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PROTOTYPES OF LEP BENDING MAGNETS WITH STEEL-CONCRETE CORES

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Summary

In the large European electron positron storage ring project (LEP), the guiding magnets have a field of 0.123 T at the maximum energy of 130 GeV obtainable with superconducting RF cavities. To take advantage of these low field levels, steel-concrete cores with a steel filling factor of 0.27 are proposed[1]. The magnets are excited by means of aluminium bars running along the circumference[2] (Fig. 1). The design features and the experience gained with prototypes are given.

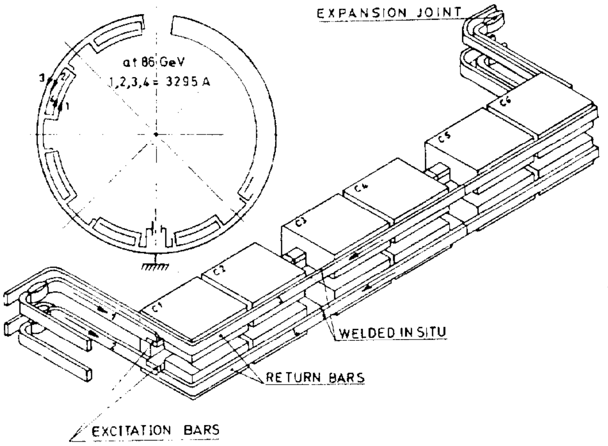

Fig. 1 LEP dipole magnet system

Steel-Concrete Cores

Each core is made of a stack of low-carbon steel laminations, 1.5 mm thick, separated by 4 mm gaps and embedded in a fine grain sand and cement mortar (Fig. 2). The gap height and the coil window are determined by the dimensions of the vacuum chamber and of the excitation bars. The gap width and the shims are calculated so as to give a field uniformity $\Delta B/B$ of the order of 10^{-4} across the beam aperture at the nominal energy. The width of the return yoke ω = 120 mm and the filling factor f = 0.27 have been optimized together so as to minimize the cost of the core while satisfying the following two constraints:

a) The gap closure due to the upper pole weight and to the magnetic attraction of the pole must be smaller than 0.03 mm.

b) The magnet induction B_s^{max} in the return yoke must be limited to 1.6 T to give an ampère-turn drop of 5 % in the yoke, which is an economic optimum.

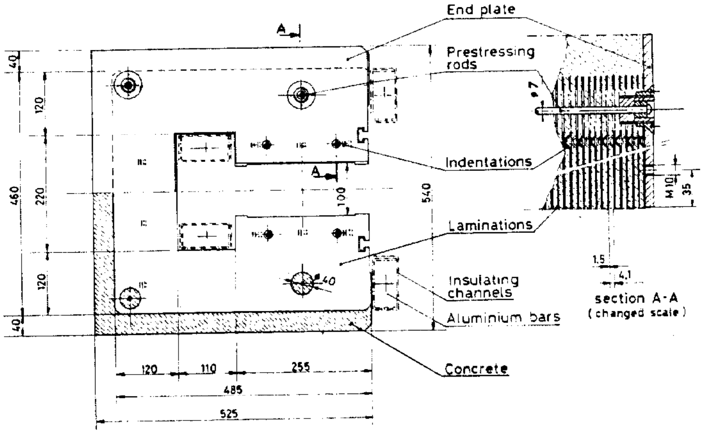

Fig. 2 Steel-concrete magnet

For a full steel magnet, a return yoke of 100 mm should be kept to fulfil condition a), but B_s^{max} is only 0.5 T at 130 GeV. In the case of a steel-concrete core, f can be reduced to 0.32 for the same yoke width before B_s^{max} reaches 1.6 T, while condition a) is still fulfilled thanks to the rigidity of the mortar. For smaller values of f, the yoke width has to be increased and the total amount of steel remains constant; the fabrication cost slightly decreases for a while due to larger interlaminar spaces which finally shifts the optimum towards f = 0.27 and ω = 120 mm.

To improve the adherence of the mortar to the laminations, a precompression is applied to the core by means of four longitudinal rods, the core behaving like a solid prestressed concrete beam. The prestress of 5 kg cm^{-2} is kept to a minimum to avoid long term deformations due to relaxation of the mortar under load; it is just sufficient to maintain all parts of the core in compression when the latter is laid on its supports with a deceleration of 2 g. The rods, which are anchored to the end plates, are tensioned during the casting and the drying out of the mortar. These small diameter (7 mm) rods are fabricated from high-tensile steel and work at the very high stress level of 90 kg mm^{-2} in order to have a lengthening much larger than all parasitic variations such as mortar shrinkage, relaxation, sliding in anchorages, etc.; as a consequence, the precompression of the core is well determined and remains constant with time. The forces exerted by the rods on the front and on the back of the core are different so as to exert a zero bending moment and thus not to deform the core. The thickness (15 mm) of the end plates has been chosen to carry, without saturation, the stray flux at the end of the magnet; the two T-slots on the front of the cores serve to fix the vacuum chamber and the excitation bars.

