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**A DEVICE TO MEASURE MAGNETIC AND MECHANICAL AXIS
OF SUPERCONDUCTING MAGNETS
FOR THE LARGE HADRON COLLIDER AT CERN**

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A Device to Measure Magnetic and Mechanical Axis of Superconducting Magnets for the Large Hadron Collider at CERN

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Abstract: *The LHC will be composed of 1232 horizontally curved, 15 meter long, cryodipoles and 474 Short Straight Sections, being assembled by different manufacturers. Magnetic axis alignment is an essential part of the magnets quality for two reasons: first, to be able to install correctly the magnets in the tunnel w.r.t. the reference beam orbit; secondly, to assess the relative alignment between the magnets composing the assembly, i.e. spool pieces for the dipoles and larger correctors for the SSS. A system called AC mole is being*

used extensively to measure magnetic and geometric axis, as well as roll angle, for every single magnet composing all the SSS. This paper describes its performance, its first years of operation, as well as the improvements that have made it very powerful, versatile and easy to use.

Keywords: *magnetic measurements, alignment of superconducting accelerator magnets, magnetic axis, mechanical axis, harmonic coils, 3D laser tracker, Large Hadron Collider*

I. INTRODUCTION

The Large Hadron Collider [1], under construction at CERN and expected to start operation in 2007, will include a total of 1232 main dipole magnets to bend the particle beams (MB) and 506 main quadrupole magnet assemblies to keep them focused (Short Straight Sections or SSS), all based on superconducting Nb-Ti coils operating at 1.9 K. Each 15.6 m long cryodipole assembly features twin apertures with opposite fields for the counter-rotating beams, with a central field of 8.34 T. The 50 mm aperture dipoles are bent with a nominal sagitta of 9.14 mm to follow the curvature of the ring. At the extremities short “spool piece” corrector magnets insure the distributed compensation of the sextupole, octupole and decapole field errors due to unavoidable persistent current effects in the superconductor. The SSS assemblies, which may have one or two apertures and be up to 11.5 m long, include different combinations of multipole corrector magnets with the purpose of compensating magnetic and lattice errors in the machine, as well as tuning the dynamic properties of the beams. These magnets are produced by several firms in Europe, USA, Japan and India and are brought to CERN for assembly into cryostats and final testing before installation in the underground tunnel. To date, more than 2/3 of the production has been completed.

The correct alignment of these magnets is critical from the point of view of both the magnetic axis and mechanics, as the beam must have sufficient clearance to pass inside the cold bore tubes (CBT). While for a dipole the only concern is the roll angle of the field, which must be normal to the orbit plane to better than a millirad to avoid orbit distortions, the magnetic axis of the multipoles (i.e. the locus where the field $B=0$) must be aligned to the reference beam orbit within a few tenths of a millimeter. In superconducting magnets the verification of these requirements is difficult because of the long and narrow shape of the apertures, and is further

complicated by the fact that at cryogenic temperatures the mechanics is not directly accessible, while the magnetic field can be measured only at great cost (due to the operation of cryogenic test benches). For these reasons it is preferable to carry out as many of the required tests at room temperature, extrapolating then the results at 1.9 K by means of suitable warm/cold correlations established on a statistical basis.

To this end, a novel device called “AC Mole” has been developed and put into production at CERN to measure simultaneously the geometry of both mechanical and magnetic axis of these assemblies with the required precision at room temperature. The measured axis is referred to a set of fiducial references (retro-reflector targets) fixed externally to the cryostat with the help of a Leica™ 3D laser tracker. This device has been extensively used to characterize and qualify in detail prototype magnets in the early phase of development and is now being routinely used to test a large fraction of the series production, providing data of critical importance for the acceptance of the assemblies and their installation in the machine.

II. HARDWARE

The AC Mole is a fully automated cylindrical scanning probe that travels inside the aperture of a magnet, taking a series of snapshots of the mechanical and magnetic geometry at selected locations. The probe includes the following three main sensors:

1. A retro-reflector prismatic target for the laser tracker, which provides 3D coordinates with an accuracy better than 10 ppm of the measured distance (at 2σ), with an additional 20 μm uncertainty due to tooling ball tolerances. Since the laser beam travels inside the Cold Bore Tube (CBT), heat sources must be minimised to

avoid temperature gradients that could perturb its propagation.

