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Physical design of superconducting magnet for ADS injection Ⅰ*

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Abstract: A superconducting solenoid prototype magnet for Accelerator Driven Subcritical System (ADS) Injection Ⅰ has been designed and fabricated, which has also been tested in a liquid Helium state inside a vertical Dewar in the Haerbin institute of Technology in November 2012. The design current was 210 A, when the test current reached 400 A no quench occurred so the solenoid magnet was forced to quench by the embedded heaters. The integral field strength, leakage field at the nearby upstream and downstream superconducting spoke cavities all meet the design requirements. At the same time, it also checked the reliability of the vertical test Dewar and the quenched detection system. The superconducting prototype magnet has accumulated valuable experiences for the coming batch magnets production and cryogenic test.

Key words: superconducting magnet, cyomodule, quench detection, vertical test

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1 Introduction

The Accelerator Driven Subcritical System (ADS), using a proton beam hitting on the target to produce neutrons for spending fuel stable increment or accelerating evolution, aims at looking for key solutions for nuclear fuel stable provision and for safe nuclear waste treatment [1]. Fig. 1 is a schematic overview of ADS linac accelerator. The injection Ⅰ and the main linac will be designed and fabricated by IHEP. The spoke 325 MHz part in injection Ⅰ has two cryomodules, each one consists of six superconducting (SC) spoke cavities, five SC magnets and five beam position monitors connected along the beam line in a series. Fig. 2 shows the layout of these accelerator components inside the cryomodule. The proton beams will be accelerated from 3 MeV at the outlet MEBT1 to 10 MeV by these six SC spoke cavities. Each SC magnet, which indeed is a

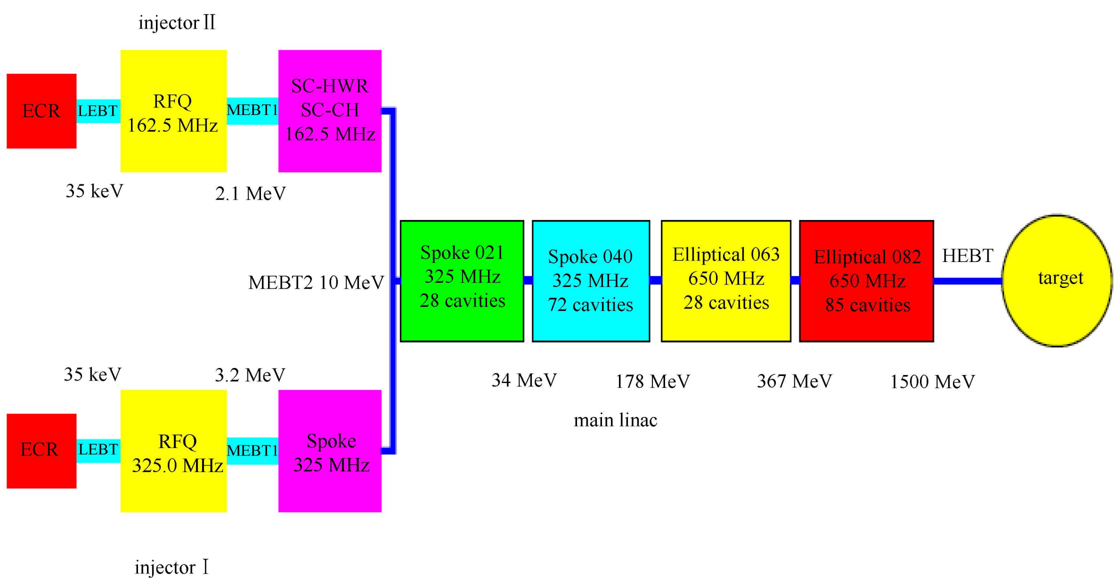

Fig. 1. Schematic overview of ADS linac accelerator.

