United States Patent [19]

Wardly

[11] **3,911,321**

[45] **Oct. 7, 1975**

[54] **ERROR COMPENSATING DEFLECTION COILS IN A CONDUCTING MAGNETIC TUBE**

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[73] Assignee: **International Business Machines Corporation,** Armonk, N.Y.

[22] Filed: **Aug. 27, 1973**

[21] Appl. No.: **391,120**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 202,440, Nov. 26, 1971, abandoned.

[52] **U.S. Cl.** **315/364;** 315/370; 335/213

[51] **Int. Cl.** **H01j 29/70**

[58] **Field of Search** .... 315/27 XY, 276 D, 27 R, 315/8, 364, 370; 313/76, 80, 84; 250/396 A, 398 D, 399; 335/213

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Primary Examiner—Maynard R. Wilbur
Assistant Examiner—J. M. Potenza
Attorney, Agent, or Firm—Roy R. Schlemmer

[57] **ABSTRACT**

This invention relates to an error compensating arrangement for use with the deflection system in a conducting magnetic tube such as that of an electron microscope or the like. More particularly, compensating coils are provided to correct time lag errors due to eddy currents set up in permeable magnetic enclosures which surround the principal deflection coils and act essentially as pole-pieces.

6 Claims, 19 Drawing Figures

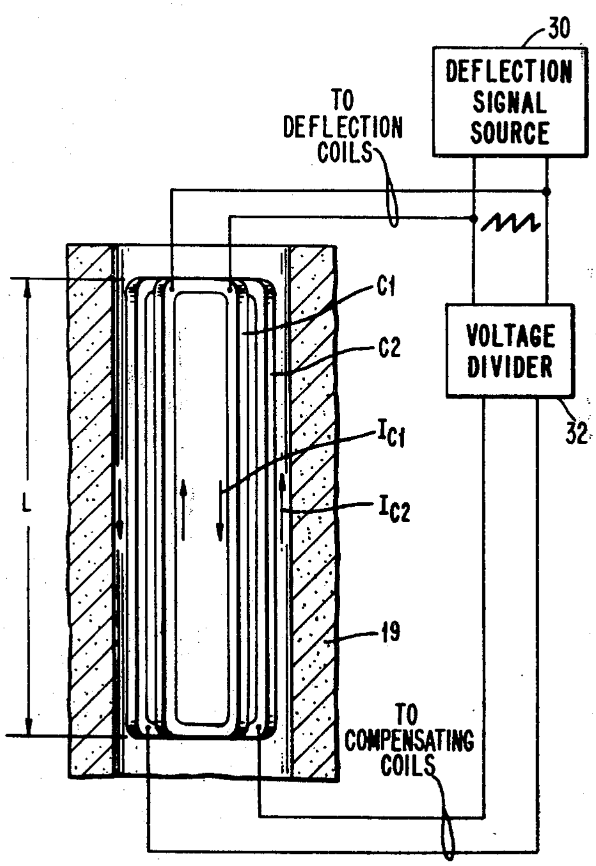


FIG. 1

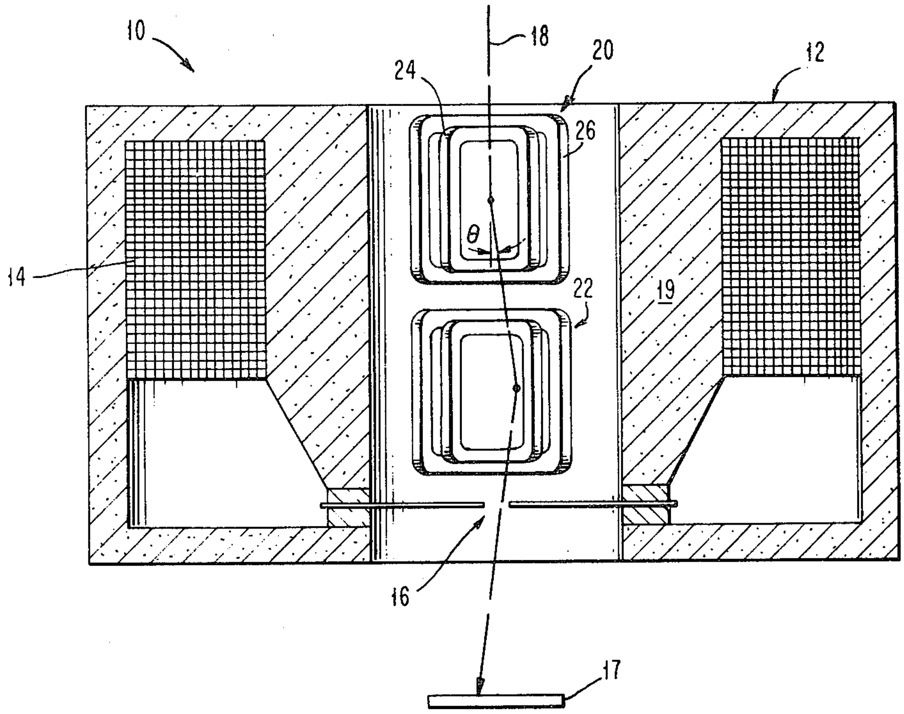


FIG. 2

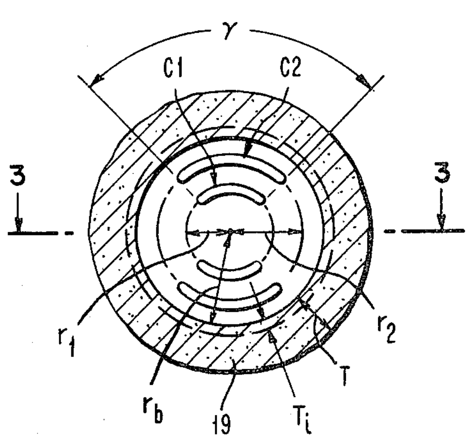


FIG. 3

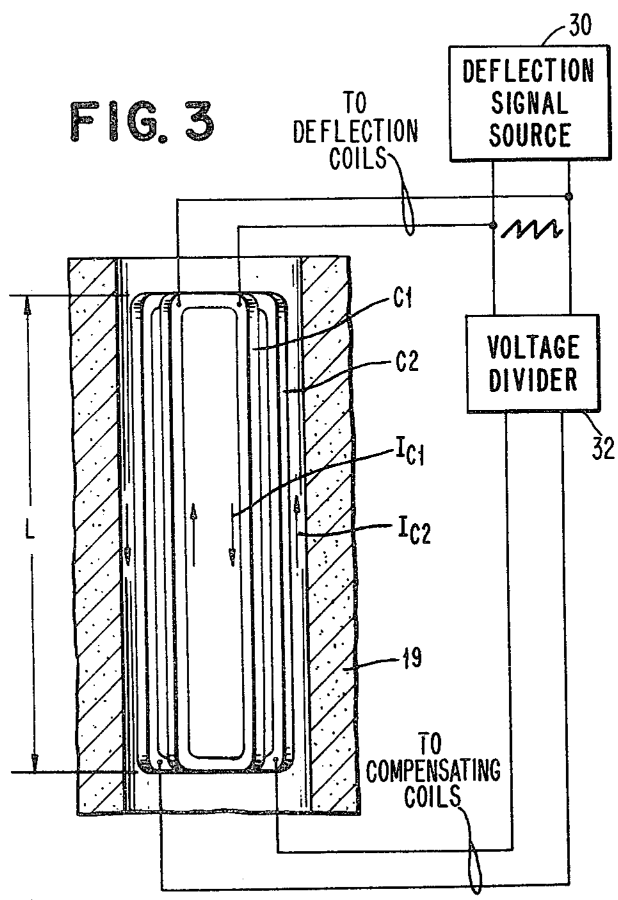


FIG. 4

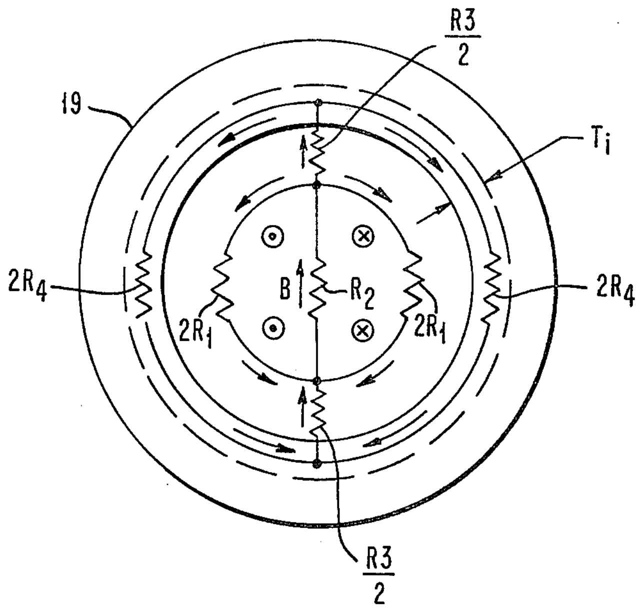


FIG. 5

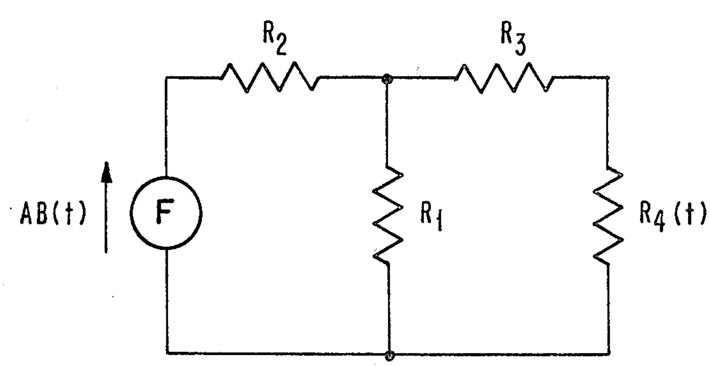


FIG. 6

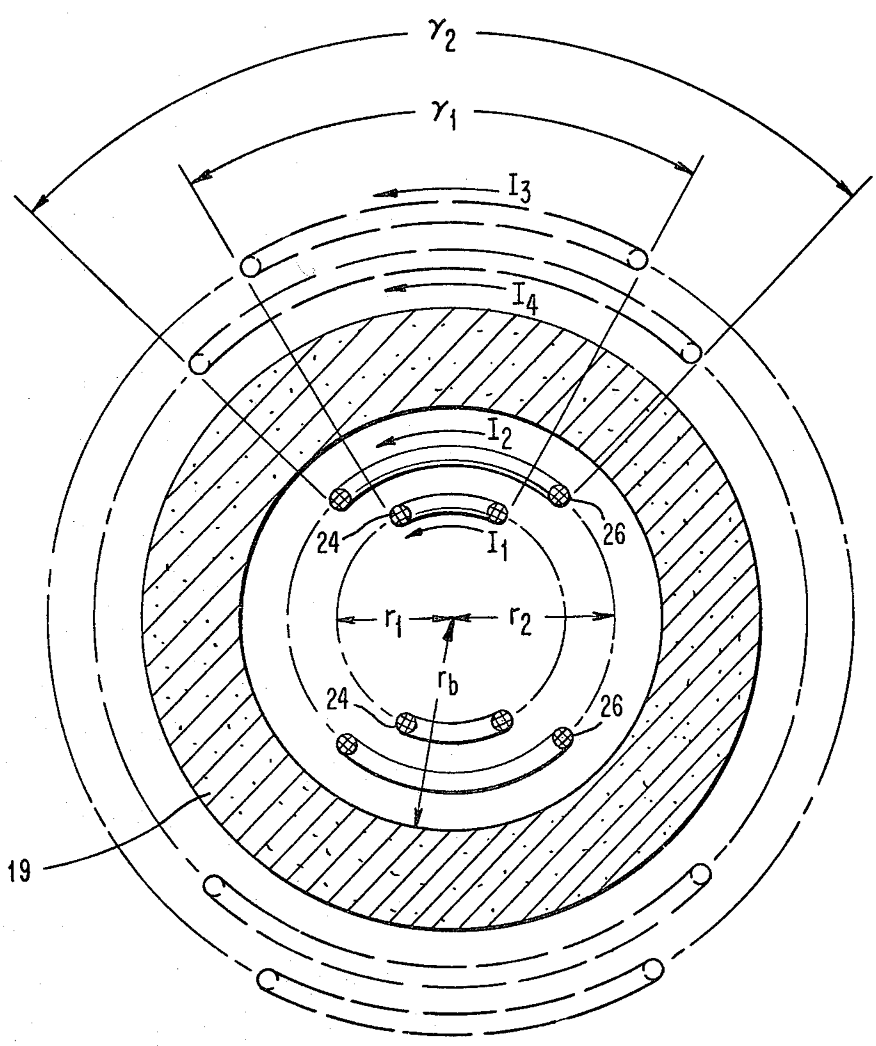


FIG. 7

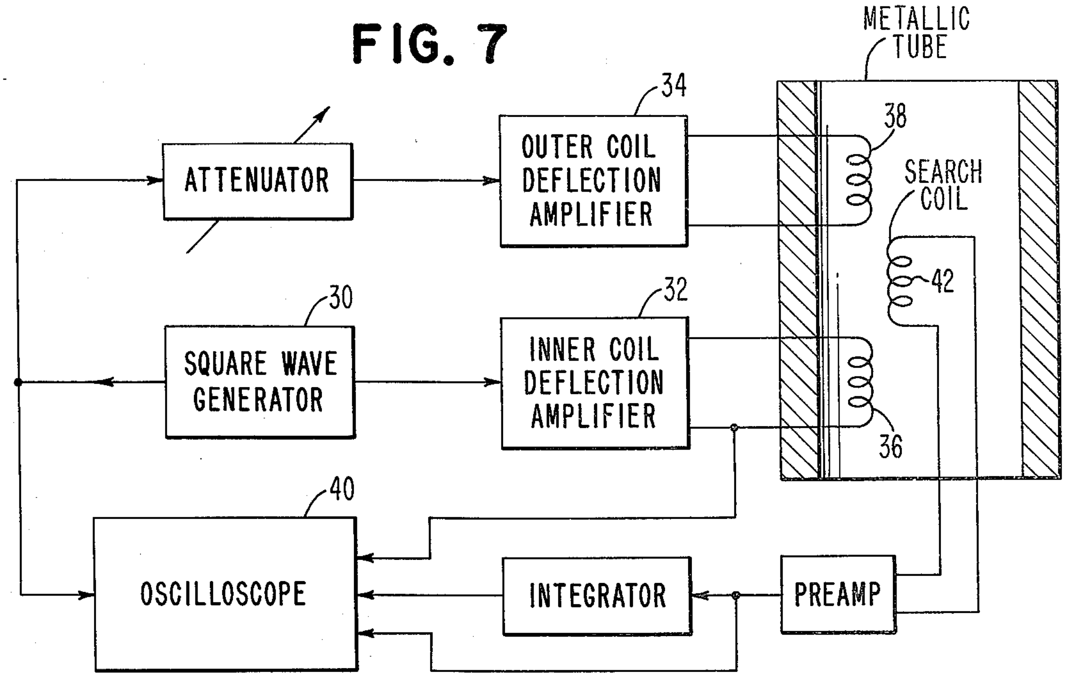


FIG. 8A

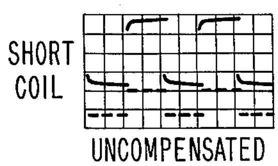


FIG. 9A

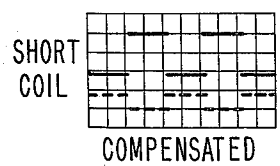


FIG. 10A

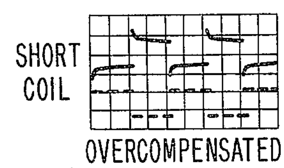


FIG. 8B

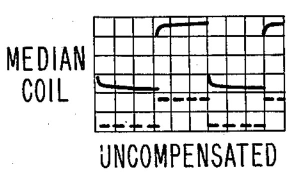


FIG. 9B

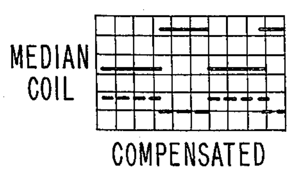


FIG. 10B

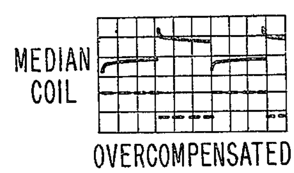


FIG. 8C

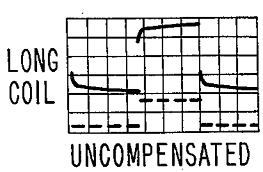


FIG. 9C

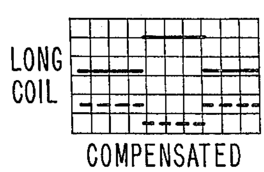


FIG. 10C

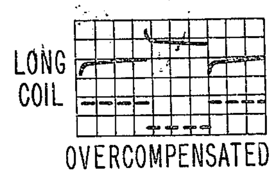


FIG. 11

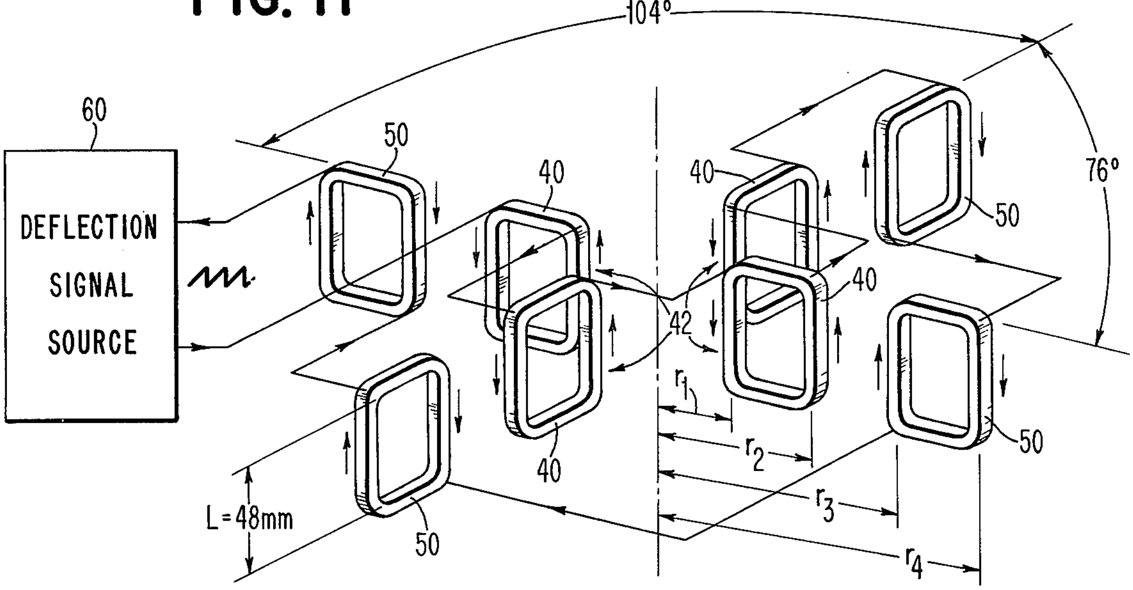
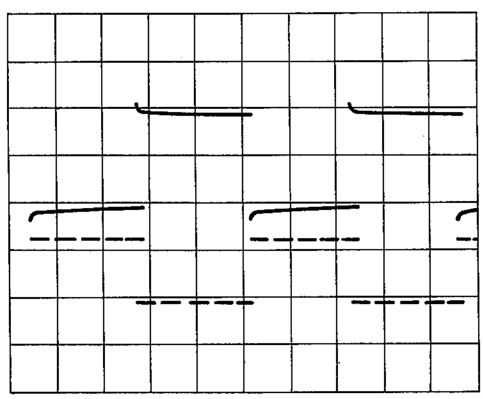
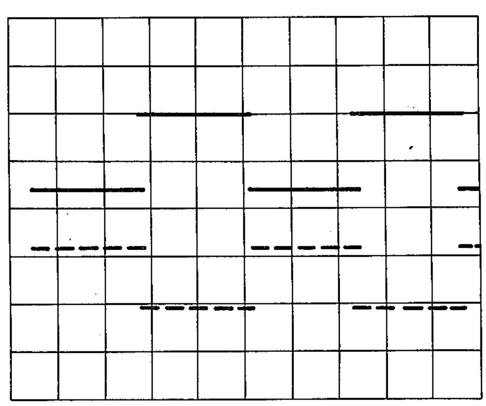


FIG. 12A



0.5 msec. / div.

FIG. 12B



0.5 msec. / div.

ERROR COMPENSATING DEFLECTION COILS IN A CONDUCTING MAGNETIC TUBE

CROSS REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of copending patent application, Ser. No. 202,440, filed on Nov. 26, 1971, and now abandoned.

BACKGROUND OF THE INVENTION

