A TWELVE-INCH MAGNETIC DEFLECTION CATHODE-RAY OSCILLOSCOPE FOR LECTURE DEMONSTRATION

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

Kenneth William Saunders

1948

This is to certify that the

thesis entitled

A TWELVE-INCH MAGNETIC DEFLECTION CATHODE-RAY OSCILLOSCOPE
FOR LECTURE DEMONSTRATION

presented by

Kenneth William Saunders

has been accepted towards fulfillment
of the requirements for

M.S. degree in Physics

Thomas H. Osgood
Major professor

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By

Kenneth William Saunders

A Thesis

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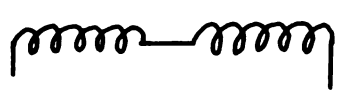
I want to express my appreciation to Dr. Ralph Bowersox for his instruction very patiently given during the course of this problem. Dr. Beryl Dickinson also willingly gave many helpful suggestions during the early part of the project for which I am grateful.

Kenneth W. Saunders

CONTENTS

I. Problems Involved

Building a cathode-ray tube into an oscilloscope involves the planning and construction of several auxillary circuits. These circuits depend considerably on the characteristics of the tube to be used. A twelve inch tube needs six to seven thousand volts of potential applied between the electron source and the high voltage electrode of the tube--according to the manufacturer's ratings. A high voltage power pack of low current output is required.

The tube may be made for electrostatic focusing or magnetic focusing. If it is focused electrostatically, about twelve to fourteen hundred volts must be available from the high voltage power pack to be applied to the focusing grid. If the tube is focused magnetically a suitable coil for a magnetic lens must be secured. The tube used in this problem is magnetically focused and depends on magnetic deflection of the stream of electrons. Characteristics of magnetic deflection coils available influence the type of deflection circuit planned. If the coils are of low inductance a much larger current is needed and, therefore, a transformer may be needed in both the horizontal sweep amplifier and vertical amplifier plate circuits to supply the right current to the defledtion coils. The coils used in this problem were of high inductance and consequently relatively small currents were required. Inductance of the deflection coils influences the form of the sweep circuit wave. The external connections to the coil windings also must be considered. If the two coils for any deflection, say horizontal, are in series and are not center-tapped as  they cannot very well be connected in a push-pull circuit which would need a center tap as 

A horizontal sweep circuit must be constructed of such wave form as to give constant current increase in the deflection coil instead of constant voltage increase as is necessary in electrostatic deflection. The sweep frequency for demonstration purposes ought to be variable from a few cycles per second to two or three thousand cps. The sweep oscillator should be provided with some means of feeding into its grid circuit some of the vertical signal so that the sweep frequency may be stabalized in reference to the vertical frequency.

Two amplifiers, one for the vertical signal and one for the horizontal sweep must be planned. They should have a fairly constant gain over the band of frequencies for which the oscilloscope is intended.

Along with the fundamental problems already mentioned there will be other miscellaneous problems encountered during experimentation such as stray oscillations occuring, induced disturbances picked up in leads, fly-back oscillations occuring at the return of the sweep, and blanking out of return sweep trace. All of these problems will be discussed in the report of the actual construction of the scope. Before this is done, a few theoretical considerations will be discussed concerning magnetic focusing lens, and magnetic deflection.

II. THEORETICAL CONSIDERATIONS

A. Magnetic focusing lens

For an electron traveling in both an electrostatic field (-grad V) and an electromagnetic field (H=curl A) in which A is a vector potential and the electron having a velocity, v, the following field and force components can be expressed:

Components of $\bar{H}$ in cylindrical coordinates are:

$$H_r = \text{Curl}_r \bar{A} = \frac{1}{r}\left[\frac{\partial A_z}{\partial \theta} - \frac{\partial (r A_\theta)}{\partial z}\right]$$

$$H_z = \text{Curl}_z \bar{A} = \left[\frac{\partial (r A_\theta)}{\partial r} - \frac{\partial A_r}{\partial \theta}\right]$$

$$H_\theta = \text{Curl}_\theta \bar{A} = \left(\frac{\partial A_r}{\partial z} - \frac{\partial A_z}{\partial r}\right)$$

Because of z axial symmetry in H

$$A_r = A_z = \frac{\partial A_\theta}{\partial \theta} = 0$$

Therefore, the components of $\bar{H}$ are

$$H_r = -\frac{1}{r}\frac{\partial (r A_\theta)}{\partial z}$$

$$H_z = \frac{1}{r}\frac{\partial (r A_\theta)}{\partial r}$$

$$H_\theta = 0$$

Expression of force on the electron in the two fields:

$$\bar{F} = m\bar{a} = -e\left[-\text{Grad}\, V + (\bar{v} \times \bar{H})\right)$$

$$\bar{a} = -\frac{e}{m}\left[-\text{Grad}\, V + (\bar{v} \times \bar{H})\right)$$

$$(4) \quad (\bar{v} \times \bar{H}) = \begin{cases} \bar{r}_1 (v_\theta H_z - v_z H_\theta) \\ \bar{\theta}_1 (v_z H_r - v_r H_z) \\ \bar{k}_1 (v_r H_\theta - v_\theta H_r) \end{cases}$$

For acceleration:

$$a_r = \ddot{r} - r\dot{\theta}^2$$

$$a_\theta = 2\dot{r}\dot{\theta} + r\ddot{\theta}$$

$$a_z = \ddot{z}$$

$$(5) \quad \text{Grad}\, V = \begin{cases} \frac{\partial V}{\partial r} \\ \frac{\partial V}{\partial \theta} = 0 \\ \frac{\partial V}{\partial z} \end{cases}$$

since V is constant and symmetrical with respect to the z axis. Using these three sets of components, the component expressions for acceleration are:

(6a) $a_r = \ddot{r} - r\dot{\theta}^2 = \frac{e}{m}\left[-\frac{\partial V}{\partial r} + \dot{\theta}\frac{\partial (r A_\theta)}{\partial r}\right]$

(6b) $a_\theta = \frac{1}{r}\frac{d(r^2\dot{\theta})}{dt} = -\frac{e}{m}\left[-\frac{1}{r}\frac{d(r A_\theta)}{dt}\right]$ (consider $\dot{r} = 0$ from

(6c) $a_z = \ddot{z} = -\frac{e}{m}\left[-\frac{\partial V}{\partial z} + \dot{\theta}\frac{\partial (r A_\theta)}{\partial z}\right]$ a to b in figure II)

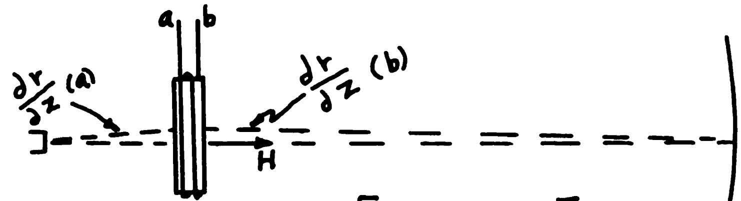


FIGURE II

integrating (6b)

$$r^2\dot{\theta} = \frac{e}{m}(r A_\theta) + C$$

At $r = 0$, $A_\theta = 0$ for an axially symmetric field. Therefore

$$(7) \quad r\dot{\theta} = \frac{e}{m} A_\theta$$

substitutin (7) in (6a)

$$\ddot{r} - \frac{1}{2}\frac{\partial(\frac{e}{m}A_\theta)^2}{\partial r} = -\frac{e}{m}\left[\frac{\partial(\frac{e}{m}A_\theta^2)}{\partial r} - \frac{\partial V}{\partial r}\right]$$

$$(8) \quad \ddot{r} = -\frac{1}{2}\frac{e}{m}\frac{\partial(\frac{e}{m}A_\theta^2)}{\partial r} + \frac{e}{m}\frac{\partial V}{\partial r} = \frac{e}{m}\frac{\partial}{\partial r}\left[V - \frac{1}{2}\frac{e}{m}A_\theta^2\right]$$

Substituting (7) in (6c)

$$(9) \quad \ddot{z} = \frac{e}{m}\frac{\partial}{\partial z}\left[V - \frac{1}{2}\frac{e}{m}A_\theta^2\right]$$

From considerations of axial distribution of potential* and equations (8) and (9) the differential equation for the trajectory of a paraxial electron in a magnetic field is:

$$(10) \quad \frac{d^2 V}{d z^2} + \frac{V'}{2V}\frac{dr}{dz} + \frac{1}{4V}\left(V'' + \frac{e}{2m}H_z^2\right)r = 0$$

If V is considered constant from a to b over the short path of influence of H then equation (10) becomes

$$(11) \quad \frac{\partial^2 r}{\partial z^2} + \frac{1}{8V}\frac{e}{m}H_z^2\, r = 0$$

integrating eq. (11) once between a and b on the z axis

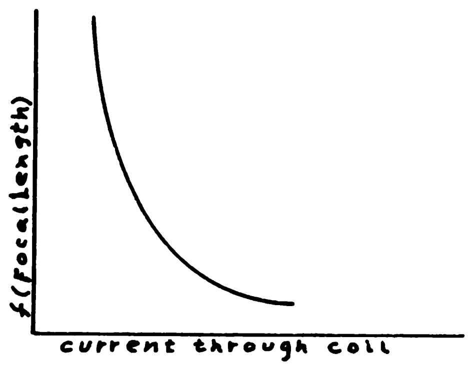
$$(12) \quad \left(\frac{\partial r}{\partial z}\right)_a - \left(\frac{\partial r}{\partial z}\right)_b = -\frac{1}{8V}\frac{e}{m}r_0\int_a^b H_z^2\, dz$$

*Electron Optics in Television by Maloff and Epstein, pgs. 76, 77, and 155.

r_0 is substituted for r because for the short distance on z for a thin lens r can be considered constant. Then $\frac{\partial r}{\partial z}(a)$ is the slope of the incident electron and $\frac{\partial r}{\partial z}(b)$ is the slope of the refracted electron. These rays are labelled in this manner in figure II. Equation (12) may be rewritten in terms of focal length of the magnetic lens.

$$(13) \quad \frac{1}{f} = -\frac{1}{8V}\frac{e}{m} r_0 \int_a^b H_z^2 \, dz$$

H_z depends upon the geometry of the coil, but can be quite easily computed as a function of z, coil dimensions, number of turns, and current, if there is no iron present in the core. From the two distances, cathode to focus coil, and focus coil to screen, the required focal length of the coil can be computed. Then, by the use of equation (13), with the appropriate substitution for H_z^2, the coil dimensions and current may be varied until the correct focal length is obtained. A plot of focal length compared to current for a short coil is given at the right.



From equation (13) it is apparent that the lens will be converging regardless of the direction of current through the focusing coil. Reversal of current results only in reversal of direction of rotation of the electron image. Since, in a scope, only a spot is desired, direction and angle of rotation of the image are of no concern.

For focusing, then, H is parallel to the general direction of the motion of the electron whereas for deflection H is perpendicular to the electron path. Since velocity (v_z) does not appear in eq. 12, the varying speed of the projected electrons from the cathode has nothing to do with where they will come to focus.