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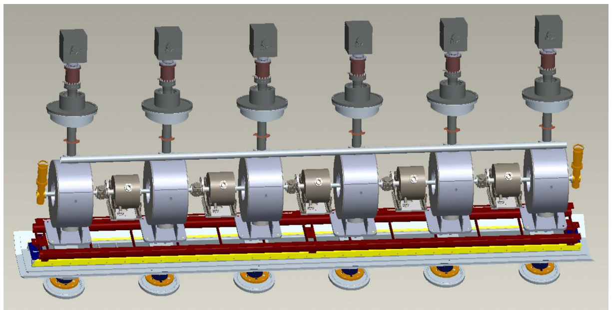

Fig. 2. Accelerator components inside the first cryomodule (along the beam line, the big one represents the superconducting spoke cavity, the middle one is the superconducting magnet, the small one is the beam position monitor).

magnet package aimed for beam focusing and orbit correction, contains a solenoid magnet, a horizontal dipole corrector (HDC) and a vertical dipole corrector (VDC). The integral field strength for the solenoid is 0.4 T-m, the maximum integral field for the HDC and VDC is 1600 Gs-cm.

2 Physical design of the superconducting magnet prototype

There is a SC spoke cavity each at upstream and downstream of the SC magnet. Leakage field, mainly coming from the solenoid, will add with the earth magnetic field and then affect the operation quality of the spoke cavity or even drive it to quench. The design aim for the leakage field reduction is to realize a less than 1 G field at the distance of 270 mm away from the solenoid center. The field inside the SC spoke cavity, with the extra magnetic shield made of high permeability permalloy covered, can be further reduced to less than 0.1 G.

At the design stage, three methods are hired to reduce the leakage field from the solenoid, they are: 1) using three solenoids with the main solenoid in the middle and a bucking solenoid at each end of the main solenoid to compensate for the tail field; 2) adding an iron return yoke surrounding these three solenoids to form the field return path; 3) with a high permeability permalloy tube covering the return yoke to reduce the small leakage field more efficiently. 2D and 3D OPERA [2] software are used to optimize the field calculation, Fig. 3 shows the 2D field calculation model for the solenoid, Fig. 4 shows the 3D field profile along the solenoid axis, the leakage field at 200 mm from the center is only 0.03 G. At the spoke cavity position 270 mm away from the solenoid center, the leakage axial field are 4.5×10^{-6} T with permalloy shield and 3×10^{-5} T without permalloy shield. The axial repulsive forces on two bucking solenoids bores are 4.7 kN, which must be eliminated by preload forces during the magnet assembly.

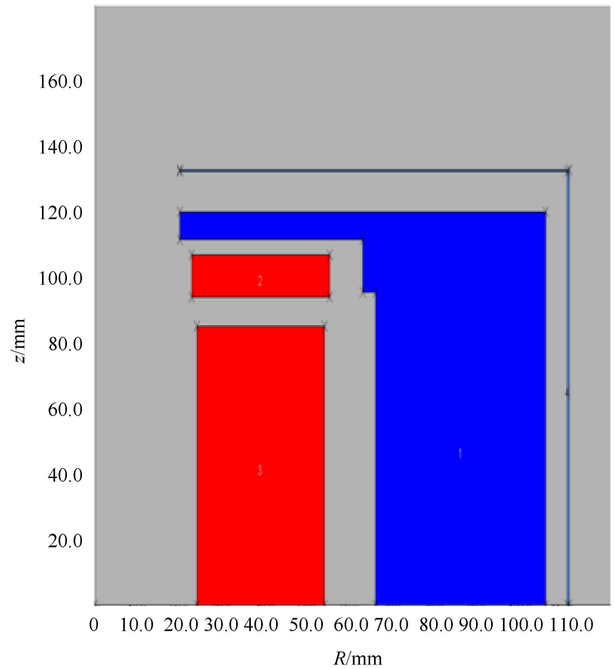

Fig. 3. 2D calculation model for the solenoid. An axis-symmetry half model is used; the proton beam is along the vertical direction (z-axis). From the center to the end are the main solenoid, the bucking solenoid, the iron yoke and the permalloy shield respectively.

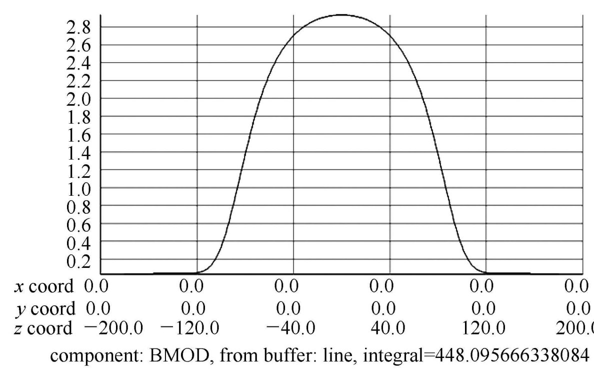

Fig. 4. 3D field profile along the solenoid axis, the leakage field at 200 mm from the center is only 0.03 G. Here, the unit for the x axis is in millimeters, y is in Tesla, z is in millimeters.

