DEVELOPMENT OF A SUPERCONDUCTING FOCUSING SOLENOID FOR CADS*

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Abstract

A superconducting focusing solenoid has been designed and developed for the China Accelerator Driven System (CADS). In order to meet the requirement of focusing strength and fringe field while minimizing physical size of the solenoid, the novel optimizing design method based on linear programming method was employed. In this report, we will introduce the design of the solenoid including magnetic field optimization, mechanical design and quench protection. The fabrication and the test results of the solenoid will also be introduced in this report.

INTRODUCTION

Accelerator Driven System(ADS) is the effective tool for transmuting the long-lived transuranic radionuclides into shorter-lived radionuclides. A project called CADS is being studied in the Chinese Academy of Sciences. Fig. 1 shows the roadmap of CADS. The linac of CADS will accelerate the proton with beam current 10mA to about 1.5GeV to produce high flux neutrons for transmutation of nuclear waste. The beam dynamics of superconducting linacs operating in the velocity range below 0.4c require a compact accelerating-focusing lattice. Superconducting solenoids together with SC RF resonators within a common cryostat meet this requirement. For its simple design, easily producing and low cost of manufacture, many typical superconducting Linac such as ISAC-II of Canada, Project X of FANL and FRIB of MSU in USA employ solenoid as focusing element[1, 2, 3].

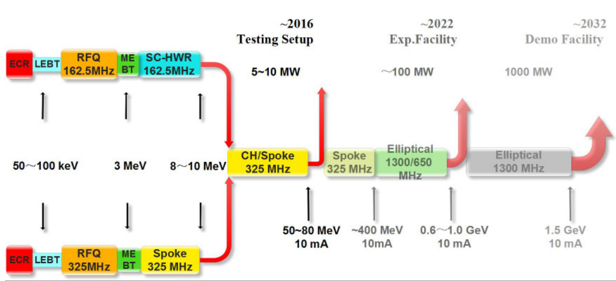

Figure 1: The roadmap of China CADS.

The solenoid will generate stray magnetic field that must be shielded to very low levels at the nearby SRF cavities. Two orthogonal steering dipoles, coaxial to each other and to the solenoid, are required to steer the beam in transverse directions. The specifications of the solenoid are summarized in Table. 1[4].

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Table 1: Specifications of SC solenoid

Parameters	Value
Center field	7 T
Effective length	150 mm
Stray field 200 Gs line	$\leq 280\ mm$ from the center
Correction of integral	$> 0.01\ T \cdot m$
Bore diameter	44 mm

MAGNETIC DESIGN

The solenoids must have low fringe fields to avoid magnetic-flux capture in the superconducting cavity. Before the SC cavity cooled into superconducting state, the level of the fringe field must be much lower than the earth-s magnetic field 50 μT and according to some estimates should be on the level of 1 μT [5]. This requires that the solenoid should be constructed only of material with low relative magnetic permeability to minimize remnant fields when the magnet is off. Once the cavity is in the superconducting state, the fringe field of the fully energized magnet is to be less than $20 \sim 40\ mT$.

The main goal of the magnetic design is to find a configuration of a solenoid that would meet the major requirements while minimizing the cost. The reverse wound active shielding coils are also used in our design to reduce stray magnetic field as ISAC-II and FRIB did. A two-step method which combines linear programming and a nonlinear optimization algorithm has been employed to design the solenoid[6, 7]. Linear Programming is used to carry out the topology optimization to get the coils' initial location and shape, and then the nonlinear optimizing methods are used as the second step to further simplified the coils' shape.

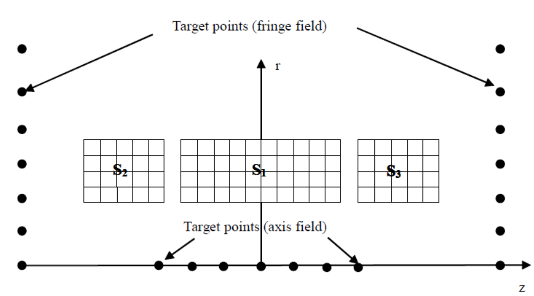

Figure 2: The feasible coil regions with numerical grid.

