. Twenty seconds later the rf equipment recycles; the time delay is required, in this case, to protect the induction regulator and the plate transformer.

## Magnet Regulator

A new magnet regulator was developed for the machine. Two feedback loops are employed in order to provide higher stable loop gain than can be obtained with a single feedback loop. The low-frequency loop receives its signal from a two-volt water-cooled shunt, which meters the magnet current. The high-frequency loop receives its signal from the generator armature voltage. A careful study was made of the transfer functions of the generator and magnet, and a system transfer function was developed that is stable with a loop gain of 10,000. (The amplifier gain is over one million.) The techniques employed here are thoroughly familiar to those who work with servo-mechanisms.

The current reference consists of a regulated power supply, which uses mercury cells as a standard and has a loop gain of 10,000.

## Conclusion

Basically, the design differences between this cyclotron and previous machines stems from the wide energy range and the location of the target in the center of the large experimental pit. The relatively long distance (about 25 feet) that the beam must travel from the machine to the target places unusually high emphasis upon beam stability. This in turn requires greater stability of the magnetic field and of the dee voltage.

The required frequency stability of the dee voltage could be obtained by either a driven system with an efficiency servo-mechanism or a self-excited system with an automatic frequency control. The wide frequency range through which the machine tunes increases the resonator mode problem. The driven system lends itself better to the latter problem and hence was chosen.

