Sept. 25, 1962 J. PARAIN 3,056,069
VARIABLE INDUCTION MAGNETS OF THE TYPE USED IN SYNCHROTRONS
Filed June 11, 1957 4 Sheets-Sheet 1

FIG. 1

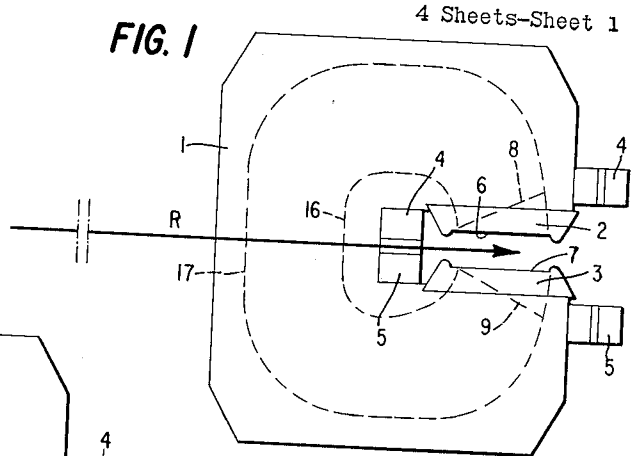

FIG. 3

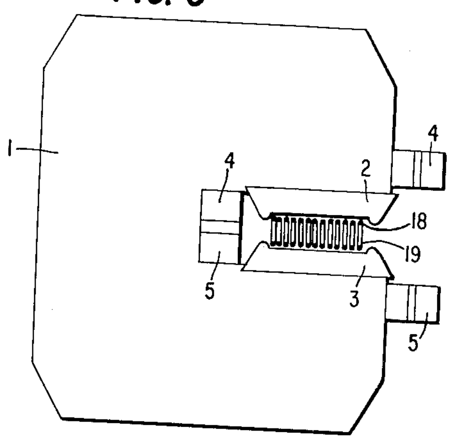

FIG. 2

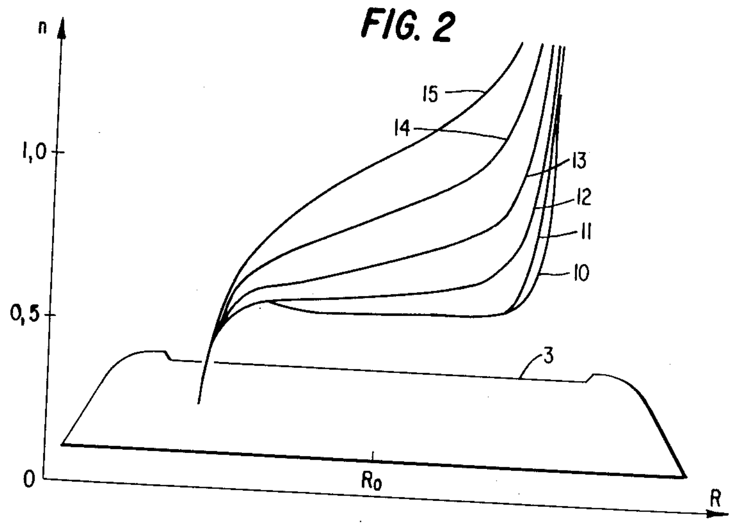

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FIG. 4

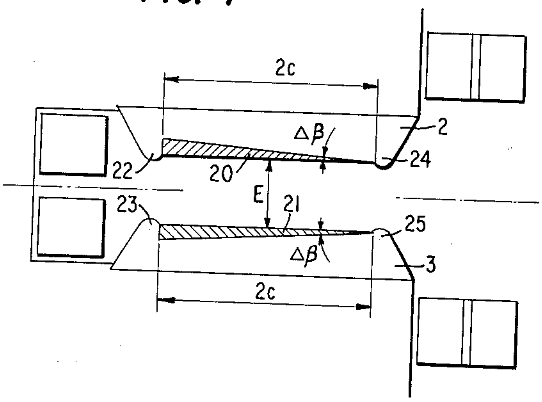


FIG. 6

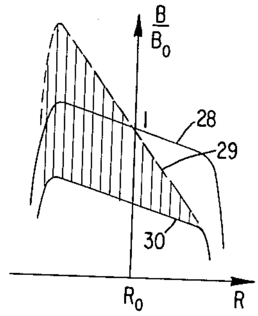


FIG. 5

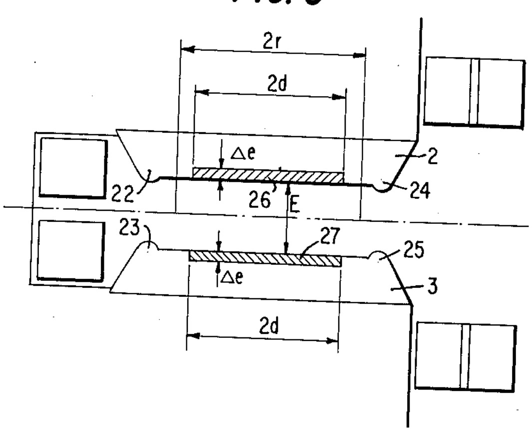


FIG. 7

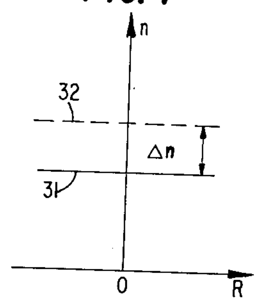


FIG. 8

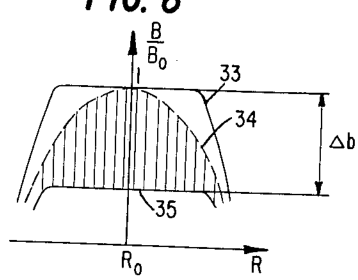
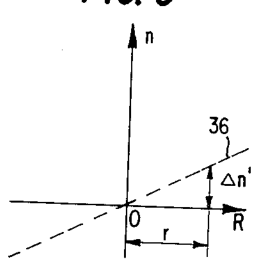