For a multi-coils magnet the feasible coil space can be divided into several regions and then each section is densely sampled by an array of candidate current loops (Fig. 2). The goal is to determine a set of current loops to create a desired field distribution at the target points while achieving a low fringe field and minimizing the coil volume. This

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problem can be converted to a standard linear programming problem

$$\begin{aligned} \text{Minimize:} \quad & 2\pi \sum r_n S_n \\ \text{Subject to:} \quad & B_0(1-\epsilon) \leq AI \leq B_0(1+\epsilon) \\ & |C_z I| \leq B_{z,shield} \\ & |C_r I| \leq B_{r,shield} \\ & 0 \leq I_n \leq Ic_n \end{aligned} \tag{1}$$

where S_n and r_n are the cross-sectional area and radii of the current loop n, respectively. After the first step, the coil domains are usually non-rectangular as shown in Fig. 3. It is difficult to fabricate a magnet with non-rectangular coils, so we have to find a solution that can be implemented with only rectangular coils. The non-rectangular domain is then divided into a set of geometrically simple parts. These parts are replaced with rectangular regions whose shape and location parameters can be determined by using the nonlinear optimizing method. Fig. 4 shows the resulting coils configuration and stray field distribution. The fringe field is less than 4 mT in the cavity zone (280 mm from the center). The maximum field in the coil is 7.45 T at the current of 204 A. 30% of the current margin is used.

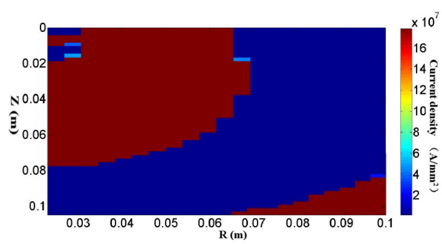

Figure 3: The resulting coil domains after the LP optimization

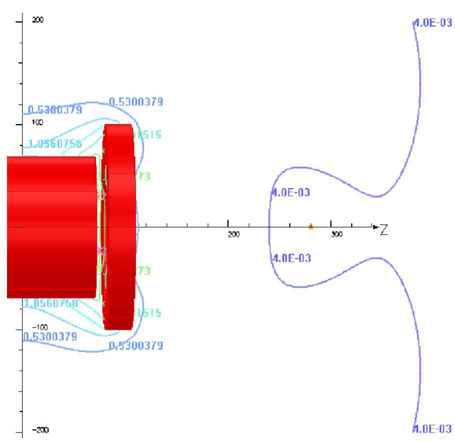

Figure 4: The resulting coil domains with the nonlinear optimizing method

pairs of steering dipole coils. All the coils are wound with NbTi/Cu composite superconducting wire and impregnated with epoxy resin to ensure mechanical stability. The integrated design of the bobbin and helium vessel is shown in Fig. 6. Stress analysis of the magnet has been performed. Fig. 7 shows that the maximum stress is only 95 MPa, which is within the allowable limits. The coil formers and helium vessel are fabricated with 316L stainless steel to ensure low relative magnetic permeability and good cryogenic mechanical properties. In order to prevent quench caused by separation of the coils inner layer from the bobbin during excitation, the aluminum alloy overbinding is applied.