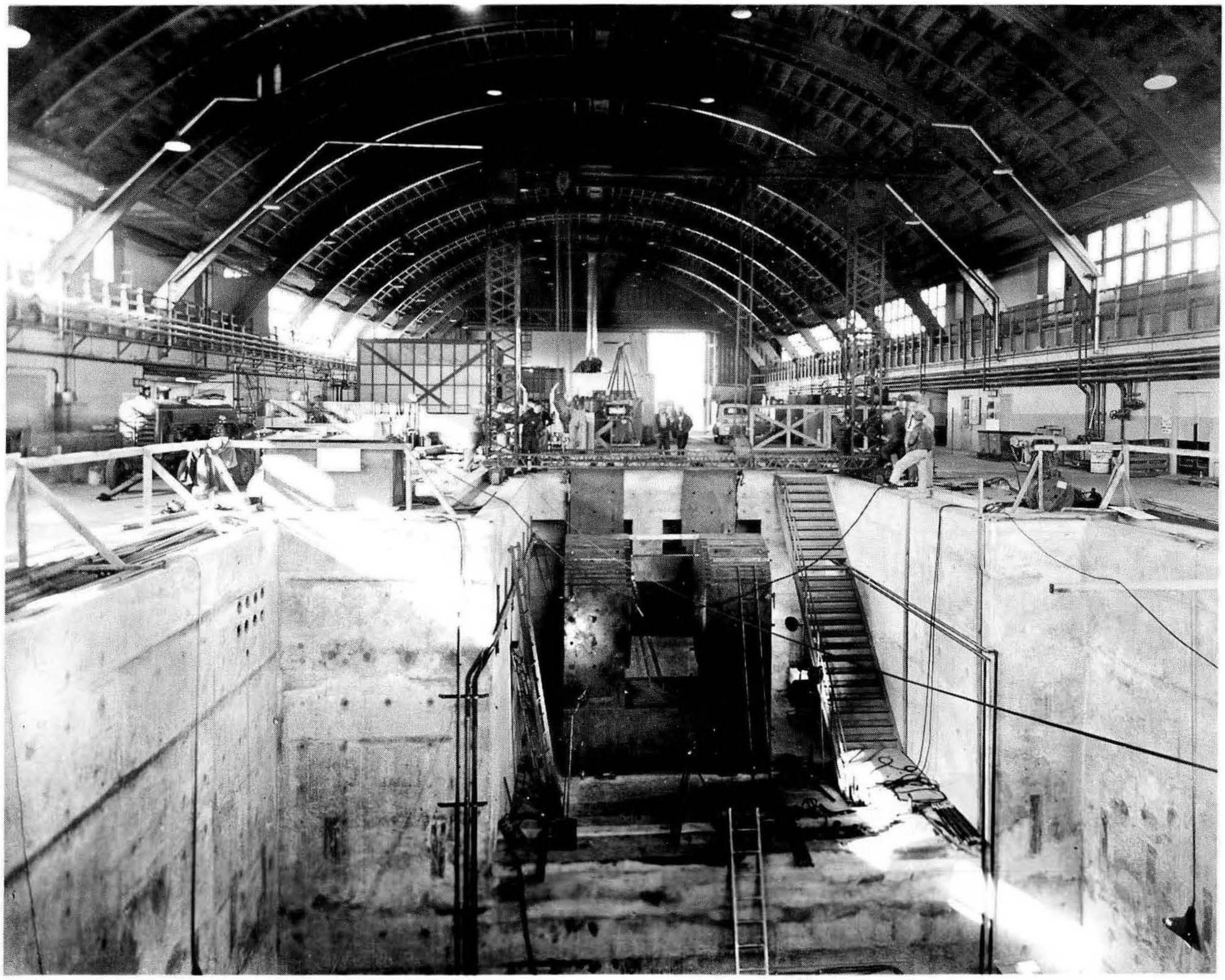


Fig. 4. The Magnet Yoke of the 90-inch Cyclotron.