2. Four 100 mm long, 600-turns tangential pick-up coils, spaced by 90° [2].
3. Four LED casting reflections on the inner surface of the CBT, imaged by an on-board CCD camera.

The sensors are precisely centred in the same cross-section to avoid parallax errors. The mole can travel inside the CBT and be positioned at any given point, where it is first oriented with respect to gravity by a dedicated levelling motor using feedback from an electrolytic tilt sensor with a $\pm 45^\circ$ range. Labview™ software is used to control the motors and the data acquisition of the level meter and search coils signal. XYZ™ software from Leica is used for the Laser Tracker.

A. OPTICAL SUBSYSTEM FOR GEOMETRIC MEASUREMENT

The relative position of the mole and the magnetic axis of the CBT is measured by analyzing the image of the diffuse reflections of the four LEDs on the CBT (Fig. 1). The four light spots can be fitted to a circle from which the centre is determined in the local reference system of the mole. The centre of the circle, referred to the retro-reflector via calibration, gives the mechanical axis of the CBT. The four residuals (i.e. the distance between the centre of gravity of each reflected spot and the best-fitting circle) give an indication of the deformation of the tube cross-section at this point. It should be noted that this method provides a highly local measurement of the axis of the CBT, in contrast to similar probes in use at CERN which are mechanically self-centring thanks to spring-loaded wheels, providing mechanically averaged results [3]. While our result is much more precise, it is also more sensitive to local mechanical defects of the tube.

B. SEARCH COILS SUBSYSTEM FOR MEASURING MAGNETIC AXIS

The AC Mole draws its name from its capability, unique amongst the various probes used at CERN, to detect the magnetic field generated by a magnet when powered in AC. This operating mode, coupled with synchronous detection via a lock-in amplifier, enhances tremendously the sensitivity of room-temperature measurements. This is normally limited by the amount of current that can be injected safely in the superconductor when in the normal state (characterised by a relatively high resistivity), which for main LHC magnets is of the order of 1 A, i.e. about 10^{-4} of the nominal current at cryogenic temperature. The amount of current may be further limited by the temperature increase in parallel protection resistors, or in the voltage taps that in some configurations represent the only external interface of a magnet once mounted in an assembly.

The definition and computation of magnetic axis relies on the customary magnetic field expansion in the complex plane:

$$B_x + iB_y = \sum_{n=1}^{\infty} (B_n + iA_n) \frac{(x + iy)^{n-1}}{r_{REF}^{n-1}} \quad (1)$$

where for LHC magnets we take $r_{REF}=17$ mm.

Two methods can be used to obtain the magnetic axis in AC mode:

1. Fixed-coil mode [5]: the AC voltages induced in the coils are synchronously detected and the magnetic centre is computed as a function of the imbalance between the signals of opposite coils. This mode requires the coils to be pre-aligned to face the poles, so a different rotation angle is given by the motor for each order and type of multipole (the type can be either “normal” or “skew”, according to the B_n or A_n coefficient being dominant, respectively). This mode, which allows for very fast operations, was the one foreseen in the original design of the probe.
2. Rotating-coil (harmonic) mode: the AC voltage of the four coils is measured at 32 discrete angular stations between -45° and 45° , and assembled to obtain a vector of 128 values which are FFT analysed to get harmonic field coefficients A_n and B_n . The axis position is then computed from feed-down of the main harmonic [4]. This method was implemented in 2003 as an upgrade to the existing system. Since the motor is controlled in open loop, the 32 stations are not equally spaced. As a consequence, the voltage readings of the four coils are computed at constant angular intervals using parabolic interpolation, so as to obtain a uniformly sampled vector suitable for processing with a standard FFT.

