Field measurement for superconducting magnets of ADS injector Ⅰ

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Abstract: A superconducting magnet prototype for Accelerator Driven Sub-critical System Injection-Ⅰ had been designed and fabricated, and tested in a new made vertical Dewar in November 2012. Batch magnet production was processed after some major revision from the magnet prototype, they include: removing off the perm-alloy shield, extending the iron yoke, using thin superconducting wire, etc. The first one of the batch magnets was tested in the vertical Dewar at the Harbin Institute of Technologyin in September 2013. A field measurement was carried out at the same time by the measurement platform that was seated on the top of the vertical Dewar，the measurement results met the design requirements. This paper will present the field measurement system design, measurement results and discussion on the residual field from the persistent current effect.

Key words: superconducting magnet, vertical test, residual field, persistent current effect

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1 Overview of ADS superconducting magnet

The Accelerator Driven Sub-critical System (ADS) is based on the superconducting accelerating structure, the purpose of which is to realize the safe disposal of nuclear waste [1]. The lattice structure for the injection-Ⅰ was designed by IHEP and described somewhere [2]. The physical design of the superconducting magnet prototype for ADS was designed by the Institute of High Energy Physics (IHEP) and tested at the Harbin Institute of Technology (HIT)[3]. Each superconducting magnet, aimed for beam focusing and beam orbit correction, contains a solenoid magnet, a horizontal dipole corrector (HDC) and a vertical dipole corrector (VDC). The designed integral field for the solenoid is 0.4 T·m, and the maximum integral field for HDC and VDC is 1600 G·cm. Fig. 1 shows the cross section of the magnet prototype, the solenoid field is realized by the main solenoid coil, the two bucking solenoid coil, and the iron return yoke, an extra permalloy tube covering the iron yoke is used to reduce the leakage field further. The final design value for the magnet prototype, the leakage fields at 270 mm away from the solenoid center are 0.045G with permalloy shield and 0.3 G without permalloy. The two correctors are wound inside the main solenoid coil, they are selected as saddle shaped coils in order to save space and hence to reduce the total store energy of the magnet. The support tube, where the superconducting coils wound on, also serves as the beam vacuum chamber and as the inner helium vessel.

In order to know the magnetic field performance at several operation currents, a vertical test system was fabricated in 2012, it had been used to test the magnet prototype and the first magnet batch was tested in November 2012 and September 2013 respectively [3].

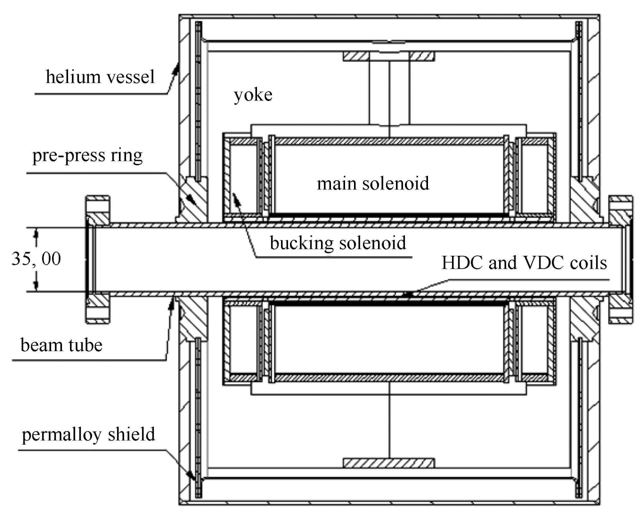

Fig. 1. Schematic overview of the superconducting solenoid magnet prototype.

