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Ozasa et al.

[11] 3,851,172

[45] Nov. 26, 1974

[54] **COMPOUND ELECTRON LENS FOR ELECTRON MICROSCOPE AND THE LIKE**

[75] Inventors: **Susumu Ozasa; Shozo Kasai,** both of Katsuta, Japan

[73] Assignee: **Hitachi, Ltd.,** Tokyo, Japan

[22] Filed: **Dec. 15, 1972**

[21] Appl. No.: **315,455**

[30] **Foreign Application Priority Data**

Dec. 15, 1971 Japan 46-100977

[52] **U.S. Cl.** **250/311,** 250/396, 313/84

[51] **Int. Cl.** **H01j 37/26**

[58] **Field of Search** 250/311, 396; 313/84

[56] **References Cited**

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Primary Examiner—James W. Lawrence

Assistant Examiner—C. E. Church

Attorney, Agent, or Firm—Craig & Antonelli

[57] **ABSTRACT**

A compound electron lens having at least two exciting coils is disclosed. A gap for bypassing the flux from the coils is disposed in the inner magnetic path located between the coils. The polarities of the exciting currents to the coils are made identical or are reversed whereby the multiplying factor of the lens is varied over a wide range with a minimum of distortion.

9 Claims, 13 Drawing Figures

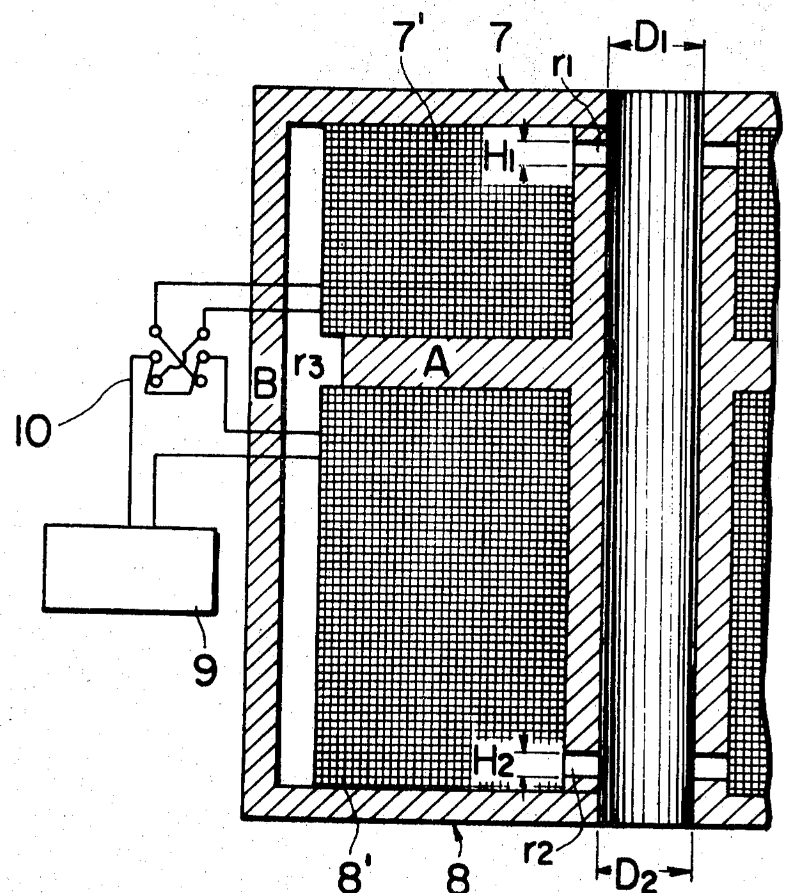


