A rotating coil transducer for magnetic field mapping

P. Arpaia, M. Buzio, E. De Matteis and S. Russenschuch

Department of Electrical Engineering and Information Technology, University of Napoli Federico II, Via Claudio 21, 80125 Naples, Italy
European Organization for Nuclear Research (CERN), CH-1211 Geneva 23, Switzerland
Department of Engineering, University of Sannio, Corso Garibaldi 107, 82100 Benevento, Italy

E-mail: Pasquale.Arpaia@cern.ch

ABSTRACT: A rotating coil transducer for local measurements of magnetic field quality in magnets is proposed. The transducer is based on (i) reduced-dimension rotating coils, as required e.g. for space charge computations, (ii) accurate transport, for longitudinal displacements inside the magnet aperture, and (iii) components with magnetic compatibility for negligible interference of the measurand field. This allows magnetic measurement requirements arisen from recently developed compact accelerator systems (with curvature radii of less than 5 m) for biomedical applications and physics research to be satisfied. In the paper, after presenting requirements and conceptual design, the architecture of the transducer is illustrated. Then, the experimental validation by tests of magnetic compatibility and rotation uniformity is reported. Finally, experimental results of repeatability, accuracy, and resolution in comparison with a reference system are discussed.

KEYWORDS: Instrumentation for particle accelerators and storage rings - low energy (linear accelerators, cyclotrons, electrostatic accelerators); Accelerator Subsystems and Technologies; Accelerator Applications; Acceleration cavities and magnets superconducting (high-temperature superconductor; radiation hardened magnets; normal-conducting; permanent magnet devices; wigglers and undulators)

1Corresponding author.
1 Introduction

In particle accelerators, new technical challenges for magnetic measurements arise mainly from curved magnets for biomedical projects with compact dimensions, needing a full characterization of the local and transversal field homogeneity and quality. Some of the new accelerator projects are also space-charge limited [1]. Indeed, magnets exhibit nonlinear intrinsic magnetic fields (introducing a corresponding nonlinear motion of the beam particles, and exciting different high-order transverse resonances), and thus limit the betatron tunability. In this condition, also a tune change in the beam distribution is generated by a space-charge defocusing force [2]. The space-charge tune shift depends on the beam distribution, and increases as the particle’s betatron amplitudes decrease. In this case, local measurements, such as fringe fields, local distributions, end field, are useful to model the actual behavior of curved/straight magnets in order to predict space charge effects on the beam lifetime.

Main sensing technologies for magnetic field mapping include Nuclear Magnetic Resonance (NMR) and Hall effect. NMR transducers are very accurate for the main field, but not applicable to field gradient measurements. Hall effect has been used in measurement systems for bent magnets
with open apertures \cite{3, 4} (C-shaped magnets) \cite{5–8}. Hall transducers are widely used for local field mapping. Their long-term gain and offset drift with time and temperature requiring frequent re-calibrations is mitigated by recent progress in accuracy, frequency response, elimination of the planar Hall effect, and sensing chip size (0.1 mm) \cite{9}.

The best suited sensor for the above-mentioned requirements remain the sensing coils \cite{10}, fixed or even rotating \cite{11–13}. They guarantee more stable measurement performance with compensation for the main field component, easy calibration procedures, and additional information on the multipole field components. At CERN, for the Large Hadron Collider (LHC) \cite{14}, transducers based on fixed or rotating coils have been used as valid alternative to single-stretched wires \cite{15} for integral field measurements and to intercept manufacturing defects by longitudinal scanning of straight magnets \cite{16}. Wire-based systems \cite{17} are used only for straight geometries and are not generally suited for local magnetic field measurements. The main coil-based systems are the Dipole or Quadrupole Industry Magnetic Measurement (DIMM and QIMM) \cite{18} and the Fast Measurement Equipment (FAME) \cite{19}. The QIMM system exploits a traveling rotating shaft (“mole”) \cite{20}, carrying from 3 to 5 sensing coils. The FAME system consists of a coil shaft up to 15 m long. Both systems are used to measure the field in superconducting magnets at room or cryogenic temperatures. In summary, these systems provide integral field measurement appropriate for long and slender apertures, such as those of the LHC magnets.

In literature, measurement systems based on a rotating coil sensor were applied to curved magnets. In \cite{21}, a 50-cm long rotating coil sensor for testing fast-ramped superconducting magnets, operated at 1 Hz at cryogenics temperatures, is presented. However, for a field mapping with spatial (or longitudinal) resolution in the order of few cm, coil dimensions of about 50 cm are still too long. Moreover, the design is specifically customized to a particular application of curved magnets \cite{22}, envisaging the use of non-magnetic components.

