Development of a superconducting solenoid for CADS *

WU Wei(吴巍)[1)] WNAG Zhi-Jun(王志军) WU Bei-Ming(吴北民) HAN Shao-Fei(韩少斐)
NI Dong-Sheng(倪东升) MEI En-Ming(梅恩铭) YANG Wen-Jie(杨文杰)
ZHU Li(朱丽) ZHENG Shi-Jun(郑石钧) YANG Tong-Jun(杨通军)
YANG Xiao-Liang(杨晓亮) MA Li-Zhen(马力祯) HE Yuan(何源)

Institute of Modern Physics, China Academy of Sciences, Lanzhou 730000, China

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 the physical size of the solenoid, the novel optimizing design method based on a linear programming method was employed. In this report, the design of the solenoid including magnetic field optimization, mechanical design and quench protection will be introduced. The solenoid has been fabricated and tested. The testing results show that the central field reached 8.4 T and the stray field was lower than 50 Gauss in the cavity zone.

Key words: ADS, focusing, superconducting solenoid, magnetic field optimization, stray field

PACS: 84.71.Ba **DOI:** 10.1088/1674-1137/38/1/017003

1 Introduction

A project called the China Accelerator Driven System (CADS) is being studied at the Chinese Academy of Sciences. Fig. 1 shows the roadmap of CADS. The superconducting linac of CADS which consists of two injectors and one main linac will accelerate the proton beam to about 1.5 GeV to produce high flux neutrons for the transmutation of nuclear waste and for producing clean nuclear power. The beam dynamics of the superconducting linacs operating in the velocity range below 0.4c require a compact accelerating-focusing lattice. Superconducting solenoids together with SRF (Superconducting Radiofrequency) resonators within a common cryostat can meet this requirement. For its simple design, easy production and low cost of manufacture, a solenoid is used as the focusing element in many typical superconducting linacs, such as ISAC-Ⅱ of Canada, Project X of FANL and FRIB of MSU in USA [1–3].

The solenoid will generate a stray magnetic field that must be shielded to be of very low levels at the nearby SRF cavities. Two orthogonal steering dipoles, coaxial

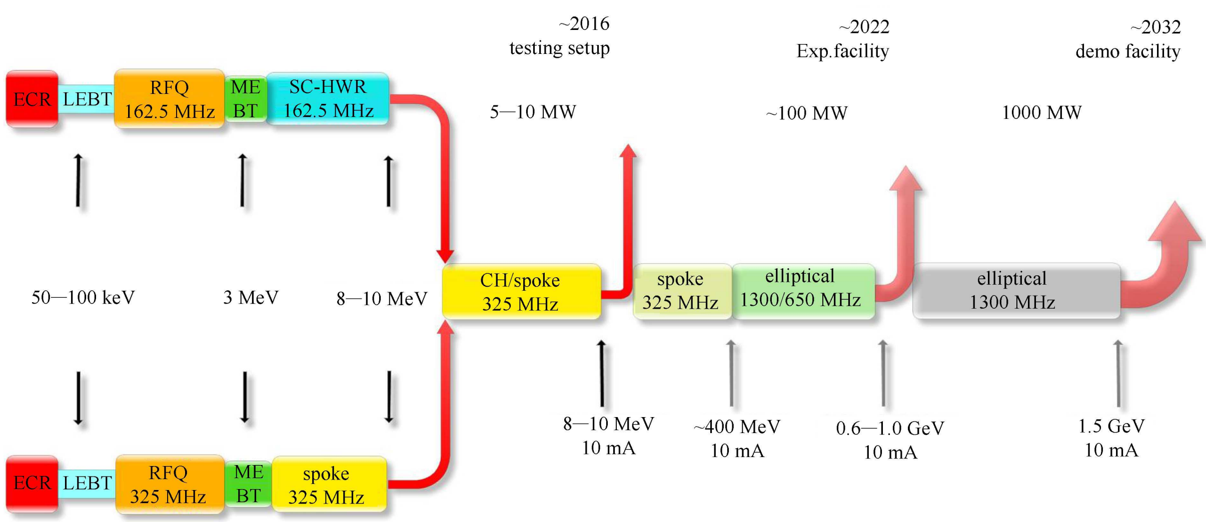

Fig. 1. (colour online) The roadmap of CADS.

