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DESIGN OF THE DIPOLE MAGNETS FOR ORBIT CORRECTION IN LEP

by

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Résumé - Le réseau magnétique du LEP contient 520 électro-aimants dipolaires de correction d'orbite dans les plans horizontal et vertical. La géométrie des circuits magnétiques et les caractéristiques des bobines d'excitation ont été choisies pour leur aptitude à répondre efficacement et économiquement au cahier des charges (niveau et qualité du champ) tout en respectant les contraintes techniques imposées par les grandes dimensions du LEP. Du fait de la gamme de fonctionnement étendue des aimants, la réduction des effets d'hystérésis a suscité des efforts particuliers, conduisant à imposer des tolérances serrées sur le champ coercitif de l'acier utilisé. Les résultats de mesures électriques, thermiques et magnétiques sur des modèles d'aimants sont présentés.

Abstract - The magnetic lattice of LEP contains 520 dipole electromagnets for vertical and horizontal orbit correction. The choice of magnetic circuit geometry and excitation coil characteristics, which satisfy the field requirements and tolerances as well as the technical boundary conditions imposed by the large size of LEP, is discussed with respect to achievable performance, economics and feasibility. Owing to the wide operating range of the magnets, particular emphasis is put on the reduction of hysteresis effects, which determines tight constraints on the coercivity of the steel. Results of electrical, thermal and magnetic measurements on model magnets are presented.

INTRODUCTION

Closed orbit distortions in circular accelerators and storage rings increase with the number of components, and hence the size of the machine. The lattice of LEP contains about 4700 bending and focusing magnets [1]; random field errors or misalignments produce distortions of the closed orbits, which may exceed the aperture and limit the performance of the machine. An efficient orbit correction system is, therefore, essential to speed up commissioning, obtain early circulating beams, and later optimize operating conditions. This system involves beam position monitoring, data transmission and processing [2], and control of the power supplies [3] feeding the correction dipole magnets. Although only the latter are discussed here, their design is consistent with the global requirements of the system.

BASIC REQUIREMENTS

The total number of correction dipoles results from the desired quality of orbit correction: analytical calculations [4] show that about three correctors per betatron wavelength give a good correction quality. In LEP, this amounts to about 260 independent correction dipoles in each transverse plane. For each magnet type, a large series is required so that careful optimization of the design is expected to result in significant overall economy.

The magnets must be strong enough to correct the closed orbit globally and compensate locally the distortions produced by quadrupole misalignments of 1 mm at maximum beam

Table 1 - Requirements for LEP correction dipole magnets

Magnet type		MCV	MCH	MCVA	MCHA
Number		176	168	88	88
Maximum field integral	[T m]	0.019	0.029	0.031	0.036
Gap	[mm]	200	102	200	102
Length of magnetic circuit	[mm]	400	400	400	400
Horizontal useful aperture	[mm]	± 35	± 59	± 46	± 59
Vertical useful aperture	[mm]	± 33	± 19	± 33	± 19

energy. Moreover, the correction dipoles will be used to produce local bumps for scanning the aperture at injection energy. The tightest criterion defines the requirements on field integral [2] listed in Table 1.

The maximum field inhomogeneity acceptable in the useful regions of the apertures, deduced from the field tolerance in the main dipole magnets, is 0.75 %. Larger values can be accepted at high excitations of the magnets, mainly used for scanning bumps. Furthermore, the setting errors must be small enough to have negligible contributions to the residual orbit, resulting in a maximum absolute error of $2\ 10^{-5}$ T m. Combining both requirements results in the global tolerances [5] of Fig. 2; a good field quality is required throughout the operating range, including at low excitations where one has to cope with non-linear effects in the magnetic properties of the steel.

The gaps of the correction dipoles must be sufficient to accommodate the LEP vacuum chamber, equipped with lead shielding and bakeout insulation, and allowing for fabrication and alignment tolerances. Longitudinal space being limited in LEP, the length of the magnetic circuits has been set at 0.4 m, resulting in rather short magnets where end effects become important.

The correction dipoles will be individually excited by bipolar power supplies through cables running along the machine tunnel. Environmental conditions during operation of LEP will be characterized by strong ionizing synchrotron radiation from the circulating beams and air temperatures ranging up to 38°C.

