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G. Diambrini: A MAGNETIC DIFFERENTIAL PROBE. ITS EMPLOYEMENT FOR THE DETERMINATION OF THE STATIC MEDIAN SURFACE IN THE GAP OF A SYNCHROTRON.

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A Magnetic Differential Probe. Its Employment for the Determination of the Static Median Magnetic Surface in the Gap of a Synchrotron.

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Summary. — A differential magnetic probe, developed for determining the median magnetic surface of the static field in a weak-focusing synchrotron gap, is described. The probe consists of two thin ferromagnetic wires subjected to equal and opposite alternating magnetic fields at 1000 Hz. The method of measurement consists in determining the position of the probe for which the components of the magnetic field along the two wires (parallel to the radius of the synchrotron and lying in a vertical plane) are equal and opposite. The arrangement described gives the localisation of the median magnetic surface within ± 1 mm in static fields between 20 and 500 gauss. The possibility is also mentioned of measuring the field index n by means of this probe with an accuracy of 5% in fields not exceeding 500 gauss. Finally the technique used for preparing the ferromagnetic wires is explained in some detail.

1. - Introduction.

Wires and strips of very permeable material are at present used for special measurements related to the magnetic field in the synchrotron gap (¹). In many cases, however, their real possibilities of employment present several doubts, and few detailed papers on this argument have so far been published. We think, therefore, that a detailed exposition of a new employment of ferromagnetic wires for the determination of the magnetic median surface (m.m.s.),

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(¹) J. M. Kelly: *Rev. Sci. Instr.*, **22**, 256 (1951); S. Giordano, G. K. Green and E. J. Rogers: *Rev. Sci. Instr.*, **24**, 848 (1953).

in a static field between 20 and 500 gauss in the synchrotron gap to an accuracy of ± 1 mm, may be useful. The differential probe constructed for this purpose is also employable for the determination of the field lines curvatures, i.e. for the measurements of the field index n (see 2·2) to a predictable accuracy of about 5%. The latter kind of measurement will not be taken into consideration in this paper. In the following we shall also explain the preparation technique of the ferromagnetic wires (see note II) and of the probe (see 3·2) as in our opinion it may be useful for some other kinds of measurement.

2. - Basic Principles of the Method and its Limitations.

2·1. - We shall now explain qualitatively the working principle of the device. Let two thin ferromagnetic wires of high permeability, supposed equal, parallel and straight, be subjected to an alternating sinusoidal magnetic field whose frequency is $r \simeq 1000$ cycles and whose amplitude is such as to saturate the ferromagnetic material. Let the field always be equal and opposite in the two wires, and each of them be surrounded in its central region by a pick-up coil (Fig. 1a). Then a series of pulses of induced e.m.f., alternating in sign, may be obtained from each of the two coils. If we series-connect the two coils in the same direction, the picked-up e.m.f. will be zero (or a minimum), since we shall have, altogether, pairs of like pulses, opposed and simultaneous (or very nearly). Now, if we subject the wires thus excited to a steady magnetic field, the pulses will shift in time in the direction indicated by the arrows in Fig. 1b. The leading of a pulse of one coil will correspond to a delay of the corresponding pulse of the other one. Thus a pulse-difference (Fig. 2) whose

