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Design of a superconducting magnet for CADS*

YANG Xiao-Liang(杨晓亮)[1,2;1)] MA Li-Zhen(马力祯)[1;2)] WU Wei(吴巍)[1]
ZHENG Shi-Jun(郑石钧)[1] DU Jun-Jie(杜俊杰)[1] HAN Shao-Fei(韩少斐)[1]
GUAN Ming-Zhi(关明智)[1] HE Yuan(何源)[1]

[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: This paper describes a superconducting magnet system for the China Accelerator Driven System (CADS). The magnetic field is provided by one main, two bucking and four racetrack coils. The main coil produces a central field of up to 7 T and the effective length is more than 140 mm, the two bucking coils can shield most of the fringe field, and the four racetrack superconducting coils produce the steering magnetic field. Its leakage field in the cavity zone is about 5×10^{-5} T when the shielding material Niobium and cryogenic permalloy are used as the Meissner shielding and passive shielding respectively. The quench calculations and protection system are also discussed.

Key words: ADS, SC solenoid design, leakage field, magnetic shielding, quench calculation

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1 Introduction

The Accelerator Driven System (ADS) is a dedicated burner reactor in Double Strata Fuel Cycle to transmute nuclear waste. ADS usually consists of an accelerator, target, coolant, sub-critical core and so on. The accelerator usually consists of a compact strong accelerating focusing lattice in the linac component, where heavy ions can be accelerated, bent and focused in a complicated distribution field of the lattice [1]. Fig. 1 shows the long-term planning of the CADS at IMP (Institute of Modern Physics, Lanzhou).

The reactor power in CIADS (China Initiative Accelerator Driven System) is about 4 MW, produced by a 10 mA particle beam of 40 MeV. A solenoid structure is widely used to provide a powerful magnetic field to control the motion of particles because it has a simple design, is easy to produce and is cheap to manufacture. Some typical linac programs such as the Canadian ISAC-Ⅱ and the FRIB from MSU in the USA employ the solenoid structure as a restrain element. The specifications of the magnet for the CADS Injector Ⅱ are summarized in Table 1.

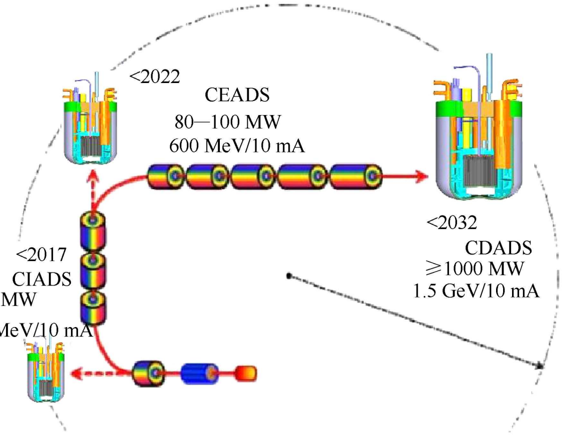

Fig. 1. (color online) CADS long-term planning. (courtesy of the FDS team, Institute of Plasma Physics [2]).

The magnet includes four racetrack coils to produce two steering dipoles for beam-centroid corrections. Active shielding of the stray fields is provided by two coils in series with the main solenoid coil.

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1) E-mail: yxl@impcas.ac.cn
2) E-mail: malz@impcas.ac.cn

Niobium and cryoperm (a special kind of MuMetal) shroud around the solenoid to provide additional passive shielding.

Table 1. Specifications of the CADS SC solenoid.

item	value
central field	7 T
effective length	150 mm
stray field (0.5 Gs line)	280 mm
correction of integral	0.01 T·m
bore diameter	44 mm

2 The electromagnetic design

In order to ensure low residual resistance of the superconducting cavity, the magnetic field at the cavity during transition must be below 10 μT for the $\lambda/4$ cavities and below 2.5 μT for the $\lambda/2$ cavities in the ADS system. Such a low residual field means that we need not only active shielding, but also passive shielding to further reduce the leakage field. However, the cavity itself also needs to be shielded from the field of other components in the cryomodule magnetized by the stray field of the magnet, and the earth's magnetic field.

2.1 The active shielding

The principle of active shielding is to counteract the effects of the magnetic field by providing the same strength field in the adverse direction, leaving a zero overall sum. The adverse direction field can be generated by simple solenoids or permanent magnets [3]. Due to the close packing of the lattice, the solenoid is equipped with bucking coils to actively limit the fringe field in the adjacent cavity. According to the Bio-Savart law, if the current loop is small enough to take the radius as a constant parameter, there is a linear relationship between the magnetic field and the magnet current. So we can use the desirable field distribution to figure out the possible magnet current density arrangement with the linear programming method. It is found that the optimal position of the coils is iterative, and in each iteration, a simplex search method is employed [3]. Obviously, many current density distributions can offer the same desirable field shape.

