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SURFACE PROXIMITY DETECTOR
for geometrical tests on the LEP dipoles

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REFERENCES
1. **INTRODUCTION**

The present report describes a system of inductive probes which has been developed in order to check the pole geometry of the LEP dipole cores (fig. 1).

The 5.7 m long cores of the dipole magnets proposed for the LEP (Large Electron-Positron storage ring) project are of a special type\(^1\). They are composed of a stack of low carbon steel laminations of 1.5 mm thickness separated by 4 mm gaps which are filled with a cement mortar. Six longitudinal rods are used to exert a precompression of 5 kg cm\(^{-2}\) on the core which behaves like a prestressed concrete beam.

The geometry of the poles must be very precise: the tolerance values for rectilinearity and twist are \(\pm 0.5\) mm and \(\pm 0.5\) mm m\(^{-1}\) respectively and the fluctuations in gap height along a magnet must be less than \(\pm 0.08\) mm. The spacing of the laminations (5.5 mm pitch) measured on the surface of the poles must be regular to within \(\pm 0.2\) mm in order not to introduce perturbations in the magnetic field. The control of these tolerances is difficult since measurements must be performed on the laminations themselves which are only 1.5 mm thick and are generally covered by a layer of cement which can be up to 0.5 mm thick.

Two types of probes have been realized. The main probe which will be used to measure the geometry of the poles covers nine laminations and is sensitive in the y-direction only (fig. 4). The distance y between the pole and the laminations is measured with a precision of \(\pm 0.01\) mm for values of y comprised between 0.5 and 2 mm and in a temperature range of 15\(^\circ\) to 35\(^\circ\)C. The thin probe is 1.5 mm thick and sensitive to one lamination at a time. It is intended to investigate irregularities in the spacing of the laminations. The main probe will work at an average distance of one millimeter while the thin probe will work as close as possible to the surface.

The instrument, with the main probe connected, is shown in fig. 2.

2. **PRINCIPLE OF OPERATION**

The principle of operation is shown in fig. 3.

The probe is a coil wound on a U-shaped ferromagnetic core. The coil is fed with a current of 220 mA effective at 80 Hz which is delivered by an oscillator followed by a power amplifier. The inductive part of the coil voltage which is roughly inversely proportional to the air gap is measured and used to calculate the air gap (Section 3). In order to detect only
this inductive part, a lock-in amplifier is used whose reference signal is shifted by 90° from the current in the probe. A second order low-pass filter rejects the alternating part of the output voltage and is connected to an analog-to-digital convertor. The ADC is controlled by a microprocessor system based on the Signetics 2650. It provides the conversion of the ADC output signal to the actual distance and the display of the value.

3. DESIGN OF THE PROBES

3.1 The main probe

3.1.1 The general shape

Calculations with the POISSON program (see § 3.1.4) applied on a U-shaped probe showed that the deviations from the idealised relationship (eq.(4), see below) arise mainly from near the pole surfaces. The calculations also showed that by a proper choice of the shape and of the placing of the coil it is possible to come close to the characteristics for the ideal probe. This means that is does not seem likely that a shape other than the U-shape (e.g. a semicircle) would improve the result very much. Measurements that were made with probes having different shapes, namely E-shape, U-shape and semicircle shape confirmed this. The following discussion is therefore limited to the U-shaped probe which is also the easiest to realize.

3.1.2 Idealised equation

Ampère's law (fig. 4,a) gives:

$$\int_{L_1} \tilde{H}_1 \, d\tilde{x} + \int_{L_2} \tilde{H}_2 \, d\tilde{x} + \frac{B_a}{\mu_0} \, 2 \, y = N \, I,$$

where \( N \) is the total number of turns in the winding, \( I \) the current and \( B_a \) the magnetic field in the gap. If it is assumed that \( H_1 \) is constant along \( L_1 \), \( H_2 \) constant along \( L_2 \) and that \( B_1 = B_a \) and \( B_2 = B_a/f \), where \( f = 1.5/5.5 \) is the filling factor reflecting the concentration of the flux lines in the steel of the magnet cores, we obtain:

