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A HIGHLY AUTOMATED MEASURING SYSTEM FOR THE LEP MAGNETIC LENSES

by

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Résumé - Les quadripôles et sextupôles du LEP seront mesurés par la méthode harmonique. Un système de contrôle complètement autonome garantit des mesures précises et rapides de la force, de la qualité du champ et de l'axe magnétique des lentilles. L'alignement des aimants sur le banc de mesure est télécommandé grâce à l'emploi de niveaux électroniques et d'un rayon laser comme ligne de référence. Ce dernier est employé pour le positionnement des mires de référence des quadripôles selon l'axe magnétique. Cet exposé détaille l'appareillage électronique et mécanique et leurs performances.

Abstract - The quadrupole and sextupole magnets of LEP will be measured by the harmonic coil method. In order to achieve precise, reliable and rapid measurements of the strength, field quality and magnetic axis of the lenses, a fully autonomous, microprocessor controlled system has been developed. Remote control of the alignment of the magnets on their measuring bench has been built-in, thanks to the use of electronic level gauges and of a laser beam as reference axis. The latter is used for positioning the reference targets of the quadrupoles with respect to their magnetic axis. Design and performance of the mechanical and electronic equipment are presented.

I - INTRODUCTION

The LEP magnet system [1] contains about 1300 quadrupole and sextupole magnets to provide the required focusing of the beams. The main characteristics of these lenses are shown in Table 1.

The supply of the magnets will take place over a period of about 34 months at a typical rate of 40 units per month. The reception tests at CERN include the measurements of the strength and field quality of each magnet to verify that the tolerances imposed by beam optics [2] are respected. The relative precision required for these measurements is a few parts in 10^4 . Furthermore, the reference targets of the quadrupoles must be aligned to ± 0.05 mm with respect to the measured magnetic axis, since they will serve as reference monuments in the LEP arcs and hence define the central orbit of the beams.

Table 1 - Main characteristics of the LEP magnetic lenses

Type	Maximum gradient	Iron length	Inscribed circle $\varnothing$	Total mass	Quantity
MQ quadrupole	9.7 Tm ⁻¹	1550 mm	125 mm	2800 kg	520
MQA quadrupole	10.9 Tm ⁻¹	1950 mm	125 mm	4000 kg	288
MSD sextupole	180 Tm ⁻²	730 mm	150 mm	920 kg	256
MSF sextupole	180 Tm ⁻²	370 mm	150 mm	500 kg	248

II - MEASURING METHOD

The harmonic coil method [3, 4] has been chosen because the beam optics requirements on field quality are expressed as tolerances on the systematic and random harmonic components of the field [2], and the misalignment between the magnetic axis and the axis of the rotating measuring coils is directly measured [3, 4].

Long coils measure directly the integrals of the field values, whereas a pair of short coils is used to assess end effects and locate the magnetic axis. For the quadrupoles, the outer radius of the rotating coils is equal to the limit of the useful aperture (59 mm). To measure the contribution of the 20-pole component to within 10^{-4} , the rotation of the coils should be circular to within $1.3 \mu\text{m}$ and the angular encoder defining the sampling intervals (see below) precise to 10^{-5} rad. By using a compensating coil (radii $C_{\text{ext}}, C_{\text{int}}, N_c$ turns) connected in opposition to the main measuring coil (radii $M_{\text{ext}}, M_{\text{int}}, N_m$ turns) in order to satisfy

$N_m (M_{\text{ext}}^n - M_{\text{int}}^n) = N_c (C_{\text{ext}}^n - C_{\text{int}}^n)$ both for $n = 1$ (to cancel the errors due to poor rotation) and $n = 2$ (suppression of the main harmonic), the requirements on purity of rotation, encoder precision and integrator linearity are appreciably reduced. In the set of possible solutions, $N_c/N_m = 2$ is a good compromise between sensibility to the sextupole term and coil manufacture, and $M_{\text{int}} = 0$ guarantees a precise measurement of the magnet strength.

III - SYSTEM LAYOUT

The system has been designed with the aim of performing rapidly and precisely the reception tests of a magnet, i.e. automatic pre-alignment on the bench, location of the magnetic axis, series measurements and alignment of the reference targets.

To achieve flexibility in the schedule and location of the measurements, each system is autonomous. Reliability and easy maintenance are provided for by a modular layout at all levels (Fig. 1). A CBM 8032 general purpose microcomputer controls the three sub-systems handling, respectively, the actual magnetic measurements, the remote-controlled alignment and the setting of the power supplies of the magnets.

IV - MAGNETIC FIELD MEASUREMENTS

The harmonic coils, supported by an appropriate rotating structure described below, achieve one full revolution in each direction. During rotation, the voltage induced at the coils' terminals is integrated and sampled at 256 equally spaced intervals.

Fig. 1 - Layout of the data treatment and control system

The voltages integrated in each interval for clockwise and anti-clockwise rotation are compared to detect anomalies and averaged to cancel the drift of the integrators. The single values are then added up and the resulting flux curve submitted to harmonic analysis. A further verification of the measurement quality is carried out by comparing the harmonic coefficients measured with the single coil to those given by the compensating coil arrangement (the corresponding integrated voltages are sampled simultaneously). A file containing the harmonic coefficients is then created, taking the main field harmonic from the single coil measurements and the higher ones from the compensating coils, and made available to the bench controller. The latter performs the calculations to assess the strength and field quality of the measured magnet. A complete measurement, including the verifications and Fourier analysis described above, takes about 20 seconds.