Received 11 December 2012

∗ Supported by National Natural Science Foundation of China (11079001)

1) E-mail: wuwei@impcas.ac.cn

to each other and to the solenoid, are required to steer the beam in transverse directions. The specifications of the solenoid for Injector Ⅱ of CADS are summarized in Table 1 [4].

Table 1. Specifications of SC solenoid.

parameters	value
center field/T	7
effective length/mm	150
stray field 200 Gs line	⩽280 mm from the center
correction of integral/(T·m)	>0.01
bore diameter/mm	44

2 Magnetic design

The solenoids must have low fringe fields to avoid magnetic-flux capture in the SRF cavity. Before the cavity is cooled into the superconducting state, the level of the fringe field must be on the level of 1 μT, which is much lower than the earth's magnetic field of 50 μT [5]. This requires that the solenoid must be constructed only using material with a 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 needs to be less than 20–40 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 the 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. Linear programming is used to carry out the topology optimization to get the coil's initial location and shape, and then nonlinear optimizing methods are used as the second step to further simplify the coil shape.

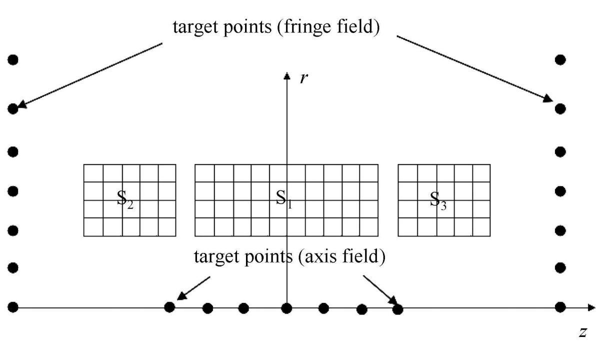

Fig. 2. The feasible coil regions with numerical grid.

For a multi-coil 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 problem is to find a set of current loops, which can generate a desired field distribution at the target points while achieving a low fringe field and minimum coil volume. This problem can be converted to a standard linear programming problem of

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

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. The black region shown in Fig. 3 represents the axisymmetric cross section of the solenoids. It is difficult to fabricate a magnet with non-rectangular coils, so we

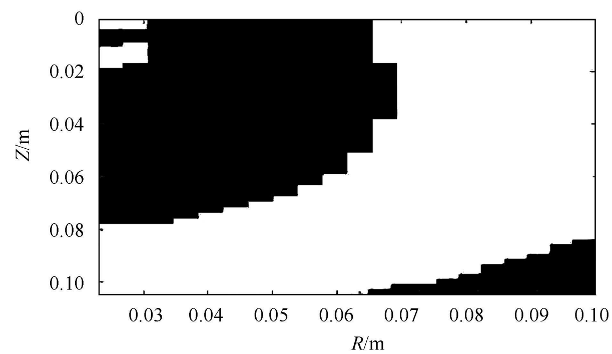

Fig. 3. The resulting coil domains after LP optimization.

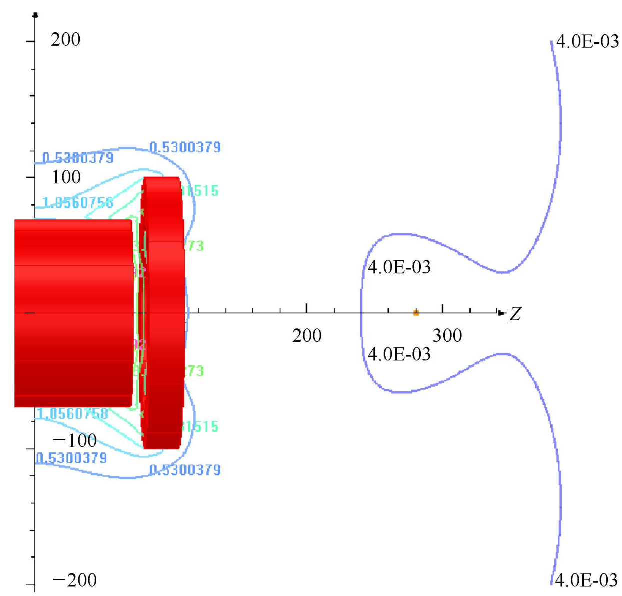

Fig. 4. (colour online) The resulting coil domains with the nonlinear optimizing method.

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 using the nonlinear optimizing method. Fig. 4 shows the resulting coil 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.

3 Mechanical design and analysis

The final coil configuration of the magnet is shown in Fig. 5. It includes one solenoid, two bulking coils and two 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 the separation of the coil's inner layer from the bobbin during excitation, an aluminum alloy overbinding is applied.

