A Mole for Warm Magnetic and Optical Measurements of LHC Dipoles

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***Abstract*—A new rotating coil probe (a *mole*) has been developed for the simultaneous measurement of the magnetic field and magnetic axis of warm superconducting LHC dipoles and associated corrector windings. The mole houses a radial rotating coil and travels inside the magnet aperture by means of an externally driven two-way traction belt. The coil is rotated by an on-board piezo motor, being tested in view of future devices for *cold* measurements as the only type of motor compatible with strong magnetic fields. A virtual light spot is generated in the coil center by a LED source. The position of this light spot is measured from the outside by a system including a telescope, a CCD camera and a DSP. Jigs on reference granite tables are used to transfer the optical measurements to the magnet fiducials. We describe here the main characteristics and performance of the mole.**

I. INTRODUCTION

The measurement of the field quality of accelerator magnets is among the main ingredients in the construction of today's accelerators. With the advent of high field superconducting magnets with long and narrow apertures, measuring technologies have had to be adapted or newly developed. Pioneering efforts had been already invested since 1985 at BNL, where the "mole" technology was first developed [1]-[2] and at DESY, where it has been further pursued for the test of HERA magnets [3].

A mole consists essentially of a slender container driven along the magnet aperture, carrying on board a rotating search coil with a motor to turn it and an angular encoder to relate induced voltage to angular position. As for previous accelerator projects like the SSC [4], moles were also taken into consideration within the scenarios developed for the tests of LHC magnets [5]. Since, however, the bulk of magnet tests at 1.8 K will be made with "long coils" for the dipoles [6] and scanning machines for quadrupoles [7], moles will only be used for the series test at room temperature of dipoles and for special sample tests of dipoles at 1.8 K. The rather low magnetic field level (30 mT) used for room temperature testing of the LHC dipoles, in addition to the comfortable 50 mm aperture size, alleviate considerably the technological challenges. This allows us to devise user friendly and reliable equipment, essential for series warm measurements of 1200 dipoles at the factories as well as at CERN. Nevertheless, we have selected most components in view of investigating them for the use in future moles for high-field tests of magnets at superfluid Helium temperature (1.8 K).

As an additional feature, an optical system was added to track the lateral position of the mole during its trip along the 14.2 m long and slightly bent aperture, with the goal to measure simultaneously the field and the magnetic axis as well as the physical center of the aperture along the dipole.

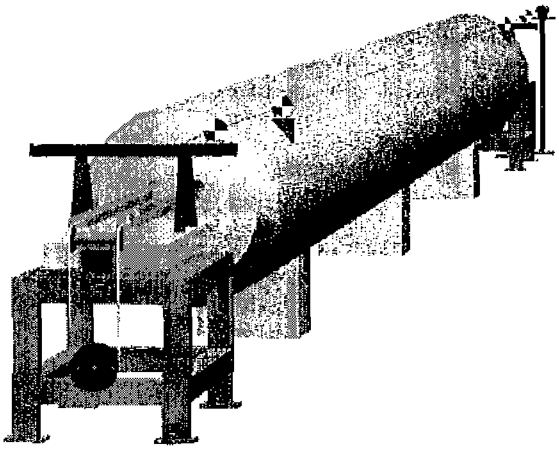

Fig. 1. Schematic mole bench layout showing a dipole under test, the mole on the rear reference bench and the transport system.

The only "accelerator typical" component in the mole is the search coil, which was therefore designed by CERN [8]. All other components such as motors, level meters, encoders, motion controls etc. represent technologies which are available today in specialized industry concerned with micro mechanics, sensorics, optics and robotics. Therefore, it was decided to develop this mole together with industry, following a CERN performance specification.

This paper describes the design and commissioning of the mole and the experience gained using it for room temperature measurements of LHC dipole prototypes.

