Beam Production in Radial Beam Tubes, Beam Power Tubes, and Other Low Voltage Electronic Devices

A. M. SKELLETT
National Union Radio Corporation, Newark, New Jersey

INTRODUCTION

OTHER papers in this series discuss the formation of beams of ions and electrons of high energy. The methods employed, based primarily on electron optics, are elegant and precise and it might be thought that by a simple process of scaling down one could use these same methods to produce sharply defined electron beams at low voltages. Such however is not the case. Two limitations become increasingly important as the voltages are lowered. These are the thermal velocities of the electrons originating at the cathode and the diverging action of the electronic charges themselves. These limitations have been studied in detail by a number of investigators[1–6]; they serve to define the fields in which practical devices may be made to function.

To define the scope of this paper we shall arbitrarily set the upper limit of potential to be applied to the electrons anywhere in the tube at 300 volts.

MAGNETIC FOCUS RADIAL BEAM TUBES

The elementary structure for this sort of tube is shown in Fig. 1. There are no focusing electrodes, the beam being formed entirely by an externally applied magnetic field. The anode structure is maintained at a positive potential with respect to the cathode and in the absence of the magnetic field the electrons would flow radially to it in all directions. The application of a uniform magnetic field whose direction is perpendicular to the axis of the structure focuses all but about 15 percent of these electrons into two flat radial beams as shown. Changing the direction of the magnetic field changes the orientation of the beams since they are always parallel to the magnetic lines of force. Thus the field serves both to focus the beams and to direct them. If the field is rotated the beams spin around with it in perfect phase and synchronism and without inertia.

The focusing is a brute force type of action; the magnetic field is so strong that an electron can never get very far from the line of magnetic force on which it started out. Yet the field strengths required are not high since only low voltages are used. Actually the field strengths required for focus range from 50 to 250 gauss. The exact value used for any particular set of conditions is not critical.

Those electrons which start out from the cathode at right angles to the lines of force are the

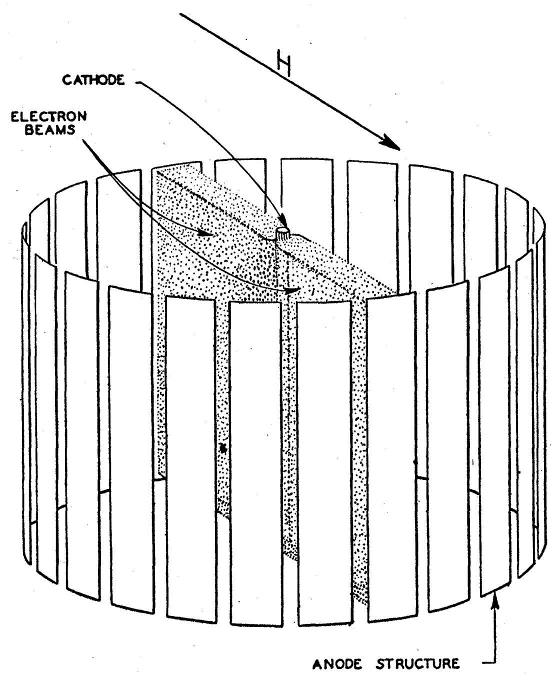


FIG. 1. Elementary tube structure showing focused beams.

[1] A. Bouwers, Physica 2, 10, 145 (1935).
[2] A. V. Haeff, Proc. I.R.E. 27, 9, 586 (1939).
[3] B. J. Thompson, L. B. Headrich, Proc. I.R.E. 28, 7, 318 (1940).
[4] J. R. Pierce, J. App. Phys. 11, 548 (1940).
[5] D. P. R. Petrie, Elec. Comm. 20, 2, 100 (1941).
[6] J. R. Pierce, Bell Sys. Tech. J. 24, 3, 305 (1945).

hardest to focus and hence they are the ones which determine the magnitude of the magnetic field strength. Now because of the cylindrical structure the electric field is concentrated near the cathode and these electrons are accelerated at right angles to the magnetic lines of force by a good sized fraction of the anode voltage. Calling this fraction K and the anode voltage V we have for the ultimate velocity in this direction

$$v=(2eKV/m)^{\frac{1}{2}},$$

where e and m are the charge and mass of the electron, respectively.

