Beam-Deflection MIXER TUBES for UHF

Deflection techniques applied to a mixer tube may permit operation of a television receiver up to 900 megacycles with performance superior to that of present receivers in regard to signal-to-noise ratio, oscillator radiation and gain

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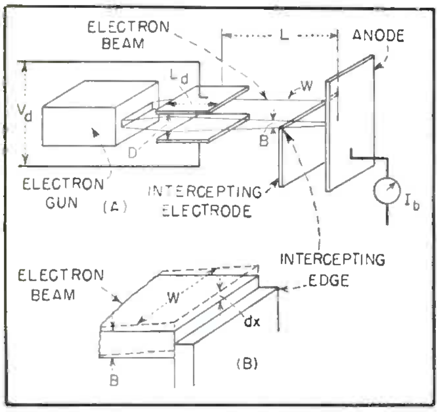

FIG. 1—Simplified beam-deflection tube: (A) schematic view; (B) enlarged view at intercepting edge

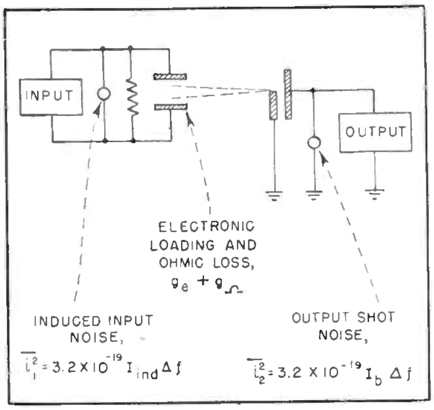

FIG. 2—Equivalent circuit of beam-deflection tube with noise generators and input resistance indicated

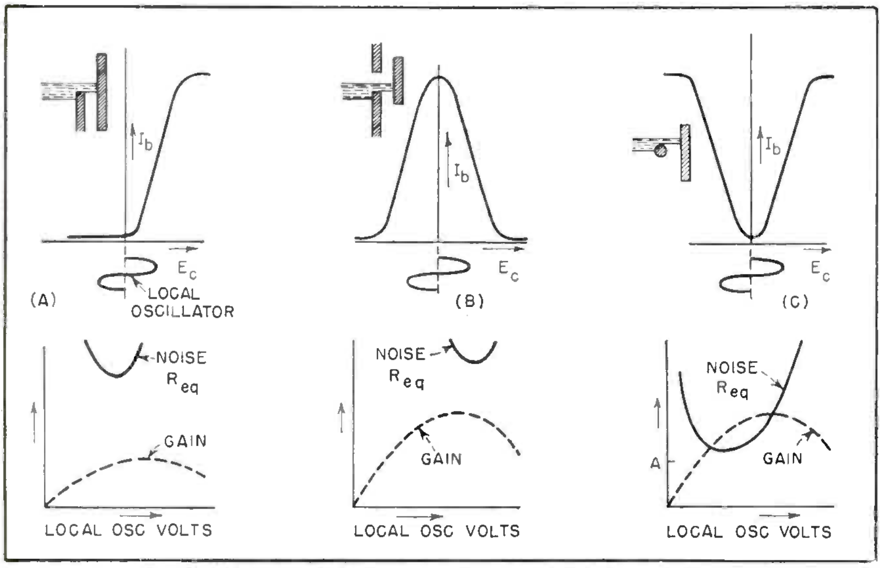

FIG. 3—A comparison of three methods of design and mixer operation for beam-deflection tubes. The method at the right gives high gain and an equivalent noise resistance not very different from that of amplifier operation, shown at *A*

AMPLIFIER AND MIXER tubes using beam deflection have been proposed in the past but the development to be described is among the few which appear to have marked advantages over more conventional tubes at the higher frequencies.

