MAGNETIC PERFORMANCE OF THE LEP BENDING MAGNETS

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Abstract

The 3304 steel concrete cores of the LEP bending magnets have been individually measured to determine the excitation characteristics (field integral on central orbit versus current) and one out of ten has been submitted to a complete measurement of the field pattern in the aperture. The end and junction effects, and the field distortion due to the vacuum chamber both in static conditions (due to residual magnetism of the chamber materials) and during field ramping (influence of eddy currents), have been determined on some average cores. The paper briefly describes the measuring benches and gives the average values and the r.m.s. dispersions of the dipole, quadrupole, sextupole, octupole and decapole components seen by the beam at different field levels and during ramping. The effects on the machine parameters are analysed for each component, and compared with results obtained in the first injection tests.

Introduction

The LEP magnet system is a separate-function structure[1]. The regular lattice periods in the middle of the arcs are 79 m long and contain two quadrupoles and two bending magnet units, each made of six equal cores of 5.75 m length (Fig. 1). At each end of an arc, there are shorter cells with four or two cores only and a last one which contains a special weak-field dipole. In the injection region, there are also a few double-field dipoles, separately powered.

The 3304 dipole cores which produce a main bending field of 0.11 T at the ultimate energy of 100 GeV are made of stacks of low-carbon steel laminations, 1.5 mm thick, spaced by 4 mm and embedded in a cement mortar. They are excited by means of four water-cooled aluminium bars, all connected in series in situ to form a single powering circuit. The implications of the low-field levels and the novel core technology have been described in other papers[2,3] and only some relevant features are elaborated below. The shrinkage of the mortar when drying out gives rise to compression stresses in the laminations which decrease their magnetic permeability and thus the field in the gap. To reduce this effect, the cores have been submitted to a stress-relieving treatment one year after manufacture. Furthermore, each core is equipped with a flux loop embedded in the lower pole. These loops, which are connected in series in the ring, permit a measurement of the field in situ and thus the elimination of the influence of temperature variations and further ageing of mortar in the determination of beam energy.

The tolerances specified for the magnets[4] will be compared below with the measured values keeping in mind that they refer to the most demanding machine conditions and are not intangible. To limit the amount of work, the measurements performed on each individual core have been restricted only to those parameters strictly needed: the gap geometry (for acceptance of the cores and determination of the median plane), the excitation characteristics (for core mixing) and the flux loop surface (for calibration of beam energy).