Presently, in scanning electron microscopes, to achieve short focal lengths in the final lens, it is necessary to place scan coils before the final lens. Since polepiece materials should have high permeability and high saturation flux density, iron or iron-cobalt alloy is normally used, both of which have a relatively high electrical conductivity. In addition these pole pieces are machined to high accuracy to avoid deviations from cylindrical symmetry which would cause a loss of resolution so that ferrite tubes placed in the lens bore would detrimentally affect the lens quality.

The existence of this iron, in the form of a tube, around the scan coils provides a low reluctance path for magnetic field lines produced by the scan coils. This is true only after sufficient time has elapsed since a certain current has to be established in the coil itself, but first eddy current effects in the iron must have completely subsided. The eddy currents, as is well known, oppose the entrance of magnetic field lines and the instant after the coil current is increased from 0 to I_T, the iron tube appears to have infinite reluctance. These eddy currents set up magnetic fields which oppose the original magnetic field and decay with time.

Since the flux density at the center of the coil is proportional to the ampere turns of the coil and inversely proportional to the total reluctance around the coil, the changing reluctance of the iron tube will time-wise alter the flux density in the center of the coil. Of course, if the coil is very small compared to the diameter of the iron tube, the effect of the iron is small, but this approach introduces coil winding problems and field gradient effects, both of which are undesirable.

The results of this time-wise alteration of the resultant flux density in the center of the magnetic tube is that the actual deflecting magnetic field which is supposed to deflect the electron beam according to some particular desired function; i.e., a ramp or sawtooth, for which a subsequent line scan is desired, will produce a flux density or displacing force pattern which will vary in slight degree both as to shape and with respect to time derivation or delay from a desired deflection pattern, determined by the coil currents. Where extremely precise work is desired as with high speed microfabrication; for example, the degradation of the ultimate sweep pattern accuracy limits the positional precision of the areas exposed to the electron beam particularly in random access deflection.