Figure 2 shows the initial contour of the solenoid current. The top half of this figure shows the main coil current density distribution and the bottom shows the bucking coil with reverse current to counteract the magnetic moment. The horizontal and vertical axis indicate the radial and axial direction of the quarter solenoid. This coil section cannot be fabricated easily; so the next step is to modify and reshape the coil section into a rectangular section. In this process, we can keep the total number of ampere turns at a constant value, in order to guarantee a small deviation of the stray field. After modification, the fringe field can be simulated in Opera-3D, the leakage field in 280 mm from the center is shown in Fig. 3 as follows.

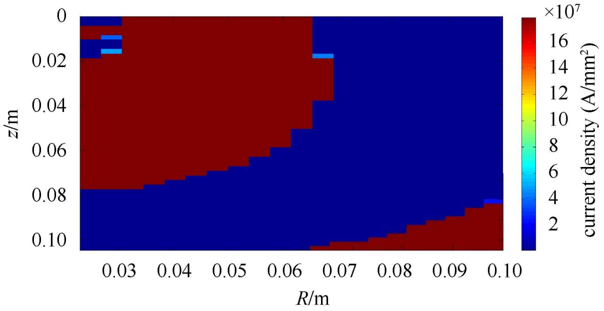

Fig. 2. The initial current shape of the half solenoid.

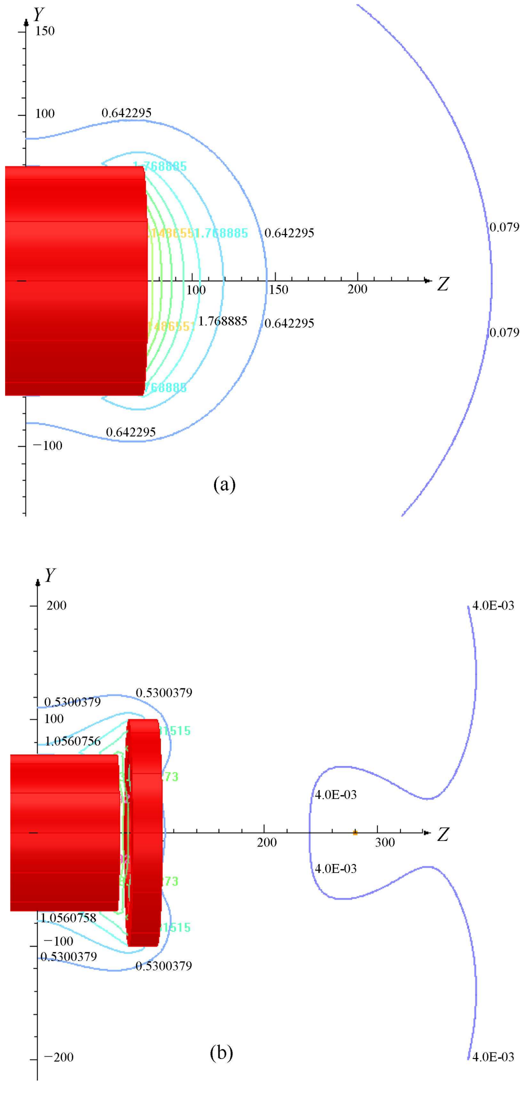

Fig. 3. Stray field with and without bucking coils.

Figure 3(a) shows the fringe field without bucking coils. The fringe field in the cavity zone is about 0.079 T. While active shielding is applied, Fig. 3(b) shows that in the cavity zone, the fringe field is about 4mT. This means the bucking coils can shield most of the main stray field.

2.2 The passive shielding

As we know, if a magnetic field is applied to the surface of a superconductor, then a screening current will be generated at the surface to oppose the applied field. Any magnetic field in the material will be expelled by the generation of screening currents. The field at the superconducting niobium material must be retained below 0.06 T to avoid exceeding the critical field of the niobium [5–7]. In theory, it would be more accurate to model the niobium layer shielding as perfect diamagnetism. Superconducting materials in the designs can be modelled as a vacuum when the material is in the normal state and as a perfect conductor in the superconducting state [3]. So a 3 mm thick niobium shield will be installed around the magnet to trap the field inside (the Meissner effect).