FIG. 1

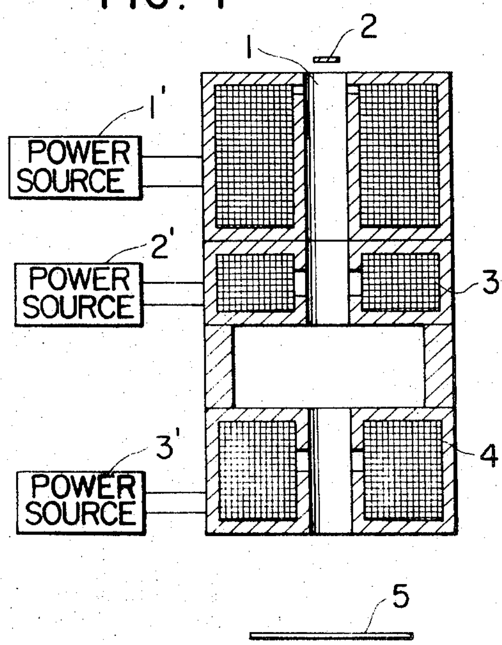


FIG. 2a

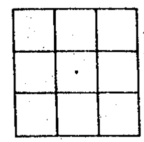


FIG. 2b

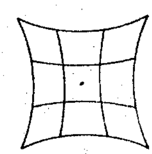


FIG. 2c

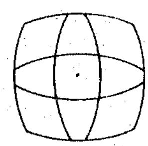


FIG. 3

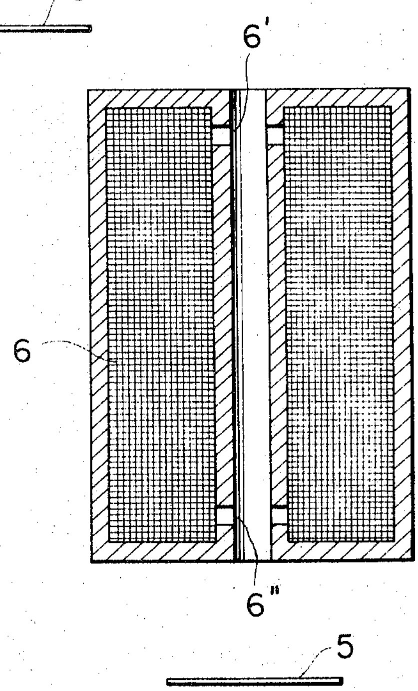


FIG. 4

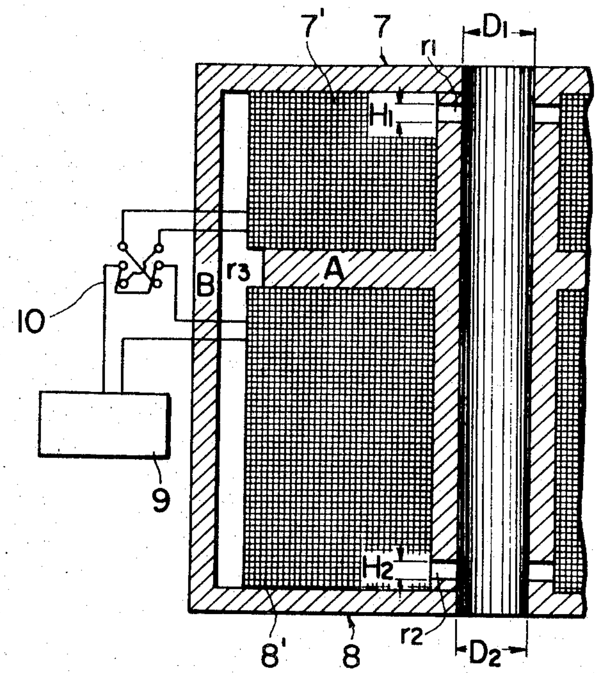

7'
7
r1
D1
H1
B
r3
A
10
9
H2
r2
8'
8
D2

FIG. 5

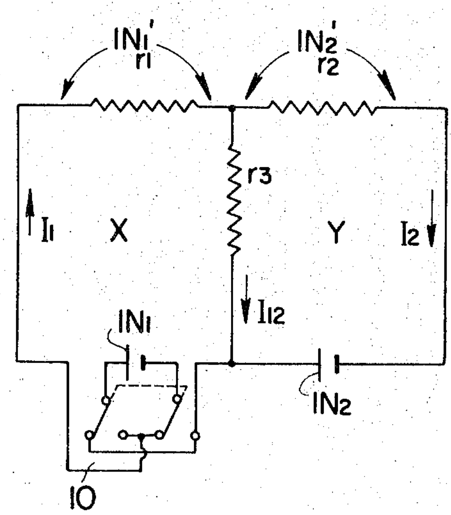

IN1'
r1
IN2'
r2
r3
I1
X
Y
I2
I12
IN1
IN2
10

FIG. 6

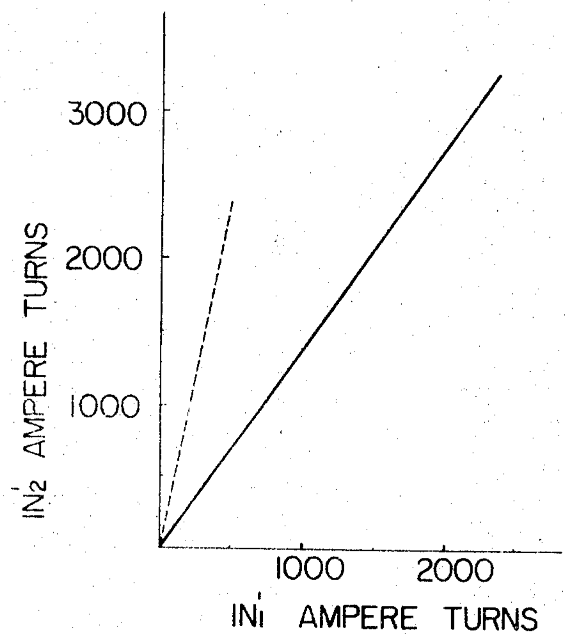

3000
2000
1000
IN_2' AMPERE TURNS
1000
2000
IN_1' AMPERE TURNS

FIG. 7

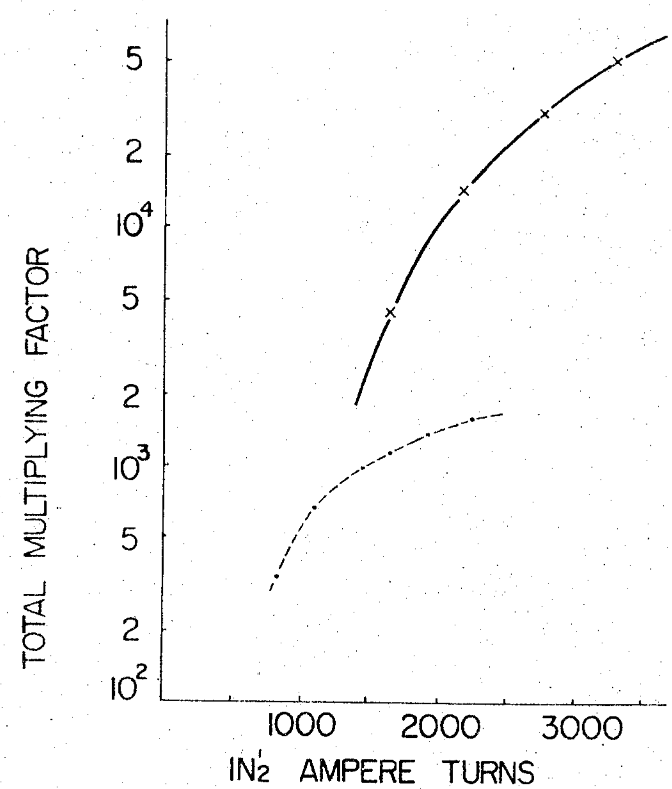