B. Magnetic Deflection

Considerations for deflection are much simpler than those for a magnetic focusing lens. A stream of electrons passing through a cross magnetic field will be deflected in the same manner as a conductor is in a magnetic field

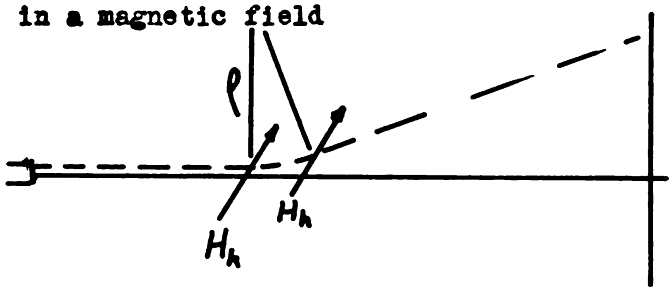


FIGURE IV

The force, $F = H_h\ ev$, which is applied to forcing the electron out of its path will be resisted by centrifugal force, $F = \frac{mv^2}{\rho}$.

Then $H_h\ ev = \frac{mv^2}{\rho}$ or

$$(13)\quad H_h = \frac{m_o}{e}\,\frac{v}{\rho}$$

e/m_o is known to be about 1.758×10^7 emu/gm and v can be computed from the relation

$$(14)\quad Ve = \tfrac{1}{2} m_o v^2$$

(The kinetic energy of the electron is equal to the work done on the charge by the potential of the propelling electric field) Relativity considerations of mass change with velocity are not necessary for velocities encountered in cathode ray oscilloscopes.* In these equations the rest mass (m_0) is used. Substituting in $(13)_a$ from (14)

$$(15)\quad H_h = \frac{1}{\rho}\sqrt{2\frac{e}{m_0}V}$$

In a tube using 6000 volts on the second anode, V would be approximately 3000 volts at the point of deflection. From the geometry of the tube ρ can be computed and, then also, the value of H from equation (15) for full width deflection. The width of deflection, then, according to equation (15), is proportional to the field, H_h, of the deflection coil and this in turn is directly proportional to the current in the coil. This current equation is given on page 15.

III. Details of Construction

A. High Voltage Power Supply

The only requirements of the high voltage power supply are that it will furnish the required high potential at low current. Most cathode ray tubes require currents not over 2 or 3 milliamperes. The transformer selected was rated at 3700 volts and 4 ma current. The secondary also had two 2.5 volt windings, one of which was connected to the high voltage winding at one end. The high peak voltage ($\sqrt{2}$ E) is about 5200 volts. After being filtered by a condenser it still measured slightly over 5000 volts .

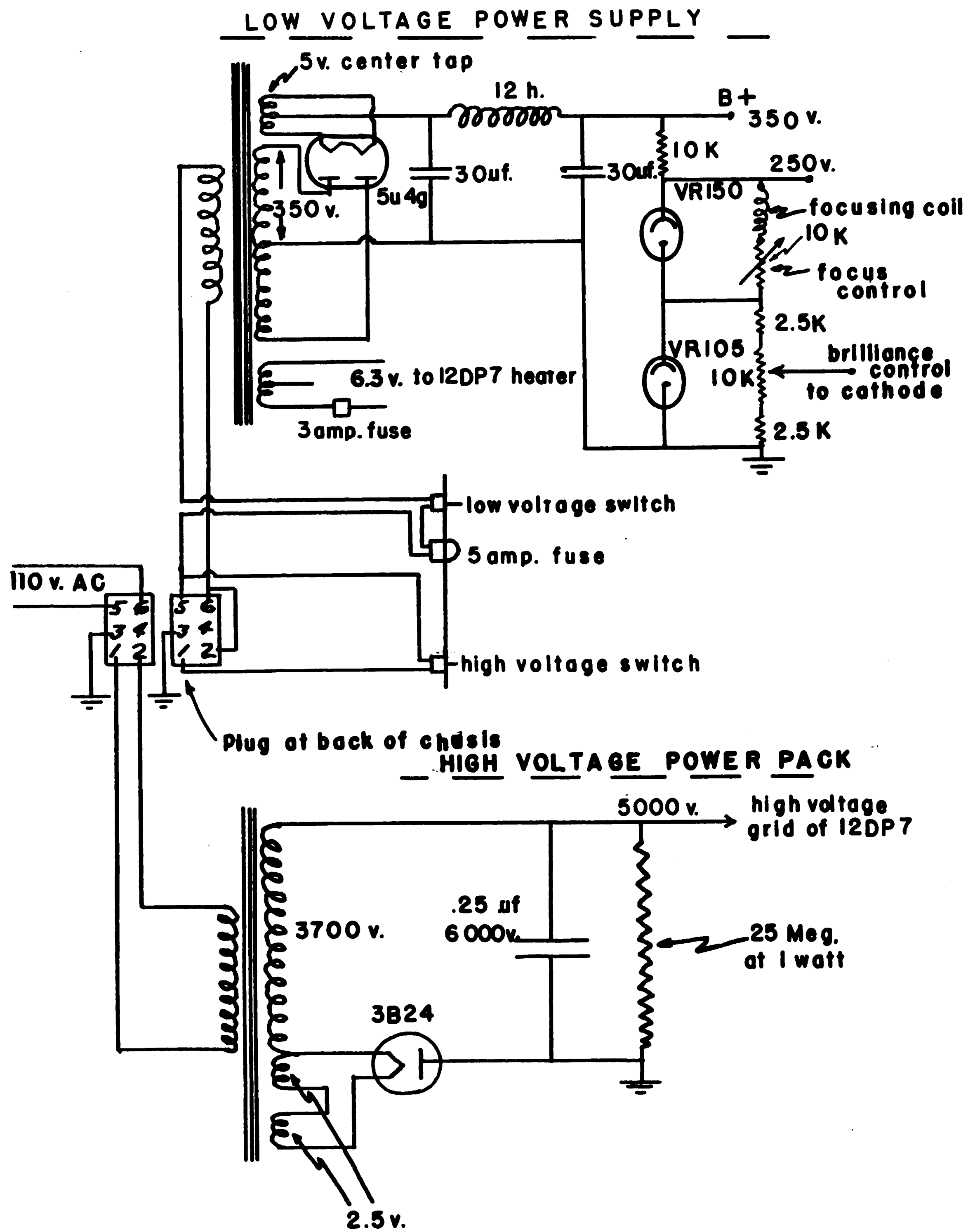
In the tube characteristics given for the 12" cathode ray tube it was stated that the operating high voltage should be between six and seven thousand volts. Operation at a lower voltage gives more deflection sensitivity but less brilliance on the fluorescent screen. At 5000 volts, control of brilliance was less sensitive and the trace could easily be made bright enough.