FIG. 9



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VARIABLE INDUCTION MAGNETS OF THE TYPE USED IN SYNCHROTRONS

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FIG. 10

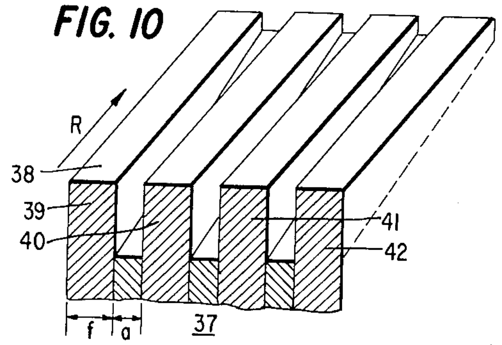

FIG. 11

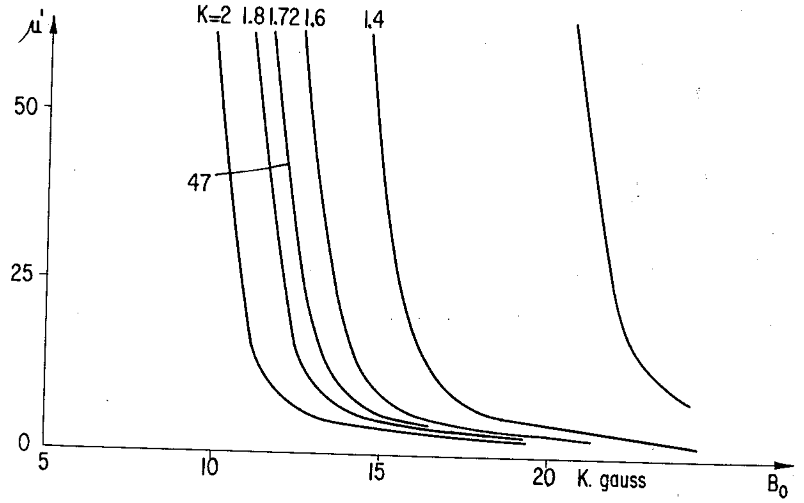

FIG. 12

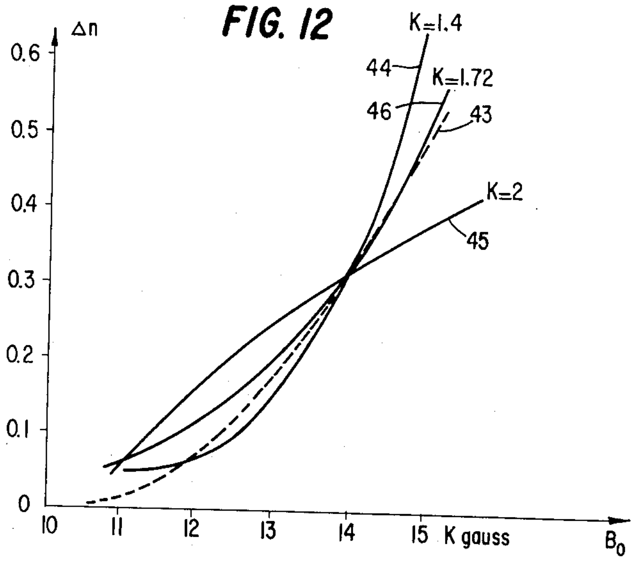

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FIG. 13

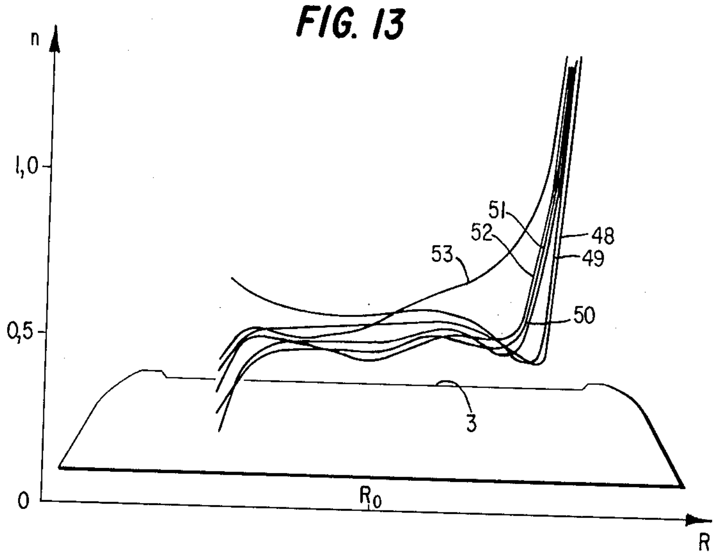


FIG. 14

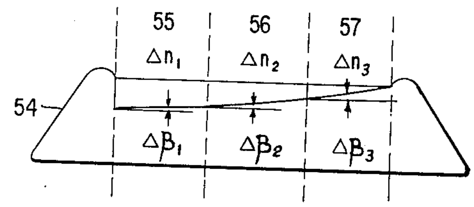
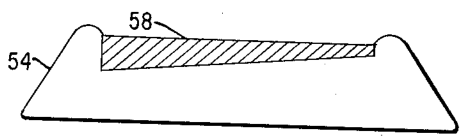


FIG. 15



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Patented Sept. 25, 1962

3,056,069

VARIABLE INDUCTION MAGNETS OF THE TYPE USED IN SYNCHROTRONS

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Filed June 11, 1957, Ser. No. 665,064
Claims priority, application France June 13, 1956
3 Claims. (Cl. 317—158)

The present invention relates to variable induction magnets of the type used in synchrotrons.

The object of this invention is to provide a magnet of this type in which the deformations of the field in the air gap due to magnetic saturation under the effect of high induction are corrected in a simple and efficient manner.

The essential feature of this invention consists in the fact that, in the portion of at least one of the pole pieces of the magnet which is adjoining the air gap, there is provided a zone the permeability of which is different from that of the material which constitutes the remainder of said pole piece, and is lower than it, so as automatically to correct at least partly the deformations of the magnetic field in the air gap for high values of the induction (that is to say for values corresponding to magnetic saturation of the air gap), said permeability being however sufficient to give the field a form which is not substantially modified for relatively low values of the induction.