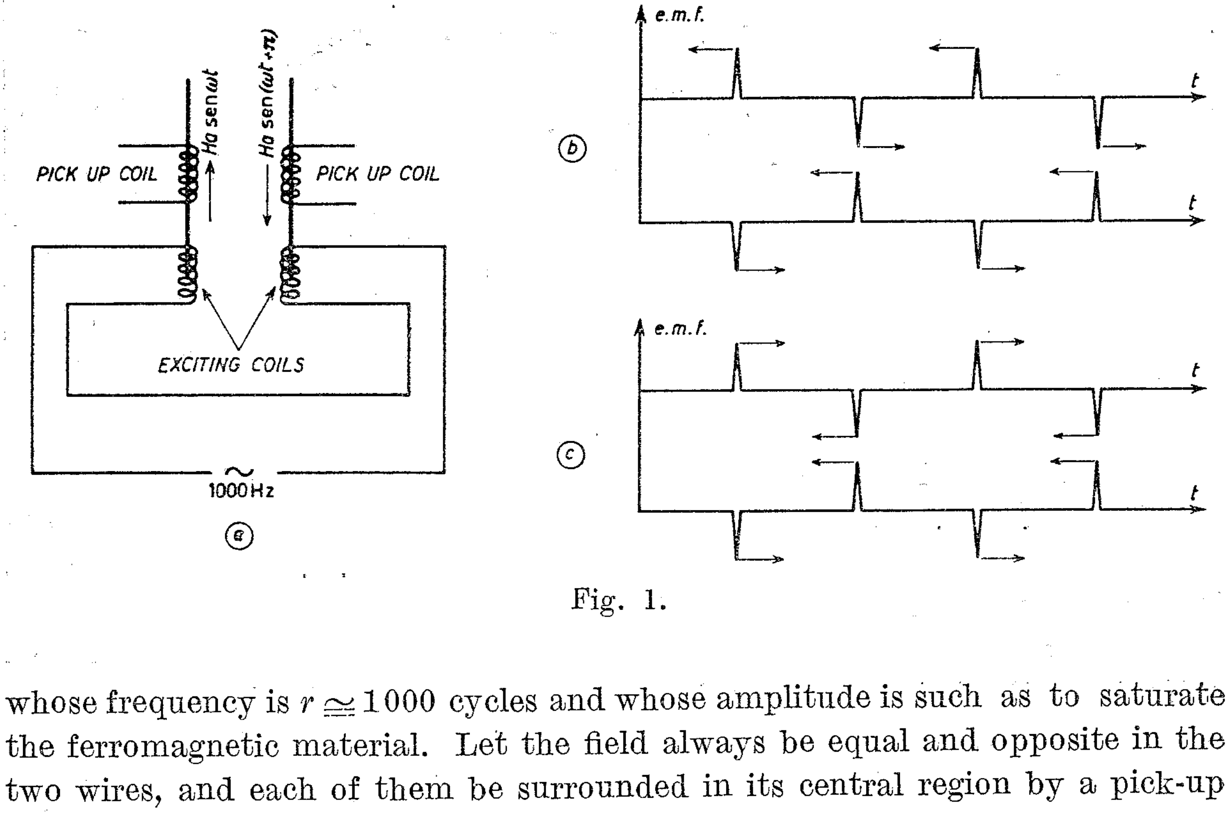

Fig. 1.

peak-to-peak amplitude is proportional, within certain limits, to the applied, steady magnetic field will arise at the output of the two series-connected coils. If, on the other hand, we subject one wire to a steady field, equal and opposite to that acting on the other, we shall again have a e.m.f. zero (or a minimum) at the output of the two series-connected coils and in the same direction, since the pulses will now be shifted as in Fig. 1c, and a pulse delay coming from one coil will correspond to an equal delay of the corresponding pulse from the other one; a similar situation will occur for the leadings.

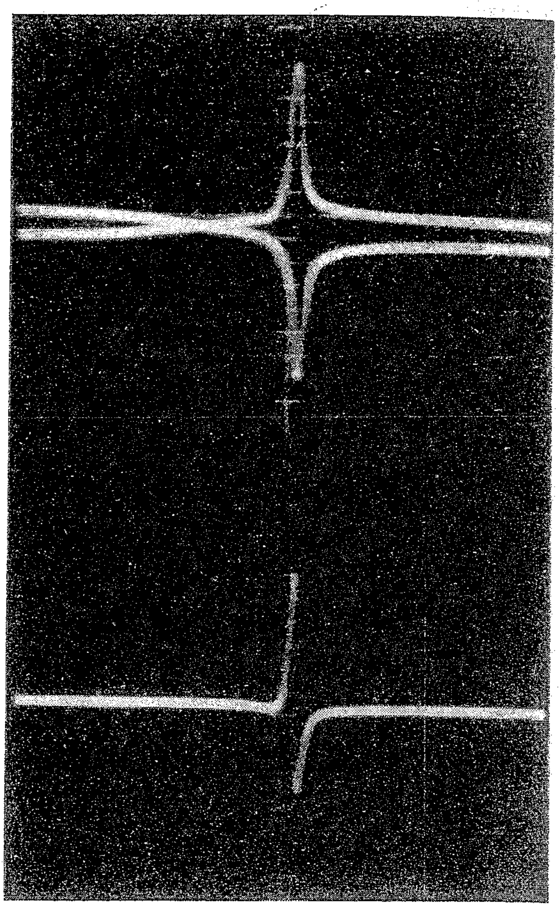

Fig. 2.

What we have said is valid in the case where the steady field is less than the alternating field-amplitude.

We thus conclude that this device may be a very sensitive detector of the function « algebraic sum » of the components along the wires of a magnetic field. If the alternating magnetic field had the same sense in the two wires at every instant the device would reveal variations of the function « algebraic difference » of the components.

As detector of the function « algebraic sum », it is employable in the determination of the m.m.s. in the gap of a magnet of sufficient size, particularly in the gap of a weak-focusing synchrotron. In fact the m.m.s. is defined as the locus of the points in which the radial component B_r of the field is zero.

In the case of a synchrotron, we may indicate the radial and vertical coordinates with origins at the centre of curvature of the circular sector of the synchrotron and on the m.m.s. respectively, by r and z. The latter represents the surface of symmetry for the field-lines; in this way one will have inside the gap:

$$B_r(r, z) = - B_r(r, -z) , \qquad B_r(r, 0) = 0 .$$

Now, if we put the wires parallel to each other, parallel to the vertical plane and to the radial direction, and displace them vertically so that this parallelism is maintained, the device will inform us when:

$$B_{1r}(r, z_1) + B_{2r}(r, z_2) = 0 ,$$

where z_1, z_2, B_{1r}, B_{2r} are coordinates of the centres of the two wires and the respective components.

Then also: $z_1 = -z_2$ and the altitude of the m.m.s. will be that of the midpoint between the centres of the two wires.

We propose to determine the position of the m.m.s. in the gap of a weak-focusing synchrotron (of radius $R = 360$ cm and with poles shaped for a field index $n = 0.6$) within ± 1 mm.

The characteristics of this synchrotron are about the same as those described in ref. (²), week-focusing solution.