Table 1 gives the tolerances on the geometry of the cores imposed by machine performance and the maximum expected stresses in concrete. The latter are much smaller than the admissible values, i.e. the main difficulties are expected to arise from the tight geometrical tolerances.

Table 1 - Main Structural Requirements for the Cores

- Vertical straightness	2 mm peak-to-peak
- Horizontal straightness	2 mm peak-to-peak
- Twist variations along the core	2 mrad peak-to-peak
- Twist stability with time, temperature, etc.	<0.2> mrad r.m.s.
- Maximum stresses in concrete:	
Compression (η)	9 kg cm^{-2}
Torsion (τ)	4 kg cm^{-2}

The maximum stresses include some reserve for a possible mishandling of the core (core deposition with a deceleration of 2 g, maximum dissymmetry of the supports in torsion - see Fig. 4). These stresses are much lower than the admissible value for the selected mortar η = 70 kg cm^{-2} and τ = 12 kg cm^{-2} (shear stress and adherence between steel and concrete).

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The mortar must be resistant to the corrosive atmosphere of LEP (15 ppm of O_3 and HNO_3) and fluid enough to fill the spaces between laminations. The compressive yield stress must be superior to 250 kg cm^{-2} to have negligible relaxation in time. However, the most stringent requirement concerns the shrinkage on drying out which has to be smaller than 2 10^{-4} to ensure the reproducibility of the core geometry within the tolerances (Table 1). The shrinkage causes not only a reduction in length but also deformations, because of the inevitable variations in the mass of the core. The selected mortar has the following composition:

- Corrosion resistant cement CPMF2	500 kg m^{-3}
- Silica sand of grain size from 0 to 2 mm (distribution of grain sizes according to the norm NF 15-403)	1700 kg m^{-3}
- Water	260 kg m^{-3}
- Additives to improve the fluidity.	

To develop the fabrication technique, a collaboration between CERN and European civil engineering industry was established. Three different firms have participated in this work and four prototypes have been built. The cores are cast in a horizontal mould in the position shown in Fig. 3. After degreasing, the laminations are stacked on the base of the mould which is equipped with a guide plate fitted with two longitudinal rails. To provide regular spacing, indentations of 4 mm height are drawn on the laminations when they are punched. The central hollow of the core is produced by means of an inflatable T-shaped former which also presses the laminations against the guide plate. This former has a filter to vent the air when pouring the mortar. The penetration of the mortar between the laminations is helped by the vibration of the mould at 150 Hz with an acceleration of 1.5 g. The drying out is done in a wet atmosphere at ambient temperature and requires at least three days before the core is sufficiently strong to be demoulded. Tests are presently being carried out to reduce this delay to a few hours by curing in hot vapour.

The geometrical measurements performed on the four prototypes are given in Table 2. The straightness in the vertical plane and the twist are a factor 2 better than the tolerances. In the horizontal plane, the straightness slowly deteriorates with time because of the long-term differential shrinkage between the back and the front of the core (top and bottom of the mould). The asymptotic value of 2.2 mm for prototypes 1 and 2 lie outside the tolerance of 2 mm. The mortar composition has been improved for the other prototypes which have a better straightness after one month. Thus, for the series production it is foreseen to leave the cores stabilizing for a few months before sealing them against corrosion with a protective paint and measuring them. Ultimately, the mould could be designed with an opposite bending.

