20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

A fluxmeter based on translating coils for axially-symmetric magnets

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***Abstract* – A fluxmeter has been designed for measuring the magnetic field of axisymmetric magnets by exploiting the inherent symmetry. The fluxmeter yields a measurement of the magnetic flux linked with a pair of searching coils as a function of longitudinal position. The induction sensor is designed to be sensitive to the axial and radial components of the magnetic field. The sensor is mounted on a transport system that moves along the axis of the magnet. By integrating the induced voltage, the method eliminates the influence of the linear speed variations, thus relaxing requirements for uniform translation. The paper describes the measurement system and gives a preliminary validation based on experimental tests.**

I. INTRODUCTION

The solenoidal magnetic lens consists of a region of cylindrically symmetric, radial and axial magnetic fields produced by axi-centered coils. Particles moving exactly along the magnetic axis of the solenoids do not experience any force. Conversely, off-axis particles are azimuthally accelerated by the radial field components in the fringe field region of the magnet, which is related to the variation of the axial field component. The resulting helical particle motion in the longitudinal field region of the magnet yields a focusing effect due to the radial Lorentz force [5]. This allows a lower particle loss rate than with a pair of quadrupoles to focus the beam sequentially in the horizontal and vertical planes [4].

Employing solenoidal lenses in order to provide the required focusing strength for charged particle beams imposes strict requirements on magnetic field measurement and axis determination. Therefore, a characterization of the magnetic field of axially symmetric magnets is clearly paramount for lattice design calculations.

Solenoid magnets are hardly compatible with standard instrumentation optimized for accelerator multipole magnets. They are routinely tested with general-purpose instruments such as 3D Hall probe mapping systems [7] [8], which are, however, poorly adapted to exploit the inherent symmetry, or with stretched [9] [6] and vibrating [5] wire systems, which only provide information about integral field properties.

In this paper, an instrument based on moving searching coils is proposed for mapping local field geometrical parameters with high accuracy in a fraction of the time needed by traditional techniques. The basic design concept is to build a reliable and high-speed measurement system for characterizing the longitudinal and radial magnetic field components, and to determine the integrated field and the magnetic axis using the measured data.

II. TRANSLATING COIL FLUXMETER

A. *Measurement principle*

The measurement is based on Faraday's induction law in its generator convention:

$$U = -\frac{\mathrm{d}}{\mathrm{d}t}\int_{\mathcal{A}} \mathbf{B}\cdot \mathrm{d}\mathbf{a}, \qquad (1)$$

that is, the flux variation in a searching coil will induce a voltage across the coil terminals. The measurements are performed on a DC solenoid magnet, therefore the induction signal is generated by moving the sensor in a static magnetic field. However, in this case the field measurement depends, among other factors, on the precision of the coil movement.

The induction sensor consists of two coaxial searching coils slightly spaced longitudinally. The coils are wound on a cylindrical core and connected in series either in the same or the opposite polarity. Therefore, this system can be operated in two measurement modes: series mode for measuring the longitudinal magnetic field and anti-series mode for measuring the radial magnetic field. Fig. 1 shows the architecture of the measurement system.

As the searching coil is moved in the non-uniform magnetic field, a voltage is induced at the terminals. The sensor position is measured by a linear laser interferometer, following a retroreflector that is rigidly connected to the cylindrical core. Hence, integrating the induced voltage between predefined positions along the longitudinal axis of the magnet allows the flux change to be obtained as a function of the linear position. The realization of a practical translating coil system is facilitated by using the po-

ISBN-14: 978-92-990073-2-7

sition pulses from the interferometer to trigger the integrator and calculate the flux increment between adjacent axial positions. This re-parametrization with respect to the axial position, eliminates the time dependence and in particular the influence of variations of the linear speed, greatly relaxing the requirements for the transport system. This is the same principle used for the rotating coil probe measurements [10].
As it is shown in the block diagram (Fig. 1), the position pulses are sent to the trigger generator, where they are counted and then used to trigger the integration of the induction voltage. The integration can be performed i) online by a digital integrator [11], releasing the value of a flux increment at each trigger signal, or ii) off-line by acquiring the position pulses and the coil signals by an acquisition device and resort afterwards to post-processing techniques for the integration.

