

Nov. 28, 1967

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3,355,622

ELECTRON BEAM FOCUSING APPARATUS

Filed Aug. 5, 1964

2 Sheets-Sheet 1

FIG. 1

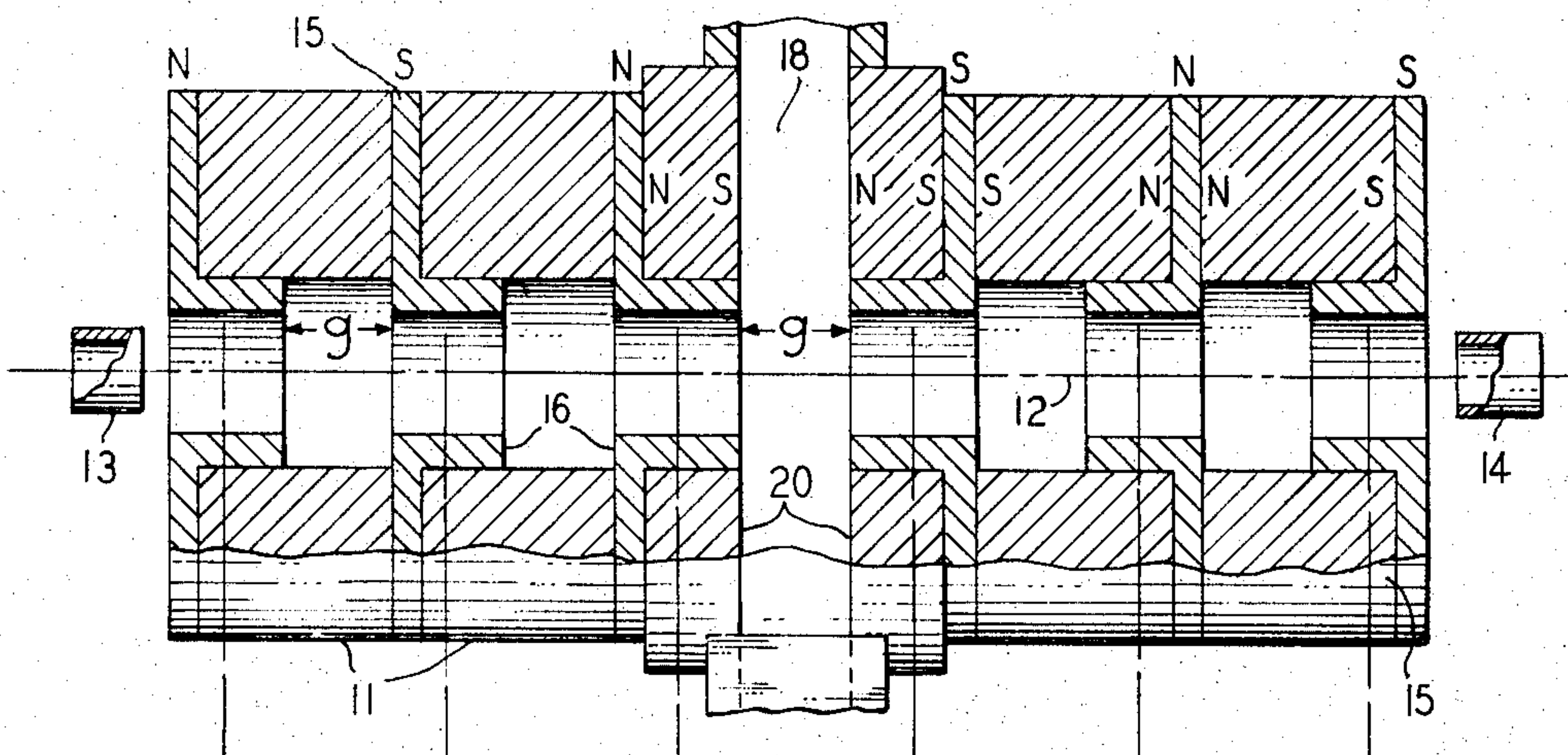


FIG. 1A

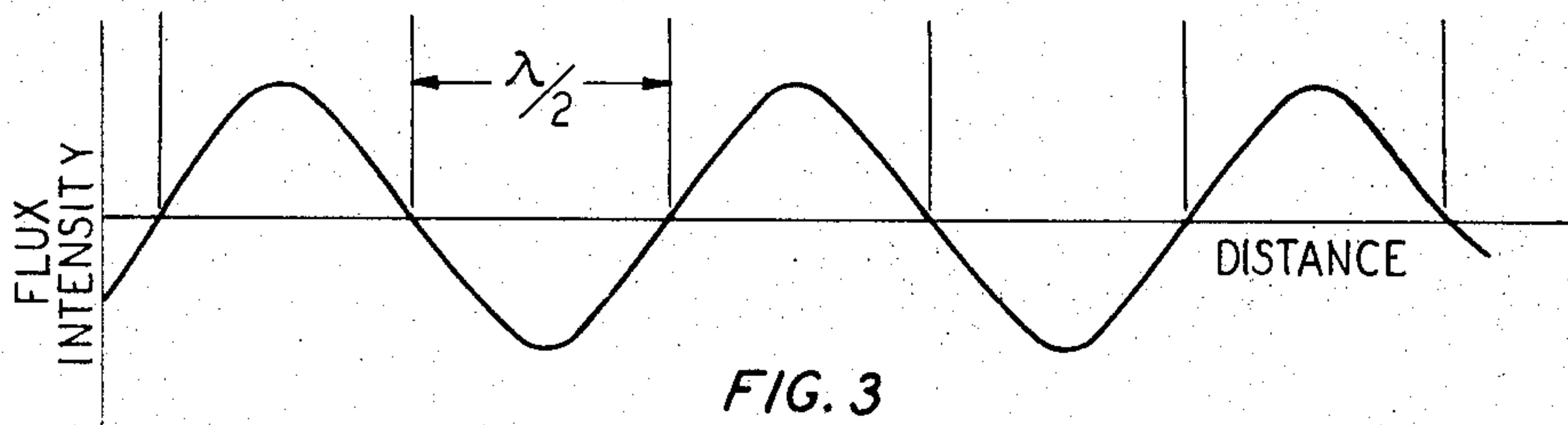
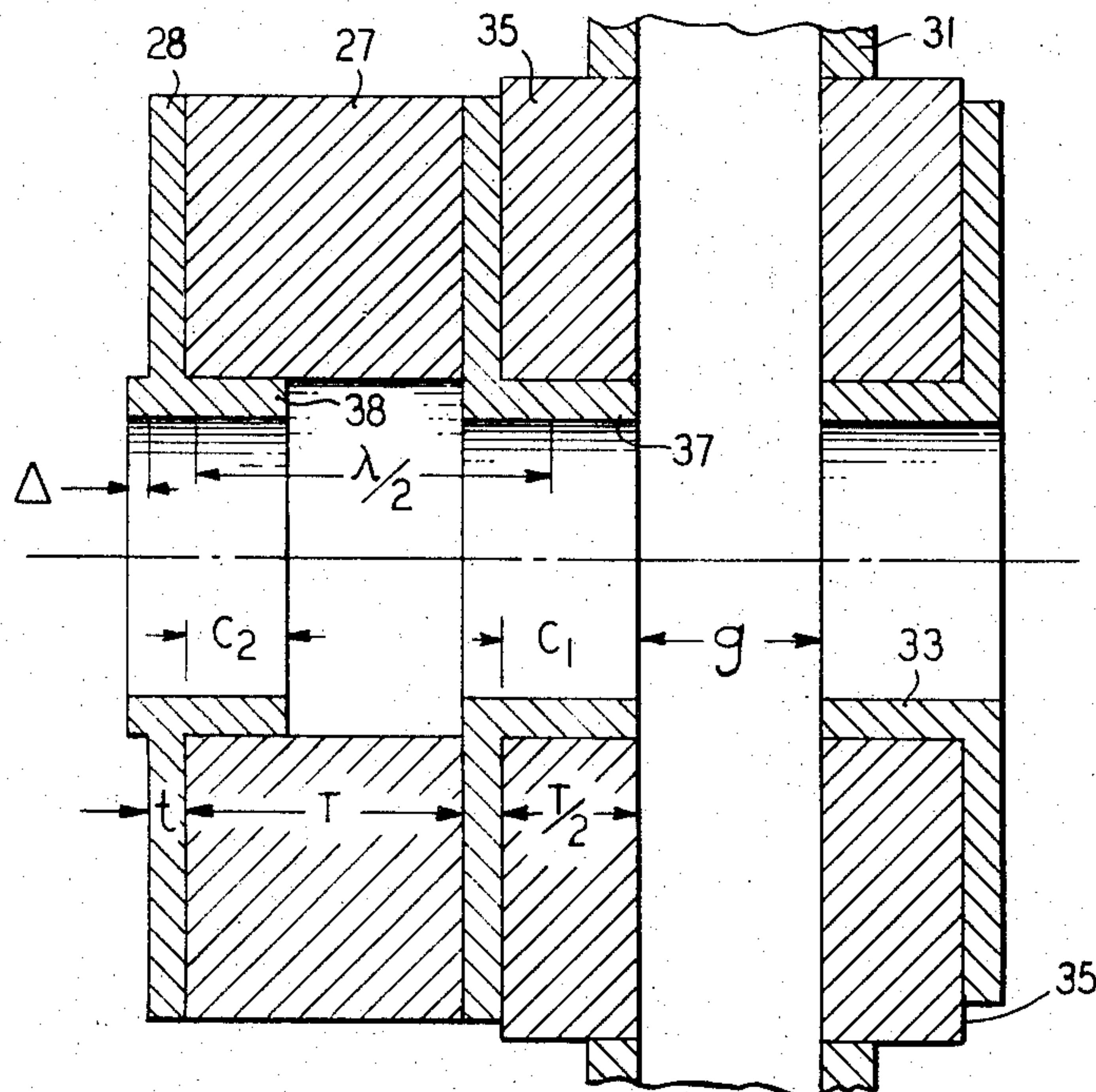


