VII. TUBE RESEARCH AND DEVELOPMENT

A. MAGNETRON DEVELOPMENT

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1. High-Power 10.7-Cm Magnetron

a. Testing and design

Magnetron MF-7B developed leaks at the joints between cathode leads and anode. The trouble occurred during bakeout at 600° C because of failure of the supervisory equipment. Prior to the failure the tube had been baking in the 500-600° C range for about 75 hours.

This accident demonstrated the quality of the metal-ceramic seals in the window and cathode leads which all tested vacuum-tight after the tube was cut off the system. It also revealed the need for improvement of the mechanical design of the cathode lead mount to accommodate the large stresses developed in the joint between two metals having different expansion characteristics. A new design has been successfully tested at 750°C for several hours on the vacuum system.

MF-8B magnetron, now being assembled, will incorporate this design change, as will future magnetrons.

A quantity of the Sealmet No. 1 chrome-steel tubing mentioned in the Quarterly Progress Report, July 15, 1950 has been received and made up into cathode lead spinnings. The higher chromium content in this alloy gave some difficulty in fabricating and nickel-plating the spinnings as compared with 430 stainless steel.

b. Thoria cathodes

A new thoria cathode test diode incorporating tantalum end mounts platinum-brazed in pure helium is on the vacuum pumps and has been baked out. After the processing of the diode is complete, significant data are expected on cathode heating power and emission. Life testing will reveal the adequacy of the present solution to the cathode mounting problem.

c. Auxiliary equipment

As a result of the failure of the temperature control of the vacuum system during bakeout of the MF-7B magnetron, the vacuum system control circuits have again been revised. The oven control relay has been replaced with a heavy-duty contactor, and the switching circuits involving the temperature controller have been simplified. The pressure recorder has also been made more reliable by separating the signal circuit from the range switching circuits, and connecting it to the potentiometer circuit by means of a two-wire shielded cable. The block diagram in Fig. VII-1 indicates the control and protection loops in the present system.

Construction of a new baking oven has been completed. The insulation is sufficient to maintain a temperature of 750°C with a power input of 2500 watts and a forming gas

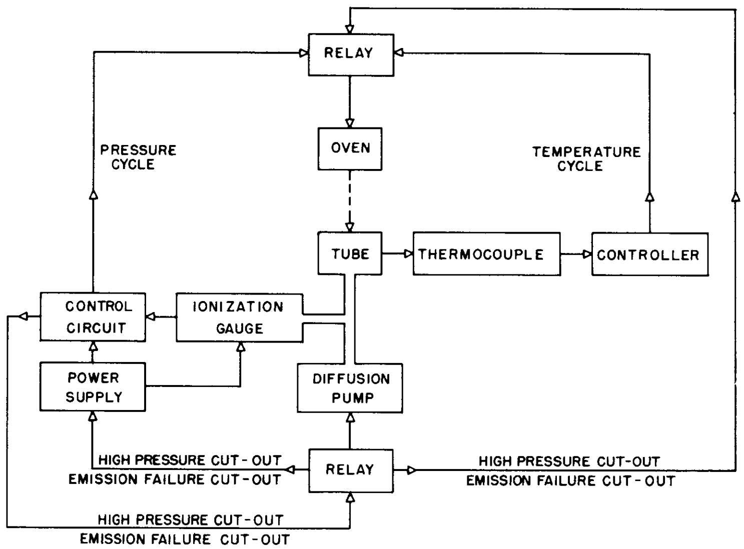

Fig. VII-1 Simplified block diagram of tube processing control circuits.

or nitrogen atmosphere. Maximum input to the oven is 5000 watts at 115 volts a-c.

The copper pumping lead stem has proved to be unreliable after the several brazing operations required to connect the tube and test joints to the vacuum system, together with baking at 750°C. To overcome this difficulty a demountable pumping lead stem made of stainless steel has been designed and is under construction. Completion is expected in time to process the next magnetron. The new lead stem will have a larger diameter than the previous one in order to secure higher pumping speed.

A demountable joint made from stainless steel with an OFHC copper gasket similar to a design first tried by L. P. Garner and P. T. Smith in 1940 has been baked at 750°C until the pressure reached 1.5×10^{-6} mm Hg. The joint was firmly welded together after this treatment, which leads to some additional minor complications in setting up the vacuum system.

