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UNCERTAINTY ANALYSIS FOR A MOVING FLUXMETER

Pasquale Arpaia [1,3], *Marco Buzio* [3], *Luca De Vito* [2,3], *Mario Kazazi* [2,3], *Stephan Russenschuck* [3]

[1] University of Naples Federico II, Naples, Italy, pasquale.arpaia@unina.it
[2] University of Sannio, Benevento, Italy, devito@unisannio.it
[3] CERN, Geneve, Switzerland, mario.kazazi@cern.ch; marco.buzio@cern.ch; stephan.russenschuck@cern.ch

***Abstract* -** This paper presents an uncertainty analysis for field measurements by means of a moving fluxmeter. The measurement method has been analysed and the most relevant uncertainty sources have been characterised. Among all the sources, it has been found that those concerning the transport system lead the most relevant contribution to the uncertainty budget. Experimental results, aiming at characterising such sources and determining their contribution to the uncertainty of the measurement, are presented.

Keywords: Magnetic measurements, Sensing coils, Uncertainty analysis.

1. INTRODUCTION

The characterisation of the magnetic field of axially symmetric (axisymmetric) magnets is paramount for focusing systems in the low energy section of accelerators [1] and other devices, such as electron microscopes [2], or electron guns. Other applications are related to the method of laser accelerated protons or ions [3]. Examples are particle therapy and short-pulse radiographic diagnostics, where axisymmetric magnets are used in order to obtain an effective method of focusing and energy selection.

The needed focusing strength imposes strict requirements on the magnetic field measurements and axis determination. Axisymmetric magnets are generally tested by means of traditional techniques, such as 3D Hall–probe mapping systems [4], which are poorly adapted to exploit the inherent symmetry of these magnets. Available state-of-the-art stretched [6] and vibrating-wire [5] systems, only provide information about integral field properties.

Measurements of the local field distribution are also important for the characterisation of axisymmetric magnets. In [7], an alternative measurement method is proposed, designed to exploit the inherent axial symmetry of the magnetic field. The magnetic flux linked with a pair of sensing coils is measured as a function of the longitudinal position. The local field geometrical parameters are mapped with high accuracy and the field integrals are measured in a fraction of the time needed by the traditional techniques.

The method has the following main advantages over standard Hall probe systems: (i) linearity; (ii) negligible temperature-related drift due the low expansion coefficient of the support (typically fiberglass epoxy); (iii) easy surface calibration with $\pm 10^{-5}$ relative precision by flipping the sensing coils in a reference magnet; and (iv) resolution in the transversal plane, since the field may be computed at any point of interest from the measured harmonic expansion.

After the successful proof-of-principle demonstration of the method [7], an uncertainty analysis must be carried out in order to characterise the method.

In particular, the required precision of the measurement device necessitates several improvements on the mechanics and calibrations of the individual parts in order to reach a prototype version of the measurement system. For this purpose, a characterisation of the uncertainty sources affecting the measurement system and an estimation of their influence on the measurement result should be carried out. Moreover, an error analysis is necessary to understand which are the parameters that contribute more in the overall uncertainty and, as a consequence, should be taken into account in the formulation of the uncertainty model.

This paper describes the uncertainty contributions of the different components of the system, with particular reference to the transport system. Such analysis will serve as basis to design a full uncertainty model of the measurement system and to study the uncertainty propagation to the measurement result.

The work is organized as follows: In Section 2, the moving fluxmeter, proposed in [7] is briefly recalled. Then, in Section 3, the measurement method is analyzed in order to list and discuss the possible uncertainty sources and to analyze their range of variation. Finally, in Section 4, some preliminary results of the characterisation of the uncertainty sources related to the transport system are reported, aiming at determining their range of variation and the contribution to the measurement result.

2. THE MOVING FLUXMETER

A detailed presentation of the method and the measurement bench is given in [7]. Here, only a synthetic description is provided. The basic concept is to build a reliable and high-speed measurement system for characterising the longitudinal and radial magnetic field components of axisymmetric magnets, and to determine the integrated field and the magnetic axis from the measurement data.

The working principle of the method is to induce a voltage in a coil translating co-axially with the magnetic field of an axisymmetric magnet, according to the Faraday's induction law (generator convention):

