

An Integrated Approach to the Design and Optimization of Resistive Large Magnets for CERN Experiments

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Magnets are essential in High Energy Physics (HEP) experiments, serving critical functions in particle accelerators and detectors. In detectors, like those in many experiments at CERN's Large Hadron Collider (LHC), large magnets are essential for particle identification by analyzing the curvature of particle tracks within a magnetic field. A consolidated design process follows a sequential process (i.e., identification of specification, analytical modeling followed by numerical validation), to balance performance and cost, meeting the physical constraints. Nowadays, any up-to-date design approach includes, within the fundamental goals, minimizing the use of energy/power and more in general material resources for sustainability, which is reflected in new guidelines at CERN. The present work aims at presenting some reformulation of resistive large magnet design procedures supporting this novel paradigm. This is obtained by developing an integrated optimization framework, that prioritizes energy efficiency, alongside performance and technical constraints, leading to a new perspective in the design exploration of the parameters space. A case study is reported for the design of spectrometer magnets for the SND@LHC upgrade project at CERN, showing the possibilities offered by such a new approach in balancing sustainability with experimental requirements and demand.

Index Terms— Sustainable development, Accelerator magnets, Mass spectroscopy.

I. INTRODUCTION

THE DESIGN of large warm magnets refers to conventional (electro-)magnets that operates at ambient temperature, primarily using a normal-conducting coil. These magnets, also called resistive, consist of a large air magnetized volume usually complemented by a soft steel return yoke, to enhance magnetic efficiency. Design procedure typically focus on optimizing the yoke's shape and the coils' structure improving efficiency at realistic current densities [1-3]. Needless to say, in many of existing or under design magnets, a large amount of power is needed, in the order of MW, when (as it often happens) superconductive solutions are not advisable, or feasible at all, due to cryogen burden, maintenance and safety, or other technical requirements [4]. The overall design process is rather complex and usually divided into sequential steps, although feedback loops may occur at certain stages. A detector magnet in a HEP beamline is not a stand-alone device, with substantial interactions with other devices, such as detectors, power supply, services as cooling plant, needing to obey safety and installation issues. Requirements, constraints, and boundaries are established at the beginning of the design process basing on the experimental needs and availabilities, including budget. From this, an analytical design is normally developed, followed by a basic numerical analysis. Once all steps are satisfactorily completed, an advanced numerical design — possibly multi-physics — with accurate field evaluation is established [4-5]. In recent years, a slight shift in perspective has emerged. In fact, traditional design procedures ground on realizing a reference field in a specified volume, with a coil balancing capital and

operational costs. Nowadays these factors, along with performance are part of a broader set of parameters' optimization space. Moreover, a special focus on energy efficiency is considered, aiming to minimize power needs, and more in general material resources, besides costs, and this reflects in new guidelines at CERN [6-7].

II. MAGNETIC SPECTROMETERS BASIC DESIGN ISSUES

Generally speaking, the main goal of the design of magnetic spectrometers is to achieve high momentum resolution on a large particle acceptance volume, within established dimensions and geometrical constraints, at minimal required electrical power and minimal construction cost. Additional constraints are basically low residual (stray) field outside, thermal and mechanical load limits. It is quite useful to give analytical (albeit approximate) expressions for the main goals as function of the design parameters, considering nonlinear effects in iron. An extensive list of such expressions can be found in [4-5], for the case of a closed end coil air spectrometer magnet. With reference to the measured momentum resolution $\Delta p/p$ [8], we have:

$$\frac{\Delta p}{p} = \frac{2\varepsilon p}{eBL\ell} \quad (1)$$

where p is the particle momentum, ε the resolution on trackers, e the electron charge, B the magnetic induction strength, L the active field region length and ℓ is the distance between trackers outside the magnet. In a conventional design approach, the expected resolution $\Delta p/p$ is fixed and this results in a required magnetic induction level B . A typical design constraints set is given when the magnet aperture is fixed, and as well its maximum transverse dimension. In this way, basically, only the ratio

between coil and iron return yoke thicknesses is free, with important consequences on the design [4].

III. AIR CORE SND@LHC MAGNET CASE STUDY DESIGN

In order to illustrate the novel design point of view we shortly report here the main results referred to a proposed open-end air coil and iron dominated magnet for the SND@LHC experiment [9], whose basic geometry is sketched in Fig. 1.