II. DESCRIPTION OF THE SYSTEM

An overall view of the mole test bench is shown in Fig. 1, while Fig. 2 shows a schematic view of the mole assembly. The main component is the Ø41 mm × 750 mm search coil (h), made of two glass-fiber reinforced epoxy half shells enclosing three 11.5 mm wide radial coils. Each coil has 400 turns and an effective surface of approximately 3.4 m^2. The coil surfaces, relevant for the measurement of the dipole strength, have been calibrated to 10^{-4} accuracy in a reference dipole [8]. The outermost radius of the two external (measurement) coils is 19.7 mm. The central coil is used for dipole bucking. The coil is supported at either end by high quality ceramic (SiN) ball bearings (f) and is enclosed in a carbon fiber shell.

An optical system tracks the transverse position of the mole in the magnet cross section, so that the magnetic axis measured in

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the reference frame of the rotating coil can be transferred to external fiducials. A light emitting diode (LED) mounted on the rotating axis of the front coil flange (i) is used to create a small light spot which is viewed from the front reference bench by a fixed, pre-aligned, high quality commercial straightness telescope. This telescope is fitted with a motorized focus, a CCD camera and a Digital Signal Processor (DSP) performing image treatment. Travelling in the bent aperture of a dipole the mole has a pitch and yaw up to 2 mrad. At such angles a reference mounted at the front of the coil has a substantial lateral error with respect to the coil center location. For this reason the light spot is viewed through a lens mounted in front of the LED, projecting a virtual image of the light spot into the center of the rotating coil.

In order to keep clear the line-of-sight for the optical tracking at the front of the coil, all other components had to be concentrated on the opposite side. These components include the hollow shaft optical angle encoder (e), with 1024 counts per revolution, and a helical damping coupling (d), made of polyimide and supporting the flexible signal cable spiral emerging from the coil. The signal cable is a bundle of 7 micro-coaxial cables, free to wind and unwind as the coil executes a cycle of three forward and backward rotations. Each measurement is taken as the average of a complete forward and backward coil revolution. In addition to this measurement turn, one complete revolution is used for the acceleration and deceleration of the coil.

An ultrasonic travelling-wave piezo-motor (b) with a 3:1 plastic reduction gear (c) is mounted downstream of the helical coupling. Such motors appeared only recently on the market, and are particularly suited for our application as they have compact size (approx. Ø30 mm × 20 mm), intrinsic slow rotation (2 Hz) and the capability to work in strong magnetic fields. Studies are still in progress to improve the control of the velocity which by now is constant within ±8%, marginally adequate for magnetic measurements. If necessary the piezo-motor could be replaced by a standard DC motor-reductor unit for low field measurements. We have made use of the through axis in the motor to install downstream an auxiliary potentiometer (a), necessary for the control and limitation of the rotation.

Each block of components in the mole is contained in a separate non-magnetic stainless steel housing. The housings are mechanically fitted to each other after interconnecting the electrical cables. This assembly forms an autonomous drive unit. The coil is mounted on the drive unit and inserted thereafter into a high strength carbon fiber tube that completes the assembly of the mole into a monolithic container. The support in the magnet aperture is provided at either end by triple rollers that permit a smooth longitudinal movement (see Fig. 3). One of the three rollers in each unit is spring loaded in order to accommodate the ±0.4 mm tolerance along the magnet aperture pipe. A triple roller unit forms part of a ring sliding around the mole container, allowing relative rotation between these two components. This mechanism is necessary to orient the mole into a proper working position. Travelling in the magnet the mole changes its orientation by up to a few degrees per meter of travel, depending on the mechanical precision of the rollers and the quality of the inner surface of the magnet aperture. This rotation must be corrected, to avoid twisting of the traction belt and of the signal cable and to get as close as possible to the zero of the mole level meter where the accuracy of the reading is the highest.