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2 Vertical test system

2.1 Overview of the vertical test Dewar and the measurement platform

Figure 2 shows the assembly structure of the top flange components, on the top of the top flange the moveable measurement platform is seated on. The bare superconducting magnet, where the outer helium vessel is not welded on, will be fixed on the hoisting flange vertically. The isolation tube, which is really a two concentric 316L stainless tubes to form a vacuum space in between, can realize the thermal isolation from liquid helium state to room temperature state. The superconducting magnet should be installed on the hoisting flange vertically and keep the support tube with the isolation tube coaxially. Fig. 3 shows the schematic layout of the field measurement platform. A three axis Hall probe, which is embedded at the end of the measuring tube, can move vertically inside the isolation tube with a maximum distance of 460 mm. The movement module, which as a whole is driven by a servo motor, could pull the measuring tube inside the isolation tube up and down with the setting steps. To keep the isolation tube and the measuring tube coaxially, the measurement platform can be adjusted in horizontal manually. Another function of the measurement platform is that it can realize the rotating coil field measurement when the measurement tube is replaced by a rotating coil.

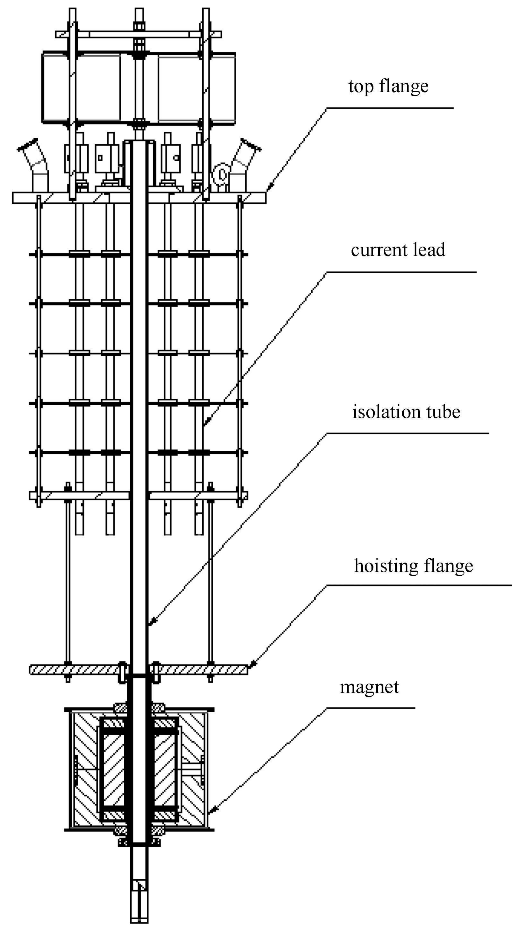

Fig. 2. The assembly structure of the top flange components.

2.2 Hardware of the measurement system

The measurement system is realized in a half-closed loop control. A grating ruler, which is glued on the side of the measurement platform, can give the moving distance in a precision of 0.5 microns. The measurement platform was controlled by an EMAC controller, it communicates with the computer via an Ethernet cable. The movement orders, which are sent from the computer to the EMAC controller, are then amplified by the servo driver and sent to the servo motor to pull the three axis Hall probe to move vertically. A domestic made CH-3600 gauss meter, with an accuracy of 0.15% and measurement range of 10T, has been calibrated with temperature compensation. The importance of which is that the isolation tube is far below the room temperature since the cold radiation from the liquid helium in the vertical Dewar. Helium gas is blown from the top of the isolation tube to get rid of ice forming inside the tube.

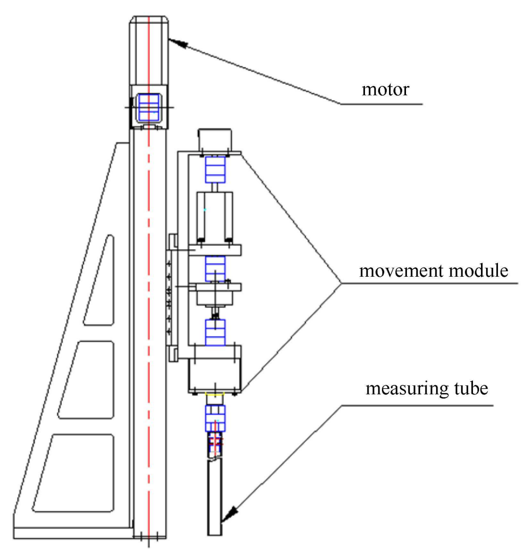

Fig. 3. Schematic layout of the field measurement platform.