FIG. 3



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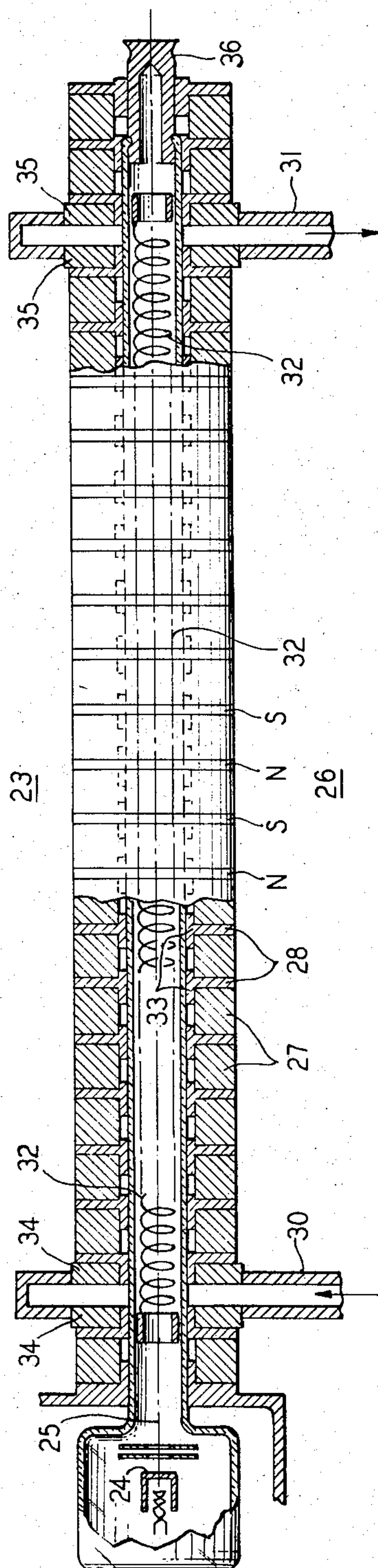
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FIG. 2



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ELECTRON BEAM FOCUSING APPARATUS
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9 Claims. (Cl. 315—3.5)

This invention relates to electron beam devices, and more particularly, to electron beam periodic focusing apparatus.

