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Dynamic Magnetic Mesurements of Superconducting Magnets for the LHC

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Abstract

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Dynamic Magnetic Measurements of Superconducting Magnets for the LHC

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Abstract - **Several superconducting dipole magnets were manufactured in industry or at CERN as model magnets for the future LHC particle accelerator. Results of the measurements of the field quality is given for current variations in the range of those expected for the accelerator operation. We present measurements of the field errors resulting from persistent currents in the superconducting filaments, eddy currents flowing in and between the strands of the superconducting cable, and current differences between the strands of the cable.**

I. INTRODUCTION

The LHC 7 Tev proton accelerator is expected to work at the beginning of the next decade [1]. The corresponding operating field for the the main dipoles is 8.32 T for a current of 12.3 kA and is obtained by NbTi multistrand cable conductors working in superfluid helium. Several 1 m long superconducting twin aperture dipole model magnets have been manufactured in European industry and measured at CERN in a vertical cryostat. Two 10 m long magnets of similar cross section were delivered in their own horizontal cryostats and tested in the first half of 1994 [2]. The priorities of these tests were towards training performances of these magnets and measurement at high field of the magnetic field quality due to conductor positioning.

Measurement campaigns were nevertheless devoted to understand the parameters of the superconducting cables and coils that dominate the field quality at injection (B = 0.58T) in the LHC accelerator and during ramp sweeps similar to those expected during beam acceleration. Time dependent field errors have been measured and are thought to be related to inhomogeneous current distribution between the strands of the cable [4], [5] and to the interstrand resistance [6].The difficulties encountered at the running-in of the Tevatron [3] and of Hera with time varying fields are expected to be enhanced for the LHC due amongst other problems, to the wider superconducting cable used.

II. DEFINITION OF FIELD ERRORS

The field $B(B_x,B_y)$ is expanded relative to the main field B_1 of the magnet at $x = r_0$:

$$B_y + iB_x = B_1 \sum_n (b_n + ia_n)(z/r_0)^{n-1}$$

Here n=1 is a dipole field, n=2 is a quadrupole field etc., z = x+iy, and i is the complex unit. The b_n and a_n represent the normal and skew relative field error at $x=r_0$.

III. PRESENT MAGNETIC MEASUREMENT EQUIPMENT

A. *Measuring coils*

The magnetic field components of the 1 m long models are measured with harmonic coils assemblies mounted on a rotating shaft and immersed in the superfluid helium. The coils cannot be displaced along the magnet's axis. It is not possible to measure axial field oscillations having a wavelength of the transposition pitch of the superconducting cable. The manufacturing of dedicated coils having a length corresponding to a integer number of transposition pitches would allow measurements insensitive to these kind of oscillations. Unfortunately, a compromise for the choice of the coil lengths is complicated by the different transposition pitches of the cables used. On the other hand, it is possible to connect in series all the coils assemblies located along the axis and to measure field harmonics integrals.

The 10 m long model magnets are delivered in their own horizontal cryostats whose cold bores are equipped with a special measurement cryostat [7]. A 14 m long rotating shaft can be displaced axially with high precision. It holds at the end harmonic coils assemblies of various lengths, easily interchangeable during a test. A 30 mm long coils assembly allows to measure predicted effects related to the transposition pitch of the cable (0.11 to 0.13 m). The maximum coil length is 0.75 m, rendering difficult the measurements of integral effects which are varying with time.

B. *Field measurement method in changing field*

Measuring the field harmonics during magnets' current sweeps brings another complication. The change of the field during the several seconds needed for a revolution of the coils assemblies introduces, in the integrated voltage measured as a function of the angle, non-linearity's seen as errors on the harmonics, mainly the lowest ones.

Two characteristics of the measuring device are used to eliminate to first order these disturbances. The measurements are performed with both directions of revolution and averaged. The current changes with a constant rate, the shaft rotation rate is constant and the same in both directions. The harmonic components that change linearly with time, i.e. the dipole component and all the harmonic components due to the geometry of the magnet coils, do not therefore bring any error. It is of course the average value of that component, over the time needed to make both turns, that will appear in the results.

The compensation scheme of the coil assemblies renders the measurement insensitive to the dipole term. The system measures only the variation with current of the higher harmonics which have a much lower amplitude. The dominating signals in these measurements come from the interstrand eddy currents in the superconducting cable. Their contributions give a constant effect on the field for a given ramp rate. The measurements are therefore not affected.

