

Oct. 21, 1947.

L. MARTON

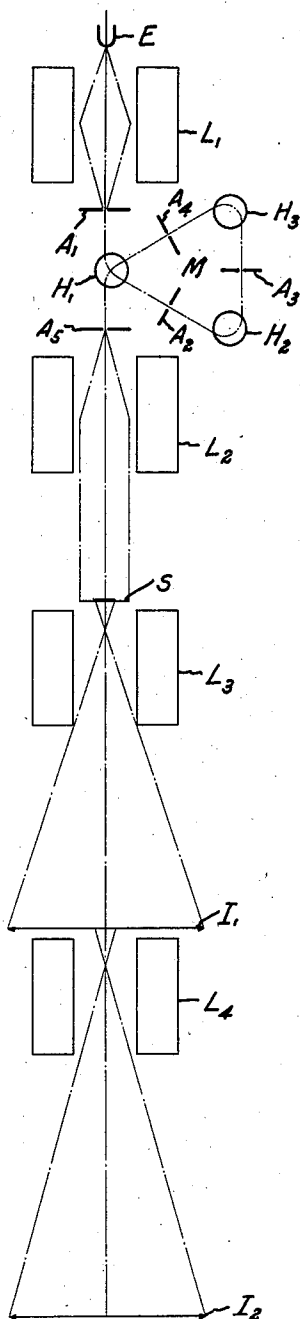
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ELECTRON BEAM MONOCHROMATOR

Filed Aug. 24, 1945

2 Sheets-Sheet 1

Fig. 1.



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Fig. 2.

