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GEOMETRY AND REMANENT FIELD SERIES MEASUREMENT OF THE LEP DIPOLE MAGNETS

by

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Résumé - Les performances magnétiques des 3304 dipôles du LEP sont déduites des mesures géométriques précises de l'entrefer et du champ rémanent de chaque noyau d'aimant. Pour éviter banc de mesure et alignement, deux chariots roulant directement sur le pôle inférieur sont utilisés. Le premier, équipé de cinq sondes de proximité, d'un niveau électronique et d'une cellule photoélectrique couplée à un faisceau laser, mesure l'entrefer. Le second chariot permet de magnétiser le bloc dont le champ rémanent est ensuite mesuré par une bobine tournante longue. L'ensemble de la mesure est contrôlé par un micro-ordinateur.

Abstract - The magnetic performance of the 3304 dipole magnets for LEP are deduced from systematic air-gap geometry and remanent field measurements. To avoid having to use a measuring bench and to minimize alignment problems, two carriages rolling directly on the lower pole face are used. The first one, equipped with five proximity detectors, one electronic inclinometer and one photoelectric cell coupled with a laser beam, measures the air-gap geometry. The second one magnetizes the yoke, to enable the measurement of the remanent field by means of a long flip coil. The measurement is fully computer-controlled.

I - INTRODUCTION

The large electron positron collider (LEP) under construction at CERN requires a large number (3304) of low field dipole magnets with steel-concrete cores [1]. For this production at the rate of six cores per day, complete magnetic measurements will be performed only on a statistical basis (using every tenth magnet core) and the magnetic properties of each core will be determined from systematic measurements of its air-gap geometry and remanent field. This is possible because the steel yoke is far from saturation (3 % ampère-turn drop in the yoke at maximum [2]). It is also more economical for the following reasons:

- there is no need for mounting the excitation bars which are foreseen to be installed on pairs of cores prior to the installation in the tunnel;
- these measurements can be combined with the straightness measurements which are needed for the vertical and horizontal alignment of the cores;
- there is no need for a series of measuring benches.

The required tolerances of the magnetic field are [3]:

- random dispersion of the bending strength : $5 \cdot 10^{-4}$ r.m.s.
- random variation of the flux density in the useful gap aperture : $2 \cdot 10^{-4}$ r.m.s.
- random tilt of the median plane : 0.2 mrad r.m.s.

II - AIR-GAP GEOMETRY MEASUREMENT

1 - Principle

The adopted solution is to introduce a carriage inside the air gap, Fig. 1. It is equipped with all the necessary detectors as shown in Fig. 2. Five proximity detectors measure the position of the carriage inside the air gap and thus the height

Fig. 1 - Schematic view of the air-gap geometry measurement system

of the horizontal and vertical straightnesses of the magnet air gap. These measurements determine the average axis of the air gap and, relying upon the high punching precision of the core laminations, give directly the corrections to apply for the

of the air gap in two points, one four-quadrant differential photocell measures the position of the carriage with respect to a laser beam and an electronic inclinometer measures the tilt of the carriage. This tilt is compared to the tilt of the core measured by a second electronic inclinometer placed on the alignment jig.

As the carriage rolls directly on the lower pole face (which, due to the presence of paint, is not a plane surface), a fluctuation of the position of the carriage in the air gap is possible (within ± 1 mm). This defines the measuring range of the proximity detectors.

The beam emitted by a laser tube placed at one end of the core and pointing a fixed photocell at the other end, defines a fixed straight line positioned within ± 1 mm from each end, enabling the measurement

Fig. 2 - Introduction of the measurement carriage in the air gap of the core

alignment in the LEP tunnel. The required measurement range of ± 5 mm for the photocell mounted on the carriage is given by the sum of possible errors in laser beam position (± 1 mm max.), on carriage position in the air gap (± 1 mm max.), and the straightness of the core (± 3 mm max.). To get a good linearity (± 0.05 mm) within that range, a 50 mm diameter photocell was selected.

The electronic inclinometers have a large measuring range: ± 20 mrad so that leveling of the magnet is not required. Their accuracy is within ± 0.04 mrad (± 0.02 mrad if calibrated daily).