5
2
10^4
5
2
10^3
5
2
10^2
TOTAL MULTIPLYING FACTOR
1000
2000
3000
IN_2' AMPERE TURNS

FIG. 8

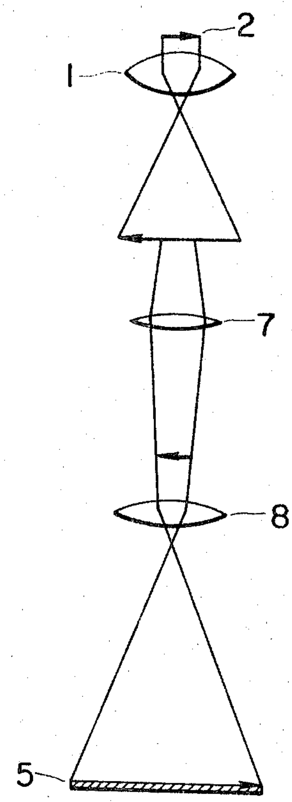


FIG. 9

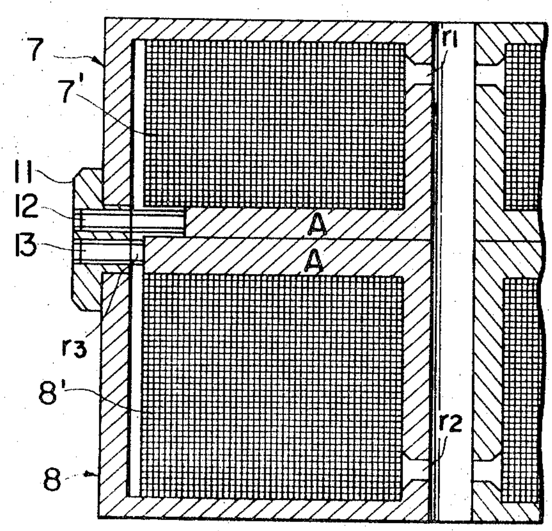


FIG. 10

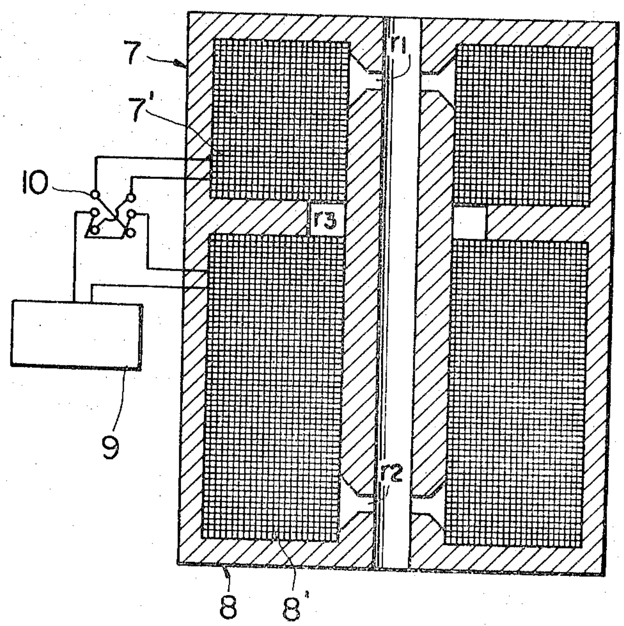
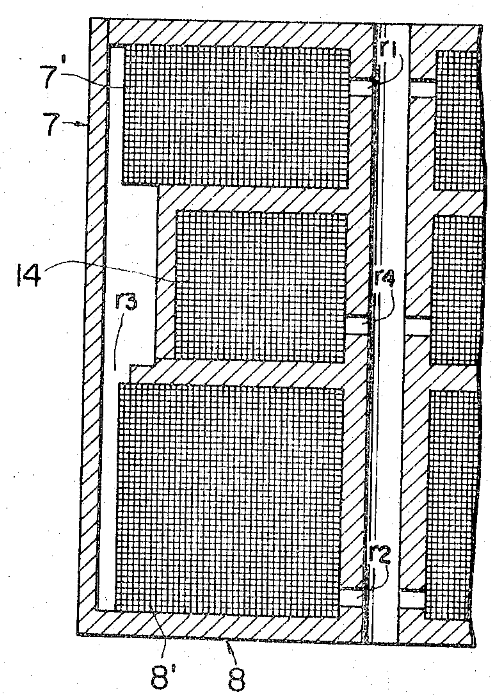


FIG. 11



COMPOUND ELECTRON LENS FOR ELECTRON MICROSCOPE AND THE LIKE

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to improvements in an electron lens of the electro-magnetic type which is capable of converging and focusing charged particle beams, especially electron beams, by the aid of a magnetic field.