* Television by Zworykin and Morton-- pg. 77

The rectifier selected was a Ratheon CEP-3B24 tube, which is rated at 20 kv. peak inverse voltage. Half of the heater can be operated at 2.5 volts or all of it at 5 volts. When the direction of EMF reverses in the secondary of the transformer after the condenser has been charged through the rectifier tube this tube has both the voltage of the condenser and the transformer added in series across it. Therefore, the tube must be rated to stand twice the peak voltage of the transformer. The circuit for this power pack is shown in figure V on the next page.

B. Focus and Deflection Coils

At the present time not much television equipment is available and for that reason suitable focus and deflection coils may be scarce. The housing, focus coil, and deflection coils for a 5-FP-7 radar tube were salvaged from the no. 1d-19/APS-3 viewer of the AN/APS-3 aircraft radar equipment. In the detailed drawing, figure VI, page 10, are given the circuit with pin connection letters and circuit constants for the convenience of anyone wishing to utilize similar equipment. Also, corresponding numbers of pins on the socket of the cable which was spliced onto these leads is given. This thirteen element cable socket plugs into the back of the chasis which mounts the electronic elements of control.


LOW VOLTAGE POWER SUPPLY
5v. center tap
12 h.
B+
350 v.
30uf.
30uf.
10K
250v.
5u4g
350 v.
VR150
focusing coil
10K
focus control
2.5K
VR105
brilliance control to cathode
10K
2.5 K
6.3 v. to 12DP7 heater
3amp. fuse
low voltage switch
5 amp. fuse
110 v. AC
5 6
3 4
1 2
high voltage switch
Plug at back of chasis
HIGH VOLTAGE POWER PACK
5000 v.
high voltage grid of 12DP7
.25 uf 6000v.
3700 v.
25 Meg. at 1 watt
3B24
2.5 v.

