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Design and Test of the Benches for the Magnetic Measurement of the LHC Dipoles

J. Billan, J. Buckley, R. Saban, P. Sievers, L. Walckiers

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Abstract - **The magnetic measurement of more than 1300 LHC dipoles comprises the content of higher harmonic field components, field direction and field integrals. The measurements will be carried out along a warm bore installed inside the magnet cold bore, thus allowing the use of rotating coils at room temperature. This coil, together with Hall and NMR detectors is mounted at one end of a 12.5 m long shaft which is specially designed for very high rotational stiffness and which is controlled from its far end by a motor, an angular encoder and a level meter, all standard components placed outside the magnetic field without space restrictions. Particular emphasis has been put on the user-friendliness of the bench and its automated, computer-controlled operation requiring a minimum of staff, an important issue during production measurements of large series of magnets. The bench and its performance and precision achieved during its commissioning are described.**

I. INTRODUCTION

The measurement of the magnetic field of long, high strength superconducting dipoles forms an important part of the commissioning of the magnets for accelerators, as recently experienced at the HERA e^- p^+ collider, and for the future SSC and LHC p^+ p^+ colliders. Although the basic techniques for the actual measurement and analysis of the field quality, using rotating coils, Hall plates and Nuclear Magnetic Resonance (NMR) devices (see e.g. [1] and further references therein), are well suited also for the measurement of multi-tesla fields, they have to be adapted to the particular environment imposed by long superconducting magnets. In order to avoid measurements inside the evacuated cold bores, warm bore anti-cryostats are inserted into the cold bores, allowing for measurements to be made at ambient temperature and atmospheric pressure.

Basically two measuring principles exist. The first consists of a mole-type device [2],[3] which travels along the aperture and which uses flexible cables from the outside, field free region for the input and output signals. This mole is fitted in addition to the actual field sensors, with motors, angle encoders, gravity level meters, etc., which all have to operate properly in an extremely limited space and in elevated magnetic fields. The second solution consists of a probe, equipped with only the field sensors, while all other services (motors, encoder, level meters) are placed at the outside of the magnet in the field free region with no limitations on space. This allows the use of standard components. In this latter case, the transmission of the required displacements, orientations and rotations is established mechanically via a long shaft. To achieve the necessary precision, in particular of the rotation of the coil, the shaft must have a very high torsional stiffness and rotating supports with low friction. It must also be made of material of high electrical resistivity to avoid eddy currents, magnetic forces and twists induced during its rotation. In view of the very limited time allowed for R+D of the LHC prototype dipole measuring system, the second solution was pursued since the only essential and critical item to be newly developed, was the shaft. Moreover, this solution also allowed the design of a measuring bench with a high degree of ruggedness, automatization, user-friendliness and with minimum content of labour of the measurements, which is an important aspect in view of the production measurement of a large series of magnets.

II. GENERAL LAYOUT

Fig. 1 shows a side view of the dipole measuring stand. The cryostat-dipole unit to be tested at superfluid helium temperature has a length of nearly 12 m and a weight of 23 t. Current and cryogenics are connected through the supply box on its left side.

Along each of the two apertures, 180 mm apart, a warm bore anti-cryostat [4] is installed which allows for an accessible diameter of 35 mm at ambient temperature over the total length of 13.8 m of the structure. On the downstream side of the dipole the magnetic measuring bench with an overall length of 14.7 m and a weight of 5.6 t is installed. It consists essentially of a carriage with a unit to rotate the 12.5 m long drive shaft and the measuring coil at its opposite end. This unit is axially mobile to position the coil along the magnetic field over its length of nearly 10 m inside the anti-cryostat. Prior to each scan the coil, and in particular its orientation, is checked in the field of a short normal conducting