While the above general description and a good deal of the subsequent description deal with electron microscopes, it should be clearly understood that the concepts disclosed herein apply equally well to other cathode ray or electron beam apparatus such as those intended for use with electron beam machining, electron beam negative exposure for use in the field of circuit miniaturization, etc., as well as in the field of electron microscopy. Thus, most electron beam devices, where extremely high precision is required and which use magnetic deflection of the electron beam in conjunction with an elongated magnetic tube forming a substantial part of the flux path for the deflecting magnetic field, suffer from the problem of time lag errors of the deflection pattern due to eddy current generation in the magnetic circuit.

As stated previously, prior attempts to modify the design of the primary deflection coil to minimize eddy current generation has produced adverse side effects and attempts to radically change the shape of the deflection source signal to allow for the time lag characteristics have not heretofore been successful.

SUMMARY AND OBJECTS

It has now been found that positional scanning errors caused by eddy current effects in conducting magnetic tubes can be significantly reduced by employing a second pair of scan coils whose scan errors oppose the first but whose on-axis field strength is weaker than the first. Thus, more accurate, rapid scanning is possible without employing high resistivity ferrites or impractically small uncompensated deflection coils.

This configuration is made practicable by the discovery that the deflection lag for coils of greater radius (displacement from the center of the tube) inside the iron tube are greater than the lag for smaller coils producing a given field in the center of the bore, the eddy current produced lag of the smaller coil can be compensated by a larger coil's lag, the latter producing a smaller opposing field than that of the smaller coil leaving a net corrected field for deflection purposes from the smaller or inner coil.

It is accordingly a primary object of the present invention to provide an improved deflection scheme for deflecting electron beams in electron microscopes and the like.

It is a further object to provide such a deflection system wherein time lag errors in the deflection system are greatly reduced.

It is yet another object of the invention to provide such an improved deflection system utilizing compensating coils together with primary deflection coils.

It is yet another object to provide such an improved deflection system wherein said compensating winding compensates for time lag errors due to eddy currents within an enclosing magnetic tube but wherein the primary deflection coils have a dominant effect on the deflection of the electron beam.