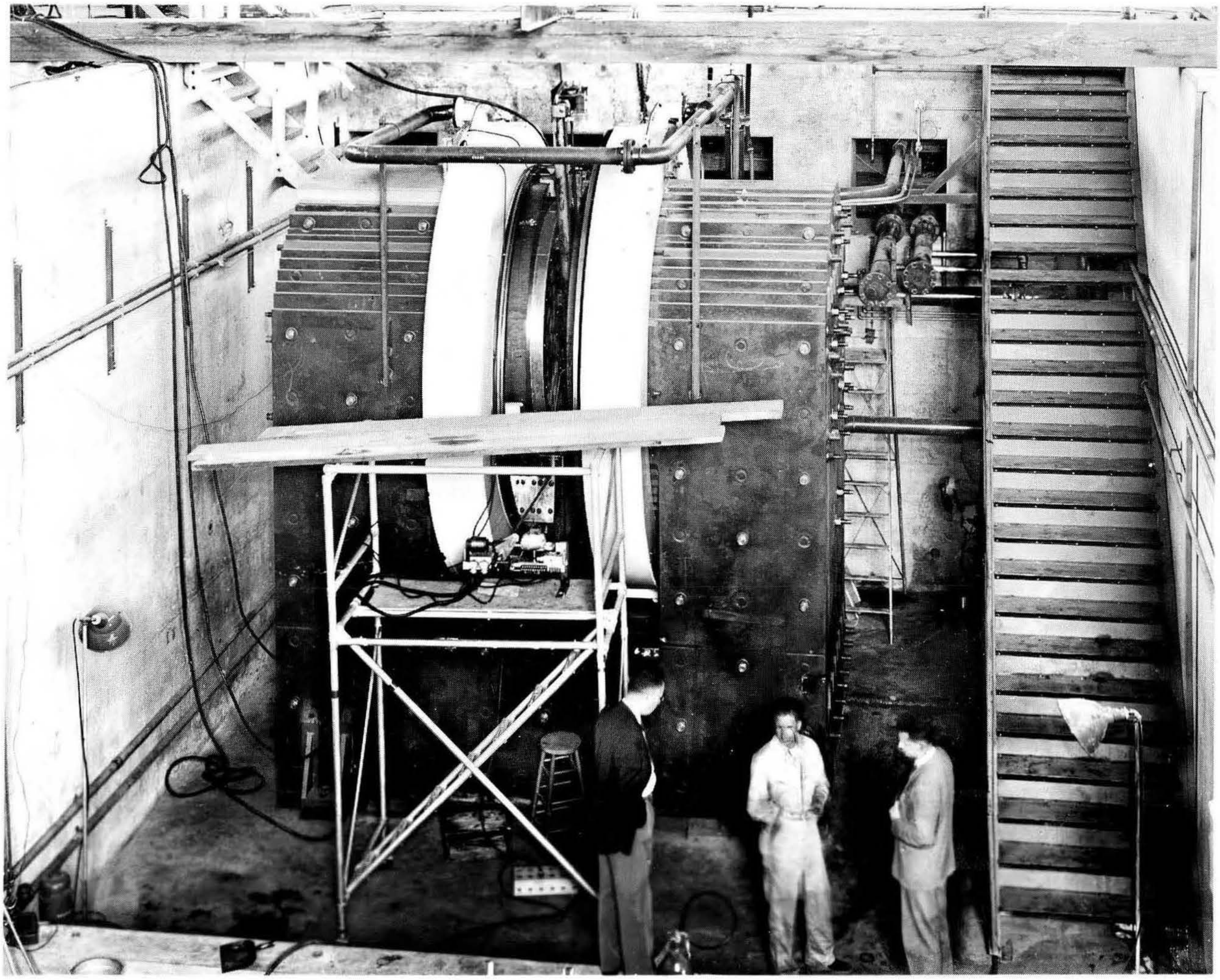


Fig. 5. The Experimental Pit (in the foreground) and the 90-inch Cyclotron Pit (in the rear).

