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H. YAMAOKA, A. YAMAMOTO, Y. MAKIDA, N. KIMURA, K. TANAKA,
H. HIRABAYASHI, R. RUBER, H. CALEN, N. TAKASU, T. DOI and S. ABE

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A Thin Superconducting Solenoid Magnet for the WASA Detector

H. Yamaoka, A. Yamamoto, Y. Makida, N. Kimura, K. Tanaka and H. Hirabayashi*
National Laboratory for High Energy Physics (KEK), Tsukuba, Japan,

R. Ruber and H. Calen
Uppsala University, Uppsala, Sweden,

N. Takasu, T. Doi and S. Abe
Nippon Kokan, Co. Ltd. (NKK), Kawasaki, Japan,

Abstract - A thin superconducting solenoid magnet has been developed for the WASA detector. The magnet consists of a pair of coils and it provides a central magnetic field of 1.3 Tesla at a 900 A in a cylindrical volume of $0.65 \text{ m}\phi \times 0.555 \text{ m}$. The features of this solenoid magnet are excellent transparency for particles, conducting cooling, thermo siphon method, applying aluminum strip for conduction cooling and corrugated outer wall. Recently, the performance test was successfully carried out. In this report, magnet design and fabrication of the WASA superconducting solenoid magnet will be presented and the test results will be described.

1. INTRODUCTION

A thin superconducting solenoid magnet for the WASA detector is being prepared for particle physics experiments at the CELSIUS proton storage accelerator ring at Uppsala University in Sweden [1]. The superconducting solenoid magnet provides a central magnetic field of 1.3T at a nominal current of 900A. As one of the most important requirement on the experiment, transparency has to be kept as minimized as possible. The solenoid coil was fabricated by using aluminum stabilized superconductor associated with conducting cooling technique [2, 3]. The cryostat outer-wall was fabricated by using corrugated cylinder and it has a high rigidity in spite of its light in weight. Based on those designs, the overall thickness was minimized to 0.18 radiation length, the transparency for particles

A magnet performance test was carried out. The magnet cooling was made by indirect cooling and thermo-siphon technique as same as the practical situation. The maximum current of 950A was successfully achieved. The magnet design, fabrication and test results are described in the following section.

2. MAGNET DESIGN

A. General Design

The design for WASA superconducting solenoid magnet was started from the initial design conditions of a 1.3 Tesla of central magnetic field with a mean coil radius of about 280mm

and a coil length of about 420mm. Additionally, this magnet is required to have a hole for hydrogen pellets to pass as target through the magnet at the axial center. An overview of the WASA superconducting solenoid magnet is shown in Fig. 1. The CsI, crystal for a calorimeter, is located radially outside of magnet with keeping only a few mm of tolerance. The coil consists of a 4 layers of solenoidal coils wound with Al stabilized NbTi/Cu superconductor with pure aluminum strips at both inner and outer sides of the coil. A load line for the WASA coil is shown in Fig. 2. Since the critical current at 2T is 1415A, a temperature margin is to be 1.2K at an operating temperature of 4.5K. Main parameters of the WASA superconducting solenoid magnet are summarized in table 1.

B. Coil Design

In order to minimize the coil thickness as thin as possible, a ratio of stored energy over effective cold mass (E/M) needs to be high. This influence is appeared when the magnet quench

TABLE 1
Main parameters of the WASA superconducting solenoid.

Cryostat:	Inner radius	245.0mm
	Outer Radius	325.0mm
	Total length	555.0mm
Coil:	Inner Radius	276.8mm
	Outer Radius	288.8mm
	Total length	465.0mm
Coil + Outer support cylinder		7mm+2mm
Electrical parameters:	Central field	1.3T
	Nominal current	900A
	Inductance	0.3H
	Stored energy	121.5KJ
	E/M	6kJ/kg
Mechanical parameters:	Cold mass	20kg
	Total weight	31kg
	Radial mag. press.	1.12MPa
	Axial comp. force	0.16MN
Superconducting wire:	Conductor	NbTi/Cu
	Stabilizer	Pure Al
	RRR in Pure Al	>1500
	NbTi:Cu:Al	1:0.89:6.4
	Outer dimension	1.2mm×1.8mm
	I _c (@2T,4.2K)	1415A
	Insulation	Formbar

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H. Yamaoka, yamaokah@kekvox.kek.jp, fax +81-298-64-2580

* Present address : Fusion Science Laboratory, Toki, Gifu, Japan

Fig.1 Configuration of the WASA superconducting solenoid magnet.

occurs. To evaluate the magnet quench behavior, the computer simulation was carried out by using Quench code [4]. Fig. 3 shows a result of the quench simulation in case of no energy extraction. And it assumed that the magnet quench was initiated at the magnet center. Since a ring for the pellet hole is located at the magnet center, two cases of quench behavior is expected. The magnet quench propagate into only a half coil or into both coils. The maximum temperature after magnet quench is computed to be 120K and 100K, respectively. Therefore, this coil configuration is reasonably safe enough. In this calculation, effectiveness of pure-Al strips has been verified. It was understood the pure-Al strips may minimize a temperature difference at 100K after quench [2, 3].

