Lawrence Berkeley National Laboratory
Recent Work

Title
The Radiofrequency System of the Berkeley Synchrotron

Permalink
https://escholarship.org/uc/item/13z9h46b

Authors
Dazey, Mitchell H.
Franck, Jack V.
Helmholz, A.C.
et al.

Publication Date
1949-08-04

eScholarship.org Powered by the California Digital Library
University of California

UCRL 406

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 5545

BERKELEY, CALIFORNIA

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

UNCLASSIFIED

Contract No. W-7405-eng-48

The Radiofrequency System of the Berkeley Synchrotron

Mitchell H. Dazey, Jack V. Franck, A. C. Helmholz,
Craig S. Nunan, and Jack M. Peterson

August 4, 1949

Berkeley, California

Unclassified Distribution

Installation	No. of Copies
Argonne National Laboratory	8
Armed Forces Special Weapons Project	1
Atomic Energy Commission, Washington	2
Battelle Memorial Institute	1
Brookhaven National Laboratory	8
Bureau of Medicine and Surgery	1
Bureau of Ships	1
Carbide & Carbon Chemicals Corporation (K-25)	4
Carbide & Carbon Chemicals Corporation (Y-12)	4
Chicago Operations Office	1
Cleveland Area Office	1
Columbia University (Dunning)	1
Columbia University (Failla)	1
Dow Chemical Company	1
General Electric Company, Richland	6
Hanford Operations Office	1
Idaho Operations Office	1
Iowa State College	2
Kansas City	1
Kellex Corporation	2
Knolls Atomic Power Laboratory	4
Los Alamos	3
Mallinckrodt Chemical Works	1
Massachusetts Institute of Technology (Gaudin)	1
Massachusetts Institute of Technology (Kaufmann)	1
Mound Laboratory	3
National Advisory Committee for Aeronautics	2
National Bureau of Standards	2
Naval Radiological Defense Laboratory	2
NEPA Project	2
New Brunswick Laboratory	1
New York Operations Office	5
North American Aviation, Inc.	1
Oak Ridge National Laboratory	8
Patent Advisor, Washington	1
Rand Corporation	1
Sandia Base	1
Sylvania Electric Products, Inc.	1
Technical Information Branch, ORE	15
U.S. Public Health Service	1
UCLA Medical Research Laboratory (Warren)	1
University of California Radiation Laboratory	5
University of Rochester	2
University of Washington	1
Western Reserve University (Friedell)	2
Westinghouse	4
Total	119

Radiation Laboratory
University of California
Berkeley, California

The Radiofrequency System of the Berkeley Synchrotron

Mitchell H. Dazey, Jack V. Franck, A. C. Helmholz,
Craig S. Nunan and Jack M. Peterson

Radiation Laboratory, Department of Physics
University of California, Berkeley, California

August 4, 1949

Introduction

The electron beam in the Berkeley synchrotron is accelerated to a peak energy of 335 Mev in three steps. The electrons are injected at a voltage of about 100 kilovolts and are then accelerated to about 2 Mev by betatron action. Finally they are accelerated to 335 Mev by a radiofrequency voltage applied across a gap in the beam orbit. This paper will describe the design, construction, and operation of the radiofrequency system now in operation in the Berkeley synchrotron.

Specifications

The Berkeley synchrotron has an orbit radius of one meter, with a magnetic gap of approximately 3 3/4 inches. The vacuum chamber is a toroid of elliptical aperture. In cross section the outside dimensions are 3 1/2 by 6 1/4 inches and the nominal wall thickness is 5/16 inch. Fused silica (quartz) was the material used for the manufacture of the vacuum chamber or donut.

Space limitations made it desirable to utilize a section of the donut as a quarter wave resonator, with the open, or high voltage, end being the gap across which the acceleration of the electrons takes place. The dielectric constant of fused silica is four, so that one-eighth of the donut was required to form a resonator with the proper frequency. For ease of manufacture and handling it was decided to have the donut made in eight 45° sections. The segment and spares to be used for resonators were ordered with slightly larger wall thicknesses, 7/16 inch, since this would lead to a 40 percent increase in the theoretical Q over a resonator with a 5/16 inch wall, and consequent reduction in radiofrequency losses and heating.

The complete donut was assembled by covering the eight joints with four inch wide, 1/16 inch thick butyl rubber bands. A smooth surface under the bands was obtained by baking on the ends of the silica segments a two inch wide band of red glyptal. Heavy lubriseal was used under the rubber bands to insure a good vacuum seal. To prevent chipping of the segments and to insulate adjacent sections from each other, the ends were separated by a 1/16 inch thick teflon gasket. This gasket was cut to the same dimensions as the outside of the quartz segments and was made 1/8 inch wide so as not to proturde inside the inner wall of the donut where it could collect charges. All of the segements except the resonator were coated inside with DuPont #4817 air drying silver and grounded so as to avoid the accumulation of static charges. The grounding circuit was designed to distribute uniformly the betatron accelerating voltage over the several gaps between segements. The circuit consists of a ring of eight 1000 ohm resistors tied to ground at the injector; the two ends of each segment (except the resonator) are connected through 10 ohm resistors to a junction between 1000 ohm resistors. The resonator segment is grounded via the transmission line to the oscillator. The details of the resonator section preparation are described later in this paper.