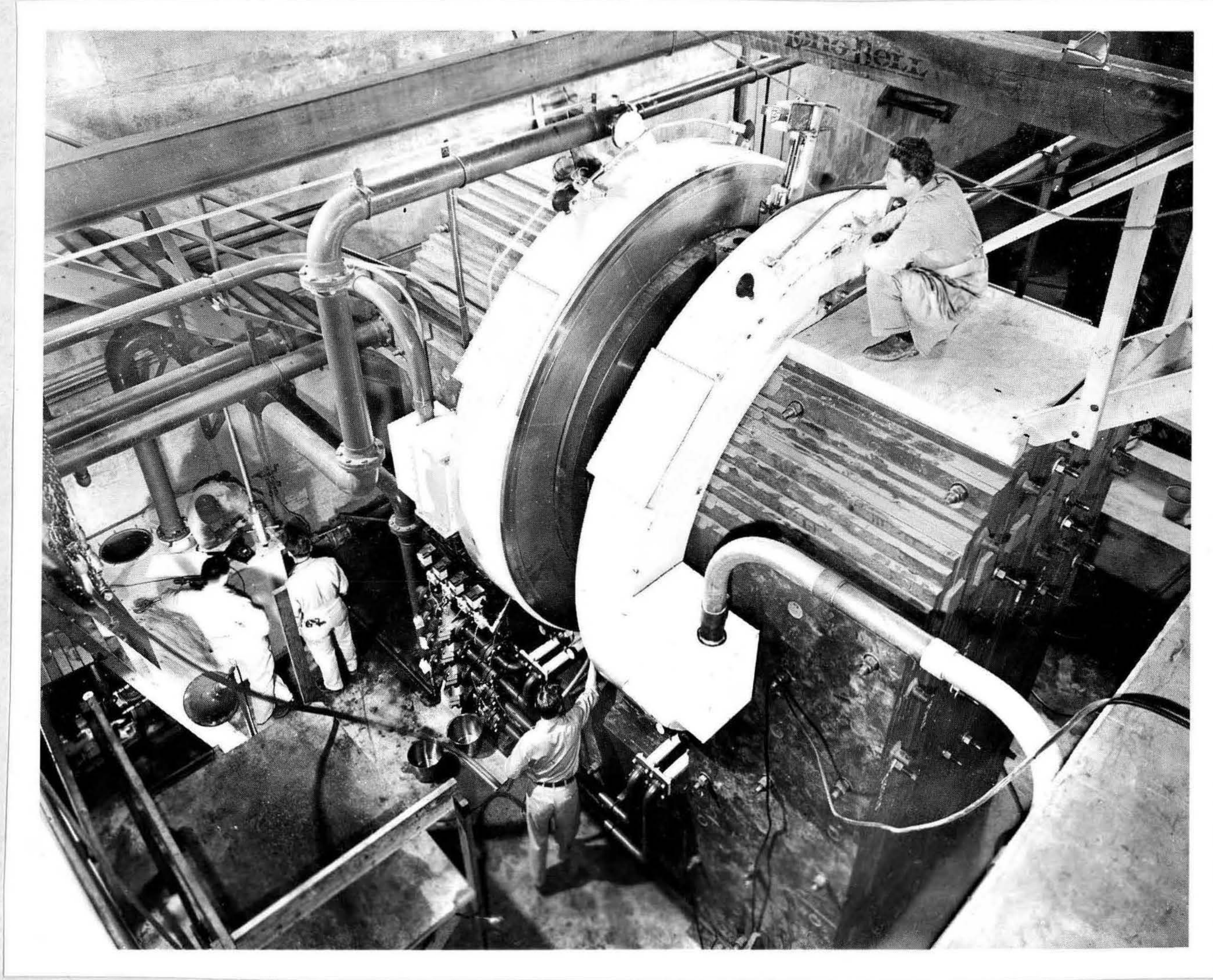


Fig. 6. The Complete Magnet of the 90-inch Cyclotron.

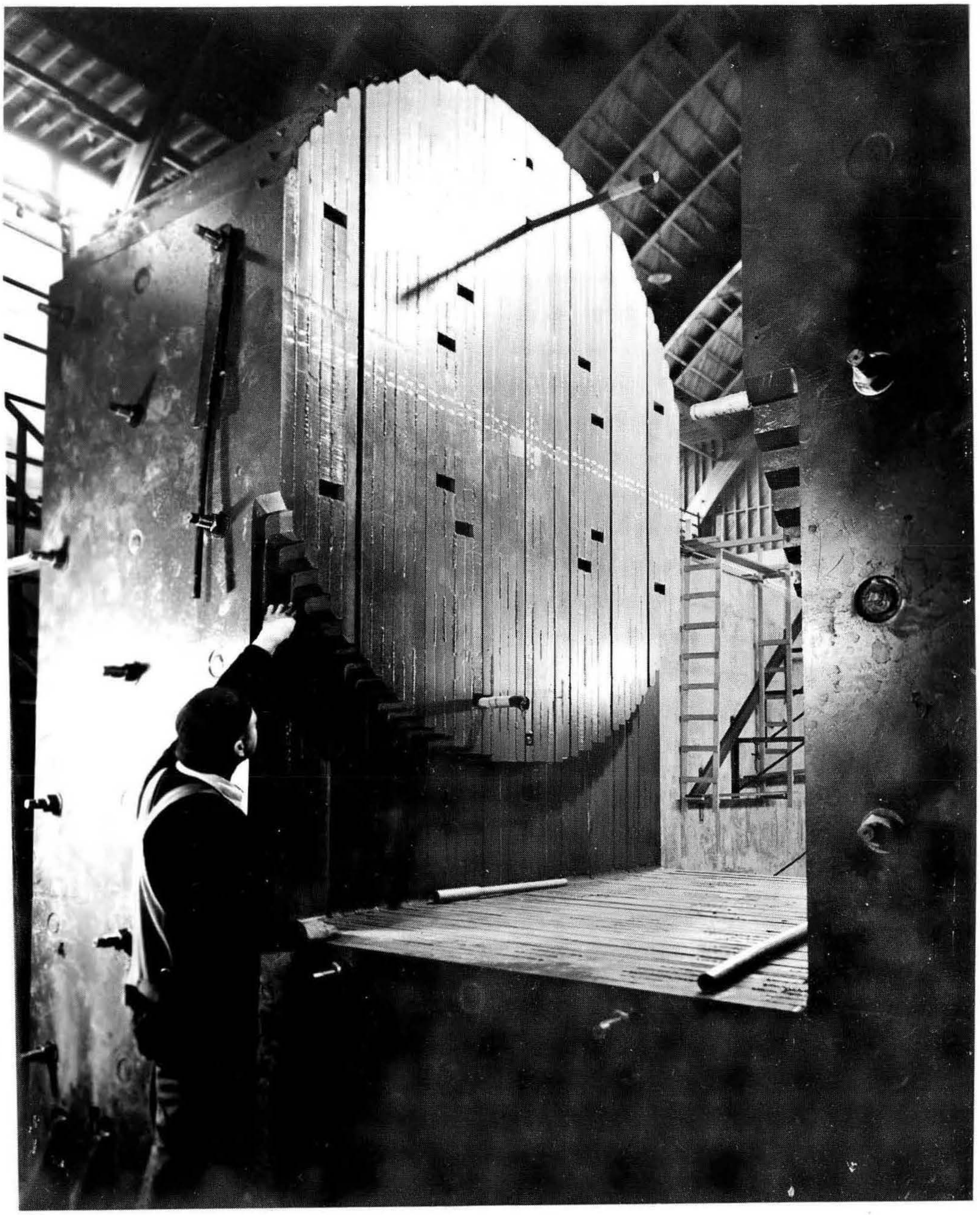


Fig. 7. Another View of the Complete Magnet of the 90-inch Cyclotron.