A valid solution turns out to be the use of fixed fluxmeter method. In \cite{23}, the integral field is measured by a curved array of printed coils (fluxmeter) and the tolerance range of magnetic field is established in ramped conditions. A fixed long-curved coil presented in \cite{24, 25} is used to scan the aperture and measure the integral field and its lateral uniformity.

In general, rotating coils provide fast measurement and very-high accuracy of the high-order harmonic field components (DC Field), especially when the main component is compensated ($10^{-6}$). However, the state-of-the-art systems are not only too big for the fine-grained mapping required by new generation of strongly-curved magnets (FAIR \cite{22}), but are also mechanically compatible with a very-restricted range of curvature radii. The choice between Hall sensors and harmonic coils of reduced dimensions depends on the geometry and mechanical requirements of the specific magnets to be mapped.

In this paper, a compact rotating coil transducer for local and integral field measurement is proposed. This transducer can be fully immersed in a strong magnetic field and, thanks to its low weight and short coil length ($30 < l_{coil} < 80$ mm) with respect to other rotating coil transducer \cite{18, 19, 21}, can be made to follow arbitrary paths throughout magnets with gaps between 40 and 200 mm, and curvature radii between 1 and 12 m. The main idea is to have a high-accuracy transducer and a fine longitudinal discretization of the magnetic field, useful to nonlinear magnetic fields investigation and space charge effects forecast. In the following sections, the requirements, the architecture, and the first prototype of the proposed transducer are described in detail. Finally,
an experimental proof-of-principle concerning field measurement, speed variation analysis, and main metrological characteristics is reported.

2 The transducer

In the following, (i) the requirements, (ii) the conceptual design, (iii) the architecture, and (iv) the prototype of the proposed rotating coil transducer for magnetic field mapping are illustrated.

2.1 Requirements

The main requirements of a rotating coil transducer for field mapping are the ability to measure local and fringe fields and the flexibility to adapt to different mechanical configurations, magnet apertures and curvatures. Therefore, the transducer must be: (i) typically 200 mm or less in length and 50 mm or less transversally; (ii) able to work inside the magnet aperture, completely immersed in the magnetic field; (iii) able to accommodate sensing coils of a few mm thick and (iv) light than 1 kg, to allow easy motion and low positioning error. Another important requirement is the need to measure precisely the angular position of the coils. This is necessary both statically, for fixed-coil measurement of pulsed magnets, and dynamically for conventional harmonic coil measurements. The longitudinal position of the transducer inside the magnet aperture must be known with a precision of $\pm 100 \mu$m or better. The requirements on the measurement result, expressed in terms of the uncertainty of the harmonic components of the magnetic field, vary according to the specific application (principally at room temperature). Typical relative targets are in the range of a few hundreds of ppm with respect to the peak field.

2.2 Conceptual design

The design of the transducer is driven by the following main aspects: magnetic compatibility, manufacturing precision, and compact size of all the components.

Magnetic compatibility of components is necessary to avoid field perturbations during the measurement or displacements of the sensor due to electromagnetic forces. Consequently, the transducer was realized free of ferromagnetic and highly conducting parts to avoid magnetization and eddy currents.

The manufacturing precision is fundamental to have low dimensional tolerances. As described in [26, 27], high rotation speeds could increase mechanical instability in traditional rotating systems [18, 19]. Specifically, speed variations must be analyzed experimentally in order to check the rotation stability and the related measurement errors on the harmonic analysis.

The compact size of the transducer improves the spatial resolution of coil measurements. In this case, according to recent developments on printed circuits [11], the coil can actually be made very compact without significant quality loss. Considering the systems presented in [18, 19], the 1-$\sigma$ relative repeatability (relative standard deviation over several revolutions) of dipole magnetic measurements is less than $\pm 10^{-4}$. Moreover, the rotation and mechanical instability effects must be considered and related to the measurement results of field quality.

The key, here, is to choose compact and magnetically compatible components. Non-magnetic technologies, like piezoelectric drives, were investigated. Optical encoders with plastic code wheel are the most compact and promise the best technical specifications (high counts per turn) and
The coils must be compact, on the order of a few cm, but with a large total surface for acquiring the signal with high signal-to-noise ratio. This requires a high precision in the mechanical parts such as the support, coil shaft, ball bearings and coupling. The choice of non-magnetic and -metallic material is fundamental, as well as the avoidance of vibrations and rotary transmission.

