Engineering evaluation of grain-oriented steel solutions for special applications in High Energy Physics

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An untraditional application of Grain Oriented steel has been suggested in recent years, namely for iron core magnets to be used as detectors or shields in High Energy Physics, as compared to conventional massive iron solutions. Nevertheless, a preliminary engineering comparative evaluation of this possibility is less trivial of what it can appear, since the difficulties in general and complete modelling of such anisotropic materials. With this study we aim at bringing to evidence the most relevant critical points, evidencing possibilities and gaps in existing literature, and trying to focus, and possibly tackle or circumvent some critical issues, to explore engineering models for basic estimates and comparisons.

Keywords: grain-oriented steel, detector magnets, High Energy Physics

1. Introduction

Grain-oriented (GO) electrical steels are widely used in power transformers due to their anisotropic magnetic properties, which provide high permeability along the rolling direction and low core losses [1]. However, their application in high-energy physics (HEP) magnets remains underexplored, despite potential benefits in efficiency and field uniformity [2]. This work evaluates the possibility of deploying GO steels in HEP systems, where performances are high demanding [3].

2. Engineering modelling problems

The adoption of GO steels in HEP magnets introduces several modeling challenges. Accurate simulation of directional permeability effects in complex geometries requires advanced treatment of field anisotropy, particularly at material interfaces where flux leakage can substantially impact performance [4]. Predicting nonlinear magnetization behavior near high-field operational limits necessitates sophisticated material models that capture the unique saturation characteristics of oriented steels [5]. Furthermore, the mechanical constraints imposed by the laminar structure of GO steel assemblies - including stress sensitivity and delamination risks - require careful consideration in large-scale magnet systems [6]. Current modeling approaches often overlook these coupled effects, highlighting the need for more comprehensive computational frameworks. At the same time, the existing body of knowledge could be more extensively employed for preliminary engineering evaluations and comparisons.

3. Case study: a HEP Muon Shield

As a case study, we consider the possibility of using GO steels for the Muon Shield's magnets of the CERN's SHiP (Search for Hidden Particles) experiment [7]. They are typical DC iron-core ones, requiring precise field level and high uniformity. GO steel solution appears to be beneficial to the above goals, in particular mitigating the effects of lack or poor direct field measurement in the active (iron-core) region.

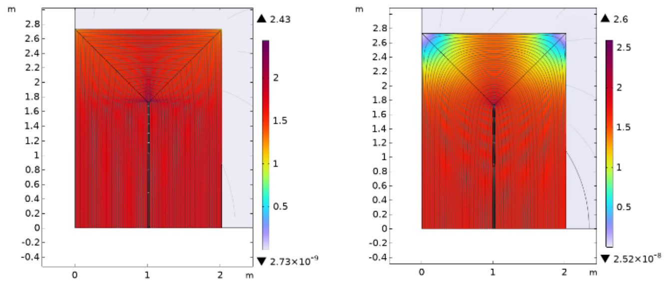

Figure 1: magnetic flux density modulus (|B|, in [T]) field distribution in a typical dipole magnet geometry (one-quarter) considering GO [8] (left) and isotropic [9] (right) steel.

A preliminary comparative 2-D FEM analysis for realistic magnet geometry and typically operating in a weakly saturated region has been carried out, demonstrating significant advantages of GO over isotropic steel in terms of field homogeneity (see Figure 1). However, further advantages of GO steels, like lower magnetomotive force and electrical power needed (considering the same average magnetic flux density within the active region), strongly depend on the operating point and should be reliably evaluated.

Besides the clear principle advantages of a GO steel structure, a more detailed analysis will be carried out within this work trying to face real-world issues, e.g. the huge dimensions of the involved magnets, possible different assembly techniques, mechanical tolerances, saturated mode working point etc.

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