The glass parts of the pumping system have been disassembled for cleaning, and to permit the use of larger diameter tubing to match the new lead stem design.

Baking tests with a dry nitrogen atmosphere have shown this gas to be a satisfactory and readily available replacement for forming gas. Although the hydrogen in the forming gas is desirable for its property of cleaning the copper tube surface, it has the disadvantage of diffusing through the stainless steel and Kovar parts of the magnetron at high temperatures, thereby limiting the minimum bakeout pressure.

In order to simplify the maintenance problem during continuous high-temperature baking, a five-cylinder portable gas manifold has been secured and installed near the tube processing bench. This arrangement will provide sufficient dry nitrogen for a minimum of nine days of continuous operation without changing cylinders.

Tests of a 60-foot length of 25-ohm experimental high power pulse cable will be made as soon as appropriate connectors have been designed and built. This cable was manufactured especially for this project by the American Steel and Wire Company at its Worcester plant through the courtesy of Mr. Victor Siegfried. The insulator bushings for the connectors have been received and the design is on the drafting board. The new cable is expected to replace the present parallel connection of two 50-ohm cables, and to improve the transmission of the high-power modulator pulse to magnetrons on the test bench.

2. Magnetron Research

a. Noise properties of the pre-oscillating magnetron

Several equipment problems in the noise test circuits have now been solved. More remain. At present, efforts are being made to reduce the noise level in the system in order to extend the region of reliability in which the noise output of the magnetron can be measured.

The output section of the insulated-end-cap magnetron mentioned in the Quarterly Progress Report, January 15, 1950, has been redesigned. The new design eliminates torch-soldered joints in the tube assembly and uses seam-welded vacuum seals which have given successful results on the high power magnetron and the thoria cathode test diode. This design also reduces the danger of damage to the glass-to-metal seals during tube assembly.

Electrically, the output section is identical with that of the Raytheon QK61 magnetron. Parts for the tube are under construction.

B. MICROWAVE TUBES

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Prof. L. J. Chu	G. Guilbaud	H. E. Rowe
A. W. Boekelheide	H. J. Krusemeijer	L. Stark

1. Noise and Space Charge Waves

The differential equation for convection current density, reported in the Quarterly Progress Report, July 15, 1950, has now been solved for arbitrary d-c space charge conditions, so that we find the convection current is

$$J = \left(\frac{A\sqrt{v_o + b}}{v_o} + \frac{b}{v_o} \right) e^{-j\omega T}$$

where A and B are arbitrary constants, v_o is the d-c velocity at the point Z, T is the transit time from the potential minimum (Z = 0) to Z, $b = \epsilon\eta C_1/2J_o$, and $C_1^{1/2}$ = electric gradient at Z = 0, where $v_o = 0$. This reduces to the previously reported solution for space charge limited flow if we let $v_o = kZ^{2/3}$ and $C_1 = b = 0$.

The kinetic power flow has been investigated and it has been shown that the a-c kinetic power $(3/2)\,(v_o/2\eta)\,\mathrm{Re}\left[v_1 \cdot J^*\right]$ is conserved under all possible variations in the d-c conditions, in the small-signal, single valued velocity, one-dimensional case. The usual noise analysis indicates a complete space charge standing wave in the drift tube between gun and helix, which means there is no a-c kinetic power. Future work will be directed toward getting a better theoretical understanding of the cathode phenomena to determine whether any a-c power is really given to the electron stream. Apparatus is being constructed to repeat Cutler's and Quate's measurements of noise space charge waves to determine whether the finite standing wave ratio which they measured was due to extraneous noise sources (partition noise), or was really due to noise power being propagated along the stream.

L. J. Chu, L. D. Smullin

2. 3-Cm Pulsed Traveling Wave Tube

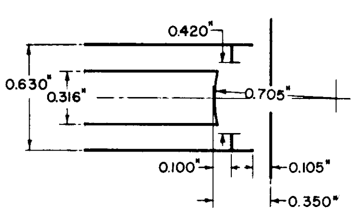

Fig. VII-2
10 kv, 0.5 ampere gun.

A tube is being designed for high pulse power operation in the 3-cm band. A tentative specification of 500 watts pulse output has been set. A duty ratio of about 1/100 will keep the collector power reasonably small.