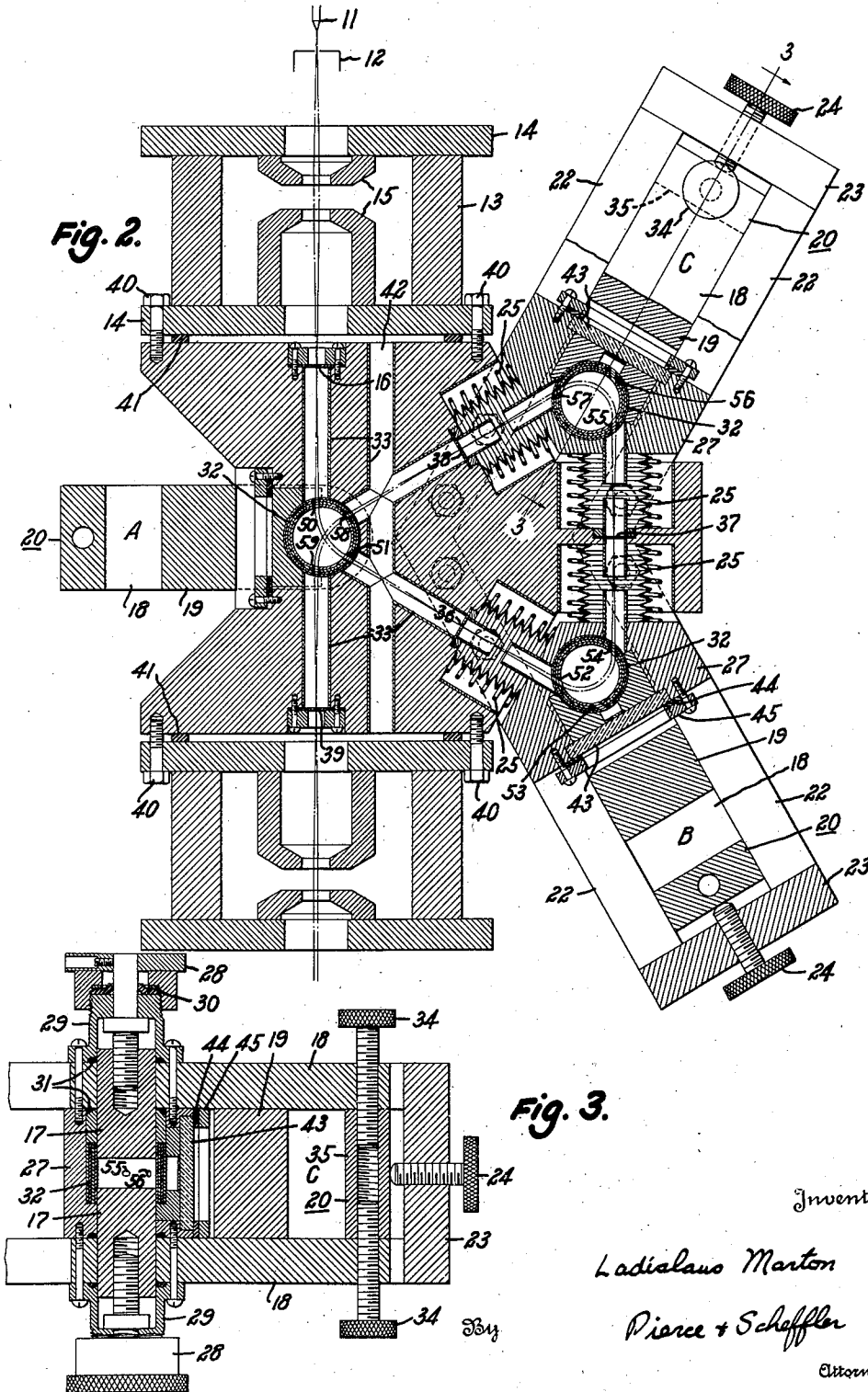


Fig. 3.

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ELECTRON BEAM MONOCHROMATOR

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This invention relates to devices for monochromatizing the electron beam of electron microscopes into electron microscopes including means for providing an electron beam of substantially uniform velocity composition.

Transmission type electron microscopes using magnetic lenses are subject to a considerable chromatic effect due to the impossibility of correcting chromatically such lenses. Expressed in light optical analogy, such microscopes have to be operated with a monochromatic beam of illumination which is produced in the conventional microscope of this type by making the source perfectly monochromatic. To achieve this, the electron sources are energized by a supply of very high constancy. The constancy requirements, as indicated by theory, are of the order of magnitude of one part in 10,000 or better. Furthermore, the lenses used in such microscopes, which are produced commonly by a current flowing through a circular coil, have to satisfy similar requirements, and it has been calculated that the constancy of the objective lens current, for instance, must be of the order of magnitude of one part in 20,000 or better, if a good resolving power of the instrument is desired.

Electron microscopes having electrostatic lenses have the advantage that no regulation of the power supply is needed, because they can be built so that the variations of the electron speed can be compensated by simultaneous variations of the lens characteristics. Furthermore, such electron microscopes have the advantage that they do not require any power for the operation of the lenses.

It has been proposed to replace the electromagnetic lenses of magnetic microscopes by permanent magnets and to achieve thus a freedom from fluctuation of the current supply and also a reduction of the necessary power for the operation of the instrument. It has been proved experimentally that such permanent magnets can replace satisfactorily the electromagnetic type. Such instruments, however, still require a very well regulated power supply for the acceleration of the electrons if a good resolving power is desired.

This difficulty is avoided by the present invention which provides an improved magnetic instrument combining the advantage of the electrostatic instruments, that is, lack of such close regulation of the power supply, with the higher inherent resolving power of the magnetic instruments. To use again light optical analogy, there are two ways of obtaining a monochromatic illumination of an optical system. One is to provide

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a perfectly monochromatic source and the other is to take a heterochromatic source and to split it into its components by the use of a monochromator. The present invention involves the provision of a monochromator for electron beams. In the electron microscope of the invention, a monochromator is combined with the instrument to select radiation of a single wave length (single electron speed) from a source operated from an unregulated power supply. By using permanent magnets for both the monochromator and for the magnetic lenses, the power requirements may be reduced to a minimum. The monochromator of the invention produces the necessary dispersion for the selection of a sufficiently small wave length range (velocity range) required for a high resolution instrument.

The monochromator of the invention comprises means providing a magnetic field substantially normal to the path of the electron beam whereby the electrons in the beam are deflected at angles proportional to their velocities and an aperture positioned substantially at the focal plane of the deflected beam to intercept electrons having velocities outside a preselected velocity range. Preferably, the magnetic field is provided by a permanent magnet linked with pole faces arranged adjacent the electron beam to provide a substantially constant uniform field normal to the beam path. It is particularly advantageous to provide a plurality of successive magnetic fields and interpositioned apertures whereby the electron beam is deflected through a series of angles totaling 360° so that the beam is returned at high uniform velocity composition into the axis of the original beam, thereby preserving the general rectilinear arrangement of the electron microscope construction. The number of deflecting fields and associated apertures is not critical, but an arrangement comprising three magnetic fields providing a total beam deflection of 360° is particularly convenient and such an arrangement will be described for the purpose of illustrating the principles of the invention with reference to the accompanying drawings.

In the drawings:

Fig. 1 is a diagrammatic representation of an electron microscope including the monochromator of the invention;

Fig. 2 shows, in vertical section along the axis of the electron beam, an electron beam monochromator embodying the principles of the invention, and

Fig. 3 is a partial section of the monochromator of the invention on line 3—3 of Fig. 2.

