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SIMULATION OF SOLENOID TO ASSIST IN EBIS DESIGN AND MANUFACTURE PHASES

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Abstract

A simulation technique is described that was applied to optimise the design and ensure the desired field quality of a superconducting solenoid. A three-section solenoid with a lengthwise split winding was chosen as a reference configuration. The design was optimized through MathCAD calculations with the Levenberg-Marquardt minimization. The calculated data enabled adjustment of the coil geometry so as to provide required field homogeneity with respect to manufacture limitations. The optimised design was validated in comparative simulations and measurements on a prototype. The study was performed within the R&D activities on construction of an original electron beam ion source (EBIS). The results of the study were reported in the project documents.

Key words

Computational models, magnetic systems, magnetic fields, EBIS.

1 Introduction

Experts recognize [Sharkov and Meshkov, 2021] that the progress of accelerator technologies is driven primarily by nuclear and high-energy physics researches. A critical requirement for experiments in high-energy physics is generation of intense beams of multiply charged ions. This requirement dictates performance criteria for ion sources, particularly, on field homogeneity and current intensity.

An attractive choice is an electron beam ion source (EBIS) with a superconducting solenoid due to its high ionization efficiency and ability to deliver highly charged ions [Sharkov and Meshkov, 2021; Donets et al., 1968]. To fully take advantage of the concept, the solenoid should be capable to provide highly homogeneous and straight magnetic field to compress and guides the electron beam [Sharkov and Meshkov, 2021; Kirtsev et al., 2023; Zapretilina et al., 2024].

In this paper we outline a numerical recipe to calculate the anticipated magnetostatic field and validate and optimise the solenoid design. The latter is achieved by minimizing the quality functional, which is a well-known approach [Arguchintsev and Kopylov, 2024; Barseghyan et al., 2025]. The study was performed within the framework of the R&D activities on the design and fabrication of a new EBIS [Zapretilina et al., 2024]. The simulated data were then compared with measurements on a prototype coil.

The use of a solenoid coil is dictated by the demand for high homogeneity of the longitudinal field. The calculation techniques to assess the field quality in solenoids are well established.

In this study we have gained high calculation accuracy by combining analytical techniques in MathCAD and numerical simulations with the code KLONDIKE [Amoskov et al., 2008]. The code solves the magnetostatic problem in the integral formulation and is intended to simulate field maps for coils of complicated geometry [Amoskov et al., 2018] with possible impact of their ferromagnetic environment [Amoskov et al., 2019].

The solenoid design was optimised using the computational technique proven in earlier projects. The following steps were used:

1. generation of a detailed numerical model of the coil;
2. validation of the model in comparative simulations with codes employing different formulations of the magnetostatic problem;
3. synthesis of a multi-section solenoid from solving the inverse magnetostatic problem;
4. derivation of the magnetic specification of the solenoid from solving the direct magnetostatic problem;
5. adjustment of the solenoid geometry with respect to the manufacture limitations.

2 Configuring solenoid

A crucial issue in the design of a superconducting solenoid is to achieve the optimal magnetic performance under a range of constraints associated primarily with manufacture and assembly limitations, i.e. dimensions, cable specification, magnetic interaction, stray field etc. Our study was targeted to the following requirements:

1. Solenoid central field B_0 is 5 T.
2. The axial field fluctuation within a cylinder with a 10 mm diameter from the geometrical axis over a length of 0.3 m in both directions from the centre of the solenoid must be within $\pm 0.16\%$.
3. Over a length from 0.3 m to 0.35 m in both directions from the centre of the solenoid, the axial field fluctuation within the cylinder with a 10 mm diameter must be within $\pm 0.7\%$.
4. The maximal field at 0.2 m and 0.6 m away from the ends of the solenoid jacket, that is at the distances 1.5 m and 1.9 m from the centre of the solenoid, must not exceed 100 mT and 10 mT, respectively.
5. The inner diameter of the winding is 0.2 m.
6. No external ferromagnetic shield.
7. The solenoid sections are powered in series with a single power source.
8. No additional coils to correct field fluctuations due to manufacture deviations from the perfect design.