2·2. – We want to show that the sensitivity of the method is broadly sufficient for this purpose and to explain the requirements which must be satisfied. Following the current symbolism in accelerator literature, we shall define, inside the gap: $n \simeq (R/B_z)\,\mathrm{d}B_z/\mathrm{d}R$, where R is the radius of the synchrotron and B_z is the z component of the field.

Since the azimuthal component of curl B is zero, and therefore:

$$\frac{\partial B_z}{\partial R} = \frac{\partial B_r}{\partial z}$$

we obtain immediately:

$$B_r = -\int_0^z \frac{n}{R} B_z\,\mathrm{d}z \cong -\frac{nB_z}{R}\cdot z\,,$$

B_r being the radial component of the field and the origin of the z-axis lying on the m.m.s.

Admitting a perfect mechanical precision in the alignment and movement of the device, to obtain a precision of Δz in the vertical localization of the m.m.s., a minimum detectable variation (of the algebraic sum of the field components) along the wires given by

$$\Delta B = \frac{2nB_z}{R}\Delta z = \frac{B_z}{3\,000}\Delta z\,,$$

is necessary, where Δz is the vertical displacement of the probe. For example, to obtain $\Delta z = 1$ mm, we may have $\Delta B = 0.03$ gauss if $B_r = 100$ gauss, etc.

Now we shall show that the device satisfies this requirement.

A convincing estimate may be made considering the concrete case of mu-metal wires, Φ 0.1 mm, length 4 cm, supplied with a 10^3 Hz alternating field of amplitude $B_a = 5$ gauss, surrounded for a length of 5 mm in their central

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(²) G. Salvini: *Suppl. Nuovo Cimento,* **2**, 442 (1955).

zone by a small coil of 400 turns of wire, Φ 0.05 mm. Under these conditions the pulse obtained is of the order of 0.10 V.

Taking $\tau = 10$ μs as « base time » for this pulse, one will have the difference pulse shifting from zero (or a minimum) to 0.10 V, when the algebraic sum of the components along the two wires becomes $\Delta B \simeq (\tau/2) B_a \omega \simeq 0.15$ gauss (note I), which corresponds to a sensitivity for the detector of the order of 1 V/gauss. It is obvious that by using amplifiers and adequate differential electronic voltmeters, threshold sensitivities of 10^{-4} or 10^{-5} gauss may be reached, values like those obtained by us experimentally.

Considering an ideal electronic chain, the limit appears to be of the order of 10^{-7} gauss (4) and it is given by the discontinuity in the changes of induction caused by the rotation of ferromagnetic domains. Therefore the sensitivity of our device may be higher than is strictly necessary for our purpose. In fact, an oscilloscope check of the form of the difference-pulse may be sufficient.

2'3. – The determination of the m.m.s. within ± 1 mm is hindered, however, by the fact that, in addition to the component B_r, the ferromagnetic wires are also submitted to a perpendicular field B_z, so that $B_r/B_z \simeq 1/3000$. This requires the following conditions to be satisfied:

a) The wires must be straight.
b) The wires must have a sufficiently large length diameter ratio.
c) The wires must form with the median geometrical plane (m.g.p.), (and with each other) an angle not greater than $2.5 \cdot 10^{-4}$ rad.

The condition indicated in *a*) is obvious. If the wire presents a finite radius of curvature in some zones, the component along the axis of the wire will not be homogeneous and in some points its value will be too high. The pulses to 1000 Hz will be « destroyed » to values lower of B_z.

For the condition indicated in *b*) we bear in mind that an infinitely long ferromagnetic wire of permeability μ, submitted to a perpendicular external field B_e, will have (3), internally, the induction:

$$B_i = \frac{2\mu}{\mu + \mu_0} B_e ,$$

for which the induction inside the wire is only twice that outside, even for an infinite permeability. A very long mumetal wire submitted to a field of $3 \div 4 \cdot 10^3$ gauss, normal to its axis, is already practically saturated transversally. Its permeability in the axial direction is practically zero.

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(3) E. Weber: *Electromagnetic Fields* (New York) p. 242.

(4) P. M. S. Blackett: *Phil. Trans. Roy. Soc. London*, A **245**, 309 (1952).

The pulses induced by axial excitation are practically «destroyed». Our experimental results relating to the mumetal wires, length 4 cm, Φ 0.1 mm, show that this destruction occurs at about 500 gauss, even with wires carefully prepared. Using wires of these dimensions the m.m.s. cannot be determined above 500 gauss.

For the requirement indicated in *b*) it may easily be seen that if the wires, supposed parallel to each other, form an angle θ with the median geometrical plane (m.g.p.), the error made in the localization of the m.m.s. is given by:

$$\Delta z = \frac{R}{n}\,\mathrm{tg}\,\theta\,.$$

Since in our case $R/n \simeq 6000$ mm it is therefore necessary, to obtain $\Delta z = \pm 1$ mm, that the alignment with the m.g.p. be maintained within an angle $\theta = \pm 2.5 \cdot 10^{-4}$ rad.

In the case of one wire aligned with the m.g.p. and the other forming an angle θ with it, the error Δz is about a half:

$$\Delta z = \frac{R}{n}\,\mathrm{tg}\,\frac{\theta}{2}\,,$$

for which $\Delta z = \pm 1$ mm for $\theta = \pm 5 \cdot 10^{-4}$ rad.