MAGNETIC CIRCUITS

Once the length of the magnets has been fixed, optimal design consists in finding a distribution of excitation coils and magnetic yoke producing the desired field level and quality, while minimizing the transverse dimensions, and hence the cost of the magnets. Several potentially suitable geometries have been investigated [6] and their relative efficiencies compared on the basis of common requirements (Fig. 1). The U-shaped solution, requiring half the conductor mass of the others, appears to be the most economical. Field homogeneity in the useful aperture is achieved by appropriate shimming of the pole pieces, adjusted by measurements on model magnets (Fig. 2).

Due to simple geometry and slow ramping rates, it was first thought to use plates of commercially pure ("Armco") iron or construction steel. However, such materials exhibit coercivities of 100 A m^{-1} and above, giving rise to remanence in the magnet

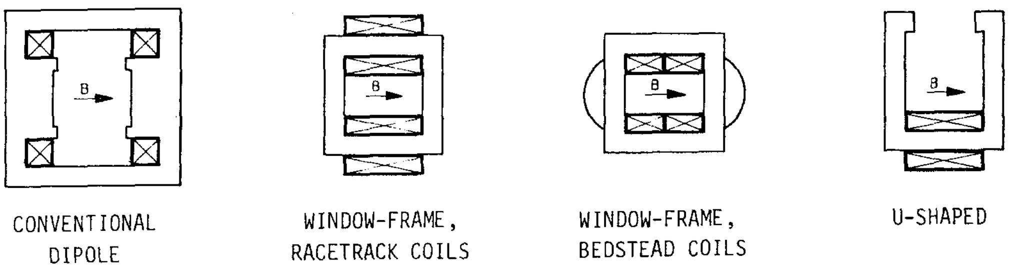

Fig. 1 - Different geometries considered for LEP correction dipole magnets

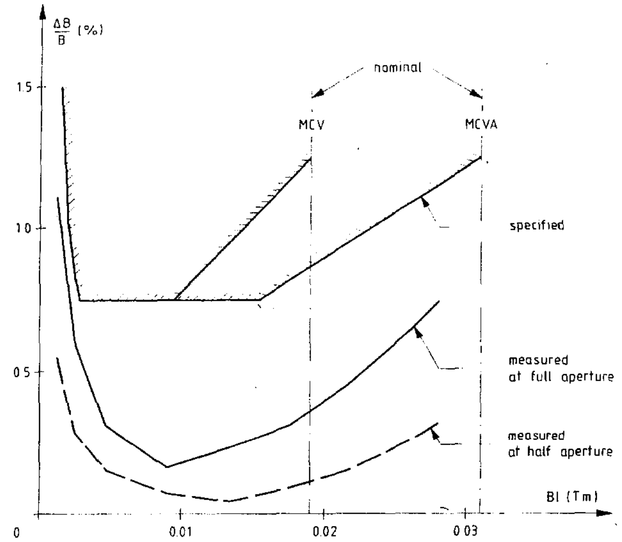

Fig. 2 - Field quality in MCV and MCVA magnets

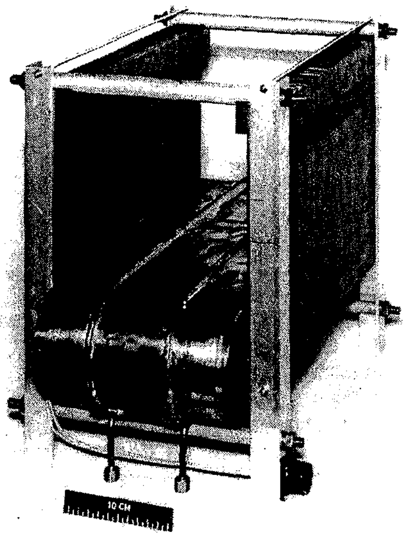

Fig. 3 - MCVA magnet model

apertures (typically 2 10^{-4} T m for MCH) exceeding the tolerance on absolute field precision. Consequently, the need for low coercive field and low dispersion in coercivity led to select a standard non-oriented silicon steel (FeV 135-50 according to EURONORM 106-71). Magnetic measurements on samples of silicon steels available from industry have shown that reproducible coercivity values of 40 ± 5 A m^{-1} can be expected. As a result, the remanent field integrals in full-scale model magnets were measured to be 2 10^{-5} T m and 5 10^{-5} T m for the MCV and MCH types, respectively.