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of the preferred embodiments of the invention, as illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional view through the final electron lens of an electron microscope or similar device showing a compensated coil pair configuration of a first embodiment of the present invention used in a double deflection system.

FIG. 2 comprises a cross-sectional view taken along a single set of deflection coils as illustrated in FIG. 1.

FIG. 3 comprises a cross-section of the deflection system of FIG. 1 taken along the axis of the magnetic tube showing the location of the deflection and compensating coils.

FIG. 4 shows a single pair of deflection coils in place within a magnetic tube with the equivalent magnetic circuit superimposed thereon.

FIG. 5 is the equivalent magnetic circuit of FIG. 4 in simplified form.

FIG. 6 comprises a cross-sectional view similar to FIG. 2 but wherein additional "image" coils are indicated in the FIG.

FIG. 7 is a functional block diagram of the circuitry used to test the presently disclosed compensation coil pairs in an operating environment.

FIGS. 8A through 8C comprise oscillographic representations of the deflection and search coil currents produced by the circuitry of FIG. 7 for conditions of uncompensated eddy currents.

FIGS. 9A through 9C comprise oscillographic representations of the deflection and search coil currents produced by the circuitry of FIG. 7 for conditions of compensated eddy currents.

FIGS. 10A through 10C comprise oscillographic representations of the deflection and search coil currents produced by the circuitry of FIG. 7 for conditions of overcompensated eddy currents.

FIG. 11 comprises a perspective view of a single deflection system for an electron microscope or similar electron beam device showing two pairs of toroidal deflection coils and two pairs of toroidal compensation coils.

FIG. 12A is an oscillographic representation of the deflection coil current and integrated search coil output voltage produced by the circuitry of FIG. 7 with the toroidal coil configuration of FIG. 11 with no compensating field.

FIG. 12B is an oscillographic representation of the deflection coil current and integrated search coil output voltage produced by the circuitry of FIG. 7 with the torodial coil configuration of FIG. 11 with a compensating field.

DESCRIPTION OF THE DISCLOSED EMBODIMENT

The objects of the present invention are accomplished in general by an electron beam deflection system adapted for use in an electron beam device wherein the electron beam is to be deflected in a direction at right angles to said beam and wherein said deflection system includes an elongated permeable tube surrounding said electron beam and having a radius r and a thickness T. A air of primary deflection coils and a pair of secondary deflection coils are located within said tube, the members of each pair are symmetrically spaced about the axis of said tube and the inner wall thereof, the pair of primary deflection coils being closer to the axis of said tube. Each of said pairs of coils is substantially but not necessarily rectangular and has at least one length dimension substantially parallel to the axis. A single energization source is provided for said two pairs of coils whereby the coils are interconnected so that the magnetic fields produced by the primary and secondary coils oppose each other and wherein the field produced by the primary or deflection coil is dominant at the center of the tube. The two coils are designed, however, such that the eddy current generation of the two coils are substantially self-balancing within the magnetic material of the permeable tube.

Thus, it may be seen that the secondary deflection coil is in essence an eddy current compensating coil and in effect has a smaller effect on the deflecting magnetic field along the axis of the tube which actually deflects the electron beam. The compensation coil does have a large effect on eddy current generation in the magnetic tube and further the spacing and size of this coil may be selected such that it very closely balances out the eddy current generation in the permeable tube due to the magnetic field from the primary deflection coils.

It will be noted in referring to the drawings and also the subsequent description that essentially two embodiments of the invention are specifically disclosed. These are shown for example, in FIGS. 1 and 11, and utilize what is known as a saddle coil configuration in FIG. 1 and a toroidal coil configuration in FIG. 11. In essence the saddle coil configuration lies essentially within a cylinder which is concentric with the axis of the tube and the normal axis of the electron beam whereas the toroidal coils each lie in planes which are radially disposed with respect to the magnetic tube and include the normal axis of the electron beam and the tube in their plane. This will of course be obvious by reference to FIGS. 1 and 11 respectively. It is to be noted however, that the operation of the compensating coils is substantially identical for both cases. A final decision as to which type of deflection and thus compensating coil configuration is to be used would depend upon the final use of the electron beam such for example, as in an electron microscope or an electron beam machining device of some sort.

As stated previously, it is the fact that the larger, compensating coil located between the smaller, primary deflection coil and the permeable tube has a larger ratio of eddy current generation to magnetic field generation than the primary coil. This makes the present compensating approach practicable. Subsequently, in the description, two different design analyses are given wherein the advantages of teh present invention are set forth; however, it is to be understood that both analytical approaches are theoretical in nature and assumptions are made which might have to be varied somewhat in practice. Tests have proved, however, that the actual improvements in time lag reduction by the present invention are quite substantial. The subsequent examples give a theoretical basis for a figure of merit to be expected from the present invention and also to some extent explains the theory of operation of the compensating coils on a quantitative basis. While these mathematical examples are presented for the purpose of helping to explain the invention, it should be understood that it is not intended that the invention in any way be limited by the precise accuracy of the assumptions made in arriving at the stated improvement factors.

It should again be emphasized that the present invention has utility in other apparatus than scanning electron microscopes. It will also be readily appreciated that the invention ahs applicability to any cathode ray device having the need for high accuracy and high scanning rates where time lag constitutes a major scanning problem.

In the majority of the following description and specifically in the derivations and examples which will follow, only one set of deflection coils is discussed, i.e., FIGS. 2–6. Since the eddy current problem is essentially linear with respect to summation of instantaneous fields along this tube axis, it is only necessary to demonstrate the mathematical calculation of deflection field for one-half of the double deflection system, it being understood that what pertains to one deflection coil set pertains equally to the other. This set, as indicated previously, comprises a primary pair of coils and a secondary or compensating pair of coils. However, it should be clearly understood that the majority of electron microscopes, microfabrication devices and the like utilize double-deflection systems. This will be shown and briefly described subsequently with reference to FIG. **1.** Briefly, a double-deflection system requires not one set of deflection coils, but two sets for each plane of deflection. This in in order to have the deflected electron beam pass through the aperture plate of the electron lens at substantially the same place, regardless of its displacement on the target surface. Thus, the first or upper set of deflection coils displaces the beam in one direction and the second set closest to the aperture displaces the beam in the other direction whereby XY deflection of the electron beam is possible while keeping the beam itself relatively centered in the aperture plate at all times. It should also be understood that even in FIG. 1 only the deflection coils (double) for one direction of beam displacement is shown and that an additional single or double set would have to be provided for the orthogonal direction of scan. Since in most scanning cathode ray devices only one direction is scanned at an extremely high rate, it would normally only be necessary to use corrected coil sets for one direction of scan. Thus, two single pairs of coils would normally suffice for said other direction since compensating coils would not be necessary. If, however, both scan directions could at times require extremely high scan rates. The use of compensating coil sets would be necessary if the disclosed advantages of the present invention are to be obtained.

Referring now to FIG. **1,** a preferred embodiment of the invention is shown. It should be understood that FIG. 1 represents only the lower portion of an electron beam device such as an electron microscope, microfabrication, or other similar cathode ray device and in essence discloses only that portion of teh device normally known as the final electron lens which, as is well known, includes the deflection coils. The electron lens is generally designated by the reference numeral **10.** The actual electron lens comprises the highly permeable magnetic pole pieces **12** and the winding **14** which as is well known, produces a field along the axis of said lens to sharply focus the electron beam passing through the aperture plate **16.** The electron beam is shown by the reference numeral **18** and falls on an appropriate target **17.** The actual double-deflection system shown in cross-section comprises the upper coil set **20** and lower coil set **22** which, as will be appreciated, deflect the beam in opposite directions in order to achieve double-deflection of the beam whereby the beam passes through the approximate center of the aperture plate **16** at all times regardless of the beam scan location on the target **17.** As is shown in the FIG., both of these deflection coil sets comprise a set of primary deflection coils **24** and a second set of coils **26** which, as will be described in detail subsequently, are in essence compensating coils which substantially eliminate eddy currents which tend to be set up in the area **19** of the pole pieces **12.**

As stated previously, the manufacture and construction of the electron lens is an extremely precise operation and the interior tubular portion of the pole pieces **12** which is designated by the reference numeral **19,** must be extremely precise in order to achieve the required degree of field uniformity and focusing of the electron beam. Thus, it is not possible to utilize a ferrite tube as an insert surrounding the deflection coils which would in essence avoid eddy current problems because of their low conductance. This is because such tubes would not have the required dimensional and positional tolerances and would thus cause poor focusing of the beam.