A gun shown in Fig. VII-2 has been designed to operate at 10 kv and produce a beam of 0.5 amp, 0.100 inch in diameter. One test model has just been completed, and gave 0.55 amp at 10 kv. The spot size was measured on a movable carbonized paper target, and its minimum value was about 0.080 inch.

Studies are being made of various helix geometries to find one that will give a good compromise between low dispersion and high impedance. Apparently no data are available for the effect of a dielectric shell outside a wire helix (as distinct from a helical sheath) where $v/c \simeq 0.2$. The experiments in Technical Report 93, Research Laboratory of Electronics, refer to values of $v/c \leqslant 0.1$ and there is no simple way of extrapolating these results to higher velocity helices with different ratios of wire diameter to helix diameter, or to pitch.

G. Guilbaud, L. Stark

3. Traveling Wave Tube Used as a Mixer

One of the 1000-volt, 1-ma, 3-cm tubes is being tested as a heterodyne converter. Both the signal and local oscillator are fed onto the helix from the input waveguide, and the beat frequency is taken off the collector electrode and fed into an i-f amplifier.

Measurements of conversion efficiency (input r-f power vs output i-f volts) are being made with various levels of local oscillator power. Preliminary measurements indicate that the conversion efficiency varies sharply with LO power, and the optimum value of this power is the one corresponding, roughly, to the knee of the curve for r-f output vs r-f input.

Quantitative results will be presented in the next report.

C. J. Brown

4. 3-Cm Traveling Wave Tubes

Since the last report, nine 3-cm traveling wave tubes have been built with net gains ranging between -5 db and $+22$ db; only one tube had the highest value.

The glass tube which supports the helix assembly is now shrunk on drill rod and ground accurately to size.

Low gain seems to be caused by helix nonuniformity or by too high loss. The loss, obtained by spraying aquadag on the supporting rods, is difficult to control.

Additional difficulties which are now being considered concern the mechanical mounting of the tubes in their magnets, and leakage to the anode. This leakage, which has appeared in a number of the recent tubes, is never detectable before the cathode is activated. It disappears when the tube is opened to air.

E. Muehe, H. Rowe

5. Operation of Pulsed Magnetrons into a High Q Load

The experiments outlined in the Quarterly Progress Report, July 15, 1950, have been largely completed. We used a 4J33 untunable magnetron whose operating frequency in a matched load was in the center of the external cavity tuning range.

The microwave circuitry arrangement is schematically drawn in Fig. VII-3.

When measurements without a ballast load were made, the slug tuners and matched load were removed and the external cavity placed a quarter wavelength to the right of the EE plane on the end of the waveguide. In working without a ballast load the waveguide system was pressurized with air up to 3 atm to prevent sparking in the waveguide. Some frequencies at which the magnetron operates without a ballast load, as a function of the distance ℓ between the equivalent planes of magnetron and cavity are listed in Table I.

Table I

$\frac{11(\lambda_g - 1)}{4} - \ell$ in cm	Wavelength in vacuum in cm	Modulator voltage in kv
0	10.585	19
0	10.810	19
0.4	10.785	19
0.9	10.766	18
1.4	10.744	19
1.9	10.736	18
2.5	10.724	19
2.9	10.714	18
3.5	10.708	19
4.2	10.702	19
7.0	10.634	19

In this table the operating wavelength of the magnetron is given as a function of the line length. The magnetron operating wavelength while working in a matched load was found to be 10.70 cm at 18 kv. Tuning of the external cavity did not change the magnetron wavelength more than 0.02 percent. The listed modulator voltages are such that the magnetron just did not spark internally. These results show that when $\ell = n\lambda_g/2$, the magnetron frequency is different from that under the matched load condition. If $\ell = n\lambda_g/2 - \lambda_g/4$, the magnetron works on the right frequency and the cavity is excited but the power level is very low because of the magnetron sparking.

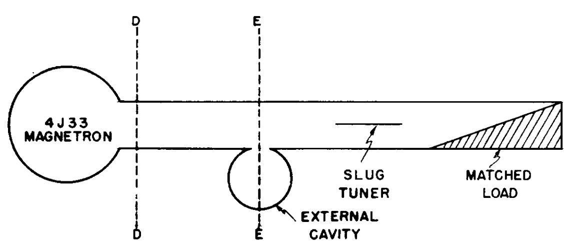

Fig. VII-3 Circuit for coupling magnetron to a high Q cavity.

