

March 24, 1942.

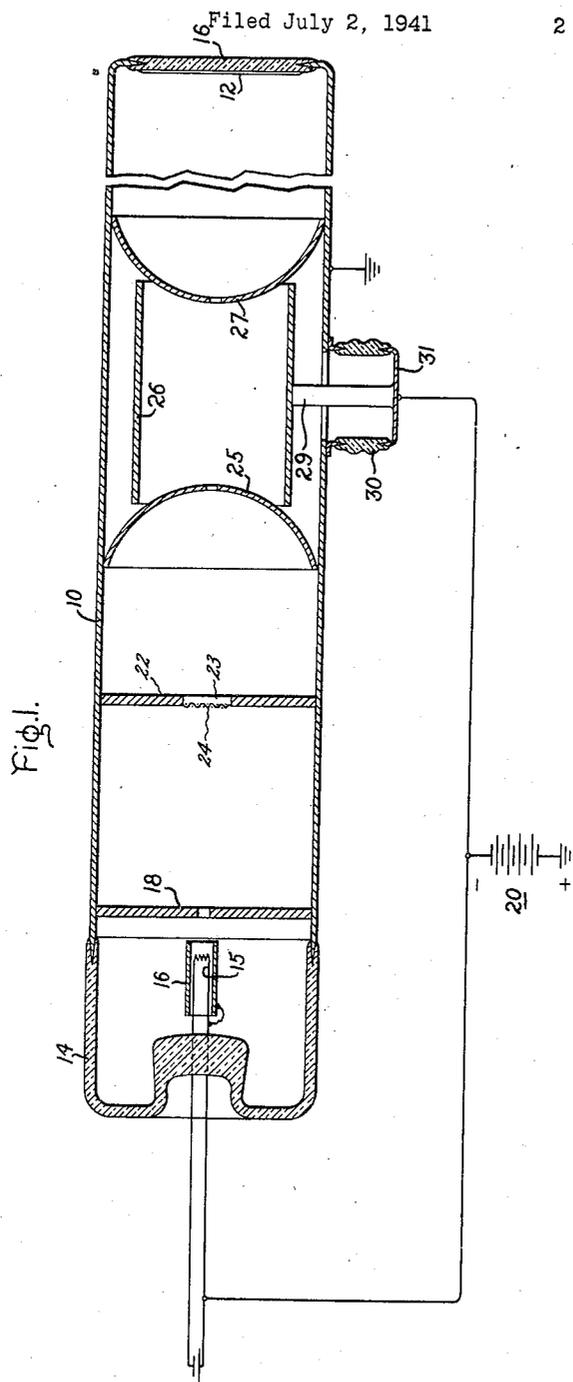
S. RAMO

2,277,414

ELECTRON LENS

Filed July 2, 1941

2 Sheets-Sheet 1



Inventor:
Simon Ramo,
by *Harry E. Dunham*
His Attorney

March 24, 1942.

S. RAMO

2,277,414

ELECTRON LENS

Filed July 2, 1941

2 Sheets-Sheet 2

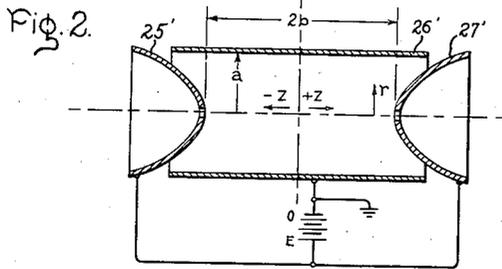


Fig. 3.

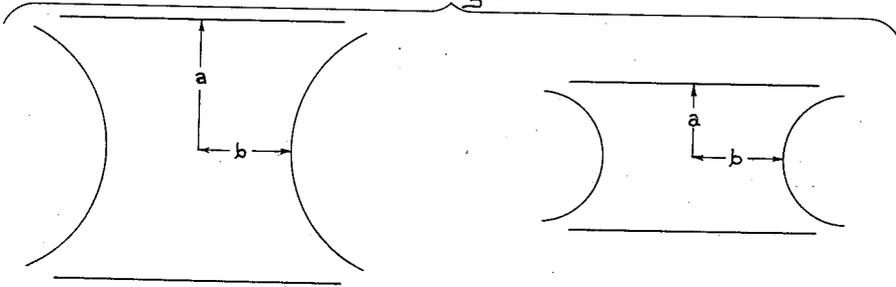


Fig. 4.

