Title
Design of the Radio-Frequency System for the 184-inch Cyclotron

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Publication Date
2010-02-16

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BERKELEY, CALIFORNIA

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Contract No. W-7405-Eng-48

DESIGN OF THE RADIO-FREQUENCY SYSTEM FOR THE 184-INCH CYCLOTRON

by

K. R. MacKenzie*, F. H. Schmidt**, J. R. Woodyard
and L. F. Wouters

Berkeley, California

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ABSTRACT

A description is given of the frequency-modulated oscillator and its associated rf circuits as used in the 184-inch cyclotron for accelerating deuterons to 190 million volts or alpha particles to 380 million volts. A 9C21 water cooled tube is used in a grounded-grid circuit which is tightly coupled to the single-dee resonant circuit so that the oscillator follows the frequency of the dee over the wide range required. During normal operation the oscillator delivers approximately 20 kw of rf power to the dee system at an efficiency of 60 per cent, giving 20 kv at the front of the dee, although the oscillator is capable of considerably more output. The frequency is swept from 12.5 mc to 9.0 mc approximately 100 times per second by a rotating condenser connected to the dee by a half-wave transmission line. Much of the history of the design, and reasons for choices made, are given, as it is felt this may be useful to others designing frequency-modulated oscillators for cyclotrons.

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To be published in the Journal of Applied Physics.

Contract No. W-7405-Eng-48.

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GENERAL FEATURES

The design of the radio-frequency system for the 184-inch cyclotron was started about April, 1946, shortly after the successful demonstration of the synchro-cyclotron principle by the 37-inch cyclotron at Berkeley(1). Initial thoughts regarding the exact form of the design were varied, but a single dee with some form of mechanical frequency modulation by a rotating condenser were fairly certain features. Consideration was given to the arrangement in which a rotating condenser is mounted directly at the rear of the dee, but eventually it was decided to build a high power version of the system used on the 37-inch cyclotron. This system had been tested, and although cumbersome, it seemed easier to design and build and was known to work; in retrospect, the exceptional ease of operation of the 184-inch cyclotron may be attributed in no small measure to this decision and to the experience gained with the smaller synchro-cyclotron.

The rf resonant system thus consists of a single dee and separate rotary capacitor connected by a transmission line, operating with a node near the middle, i.e., essentially the half-wave mode. The frequency range required for 200 Mev deuterons is 11.5 to 9.8 mc.; additional leeway is provided for tolerance and adjustment. It may be worth-while to review the considerations involved in the initial choice of this arrangement for the 37-inch and subsequently for the 184-inch cyclotrons:

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(1)Richardson, MacKenzie, Lofgren, Wright, Phys. Rev. 69, 669 (1946)

1. The rotary capacitor could operate outside of the magnetic field.

2. Dee and capacitor design and construction could proceed independently. (This saved considerable time, as the dee design was essentially complete before a number of basic questions regarding the rest of the rf system had been answered.)

3. Many of the problems involved in the design of the capacitor had been worked out.

4. Vacuum systems for the cyclotron dee and for the capacitor could be independent; little was known at that time concerning the relative vacuum requirements of the two units.

5. It was shown in the 37-inch cyclotron, that positive bias on the dee very often increased the beam current, and it was felt desirable to retain the possibility of similarly biasing the 184-inch dee. In addition, a bias on the dee is the surest way of providing a sweeping field to remove electrons trapped in an rf discharge.

6. The oscillator could be coupled to the rf system in air near the nodal point of the transmission lines, greatly simplifying oscillator design and adjustment.

7. The system is readily adjustable to give the desired shape of dee voltage versus frequency.

The 37-inch cyclotron had been intended as a model to test only the synchro-cyclotron principle in the case where the relativistic mass increase was 11 per cent; with a similar choice of rf system for the 184-inch cyclotron, it became more nearly a true scale model than originally anticipated. A new oscillator was then built for the 37-inch cyclotron, mechanically similar to the contemplated 184-inch oscillator, of which the construction and theory of operation have been described in a previous paper(2).

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(2) K. R. MacKenzie and V. Waithman, Rev. Sci. Instr. Dec. 1947.

For the accurate determination of resonant system dimensions and characteristics, as well as coupling and performance of the oscillator, it was necessary to build a scale model of the complete 184-inch rf system. These tests were not started until a most probable mechanical layout had been completed, based on approximate calculations. Final mechanical design and model tests were then initiated simultaneously, and the former was altered from time to time as indicated by results from the latter. However, because of its relatively straightforward nature, the design of the dee was already almost complete.

DESIGN OF RESONANT SYSTEM

As mentioned, the theoretical frequency shift required is 11.5 to 9.8 mc.; at the time it was considered undesirable to have the frequency-time curve convex upward in any part of the useful range. It was thus decided to allow most of whatever extra range was provided, at the high frequency end; the ions could then start (as well as finish) where the curve was concave upward. The desirable frequency limits were tentatively set at 12.5 and 9 mc. In order to insure that the higher limit would be sufficiently high, the initial layout was designed for operation between 13 and 9.5 mc. It was planned to increase the line length in order to lower both limits if necessary, by insertion of an extra line section. For this reason, the oscillator and rotary condenser are mounted on a truck which can move back as much as 3 feet on rails. The rail arrangement also permits more facile assembly and dis-assembl of the rf system as well as withdrawal of the dee face plate (also mounted on a truck) from the vacuum tank.

It was obvious, that if the rotary condenser was to be in a negligibly weak field, the line connecting the dee to the condenser had to be quite long, and consequently of the lowest possible impedance (around 10 ohms). An easy way to reduce impedance was to add lines in parallel, which had the advantage over a single low impedance line, that something like an optimum ratio of inner to outer conductor could be maintained.

Since it seemed mechanically desirable to support both the dee and the rotary condenser stator assembly on sets of four large insulators, a four line system was the natural choice. The arrangement shown in Figs. 1 and 2 has the advantage of permitting almost any desired degree of coupling to the oscillator without the use of auxiliary transmission lines. It conveniently permits an oscillator structure which fits in the distance between the capacitor and the dee tank.

The inner transmission line conductors consist of rolled sheet copper cylinders with appropriate cut-outs for the coupling loops, water lines and so forth. They are supported directly by their connections to the corresponding dee and condenser insulators. The outer transmission line conductor consists of an aluminum angle frame mounted on a truck, with provisions for increasing its length by replaceable end sections. This frame is the support for copper-lined masonite panels, reinforced on the edges by aluminum angles.

To minimize rf power losses, all steel surfaces exposed to rf fields are copper-plated. Wherever pressure contacts exist outside of the vacuum systems, good contact is established by the use of strips of thin soft copper sheet backed by foam rubber pads. Oscillator doors and transmission line covers are lined in this manner all around their edges; under pressure from suitable clamp, these contact strips deform to match the irregularities of the surfaces which they contact, hence increasing manyfold the contact area for rf current flow.

The dee design progressed quite rapidly, the principal criterion being that the vacuum gap be sufficient to withstand 50 kilovolts rf at the accelerating gap. Consequently, a minimum of 3" spacing was employed in the vicinity of the open front end of the dee; near the rear end, (i.e. supported end) a minimum of 2" was allowed. In shape, the dee tapers from a maximum width of 15'3" to a width of 4'3", at the same time thickening from a height of 7" to a height of 36" at the back end (Fig. 3) where the vacuum space bulges out around the pole pieces as illustrated. Its structure consists essentially of a copper covered frame having cross wise reinforcing members, at the back of which are attached four long sturdy threaded shafts. These shafts support the weight of the dee on the four dee insulators, the mechanical system being so arranged that the upper two insulators are under pure compression, the lower two under pure tension. The threads permit slight lateral and vertical adjustment of the dee position. The rf current is carried through the insulators by means of large sheet copper cylinders.

The rf liners are simply copper sheets bolted to the magnet pole faces within the vacuum chamber. Their rear edges are crimped over the edge of the vacuum tank opening so that upon fastening the dee faceplate, they contact a copper sheet lining on that face plate, thereby completing the rf current return path within the vacuum system. On the air side of the dee face plate, the return path for the current carried to the condenser by the transmission lines, is formed by the transmission line housing, whose ends are firmly connected to the insulator flanges both at the dee face plate and at the condenser vacuum tank cover plate.

The condenser copies the 37-inch rotary capacitor design in its fundamental aspects(3). It is similar in general appearance, but of course has many more sets of blades as shown in Figs. 4 and 5. A total of seven disks, two feet in diameter, with 24 teeth each, are used in the rotor; the 8 stator rings with a matching set of blades are mounted by means of four cylindrical stems onto the four large insulators, which are in turn fastened to the condenser vacuum tank cover plate. The rotor ground coupling capacitor consists

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(3) F. H. Schmidt, Rev. Sci. Instr., 17, 301 (1946).

of seven solid rotor disks spaced .05" from a similar set of grounded disks. In order to prevent appreciable bypassing of rf current through the steel rotor shaft, the rotor parts are fastened to the shaft by means of two doughnut-like zircon insulators. The shaft is hollow and carries water cooling through a concentric pipe arrangement to the sealed hollow space within the rotor insulator. Because of the residual capacitance of the rotor to its shaft of 100 μμf or so, it is necessary to protect the bearings at each end of the rotor shaft by sets of brushes which bypass the residual rf current.

The condenser rotor is mounted on the same steel plate as the stator insulator assembly in order to facilitate alignment of the two sets of teeth. The entire weight of the rotor is supported on a set of bearings fastened to this plate. It is driven by a removable shaft which engages the rotor at the other end and which also serves as a means of introducing the cooling water. This permits easy accessibility since the shell-like capacitor vacuum tank, and the driving shaft, together with the vacuum pumps are mounted on a truck which may be moved completely out of the way on the rail system. The rail arrangement is shown in Fig. 1. In practice during repairs and overhauls, the capacitor cover plate (which is also mounted on its own truck), remanis undisturbed. As was later determined, the effective capacity range of this rotary condenser is 400 μμf to 2400 μμf.

It should be mentioned that extensive air and water cooling is provided for all surfaces carrying rf current, since operation at a power level as high as 100 kilowatts was originally contemplated. The condenser stator rings and support stems are cooled by copper water lines soldered to them, as are the insulator flanges and dee support stems. Likewise the dee and liners have a labyrinthian network of cooling pipes. All such pipes at rf potential are brought to sets of hose connections in the vicinity of the nodal region; these connecting sections also serve to cool the transmission lines. The water circuit is completed to ground potential by means of sets of flexible polyethylene tubing, each several feet long. Treated water of low conductivity is used here to minimize current leakage resulting from the dee bias voltage.

Air blast cooling from a blower is directed onto the rotary condenser insulators; this air exits mainly by being funneled past the dee support insulators. On its way through the transmission line housing it serves to cool the outer panels. Total air flow in this system is about 2000 c.f.m.