~~Integrator and angular encoder~~ - The integrator is based on the use of a high-quality ~~input amplifier connected to a~~ voltage-to-frequency converter (max. frequency 1 MHz) feeding a 32-bit binary counter. The highest resolution is 0.1 μ Vs per bit at an input drift lower than 5 μ V.

To find the magnetic axis of the quadrupoles to within 0.02 mm, the angles at which the integrated voltages are sampled must be precise to within $2 \cdot 10^{-4}$. For this purpose, a 15-bit absolute encoder is used; to achieve the nominal precision, any radial load on the encoder shaft must be avoided.

Measuring cylinders - Hollow cylinders, which should ideally show no sag to guarantee constant coil geometry, support the two long coils and the two short end coils used for the measurements. A glass-fibre epoxy tube (1.37 m long, $\varnothing = 140$ mm) is used to measure the sextupoles, and Kevlar[®] epoxy tubes (2.48 m and 3.0 m long, respectively, $\varnothing = 115$ mm) have been chosen for the MQ and MQA quadrupoles (the ratio tensile strength/density of impregnated Kevlar is 2.6 times that of impregnated E-glass). Special tools had to be developed to overcome the poor machinability of Kevlar. The glass-fibre and Kevlar tubes are manufactured using the filament winding technique.

The measuring cylinders are loaded with counterweights at both ends to minimize their sag which can so be kept below 0.02 mm for even the longest ones.

The coils are made with multistrand wires put under tension at one end, supported on the cylinders at points spaced at maximum by 0.7 m to limit the wire sag to 0.02 mm and avoid vibration problems. Copper wire has been used up to now (strand diameter 0.07 mm, tension force 2.8 N/strand), but tungsten wire (gold plated, strand diameter 0.05 mm, tension force 4.5 N/strand), is being tested because it shows a sag four times smaller than that of copper wire.

The measuring cylinders are supported near to the magnet ends by non-magnetic, frictionless aerostatic journal bearings [5], which ensure a rotation concentricity of better than 0.01 mm.

V - REMOTE-CONTROLLED MAGNET ALIGNMENT

Sensors - In the past, the virtual reference axis has been defined by a telescope and Taylor-Hobson targets, but the alignment procedures were lengthy and prone to human error. By using a laser beam acting on quadrant photo-diodes, a magnet can be automatically aligned. A precision of the virtual axis of ± 0.01 mm at 4 m distance from the source can be obtained by shielding the outgoing beam from air movements over a length of 400 mm, and by a careful design of the support of the laser tube (HeNe, 1.5 mW).

Level measurements are carried out with electronic levels achieving a precision of 10^{-5} within a setting time of a few seconds.

Positioning mechanisms - The magnets are displaced on commercially available air thrust bearings (air-film thickness 0.03 mm) to ensure a high resolution (0.01 mm) positioning. Consequently, the alignment of the magnets in the horizontal plane is

practically frictionless (provided the compressed air is oil-free), so that the three driving stepping motors and guiding mechanisms need only to withstand the forces arising from the inertia of a magnet and the residual slope of the sliding surfaces. Three other more powerful stepping motors are coupled to the jacks for vertical adjustments.

Pre-alignment - Magnets must be pre-aligned to within 0.5 mm with respect to the theoretical axis so as to be able to install the measuring cylinders. A jig carrying two electronic levels and a photo-diode is positioned on the the magnet's reference surfaces. All displacements are made automatically, except the angular misalignment around the vertical axis, which is corrected by observing the reflection angle on the photo-diode of the incoming beam. The whole procedure takes less than ten minutes.

Location of the magnetic axis - Following the first magnetic measurement, the bench controller computes the offset between the theoretical and the measured magnetic axes from the harmonic coefficients obtained from the short end coils. This information is used to adjust the magnet position in order to cancel (within 0.02 mm) the measured offset. It may take up to four iterations, each lasting about five minutes, to achieve the required precision in magnet position.

Once the magnetic axis coincides with the axis of the rotating coils, which in turn is in the same vertical plane as the laser beam, the reference targets of the magnet are then manually aligned with respect to that beam.

VI - OVERALL SYSTEM PERFORMANCE AND CONCLUSIONS

A prototype measuring bench has been used to measure the prototype LEP lattice quadrupole. Systematic errors due to mechanical asymmetries in the system were estimated by turning the measuring cylinder end to end and by starting the measurement at different angles. Expressed in terms of relative error on the gradient at the useful aperture, a precision of $\pm 10^{-4}$ on the contribution of each harmonic coefficient up to $n = 15$ has been achieved. 8-pole and 16-pole terms created by an asymmetry in the assembly of the prototype quadrupole have been measured and found to be in excellent agreement with the values predicted by the perturbation method [6, 7]. The magnetic axis of the quadrupoles can be found to within ± 0.01 mm.

Thanks to the complete on-line data reduction and to the automatization of the alignment, the time needed to make all the reception tests of a magnet is reduced to less than half a normal working day. Three benches, one for the two types of sextupole and one for each type of quadrupole, are now being assembled to measure the 1300 magnetic lenses needed for LEP.

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