2.3 Architecture

The above requirements have been satisfied by the architecture shown in figure 1: a piezomotor, an angular encoder, and a rotating shaft carrying the sensing coil are mounted on a non-magnetic aluminum support. A preliminary prototype made of plastics did not show suitable mechanical stability. A plastic coupling between the motor and the encoder allows motor vibrations to be damped. Moreover, slip rings contacts are provided for voltage signal transmission.

2.4 Prototype

A piezoelectric motor, ER-15 of Nanomotion [28] was selected for driving the shaft (figure 2 A). The main suitable features of ER-15 are: diameter of 15 mm, length of 22.5 mm, weight of 12 g, variable speed of rotation from 40 to 180 rpm, and a more than adequate torque from 6 to 4 N·mm. Like most similar devices this motor includes some ferromagnetic components, such as the ball bearings and the shaft, the effects of which have to be checked experimentally. The optical encoder HEDM 5505-J13 of Avago Technologies [29] (figure 2 B) has specifications matching the design goals: non-magnetic material (plastic code wheel), compact dimension (41 × 30 × 18 mm), and an adequate resolution (1024 cycles per revolution).

The coil shaft is realized in fiberglass to ensure suitable rigidity and magnetic compatibility during the rotation. Two coils (figure 2 C) of dimensions 40 × 10 mm, with a total sensing (or equivalent magnetic) surface area of 0.12367 m², 485 turns, and a resistance of 420 Ω each are mounted on the shaft (figure 3) in tangential configuration (i.e. intercepting the radial magnetic flux density) without compensation coil. One coil measures the field, while the other is kept as a spare and, at the same time, balances mechanically the shaft. The length of the coil is determined by the required longitudinal resolution of the measurement, while the width is constrained by the magnet gap and shaft size. The number of turns determines the total coil area, which must be
Figure 2. Main components of the transducer prototype: A) piezomotor ER-15 by Nanomotion, B) encoder HEDM 5505-J13 by Avago Technologies, and C) sensing coils (40 × mm, area: 0.12367 m², resistance: 420 Ω).

Figure 3. Prototype of the rotating coil transducer: A) piezomotor, B) encoder, and C) sensing coils.

chosen so as to obtain coil signals of the order of a few V in the given magnetic field at the given rotation speed (typically of the order of 1 rps).

3 Experimental validation

The design of the rotating coil transducer has been validated experimentally by tests of (i) magnetic compatibility, in order to verify the impact of the transducer on the measurand field, and specifically the effect of the martensitic components of the motor, and (ii) speed variation, to check the motor drive and confirm the mechanical stability in comparison with reference systems at CERN [26, 30].
3.1 Magnetic compatibility

The aim of the test is to verify the magnetic field variation due to the presence of the transducer inside the magnet with respect to a threshold (typically of 100 ppm). The only component with ferromagnetic parts is the piezomotor ER-15. The test procedure is to put the piezomotor into the aperture of a reference dipole magnet with a static magnetic field, and to measure the field before and after the motor insertion.

The measurement setup is composed by a NMR Teslameter (Metrolab PT2025 [31]), the 1-T dipole reference magnet used at CERN, and the piezomotor ER-15 under test (figure 4).

Two different configurations of the piezomotor with respect to the NMR Teslameter probe were investigated (figure 5): (A) aligned along the axis and (B) in a lateral position. The test was carried out at increasing magnetic field levels ([0.4, 0.5, 0.8, 1.0] T) with the motor both switched off and on. The test at 1.0 T in alignment configuration (figure 5 A) turned out to be the worst case. The measured variations in magnetic field, with motor off and on, at different distances are reported in table 1. The trend and the threshold are highlighted in figure 6. The minimum distance in order to have an influence on the field lower than the threshold is 4 cm. This result was taken into account for positioning the coil on the shaft in the prototype.

This analysis aims at highlighting the field disturbance due to ferromagnetic motor components. However, the NMR probe is only sensitive to the magnitude of the field at the probe, whilst relatively large transverse field components can be present, e.g. 1%, producing only 0.01% change in the magnitude. Such errors could be important in determining normal and skew harmonics of a magnet and will be the focus of future investigation in on-field validation.