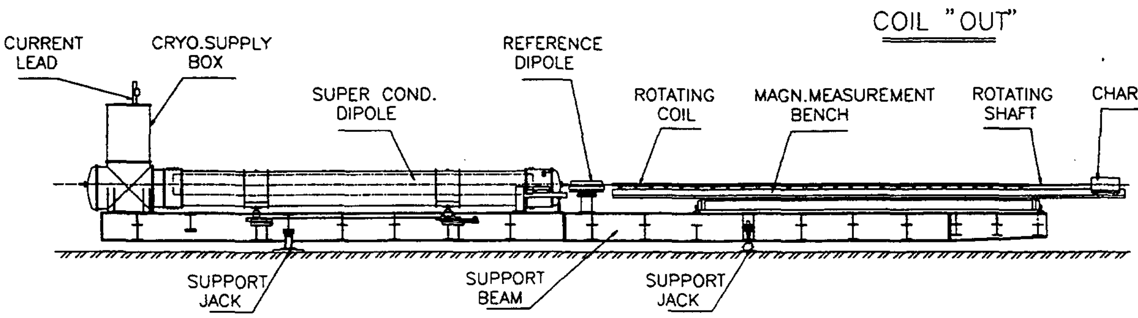

Fig. 1. Test stand for LHC prototype dipoles. The supply box, the magnet and the measuring bench are installed on a common girder which allows to make tests with the magnets tilted by at most ± 1.5%.

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reference dipole (see Fig. 1) with well known field strength and direction. All components are placed onto a common support girder of 27 m length, which permits measurements with the magnet inclined by ± 1.5 %, to simulate the tilt of the LEP/LHC tunnel.

III. MEASURING BENCH

The carriage, carrying the rotating unit for the shaft, is driven on linear ball bearings and precision rails by a d.c. motor, also mounted onto the carriage and engaged via a pinion to a rack on the stationary support of the bench. The axial position is recorded with an angular encoder on the carriage and engaged to the same rack. A precision and reproducibility of ± 0.1 mm is readily achieved over the total range of 13.5 m. Its absolute length, independent of temperature variations of the structure will be measured by stretching along the bench an invar-wire of well defined length. This should allow determination of the field integral $\int B\, dl$ with a precision of better than 10^{-4}.

The layout of the rotating unit on the mobile carriage is shown in Fig. 2 . The signal cables from the coil pass through the hollow shaft and through the rotating unit and emerge at its end in form of a spiral which allows for 3 turns of the unit of which one is used for smooth acceleration before activating the measurement of the field over one turn. The rotation is made by a micro-stepping motor (5×10^{4} steps/turn) and a 1:4 reduction. This provides the capability to place the shaft into precise and reproducible angular positions, opening further options for the measurements of field direction and the axis of quadrupoles at a later stage. Upstream of the motor, a hollow shaft encoder with a resolution of better than 10^{-4} rad measures the angular position of the coil, the central issue of harmonic field analysis. The housing of this encoder can be oriented manually around its axis in order to "zero" the encoder at the angular reference position of the coil as defined by the reference magnet. The housing of the encoder is fitted with a high precision electronic level meter, which again can separately be adjusted to "zero" around the axis of the rotation. Thus the zero of the encoder and of the level meter can be made to coincide with the angular zero position of the coil as defined by the field orientation of the reference magnet. Any change in orientation of the carriage during its axial travel relative to the vertical is precisely measured by the level meter.

Between the shaft and the rotating unit, a piezo torque meter is installed which monitors the friction in the rotating supports of the shaft, and thus its twist and angular precision. Moreover, this detector measures axial forces. By setting predefined maximum values triggering an interlock, the system is well protected against mechanical faults, and in particular errors in angular position.

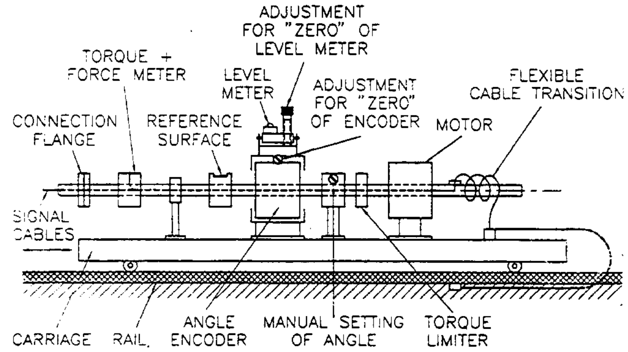

Fig. 2.. Rotating unit to drive the shaft, mounted on the mobile carriage.

