Twin Rotating Coils for Cold Magnetic Measurements of 15 m Long LHC Dipoles

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***Abstract*—We describe here a new harmonic coil system for the field measurement of the superconducting, twin aperture LHC dipoles and the associated corrector magnets. Besides field measurements the system can be used as an antenna to localize the quench origin. The main component is a 16 m long rotating shaft, made up of 13 ceramic segments, each carrying two tangential coils plus a central radial coil, all working in parallel. The segments are connected with flexible Ti-alloy bellows, allowing the piecewise straight shaft to follow the curvature of the dipole while maintaining high torsional rigidity. At each interconnection the structure is supported by rollers and ball bearings, necessary for the axial movement for installation and for the rotation of the coil during measurement. Two such shafts are simultaneously driven by a twin-rotating unit, thus measuring both apertures of a dipole at the same time. This arrangement allows very short measurement times (typically 10 s) and is essential to perform cold magnetic measurements of all dipoles. The coil surface and direction are calibrated using a reference dipole. In this paper we describe the twin rotating coil system and its calibration facility, and we give the typical resolution and accuracy achieved with the first commissioned unit.**

I. INTRODUCTION

The LHC quality assurance plan foresees the test of all superconducting magnets at superfluid helium temperature of 1.8 K. At present, up to twelve test stands are foreseen to make cryogenic and quench performance tests as well as magnetic field measurements up to the nominal field values on all lattice magnets (about 1200 dipoles and 400 quadrupoles). To accomplish this task within the given time, highly efficient test equipment and procedures have to be devised. User-friendliness, ruggedness and reliability are the main ingredients required for such systems to be operated around the clock over several years. Similar tasks, however for about 3 times less magnets, were successfully accomplished for HERA [1] and RHIC [2], while conceptual ideas and prototypes were developed at SSC [3].

In 1994, during the initial phase of LHC design, automated test equipment for dipoles which at that time had a length of 10 m, was successfully commissioned [4]. It consisted essentially of a single, rotating search coil with a length of 750 mm which was driven stepwise by a long and slender ceramic shaft along each of the two apertures of the magnets. However, with a final dipole length of 14.2 m together with the limitation in test duration (below 48 hours per dipole), number of benches, space and budget, the above equipment was no longer acceptable.

Based on the experience gained previously with long, slender ceramic structures, an R&D program was launched to devise and to construct long rotating coils which, in pairs, measure simultaneously the fields over the total length of both dipole apertures, thus reducing the actual measuring time at one field level to below 10 seconds.

II. COIL SHAFT DESIGN

During the cold tests the LHC dipoles are equipped with an anticryostat (a warm bore) with a 40 mm inner diameter. This imposes a maximum outer diameter of 36 mm to the rotating coil, to leave enough clearance for installation and operation. A single coil shaft, more than 15 m long and with a 36 mm outer diameter is not feasible using present technology. Mechanical tolerances, bending stiffness requirements, equipment handling and, last, cost issues have driven the design of the shaft towards a modular solution. A 16 m shaft is obtained by assembling 13 modules of approximately 1.25 m length each. This covers readily the 15 m length of the LHC Dipole and the adjacent corrector magnets. All modules are identical and designed to allow interchange of position and easy management of spares. The module cross section is shown in Fig. 1. Ceramic (Al_2O_3) has been chosen as support material because of the high rigidity and geometric stability, both mandatory for proper calibration of the coil sensitivity. In addition ceramic is non-magnetic and non-conducting, thus can turn freely in a magnetic field without perturbing it. Because of their hardness, ceramic materials are difficult to machine. This has driven the design of the support towards a simple geometry, i.e. a hollow cylinder equipped with tangential coils.