B. Induction sensor design

The induction sensor consists of two identical searching coils, coaxially mounted on an accurately machined cylindrical core. The coils have a diameter of 85 mm and are spaced by 2 mm (Fig. 2).

The coils are made of a 16-strand copper wire, wound in 16 layers for a total of 256 turns per coil. The total effective area thus obtained is about 2.6 m^2. Multi-strand coils allow a more precise layering than single turns, which leads to more uniform geometries and thus more accurate measurements [12]. Furthermore, this choice allows a regular square cross-section that makes easier the calibration of the coupling coefficient. The complete sensor is designed to be used in a magnetic field, thus (i) the electrical connections must present the smallest possible area to the changing flux, and (ii) the coil core is made by a mechanically rigid but non-conductive and non-magnetic material.
The two coils are designed to be perfectly co-axial and to have the same sensitivity (or the same effective surface) with respect to the longitudinal component of the magnetic field. When the coils are connected in series, they operate like one single coil with the number of turns equal to the sum of the single coils. In this case, the sensor is sensitive to the longitudinal component B_z of the field. On the other hand, when the coils are connected in opposite polarity, the longitudinal component is compensated and the radial component B_r is measured. The two coils must cover identical area and should be large enough to get a significant output voltage. The measurement accuracy of the radial field depends strongly on the difference between the effective surfaces of the two coils. The more minimized the surfaces' difference, the higher the accuracy obtained. It is not convenient to calculate the surface difference of the coils from their dimensions and the number of turns. A more reliable way to obtain the coils' surface is by calibration.

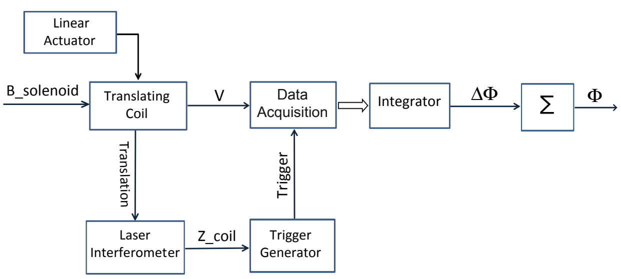


Figure 1: Architecture of the translating coil method

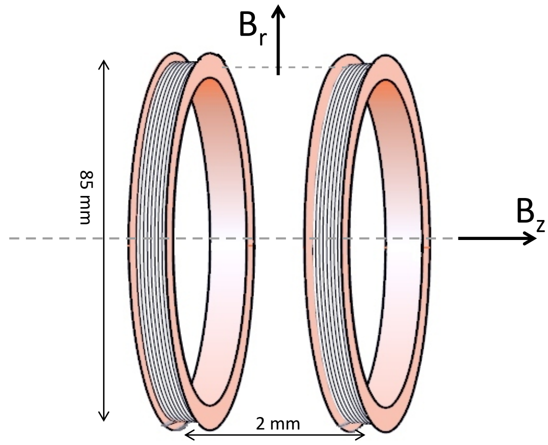


Figure 2: The field sensor made of two co-axial search coils

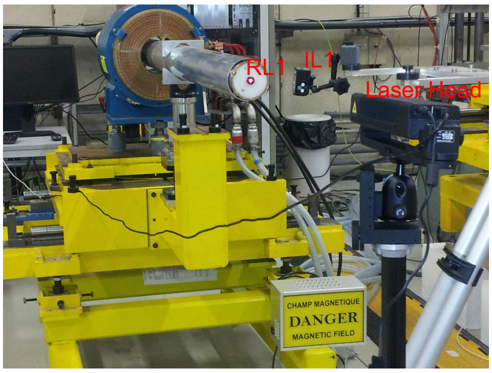
C. Translation system and position measurement

