A Rotating-Coil Scanner for the Precise Magnetic Characterization of Superconducting Accelerator Magnets at Ambient Temperature

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This article presents a versatile scanning system for the magnetic measurements of the accelerator magnets. This system, based on a rotating-coil magnetometer, has been developed to meet the accuracy requirements imposed by the inner-triplet quadrupoles for the High Luminosity Large Hadron Collider (HL-LHC) project at CERN. The main field strength of the magnet must be measured with an accuracy of 100 ppm, and the required accuracy for the angle and the axis are 0.1 mrad and 0.1 mm, respectively. All these parameters must be measured both locally and integrated over the entire magnet length at various stages of production. In this way, it is possible to intercept the manufacturing errors at an early stage of production. Moreover, these measurements are used for the alignment of the magnet assembly in its cryostat. The measurements are performed at an ambient temperature, with low excitation currents. The presented system provides a full set of data for the characterization of the magnet in a single measurement run, including the field quality (multipole field errors) and the magnetic axis location at several longitudinal positions in the magnet bore. The system is able to achieve the required accuracy by using induction coils based on the printed circuit board (PCB) technology, a high-resolution encoder, and retro-reflectors for the laser tracker positioned directly on the PCB. The system is also equipped with a motor unit that allows a high degree of automation in the measurements.

Index Terms—**Accelerator magnets, automatic test equipment, magnetic fields, magnetometers.**

I. INTRODUCTION

THE High Luminosity Large Hadron Collider (HL-LHC) project [1] requires new superconducting magnets for the interaction regions. Their production and installation impose strict accuracy requirements on the magnetic-measurement systems. In particular, the inner-triplet quadrupoles, based on the Nb_3Sn technology, present the biggest challenge. Field parameters, such as the gradient, direction, magnetic axis, and harmonic content [2], must be measured globally (integrated) and locally (as a function of the longitudinal position) at various stages of production. The measurements are also used to control the manufacturing process, to check the exact positioning of the collared-coil pack in its iron yoke, and the alignment of the so-called cold mass in its cryostat. In addition, the longitudinal center of the magnetic field must be provided with the geometrical accuracy of 1 mm. This is challenging due to the overall dimensions of the accelerator magnet of up to 10 m.

II. MEASUREMENT REQUIREMENTS

The requirements for the measurement accuracy are derived from the HL-LHC insertion region layout. A summary is given in Table I. These values are given for the measurements at ambient temperature at various stages of magnet production.

TABLE I
MEASUREMENT ACCURACY REQUIREMENTS FOR THE CHARACTERIZATION OF THE HL-LHC MAGNETS [1]

Parameter	Unit	Accuracy
Main field	ppm	100
Main field direction	mrad	0.1
Harmonics	ppm	1
Magnetic axis	mm	0.15
Longitudinal magnetic center	mm	1

Most of the integral parameters can be measured with the required accuracy using the stretched-wire systems [3]. However, the field harmonics and the longitudinal magnetic center cannot be measured with sufficient accuracy; the achieved value for the longitudinal magnetic center is 3 mm using the stretched-wire system [4]. The local quantities can be measured using the rotating-coil scanners such as the Ferret [5] or QIMM [6]. Their strongest limitation is the measurement of the local and integral field gradients, with an accuracy of 0.1% [7]. Recent advancements, using the induction coils based on the printed circuit board (PCB) technology, promise to improve that value to be better than 0.02% [8]. In any case, using two separate acquisition systems for the magnet characterization substantially increases the necessary measurement time and resources.

Moreover, the magnets for HL-LHC will be produced in a variety of different apertures, but at low numbers: not more than 20 magnets of each type will be produced. It would, therefore, not be economical to develop a dedicated measurement system for each magnet type. This fact and the necessity of measuring the magnet at various stages of the assembly process require a system that must be adaptable to different apertures with a minimum setup time.