FIG. **2** is a detailed cross-sectional view showing only the tubular portion **19** of the pole piece **12,** said portion being designated again by the reference numeral **19** in FIGS. **3** and **6.** The cross-section is taken in a plane perpendicular to the axis of the lens assembly **10** showing the placement of the two pairs of deflection coils in the magnetic tube and also specifying certain of the physical parameters of the system utilized in subsequent calculations. Thus, the primary deflection coil **C1** has a radius r_1. The secondary deflection coil, or compensating coil, **C2** has a radius r_2. The inner diameter of the tube or pole piece **19** is indicated as r_0. The distance T_i represents the penetration depth of the magnetic field into the permeable tube **19** with the resultant generation of eddy currents in this portion of the magnetic tube. The angle γ or winding angle represents the angle formed by passing a plane through the two outer lengthwise conductors of a given coil and the axis of the tube. In the embodiment of FIG. **2,** this angle is shown to be the same for both the primary and secondary coils. It should be noted that this angle could in actuality vary (i.e., FIG. **6**); however, the calculations of merit for the improvement to be gained by the system become considerably more complex.

FIG. **3** is a view taken along line **3—3** of FIG. **2** showing an elevational cross-section through the magnetic tube **19** illustrating the relative shape and location of an individual primary and secondary coil C1 and C2 and also showing the length dimension L of the coil utilized in the first example.

Deflection signal source **30** is also shown in FIG. **3** connected to the deflection coil **C1.** Voltage divider **32** is shown for illustrative purposes connected across the deflection signal source which is in turn utilized to provide the compensating signal to the compensating coil **C2.** A ramp wave form is shown at the output of the deflection source it of course being understood that the particular deflection signal could vary widely depending upon the particular use to which the apparatus is to be put.

FIGS. **4** and **5** represent equivalent magnetic circuits for a single coil pair in the magnetic tube and illustrate how the examples' calculations are approached. Specifically, FIG. **4** shows a superposition of the magnetic circuit directly over the magnetic tube **19** and indicates an assignment of lumped reluctances R1 through **R4.** FIG. **5** comprises a simplified schematic derived from FIG. **4.**

FIG. **6** is a cross-sectional view of a compensated coil pair constructed in accordance with the present invention which is very similar to the cross-sectional view of FIG. **2** described above. It will be noted in this FIG. that some of the symbols referring to the radius of the inner and outer coils, the two winding angles γ_1 and γ_2, as well as the coil current indications are somewhat different from those of FIG. **2.** This FIG. represents the image current method of calculating the required compensating coil field set forth in the examples which follow. In this FIG., the two image coils or image currents are shown to lie outside of the tube body **19** or at a point further removed from the axis of said tube than the actual deflecting coil pair **24** and the compensating coil pair **26.** It will be noted that these images are shown in dotted lines since they do not actually exist but are utilized to explain the generated magnetic fields and compensating effect as will be apparent from the subsequent example. It will be noted that the four currents I_1 through I_4 are all shown as flowing in the same direction. It should be understood that these current flows are not actual but in essence are algebraic representations. The example specifies the actual current relationships. As stated previously, the exact definition of the various other symbols shown in FIG. **6** will be apparent from the subsequent computations. It should also be noted in passing that the winding angle γ_1 of the primary deflection coil pair **24** is different from the winding angle γ_2 of the compensating coil pair **26** as contrasted with the embodiment of FIG. **2** where the winding angles are the same in both cases.

There will now follow a description of two different design analyses of a corrected set of deflection coils which reduces positional errors during the electron beam scan. The first example derives the error produced in the scan from the ideal using the image method shown in FIG. **6.** The various symbols and constants used in all of the calculations are defined in the computation and follow strightforward magnetic circuit analysis and electromagnetic theory as regards the deflection of the electron beam by a given field, field generation, etc.

EXAMPLE I — IMAGE METHOD

We are considering here, the effect of adding a compensating deflection coil pair to form a four coil structure with decreased time lag in the cross-axis magnetic field when a step function current drives the coil assembly. Of course, a conducting magnetic tube **19** is situated about the coils. The purpose of this calculation is to show that with compensating coils, the cross-axis field at the start of a step function drive current can be made equal to the cross-axis field long after the start of the step function drive current is first applied. For this purpose, the method of images can be successfully applied, as described in Binns and Lawrenson, *Electric and Magnetic Field Problems*, Macmillan, N. Y. 1963, page 49.

FIG. 6 shows a view along the axis of the cylinder and indicates the two coil pairs and their images, which appear to be located outside the inside diameter of the cylinder. Azimuthal closure windings are drawn as arcs of circles connecting the important portion of the coils, which are the portions which run parallel to the axis of the tube. Calling these latter portions the vertical sections, they each have a radius r from the axis, a length 2L along the axis and are situated at an angle γ from the line of coil symmetry which is parallel to the cross-axis field. Each vertical section carries a current I(O) at the start of the step function which we will consider the zero time. After a very long time the coil current is $I(\infty)$. The properties of the two real coil pairs and their images will be denoted by the subscripts **1** for the inner coil, two for the outer coil, three for the image of the inner coil and four for the image of the outer coil. If r_b

is the radius of the base of the cylinder, the radii of the two image coils are:

$$r_3 = \frac{r_b^2}{r_1} \qquad r_4 = \frac{r_b^2}{r_2} \qquad (1)$$

and also

$$L_1 = L_3,\ L_2 = L_4,\ \gamma_1 = \gamma_3,\ \gamma_2 = \gamma_4. \qquad (2)$$

The currents in the coil pairs at time $t = 0$ are $I_1(O)$, $I_2(O)$ and the image currents are:

$$I_3(O) = -I_1 \text{ and } I_4(O) = -I_2 \qquad (3)$$

since the eddy currents oppose the change in field in the conducting cylinder. However at time, $t = \infty$, after eddy currents have subsided, the high permeability of the magnetic cylinder adds to the cross-axis deflecting field. The image currents at this time become:

$$I_3(\infty) = I_1 \text{ and } I_4(\infty) = I_2 \qquad (4)$$

Now each of the coil pairs **1, 2, 3** and **4** contributes to the total angular deflection; θ where

$$\theta = \sum_{n=1}^{4} \theta_n = \sum_{n=1}^{4} \sqrt{\frac{e}{2mV}}\ \frac{4\mu_o}{\pi}\ \frac{I_n L_n}{r_n} \sin \gamma_n \qquad (5)$$

where it is assumed the coil lengths and radii are small compared to the total axial travel of the electron beam. Otherwise, a cumbersome coefficient would be used for each θ_n.

Now θ_1 and θ_2 are time independent but θ_3 and θ_4 are not. By requiring that $\theta_3 = -\theta_4$ at both $t = 0$ and $t = \infty$ and using Equations 3 and 4 we have from Equation 5 that the following conditions must hold.

$$\frac{I_3 L_3}{r_3} \sin \gamma_3 = -\frac{I_4 L_4}{r_4} \sin \gamma_4 \qquad (6)$$

which by Equations 1 and 2 becomes:

$$I_1 L_1 r_1 \sin \gamma_1 = -I_2 L_2 r_2 \sin \gamma_2 \qquad (7)$$

at both $t = 0$ and $t = \infty$.

Summarizing, it is possible to negate the effects of the image coils at time $t = 0$ and $t = \infty$, thereby assuming the same electron beam deflection at $t = 0$ and $t = \infty$.

Equation 7 provides the relationship which exists for this condition. For equal coil lengths $L_1 = L_2$, equal coil angles $\gamma_1 = \gamma_2$ and unequal radii, $r_2 = 2r_1$, the coil current I_2 should be one half the negative of I_1 or

$$I_2 = -\frac{1}{2} I_1 \qquad (8)$$

Then the deflection by Equations 5, 7 and 8 is:

$$\theta(O) = \theta(\infty) = \sqrt{\frac{e}{2mV}}\ \frac{3\mu_o}{\pi}\ \frac{I_1 L_1 \sin \gamma_1}{r_1} \qquad (9)$$

which is 75% of the deflection of coil **1** alone and without the conducting magnetic cylinder.