The SC cables used for the solenoid coils are Chinese domestic products, the Cu:SC ratio is 4:1，the critical current is 700 A at 6 T. The design operation current is 210 A, which has a high safety margin.

Tbe saddle shaped coil will be selected for HDC and VDC, which can save spaces and then reduce the magnet energy. Fig. 5 shows the 3D field calculation for the correctors. The coil first wound in a flat pattern, then wrapped around the support tube into a saddle shape.

Table 1. Design Parameters for ADS superconducting magnet prototype.

	main solenoid	bucking solenoid	HDC and VDC
dimension for SC cables	1.2 mm×1.8 mm	1.2 mm×1.8 mm	ϕ0.35 mm
Cu:SC ratio	4:1	4:1	0.67:1
maximum field on the coil	3.3	—	3.2
total turns	2208	182×2	60
layers/turns per layers	24/92	26/7	1/30
operation current/A	210	210	12
coil length/mm	170.2	13	—
current density $J_0/(\mathrm{A/mm^2})$	110	110	170
store energy E_0/kJ	2.6	0.02	0.002
inductance/mH	120	1.2	25
$E_0J_0^2/(\mathrm{A.J/m^4})$	6.0×10^{20}	—	—
$F(T_{\max})/(\mathrm{A.s/m^4})$	1.19×10^{16}	—	—
hot spot temperature/K	40	—	—

Superconducting wire with 0.35 mm in diameter and 0.67:1 for Cu:SC is used for winding the correction coils. The design current is 12 A and the critical current is 100 A at 3 T.

Calculation methods in Ref. [3] are used to determine the setting threshold for the quench detection time, which is 50 ms. Taking the solenoid magnet coil as an example, the maximum hot spot temperature inside the coil is 40 K, as shown in Table 1. Including the quench action time, the total quench protection time should be less than 60 ms.

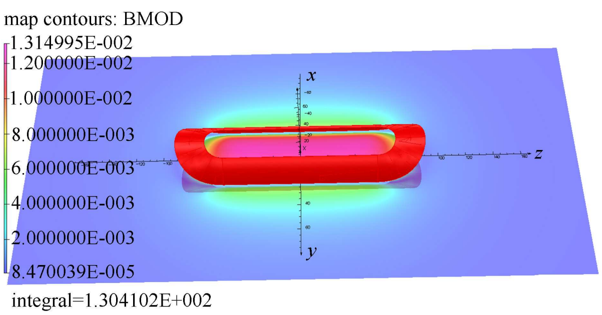

Fig. 5. 3D magnetic field calculation for the corrector. Here units for the x, y and z axes are all in millimeters, while the field strength is in Tesla.

3 Magnet fabrication and vertical test

Including the end connection flanges, the total length for the magnet is only 300 mm. In order to connect the upstream BPM flange, an asymmetric structure where the liquid helium vessel is 15.8 mm shifted to the spoke cavity side is selected for the magnet cryostat. The magnet cryostat is put inside the whole vacuum space of the cyomoudle, no liquid nitrogen shield is needed, and the beam vacuum chamber is also used as the coil support tube and as the inner liquid helium vessel. Fig. 6 shows the mechanical cross section view of the magnet cryostat. For easily shaping and fixing, the permalloy shield is immersed in the liquid helium space.

The bare magnet, where the outer liquid vessel is not welded on, will be tested in the 4.2 K liquid helium state for quench testing and field measurement. Fig. 7 shows the superconducting magnet hanging at the bottom of the test stand, here the whole top flange set is taken out from the vertical test Dewar in order for the magnet installation and signal wires connection.

An active quench protection scheme is selected for the ADS superconducting magnet. Quench testing was the first process after enough liquid helium accumulated inside the vertical Dewar feed by a cryogenic system. The excited current for the solenoid magnet successfully reached 400 A after several current steps without quench. No quench occurred after the solenoid operated at 400 A for 10 min. Then the solenoid was forced to quench by electrical heaters embedded in the inner layers of the main solenoid coil; the quench detection system was triggered in time. The informed power supply was cut off almost simultaneously at the same time; a 1.0 Ohm dumping resister was put into the quench protection circuit to keep the magnet in safety. Both the two corrector magnets reached 30 A without quench, which are much higher than the designed current.