2.3 Software design of the measurement system

The measurement software was written in VC++ 6.0, which includes: system initialization, servo motor control module, data acquisition and data storage.

The system initialization is to realize the connection between the computer and EMAC controller, the connection between the computer and the gauss meter. The computer reads the measurement field data from the gauss meter through the RS232 serial port. The total moving distance, moving distance for each step, moving velocity and acceleration of the servo motor are set all together. The minimum time delay requirement for the Gauss Meter and a stable reading for the Hall probe have driven us to set the time stop in each measurement step as 3 s.

Data acquisition is carried out after system initialization. The measurement process starts from the original point which is set by the grating ruler, where the series measurement positions are made by the servo motor and read out by the grating ruler. As the Hall probe moves to the setting position, the delay program is executed, and magnetic field data from the three data channels are obtained by the computer after the data reading instructions are sent to the Gauss Meter. The data judgment in the software helps to ensure that data collection is completed and data format are correct before moving to the next step. All the measurement data and the real positions of the Hall probe will be displayed and stored in a file in real time.

When a test procedure is finished, the measurement module will then go back to the original position automatically by click the back to the zero button and going on to the next measurement sequence.

3 Field measurement results

Magnetic field distribution of the magnet is crucial to examine the magnet design and for beam commissioning. Field measurements for the first of the batch magnets were made in HIT in September 2013. Fig. 4 showed the vertical test stand, where the field measurement platform is seated on top of the vertical Dewar.

In order to eliminate the influence from the cold temperature, the Hall probe together with the measuring tube was put into the isolation tube for some time before the magnet excitation. After the temperature of the Hall probe was consistent with the test environment, the measuring tube was pulled out from the vertical Dewar. The Hall probe was then shielded magnetically by a perm-alloy tube and reset to zero for each channel manually.

3.1 Solenoid field performance

The quench performance test showed that the operation current of a solenoid magnet can finally reach above 300A after three times of natural quenching (260 A, 268 A, 308 A) during the current ramping. The combined field excitation was successfully withstood, the solenoid operated at 230 A, the two correctors operated at 20 A. The field measurement test was going at 50, 100, 150, 182, 210 A for the solenoid in the moving distance of 460 mm with 230 steps. Fig. 5 showed the central field B_0 and the integral field for the solenoid at the measurement currents. It was found that the locations of the maximum field at different currents were not consistent, the maximum difference was about 5 mm at the low current compared with that of at the high current, the reason is not made clear yet. It was also exhibited that the central fields nearly keep a linear relationship with the currents, no saturation was found in the iron yoke for the whole current excitation process.

Fig. 4. Vertical test for the superconducting magnet.

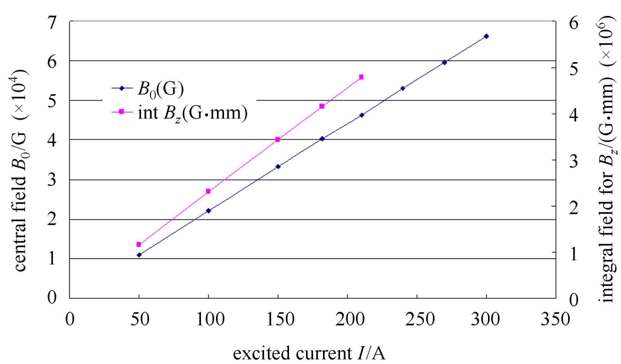

Fig. 5. Central fields and integral fields for the solenoid at several measurement currents.

The designed operation current for the solenoid is 182 A. In order to reduce the measurement error, the magnetic fields were measured for two times. Fig. 6

shows the axial field profile at 182 A. The difference between the two measurement results is less than 0.1%. The integral field is 0.416 T·m. The leakage field is less than 1G at the distance of 270 mm away from the solenoid center, which meets the requirements from the upstream and downstream spoke cavities.