3.2 Speed variations

The aim of this test is to check the stability of the rotation speed stability of the piezomotor and to compare it to reference systems at CERN [26, 30]. The measurement setup (figure 7) is based on a data acquisition board (NI PXI 6289 [32]), a power supply for the encoder, and a Fast Digital Inte-
Figure 5. Magnetic compatibility test configurations: motor and NMR probe in position (A) aligned along the axis and (B) lateral (d: distance).

Table 1. Magnetic compatibility test results: magnetic field differences between the reference NMR measurements without and with motor (off and on) at 0.8 T at varying distance.

| Distance (cm) | $\Delta B/B$ (motor off) (ppm) | $\Delta B/B$ (motor on) (ppm) |
|---------------|--------------------------------|-------------------------------|
| 2             | 537                            | 535                           |
| 3             | 219                            | 219                           |
| 4             | 95                             | 94                            |
| 5             | 36                             | 36                            |
| 6             | 17                             | 17                            |
| 7             | 7                              | 7                             |
| 8             | 4                              | 4                             |
| 9             | 2                              | 2                             |

Grator (FDI) with an encoder interface used to acquire the encoder pulses [33]. The measurement is carried out by means of the Flexible Framework for Magnetic Measurements (FFMM) [34], a C++ program running on a PXI PC workstation. Result analysis was done in Matlab®.

Three different case studies were considered to assess the variation of the angular speed $\omega$: (i) stand-alone configuration, that is, only motor and encoder; (ii) complete configuration in a field-free region, in order to determine the optimal controller settings; and (iii) complete configuration in a reference dipole, to check the transducer rotation in presence of different levels of magnetic field.
3.2.1 Case study 1: stand-alone configuration

In this case study, the intrinsic rotation features of the piezomotor ER-15 by Nanomotion [28] (figure 2A) are tested in the minimal setup of figure 8. A flywheel of about 50 g was used to increase the inertia of motor, and thus, to emulate the mechanical load of the coil. The quality of rotation in term of acceptable speed fluctuations, i.e. RMS and peak-to-peak percent variations of the angular velocity $\omega$, has been measured.

Preliminarily, the motor operation was tuned by setting the drive and feedback loop gain of its controller Nanomotion XCD [35]. The objective is to optimize the velocity loop with respect to the applied load. The speed variation depends mainly on these parameters and on the weight of the rotating shaft. The results for the speed variation are reported in table 2, expressed as reference and measured speed, as well as root mean square (RMS) and peak-to-peak of their relative difference.
Figure 8. Setup (encoder, motor and flywheel) for assessing the intrinsic rotation speed features of the piezomotor ER-15 of Nanomotion [28].

| Reference (rps) | Average (\(\bar{\omega}\)) (rps) | RMS (\(\Delta\omega/\bar{\omega}\)) (%) | (\(\Delta\omega/\bar{\omega}\))\(_{pp}\) (%) |
|----------------|-------------------------------|---------------------------------|---------------------------------|
| 1.000          | 1.036                         | 3.28                            | 19.92                           |
| 2.000          | 2.071                         | 2.08                            | 12.30                           |
| 3.000          | 3.108                         | 2.00                            | 11.38                           |

The results show that speed variations decrease as the speed increases, consistently with the behavior of similar systems based on step motors.

3.2.2 Case study 2: complete configuration in a field-free region

The second speed variation test was made with the complete transducer (figure 3). The results are given in table 3. The measured RMS and peak-to-peak speed variations are compatible, according to the definition [36], with the previous ones (table 2), independently of the motor load. In table 4, the rotation performance of the proposed transducer and the motor unit of main current CERN benches (LINAC4 [30] and Motor Rotating Unit (MRU) [26]) is compared. The amplitude of RMS speed variations is about three times higher than that the best similar systems in operation at CERN, due to the piezoelectric nature of the motor. This is still acceptable if the measurement time is kept sufficiently short so that any input voltage offset can be considered constant throughout a coil rotation, since in this case the resulting drift can be corrected exactly by post-processing [37]. The impact of speed fluctuations on high-order harmonics will be the object of future tests with a compensated coil setup.
Table 3. Speed variation results: complete configuration in a field-free region.

| Reference (rps) | Average (\(\bar{\omega}\)) (rps) | RMS (\(\Delta \omega / \bar{\omega}\)) (%) | (\(\Delta \omega / \bar{\omega}\)) pp (%) |
|----------------|----------------------------------|------------------------------------------|------------------------------------------|
| 1.00           | 1.036                            | 3.04                                     | 21.60                                    |
| 2.00           | 2.072                            | 1.96                                     | 14.48                                    |
| 3.00           | 3.108                            | 1.68                                     | 12.76                                    |