If it were possible to make the axis of symmetry of the wires parallel to the m.g.p., the error Δz would be zero for obvious reasons of simmetry, and a large angle of divergence between the projections of the wires on the (z, r) plane would be tolerable up to the point in which the components of the field become large with respect to the amplitude of the exciting field.

The angle formed by the wires with the vertical radial (z, r)-plane is not critical. The same can be said for the angle between the latter and the plane defined by the two wires (supposed coplanar).

3. – Experimental realization.

3·1. – We shall now explain the details of the experimental realization of the mechanical part of the device and of the method of calibration used.

It must first be noted that the pulses produced by the two wires will generally never be symmetrical about the time-axis and that therefore the resultant signal will never be zero. They have been given a suitable shape, to obtain, in the simplest case (sufficient for our purpose), a difference pulse in the form of two adjacent peaks of like amplitude. This is useful as a sure oscilloscopic reference, and was obtained by differentiating one of the pulses. Otherwise a series of difference pulses alternately positive and negative (see Fig. 4) can be obtained by the circuit of Fig. 3, which differentiates one pulse and fits the amplitude of the other. In this case, if the algebraic sum of the steady magnetic fields acting along the wires varies, the pulses in one part of the time-axis increase while the others decrease. It is known (⁵) that this arrangement permits high sensitivities to be reached by the use of an electronic device.

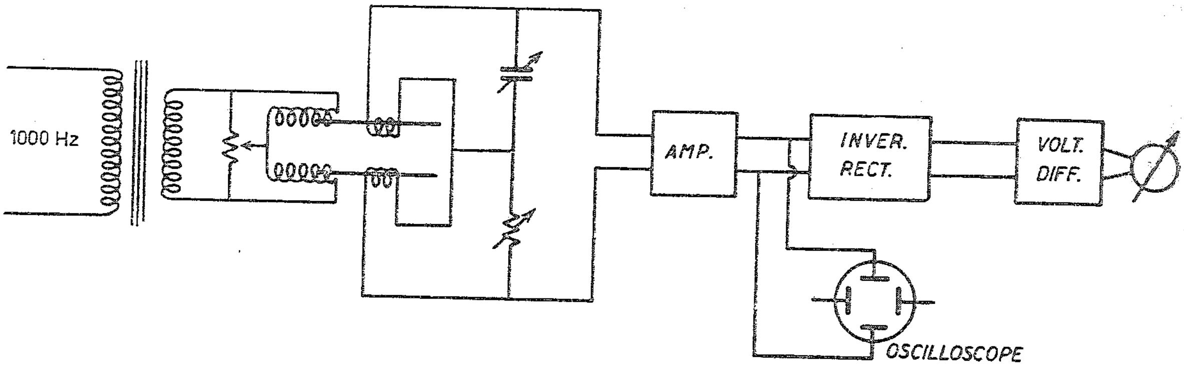

Fig. 3.

With both these methods, however, it is important to obtain experimentally an output reference signal (oscilloscopic or electronic) relative to a zero axial field. The device must therefore be calibrated. This reference will not alter if the two wires are submitted to equal opposite fields until these fields are small with respect to the amplitude of the exciting field.

3·2. – One of the types of differential probe made according to the circuit of Fig. 3 is shown in Fig. 5. The two exciting toroidal coils are wrapped on a small lucite tube of rectangular form. In the type shown in Fig. 6 the frame of the toroidal coils is a sterling tube of ellipsoidal form. They are made of a single enamelled copper coil ∅ 0.15 mm. In the longer side of each toroidal coil and on the same side are threaded the peaking strips, in the form of a small glass tube containing a mumetal wire ∅ 0.1 mm, length 4 cm, main-

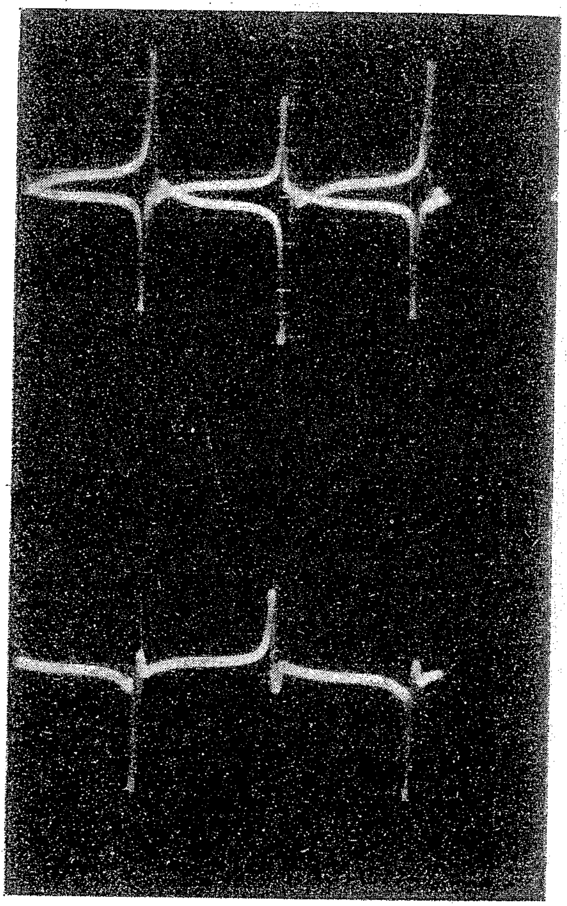

Fig. 4.

