Feb. 16, 1960 M. S. GLASS 2,925,517

ELECTRON BEAM FOCUSING MAGNETIC CIRCUIT

Filed May 23, 1957 3 Sheets-Sheet 1

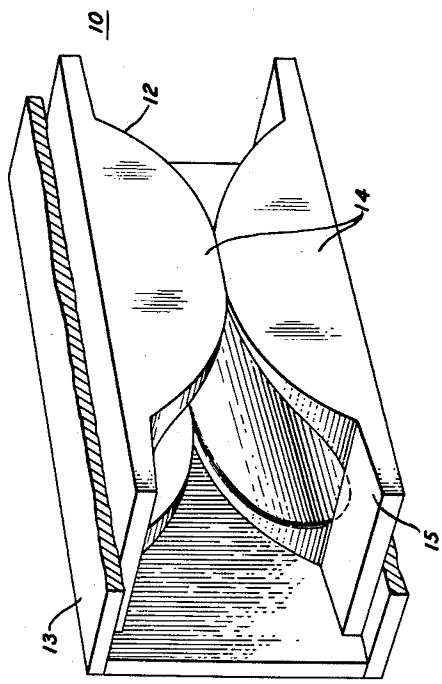

FIG. 1

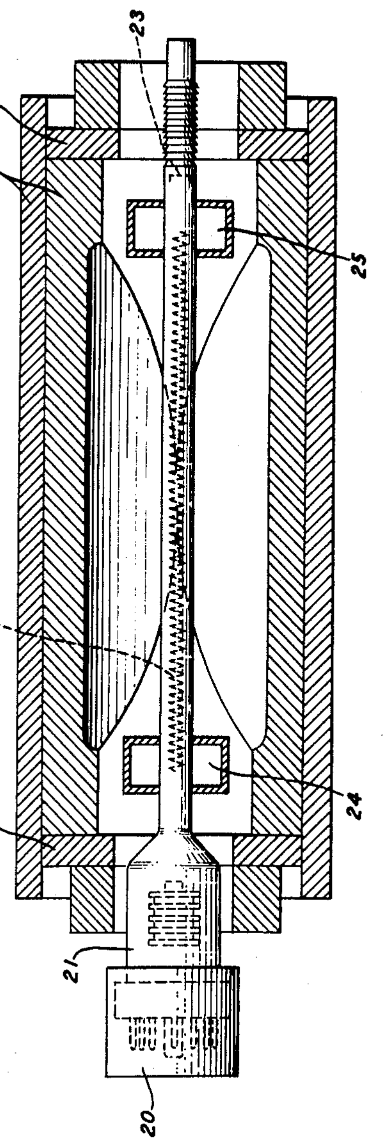

FIG. 2

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FIG. 3

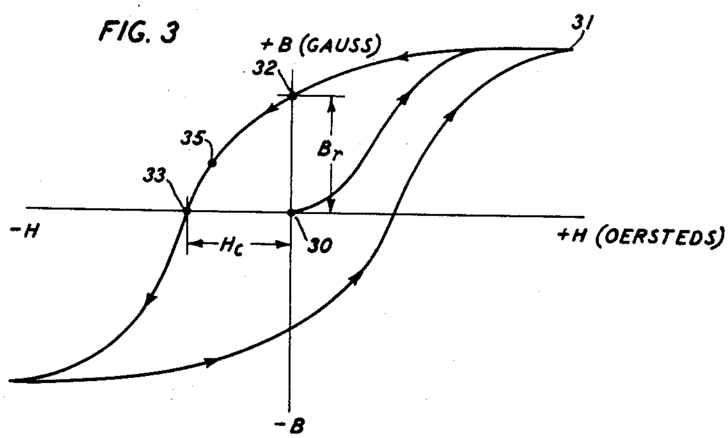
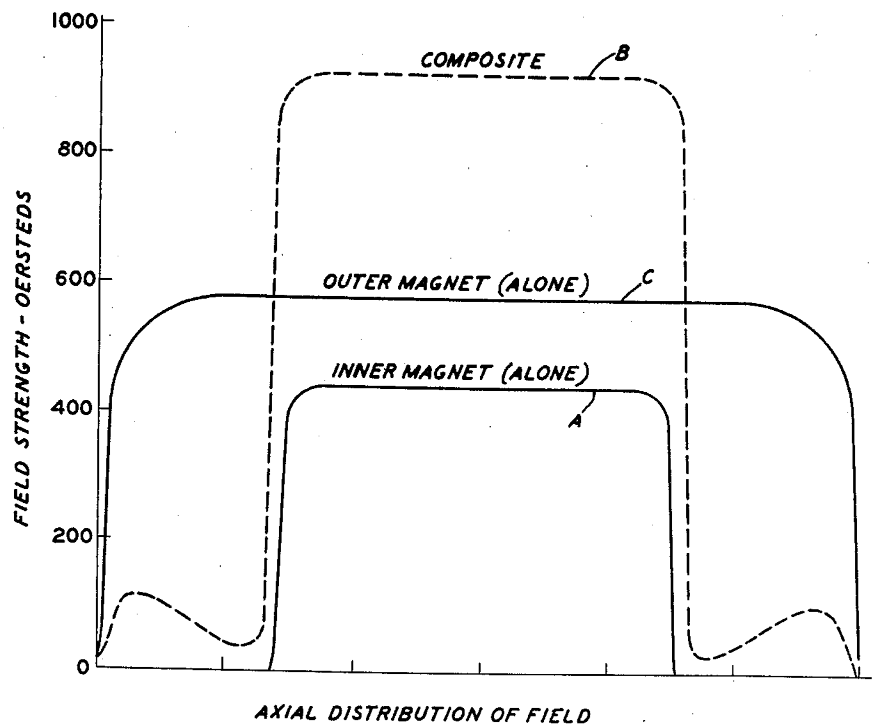