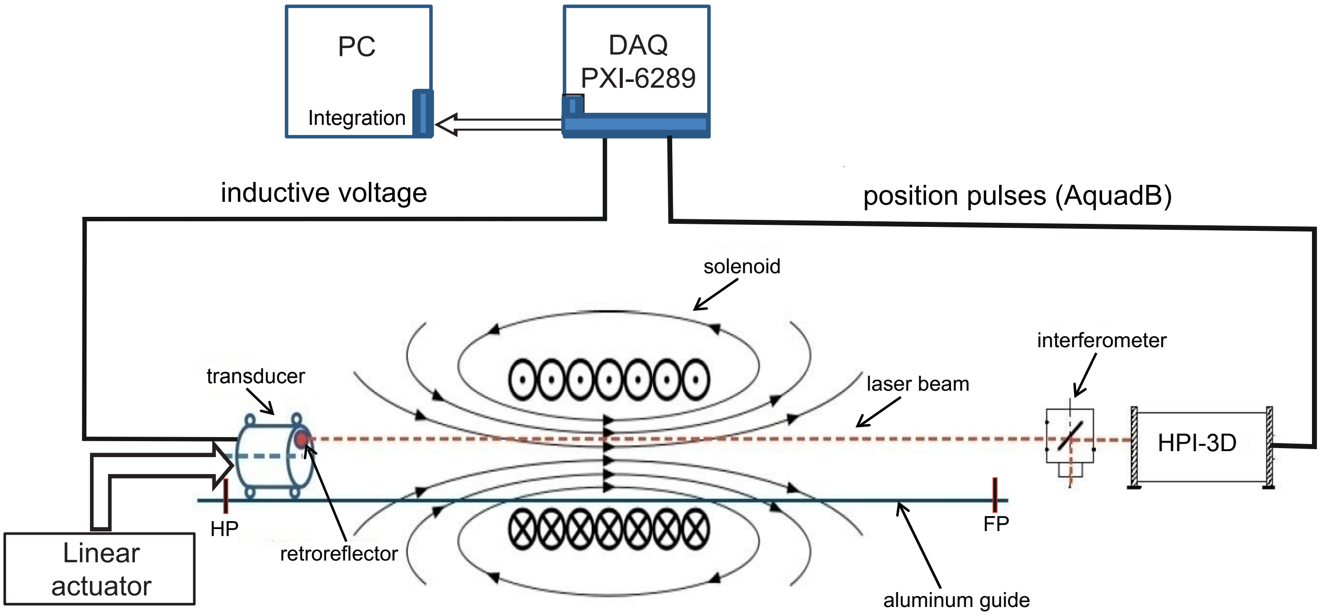

Fig. 1. General layout of the measurement set-up.

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\begin{aligned}
U &= -\int_{\mathcal{A}} \left(\frac{\partial \mathbf{B}}{\partial t} + curl(\mathbf{B} \times \boldsymbol{v}_p) \right) \mathrm{d}\mathbf{a} \\
&= -\frac{\mathrm{d}}{\mathrm{d}t} \int_{\mathcal{A}} \mathbf{B} \cdot \mathrm{d}\mathbf{a}, \qquad (1)
\end{aligned}
$$

where U is the induced voltage, $\mathbf{B}$ the magnetic field and $\boldsymbol{v}_p$ is the path velocity of the moving surface [8].

The measurement set-up, designed and constructed for a proof-of-principle demonstration is presented in Fig. 1.

The movement of the transducer is performed by a linear actuator that pulls the sensor along an aluminum guide. The voltages induced at the terminals of the two coils are acquired by an NI PXI-6289 data acquisition card (DAQ) [9]. 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 longitudinal position of the coils is acquired. For this reason, the measurement set-up is equipped with a laser measurement system (HPI-3D from Lasertex). The position pulses in output from the interferometer are acquired and counted by the Data Acquisition System Timing Controller (DAQ-STC), which incorporates all data acquisition counter/timer functionality of the DAQ. When the transducer hits the home position on the longitudinal axis (HP in Fig. 1), a LabVIEW software simultaneously stores the position, the inductive voltage, and the time duration within each acquisition step. The voltage samples are integrated numerically in MATLAB® yielding the flux increment between trigger pulses.

3. UNCERTAINTY SOURCES

The target precision of the method requires a careful assessment of the uncertainty sources, introduced either by the method or by the measurement instruments.
Here the measurement method is investigated in order to understand the non-ideal behavior of the measurement instruments, which clearly affects the measurement quality. Looking at the method presented in the previous Section, a set of uncertainty sources have been identified for each section of the measurement system:

Transport system: In the proof-of-principle demonstration of the moving fluxmeter presented in [7], the coils are assumed to move precisely vertically and coaxially to the magnet axis. Furthermore, the measured position of the coils' system is considered exact. Obviously, this is an ideal behavior.
Therefore, it should be taken into account the radial displacement of the coil from the magnetic axis of the magnet and the pitch angle variation of the coil from the orthogonality to the magnetic axis. Since the transport system used for the proof-of-principle has been realized for the purpose, the impact of such uncertainty sources must be determined by experimentally characterising the transport system. In the following Section, the results of this characterisation is reported and discussed.