2 - The Proximity Detectors

The main challenge was in fact to measure the effective height of the magnetic air gap which, due to the penetration of the flux lines inside the spacing between laminations (Fig. 3) is about 1.0 mm larger than the mechanical gap. A magnetic proximity detector (Fig. 4) has been specially designed to measure this effective gap. It consists of a U-shaped circuit which closes through the magnet pole via two air gaps. These air gaps are determined by the measurement of the self-inductance of the coils excited by a 80 Hz synthesized current. A local microprocessor controls the five probes and permits a resolution of 0.001 mm and an accuracy of ± 0.005 mm.

The difference between magnetic and mechanical gap height, h , depends on the thickness, e , the pitch, p , and the shape of the cut edges of the laminations. Theoretical computations, with the two-dimensional POISSON program in its "electrostatic" version, were in good agreement with experimental results using samples where only one of those three parameters was varied at a time. For small variations, Δp and Δe , around the nominal values of $p = 5.5$ mm and $e = 1.5$ mm:

$$h = 1.02 + 0.35 \Delta p - 0.59 \Delta e \quad \text{in mm.}$$

The lengthening of the magnetic flux lines, due to the deformation by punching of the cut edges of the lamination, was measured and found to be of the order of 0.05 mm per pole, i.e. 0.10 mm for the total air gap.

Fig. 3 - Flux line configuration at the pole face

- ① Excitation coils (2 x 125 turns)
- ② Fe-Si magnetic circuit
- ③ Glass-fibre epoxy core
- ④ Aluminium case

Fig. 4 - Cross-section of the proximity detector

A measurement distance between probe and pole face of $3 \text{ mm} \pm 1 \text{ mm}$ was chosen because below 2 mm, the probe signal is modulated by the discontinuous structure of the magnet core. The length (200 mm) of the probe results from a compromise between good mechanical stability and the choice of a reasonable number of measurement points over the length of the magnet.

3 - Measurement Procedure and Performance

The preparation of the measurement consists of mounting the guiding rail, fixing the laser tube at one end of the core, and introducing the carriage inside the air gap with its photocell retracted to permit the alignment of the laser beam with respect to the fixed photocell mounted at the other end.

Moved by a stepping motor, the carriage stops every 200 mm at the 28 measuring points, thus covering the entire core length. The complete measurement is

controlled by a microcomputer which calculates at each point the effective gap height in two transverse positions (± 77 mm), the tilt of the median plane and the position of the laser beam on the photocell. At the end of the measurement, it deduces -

- the average effective gap height which is correlated to the magnetic field for a given excitation (within ± 0.01 mm, i.e. $\Delta B/B = \pm 10^{-4}$);
- the mean error of parallelism of the pole faces, which is correlated to the field inhomogeneity in the useful gap aperture (within $\pm 10^{-4}$ at ± 77 mm);
- the average tilt of the median plane with respect to the reference jig (± 0.1 mrad) and the twist of the core;
- the horizontal and vertical positions of the longitudinal core axis with respect to the alignment reference jigs (± 0.1 mm).

III - REMANENT FIELD MEASUREMENT

The steel of the core is first magnetized up to a level similar to that reached by the magnet at maximum excitation. In the absence of the magnet coils, this magnetization is done by closing the air gap with a short magnetic block leaving a clearance of only 2 mm at each pole face. The necessary excitation current in the coil, wound around this block, is thus strongly reduced. A block length of 100 mm was found to be sufficient.

Since the magnetization is done with asymmetrical cycles ($0 - B_{\max} - 0$) far from saturation, the remanent field increases with the number of cycles to reach asymptotically its maximum value. At maximum excitation, the remanent field is reached in four cycles. For that reason, two magnetizing blocks have been mounted on the same carriage, thus producing two cycles at each passage along the core. This carriage (Fig. 5) uses the same driving system as the air-gap geometry measurement carriage.

After magnetization, a long rotating coil is inserted into the air gap for measuring the remanent field. The measurement accuracy is better than $\pm 5 \cdot 10^{-6}$ T.

Fig. 5 - The magnetizing carriage and the measuring equipment

Since the level of magnetization reached is about twice the level in phase I of LEP (60 GeV), a demagnetization is necessary after measurement. This is obtained by making a passage of the carriage excited by 50 Hz a.c. current.

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