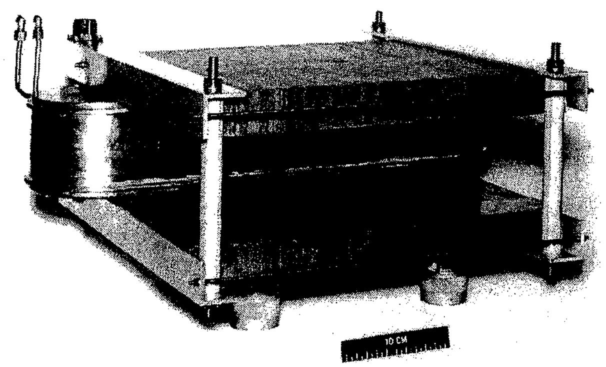

Fig. 4 - MCHA magnet model

The choice of silicon steel imposes a laminated construction. For the sake of scale economy, only two types of magnetic circuits have been designed, one common to MCV and MCVA, and the other common to MCH and MCHA magnets (Figs. 3 and 4). Each circuit is made of two stacks of L-shaped laminations, glued together with epoxy resin. The mechanical precision required by the desired field quality is ensured by the close tolerances on the punched laminations (0.02 mm) and on the glued stacks, held together by means of an external Al-alloy frame and stainless steel tie-bolts which guarantee the precise aperture of the magnet gaps.

EXCITATION COILS

The choice of current density in magnet windings usually results from minimization of capital and integrated operation costs. The latter can be neglected in the case of correction magnets, expected to have a low r.m.s. excitation level. For the magnets in the machine arcs (MCV and MCH), the definition of current densities results from the cabling lengths (up to 1900 m) imposed by the layout and the limited voltage (design value 120 V) available at the power supply terminals: satisfying these conflicting requirements leads to low design currents. In this range, minimizing the total cost of the system also minimizes the mass of conductor in the cable and excitation coil [6]. This condition leads to the sets of characteristics in Table 2, based on currently available cross-sections of copper wires and cables. The use of aluminium conductor has not been considered due to the lack of commercially available products.

Table 2 - Characteristics of LEP correction dipole magnets

Magnet type		MCV	MCH	MCVA	MCHA
Number of turns in coil		2420	2050	1980	1300
Nominal wire diameter	[mm]	1.6	1.5	1.9	1.9
Maximum excitation current	[A]	2.5	2.5	5.0	5.0
Maximum power dissipation	[W]	160	150	320	210
Electrical resistance of coil at 20°C	[Ω]	21.2	20.4	12.3	8.1

The moderate current densities in the MCV and MCH coils result in low power densities. Calculations [6] and measurements on models have shown that the bulk thermal conductivity of the coils allows them to be cooled from their surface only. Moreover, the low absolute values of power dissipation suggested air cooling. A surface thermal resistance of about 0.15 K W^{-1} was measured on model coils fitted with black anodized finned aluminium profiles glued on their outer surface. For the MCV and MCH magnets, this permits natural convection in air to keep the maximum coil temperatures below 70°C in the worst operating conditions. MCVA and MCHA magnets, located in the acceleration regions of LEP, are stronger but can accept higher current density because of shorter cables, resulting in higher power dissipation which requires water cooling (Fig. 5).

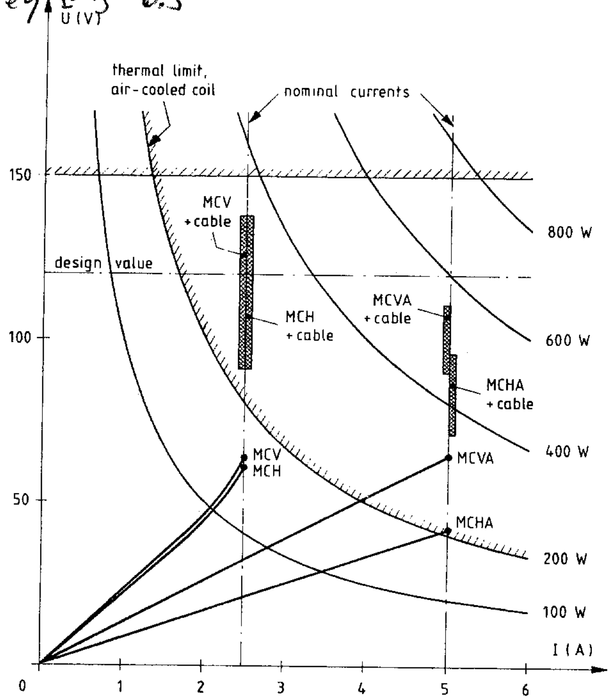

Fig. 5 - Working lines of LEP correction dipole magnets

Copper wire of round cross-section, insulated with a polyamide-imide enamel of thermal class H, is used to wind the coils, later impregnated under vacuum with an epoxy resin. Insulation to ground is ensured by glass-fibre epoxy coil formers and glass-fibre tape.

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