The reference configuration selected for the solenoid is shown in Figure 1. The solenoid is formed with three sections with a lengthwise split winding. Such configuration allows:

1. individual fabrication of the coil sections;
2. easying cryogenic aspects;
3. use of a single copper tube as a former;
4. rearrangement of turns on separate coil sections, if necessary.

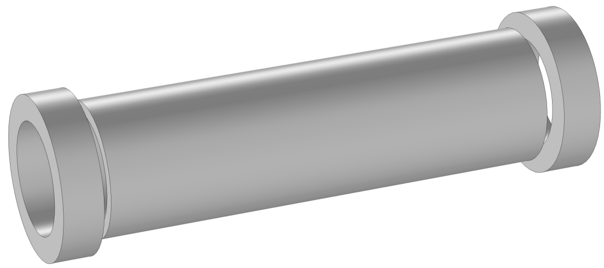

Figure 1. Layout of three-section solenoid.

3 Design optimization

The solenoid sections are wound with a NbTi-Cu composite wire at 4.2 K. The outer diameter D of the insulated wire is 1 mm. The operational current I in the winding is taken near 200 A assuming a 50% margin for critical current. The design number of the winding layers n for a solenoid with a high length to diameter ratio is evaluated as:

$$n = \frac{B_0 D}{\mu_0 I} = \frac{5\,\mathrm{T} \cdot 0.001\,\mathrm{m}}{4\pi \cdot 10^{-7}\,\mathrm{H/m} \cdot 200\,\mathrm{A}} \approx 20, \qquad (1)$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the vacuum permeability.

A special attention has been paid to optimize dimensions of the coil-end winding layers with respect to predetermined solenoid sizes and manufacture tolerances.

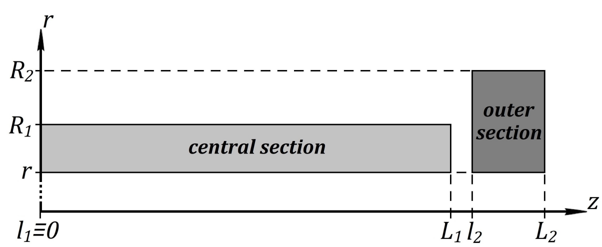

Figure 2. Lengthwise split winding (1/2 of axial cross-section).

The cylinder region, where the desired field quality is assessed, is much lesser in diameter as compared to the designed solenoid. For this reason, the simulated field is simplified to a longitudinal field distribution along the axis z of the round solenoid. The field expected in 3

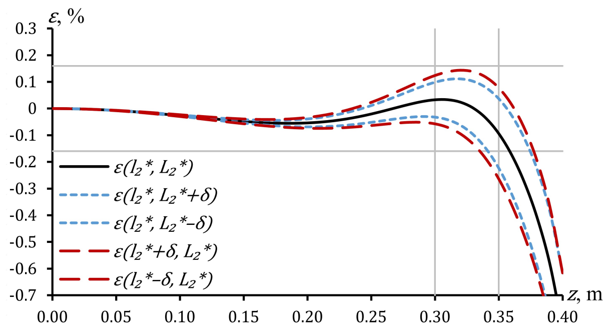

Figure 3. Field fluctuation for optimised solenoid configuration.

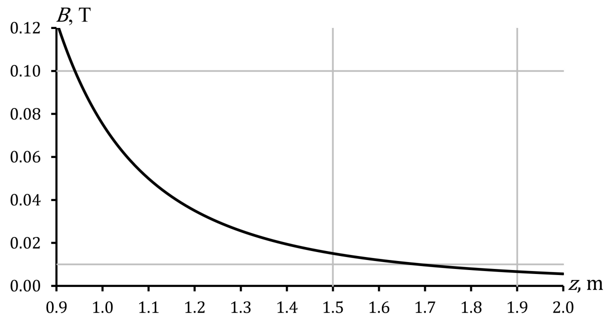

Figure 4. Decrease of longitudinal field B along solenoid axis.