It should be remembered that in apparatus such as synchrotrons the induction in the air gap increases during the whole particle acceleration cycle and that it is generally desired to maintain, during this cycle and at every point of the useful zone of the air gap, the gradient

$$\frac{dB}{dR}$$

of the induction in the radial direction as constant as possible.

For the sake of clarity, the term "index" of the magnetic field will be used to designate the quantity:

$$n = -\frac{R_0}{B_0} \cdot \frac{dB}{dR}$$

where R_0 is the radius of the stable orbit of the particles (which is constant for a given apparatus), and B_0 is the induction along this orbit; this index n ranges from 0.5 to 0.75 in conventional synchrotrons.

As the induction in the air gap may generally vary from 300 to 15,000 gausses for instance, it is not possible to avoid, for values of the induction above approximately 10,000 gausses, a saturation of the magnetic circuit of the magnet (yoke and pole pieces) which deteriorates the chart of the field and leads to a substantial increase of index n.

The solutions generally adopted to obviate these drawbacks will be summed up with reference to FIGS. 1 to 3.

FIG. 1 is a diagrammatic sectional view of a magnet including yoke **1**, pole pieces **2** and **3** removably fixed on said yoke and excitation windings **4** and **5**.

For low values of the induction, the faces **6** and **7** of pole pieces **2** and **3** are equipotential surfaces of the magnetic field; when the induction gradually increases, during the cycle of operation of the machine, the magnetic circuit becomes saturated and the above mentioned equipotential surfaces **6** and **7** no longer coincide with the faces of the pole pieces; they become oblique thereto, as shown at **8** and **9**, which has for its effect to modify the field in the air gap in an undesirable manner.

The curves of FIG. 2 illustrate the modification of the field in the air gap of a synchrotron magnet. In said FIG. 2 the values of the index n of the field are plotted along the ordinates, and for points of the air gap the positions of which, with respect to the pole pieces, are plotted along the abscissa. R_0 is the radius of the stable orbit, the radii increasing from left to right in the direction of arrow R.

FIG. 2 shows curves **10**, **11**, **12**, **13**, **14** and **15** representing the variations of the field index n at different points of the air gap for the following values of the induction B_0:

Curve **10**—from 3,000 to 7,000 gausses,
Curve **11**—10,000 gausses,
Curve **12**—12,000 gausses,
Curve **13**—13,000 gausses,
Curve **14**—14,000 gausses and
Curve **15**—15,000 gausses.

These curves show that saturation of the magnetic circuit for high values of the induction has truly the effect to produce an increase of the index n of the field which at the point corresponding to the stable orbit of radius R_0 increases in the example illustrated in FIG. 2 from 0.55 to 1.04 when the induction increases from 3,000 to 15,000 gausses.

This increase of the field index n is due to the fact that the difference of consumption of ampere-turns in the yoke along two induction lines of different total lengths, such as **16** and **17** on FIG. 1, has a greater influence for high values of the induction.

If, now, it is desired to keep index n below for instance 0.75, the curves of FIG. 2 show that the limit of utilization of the magnet would be, in the example that is considered, below 13,000 gausses. As it is advantageous to operate the synchrotron with an induction as high as possible (the energy of the accelerated particles increases substantially as the induction itself), this limitation of the induction cannot be accepted for practical purposes.

In order to obviate this drawback, it has already been proposed to correct the chart of the field for high values of the induction by means of correcting windings constituted by conductors placed in the air gap and parallel to the stable orbit of the particles. This is in particular the solution adopted for the Cosmotron of Brookhaven.

FIG. 3 shows such correcting windings **18** and **19**, a current flowing through said windings so that the auxiliary field that is produced restores the initial conditions of the field existing in the air gap before saturation; it is thus possible to keep the field index n approximately constant at all points of the air gap during the cycle of acceleration of the particles.

However, such correcting windings may involve drawbacks in some applications.

The present invention gives a solution of the above stated problem which is simple and avoids such drawbacks.