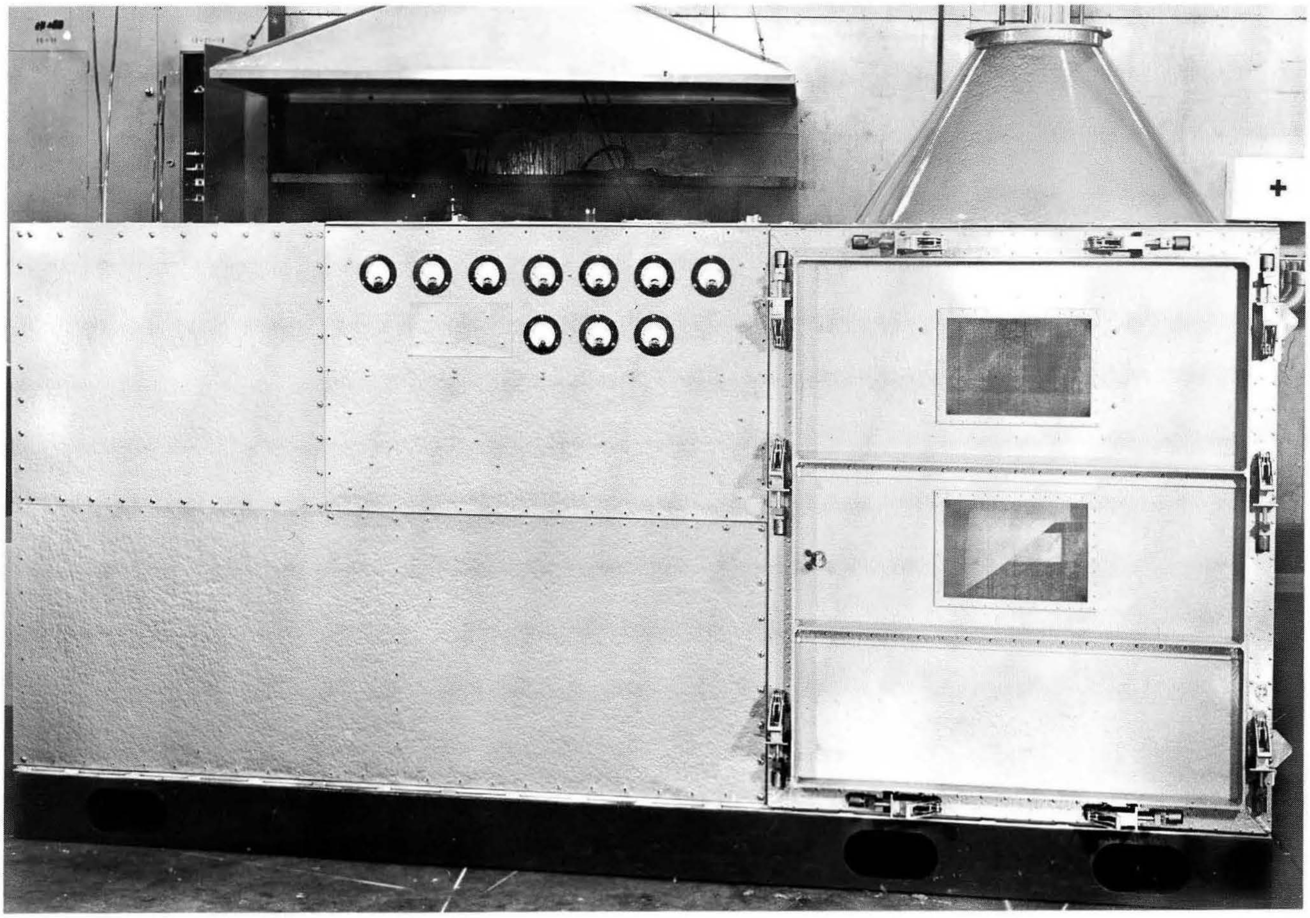


Fig. 8. The Driver and Final Amplifier of the 90-inch Cyclotron

Fig. 9. An interior view of the final amplifier of the 90-inch cyclotron showing the filament transformer, grid capacitor, and ground plane. (The A2332 is removed.)