C. *Measurement errors*

The two following checks were performed to verify that second order effects do not perturb the results.

The rotating coil assemblies are composed of two external coils located symmetrically on each side of the central one used for the compensation of the dipole term. Separated measurements with these two external coils must give equal even harmonics but inverse signs for the dipole term and the higher odd harmonics. Non-linearity's due to changing odd harmonics at a ramp rate of 24 A/s are measured to affect the quadrupole term by less than 0.05 mT at 10 mm and the octupole by less than 0.001 mT.

The ramp sweep must double the error on the results if the rotation rate of the shaft is divided by two. The equivalent measured errors at 10 mm for a ramp rate of 24 A/s are smaller than 0.01 mT for the quadrupole and the sextupole and than 0.001 mT for the octupole harmonic.

IV. EFFECT OF CURRENT DISTRIBUTION BETWEEN THE STRANDS

A. *Axial oscillations of the field*

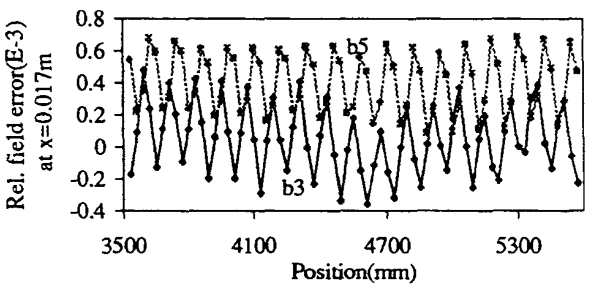

Fig.1a. Axial variation of sextupole(b3) and dodecapole(b5) errors in the 10 meter model MTP1A2 at 2 Tesla. The oscillation wavelength corresponds to the twist pitch of the cable(120mm). The measurements are started 10 min. after current stabilization, duration ca. 2 hours.

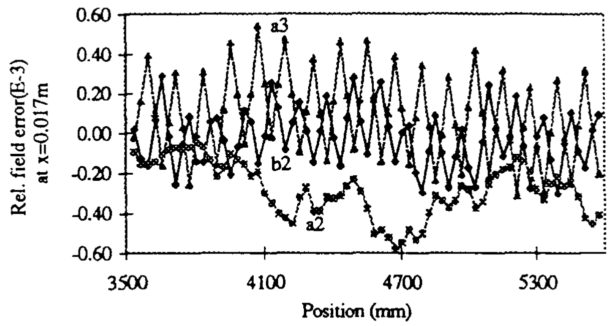

Fig1b. Axial variation of quadrupole(b2) and skew sextupole(a3) in the 10 meter model MTP1A2 at 2 Tesla. The phase of a3 is the same as of the normal sextupole. Curiously the skew quadrupole(a2) does not show the same oscillation.

Axial variations of the field were measured on two 10 m long dipole models by a 30 mm long coil placed at the end of the harmonic measurement shaft. The measured oscillations are correlated to the transposition pitches of 120 mm and 130 mm respectively. They are observed with different phases for all normal and skew harmonic components (Fig. 1). The amplitude of this effect is measured to be of about the same at 0.6 T (LHC injection field) and 8.5 T.

B. *Time dependence of the oscillation amplitude*

On the 10 meter model MTP1A1, the amplitude and phase of these oscillations vary with time in the first few minutes after stabilization at 0.38 T following a ramp from high field (Fig. 2 and 3). This time dependence, giving a corresponding time constant of about 2 min., is believed to be related to the low interstrand resistance, 1.4 $\mu\Omega$, of this magnet. Due to lack of time, it was not possible to make the same measurement on magnet MTP1A2 having an interstrand resistance of 7 $\mu\Omega$.

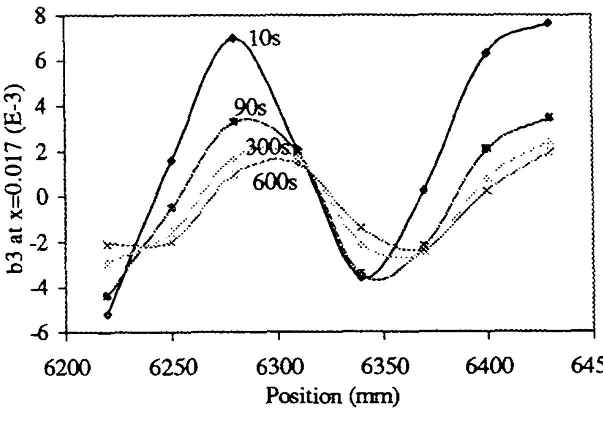

Fig 2. Sextupole error along a bore of MTP1A1 after a ramp with 50 A/s, as function of time. The field is 0.38 T.