The rotating-coil method is generally more precise and provides additional information such as the field direction and harmonics, even though it carries a time penalty, and is therefore used for all main quadrupole magnets as well as for all kinds of correctors. To date, the fixed-coil method is used only to measure the magnetic axis of the main dipole when powered in the so-called quadrupole configuration (“Quadrupole-Configured Dipole” or QCD), obtained by feeding current of opposite sign in the top and bottom half-poles, which is used to represent approximately the geometric centre of symmetry of the superconducting coil. In this case, precision requirements are not critical and the time saving over the full 15.6 m length is significant.

Magnetic axis measurements are taken with respect to the retro-reflector at the same time as mechanical axis ones, thus giving high local precision. Peak signal levels are of the order of 1 to 5V for some magnets (main quadrupole, dipole and octupole correctors) and can be much smaller for others (e.g. 0.16 V for sextupole correctors), depending on the presence of a parallel protection resistor.

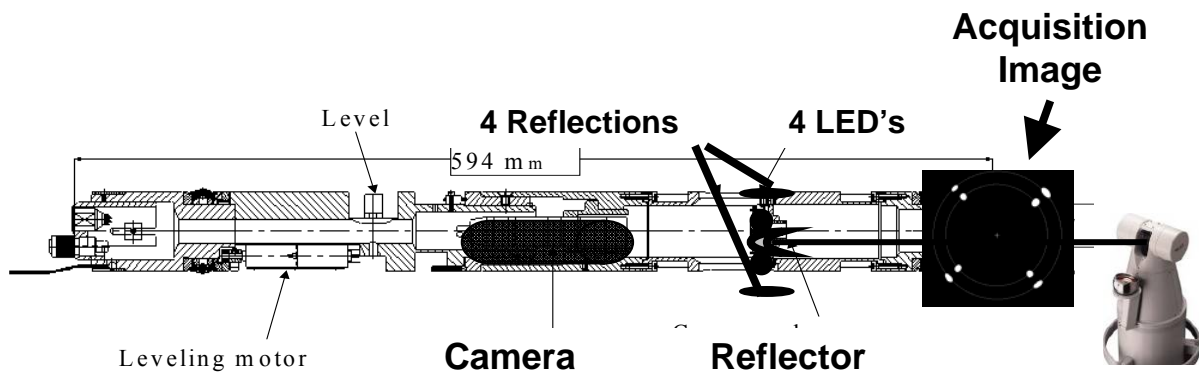


Fig. 1 Mechanic axis measurement using 4 LEDs and the CCD camera

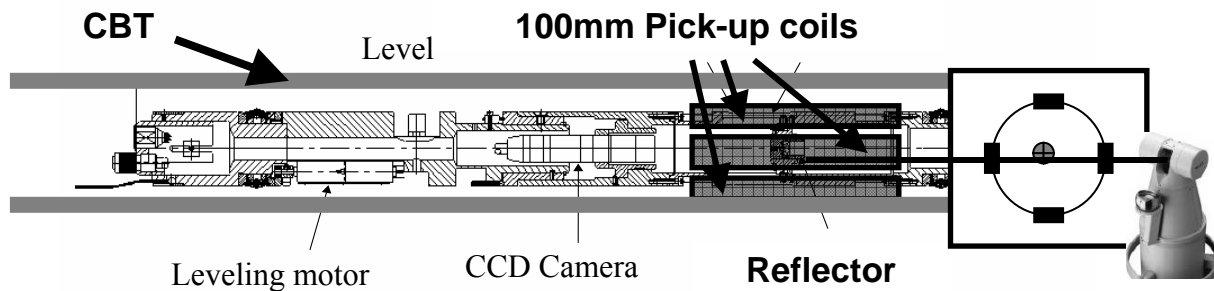


Fig. 2. Magnetic axis measurement through 4 tangential coils and synchronous detection of signal

III. CAPABILITIES AND PERFORMANCE

The AC mole is a versatile instrument, as shown by the different kinds of measurements that can be made [5]. Installation is simple and operation has been made fully automatic to cope with the high workload of the LHC series magnets. Automation includes two main facilities:

1. longitudinal positioning capability by means of a steel cable pulled at both ends by DC motors, using feedback from online laser tracker measurements;
2. automatic powering of the magnets inside the assemblies through a programmable Kepco power supply and a software data base, which associates specific magnets to the current longitudinal position in a given assembly type.