In the electron microscope diagrammatically

shown in Fig. 1, E represents an electron source, such as the typical electron gun. The beam from the electron gun is focussed on entrance aperture A₁ of the monochromator M by magnetic condenser lens L₁. The slightly divergent beam from aperture A₁ passes through magnetic field H₁ which deflects the beam by 60°, through aperture A₂, through magnetic field H₂ which deflects the beam by 120°, through aperture A₃, through magnetic field H₃ which again deflects the beam by 120°, through aperture A₄ and again through magnetic field H₁, which deflects the beam a further 60°, giving an aggregate deflection of 360°, and directs it through aperture A₅. From A₅ the beam passes through a conventional electron microscope arrangement comprising magnetic condenser lens L₂ which collimates the electron beam, specimen stage S, magnetic objective lens L₃ which produces an intermediate image at I₁, and magnetic image projector lens L₄ which produces at I₂ a highly magnified image of a portion of the intermediate image.

The following numerical data are given as an example:

Diameter of the first field H₁, 3.006 cm., radius of curvature of the beam in the field 3.00 cm. Such a field is "direction focussing" and its focal length is 5.6 cm. The position of the cardinal points being 4.1 cm. and -1.5 cm. and assuming 1 to 1 object to image ratio, the object and the image distances are 9.7 cm.

The second and third fields may be calculated similarly and the following data are typical:

Radius of curvature of the deflected beam 4.55 cm., diameter of the deflecting field 9.10 cm., focal length 3.94 cm., the cardinal points are located at 0 cm. and -3.04 cm., the object and image distances thus becoming 3.94 cm. Apertures are placed at the points indicated by A₁, A₂, A₃, A₄ and A₅, where object and image points of the combined monochromator system lie. The dispersion of the total system at the point A₅ in terms of variation of the acceleration potential can be calculated. For an accelerating potential of 100,000 volts, 10 volt variation, corresponding to one part in 10,000 causes a deflection of 1.4 mm. A beam accelerated by a potential difference of one million volts for a similar variation of one part in 10,000, that is 100 volts, will cause a deflection of 2 mm. By making the exit aperture A₅ of a sufficiently small diameter, say 0.5 mm., only electrons of the required narrow velocity range can enter the optical system of the microscope.

The following data are illustrative of the dimensioning of the magnetic circuits of the monochromator elements. Assuming that a permanent magnet material of an energy value $H \times B = 1.6 \times 10^6$, is used, for an electron beam accelerated by 50,000 volts and for a field H₁ with a gap length of 1.0 cm., the steel cross-section times the steel length becomes .4 cm.³. For the second and third fields the same cross-section times length becomes 1.01 cm.³. The same data for one million volts are 15 and 70 cm.³, respectively.

In the specific form of the monochromator shown in Figs. 2 and 3, an electron beam is generated from the filament shaped cathode 11 and accelerated by a high positive potential applied to the anode 12. Passing through the aperture of the anode, it enters the field of a magnetic condenser lens comprising a ring-shaped permanent magnet 13, two flat discs 14, and two pole pieces 15. This lens focuses the beam on the entrance aperture 16 of the monochromator.

The resulting slightly divergent beam is deflected by the first magnet A composed of pole pieces 17, yokes 18, and permanent magnet 19. A magnetic shunt 20 is provided for adjustment of the field. Further details of the construction of the magnet are given below.

After being deflected, the beam passes through a second aperture 36 to enter the field of the second magnet B. Both second and third magnets are exactly alike. They are composed of pole pieces 17, yokes 18, permanent magnet 19, shunt 20. Whereas, however, the first magnet A is mounted in a fixed position, the second B and third C are adjustable. This adjustment of position is effected by mounting the magnet between four rails 22, bolted to the body of the monochromator and connected together at their outer ends by a heavy plate 23. Plate 23 carries an adjusting screw 24 against which the magnet is pressed by two springs 25. Vacuum tight connection is established between the deflecting chambers of magnets B and C and the body of the monochromator by means of flexible metallic bellows 26.

Details of the pole piece adjustment and of the magnetic shunt are shown particularly in Fig. 2. The cylindrical pole pieces 17 can be moved up and down in the deflecting chamber housing 27 by means of the adjusting screws 28. The screws are mounted on a small cap 29 provided with a vacuum tight "rubber gland" type seal 30 giving full flexibility without letting air in the chamber. The adjustment of the two pole pieces is shown as being independent. It will be obvious, however, that very simple mechanical devices can be provided for simultaneous and symmetrical movement of the two pole pieces.