Figure 8 shows the magnet undergoing a vertical test process; the field measurement platform was installed on the top of the vertical Dewar. The moving module, which sits on the top of the vertical test Dewar, pulls a 3D hall probe moving in an isolated warm bore tube in every 1 mm step vertically, the maximum moving distance is 460 mm. The test results show that the solenoid integral field is 0.3810 T·m at 210 A, which is smaller than the designed value, since the measured rod where the hall probe was put in is not long enough to cover the tail of the solenoid field. For leakage field, including the earth field, the axial field is only 0.8 G at 200 mm away from the magnet center, which is much lower than the

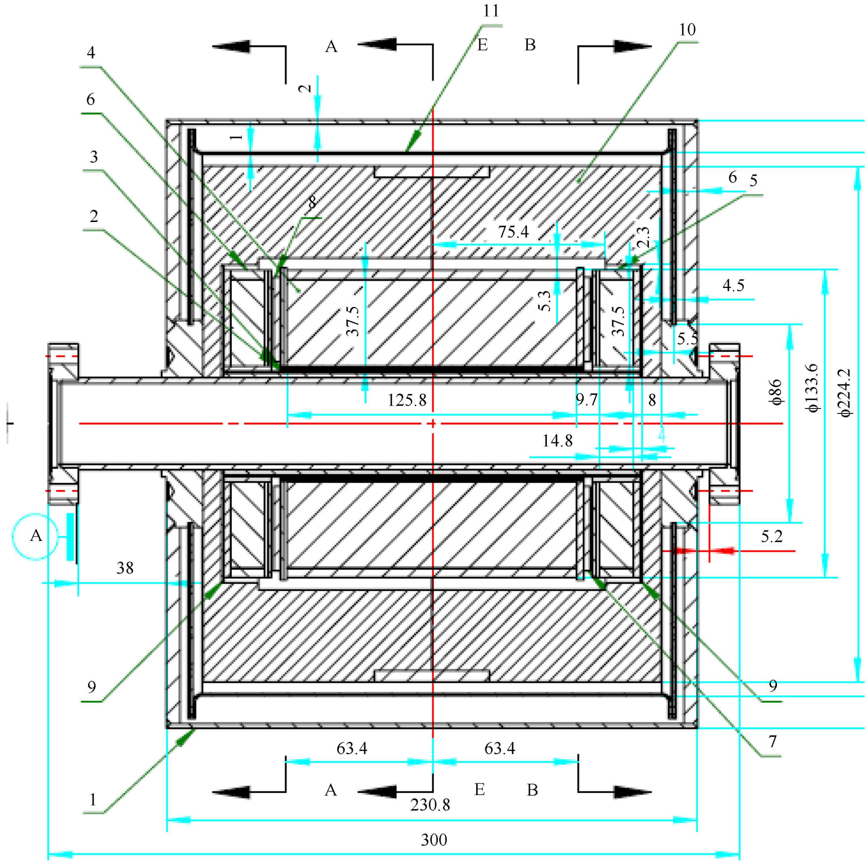

Fig. 6. Cross section overview for the superconducting magnet cryostat.

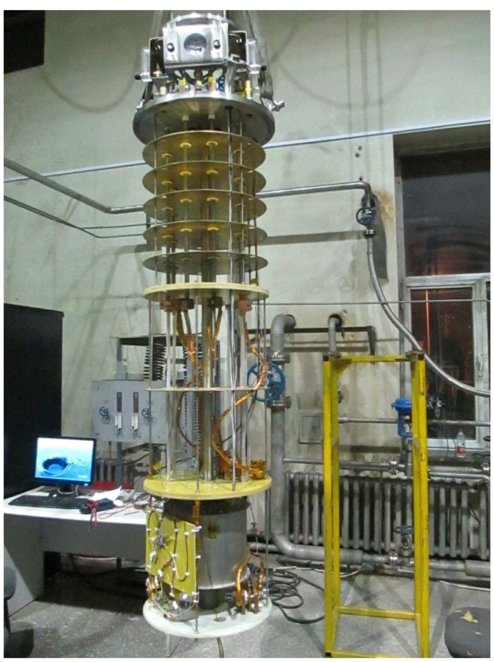

Fig. 7. Superconducting magnet installed at the bottom of the vertical test stand (the superconducting joints are welded and fixed on the G10 board).