Electron beam devices such as the traveling wave tube normally use a magnetic field to focus the electron beam; that is, to constrain the beam to follow a predetermined path and to prevent it from diverging. It is well known that the size and weight of the magnetic apparatus for producing this focusing field can be considerably reduced by employing the principles of periodic focusing. Periodic focusing requires, among other things, the establishment of a spatially alternating magnetic field along the path of the electron beam. This is normally accomplished by a stacked array of equally spaced annular permanent magnets which are coaxial with the electron beam path. The polarities of the permanent magnets and their spacings are arranged so that the direction of a major magnetic field component that is parallel with the beam path periodically reverses direction, with its intensity varying sinusoidally with respect to distance.

A major requirement of any periodic focusing field is that its sinusoidal variations should be uniform along the beam path; i.e., the magnitude and the length of the period of each field alternation should be substantially equal to that of neighboring sinusoidal alternations. If the periodic alternations are not uniform, perturbations and turbulences may be created in the beam, resulting in a condition known in the art as beam scalloping.

Virtually all periodically focused electron beam devices employ input and output devices for transmitting electromagnetic wave energy to and from the electron beam. In a traveling-wave tube, for example, waveguides are typically used to transmit wave energy to and from a helical slow-wave circuit which propagates the wave energy in close proximity to the beam to amplify it by the known principles of traveling-wave interaction. These waveguides necessarily extend through the array of permanent magnets and therefore tend to disrupt its uniformity. In many cases it is therefore difficult to maintain a sufficiently uniform magnetic field periodicity along the beam path as required to avoid beam scalloping.

I have found that accurate compensation can be made for interruptions or discontinuities in a periodic magnetic focusing structure of the type comprising an array of cylindrical permanent magnets arranged end to end, with adjacent ends of successive magnets being of like polarity. An annular pole piece is located between each pair of magnets for guiding the magnetic flux and establishing alternating magnetic polarities along the beam path. In accordance with the invention, the inner surface of each pole piece is defined by a cylindrical hub that has an appreciable axial dimension. These hubs are displaced from their respective pole pieces in the direction of the interruption or discontinuity. The hubs on the opposite sides of the discontinuity are therefore displaced toward each other. The distance between the hubs on opposite sides of the discontinuity is substantially equal to the distance between the other successive hubs of the array. Two permanent magnets which together are of approximately the same total size and magnetic strength as each of the other permanent magnets of the array, are located between the discontinuity and the two pole pieces adjacent the discontinuity. Under these conditions, the magnitude and the length of the period of the magnetic field along

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the beam path in the region of the discontinuity will be equal to the alternating magnitude and the period lengths of the field along the rest of the beam path, as is required to avoid beam scalloping.

In accordance with another feature of the invention, where two discontinuities in the focusing structure occur, as is normally the case with traveling wave tubes having input and output waveguides, the displacement of the hubs between the two discontinuities from their respective pole pieces varies in inverse proportion to their respective distance from the discontinuity. The hub which is equidistant from the two discontinuities is not displaced, with other hubs having progressively increasing displacements in the direction of the nearest discontinuity. The location of the magnets and hubs on opposite sides of each discontinuity is as described above. The specific displacements of the various hubs to give uniform separation therebetween along the entire beam path will be described in detail below. With this arrangement a uniform sinusoidally alternating field is established along the entire focused path including the regions of the discontinuities.

These and other features of my invention will be more fully appreciated from a consideration of the following detailed description taken in conjunction with the accompanying drawing in which:

FIG. 1 is a schematic view of one embodiment of the invention;

FIG. 1A is a graph of flux intensity versus distance along the central axis of the device of FIG. 1;

FIG. 2 is a schematic illustration of another embodiment of my invention; and

FIG. 3 is a schematic illustration of a focusing structure of the type shown in FIG. 2.

Referring now to FIG. 1 there is shown a schematic view of periodic focusing apparatus comprising an array of hollow cylindrical permanent magnets 11 having a common central axis 12. Located at one end of the array is a cathode 13 for forming and projecting a beam of electrons along the central axis 12 toward a collector 14. The magnets 11 are separated by annular ferromagnetic pole pieces 15, each having a cylindrical hub portion 16. Successive magnets are arranged with their common magnetic poles abutting the intervening pole piece 15, thereby establishing alternating magnetic polarities on successive pole pieces, as indicated by the north and south notations on the drawing. The alternating magnetic polarities on the pole pieces establish a magnetic field component along the central axis 12 which is parallel with the central axis and which reverses direction at each successive pole piece. The intensity of this magnetic field component further alternates sinusoidally with distance as shown in FIG. 1A, which is a graph of flux intensity in the axial direction along central axis 12, versus distance. The purpose of this magnetic field is to constrain the electron beam to flow along central axis 12 in accordance with the principles of periodic focusing.

