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OF THE LEP DIPOLE CORES

by

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Abstract: The steel-concrete cores of the LEP dipole magnets are built of regularly spaced soft magnetic steel laminations, the spaces being filled with cement mortar. Mortar shrinkage at hydration is prevented in the transverse plane by the steel laminations and therefore induces compressive stresses in the steel and tensile stresses in the mortar. The effect of compressive stresses on the permeability and the coercivity of soft magnetic steel has been measured on samples and the consequences on the magnetic characteristics of the cores have been evaluated. By a controlled straining of the aged cores in a hydraulic device, the tension in the mortar is brought locally to exceed the rupture limit. Thus, the compressive stresses in the steel laminations are partially relieved and the loss of bending strength in the dipoles is reduced. The excitation characteristics of the cores are measured by means of a fixed set of excitation windings and measuring coils into which the cores are moved after stress relieving. These measurements include the determination of the equivalent surface areas of "flux loops" which are embedded in the lower poles and which will permit the measurement of the field integral on the centre line during LEP operation.

Introduction

The LEP main ring magnet system [1] contains 3280 equal dipole cores, each 5.75 m long, excited in series: the vacuum chambers in which the particles will circulate are located in their 100 mm high air gaps. The magnetic field on the equilibrium orbit will rise from 0.0218 T to 0.1090 T from the beam injection energy of 20 GeV to the energy of 100 GeV. For an economical exploitation of the steel, the field in the return yokes should be more than ten times higher: this effect is achieved partly by reducing the transverse dimensions of the steel laminations and partly by spacing them longitudinally along the beam orbit. The spaces are filled with cement mortar, which is a strong bonding agent and ensures the mechanical rigidity of the cores [2]. This structure is illustrated in Fig. 1.

Stresses Induced into the Steel Laminations by Mortar Shrinkage

Mortar shrinkage at hydration has different effects in the longitudinal and transverse directions. Longitudinally, it influences the stability of the core geometry, which is, however, maintained within the

required tolerances by an appropriate adjustment of the pre-stress applied by means of four steel rods. In the transverse plane, the steel laminations oppose the shrinkage of the mortar layers so that tensile stresses build up in the mortar and compressive stresses in the laminations. These stresses are much larger than the longitudinal ones and significantly influence the magnetic properties of the steel.

Taking into account the elastic moduli of steel, E_{Fe} , and mortar, E_m , and their respective cross-sectional areas orthogonal to the direction of the stress, S_{Fe} and S_m , and neglecting mortar creep, the maximum stresses that can be induced by a linear shrinkage ϵ of the mortar in the plane of each layer are:

- tensile stress in the mortar:

$$\sigma_m = \epsilon E_m \frac{1}{1 + S_m E_m / S_{Fe} E_{Fe}},$$

- compressive stress in the steel:

$$\sigma_{Fe} = \frac{S_m}{S_{Fe}} \sigma_m.$$

For $S_m/S_{Fe} = 3.1$, $E_m = 3 \times 10^4 \text{ N mm}^{-2}$, $E_{Fe} = 2.1 \times 10^5 \text{ N mm}^{-2}$, as we have in the cores, the above formulae give:

$$\sigma_m = 2.1 \times 10^4 \epsilon \text{ N mm}^{-2}, \quad \sigma_{Fe} = 3.1 \sigma_m.$$

A mortar shrinkage of 5×10^{-4} could therefore produce a tensile stress of about 10 N mm^{-2} , near the upper limit of mortar yield strength, and the compressive stress in the steel could approach 30 N mm^{-2} .

Relation Between Stresses and Magnetic Properties of the Cores

In order to determine the quantitative relation between compressive stress and magnetic characteristics of the steel sheet used for the dipole cores, measurements were performed on packages of "window frame" samples of steel sheet, equipped with excitation and detection windings. Variable compressive forces were applied to two parallel sides of these packages by means of suitable U-shaped yokes, and coercivity and permeability were measured by the same method as used with the permeameter [3]. The apparatus is shown schematically in Fig. 2 together with some graphs of the values of permeability and coercivity, measured at different compressive stresses, as a function of the maximum induction B of symmetrical cycles. The compression increases the coercivity and decreases the permeability by substantial amounts: the relative reduction in permeability $\Delta\mu/\mu$ is maximum at the induction values corresponding to high permeabilities.