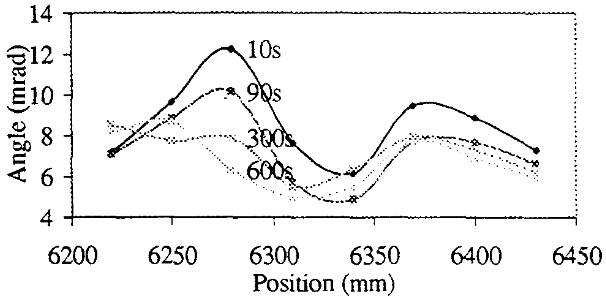

Fig 3. Deviation of the direction of the main field from the mean along a bore of MTP1A1 after a ramp with 50 A/s, as function of time. The field is 0.38 T.

C. *Time dependence of the field integral over the whole magnet*

As can be seen in Fig. 2, not only the error amplitude, but also the mean value over one transposition pitch varies with time. To verify this, integrals of the field harmonics over a whole magnet were measured on a 1 m long model after performing a ramp. A decay with a similar time constant of about 2 min. is clearly visible (Fig. 4) and followed by a much slower variation. This indicates that a temporal redistribution of current between the strands gives a net effect on the magnetic field integrated over the length of a magnet.

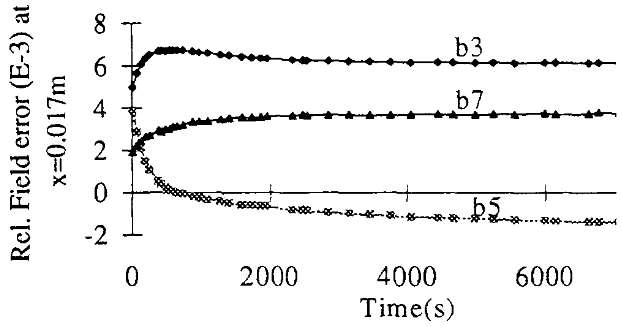

Fig.4. Integral of field errors of dipole symmetry as function of time along a bore in the 1 meter model MTA1E, after a ramp with ramprate of 50A/s. The field is 0.38 Tesla.

This 2 min. time constant can hardly be attributed to single loops over half a transposition pitch of the cable. These single loop currents give measurable effects with a much faster variation (see sect. V). The time constant is furthermore observed to be approximately the same for magnets having a straight part of 0.6 m and of 10 m respectively. The fact that this time constant does not depend on the magnets length seems to exclude an effect due to the termination resistance of the cable.

Note that a similar time constant was measured on several 1m long LHC models, together with a much slower variation [8]. The long time constant is perhaps related to the soldered connections to the current leads at the end of the cable.

TABLE I

MEASURED INTERSTRAND FIELD ERROR DURING THE RAMP IN TWO 10M LONG MODELS. THE ERRORS HAVE BEEN SCALED TO A RAMPRATE OF 6.6mT/s (=8T/20min) AND ARE EXPRESSED RELATIVE TO THE LHC INJECTION FIELD OF 0.58T AT X=0.01m. IN UNITS OF (1.E-4)

Error	MTP1A1 aperture 1	MTP1A2 aperture 1	MTP1A2 aperture 2
b_1	87.9		10.8
b_2	0.96	-1.11	0.59
a_2	-10.8	0.89	-1.82
b_3	-4.6	0.94	0.68
a_3	0.17	-0.19	-0.11
b_4	-0.45	-0.13	0.034
a_4	-0.82	0.079	-0.15
b_5	-2.1	0.045	-0.0034
a_5	0.34	-0.018	0.0008

V. Interstrand Eddy Currents During Ramping

These errors are proportional to the twist pitch and inversely proportional to the interstrand contact resistance [9] and their time constant is of the order of a second in the models. They can be separated from the errors in section IV by performing the measurement over a integer number of twist pitches or by taking a sufficiently long measurement coil. In table I the measurement results of the two 10 meter long models are compared, while Fig. 5 shows how the actual hysteresis loops look like at different ramp rates. The errors are quite different for the two magnets, indicating a different interstrand contact resistance. From field and loss measurements the average contact resistance was estimated to be 1.4 $\mu\Omega$ for MTP1A1 and 6-8 $\mu\Omega$ for MTP1A2.