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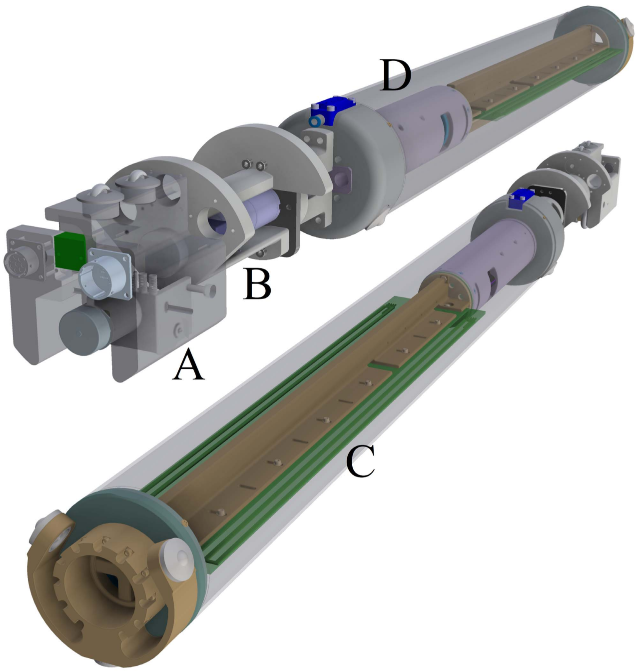


Fig. 1. Rendering of the system from both sides. The tube is transparent to show the inner parts of the system. A—longitudinal displacement motor; B—rotation motor; C—rotating support shaft with the PCB; D—probe base with electronics.

III. ROTATING-COIL SCANNER DESIGN

The recently developed prototype of the rotating-coil scanner [9] indicates that it is possible to acquire all the required parameters with a single system. However, the stability of the prototype needs to be improved, as well as the accuracy in the measurements of the geometric quantities, such as the magnetic field axis and the longitudinal center. Based on the feedback from the prototype system, we were able to choose the most promising solutions to implement in the new rotating-coil scanner (see Fig. 1) in terms of accuracy and stability. The basic principle remained the same, with improvements mostly in the mechanical structure. The required accuracy of 100 ppm for the field-gradient measurements can be reached by using the induction coils based on the PCB technology, thanks to the high precision of the track positioning. It is also possible to locate the magnetic axis, as well as the longitudinal center, by using a laser tracker to follow the position of the transducer in the magnet aperture. To achieve the required accuracy in the measurement of the magnetic axis and the longitudinal center, we positioned the retro-reflectors directly on the PCB. The system can measure the local quantities in several positions along the longitudinal axis of the magnet. They are combined in post-processing to provide the integral values.

The scanner is equipped with an on-board motor unit that allows the automation of the measurements and simplifies the setup procedure. The motor unit is composed of two motors: one for the longitudinal displacement in the magnet bore and one for the rotation of the induction coils. They are mounted directly to the scanner housing and travel together with it in the magnet aperture. Placing the coil-rotation motor close to the probe has an advantage of a simpler transmission of the drive, with less intermediate connections that introduce friction and vibrations. The resulting smoother rotation reduces the errors caused by the vibration of the shaft.

Thanks to a precise angular encoder with the resolution of 65 536 steps, it is also possible to avoid leveling the entire probe, which would increase the complexity by requiring either an additional motor or a sophisticated mechanics to overcome the much higher friction between the probe and the magnet tube. Therefore, only the rotating-coil shaft is leveled, using the rotation motor, to establish a new index of the encoder, which is used as a starting point for data acquisition.

The step size of the encoder and, therefore, the expected field angle measurement resolution are $\pm 100\ \mu$rad. The stability of this approach was tested by the repeated positioning of the coil shaft at the encoder index and checking the reading of the level meter that is mounted directly to the coil shaft. Even after multiple rotations in both directions, the results were consistent with $\pm 100\ \mu$rad, which is in line with the encoder step size. This proves that the probe does not change its orientation during the measurement.

Because of the precise and fast angular positioning with the coil-rotation motor, the scanner can also be used to measure the magnets in the ac powering mode. The only modification necessary is changing the protection tube to a non-conducting one in order to suppress the eddy-current effects. The fiberglass-epoxy composite material can be used for such tubes.