Table 4. Speed variation results: performance comparison with other CERN benches, LINAC4 [30] and MRU-based [26] systems.

| Bench       | Reference (rps) | Average (\(\bar{\omega}\)) (rps) | RMS (\(\Delta \omega / \bar{\omega}\)) (%) | (\(\Delta \omega / \bar{\omega}\)) pp (%) |
|-------------|-----------------|----------------------------------|------------------------------------------|------------------------------------------|
| Transducer  | 1.00            | 1.036                            | 3.04                                     | 21.60                                    |
| MRU         | 1.00            | 0.989                            | 0.74                                     | 3.84                                     |
| LINAC4      | 0.500           | 0.499                            | 1.82                                     | 10.36                                    |

Table 5. Speed variation results: complete configuration in a reference dipole.

| Field (T) | Reference (rps) | Average (\(\bar{\omega}\)) (rps) | RMS (\(\Delta \omega / \bar{\omega}\)) (%) | (\(\Delta \omega / \bar{\omega}\)) pp (%) |
|-----------|-----------------|----------------------------------|------------------------------------------|------------------------------------------|
| 0.0       | 2.000           | 2.072                            | 1.96                                     | 14.48                                    |
| 0.2       | 2.000           | 2.073                            | 2.00                                     | 14.22                                    |
| 0.4       | 2.000           | 2.073                            | 1.88                                     | 14.36                                    |
| 0.6       | 2.000           | 2.073                            | 1.98                                     | 14.48                                    |
| 0.8       | 2.000           | 2.073                            | 2.04                                     | 15.16                                    |
| 1.0       | 2.000           | 2.073                            | 1.94                                     | 14.30                                    |

3.2.3 Case study 3: complete configuration in a reference dipole

In this test, the speed variation is measured at different angular speeds \(\omega\) ([1.000, 2.000, 3.000] rps), at different dipole magnetic fields \(B\) ([0.0, 0.2, 0.4, 0.6, 0.8, 1.0] T), in the transducer complete configuration. In figure 9, a typical angular speed measurement is shown as a function of azimuthal angle. As an example, table 5 and figure 10 show the rotation speed results for 2.000 rps and different magnetic fields. Results of all the tests show the independence of speed variations upon the magnetic field.

4 Metrological characterization

This test aims at characterizing the transducer as a whole (figure 3) by evaluating the quality of its magnetic field measurement in terms of:

- **repeatability**:

\[
\pm \sigma_{B_1} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (B_1 - \bar{B}_1)^2}
\]  

(4.1)
Figure 9. Angular speed signal for magnetic field of 1.0 T and nominal speed of 2 rps.

Figure 10. Percent RMS and peak-to-peak variations of speed at different magnetic field.
where $\bar{B}_1$ is the average and $N$ the number of consecutive measurements. The relation 4.1 is useful also for assessing the coils mechanical stability in a predefined rotation time interval [26, 27].

- **accuracy**, assessed as the deviation from the reference field $B_{1}\text{ref}$ measured by NMR:

$$\Delta B_1 = (\bar{B}_1 - B_{1}\text{ref}) + C$$

where $C$ is a term of correction, accounting for the different position of transducer and NMR probe in the magnet (0.08\% of difference), as well as for the gain error of the integrator (0.2–0.3\%, according to the gain, without self-calibration).

- **resolution**, that is the minimum level of field variation appreciable by the transducer, assessed as the repeatability in absence of measurand, and thus in presence only of the earth magnetic field.

4.1 Experimental setup

The measurement setup (figure 11) is the same as in the previous test, and the FDI is used to acquire and integrate the coil voltage signal.

4.2 Test procedure

The measurement procedure consists of setting the magnetic field level $B$ inside the reference dipole ([0.0, 0.2, 0.4, 0.6, 0.8, 1.0] T) and measuring it through the transducer for different angular rotating...
Table 6. Field measurement quality results with transducer in longitudinal position and nominal $\omega$ of 2 rps.