The electrical specifications were as follows:

(a) Frequency. The period of the radiofrequency voltage is just the time of one revolution of the electron beam, which is traveling essentially at the velocity of light (c). Since the mean radius (r_o) of the orbit is one meter, the mean frequency (f_o) is

$$f_o = \frac{c}{2\pi r_o} = 47.7 \text{ megacycles.}$$

The desired tuning range is determined by the radial width of usable magnetic field at the orbit. Since the usable field extends from 36 3/4 to 41 3/4 inches of radius, the desired tuning range of the radiofrequency is from 45.0 to 51.1 mc.

(b) Voltage. The required voltage gain per turn of the electron beam is determined by the rate of rise of the magnetic field at the orbit. Throughout the radiofrequency acceleration period the electron energies are essentially relativistic and proportional to the value of the magnetic field.. The fundamental frequency of the magnetic field is 30 cycles per second. Therefore, assuming a final energy of 335 Mev, the instantaneous energy (E) of the electrons can be written as a function of time (t), thus

$$E = 335 \times 10^6 \sin (2\pi 30\ t)\ \text{eV}$$

The mean energy gain per turn (V_t) is then

$$V_t = \frac{1}{f_o} \frac{dE}{dt}$$

$$= \frac{2\pi 30}{47.7 \times 10^6}\ 335 \times 10^6 (\cos 2\pi 30\ t) = 1325 (\cos 2\pi 30\ t) \text{ electron volts per turn.}$$

Thus, if we ignore for the time being other acceleration effects, such as residual betatron action and radiation loss, we see that the mean voltage gain per turn is largest in the beginning of the acceleration cycle and is then equal to 1325 volts. Experience with the General Electric 70 Mev synchrotron(1) indicated that a gap voltage of two or three times the minimum is adequate for accelerating the electron beam. For this reason there was specified a voltage of up to 3500 peak volts at the radiofrequency gap in the electron orbit.

(c) Pulse length. Since the acceleration period of the synchrotron is one-quarter of a 30 cycle period, the radiofrequency pulse must last 8,300 (1/4 x 1/30) microseconds to accelerate electrons to the full energy. Reducing the pulse length is a convenient way to reduce the energy of the output beam, and the pulse length was specified to be variable from zero to greater than 8,500 microseconds.

(d) Pulse shape. The envelope of the radiofrequency pulse was specified as

---

(1) F. R. Elder, A. M. Gurewitsch, R. V. Langmuir, and H. C. Pollock, Journal of Applied Physics <u>18</u>, 810 (1947)

a square wave with a rise time to full voltage of about 10 microseconds.

(e) Starting time jitter. The jitter of the turning-on time of the radiofrequency pulse was specified as not more than 0.1 microsecond. This amount was felt to be readily obtainable and adequate for catching the electrons into phase stable orbits.(2) It was later found operationally that a much larger variation in radiofrequency turn-on time is allowable.

(f) Repetition rate. The repetition rate of the radiofrequency system, is, of course, just that of the magnet, which is a maximum of six pulses per second. It was specified that the timing of the radiofrequency pulse should be controlled by a pulse supplied by a circuit associated with the magnet.

(g) Eddy currents. An important requirement is that eddy currents induced in the conducting surfaces of the resonator by the alternating magnetic field be small, both to preserve uniformity of magnetic field and to avoid excessive heating. For ease of compensation it was specified that the mean eddy current field be less than 0.8 gauss; to avoid excessive distortion of the electron orbit, the maximum deviation of the eddy current field from its mean was specified as 0.2 gauss.

The Resonator

A quarter wave resonator, somewhat similar to the one used in the General Electric synchrotron,(1) was constructed. The fused silica, supplied by Amersil Corporation, had a glazed inner surface and a rough, sandy exterior which varied considerably in wall thickness. The exterior of the resonator section was ground with silicon carbide grinding wheels to obtain a smooth surface and a thickness uniform within ± 1/32 inch. The resonator section, shown in Figure 1, was treated by the following procedure:

The section was filled with hydrofluoric acid for about 24 hours to etch the inner surface glaze. The section was then cleaned by carefully washing in

---

(2) D. Bohm and L. Foldy, "The Theory of the Synchrotron," Phys. Rev. 70, 249 (1946)

acetone and then fired at a temperature of about 1200° F in order that any organic matter that remained be oxidized. After the section had cooled, Liquid Bright platinum solution was applied by brush. The section was then fired in an amply ventilated furnace. The temperature was brought up slowly while the organic material in the Liquid Bright solution was burned out. When the temperature was about 600° F, most of these materials had been vaporized and the coating was then "set" by running the temperature up to about 1150° F for a short period of time. Two or three coats give sufficient surface conductivity to allow good electroplating.

Eddy currents in conductors in a magnetic field go up rapidly as the area of the conductor is increased, so it was necessary to scribe "stop-off" lines before electroplating, leaving strips of metal to form the resonator. Scribe lines (see Figure 1) were laid out by painting glyptal on with a rotating wheel device attached to a long radius arm.