2. Description of the Prior Art

A prior art electron lens is illustrated in FIG. **1**, which is capable of focusing an electron beam on an observed specimen **2** through an objective lens **1**, whereby an expanded image of the specimen may be obtained on a fluorescent screen **5** by changing the field of excitation provided by an intermediate lens **3** and a projection lens **4.** The final multiplying factor M on the fluorescent screen **5** may be expressed as: $M = M(o) \times M(i) \times M(p)$, where $M(o)$ denotes the multiplying factor of the objective lens **1,** $M(i)$ the multiplying factor of the intermediate lens **3,** and $M(p)$ the multiplying factor of the projection lens **4.** The numerals **1'**, **3'** and **4'** represent power sources for the lenses **1, 3** and **4,** respectively.

Generally, the final multiplying factor is changed not by changing the multiplying factor $M(o)$ of the objective lens, but by changing either the multiplying factor $M(i)$ or $M(p)$. This is because the position of the specimen should be changed with respect to the objective lens if the multiplying factor of the objective lens is changed. In order to control the final multiplying factor M to range between five hundred and several thousand, it is necessary to set a specific condition for both the intermediate and projection lenses. Without this condition being satisfied, an enlarged image of a square specimen, as shown in FIG. **2**(*a*), is distorted to appear like a spool, as shown in FIG. **2**(*b*), or as a cask, as shown in FIG. **2**(*c*).

Another prior art example is illustrated in FIG. **3** in which a compound electron lens **6** is used in place of the intermediate lens **3** and projection lens **4** of FIG. **1.** This compound electron lens has its magnetic circuit provided with two magnetic poles **6'** and **6''** which serve as lenses. The compound electron lens is advantageous because the maximum multiplying factor is high owing to the use of two lenses, and one power source (not shown) suffices. On the other hand, however, the amount of excitation on the two poles is not large enough to satisfy the condition necessary for reducing the distortion of image due to spherical aberration, with the result that the image distortion becomes unnecessarily large.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a compound electron lens which is simple in construction and capable of operation with a minimum of distortion.

Another object of the invention is to provide a compound electron lens which is capable of operation with a minimum of distortion and permits its multiplying factor to be changed over a wide range.

Still another object of the invention is to provide a compound electron lens which makes alignment possible and is capable of operation with a minimum of distortion.

Still another object of the invention is to provide a compound electron lens in which the quantity of ampere turns is least affected by the variation in the temperature of the exciting coils.

Briefly, the compound electron lens of the invention is characterized by its provision of at least two exciting coils surrounded commonly by a magnetic member, a gap, disposed in part of the inner magnetic path of said cover member, for bypassing the flux from said coils, and a means for switching the polarities of exciting currents to said coils.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram in section showing a conventional magnifying lens system;

FIGS. **2***a* through **2***c* are diagrams showing various examples of image distortion;

FIG. **3** is a schematic diagram in section showing a conventional compound electron lens system;

FIG. **4** is a schematic diagram in section showing one example of a lens system embodying the present invention;

FIG. **5** is an equivalent circuit diagram of the electron lens system of FIG. **4**;

FIG. **6** is a graphic diagram showing the relationship between the ampere turns under different conditions;

FIG. **7** is a graphic diagram showing the total multiplying factor in connection with ampere turns;

FIG. **8** is a schematic diagram of a three-stage lens system; and

FIGS. **9** through **11** are schematic diagrams in section showing electron lens systems of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Features and advantages of the present invention will be described in detail by referring to FIGS. **4** through **11.** FIG. **4** is a diagram showing an embodiment of the invention, in which numeral **7** denotes a first lens which corresponds to the intermediate lens **3** of FIG. **1,** and **8** designates a second lens which corresponds to the projection lens **4** of FIG. **1.** The first lens is provided with a pole with a magnetic pole gap H_1 and reluctance r_1, and the second lens is provided with a pole with a magnetic pole gap H_2 and reluctance r_2.

