United States Patent

Bassett et al.

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[54] MAGNETIC LENSES

[72] Inventors: **Richard Bassett**, near Cheltenham; **Thomas Mulvey**, Birmingham, both of England

[73] Assignee: **National Research Development Corporation**, London, England

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[21] Appl. No.: **126,930**

Related U.S. Application Data

[63] Continuation of Ser. No. 753,127, Aug. 16, 1968, abandoned.

[30] **Foreign Application Priority Data**

Aug. 18, 1967 Great Britain....................38,250/67

[52] **U.S. Cl.**.........**250/49.5 PE,** 250/49.5 D, 313/84, 335/213, 335/214

[51] **Int. Cl.**.........................**H01j 37/26,** G01n 23/22

[58] **Field of Search**.....250/49.5 D, 49.5 PE; 313/84; 335/210, 213, 214, 299, 300, 301; 336/231

[56] **References Cited**

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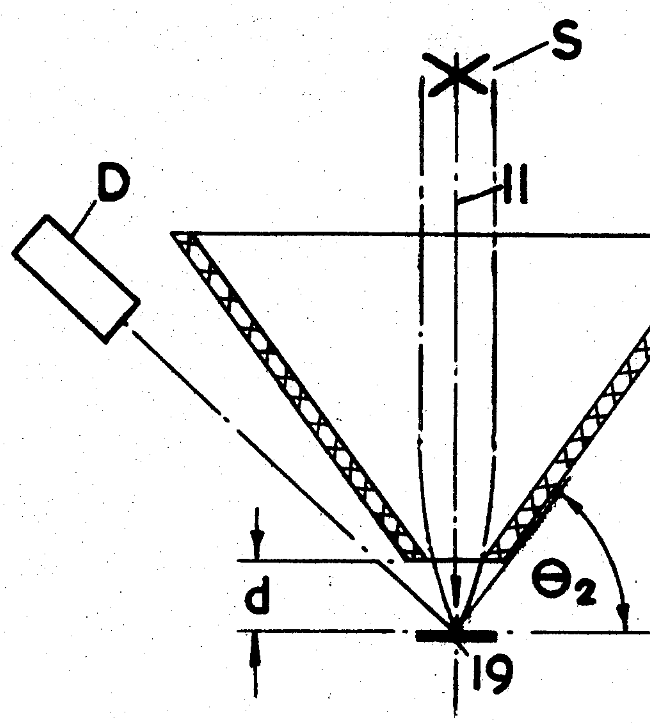
Primary Examiner—William F. Lindquist
Attorney—Cushman, Darby & Cushman

[57] **ABSTRACT**

A magnetic lens, for focusing a beam of charged particles, includes a coil at least part of which, at an end thereof, tapers conically with a half-angle between 20° and 85°. The coil may comprise a plurality of conductors laid concurrently, and cooling means may be provided in contact with the inner surface. Desirably, the coil is shrouded, at least in part, with material of high magnetic permeability. Radiation such as X-rays, from a target in focus beyond the tapering end of the coil, may be detected over a large solid angle.

11 Claims, 10 Drawing Figures



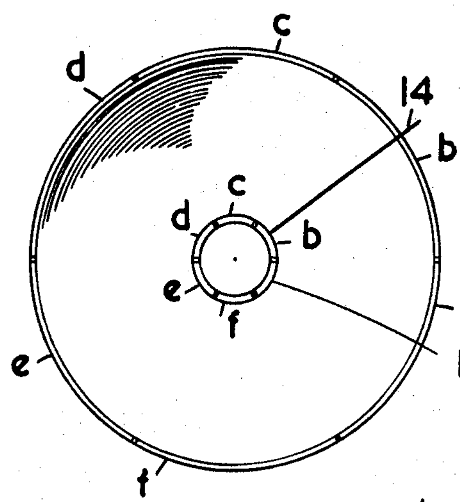


FIG 1(a)