In addition to the searching coil, the two other fundamental parts of the measurement system are:

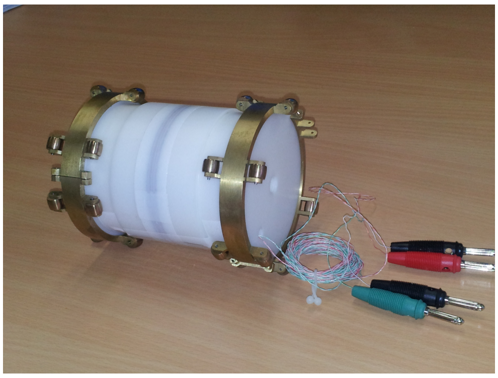
- the transport system, which enables the movement of the measuring system,
- the position measurement system consisting of a linear interferometer.

The transport system includes an aluminum tube, which can be centered in the magnet aperture (Fig. 3a), together with a linear actuator that enables the movement of the sensor along the tube. The coils' core moves on non-magnetic rollers, mounted as shown in Fig. 3b. The linear actuator pushes and pulls the sensor from an initial to a final position, such as to cover the entire field of the magnet, including the fringe field.

The uncertainty on the position measurement has a direct bearing on the system's accuracy, therefore special



(a) Aluminium tube centered with respect to the magnet.



(b) Rollers mounted on the core coil.

Figure 3: View of the measurement bench with the aluminium tube centered inside the solenoid (left), and of the rollers mounted on the core allowing the displacement of the sensor inside the tube (right).

attention is given to the linear position measurement of the inductive sensor. The position is measured by a high-performance, heterodyne laser interferometer. The laser beam, generated in the laser head, consists of two polarizations: horizontal and vertical. The linear interferometer (IL1) splits the beam into two parts. The horizontally polarized beam is reflected back to the laser head and the vertical polarized beam is directed to the linear retroreflector (RL1), which is attached to the translating sensor (see Fig. 3a). The frequency of the vertical beam is changed according to the Doppler effect when the retroreflector is in motion.

III. EXPERIMENTAL VALIDATION

A. *Measurement set-up*

The measurement set-up, designed and constructed for a proof-of-principle demonstration is presented in Fig. 4.

The sensor is sensitive to the longitudinal and radial components of the magnetic field. The movement is performed by a linear actuator that pushes and pulls the sensor (covering a distance of about 3 m in 6 s) inside a guiding aluminum tube as shown in Fig. 2. The voltages induced at the terminals of the two coils are acquired by an NI PXI-6289 data acquisition card (DAQ) [13]. In particular, the resulting voltage arising from the series and anti-series combination of the two coils is recorded. Simultaneously with the coil voltages, the signal output from the position sensor is acquired. The measurement set-up is equipped with a laser measurement system (HPI-3D from Lasertex) in order to measure the linear position of the coils. The device operates according to the laser interferometer principle and is able to measure objects moving with speeds up to 7 $\mathrm{m/s}$ with a nominal resolution of 0.1 nm. The linear optics, consisting of a interferometer and a retroreflector, is employed for precise recording of the induction sensor displacement. The interferometer is fixed outside the guiding tube whereas the retroreflector is attached to the core coil, as shown in Fig. 4. The relative linear motion between the optical components is detected. A digital A-Quad-B signal in 5 V CMOS standard is available on the output of the HPI-3D. The position pulses are acquired and counted by the Data Acquisition System Timing Controller (DAQ-STC), which integrates all data acquisition counter/timer functionality of the DAQ. When the translation position hits the home position on the longitudinal axis, a LabVIEW software simultaneously saves the position on the longitudinal axis, the inductive voltage, and the time duration within each step to its memory. The integration of the voltages, yielding the flux increment between adjacent linear positions, is done by a numerical integration techniques in Matlab.

B. *Preliminary results*

The experimental validation of the fluxmeter based on translating coils is performed by checking the results against a reference measurement method. The longitudinal and the radial components of the magnetic field measured by the fluxmeter are compared to the measurements carried out by a 3D Hall probe mapping system.