The most conspicuous effect of the permeability reduction induced by mortar shrinkage is a change of the excitation characteristic of the cores. At any given excitation current, the value of the magnetic field on the centre line of the gap of a steel-mortar core, B, differs from that of a "dry stack" of laminations, B_0 , by an amount ΔB . The relative field reduction $\Delta B/B_0$ is a function of the compressive stress in the steel and therefore depends on mortar composition and age. The evolution of $\Delta B/B_0$ with age takes place

Fig. 1 Dipole Core Structure

Fig. 2 Magnetic Properties of the LEP Dipole Steel Sheet under Compression

with the typical mortar time constants of between 6 and 12 months: measurements on early production cores have shown that asymptotic values were practically reached after two to three years.

Fig. 3 Average Field Reductions in Aged Cores With Respect to a Reference "Dry Stack"

Figure 3.a) shows the average values of $\Delta B/B_0$ in representative samples of cores, 12 to 14 months old, produced by the two contractors, who received the punched laminations from the same factory but used cement mortars of different composition, according to their own supply and processes: it is evident that the built-up stresses are distinctly different in the two cases. For the cores of each make, two curves are shown, which correspond to the excitation cycles for 66 GeV and 100 GeV maximum LEP energies, respectively. The values of $\Delta B/B_0$ are lower at low excitation, but not very different for the two cycles and, in particular, about the same in the region of 60 GeV: at this excitation level, the induction in the return yoke corresponds to the region of high permeabilities, and the value of $\Delta B/B_0$ can be computed with a good approximation as a function of maximum $\Delta\mu/\mu$.

From the experimental values of $\Delta\mu/\mu$ at different stresses, we have thus derived the graph of $\Delta B/B_0 = f(\sigma_{Fe})$, shown in Fig. 4, which allows us to correlate the internal stresses in the steel laminations with the relative field reductions on the gap centre line at LEP energies near 60 GeV.

Fig. 4 Relative Field Reduction at about 60 GeV as a Function of the Compressive Stress in the Steel

The variations of coercivity and magnetic permeability due to mortar induced stresses modify also the field pattern in the air gap at any given excitation level. As, however, the two effects tend to compensate each other at low fields and as the steel is still far from saturation even at 100 GeV, the field quality remains within beam dynamics tolerances from injection to maximum energy.

Stress Relieving in Aged Cores

The influence of internal stresses on magnetic permeability could be seriously detrimental to the uniformity of the bending field along the equilibrium orbit of LEP, as the dipole magnets are all excited in series. The systematic field differences resulting from the specific properties of the mortars used by the two core manufacturers will be evened out in the field integrals over the assembled magnet pairs, each of which will contain a core of each make. It was feared, however, that the spread in bending strength resulting from the differences in internal stresses in the cores from each manufacturer might still ultimately exceed the tolerances by almost a factor two, if no preventive action were undertaken.

It was therefore decided to systematically relieve the mortar-induced compressive stresses in the

steel laminations of the cores by means of a partial fissuration of the mortar layers, after the cores had aged for more than 12 months. For this purpose, transverse forces are applied, by means of a hydraulic system, all along the poles, to close and open alternately the air gaps of the cores by up to ± 3 mm, thus inducing alternating flexural stresses in the yokes. The intrinsic limitation of this treatment, namely that the mortar near the neutral plane is not fissured, appeared to be acceptable after a number of tests.

The straining machine is shown in Fig. 5. It consists of a strong frame, into which the core is moved on a carriage on rails, until it is properly located with respect to the hydraulically inflatable hoses, which then apply the required pressure cycles. Appropriate dial gauges allow the operator to check that the core is finally made to recover its initial geometry. As it can be seen from the picture, the straining machine is aligned with a bench, equipped with special excitation coils and measuring coils, for the measurement of the excitation characteristics of the core (field integral versus excitation current). The ends of the excitation coils are so shaped that they can pass through the air gap when the core is shifted, on its carriage, to the measuring position.

Spread of the Dipole Bending Strength

From measurements performed on statistical samples of more than 5 % of the cores from each of the two manufacturers, it appears that the stress-relieving treatment reduces, on average, the compressive stresses in the laminations by more than a factor two. The improvement in the average values of $\Delta B/B_0$ can be seen by

comparing graphs a) and b) in Fig. 3. The improvement is obviously larger in the cores which had reached higher internal stresses: the result is a substantial convergence of the average fields of the two samples. Within each sample, the improvement varies from core to core, but in both the spread is also reduced: the standard deviations of $\Delta B/B_0$ at 66 GeV before and after stress relieving were respectively 0.097 % and 0.060 % for the cores from manufacturer A, 0.075 % and 0.056 % for those from manufacturer B.