The resonator was placed in a copper sulphate bath, taking care that no air bubbles were trapped. Fixed anodes were shaped so as to be approximately equidistant from the surfaces to be plated. For instance, a 1/8 inch high by 2 1/2 inch wide copper strap was formed in an arc and placed along the centerline inside the resonator. Copper fingers were added to protrude into the resonator bumps at the feedpoint and near the gap. This gave an anode to resonator distance of about 1 1/4 inches at all points. The fixed anodes were wrapped with insulating material at areas near the edges of the resonator to prevent excessive plating of the edges. It was found desirable to flash plate at about 15 amperes total current, using a small movable anode to plate areas which did not plate from the fixed anodes. After the complete surface was covered with a thin coat, the current was reduced to 5 amperes total and the plating was built up uniformly, using movable and fixed anodes. A reverse-plating method was used which consisted of 10 seconds plating, and 2 seconds de-plating. Although it was not possible to measure the thickness of the plating with any accuracy, it was estimated that about .003 inch of metal was applied.

After the plating, the glyptal was dissolved from the scribe lines with methyl ethyl ketone; some of the metal from the Liquid Bright solution was ground out by an abrasive cut-off disk (carborundum) mounted on a radius arm. It was found impossible to grind out all traces of the metal, so the remaining metal was burned out by connecting the output of a 5 volt, 200 ampere filament transformer across each scribe line. Further burning at 115 volts, 1/2 ampere maximum brought the resistance across each line to ~ 100,000 ohms.

After the scribe lines were cleaned up, a coupling strap was painted around the resonator using DuPont Air Drying silver solution #4817 both on the inside and outside surface at a position which experimentally was found to give the highest Q. This strap was then electroplated by coating the resonator heavily with glyptal, except at the strap, and using the reverse-plating method as described above, after which the glyptal was removed with methyl ethyl ketone.

The resonator has a 3/8 inch wide accelerating gap and is driven at the half voltage point by a coaxial transmission line from the oscillator. The plating on the inside surface is brought out through a hole and a copper plated quartz plug is soldered into the hole to allow connection to the transmission line inner conductor.

When the resonator is installed in the synchrotron, there is 1/8 inch clearance top and bottom between the resonator and the magnet pole tips. This small clearance allows considerable radiofrequency power to be dissipated in the pole tips. When the cross-strap was painted at the accelerating gap, the resonator Q was measured as 225 between the pole tips and 409 when away from the pole tips. The optimum position for the cross-strap was found to be about 45 percent of the distance from the gap to the high current end of the resonator. With the cross-strap in the optimum position, a smaller percentage of the total radiofrequency power loss is lost to the pole tips, the Q's being 445 between pole tips and 545 away from the pole tips. These figures refer to the resonator shown in

Figure 1. Note that at the ends of the resonator the scribe lines connecting inner and outer surfaces are "radial" (i.e., perpendicular to the inner and outer surfaces). Another resonator was constructed in which the scribe lines were arranged vertically above each other and the scribe lines at the ends ran vertically from inner to outer surface. It was expected that this arrangement would produce smaller eddy current fields, but the fields actually turned out to be comparable to that of the above resonator. However, the Q was much lower, being 225 between the pole tips and 342 away from the pole tips with the cross-strap in the optimum position.

The resonator was then placed in an alternating magnetic field and the delay in time of zero field due to eddy currents in the plating was measured with peaking strips. The delay was between .6 and 1.2 microseconds everywhere within a 4-inch radial aperture except for a 3-inch strip under the cross-strap where a peak of 3.2 microseconds was measured. In 30 cycle operation the rate of rise of primary magnetic field at the time of injection is .7 gauss per microsecond so the above delay times correspond to eddy current vertical magnetic fields of .4 to .8 gauss over the 4-inch radial aperture except at the cross-strap where the peak field was 2.2 gauss. Most of the variation was azimuthal; the maximum radial variation over the 4-inch radial range was measured as .15 gauss. The resonator field is compensated along with the rest of the magnetic field by coils around each 45° segment of the pole tips. The eddy current heating is still large enough so that it is necessary to cool the resonator with a blower supplying 200 cubic feet/minute and calculated to produce 30 feet/second flow of air over the resonator surface. Without this, the lubriseal used with the wide rubber bands to make the vacuum seal from one section to another becomes warm and flows. Dielectric heating of the quartz is negligible.

Electrical

In this radiofrequency system, the quartz resonator, the transmission line to the tube, and the tube with its associated circuit components comprise a single resonant circuit. In terms of transmission lines, the resonant circuit is three-quarters of a wave length long; the quartz section is equivalent to a quarter of a wave length; and the transmission line with the tube and its associated circuit components is electrically a half wave length long. Figure 2 represents, approximately, the voltage distribution along the quartz resonator and the transmission line to the oscillator tube.

Figure 3 is a schematic diagram of the circuit and indicates the approximate location of components; Figures 4 and 5 show the oscillator. The 2500 watt air-cooled oscillator tube, (Eimac 3X2500A3) is connected in a grounded grid circuit across the high voltage end of the transmission line. The tuning capacitor (C_1) controls the frequency of the entire radiofrequency system between 45 mc and 51 mc. It is located at the top of the oscillator tube housing and is remotely controlled from the synchrotron control desk with a selsyn motor.