Passive shielding is quite different from Meissner shielding (perfect shielding) as it uses a highly permeable material to alter the path of the magnetic field lines which always travel from the *N* pole of the source to the *S* pole. Theoretical magnetic shielding formulae tend to describe the geometry of either spherical shells or infinite cylindrical shells, since these forms have a high degree of symmetry and are therefore easy to model. For a cylindrical shell with an inner radius *r* and outer radius *R* and of infinite length in a transverse field, the attenuation ratio can be calculated by [7]

$$A_{\mathrm{cyl}\infty\perp} = \frac{(\mu_r+1)^2(r/R)^2-(\mu_r-1)^2}{4\mu_r}+1,$$

$$\begin{aligned} A_{\mathrm{cyl}\perp}(\mu\to\infty) &= \frac{1}{4}\mu_r(1-r^2/R^2)+1 \\ &\approx \frac{1}{2}\mu_r t/R+1, \qquad (1) \end{aligned}$$

where μ_r is the relative permeability and thickness $t=(R-r)\ll R$. Cryoperm (a type of MuMetal designed for magnetic shielding at low temperatures) is used to further reduce the leakage field. The permeability of cryoperm increases sharply when the temperature is decreased, as its relative permeability is 65000 at 4.2 K, the saturation polarization is about 0.9 T, and the coercive force is 2A/m. The high permeability of this material provides a low-reluctance path for magnetic flux. If the attenuation of a single layer of mumetal is not ideal enough, we will increase the shielding performance by adding additional layers or increasing the thickness of the material. In practice, increasing the material thickness or layers, using a multi-material approach and orienting the shield to avoid a saturating field can be employed for passive shielding. For superconducting cavities, 2.5 μT can be retained by an attenuation factor of 20. A layer of cryoperm is also placed around each cavity for additional shielding of the magnet fields and the Earths field. The design sketch of the SC solenoid is showed in Fig. 4.

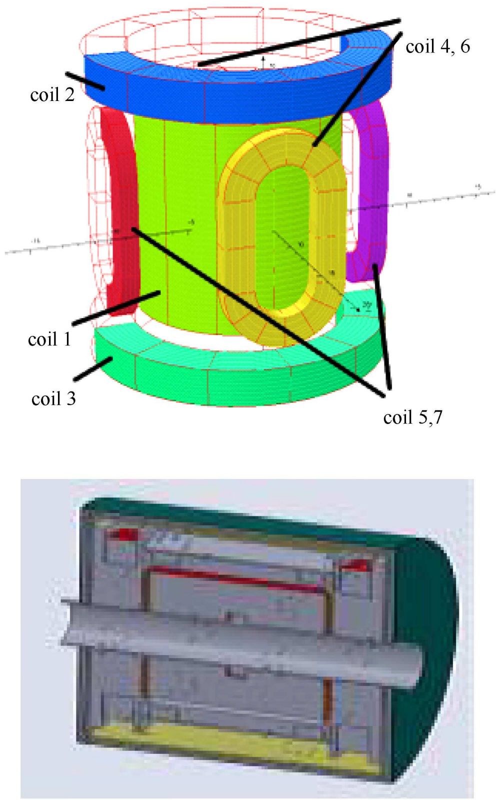

Fig. 4. The sketch map of the coils location and shielding layers.

3 Quench protection

The magnet is composed of 7 coils and operates in nonpersistent mode with a total energy of 27 kJ. Although the energy is not as enormous as typical NMR superconducting magnets, the quench protection system is still strictly necessary to prevent the magnet from being damaged. A passive protection system is adopted to protect the superconducting magnet from damage caused by quenching. Cold diodes are laid across the subdivision to reduce both the voltage and temperature of the hot spots [9]. The magnet is assumed to be in an open loop state with an operating current of 180 A. The coils will have 3 subdivisions, and each has a pair of back to back cold diodes in series with no dump resistor as shown in Fig. 5. The forward voltage of the high current diode (Model R620) is about 4.5 V.

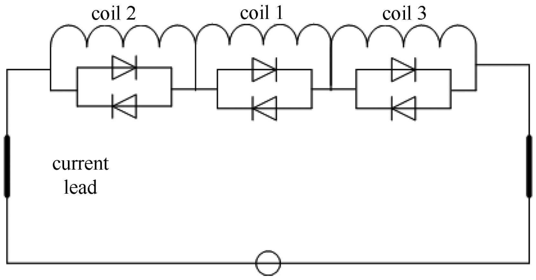

Fig. 5. Schematic diagram of the electric circuit of quench protection.

Computational simulations have been carried out on the Opera quench. In the simulation, both the ohmic heat from the normal zone and coupling current loss contribute to heating power. Before the quenching progress, the circuit, inductance matrix, boundary conditions, symmetry, initial current, heat flux and other conditions should be carefully set. In this simulation, we assume that the coil is applied in the highest magnetic field with the highest current quench first. Bucking coils 2, 3 and steering coils 4, 5, 6, 7 are affected by the electrical inductance matrix coupling and heat transfer. Fig. 6 shows the computational results obtained from the finite element model.