| $B_1^{\text{nom}}$ (T) | $\bar{B}_1$ (T) | $\sigma_{B_1}/\bar{B}_1$ (ppm) | RMS ($\Delta \omega/\bar{\omega}$) (%) | ($\Delta \omega/\bar{\omega}$)$_{pp}$ (%) |
|-------------------------|-----------------|-------------------------------|-------------------------------------|----------------------------------|
| 0.0                     | 0.002301        | 74                            | 1.96                                | 14.48                            |
| 0.2                     | 0.199639        | 110                           | 2.00                                | 14.22                            |
| 0.4                     | 0.398831        | 72                            | 1.88                                | 14.36                            |
| 0.6                     | 0.598293        | 104                           | 1.98                                | 14.48                            |
| 0.8                     | 0.797384        | 86                            | 2.04                                | 15.16                            |
| 1.0                     | 0.999239        | 72                            | 2.04                                | 15.30                            |

speeds $\omega$ ([1.000, 2.000, 3.000] rps). According to the classical procedure for rotating coil measurements [38], the magnetic flux is computed by integrating the coil voltage and adding the flux increments measured by the FDI triggered by the encoder pulses. In this test, only the main dipolar field component $B_1$, obtained from the fundamental harmonic of flux, is considered, because the transducer includes only an absolute coil (uncompensated coil, i.e. without a compensation coil).

4.3 Experimental results

In table 6, the dipole field measurements (averaged on 20 revolutions) $\bar{B}_1$, the field relative repeatability $\pm \sigma_{B_1}/\bar{B}_1$, as well as the RMS and peak-to-peak ($\Delta \omega/\bar{\omega}$)$_{pp}$ of the speed relative difference are given for a nominal $\omega$ of 2 rps at varying the nominal magnetic field $B_1^{\text{nom}}$. As shown in figures 12 A and B, the 1-$\sigma$ repeatability does not appear to be correlated neither to the field level, nor to rotating speed fluctuations.

In order to check the eventual effects of speed variation, the relative difference $\Delta B_1/B_1^{\text{ref}}$ (4.2) is considered with respect to the field measured by the reference NMR probe [31], for different $\omega$ and for 2 levels of $B_1$. The results in table 7 show that the measured field is repeatable within about a hundred of ppm with respect to the NMR reference (the systematic difference is due to the non-uniformity of the field inside the magnet gap). Furthermore, the repeatability gets worse as the rotation gets faster. The repeatability is better than the typical target value of 100 ppm at both the nominal field levels when $\omega$ is 1 rps, which is fast enough for practical applications. This result demonstrates the possibility of measuring magnetic field with the required repeatability of $\pm \sigma_{B_1}/\bar{B}_1 < 100$ ppm, without a very-high uniformity in the rotation speed (RMS ($\Delta \omega/\bar{\omega}$) > 2%, and ($\Delta \omega/\bar{\omega}$)$_{pp}$ > 10%). Indeed, the digital integrator (FDI) triggered by the angular encoder allows speed irregularity to be compensated, by confirming precedent results [37].

In table 8, the results of the test carried out outside the reference magnet in presence of only the earth magnetic field are reported. These results highlight the transducer capability of measuring fields down to about 30 $\mu$T, with a relative 1-$\sigma$ repeatability per revolution of $\pm 0.2\%$. From these results, the resolution can be assessed as the minimum variation appreciable of magnetic field. This is the repeatability in presence only of the earth magnetic field, equal to 0.07 $\mu$T (worst case, north-pole aligned orientation).
Figure 12. Comparison (A) and uncorrelation (B) between magnetic field relative repeatability ($\pm \sigma_{B_1}/\bar{B}_1$) and relative angular speed rms [RMS ($\Delta \omega / \bar{\omega}$)].
Table 7. Field measurement quality results at varying $\omega$, for nominal magnetic field of 0.8 and 1.0 T.

| $\omega$ (rps) | $B_{1\text{ref}}$ (T) | $\bar{B}_1$ (T) | $\Delta B_1/B_{1\text{ref}}$ (10^{-4}) | $\sigma_{B_1}/\bar{B}_1$ (ppm) | RMS ($\Delta \omega/\bar{\omega}$) (%) | $(\Delta \omega/\bar{\omega})_{pp}$ (%) |
|----------------|----------------------|----------------|----------------------------------------|-----------------------------|-------------------------------------|-------------------------------------|
| 1.0            | 0.799788             | 0.797341       | -0.41                                  | 102                         | 3.32                                | 23.54                               |
| 2.0            | 0.799788             | 0.797384       | 0.22                                   | 86                          | 2.04                                | 15.16                               |
| 3.0            | 0.799788             | 0.797381       | 0.19                                   | 214                         | 1.92                                | 12.12                               |
| 1.0            | 0.998848             | 0.996394       | -0.01                                  | 98                          | 3.08                                | 24.08                               |
| 2.0            | 0.998848             | 0.996396       | 0.01                                   | 128                         | 2.14                                | 16.74                               |
| 3.0            | 0.998848             | 0.996395       | 0.00                                   | 138                         | 1.68                                | 12.66                               |