(⁵) R. O. Wjchoff: *Geophysics*, 13, 182 (1948).

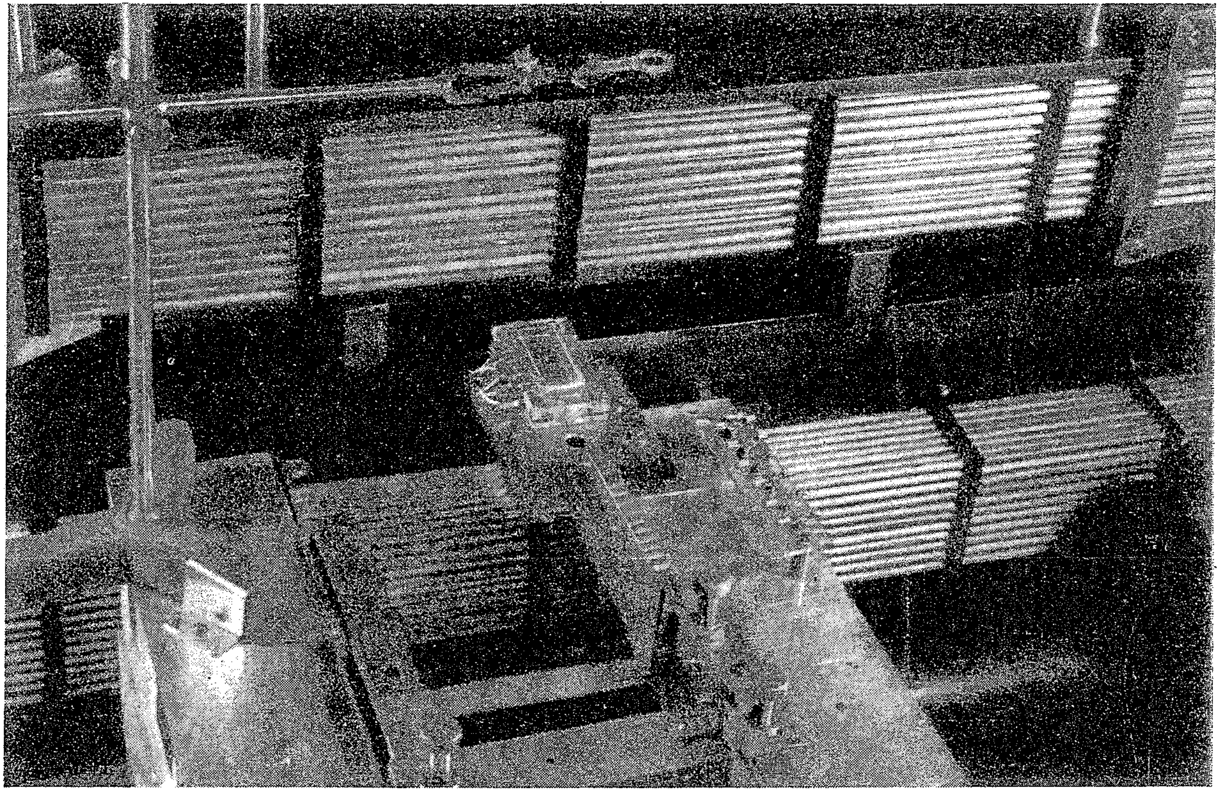

Fig. 5.