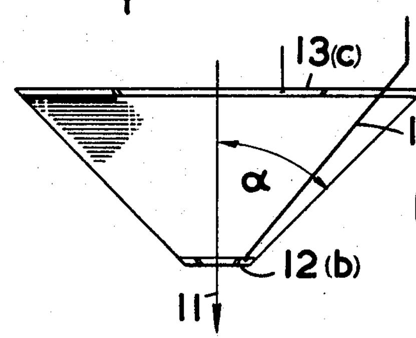


FIG. 1(b)

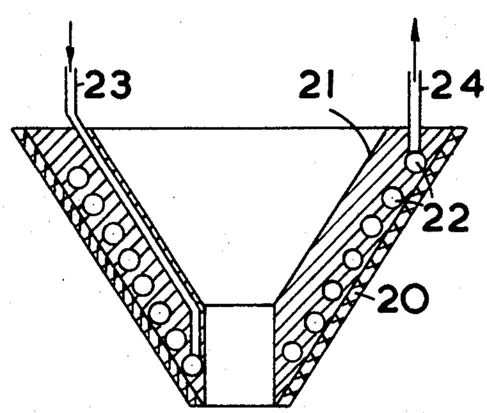


FIG. 4

Richard Bassett
Thomas Mulvey
Inventors
By
Cushman, Darby & Cushman
Attorneys

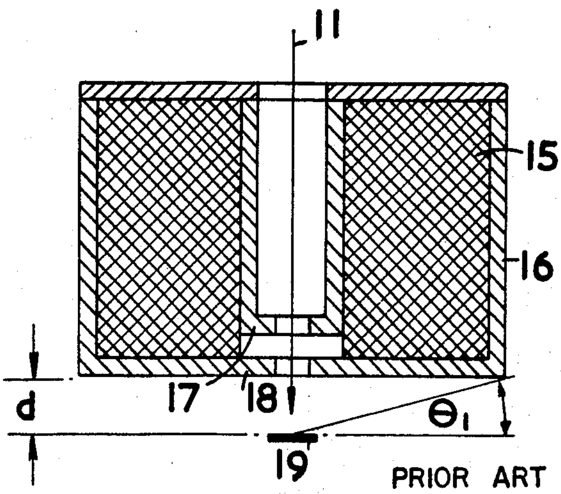


FIG. 2

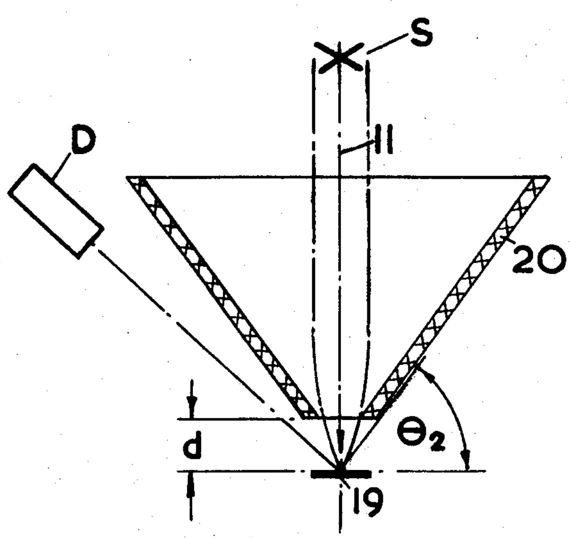


FIG. 3

Richard Bassett
Thomas Mulvey
Inventors

By
Cushman, Darby & Cushman
Attorneys

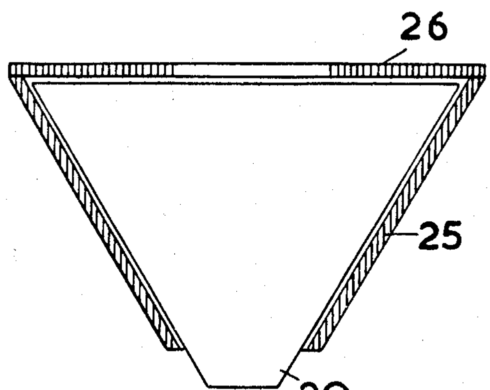


FIG 5

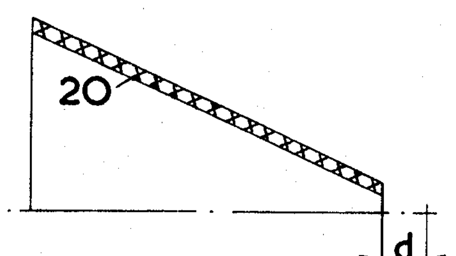


FIG 6(a)