A major structural and electrical problem in connection with the resonant system design was posed by the feed-through support insulators used for both the dee and the condenser stator stems. These are 15 inches in diameter and 18 inches long. A test apparatus consisting essentially of a high-Q quarter-wave resonant line was constructed(4). At the open end of the line, the insulators could be operated under simulated vacuum and electrical cyclotron conditions. Over 50 kilovolts rf could be developed across the insulator at 13 mc by a 5 kilowatt oscillator. Dimensions and electrical arrangement are illustrated in Fig. 6. Under the most severe test conditions, air blast cooling of the insulators was found necessary.

The same apparatus was employed to measure breakdown between test condenser blades under conditions likely to prevail in the actual rotary capacitor. It was found that a .080" gap between copper or copper-plated surfaces having a reasonable polish would hold a maximum of 50 kilovolts at 13 mc at a pressure of about 5 x 10^{-6} mm. It was therefore expected that a voltage of about 40 kv could be held in the operating unit. The behavior of the capacitor and of the insulators in actual practice will be discussed.

SCALE MODEL TESTS

The design had thus progressed a long way, even though a number

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(4) F. H. Schmidt, High Frequency Insulator and Vacuum Breakdown Tests, AEC Report No. MDDC-473 (Declassified)

of dimensions were not well established. The rotary condenser capacitance and the transmission line length were particularly uncertain, but because of the flexible arrangement, they could be easily adjusted within reasonably certain limits. For the accurate determination of these values, as well as for determining rf power requirements and testing oscillator layout designs, it was necessary to build a scale model of the rf system. For reasons of convenience, a quarter scale was chosen (Fig. 7). The resonant frequency is then increased fourfold and all inductances and capacitances are reduced by a factor of four. The frequency range is thus around 40 to 50 mc, which is still not too high to be handled by ordinary triodes. For a given dee voltage, the required power is doubled. If an accurately scaled version of the coupling arrangement is used, the impedance as seen by the oscillator is halved, the Q of the scaled system being one-half the Q of the actual system.

The criterion used for determining the capacitance and line length, besides that imposed by the frequency range, was that the capacitor voltage should not exceed the dee voltage at the highest frequency. This is of course realized if the minimum capacity of the condenser just equals the effective capacity of the dee. The basis for this adjustment of the resonant system is that since the insulators are the weakest link in the rf system, it is preferable to arrange matters so that the condenser insulators are not under any worse condition than the dee insulators.

The scale model tests immediately showed that under such conditions, the line length in air would have to be about 10 feet; at 12.5 mc the required capacitance would then have to be 700 $\mu\mu f$; at 10 mc it would have to be 1850 $\mu\mu f$. The dee and condenser voltage became equal at about 13.5 mc where the minimum capacitance is 500 $\mu\mu f$. This indicated that the effective dee capacitance would be 500 $\mu\mu f$, even though a capacitance measurement indicated it to be 1600 μμf. To the extent of this difference, the dee acts as a line, because of its appreciable size relative to a wave length.

In the initial scale tests, a large parallel plate condenser having polystyrene insulation was substituted for the rotary capacitor. Variation in capacitance was obtained by changing the gap. For the final frequency and power measurements, a quarter-scale rotary capacitor which is shown in Fig. 8 was employed. It was correct in all respects, except that the ground coupling capacitor and zircon shaft insulator were omitted. A stack of copper disks was inserted in the rf current path behind the rotor to simulate the loss in the coupling capacitor. The tests with this model showed that the minimum capacity was so low that the condenser voltage was already 25% higher than the dee voltage at 12.5 mc. Padding capacitors were then added to the transmission lines at the condenser insulator flange in order to increase the minimum capacity and provide some degree of frequency range adjustment. Their effect at the low frequency end is negligible, however, since the voltage node has then shifted quite close to them.

Initially the model condenser blades were bare steel. As had been expected, the Q dropped by a factor of two at the lowest frequency, so all surfaces were copper-plated. Measurements then showed that the condenser should absorb only 25% - 30% of the total rf input power when fully meshed.

The initial estimates of power loss in the resonant system disregarding losses in the rotary capacitor, indicated an rf power requirement of about 75 kilowatts for a dee voltage of 45 kilovolts. For these tests, a t.p.t.g. 35 T oscillator was connected to the front edge of the dee, the model resonant circuit acting as the tuned plate impedance. Power measurements were made by comparison of input power for the same optically determined plate temperature under oscillating and under non-oscillating conditions.

THE OSCILLATOR

The choice of a grounded grid oscillator was an almost foregone conclusion in view of the unequalled success of this arrangement in all recent Radiation Laboratory rf installations requiring high power at moderately high frequencies. The oscillator circuit was chosen identical to that of the 37-inch oscillator, since this type of circuit produces the desired(5) rf dee voltage rise during acceleration (Fig. 9). Full power is needed only at the lowest frequency, 37-inch experience indicating that average power was about 25% less than maximum power.

The only commercial tube suitable for grounded grid operation in this power range is the 9C21, rated at 9 amps plate current for 17 kv plate voltage at 12 mc. It was planned to install this tube together with its associated circuit elements in a large shielded enclosure whose rear wall would form essentially one side of the transmission line housing, as shown in Fig. 10. In its final form the oscillator tube jacket is supported by a large ceramic insulator near the right side of the oscillator box. A horizontal partition shields the cathode circuit from the plate circuit, the tube being inserted in its jacket through a suitable hole in that partition.

The choice of a 4-line resonant system makes it very easy to couple plate and cathode loops thereto with the shortest possible uncoupled lengths. These emerge through the rear wall of the oscillator box, each opposite a transmission line, and fit into slots cut in those lines to achieve maximum coupling with adequate high voltage clearance. These slots may be seen in Fig. 2. The end of each loop is thus automatically located opposite the particular tube electrode to which it connects. The plate loop (lower) is directly grounded to the oscillator box at its other end. The high voltage power supply thus operates with its positive side grounded, eliminating the necessity of supplying low-conductivity water to the tube jacket, the water

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(5) Bohm and Foldy, Phys. Rev. 72, 649-661, Oct. 15 (1947).

lines being piped through the plate loop. The cathode loop (upper), which is bypassed to ground at its far end by means of a ring of 10 fixed vacuum condensers (about 500 μμf total), serves as one side of the filament heating circuit, the other side consisting of 4 heavy cables passing through the loop. The ring of high-vacuum condensers also acts as the cathode circuit phasing capacitor to correct for the phase difference introduced between cathode voltage and plate voltage by the cathode loop self-inductance. Adjustment is obtained by exchanging one or more of the condensers for one or more of different value.

The grid is grounded for rf voltage by a similar ring of fifteen 50 μμf capacitors. The total capacity is chosen so that in conjunction with the grid leak, its charging time is small enough when compared to the charging time of the resonant circuit to prevent intermittent oscillation.

In this coupling loop arrangement there exists a negligible amount of coupling between plate and cathode circuits, consequently that parasitic mode in which most of the energy is in the plate loop, cannot be excited.

The degree of amplitude modulation depends on the plate-loop resonant frequency, decreasing in percentage as this frequency is raised as far as possible above the cyclotron frequency. On the other hand, if the plate-loop resonant frequency can coincide with a harmonic of the dee system frequency, a serious dip will occur in oscillation amplitude as the fm cycle passes through that frequency. Since the tube capacity and loop inductance put an upper limit to the plate loop frequency of about 20 mc, it was necessarily lowered by addition of the vacuum capacitors shown between water jacket and ground, until the frequency was under 18 mc (twice the lower limit of the cyclotron frequency). Again, this can be adjusted by exchange of vacuum condensers, hence serving as a convenient means of control of the percentage of amplitude modulation.

This argument does not apply to the filament loop, so that its frequency was made as high as posiible by taking great pains to reduce the self-inductance not serving as mutual inductance in the dee circuit. This has the desirable effects of reducing the phase shift between cathode and plate rf voltage, and of insuring that the excitation represents a fairly constant fraction of the dee voltage. Actually, because of the dee voltage rise with lowered frequency, the excitation also rises, although not quite so rapidly. This is desirable, since the tube must supply considerably more power at the low frequency end, and consequently requires more cathode driving voltage. While this power increase is principally due to the increase in dee voltage, it is also in part due to the fact that the condenser losses are greatest when the teeth are fully meshed.

In connection with the problem of oscillator design, the impression should not be gained that the design finally attained and described here was initially so definite. While all of this actually already existed on drafting boards, the oscillator model tests described below gave the confirming evidence which resulted in construction and assembly. In particular, the principal unknown which could only be roughly estimated was the matter of loop size and coupling.

It is perhaps worth mentioning a few additional facts about the components and their arrangement before proceeding to the matter of model oscillator tests.

The filament heating power is provided by a specially insulated transformer having appropriately poor regulation characteristics to meet the specifications of the tube manufacturer in connection with limiting the initial tube heating current. A set of line phase factor correcting condensers can be seen in the photo in their rack above the filament transformer. The secondary is enclosed in a slotted Faraday shield which extends away from the transformer and is connected peripherally to a copper sheet duct within which copper bus bar conducts the filament current into the upper left-hand oscillator compartment. The transformer is air blast cooled, both by residual air flowing down through the duct, and by a small blower directed on the primary and the core. The bus bar terminates on two large mica condensers which bypass any residual rf current to ground and which serve as supports for the two filament chokes. These are necessary because of the rf phasing voltage appearing at the end of the cathode loop. Their upper ends are connected, one to the cathode loop itself, the other to the 4 concentric filament leads previously mentioned. Throughout the filament circuit, the two sides are extensively bypassed to each other at strategic points, to prevent rf voltage from appearing across the tube filament or the transformer winding.

The grid choke is likewise needed because about 8% of the plate rf voltage appears across the grid grounding capacitor. The grid leak is mounted on insulators on one of the oscillator house doors (see below); connection is made automatically by a pair of clips and jacks which engage when the door is shut. This resistance consists of twenty-eight 10,000 ohm, 200 watt resistors in series-parallel, (1400 ohms net) and constitutes one good reason for supplying air blast cooling to the oscillator enclosure. Because the grid circuit is at high d.c. voltage, a special circuit was devised (Fig. 9) to allow the grid current to be read directly at the control desk.

Peak reading voltmeters are installed to read rf plate voltage, positive rf grid swing and rf cathode excitation. To prevent the disastrous consequences of positive d.c. grid swing, a rectifier is bridged across the grid leak. Its filament voltage is derived through a small shielded transformer from the 9C21 filament supply.

The walls of the oscillator enclosure are made of 1/4" steel, as are the 4 doors; the inner face, or back, is made of 1/2" steel. Consequently, this house serves as a magnetic shield for the oscillator tube. A crude replica (1/16 size) was tested by the magnetic measurements group at the Radiation Laboratory, using the 1/16-scale 184-inch model magnet, and this shielding was found sufficiently effective, the field being cut from 140 Gauss to less than 20 Gauss. This is further reduced at the 9C21 elements by means of a 1/2" steel sleeve slipped over the cooling jacket. The magnetic force on the oscillator box amounts however to 450 lbs. In addition to the horizontal steel partition there is also a central vertical partition. In the upper half it consists of a polystyrene plate, which acts as an air stream baffle and as a support for the grid choke. In the lower half it is made of steel as a further rf shield between plate circuit and the filament transformer located in the lower left-hand compartment. To reduce loss from exposed iron, the inside of the oscillator box is copper-plated. When shut, the doors are firmly compressed against an "rf gasket" arrangement as described in connection with the transmission line housing, by means of numerous large hinged C-clamps.