Subsequently the admittance was calculated for the microwave circuitry as seen by the electron stream. The calculations are based on the lumped constant model of the arrangement in Fig. VII-3 as sketched in Fig. VII-4. The following assumptions were made during these calculations: (a) The transducer AADD is lossless and its elements are independent of frequency in the explored frequency range. (b) The line between magnetron and external cavity is uniform and lossless. (c) The cavity attached to the side of the waveguide with its iris of finite thickness can be represented at the middle of the waveguide as a series LCR circuit. (d) The ballast load is so adjusted that it appears as a frequency-independent pure conductance at the waveguide plane EE (Fig. VII-3).

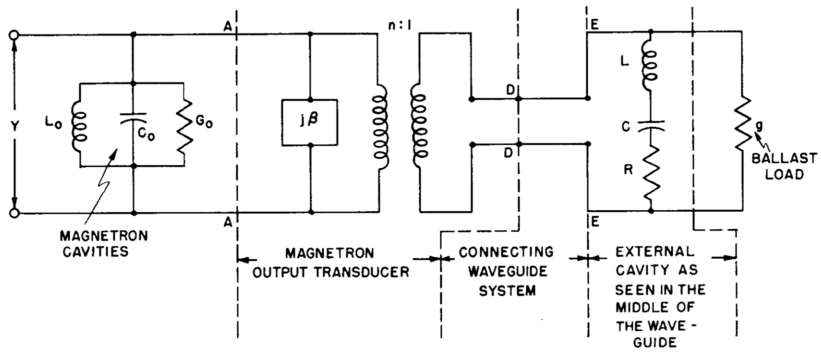

Fig. VII-4 Lumped constant equivalent circuit of Fig. VII-3.

The admittance Y of the circuitry as seen by the electron-stream was found to be

$$\frac{Y}{\omega_o^1 C_o} = \frac{1}{Q_u} + \frac{1}{Q_{E_1}} \cdot \frac{\alpha\delta^2 + \beta}{\gamma\delta^2 + (\beta - \xi\delta^2)^2} + j\left[2(\delta - \delta'') + \frac{1}{Q_{E_1}} \cdot \frac{\zeta\delta + \eta\delta^3}{\gamma\delta^2 + (\beta - \xi\delta^2)^2}\right] \cdots \qquad (1)$$

with $\alpha = (g+1)Q_{E_2}^2 + 4g\,Q^2$; $\beta = g + 1$; $\gamma = (Q_{E_2} + 2qQ)^2$; $\zeta = (g^2 + 2g)Q_{E_2} + 2Q$; $\eta = Q_{E_2}\,Q\left[-2Q_{E_2} - 4(1 - g^2)Q\right]$; and $\xi = 2Q_{E_2}\,Q$. Q_{E_1} is the external q for the magnetron cavity while working into a matched load. $Q_{E_2} = \frac{2\pi\ell K}{\lambda_{go}}$; $\ell = \frac{(2n-1)\lambda_{go}}{4}$; $n = 1, 2, \ldots < 8$; $K = \left[1 - \left(\frac{\lambda_o}{\lambda_c}\right)^2\right]^{-1}$; λ_o is the resonant wavelength of the external cavity. λ_c is the cut off wavelength of the waveguide. $\delta = \frac{(\omega - \omega_o)}{\omega_o}$; $\omega_o = 2\pi \times$ resonant frequency of the external cavity. Q is the measured unloaded q of the external cavity; $\delta'' = \delta - \delta'$; $\delta' = \frac{\omega - \omega_o^1}{\omega_o^1}$; ω_o^1 = angular resonant frequency of the magnetron cavity.

In Figs. VII-5 and VII-6 are plotted the imaginary against the real part of $\frac{Y}{\omega_o^1 C_o}$ as a function of frequency for $Q = 15,600$; $Q_{E_1} = 85$; $Q_u = 900$; $n = 6$; $\lambda_{go} = 16$ cm; $K = 2.3$; $g = 0.02$ for Fig. VII-5 and $g = 1$ for Fig. VII-6. Q_u and Q_{E_1} were determined