The correction of the orientation is done by means of an active on-board auto-leveling system, consisting of a coarse (±10°) and a fine (± 2.5°) level meter piloting a motor. The motor engages via a pinion system into the rear triple roller support, thus changing the orientation of the mole unit relative to this roller support. Since friction blocks the latter against azimuthal rotation in the aperture pipe of the magnet, it is actually the mole which orients itself into the desired position. The coarse level meter is used to level the mole to within a few mrad. The fine level measures the final orientation with a precision of ±0.02 mrad. A reference surface on the outside of the mole container can be used to verify on the reference benches the orientation of the mole against the level meters.

The motorized drive mechanism for longitudinal displacement and positioning of the mole is shown in Fig. 4, together with one of the two granite tables placed at either end of the test bench and used to establish the necessary reference positions. The supports installed on each table, made of two half shells, serve primarily for ease of installation and to "park" the mole outside of the magnet. They have the same inner diameter as the magnet aperture, thus ensuring smooth movements into and out of the magnet. The supports are duplicated for each aperture of the magnet, and the mole has to be moved manually from one aperture to the other.

A non-magnetic Inconel transport tape is attached at either end of the mole (see detail in Fig. 3). The tape forms a loop closed through the other magnet aperture. A pre-tension of about 150 N is applied to ensure precise and reproducible axial positioning. The longitudinal position is monitored continuously via an external angular encoder, driven by the transport tape, and is checked at reference positions at the end of each trip. These references are materialized by light reflection detectors on the half shells. The longitudinal position has a reproducibility better than 0.2 mm at the references, while the overall precision of the

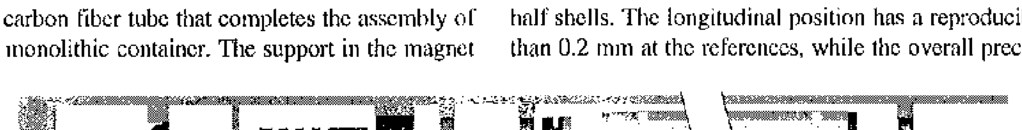

Fig. 2. Schematic drawing of main mole components: (a) multiturn potentiometer, (b) piezo-motor, (c) 3:1 reduction, (d) helical coupling, (e) encoder, (f) ceramic ball bearing, (g) Ti coupling, (h) coil, (i) LED and optics. See text for a detailed description.

longitudinal positioning over the whole magnet length, important for integral field measurement, is better than 0.5 mm, i.e. less than 10^{-4}.

One single multi-wire signal cable collecting all electrical connections, emerges at the rear of the mole (see Fig. 3) and is pulled together with it back and forth along the magnet. The excess of cable is stored via a motorized drive in a container placed in front of the rear bench (see Fig. 4).

The reference benches, at the two magnet ends, provide the mean to transfer the optical measurements inside the magnet to the outside fiducials of the magnet. This is done in subsequent steps. In the first step the telescope-CCD unit is used to measure the position of the light-spot with the mole placed into precise and reproducible reference supports on the granite base of each reference bench. The transfer from the granite base to auxiliary fiducials, in line of sight with the outside magnet fiducials, is established by thermally stable jigs, made of carbon reinforced structures, firmly mounted onto the granite base and carefully surveyed. The auxiliary fiducials are finally related to the outside magnet fiducials by standard surveying techniques.

III. SYSTEM PERFORMANCES

A. Field Measurements

The main task to be accomplished by the mole is the measurement of the absolute value and direction of the dipole field, as well as the higher order multipoles along both apertures of a magnet. These are obtained applying standard techniques for search coils. The field integral in the magnet, relevant for the accelerator performance, is obtained scanning the whole aperture in steps equal to the coil length. As an example we show in Fig. 5 results of the measurements of the 10-m long prototype dipole MBL1N1. We have reported there the measured dipole field, its direction and the modulus of the higher order harmonics relative to the dipole field and scaled by a factor 10^4 (i.e. in units). The compensation of the main dipole component necessary for an accurate measurement of the harmonics is performed analogically, subtracting the signal of the central coil from the reading of the measurement coil. The compensation ratio obtained is about 2000, averaged between forward and backward rotation. We have achieved a measurement reproducibility of the order of $2 \cdot 10^{-6}$ relative to the main dipole component up to order 15.