Acquisition system: the acquisition system measures the voltage signals induced in the sensing coils and counts the rising edges of the position pulses, coming from the interferometer. Therefore, the uncertainty on these two quantities must be taken into account. Their range of variation can be obtained from the DAQ datasheets. In particular, considering that the voltage range used for the measurements is $[-1.0, 1.0]$ V and that the measured values are in the range $[-0.2, 0.2]$ V, according to the NI PXI-6289 specifications, the uncertainty effect on the measurement of the voltage signal is in the range $[\pm 140, \pm 157]$ µV. Instead, the time measurement uncertainty is determined by the time resolution equal to 100 µs.

Position measurement system: The linear position measurement has a direct impact on the overall system's precision. Therefore, special attention was paid to its quality by using a high-performance, heterodyne laser interferometer. According to its specifications, the device operates according to the laser interferometer principle and is able to measure the linear position with a nominal resolution of $0.1\,\mathrm{nm}$ and an accuracy of $0.4\,\mu\mathrm{m/m}$. Since the distance measured by the interferometer is in the range $[0.2, 2.0]\,\mathrm{m}$, the uncertainty range of position measurement is $[\pm 0.1, \pm 0.8]\,\mu\mathrm{m}$.

4. CHARACTERISING THE UNCERTAINTY OF THE TRANSPORT SYSTEM

A geometrical error is caused by the tolerances of the absolute position of the sensing coils and their orientation inside the transducer core. These two tolerances sum up to a total positioning error, resulting in a systematic effect on the final result. Nevertheless, this effect can be detected by calibration and the value can be used to compensate the measurements.

A leading cause of the measurement uncertainty is the transport system. The transport system includes an aluminum guide, non-magnetic rollers, together with a linear actuator that pulls the transducer along the longitudinal axis. The translation of the transducer is not perfectly linear along the longitudinal axis. In fact, the surface contact between the guide and the rollers mounted on the transducer introduces some perturbations during the motion of the coils. These perturbations result in displacements in the radial direction and a pitching in the orientation of the coils that heavily contribute in the uncertainty budget of the measurement method.

For this reason, an experimental analysis was carried out so as to characterise these effects. The laser interferometer HPI-3D from Lasertex [10] was used for measuring the displacements along the axis X and Y during the translation of the transducer along the longitudinal axis. As shown in the Figs. 2 and 3, the radial displacement is more significant in the X-axis for a maximum value of 0.6 mm.

By substituting the angular optics (angular interferometer and angular retro-reflector) in the HPI-3D, the variation of the pitch angle during the motion was monitored. The results are illustrated in Fig. 4. Each measurement is repeated 15 times and all the results are plotted together. It is interesting to note that both the radial displacements and the pitch variation follow a determined trend during the translation along the longitudinal axis, as it is showed from the traces of Figs. 2–4. It means that these effects have a relevant systematic component, completely related to the quality of the transport system, that can be compensated, thus increasing the accuracy of the result.

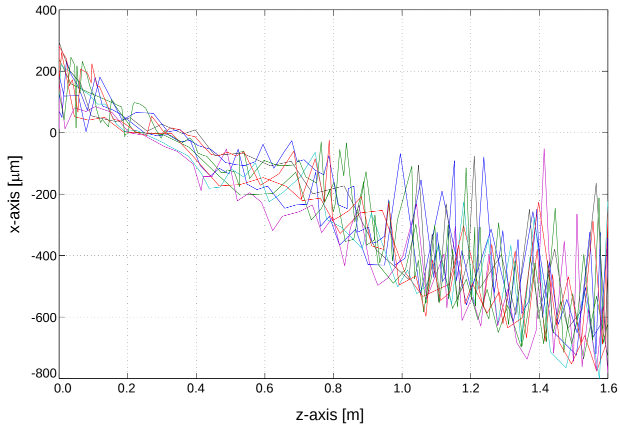

Fig. 2. X-axis displacement of the coils during the longitudinal translation.

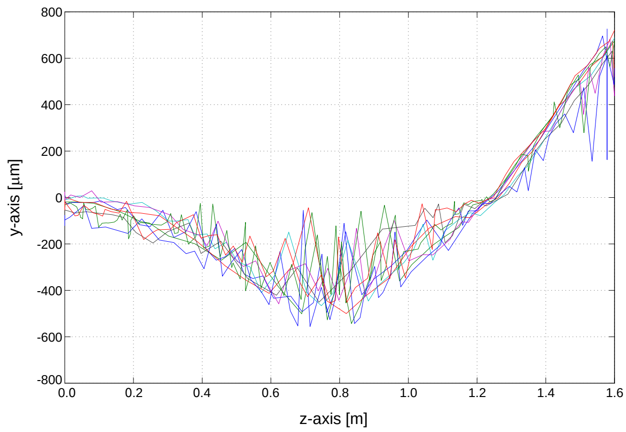

Fig. 3. Y-axis displacement of the coils during the longitudinal translation.