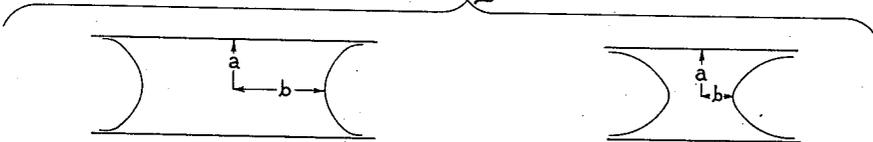


Fig. 5.

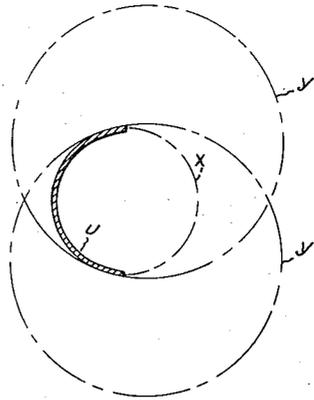
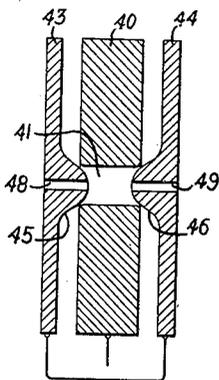


Fig. 6.



Inventor:
Simon Ramo,
by *Hany E. Simhaus*
His Attorney

UNITED STATES PATENT OFFICE

2,277,414

ELECTRON LENS

Simon Ramo, Schenectady, N. Y., assignor to
General Electric Company, a corporation of
New York

Application July 2, 1941, Serial No. 400,809

7 Claims. (Cl. 250—162)

The present invention relates to an improved electron lens.

It is known that the component rays of an electron beam can be focused by the action of apertured electrodes spaced along the beam path and supplied with suitable potentials, this combination being appropriately designated an "electron lens." The focusing produced by such a lens is a function of the strength and form of the electrostatic fields existing between the various lens electrodes and is strikingly analogous to the focusing of a light beam by an optical lens. It has been usefully employed in one instance in the so-called "electron microscope," which is an apparatus for obtaining a greatly enlarged electron-optical image of a minute object desired to be investigated.

Like uncorrected optical lenses, electron lenses as heretofore employed are subject to spherical aberration. In both types of lens, the presence of spherical aberration leads either to blurring of the resultant image or to the enforced use of a construction in which only a limited portion of the lens area (that nearest the lens axis) is usefully employed.

It is an object of the present invention to provide an electron lens construction in which spherical aberration is minimized or substantially avoided.

In this connection an important feature of the invention consists in a three-electrode construction in which the central electrode is provided with a generally cylindrical opening and in which each of the other two electrodes presents to an extremity of the said opening a convex surface of revolution. In the preferred case, the generatrix of the convex surface so presented is defined by a particular relationship between the principal dimensional parameters of the lens, this relationship being set forth and explained in the following.

The features which I desire to protect herein are pointed out with particularity in the appended claims. The invention itself, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawing in which Fig. 1 is a longitudinal sectional view of an electron microscope suitably embodying the invention, Fig. 2 is a diagrammatic representation useful in explaining the invention, Figs. 3 and 4 illustrate varying electrode configurations within the scope of the invention, Fig. 5 depicts a practical method of forming a

lens electrode, and Fig. 6 illustrates a modification of the invention.

Referring particularly to Fig. 1, there is shown an electron microscope comprising an elongated vacuum-tight container which consists mainly of a cylindrical metal part 10. At one end the container is closed by a glass window 11 having a fluorescent material 12 on its inner surface, and at the other end of the container there is provided a glass insulator 14, which serves to support an electron source in the form of a cathode 15. The cathode 15 is surrounded by a tubular metal member 16 which confines the emitted electrons to a narrow beam and is cooperatively positioned with respect to an apertured electrode 18 which is in contact with the main envelope part 10. In the normal use of the apparatus the envelope 10 and the apertured electrode 18 are maintained at ground potential and the cathode is maintained at a high negative potential (e. g. by connection to a potential source 20) so that electrons emitted from the cathode are projected toward the fluorescent screen 12.