The fraction of the mortar layers which remains undisturbed in a core after stress relieving can be computed from the results of magnetic measurements before and after the treatment, by making use of the relation between $\Delta B/B_0$ and σ_{Fe} plotted in Fig. 4. In this part of the mortar, the internal stresses will still increase with further ageing, but creep will limit them asymptotically as they slowly approach the mortar yield strength. An upper limit to the ultimate compressive stress which may be applied by the shrinkage of the non-fissured mortar in the core and the resulting ultimate field reduction $\Delta B/B_0$ at medium excitation levels can consequently be computed. This computation was performed for the cores in the statistical samples from the two manufacturers, on the assumption that their mortars would asymptotically reach their limit yield strengths of 8 N mm^{-2} and 10 N mm^{-2} , respectively. The resulting asymptotic standard deviations for $\Delta B/B_0$ would turn out to be 0.088 % for the A-cores and 0.072 % for the B-cores.

The contribution of the initial dispersion of the magnetic permeability in the steel sheets, measured

Fig. 5 Core Straining Machine and Measuring Machine

during their production, would be negligible with respect to the above values, thanks to the beneficial effect of the controlled mixing of the packages of laminations in the cores [4].

In pairing the cores from the two manufacturers, account will be taken of their excitation characteristics, as measured after stress relieving. A procedure has been defined whereby, within the groupings imposed by the limited storage facilities, cores from maker A having, inside their own population, relatively high values of B/I at the top of the 66 GeV cycles will be paired with cores from maker B having relatively low values, and reciprocally. According to available statistics, this procedure will reduce the dispersion in bending strength of the pairs by at least a factor 1.5 more than random pairing. Because of the internal correlation between B/I and non-fissured fraction of mortar existing among the cores of each maker, a reduction of the ultimate spread in bending strength can also be expected. This improvement may, however, be partly offset by fluctuations in the ageing behaviour of the cores. If we estimate the ultimate r.m.s. dispersion of the bending strength of the dipole pairs at medium fields by a simple quadratic combination of those computed for the two samples, we obtain

$$\sigma_{\text{pair},66} = \left[\frac{\left(\Delta \int_{\text{pair}} B \, ds \right)_{\text{rms}}}{\left\langle \int_{\text{pair}} B \, ds \right\rangle} \right]_{\text{asy},66} \approx 0.6 \times 10^{-3}.$$

A comparison of the statistics of measured field spreads at the tops of the two excitation cycles and of the effects of the measured dispersion in permeability in the steel sheet at the corresponding flux densities leads to predict a value of σ_{pair} between 0.07 % and 0.08 % at 100 GeV.

The B6 dipole magnet units in the LEP arcs will be made of three randomly collected pairs: the r.m.s. dispersion of their bending strengths will therefore remain below the limit of 0.05 % up to 100 GeV.

Field Integral on the Equilibrium Orbit

The dependence of mortar-induced stresses on the age of the mortar produces a variation of the relative steel permeability with time. For an accurate determination of the field integral on the centre line of the LEP magnet system at the time of operation, it is therefore desirable to have, in addition to a reference "dry-stack" magnet, equipped with measuring coils, direct information on the variation of the magnetic field in the dipole gaps in the ring as a function of the excitation current.

The presence of a thin mortar layer on the pole faces of the dipole cores, in the proximity of the shims, has made it possible to grind with high precision two small grooves on each lower pole, into which two wires could be embedded, to form a loop linking the useful magnetic flux.

The ratio of the flux linked by the flux loop to the average field on the gap centre line, which may be called "effective surface area", of the loop, has

been determined for each core in the course of the measurements of the excitation characteristics after the stress-relieving treatment. Periodic repetition of these measurements on a sample of cores has shown that the effective surfaces are stable in time, on average, to better than 10^{-4} . The measured surface areas on more than 1000 cores of each make have a gaussian distribution around a central value, with a relative standard deviation of less than 10^{-3} . As the standard deviations of the fields in the cores are also of the order of 10^{-3} , and as the flux loops of about 400 cores in each octant of LEP will be connected in series to feed an integrator, the contribution of this dispersion to the error in the determination of the field integral over the machine circumference from the measurement of the total flux will be negligible with respect to the overall calibration error of $\pm 2 \times 10^{-4}$.

The flux variation may be measured at each of the LEP acceleration cycles during normal operation. In addition, in order to evaluate the contribution of the remanent field to the field integral, the flux variation in the loops will also be measured, from time to time, during a symmetrical excitation cycle, in which the current in the dipoles will be reversed. The output of the flux loops will be generally used to calibrate the field display system which will continuously monitor the field in the reference magnet by means of measuring coils. Detailed error analysis shows that this equipment will permit to know the field integral on the LEP centre line, including end effects and transition effects, to better than $\pm 5 \times 10^{-4}$ at all beam energies above 30 GeV.

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