The invention consists essentially in creating in the portion of at least one of the pole pieces of the magnet which adjoins the air gap a zone of correction of a permeability different from, and generally lower than, that of the material of which the remainder of the pole piece is made.

For the average values of the induction, the permeability remains however important in the correction zone and the form of the field is determined by the surface of the pole piece itself. But for high values of the induction, the saturation of this correction zone makes it possible to produce a fictitious variation of the cross section of the pole piece in accordance with the value of the induction in the air gap, thus compensating for the displacement of the equipotential surfaces as shown at **6** and **7** on FIG. 1.

The form of this correction zone and the permeability of this zone are determined in accordance with the desired chart of the field to be obtained.

One of the main advantages of this arrangement according to the present invention is that the correction of index n is thus automatically obtained and does not require, as in the case of correcting windings, the provision of means for controlling the correction as a function of the induction. Furthermore, the fictitious increase of the air gap for high values of the induction, due to saturation of the correction zone, is much smaller than the space necessary for housing the correcting windings which otherwise would have to be used. This ensures a substantial saving of the excitation ampere-turns of the magnet.

Correction of the defects of the field index for high values of the induction by creating a correction zone in the pole piece therefore permits of eliminating the drawbacks of correcting windings and of increasing the potentialities of a magnet intended to work with a variable induction (synchrotron or mass separator magnet for instance).

The defects of the magnet resulting from magnetic saturation may thus be corrected according to the invention in two different manners, corresponding to two different causes:

(*a*) the increase Δn of the field index n due to saturation of the whole of the magnetic circuit, when the induction increases from its initial value $(B_o)_1$ (unsaturated circuit) to its maximum value $(B_o)_m$, is compensated for by providing correction zones of variable thickness,

(*b*) the effect of the projecting edges (hereinafter called "horns") of the pole pieces, which is less important than the first mentioned defect, is compensated for by providing correction zone of uniform height in the central portion of the pole pieces.

Preferred embodiments of my invention will be hereinafter described with reference to the appended FIGS. 4 to 15 exclusive, given merely by way of example and in which:

FIGS. 4 and 5 are diagrammatic cross sections of pole pieces made according to the invention to correct the two above mentioned defects respectively.

FIGS. 6 and 7 on the one hand, and FIGS. 8 and 9, on the other hand, give curves showing the influence upon induction B and index n of the correction zones illustrated by FIGS. 4 and 5 respectively.

FIG. 10 is a part perspective view of the surface of a pole piece, provided with notches, made according to my invention, said pole piece being intended to be used in a synchrotron.

FIG. 11 shows curves giving the equivalent permeability μ' of the correction zone as a function of the induction B_o and of the dimensions of the above mentioned notches.

FIG. 12 shows curves giving the variation Δn as a function of the same parameters.

FIG. 13 shows curves giving the values of index n as a function of the radius R in the air gap.

FIGS. 14 and 15 diagrammatically illustrate modifications of the correction zone according to my invention.

On FIG. 4, the correction zones **20** and **21** are of varying thickness from one edge to the other of the air gap so as to compensate for the increase of the field due to saturation of the whole of the magnetic circuit. FIG. 5 shows correction zones **26** and **27** of uniform thickness used to compensate for the effect of the saturation of the pole piece horns **22**, **23**, **24** and **25**.

As a matter of fact, the two above mentioned defects exist simultaneously in the magnet and the correction zone that is actually used is either a combination of the arrangement of FIGS. 4 and 5 or possibly an arrangement according to only one of these figures.

FIG. 6 shows curves obtained by plotting in ordinates the induction in the air gap at different points and in abscissas the radial distances of said points. On FIG. 7 the field index in the air gap is plotted in ordinates and the radial distances in abscissas.