In using the apparatus as an electron microscope it is desired to cause the electron stream proceeding from the cathode 15 to produce in the plane of the screen 12 an enlarged electron-optical image of a minute object to be investigated. To this end there is provided a suitable means for supporting an object of the type in question in the path of the electron stream, such means being illustrated in the present case as a metal diaphragm 22 provided with a central opening 23 and having a fine mesh screen 24 covering this opening. The object to be investigated (not shown) is applied to the screen 24 in a region overlying a screen opening which is traversed by the longitudinal axis of the microscope. The introduction of the object is accomplished through a suitable vacuum-lock (not shown) provided in a wall of the microscope, and the microscope is thereafter evacuated by connection to an appropriate pumping system.

Between the object support 22 and the selected imaging plane (i. e. the screen 12) there is provided an electron lens for exerting refractive forces on the electron rays proceeding from the object. According to the present invention this lens comprises a series of three electrodes 25, 26 and 27, these being of a particular configuration determined in a manner to be set forth in the following.

The electrodes 25 and 27 are of substantially identical form and are both supported directly from the main envelope part 10 so as to be at the

same potential as that part. The central electrode 26 is insulatingly supported by the combination of a heavy conductor 29 and a vitreous insulating cylinder 30. A metallic disk 31 which is peripherally sealed to the cylinder 30 and which is centrally joined to the conductor 29 provides an accessible terminal for connecting the electrode 26 to the potential source 20. By establishing a potential difference between the electrode 26 and the electrodes 25 and 27, a lens field may be set up in the interelectrode space of such character as to focus a magnified image of the object under investigation on the screen 12.

It is highly desirable that the image thus produced be free from blurring due to spherical aberration of the lens system, and it will be shown in the following that this can be accomplished by proper shaping of the lens electrodes.

It has been demonstrated in a paper by Frank Gray published in the Bell System Technical Journal for January, 1939, pages 1 to 31, that the spherical aberration characteristics of an electron lens may be expressed by the relationship—

$$\frac{1}{d} = \frac{A + Br^2 + Cr^4 + \dots}{\sqrt{2V}} \quad (1)$$

in which d is the so-called focal distance of a given electron and is measured by the distance between the transaxial plane which contains the electron at a selected instant of time and the point at which the electron, if undeflected from its instantaneous direction of travel, would intersect the lens axis; A is a function of the position z of the given electron as measured along the lens axis and depends on the starting conditions of the electron and the lens potential distribution; V expresses the potential distribution along the lens axis and is thus obviously a function of z ; r is the radial displacement of the given electron from the lens axis, and B and C are quantities similar to A and of relative magnitude determined by the design of the lens system in question.

The avoidance of spherical aberration is accomplished if all electrons which start from a particular point on the lens axis have the same focal distance when they pass through a given transaxial lens plane, irrespective of the radial displacement of the various electrons at the instant of such traversal. This obviously means that in such an aberration-free lens, focal distance must be independent of radial displacement from the lens axis or, in other words, that the terms Br^2 , Cr^4 , etc. in Equation 1, above, must vanish.

In a system such as that under consideration the radial displacement r is necessarily very small, so that the Cr^4 term and all terms containing higher powers of r may be neglected. The conclusion is therefore indicated that if the coefficient B in Equation 1 can be made zero, aberration will be avoided, at least to a first approximation.

The publication of Gray above referred to shows that a sufficient condition for B to be zero is that indicated by the following differential equation:

$$\frac{d^4 V}{dz^4} - \frac{(d^2 V)^2}{dz^2} = 0 \quad (2)$$

in which V is the potential distribution along the lens axis (z).

A solution of this equation which is relevant to the present invention is as follows:

$$V = F \cosh wz J_0(wr) \quad (3)$$

where J_0 indicates a Bessel function, and F and w are arbitrary constants. It will now be shown that this equation may be satisfied by the use of a lens comprising a central electrode of cylindrical character and a pair of complementary electrodes each of which presents to one extremity of the central electrode a convex surface of revolution whose generatrix is determined (in the ideal case) by the following equation:

$$\cosh 2.4 \frac{b}{a} = \cosh \frac{2.4}{a} z \cdot J_0\left(\frac{2.4}{a} r\right) \quad (4)$$

where b and a are identified in Fig. 2 as fixed parameters, and z and r are variable parameters measured respectively from the central transverse plane and from the longitudinal axis of the lens system illustrated.