Winding of the coil directly on the ceramic support is in principle possible. It is however a cumbersome technique, executed by hand, without guarantee of reproducible results. We deemed such a solution not suitable for the production of the large number of modules required for the series tests of the LHC dipoles. We have developed in the past a technique to wind coils on glass-reinforced epoxy supports using a dedicated winding machine [5]. This winding process can be extrapolated to the production of several tens of units. Each coil can be calibrated individually and matched to other coils

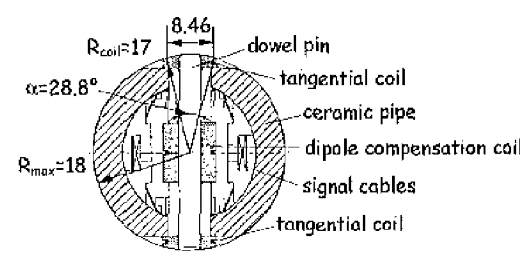

Fig. 1. Cross-section of a module showing details of support and coils.

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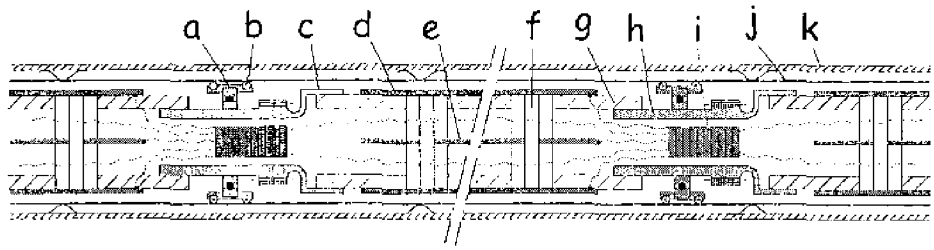

Fig. 2. Schematic assembly of a module showing the main components: (a) ball bearing, (b) bronze cage with roller, (c) Ti-bellow, (d) tangential coil, (e) central coil, (f) dowel pin, (g) ceramic support, (h) SiN flange, (i) cable connector, (j) anticryostat, (k) cold bore.

with the same cross section to achieve the highest possible dipole compensation ratio. We have therefore decided to adopt this technique, which involves mounting the single coils onto reference surfaces machined along the outside of the ceramic pipes and fixed to it with precise dowel pins. Flatness and parallelism of this fitting is better than 20 μm.

In principle a single coil would be sufficient to perform the measurement. Two symmetric coils, however, offer several advantages such as availability of a spare, the possibility to verify the measurement accuracy using symmetry properties, and better rotational inertia properties. For the accurate measurement of the higher order harmonics it is common practice to suppress the contribution of the dipole field from the signal of the measurement coil. In our case this is done analogically, subtracting from the signal of the tangential coil the one produced by the coil housed in the central hole of the module. The compensation coil is maintained in position by the same centering pins that fix the two tangential coils.

The sensitivity of a tangential coil to a harmonic of order n depends strongly on the opening angle α of the coil. In particular the sensitivity of the coil is zero when the harmonic order is equal to a critical value $n = 2\pi/\alpha$. The opening angle is a geometrical quantity defined by the coil rotation radius and the width of the coil (see again Fig. 1). The coil rotation radius is maximized to increase the sensitivity to higher order harmonics. In our case this radius is limited to about 17 mm by the space available in the anticryostat. We have then chosen a nominal opening angle of 28.8 degrees, that corresponds to zero sensitivity to the harmonic of order 12.5. A dedicated calibration in a reference quadrupole showed that this value is between 12.3 and 12.7. This choice guarantees acceptable sensitivity for harmonics 11 and 13, and results in a coil width of approximately 8.5 mm, which is within the feasible range for the winding technique adopted. Note that decreasing the coil width to push the critical order towards a higher harmonic would result in a smaller coil, more difficult to manufacture and mount accurately, and with higher errors in the sensitivity to the harmonics.

The length of the coils and the width of the gap necessary to house the junction between the modules have been designed to reduce the effect of the field periodicity (periodic pattern) induced by the twist of the strands in the superconducting cables [6]. To this purpose, the length of each coil and the sum of the gaps has been chosen equal to an integer multiple of the nominal cable twist pitch. This guarantees that the effect of the periodic pattern cancels in the total field integral. Furthermore, the longitudinal position of the shaft must be carefully chosen in order, *inter alia*, to avoid end effects. A number of different, standardized longitudinal positions have been defined and optimized for the exigencies of magnetic measurement of the dipole and associated correctors, quench detection and calibration. Moreover, as the coil includes an additional module, in situ cross checks can be made by shifting the axial position of the coil by the length of one unit.