The well-known relationship between the radius r of the spiral path and the magnetic field strength H is

$$r=mv/eH.$$

The beam width is approximately equal to the diameter of the cathode plus twice the radius of curvature of the spiral paths as determined above. Thus

$$A \fallingdotseq D+6.7(KV)^{\frac{1}{2}}/H,$$

where A is the beam width and D is the diameter of the cathode in centimeters and V is in practical volts. K has been measured experimentally and is about 0.7 for all the designs that have been

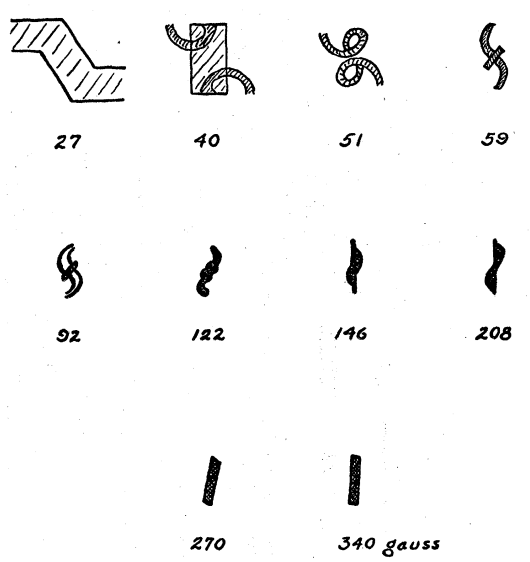


FIG. 2. Drawings of the patterns obtained with a fluorescent coating on the inside of the anode when the magnetic field strength is increased from zero to the focus values.

made to date. There is little to be gained by going to high magnetic field strengths since the minimum width of the beam is the cathode diameter itself.

Figure 2 shows the cross section of the beam at the anode for various values of magnetic field strength. The cathode diameter for these tests was 0.0625 inch with a coated length of $\frac{1}{2}$ inch and the anode diameter was 2.5 inches. There was a potential difference of 150 volts between anode and cathode. The images at 270 and 340 gausses appeared to be the same length as the coating on the cathode.

The photographs of Fig. 3 show some of the electron trajectories made visible by introducing argon into the tube at a pressure of about 1 micron. The electrons emanate from only two small spots of active material on the cathode located at opposite ends of a diameter.

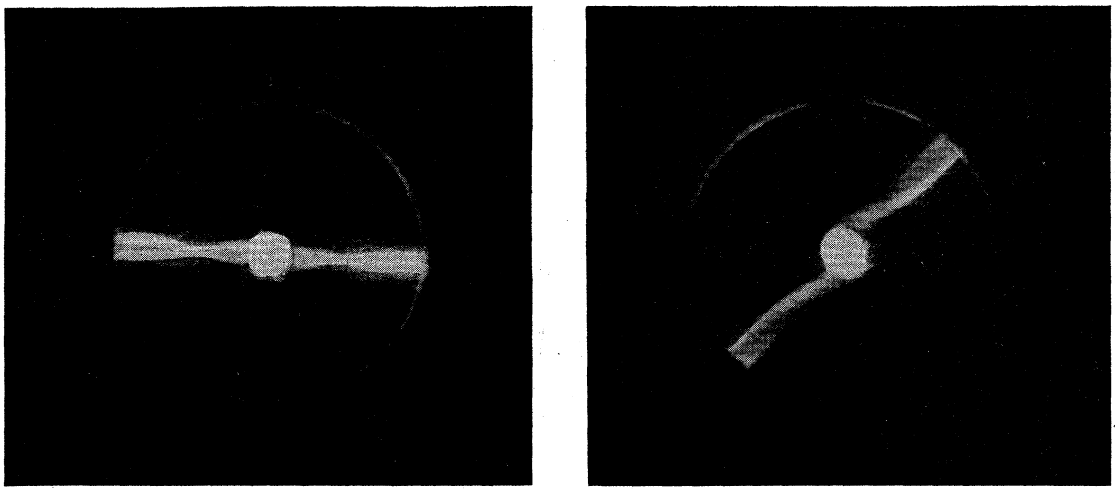
For most applications it is desirable to eliminate one of the two beams. This may be done by the use of a uniform electrostatic field in the tube parallel to the magnetic field. Ideally such a field is obtained by applying voltages around the perifery of the anode structure that vary according to the cosine of the azimuthal angle. This is the same field that exists between two parallel plates held at different potentials. An approximation to this field however may be obtained by applying the instantaneous values of four or six phase potentials to the anode structure split into four or six elements. By the continued application of such potentials the electric field may be rotated in phase with the magnetic field.