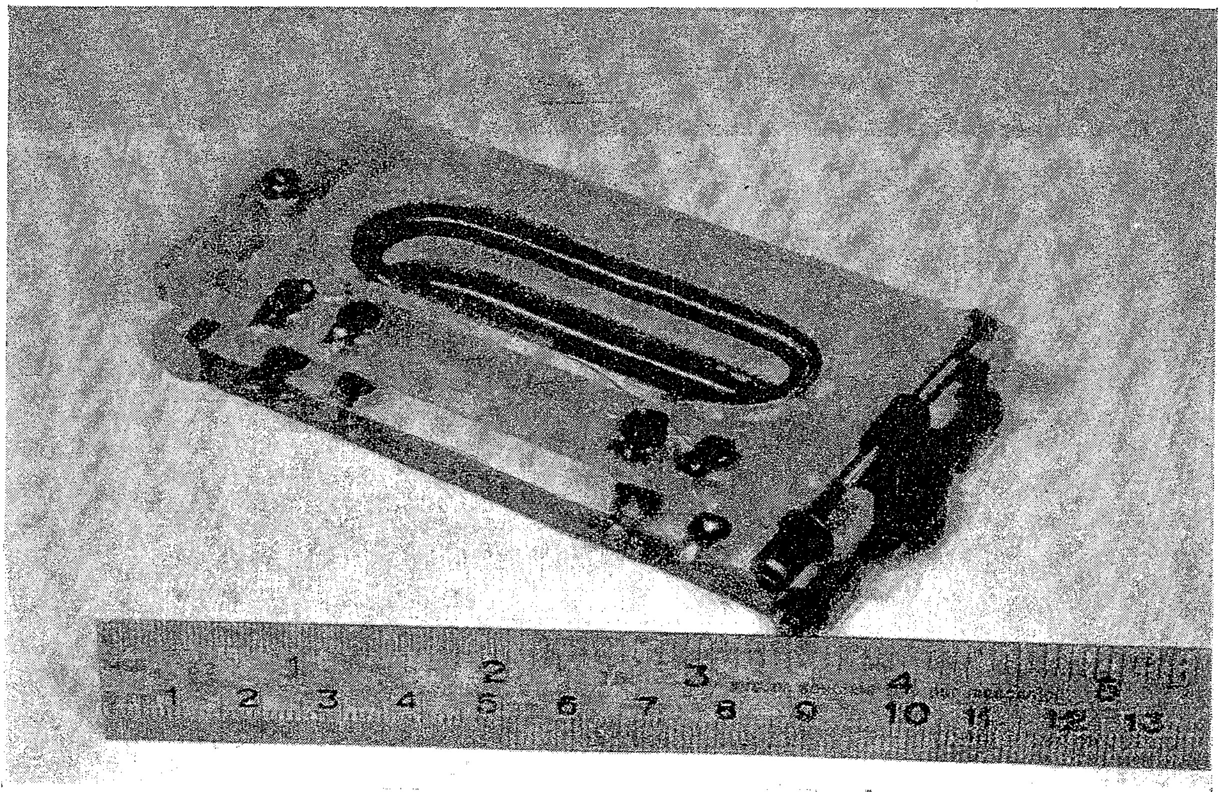

Fig. 6.

tained under tension with an araldite filling (see note II). In its central part it has a 400-turn coil length 5 mm, of wire ∅ 0.05 mm. Toroidal coils have been adopted both to obtain a greater uniformity of field with the same radial extension, and to minimize the dispersed flux, thus minimizing any eddy currents in the iron and inductive coupling between the coils. The two toroidal coils lie firmly stuck and clamped in two lucite planes, which have the two angular degrees of freedom necessary to make the wires parallel. They are series-connected and in opposition to the ends of the secondary circuit of the output transformer of a 1 Hz oscillator. The r.m.s. current that flows through them is normally 125 mA eff. corresponding to an amplitude B_a of the alternating field of about 10 gauss produced along the axis. The distance between the two wires, parallel and in a vertical plane, is 1.5 cm in the model shown in Fig. 6, and 1 cm in that shown in Fig. 5.

3'3. – We shall now explain the alignment and calibration method successfully experimented. The lucite frame is fixed on a brass plate supported by a brass bar (see Fig. 5), whose height and inclination may be regulated by three adjusting screws placed on the vertices of a right-angled triangle with a cathetus parallel to the peaking strips. The brass plate, supporting the probe, has three reference screws (see Fig. 5) electrically insulated from the plate itself, as a connection to the warning light, and placed on the vertices of a right-angled triangle with a cathetus parallel to the peaking strips. Procedure is as follows. The differential probe is introduced into the gap of a standard magnet, which guarantees a magnetic field perpendicular within $\pm 0.5'$ to the parallel surfaces of the poles, in such a way that the wires are coplanar in a plane nearly orthogonal to the above-mentioned surfaces. After demagnetization, the magnet is excited up to a field B of 100 or 200 gauss and only the pulses coming from the lower wire to the oscilloscope are observed. By inversion of the field, if the component B_l exists, it is reversed along the wire and so the pulses « shift » along the time-axis by an amount

$$\Delta\tau \cong \frac{2B_l}{B_a\omega} = \frac{B_l}{3\cdot 10^4}\,\mathrm{s} \qquad \text{for } B_l \ll B_a\,.$$

The angle of 1′ between the normal to the wire and the field B therefore produces a pulse shift:

$$\Delta\tau \cong \frac{2B_l}{B_a\omega} = \frac{2B\cdot 2.5\cdot 10^{-4}}{B_a\omega} \cong 2\ \mu\mathrm{s}\,,$$

for $B = 200$ gauss which may be observed.

It is therefore necessary to correct the inclination of the wire by the adjusting screws outside the magnet at the end of the bar (see Fig. 5), until the pulses remain unchanged after the inversion of the field. The same must be done with the upper wire, by manipulating the screws of the lucite hinge (see Fig. 6), on which the upper toroidal coil rotates. At the end of this lining up the wires will be perpendicular to the standard magnet field, certainly within 1′, and parallel to the surface of the poles within the same limit. Their projections on a plane normal to the polar surfaces will also be parallel within 1′, while there is no need to worry about the parallelism of their projections on the polar surfaces, since this need only be respected the within 1°.