Air cooling is supplied to the right half of the box by a blower whose air blast is directed on the tube filament seals by means of polystyrene guides. From there the air is funneled past the ring of grid bypass condensers and the grid and anode seals by cylindrical polystyrene guides. On the left side, a second blower cools the grid leak. The air then leaks out through the filament lead duct as described, and around the cathode phasing capacitors to supplement the air cooling to the transmission line box.

OSCILLATOR MODEL TESTS

For the purpose of coupling loop measurements, it was necessary to electrically duplicate in the scale model, the behavior of the 9C21. The only low-power tube then available which seemed to fit the scale requirements, as well as having easily accessible electrodes, was the Eimac 304TL. This tube operates with about the same effective plate resistance as the 9C21, but since the load impedance in the model is reduced by a factor of two (because of the non-scaling of Q) it was necessary to use two tubes in parallel. This arrangement had the fortuitous circumstance of having scaled interelectrode capacitances about equal to those of the 9C21. However the 304-TL requires approximately twice the relative grid driving voltage. With a 1/4-scale version of the coupling loops, the 304TL's were thus underdriven by almost a factor of two and operated at around 40% efficiency at the low-frequency end of the range. This corresponds to about 75% efficiency in the actual cyclotron oscillator. Operation of the model under these conditions was thus much more difficult than of the full scale oscillator, but had the advantage that if the model worked, the full scale version was even more certain to work. Because of this non-linear scaling of efficiency it became extremely difficult to predict the amplitude modulation shape from the behavior of the model. The 1/4-scale model oscillator is illustrated in Fig. 11.

The model plate loop was made as long as possible consistent with the resonant frequency criterion previously discussed. It turned out that this was just large enough to properly match the oscillator's capabilities; at maximum induced dee voltage, the tube should operate at its maximum current and voltage ratings.

The cathode coupling loop was adjusted to operate well with 304TL's, also keeping in mind the design criteria already mentioned. It was originally planned to make this loop adjustable, since the required 9C21 driving voltage was the most obscure characteristic of the entire rf system.

In lieu of this arrangement, a fixed loop was installed in the full-scale oscillator (in full realization that it might have to be replaced) based on information obtained from an exact dummy oscillator model, as shown in Fig. 12. In this model, a true quarter-scale oscillator box, coupling loops, condensers and dummy 9C21 were reproduced. The interelectrode capacities were duplicated by midget capacitors, the internal grid support inductance was duplicated by small wires, the vacuum capacitor rings were duplicated by ring-shaped polystyrene-insulated capacitors. The scale resonant system was then excited by the t.p.t.g. 35T as described, and measurements were made at the various "dummy" electrodes. Together with the known characteristics of the 9C21 and the behavior of the 304TL model, the results of these tests gave the most accurate possible estimate of required loop size and coupling.

OPERATING CONDITIONS AND EXPERIENCES

Initial tests of the full scale rf system shown in Fig. 13 disclosed a re-entrant cavity resonator mode between the two pole pieces of the magnet with the vacuum tank walls as the return circuit resonant near the lower frequency limit. This was easily suppressed by strapping the pole pieces together at their outer edge. It was also found that the frequency range did not extend low enough by almost one megacycle, even after extensive padding of the resonant system. Since the extra line section had not been made, the easiest solution was the removal of one of the two transmission lines not associated with the oscillator coupling system. This more than sufficiently reduced the frequency limits (about 10%). While the effect of this change had previously been measured on the model, it had not been seriously intended that a correction be made in this way. The consequent reduction in efficiency was of no importance, as the high rf dee voltage of the 40 kv was not found necessary. The evident discrepancy in transmission line length was eventually traced to a cumulative error of about two inches in various small errors in model dimensions.

The plate circuit resonant frequency turned out to be too close to the second harmonic of the lower limit of frequency modulation as evidenced by severe amplitude modulation. Considerable plate capacity was eventually added to improve this situation. The lack of sensitivity of the beam to even such severe amplitude modulation is of particular interest. Fig. 14 plots the amplitude and frequency modulations as a function of time. Insofar as cathode excitation is conerned, it appears adequate over the frequency range of deuteron acceleration, though not being as great as anticipated at the extreme low frequency end.

Under vacuum, some difficulty was experienced due to discharge in the large spaces around the dee. It was easily shown that rf field conditions can exist which permit electrons to execute resonant oscillations at these frequencies and the appearance of the discharges seem to fit such a theory fairly well. In the particular case of those discharges quite far removed from the immediate vicinity of the dee, where the rf field is relatively weak, the picture of resonant electrons fits better than does the picture of the non-resonant type of discharge as exists in Philips ion gages. It is suspected that secondary electron multiplication ("multipactor action") may also be taking place. This does not preclude the Philips gage type of discharge near the dee, since here an electron has ample time and energy to perform numerous vertical excursions during a positive rf cycle. All discharges were eliminated by cutting down the available volume by means of perforated shields around the sides of the dee, by adding a grounded "dummy" dee and by applying a negative bias to the dee as shown in Fig. 15

There is sufficient magnetic field at the rotary condenser to allow a Philips gage discharge when positive bias is applied; a negative bias is therefore imperative. Fortunately the beam does not seem sensitive to bias, as it often was in the 37-inch cyclotron with positive bias voltage. The increase in beam obtained there, may presumably have been due to just such a discharge which increased the ion supply near the ion source.

Several days after the beam was obtained with but 15 kv rf dee voltage(6), troubles occurred with the rotary capacitor, characterized by increasing sparking and mechanical sticking. This was found to be due to warpage of the copper-plated stainless steel disks used in the bypass condenser because of poor heat conduction. Spacings were increased, but this afforded only temporary relief. Copper replacement parts then became available and no further difficulties have occurred since their installation.

The blade gap only holds about 30 kv rf and this may be attributable to the lessened clearance (.06" instead of .08") in the final unit, in addition to the severe overall roughening of the surfaces by discharges taking place during bakeout and sometimes during operation. Occasional water leaks occur around the rotor insulator gaskets, but these have been insufficiently frequent to warrant any major revision.

The rf insulators have given no trouble whatever since installation one year ago, though at the time of assembly, their fragility was evidenced insofar as shear forces were concerned. The care taken in insuring that only pure tension and compression forces would be applied was thus well justified.

The average power required for a given dee voltage is essentially the same as predicted from the model and is around 40 kilowatts for an amplitude variation from 20 to 30 kilovolts through the fm cycle. Provision was made in the power supply for arbitrary amplitude modulation by insertion of three parallel 893 power triodes in the d.c. plate power circuit, but they have been used thus far only as current limiters and voltage adjusters.

The authors wish to express their gratitude to Professor E. O. Lawrence and the staff of the Radiation Laboratory for advice and encouragement throughout the progress of the work. In particular, the assistance and

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(6) Brobeck, Lawrence, et al, Phys. Rev. 71, 449 (1947)

suggestions of W. M. Brobeck, R. L. Thornton, E. M. McMillan and L. W. Alvarez have been greatly appreciated. The authors also wish to thank certain groups of people in the laboratory who contributed no small part to the successful operation of the rf system for the 184-inch cyclotron. The model tests and high voltage tests were conducted by J. Riedel, R. Anderson, F. Yeater and W. R. Baker. The metering and control circuits were devised by C. Park and J. C. Kilpatrick, and the mechanical parts were designed by J. Bell, R. Peters and O. Callahan under the direction of W. M. Brobeck.

This paper is based on work performed at the Radiation Laboratory, University of California, Berkeley, California, under contract No. W-7405-Eng-48, with the Atomic Energy Commission.

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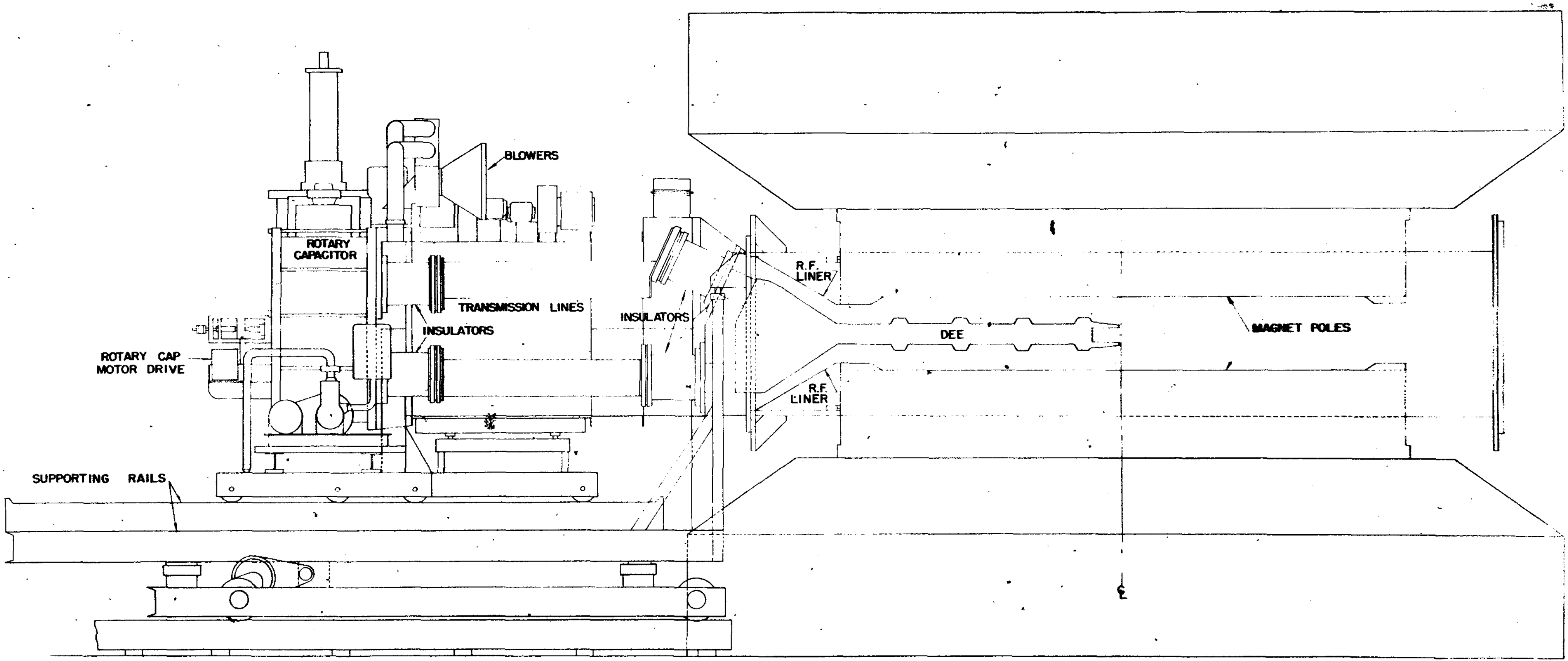