FigureV

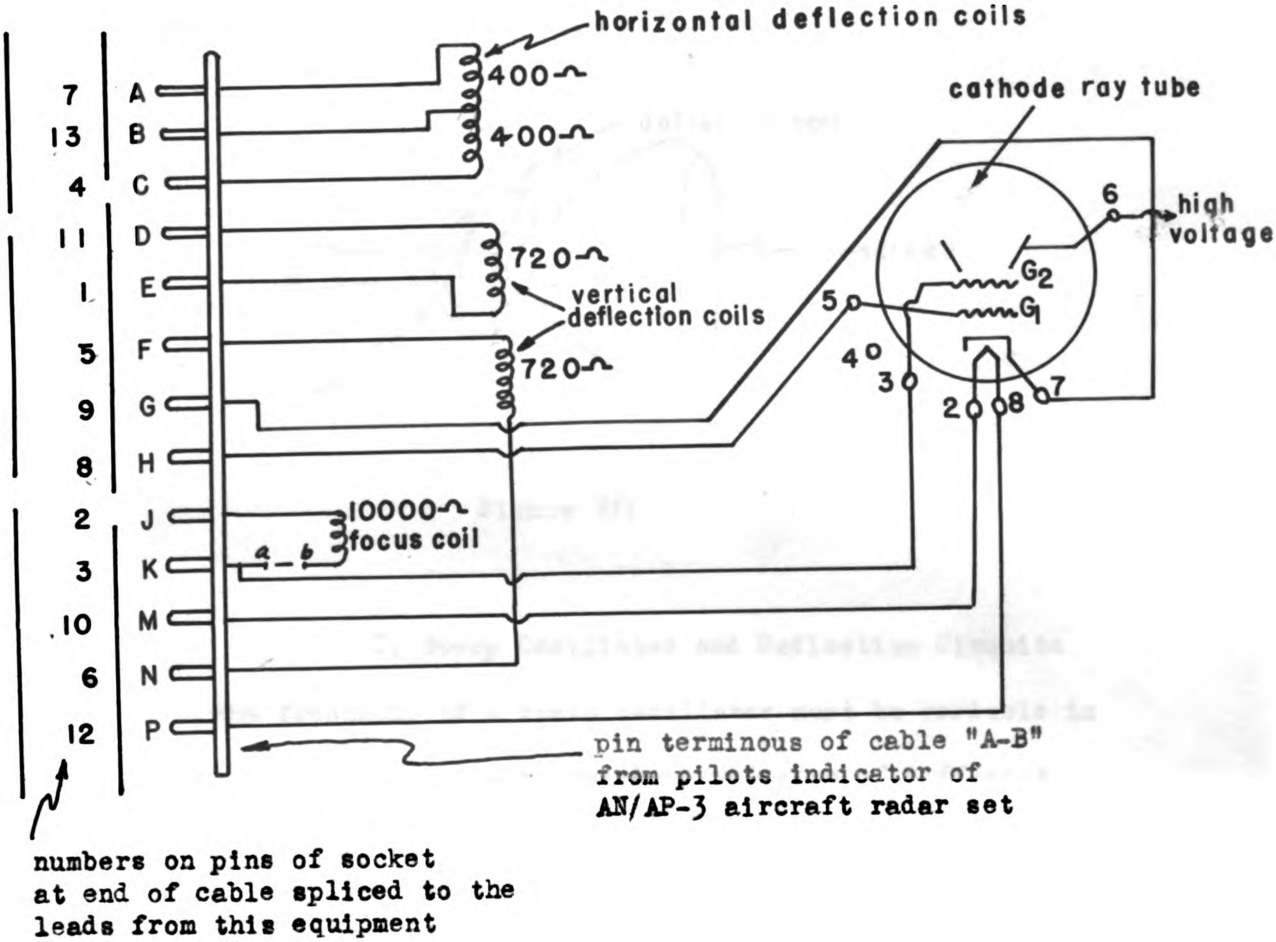


Figure VI

The housing of this unit was used along with the focus and deflection coils, cable and cathode ray tube socket. Some alterations had to be made in the flare end of the aluminum housing to allow the larger 12" tube to fit into the coils far enough. But making use of this housing and accessories saved quite a lot of time in coil mounting and cable constructions. The 10000 ohm variable carbon resistor used in controlling focus was removed from the (k) lead between points a and b and placed in series with the focusing coil as shown in figure V. Points a and b were then connected.

The relative positions of tube and coils is given in figure VII below.

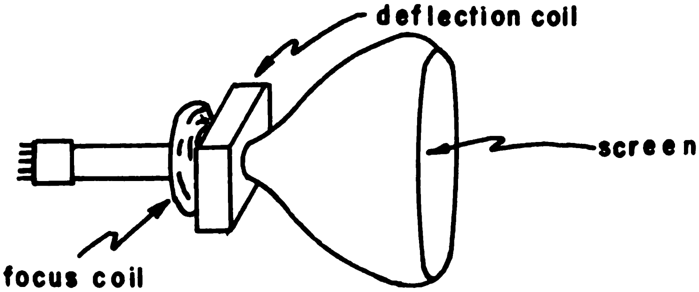
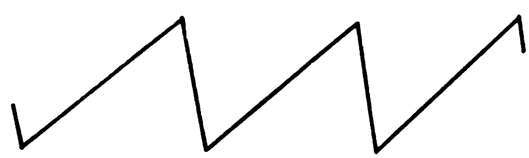


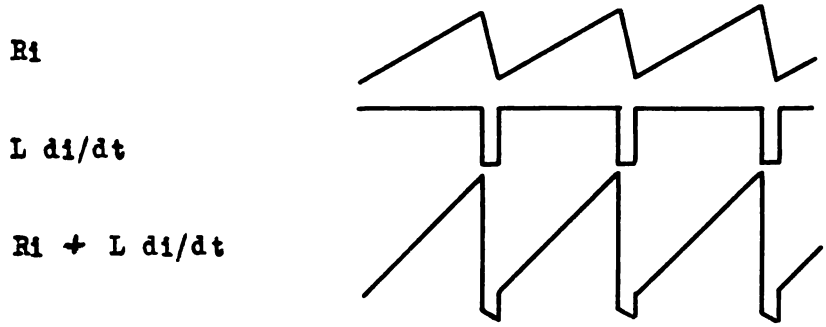
Figure VII

C. Sweep Oscillator and Deflection Circuits

The frequency of a sweep oscillator must be variable in order to be useful for sweeping vertical voltages of different frequencies. Another and very important requisite is that it will sweep the spot across the face of the tube at a constant speed. A sawtooth wave of the form



will give such linearity of sweep for electrostatic deflection systems but may not for electromagnetic deflection. For magnetic flux to increase at a steady rate in a coil di/dt must be a steady change. This means that the inductive reactance voltage is constant. It then needs a square voltage wave. However, the Ri voltage required for the coil will be of sawtooth form. Adding these together the voltage applied to a coil should be Ri + L di/dt



This type of sawtooth wave will result across a condenser and resistor in series, in an oscillator, between points a and b as shown in figure VIII.

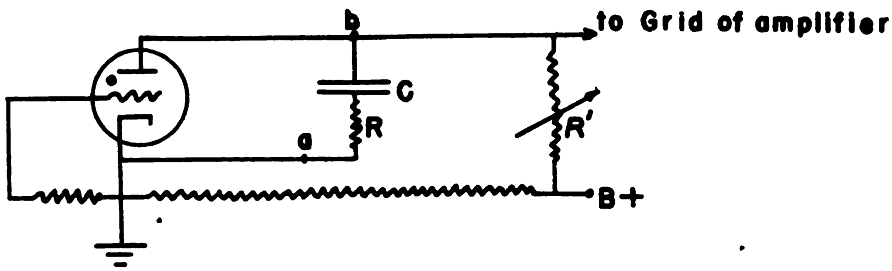
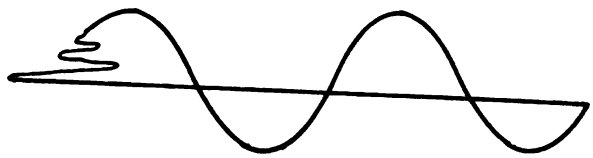


Figure 8.

However, if the inductance is not high in comparison to the resistance of the coil, the resistance, Ri in figure VIII can be discarded. The resistance and inductance of the horizontal deflection coil were read at 1000 cps. and found to be 650 ohms and 5.2 mh., respectively. So the reactance of the coil is about 32 ohms as compared to a resistance of 650 ohms. It was found that a sawtooth wave would work satisfactorially for a magnetic sweep pulse. Therefore, it is possible to use the sweep from a Dumont 208-B oscilloscope in parallel with the deflection coils of the 12" tube.

