Magnetic field mapper based on rotating coil

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***Abstract*—A magnetic field mapper based on (i) a rotating coil transducer [1] of $40 \times 10\ \mathrm{mm}^2$ with a total coil surface of $0.1237\ \mathrm{m}^2$, and (ii) a train-like system for longitudinal motion and positioning inside magnet bore, is proposed. The mapper allows a localised measurement of magnetic fields and the variation of the harmonic multipole content in the magnet ends. After an introduction to the measurement needs and problems, the magnetic measurement system is presented, focusing on the requirements, the architecture and conceptual design, and the prototype for straight magnets. Functional tests of the longitudinal position measurements of the system are reported and results of the experimental characterization are presented in terms of repeatability and resolution.**

***Keywords*—magnetic measurements, field mapping, measurement system, rotating coil;**

I. Introduction

In the quality assurance process for particle accelerator magnets, magnetic measurements are required for checking the field uniformity, the magnetic length, and the extension of the fringe-field region. In literature, the related measurement systems are based on different technologies, like Hall sensors, Nuclear Magnetic Resonance (NMR), and rotating-coil technologies.

NMR transducers are very accurate for the main field, e.g., Metrolab PT2025 NMR [2], ± 5 and ± 0.1 ppm, absolute and relative accuracy, respectively. However, they are not suitable for gradient measurements (e.g. fringe fields), and have limited lower range of operation (e.g. Metrolab PT2025 probe, 0.043 T) [2]. Often, the NMR transducers support other measurement systems, such as Hall probes, which are are widely used for local mapping of straight and curved magnets [3]–[5]. Main advantages are high spatial resolution due to the size of the sensing element (e.g. $11\ \mathrm{mm}^2$ for 3D Hoeben electronics [6]), a wide range of field, and the use for non-homogeneous fields both in static and dynamic conditions. Main disadvantages are the relatively low accuracy (0.1%) and the strong temperature dependence of the metrological performance. Moreover, the mechanical limit of these systems, and i.e. the measurement precision, is the difficulty to align the Hall probe characterized to small sensing element, with respect to the mechanical system.

In most cases, the best suited sensor for field uniformity check remain the sensing coil, fixed or moving. Main advantages are stable measurement performance, easy calibration procedures for small dimension coils, and multipole-field measurements. Rotating coil systems, such as the QIMM [7] and FAME [8] systems at CERN, are used for integral field measurement of LHC magnets. Regarding curved magnets, the main systems use fixed coils, such as the curved printed coil array [9] and long, curved coils [10], applied mainly to measure field uniformity. Measurement systems based on rotating coils were also applied to curved magnets. As an example, a 50-cm long rotating coil sensor for testing fast-ramped superconducting magnets is presented in [11], [12]. Moreover, magnets with large acceptance (i.e. a large length to aperture ratio) for separators and mass spectrometers [13], [14] require local mapping for track reconstruction.

In this paper, a magnetic measurement system capable of satisfying the abovementioned requirements in a single system is presented. In Section II, the main measurement problems are highlighted. Section III presents the magnetic field mapper, in terms of requirements, architecture, analytic approach, design, and prototype validation. The functional tests for checking the trolley speed and position measurements are reported in Section IV. Finally, the experimental characterization of the system is reported in Section V.

II. Measurement Requirements

Rotating coil systems are useful for multipole measurement on the full length magnet. In fact, when the magnetic length of a magnet is much less than the beam synchrotron wavelength, accelerator magnets can be approximated as thin lenses in the beam optical computations. Otherwise, this approximation is not allowed and a local multipole analysis must be evaluated. In addition, an optimized fringe field investigation and the related harmonic content can be included into particle tracking simulations [15].

Another important point is the lack of systems able to measure static and dynamic fields of DC and pulsed magnets, respectively. For the former ones, moving coils such as rotating and translating sensors [10], [16], and Hall probe systems [4] are used. For the dynamic case, fixed coil systems, such as curved fluxmeter [9], [17], [18], are employed. Especially for high-curvature magnets (radius < 20 m), the trend is to customize the measurement systems in order to satisfy specific requirements. Comparing the different systems, the rotating coil guarantee less spatial resolution than hall probe, but more execution speed. Small coil have more spatial resolution with respect to long coil

III. Magnetic Measurement System

The following section highlights the main project steps for the definition and realization of the proposed rotating coil field mapper.