Exciting coils **7'** and **8'** excite the first and second lenses, respectively. These coils are split by an inner magnetic path A and are supplied with current from one power source **9.** The exciting polarity of the first lens **7** is changed by a current switch **10** interposed between the two coils. D_1 and D_2 represent diameters of the magnetic pole apertures of the first and second lenses respectively. Instead of this arrangement, respective power sources may be provided for each of the coils, and the switch may be disposed between either one of the power sources and the coil.

In the compound electron lens system of FIG. **4,** magnetic interference is produced between the quantity of ampere turns of the first lens **7** and that of the second lens **8** because there is a gap of reluctance r_3 between the inner and outer magnetic paths. The substantial quantity of excitation IN'_1 of the first lens **7** changes with the quantity of excitation of the second lens **8.** Similarly, the substantial quantity of excitation IN'_2 of the second lens **8** changes with the quantity of excitation of the first lens **7**.

The substantial quantity of excitation IN'_1 and IN'_2 of the lenses **7** and **8** are determined by the magnetic interference factors, namely reluctances r_1 and r_2 of magnetic pole part, magnetic pole reluctance r_3, and exciting coil turns N_1 and N_2 of the first and second lenses. FIG. **5** is an equivalent electric circuit diagram of an electron lens system. From FIG. **5** the relationship between the substantial quantity of excitation and the apparent quantity of excitation of the first and second lenses is found. The quantities of excitation IN'_1 and IN'_2 correspond to potential differences in this equivalent circuit. Similarly, the reluctances r_1, r_2 and r_3 correspond to electric resistances. In FIG. **5**, the substantial potential differences IN'_1 and IN'_2 across the resistors r_1 and r_2, respectively, represent the substantial quantities of excitation of the first and second lenses **7** and **8**. The substantial quantities of excitation IN'_1 and IN'_2 assume different values, depending on the polarities of the apparent potential differences IN_1 and IN_2. Hence IN'_1 and IN'_2 should be separately considered. In the circuit of FIG. **5**, the following Equations (1) through (3) are established with I_1, I_2 and I_{12} determined according to Kirchhoff's law. ($\pm$) indicates identical polarities, and ($\mp$) reverse polarities. The closed circuit X corresponds to the first lens **7**, and the closed circuit Y to the second lens **8**.

$$IN_1 = r_1I_1 \mp r_3I_{12} \quad (1)$$

$$IN_2 = r_2I_2 + r_3I_{12} \quad (2)$$

$$I_2 = \pm I_1 + I_{12} \quad (3)$$

From these equations the potential differences across the resistors r_1 and r_2 are obtained, whereby the substantial quantities of excitation applied to the first and second lenses can be found. The following Equations (4) and (5) define the substantial quantities of excitation IN'_1 and IN'_2 on condition that IN_1 and IN_2 stand at the same polarity, and Equations (6) and (7) define the substantial quantities of excitation IN''_1 and IN''_2 on condition that IN_1 and IN_2 stand at mutually reverse polarities.

$$IN'_1 = (r_2 + r_3)N_1 + r_3N_2/(r_1 + r_3)\ (r_2 + r_3) - r_3^2\ r_1I \quad (4)$$

$$IN'_2 = (r_1 + r_3)\ N_2 + r_3N_1/(r_1 + r_3)\ (r_2 + r_3) - r_3^2\ r_2I \quad (5)$$

$$IN''_1 = (r_2 + r_3)\ N_1 - r_3N_2/(r_1 + r_3)\ (r_2 + r_3) - r_3^2\ r_1I \quad (6)$$

$$IN''_2 = (r_1 + r_3)\ N_2 - r_3N_1/(r_1 + r_3)\ (r_2 + r_3) - r_3^2\ r_2I \quad (7)$$

Substituting specific values for r_1, r_2, r_3, N_1 and N_2 in Equations (4) through (7), the substantial quantities of excitation on the first and second lenses are obtained in the following manner.