On FIG. 6, curve **28** shows the initial induction $(B_o)_1$ (the magnetic circuit being unsaturated) and curve **29** shows the maximum induction $(B_o)_m$ (the magnetic circuit being saturated); the values of the induction are measured with units equal to B_o. The curve **30** is obtained after correction, which curve is substantially the same for all values of induction B_o. The cross-hatched area clearly shows the effect of the correction zone of variable height. FIG. 6 also shows that, in the central portion of the pole piece where curves **28** and **30** are substantially rectilinear, said curves have the same slope which means that index n, according to the invention, has been kept practically constant for the whole range of variations of the induction, that is to say from $(B_o)_1$ to $(B_o)_m$.

FIG. 7 shows straight lines **31** and **32** which respectively represent the values of index n for inductions equal respectively to $(B_o)_1$ and $(B_o)_m$ when there is no correction zone; the difference between these two values of index n is equal to the above defined quantity Δn. When a correction zone according to the invention is provided, the field index n remains at its initial value (curve **31**) for all values of the induction, even $(B_o)_m$.

In a likewise manner, FIG. 8 shows curves where the induction in the air gap has been plotted in ordinates and the radial distances in abscissas. FIG. 9 shows in ordinates the field index in the air gap and in abscissas the radial distance.

On FIG. 8, **33** is the curve corresponding to the value $(B_o)_1$ of the induction (pole piece horns being unsaturated) and **34** is the curve corresponding to the maximum value $(B_o)_m$ of the induction (pole piece horns being saturated). In this case also, the values of the induction are relative and equal to

$$\frac{B}{B_o}$$

Furthermore, for the sake of clarity, these figures correspond to the case where the pole pieces of the magnet are parallel ($n=0$). The curve **35** is obtained after correction, which curve is substantially the same for all values of induction B_o. The cross-hatched area clearly shows the effect obtained by means of a correction zone of uniform thickness.

Curve **34** is substantially a parabola, and consequently curve **36** of FIG. 9 which represents, for induction $(B_o)_m$, the variations of index n as a function of radius R, is practically a straight line. The following, $\Delta n'$ will designate the variations, measured at the limit of the useful zone having a half length equal to r, of the field index n due only to saturation of the pole piece horns (FIG. 9).

In these conditions, a mathematical study of the problem shows that μ' being the permeability of the correction zone, supposed to be made of the same material for both correction zones, and μ' being lower than the permeability μ of the remainder of the pole piece, the angle $\Delta\beta$ of the correction zones **20** and **21** of FIG. 4 is given by the following formula:

$$\text{(I)} \qquad \Delta\beta = -\Delta n \cdot \frac{E}{2R_o} \cdot \mu'$$

in which E is the dimension of the air gap.

Angle $\Delta\beta$ must of course be of a direction such that it produces a correction zone opposed to the defect to be corrected.

This angle $\Delta\beta$ being constant for a given pole piece, same as the quantity

$$\frac{E}{2R_o}$$

it follows that for any value of induction B_o there is a relation such as:

$$\text{(II)} \qquad \Delta n \cdot \mu' = A$$

in which A is a constant for a given angle $\Delta\beta$.

This relation (II) is very important because, since the curves of FIG. 2 give the value of Δn as a function of B_o, the law of variation of μ' as a function of said induction B_o is thus known, which practically determines the choice of the material of which the correction zone is made.

In the case of a magnet to be established, it is of course not possible experimentally to plot the curves of FIG. 2, and use is made, in order to find the law of variation of μ' as a function of B_o, of the known relation:

$$\Delta n \cdot \mu_c = D$$

in which:

μ_c is the value of the permeability in the yoke,
D is a constant for a given magnet.

As for the correction zones **26** and **27** of uniform height, they are characterized by their thickness Δe (FIG. 5) the value of which is given by the following formula:

$$\text{(III)} \qquad \Delta e = \frac{\Delta b}{B_o} \cdot \frac{E}{2} \cdot \mu'$$

in which Δb is the reduction of induction that must be produced at a point of radius R_o (FIG. 8).

In the particular case where a linear approximation is considered as sufficient (FIG. 9), Formula III becomes

$$\text{(IV)} \qquad \Delta e = \frac{1}{2} \cdot \Delta n' \cdot \frac{E}{2R_o} \cdot r \cdot \mu'$$

r having already been defined above.