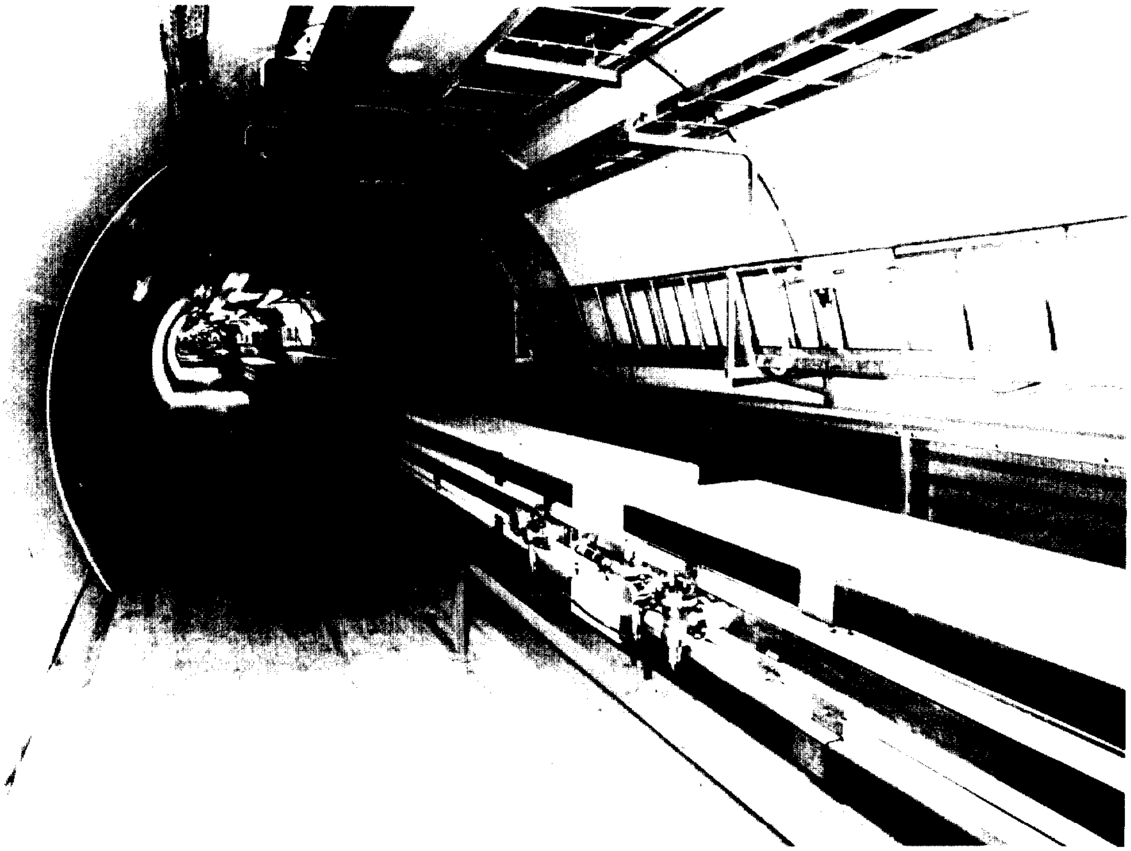

Fig. 1 Bending magnets in the LEP tunnel

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Measurement of Gap Geometry and Median Plane

Four months after manufacture, each core has undergone systematic reception tests[5]. The measurements have been made by means of a computer-controlled carriage equipped with five proximity detectors measuring the distance to the magnetic pole surface to within ± 0.003 mm, a levelmeter measuring the tilt of the median plane with an accuracy of ± 0.02 mrad and a four-quadrant photocell which, associated with a laser beam, measures the straightness of the cores to within ± 0.05 mm. No bench was used and the only references were the carriage itself, the laser beam and a second levelmeter fixed on the alignment jig to which the tilt of the median plane is actually referred. Out of the 3360 cores ordered, only three had to be rejected due to an excessive horizontal bending (> 2 mm over the length).

From these measurements, the standard deviation of the 100 mm gap height was 0.016 mm, corresponding to an r.m.s. dispersion of the bending field of 1.6×10^{-4} from core to core; the defect of pole parallelism, defined as the relative difference in gap height from the centre to the aperture limit of 59 mm, shows an average value of -1.8×10^{-4} and a standard deviation of 0.5×10^{-4}. As shown below, these values are much smaller than the actual field errors deduced from magnetic measurements. On the other hand, while the mean value of the tilt of the median plane is acceptable (0.04 mrad), the r.m.s. dispersion of 0.26 mrad is larger than the 0.2 mrad tolerance which corresponds to an r.m.s. vertical orbit distortion of 0.5 mm. As a consequence, the tilt of each core has been taken into account for the levelling in the LEP tunnel.

Measurement of Field Strength

The excitation curve was measured at different field levels using a string of rectangular flip coils covering the length of the dipole core. The measurement was carried out for two different excitation cycles corresponding to maximum beam energies of 66 GeV and 100 GeV. The accuracy of this measurement was better than 10^{-4} and the standard deviation of the measured field integrals ranged from 4×10^{-4} at the 20 GeV level to 7×10^{-4} at the 100 GeV level. The results of these measurements were used when combining the magnet cores into pairs: one core from each of the two manufacturers was selected according to its magnetic strength. The dispersion of the bending strength of the six-core units estimated from the measurements and taking into account the further ageing of the mortar is less than the tolerance of 5×10^{-4} (horizontal closed orbit distortion of 2.5 mm r.m.s.) up to field values corresponding to 100 GeV[3]. This low dispersion was confirmed during beam injection tests into the first octant in July 1988, where orbit distortions of less than 3 mm r.m.s. were measured[6].

The calibration of the flux loops was obtained by measuring simultaneously the flux change in the flip coil and in the flux loop during multiple cycling of the magnet excitation current. The magnetic surface area of a flux loop is defined as the ratio of the flux variation in the loop to the field measured by the flip coil. The accuracy of this measurement was about 10^{-4} and the overall r.m.s. dispersion of the measured surface areas was less than 10^{-3}.

