Doctoral Dissertation
Doctoral Program in Metrology (XXXIV cycle)

Characterization of magnetic materials at extreme ranges of field, temperature, and permeability

By

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Abstract

Materials shall display properties compatible with their target application. In particle accelerators, the trajectory of the particle beam is controlled using magnetic fields. These magnetic fields do not interact only with the beam but also with the surrounding elements of the machine. Some components generate the magnetic field, while others are used for different purposes and passively interact with it. In this context, the magnetic properties of materials are of great relevance, and requirements are specified. Verification of the magnetic properties relies on consolidated standards, which are not all-purpose, implying that complementary methods are necessary to cover all the requirements, and present different limitations.
In high-energy accelerators, such as the Large Hadron Collider at CERN, materials and components work in a harsh environment, under strong magnetic fields, and at a temperature of 1.9 K. In the context of the High Luminosity upgrade of the LHC, new superconducting magnets will be installed, including 11-T dipole magnets and the new quadrupoles to be installed at the sides of the intersection points. Simulations of these magnets showed that the iron yoke is heavily saturated when they are operated at their nominal field, reaching a magnetic flux density of about 3 T around the aperture, and with a significant impact of the yoke magnetic properties in the saturation region. The iron yoke material data at these fields are not available in the literature and therefore, they need to be measured. However, generating magnetic field values to obtain a flux density of 3 T in the iron is the main technical challenge. On the other hand, many other elements shall weakly interact with the field to not modify the field distribution and perturb the beam. The requirements are generally specified at room temperature. Various solutions are available in the literature, each one presenting limitations in terms of specimen size and range of test field. The twofold goal of this dissertation is to tackle these problems by developing two new measurement systems. The first is a superconducting permeameter to characterize soft ferromagnetic steels up to 2.8 T and at 4.2 K. As a case study, the

magnetic characterization of ARMCO® Pure Iron, the iron yoke material of the new LHC superconducting magnets, is presented. The second goal is to propose a measurement method for characterizing feebly magnetic materials with accuracy and resolution comparable with state-of-the-art solutions. The method fully exploits the flux-distortion detection method, works on bulky specimens arbitrarily shaped, and can therefore be used to test specimens or finished parts.

Keywords – Magnetic materials, particle accelerators, superconducting permeameter, static-sample magnetometer, vibrating sample magnetometer, stainless steels, radiation shielding, NMR, cryogenic measurement, flux-metric methods.