An induction rotating coil for longitudinal scanning
of particle accelerator magnets

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Abstract. In this paper, the concept design of an induction rotating coil for magnetic measurements in accelerator magnets is discussed. In particular, the idea of a new sensor to be applied for longitudinal scanning is presented. This sensor is designed for measuring the magnetic field profile with extremely high signal to noise ratio and to be able in measuring the harmonics in fringe field regions. This paper is focused on the sensor sizing and production.

1. Introduction
Magnetic measurements are becoming more and more demanding in industrial and medical applications such as, accelerator complex for hadrontherapy, magnetic resonance imaging, food quality, and so on.

In particular, for some 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. As a matter of fact, local measurements are the best candidate to achieve the final application goals of design and end use. Unfortunately, in the magnet extremities, highly non-linear field distributions arise and the multipole coefficients 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].

A mathematical approach was proposed in [3]: it was proved that the traditional rotating coil cannot be used in regions where a significant field component is present along the longitudinal magnet dimension. The proposed solution requires a short 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 as a whole through Hall sensors. Unfortunately, hall transducers cannot guarantee the desired precision and accuracy. An alternative solution could be to use a translating-coil scanner on the magnet’s mid-plane [5]. In this case, the harmonics number are limited by the transversal resolution. Another possible solution could be to use a FEM/BEM analysis, validated or corrected by suitable experiments [6]. In this case, manufacturing errors and dynamic effect are not considered. Consequently, a new design for rotating-coil magnetometers is required.
In this paper, the short iso-perimetric rotating coil, developed and produced at CERN, is presented.

2. Sensor Design
A lack of sensitivity to the z-field component is to be guaranteed in order to be able to measure in the fringe field region of the magnet. At this aim, a sensor with more induction coils (sensing elements) on the same radius is to be designed. The sensor shall have adequate sensitivity to the main magnetic flux density and for high-order harmonics.

In Fig. 1, the section view of the concept idea is shown. This design highlights that, performing one elementary turn, each single loop remains on the same radius and it is not affected by the longitudinal field component. In fact, according to this geometry, only the perpendicular field component will induce electromotive force on the loop.

Figure 1. Rotating sensor section view.

The sensor design was based on the standard sensitivity factors equation:

$$K_n = K_{rad}^n + iK_{tan}^n = \frac{NI}{n}(r^n_2 e^{in(\varphi_2-\varphi)} - r^n_1 e^{in(\varphi_1-\varphi)}),$$

where $M$ is the number of turns or 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).

Main design goal was to find the position of each coil on the x-y plane that guarantees the desired sensitivity factors. The coordinates of each single coil were calculated by the CERN
Roxie simulation program. It combines powerful geometry macros with the numerical accuracy of BEM-FEM coupling, hundreds of design variables and objective parameters, powerful optimization algorithms, and CAD/CAM interfaces.

3. Sensor Production

According to the design result, the number of coils, the distance between each tack, the shape of the sensor, and the required precision, the Flexible Printed Circuit (FPC) technology was chosen. In fact, it matches perfectly all the desired requirements having a considerably low cost and easy manufacturing.

The sensor production was carried out by the Experimental Physics Department, Detector Technologies Group, Engineering Facilities section (EP-DT-EF), under the supervision of the Technology Department, Magnets, Superconductors and Cryostats Group, Magnetic Measurements Section (TE-MSC-MM).

In Fig. 3 (left), the rendering of the sensor is shown. The first produced prototype is shown in Fig. 3 (right). The inner coil represents the main coil, while the external is the compensation coil.

The proposed rotating coil sensor has a total length of 98.2 mm, with 61 mm and thickness of 240 µm. The main coil consist in 59 turns with a effective area of 0.129 m² and effective length 84.308 mm. The compensation coil consist of 11 turns with effective length of 90.982 mm.

![Figure 3. Sensor rendering (left) and first produced prototype (right)](image)

The things in favor of the developed sensor are the no-sensitivity for the $z$-field component and the considerably high sensitivity for high harmonic order. In Fig. 4 the sensitivity factors for the main coil (red) and the compensation coil (blue) are plotted.

![Figure 4. Sensitivity factors at radius 19.065 mm](image)
4. Conclusion
The design and the production of an Iso-Perimetric induction coil has been presented. The developed induction coil sensor is characterized by negligible sensitivity to the $z$-field component and high sensitivity to high harmonic order. It was produced in FPC in order to obtain the desired characteristics.

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