The laser tracker constitutes a major component in the overall system cost and requires a considerable setup time. However, as not all measurements require the full set of data, we equipped the system also with a draw-wire encoder for measuring the longitudinal position of the system in the magnet, thus allowing the automatic acquisition of all the parameters except for the magnetic axis. We chose an encoder with 1 mm accuracy, which is required for the main field measurements, according to the calculation based on the numerically computed longitudinal magnetic-field profile in the magnet.

The PCB contains five identical coils, which are used for the compensation of the quadrupole component, placed alongside each other. They are equally spaced across the board, with 25 mm distance between their geometric centers (see Fig. 2). We used 24 layers, similar to the prototype. The choice of a multiple-of-six number of layers is advantageous, as it allows connecting the coils also in a sextupole compensation scheme.

As the dipole field is constant and the quadrupole field increases linearly with radius, it is possible to compensate both components by connecting coils A–D in series, with coils B and C in opposite polarity (that is, $+\mathrm{A} - \mathrm{B} - \mathrm{C} + \mathrm{D}$). To compensate also for the sextupole component, which is proportional to the square of the radius, the coils can be connected as $+(1/3)\mathrm{A} - \mathrm{B} + \mathrm{C} - (1/3)\mathrm{D}$. The factor $(1/3)$ is realized by connecting only the inner-third of the layers.

As with the prototype, the PCB has been measured with a calibrated X-ray machine to establish the manufacturing tolerances and the possible shrinking of the board during the pressing process. The coil surfaces are calibrated in a reference dipole [10]. This step is also required to check for the presence of the inter-turn short-circuits that cannot be

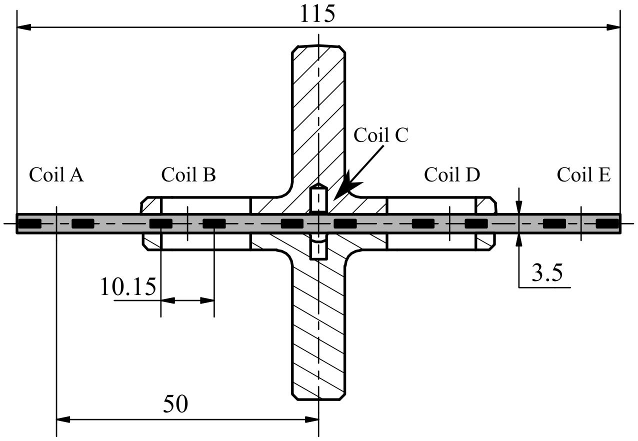


Fig. 2. Cross section of the PCB and support shaft with the main dimensions given in millimeter. The PCB is marked in gray, whereas the coil windings are in black. The magnetic length of the coil is 600 mm. The length of the entire board is 650 mm to fit the wire connections and holes for the retro-reflectors.

intercepted by the coil-resistance measurements, due to their insufficient sensitivity.

The quadrupole gradient measurements rely not only on the coil surface but also on the coil-rotation radius. The standard radius calibration accuracy is approximately 0.1% and does not fulfill the requirements. Therefore, we decided to rely on the high precision of the PCB copper track positioning and the measurements with the X-ray machine, with an accuracy of the order of 10 μm. Considering the PCB width of 115 mm, the geometric measurement accuracy translates to an uncertainty in the gradient measurement of approximately 100 ppm. The results presented in Section IV were obtained using the coil radii computed from the geometric measurements of the PCB. They have also been corrected for the coil resistance (6 kΩ), as it is not negligible compared with the input impedance of the acquisition system (400 kΩ).

IV. VALIDATION RESULTS

To characterize the system performance in terms of measurement accuracy and stability for the required parameters, we measured a number of different magnets in varying operation conditions. Apart from the Q2 quadrupole prototype [1], with the aperture of 150 mm and magnetic length of 7.15 m, we acquired complementary data in shorter magnets. The system was tested at various field levels, and the results were compared with the stretched-wire measurements.

A. Field Gradient

The results of the field gradient measurements in the long quadrupole prototype are shown in Fig. 3. They represent three complete scans of the magnet, with the system returning to the starting point at the end of each scan. The repeatability is better than 200 ppm. The same is true for the integrated gradients, computed by summing the local gradient measurement multiplied by the coil length. In that case, the magnetic length of the coil as well as the positioning accuracy have a strong effect on the results. The integral gradient measurements were compared with the stretched-wire measurements of the same magnet.