Located in the array of permanent magnets is a discontinuity 18 which may be used, for example, to permit access of a waveguide to the electron beam. An example of a tube using a single waveguide in this manner is the high frequency triode in which an electromagnetic wave becomes amplified as it propagates transversely across an electron beam. The device of FIG. 1 could also use a grid modulated electron beam in which a single waveguide or cavity resonator is used to abstract energy from the beam. In spite of the discontinuity 18, a substantially uniform periodic magnetic intensity must be maintained along central axis 12 for effective periodic focusing of the beam.

In accordance with my invention this objective is achieved by displacing hubs 16 from their respective pole pieces 15 in the direction of the discontinuity 18. The

axial length of each hub is chosen such that the gap g between successive hubs is equal to the axial length of the discontinuity 18. Immediately adjacent the discontinuity are two "half-length" permanent magnets 20, each of which is half as long in the axial direction as are the permanent magnets 11. The hubs 16 essentially constitute flux guides which, because of their displacements, displace the periods of magnetic field alternation in the direction of the discontinuity. Because of well-known principles of magnetic conduction, it is characteristic of hubs 16 that a zero axial magnetic field intensity will occur at the midpoints of the hubs as shown by the projection from FIG. 1 to FIG. 1A. This characteristic can be appreciated by considering the flux paths between adjacent hubs 16 which penetrate the beam and which follow paths of least reluctance. Since the distances between the midpoints of successive hubs 16 are equal along the entire beam path, and since substantially the same magnetic potential is generated by permanent magnets between successive hubs, the magnetic field along the axis 12 will be uniform in terms of both periodicity and alternating magnitude as shown in FIG. 1A.

Greater leakage flux normally occurs between magnets 20 than between other magnets. To compensate for this, magnets 20 are made with a slightly larger outside diameter than the other magnets. This leakage flux constitutes a second order effect for which compensation can be made without undue experimentation. The axial lengths of gaps g and half-magnets 20 are preferably equal, but this need not necessarily be the case, as will be appreciated from a consideration of FIGS. 2 and 3.

Referring now to FIG. 2 there is shown a traveling-wave tube 23 having a cathode 24 for projecting an electron beam along a central axis 25 toward a collector 36. The beam is focused along axis 25 by a periodic focusing structure 26 comprising an array of permanent magnets 27 each separated by ferromagnetic pole pieces 28. Located at opposite ends of the traveling-wave tube are an input waveguide 30 and an output waveguide 31. Extending along the major portion of the traveling-wave tube is a conductive helix 32 for transmitting wave energy from input waveguide 30 to the output waveguide 31 in close proximity to the electron beam. As the wave energy propagates along the helix it becomes amplified through the known principles of traveling-wave interaction.

Waveguides 30 and 31 constitute discontinuities in the focusing structure 26 which, in the absence of any modification of the focusing structure, would tend to cause beam scalloping and electron impingement on helix 32. In accordance with the invention, a uniform periodic intensity of the focusing field along the beam path is maintained by pole piece hubs 33 which constitute flux guides and which alter the periodicity of the magnetic field in much the same manner as described above. The hub 33 which is directly between the input and output waveguides is not displaced from its respective pole piece 28, but all of the other hubs are displaced in the direction of the waveguide discontinuity to which it is nearest. The displacement of each hub 33 from its respective pole piece 28 is inversely proportional to its distance from the closest waveguide. Hence, the hubs nearest the waveguides are displaced the most, with successive hub displacements decreasing in the direction of the center of the focusing structure.

By observation it can be seen that the gaps between all of the successive hubs 33 are of uniform axial length and that the magnets located between each successive pole piece are of the same size to generate the same magnetic flux. Half-magnets 34 which are on opposite sides of waveguide 30 and half-magnets 35 which are on opposite sides of the waveguide 31, are each half the axial length of the permanent magnets 27 so that each pair of half magnets generates the same magnetic potential as one magnet 27. Each half-magnet is made with slightly larger

outside diameter than the other magnets to compensate for leakage flux as described above. Because of the uniform distances between the centers of hubs 33 and because of the uniform flux density generated between these hubs, a uniform periodic magnetic field is produced along central axis 25 as required for dependable periodic focusing.