FIG. 4



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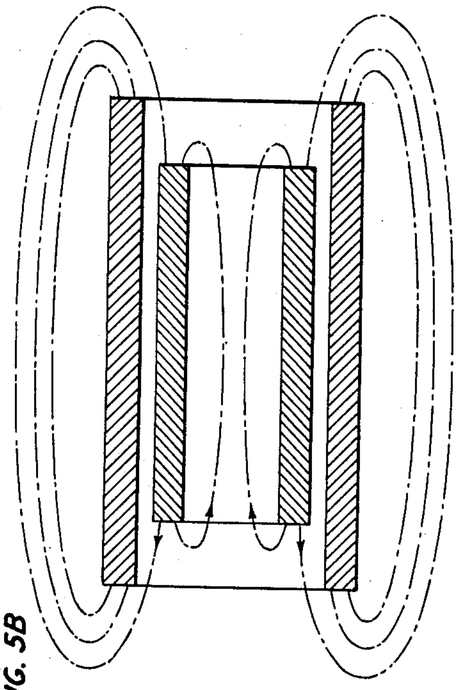

FIG. 5B

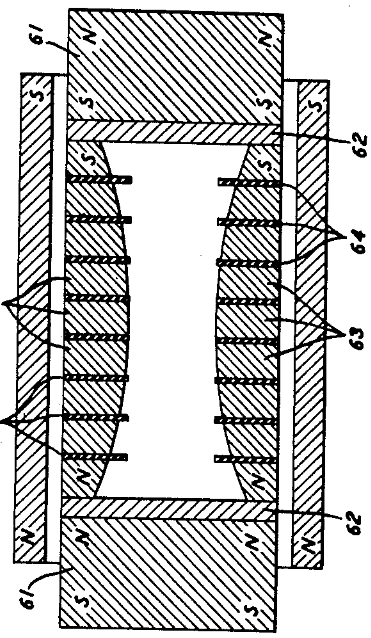

FIG. 6

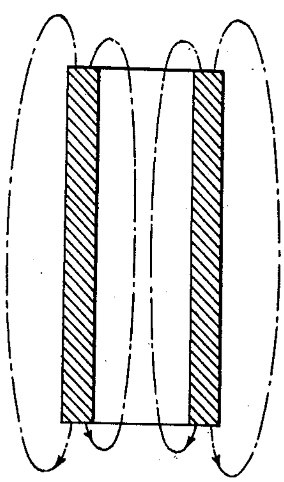

FIG. 5A

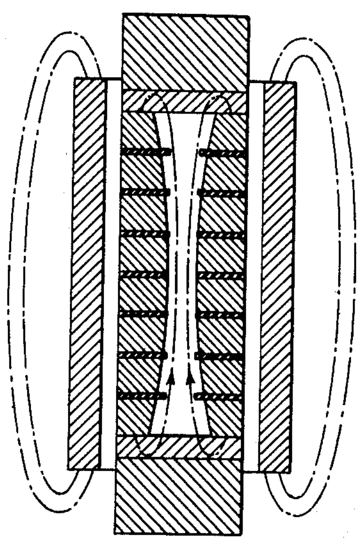

FIG. 5C

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ELECTRON BEAM FOCUSING MAGNETIC CIRCUIT

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12 Claims. (Cl. 315—3.5)

This invention relates to apparatus including magnetic structures and more particularly to such apparatus including traveling wave tubes wherein an electron beam is focused by a magnetic field along a relatively long path.