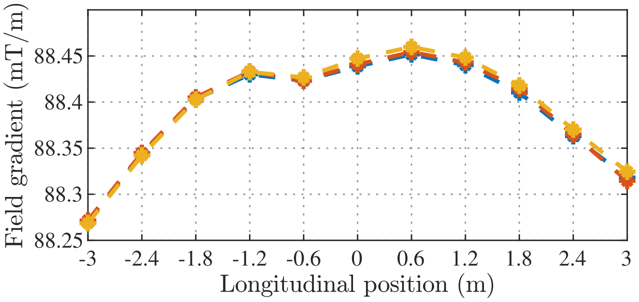


Fig. 3. Field gradient measurement results of three scans.

The difference is below 200 ppm; therefore, the final absolute accuracy of the system is estimated at a 200 ppm level. The same results were obtained in shorter, 1-m long magnets. One was scanned 20 times from each side and the other three times from one side.

The results were obtained by connecting two external coils with opposite polarity, to form a so-called gradient coil arrangement. This way, the gradient measurement is insensitive to a possible PCB offset from the rotation axis and relies instead on the well-defined distance between the coils on the board. This characteristic is similar to the dipole-compensation scheme described in [8], but has the advantage of doubling the signal amplitude.

The accuracy limit is given mostly by the uncertainty of the longitudinal positioning system. In shorter magnets of approximately 1 m, the longitudinal positioning error of 0.5 mm can cause more than 200 ppm variation on the integrated gradient. This effect reduces with the magnet length; therefore, in an 8-m long magnet, the measurement uncertainty caused by the positioning errors is below 50 ppm.

B. Magnetic Axis and Field Direction

To establish the accuracy of the magnetic-axis measurement, we scanned a magnet several times from both sides and related the measurements to the common geometrical reference that was also used in the stretched-wire measurements. The results are shown in Fig. 4 and agree within 100 μm with the stretched-wire measurements. There is no offset expected, as the laser tracker records the entire rotation of the retro-reflectors and the rotating axis of the coil shaft is established by finding a center of a fitted circle. The measurements are acquired in favorable conditions for the laser tracker, where the temperature in the magnet aperture is stable and equal to that of the environment. Hence, there are no thermal gradients causing the refraction of the laser beam between the source and the retro-reflectors. The stability of the laser tracker and the external reference points (fiducials) are the limiting factors in the measurements, which is shown by comparing the scan results with the results at a single position.

Single position measurements are repeatable to 20 μm, even in the long-term tests. In that case, the scanner is not moved between the measurements to eliminate the uncertainty introduced by the laser tracker. Since the probe is resting in the same position during the entire test, its stability and signal noise are the only sources of measurement uncertainty.

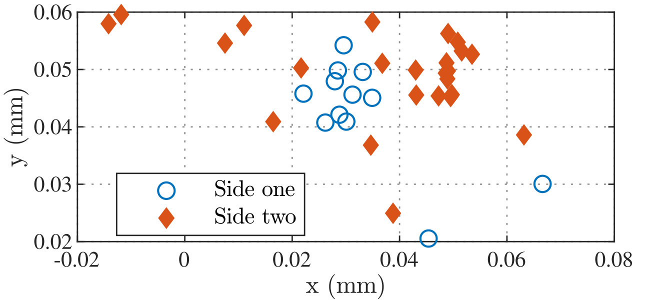


Fig. 4. Magnetic axis measurement results. The plot shows multiple scans from both directions of the magnet. Coordinates are centered by the results of the stretched-wire system.