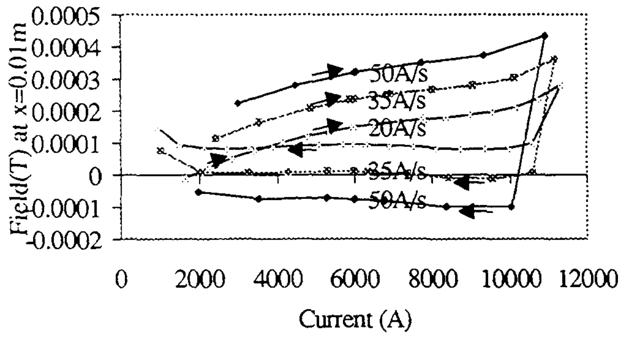

Fig. 5. Sextupole error during cycling in the 10 meter model MTP1A2. The curious form of the loops is due to the opposite sign of the sextupole error coming from interstrand eddy currents and strand filament magnetization.

VI. Persistent Currents in Strand Filaments

The field errors due to the persistent currents in the superconducting filaments are hardly separable from those described above. The varying interstrand current redistribution is likely to influence the filaments magnetization. The best way seems to be a measurement at very low ramprate with a long measurement coil.

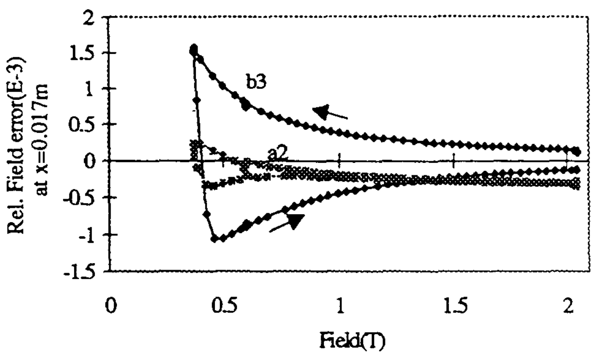

Fig. 6. Sextupole(b3) and skew quadrupole(a2) errors in the 10 meter model MTP1A2 due mainly to persistent currents in the strand filaments. Measured by cycling at 2A/s with several stops to check for time dependence. The small skew quadrupole is believed to be due to difference in filament magnetization in upper and lower pole.

Fig.6 shows a measurement in a 10 m model, where the strand filament has a diameter of 7.8 μm. The small skew quadrupole observed is believed to be due to a difference in magnetization between upper and lower pole.

VII. Implications for Future Measuring Systems

Three different time dependent effects will therefore have to be measured on the LHC magnets. The short and intermediate ones are clearly correlated with the transposition pitch of the cable. The fastest effect attributed to coupling current between the strands is also known to depend on the longitudinal position, mainly in the ends where the compression of the cable is appreciably different.

The measurements performed have shown that a higher interstrand resistance is needed to avoid prohibitive values of all harmonics during ramp sweeps. There is some hope that a higher interstrand resistance would also decrease the current sharing effect with its 2 min. time constant.

Meanwhile two solutions are presently under study to measure reliably the time dependent field errors over the full length of the magnets, which are the only relevant measurements for the use of these magnets in a real accelerator

- Connecting in series two coils assemblies separated longitudinally by an empty space adapted to the transposition pitch would render the measurements insensitive to longitudinal oscillations. This space can easily be dimensioned for different transposition pitches.
- A 14 m long coil can be assembled in a rotating shaft with intermediate bearings. The consecutive longitudinal empty spaces must then also have the right length to render the measured signals insensitive to the cable pitch.

Conclusions

The measured field quality of the LHC model magnets indicates important variations with the current ramp rate and with time at injection field. These errors are linked to coupling currents between the strands of the superconducting cables. Interstrand resistance of at least 10 μΩ seems desirable from beams optics consideration. More measurements will be performed to understand why the axial variations of the field correlated with the transposition pitch change with time after a current ramp.

Acknowledgment

The various persons involved in the operation of the tests and in the tedious measurements have to be thanked for their support and their devotion.

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