The two yokes 18 are clamped in between caps 19 and deflecting chamber 27 by means of vacuum tight seals 31. The center part of the deflecting chamber is shielded with a composite magnetic shield 32 consisting, beginning from the inside, of an inner copper tube, a high permeability alloy layer, a second copper layer and a second high permeability layer. Apertures are provided at the proper places in the composite shield 32 for the entrance and exit of the electron beam. High permeability magnetic shields 33 are also provided along the passage of the beam to eliminate the effect of stray magnet fields.

The magnetic shunt 20 includes two screws 34 of ferromagnetic material, screwed into the non-magnetic spacer 35. The same spacer also provides the surface of attack for the adjusting screw 24.

Halfway between each deflecting magnet, apertures are provided for screening off the unwanted portion of the beam. These apertures 36, 37 and 38 are mounted in fixed positions and made of thin metallic sheets which can be taken out for cleaning and inspection.

The beam, after full deflection, enters the exit aperture 39 and is directed toward the microscope proper by means of a second condenser lens with identical elements as the one described above. Both condenser lenses are attached to the monochromator chamber by means of bolts 40 compressing a vacuum tight gasket 41. Appropriate channels 42 are provided also for maintaining a good vacuum in every part of the apparatus.

For the purpose of a first calibration of the instrument, the permanent magnets 19 are taken out and an electron beam, accelerated by a known constant potential, is sent through the mono-

chromator. For the purpose of avoiding any deflection at this stage, small auxiliary coils, not shown on the drawing, are inserted in the space left free by the permanent magnets. By decreasing steadily an alternating current passing through the coil, the magnetic system can be demagnetized in a well known manner. After aligning the electron beam so that it passes without hindrance through the two condenser lenses and apertures 16 and 39, the permanent magnet of the first magnet A is inserted and its strength adjusted by changing the pole piece distance and changing the position of the magnetic shunt until the beam is properly deflected in the direction of aperture 36 and passes through the holes 50 and 51 of the shielding of the first magnet. If the distances of the apertures 16 and 36 are properly chosen and the beam enters the homogeneous circular magnetic field at the proper angle, direction focussing will occur and an image of aperture 16 will be produced on aperture 36. For the observation of such focussing, the beam can be observed after passage through holes 52 and 53 of the shielding of the second magnet B. A transparent window 43 coated on its inner surface with fluorescent material, is provided at this point and the proper focussing can be achieved by observing the intensity of the incident beam. This window 43 is mounted on the back surface of the deflecting chamber 27 by means of gasket 44 and clamping ring 45.

After adjusting the first deflecting magnet, the second permanent magnet is inserted in position and the same procedure repeated by observing the intensity of the beam on the window provided on the third deflecting chamber. The deflected beam should now pass through hole 54, aperture 37 and holes 55 and 56. For optimum operation, both the field strength and the position of the deflecting magnet have to be adjusted in the manner described above.

The last step of adjustment is made by reinserting the permanent magnet of the third magnet C and thus deflecting the beam again through the hole 57 and aperture 38. The beam, after proper adjusting of the third magnet, should enter the field of the first magnet A through the hole 58 and leave it through hole 59. With proper adjustment, the deflection on the first magnet should be exactly like the one suffered in the first place and the beam is focussed on aperture 39.

The entire monochromator is advantageously enclosed in a cover made of high permeability material not shown on the drawing. The purpose of such a cover is twofold: it provides additional shielding against stray magnetic fields and it prevents any accidental changing of the adjustment of the monochromator.

It will be obvious that the number of magnetic fields and the amount of angular diversion of the beam in each field may be varied for the purpose of securing the desired purity of the velocity spectrum of the electron beam and to adjust the direction of the electron beam with respect to the type of instrument with which it is used.

I claim:

1. An electron beam monochromator comprising means providing a plurality of successive beam-deflecting magnetic fields substantially normal to the path of the electron beam at the respective positions of the fields and apertures

positioned substantially at the focal plane of the deflected beam leaving each of said fields to intercept electrons having velocities outside a preselected velocity range.

2. An electron beam monochromator comprising means providing a beam-deflecting magnetic field substantially normal to the path of the electron beam, means providing a plurality of further beam-deflecting magnetic fields substantially normal to the path of the deflected beam at the positions of the fields the strength of said further fields being selected to cause the deflected beam from the last of said further fields to pass through said first magnetic field, and apertures positioned substantially at the focal plane of the deflected beam leaving each of the magnetic fields to intercept a preselected portion of the diverted beam.