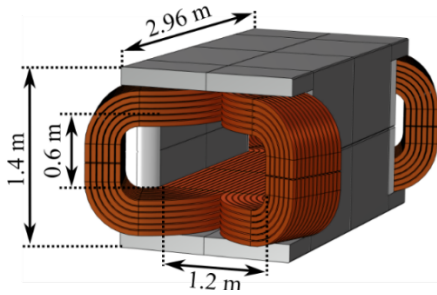


Fig. 1. Schematic sketch of the open-end air core and iron dominated magnetic spectrometer with geometrical parameters.

At fixed $\Delta p/p$, and correspondingly B , the main design figure of merit can be analytically expressed as function of the coil thickness, as it is shown in Fig. 2 for the reference case.

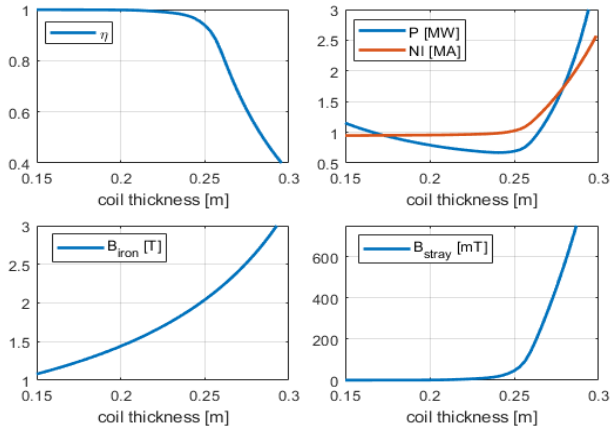


Fig. 2. Main figures of merit as functions of the coil thickness: magnet efficiency (top left), power and Magnetomotive Force (top right), magnetic flux density in the iron (bottom left) and stray magnetic flux density (bottom right). The presence of a minimum in the power P is consequence of the fixed total magnet height, as required by relevant prospective CERN experiments [4].

A more general approach provides the possibility of tracing optimal Pareto fronts [10]. Once the magnetic induction B is let free, one can calculate the power consumption as a function of $\Delta p/p$ and the coil thickness, identifying the curve of minimal power. In Fig. 3 the surface representing the power as function of momentum resolution and coil thickness is reported for the case study. At this point the choice of a good compromise between power and performance is let completely available to the designer. After deciding for a momentum resolution of 0.25, a set of optimal parameters is identified, and the corresponding main figures are reported in Table I.

Finally, a complete electromagnetic simulation for the optimized case study is performed in this way validating the parameters' set, as well giving a punctual description of fields in the active region and the stray field outside the structure (Fig. 4).

TABLE I
THE OPTIMAL CHOICE SET OF PARAMETERS

Magnet feature	Unit	Value
Momentum resolution R	-	0.25
Reference field B	T	1.01
Magnetomotive force	MA	0.985
Max stray field B_{stray}	mT	19
Magnet efficiency	-	0.9746

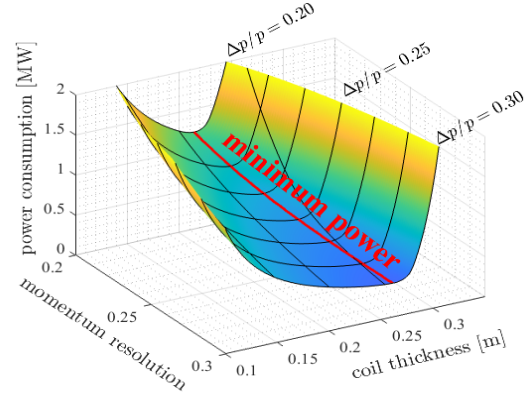


Fig. 3. Power as function of momentum resolution and coil thickness.

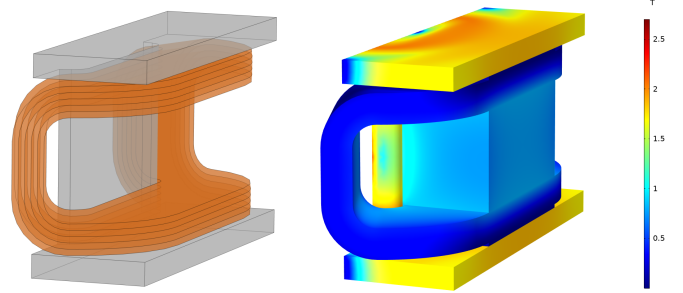


Fig. 4. FEM numerical analysis and validation of the case study at the optimized parameters' set (half structure simulated because of symmetry). Mechanical structure of the coil and return iron yoke (left) and magnetic flux density - modulus - distribution (right).

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