The present work started[1] because of an interest in multistage secondary-emission amplifier tubes, which require a higher ratio of transconductance to current than can be obtained with grid control. It was later found that beam-deflection tubes were advantageous by themselves, particularly for achieving a high signal-to-noise ratio independently of the use of a secondary-emission multiplier. Since it had already been shown that beam-deflection control was particularly well suited for superheterodyne mixer tubes,[2] this method of operation was given most attention.

Beam-Deflection Control

The general principles of beam-deflection control for amplifiers are perhaps most easily understood by reference to Fig. 1A, which shows a simplified beam-deflection tube. An electron gun forms a beam of rectangular cross section which passes between two deflection plates and is focused onto an intercepting edge. When deflection occurs, more or less current reaches the output anode so that an input V_d, which is applied between the deflection plates, causes a change in output current. Modifications, such as either a suppressor for secondary electrons, or use of an electron multiplier ahead of the anode, or addi-

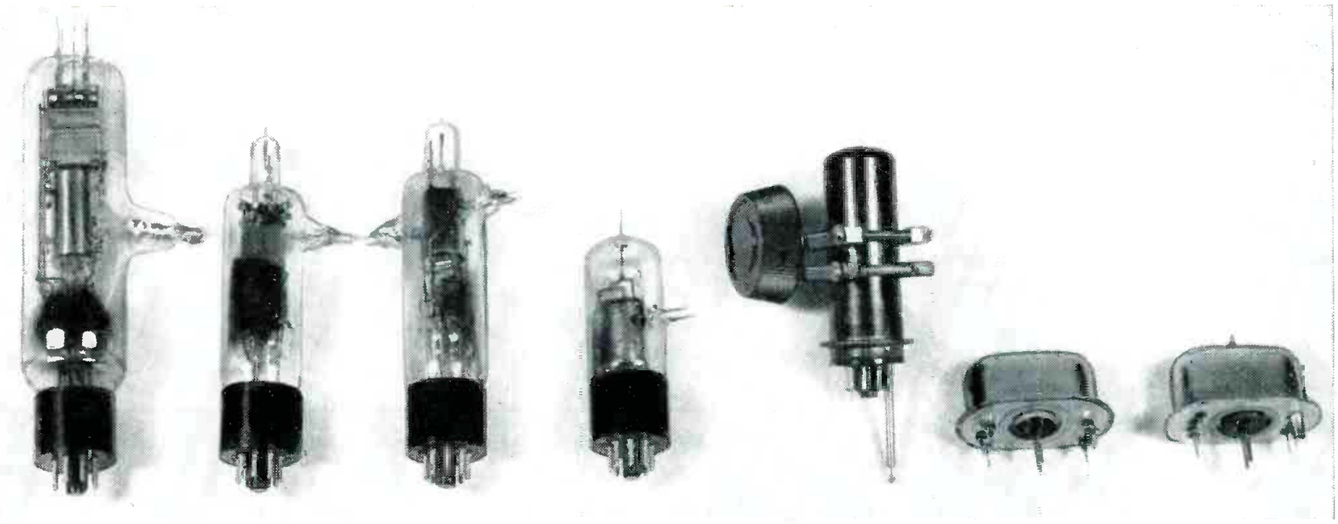

FIG. 4—Group of experimental beam-deflection tubes

tional pairs of deflection plates, are not shown but can be advantageously incorporated.

The reason a rectangular beam is used will be seen from Fig. 1B which indicates how the transconductance of such a device can be determined. The drawing shows an enlarged view of the electron beam as it reaches the intercepting edge on which it is focused. When the beam is deflected a small distance, dx, at the intercepting edge, a cross-sectional area, $W\ dx$, of beam is allowed to pass. This leads to an incremental change in anode current dI_b, which is the product of this area and the current per unit area, j_i, otherwise called the current density: thus

$$dI_b = j_i\ W\ dx.$$

Dividing this expression by the incremental deflection voltage, dV_d, gives the transconductance

$$g_m = \frac{d\,I_b}{d\,V_d} = j_i\ W \frac{dx}{d\,V_d} = j_i\ W\ S \qquad (1)$$

where S is the deflection sensitivity.