Consider the idealized field in which the periferal voltage varies according to the relation

$$V=V_m \cos\theta,$$

where V is the voltage at any point of the anode structure, V_m is the maximum value of V, and θ is the azimuthal angle. The cathode is at a point of zero potential and all voltages on one side of the tube are positive while those on the other side are negative. Thus the electrons on the negative side of the cathode are prevented from leaving it. The magnetic lines of force are lined up with this field so that all of the electrons leaving the positive side of the cathode are gathered into a single beam.

This type of focus requires less magnetic field



a b

FIG. 3. Electron trajectories made visible with a small amount of gas. a. Magnetic field lined up with active spots on the cathode. b. Magnetic field at 45° with respect to the active spots.

and gives a true electron optical image of the cathode at the anode structure. The conditions for focus are that the electrons make one revolution around the magnetic lines of force during their transit from cathode to anode.

Neglecting the distortion of the field in the vicinity of the cathode, the force equation for an electron is

$$md^2x/dt^2 = eV/R,$$

where V is the maximum value (V_m) of the anode voltage, R is the radius of the anode structure, and x is taken in the direction $\theta = 0$, i.e., in the direction of the beam.

The acceleration is uniform so that the transit time t, may be obtained from the elementary dynamical expression

$$\tfrac{1}{2}(d^2x/dt^2)t^2 = R.$$

Combining these equations gives

$$t = \frac{R}{(Ve/2m)^{\frac{1}{2}}}.$$

The well-known expression for the angular velocity of an electron in a magnetic field is

$$\omega = He/m.$$

Conditions for focus as discussed above may be written

$$\omega t = 2\pi,$$

which by substitution from the equations above gives the equation for focus

$$H = \frac{2\pi}{R}\left(\frac{m}{2e}V\right)^{\frac{1}{2}}.$$

Reduced to practical units this is

$$H = \frac{10.6\sqrt{V}}{R}$$

with H in gausses, R in cm, and V in practical volts.

This equation has been derived neglecting space change. Now the increase in transit time in a plane parallel diode due to space charge[7] is $\frac{3}{2}$. Introducing this figure the equation for focus with space charge is

$$H = 7.1\sqrt{V}/R.$$

This formula checks well with the experimental data.

The practical designs of the tube are generally more complex than that described above but the focusing conditions are the same. For example the simple anode structure of Fig. 1 is generally replaced by a positive structure of similar design, usually called the screen, with windows through which the beam may pass on to individual control

[7] J. Millman and S. Seely, *Electronics* (McGraw-Hill Book Company, Inc., New York, 1941), Chap. 7, p. 231.

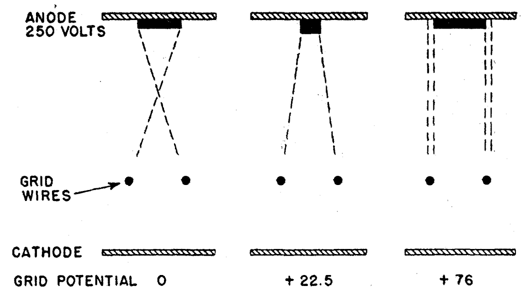


FIG. 4. Beam forming action of grid wires in a plane parallel structure.

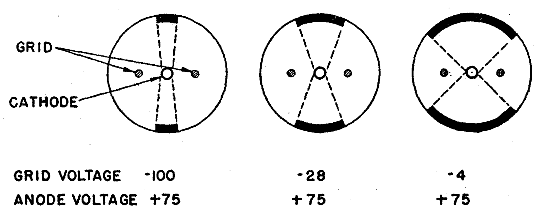


FIG. 5. Beam forming action of grid wires in a cylindrical structure.

grids and anodes. A positive or negative grid closely surrounding the cathode is sometimes used and has little or no effect on the focusing action. Other means of eliminating the effect of one of the beams have been described in a previous publication[8] to which the reader is referred for a discussion of the applications, the magnetic field structures, and the more complex tube designs.