Assume that the ratios among r_1, r_2 and r_3 are

$$r_3/r_2 = 1/2,\ r_3/r_1 = 1/2$$

and ratio between N_1 and N_2 is $N_1/N_2 = 1/2$

Under these conditions, the substantial quantities of excitation on the first and second lenses are calculated as shown in FIG. **6**. This calculation is based on the assumption that the maximum value of excitation IN_1 on the first lens, i.e., $IN_1 = 1{,}890$ ampere turns, and the maximum value of excitation IN_2 on the second lens, i.e., $IN_2 = 3{,}780$ ampere turns. The relationship between IN'_1 taken when IN_1 and IN_2 stand at the same polarity is shown by the solid line in FIG. **6**, and the relationship between IN''_1 and IN''_2 taken when IN_1 and IN_2 are at reverse polarity is indicated by the dashed line.

It is apparent from FIG. **6** that at the same polarity the substantial quantities of excitation on the first and second lenses are both large, while at reverse polarity, the substantial quantity of excitation on the first lens is about one-fifth of that on the second lens. If the ratio between the quantities of excitation is controlled by resistance division, as with the case of the prior art, it is impossible to maintain a constant ratio of resistance division because the dividing ratio is changed due to the difference in heat produced in the dividing resistor.

FIG. **7** shows the total multiplying factor calculated for the compound electron lens system (FIG. **4**) having the above-mentioned excitation characteristics. In this electron lens system an objective lens is used additionally.

The diameters D_1 and D_2 of the magnetic pole apertures of the first and second lenses are both 10mm ($D_1 = D_2$); the magnetic pole gaps H_1 and H_2 are both 4mm ($H_1 = H_2$); the focal length of the objective lens is 2mm; the distance between the objective lens and the first lens is 122mm; the distance between the first and second lenses is 99mm; and, the distance between the second lens and the fluorescent screen is 330mm. In FIG. **7**, the solid line indicates the values taken when excitation is at the same polarity, and the dotted line indicates the values obtained at reverse polarity. It is apparent from FIG. **7** that the multiplying factor can be changed from 500 to 3,000 when excitation is continually changed on condition that the first and second lenses are excited at mutually reverse polarities. Then, by increasing the quantity of excitation through switching the polarity of current supplied to the first lens, the multiplying factor can be changed from 3,000 to 50,000. In other words, the multiplying factor can be changed continually over a wide range, such as from 500 to 50,000, by merely changing the polarity of excitation on the first lens under the same apparent quantity of excitation.

According to this invention, the image magnified by the objective lens can be contracted instead of being enlarged by the first lens, as shown in FIG. **8**, since the excitation on the first lens can be reduced even at a low multiplying factor. More specifically, the first lens gives a long focal point because its excitation is weak and hence the rear focal plane where the electron beams passing through the first lens are converged is located nearer the fluorescent screen than the second lens. In this case, the image distorts like a cask due to spherical aberration, as shown in FIG. 2(*c*). The image contracted by the first lens is enlarged by the second lens and then projected on the fluorescent screen. Because the second lens is used for magnification, the image distorts like a spool due to spherical aberration, as shown in FIG. 2(*b*). The distortions caused by the first and second lenses are cancelled by each other, to result in the least distorted image.

FIG. **9** illustrates an embodiment of the invention wherein the part A of the inner magnetic path is split into two parts; one part is allocated to the first lens and the other part is allocated to the second lens. The inner magnetic paths of the first and second lenses are mutually independently adjusted from outside the vacuum by means of inner magnetic path adjusting screws **12** and **13** which are incorporated into a spacer equipped to the outer magnetic paths. Thus, the compound electron lens can be readily aligned.

FIG. **10** illustrates another embodiment of the invention which is similar to that shown in FIG. **4,** with the exception that the gap portion between the inner magnetic path and the outer magnetic path is disposed on the side of the inner magnetic path instead of outer magnetic path, as provided in FIG. **4.**

FIG. **11** illustrates another embodiment of the invention including an electron lens part **14** disposed between the first lens **7** and the second lens **8.** Furthermore, a gap r_3 for bypassing the flux is disposed between the electron lens **14** and the outer magnetic path. Thus, the adjustable range of multiplying factor is increased. In FIG. **11** the switch and power source of the prior embodiments are to be included, but they are not shown.