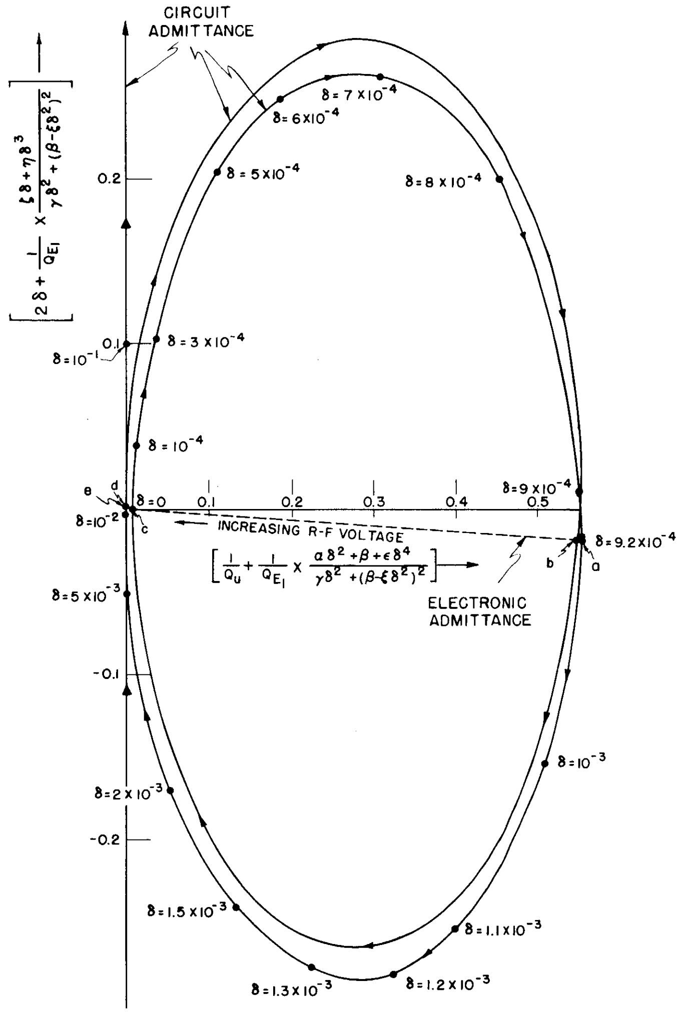

Fig. VII-5 Circuitry admittance curve for g = 0.02, Q = 15, 600, Q_{E_1} = 85, Q_{E_2} = 38, Q_u = 900.

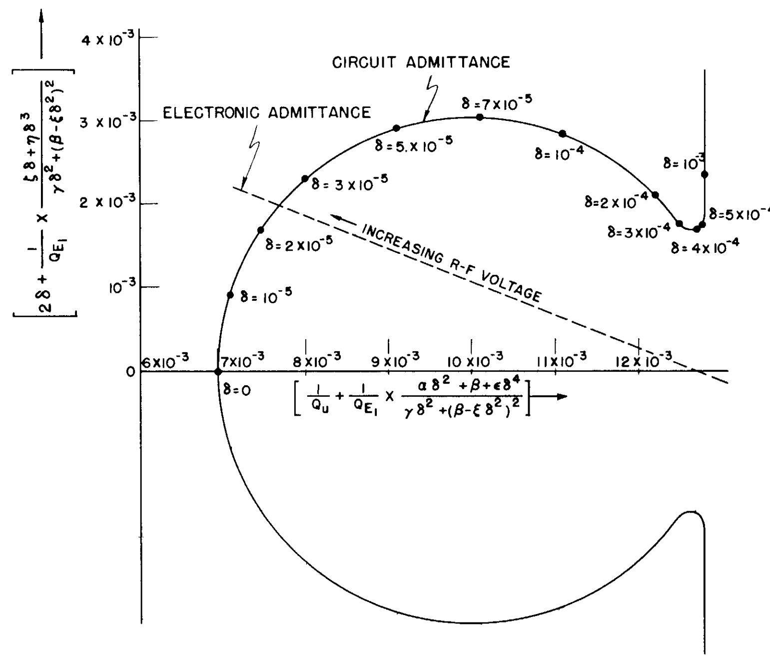

Fig. VII-6 Circuitry admittance curve for g = 1, Q = 15, 600, Q_{E_1} = 85, Q_{E_2} = 38, Q_u = 900.

from cold measurements on the magnetron. The intersections of these curves with the curves of the negative susceptance multiplied by $(\omega_o^1 C)^{-1}$ vs negative conductance of the electron stream multiplied by $(\omega_o^1 C)^{-1}$ give the possible operating points of the magnetron with real frequencies. The admittance curve for the electron stream was not determined for the magnetron used but it is known that a straight line, as drawn in Figs. VII-5 and VII-6, is a good approximation. The parameter on this curve is only the r-f voltage on the vanes of the magnetron, because in the small frequency range that we are investigating, the behavior of the electron stream is frequency-independent. The negative electronic admittance curve intersects the abscissa in the point $1/Q_u + 1/Q_{E_1} + 2j\delta''$.