The main capabilities can be summarised as follows:

1. Magnetic axis and field direction (harmonic mode). For the magnetic axis the resolution is better than 0.01 mm, while the estimated accuracy including transfer to

- fiducials is between 0.1 and 0.2 mm. For the magnetic field direction, obtained as the phase of the main harmonic, resolution is about 0.1 mrad, with an absolute accuracy better than 1 mrad. This result is much better than the uncertainty of individual tilt sensor readings, which is about 8 mrad, due to the averaging effect carried out by the FFT applied to the vector of 32 measurements.
2. Mechanical axis (CBT centre). The resolution of the vertical and horizontal displacement detection is better than 0.01 mm, while the absolute accuracy including transfer to fiducials can be estimated about 0.11 mm from comparison with other instruments [7].
3. CBT diameter and shape: by orienting the mole at different angular positions one can measure several diameters and assess ovalisation with a resolution better than 0.01 mm. The plot in the Figure 3 shows the results of an ovalisation test. One can see the very good linearity between the vertical external contraction and the internal measurements of the LED-CCD system.

IV. EXAMPLES OF MEASUREMENT

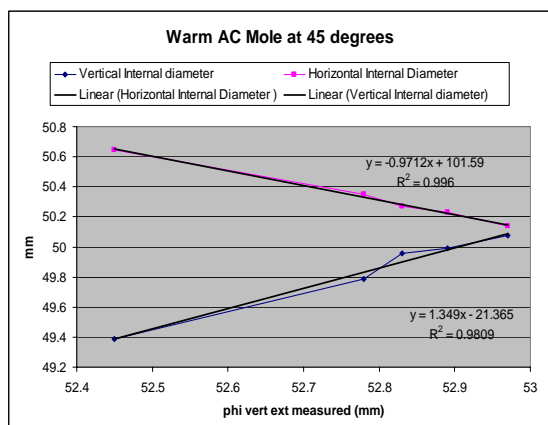


Fig. 3. Plots showing capacity of detecting a CBT ovalisation. Tube was deformed vertically and the ovalisation is visible as an increase of the horizontal diameter and shrinkage of the vertical one.

The sensitivity of the system in a Quadrupole Configured Dipole (QCD) is shown in Table I, where one can see that a field around 30 μT (measured at the reference radius of 17 mm), produced by an AC current of 10 mA, still gives a repeatability of 2 μm with the Fixed Coil method. The dependence of axis measurements upon the AC excitation frequency has also been studied with the same test setup. A priori, one can expect the sensitivity to drop below noise levels as the frequency approaches zero, while on the other hand too high frequency may perturb the field configuration due to undesired eddy currents. Figure 4 indicates stable measurements within ± 0.01 mm for frequencies ranging from 2 to 50 Hz. The actual working frequency of 25 Hz has been chosen as an integer fraction of the power grid frequency, so as to avoid interference.

Coil Voltage (mV)	Input Current (mA)	Field at r=17 mm (T)	Sensitivity (μm)
37	100	3.10-4	<1
3.7	10	3.10-5	2
0.37	1	3.10-6	10

Table I. Sensitivity of the AC system in an LHC main dipole at room temperature in the quadrupole configuration (fixed coil method).

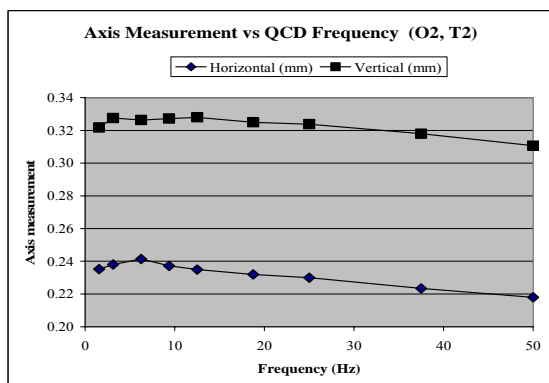


Fig. 4. Variation of magnetic axis offset vs frequency of the magnet current.

