A rotating-coil magnetometer for the scanning of transversal field harmonics in particle accelerator magnets

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Abstract. The conceptual design of a rotating-coil magnetometer for magnetic field measurements in accelerator magnets is discussed. The magnetometer is designed for a high signal-to-noise ratio and the ability to measure the transversal harmonics in the fringe-field region of the magnet. The paper focuses on the coil design and production technology.

1. Introduction
For certain accelerator magnets, such as curved magnets for biomedical projects with compact dimensions, or mass spectrometry magnets, a complete mapping of the magnetic field is required. In the magnet extremities, highly non-linear field distributions arise and the classical multipole description is no more appropriate, because the Fourier series do not constitute a complete orthogonal function set for the field solution [1]. This gives rise to pseudo-multipoles, which result from the magnet field variation in axial direction [2].

The mathematical treatment of the problem is presented in [3]: it was shown that the classical rotating coil cannot be used in regions where a significant, axial field component is present. Moreover, the usual scaling laws cannot be applied to design a magnetometer with a compensation scheme for the main field harmonic (bucking). The magnetic measurements in the fringe-field region requires a short, saddle-shaped, iso-perimetric coil for measuring the linked magnetic flux.

There are several techniques available for acquiring the local field distribution. One of these, as described in [4], is to measure the longitudinal profile by mapping the magnet by means of Hall sensors connected to a 3D precision stage. Unfortunately, Hall sensors cannot guarantee the desired precision and accuracy in the range of 1 unit in 10 000. An alternative solution could be to use a translating-coil scanner on the magnet mid-plane [5]. In this case, the harmonic order is limited by the transversal resolution. Moreover, this method cannot account for top-down asymmetries in the magnet. Another possible solution would be to use a FEM/BEM analysis, validated or corrected by suitable experiments [6]. But in this case, dynamic effects cannot be considered. Consequently, a new design for rotating-coil magnetometers was required.
2. Sensor Design
A lack of sensitivity to the z-component (longitudinal component) of the magnetic field must be guaranteed in order to measure in the fringe field region of the magnet. Therefore, a sensor with more induction-coil turns on the same radius is to be designed. The sensor shall have adequate sensitivity to the main magnetic flux density and to high-order harmonic fields.

Fig. 1 shows the cross-section view of the conceptual design. With a saddle-shaped, iso-perimetric design each loop remains on the same radius and is thus not affected by the longitudinal field component when rotated around its axis. Only the perpendicular field components will induce an electromotive force on the loop.

\[ K_n := K_n^{\text{rad}} + iK_n^{\text{tan}} = \frac{NI_n}{n} \left( r_2^n e^{in(\varphi_2 - \varphi)} - r_1^n e^{in(\varphi_1 - \varphi)} \right), \]  

where \( r_1 \) and \( r_2 \) are the radii of the go and return windings and \( \varphi_2 - \varphi_2 \) their opening angle. Thus for a number of \( M \) windings:

\[ K_n = \sum_{m=1}^{M} \frac{NL(m)}{n} \left( Z_{2(m)}^n - Z_{1(m)}^n \right), \]

where \( M \) is the number of induction coils, \( N \) the number of layers, \( L(m) \) the length of each single turn (Fig. 2b), \( n \) the harmonic order, and \( Z_{1(m)} \) and \( Z_{2(m)} \) are the complex coordinates of each single turn (Fig. 2a).

The main design objective was to optimize the positions of each turn in the \( x-y \) plane that guarantee the desired sensitivity factors. This was done with the CERN field computation program ROXIE that incorporates the routines for mathematical optimization. Two coils are combined on a common shaft. The center one, with the small opening angle will be sensitive to higher-order field harmonics. The lower coil (with the larger spacing between turns) is designed...
to be sensitive only to the main dipole field component. From the theory of so-called \( \cos \Theta \) coils, we know that a single shell of 60 deg. creates the smallest amount of higher-order field errors. Consequently, such a coil has also a low sensitivity with respect to higher-order field errors. The two coils are then connected in series with opposite polarity so that the main field component is cancelled out and thus the signal-to-noise ratio is increased.

3. Sensor Production

According to the design result, the required number of turns, the distance between each turn, and the shape of the sensor, the Flexible Printed Circuit (FPC) technology was chosen.

The sensor production was carried out in-house by CERN’s PCB service (EP-DT-EF). Fig. 3 (left) shows the rendering of the sensor. The first prototype is shown in Fig. 3 (right). The inner coil is the main search coil, while the external is the compensation coil.

The sensor has a total length of 98.2 mm, 38.13 mm diameter and thickness of 240 \( \mu \)m. The main coil consist in 59 turns with an effective area of 0.129 m\(^2\) and an effective length of 84.308 mm. The compensation coil consist of 11 turns with effective length of 90.982 mm. The flexible PCB is then mounted on a fibre-glass epoxy shaft using a number of alignment pins and a clamping mechanism. As a proof of principle, the prototype PCB was glued on a shaft made by rapid prototyping. This technique is, however, not precise enough as can be seen by a sensitivity analysis of the sensitivity factors.

![Sensor rendering and prototype](image)

**Figure 3.** Sensor rendering (left) and first produced prototype (right)

First tests have proven that the developed sensor is not sensitive to the \( z \)-component of the magnetic field, but has a high sensitivity for higher harmonic orders.
In Fig. 4 the computed sensitivity factors for the main coil (red) and the compensation coil (blue) are plotted.

4. Conclusion
The design and the production of an iso-perimetric induction coil is possible using a flexible PCB technology. The coil sensor is characterized by negligible sensitivity to the \(z\)-field component and high sensitivity to high harmonic order. It can thus be used for extracting pseudo-multipoles from the longitudinal scanning of transversal field harmonics in the magnet extremities.

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