Periodic measurements of the total flux variations in the magnets installed in the tunnel will provide a precise determination of the overall bending power and thus of beam energy. The calibration procedure is shown in Fig. 2. Measurements of the flux change from B_{r+} to B(I) will be correlated with field measurements in a reference magnet which is connected in series with the main dipole string. A change of polarity is necessary in order to determine the remanent field B_{r+} in the ring magnets. The positive and negative values of the remanent field are not symmetrical, but the ratio of these values has been measured in some magnets and will be used to determine B_{r+} from the measurement of ΔB_r. Detailed measurements of end and junction effects provide the necessary corrections to the flux-loop calibration and permit the determination of the absolute value of beam energy at central orbit to better than $\pm 5 \times 10^{-4}$. At a later stage, this value will permit unambiguous detection of the depolarization resonances distant by 440.65 MeV and to improve the accuracy of the beam energy calibration to within 10^{-4}.

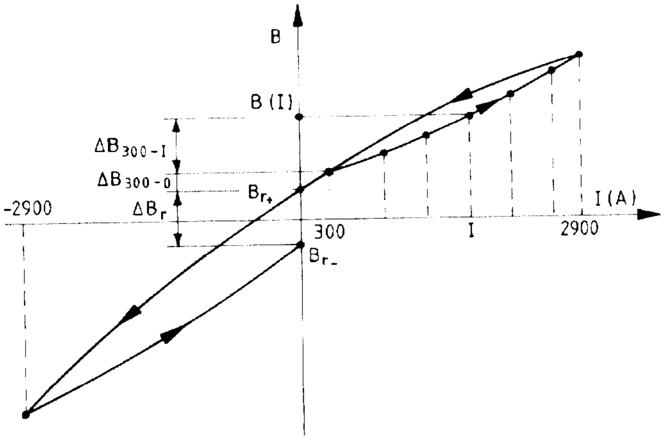

Fig. 2 Principle of beam energy calibration

Measurement of Field Quality

Complete magnetic measurements were performed on approximately 10 % of the dipole cores. A carriage holding the search coils was displaced longitudinally on a measurement bench placed in front of the magnet. Measurements were performed at seven longitudinal positions in order to obtain the field integrals throughout the magnet. The same flip coil was used to determine both the field along the central orbit and the transverse field uniformity over a distance of ± 72 mm.

A special search coil oriented near zero-flux position and fitted with a level gauge was used to determine the angle of the magnetic median plane by measuring the flux variation when changing the field strength. Angular errors between the coil plane and the supporting structure are eliminated by making two measurements where the coil is rotated by 180°. The overall accuracy is better than 0.05 mrad. The results were compared to those obtained with the gap-geometry measuring system mentioned above; the systematic difference between the results obtained by the two methods was of the order of 0.1 mrad.

The results of the field uniformity measurements are given in Fig. 3 and Table 1 for the dipole pairs which are the basic units in the tunnel. The field variation across the aperture is decomposed into its main components and for each of them, the average value and the r.m.s. dispersion are given as the corresponding field variations at the aperture limit of x = +59 mm. Table 1 also gives the tolerances. The average quadrupole and sextupole components can only be corrected to the first order by the localized lenses. The tolerance on the average quadrupole component is deduced from the perturbation of the damping partition number which has been limited to $\Delta J_x = 0.05$. For the other tolerances, the criteria were the reduction of dynamic aperture, the tune shift with amplitude and the excitation of non-linear resonances.