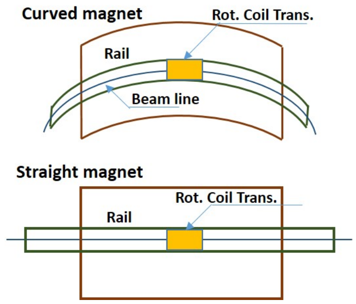

Fig. 1. Rotating coil field mapper: architecture for curved (up) and straight magnets (bottom).

A. Requirements

From the proof of principle presented in [1] and the above mentioned aspects, the proposed system should satisfy the following general requirements:

1) *Applicability to straight and curved magnets*: in order to have an universal system suitable to measure different magnet aperture geometries, and/or easy to be customized;
2) *Local and integral field investigation*: flexibility of the system with respect to measurement requirements, such as fringe fields, local, and/or integral measurements on the full magnet length;
3) *Increasing the absolute measurement precision (by a factor 10) without Hall probe mapping*: the idea is to find a trade-off between the spatial and measurement precision. This should be possible in changing the standard hall mapper against a more precise system (absolute precision less than 10^{-4} and relative precision less than 10^{-5});
4) *Integration with the existing CERN platform*: the Fast digital integrator (FDI [19]), and the Flexible Framework for Magnetic Measurement (FFMM [20]) are two consolidated components of the magnetic measurement benches at CERN, and for this reason the new mapper must be compatible with them;
5) *Versatility*: the aim is to have a reusable system avoiding to build custom systems for each different magnet design;
6) *Optimization of the measurement procedure*: the main basic idea is to reduce the number of points to be mapped by suitable field modelling.

B. Architecture

The above requirements have been satisfied by the architecture shown in Fig. 1, based on a scanning transducer, and a ”train-like” motion and positioning system. As presented in [1], the scanning transducer is adapted to different magnet geometries. The transducer is of compact physical dimensions (200 mm or less in length and 50 mm transversally) and light weight (less than 1 kg). The rotating coil technology allows both local and integral measurements by compact coils, to improve spatial resolution.

The train-like motion and positioning system was chosen for transporting the rotating coil transducer longitudinally in the magnet bore (Fig. 1). Underlying basic ideas comprise (i) automatize the measurement procedure, integrating the transducer and the motion system on the same device, and (ii) limit the mechanical adjustments, in particular for curved magnet shapes. These goals are reached by a trolley moving on a rail with the rotating coil transducer on board, whereas the rail is the only element to be customized for different magnet geometries.

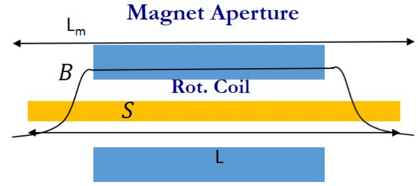

Fig. 2. Rotating coil measurements: traditional approach.

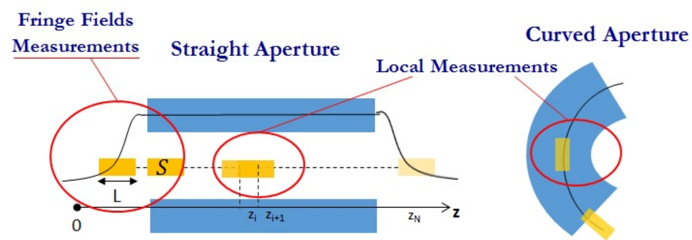

Fig. 3. Rotating coil measurements: proposed approach.

1) Proposed Approach: When the thin-lens approximation is not valid ($L \approx L_m$, Fig. 2) for beam optics calculations or the accelerator is space charge-limited, a careful investigation of the local field distribution is required. Other needs arise from large-aperture magnets with highly homogeneous field, such as in mass spectrometers and separators (BigRIPS [14], SuperFRS [13] and SAMURAI).