We shall call an oscillation stable against its own transition when the oscillation will try to restore its original amplitude if for some reason the amplitude of this oscillation is changed. The criterion that an oscillation with a real frequency corresponding with an intersection point is stable against its own transition is that the angle over which the tangent to the circuitry admittance curve pointing in the direction of increasing frequency has to be turned, to give it the same direction as the tangent of the negative electron stream admittance curve pointing to increasing voltage, is smaller than π (see reference 1). In Fig. VII-5 only the intersections c, d and e are stable in this respect. The intersections with negative susceptance are unstable.

For every fixed value of Y in Eq. 1 there are five real or complex values for δ, corresponding with real or complex frequencies. If the complex frequency at intersection c had a negative imaginary part, a second mode with increasing amplitude would be possible at intersection c with the consequence that the admittance point on the electronic admittance curve would move to the left; that is, to intersection d or e depending on the stability of d. Because of the nonlinear behavior of the electron stream the different modes are coupled, and one mode loads the other modes in proportion to its amplitude. The mode which can establish itself first has the best chance.

The oscillation corresponding with the real value of δ in Fig. VII-5 has a frequency in the absorption band of the cavity and for that reason will store the most energy in the microwave circuitry so that it will build up comparatively slowly. There is a reasonable agreement between frequencies in the table and the ones corresponding with intersections of type d just below or above the abscissa. When the admittance curve of the circuitry as a whole moves up a little or the negative electronic admittance curve moves down, so that intersection d becomes a point on the abscissa, then two oscillations with real frequencies are possible for this point. This is in agreement with the observation that, at a certain distance between the equivalent planes of magnetron and cavity, two oscillations are possible. This phenomenon may be used to determine accurately the equivalent planes of magnetrons.

The sparking which began at rather low voltage levels may be explained by noticing that intersection d corresponds to a higher r-f voltage on the magnetron vanes than when the magnetron works in a matched load. This may cause an r-f spark between the magnetron vanes which starts the spark between cathode and anode. In Fig. VII-6 the admittance curve of the circuitry is drawn for g = 1. Operation in the right mode is possible here (2).

Experiments have been made in which the characteristics of the circuitry were altered during a pulse by using a gas discharge. First, the magnetron is allowed to start in the proper mode, using a ballast load as in Fig. VII-3, and Fig. VII-6 applies. When this mode has reached a sufficient amplitude, the load is short-circuited by a gas discharge across the waveguide. This discharge is in a quartz tube about 3/4 λ_g from the cavity, so that when it fires Fig. VII-5 applies. Preliminary experiments indicate that if the discharge occurs at the right time, the magnetron continues to operate in the right mode, and builds up still further. The time of discharge is controlled by the pressure in the tube, and about 7 cm Hg of air seemed to be the best value using this scheme; the peak power in the cavity was about 1.6 times greater than with a matched ballast load and no switch. It was also found that the magnetron could be pulled over at least the entire tuning range of the cavity (3/4 percent) when the switch was used.

References

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2. J. C. Slater: Microwave Electronics, Bell Telephone Laboratories Series (D. Van Nostrand Co., New York, 1950) p. 199.

H. J. Krusemeijer

C. HIGH-ENERGY ELECTRON SOURCE

A pulse transformer for operation at one million volts and a 10-amp peak pulse current, similar to a design by the University of California at Berkeley, was built during the summer by H. Haus. The unit is built of aluminum foil windings, with a nonmagnetic core, and is enclosed in a bakelite case filled with deaerated 10C insulating oil.

This transformer was successfully tested, unloaded, and was found to deliver an open circuit pulse of approximately 600 kv with a primary input of 8.7 kv, at a pulse-repetition frequency of 80 pps. The voltage was limited by the maximum output of the particular line-type modulator that was used, and it is believed that the figure can be exceeded when a larger modulator designed especially for this particular system is built.

