A Small-Radius Rotating-Coil Measurement System for Field Characterization of Small-Bore-Diameter Magnets

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Abstract

This thesis introduces a novel version of a rotating-coil measurement system based on PCB technology, specifically designed for the field characterization of small-bore quadrupole magnets. The proposed magnetic measurement system development was carried out in the context of the EuPRAXIA project, which aims to produce high-energy electron beams using a compact plasma-based particle accelerator. Quadrupole magnets play a crucial role in any accelerator complex, and small-bore quadrupole magnets are particularly important in plasma-based accelerators, where high acceleration gradients must be achieved over short acceleration lengths. Accurate magnetic measurements are essential to limit orbit distortions and resonances in the particle beam and ensure that quadrupole magnets meet the required specifications for controlling beam trajectory and generating homogeneous magnetic fields.

The proposed measurement system is designed to address the challenges posed by the accurate characterization of EuPRAXIA quadrupole magnets, particularly regarding geometric constraints such as a bore diameter of at least 30 mm. The design proposal aims to simplify the design as much as possible by using low-cost, off-the-shelf components, including the shaft housing the PCB magnetometer, and open-source software packages, thereby increasing the accessibility of this technology.

The thesis presents a detailed description of the proposed small-radius rotating-coil measurement system with a diameter of 26 mm, including the layout, fabrication, and calibration of the PCB-based magnetic field sensor, as well as the shaft motion unit, acquisition chain, harmonic analysis, and post-processing software structure. Notably, the presented rotating coil system relies on a novel mechanical asset, based on a commercial carbon fiber tube, in which the PCB magnetometer is directly inserted.

The thesis also presents the numerical validation and metrological characterization of the system, including sensitivity and stability assessments. Experimental measurement results demonstrate the feasibility and effectiveness of the proposed PCB-based rotating coil system in achieving the target accuracy in the field characterization of permanent and resistive quadrupoles with a bore diameter of 45 mm. The proposed system can achieve the absolute accuracy of the main integrated gradient of 50 ppm, with a repeatability of 10 ppm, while the accuracy of high-order compensated harmonics is 100 ppm with a repeatability of 10 ppm. This performance meets the requirements for the measurement of the EuPRAXIA magnets.

Overall, this thesis contributes to the development of advanced measurement techniques based on rotating coil systems for particle accelerator magnets, providing a valuable tool for designing, testing, and optimizing quadrupole magnets for various scientific and engineering applications.