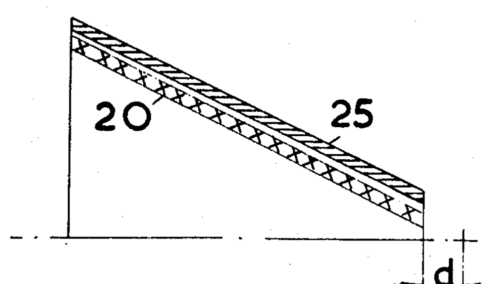


FIG 6(c)

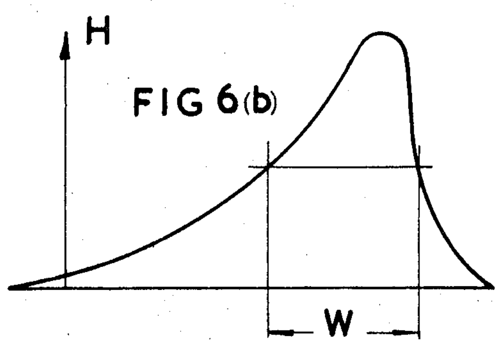


FIG 6(b)

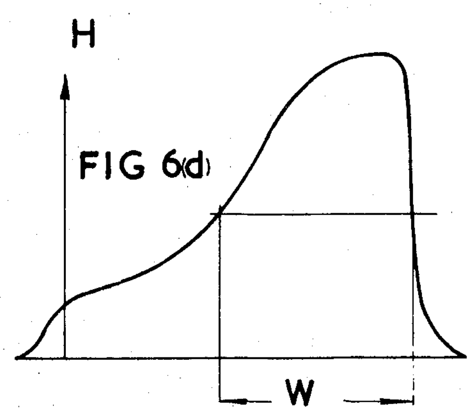


FIG 6(d)

Richard Bassett
Thomas Mulvey
Inventors

By
Cushman, Darby & Cushman
Attorneys

MAGNETIC LENSES

This application is a continuation of our earlier copending application Ser. No. 753,127 filed Aug. 16, 1968, now abandoned.

This invention relates to magnetic lenses for the focusing of beams of charged particles, in particular of beams of electrons.

It has been known for many years to focus a beam of electrons by causing it to pass axially through a magnetic field of symmetrical distribution, the magnetic field being produced by a current carrying coil, shrouded or unshrouded, of substantially cylindrical form. The focusing of electron beams is required, for example, in cathode ray tubes, electron microscopes and electron probe X-ray micro-analysis apparatus. It is towards the last that the present invention is more especially directed. In this form of microanalysis an electron beam is focused on a small area of a specimen to be investigated. It is desirable that the area in which the beam is concentrated should be as small and compact as possible and it is therefore essential that the aberrations of the lens and in particular the spherical aberration, should be as small as possible. This form of microanalysis depends on the detection of X-rays emitted from the region of a specimen bombarded by electrons, the X-rays being characteristic of elements present at the region of bombardment. With commonly known forms of lens only a relatively small proportion of the X-rays emitted can be received by a detector, and these at an angle to the normal to the surface of the specimen approaching 90°, on account of the bulk of the lens and its proximity to the specimen. This is a disadvantage in that the sensitivity of the apparatus is reduced, since so much of the X-radiation goes undetected.