The total current in the beam, $I_{b\max}$, is the product of the entire beam area with the current density j_i

$$I_{b\max} = j_i\ W\ B \qquad (2)$$

Although j_i may vary across the beam thickness, the equation is made valid by defining B as an *effective* thickness and letting j_i represent the current density at the center of the beam. It is seen that the ratio of transconductance to current is S/B, which is independent of everything except deflection sensitivity and effective beam thickness. To appreciate the significance of this, it must be remembered that for ordinary grid control the initial velocity distribution of electrons limits the ratio of transconductance to current to a value of about 10 volts^{-1} theoretically, and 1 to 3 volts^{-1} practically. Beam deflection tubes, on the other hand, have been made to have a ratio of several hundred and are limited only by the practical difficulties of aligning a thin beam.

From Eq. 1, it is seen that the important factors in determining the transconductance are the beam width, W, and the current density j_i. To maximize these, the pencil-like beam and spherical lens optics of the cathode-ray or television picture tube is replaced in the present case by a rectangular beam with cylindrical optics to produce a high current density image. It is known[3] that the maximum achievable current density for a line focus is limited by the distribution and random direction of initial velocities of electrons from the thermionic cathode to approximately

$$j_{\max} \approx j_0 \frac{2}{\pi^{1/2}} \left(\frac{e V_0}{k T_k} \right)^{1/2} \sin\theta \qquad (3)$$

where j_o and T_k are current density and temperature of the thermionic emitter, V_0 is the beam voltage at the focus and θ is the angle (from the axis) at which the beam converges upon the focus point. For practical deflection tubes, which have a lens system and deflection plates between the object and image (see Fig. 1) θ will be small and cannot exceed $D/2L$ where D is the deflection-plate spacing and L is the distance from the deflection plates to the focus point (the "lever arm" of the deflection system). Thus, for an oxide-coated cathode at 1,000 K, Eq. 3 reduces to approximately

$$j_{\max} \approx 1.9\, j_0 \frac{D}{L} V_0^{1/2} \qquad (3A)$$

The low-frequency deflection sensitivity, using a modification of a standard formula,[4] is

$$S \approx \frac{L\,L_d}{2\,D\,V_0} \left(\frac{V_0}{V_1} \right)^{1/2} \qquad (4)$$

where L_d is the length of the deflection plates (assumed short compared to L), and V_1 is the average voltage of the deflection plates, while V_0 is the voltage of the subsequent parts of the system. Using Eq. 3A and 4 in Eq. 1, the maximum low-frequency transconductance becomes

$$g_{\max} \approx 0.95 j_0\, W \frac{L_d}{V_1^{\ 1/2}} \qquad (5)$$

This is independent of deflection-plate spacing and lever arm length but does depend on L_d, the deflection plate length.

For the higher frequencies, it is found that the useful length of the deflection plates is limited by the transit time. If this time is longer than one-half period of the applied frequency, the deflection field reverses during the time of transit and begins to cancel the deflection markedly. At a transit time equal to one-half period, the deflection is already down to a little over half that of Eq. 4 above.[1] Since the transit time in seconds over the length L_d (in cm) is given by $\tau = 1.7 \times 10^{-8} L_d/V_1^{\frac{1}{2}}$, if we let this equal one-half of the period of the applied frequency, f, the $L_d/V_1^{\frac{1}{2}}$ in Eq. 5 is replaced by a quantity proportional to the reciprocal of frequency. Inserting this quantity in Eq. 5, and putting in the proportionality constant which includes the approximate loss in deflection, gives

$$g_{\max} \approx \frac{18\, j_0\, W}{f_{\mathrm{mc}}} \text{ mhos} \tag{6}$$

where j_0 is in amperes per cm², W is in cm, and the frequency is in megacycles. When a beam-deflection tube is used as a mixer, the best conversion transconductance is between 50 and 60 percent of this amplifier transconductance (see later discussion).