As shown in Fig. 2, each coil module is completed at one end with a ceramic (SiN) flange (h) that houses an integrated ceramic ball bearing (a) in a brass cage equipped with beryllium-copper rollers (b). At the other end a small Ti-bellows is glued on the module (c). The titanium bellows has a flange mating with the opposite ceramic support, so that the modules can be mechanically assembled. The function of the bellows is to accommodate the curvature of the dipole cold bore (k) (0.4 mrad at each junction) as well as the anticryostat (j) centering errors in vertical and horizontal direction. It guarantees however high torsional rigidity, as required for the measurement of the dipole field direction. In addition, its small size and high electrical resistivity are such that eddy current effects are negligible.

Once assembled the modules are supported at each junction by the ceramic ball bearings, either directly through the flange or indirectly through the bellows. The outer races of the ball bearings sit in bronze cages, fitted with fixed and spring-loaded rollers that allow longitudinal movements along the anti-cryostat as necessary during installation and removal of the complete shaft. During the rotation of the shaft the outer race of the ball bearings and the bronze cage remain stationary. Hence no perturbation due to induced eddy currents can occur. The frictional torque for the whole shaft is 0.03 Nm, extremely small thanks to the high quality of the ball bearings. This torque results in a maximum twist of 0.0026 mrad along the shaft.

In order to pass the signals from all coils in a modular manner we have fitted each module with 39 twisted pairs guided inside the ceramic pipe aside the central coil (see Figs.1 and 2) and equipped with micro-connectors (i) at both ends of each module. This system allows interchanging of modules without need for recabling the complete shaft. The main disadvantage is that the signals from modules at the far end of the shaft are connected to the acquisition system through all other intermediate modules. This leads to an increased number of interconnections.

The link from the rear of the coil to the outside rotating unit (see later) located at a distance of 1.4 m, is made by an interconnection ceramic pipe fitted with the necessary cables and plugs. In addition the end of this interconnection pipe is equipped with a reference surface that provides the angular fiducial for all coils.

III. ROTATING UNIT

The two coil shafts are driven by a Twin Rotating Unit (TRU) shown in Fig. 3. Each unit includes a stepping motor with 7:1 reduction gearbox, necessary to achieve the nominal rotation speed of 1 Hz with variations smaller than 3%. The power driver for the stepping motor is on-board and shielded from the signal cables, so that the coil signal is not affected by high-frequency noise. The operation of the unit is remotely controlled by the acquisition software.

Downstream of the motor a torque meter, an elastic coupling and a linear potentiometer (screw-driven by the shaft and monitoring its angular position) are provided to increase the safety of the mechanism.

The angular position of the shaft is given by an angular encoder with 4096 counts per revolution plus a "zero" pulse on a separate channel. The encoder housing is rigidly connected to an electronic inclinometer, giving an absolute reference for the orientation of the encoder "zero". The reading of the inclinometer is used to establish the relation between the field direction, measured in the reference frame determined by the "zero" pulse of the encoder, and gravity direction.

A precision coupling is used to connect the coil reproducibly to the rotating shaft. Furthermore the TRU side of the shaft is provided with a reference surface, approximately aligned with the reference surface on the coil shaft. The relative angle between the two reference surfaces is verified every time that the shaft and the TRU are assembled.

For the connection of the signal cables we have rejected the possibility of sliding connectors on the basis of excessive size and cost for the very large number of contacts required (78 for each shaft). The coil cables emerging from a shaft are connected to a flat cable in the TRU that is wound up in a spiral around the rotation axis and terminates in a fixed connector. This configuration allows a maximum of three complete revolutions of the shaft. Each measurement cycle consists of three turns in alternating direction, during which the flat cable winds and unwinds. The central turn in each direction is used to measure while the other two turns serve to accelerate and decelerate smoothly. The final measurement results are obtained from the average of the forward and backward revolutions. As can be seen in Fig. 3, each rotation unit can be manually displaced axially by the length of one coil module, providing a very efficient means of cross calibration.