FIG 1a
RESONANT SYSTEM — ELEVATION

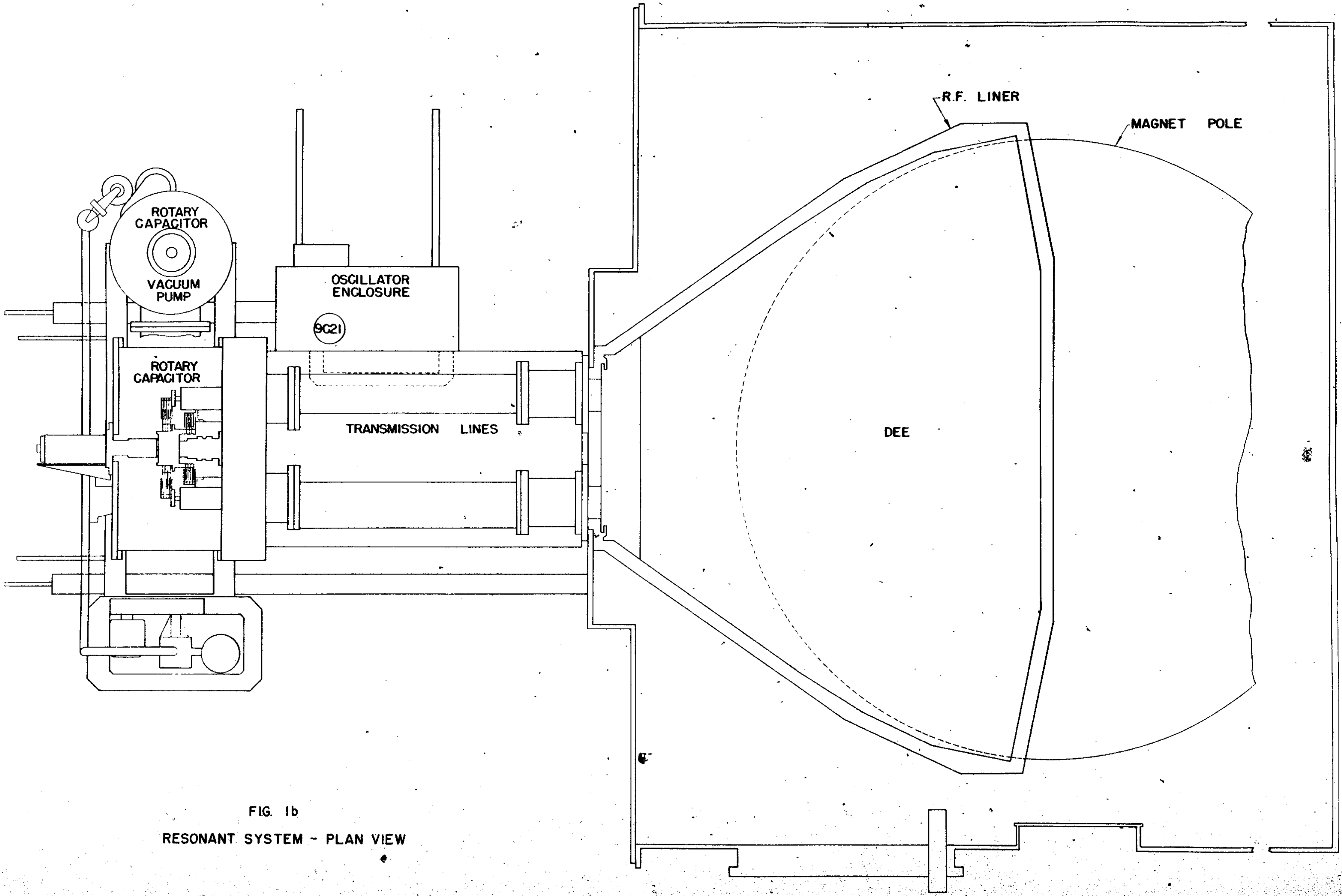


FIG. 1b

RESONANT SYSTEM - PLAN VIEW

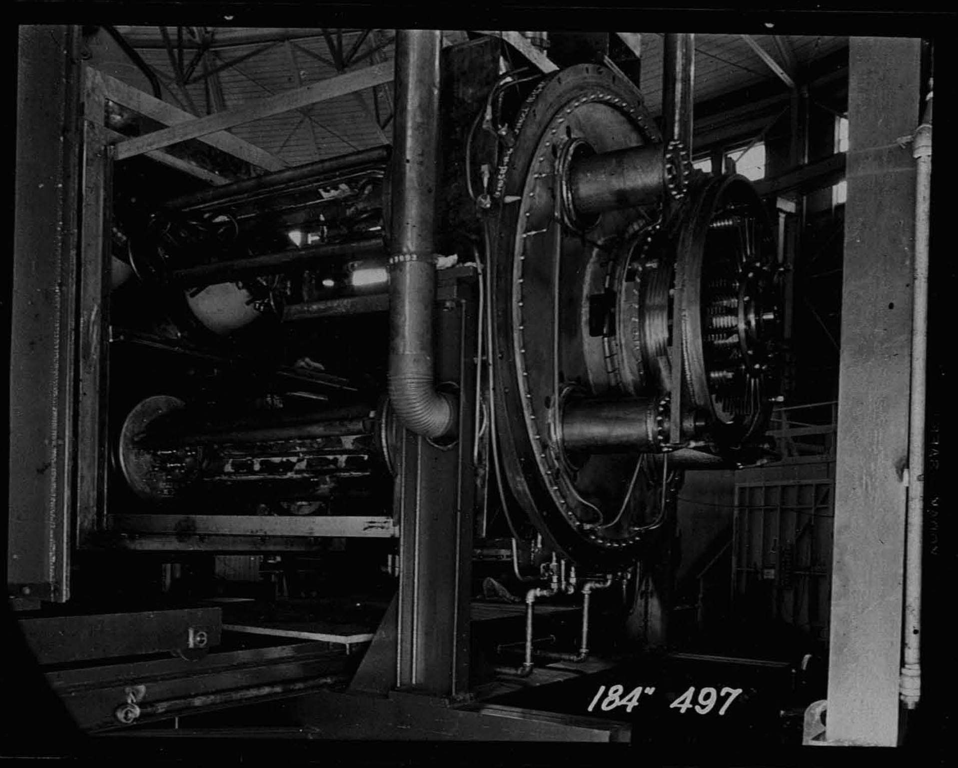


Figure 2. Transmission lines. Note the shots for the coupling loops shown in Figure 10d.

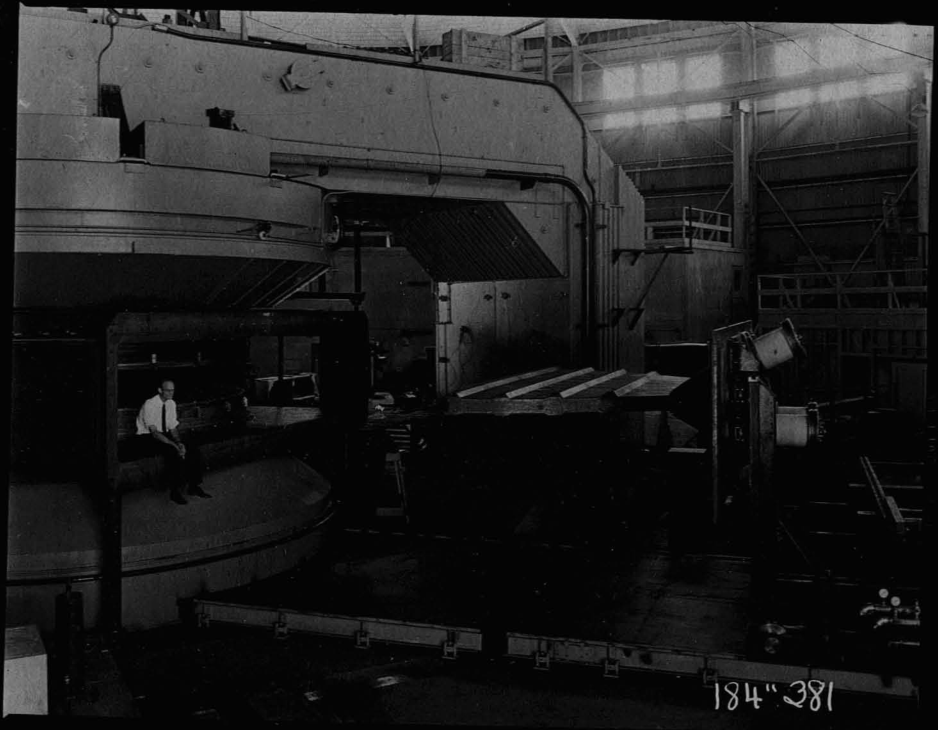


Figure 3a. 184" Cyclotron dee, faceplate and support insulators

Figure 3b. Head-on view of 184" dee.

Figure 3c. View of vacuum tank from dee faceplate side. Note rt liner arrangement