In certain electron discharge devices, such as traveling wave tubes, an electron stream is projected into an interaction space generally defined by a helix, where it is made to interact with an electromagnetic wave traveling along the helix. Optimum operation is achieved when the electron stream is confined to a substantially cylindrical form having electrons at its radial extremities close to but not impinging the helix throughout the interaction space. It has been the practice to establish a longitudinal magnetic field along the path of electron flow to confine the beam as desired.

It is an object of this invention to improve magnetic focusing of electron beams in electron discharge devices such as traveling wave tubes.

More specifically, it is an object of this invention to provide a magnetic field which will focus an electron stream over a relatively long path, confining the stream to a uniform shape within narrow limits.

Another object of this invention is to provide a uniform straight magnetic field of sufficient strength to achieve the desired focusing of an electron beam while reducing the size and weight of the focusing equipment.

In electron discharge devices employing high density electron beams, such as traveling wave tubes, a strong magnetic field is provided over a substantial portion of the electron beam path. Electrons entering this field attain an angular velocity proportional to the difference in magnetic flux encountered in passing from a shielded electron gun region into the field region. The inward or focusing force per charge derived from the angular velocity and the magnetic field must be adjusted to counterbalance exactly the sum of outward mutually repulsive forces of the electrons, generally described as space charge forces, and the outward centrifugal force of the spiraling electrons in order to effectively confine the beam to a cylindrical channel within the helix throughout the interaction space.

Permanent magnet structures have been employed to achieve a uniform, straight magnetic field as required for electron beam focussing over a relatively long electron beam path. One such structure is disclosed, for example, in my Patent 2,791,718, issued May 7, 1957, wherein a permanent magnet assembly encloses the interaction space in a longitudinal aperture in the magnet. The magnetic field is directed along an axial path in the aperture and serves to focus an electron beam directed into the aperture. Proper design of the magnet structure results in a strong straight field in the aperture with a compact light-weight magnet suitable for portable applications such as in airborne equipment.

The various materials suitable for permanent magnet usage have distinct characteristics which may be determined from the familiar B–H curve or hysteresis loop

for each material. Coupled with the magnet dimensions, these characteristics demonstrate the magnetic limitations of any given material.

When magnet material is disposed symmetrically about an axis, with a free space along the axis terminated by pole pieces, and magnetized parallel to the axis, there results along the axis between the pole pieces a magnetomotive force determined by the magnet size and operating point on the characteristic B–H curve. The flux along the axial gap and the external leakage flux, combined, are equal to the flux in the magnet itself and serve to establish the optimum operating point for the magnet. Thus a magnetic material characterized by a large coercive force (capable of providing a high field strength) is limited in the field strength actually provided in the aperture by the flux density (B) it must maintain to satisfy the leakage flux requirement. As the leakage flux requirement increases, the actual field strength decreases, and the magnet size must increase to maintain a high level of magnetomotive force in the gap to properly focus the beam.

Certain magnet materials are characterized by high coercivity (H_c) providing a relatively strong demagnetizing force ($-H_m$) at the optimum working point of the magnet ($BH_{max.}$). Other magnet materials are characterized by high remanence (B_r) having a relatively high flux density at $BH_{max.}$. Unfortunately magnet materials which exhibit high coercivity are generally incapable of high flux density. Magnet materials are available which exhibit sufficiently high coercivity to satisfy the focusing requirements of some traveling wave tubes with small light-weight magnet assemblies despite heavy leakage flux requirements. However, in instances where the axial field requirements are greater than the usable values of field strength available in known magnetic materials, increased size and weight of single magnet structure are required.

I have found that the two sets of magnetic requirements for traveling wave tube operation; i.e., high coercive force or field strength in the axial gap and high flux density to support the leakage flux path outside the gap, can be satisfied by a combination of two magnetic materials so shaped as to form two coaxial magnets. The inner magnet is formed of some magnet material of high coercive force to supply the required high field strength on the axis. The outer magnet is formed of a magnet material which is characterized by high flux density.