$$B_a = \frac{\mu_0 \, N \, I}{\frac{L_1}{\mu_{rI}} + \frac{L_2}{\mu_{rII}} + 2 \, y},$$

where \( \mu_{rI}, \mu_{rII} \) are the relative permeabilities for regions I and II.
If we assume \( B_A \) to be constant and limited to the pole area and also that we have the same flux through each turn we arrive at the following expression for the self-inductance, \( L \):

\[
L = \frac{\mu_0 N^2 S}{\frac{L_1}{\mu_{rI}} + \frac{L_2}{\mu_{rII}} + \frac{2y}{\mu_{rII}}}.
\]  

(3)

where \( S \) is the area of the pole face. Normally \( \mu_{rI} \) and \( \mu_{rII} \) are so big that

\[
\frac{L_1}{\mu_{rI}} + \frac{L_2}{\mu_{rII}}
\]

can be neglected, so giving the ideal expression for \( L \) versus \( y \):

\[
L = \frac{\mu_0 N^2 S}{2y}.
\]  

(4)

3.1.3 Equation for the real probe

The relation between \( L \) and \( y \) in the real case may be expressed as:

\[
L = \frac{a}{(y+b) + c(y+b)^2} \ldots,
\]  

(5)

where \( a, b, c, \ldots \) are constants. The deviation from the ideal expression (4) originates from the leakage flux (flux that passes outside the pole faces), the finite permeabilities, the fringe field and from the distortion of the field lines caused by the laminated structure (Fig. 4.b). The last effect gives an average elongation of the field lines in the air gap which was found to be almost constant in the interval (§ 3.1.6). It is described by the term \( b \) in the expansion. This term also gets a contribution from the error in the zero setting which springs from the irregularities in the surface of the probe.

For the conversion of the inductive voltage, \( V_L \), to the actual distance, \( y \), the following expression, deduced from (5), is used:

\[
y = \alpha + \frac{B}{V_L} + \frac{\gamma}{V_L^2} + \frac{K}{V_L^3}.
\]  

(6)
The probe quality can be defined by:

$$\eta = \left| \frac{dL/L}{dy/y} \right|$$  \hspace{1cm} (7)

where it is desirable to have $\eta$ as close as possible to one (ideal case).

By optimising the probe in order to get $\eta$ as close as possible to the ideal case, it seems obvious that the leakage flux and the influence of the fringe field should be reduced as much as possible. Calculations with the POISSON program confirm this.

3.1.4 Optimisation of the shape

The optimisation of the shape of the probe was made by using the POISSON program which have been developed at Lawrence Berkeley Lab 2). The program calculates among other things the magnetic field and the stored energy, $W_e$, for a two-dimensional problem. Examples of the field distribution for different geometries are shown in fig. 5.

The program was used to determine $\eta$ for different geometries, currents and probe materials. The following approximation for $\eta$ was used:

$$\eta = 10 \left( \frac{L_{0.9} - L_{1.1}}{L_{1.1} + L_{0.9}} \right)$$  \hspace{1cm} (8)

where $L_i$ is the inductance at $y = i$ mm. $L$ was obtained from the stored energy, $W_e$, using the relation between $L$ and $W_e$, where $W_e = 0.5 L I^2$, (which is strictly valid if $L$ is independent of the current).

In the calculations the probe was generally taken to be made of silicon steel except in one case where it was made of ISR steel in order to get a comparison of $\eta$ for materials with different permeabilities. There were 30 ampere turns per pole, except in one case where there were 5. The magnet steel was in all cases ISR steel with a filling factor $f = 1$ as the program has been found not to work well with other choices of $f$. It is assumed that the qualitative conclusions below are also valid for filling factors different from one.