It is worth examining Eq. 6 to determine the practical limitations on the quantities which are contained in it. These may be listed as follows: (1) The oxide-coated thermionic cathode limits the transconductance both through its temperature (which appears in the multiplying constant) and through its current density, j_0, which has an upper limit depending upon the life desired from the tube. (2) The beam width, W, is limited to such values which can still be aligned with an intercepting edge. (3) The deflection plates cannot practically be made as long as desirable for the lower radio frequencies because of contact potential variations over their surface, which produce random deflections and distort the beam. Thus, one cannot attain the transconductance of Eq. 6 at low frequencies. (4) One cannot ordinarily use a beam which grazes the deflection plates, as required by the derivation above, because of electron-optical aberrations and because, at high frequencies, there is then a serious increase in noise induced in the input circuit by the beam.

Signal-to-Noise Ratio

The fluctuation noise generators are shown in Fig. 2, in which the output noise is shown as the same as the temperature-limited shot noise formula.[5] Some of the early tubes had noise in excess of this due to a new phenomenon called "space-charge interaction noise" which was substantially eliminated by a reduction in beam length in the later designs. As in all tubes at high frequencies, a second major source of noise is found in the interaction of the beam with the input (deflection plates). Fortunately, when a balanced input circuit is used, the noise effects are largely balanced out and the equivalent shot-noise current, I_{ind} of Fig. 2, is of the order of only 10 percent or less of the beam current. Since the beam current itself can be made small without loss of transconductance, this gives the deflection tube a large advantage over grid control or velocity - modulation tubes.

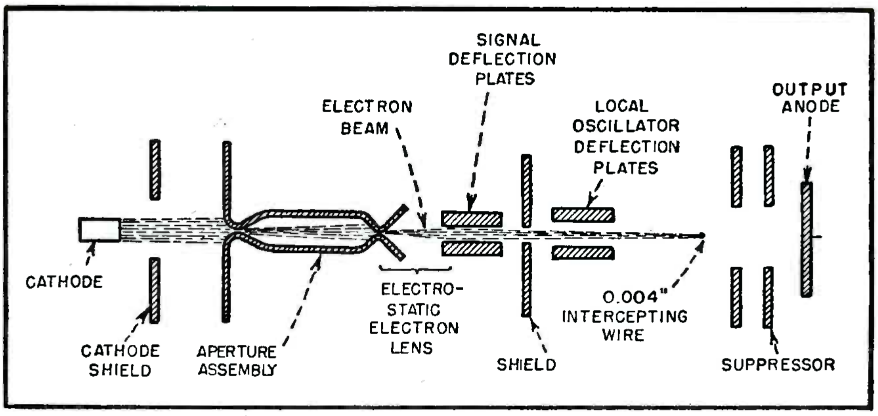

FIG. 5—Schematic cross section of double-deflection, nonradiating mixer tube

Since the signal-to-noise ratio is also dependent on the input resistance, Fig. 2 also shows this as a resistor comprised of the parallel electronic input conductance g_e and the ohmic conductance (due to circuit loss g_ω. The former is ordinarily negligible in comparison with the latter because of the small beam currents, which is again in contrast to conventional tubes. In beam tubes, there is no relation between the electronic loading and the induced input noise in a balanced input circuit.

The signal-to-noise ratio is best expressed in terms of the noise factor, which depends chiefly on the ratio of equivalent noise resistance to input resistance.[6] The former is given by

$$R_{\mathrm{eq}} = \frac{2\, e\, I_b}{4\, k\, T_R\, g_m^2} = \frac{20\, I_b}{g_m^2}$$

where T_R is room temperature. As an amplifier, maximum transconductance will occur when the beam is split in half by the intercepting edge so that $I_b = \frac{1}{2} I_{b\max}$ and

$$R_{\mathrm{eq}}\Big]_{\text{amplifier}} = \frac{10\, I_{b\max}}{g_m^2} \tag{7}$$

In the experimental tubes, values of equivalent noise resistance of the same order as conventional amplifier tubes were obtained but with very much higher input resistance and much lower capacitances.