Thus the outer magnet in effect supplies the flux in the external leakage path of the inner magnet and permits operation of the inner magnet with a much greater coercive force than could be achieved by the inner magnet operating alone. Axial extension of the outer magnet beyond the ends of the inner magnet enhances the shielding of the inner magnet, further reducing the flux requirement of the inner magnet. With the inner magnet operating at a suitable point on its B–H characteristic curve to provide the required high field strength on the axis, the size and weight of the composite magnetic structure is appreciably reduced from that required by a single magnet having the best available characteristics to provide the same field.

Also in accordance with this invention further improvement in performance is obtained by employing reverse polarity magnets adjacent the ends of the inner magnet. The leakage path of the inner magnet thus is further restricted, and the flux producing requirement in turn is further reduced.

Transverse or stray fields present in the interaction space due to imperfections in the magnet materials may be eliminated by the use of thin high permeability discs positioned about the interaction space in parallel planes perpendicular to the field through the interaction space. Such a field straightener assembly is disclosed by C. C. Cutler in his application Serial No. 168,202, filed June 15, 1950. I have found it advantageous, in accordance with one embodiment of this invention, for the inner magnet to comprise a series of discs interleaved with the high permeability field straightener discs. In this fashion a compact structure with a smaller aperture for the interaction space is permitted than would be possible if an independent field straightener assembly were utilized. The characteristics of such an inner magnet structure are essentially the same as displayed by a single inner magnet of the same proportions.

It is a feature of this invention that electron beam focusing apparatus comprise a composite permanent magnet assembly having a first magnet structure displaying high coercive strength apertured to pass the electron beam therethrough and a second magnet structure displaying high flux density coaxially surrounding the first magnet structure.

It is another feature of this invention that the second magnet structure extend axially beyond the ends of the first magnet structure.

It is a feature of one embodiment of this invention that the first magnet structure comprise coaxial spaced-apart sections poled in the same direction and interleaved with high permeability members substantially in parallel planes perpendicular to the field through the aperture of the first magnet structure.

It is another feature of this embodiment of the invention that the inner magnet structure have magnets adjacent the ends thereof which are poled in the opposite direction to the polarity of the inner magnet sections.

A complete understanding of this invention and of the various features thereof may be gained from consideration of the following detailed description and the accompanying drawing in which:

Fig. 1 is a perspective view partly in section of a permanent magnet assembly utilized in one specific embodiment of this invention;

Fig. 2 is a side view partly in section of apparatus utilized in one specific embodiment of this invention employing the magnet assembly of Fig. 1;

Fig. 3 is a B–H characteristic curve or hysteresis loop demonstrating the desirable characteristics of magnetic materials utilized in the embodiments of this invention;

Fig. 4 is a chart showing axial field distribution of magnetic materials utilized in the magnet assembly of Fig. 1;

Fig. 5 is a series of charts illustrating magnetic lines of force for various arrangements of magnets of the type employed in embodiments of this invention; and

Fig. 6 is a side view in section of a permanent magnet assembly in accordance with another specific embodiment of this invention.

The specific illustrative embodiment of this invention as depicted in Fig. 2 comprises a permanent magnet assembly **10** best seen in the perspective view of Fig. 1. As seen in Fig. 1 the permanent magnet assembly **10** comprises a first magnet structure **12** symmetrically disposed about an air space and a second magnet structure **13** surrounding the magnet **10** and having the same axis of symmetry.

In order to provide a uniform magnetic field in the aperture of the inner magnet structure the assembly is designed to dispose the magnetic material symmetrically about a common axis through the aperture. Also the inner magnet **12** is shaped so as to concentrate magnetic material at its mid-section to bolster the otherwise weakened magnetic field in that section of the aperture along the axis. However, any magnet configuration satisfying these general requirements may be employed in various embodiments of this invention. The magnets illustrated in Fig. 1, for example, have flat outer surfaces which promote a rugged, readidly assembly structure. The outer magnet **13** comprises four plates positioned in quadrature symmetrically about the axis through the inner aperture. The inner magnet **12** is also symmetrically arranged about the axis and provides a concentration of magnetic material in the central section by means of the protuberances **14** from the flat bed portions **15** tapering toward the ends of the structure and the median of each bed portion **15**. This design is in accordance with that disclosed in my Patent 2,791,718 cited hereinbefore. It affords adequate space for a traveling wave tube assembly and openings in the tapered sides for insertion of wave guide couplings for such an assembly.