At this point the output of two peakers placed in series and in the same direction is observed, and the capacities and resistances for obtaining the required electronic or oscilloscopic reference are arranged. Finally the reference screws are advanced until the lighting of three warning lights advise us that contact with the surface of the lower pole has taken place. At this point it may be said that the mumetal wires are also parallel to the plane defined by the extremities of the three reference screws. Now the probe is ready to be introduced into the synchrotron gap, in order to determine the m.m.s. If we consider the case in which the m.g.p. is not horizontal, the three screws must be pushed on in simultaneous contact with the lower pole; the probe will be rotated by $\frac{1}{2}\alpha$ (where α is the angle between the surfaces of the two poles) in such a direction that the wires are placed parallel to the m.g.p. (within $\pm 1'$). Then the probe is raised parallel to itself until the same oscilloscopic or electronic reference that there was in the magnet with the strips normal to the field, becomes visible at the output. In this position the components B_r will be equal and opposite on the two wires and the position of the midpoint between the two pick-up coils will coincide with the position of a point on the m.m.s.

The measurement was actually carried out in a magnet with $\frac{1}{2}\alpha = 14'$. An optical system allowed both the angle to be read and the raising of the probe to be controlled.

Of course, if the p.g.m. can be assumed horizontal, it becomes superfluous to measure the angle $\frac{1}{2}\alpha$. The optical control also becomes superfluous if an accurate enough mechanical raising device is available.

The electronic device (Fig. 3) consists in an amplifier with gain ×800, whose output is connected to an inverter rectifier and to a differential voltmeter whose sensitivity in output current is 0.5 mA/V for difference in tension applied to the two input grids. With a full-scale milliameter of 1 mA the sensitivity obtained was $4\cdot10^{-4}$ gauss per division.

4. – Measurements and conclusions.

The measurements carried out with this first mechanical realisation have confirmed the expectations, allowing the expected measurement of the m.m.s.

The error in the relative distances between the various points of the m.m.s. is not usually greater than ± 0.25 mm, while their absolute distances from the m.g.p. require a careful calibration since they are determined to ± 1 mm. As an example we report a result obtained concerning the behaviour of the m.m.s. in the gap of a cast iron magnet (Fig. 5); the gap is 4 cm high and 12 cm deep. With a field of 230 gauss the three series of measurements were carried out in the following way: the first under normal conditions, the second threading a thin strip 0.35 mm thick in the 1 mm gap present between the upper surface of the upper pole and the surface of the C-shaped magnet, the third unscrewing completely the bolts which press the upper pole against the supporting columns. The presence of the thin 0.35 mm strip produces a rise of 3 mm of the m.m.s. in the centre of the gap. Unscrewing the bolts lowers the m.m.s. by 1 mm.

With this device the curvature of the lines can also be determined point by point and the field-index n can also be measured, bearing in mind the relation:

$$n = \frac{R}{z}\,\mathrm{tg}\,\theta$$

and by a relative error:

$$\frac{\Delta n}{n} \cong \frac{\Delta z}{z} + \frac{\Delta\theta}{\theta},$$

which may be estimated at 5%.

This error is essentially due to the measurement of the angle θ, which is measurable to within 3÷4% with an optical device.

Of course, this measurement would also be limited to fields lower than 500 gauss, i.e. to the value for which transverse saturation of the wires used by us takes place.

* * *

The author wishes to thank Professor GIORGIO SALVINI, Director of the « Sezione Acceleratore », for the stimulating criticism shown in many discussions on this subject, and Professor ITALO F. QUERCIA for projecting the electronic part of the device and for discussing in detail the basic ideas of this work.

The author also wishes to thank all his colleagues and particularly Dr. GIORGIO GHIGO and Dr. FRANCO CORAZZA for valuable discussions.

The mechanical construction of the probes was carried out by Mr. V. BETTINI and Mr. P. BELLAGOTTI.

Note I

Let us suppose that the ferromagnetic wire has dimensions such as to allow the formation neither of induced currents nor of demagnetising field. Neglecting hysteresis, we approximate the magnetization cycle of the ferromagnetic material used by the function:

$$B = \frac{2}{\pi} B_s \operatorname{arc\,tg} \frac{H'(t)}{H_0} ,$$

where B_s is the saturation induction, H_0 is the value for which $B = \frac{1}{2}B_s$ when $H' = H_0$; $H'(t)$ is the instantaneous total field acting along the wire. We have

$$H'(t) = H_a \sin \omega t + H ,$$

where H is the steady field. Thus H_0 and B_s determine the shape of the magnetization cycle. The induced e.m.f. picked up on a peaker will thus be given by:

$$V_i = -A \frac{\mathrm{d}B}{\mathrm{d}t} = -\frac{2AB_sH_a\omega}{H_0} \cdot \frac{\cos \omega t}{\left[1 + \frac{(H'(t))^2}{H_0^2}\right]} ,$$

where A = area-spire of peaker, ω and H_a are the pulsation and amplitude of the excitation field.