The manner of determining the precise displacement of hubs 33 can be appreciated from consideration of FIG. 3 which is an enlarged section of part of the output waveguide 31 and immediately adjacent structure. As pointed out above, a zero magnetic field intensity occurs at the midpoint of each of the hubs. The distance between the midpoints of adjacent hubs is therefore equal to one-half the wave length of the spatially alternating field as indicated by $\lambda/2$ on FIG. 3. Uniform periodicity is maintained by using a gap length g between all the hubs which is equal to the axial length of the discontinuity defined by the waveguide.

The hub 37 which is nearest the waveguide is maximally displaced from its pole piece and extends in the direction of the waveguide a distance c_1 . The hub 38 which is next removed in the direction of the center of the tube is displaced a smaller distance c_2 . The difference Δ of these displacements is

$$\Delta = c_1 - c_2 \quad (1)$$

By observation it can be seen that the length of one-half of a period is equal to the distance T between adjacent pole pieces plus the thickness t of each pole piece plus Δ or,

$$\lambda/2 = T + \Delta + t \quad (2)$$

At the waveguide 31 it is seen that the length of one-half of a period can be expressed as,

$$\frac{\lambda}{2} = g + \frac{T}{2} + t \quad (3)$$

Combining Equations 2 and 3 gives

$$\Delta = g - \frac{T}{2} \quad (4)$$

Referring again to FIG. 2, the total change of displacement of hubs 33 occurs over one-half the distance between waveguides 30 and 31. Since at the point equidistant between the two waveguides the hub is positioned symmetrically about the pole piece, the total change of displacement is one-half the length of the hub in excess of the thickness of the pole piece or $(1/2)(T/2)$. Furthermore, if n is the number of pole pieces between the waveguides, $(n-1)$ is the number of gaps between the pole pieces and $1/2(n-1)$ is the number of gaps over one-half the distance between waveguides. Hence Δ can be defined as:

$$\Delta = \frac{\frac{1}{2}\left(\frac{T}{2}\right)}{\frac{1}{2}(n-1)} = \frac{T}{2}\left(\frac{1}{n-1}\right) \quad (5)$$

and, from Equation 4,

$$g = \frac{T}{2}\left(\frac{n}{n-1}\right) \quad (6)$$

The length L between waveguides 30 and 31 is

$$L = n \frac{\lambda}{2} \quad (7)$$

n typically may be 19 for the usual form of traveling-wave tube.

The foregoing derivations are made on the assumption that all the hubs are of the same axial length, the pole pieces are the same thickness, and that half-length magnets 35 are one-half the axial lengths of magnets 27. These conditions simplify the analysis, but they are not indispensable for constructing the device. For example, it may be desirable to alter the dimensions of the various elements

adjacent the waveguides. Judicious compensation can be made of the variables involved to give the desired uniformity of field in spite of these alterations. Various other arrangements may be made by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. An electron beam focusing device comprising:
means including an array of permanent magnets for producing a spatially periodic magnetic focusing field along a central axis;
a discontinuity within the array of magnets; and
means for maintaining a substantially uniform periodic magnetic intensity along the central axis despite the discontinuity comprising an array of pole pieces each being located between successive magnets of the array and each having a hub portion parallel with the central axis;
a constant predetermined axial separation between successive hub portions;
each hub portion and each pole piece having a center plane that is perpendicular to the central axis;
the center plane of each hub portion being displaced from the center plane of its associated pole piece in the direction of the discontinuity.
2. The electron beam focusing device of claim 1 wherein:
the axial length of all of the permanent magnets except those contiguous with the discontinuity are substantially equal;
and the axial length of each of the permanent magnets contiguous to the discontinuity is substantially equal to half the axial length of each of the other permanent magnets.
3. The focusing device of claim 2 wherein:
the axial length of each of the hub portions is substantially equal to the axial length of each of the permanent magnets which is contiguous to the discontinuity.
4. An electron beam focusing device comprising:
an array of hollow cylindrical permanent magnets arranged end-to-end for producing a spatially periodic magnetic focusing field along a central axis;
a discontinuity within the array of magnets;
two magnets of the array which are immediately adjacent the discontinuity each having axial lengths which are substantially equal to one-half the axial length of each of the remaining magnets;
adjacent ends of the said two magnets having opposite magnetic polarities;
adjacent ends of the remaining magnets having like magnetic polarities;
and an annular ferromagnetic pole piece located between each of the said remaining magnets;
a ferromagnetic cylinder located on the inner surface of each pole piece;
the axial distance between adjacent ferromagnetic cylinders being substantially equal along the entire array;
the ferromagnetic cylinders adjacent to the discontinuity being each attached at one end to its respective pole piece and extending in the direction of the discontinuity.
5. Apparatus for focusing an electron beam and constraining it to flow along a predetermined path comprising:
means including an array of permanent magnets for producing a spatially alternating magnetic focusing field along said predetermined path;
at least one discontinuity within the array of magnets;
means for maintaining a substantially uniform alternating magnetic intensity and periodicity along the path comprising an array of ferromagnetic pole pieces each being located between successive magnets of the array and each having an extended portion adjacent with and parallel to the path;