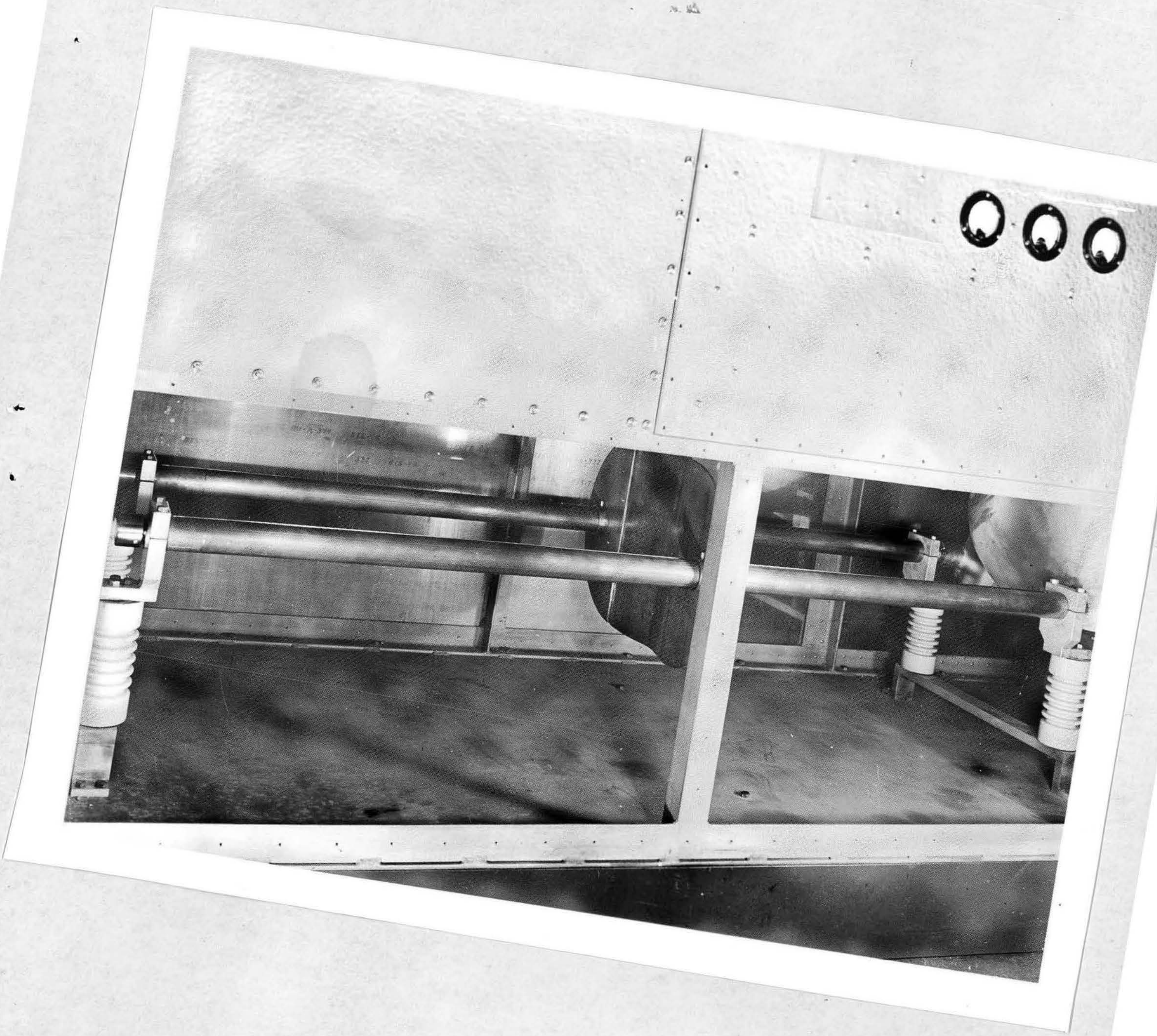


Fig. 10. The Grid Resonator of the Final Amplifier. The position of the shorting plane is adjusted by means of lead screws within the grid lines.