The traveling wave tube **20**, shown in Fig. 2, may be of any type known in the art. It is inserted in the inner magnet aperture and extends over the length of the magnet assembly. The tube comprises essentially an electron gun **21**, a helix transmission circuit **22** and an electron collector **23**. Input and output wave guides **24** and **25** are positioned within the end sections of the magnet assembly **10** transverse to the axis of the traveling wave tube **20** in energy coupling relationshp to the input and output ends of the helix transmission circuit **22**. The helix **22** extends within the magnet assembly **10** from the input wave guide **24** to the output wave guide **25**. Pole pieces **26** advantageously abut directly against the ends of the inner magnet bed portions **15** of the magnet assembly **10** enclosing the space therebetween to define the axial gap for the straight magnetic field. The pole pieces **26** are apertured to accommodate the envelope of the traveling wave tube **20**.

Permanent magnet materials have characteristics generally defined by the familiar B–H curve or hysteresis loop as shown in Fig. 3. Initial magnetization of the material by an external saturation field causes saturation of the material or movement from **30** to **31** on the B–H curve. Upon removal of the external field, permanent magnet material retains a portion of its magnetism, moving from the saturation point **31** to a position of remanence **32** defined as the magnetic flux density B_r, retained by the material in a closed circuit when the external field is removed. In normal usage, closed circuits do not obtain, and the presence of an air gap constitutes a demagnetizing field, or a field in the opposite direction tending to reduce the magnetization of the material. Such a field H tends to move the operating point of the material from **32** to **33** thus reducing the magnetization or retained flux to zero. The demagnetizing force or field strength in the air gap required to reduce the retained flux to zero is known as the coercivity H_c. If the magnet is demagnetized by the gap alone, the working point is on the main demagnetization curve between **32** and **33**. The particular working point is determined by the unit permeance which is independent of the magnetic material employed and comprises such factors as magnet and gap dimensions and leakage.

It is apparent from the demagnetization quadrant of the B–H curve, that as the field strength (−H) is increased, to supply a given requirement in the gap, the flux density B is decreased and vice versa. Thus, though it may be desirable to operate with a given material at a point **35** on the curve to supply a relatively high coercive force required in the interaction space of a traveling wave tube, the flux density at this point may be inadequate to supply the flux required in the air gap plus that required in various leakage paths. The problem is aggravated by the fact that the magnet materials which exhibit sufficiently large coercivity for many traveling wave tube applications are generally incapable of high flux density and a suitable operating point on the demagnetization curve for such materials is difficult to obtain due to the large leakage flux demand without sizably increasing the dimensions of a single magnet circuit.

Curve A in the axial distribution curves of Fig. 4 illustrates this situation. This curve shows the field strength in oersteds produced by a single magnet along the length of an aperture therethrough. The magnet material is characterized by coercive strength sufficient to satisfy the strong, straight field demands of some traveling wave tubes (above 900 oersteds), but due to its low flux density potential and the large leakage path to be satisfied in a single magnet structure, the magnet operates at a point on the B–H curve at which the coercive strength is totally inadequate. Increasing the magnet dimensions to improve the operating point results in a bulky and heavy structure which is unsatisfactory for many applications.

Fig. *5a* illustrates the large leakage paths which must be satisfied in a single magnet structure shown in cross section magnetized parallel to an axis of symmetry along an air gap. The flux required in the leakage paths is far in excess of that required in the air gap through the magnet and appreciably lowers the effective field strength in the gap. By surrounding this magnet structure with a second magnet structure extending longitudinally beyond the limits of the first magnet structure, in accordance with this invention, the leakage path of the first magnet structure is reduced as shown in Fig. *5b*. The first magnet structure, freed of a large leakage flux requirement, operates at a more favorable point on its B–H curve and produces the requisite field strength in the gap as illustrated by curve B in Fig. 4. The outer magnet structure is not required to possess a large coercive force, so that a material characterized by large remanence may be selected. Curve C in Fig. 4 illustrates the field strength provided by such a material when operating alone. Again it is seen that the field is inadequate for the single magnet structure.

Fig. 6 illustrates another embodiment of the invention which further improves upon the strong, straight field requirement while permitting further reduction in dimensions of the magnet structures employed. The magnets **61** abutting the pole pieces **62** of the inner magnet structure **63** have polarity opposite to that of the inner magnet structure. In this fashion the leakage path of the inner magnet structure is further reduced as indicated in Fig. *5c*.