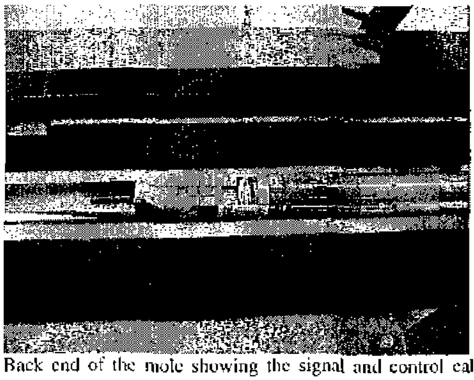

Fig. 3. Back end of the mole showing the signal and control cable, the connector and a triple roller unit.

The measured dipole direction is shown in detail in Fig. 6, and compared to independent measurements taken using different equipment [7]. The angle is corrected after the measurement for the local residual vertical tilt of the mole and for the systematic offset between the on-board level-meter and the encoder "zero" pulse. The latter is a constant that we have obtained from a calibration measurement in a reference dipole with a well-known field direction, observing the phase of the main harmonic relative to the orientation of the mole. The estimated precision of the angle measurement is about 0.2 mrad.

The location of the magnetic axis relative to the rotation axis of the search coil is computed from the measured harmonics. For the LHC dipoles we have found that a good working definition of the magnetic axis is given by the location in the magnet cross section where the non-allowed multipole of order 10 vanishes. This corresponds to the assumption that the component of order 10 is entirely caused by feed down from the higher order harmonics. In fact the LHC dipoles have a strong intrinsic geometric multipole of order 11, thus justifying the assumption. The coil rotation axis is measured optically and transferred to the magnet fiducial reference frame (see next section). In this way, all parameters relevant for the measurement of the magnetic fields in the LHC dipoles are achieved simultaneously by a single passage of the mole, which is vital for the efficient and speedy acceptance procedure of magnets during series production. A single, local magnetic measurement takes in fact only a few seconds. At present every measurement is repeated at least 10 times, in order to build up statistical confidence. The scan of both apertures of a whole magnet can be accomplished in about one hour.

B. Optical Measurements

The transverse position of the light spot is obtained calculating the center of gravity of the image on the CCD. A given number of takes (typically 30) are averaged to reduce the influence of air turbulence. A preloaded software calibration

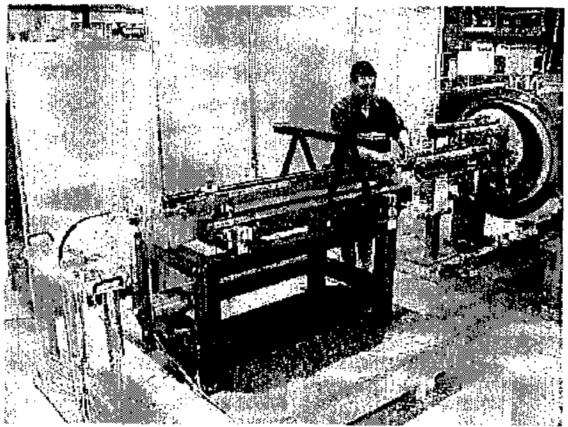

Fig. 4. Rear reference bench with granite table, supporting half-shells, reference jig, transport system and cable container.

map is used to compensate for longitudinal distance effects. The measuring range of this system is ±2 mm vertically and ±7 mm horizontally (as required to cover the 9 mm sagitta of a curved, 15-m long dipole magnet aperture). The precision after calibration is better than 60 μm over a 20 m range, well exceeding specifications (100 μm).