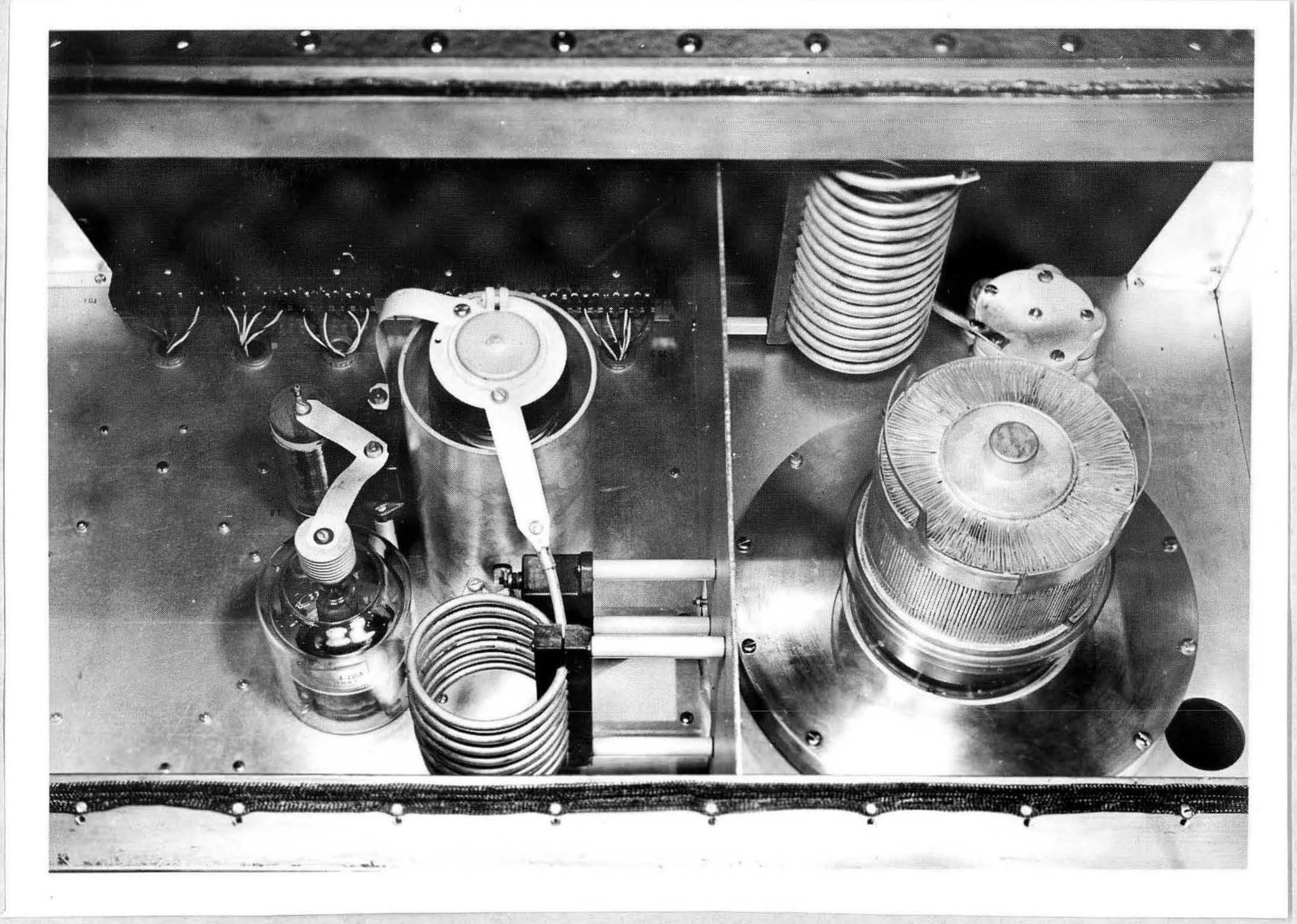


Fig. 11. The Driver Amplifier of the 90-inch Cyclotron. The tubes shown are the 4-250 and the 6166.