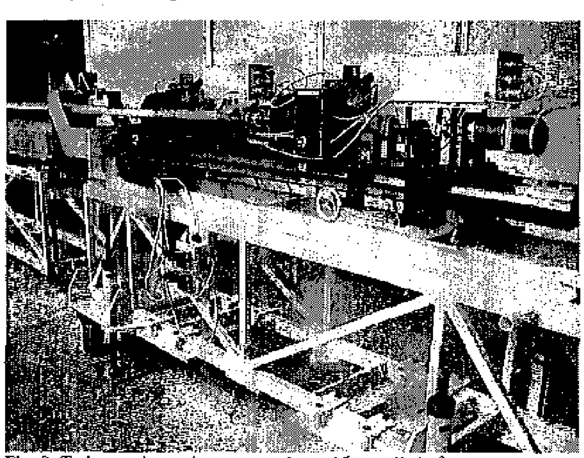

Fig. 3. Twin rotating unit, connected to a 15 m coil shaft.

IV. ACQUISITION SYSTEM

The voltage signals from the rotating coils are first pre-amplified and then read-out simultaneously by a battery of 52 digital integrators. The integrators are triggered in two groups by the angular encoders connected to the two shafts. The integrated voltage signals delivered by the integrators are equal to the flux changes through each measuring coil for all angular steps, and rotation velocity variations during these measurements are compensated up to the first order. A real-time processor configures the integrators and reads the integrated voltages. Overall control of the power supply, of the precision current reading, of the motor rotating the shaft and of the integrators is achieved using LabVIEW software running on a SUN Ultra-2 workstation.

V. SYSTEM CALIBRATION

We have adopted a sophisticated calibration procedure to achieve the required precision in the measurement of dipole strength and direction. This is mainly required in order to compensate for the angular tolerances inherent in the assembly of the coil segment (see results in the next section), as well as to monitor the geometrical stability of the coils over several years.

The shaft calibration is carried out on an auxiliary bench, provided with a water-cooled 0.5 T reference dipole with a length of approximately 1.5 m, well above the length of a single coil module. The reference dipole is mounted on a motorized vehicle that can scan the whole length of the shaft under calibration. This magnet has been NMR-mapped and is fitted with a fixed reference NMR probe, used to scale the whole field depending on the exact current applied. For the field direction we use as fiducials two reference surfaces machined on the magnet poles. The angle between the dipole field and reference surfaces was measured independently with an AC search coil method. The tilt of the magnet on the calibration bench is constantly monitored with two inclinometers mounted on the reference surfaces.

Each coil of the shaft is used in turn to measure the reference field and its direction. Relating the measured field strength to the NMR map it is possible to calculate the effective coil surface. Similarly, the measured field direction is related to the information on the real field inclination, the inclination of the encoder on the TRU and the relative tilt between the reference surfaces on the TRU and on the shaft to calculate the twist between the shaft reference surface and the coil under calibration. This calibration leads to an estimated relative accuracy of 10^{-4} on the dipole strength, and 0.2 mrad on the dipole direction.

Note that the relative angle between the reference surfaces on the shaft and on the TRU may in principle change from the calibration bench to the test bench, and has therefore to be taken into account.

VI. Measurement results

A. *Field measurements*

We have used the long coils during tests of the first two 15 m long, MBP1A1 and MBP2N1 prototype dipoles. Here we report as an example results from the measurements performed on MBP2N1. The first result of interest is the field integral and the effective magnetic length, defined as the ratio between integrated field and the field measured in the center of the magnet. As previously mentioned, the coils do not cover the full length of the magnet because of the gap between modules. For the calculation of the field integrals we have therefore corrected for the "missing" length assuming that the field in a gap is the average of the values measured by the two neighboring coils. In the case of the gap between a coil covering a magnet end and a coil inside the straight part, the "missing" field has been assumed equal to the one measured by the coil in the magnet. The resulting field integrals measured at the nominal operating current of 11.75 kA (8.3 T) are 119.46 Tm (in aperture 1) and 119.53 Tm (in aperture 2). From these integrals, and the value of the field measured in the center of the magnet we have then computed the magnetic length. The computed magnetic lengths of the two apertures are 14.407 m (aperture 1) and 14.413 m (aperture 2), with a relative difference of 6×10^{-4}.