Fig. 8. Ongoing vertical test for the superconducting magnet.

requirement. The field at the spoke cavity position, the field will be dropped much lower. A more detailed measurement process will be done in the horizontal test.

4 Design improvement for the batch magnet production

A total of 12 SC magnets will be fabricated and tested for injection Ⅰ. From the prototype magnet design, coil winding, installation and vertical testing, several problems should be solved before batch magnet production. The permalloy magnetic shield tube will be removed since it is not easily machined and assembled, the small place between the iron yoke and the permalloy shield is difficult for SC cables and signal wires pulling through. For a better leakage field reduction effect, the iron yoke will be extended to the previous permalloy position for more iron to confine the leakage field. Fig. 9 shows the new 2D design scheme, the calculation result is better than that of the prototype magnet. 3D magnetic calculation was done for consideration of the holes on the return yoke for cables and cryogenic channels; the used calculation model is shown in Fig. 10. Small dimensions with a cross section of 0.55 mm×0.85 mm SC cable will be used for the solenoid coil winding in order to reduce the heat load to the cryogenic system. The main solenoid coil was shortened and the peak field was increased to 4.5 T, but is still in a high safety margin.

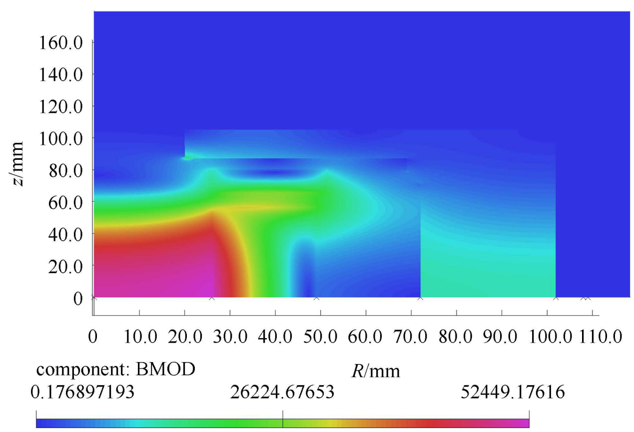

Fig. 9. 2D field profile for the batch magnet (the calculated current is 20% higher than the design value).

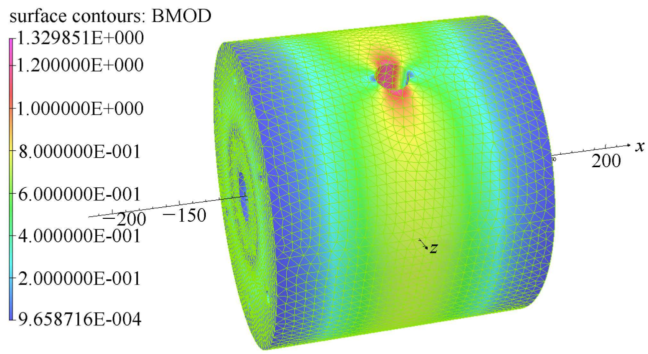

Fig. 10. 3D field calculation model for the batch magnet. Here the unit for the x axis is in millimeters.

5 Conclusion

A superconducting magnet prototype for ADS injection Ⅰ linac has been designed, fabricated and tested. The reliability of the vertical test Dewar and the quenched detection system have been checked at the same time. We have accumulated valuable experiences and directions for the batch magnets production and cryogenic test. Some modifications will be taken for future batch magnet production, which include reducing the design current, removing the permalloy shield and prolonging the iron yoke.

References

1 Future Advanced Nuclear Fission Energy-Plan Implement Book for ADS Evolution System (in Chinese), 2010

2 Opera Manager User Guide (manual), Version 14R1, Vector Fields Software, July 2011

3 GREEN M A, WITTE H. Quench Protection and Magnet Power Supply Requirements for the MICE Focusing and Coupling Magnets. Oxford Physics Engineering Report 15, LBNL-57580, 2005