The feedback for the oscillator tube is obtained by coupling to the magnetic field in the transmission line with an adjustable loop. A series connected variable capacitor or phasing capacitor (C_2) compensates for the effect of the self inductance of the feedback loop. This circuit allows the drive to be adjusted in phase as well as in amplitude. The transmission line is "curled back" upon itself to keep this feedback circuit as short as possible and at the same time have the loop couple near a magnetic field maximum.

Directly under the tube and extending downward is the filament transmission line. This line and its tuning capacitor (C_3) increase the stored energy in the drive circuit and at the same time act as a radiofrequency choke in the filament leads to the tube.

Since the tube filaments are connected to the d.c. ground it is necessary to use a plate d.c. blocking capacitor (C_4) and a grid d.c. blocking capacitor (C_5). A copper plated disk of titanium dioxide was used as a plate blocking capacitor since this shape fits into the geometry of the circuit and gives the necessary voltage insulation (6000 vdc) and capacity (approximately 2000 $\mu\mu$f). This capacitor is clamped between two rows of spring fingers; one row fastened to the under side of the tuning capacitor stator and the other row mounted on top of the tube. The tube rests upon its grid connector which is part of a brass disk forming the grid blocking capacitor. Two pieces of .005 inch sheet polystyrene are used as the dielectric to give a capacity of about 800 $\mu\mu$f and to insulate for 2000 volts d.c.

The grid bias resistor (R_1) for the oscillator is mounted in the pulser chassis about fifty feet away, and is connected to the grid of the tube by a length of low capacity coaxial cable (RG63/U). In series with this lead at the oscillator is a low pass filter which keeps radiofrequency power out of the pulser.

The d.c. power is fed to the plate of the tube through a radiofrequency choke consisting of a foreshortened section of coaxial line and a radiofrequency bypass capacitor (C_6).

The tickler oscillator (tube type 2C26A) is mounted in the small box bolted to the outside of the filament transmission line. This oscillator generates a small amount of radiofrequency power (less than one watt) which reduces the jitter time to less than five radiofrequency cycles (0.1 microsecond). The tickler oscillator is capacitively coupled to the drive circuit of the main oscillator. Its adjustment is not critical and is not adjusted from the synchrotron control desk. When the oscillator was firstetested, two spurious modes of oscillation were observed. These were eliminated by installing a 300 ohm globar mode suppressor resistor across the transmission line at the voltage node of the fundamental mode.

The resonator is driven at the half voltage point rather than at the gap in order to simplify the design of the insulating surfaces at the feedpoint. Between the mode suppressor and the resonator is a section of transmission line (approximately an eighth wave length) using zircon as the dielectric. This section of low impedance line acts as an impedance transformer to allow the oscillator tube to operate at approximately twice the feedpoint voltage in order to obtain good oscillator efficiency.

The oscillator delivers approximately 2 kw peak power at approximately 60 percent plate efficiency when operating at the maximum gap voltage (3500 volts peak) and the nominal pulse length (8300 microseconds). At the maximum repetition rate (6 cps) the duty cycle is 1/20. Most of the energy goes into conduction losses in the resonator plating and in the transmission line. The forced air cooling mentioned in connection with eddy currents dissipates this heat. Forced air cooling is used to cool the grid-to-plate seal and the plate of the oscillator tube. The filament seals of the tube are cooled by high pressure air supplied through the inner conductor of the filament transmission line.

The main oscillator is keyed by controlling the grid bias voltage with the pulser shown in Figure 3. During the off-time the pulser holds the grid of the oscillator tube at about 1 1/4 times the cut-off voltage. To initiate the radiofrequency pulse, the leading edge of a negative square wave of voltage from a "one-shot" multivibrator cuts off the 807 switch tubes, allowing the bias voltage on the oscillator grid capacitor to discharge through the grid resistor R_1. When the bias rises above cut-off, the tube functions as a class C oscillator, establishing its own bias across R_1. To terminate the radiofrequency pulse, the trailing edge of the negative square wave puts the 807's sharply into conduction, which places sufficient negative bias on the grid of the oscillator to stop the oscillations.

The length of the negative square wave of voltage generated by the one-shot multivibrator is varied by a potentiometer adjusted from the synchrotron control desk by means of selsyn motors.

Operation

None of the radiofrequency pulse parameters has been found to be critical. In normal operation the electrons are accelerated by betatron action for the first 100 microseconds to 2 Mev, a booster coil around the flux bars being energized for the last 40 microseconds to compensate for saturation of the flux bars. Under these conditions the radiofrequency pulse can be started at any time over a 5 microsecond range without appreciable difference in x-ray beam intensity. The resonator is driven at 47.0 mc./sec. The beam intensity decreases rapidly when the frequency is tuned beyond 48.1 or 46.6 mc./sec. and is fairly constant between these limits.