EXAMPLE II

In the foregoing example it was shown that the initial and final cross axis magnetic field can be made equal for a step function current (deflection signal) applied to the compensated deflection coils. Thus, it is to be expected that eddy current effects in the intervening time are substantially reduced compared to an uncompensated coil. The purpose of this example is to roughly determine the magnitude of the improvement during the intervening times. In particular, the error that is to be considered is the difference between the desired beam deflection determined by the coil current and the actual deflection which includes eddy current effects.

In FIG. **3**, a view along the axis of tube **19** shows the vertical winding portions of two pairs of deflection coils inside the tube **19.** The inner coil has windings at radius r_1 and the outer coil has windings at r_2 inside the tube **19** of inner diameter r_b. We shall consider only one coil at first, where in FIGS. **4** and **5** the lumped parameter, equivalent reluctance circuit is shown. The magnetic field is shown by arrows as if it were a current passing through the lumped reluctances. The magnetic circuit is divided into regions each of which is assumed to have a specific reluctance. R_2 is the reluctance carrying the flux between the two coils. R_3 carries flux between the coils and the tube, R_1 carries flux around the outside of the two coils, and not in the magnetic tube. R_4 is the reluctance in the tube itself, which, with R_3, parallels R_1. Eddy currents within the tube are generated with a changing coil drive current and at first totally exclude flux from entering the iron. Thus, R_4 is actually a function of time. In the spirit of simplicity the flux in the tube can be considered to exist only in a thin shell, the thickness of the penetration depth, T_i where

$$\frac{1}{R_4}\ \boldsymbol{\delta}\ T_i \sim \sqrt{\frac{t}{\mu\sigma}} \tag{1}$$

where t = time, μ = persistivity of iron, σ = conductivity of iron. (Panofsky and Phillips, Classical Electricity and Magnetism, Chapter 12)

The other reluctances are assumed to be relatively time independent.

Under these conditions, a magneto-motive force (mmf), F, will produce a flux such that the central field varies with time as:

$$B \approx F\delta\ \frac{\sqrt{t}+b}{\sqrt{t}+a} \tag{2}$$

where

$$\delta = \frac{1}{AR_2}\ \frac{P_1+P_3}{P_1+P_3+P_1P_3} \tag{3}$$

$$b = Q/(P_1+P_3) \tag{4}$$

$$a = Q(1+P_1)/(P_1+P_3+P_1P_3) \tag{5}$$

$$Q = P_4\ \sqrt{t} \tag{6}$$

So that a and b are time independent and P_1, P_3 and P_4 are the above respective reluctances normalized to R_2, and A is the area of each coil.

The resulting small angle beam deflection for a sensitivity S, and an axial coil length, L, is:

$$\theta = \mathrm{SLB} = F\delta'\ \frac{\sqrt{t}+b}{\sqrt{t}+a} \tag{7}$$

This equation enables the experimental determination of the coil constants a, b and δ' for a step function coil current.

In raster scanning the mmf is a ramp function of time or:

$$F(t) = \frac{dF}{dt}t \tag{8}$$

which is the integral of step functions. The angular response of the system is then:

$$\theta(t) = \mathrm{SLB}(t) = \delta'\ \frac{dF}{dt}\int_o^t \frac{\sqrt{t}+b}{\sqrt{t}+a}dt \tag{9}$$

which becomes on integration:

$$\theta(t) = \delta'\ \frac{dF}{dt}\left[t-2(a-b)\ \left(\sqrt{t}-a\ 1n\left(1+\sqrt{\frac{t}{a}}\right)\right)\right] \tag{10}$$

The term linear in time is the desired response $\theta_o(t)$ whereas the remainder contributes a relative error R.E. in deflection of:

$$R.E._o = \frac{\theta(t)-\theta_o(t)}{\theta_o(t)} = \frac{-2(a-b)}{t}\left[\sqrt{t}-a\ 1n\left(1+\frac{\sqrt{t}}{a}\right)\right] \tag{11}$$

Now if a compensating coil is added about this first coil the angular response becomes, by addition:

$$\theta(t) = \delta_1'\ \frac{dF_1}{dt}\Big\{(1+T)t-2\ \sqrt{t}[(a_1-b_1)+T(a_2-b_2)] +2a_1(a_1-b_1)\ 1n\left(1+\frac{\sqrt{t}}{a_1}\right)+2Ta_2(a_2-b_2)1n\left(1+\frac{\sqrt{t}}{a_2}\right)\Big\} \tag{12}$$

where the parameter T is defined as:

$$T = \left(\delta_2'\ \frac{dF_2}{dt}\right)/\left(\delta_1'\ \frac{dF_1}{dt}\right) \tag{13}$$

and the subscripts above refer to the inner (**1**) and outer (**2**) coil. The coefficient of the $\sqrt{t}$ is nulled when

$$T = T_{comp} = -\frac{(a_1-b_1)}{(a_2-b_2)} \tag{14}$$

which leaves an improved relative error $(R.E.)_c$, where

$$(R.E.)_c = \frac{2(a_1-b_1)\left[a_1 1n\left(1+\frac{\sqrt{t}}{a_1}\right)-a_2 1n\left(1+\frac{\sqrt{t}}{a_2}\right)\right]}{t\left[1-\frac{(a_1-b_1)}{(a_2-b_2)}\right]} \tag{15}$$

An estimate will now be made here for long coils similar to those treated in Example I. We denote the coil size as a ratio of the winding radius to the base.

Defining Relation	Coil 1	Coil 2
$x_i = \frac{r_i}{r_b}$ radius	0.4	0.8
$P_1 = \frac{R_1}{R_2} \sim \frac{0.5(1+x)}{(1-0.85x)}$	1.04	2.76
$P_3 = \frac{R_3}{R_2} \sim \frac{2.1(1-x)}{1+x}$	0.90	0.233
$Q \sim 0.98 r_b \sqrt{\frac{\mu_o}{\mu_m} \mu_o \sigma}$	Q_1	Q_2
$R_2 \sim \frac{1.2}{\mu_o L}$ ~ coil length	$\frac{1.2}{\mu_o L_1}$	$\frac{1.2}{\mu_o L_2}$
a (See Equation 5) ~	$0.709Q$	$1.034Q$
b (See Equation 4) ~	$0.515Q$	$0.321Q$
δ' (See Eq. 3 and 7) ~	$\frac{0.994\mu_o \delta L_1}{r_b}$	$\frac{0.603\mu_o \delta L_2}{r_b}$

T_c (See Equation 14)
$T_c \sim -0.273$

Then the ratio of ampere turns or mmf is by Equation (13)

$$\frac{dF_2}{dt} = -0.45 \frac{dF_1}{dt};$$

This compensated ampere turn ratio is nearly the same as for Example I. However, the improvement in relative error is also calculable. We shall employ the following system parameter values.

$r_b = 0.020 m$
$\mu_o = 4\pi \times 10^{-7}$

$$\frac{\mu_m}{\mu_o} = 10^3$$

$$\sigma = 10^7 \frac{mho}{m}$$

scan time $t = 10^{-3}$ sec.
Then the uncorrected coils, relative scan error is

$(R.E.)_o \approx -2.3 \times 10^{-2}$ from Equation (11)

while the compensated pair has a relative error of

$(R.E.)_c \approx -0.165 \times 10^{-2}$ from Equation (15)

Thus the compensated scan coil pair has a decreased time lag error by about an order of magnitude, as this calculation demonstrates. Of course, as stated previously, the exact value of the improvement is dependent upon a more precise calculation than the one performed above. However, the procedure for compensating the deflection coils, has been well outlined.

The following experimental data proves conclusively that the eddy current compensation concepts of the present invention perform in the manner set forth and described previously. A number of assumptions and simplifications were made in the theoretical discussion previously, however the following examples and especially the data clearly shown in the graphical representation of FIGS. **8–10** clearly prove the enhanced operation of the magnetic deflection field obtained by utilizing the present invention.

EXAMPLE

Three saddle yokes were built for this example on specially machined ABS bobbins. Each yoke consisted of two separate saddle yokes schematically pictured in FIG. **1.** The inner and outer saddle yokes were wound on 3.8cm and 5.7cm diameter cylindrical surfaces, respectively. All contained 10 turns of No. 24 AWG copper wire on each winding. The angular separation between wire elements is 120° (i.e., γ in FIG. **2** and FIG. **6**) in order to obtain a relatively uniform deflection field. The lengths of the three yokes were 3.8cm, 7.6cm and 15.2cm.