Two types of rotating shafts were developed. The first consists of eight segments of extruded alumina (Al_2O_3) pipes with an OD = 32 mm and an ID = 24 mm and a length of 1.5 m each. The second shaft is made from shorter pipe segments (1.3 m) of high strength carbon fiber pre-pregs [5]. A particular fiber orientation in combination with intermediate insulating glass layers had to be selected to minimise eddy currents and magnetic torques in the shaft when rotating with an angular velocity of 1 turn /s in a dipole field of up to 10 T. The pipe segments are connected together with fittings of reduced diameter to provide sufficient radial space for the supporting ball bearings as shown in Fig. 3. Again to reduce magnetic and mechanical torques, high quality ball bearings of Si_3N_4 ceramic were used. In addition to the rotation, easy axial displacement of the shaft is provided by clamping around the outer race of each ball bearing a ring fitted with spring loaded axial rollers (see Fig. 3). Since these units are stationary during the magnetic measurement they are made of brass. To suppress any lateral forces due to angular errors or kinks at the fittings a flexible universal joint is mounted between the flanged connections close to the measuring coil. A photograph of a coupling is shown in Fig. 4.

The stiffness of both types of shafts completely assembled, were 580 Nm/rad and 210 Nm/rad for the ceramic and reinforced carbon respectively. The torque required to rotate the shaft with about 1 turn/s was at most 6×10^{-3} Nm which should lead to an angular twist of at most 0.03 mrad between both ends.

Clearly, the long slender shaft has to be continually supported on the bench all along its length during its axial travel. Pairs of mobile half shells with a length of 1.3 m and with an open inner diameter of 35 mm (equal to the warm bore inside the dipole) are progressively removed horizontally by pneumatic jacks (see Fig. 5), thus liberating the space for the rotating unit during its advance. The reverse, closing procedure is applied during the return of the carriage. The coordination between the movements of the carriage and the support shells forms part of the process control system of the bench and is in addition hardwire protected against malfunction and errors. Fig. 6 shows a view along the measuring bench with the magnet at its far end.

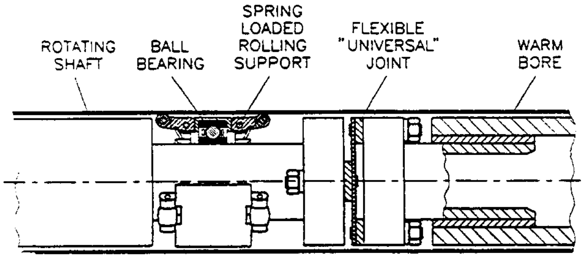

Fig. 3. Coupling between segments of the rotating shaft with ball bearings for the rotation and with spring loaded rolling supports for the axial displacement along the warm bore.

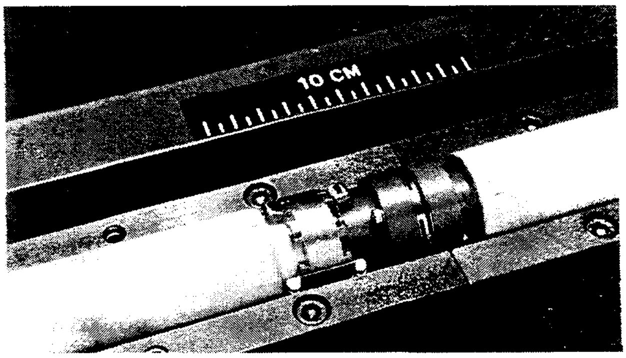

Fig. 4 . Flanged coupling between two ceramic segments of the rotating shaft as schematically shown in Fig.3.

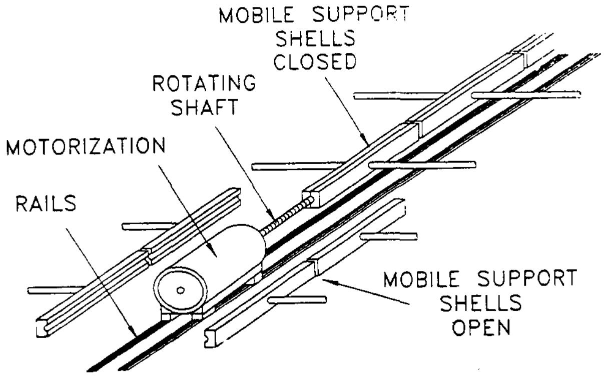

Fig. 5. Segmented, mobile support system for the shaft, progressively liberating the space for the motorization unit during its advance.