Earlier we have shown that the theoretical minimum radiofrequency voltage at which electrons can be accelerated to the full energy is 1325 volts. This threshold voltage has been measured as 1200 volts by a voltmeter which reads proportional to the radiofrequency magnetic field intensity at the node point of the oscillator transmission line. Before the top part of the synchrotron magnet was installed this voltmeter was calibrated by an 8013A diode voltmeter at the gap of the resonator. The difference between measured and theoretical threshold radiofrequency voltage can perhaps be attributed to inaccuracies in calibration of the voltmeters or to subsequent changes in transmission line geometry due to assembly and disassembly.

The beam intensity increases rapidly as the radiofrequency voltage is increased above threshold, the intensity reaching a maximum at about twice threshold voltage. Further increase in radiofrequency voltage does not increase the beam intensity appreciably and sometimes it decreases the beam intensity slightly.

In normal operation at full energy the electrons begin to strike the target about 120 microseconds after the end of the radiofrequency pulse and the x-ray beam lasts for about 10 microseconds. For some types of experiments it is desirable to have the x-ray pulse last for a longer period in order to allow counters to function for a longer time during each synchrotron pulse; for a given beam intensity the pile-up of independent counts within the resolving times of the counters is correspondingly reduced. For this purpose the duration of the x-ray pulse has been increased by slowing down the rate of decay of radiofrequency voltage at the end of the radiofrequency pulse. This was accomplished by inserting a 500 ohm resistor in series with the high voltage supply to the oscillator and by shunting the oscillator high voltage input with a 0.34 henry choke, 0.2 μf capacitor and 5C22 thyratron connected in series. The thyratron is fired by a delay channel 400 microseconds before the end of the radiofrequency pulse. The current charging the 0.2 μf capacitor follows 90 degrees of a sine wave and the oscillator voltage drops to about 70 percent of normal, at which time the radiofrequency pulse is terminated by the oscillator grid pulser. The charge left on the 0.2 μf capacitor is bled off by a 1/4 megohm resistor between pulses.

At 335 Mev the electrons lose energy by radiation at the rate of about 1080 volts per turn. In order that all of the electrons will strike the target before the end of the radiofrequency pulse, the oscillator voltage is reduced so that the end of the radiofrequency pulse is less than 1080 volts. The flat portion of the radiofrequency pulse is then about 1550 volts. Under these conditions of operation the x-ray beam is spread over 140 microseconds and the x-ray beam intensity (measured with a photomultiplier behind 1/4 inch of polystyrene) is uniform within a factor of 2 over this period. This type of operation has been of considerable value in experiments involving proportional and scintillation type counters.