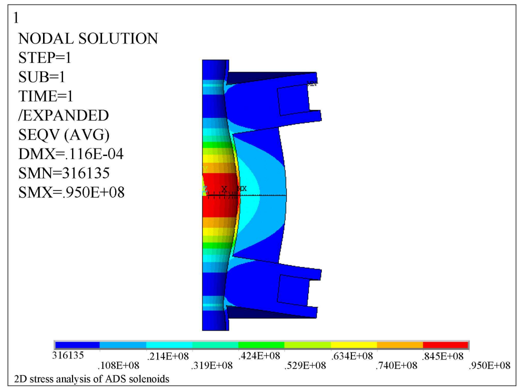

Fig. 7. (colour online) Simulated stress distribution of the solenoid caused by the electromagnetic forces.

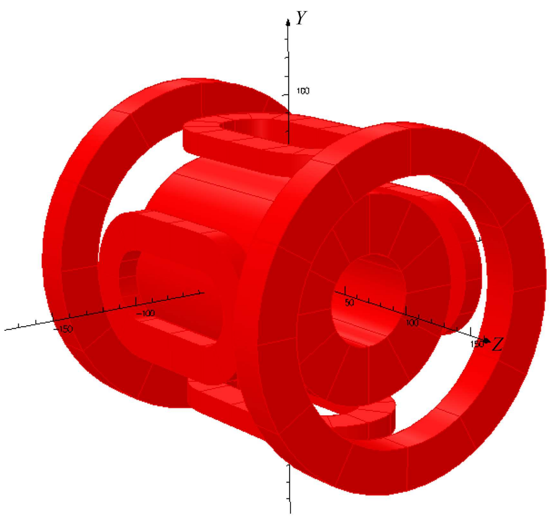

Fig. 5. (colour online) Coils configuration of the CADS solenoid.

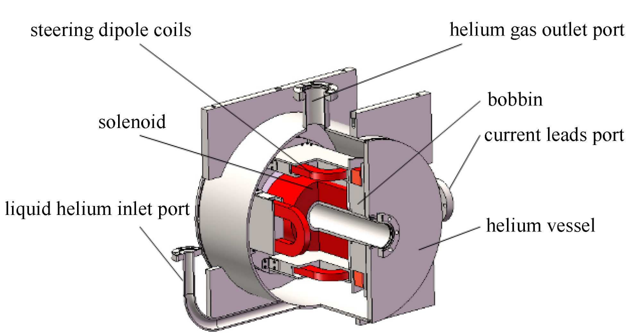

Fig. 6. (colour online) CADS solenoid assembly.

4 Fabrication and testing results

The solenoid has been built and tested at IMPCAS. The solenoid was installed into a vertical experimental testing dewar; Fig. 8 shows the assembly of the test insert for the magnet. Because of the small storage energy (24 kJ), cold diodes have been used to protect the magnet from quench. Fig. 9 shows the quench protection circuit for the magnet. Three coils are connected in a series and each coil is protected by a couple of diodes connected in parallel.

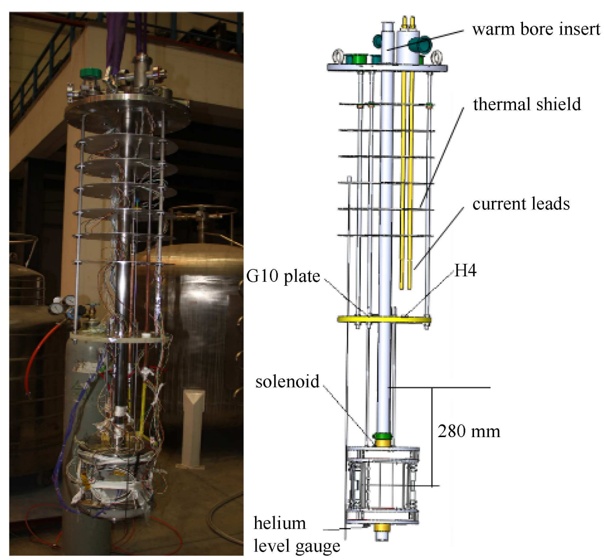

Fig. 8. (colour online) Assembly of test insert for CADS solenoid.