In Fig. 7 we show an example of the measured trajectory of the coil center in the aperture of the MBL1N1 dipole. The mole follows the curved aperture pipe, with a sagitta in x (horizontal) direction of approximately 8 mm. Our results are compared to an independent measurement taken with a combined laser/PSD system [9]. The average difference between the two measurements is 74 μm. It should be noted that geometrical errors of a few μm in the optical unit assembly can lead to a transverse displacement of the virtual spot of a few tenths of mm, due to the magnifying effect of the lens. This has been observed and corrected taking the average of two measurements at coil orientations 180° apart.

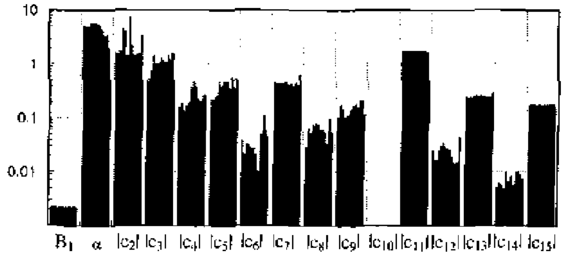

Fig. 5. Field measurement in MBL1N1 prototype dipole, each bar representing a different longitudinal position (B_1 is in T, the angle α is in mrad, the harmonics are in units @ 17 mm).

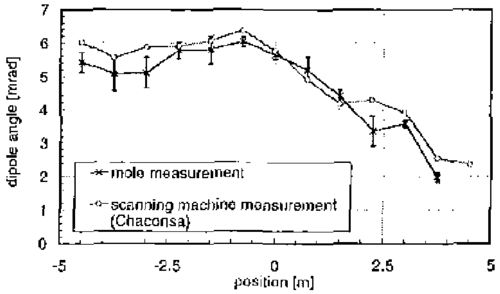

Fig. 6. Comparison of measured field angle with the mole and with an automated scanning machine [7] in the MBL1N1 LHC prototype dipole.

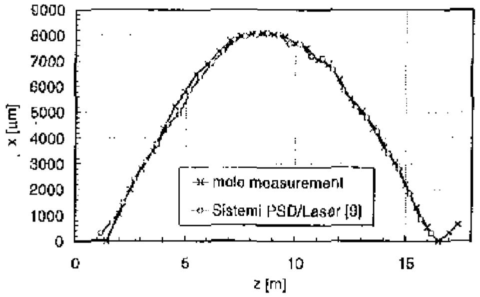

Fig. 7. Example of optical measurement: beam pipe curvature in the midplane of the MBL1N1 dipole prototype, compared to results from [9].

The Joule power heating the magnet during magnetic measurements can impair severely this excellent performance. Thermal gradients in the aperture deviate the optical path up to a few tenths of a mm. Several solutions are being considered, including a small controlled gas flow along the magnet's aperture pipe, making optical measurement runs before powering the magnet and, most promisingly, the adoption of a very low power quadrupole configuration in the dipole for magnetic axis measurement.

IV. CONCLUSIONS AND OUTLOOK

Our initial experience with the mole shows that this probe is able to carry out magnetic and geometrical measurements with a precision equal to or exceeding the specifications. Reliability and user-friendliness, so far, appear to be compatible with the severe demands of the series LHC dipoles test campaign.

Much of the mole's complexity stems from the requirement to measure the magnetic axis relative to the magnet fiducials. In fact, if the goal were simply to measure the axis position relative to the cold bore, the system of reference jigs and surfaces, as well as the auxiliary system to measure their alignment with respect to the magnet fiducials could be dropped. Moreover, were the axis not required at all, the optical measurement components could be eliminated altogether and both the transport mechanism and the internal layout could be simplified.

The next major target now is to supply a mole for measurements of dipoles (and, possibly, of LHC quadrupoles) at liquid helium temperature, one of which has already been ordered. This probe represents a more difficult challenge as it must work, among other things, under vacuum (to avoid thermal gradient effects on the optical path) and within a more restricted volume (Ø40 mm anticryostat). This mole will only be used for spot checks including the detection of the magnetic axis at high field.

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