The half width of said correction zones **26** and **27** of constant height (FIG. 5), is chosen in such manner that the correction that is obtained compensates radially for the defect.

The consumption of ampere-turns for exciting the magnet in order to effect these corrections is small.

This results from the fact that, if Δh is the equivalent height of air of the total zones of correction taken on the stable orbit of radius R_o, the following relation exists:

$$\text{(V)} \qquad \Delta h = \frac{E}{R_o}\left(\Delta n \cdot c + \frac{1}{2}\Delta n' \cdot r\right)$$

r (FIG. 5) being the half width of the useful zone and c (FIG. 4) the half width of the correction zone of variable thickness. This Formula V gives a thickness Δh which is always very small.

FIGS. 10 to 15 illustrate different embodiments of the present invention as applied to variable induction magnets of the type used in synchrotrons.

In the preferred embodiment of the invention shown by FIG. 10, the correction zone consists partly of iron and partly of air so as to comply with condition (II). For this purpose, notches are provided in pole piece **37** by juxtaposing metal sheets of different outlines, **38** being the initial outline of the pole piece.

For rectangular notches it is possible to calculate the equivalent permeability μ' of the correction zone (the permeability of the iron that is used μ_f being known) by means of the following formulas:

$$\text{(VI)} \qquad \mu' = \frac{\mu_f}{k} + \frac{k-1}{k}$$

$$\text{(VII)} \qquad B = \mu' \cdot \frac{B_f}{\mu_f}$$

in which:

k is a geometrical coefficient such that

$$k = \frac{a+f}{f}$$

(FIG. 10), a being the width of every notch and f the distance between two consecutive notches,

B_f the induction in teeth **39**, **40**; **41** and **42** (FIG. 10), μ_f the permeability of iron corresponding to B_f,
and B the induction in the pole piece of the magnet (B is different from B_o).

It is then possible to establish the curves of μ' as a function of B_o for different values of k (FIG. 11). For this purpose, for a given value of k, B_f is chosen at will so that, knowing the curve $\mu_f = F(B_f)$ for the iron that is used, first μ_f, and then μ' are deduced by means of Formula VI. Formula VII then gives B so that one point of the curve of FIG. 11 is obtained.

The determination of $\Delta\beta$, Δe and k permits subsequently of establishing a correction zone in the pole piece.

The influence of k is illustrated by the curves of FIG. 12 which shows as a function of induction B_o, in dotted lines, the curve **43** representing the variations of Δn on the stable orbit in the absence of any correction and in solid lines the curves **44** and **45** representing the variations Δn due to the presence of correction zones according to the invention for two respective values of k ($k=1.4$ and $k=2$).

The value of $\Delta\beta$ in each of these two cases has been chosen in such a manner as to compensate exactly for the variation Δn of index n when the induction is equal to 14,000 gausses.

It will be seen that the value $k=1.4$ produces too great a correction for inductions higher than 14,000 gausses (curve **44**, FIG. 12) and that the value $k=2$ does not give a sufficient correction for values of the induction above 14,000 gausses (curve **45**, FIG. 12).

By then plotting the correction surfaces for different values of k, it is found that $k=1.72$ gives a satisfactory correction of the field index over the whole cycle (curve **46**, FIG. 12).

In these conditions, when the induction is equal to 15,000 gausses $\mu'=5.2$ (value given by curve **47**, FIG. 11).

In the example described:

$\Delta n = 1.04 - 0.55 = 0.49$

$\frac{E}{R_o} = 2.06 \times 10^{-2}$

$r = 180$ mm.

$c = d = 250$ mm.

$\Delta n' = 0.66$ for $r = 180$ mm. (curve **36**, FIG. 9)

consequently

$$\Delta\beta = 0.490 \times 1.03 \times 10^{-2} \times 5.2 = 26, 10^{-3} \text{ radian (Formula I)}$$

and

$$\Delta e = \frac{0.660}{2} \times 1.03 \times 10^{-2} \times 180 \times 5.2 = 3.2 \text{ mm} \qquad \text{(Formula IV)}$$

The increase of the consumption of ampere-turns of excitation of the magnet corresponds to a height of air Δh:

$$\Delta h = 2.06 \times 10^{-2} \times \left(0.490 \times 250 + \frac{0.660}{2} \times 180\right) = 3.8 \text{ mm.} \qquad \text{(Formula V)}$$

whereas for the same magnet, correcting windings would occupy 16 mm. of the air gap. The consumption of the correction zone is thus about only 2% of the total consumption of the machine.