Table 8. Field measurement quality results in free space (earth magnetic field) with $\omega$ of 2.0 rps, and transducer aligned or perpendicular to north pole.

| North-pole orientation | $\bar{B}_1$ (µT) | $\sigma_{B_1}/\bar{B}_1$ (%) |
|------------------------|------------------|------------------------------|
| aligned                | 36.00            | 0.2                          |
| orthogonal             | 62.00            | 0.2                          |

5 Conclusions

In this paper, the proof-of-principle demonstration and the experimental characterization of a prototype rotating-coil transducer designed for magnetic field mapping is presented. The main objective of the transducer is to satisfy the magnetic measurement needs of the next generation of compact accelerators.

Results of tests on the magnetic compatibility of the motor point out a perturbation tolerance area with a radius of 4 cm. Test results about of speed variation show a RMS and peak-to-peak fluctuations of about 2% and 20%, respectively. However, these are well acceptable for magnetic measurements in the rotating coil method using a digital integrator for determining the flux increment between two trigger signals from the angular encoder. As a matter of fact, the inherent re-parametrization with respect to the shaft’s angular position makes the method intrinsically robust to the speed variations, if the input voltage offset is constant during the measurement. The impact of vibrations on the measurement of harmonics remains to be assessed. The 1-σ repeatability per revolution of magnetic field absolute measurements (dipole $B_1$) is less than ±100 ppm and the relative difference is about constant in the same condition. Another important result is the transducer resolution, about 0.07 µT, assessed as the minimum appreciable variation in measuring only the earth magnetic field for different orientations of the transducer.

Acknowledgments

The authors thank Naim Bruti, Olaf Dunkel, Lucette Gaborit, Xavier Gontero, and Ricardo Beltron Mercadillo of CERN’s Magnetic Measurement section, for their technical assistance.
References

[1] K. Schindl, Space charge, in Beam measurement, Proceedings of the Joint US-CERN-Japan-Russia School on Particle Accelerators, Montreux Switzerland (1998).

[2] H. Hotchi et al., Effects of magnetic field tracking errors on beam dynamics at J-PARC RCS, in Proceedings of PAC07, Albuquerque U.S.A. (2007).

[3] J. Muratore et al., Magnetic field measurements of an HTS retrofit synchrotron dipole, IEEE Trans. Appl. Supercon. 21 (2011) 1653.

[4] A. Batrakov et al., Bending magnets for the SAGA Storage Ring, Nucl. Instrum. Meth. A 543 (2005) 47.

[5] J. Campanany et al., Looking for a Hall probe bench for closed big magnetic structures, in Proceedings of the IMMW17 — International Magnetic Measurement Workshop, Terrassa-Barcelona Spain (2011).

[6] C.W. Ostenfeld, Measurements of Max-IV girder systems, in Proceedings of the IMMW18 — International Magnetic Measurement Workshop, Brookhaven National Laboratory Upton, New York U.S.A. (2013).

[7] M. Negrazus et al., Magnet design and measurement results of the solenoids and bunch compressor bending magnets of the SwissFEL Test Facility, IEEE Trans. Appl. Supercon. 22 (2012) 4101104.

[8] A.M. Batrakov et al., Nine tesla superconducting bending magnet for BESSY-II, Nucl. Instrum. Meth. A 543 (2005) 35.

[9] D. Popovic Renella, S. Dimitrijevic, S. Spasic and R.S. Popovic, High-accuracy teslameter with thin three-axis Hall probe, in Proceedings of the 20th IMEKO TC4 International Symposium, Benevento Italy (2014), pp. 926–931.

[10] S. Tumanski, Induction coil sensors — a review, Meas. Sci. Technol. 18 (2007) R31.

[11] J. Di Marco, Application of PCB and FDM technologies to magnetic measurement probe development, in Proceedings of the IMMW18 — International Magnetic Measurement Workshop, Brookhaven National Laboratory Upton, New York U.S.A. (2013).

[12] A. Jain et al., Measurements of the field quality in superconducting dipoles at high ramp rates, IEEE Trans. Appl. Supercon. 16 (2006) 1370.

[13] K.H. Park, B.K. Kang, M. Yoon and J.H. Lim, Rotating coil method for the measurement of deflecting magnetic fields in cathode ray tube, Sensor. Actuator. A 86 (2000) 159.