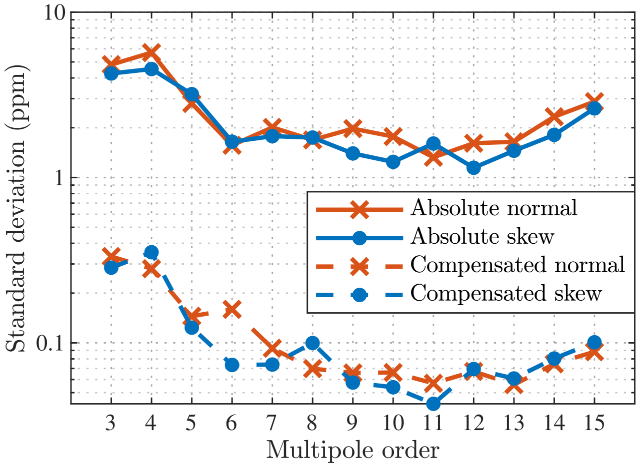


Fig. 5. Standard deviations of the harmonics in a single position computed over 20 repetitions at the reference radius of 50 mm.

We established the accuracy of the field-direction measurement in a similar way as for the magnetic axis. The level meter is positioned directly on the PCB shaft. In this way, a small residual offset remains after leveling, which can be calibrated by measuring the magnet from both sides. The deviation of the field-direction measurements from the stretched-wire reference is within ±100 μrad and is mostly random and uniformly distributed. This is an expected result, considering the encoder resolution of 65 536 quadrature counts, which translates to ±100 μrad positioning precision.

C. Field Harmonics

The precision of the harmonic measurement can be expressed in two ways. Locally, by analyzing the standard deviation of multiple turns in a single position as in Fig. 5, which shows the standard deviation of the harmonics at one position, both for the acquisition with a single coil and with the coils in the quadrupole-compensation arrangement. The precision in the single position is better than 1 ppm for the compensated signal. The plot shows clearly the advantage of the compensation scheme over a single-coil (absolute) acquisition. The compensation removes the influence of several systematic effects on the harmonics, improving not only the precision but also the accuracy of the measurements. These effects are related to the mechanical vibration and misalignment of the coil shaft, which cause the large field components to spread to the neighboring harmonics. In this case, the mostly affected component is the sextupole, which should be naturally small in a quadrupole. The vibration creates a spurious sextupole from the large quadrupole signal. In the compensation scheme, the quadrupole signal is significantly reduced, thus minimizing the effects of vibration [11].

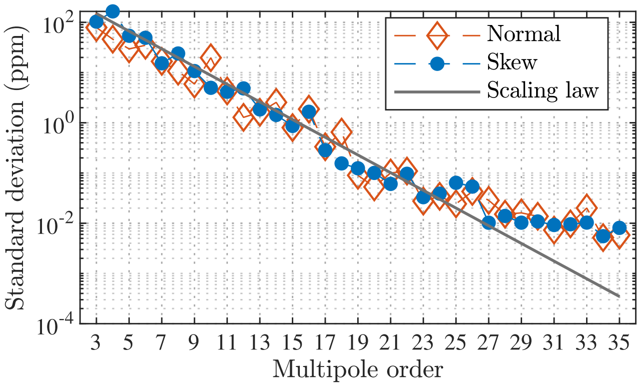


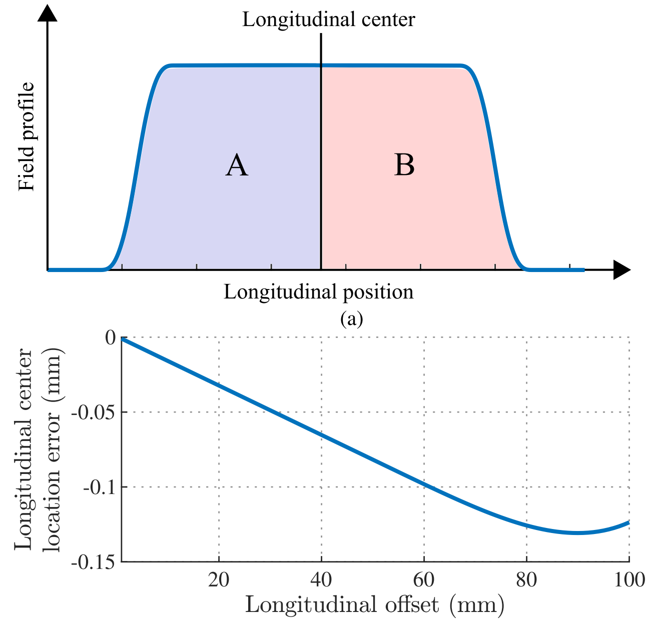
Fig. 6. Standard deviations of the field harmonics computed over the results at various positions in the magnet. The reference radius is 50 mm, and the harmonics at each position have been averaged over 20 rotations.