For $H = 0$ the maximum amplitude, which occurs with alternate signs, for $\omega t = n\pi$ ($n = 0.\ 1.\ 2, \ldots$), takes the value:

$$V_{i\,\max} = \pm \frac{2AB_sH_a\omega}{H_0} .$$

Assuming, in our case, $A = 3.2 \cdot 10^{-2}\ \mathrm{cm}^2$, $B_s = 5 \cdot 10^{-3}$ gauss, $\omega = 6.3 \cdot 10^3\ \mathrm{s}^{-1}$, $H_0 = 0.1$ gauss, one obtains $V_{i\,\max} \simeq 0{,}3$ V, an order of magnitude in agreement with experimental results relating to very long mumetal wires. The peak value just estimated, which exists at time $t = 0$ when $H = 0$, will exist at a time t^* when $H \neq 0$. The function $t^*(H)$ is obviously obtainable from $\dot{V}_i = 0$. If we neglect the term in $\sin^3 \omega t$ in the latter equation, and consider the pulse in the region of $t = 0$, we get for the function $t^*(H)$:

$$t^* = -\frac{1}{\omega} \operatorname{arc\,sin} 2 \frac{H/H_a}{2 + (H_0/H_a)^2 + (H/H_a)^2} .$$

For $H_0^2 + H^2 \ll 2H_a^2$ this reduces to

$$t^* \cong \frac{H}{H_a\omega} .$$

NOTE II

Here we shall give some details of our technique for the preparation of peaking strips.

Our aim was to obtain perfectly straight mumetal wires (available for us with Φ 0.1 mm) 4 cm long. To obtain this by means of a permanent applied tension, the wire must be prevented from magnetically destructive torsion. The reversing of the magnetization of our wire takes place by a rotation of the domains mainly with a displacement of 180° of the walls and the consequent enucleation of adjacent domains with opposite magnetization (6). If the wire is subjected to a torsion, the helical lines along which it acts constitute directions of easy magnetization, so that the final orientation forming the smallest angle with these lines will be preferred. The resultant macroscopic effect will thus be an inclination of the magnetization with respect to the axis of the wire, a variation of the permeability of and the pulses picked up with an axial coil.

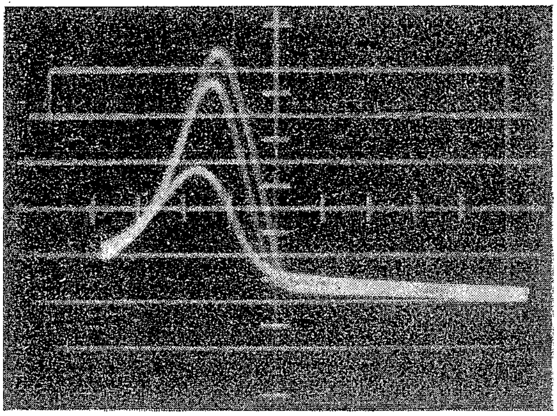

Fig. 7.

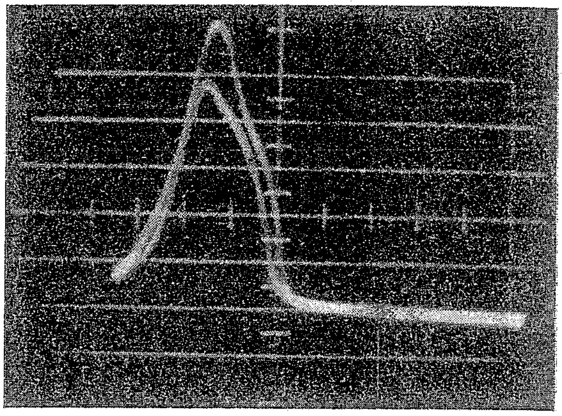

Fig. 8.

The following device was therefore used. The mumetal wire held taut by a suitable weight and passing through a small glass tube covered by the 400 turns and through a larger exciting coil of 1000 Hz, can be controlled by the pulses it generates, which are observable on the oscilloscope. The tension and torsion of the wire are regulated freely until the pulses are satisfactory. Then we alide the exciting coil so as to uncover the small glass tube and fill it with a colt type *D* liquid araldit (CIBA) which enters by capillarity up to the opposite end. Once the araldit is well set, the wire at each end is cut, and the peaking strip is ready for use and to support a field of $5\cdot10^2$ gauss normal to the wire.

The results have been satisfactory. Fig. 7 shows the variations in the form of a pulse when the wire is subjected to a torsion of several rotations (lowest pulse) and when this torsion is removed (mean pulse). The highest pulse is obtained when the tension (8 kg/mm^2) is removed as well.

Fig. 8 shows the case where the pulse amplitude increases with application of tension. The time scale is 0.05 gauss/cm and the ordinate scale is 0.03 V/cm.

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(6) *Journn. Appl. Phys.*, **26**, 8 (1955).

RIASSUNTO

Viene descritta una sonda differenziale magnetica realizzata con lo scopo di determinare la superficie magnetica mediana del campo statico nell'intraferro di un sincrotrone a focalizzazione debole. La sonda è costituita da due sottili fili ferromagnetici sottoposti a campi magnetici alternati a 1000 Hz uguali e opposti in ogni istante. Il metodo di misura consiste nel determinare la posizione della sonda per cui le componenti del campo magnetico lungo i due fili (paralleli al raggio del sincrotrone e giacenti in un piano verticale), sono uguali e opposte. Il dispositivo descritto permette la localizzazione della superficie magnetica mediana entro ± 1 mm in campi statici tra 20 e 500 gauss. Si accenna pure alla possibilità di misurare l'indice di campo n mediante questa stessa sonda con la precisione del 5 % in campi non maggiori di 500 gauss. Infine viene esposta con qualche dettaglio la tecnica usata per la preparazione dei fili ferromagnetici.