The 7.6cm outside diameter of each bobbin fits inside the 7.6cm inside diameter of three different thick walled, 20cm long metallic tubes of 1018 C.D. mild steel, aluminum and mu-metal.

The 2.2cm inside diameter of each bobbin allowed the entry of an identically sized search coil probe. This probe held a 500-Turn search coil of AWG No. 33 copper wire. The coil had a length of 6.4 mm and an average diameter of 9.5 mm.

The block diagram of FIG. **7** shows the experimental apparatus used in the present example. All of the blocks of the apparatus are clearly marked and their function is believed to be obvious. Measurements were made on the deflection yokes as follows. The square wave generator **30** provided independently variable input signals to two deflection amplifiers **32** and **34** which in turn supplied opposing currents to the inner and outer saddle coils **36** and **38.** These currents were displayed on the oscilloscope **40.** The search coil **42** was oriented inside the bobbin. Its output voltage was amplified to display the detected deflection field on the oscilloscope. A 2.2 KΩ and 500 pf load across the approximately 3mHy search coil introduces a response time of about 2μ sec., thereby making temporal field measurements, in the millisecond range, reliable.

As will be apparent in the above example, the pick-up coil would not necessarily be present in an operating embodiment, however, it is believed that its use clearly demonstrates the effect of the compensating winding which compensates for the eddy currents generated in the surrounding tube structure by the primary coil and virtually eliminates transient effects due to such eddy currents. It is further submitted that these experiments clearly show the applicability of the present invention for the purpose intended and work is currently going on to actually modify scanning electron microscopes in accordance therewith.

The combined effects of simultaneously driving the inner and outer coils with opposing currents are summarized in FIGS. **8** through **10.** Nine oscillographs are organized into three rows (a, b, and c) for each of the yoke lengths and into three columns FIGS. **8, 9,** and **10** for the uncompensated, compensated and overcompensated conditions respectively. The upper trace of each oscillogram (solid line) is the integrated search coil output which reconstructs the functional form of the cross-axial deflection field. The lower trace (dotted line) of each oscillogram displays the coil drive current. In FIGS. **9** and **10** the variable outer coil current is shown while in FIG. **8** the unvaried inner coil current employed for each coil length is shown. In all nine of the oscillograms of FIGS. **8, 9,** and **10,** each horizontal division equals 0.5 milliseconds.

There is no outer coil current for the uncompensated cases. The square wave inner coil current steps cause an almost discontinuous change in field (in less than 5μ sec.), but thereafter the field slowly tends toward its steady state value over periods of milliseconds, with its approximately reciprocal square root of time dependence. One does notice the effect of yoke length, whereby the eddy current error decreases for shorter saddle yokes. Since deflection yokes are normally driven by ramp generators such visually dramatic eddy current effects tend to be obscured.

The overcompensated case, FIG. **10,** demonstrates the effect of overdriving the outer coil. This particular case has roughly equal inner and outer coil currents and corresponds to the type of eddy current errors produced by toroidal deflection yokes. The net effect of eddy currents here is to produce an overshoot of the desired deflection field, by the dominance of the outer coil transient. Again, the magnitude of the transient diminishes for shorter yoke lengths.

Finally, as shown in FIG. **9,** the outer coil current has been adjusted to an intermediate value. At this point the eddy current errors are greatly reduced and the cross-axial field possesses the square wave shape of the yoke drive currents. In each case, the field produced is somewhat reduced from the uncompensated field, but a reduced deflection sensitivity is a minor price to pay for the greatly improved deflection accuracy.

The outer to inner coil current ratio shown in Table 1 below for a steel tube which produced compensation for each yoke, did so for each of the three metallic tubes. In fact, the central compensated field has remained unchanged as one slides the various tubes off the yoke. Therefore, one might say that compensation decouples the yoke from its surroundings.

TABLE 1

For 3.8 cm yoke	$I_2 = -0.59I_1$
For 7.6cm yoke	$I_2 = -0.62I_1$
For 15.2cm yoke	$I_2 = -0.66I_1$

For the uncompensated yoke, the three tubes behaved somewhat differently: the transient for mu-metal decayed roughly twice as fast as that for mild steel; while that for aluminum decayed so slowly it was difficult to display. It is thus clear that the present concept works equally well for all three materials used.

Referring now to FIG. **11,** a toroidal deflection coil system is illustrated in its most elemental form. The inner coils designated **40** comprise the primary deflection coils and the outer coils designated by the reference numeral **50** comprise the compensating coils. The four toroidal coils **40** are the equivalent of the saddle coil pair C1 shown in FIGS. **1** and **3** it being understood that for a double deflection system there would have to be two stacked layers of such coils. It should be further noted that the coils **40** provide coils for a single access of deflection, i.e., the x axis and that an additional coil structure rotated 90° from those shown in FIG. **11** would have to be provided with a suitable separate deflection signal source for the other orthogonal deflection direction. A deflection signal source **60** is shown connected in series with the deflection and compensating coils. This series connection is shown diagrammatically in the FIG. It is to be noted that the required relative direction of current flow within the coils is clearly shown by the arrows adjacent the respective coils **40** and **50.** It will be further noted that the current flow in each individual compensating coil is opposite to that in its directly associated deflection coil. By comparing FIG. **11,** with for example, a structure such as shown in FIG. **3** the four coil legs **42** of the respective coils **40** provide the primary deflecting field in the center of the tube or along the axis of the electron beam system.

The operation of the configuration of FIG. **11** is quite similar to the configuration of FIG. **3** in terms of the deflection field produced by the inner conductors **42** which are in essence the equivalent of a pair of saddle coils.

Applying the design parameters and mathematical relationships which were described in the previous mathematical examples the following relationship was found to apply for the embodiment of the invention set forth in FIG. **11.**

$$N_{12}I_{12}(r_2-r_1) \approx N_{34}I_{34}(r_4-r_3)$$

In this approximate formula, r_1 through r_4 are the three dimensions shown in FIG. **11.** $N_{12}I_{12}$ comprises the ampere turn figure for the two inner or deflection coils pairs **40** shown in FIG. **11.** The parameter $N_{34}I_{34}$ is the ampere turns figure for the outer or compensating coils **50** of FIG. **11.** As will be apparent the numbers of turns N is fixed as are the radii r_1 through r_4 hence the parameters subject to variation are the currents I_{12} and I_{34}. With the physical configuration shown in the subsequent example it was acceptable to make these currents equal wherein both the deflection and compensating coils were driven in series from a single deflection source such as **60** in FIG. **11.**

The following example represents tests run on a toroidal coil structure such as illustrated in FIG. **11** wherein the coil structure was located in a mild steel can and driven from an appropriate square wave generator which waveform shows most dramatically the effects of the eddy current compensation in so far as time lag of the primary deflection field is concerned.

EXAMPLE

In this example the coil spacing or angles were 104° and 76° as shown in FIG. **11.** The dimensions r are as follows:

r_1 = 17.5mm
r_2 = 30.8mm
r_3 = 36.7mm
r_4 = 49.1mm

Each of the individual deflection and compensating coils **40** and **50** were comprised of 20 turns each of AWG No. 24 copper wire. The total length of each coil was 48mm.

The deflection coils and compensating coils were actually wound on cylindrical bobbins having appropriate slots for carrying the coils and which could be symmetrically mounted within each other. The bobbins were magnetically inert plastics whereby the effective magnetic structure is as shown in FIG. **11.** The bobbins were in turn placed inside a mild steel can having an inside diameter of 15cm and an inside height of 17cm. The metal thickness of the can was approximately 3mm. The 500 turn search coil probe was used to detect the cross-axial field as with the previously described examples for the saddle coil arrangements.

The result of tests run utilizing the circuitry set forth in FIG. **7** are shown in FIGS. **12A** and **12B.** FIG. **12A** is the result of runs with no current in the compensating coils. The upper curve shown in solid line is the current picked up in the search coil and directly indicates the magnitude of the cross-axial field along the axis of the structure. The time-lag effects due to the eddy currents are clearly shown in the left-hand portion of each of the horizontal traces. The lower dotted line represents the square wave applied to the deflection coil assembly which produced the cross-axial field picked up by said search coil.