Another way of evaluating the harmonic measurement precision is based on the Cauchy integral formula (i.e., the logarithmic decay of the higher order harmonics). Both the strength and variation of the field harmonics must decrease. Therefore, the variation of the harmonics acquired at different longitudinal positions in the magnet is a measure for the resolution limit of the probe [12]. Fig. 6 shows the measurement results with the scaling law as a reference. The slope of the theoretical line depends on the ratio between the reference radius and the magnet pole radius. In our case, they are equal to 50 and 75 mm, respectively. We increased the order of the considered harmonics from 15 to 35 to include the order at which the results diverge from the scaling law. The 0.01 ppm level is the sensitivity limit of the system, where noise starts dominating the measurement results. This is the effective noise-floor of the system.

We estimated the accuracy of the harmonic measurement by comparing the results with other rotating coil systems as well as with the integral harmonic measurements using a stretched-wire system. As none of the available systems is able to reach a similar level of precision, the accuracy of the harmonic measurements cannot be assured at the 1 ppm level. This is still acceptable, because the high measurement repeatability allows us to establish the magnet-to-magnet reproducibility at various production stages and, thus, to intercept the assembly errors at an early stage of production.

D. Longitudinal Center

The longitudinal center of the magnet can be defined as the barycenter of the longitudinal field profile. This can be found by weighing the known longitudinal positions of the scanner by the field strength measured at these positions. We first validated this method by applying it to a simulated field profile.



(a)

(b)

Fig. 7. (a) Definition of the longitudinal center on the simulated field profile. Area A is equal to area B. (b) Error in the center location due to the initial positioning error. The coil end starts intercepting the axial field components at approximately 60 mm offset.

The method is insensitive to the absolute error in the initial position of the coil with respect to the magnet as long as all the positions are measured with a high precision relative to this initial position (see Fig. 7). A prerequisite is that the extremities of the induction coils are always in the field regions that are free of the axial (z) components.

To determine the accuracy of the longitudinal center measurement, we also compared the results of the scans conducted from both sides of the magnet, using the position measurements from both the laser tracker and the draw-wire encoder. When the laser tracker is used, which is required whenever the magnetic axis is to be located, the longitudinal center location accuracy is in the order of 500 μm (considering the offset between the coil center and the retro-reflector). If the center is located with the draw-wire encoder, we can achieve a repeatability of about 1 mm.

V. CONCLUSION

The results of the metrological characterization of the system confirm that the scanner is able to fulfill the accuracy requirements for the measurement of the HL-LHC magnets. The system is able to measure the local field gradient with an unprecedented accuracy of 200 ppm by using the coils based on the PCB technology. High degree of control over track positioning in their production allows determining the coil-rotation radius based on the PCB geometry measurements, thus overcoming the limitations of the standard radius calibration. The integral values can be calculated from the local measurements with the same, high accuracy thanks to the high-precision longitudinal positioning system.

This also results in high accuracy in the location of the longitudinal center, below 1 mm. The system can, therefore, be used in the place of the stretched-wire system for the integral measurements of the long superconducting accelerator magnets.

Moreover, it is able to acquire a full set of data much faster than the legacy systems, requiring only 2 h for an 8-m long magnet. Thanks to the built-in motor unit, it can operate automatically and requires minimal setup time and space around the magnet. Finally, adapting the system to any aperture between 80 and 200 mm requires only an exchange of the PCB, protection tube, and three support parts, without complicated disassembly.

Further improvements could be achieved with a higher-resolution encoder for the field-direction measurement. Adding temperature and humidity sensors could allow a correction for the environmental effects on the PCB. Additional tests are foreseen to study these environmental effects and their compensation that can result in further improvement of the main field measurement accuracy.

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