The potential distribution of a system of the type shown may be determined by consideration of Laplace's equation for an axially symmetrical system. This equation is:

$$\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r} \frac{\partial \phi}{\partial r} + \frac{\partial^2 \phi}{\partial z^2} = 0 \quad (5)$$

where ϕ is potential at any point. One solution of this equation is:

$$\phi = K_1 \cosh K_2 z \cdot J_0(K_2 r) \quad (6)$$

where K_1 and K_2 are perfectly arbitrary constants.

Let K_1 be set equal to

$$\frac{E}{\cosh 2.4 \frac{b}{a}}$$

and K_2 equal to $2.4/a$ where E (i. e., the potential of 26'), b and a are quantities identified in Fig. 2. Then Equation 6 becomes

$$\phi = \frac{E}{\cosh 2.4 \frac{b}{a}} \cosh \frac{2.4}{a} z \cdot J_0\left(\frac{2.4}{a} r\right) \quad (7)$$

which is an equation precisely in the form of Equation 3 specified above as determinative of the condition of minimum first order spherical aberration of the lens in which the arbitrary constant F takes on the particular value

$$\frac{E}{\cosh 2.4 \frac{b}{a}}$$

and the constant $w = 2.4/a$. Moreover, Equation 7 complies with the condition that the geometry of the end electrodes 25' and 26' shall be determined by Equation 4, according to which

$$\cosh 2.4 \frac{b}{a} = \cosh \frac{2.4}{a} z \cdot J_0\left(\frac{2.4}{a} r\right)$$

For when the latter equation is satisfied (which is true only on the surface of the end electrodes), the potential ϕ of Equation 7 becomes

$$\phi = \frac{E}{\cosh 2.4 \frac{b}{a}} \cdot \frac{\cosh 2.4 \frac{b}{a}}{J_0\left(\frac{2.4}{a} r\right)} J_0\left(\frac{2.4}{a} r\right) = E \quad (8)$$

which obviously accords with the situation illustrated in Fig. 2. Also, when r equals a (which

is true at the surface of the central electrode 26')

$$J_0\left(\frac{2.4}{a}r\right) = J_0(2.4) = 0$$

and from (7)

$$\phi = 0$$

which correctly describes the postulated potential condition of electrode 26'.

The electrode shape defined by Equation 4 obviously varies with the dimensional parameters a and b , and in Figs. 3 and 4 there are shown a series of configurations which result when different dimensions are chosen. Figure 3 illustrates particularly the effect of changing the diameter a of the central electrode while leaving the spacing b of the end electrodes fixed, and Fig. 4 illustrates the result of changing the spacing b while maintaining a fixed diameter of the central electrode.

It will be apparent from what has been said in the foregoing that the ideal case from the standpoint of avoiding aberration is realized when the end electrodes correspond exactly to the configuration defined by Equation 4. It is found, however, that in many instances an adequate approximation may be obtained by the use of a convex surface of revolution of generally spherical character, the radius of curvature of the surface being chosen to cause the surface to conform as nearly as possible to the ideal shape. Where a still closer approximation is desired, this may be obtained by the use of an electrode formed with two merging spherical surfaces of different radii of curvature as indicated in Fig. 5. (In this latter figure the two merging spheres are designated as x and y and the solid line u depicts the resultant electrode structure.)

In view of the foregoing it will be understood that the advantages of the present invention may be realized to a substantial degree not only by the exactly formed structures described by Equation 4 but also by the use of convex end electrodes whose surfaces are quasi-spherical (including spherical) sections formed to approximate but not necessarily to coincide with the ideal case. Accordingly, it is considered that constructions of the latter character are within the generic scope of the invention.

It is, of course, unnecessary that the electrode structures be of the precise character illustrated in Fig. 1, and in Fig. 6 there is shown a construction which may be alternatively employed. In this case the central electrode 40 is in the form of a thick circular plate having a central opening 41 of generally cylindrical form. This is positioned between two additional plate-like members 43 and 44 which act as complementary lens electrodes and which are assumed to be maintained at a common potential difference with respect to the electrode 40. In order to minimize spherical aberration effects the electrodes 43 and 44 are provided centrally with protuberances 45 and 46 in the form of quasi-spherical sections which face the respective extremities of the opening 41. Each of the electrodes is provided with a small central aperture (numbered 48 and 49 respectively) which is in alignment with the opening 41 and which serves to permit the passage of an electron stream through the lens system.