As shown in Fig. 3, the proposed approach is based on a discretization of the magnetic length by a short rotating coil transducer ($L < L_m$). Apart of the possibility of local measurements, the main advantage is the high longitudinal resolution of the transducer. This approach allows manufacturing investigation (fault detection or diagnosis), and fringe field reconstruction profile (to check eventually the magnet shimming). For curved magnets, the main advantage is the possibility of reconstructing the longitudinal profile of field harmonics, with the consequent validation by numerical comparison from magnet model data.

In this case, the magnetic field cannot be approximated in terms of transversal field harmonics, because the longitudinal field component is not negligible. In fact, in a measurement by a short coil ($L << Lm$), the multipole coefficients depend also on the longitudinal z-component, i.e. the axial field variation carries out the occurrence of pseudo multipoles [21].

C. Conceptual Design

The above analysis highlights some technical issues to be faced: magnetic compatibility, mechanical stability, and high precision of the positioning system. Considering the measurement features of the proposed system, the transducers and

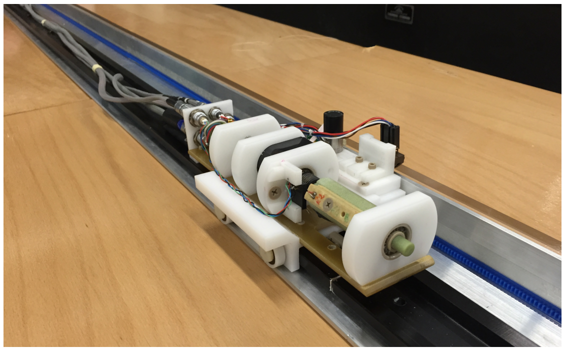

Fig. 4. Train-like motion system prototype.

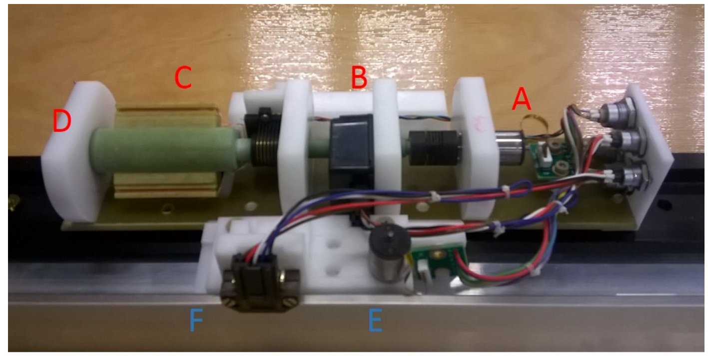

Fig. 5. Rotating coil transducer: (A) piezomotor for rotating coil, (B) rotary optical encoder, (C) coils, (D) plastic support and trolley, (E) piezomotor for longitudinal motion, and (F) linear optical encoder.

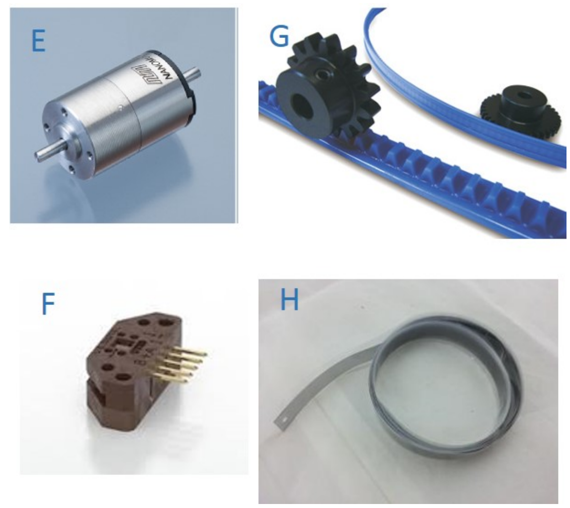

Fig. 6. Train-like motion and positioning system components: piezomotor, linear, plastic rack and pinion, and flexible codestrip.

motion/positioning parts should be magnetically compatible and, in particular, the moving components should be free of metals, in order to avoid field perturbation by eddy currents. In fact, the transducer operates inside the magnet aperture, completely immersed in the magnetic field, as presented in [1]. The mechanical stability is a pre-requirement for each measurement system. This must be achieved by a high manufacturing precision. The high-precision positioning system is based on the linear actuator and the related components, such as the linear encoder.