The measuring head, shown in Fig. 7 at the end of the rotating shaft, is composed of an NMR probe, two perpendicular Hall plates and a set of three radial harmonic coils wound onto a fiber glass reinforced epoxy structure. The coils are made identical in area and in parallelism to within 10^{-3} by precise machining of their core, and windings are made with flat multiwire cables. No skew coil for compensating their lack of parallelism is foreseen. The external windings of the measuring coils rotate on a radius of 15.4 mm inside the radius of the warm bore of 17.5 mm. The arrangment of three coils is used for ease of fabrication, symmetry and redundancy and to determine the off-centering of the measuring coils with respect to their true axis of rotation [6]. In order to maintain the sag below 0.1 mm, the length of the unit has been limited to 750 mm.

The motorization of the test bench has followed the industrial control line adopted for all the equipment associated to the dipole test stand namely, the cryogenics infrastructure and demineralized water plant. This implied the usage of commercially available programmable logic controllers (PLC's), communication and supervision systems. Together with the functionality of the equipment, the data structures for the exchange of information between the operator and the equipment were specified and agreed with the suppliers. The applications for the supervision were designed and developped in house using a workstation based commercial industrial supervision package.

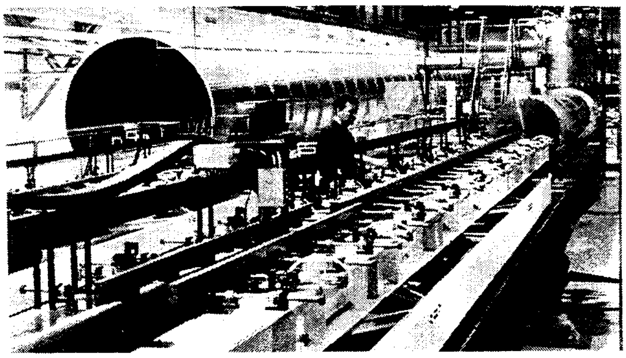

Fig. 6. The measuring bench with the carriage half way down its stroke between the opened support shells of the shaft and with the magnet cryostat and cryogenic supply at the far end.

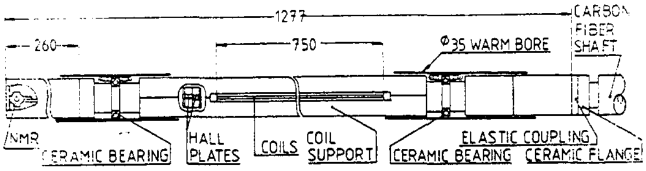

Fig. 7. Measuring head at the end of the rotating shaft fitted with the various field probes (Dimensions in mm).

VI. MEASUREMENTS

To assess the initial performance and precision of the magnetic measurement system and in particular the crucial item, the shaft, we investigated its dynamic response to the rotation [7]. A second encoder was mounted provisionally at the downstream end of the carbon reinforced shaft which allowed measurement of rotational velocities and relative angular oscillations between the two ends of the shaft. Fig. 8 shows clearly a relative oscillation of 100 Hz which corresponds well to the torsional natural frequency of the shaft [7] and its oscillation amplitude is ± 0.1 mrad. They are correlated to the oscillations of the torque, measured at the upstream end which are shifted, as expected by 90 degrees. At rotation speeds below 0.1 turns/s the upstream end starts to turn less regular while at velocities between 0.25-1 turns/s the oscillation amplitude remains about constant. Smaller vibrations have been observed with the ceramic shaft due to its much higher stiffness. The torque driving these oscillations comes mainly from the pinions at the motor and damping elements are being prepared to reduce these oscillations. Further measurements with the completed carbon fiber shaft unit rotating inside the dipole reference magnet at 0.13 T revealed again oscillations of the coil during its rotation, clearly visible when passing parallel to the dipole field. As before they are correlated to the torque at the upstream end (see Fig. 8).