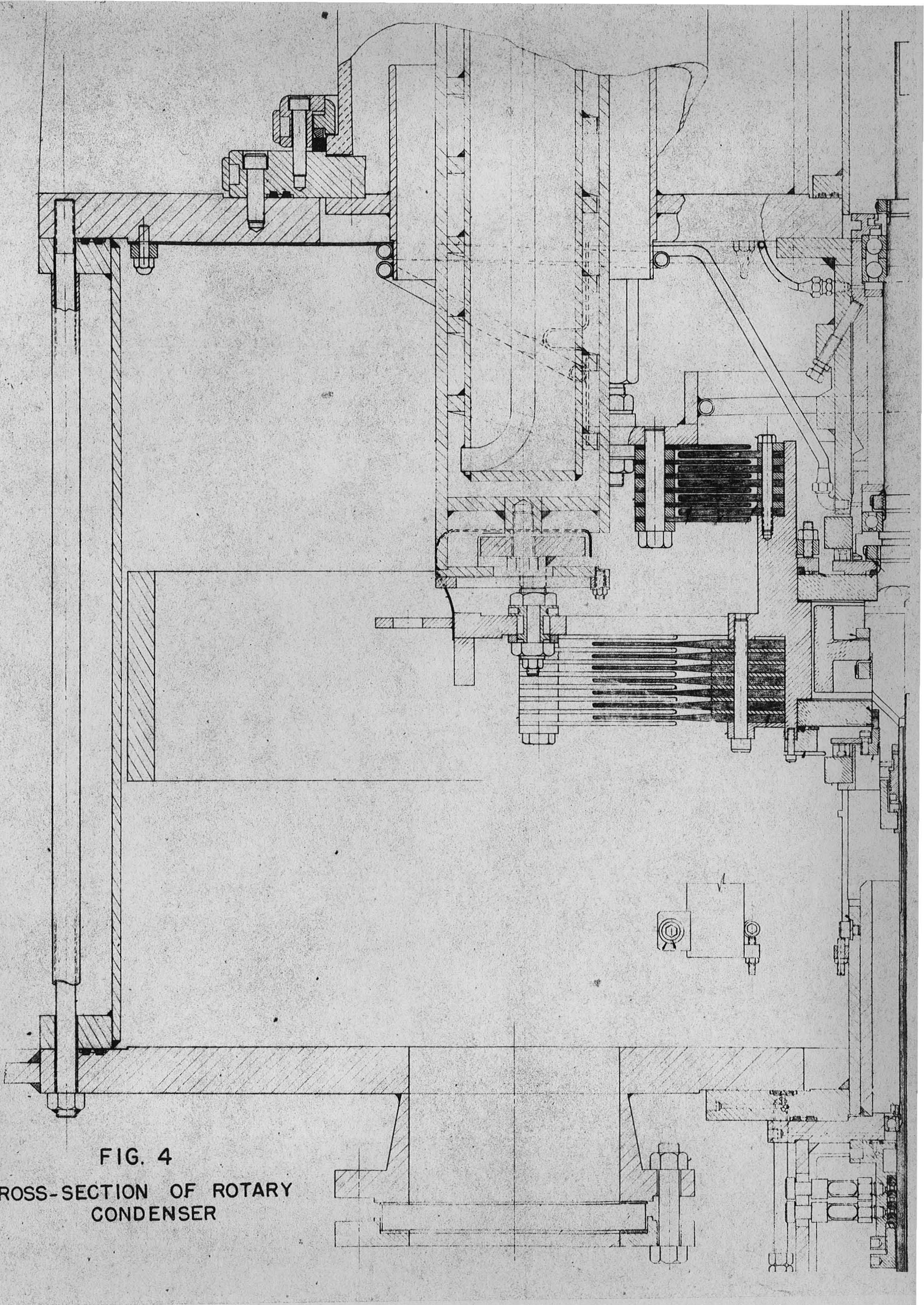


FIG. 4

CROSS-SECTION OF ROTARY CONDENSER

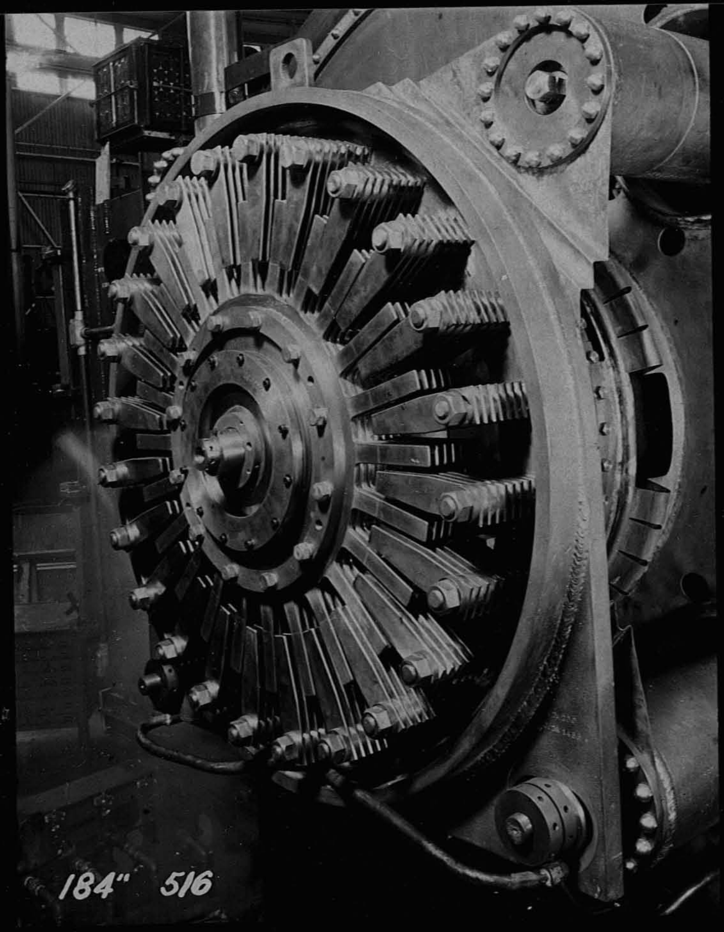


Figure 5a. Rotary Condenser before initial operation.

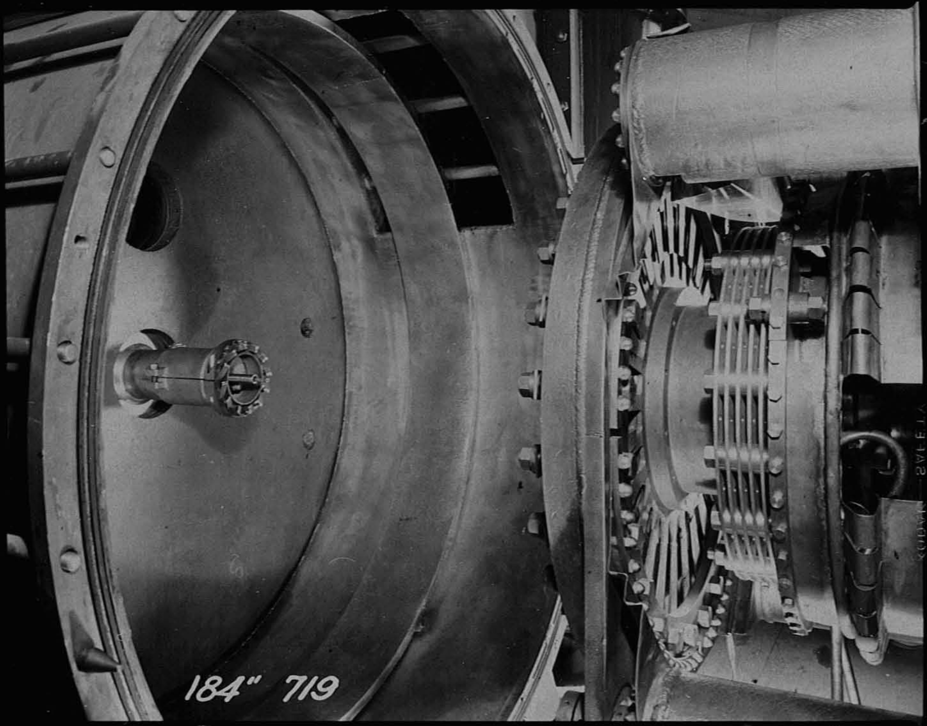


Figure 5b. Rotary condenser vacuum tank.

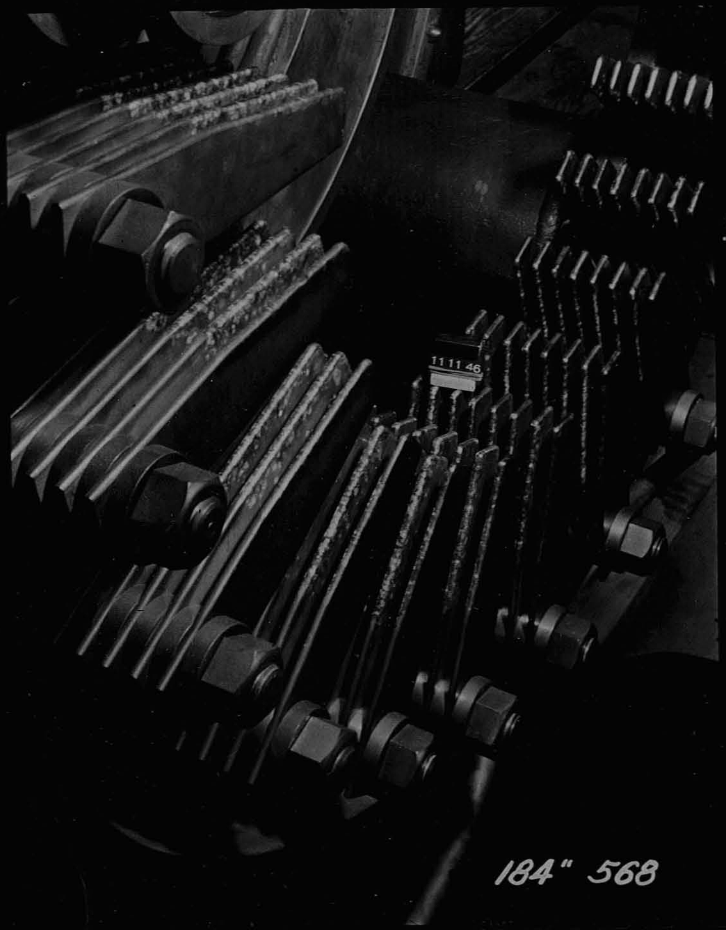


Figure 5c. Close-up of stator teeth after operation.

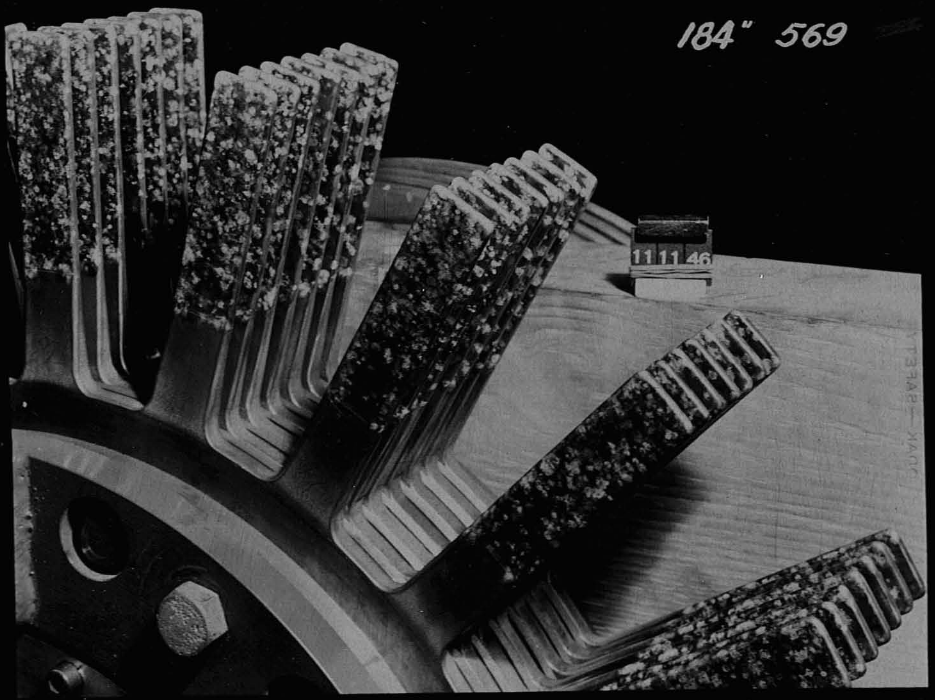


Figure 5d. Close-up of rotor teeth after operation.