solenoid sections with identical current density J and inner radius r is calculated [Montgomery, 1980] as:

$$\begin{aligned} B_z(z) &= \frac{1}{2}\mu_0 J r \\ &\times \left[F\left(\frac{R_1}{r}, \frac{L_1+z}{r}\right) + F\left(\frac{R_1}{r}, \frac{L_1-z}{r}\right) \right. \\ &+ F\left(\frac{R_2}{r}, \frac{L_2+z}{r}\right) + F\left(\frac{R_2}{r}, \frac{L_2-z}{r}\right) \\ &\left. - F\left(\frac{R_2}{r}, \frac{l_2+z}{r}\right) - F\left(\frac{R_2}{r}, \frac{l_2-z}{r}\right) \right] \end{aligned} \quad (2)$$

where

$$F(\alpha, \beta) = \beta \cdot \ln\left(\frac{\alpha + \sqrt{\alpha^2+\beta^2}}{1+\sqrt{1+\beta^2}}\right).$$

Here R_1, R_2 are the outer radii of the solenoid sections; $\pm L_{1,2}$ and $\pm l_2$ ($l_1 \equiv 0$) are the winding coordinates along the axis z with respect to the solenoid centre $l_1 = 0$, see Figure 2. The current density is determined as $J = I/D^2$.

Field fluctuation ε along the solenoid axis is determined as:

$$\varepsilon(z, L_2, l_2) = \frac{B_z(z) - B_z(0)}{B_z(0)}. \quad (3)$$

The solenoid configuration was optimized via parameters L_2 and l_2. The optimisation function with respect to the above constraints was taken as:

$$\int_0^{\tilde{z}} \left(\varepsilon^2(z, L_2-\delta, l_2) + \varepsilon^2(z, L_2+\delta, l_2)\right) dz \to \min, \quad (4)$$

where $\pm\delta = 1.0$ mm is the allowable manufacture tolerance. $\tilde{z}$ takes its value inside the region of inhomogeneity minimization. In this work, $\tilde{z} = 0.325$ m is chosen according to numerical experiments to reduce the affect of manufacture tolerance δ.

The function (4) was minimized in MathCAD v.15 calculations using the Levenberg-Marquardt method [Levenberg, 1944; Marquardt, 1963]. At $R_2 \approx r + n_2 D = 0.14527$ m ($n_2 = 44$) and $L_1 = 0.40723$ m we obtained $L_2^* = 0.49979$ m and $l_2^* = 0.428$ m. These values were adopted in the optimised solenoid configuration.

Figure 3 illustrates simulated fluctuations ε of the longitudinal field for the optimised solenoid configuration with perfect L_2^*, l_2^* and with respect to the manufacture tolerance $\pm\delta$.

The field is expected to decrease along the axis z with the distance from the jacket ends as shown in Figure 4. The maximal field of the optimised solenoid is found to be below the specified thresholds of 100 mT and 10 mT.

To verify the computational model, additional modeling of the magnetic field was performed using the KLONDIKE software package. Figure 5 shows the absolute and relative deviations of the results obtained using expression (2) in the MathCAD software environment from those obtained using KLONDIKE.

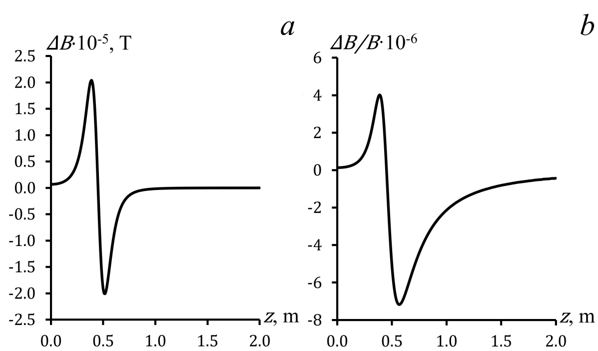

Figure 5. Absolute (a) and relative (b) deviation of the magnetic field obtained with MathCAD from the one obtained with KLONDIKE.