Mixer Operation

Figure 3 shows three possible ways of designing and operating the beam-deflection tube as a mixer, assuming additive deflection by signal and local-oscillator voltages. Their characteristics can be calculated by one of the usual methods.[7] Figure 3A is the conventional method, which leads to low gain and high equivalent noise resistance. By use of an aperture and phase-reversal conversion, the gain limitation can be overcome as in Fig. 3B, whereas the use of an intercepting wire as in Fig. 3C allows both low noise and high gain to be achieved.[8] For the latter case, Fourier analysis shows that the average mixer anode current is only 17 percent of the beam current and the conversion transconductance is 50 percent of the amplifier g_m. Thus

$$R_{\mathrm{eq}}\Big]_{\text{mixer}} = \frac{20\, I_b}{g_c^2} = \frac{14\, I_{b\max}}{g_m^2} \tag{8}$$

which is only 1.5 db higher than the amplifier value of Eq. 7 (point A in Fig. 3C). This is very remarkable compared with conventional mixer tubes which always have much poorer signal-to-noise performance than amplifier tubes. In the present instance, experimental work was done on both amplifier and mixer beam-deflection tubes but, since it was found possible to overcome all the major disadvantages of the mixer, this type was emphasized.

Experimental Tubes

A photograph of some of the tubes which were made is shown in Fig. 4. At the extreme left is an early amplifier tube with a multistage electron multiplier. An experimental tube similar to the one in the photograph, but with a 5-stage electron multiplier, was built before the war[1] and had a transconductance of 100 milliamperes per volt, a plate current of only 5 milliamperes, an input capacitance of only 1.5 μμf, and an output capacitance of 3.5 μμf. Such a tube is capable of amplifying a band of 300 mc with a gain of 10, which is about thirty times as good as a conventional 6AK5.

The next two tubes in the photograph are early mixers and amplifiers using one-stage multipliers and particularly designed for high signal-to-noise ratio in the 300 to 1,200-megacycle range. The fourth tube is the type 1636, a 400-600 megacycle mixer which was produced for a time during the war but is now found only on surplus lists. The large metal tube is a 10,000-megacycle mixer with a built-in resonant cavity and a multiple deflection system consisting of tiny wires. Work at this frequency was slowed up when crystal mixers became so successful. The last tube, at the right, is a recent experimental tube for 300-1,500 megacycles in which local-oscillator radiation was eliminated. This tube is illustrative of the more recent type of experimental construction which has been used and so will be described in detail.

Deflection Elements

Figure 5 shows a cross-sectional view of the electrode arrangement. Two sets of deflection plates are used, the first pair for the signal and the second for oscillator voltage. One of the unique advantages of beam deflection is that such a separation is possible without loss in signal-to-noise ratio, such as occurred when pentode mixers were replaced by pentagrid mixers and converters. A shield between the two sets of deflection plates eliminates all coupling except a negligible amount through the central aperture. The signal plates are brought out through a pair of heavy parallel leads, in balanced fashion, while the oscillator deflection leads are brought out through a coaxial arrangement.

The electron gun is composed of a cathode and two narrow slits operated at +300 volts with respect to cathode. The electrostatic field between the last of the slits and the first set of deflection plates (which are at +140 volts, approximately) is used as a lens and focuses the beam. The second pair of deflection plates are again +300 volts, as is the intercepting wire, which is used in accordance with the discussion of Fig. 3 and is only 0.004 inch (0.01 cm) in diameter. The two small apertures allow a thin beam about 0.6 cm wide and 0.01 cm in thickness to enter the lens region. The deflection plates are made sufficiently short (the effective length is 3 mm) so that the transit time is about ½ period at around 1,200 mc.