3. An electron beam monochromator as defined in claim 2 wherein the strengths of the magnetic fields are selected to effect an aggregate deflection of the electron beam of 360°.

4. An electron beam monochromator comprising means providing a beam-deflecting magnetic field substantially normal to the path of the electron beam including a permanent magnet, yoke members, and pole pieces adjustably positioned in spaced relation on either side of the beam path, means providing a plurality of further beam-deflecting magnetic fields substantially normal to the path of the deflected beam at the position of said fields and each including a permanent magnet, yoke members and pole pieces positioned in spaced relation on either side of the beam path, and apertures positioned substantially in the focal plane of the deflected beam leaving each of the magnetic fields to intercept a preselected portion of the diverted beam.

5. An electron beam monochromator comprising means providing a beam-deflecting magnetic field substantially normal to the path of the electron beam including a permanent magnet, yoke members and pole pieces adjustably positioned in spaced relation on either side of the beam path, means providing a plurality of further beam-deflecting magnetic fields substantially normal to the path of the deflected beam at the position of said fields and each including a permanent magnet, yoke members and pole pieces positioned in spaced relation on either side of the beam path, magnetic-field-shield means surrounding the pole-gaps of each of said magnetic fields providing means including openings therein for the inlet and outlet of the electron beam, and apertures positioned substantially in the focal plane of the deflected beam leaving each of the magnetic fields to intercept a preselected portion of the diverted beam.

6. An electron beam monochromator comprising means providing a beam-deflecting magnetic field substantially normal to the path of the electron beam including a permanent magnet, yoke members, and pole pieces adjustably positioned in spaced relation on either side of the beam path, means providing a plurality of further beam-deflecting magnetic fields substantially normal to the path of the deflected beam at the position of said fields and each including a permanent magnet, yoke members and pole pieces positioned in spaced relation on either side of the beam path, magnetic-field-shield means surrounding the pole-gaps of each of said magnetic fields providing means including openings therein for the inlet and outlet of the electron beam and openings diametrically opposite the beam in-

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let openings, and apertures positioned substantially in the focal plane of the deflected beam leaving each of the magnetic fields to intercept a preselected portion of the diverted beam.

7. An electron beam monochromator comprising means providing a beam-deflecting magnetic field substantially normal to the path of the electron beam including a permanent magnet, yoke members and pole pieces adjustably positioned in spaced relation on either side of the beam path, means providing a plurality of further beam-deflecting magnetic fields substantially normal to the path of the deflected beam at the position of said fields and each including a permanent magnet, yoke members and pole pieces positioned in spaced relation on either side of the beam path, magnetic-field-shield means surrounding the pole-gaps of each of said magnetic fields providing means including openings therein for the inlet and outlet of the electron beam and openings diametrically opposite the beam inlet openings and fluorescent layers positioned to intercept an electron beam emerging from said last-named opening in the absence of the associated magnetic field, and apertures positioned substantially in the focal plane of the deflected beam leaving each of the magnetic fields to intercept a preselected portion of the diverted beam.

8. An electron microscope including means providing an electron beam, a beam velocity selector comprising means providing a plurality of successive deflecting magnetic fields substantially normal to the path of the electron beam at the respective positions of the fields and apertures positioned substantially at the focal plane of the deflected beam leaving each of said fields to intercept a preselected portion of the beam, means for passing said velocity selected beam through a specimen and means for magnifying the electron image thereby produced.

9. An electron beam monochromator comprising means providing a beam-deflecting magnetic field substantially normal to the path of the elec-

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tron beam including a permanent magnet, yoke members, and pole pieces adjustably positioned in spaced relation on either side of the beam path, means providing a plurality of further beam-deflecting magnetic fields substantially normal to the path of the deflected beam at the position of said fields and each including a permanent magnet, and adjustable shunt means for varying the strength of the magnetic field, yoke members and pole pieces positioned in spaced relation on either side of the beam path, and apertures positioned substantially in the focal plane of the deflected beam leaving each of the magnetic fields to intercept a preselected portion of the diverted beam.

10. An electron beam monochromator comprising means providing a beam-deflecting magnetic field substantially normal to the path of the electron beam including a permanent magnet, yoke members, and pole pieces adjustably positioned in spaced relation on either side of the beam path, means providing a plurality of further beam-deflecting magnetic fields substantially normal to the path of the deflected beam at the position of said fields and each including a permanent magnet, yoke members and pole pieces positioned in spaced relation on either side of the beam path, means for varying the gap between the pole pieces, and apertures positioned substantially on the focal plane of the deflected beam leaving each of the magnetic fields to intercept a preselected portion of the diverted beam.

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