One defect in using a sawtooth sweep was that on flyback of the spot, oscillations were set up in the coil circuit by the sudden change involtage. This resulted in a scope configuration such as

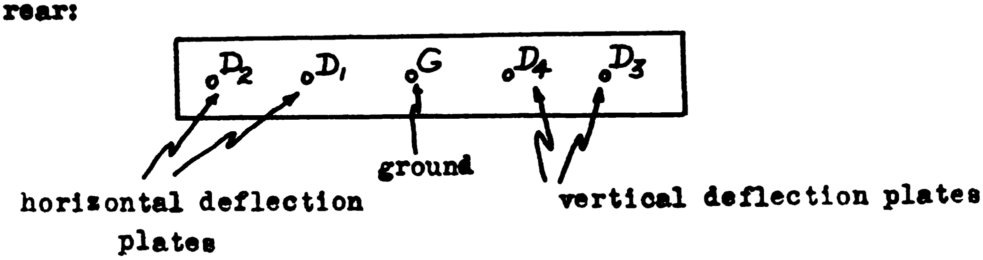


These harmful oscillations may be eliminated by "blanking out" the spot during the interval of fly-back. This is accomplished as explained in discussion of the blanking circuit on page 16.

D. 12 D P 7 Tube in Parallel with a Dumont 208-B Scope

Probably the easiest and most satisfactory way to build a large demonstration scope is to parallel a large tube with the circuits of some smaller scope commercially constructed. Added to the advantage of eliminating a lot of circuit construction is the advantage that the lecturer may observe what he is doing on the smaller scope and have the audience get an unobstructed view of what is taking place on the large tube. Certain balancing adjustments need to be made to parallel the behavior of the two scopes. A discussion of the work along with pertinent circuits follows.

At the rear of a Dumont 208-B scope is an outlet plate of contacts with the four deflection plates arranged as follows viewed from the rear:



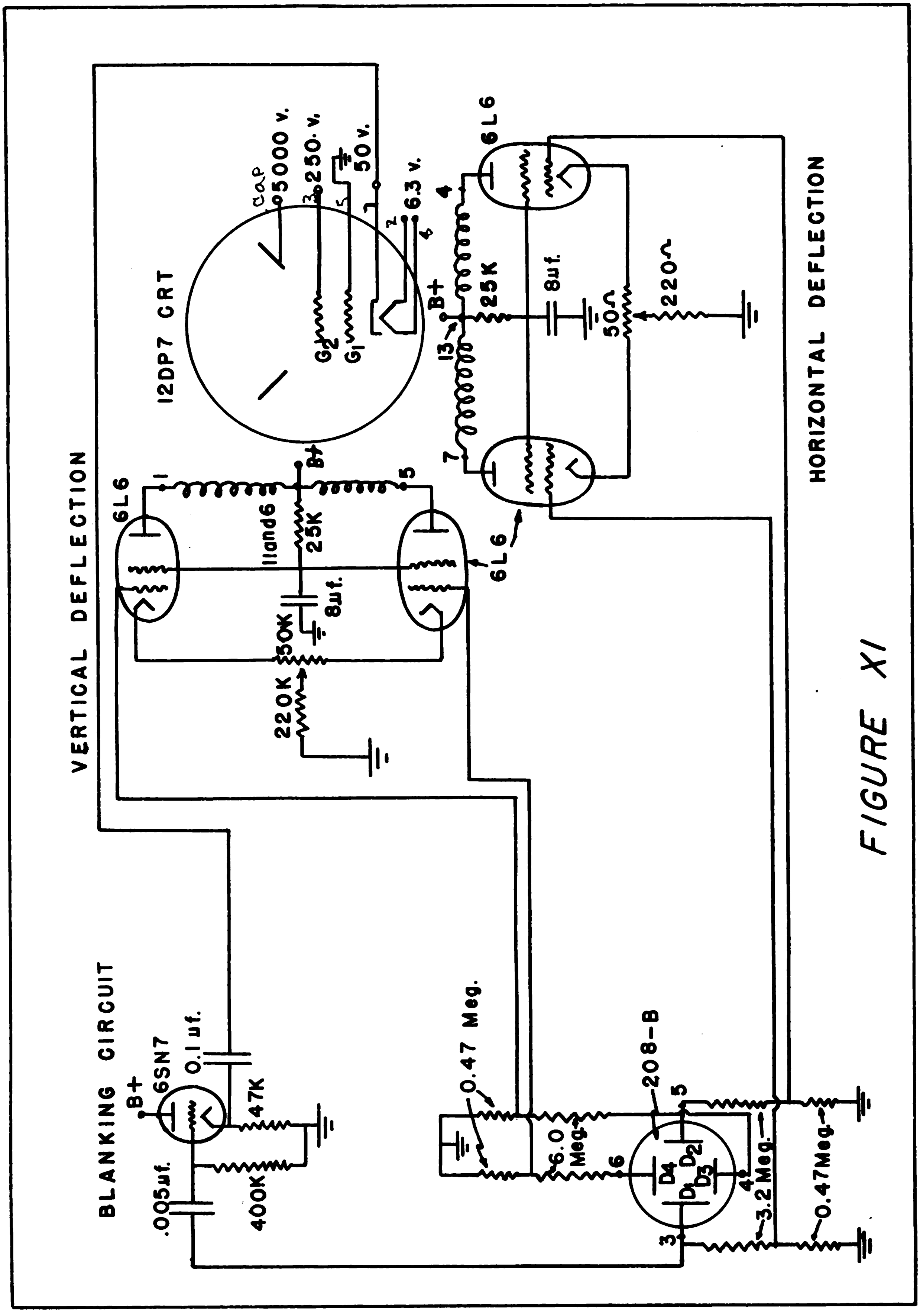

VERTICAL DEFLECTION
HORIZONTAL DEFLECTION
BLANKING CIRCUIT
12DP7 CRT
cap
5000 v.
250 v.
50 v.
6.3 v.
G2
G1
B+
6L6
6L6
6L6
6L6
25K
8 uf.
50Ω
220Ω
11and6
25K
8 uf.
50K
220K
6SN7
0.1 uf.
47K
400K
.005 uf.
0.47 Meg.
6.0 Meg.
208-B
3.2 Meg.
0.47 Meg.