BEAM POWER TUBES

A good many years ago some triodes were made up for demonstration purposes with fluorescent material on the inside of the anode and it was noted that the shadows of the grid wires varied in extent with the grid potential. It was not recognized however that the grid wires were forming focused beams until the science of electron optics was developed. The first ones to study this action apparently were M. Knoll and J. Schloemilch[9–10] in Germany and later H. C. Thompson[11] in this country. The former recognized that a pair of parallel grid wires constitutes a cylindrical electron lens. The electron optical theory has more recently been considered by Bull[12] who, starting with the field due to grid wires in a triode obtained an equation for focus that is identical with the equation for a cylindrical lens originally stated by Davisson and Calbick.[13]

H. C. Thompson coated the inside of the anode in his tubes with fluorescent powder so that the beam width at this electrode could be observed. Figures 4 and 5 are taken from his paper. They show the focusing action of a pair of wires in a plane and in a cylindrical structure. Figure 6 shows sections through two types of beam power tetrode. In the design labelled "a" the electrons are focused into two broad beams by the action of the grid support wires alone. This design was developed in England by J. H. O. Harries[14] and is sometimes referred to as a "critical distance" tube because there is a critical distance from screen to plate which must be exceeded. Stated in another way the beam has a minimum length for satisfactory operation. The design of Fig. 6b was developed by O. H. Schade[15] in this country. Here the focusing action of the grid support wires is augmented by the beam forming plates which are held at cathode potential. The result is a narrower beam than that obtained in the Harries' tube.

By confining the space current of these tubes into two beams of considerable extent the mutual repulsion of the electrons gives rise to a region of space charge between the screen grid and anode. The potential minimum thus formed prevents the secondary electrons liberated at the anode sur-

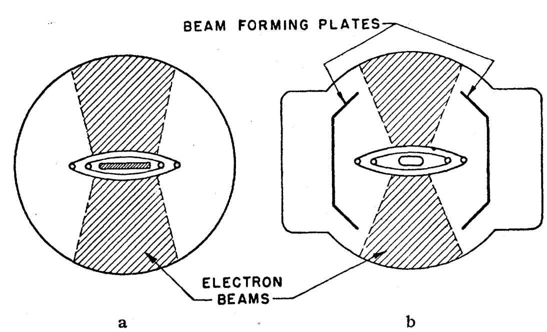


FIG. 6. Sections through beam power tubes.

[8] A. M. Skellett, Bell Sys. Tech. J. **23**, 2, 190 (1944).
[9] M. Knoll and J. Schloemilch, Archiv. f. Elektrotechnik **28**, 507 (1934).
[10] M. Knoll, Zeits. f. tech. Physik **15**, 584 (1934).
[11] H. C. Thompson, Proc. I.R.E. **24**, 1276 (1936).
[12] C. S. Bull, J. A.I.E.E. **92**, 18, 86 (1945).
[13] C. J. Davisson and C. S. Calbick, Phys. Rev. **38**, 585 (1931); **42**, 580 (1932).
[14] J. H. O. Harries, Electronics **9**, 33 (1936).
[15] O. H. Schade, Proc. I.R.E. **26**, 137 (1938).

face from reaching the screen grid, the action being similar to that obtained by the use of a suppressor grid.

The use of this space charge instead of the suppressor grid results in a number of advantages. One of these is a more uniform potential minimum in front of the anode giving rise to a lower anode voltage for saturation and hence a sharper knee in the anode voltage characteristic. In the American tube the wires of the two grids are lined up so that between each pair of wires the electrons are focused into a flat sheet which misses the screen wires. In addition, because of the more uniform velocities of the electrons at the potential minimum, fewer of them are returned to the screen grid at low anode voltages. Thus the screen current is greatly reduced in comparison with that for a pentode.

OTHER LOW VOLTAGE BEAM TUBES

Figure 7 shows an interesting case of negative beam formation. The control electrode is run near cathode potential and electrons flow to the anode in all directions except in its vicinity. By changing its potential the shadow angle is varied. This is the electrode arrangement in the "electron ray tube" or "magic eye" that is used as a tuning indicator in radio receivers. The anode is conical and covered with fluorescent powder so that the negative beam appears as a dark sector of varying angular width.