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

Information Division
8/22/49 md

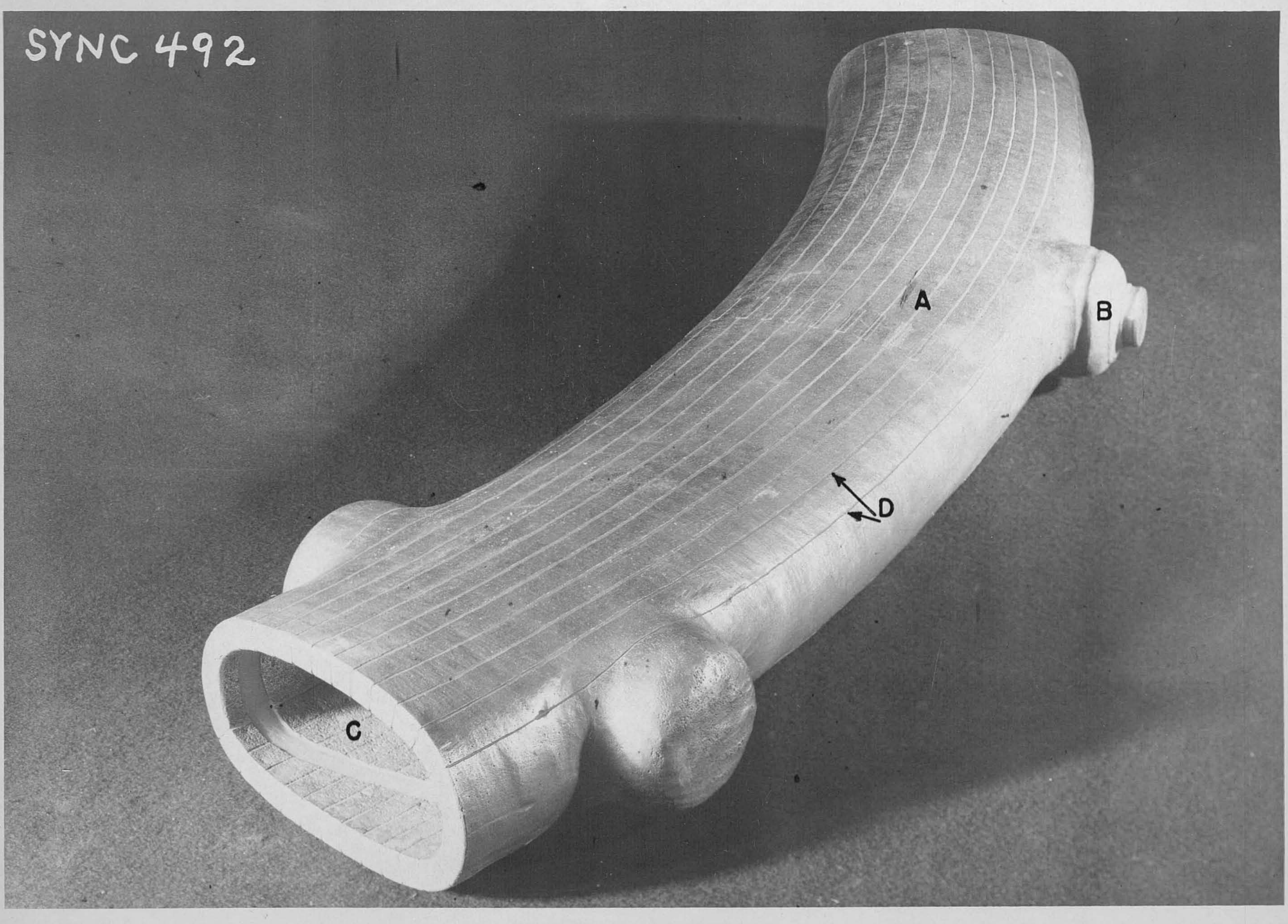

FIG. I RESONATOR

(A) CROSS STRAP (B) FEEDPOINT (C) ACCELERATING GAP (D) SCRIBE LINES

97 56

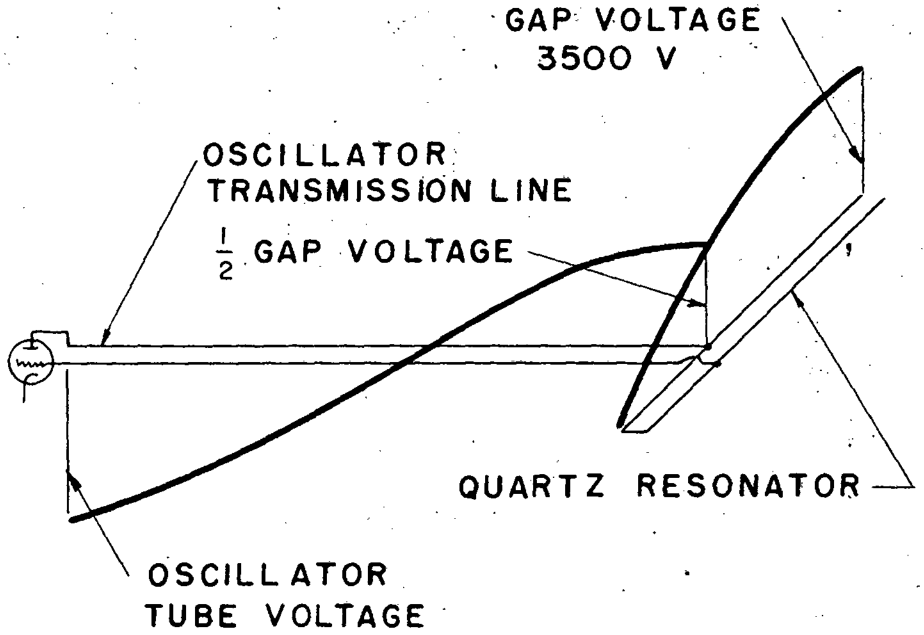

FIG. 2