FIGURE XI

Figure XI on page 14 shows how these plate connections are utilized to actuate signals for the large tube. The chases of both scopes are connected by one lead from G to the chasis of the large scope. All four plates of the 208-B are grounded through high resistance which act as potential dividers so that parts of the plate fluctuations of the 208-B are fed directly to the grids of the push-pull amplifiers of the horizontal and vertical deflection circuits. The high resistance is used as potential dividers to prevent overloading the plates of the Dumont Oscilloscope.

Examine, now, the behavior of the horizontal deflection system. As D_2 becomes more positive than D_1 the spot of the 208-B is deflected to the right. Simultaneously the grid of the right hand 6L6 tube becomes more positive than that of the left hand 6L6. Since both tubes have the same bias furnished by the 220 ohm cathode resistor the right hand tube will be more conductive. Coil 13-4 will be carrying more current than 13-7 so the beam of the 12 D P 7 will be magnetically deflected to the right. If V_g is the signal from D_2 which is fed to the grid of the right hand 6L6 tube; then the current equation for coil (13-4) is:

$$i_{13-4} = \frac{\mu V_g}{[r_p + r_L + j\omega L + (1+\mu) r_k]}$$

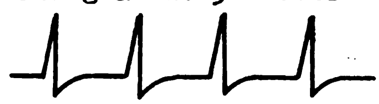
$r_p = 18000$ ohms $\quad wL = 32$ ohms $\quad$ r(cathode) or $r_k = 220$ ohms

$r_L = 650$ ohms $\quad u = 6$

About 70 volts on D_2 is required by the 208-B scope for center to outside deflection. About 1/7 of this is applied to the grid of the right-hand 6L6 tube. Then i (13-4) is about 3 ma. when Vg is 10 volts.

Selecting the right amount of potential from the plates,

D_1 and D_2, to be fed to the grids of the two 6L6's, makes the two scope patterns relatively the same size. To return the spot to the left side D_1 becomes more positive than D_2 and the left 6L6 is more conductive than the right 6L6. The return of the spot takes place on the downward stroke of the sawtooth wave from the oscillator. This is a relatively short event as compared to the forward sweep, but still the spot can be seen in its return trace although not as brightly as in the forward direction. This return trace is objectionable but can be blanked out if more bias voltage is applied between G_1 and the cathode of the 12 DP 7.

In order to accomplish this blanking some signal from D_1 is fed through a 6SN7 tube as a cathode follower amplifier and on to the cathode of the 12 D P 7 which is already operating about 50 volts above G_1 voltage. This positive pulse of the form  is enough to blank out the beam of the 12 D P 7 on return sweep. In Order to prevent the 6SN7 from passing on the DC potential changes of D_1 , 0.005 uf. condenser is used in the feed line from D_1 and the grid DC potential of the 6SN7 is made more stable by the grid resistor of 400,000 ohms.

The characteristics of the two 6L6's may not be exactly the same or for some other reason the spot of the 12 D P 7 may not be centered when the spot of the 208-B is at center position. A 50 ohm potential divider is provided in the cathode circuit of the 6L6's so that the relative grid biases of the two tubes may be varied to accomplish centering.

Variations of vertical plate voltages from D_3 and D_4 are likewise fed through another similar push-pull cirduit to the vertical deflection coils of the large scope.

E. Low Voltage Power Supply

The circuits of figure XI show that there are various other voltage requirements in the large scope in addition to the high voltage of 5000 volts. The 6L6's operate at about 350 volts and the deflection coils require about 85 ma of current, each, for horizontal and vertical full scale deflection. The focusing coil requires approximately 10 ma. so the current requirements are roughly 200 ma. Voltages of 350, 250, and 50 golts are needed for the elements of the 12 D P 7.

A transformer made by the Standard Transformer Corporation was chosen which had the following specifications on secondary:

High voltage	700 volts ct at 200 ma.
Rectifier heater	5 volts at 3 amp.
Filament	6.3 volts at 5.5 amps.

The low voltage power circuit was constructed as shown in the upper half of figure V. The 5U4G gives full wave rectification. Two 30 uf. condensers and a 12 henry inductance coil form a suitable Pi filter. The two VR tubes stabalize the 12 D P 7 grid voltages from fluctuating when focusing is being accomplished.

Figure XII shows the assembly plan of the three main elements, 12 D P 7, tube housing, high voltage power supply, low voltage supply and push-pull amplifier circuits.

IV. Performance of the 12" Oscilloscope

The 12" oscilloscope works well in conjunction with the Dumont 208-B oscilloscope from very low frequencies up to about 3500 cps. for