It is possible, with the correction device according to the invention, to operate the magnet under an induction of 15,000 gausses without any reduction of the efficiency of the correction. Curves **48**, **49**, **50**, **51**, **52** and **53** of FIG. 13 represent, in an improved magnet according to the invention, the variations of index n as a function of the radius for the same values of the induction as in FIG. 2 (that is to say respectively from 3,000 to 7,000 gausses, and for 10,000, 12,000, 13,000, 14,000 and 15,000 gausses) and show by comparison with said FIG. 2 the efficiency of the correction zone thus obtained.

In another embodiment of the invention illustrated by FIG. 14, a more accurate correction is obtained by varying the angle $\Delta\beta$ radially, every value of $\Delta\beta$ ($\Delta\beta_1$, $\Delta\beta_2$,

$\Delta\beta_3$) serving to correct corresponding defects Δn_1, Δn_2, Δn_3.

For this purpose, pole piece **54** is divided into three elementary portions **55**, **56** and **57** for each of which the index variation Δn and the corresponding angle $\Delta\beta$ have been determined by means of the above Formula I.

In a general manner, while I have, in the above description, disclosed what I deem to be practical and efficient embodiments of my invention, it should be well understood that I do not wish to be limited thereto as there might be changes made in the arrangement, disposition and form of the parts without departing from the principle of the present invention as comprehended within the scope of the accompanying claims.

For instance, the correction, instead of being obtained by providing radial notches, might be achieved by making use of different geometrical arrangements (holes transverse grooves in the pole piece) or by making use of a homogeneous material such as a sintered alloy. In this case, the correction zone would consist of a plate **58** (FIG. 15) fixed on the pole piece.

For low values of the induction, the defects due to the remanant field may also be corrected by a correction zone according to the invention.

What I claim is:

1. In a synchrotron, of a type having an axis about which a stream of particles orbit, a variable induction magnet of the type for establishing inductions varying from very high values, close to iron saturation value, to relatively low values, comprising in combination;

a substantially annular yoke of magnetic material having said axis as a center and a substantially C-shaped cross section along its annular length,

annular pole pieces in opposed face to face relationship terminating the ends of said yoke and having substantially parallel surfaces defining an air gap therebetween in which the orbit of said particles falls,

an annular correction zone substantially co-extensive with at least one of said pole pieces of a magnetic permeability lower than that of the material of which the remainder of said yoke is made,

said annular correction zone partially defined by an annular inner edge closest to said axis,

and an annular outer edge furthest from said axis, the thickness of said correction zone defined by one of said surfaces and a second surface tapering from a depth defining the thickest portion of said zone at said inner edge to a depth defining the narrowest portion of said zone at said outer edge, and having a uniform depth at points equal distances from said axis,

the angle of taper of said second surface with said one of said surfaces computed by the formula

$$\Delta\beta=\Delta n\times\frac{E}{2R_o}\times\mu'$$

β is said angle;

E is the distance between said parallel surfaces;

R_o is the radius between said axis and said orbit; and

μ' being the permeability of the material of which said correction zone is made; and

$$\Delta n=\frac{R_o}{B_o}\times\frac{dB}{dR}$$

where B_o is the value of the magnetic field along said orbit, and the

$$\frac{dB}{dR}$$

is the derivative of the magnetic field value with the orbit radius,

whereby said zone at least partly corrects the deformations of the magnetic field in said air gap for high values of induction.

2. The induction magnet defined in claim 1 wherein the depth of said zone varies continuously from said first edge to said second edge.

3. The induction magnet defined in claim 1 wherein the depth of said zone is determined by a plurality of connecting planes each of which are angularly disposed at different angles to said axis.

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