Consecutive measurements of the angle of the dipole field at 0.13 T gave a short term reproducibility of better than 0.1 mrad with the carbon as well as with the ceramic shafts. Since the average temperature along the shaft may vary with its axial position due to different thermal conditions along the bench and inside the anti-cryostat of the magnet, the twists of both shafts as a function of their temperature was measured. The carbon shaft when heated over its total length showed a pronounced temperature related twist of about 0.6 mrad/K, which is most likely due to its strongly non uniform fiber structure, although the fiber layers were placed with alternating orientation. Even if the precise temperature regimes of the bench and the anti-cryostat are not yet known the improvement of the thermal stability of this shaft will be pursued. To the contrary, the ceramic shaft showed, within the measurement errors, no such thermally induced twists, as expected from the uniform structure of its material.

The relative field harmonics expressed at 15.4 mm, the outer radius of the measuring coil, were measured with a reproducibility of 10^{-5} for all orders. This precision is expected to improve since the coil surfaces and the electronics are adapted for the much higher field level of the superconducting dipoles.

V. CONCLUSION AND OUTLOOK

The basically simple concept developed at CERN for the measuring benches of the LHC prototype dipoles allowed for design and fabrication of these benches entirely by industry in turnkey style, following a CERN performance specification. The main issue of these benches, the long, slender rotating shaft made of ceramic performed well within the required specification. For the carbon shaft further development is needed to reduce its thermally induced twist.

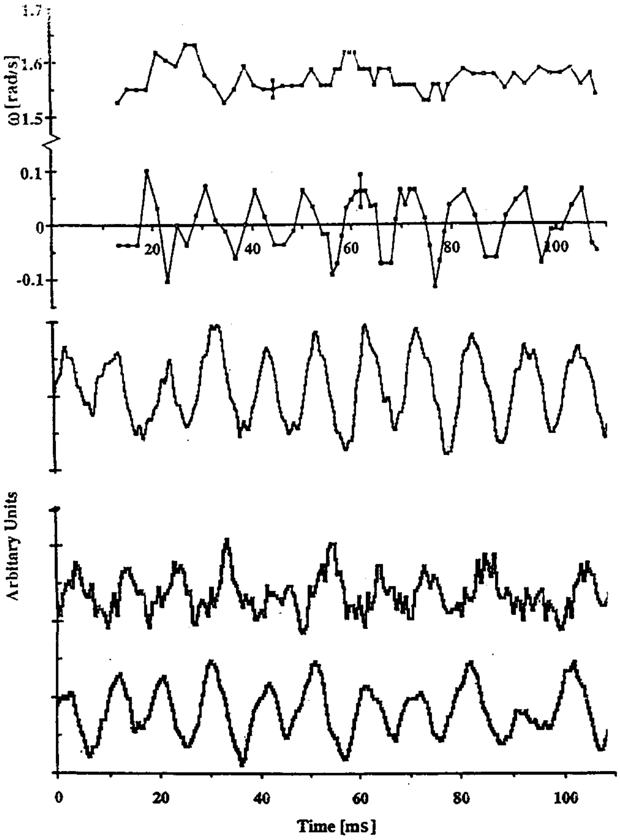

Fig. 8. Rotation velocity ω at the upstream end of the shaft, and the difference in ω between both its ends and the torque at its upstream end versus time (top). Below are shown for a different run the voltage induced in the coil rotating inside the reference magnet at the downstream end and the torque at the upstream end.

Small residual rotational oscillations of the measuring coil of about 100 Hz, inherent in the system, are sufficiently rejected by the harmonic analysis. In view of the increased magnetic length of the future LHC dipoles of above 13 m with a slightly bent aperture, tests have shown that shafts of increased length can still be used, in particular since their diameters, and thus their rigidity, can be increased due to the enlarged aperture of these magnets.

Thanks to the fully automatic measurement cycles, later during production measurement one operator will be able to supervise simultaneously several measuring benches. Since the actual time devoted to the field measurement of each dipole is only about 20-30 % of the turn around time of a test stand these benches should be rendered easily mobile from one stand to another which could limit the number of required benches to four if in total 16 tests stands are envisaged.

Finally the developed system can naturally be extended to the magnetic measurement of the short straight section units with an overall length of 6.5 m, comprising the main quadrupole and correction magnets, where, in addition to the multipole content of the fields and the orientations, the field axis has to be measured. By adding an appropriate laser tracking system, detecting the lateral position of the coil, the dipole measuring benches can also serve to measure quadrupoles. This laser tracking system is presently being developed.

ACKNOWLEDGMENT

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