It will be readily apparent that insofar as the lens-forming surfaces are concerned the electrode arrangement of Fig. 6 is the equivalent of that of Fig. 1. That is to say, assuming the protuber-

ant surfaces 45 and 46 to be appropriately shaped with reference to the spacing of their respective electrodes and the diameter of the opening 41 (i. e. in accordance with Equation 4, above), the lens action occurring in the interelectrode space will be free or substantially free of spherical aberration.

In most constructions, it will prove desirable to arrange the various electrodes so that at least a portion of the convex surface of each of the end electrodes extends within the opening of the central electrode. Accordingly, this arrangement may be considered a preferred, although not essential embodiment of the invention.

While the invention has been described mainly by reference to particular structures and to a particular application, it will be understood that numerous modifications both of construction and use will occur to those skilled in the art. I, therefore, aim in the appended claims to cover all such equivalent variations as come within the true spirit and scope of the foregoing disclosure.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. An electron lens comprising a first electrode having a generally cylindrical opening therethrough and a pair of complementary electrodes on opposite sides of the first electrode and having relatively small openings in alignment with the opening in said first electrode, said complementary electrodes each presenting to said first electrode a convex surface of revolution in the form of a quasi-spherical section which is symmetrical about a line directed through said openings, whereby spherical aberration of said lens is minimized.

2. An electron lens comprising a first electrode having an opening through it of generally cylindrical form and a pair of complementary electrodes on opposite sides of the first electrode and each presenting to it a convex surface of revolution in the form of a quasi-spherical section having a small aperture in axial alignment with the said opening, the said complementary electrodes being adapted to be maintained at a common potential difference with respect to the first electrode during normal use of the lens, whereby the lens field produced by the electrodes is symmetrical with reference to the central transverse plane of the said opening.

3. An electron lens comprising a cylindrical tubular electrode and a pair of complementary electrodes adjacent to the respective extremities of the tubular electrode and adapted to be maintained at a common difference of potential with respect to it, the said complementary electrodes each having an aperture aligned with the axis of the tubular electrode and each presenting to said electrode a convex surface of revolution in the form of a quasi-spherical section which is symmetrical about said axis.

4. An electron lens comprising a first electrode having an opening through it of generally cylindrical form and a pair of complementary electrodes on opposite sides of said electrode and each presenting a convex surface of revolution which extends partially within the said opening, said complementary electrodes having relatively small openings which are respectively coaxially aligned with the opening in said first electrode, and the said convex surfaces being symmetrical about the common axis of the various openings.

5. An electron lens comprising a first electrode having through it a generally cylindrical opening

and a pair of complementary electrodes on opposite sides of the first electrode and each having a relatively small aperture in alignment with the said opening, each of the said complementary electrodes presenting to the first electrode a convex surface of revolution the generatrix of which is defined at least approximately by the equation:

$$\cosh 2.4 \frac{b}{a} = \cosh \frac{2.4}{a} z \cdot J_0 \left(\frac{2.4}{a} r \right)$$

where a is the radius of the said opening, b is one half the spacing of the complementary electrodes, and r and z are variable distances measured respectively from the longitudinal axis and from the central transverse plane of the lens.

6. In electronic apparatus for producing in a selected plane an electron-optical image of an object desired to be investigated, the combination which includes an electron source, means for supporting the object to be investigated in the path of electrons projected from said source, and an electron lens positioned between the said object-supporting means and the selected imaging plane, said electron lens comprising a first electrode having through it a generally cylindrical opening adapted to be traversed by electrons proceeding from the object-supporting means

and a pair of further electrodes each presenting to an extremity of the said opening a convex surface of revolution in the form of a quasi-spherical section and having a relatively small aperture in alignment with the opening.

7. In electronic apparatus for producing in a selected plane an electron-optical image of an object desired to be investigated, the combination which includes an electron source, means supporting the object to be investigated in the path of electrons projected from the said source, and an electron lens positioned between the said object-supporting means and the selected imaging plane, said electron lens comprising a central electrode having through it a generally cylindrical opening adapted to be traversed by electrons proceeding from the object supporting means, a pair of further electrodes each presenting to an extremity of the said opening a convex surface of revolution and having a relatively small aperture in alignment with the opening, and connections for maintaining said further electrodes at a common potential difference with respect to the central electrode, whereby the lens field produced by the electrodes during normal use thereof is symmetrical with reference to the central transverse plane of the lens.

SIMON RAMO.