According to the invention, as described above, a wide range of continuously variable multiplying factor can be realized by the use of one exciting source. The magnetic interference dependent upon the polarity of exciting current for the electron lenses is utilized whereby a lens system with a high multiplying factor is achieved, and a lens system for contraction can be obtained in one compound electron lens system. Thus, the final image is obtainable at a low multiplying factor with the least distortion. Furthermore, the quantity of excitation is not affected by the variation in the temperature of the exciting coils, unlike the prior art lens system, which depends on resistance division for the adjustment of the quantity of excitation.

What we claim is:

1. A compound electron lens comprising:
at least two annularly wound exciting coils disposed coaxially;
magnetic cover means surrounding said exciting coils to form a closed magnetic circuit common to said exciting coils;
at least one magnetic pole portion formed in the annular hollow of each of the coils;
magnetic path means disposed between the two exciting coils to form a magnetic path extending from said magnetic pole portion to said cover means;
air gap means positioned in said magnetic path means for bypassing flux generated by the coils and flowing through the closed magnetic circuit;
means for supplying exciting current to the individual coils; and
means for switching the polarity of the exciting current supplied to one of the coils with respect to the other coil so that spherical aberration is minimized over a wide range of magnifications.

2. A compound electron lens as defined in claim **1,** further including at least one alignment adjusting screw extending through said magnetic cover means for finely adjusting the length of the gap in said magnetic path means.

3. A compound electron lens as defined in claim **1,** further including another annularly wound exciting coil disposed between said two coils and an additional magnetic pole portion formed in the annular hollow of the additional coil.

4. A compound electron lens as defined in claim **1,** in which said exciting current supplying means comprises one adjustable power source, and said exciting current polarity switching means comprises one switch, said power source being connected to each of the coils through said switch, whereby the polarity of the exciting current supplied to one of the coils with respect to the other coil can be switched by means of said switch.

5. A compound electron lens comprising: at least two annularly wound exciting coils disposed coaxially, a magnetic cover surrounding said exciting coils in common and having first and second lens gaps therein formed in the portion extending within the annular hollow of the coils adjacent the respective coils, an inner magnetic path member extending as a partition within the cover between said coils, said inner magnetic path member being spaced from said cover at one end thereof so as to leave a gap for bypassing the flux from the coils, means for supplying exciting current to the individual coils, and means for switching the polarity of the exciting current supplied to one of said coils so that spherical aberration is minimized over a wide range of magnifications.

6. A compound electron lens as defined in claim **5,** wherein said inner magnetic path member is split into two adjacent portions connected respectively to the inner magnetic cover portions forming part of the first and second lens gaps, and further including at least one alignment adjusting screw extending through said magnetic cover for adjusting the position of at least one of the adjacent portions of said inner magnetic path member.

7. A compound electron lens as defined in claim **5,** wherein the gap formed by said inner magnetic path member is disposed inside the inner magnetic cover portion forming part of said first and second lens gaps.

8. A compound electron lens as defined in claim **5,** further including another annularly wound exciting coil disposed between said two coils and having a cavity with a magnetic pole portion formed in the annular hollow of the additional coil.

9. A compound electron lens comprising:
first, second and third annularly wound exciting coils disposed coaxially;
magnetic cover means surrounding said exciting coils to form a closed magnetic circuit common to said exciting coils;
at least one magnetic pole portion formed in the annular hollow of each of the coils;
first and second magnetic path means disposed between the first and second exciting coils and the second and third exciting coils, respectively;
air gap means positioned in said magnetic path means for bypassing flux generated by the coils and flowing through the closed magnetic circuit;
means for supplying exciting current to the individual coils; and
means for switching the polarity of the exciting current supplied to one of the coils with respect to the other coil so that spherical aberration is minimized over a wide range of magnifications.

* * * * *