The magnetic compatibility is guaranteed by choosing suitable components, such as rotary piezomotor, optical encoder, and non-metallic materials for the support [1]. The mechanical stability is given by a precision manufacturing of the components. Apart the choice of metal-free components, a high-precision positioning system can be realized by a piezomotor-actuator and an optical encoder, used for the transducer. Another important component for the positioning is represented by the general support. In particular, for the trolley rail, the right trade-off between low mechanical tolerance (running clearance less than $100\ \mu$m) for guaranteeing the precision, and the lowest possible friction between the trolley and the rail is to be defined.

D. Prototype

The prototype of the magnetic measurement system is composed of two parts: (i) the rotating coil transducer, and (ii) the train-like system (Figs. 4 and 5). The prototype of transducer presented in [1] is composed of (i) a piezoelectric motor, ER-15 of Nanomotion [22] (Fig. 5A), (ii) an optical encoder HEDM 5505-J13 of Avago Technologies [23] (Fig. 5B), (iii) two coils of dimensions $40 \cdot 10$ mm (Fig. 5C), with a total equivalent coil area of $0.1237\ \mathrm{m}^2$ in tangential configuration, and (iv) the coil shaft (Fig. 5D), realized in fiberglass to ensure suitable rigidity and magnetic compatibility. With respect to the previous transducer, the new prototype was mounted on a plastic trolley made in POM (Polyoxymethylene, Delrin®), with three wheels (ceramic ball bearing), and a support plate in fiberglass. The longitudinal motion of the trolley is determined by a couple rack-pinion in plastic [24] (Fig. 6G), actuated by means of a rotary piezomotor, ER-15 Nanomotion [22] (Figs. 5E and 6E). The trolley position is measured by an optical encoder, HEDS-9200 360 [23] (Fig. 6F), with a pitch per count of $70\ \mu$m, using an high-precision flexible codestrip [25] (Fig. 6H).

IV. Functional Tests

The functional tests have dealt with the performance of the system in terms of longitudinal position measurements. The experimental validation of the transducer was already carried out [1], by checking in particular the magnetic compatibility and the speed variation of the piezomotor. The piezomotor ER-15 Nanomotion [22] was adopted also for the longitudinal motion. The installation of the motor on the trolley has followed the indication of the previous test of compatibility. In fact, the distance between the motor and the rotating coil is larger than $5\ cm$, such as the rotary one, in order to avoid magnetic perturbation. Another preliminary check consisted of measuring the necessary torque with respect to the trolley weight. The longitudinal position of the trolley was measured by a laser interferometer (Lasertex HPI-3D [26]), by assessing the positioning repeatability (absolute and relative) and the effective motor step length. In Tab. I, the results of mean and standard deviation over 20 consecutive measurements of about $1-2$ steps ($40-80\ \mu$m) for three different motor step numbers ($10000, 22000, 25000$) are reported for the same motor step length (0.0400 mm). This result confirmed the precision of the positioning system ($< 100\ \mu$m). The ferromagnetic components of the piezomotor (shaft and ball bearings in martensitic

TABLE I. POSITION MEASUREMENTS BY INTERFEROMETER: MEAN AND REPEATABILITY OVER DIFFERENT LENGTHS.

Mot. steps N_s	$\bar{s}$	l_{step}	σ (l_s)	σ (N_s)
–	(mm)	(mm)	(mm)	–
10000	400.8048	0.04009	$0.034E-04$	0.86
22000	881.9611	0.04009	$0.009E-04$	0.49
25000	1100.0586	0.04009	$0.009E-04$	2.05

steel) limit the use of this motion system in the magnetic field. In fact, for a field bigger than 0.4 T, the piezomotor is not able to actuate correctly the trolley in the fringe fields of the magnet. The positioning performance is confirmed in an uniform field until 1.0 T.