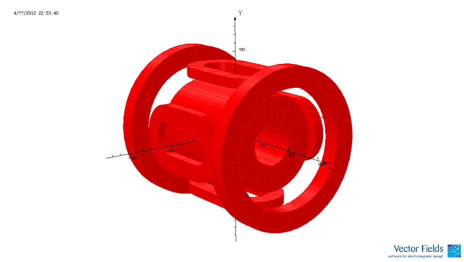

Figure 5: Coils configuration of CADS solenoid

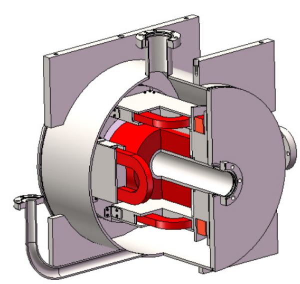

Figure 6: CADS solenoid assembly

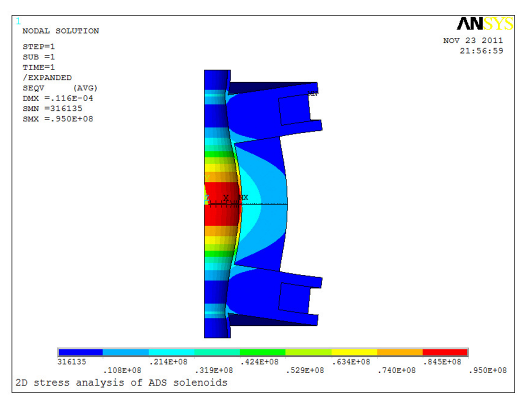

Figure 7: Simulated stress distribution of the solenoid caused by the electromagnetic forces

MECHANICAL DESIGN AND ANALYSIS

The final coils configuration of the magnet is shown in Fig. 5. It includes one solenoid, two bulking coils and two

FABRICATION AND TESTING RESULTS

The solenoid have been built and tested in Institute of Modern Physics (IMP). The solenoid was installed into a vertical experimental testing dewar and Fig. 8 shows the assembly of the test insert for the magnet. Because of the s-mall storage energy (24 kJ), the cold diodes have been used to protect the magnet from quench. Fig. 9 shows the quench protection circuit for the magnet.

Figure 8: Assembly of test insert for CADS solenoid

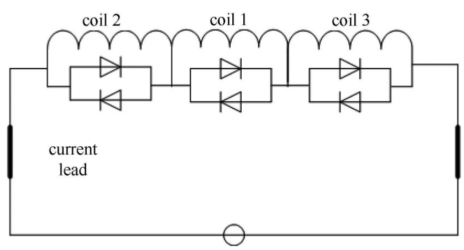

Figure 9: Quench protection circuit

The maximum central field of the solenoid reached 8.2 Tesla. The magnetic field along the axis was measured with hall probe and the result is shown in Fig. 10. When the current is 180 Ampere, the central field is 7.321 Tesla. The measured effective length is about 134mm. The fringe field on the cavity surface was also measured. Fig. 11 draws a comparison between the measured fringe field and the calculated value.

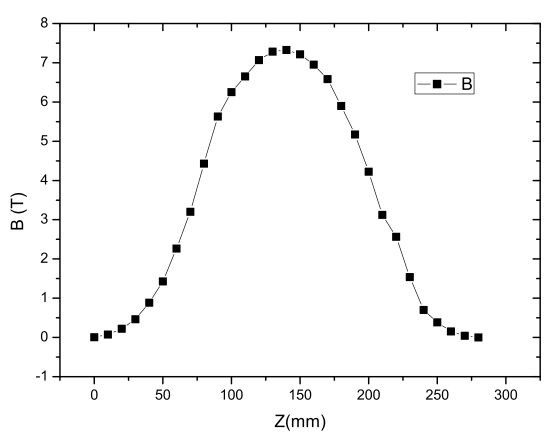

Figure 10: The measured magnetic field distribution along the axis of the solenoid

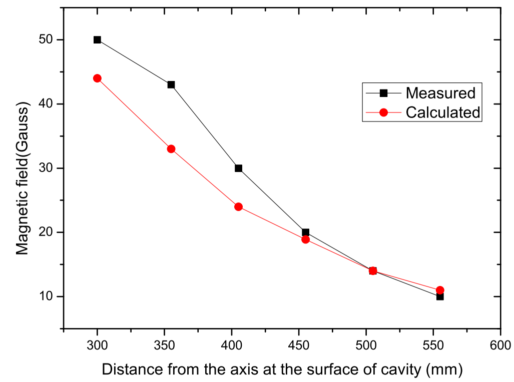

Figure 11: Comparison between the measured fringe field and the calculated value

SUMMARY

In this paper we present the design, fabrication and test of the superconducting solenoid for CADS-linac. A two step method combined Linear Programming and nonlinear optimization method was used to optimize the coils configuration. The fabrication and the test results of the prototype validates the magnetic and mechanical design of the magnet. The steering dipole will be finished and integrated to the solenoid and tested by the end of the year.

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