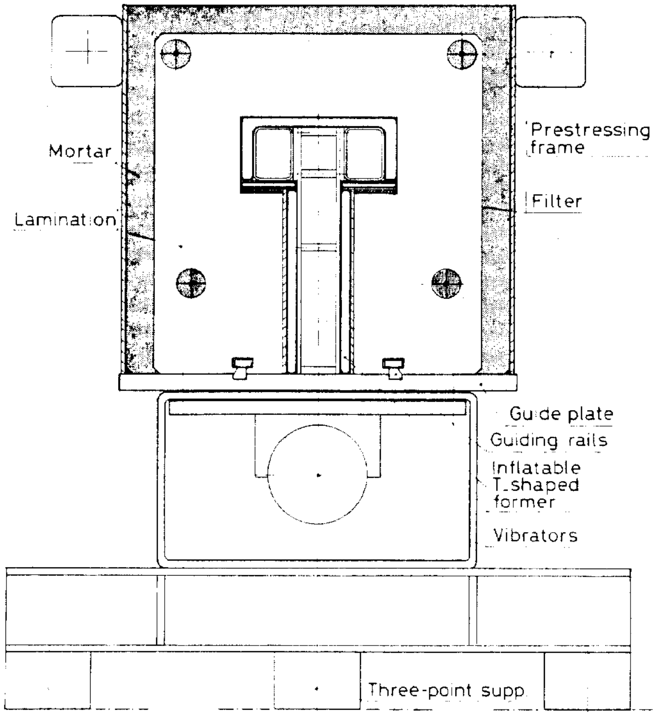

Fig. 3 Casting of a core

Table 2 - Geometry of the Prototypes

	Straightness (mm peak-to-peak) horizont.	Straightness (mm peak-to-peak) vertical	Twist (mrad p-t-p)
Prototype 1:			
Age 4 months, temp. 21°C	1.6	0.3	1.0
Age 5 months, temp. 10°C	1.9	0.3	0.9
Age 19 months, temp. 19°C	2.2	0.4	0.9
Prototype 2:			
Age 1 month, temp. 21°C	1.0	0.4	1.2
Age 1 year, temp. 18°C	2.2	0.6	1.2
Prototype 3: age 1 month	0.5	0.3	0.6
Prototype 4: age 1 month	0.6	0.4	1.0

The structural rigidity of the cores has been measured in both torsional and flexural modes. In the torsion test, shown schematically in Fig. 4, the twist θ_{max} measured by the difference of the two levels A and B is 0.38 mrad when one of the four supports is unloaded (F = 0). This is only 1/20th of the value measured on a full laminated steel magnet. The strain-

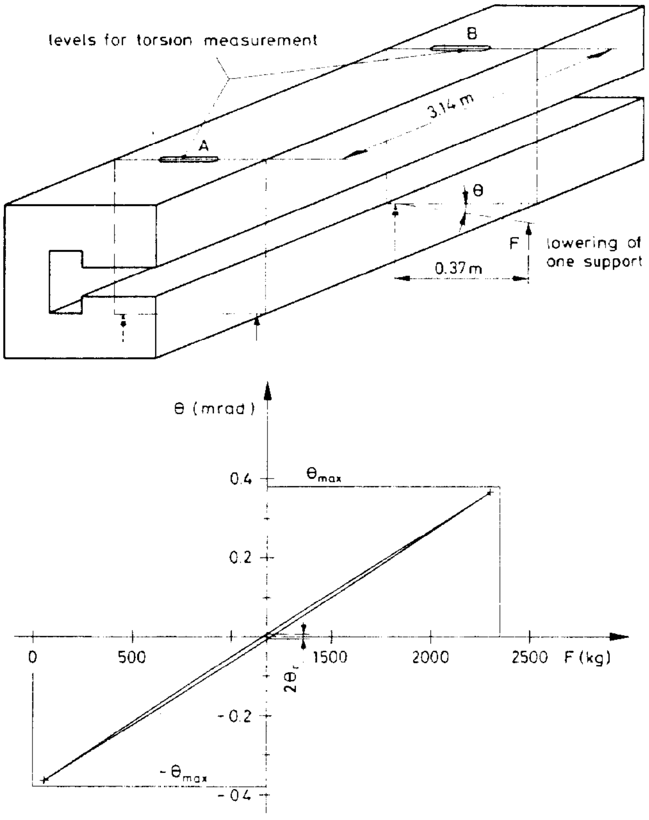

Fig. 4 Torsion test

stress hysteresis, i.e. the deformation which remains once the torsion torque has been suppressed, is not measurable ($\theta_r/\theta_{max} < 1$ %) while it is typically 20 % for a conventional core. As a consequence of this strong rigidity and pure elastic behaviour, a three-point support can be used, which facilitates considerably the alignment in the tunnel. For the deflexion test, the core rests on its three supports and a hydraulic jack applies a force in the middle of the core. From the measured deformation, one can deduce the sagitta of the core under its own weight: 0.02 mm on the front of the magnet and 0.01 mm on the back. The transverse and longitudinal elastic modulus $G = 110'000$ kg cm^{-2} and $E = 220'000$ kg cm^{-2} are in good agreement with the values known for mortar, which means that the core behaves like a monolithic beam.