From the computer runs the following conclusions were drawn:

a) The positioning of the coils was crucial in reducing the leakage flux and hence in increasing $\eta$. This flux is lowest when the coils are placed as close as possible to the gap.

b) The width of the pole faces, $b$ (fig. 4), was shown to have a major effect on $\eta$ at the dimensions we consider; when $b$ was decreased from 5 to 3 mm $\eta$ decreased by 10%. This is due to the increased influence of the fringe field when $b$ is small.
c) The magnetic length, \( L_1 \), of the probe was shown to have only a minor influence on \( \eta \); when \( L_1 \) was decreased by 65\%, \( \eta \) increased by 1\%. When the ampere turns per pole were decreased from 30 to 5, \( \eta \) decreased by 3.6\%. When the probe material was ISR steel (which has lower permeability than silicon steel) \( \eta \) decreased by 0.5\%. The small influence of these latter changes is due to the minor influence of

\[
\frac{L_1}{\nu_{r1}} + \frac{L_2}{f \nu_{r11}}
\]

compared to the gap length in eq. 3.

3.1.5 The design of the actual probe

a) Choice of probe material.

The probe is made of 0.5 mm thick laminations of a silicon steel, especially made for transformer applications at 50 Hz, which was chosen because of its high permeability for relatively low fields (0.02 - 0.04 T) and for its low losses.

b) Choice of frequency

Measurements on a silicon steel test probe at the following frequencies: 80, 300, 100 and 2000 Hz showed that \( \eta \) was falling with frequency. However, the difference between 80 Hz and 300 Hz was very small. The chosen frequency shall not coincide with a harmonic of the frequency of the mains. The above led to a choice of 80 Hz.

c) Mechanical shape.

The measurements are intended to be made partly along the shims on the poles of the magnet. The width of the most narrow shim is 20 mm. To avoid additional fringe effects, the width of the probe (A in fig. 4) is chosen to be 15 mm. To assure the main part of the non-leakage flux to pass through the magnet, the conditions \( a > 2 y \) was set as a requirement. At the same time, \( b \) is desired to be as big as possible according to § 3.1.4. These two conditions lead to a choice of \( a = b = 5 \) mm.

Owing to the laminated structure of the magnet, the field shape at the ends of the probe will be dependent on the location of the probe. This causes a variation of \( L \) when the probe is moved along the magnet at a fixed value of \( y \). This variation becomes smaller the longer the probe is. Measurements on a test probe showed that a length of about 50 mm is sufficient to give the required precision. This length provides a longitudinal resolution which is higher than necessary for the control of the geometry of the dipoles.
d) \textbf{Number of turns, } N

The stability of the phase-shift of the reference signal of the lock-in amplifier puts certain conditions upon \( Q \), where \( Q = \omega \ L/R \) (\( R \) is the resistance of the probe). A variation \( \Delta \theta \) of the phase introduces a variation of the output voltage of the lock-in amplifier of

\[
\xi = \frac{R \sin \Delta \theta}{\omega \ L} \approx \frac{\Delta \theta}{Q}.
\]

(9)

\( \xi \) has to be smaller than the variation \( \xi_0 \) corresponding to a variation of \( y \) of 0.01 mm in the air gap. According to measurements made with a test probe the minimum value of \( \xi_0 \), which occurred at \( y = 2 \) mm, is 0.0018. The phase uncertainty \( \Delta \theta \) as measured in § 4.3 is 0.5 mrad which gives the condition

\[
Q \geq 0.28.
\]

(10)

Resistance \( R \) is the sum of two terms namely the resistance of the wire of cross-section \( A_w \) and resistivity \( \rho \):

\[
R_c = 2(b+1)N \rho/A_w
\]

(11)

and the resistance arising from the losses in the steel:

\[
R_1 = W_e m/I^2,
\]

(12)

where \( W_e \) is the loss per kg and \( m \) the mass of the steel. For the designed probe, \( R_1 \) is about 3 m\( \Omega \) due to losses in the silicon steel of the probe, while \( R_c \) is 15 \( \Omega \). Hence \( R_1 \) can be neglected even if the contribution of the magnet steel is appreciably higher than that of the silicon steel.