To minimize lens aberrations and induced noise, the beam occupies only about ⅓ of the spacing between deflection plates. It is of interest that the input capacitance is only a little over 1 μμf, most of which is in the leads.

This tube uses a suppressor and output anode, since no electron multiplier is needed to obtain the required performance. Since the war, tubes of similar construction have been made with very small two-stage and four-stage electron multipliers; they are similar in performance and external appearance to the right-hand tube in the photograph, except for much higher gain.

It is of interest to compare the performance of such a tube, without multiplier, with the theoretical values derived above. The cathode current density was about 150 ma per cm^2 and the beam current through the two fine slits was 200 microamperes. If the deflection plates are placed at minimum spacing, so that they are grazed by the beam, Eq. 5 shows that

$$g_{\max} = 0.95 \times 0.150 \times 0.6 \frac{0.3}{140^{1/2}}$$
$$= 2.2 \text{ ma per v.}$$

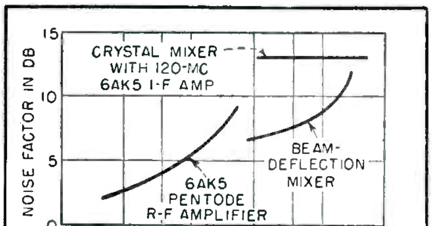

FIG. 6—Comparative noise factors as a function of frequency

Since the deflection plates actually were spaced by about 3 times the grazing distance, we would expect about ⅓ of this or 0.7 ma per v. This is approximately the very best of the measured low-frequency values, but the average of a number of tubes is about 0.5 ma per v. The theoretical 1,200-megacycle value (Eq. 6) is about 60 percent of these figures, due to the transit-time loss.

Using Eq. 8, the mixer equivalent noise resistance of an average tube at 1,200 megacycles is computed to be 30,000 ohms. Since the input equivalent shunt resistance (which was almost entirely due to lead loss) was independently measured to be of the order of 20,000 ohms, if the induced noice is assumed to be about 10 percent of the shot noise in the entire beam, the minimum noise factor (using Eq. 30 of Reference 6) is

$$F_{\text{calc}} = 1 + 2\frac{R_{\text{eq}}}{R_{\text{in}}} + 2\sqrt{\left(\frac{R_{\text{eq}}}{R_{\text{in}}}\right)^2 + \left(\frac{R_{\text{eq}}}{R_{\text{in}}}\right) + 20\, I_{\text{ind}}\, R_{\text{eq}}}$$
$$= 12 \text{ (or 10.8 db)}$$

This is within a few tenths of a db of the average of measurements on an overall receiver in which each of a considerable number of tubes was tested. The best tube tested, which had close to the theoretical transconductance, gave an overall noise factor about 2 db better. A curve of overall noise factor versus frequency for this receiver, using an average tube, is shown in Fig. 6. The noise factor, of course, is a direct measure of noise-to-signal ratio, since it compares the actual ratio to the minimum existing in the antenna. Because of the interest in 500 to 1,000-megacycle television, comparative curves are given for a typical crystal mixer system using a 120-megacycle intermediate-frequency amplifier which has a 6AK5 pentode as first tube. The 6AK5 pentode noise factor is also given in the figure. The beam-deflection tube, over the 500-1,000 megacycle range, is substantially better than the other receiving methods.

With respect to freedom from local oscillator radiation, a table has been prepared showing the relationship of the beam-deflection mixer, of the type described, to other receiving systems. Table I shows that the radiation of the beam-deflection mixer as measured is sufficiently small to be called negligible for television service.

The comparisons of the table are made with the type of receiving systems in common use or commonly proposed for television service. In contrast to the crystal mixer, which would radiate enough from a dipole to give a field of several millivolts per meter at 100 feet, the beam-mixer radiation would be well below the noise level of a nearby television receiver, provided the local oscillator itself is sufficiently well-shielded.