OSCILLATOR VOLTAGE DISTRIBUTION

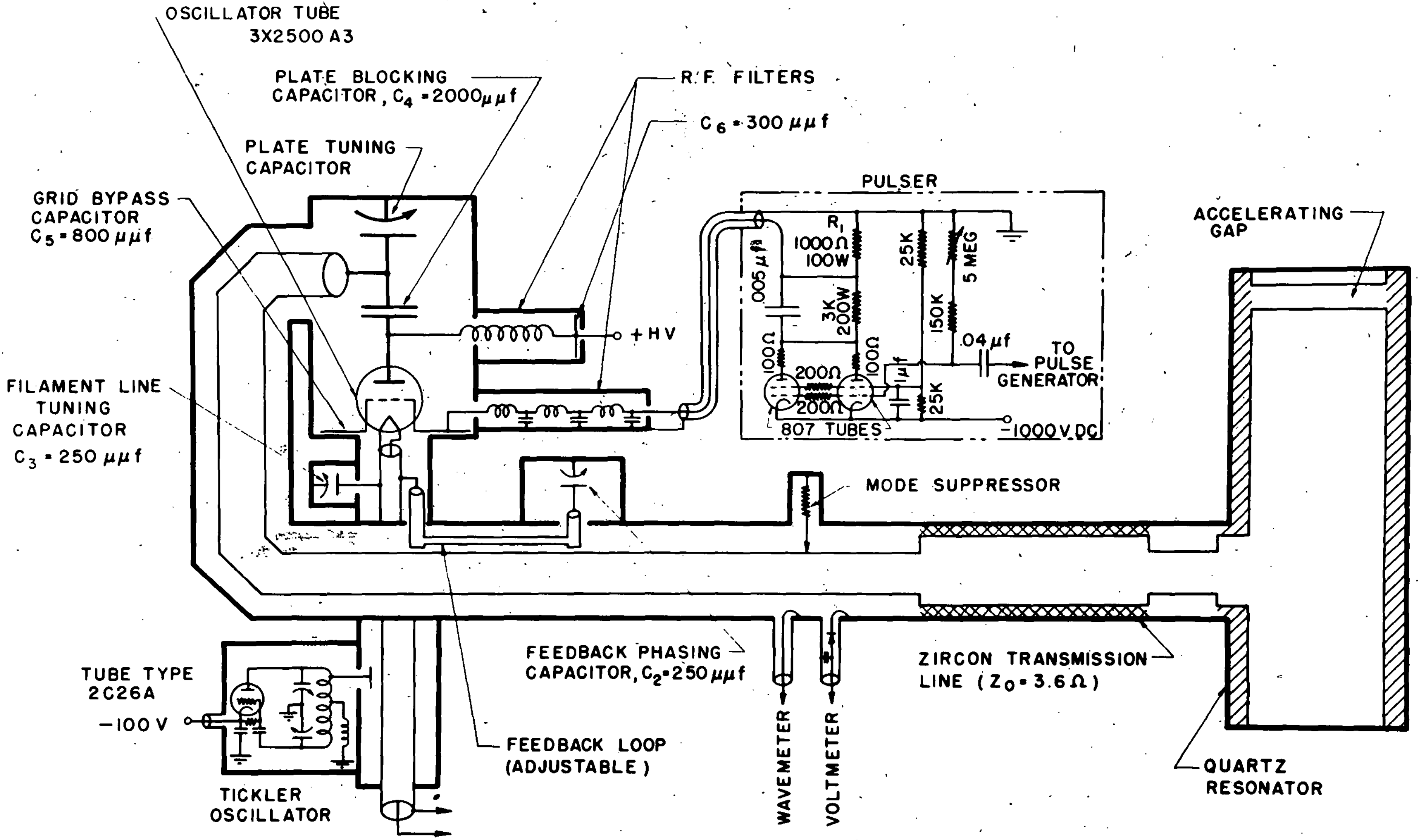

FIG. 3

SCHEMATIC DIAGRAM OF RADIO FREQUENCY OSCILLATOR

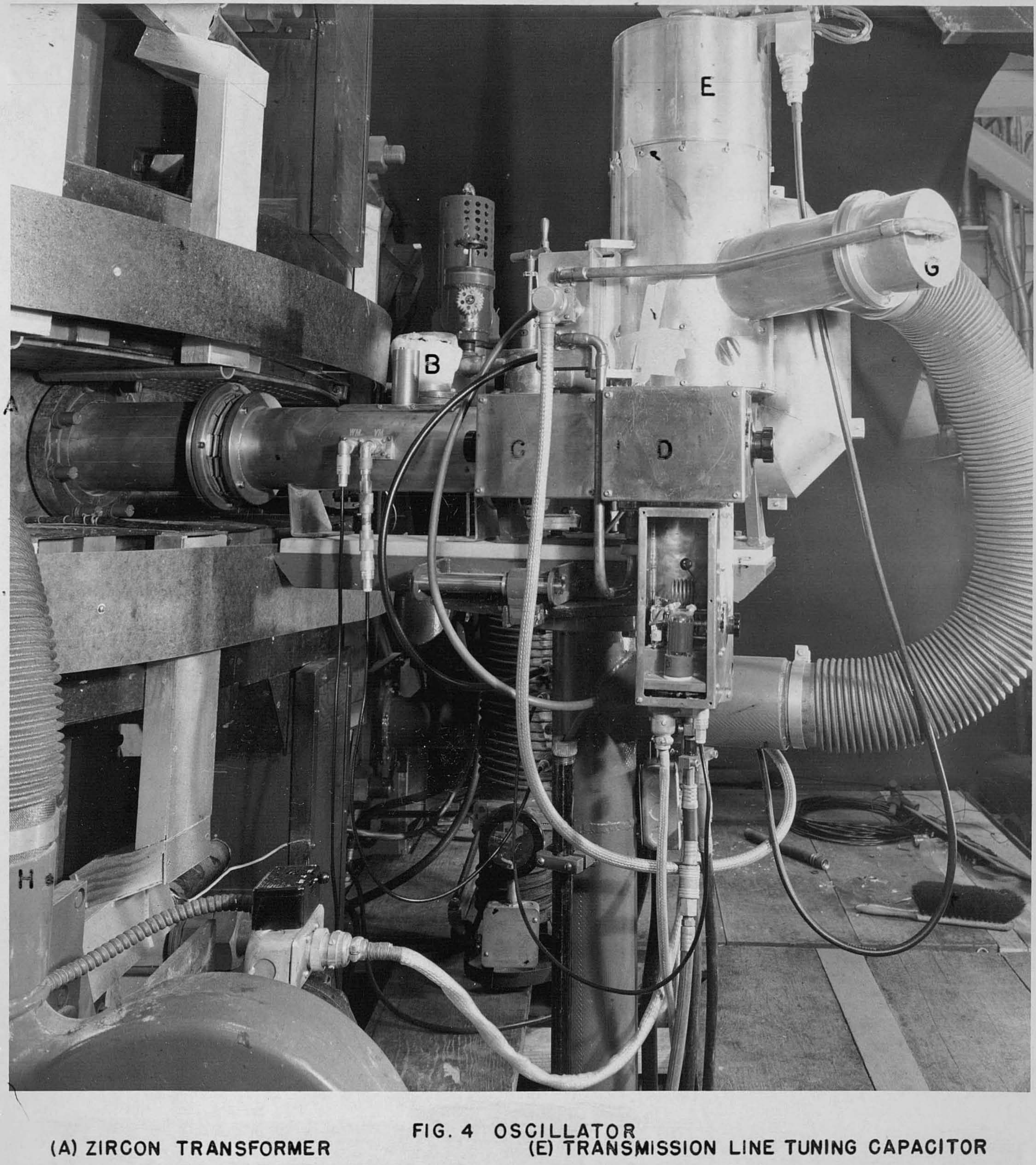

FIG. 4 OSCILLATOR

(A) ZIRCON TRANSFORMER
(B) GLOBAR MODE SUPPRESSOR
(C) COUPLING LOOP PHASING CAPACITOR