By inserting eq. (11) and \( L=1.36 \times 10^{-7} N^2 \) obtained from the test probe at \( y=2 \) mm in expression (10), we obtain:

\[
NA_w \geq 7.5 \times 10^{-6}.
\]

(13)

This has been fulfilled using a coil of 250 turns wound with a copper wire of 0.2 mm diameter (0.22 mm with insulation). With these dimensions the minimum depth \( e \) of the coil window (fig. 4) is 4 mm if one assumes a packing factor of 1.1 in the coil and a ground insulation of 0.5 mm around the coil. However, to leave a possibility to increase the number of turns, \( e \) was chosen to be 6 mm for the first probe. The final characteristics of the main probe are:

\[
1 = 50 \text{ mm}, \ a = b = 5 \text{ mm}, \ e = 6 \text{ mm}, \ c = 11 \text{ mm}, \ N = 250
\]

(conductor diameter of 0.2 mm).
3.1.6 Calibration

The calibration curve showing $V_L$ versus $y$ is shown in fig. 6. $V_L$ is the voltage at the input of the ADC. To simulate the magnet surface, a stack of 1.5 mm thick steel laminations, spaced at a 5.5 mm pitch, was used. The surface of the stack was $15 \times 20 \text{ cm}^2$ (the calibration curves for the shims will probably be slightly different). In the calibration the probe was mounted on a precision table which gave a precision better than 0.005 mm. As was mentioned in § 3.1.3, the origin of the curve has an uncertainty of about 0.1 mm.

Curves were also taken up for 4.5 mm and 6.5 mm pitches and by using a 10 mm thick steel plate (fig. 6). The curve for the nominal pitch of 5.5 mm is shifted by $b = 0.40 \pm 0.01$ mm with respect to the one for the steel plate. This value represents the increase of the air gap due to the laminated structure. It is in good agreement with the increase of effective gap measured on the first LEP dipole prototype (0.8 ± 0.2 mm) which is equal to $2b^3$. For a 6.5 mm pitch, the shift varies from 0.55 to 0.61 mm depending on $y$. A measurement made on a short LEP dipole with the same pitch showed an effective increase of the gap of 0.57 ± 0.03 mm.

From these figures it is concluded that the probe measures the effective gap of the cores with a precision of 0.01 mm if the variations of the pitch are limited to ±0.2 mm as specified in the tolerances of the core.

3.2 The thin probe

The purpose of this probe is to measure the distance between the laminations. This will be done by registering the location of the maxima while the probe moves along the magnet. The simple mode of operation makes it less sensitive to imperfections in the electronics, e.g. temperature drift, and therefore it is easy to realize. To have a strong dependence of $V_L$ on $z$ the probe has a length of only 1.5 mm. The other dimensions are the same as for the main probe. Examples of thin probe measurements are shown in fig. 7.

4. CIRCUIT DESCRIPTION

The circuit (figs. 8-10) is a combination of parts that have already been used in different applications in the ISR-BM group. Some modifications have been made to improve the temperature stability.
4.1 The oscillator

The oscillator, which is of the quadrature type, shows a high stability in both frequency and output voltage. The two time constants $R_1C_1$ and $R_4C_2$ are equal and the frequency is given by:

$$\frac{\omega_0}{2\pi} = \frac{1}{2\pi R_1C_1} = \frac{1}{2\pi R_4C_2}.$$  

When the condition of oscillation

$$\frac{R_2^2}{R_2R_3} > 1$$

is fulfilled, the amplitude of the signal stabilizes to a level defined by the two reference diodes $D_1$ and $D_2$.

The stability of the frequency $f$ and output voltage $V$ with temperature was measured. The variation between $15^\circ$ and $35^\circ$C is given below:

$$\Delta f/f = 1.7 \times 10^{-3},$$
$$\Delta V/V = -3.5 \times 10^{-3}.$$  

4.2 The power amplifier

The power amplifier consists of an operational amplifier followed by a power stage. The output current is related to the input voltage by:

$$I = \frac{R_{10}}{R_{9}R_{23}} \frac{V}{V_{23}} = 220 \text{ mA}.$$  

The precision resistance $R_{23}$ ensures a high stability in output current.