Table I—Local Oscillator Radiation

Receiver System	R-F mc	I-F mc	Micro-watts Radiated
6AC7 Mixer	50–100	10	700.0
Triode R-F Stage	50–100	20	0.2
Crystal Mixer	500–1000	120	100.0
Beam-Deflection Mixer	500–1000	120	0.02

The addition of a 1, 2 or 4-stage electron multiplier, in place of the suppressor and anode, increased the gain by a factor of 4, 10 or 100, respectively, but the signal-to-noise performance was found to be substantially unaffected. Though a small increase in noise factor had been anticipated due to multiplier noise, this was not apparent.

Constructional Details

An important feature of tubes of the type described is the mechanical arrangement of parts. In the earliest work, cathode-ray tube technique was used, but was relatively unsatisfactory for the rectangular type of beam employed. Considerable credit must be given to two RCA Victor engineers, N. H. Green and W. H. Warren, who proposed a novel mechanical arrangement which was modified to meet the objective of the beam-deflection mixer. The photograph of Fig. 7 shows a view of the complete assembly and some of the parts of the tube. The entire assembly is based on the two metal stampings shown, which are welded together to form a rigid frame.

The deflection plates are made of pieces of mica wrapped with foil made of gold to eliminate chemical contamination on the surface. These deflection plates are riveted to the frame to assure alignment. The small intercepting wire is also accurately aligned with the electron optical system by means of this frame. All parts, including the envelope are nonmagnetic. The complete assembly is shown in the photograph with the cathode end at the left and the signal-deflection plates brought out through the heavy central leads for the signal input. The local-oscillator deflection plates are shown to the right of the central shield and are brought out single-ended fashion through a coaxial connector at the right of the photograph.

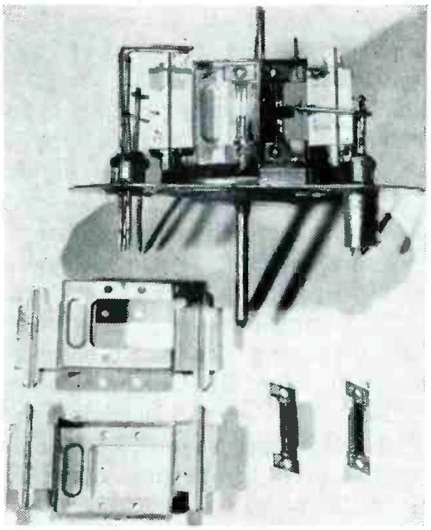

FIG. 7—Internal structure, frame stampings and deflection plates of experimental beam-deflection tube

In spite of the great accuracy with which the parts are aligned using the metal-frame technique, it was found that the transconductance and noise factor of some tubes could be improved by use of a fixed, correctly-oriented, nonuniform magnetic field, such as from a very small bar magnet. By using a cathode-ray tube characteristic trace, it could quickly be determined whether such a magnet would give an improvement in transconductance and its proper orientation could be found. On some tubes, therefore, this correcting magnet was soldered permanently in place on a stainless-steel envelope and was found to be entirely satisfactory under all normal operating conditions.

Conclusions

The work which was done in the application of beam-deflection principles to amplifiers and mixers has shown clearly that these principles are advantageous for reception above 300 megacycles. On the other hand, the limitations which were encountered are such that it is not likely that a beam-deflection type of tube can compete in performance with grid-controlled tubes below 30 megacycles, except for special applications. Limited experience obtained during the war in building small quantities of beam-deflection tubes has shown that many production problems must be solved before such tubes can be considered ready for commercial manufacture. Such tubes, at present, are still in the laboratory stage.

Contributions to the tube developments described herein were made by many colleagues at RCA Laboratories and the RCA Victor Division at Harrison among whom may be mentioned H. A. Finke, H. C. Thompson, H. Schwalbach and K. McLaughlin. Much of the work was supported by Signal Corps contracts during the recent war and, in one case, by a Navy contract.

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