According to the present invention a magnetic lens, particularly for focusing beams of charged particles such as electrons in apparatus, such as for example an X-ray micro-analysis apparatus, comprises a coil of which at least an end part thereof is substantially frusto-conical and tapers towards the end of the coil with a half angle which lies between 20° and 85°, preferably between 20° and 75°. In use in an apparatus the coil is positioned around the beam of charged particles with its frusto-conical end nearest the object being irradiated and as a result the obstruction of emitted radiation on its way to a detector may be considerably reduced. Preferably the coil is cooled by means located on its inner surface, which further reduces obstruction to emitted radiation. To improve distribution of the magnetic field produced, the coil is preferably wound with a plurality of separate, concurrently laid lengths of conducting wire, the field distribution being further improved by enclosing the coil, at least in part, by a shroud of material of high magnetic permeability.

The cooling of the coil is assisted by making its radial depth small compared with its dimension in the direction of a generator of the coil surface, and the ratio of said dimension to the radial depth is preferably not less than 5:1.

The half width, as defined herein, of the axial distribution of the magnetic field of the lens is preferably large compared with the working distance, as defined herein, from the lens to its focus.

The invention will be further described, by way of example only, with reference to the accompanying drawings in which:

FIGS. **1**(*a*) and **1**(*b*) are plan and elevational views of a magnetic lens coil according to the invention.

FIGS. **2** and **3** are cross-sectional views respectively of a conventional magnetic lens and a magnetic lens in use according to the invention.

FIG. **4** illustrates means for cooling a magnetic lens coil according to the invention.

FIG. **5** illustrates an alternative form of lens construction according to the invention.

FIGS. **6**(*a*) (*b*) (*c*) and (*d*) illustrate axial distribution of magnetic field within a magnetic lens coil according to the invention.

A magnetic lens, according to the invention, for focusing a beam of electrons, is illustrated in FIGS. **1**(*a*) and (*b*), (*a*) being a plan and (*b*) an elevation. The direction of flow of electrons through the lens is indicated by the arrow **11**. The coil consists of a number of separate, concurrently laid lengths of conducting wire wound side by side, the construction illustrated being for six such conductors. Other numbers could be employed equally well, but preferably not fewer than six. At each end of temporarily. coil is an annulus of conducting sections, insulated from each other and indicated by **12**(*a*) to (*f*) and **13**(*a*) to (*f*). One conductor of the coil may, for example, commence at section **12**(*b*) and terminate at section **13**(*c*). Another would commence at **12**(*c*) and terminate at **13**(*d*) and so on. As indicated in the figure, the conductors are wound on the surface of a cone and to this end a conical former is used to which the part-annular sections **12**, **13** are attached temporarily. The conductors are wound preferably three or more at a time and if multilayer construction is required, the conductors are all wound in the same axial sense by returning the conductor from the end of one layer, along a generator of the cone, to the commencement of the next. In order to obtain satisfactory bedding of the conductors it is found necessary to wind from the smaller to the larger end of the cone. Preferably, each layer of conductors is bonded to the next layer below by the application of a coating of a thermosetting resin of good electrical properties, e.g. an epoxy resin. When a sufficient total number of turns of conductor have been applied, the whole may be removed from the conical former.

It is found that a magnetic field of satisfactory circumferential uniformity is obtained if the current is fed as nearly as possible symmetrically to the coil. This is the reason for winding the coil in sections. Uniformity is most important at the smaller diameter end of the coil, where the field is strongest and the greatest focusing effect takes place. To minimize stray unbalanced magnetic effects from the supply leads to the coil, these may be brought to the larger end of the coil and then to the smaller end along generators of the cone as indicated at **14**. A coil with six conductors could be arranged for example so that all six were fed with current in parallel; or three symmetrically disposed conductors in parallel could be connected in series with the remaining three, also symmetrically disposed, again in parallel. Arrangements of a similar sort may be made with larger numbers of conductors. The number of conductors is desirably a multiple of three.