In order to remove transverse field components in the axial field, a field straightener assembly comprising a series of thin, high permeability discs **64** is disposed about the interaction space in parallel planes perpendicular to the desired longitudinal field. In order to accommodate the discs **64** without increasing the overall size of the magnet assembly, the inner magnet structure is composed of a series of annular sections in which the high permeability discs are interleaved. Proper shaping of the inner magnet structure to concentrate magnet material in the central section is required to provide the desired uniform field throughout the interaction space as demonstrated by the curves in Fig. 4. No decrease in field strength over a solid inner magnet structure is evident.

A particular application of this magnet assembly, requiring a field strength of more than 9000 oersteds, employs materials known in the art as oriented Ferroxdure characterized by high coercive force in the inner magnet and Alnico V characterized by high flux density in the outer magnet. The resultant structure provides a reduction in magnet weight by a ratio of four to one over a single magnet structure of Alnico V providing the same field strength. The field straightener assembly employs discs having an optimum permeability of about 20,000. Transverse field components produced by the magnetic structure were removed by this assembly.

It is to be understood that the above-described arrangements are illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of this invention.

What is claimed is:

1. Electron beam focusing apparatus comprising a first permanent magnet structure apertured for passage of an electron beam and a second permanent magnet structure coaxially surrounding said first permanent magnet structure, said first permanent magnet structure being of higher coercivity and of lower remanence than said second permanent magnet structure.

2. A magnetic system for focusing an electron beam comprising a pair of permanent magnet structures disposed about and magnetized in the direction of a common axis of symmetry so as to provide a straight magnetic field along an axial passage therethrough along which said beam is focused, one of said magnetic structures effectively enclosing the other and being of a higher remanence and lower coercivity than said other to limit the leakage flux of said other.

3. A permanent magnet assembly comprising a first elongated annular permanent magnet structure magnetized parallel to its length and a second elongated annular permanent magnet structure positioned coaxially within the aperture formed by said first structure, said first structure being of higher remanence and lower coercivity than said second structure.

4. Electron beam focusing apparatus in accordance with claim 1 wherein said second structure extends axially beyond the ends of said first structure.

5. Electron beam focusing apparatus comprising a first permanent magnet structure apertured for passage of an electron beam and a second permanent magnet structure coaxially surrounding said first magnet structure, said first permanent magnet structure comprising a series of spaced annular members, the members at each end being poled in one direction and the remaining members being poled in the opposite direction, said first permanent magnet structure being of higher coercivity and of lower remanence than said second permanent magnet structure.

6. Electron beam focusing apparatus in accordance with claim 5 and further comprising high permeability annular members interjacent said spaced annular members.

7. Electron beam focusing apparatus comprising first and second structures of permanent magnet material disposed symmetrically about an axis and magnetized in the direction of said axis, said first structure being positioned between said axis and said second structure to provide a strong magnetic focusing field in the aperture formed by said first structure along said axis, and said second structure being of higher remanence than said first structure to provide external flux otherwise provided by said first structure.

8. Electron beam focusing apparatus in accordance with claim 7 wherein said second permanent magnet structure overlaps said first permanent magnet structure.

9. Electron beam focusing apparatus comprising first and second structures of permanent magnet material disposed symmetrically about an axis and magnetized in the direction of said axis, said first structure being positioned between said axis and said second structure to provide a strong magnetic focusing field in the aperture formed by said first structure along said axis, said second structure overlapping said first permanent magnet structure and being of higher remanence than said first structure to provide external flux otherwise provided by said first structure, said first structure comprising a plurality of coaxially aligned, spaced apart members symmetrically disposed about the axis and poled in the same direction parallel to the axis.

10. Electron beam focussing apparatus in accordance with claim 9 and further comprising thin, high permeability discs interleaved with said spaced-apart members.

11. Electron beam focussing apparatus in accordance with claim 9 and further comprising magnet means adjacent each end of said first permanent magnet structure,

poled parallel to the axis in the opposite direction to the polarity of said first structure and separated from said first structure by pole pieces.

12. In combination, a traveling wave tube and a permanent magnet electron beam focusing structure therefor, said focusing structure comprising a first magnetic member encompassing an air gap in which the tube is situated, a second magnetic member encompassing said first magnetic member and of a material having a higher remanence and lower coercivity than said first magnetic material, and a permanent magnet across each end of said first magnetic member.

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