Fig. 5 shows an actual example of measurement of a series Short Straight Section, which includes mechanical axis measurement of the whole cold bore plus magnetic axis of the main quadrupole with an octupole and sextupole correctors. The mechanical measurement is doubled up with a different device (marked as “WP18-FID”) which is used for cross-check purposes. Considering the whole sample of 180 cryo-assemblies of this type measured to date, the two methods differ on average by 0.0 and 0.1 mm in the horizontal and vertical directions, with a standard deviation of 0.09 mm and 0.06 mm respectively. The characteristic “saw tooth” pattern which results from the combination of two scans taken from opposite sides of the magnet is due to two main error sources, namely laser tracker orientation and calibration errors (the latter only for the horizontal coordinate), and its amplitude is usually smaller than 0.16 mm. Considering magnetic axis results, the deviation over the 180 measured cryo-assemblies is about 0.2 mm RMS, in line with machine requirements.

The system was originally designed to measure mechanic and magnetic axis of the main dipole. In particular one can measure the position of the small sextupole corrector at the end of the dipole. The transverse alignment of the sextupole correctors is very important, tolerance being only 0.3 mm, and the AC mole is the only instrument capable of measuring its magnetic axis, because the corrector is hidden in the cold mass., The important element about the dipole axis, measured by the QCD method, is to make sure that there is no difference between the mechanical and magnetic axes of the relatively strong sextupole component present in the dipole. Measurements carried out on several prototype and pre-series magnets showed that the offset is smaller than 0.2 mm, which does not represent a problem for the aperture.

Another important issue is the change of shape of the dipoles when cooled down at 1.9K, an example of which is given in Fig 6. This deformation, which amounts to an increase of the radius of curvature in the horizontal plane, may occur as a consequence of the constraint represented by the three composite posts supporting the magnet and may have detrimental consequences on the mechanical aperture available to the beam. To address this problem, a cold version of the probe was developed to operate inside a 40 mm aperture anti-cryostat, i.e. a heated pipe placed inside the magnet aperture to provide room-temperature access when the magnet is at 1.9 K. Besides being narrower, the Cold AC Mole lacks the LED-CCD mechanical axis measurement subsystem as the CBT is no more visible. An additional problem is represented by the thermal gradients induced in the air by the anti-cryostat, which may perturb the optical path of the laser tracker beam by up to several millimetres. To solve this problem, it is possible to operate the probe in a vacuum and track it through an optical window, albeit at the cost of added complexity.

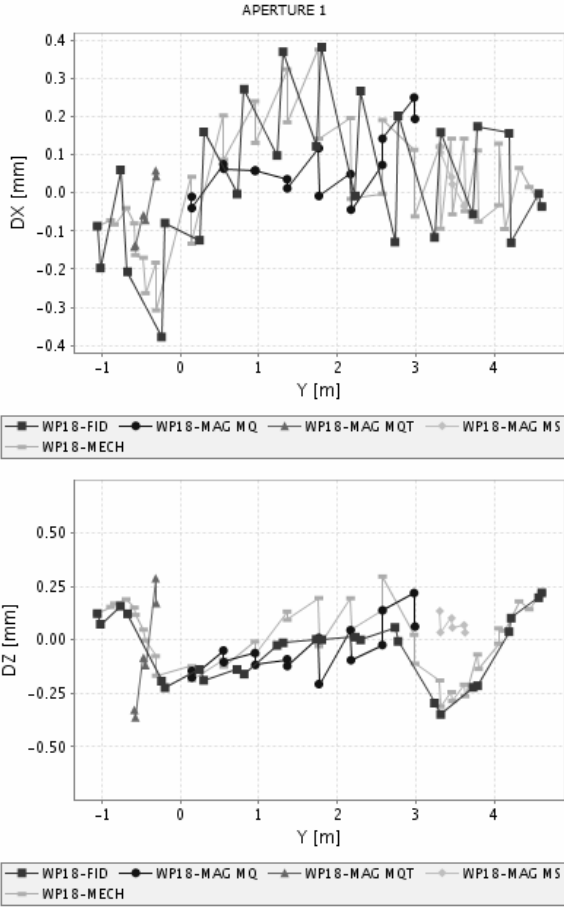


Fig. 5. Results of the mechanic and magnetic axis measurement on a Short Straight Section containing main Quad and several correctors. In black squares another mechanic axis measurement done with different type of mole