[14] CERN, The Large Hadron Collider, http://home.web.cern.ch/topics/large-hadron-collider.

[15] P. Arpaia, M. Buzio, C. Petrone, S. Russenschuck and L. Walckiers, Multipole correction of stretched-wire measurements of field-gradients in quadrupole accelerator magnets, 2013 JINST 8 P08010.

[16] E. Wildner et al., Production follow-up of the LHC main dipoles through magnetic measurements at room temperature, IEEE Trans. Appl. Supercon. 14 (2004) 173.

[17] A.V. Veryaskin, Magnetic gradiometry: a new method for magnetic gradient measurements, Sensor. Actuator. A 91 (2001) 233.

[18] J. Garcia Perez et al., Performance of the room temperature systems for magnetic field measurements of the LHC superconducting magnets, IEEE Trans. Appl. Supercon. 16 (2006) 269.

– 16 –
[19] P. Arpaia, L. Fiscarelli, G. Montenero and L. Walckiers, Active compensation of field errors within ±2 ppm in superconducting magnets, Nucl. Instrum. Meth. A 638 (2011) 176.

[20] L. Bottura et al., A mole for warm magnetic and optical measurements of LHC dipoles, IEEE Trans. Appl. Supercon. 10 (2000) 1454.

[21] P. Schnizer et al., Mole for measuring SIS100 magnets commissioning and first test results, IEEE Trans. Appl. Supercon. 20 (2010) 1977.

[22] E. Fischer et al., Status of the superconducting magnets for FAIR, IEEE Trans. Appl. Supercon. 24 (2014) 4004007.

[23] G. Golluccio et al., Overview of the magnetic measurements status for the MedAustron project, in Proceedings of the IMMW18 — International Magnetic Measurement Workshop, Brookhaven National Laboratory Upton, New York U.S.A. (2013).

[24] H. Leibrock et al., Prototype of the superferric dipoles for the Super-FRS of the FAIR-project, IEEE Trans. Appl. Supercon. 20 (2010) 188.

[25] W. Chen et al., A flipping-coil field measurement system for the CSNS/RCS dipole magnet, in Proceedings of the IMMW18 — International Magnetic Measurement Workshop, Brookhaven National Laboratory Upton, New York U.S.A. (2013).

[26] N.R. Brooks, L. Bottura, J.G. Perez, O. Dunkel and L. Walckiers, Estimation of mechanical vibrations of the LHC fast magnetic measurement system, IEEE Trans. Appl. Supercon. 18 (2008) 1617.

[27] J. DiMarco et al., Influence of mechanical vibrations on the field quality measurements of LHC interaction region quadrupole magnets, IEEE Trans. Appl. Supercon. 10 (2000) 1458.

[28] Johnson Electric, ER-15 rotary piezomotor, http://www.johnsonmotor.com/en/features/rotary-piezo-motors-for-defense-industry.html.

[29] Avago Technologies Group, Optical encoder HEDM 5500-J13, http://www.avagotech.com.

[30] G. Golluccio et al., Magnetic measurements of permanent and fast-pulsed quadrupoles for the CERN LINAC4 project, in Proceedings of IPAC’10, Kyoto Japan (2010).

[31] Metrolab, NMR precision teslameter PT2025, http://www.metrolab.ch/.

[32] National Instruments, NI PXI 6120, http://www.ni.com/.

[33] P. Arpaia, L. Bottura, L. Fiscarelli and L. Walckiers, Performance of a fast digital integrator in on-field magnetic measurements for particle accelerators, Rev. Sci. Instrum. 83 (2012) 024702.

[34] P. Arpaia, M. Buzio, L. Fiscarelli and V. Inglese, A software framework for developing measurement applications under variable requirements, Rev. Sci. Instrum. 83 (2012) 115103.

[35] Johnson Electric, Piezo motors, http://www.johnsonelectric.com/en/product-technology/motion/piezo-motors-subsystems/silent-piezo-motors.

[36] Bureau International de Poids et Mesures, VIM3 international vocabulary of metrology, http://www.bipm.org/en/publications/guides/vim.html.

[37] L. Walckiers, The harmonic-coil method, in Proceedings of the CAS — CERN Accelerator School: Magnetic measurement and alignment, Montreux Switzerland (1992), pp. 138–166.

[38] L. Bottura, Standard analysis procedures for field quality measurement of the LHC magnets. Part I: Harmonics, Engineering Specification, CERN Internal Note LHC-MTA-IN-97-007 (1997).