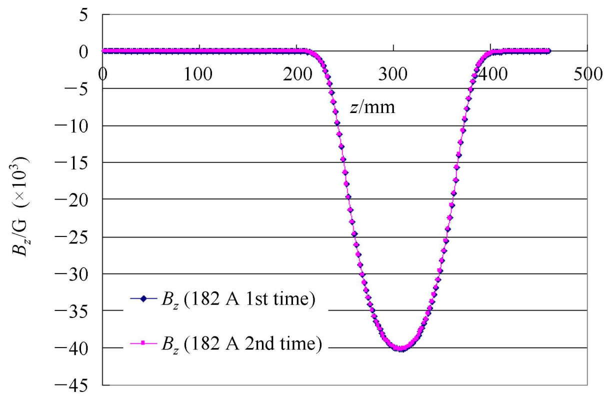

Fig. 6. Axial field (B_z) distribution for the solenoid at 182 A.

3.2 Magnetic performance of the correctors

Figure 7 shows the field profile of the HDC at 10 A, in its maximum operation current. The measured integral field is 2355.7 G·cm which is far above the designed 1600 G·cm. Compared with the solenoid field as shown in Fig. 6, the field profile for HDC as shown in Fig. 7 has a longer flat pattern, the reason is that the HDC corrector has a longer coil that covers the overall length of the main solenoid and the bucking solenoids.

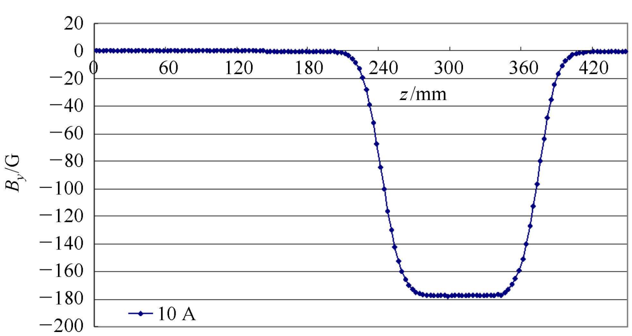

Fig. 7. Field profile of the HDC at 10A.

3.3 Discussion on the residual field from the solenoid

Residual field of the solenoid field was measured when the solenoid current ramp down to 0 A, Fig. 8 shows the Residual field profile along the beam line. The maximum axial field at the main solenoid is −69 G, where the peak field at the bucking solenoid is 60 G. An important issue is that the field integral for the residual field near to zero, is similar to that of the High Intensity Neutrino Source (HINS) magnet [4]. That is to say, the magnet will affect the proton beams a little when one of the solenoid magnets quenches.

The superconducting wire used for the solenoids is from a German company, it contains 36 filaments

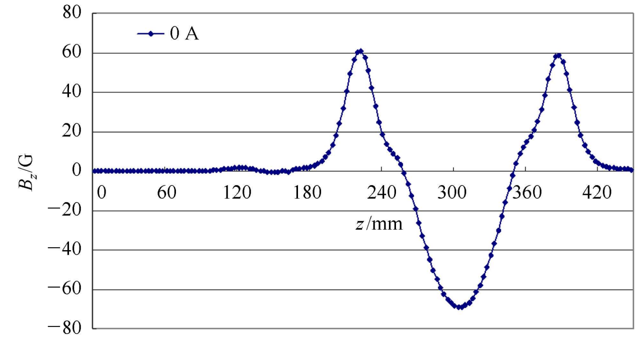

Fig. 8. Residual field distribution of the solenoid.

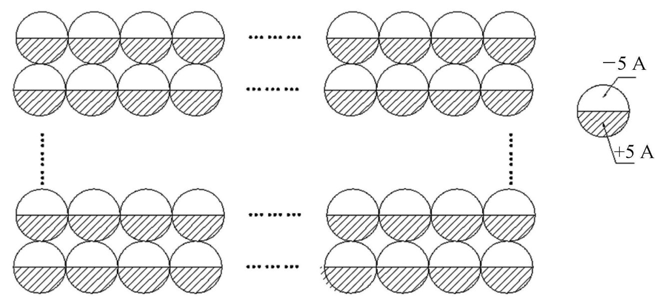

Fig. 9. Added principle for the residual field calculation.