Recent work has been confined to the design of a diode of the Pierce-gun type as a load for the transformer. The design has now been completed, and construction of the tube has begun. A cut-away section of the transformer and tube is shown in Fig. VII-7.

The glass-enclosed section of the tube will be inserted in the transformer case and

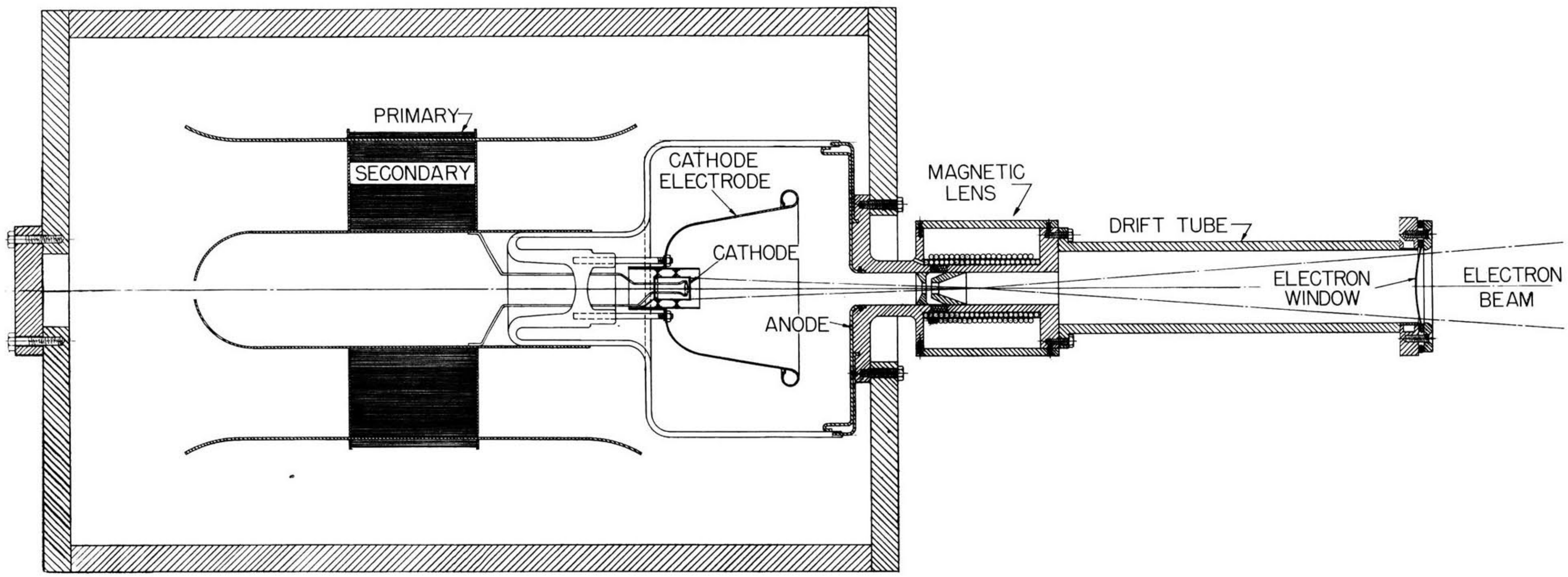

Fig. VII-7 High-energy electron source.

surrounded by oil. The electron beam emitted from the negative cathode of the Pierce gun will be accelerated by the grounded anode, converged by the magnetic lens, and allowed to pass its focal point in the cylindrical drift tube. It ultimately will diverge until it reaches a current density small enough to be passed through the 0.001-inch thick stainless steel window from the evacuated tube into the atmosphere. A considerable amount of heat must be dissipated by this window, as, even with a duty ratio of 0.5×10^{-3}, it will absorb 13 watts/cm^2 of time-average power. This will require the window to be operated at a temperature of 650 C.

Various applications can be made of such an electron beam, once it is produced and released. Among those which have been tested in other laboratories and shown to be practical are use in therapy, in which the effects of an electron beam can be concentrated below the surface to produce less skin damage than corresponding X-rays (1); in food sterilization after packaging (2); and in radiography, in which, as in therapy, more internal penetration with less surface effect than with X-rays can be obtained. The expected advantages of the proposed source over those already in existence will be its much smaller size and weight and a considerably lower production cost.

References

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