Figure 6(a) illustrates that the temperature goes up quickly in the first two seconds just after the quench happens, then the temperature stabilizes at 55.79 K. In the meantime, bucking coils 2 and 3 and steering coils 4, 5, 6 and 7 are still in a superconducting state as the temperatures stay below 4.2 K. In Fig. 6(b), it's clear that the coils resistance variation has a similar trend as hot pot temperature. The resistance value of coil 1 rises from 0 Ω (still in the superconducting state) to a final constant of 2.11 Ω, while other coils do not quench and their resistance remains zero. Fig. 6(c) and (d) show the current attenuation and voltage impact. The peak voltage of coil 1 is 37.64 V which then reduces quickly, this value is quite small compared with the typical security threshold value 200 V. This means that the design of quenching protection is quite reasonable.

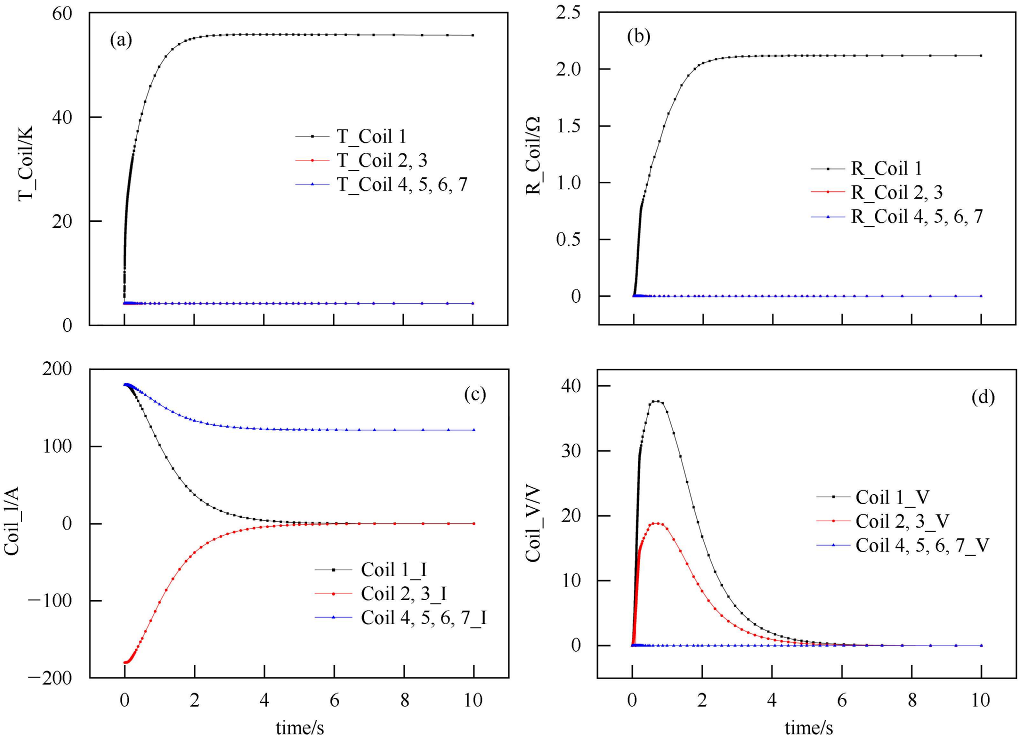

Fig. 6. Variation of temperature, resistance, current and voltage with time from 0 s to 10 s during the quenching progress.

4 Results

The bulking coils are designed to reduce the fringe field in the cavity region to make it sufficiently small to operate the cavities even at the peak solenoid field without quenching. The final design parameters are showed in Table 2.

Figure 7 shows the mechanical workings. The solenoid is now being manufactured at IMP, the main body has been completed and some accessories will be improved in future.

Fig. 7. The manufactured components.

Table 2. Parameters of the final SC solenoid design.

parameter	value
central field	7.18 T
effective length	143 mm
correction of integral	0.014 T·m
aperture diameter	44 mm
mechanical length	250 mm
fringe field after active shielding at 280 mm from center	40 Gs
fringe field after passive shielding at 280 mm from center	0.5 Gs
current density of main coil	180 A/mm^2
current margin	0.72

5 Conclusions

In this paper we discussed a magnet with a low fringe field using a two-step shielding method. In the active shielding step, we used linear programming to obtain an initial ideal coil arrangement and then to reshape the coil section to fabricate a rectangle shape. In the passive shielding step, both the shielding materials, Niobium and cryoperm are used as a Meissner shield and normal passive shielding. According to the proposed shielding method, a low leakage field magnet can be designed. The quench simulation indicates that a simple passive quench protection system can prevent damage as the storage energy of the magnet is not very big.

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