Excitation Bars

These are extruded from 99.5 % pure aluminium and have a cross-section of 3600 mm^2, corresponding to an optimum current density of 1 A mm^{-2} at the nominal energy of 86 GeV. The bars are insulated by two overlapping U-shape channels. These profiles, made of 70 % fibre glass and 30 % polyester resin, are obtained by extrusion. They are much cheaper than a conventional glass-epoxy insulation and have sufficient radiation resistance[3]: no deterioration of mechanical properties has been detected on samples irradiated to doses up to 2 10^9 rad. The slippage path between the two insulating channels is resistive enough to give rise to negligible leakage currents to ground. It is, however, foreseen to glue the two channels together in order to avoid their deformation with time.

The bars and the channels can be delivered in lengths of 13 m in order to equip one pair of dipoles (Fig. 1). They have to be installed in the tunnel once the dipoles are roughly aligned. For the junction between the pairs, two techniques are under study: metal inert gas welding (MIG) and cold welding. The return bars, which were located behind the magnet along the tunnel wall in the first proposal[2] are now installed on the front of the cores. This modification was made necessary by the adverse effects of the stray fields. At the ends of the arcs, the four bars are interconnected so as to have only two bars in the straight sections (Fig. 1). When compared to traditional coils, the LEP dipole excitation system is not only much cheaper but leads to a minimum of space being lost between cores.

Magnetic Measurements

The magnetic behaviour of these magnets is analysed in Ref. 1. The excitation curve has a slope $B/I = 2\mu_0/L_0$ which corresponds to an effective gap L_0 of 101.8 mm. The increase of 1.8 mm of the gap is the additional path of the flux lines in the air between the laminations at the pole-gap boundary. For an excitation cycle going to 130 GeV, the remanent field is 6.5 G and the ampère-turn drop in the steel at the highest field is 5 %. These values are slightly higher than for a full steel magnet because of the higher induction in the steel. The field variations across the aperture are given in Fig. 5 for several field levels. The uniformity of 2 10^{-4} at medium field agrees with the computed value which confirms that the geometry of the laminations is maintained after casting. The uniformity is worse at injection but still compatible with good machine performance, the quadrupole and sextupole components being easily compensated by a modest excitation of the lattice quadrupole and sextupole magnets; the inhomogeneity, which is due to the influence of H_c partially compensated by the low permeability in the steel, would be even worse for a full steel core[1]. A calculation of the longitudinal variation of the field connected with the discontinuous core structure has been made using a two-dimensional model in which the laminations are simulated by a distribution of magnetic charges[4]. It gives a modulation $\Delta B/B = 0.23\ 10^{-7}$ at the vertical aperture ± 33 mm, and respectively 0.01 and 0.1 at distances of 3.9 mm and 1.8 mm from the pole surface, the latter values being well verified from measurements.

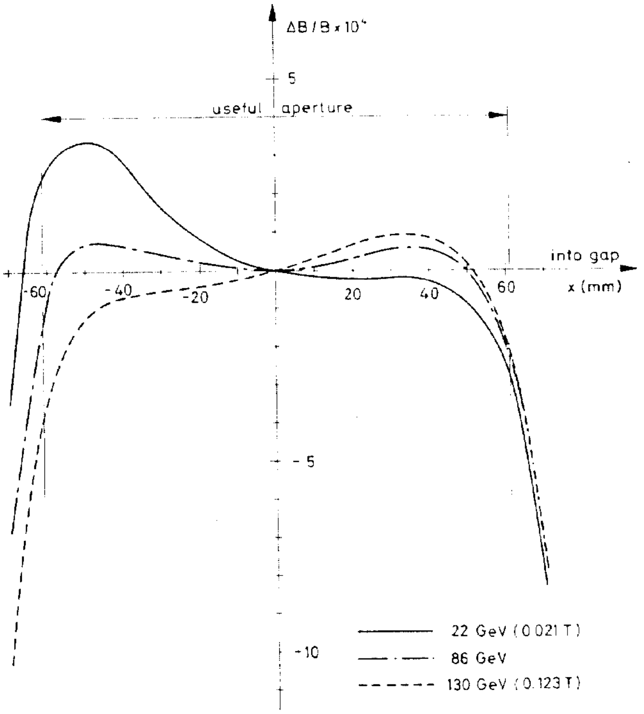

Fig. 5 Field uniformity in the aperture

Conclusions

The described LEP dipole system satisfies the requirements imposed by machine performance and is cheaper than a conventional solution using steel cores and wound coils. The steel-concrete cores are lighter and more rigid than all-steel cores, and the use of excitation bars offers a very compact dipole arrangement. Prototype work continues in order to finalize the fabrication and assembly techniques and simultaneously to assess reproducibility under series production.

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