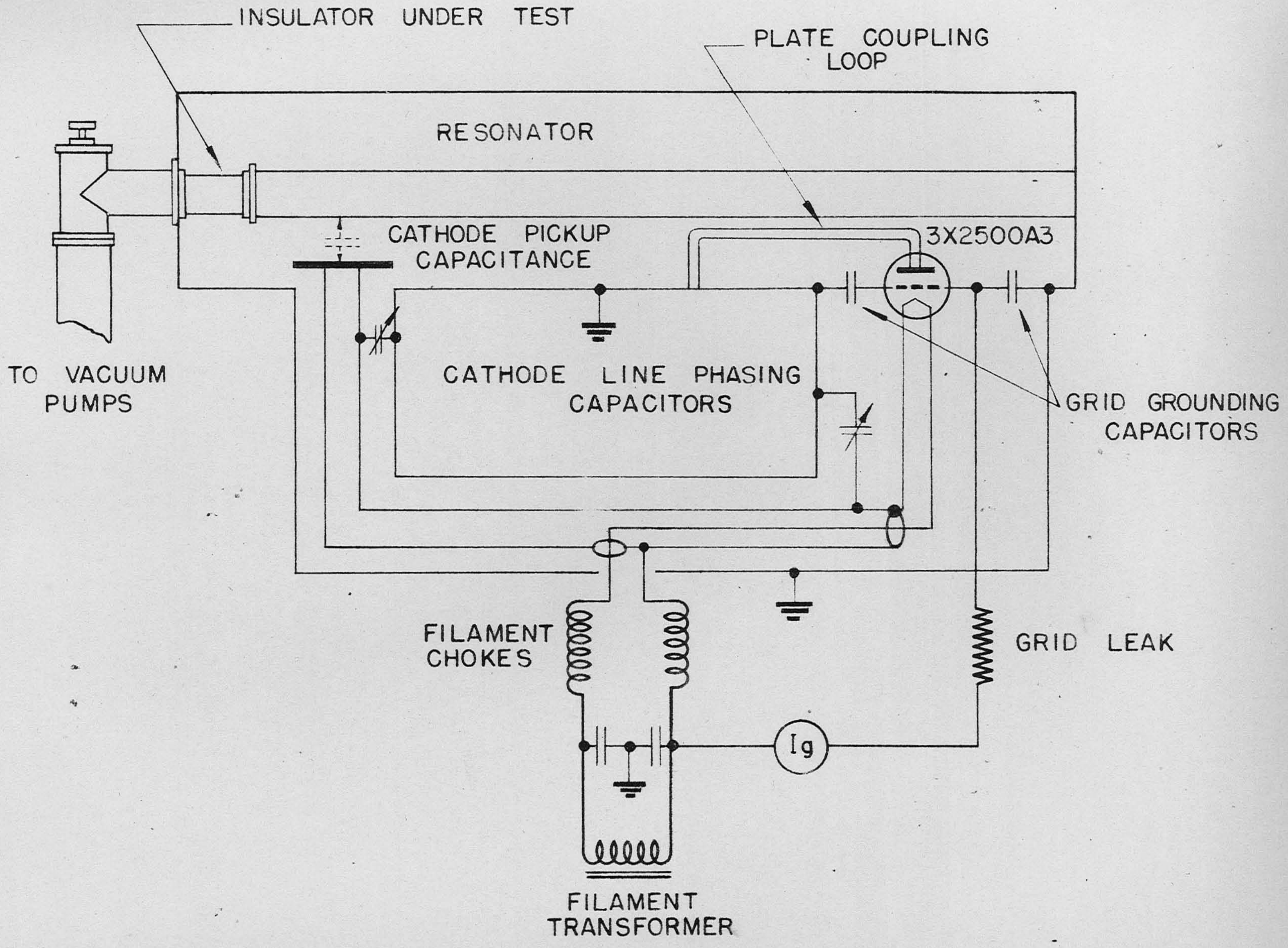


Figure 6 Schematic Diagram of High Voltage RF Testing Unit (Pandora)

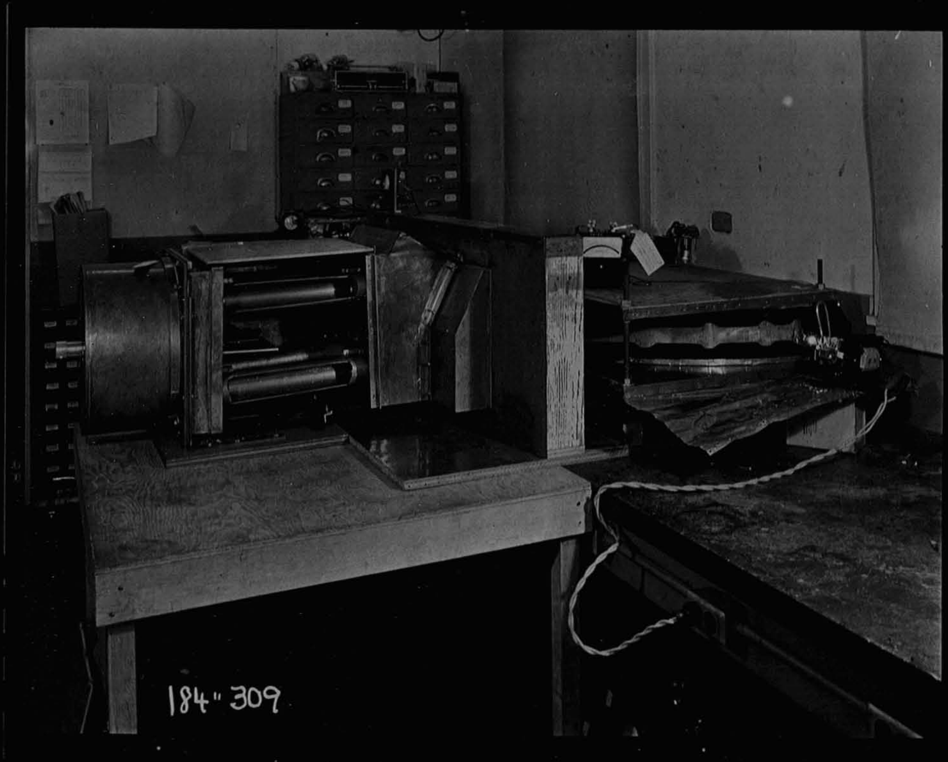


Figure 7. General view of 184" cyclotron model oscillator.

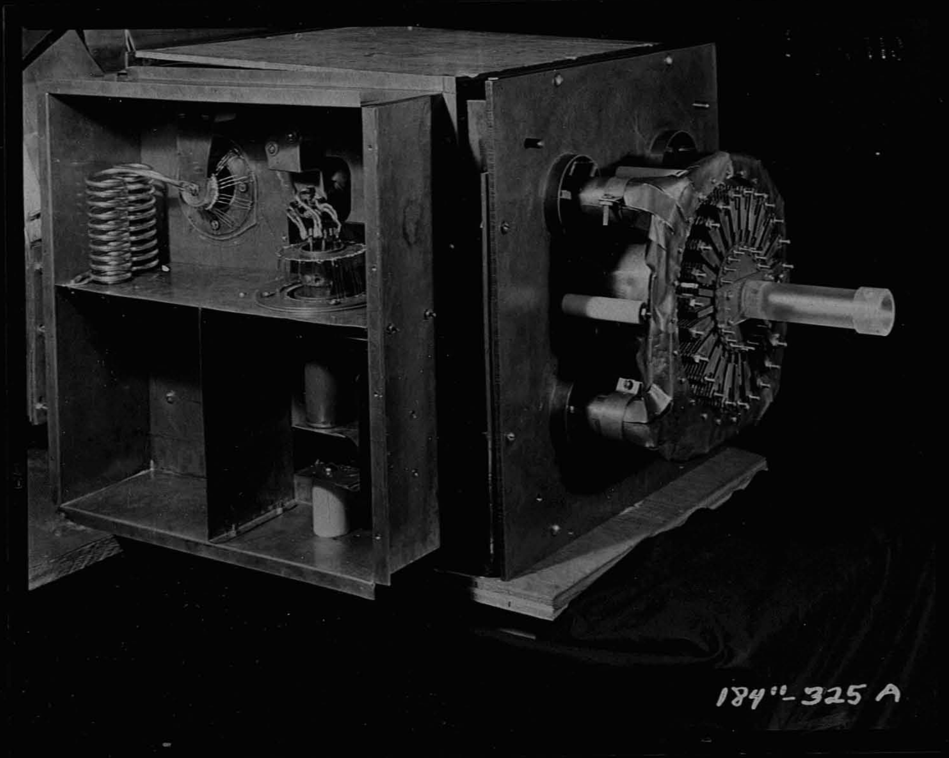


Figure 8. Close-up of model rotary condenser.