The comparison is done in a cylindric region that passes through the solenoid aperture. This region is delimited by the maximum displacement of the mapping system, along the longitudinal axis of the solenoid, and by the coils' surface in the transverse plan. In comparing the measurements' results, it is obtained a good degree of concordance among the two measurement methods. The obtained measurements agree within 0.3% for the longitudinal component of the magnetic field B_z and within 1.2% for the radial component B_r.

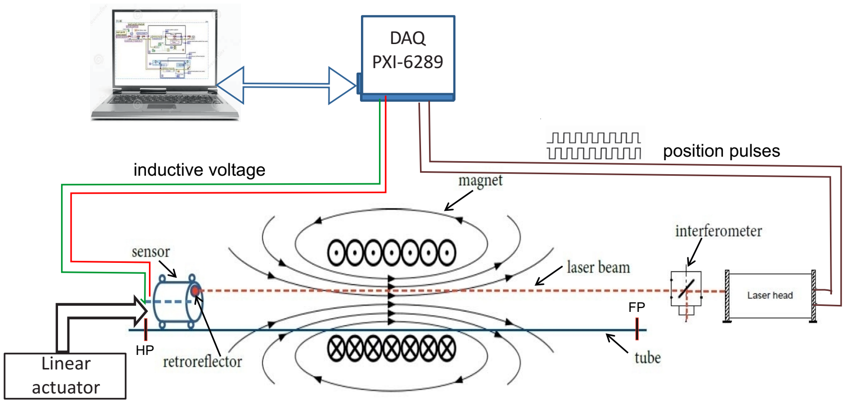


Figure 4: General layout of the measurement set-up.

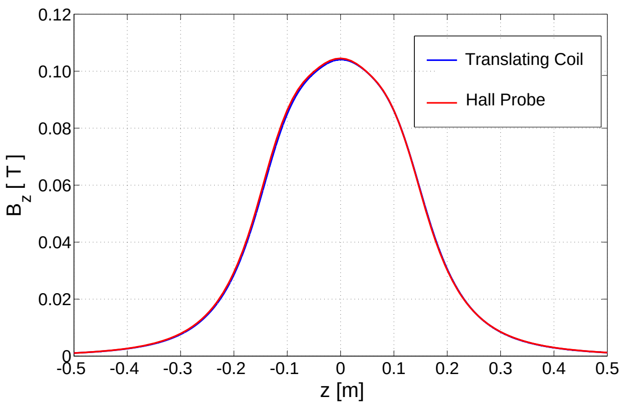


Figure 5: Longitudinal component of the magnetic field.

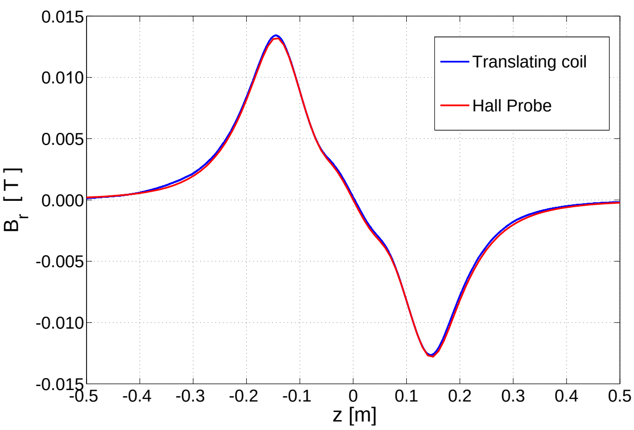


Figure 6: Radial component of the magnetic field.

IV. CONCLUSIONS

This paper presents a method based on translating coils for the magnetic field measurement of axially symmetric magnets.

An induction sensor, sensitive to the longitudinal and radial components of solenoids, has been designed and constructed. The method validation has been performed with success.

The required accuracy of the measurement device necessitates several improvements on the mechanics and calibrations of the individual parts in order to arrive at a prototype version of the measurement system.

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