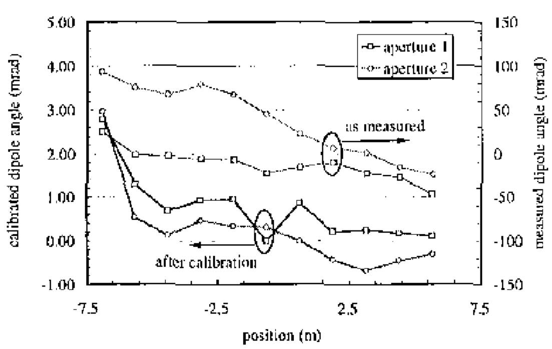

Fig. 4. Result of field direction measurement in the MBP2N1 dipole prototype. The measured data (right axis) have been corrected using the calibration curve obtained in the reference bench, obtaining the real field angle after calibration (left axis).

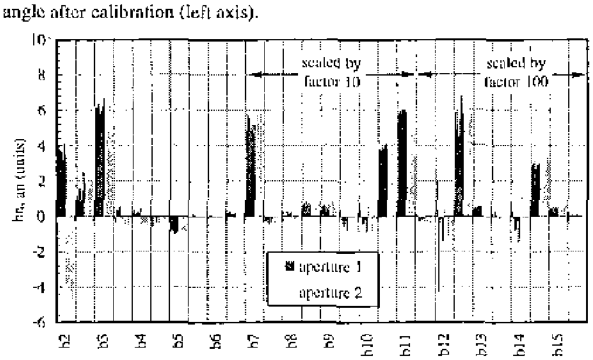

Fig. 5. Result of harmonic measurements in the MBP2N1 dipole prototype. Note the scaling factors applied for order higher than b7.

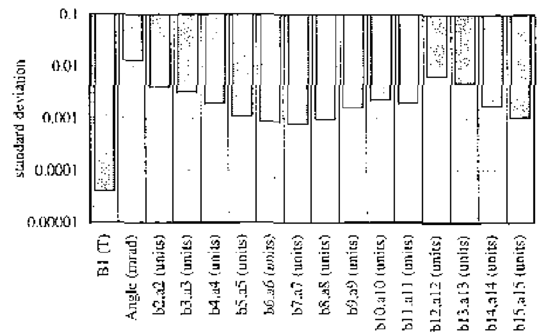

Fig. 6. Average reproducibility (random error) of dipole field, field direction and main harmonics.

The dipole field direction along both magnet apertures can be seen in Fig. 4. We report there the measured values and the values after the correction established in the calibration bench (see previous section)[1]. Comparing the two curves we see that the shafts have a twist in the range of 70 and 120 mrad. This twist is due to the assembly tolerances and is corrected by the calibration below the mrad level, where the features of the magnet become visible. Both apertures have a very good straightness, with a twist from connection end to the non-connection end of less than 1 mrad. The large twist at –7.5 m is probably due to a systematic end effect at the magnet connection end.

For harmonic measurements we use an analog compensation of the dipole component. The typical compensation ratio obtained on the various coil modules are in the range of 350 to 1000. In Fig. 5 we report the multipoles measured in the two apertures of MBP2N1 at intermediate current (9 kA), where the field quality is dominated by the superconducting coil geometry. Their value is given relative to the dipole field and scaled by a factor 10^4 (i.e. in *units*). Each bar in the graph corresponds to one coil, and the two apertures are plotted side by side. Note that for this measurement the acquisition of all coils in one aperture was performed simultaneously, requiring about 10 s. Looking at the results we see that the allowed multipoles of order higher than 7 have an appreciable strength. They are a characteristic of the coil geometry and we expect them to be constant along

[1] Since the calibration facilities are still being commissioned, at the time of writing only the relative angle in each aperture is available.