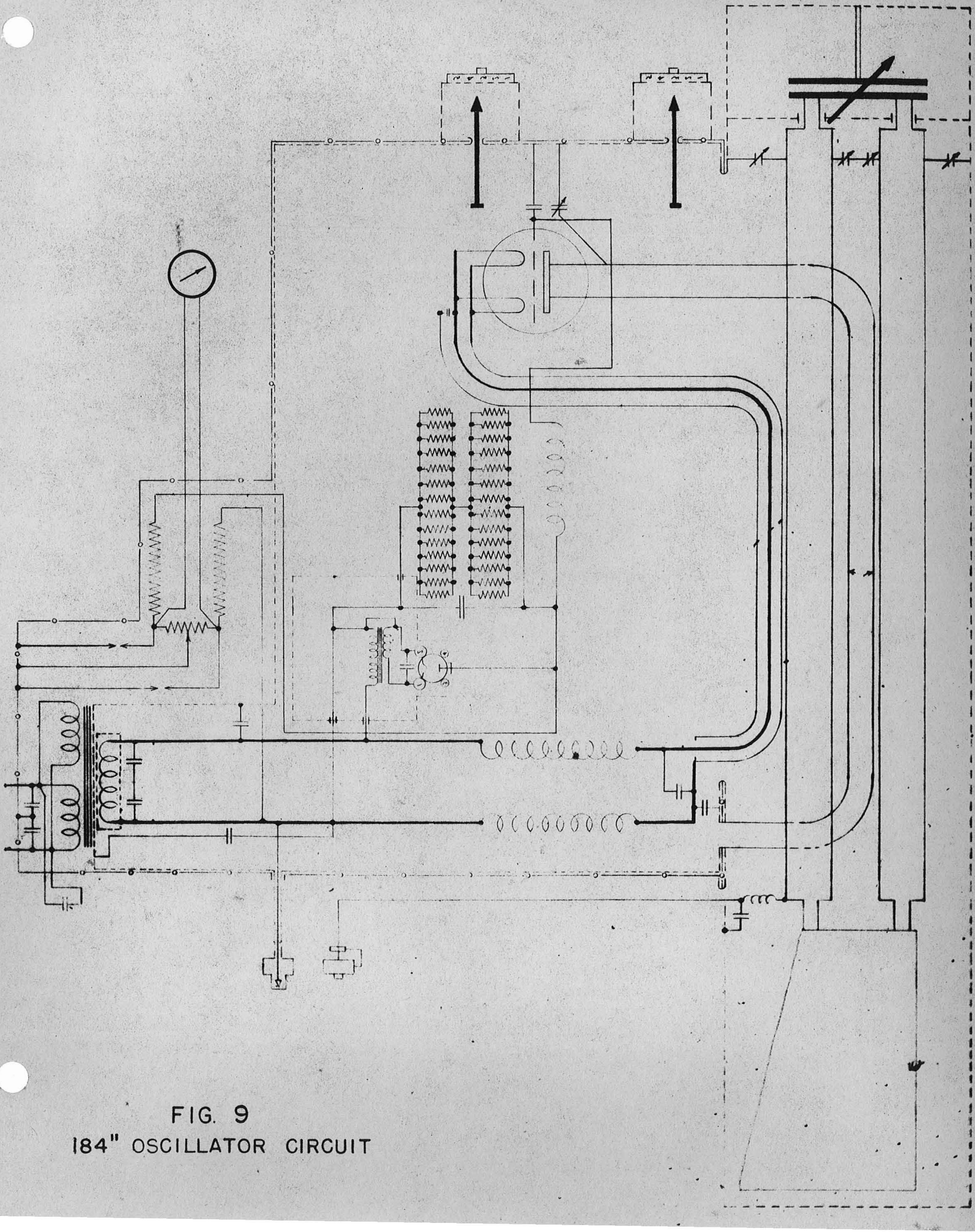


FIG. 9
184" OSCILLATOR CIRCUIT

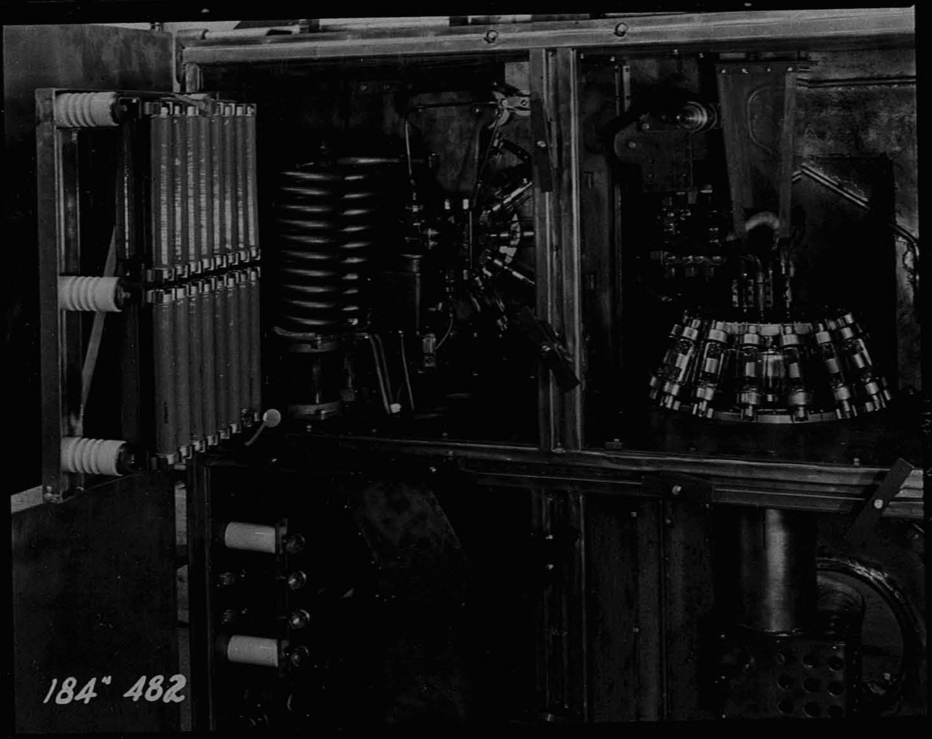


Figure 10a. Close-up of the upper deck of the 184" oscillator, showing from left to right the grid leak, filament chokes and by-pass condensers, cathode phasing capacitor ring(in rear), and grid capacitor ring surrounding the 9c21 oscillator tube.

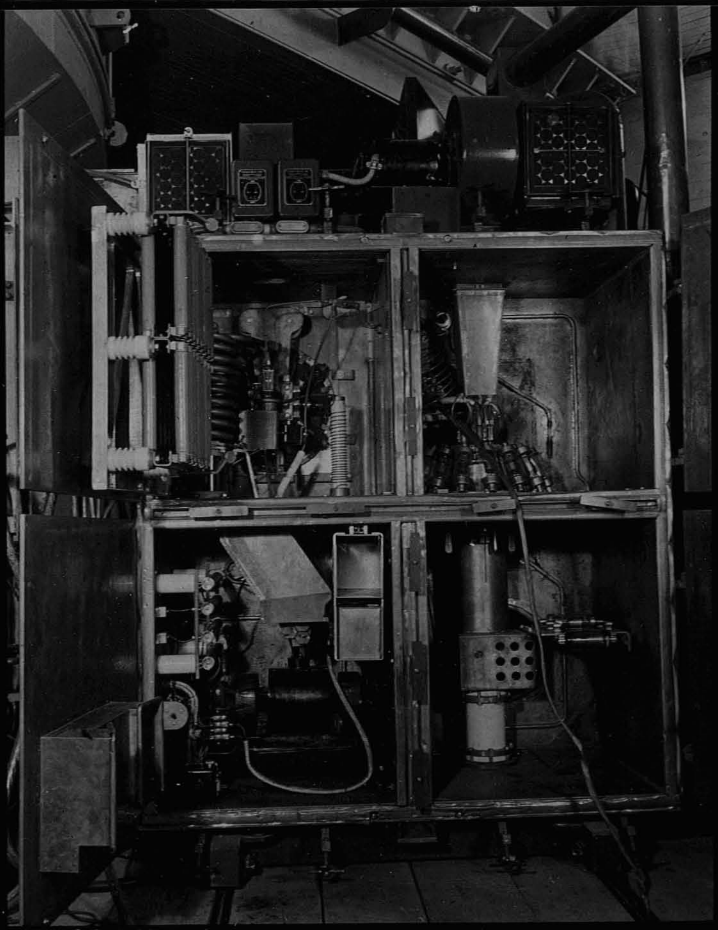


Figure 10b. Front view of oscillator with doors open.

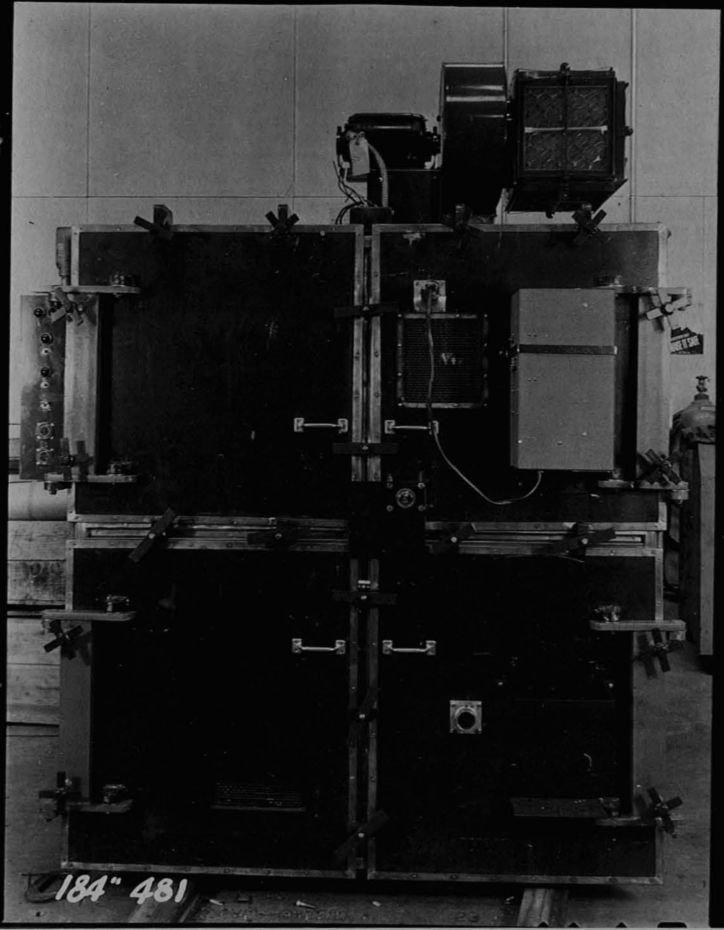


Figure 10c. Front view of oscillator with doors closed.

Figure 10d. Rear view of oscillator showing rf coupling loops.

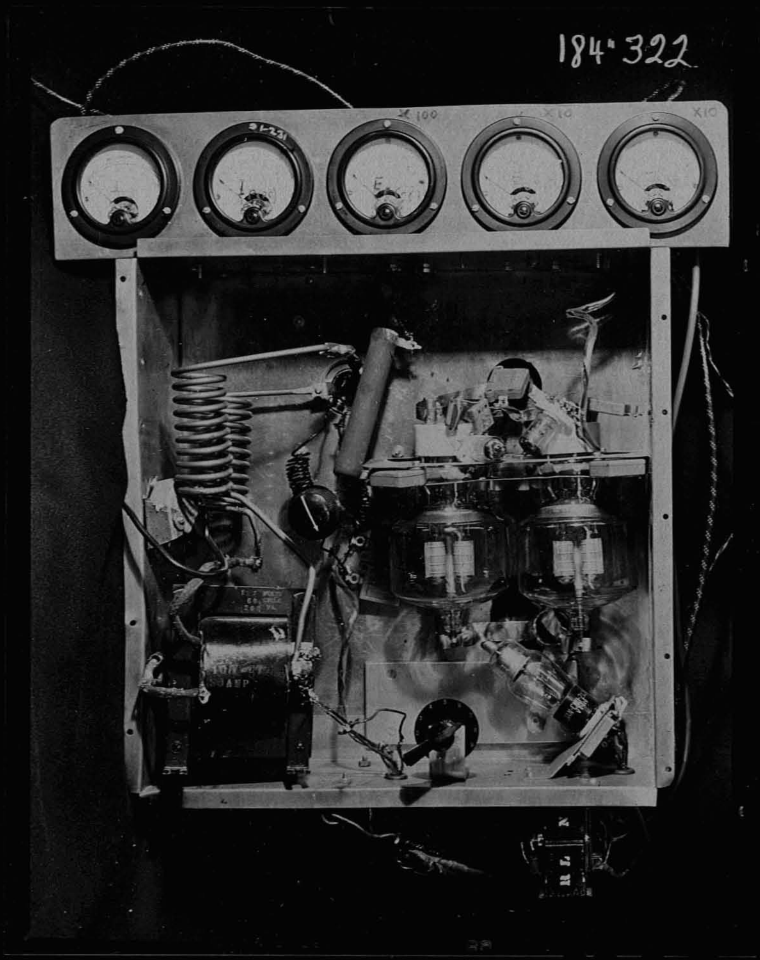


Figure 11a. 304 TL model oscillator-front view.