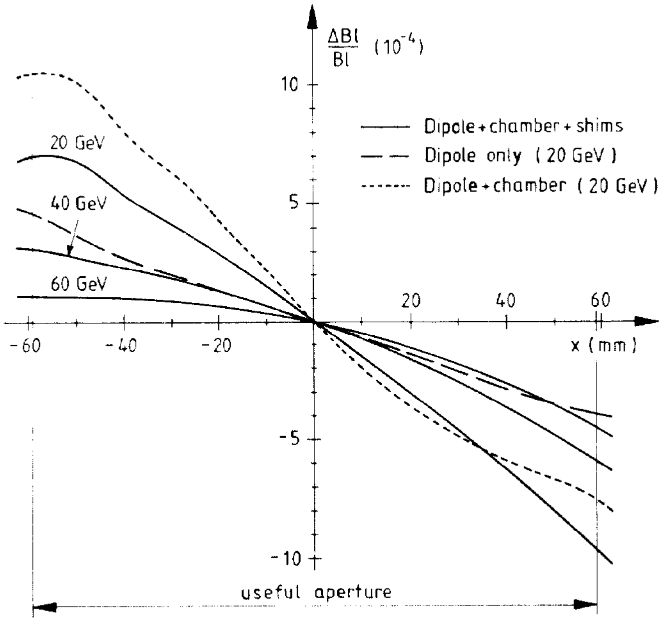

Fig. 3 Field uniformity

For the magnets without vacuum chamber, both the average and random components are well within tolerances. The first injection tests revealed, however, a small difference in vertical and horizontal phase advance which was traced back as being produced by a 7 μm nickel layer which is deposited on the vacuum chamber to ease the soldering of the lead shielding. This layer, which is fully saturated, produces a field perturbation which exceeds the tolerances at injection. To compensate this effect, simple shims were defined and mounted on each end of the pairs. The thickness of the shims has been chosen such that their saturation characteristics match those of the nickel layer. The results shown in Table 1 include the effects of vacuum chamber and correcting shims. All components are well within the tolerances with the exception of the average quadrupole which is marginally out at 20 GeV; after retuning with the lattice quadrupole magnets, however, the remaining perturbations of J_x (0.055), beta values (1 %) and dispersion (3 mm at the crossing points) are very small and can be partially compensated by changing the RF frequency and rematching the dispersion suppressor and straight-section cells.

Table 1

Field uniformity expressed in 10^{-4} field variations at x = +59 mm

Multipoles		Energy/Cycle (GeV)			Tolerances
		20/66	60/66	100/100	
Quadrupole	average	-8.8	-2.6	-3.1	± 8
	r.m.s	1.2	1.2	1.2	2
Sextupole	average	-0.8	-1.8	-2.0	+2/-5
	r.m.s.	1.0	0.8	1.0	3
Octupole	average	0.5	-0.2	-0.3	± 0.7
	r.m.s.	0.5	0.4	0.4	2
Decapole	average	-0.6	0.1	-0.2	± 1.3
	r.m.s.	1.1	0.9	1.2	2

Field Perturbation During Ramping

During ramping, eddy currents are generated in the aluminium vacuum chamber and in its lead shielding. The resulting field perturbation has been calculated by adding a subroutine to the magnet computing program POISSON; this subroutine calculates the eddy currents from the unperturbed vector potential and then the field perturbation that they create. For the ramp rate of 0.5 GeV s^{-1} which is presently retained, the field perturbation can be developed as follows:

$$\Delta B = -0.286 + 0.527\ x + 7.07\ x^2 - 17.6\ x^3 + 1710\ x^4\ ,$$

with ΔB in G and x in m. A field measurement performed with a coil centred inside a sample of vacuum chamber confirmed quite well the validity of the calculation.

At the injection energy of 20 GeV, the amplitude of the various components expressed in 10^{-4} field variations at x = +59 mm are respectively; -13.3 (dipole), +1.4 (quadrupole), +1.1 (sextupole), -0.2 (octupole) and +0.9 (decapole); these values must be added to those of Table 1 to give the actual field seen by the beam when ramping starts at 20 GeV. The global field components remain within tolerances but are large enough to require a correction by the localized quadrupole and sextupole magnets in order to maintain the tune values and the chromaticity; this is done by advancing the ramp of the bending magnets and by injecting current offsets in the quadrupole and sextupole magnets.

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References

[1] L. Resegotti, "The LEP magnet system", in Journal de Physique, Vol. 45, Colloque C1, 1984, pp. C1-233 - C1-239.

[2] J.P. Gourber, J. Billan, H. Laeger, A. Perrot and L. Resegotti, "On the way to the series production of steel-concrete cores for the LEP dipole magnets", in IEEE Trans. on Nucl. Sci., Vol. NS-30, No. 4, Part. II, 1983, pp. 3614-3616.

[3] J. Billan, J.P. Gourber, K.N. Henrichsen, H. Laeger and L. Resegotti, "Influence of mortar-induced stresses on the magnetic characteristics of the LEP dipole cores", in IEEE Trans. on Magnetics, Vol. 24, No. 2, 1988, pp 843-846.

[4] G. Guignard, "Tolerances for the magnetic elements of the LEP lattice", in Proc. 12th Int. Conf. on High-Energy Accelerators, Fermilab, 1983, pp. 167-169.

[5] J. Billan, J.P. Gourber and K.N. Henrichsen, "Geometry and remanent field series measurement of the LEP dipole magnets", in Journal de Physique, Vol. 45, Colloque 1, 1984, pp. C1-953 - C1-956.

[6] LEP Commissioning Team, "Injection and transport of beams of positrons into and through an octant of LEP", Paper presented at this Conference.