The coil in FIGS. **1**(*a*) and **1**(*b*) has a half conical angle of 45° and the coils of greatest utility have a half angle lying in the range 30° to 60°. However, useful results may be obtained with half angles within the range 20° to 85°. Purely by way of example, a coil might have a larger diameter of 3 inches and be wound with enamelled copper wire of 32 s.w.g.; the half-angle being 45°.

A comparison of FIGS. **2** and **3** illustrates an advantage of the magnetic lens according to the invention over magnetic lenses of conventional form. FIG. **2** illustrates a conventional lens, the arrow **11** indicating the direction of electron flow. The lens comprises a coil **15** enclosed within a shroud **16** of material of high magnetic permeability. The shroud is formed with close-set annular pole pieces **17, 18**, concentric with the average path followed by the electron beam as indicated by arrow **11**. The magnetic field between the pole pieces focuses the electrons in the beam on to the specimen under investigation at **19**. The working distance of the lens is here defined as the distance *d*, that is the shortest distance between the lens structure and the specimen.

FIG. **3** illustrates diagrammatically a magnetic lens in use according to the invention. A beam of electrons from a source S is focused by the lens coil **20** on to a specimen **19**, the arrow **11** indicating the sense and average path of the electron beam. Radiation emitted from the specimen **19** is detected by a detector D, which is designed and positioned to receive the emitted radiation desired. The working distance *d* is the same as in FIG. 2.

A comparison of angle θ_1 in FIG. **2** with angle θ_2 in FIG. **3** demonstrates that in the case of the conical lens, radiation from the specimen may be received over a much greater angle than is possible with the conventional form of lens; as shown, over three times greater.

Frequently, large magnetic fields must be generated in a lens and these are in general accompanied by large current densities in the conductors of the lens coil with consequent increase in temperature. The temperature increase could be enough to cause damage if no cooling means were provided. FIG. **4** illustrates cooling means according to the invention. Inside the coil **20** and in close thermal contact therewith is a block **21**. This block contains cooling passages **22**, as close as practicable to the inner surface of the coil. The cooling passages are provided with an inlet, **23**, and an outlet, **24**, through which cooling fluid may be passed in order to remove heat conducted from the coil. The cooling passages may be in the form of a tube around which the block **21** is cast. The block **21** is desirably of material having a high thermal conductivity, e.g. copper. Conveniently the block **21** may serve as the former on which the coil **20** is wound. FIG. **4** illustrates another desirable feature of the invention, viz. that the coil is of small radial depth or thickness in comparison with its slant height, and desirably the ratio of slant height to radial thickness would not be less than 5:1, but could be very considerably greater. Small thickness of the coil is desirable in order to facilitate removal of heat therefrom and also to maximize the angle θ_2 shown in FIG. **3**. It is possible to avoid all heating effects in the coil by operating it at superconducting temperatures, but it is difficult to arrange this and at the same time preserve a large angle θ_2 as mentioned above, because the cryogenic equipment tends to be bulky.

Even with the greatest care in winding the coil it is possible for some minute non-uniformity to exist, and a corresponding lack of symmetry in the magnetic field pattern of the coil is produced. It is found that such small non-uniformities can be to a large extent nullified by shrouding the outside of the coil with a fitting conical shell of material of high magnetic permeability. This is shown in FIG. **5** at reference **25**. It is, in any event, necessary to shield the electron beam from the effects of the Earth's magnetic field, and any other stray magnetic field, and the shroud thus performs a dual function. Further control of the focusing of the electron beam can be achieved if the shrouding is extended by an annular re-entrant portion, **26**, in magnetic contact with the portion **25**.