4.3 The lock-in amplifier

The input stage of the signal chain is a differential amplifier with a gain $g = 2.0$. To obtain a full-wave rectification the semiconductor switch (IC9) is fed with two inverted signals. The harmonics of the 80 Hz signal are damped by a second order low-pass filter with a cut-off frequency $f_0 = 1$ Hz.

The reference chain consists of a phase shifter followed by a square wave generator whose output signal directs the switch. The phase shifter is made using operational amplifiers which gives a high stability with temperature. If the output signals from IC12 and IC13 are equal in magnitude but of opposite sign, we get the following phase shift at the output of IC14:

$$\theta = \pi - 2 \tan^{-1} (\omega RC),$$

where $C = C_5$ and $R = R_{41} + P_2$. The variation in phase for a change in temperature of $15^\circ$ to $35^\circ$C, is $\Delta \theta = -0.5$ mrad.
Let $V_{ADC}$ denote the output voltage from IC10:

$$V_{ADC} = V_L \sin \theta + \frac{V_L}{Q} \cos \theta.$$  

The inductive voltage $V_L = G \omega L I$, where $G$ is the total gain. If we consider small changes with temperature we have ($\theta \approx \pi/2$):

$$\frac{\Delta V_{ADC}}{V_{ADC}} = \frac{\Delta V_L}{V_L} - \frac{\Delta \theta}{Q}.$$  

The temperature variation for $V_L$ is $\Delta V_L/V_L = -1 \times 10^{-3}$. This means that the given requirements of precision ($\Delta V_{ADC}/V_{ADC} \leq 0.0018$ corresponding to a gap variation of 0.01 mm) will be fulfilled provided a proper value of $Q$ is chosen ($\S$ 3.1.5).

4.4 The digital circuit

The output from the lock-in amplifier is fed into a 12-bit analog-to-digital converter AD572 (fig. 9). It is triggered either continuously by pulses coming from the microprocessor or manually from the front panel.

The microprocessor system (fig. 10) is a general purpose system, based on the Signetics 2650. In our application, the following external lines are used:

- DATA lines,
- Sense line connected to the status line of the ADC to check for a conversion finished signal,
- REDE 1X to read the ADC MSB and front pane switch buffer,
- REDE 2X to read the ADC-LSB buffer,
- REDE 3X to reset the trigger flipflop,
- REDE 4X as trigger pulse in the continuous trigger mode,
- WRITE 1X to write mm into the display,
- WRITE 2X to write 1/10 of mm into the display,
- WRITE 3X to write 1/100 of mm into the display,
- WRITE 5X to write into trigger mode buffer.

Due to the difficulty to foresee the future operational needs, the present program only performs the calculation and the display of the distance (fig. 11). By changing the program it would, for example, be possible to carry out remotely all the operations, e.g. triggering of a measurement.
5. CONCLUSION

This work has led to the development of a high precision measuring system intended to be used to record the geometry of the gap of the LEP steel-concrete cores. The main probes are sensitive to the effective gap which is slightly different from the mechanical gap and which completely determines the field pattern of the magnet. Thus, by using these probes in the measurements of the magnet series it is hoped that the magnetic field measurements could be reduced to a minimum.

The thin probe has already been used successfully to detect irregularities in the spacing of the laminations of the first LEP magnet prototype.

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REFERENCES


Fig. 1 Steel-concrete magnet core
Fig. 2 The distance meter

Fig. 3 Block diagram of the distance meter
Fig. 4 The U-shaped probe (I). Region II is the magnet region which consists of 1.5 mm thick steel laminations separated by concrete layers of 4 mm thickness.
Fig. 5 Flux lines for different shapes of coils. The coil surface and the number of ampère turns are the same for all shapes.
Fig. 6 Inductive voltage versus distance for pitches of 6.5 mm, 5.5 mm (calibration curve), 4.5 mm and for a 10 mm thick steel plate.
Fig. 8 Surface proximity detector
Fig. 11 Flow chart main program