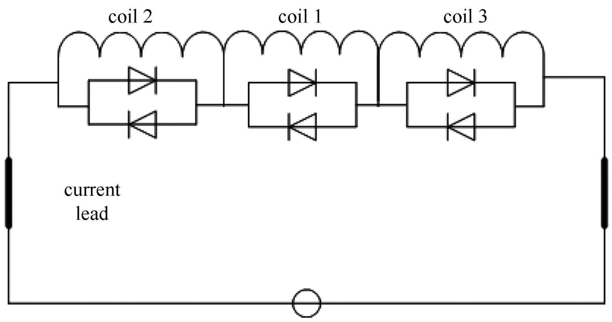

Fig. 9. Quench protection circuit.

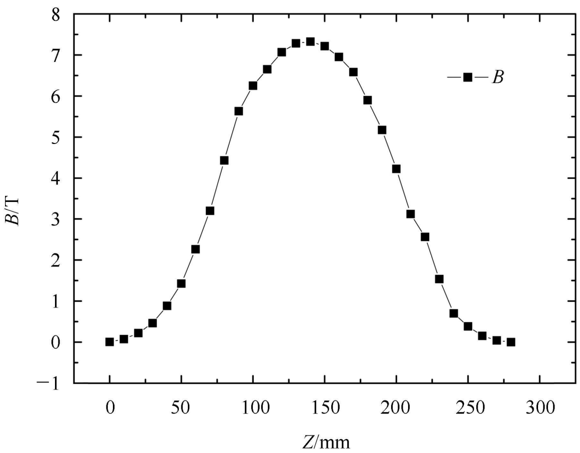

Fig. 10. The measured magnetic field distribution along the axis of the solenoid.

The maximum central field of the solenoid reached 8.2 T. The magnetic field along the axis was measured with a Hall probe and the result is shown in Fig. 10. When the current is 180 A, the central field is 7.321 T. The measured effective length is about 134 mm. The fringe field on the cavity surface was also measured. Fig. 11 shows a comparison between the measured fringe field and the calculated value. The deviation may be due to the poor positional accuracy of the measured points, the magnetization of the dewar wall and the fabrication error of the coil.

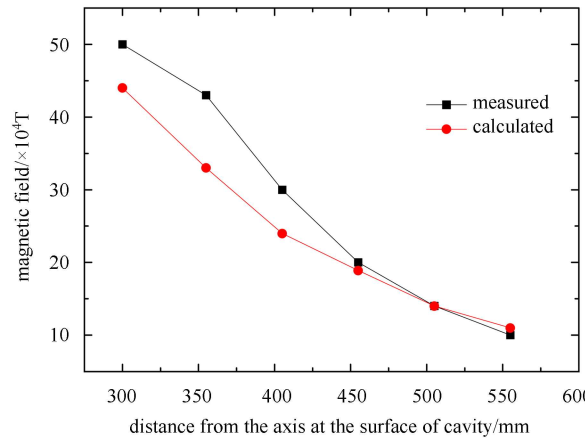

Fig. 11. Comparison between the measured fringe field and the calculated value.

5 Summary

In this paper, we present the design, fabrication and test of the superconducting solenoid for CADS. A two-step method combining Linear programming and nonlinear optimization was used to optimize the coil's configuration. The fabrication and the test results of the prototype indicate that the magnetic and mechanical design of the magnet are very reasonable. The steering dipoles have been finished and integrated in the solenoid and will be tested soon.

References

1 Ostroumov P N, Kim S H, Lessner E S, Shepard K W, Laxdal R E, Wheatley R. A New Generation of Superconducting Solenoids for Heavy-Ion Linac Application. LINAC2003, Gyeongiu, 2002

2 Davis G, Kashikhin V V, Page T, Terechkine I, Tompkins J, Wokas T. IEEE Transactions, 2007, **17**(2): 1221–1224

3 Terechkine I, Kashikhin V V, Page T, Tartaglia M, Tompkins J. Focusing Solenoid for the Front End of a Linear RF Accelerator. In Particle Accelerator Conference, 2007. PAC. IEEE, 2007. 473–475

4 YANG Xiao-Liang, MA Li-Zhen, WU Wei, ZHENG Shi-Jun, DU Jun-Jie, HAN Shao-Fei, GUAN Ming-Zhil, HE Yuan. Chinese Physics C (HEP & NP), 2012, **36**: 886–890

5 CHAO A W, Tigner M. Handbook of Accelerator Physics and Engineering. World Scientific Publishing Co. Pte. Ltd., 1998. 531