Referring now to FIG. **12B** the results of the same experiment are shown wherein the deflection and compensating coils of FIG. **11** are connected directly in series to the square wave generator **30.** It is to be noted that with the series configuration possible with the toroidal embodiment of FIG. **11,** it is not necessary to utilize an outer deflection coil amplifier **34** shown in FIG. **7** as both the inner deflection coils and the outer compensating coils are simply connected in series to the deflection amplifier **32.** The results of this compensation are shown quite drammatically in FIG. **12B** wherein the upper trace representing the cross-axial field as measured by the search coil shows virtually no time lag errors due to said eddy current generation. Again the lower trace shown in dotted line represents the square wave applied to the deflection coil **40.**

Thus for the toroidal embodiment as well as for the saddle coil embodiment the advantages of the present invention are clearly apparent.

CONCLUSIONS

From the above operating examples, the advantages to be gained from the present invention are clearly shown. It should, of course, be reiterated that the calculations in the earlier portion of the specification are approximations. However, it is quite clear from the operating examples that the advantages set forth and described theoretically herein are obtainable in a practical operating environment. As set forth previously, the significant discovery which allows the present invention to be practically realizable, is the fact that the outer or compensating coil pair may be chosen to be of such a size; i.e., ampere turns as well as dimension and location so as to balance out eddy current time lag effects but at the same time have a reduced effect on the beam deflection field produced by the primary deflecting coil pair.

In the two disclosed preferred embodiments of the invention as exemplified by FIGS. **1** and **11** saddle compensating coils were disclosed for compensating saddle deflection coils and similarly toroidal compensating coils were utilized to compensate toroidal deflection coils. However, it should be understood that it would be possible to utilize a saddle coil configuration to compensate toroidal deflection coils and similarly the toroidal compensating coil configuration to compensate saddle deflection coils. It may thus be seen that there are a number of design possibilities utilizing the basic concepts set forth and described herein.

In an existing operating electron beam device, the deflection coil designer would utilize the teachings of the present invention in a straightforward manner to design a set of compensated deflection coils according to the present invention. While the disclosed embodiment implies that the deflecting and compensating coils be connected in series with the ramp or other deflecting signal source as illustrated in FIGS. **3** and **11,** it should be understood that it would also be possible to connect the two coils in parallel providing, of course, that compensating circuits are added to assure required proportionality between the ampere turns of both coils. This latter arrangement would also allow some fine tuning of the compensating network by, for example, placing a variable resistor in series with the compensating coil providing, as stated above, that the respective fields generated by the two sets of coils were kept in proper phase relationship.

What is claimed is:

1. In a device utilizing a directionally controlled electron beam including means for generating an electron beam, electromagnetic means for deflecting said beam with a deflecting force at substantially right angles to the direction of said beam, said deflection means including an elongated electrically conductive tube surrounding said deflection means having a radius r_b and a thickness T, a pair of primary deflection coils located within said tube on opposite sides of said electron beam, a pair of secondary compensating coils located within said tube, each coil being located between one of said primary coils and the inner wall of said tube and two of their sides being substantially parallel to the axis of said tube, the conductors comprising at least one axial side of each of the primary and secondary coil pairs lying substantially within the surface of inner and outer cylinders, respectively, having radii r_1 and r_2, means for connecting said two pairs of coils to a common deflection signal source for causing said electron beam to follow a predetermined scan pattern, said deflection and compensating coils being connected so that their respective magnetic fields oppose each other, the ampere turns ratios of said two pairs being such that the magnetic field at the center of the conductive tube due to the primary deflection coils is controlling but wherein the eddy current generation effect in said tube due to the secondary compensating coils opposes the eddy current generation effect due to the primary coils and substantially cancels same, whereby the eddy current generation by the two sets of coils is substantially self-canceling but wherein the deflection field generated by the primary deflection coils is of sufficient magnitude to effect the desired scan pattern by the electron beam.

2. In a device utilizing a directionally controlled electron beam including means for generating an electron beam, electromagnetic means for deflecting said beam with a deflecting force at substantially right angles to the direction of said beam, said deflection means including an elongated electrically conductive tube surrounding said deflection means having a radius r_b and a thickness T, a pair of primary deflection coils located within said tube on opposite sides of said electron beam, a pair of secondary compensating coils located within said tube, each coil being located between one of said primary coils and the inner wall of said tube and two of their sides being substantially parallel to the axis of said tube, the conductors comprising the axial sides of the primary coil pair lying substantially within the surface of inner and outer cylinders, respectively, having radii r_1 and r_2, and the conductors comprising the axial sides of the secondary coil pair lying respectively within the surface of inner and outer cylinders respectively, having radii r_3 and r_4 and wherein the relationship of the radii is $r_1 < r_2 < r_3 < r_4 < r_b$, both the primary and secondary coil pairs lying substantially within a common plane including the axis of said conductive tube, means for connecting said two pairs of coils to a common deflection signal source for causing said electron beam to follow a predetermined scan pattern, said deflection and compensating coils being connected so that their respective magnetic fields oppose each other, the ampere turns ratios of said two pairs being such that the magnetic field at the center of the conductive tube due to the primary deflection coils is controlling but wherein the eddy current generation effect in said tube due to the secondary compensating coils opposes the eddy current generation effect due to the primary coils and substantially cancels same, whereby the eddy current generation by the two sets of coils is substantially self-canceling but wherein the deflection field generated by the primary deflection coils is of sufficient magnitude to effect the desired scan pattern by the electron beam.

3. In a device utilizing a directionally controlled electron beam including means for generating an electron beam, electromagnetic means for deflecting said beam with a deflecting force at substantially right angles to the direction of said beam, said deflection means including an elongated electrically conductive tube surrounding said deflection means having a radius r and a thickness T, a pair of primary deflection coils located within said tube on opposite sides of said electron beam, a pair of secondary compensating coils located within said tube, each coil being located between one of said primary coils and the inner wall of said tube and two of their sides being substantially parallel to the axis of said tube, the conductors comprising said axial sides of each of the primary and secondary coil pairs lying substantially within the surface of inner and outer cylinders, respectively, having radii r_1 and r_2, means for connecting said two pairs of coils to a common deflection signal source for causing said electron beam to follow a predetermined scan pattern, said deflection and compensating coils being connected so that their respective magnetic fields oppose each other, the ampere turns ratios of said two pairs being such that the magnetic field at the center of the conductive tube due to the primary deflection coils is controlling but wherein the eddy current generation effect in said tube due to the secondary compensating coils opposes the eddy current generation effect due to the primary coils and substantially cancels same, whereby the eddy current generation by the two sets of coils is substantially self-canceling but wherein the deflection field generated by the primary deflection coils is of sufficient magnitude to effect the desired scan pattern by the electron beam.

4. In a device utilizing a directionally controlled electron beam including means for generating an electron beam, electromagnetic means for deflecting said beam with a deflecting force at substantially right angles to the direction of said beam, said deflection means including an elongated electrically conductive tube surrounding said deflection means having a radius r and a thickness T, at least one pair of toroidal primary deflection coils located within said tube, one coil of each pair lying on opposite sides of said electron beam, at least one pair of secondary compensating coils located within said tube each compensating coil being located between one of said primary coils and the inner wall of said tube, each of said pairs of coils having a length to width ratio greater than one, their length dimensions being substantially parallel to the axis of said tube, the conductors comprising one of said long sides of each of the pairs of primary coils lying substantially within the surface of an inner cylinder, at least one of said long sides of each of said compensating coils lying within the surface of an outer cylinder, means for connecting said two pairs of coils to a common deflection signal source, the magnetic field produced by said primary coils causing said electron beam to follow a predetermined scan pattern, said deflection and compensating coils being connected so that their respective magnetic fields oppose each other, the ampere turns ratios of said two pairs being such that the magnetic field at the center of the conductive tube due to the primary deflection coils is dominant but wherein the eddy current generation effect in the inner surface of said tube due to the secondary compensating coils opposes the eddy current generation effect due to the primary coils and substantially cancels same, whereby the eddy current generation by the two sets of coils is substantially self-canceling but wherein the deflection field generated by the primary deflection coils is of sufficient magnitude to effect the desired scan pattern by the electron beam.

5. A deflection means as set forth in claim **4** including a plurality of pairs of toroidal primary deflecting coils pairs for each orthogonal deflection axis and a plurality of toroidal compensating coil pairs, one for each toroidal deflecting coil pairs.

6. A deflection means as set forth in claim **5** wherein each toroidal primary deflection coil pair and its associated compensating coil pair lie substantially in a common plane including the axis of said tube.

* * * * *