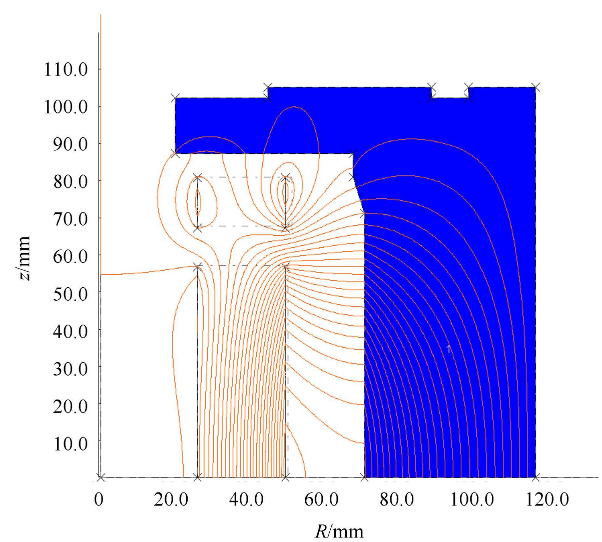

Fig. 10. OPERA-2D model for the residual field calculation. The two upper regions represent the current sheets for the bucking solenoid, whereas the two lower regions are the current sheets for the main solenoid.

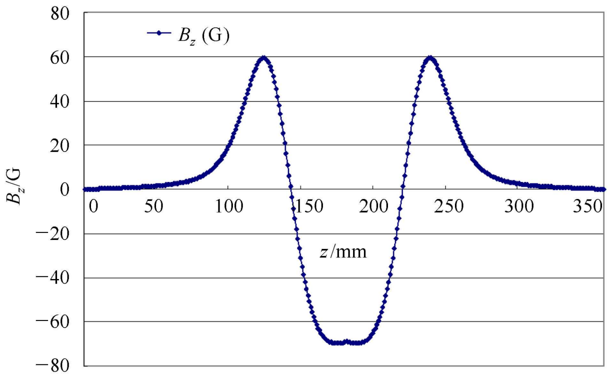

Fig. 11. Residual field calculation result for the solenoid.

with each 84 microns in diameter in a cross section of 1.32 mm×0.85 mm, the Cu:SC ratio is 4:1. The persistent current will be formed in each filament during the current ramping process, and last several hours even if the magnet power supply is switched off [5]. Each filament will be fully magnetized by the Meissner effect when the applied outer field is higher than 0.66T by calculation in the coil region, which is easily met during the current ramping. Each filament will carry a current of 5.5A in its two circle halves with the opposite direction, and form a small magnetization of 0.1T. Since superconducting wire consists of 36 filaments, the field contributions from the opposite currents in the two adjacent filaments will be cancelled in the radial direction, but in the axial direction their contributions by the two adjacent filaments will be added. More generally, they can be extended to more layers. Fig. 9 shows the added principle for the residual current carrying filaments in the superconducting wires layer by layer. For simplicity, the residual field from the solenoid coil can be regarded as two thin layers carried with opposite current directions, and can be calculated in the current sheet model, similar to the field from a permanent magnet [6]. Fig. 10 shows the residual field calculation model for the half length of the solenoid by using OPERA-2D [7]. Fig. 11 shows the calculation results, the integral field for on axis B_z nearly to zero.

4 Conclusion

The superconducting magnet prototype and one of the batch magnets for ADS have been tested by using the dedicated measurement platform. The measurement results agree with the design requirements in its integral field and leakage field for the solenoid magnet. The vertical test has accumulated valuable experience in quench detection and field measurements, and will give valuable directions for the subsequent horizontal test. Beyond that, the study on the persistent current effect lets us know the residual field analysis has no impact on the passing proton beams when one of the superconducting magnets quenched.

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