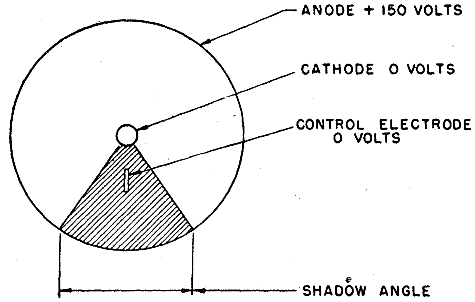


FIG. 7. Electrode arrangement in "magic eye" tuning indicator tube.

Two types of cathode-ray tubes operating at voltages of 300 or below have been marketed. The first of these is attributed to J. B. Johnson[16] and was widely used about fifteen years ago. It employs argon at about 10 microns of pressure to focus the beam. The electron gun is simple consisting of a filament and tubular anode through which the electrons start out in a divergent beam of small diameter. During their travel down the tube the positive ions resulting from their bombardment of the gas congregate along the center of the beam and cause the formation of a negative space charge around the outside. This gives a radial component of force directed toward the center which focuses the beam at the target. The relatively short life of the cathode due to ion bombardment prevents the use of this type of focusing at higher voltages.

Another type of low voltage cathode-ray tube[17] operating at 250 volts enjoys a limited use. It is a hard tube and has a typical electrostatic gun similar to those in high voltage tubes but because of the limitations mentioned in the introduction beam currents must be kept very small and the light output is poor.

The orthicon[18] pick-up tube for television uses an electron beam with an accelerating voltage of only 100 volts. The gun is simply a small cathode followed by a grid aperture and an anode aperture, the latter of the same size as the focused spot. Focusing is obtained by a strong uniform magnetic field parallel to the axis which brings the electrons in the beam to a focus many times as it traverses the tube. Since the beam current is very small (about one microampere) the spreading due to electron repulsion is negligible.

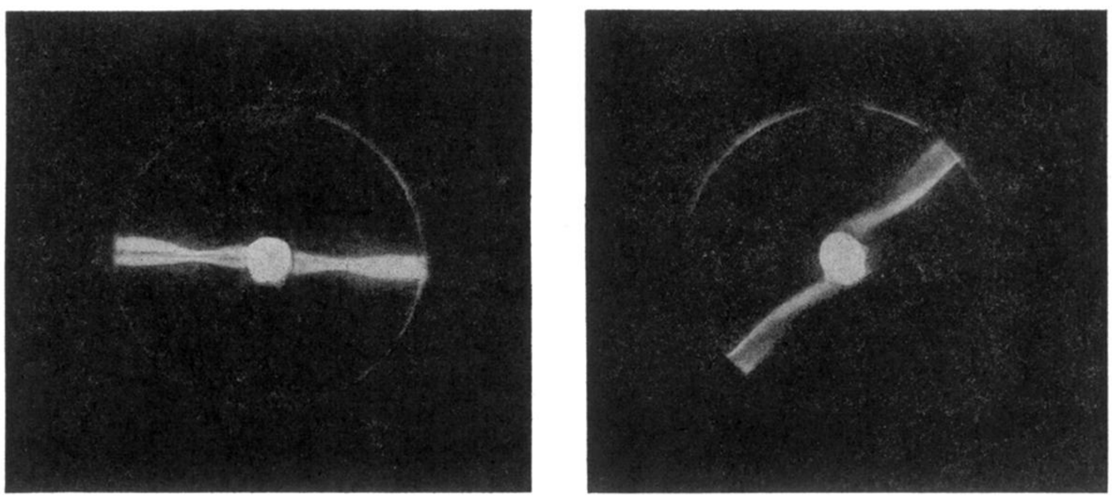
A number of low voltage beam tubes have been made experimentally for use as deflection type amplifiers. One of these is the so-called Renode[19] which was developed in Denmark. None of these has employed anything unusual in the method of focusing and since they have not been able to compete commercially with the ordinary type of vacuum tubes employing grid control they do not warrant discussion here.

[16] J. B. Johnson, Bell Sys. Tech. J. **11**, No. 1, 1 (1932).

[17] L. M. Myers, *Electron Optics* (D. Van Nostrand Company, Inc., New York, 1939), p. 475.

[18] A. Rose and H. Iams, R.C.A. Rev. **4**, 2, 186 (1939).

[19] Electronics **9**, 46 (1936).



a b

FIG. 3. Electron trajectories made visible with a small amount of gas. a. Magnetic field lined up with active spots on the cathode. b. Magnetic field at 45° with respect to the active spots.