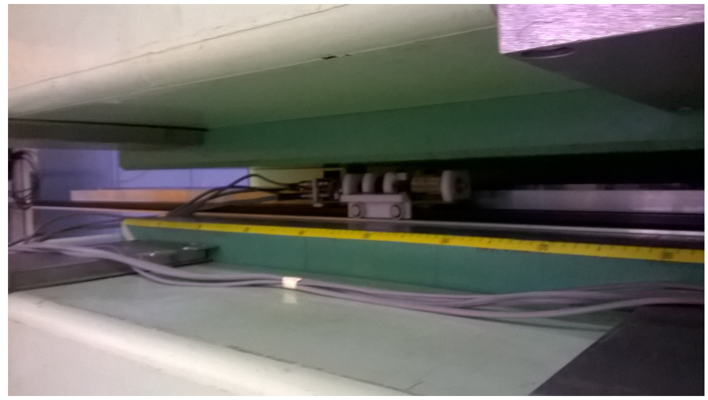

Fig. 7. Characterization measurements of the full system in a dipole magnet.

V. EXPERIMENTAL CHARACTERIZATION

The experimental characterization of the bench was aimed to verify the quality of the magnetic field measurements in terms of repeatability, linearity, and resolution. The second topic is to verify the results with respect to the previous experience presented in [1]. In particular, the impact of the train-like motion system on the measurements must be checked, as the previous transducer was positioned and fixed manually in the magnet.

The measurement setup (Fig. 7) is based on a Fast Digital Integrator (FDI [19]) used to acquire and integrate the coil voltage signal, and an interface device with two motor controller cards (longitudinal and rotating motors), a power supply block, and an encoder interface used to acquire the encoder pulses. The measurement was elaborated by means of the Flexible Framework for Magnetic Measurements (FFMM) [20] (C++ program) running on a PXI PC workstation, and the results were analyzed in Matlab®. The measurement procedure was to set the magnetic field inside the reference dipole and to measure it through the rotating coil (Fig. 5) in a fixed position of the magnet (Fig. 7).

TABLE II. MAGNETIC FIELD MEASUREMENTS FOR EXPERIMENTAL CHARACTERIZATION OF BENCH.

ω	B_1^{ref}	$\bar{B}_1$	$\Delta B_1/B_1^{ref}$	$\sigma_{B_1}/\bar{B}_1$
(rps)	(T)	(T)	(10^{-4})	(ppm)
1	0.399539	0.399480	-1.23	18
1	0.998848	0.998570	0.19	27

In Tab. II, the measurements of the dipole field $\bar{B}_1$ (averaged over 20 revolutions), the field relative repeatability $\sigma_{B_1}/\bar{B}_1$, and the relative accuracy $\Delta B_1/B_1^{ref}$ are reported for two nominal field values B_1 (0.4 and 1.0 T). The results show that the measured field is repeatable within about 10^{-4} with respect to the average value $\bar{B}_1$. The relative accuracy $\Delta B_1/B_1^{ref}$ is equal or less of about $1 \cdot 10^-4$. These preliminary results confirmed what was previously experienced in [1], and the positioning system did not worsen the measurement performance.

VI. CONCLUSIONS

In this paper, a field mapper based on rotating coils was presented. The requirements, architecture, conceptual design and the prototype for straight magnets were shown. The functional tests have shown that the motion system satisfies the requirements of precision (< 100 μm). The ferromagnetic components of the piezomotor limit the use of this (magnetic field less than 0.4 T). Regarding the experimental characterization of the prototype, the preliminary results confirmed the magnetic measurement performance in terms of repeatability and linearity with respect to previous transducer [1]. The ongoing activities will regard a full measurement campaign focused on the fringe fields measurements of straight dipole magnets, longitudinal multipole reconstruction, and traditional measurement such as the integral field measurements. The rotating coil mapper will use traditional and iso-perimetric PCB coils, in order to have more accurate effective coil areas for absolute and relative measurements.

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