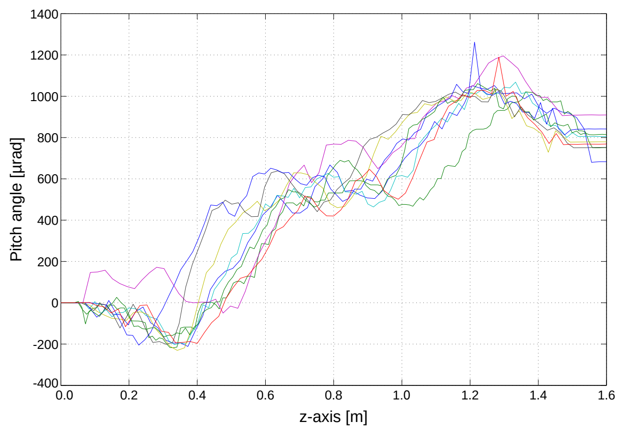

Fig. 4. Pitch variation of the coils' orientation during the longitudinal translation.

Numerical simulations showed that the pitching of the coils

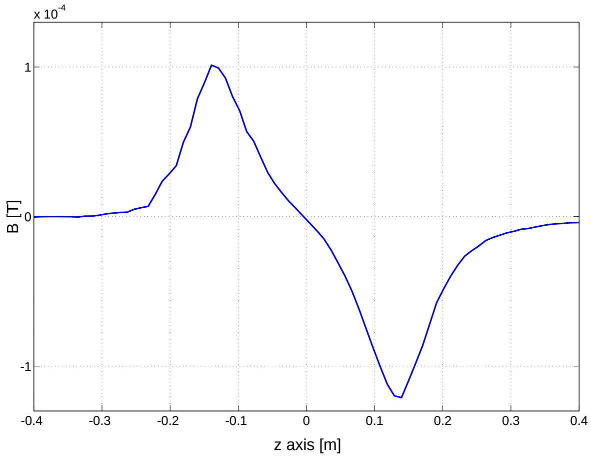

Fig. 5. Field error introduced by the pitch variation of the coils' orientation during the longitudinal translation.

has a major effect on the measured flux with respect to the radial displacements. For this reason, an evaluation of the error in terms of measured flux related to the pitch variation of Fig. 4 has been carried out. In the ideal case, $\vartheta(z) = 0$, the pitch angle does not change during the translation and the flux is simply given by:

$$\Phi_{id}(z) = B_z A_1. \tag{2}$$

When the pitch variation $\vartheta(z)$ is considered the coils are sensitive also to the radial component of the field and (2) becomes:

$$\Phi_m(z) = B_z A_1 \cos(\vartheta(z)) + B_r A_2 \sin(\vartheta(z)) \tag{3}$$

where B_z and B_r are the longitudinal and transversal field components, A_1 and A_2 are the coil surfaces sensitive to the longitudinal and transversal field components respectively, and $\Phi_m(z)$ is the measured flux.
The difference between (2) and (3) has been plotted as a function of the longitudinal position in Fig. 5. As expected, the error has a peak in correspondence of the magnet ends, where the radial field increases to its maximum value.

As result of the uncertainty analysis carried out in this work, a summary of the uncertainty sources, with their variation ranges, is reported in Tab. 1. As previously mentioned, the uncertanty ranges of the acquisition system and of the position measurement system have been determined acccording to the instrument specification, while those of the transport system have been experimentally determined, as shown above in this Section.
In the Table, even the ranges of uncertainty related to the calibration of the distance of the coils and the surface of the coils are reported. A further characterization about the reltive orientation of the coils is currently ongoing.

5. CONCLUSION

In this paper, an uncertainty analysis of the moving fluxmeter for the measurement of the longitudinal fields in axisymmetric magnets has been presented. The analysis aimed at examining the uncertainty sources that can contribute to the uncertainty of the field measurements. Among all the uncertainty sources, it has been found that those related to the transport system have a relevant amount and can have an unacceptable contribution to the field measurement result.
Therefore, efforts must be concentrated to an improvement of the transport system, in order to minimize the radial coil displacement and pitch, as well as to design a complete uncertainty model, where the propagation of each uncertainty source is evaluated.

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Table 1. Main source errors in the moving fluxmeter system. The calibration of the orientation of the coils is currently under investigation.

System	Uncertainty source	Uncertainty range
Position measurement system	Laser interferometer HPI-3D	$[\pm 0.1, \pm 0.8]$ µm
Transport system	Radial displacement of the coil system	± 0.6 mm
	Pitching of the coil system	± 1.2 mrad
Acquisition system	DAQ accuracy in measuring the induced voltage	$[\pm 140, \pm 157]$ µV
	Time base	± 100 µs
Calibration	Surface calibration	$\pm 1 \times 10^{-4}$ T
	Distance calibration	$\pm 1 \times 10^{-4}$ T
	Calibration of the orientation of the coils	To be evaluated

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