ASSEMBLY PLAN

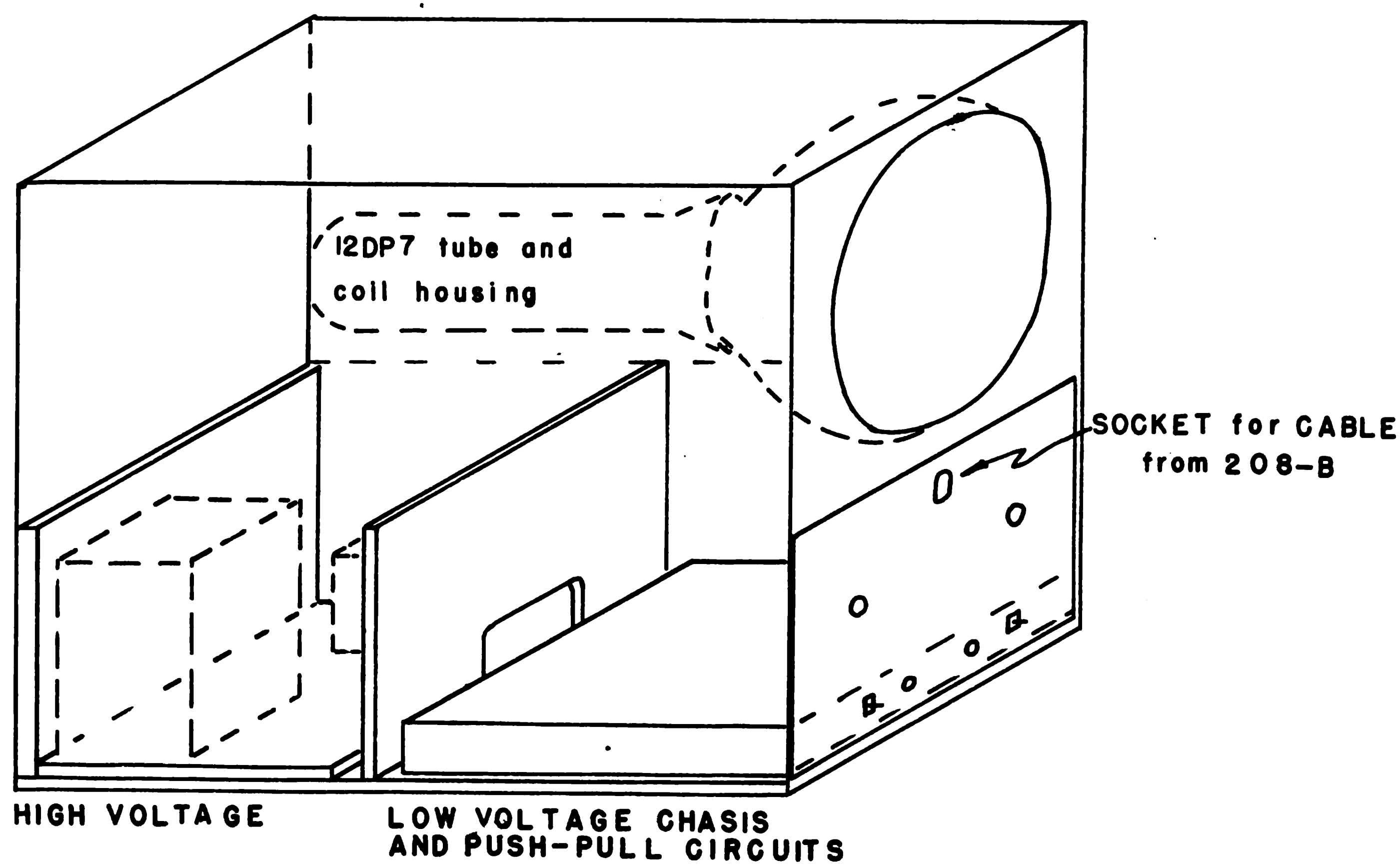


FIGURE XII

vertical signals. Above this frequency the patterns of both scopes begin to show distortion. The distortion may be due in part to overloading the plates of the smaller scope at higher frequencies and to the failure of the 6L6 amplifiers to give consistant gain at higher frequencies. However, as the photographs of figure XIII show, both scope patterns begin to show distortion at about the same frequencies. This would indicate that the plates of the 208-B were being overloaded.

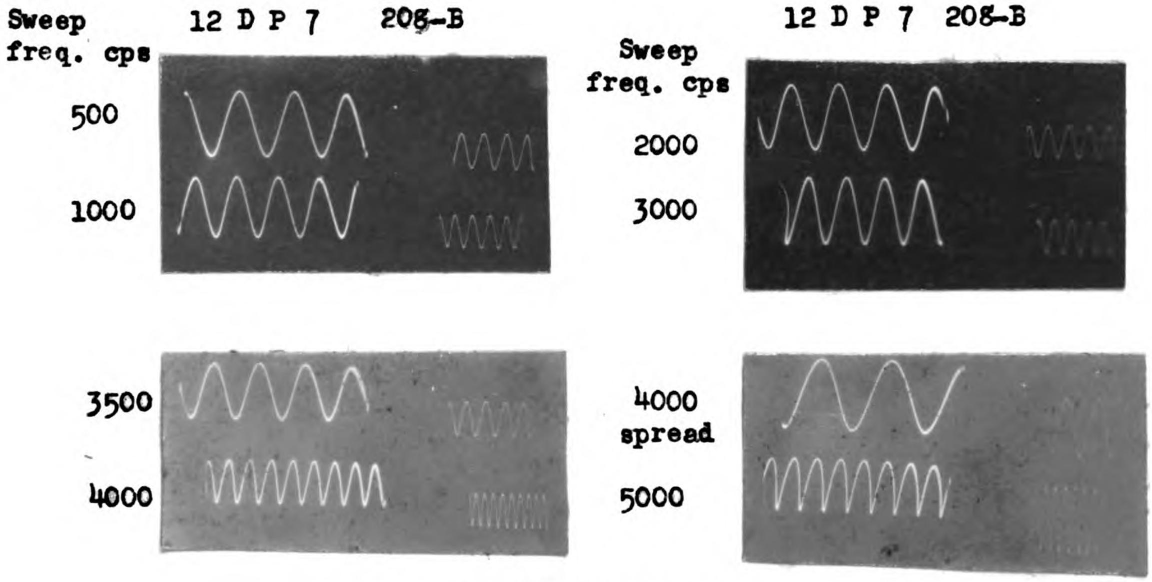


FIGURE XIII

Sweep frequencies up to about 800 cps. may be used. Above this point the sweep velocity is no longer a constant, but is faster at the ends than at the middle and the length of pattern begins to decrease. These faults appear on the 12" tube only, indicating that failure may be the horizontal amplifier's poor gain characteristics at higher frequencies. The system will work well, however, at frequencies used for most demonstration purposes in elementary physics study.

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