The coil shown in half section in FIG. **6**(*a*) produces a magnetic field which varies in strength along the axis of the coil. The variation of the field strength on the axis, that is on the path followed on the average by an electron beam passing through the coil, is shown in the curve at FIG. **6**(*b*). The half-width of the curve is defined as the distance between the points at which the field strength has half its maximum value, and is indicated by W in FIG. **6**(*b*). In FIG. **6**(*a*) the working distance *d* is indicated, that is the distance between the extremity of the coil and the location of the focus of the electron beam and also of the specimen. It is a characteristic of the invention that the half-width as defined above is substantially larger than the working distance, and in general the half-width will not be less than twice the working distance. FIG. **6**(*c*) is a half section of a shrouded coil. The effect of this on the field strength is shown in FIG. **6**(*d*) viz. to increase the field strength generally and to broaden the peak of the curve. The definition of half-width remains as before and the tendency is to increase the ratio between half-width and working distance.

Although a magnetic lens, in use with the invention, has been described, with reference to the drawings, for the focusing of a beam of electrons, such magnetic lens could be employed for focusing a beam of any other charged particles.

We claim:

1. An electromagnetic lens for focusing a beam of charged particles, said lens comprising:

a coil wound with a plurality of separate concurrently laid lengths of electrically conducting wire said lengths extending from one axial end of said coil to the other axial end thereof with the ends of the separate lengths being uniformly distributed around the circumference of said coil whereby substantial circumferential magnetic field uniformity is insured by electrical interconnections of said separate lengths with each other and with a source of electrical current,

said coil having two open substantially magnetically unshrouded ends and an inner and an outer surface, at least an end part of which is substantially frusto-conical in shape tapering towards one unshrouded end of the coil with a half conical angle lying between 20° and 75°, said frusto-conical shape causing an increased magnetic field intensity towards said one unshrouded end of the coil to result in focussing an axially directed beam of charged particles.

2. An electromagnetic lens as in claim **1** further including:

a plurality of annular conducting sections at each end of said coil for making external electrical connections to said separate lengths of wire.

3. An electromagnetic lens as in claim 1 further including:

return conductor means disposed substantially parallel to a geometrical generator of said frusto-conical coil end for providing an external electrical connection to the small end of said coil.

4. An electromagnetic lens as in claim 1 wherein said separate lengths of conducting wires are all laid in the same axial sense around said coil.

5. An electromagnetic lens as in claim 1 wherein said plurality of lengths comprises an even number whereby alternate lengths can be electrically connected in parallel to form two such parallel circuits which, in turn, may be connected in series with each other to help insure circumferentially uniform current distributions.

6. An electromagnetic lens as in claim 1 in which the half conical angle lies between 30° and 60°.

7. An electromagnetic lens as in claim 1 in which the coil is cooled by means located on its inner surface.

8. An electromagnetic lens as in claim 1 wherein said coil is constructed to have a radial depth as measured between the inner and outer surfaces of the coil winding is not more than one-fifth of the dimension of the coil in the direction of a generator of the frusto-conical coil surface.

9. An electromagnetic lens as in claim 1 in which the coil is enclosed on the outer surface only thereof, at least in part, by a shroud consisting of material of high magnetic permeability.

10. An electromagnetic lens as in claim 1 wherein said coil is constructed to cause the distance between the points at which the field strength on the axis of the lens has half its maximum value is large compared with the distance from the smaller end of the lens to the location at which a beam of charged particles is focused by the lens.

11. An apparatus for analyzing an object of which comprises:

a source for producing a beam object charged particles which is directed onto said object,

a detector for detecting characteristic radiation emitted from said object, and

a magnetic lens for focusing said beam of charged particles onto said object, the magnetic lens comprising;

a coil wound with a plurality of separate concurrently laid lengths of electrically conducting wire said lengths extending from one axial end of said coil to the other axial end thereof with the ends of the separate lengths being uniformly distributed around the circumference of said coil whereby substantial circumferential magnetic field uniformity is insured by electrical interconnections of said separate lengths with each other and with a source of electrical current,

said coil having two open substantially magnetically unshrouded ends and an inner and an outer surface, at least an end part of which is substantially frusto-conical in shape tapering towards one unshrouded end of the coil with a half conical angle lying between 20° and 75°, said frusto-conical shape causing an increased magnetic field intensity towards said one unshrouded end of the coil to result in focussing an axially directed beam of charged particles.

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