(D) FILAMENT LINE TUNING CAPACITOR
(E) TRANSMISSION LINE TUNING CAPACITOR
(F) TICKLER OSCILLATOR
(G) PLATE CHOKE STUB
(H) BLOWER FOR COOLING RESONATOR

OZ 559

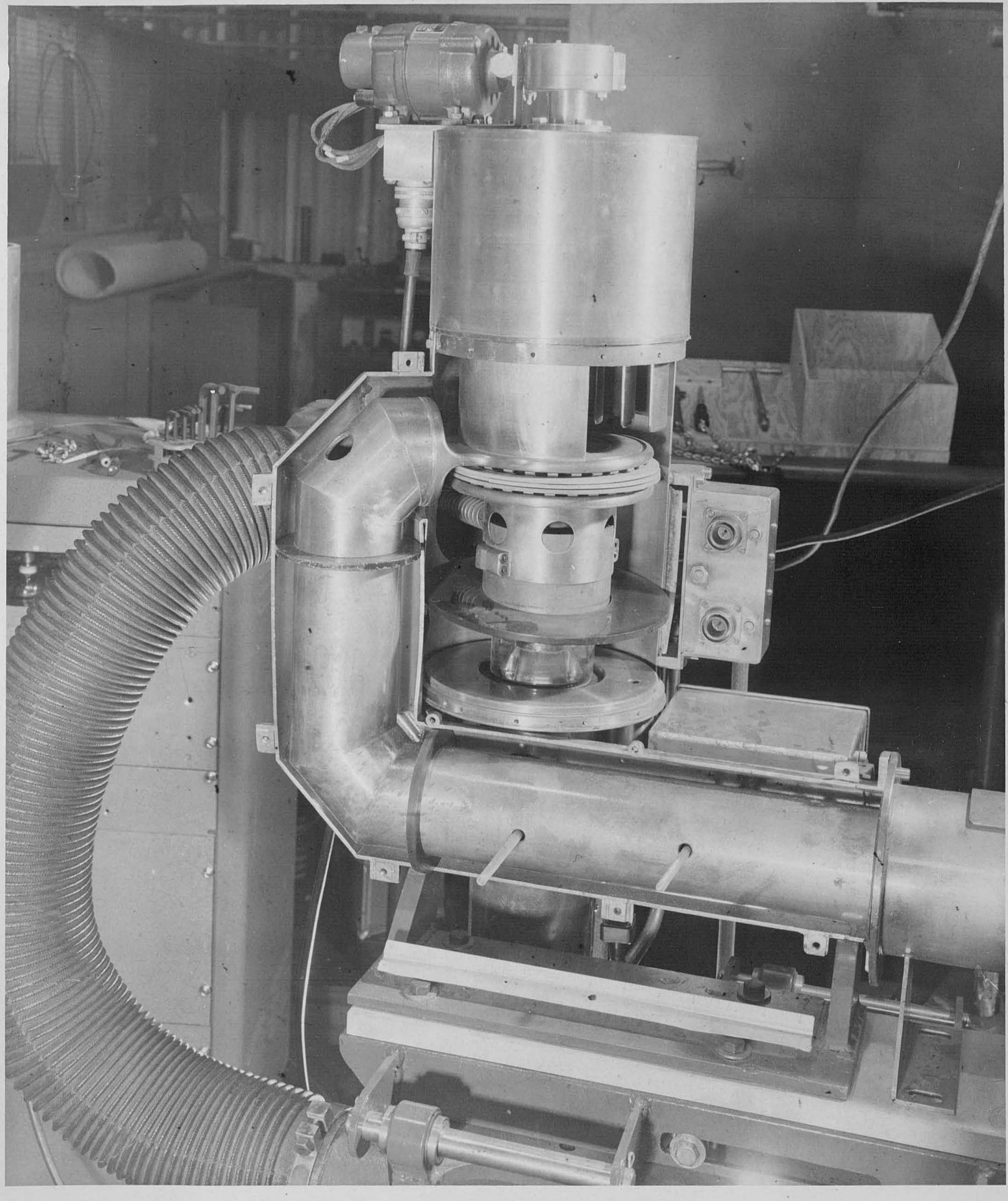

FIG. 5 OSCILLATOR PARTIALLY ASSEMBLED

OZ 560

KODAK — [illegible]