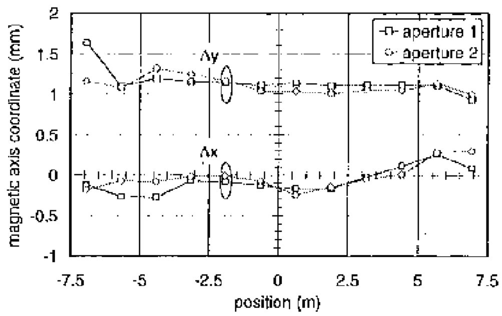

Fig. 7. Magnetic axis coordinate in the reference frame of the rotating coils, as computed using the measured harmonics of order 10 and 11.

the magnet length and equal in both apertures, as indeed is found experimentally. It should be noted that, in spite of the fact that the tangential coils have zero sensitivity at harmonic order 12.5, the measured values of b_{13} and b_{15} are largely constant, as expected, and in reasonable agreement with the value computed for the 6-block coil geometry (b_{13}=0.08 units @ 17 mm, b_{15}=0.03 units @ 17 mm).

Fig. 6 shows the typical reproducibility achieved, obtained as the standard deviation over several (20) consecutive measurements. The random error on the dipole is about 4×10^{-5} [T], the angle is constant within 0.01 mrad and the harmonics are affected by a random error below 0.01 units. The random error peaks between harmonic 12 and 13, where the coil sensitivity goes to zero.

The harmonics in Fig. 5 are reported in the reference frame of the rotating coils, essentially determined by the position of the anticryostat. This is suspended inside the cold bore and not necessarily aligned with the geometric axis of the dipole. Indeed the results show large skew, high-order non-allowed harmonics. The location of the magnetic axis relative to the coil center has been computed using the measured harmonics of order 10 and 11, assuming that the value of the harmonic of order 10 is entirely due to feed-down from the order 11. In Fig. 7 we show the coordinates of the magnetic axis in the reference frame of the rotating coil. The systematic vertical offset found can be explained by the weight of the coil, displacing the anti-cryostat downwards on its flexible supports. Horizontal displacements, on the other hand, fit well with expected mechanical tolerances.

Finally, it is found that for the alignment of the magnet in the ring the magnetic axis should be transferred to the magnet fiducial reference frame. This operation would require knowledge of the lateral position of each coil, which is impossible to get with a solid shaft. Therefore a travelling probe, described elsewhere in this conference [7], has been designed and implemented for this purpose.

B. Quench location

As we have anticipated, the shafts can be used to localize the origin of a quench and follow its propagation [8]. Fig. 8 shows as an example the typical signals that are obtained during the initiation (precursor) and early development of a quench. Thanks to a good compensation among coils it is possible to clearly distinguish the signal features associated

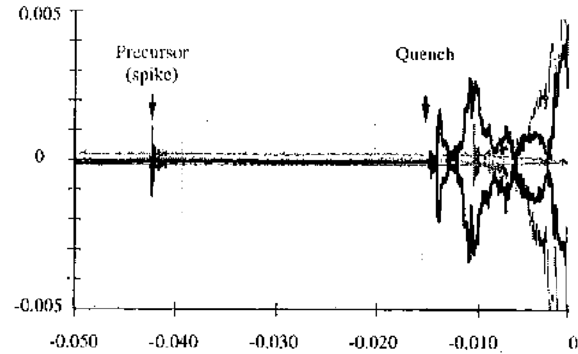

Fig. 8. Quench location signals from coils on the shaft (vertical axis in [V]) vs. time (horizontal axis in [s]).

with the current redistribution in the cable during a quench. Furthermore the signal level is well above the background noise.

The use of the same equipment for magnetic measurement and quench location is mandatory to increase testing efficiency. Thanks to the satisfactory performance obtained the long shafts will be the only additional diagnostic needed for quench studies during series tests.

VII. CONCLUSIONS

The initial experience with the long coil shafts and the rotation units show that they can meet the tough requirements for the series measurements of LHC dipoles in terms of both precision and reliability. The possibility to measure simultaneously a whole magnet, and their use for other measurements such as quench location, has provided the major productivity boost that was necessary to attack series measurements of the LHC dipoles.

The system is still being improved, e.g. in the areas of vibration control and mechanical stability of the shaft in torsion. Much effort is being devoted to the debugging and fine-tuning of the related software tools.

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