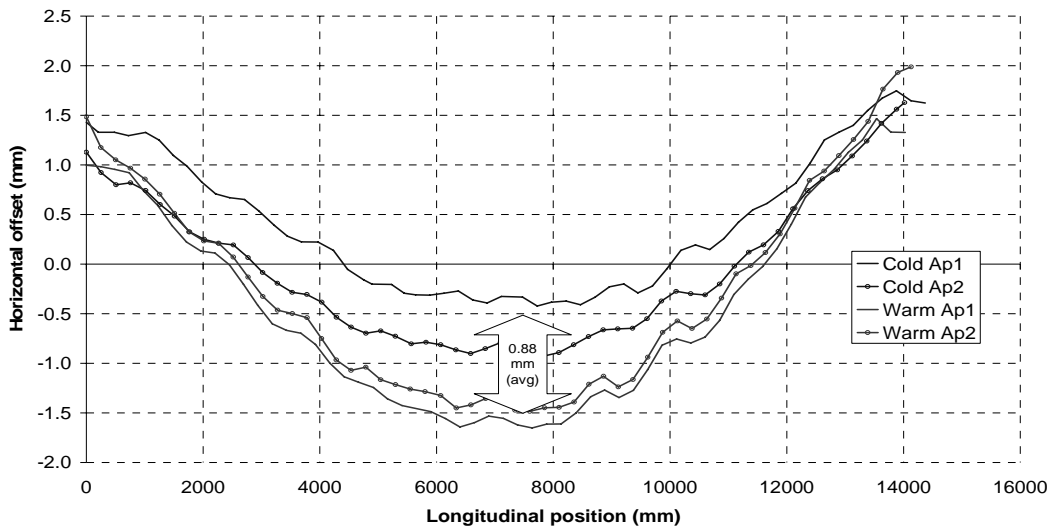


Fig. 6. Measurement of a dipole magnetif axis (Quadrupole configuration) at 1.9 K and room temperature. Deviation from nominal arc shape (sagitta = 9.14 mm) in the horizontal plane.

Preliminary tests have shown that the system can still provide adequate accuracy, as indicated for example by measuring the amount of vertical thermal contraction which is very close to the expected value (about 1.3 mm).

V. FUTURE DEVELOPEMENTS

To complete the full characterisation of LHC magnets in time for the commissioning of the machine during the next years, and in view of possible future measurement campaigns of spare and reference magnets, a number of development projects are ongoing to improve and extend the AC Mole system. These include:

1. Optical measurements: the detailed qualification of laser tracker measurements through a window still needs to be completed, including an analysis of the effects of parallax and refraction. The possibility of using two reference quadrupole magnets at both ends of the assembly to be measured to establish fixed control points must be assessed.
2. High field measurements: some hardware improvements are necessary to be able to measure the magnetic axis at nominal field values of several Tesla DC, with an additional AC component superimposed. This capability would allow measurements of the change of shape of the magnets as a function of the Lorentz forces during operation. Possible upgrades include the replacement of the DC motor with one compatible with high fields (e.g. the ultrasonic piezoelectric type), the establishment of a suitable calibration method for the tilt sensor, and the elimination of all magnetic materials in the probe.

3. Harmonic measurements: moles with the same diameter are regularly in use to measure the field harmonics [8]. They are based on coils making a full rotation with angular position measured by an encoder. The standard way to improve these measurements is adopting a compensation (bucking) scheme, in which the signals from several coils are combined to cancel the main field harmonic, leaving only the field error components which can then be amplified and measured with a much higher S/N ratio. Such scheme can be adapted to the AC-mole equipment with minor modifications.

VI. CONCLUSIONS

The AC mole system has been used at CERN for several years to measure many different types of superconducting LHC magnets in different conditions, and it has been proved to be flexible, accurate and robust enough for series tests of hundreds of units. By means of the improvements suggested, we plan to extend its useful life well into the commissioning and operating phase of the accelerator.

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