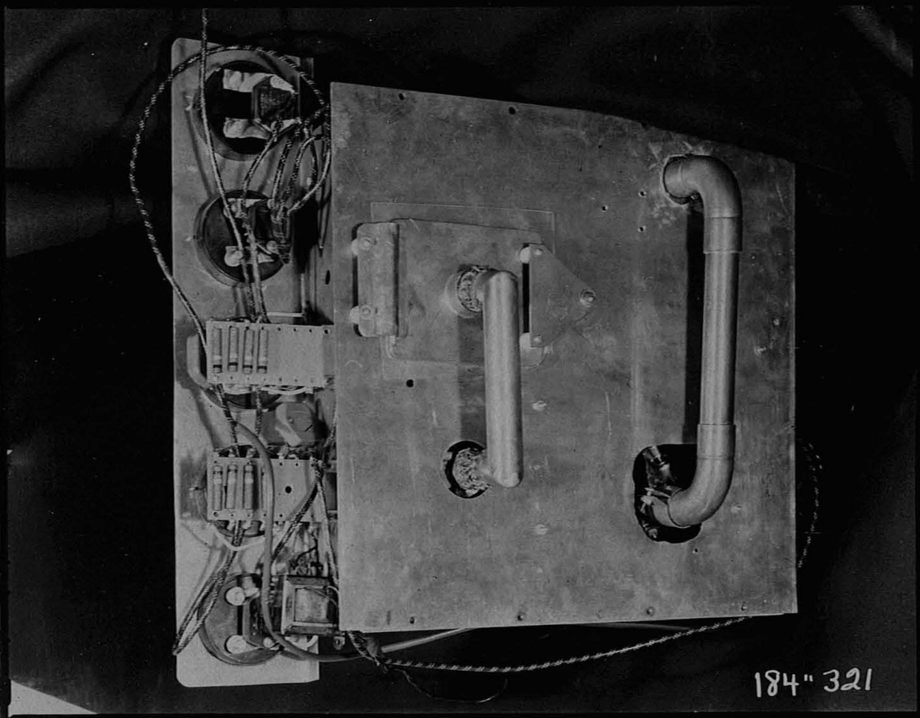


Figure 11b. 304TL model oscillator-rear view.

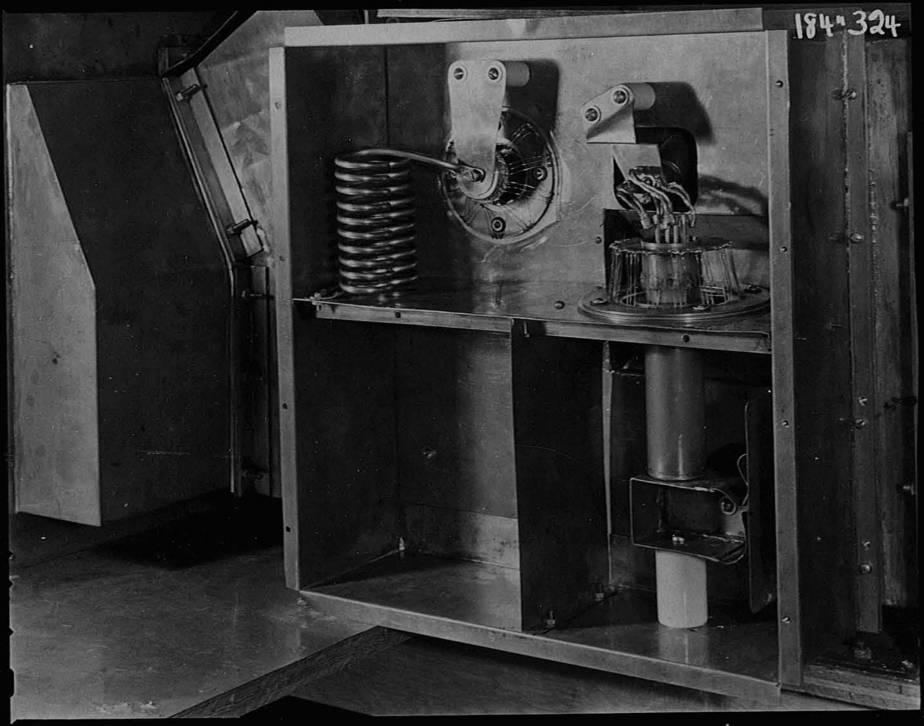
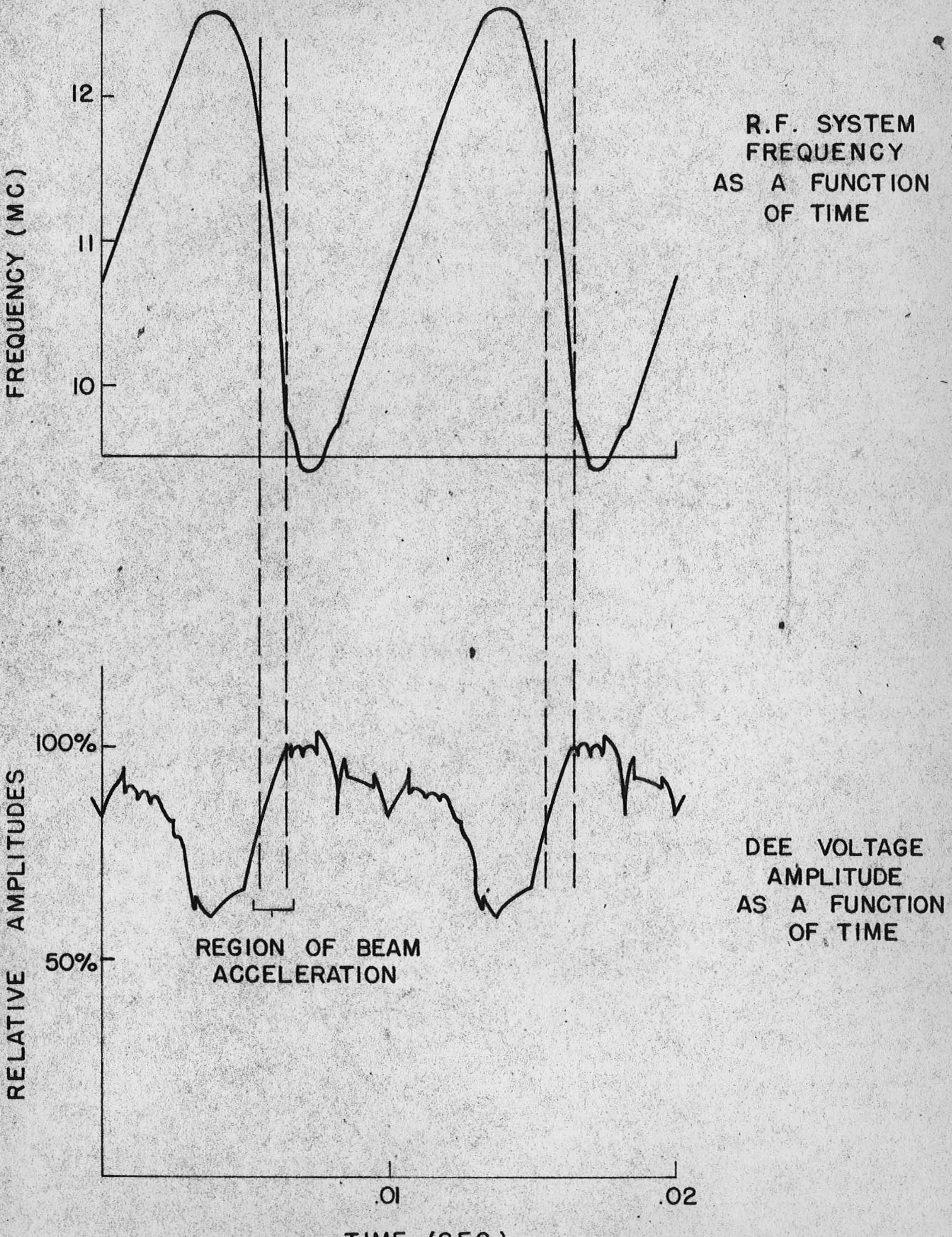


Figure 12. 9c21 scale model "dummy" oscillator. Note the wires used to simulate condenser and grid lead inductances.

Figure 13. General view of 184" cyclotron showing various rf circuit components in position for operation.



12
11
10
FREQUENCY (MC)
R.F. SYSTEM FREQUENCY AS A FUNCTION OF TIME
100%
50%
RELATIVE AMPLITUDES
REGION OF BEAM ACCELERATION
DEE VOLTAGE AMPLITUDE AS A FUNCTION OF TIME
.01
.02
TIME (SEC.)

Figure 14

Figure 15a. View inside cyclotron facing the dee and showing the grounded "dummy dee".

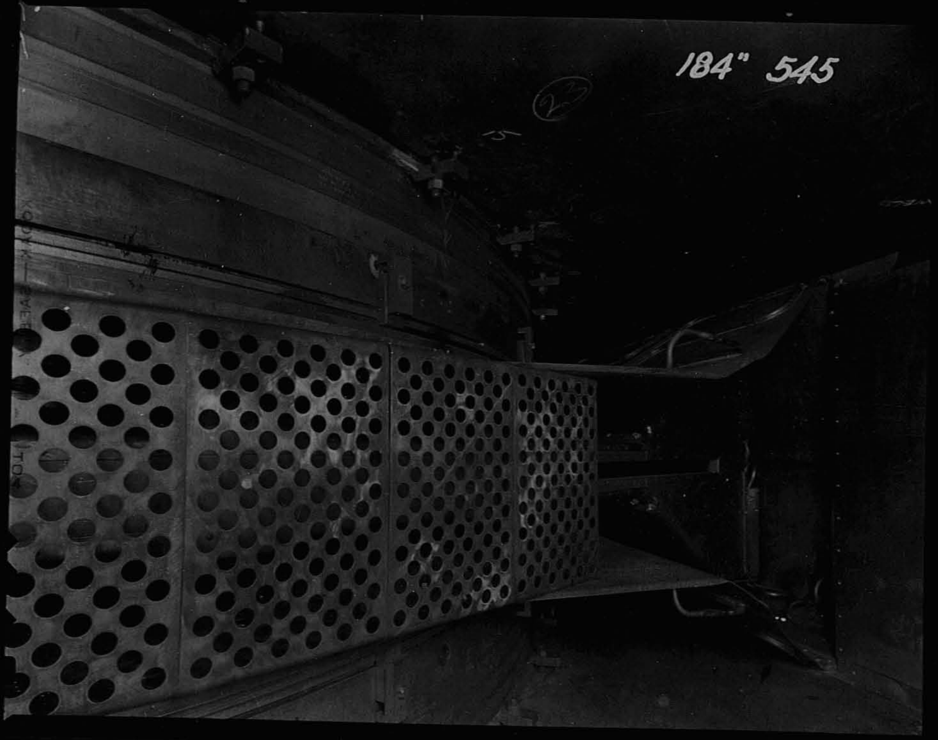


Figure 15b. View along edge of the dee showing rt discharge suppressing shields.