4 Winding adjustment

In the simulations the conductor was assumed to be wound evenly along the coil. However, a stable decrease of 3.18% in the turn density at the coil-end winding layers was actually revealed during the prototype fabrication due to process features. This resulted in local loss

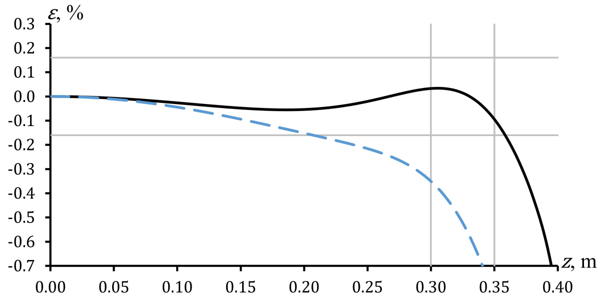

Figure 6. Field fluctuations along axis z for optimized design (solid line) and prototype coil (dashed line).

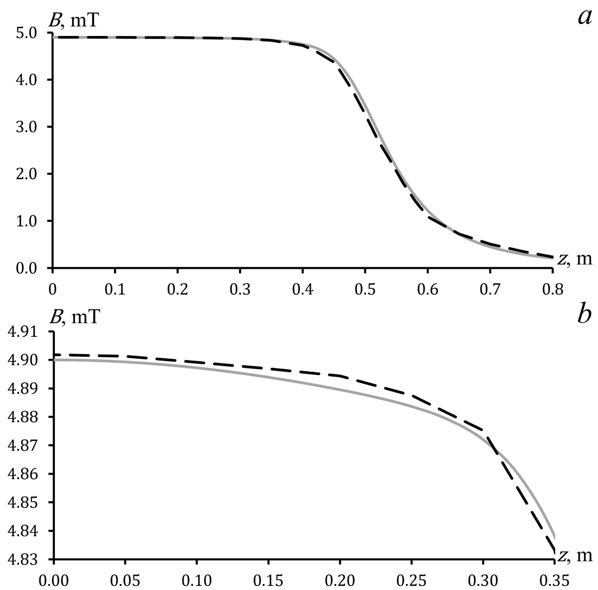

Figure 7. The calculated (solid line) and measured (dashed line) magnetic field distribution along the solenoid's axis. The distribution is shown in two different scales.

of amper turns and deterioration of the field homogeneity.

Figure 6 shows a comparison of expected field fluctuations ε along the solenoid axis for the perfectly spread winding and the prototype winding.

To compensate the field deterioration at the end turns, we proposed to increase the number of winding layers at the outmost coil sections from $n_2 = 44$ to $n_2 = 46$ while 3 turns were deleted in each layer. This would change the end coil sizes to $L_2 = 0.497$ m and $R_2 = 0.147$ m.

The simulated field was compared with the results of warm measurement on the prototype energized with a low current to a field level of 4.9 mT. Figure 7 shows the measured axial field distribution in comparison to the curve calculated with respect to the end field inhomogeneity. It is reasonable to say that the measurement agrees well with the calculation and has demonstrated desired field quality over the specified region of ± 0.35 m from the centre of the solenoid.

5 Conslusions

Methods for optimising the geometric parameters of magnetic systems contribute to the development of electrophysical facilities, employed, for instance, in accelerator and nuclear physics. This paper is devoted to the development of a precise superconducting magnetic system for an original version of EBIS intended for the generatio of intense beams of multiply charged ions. An optimisation method for the EBIS magnetic system takes into account the parameters of a specific device and the constraints of the manufacturing process. The proposed approach enables near-real-time design support during EBIS development.

The comparison of the simulated field profile with the measurement on the completed prototype has demonstrated that described approach is feasible to create a reliable model and gives a starting point for synthesis of an EBIS magnet with required performance. The field inhomogeneity does not exceed 0.12% within a 10-mm-diameter cylinder over 0.3 m from the solenoid center, and 0.37% over 0.3–0.35 m wiprecise th a 1 mm manufacturing tolerance. The simulation and measurement process can be iterated until a high field quality is assured. The magnet design is thereafter optimised with respect to a range of factors, including manufacture tolerances and displacements. The optimised design obtained in this study has been included in the project documents.

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