- a constant predetermined separation between successive extended portions;
each extended portion and each pole piece having a center plane that is perpendicular to the electron beam path;
the center plane of each extended portion being displaced from the center plane of its associated pole piece in the direction of the discontinuity to which it is nearest.
6. Electron beam focusing apparatus comprising:
an array of hollow cylindrical permanent magnets arranged end-to-end for producing a spatially periodic magnetic focusing field along a central axis;
two discontinuities within the array of magnets;
means for establishing an alternating magnetic intensity along the central axis in the region of the discontinuities which is substantially equal to the alternating magnetic intensity along the remainder of the central axis comprising an array of ferromagnetic pole pieces each being located between successive magnets of the array and each having extended hub portions adjacent to and parallel with the central axis;
a constant predetermined gap between successive hub portions;
each hub portion and each pole piece having a center plane that is perpendicular to the central axis;
the center plane of each of said hubs being displaced from the center plane of its associated pole piece in the direction of the discontinuity to which it is nearest;
the displacement of each hub being inversely proportional to its distance from the discontinuity to which it is nearest.
 7. The apparatus of claim 6 wherein:
all of the permanent magnets except the magnets immediately adjacent the discontinuities have an equal axial length T and all of the pole pieces have an equal thickness t ; and wherein
the difference Δ of the displacement of any given hub between the two discontinuities and the displacement of another hub between the two discontinuities which is immediately adjacent the given hub is substantially determined by

$$\Delta = \frac{\lambda}{2} - T - t$$

where λ is the length of one period of said spatially periodic magnetic focusing field.

8. The apparatus of claim 7 wherein:
the axial length g of the gap between successive hubs is substantially determined by,

$$g = \frac{T}{2} \left(\frac{n}{n-1} \right)$$

where n is the number of pole pieces between the two discontinuities.

9. An electron beam device comprising:
means for forming and projecting a beam of electrons along a path toward a collector;
an input waveguide and an output waveguide located near opposite ends of the path;
a conductor extending between the input and output waveguides in close proximity to the beam for transmitting wave energy in interacting relationship with the beam;
means for focusing the beam comprising an array of hollow cylindrical permanent magnets surrounding a major portion of said path;
an array of annular pole pieces each being located between successive magnets of the array;
a ferromagnetic cylinder which is coaxial with the path being attached to the inner surface of each annular pole piece;
each ferromagnetic cylinder portion and each pole piece having a center plane that is perpendicular to the electron beam path;

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the gaps separating successive ferromagnetic cylinders being substantially equal;
a first group of ferromagnetic cylinders being located between the input and output waveguides but being closer to the input waveguide than the output waveguide;
a second group of ferromagnetic cylinders being located between the input and output waveguides but being closer to the output waveguide than the input waveguide;
the center plane of each of the cylinders of the first group being displaced from the center plane of its associated pole piece in the direction of the input waveguide, said displacement being in inverse proportion to its distance from the input waveguide;

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the center plane of each of the cylinders of the second group being displaced from the center plane of its associated pole piece in the direction of the output waveguide, said displacement being in inverse proportion to its distance from the output waveguide.

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