Fig.2 Result of quench simulation for the WASA solenoid.

The calculated magnetic force is to be a 45MPa in equivalent maximum stress resulting in a deformation of 0.2mm in radial direction. Since the yield strength of the conductor is 107MPa, this stress level is sufficiently small. Iron yoke structure for the WASA detector is axially asymmetric and the axial magnetic center is not corresponding to the physical center. Therefore, it was designed that the magnet can withstand sufficiently against 5.1kN per 10mm axial movement due to decentering force [5].

C. Cryostat Design

In design of the outer vacuum shell, a corrugated structure was chosen from the viewpoint of weight reduction ratio. The shell was made of high strength aluminum alloy (JIS A5083-O). It has a tensile strength of 295MPa and a yield strength of

Fig. 2. Load line for the WASA coil.

TABLE2. Radiation thickness of each component.

Elements	Effective thickness(mm)	Radiation length(X_0)	
		X_0 /mm	X_0
Outer vacuum wall	1.0	0.0112	0.011
Outer 80K shield	0.5	0.0112	0.006
Outer support cylinder	2.0	0.0112	0.022
High purity Al strip	0.4	0.0112	0.0045
Al wire(NbTi/Cu)	5.2	0.0208	0.11
Insulation	1.15	0.007	0.008
Total			0.18

150MPa, respectively. A design criterion of the buckling pressure was 0.2MPa. Evaluations were carried out by using finite element method and it resulted in a buckling pressure of 0.28MPa at a 1mm thick corrugated wall. The maximum stress on the cryostat was calculated to be 63MPa with a deformation of 0.15mm. The weight reduction ratio of the outer vacuum shell could be minimized by factor of 0.37 compared with that of solid plate. A radiation shield with a thickness of 0.5mm was provided to minimize radiation load. An overview of radiation thickness of the WASA magnet is given in table 2.

D. Cryogenic Design

For liquid helium circulation, thermo siphon technique has been chosen. The coil is cooled by the thermal conduction through the magnet support structure. The cooling tube is brazed with one pass at one axial end of the coil. The estimation of thermal load in steady state is given in table 3 [6].

The magnet is indirectly cooled by using a helium refrigerator with a mass flow capacity of 0.198g/s for liquid helium requirements of 0.02g/s for the coil and chimney, 0.037g/s for the 80K shield and 0.059g/s for current leads.

3. FABRICATION

A temporal bobbin was used for the coil winding. The superconducting wire is wound on the temporal bobbin and surrounded by glass-kapton-glass tape(GKG) as layer insulation. A photo taken during the coil winding is shown in Fig. 4. Finally, an outer support cylinder was assembled by using shrink fit technique. A mechanical bonding strength of

Fig. 4. Photo taken during the coil winding using tempolary bobbin.

5MPa in epoxy-resin was verified with sample measurement. After the coil curing, the temporal bobbin was taken out.

In the fabrication of the cryostat, very careful process was required because of a 1mm thick corrugated outer wall as shown in Fig. 5. The fabrication of corrugated outer wall are processed in three steps; (1) cylinder by rolling, (2) corrugation process by variegation and (3) butt welding.

During the cryostat fabrication, a leak tightness and deformation under the vacuum condition were verified. Radial deformation of the cryostat after evacuation was measured to be about 0.14mm, and it was consistent with the design value.

4. PERFORMANCE TESTS

The magnet test by using a indirect cooling and thermo siphon technique has been carried out to verify the magnet performance. The different point between the practical situation is only setup configuration of the coil. The coil is placed vertically in a cryostat, instead of in horizontal position.

To cool down the magnet, it took two days including LN₂ pre-cooling. During the magnet cooling, the temperature difference was kept within 10K. LN₂ amount of 36 liters was spent for precooling. Total required liquid helium was 288 liters. When the transition to the superconducting state oc-

Fig 5. Cryostat for the WASA solenoid during leak test.

TABLE 3. Estimation of the termal load.

		Q(80K)W	Q(4.2K)W
Coil	Radiation	2.92	0.011
	Conduction	3.59	0.096
Chimny	Radiation	0.27	0.0056
	Conduction	0.45	0.028
Insulation			0.1
Dewar	Radiation	3.13	0.066
	Conduction	1.31	0.082
Others		3.27	0.449
Total		14.94	1.00

Fig. 6. Hoop strain at the magnet center.

curred at 9.2K, RRR of aluminum stabilizer was measured to be 1500. This number is consistent with the specification of the superconductor.

In the steady state condition, the required liquid helium was 6.6 l/h. Mass flow rate from the radiation shield and current leads were 28 l/min and 20.5 l/min, respectively [7].

A nominal current of 900A was successful achieved. The maximum ramp rate to reach 900A was 1000A/min. The maximum excitation current was 950A. A hoop strain at the magnet center was measured 600μstr at 950A as shown in Fig. 6. This strain level is within the elastic range. Others strain in the circumferential direction were measured to be between 300μstr and the 400μstr during excitation up to 900A.

The fast excitation test at a various ramp rate have been carried out to measure the observe dependency. The ramp rate was changed between 100A/min and 1600A/min. The maximum temperature in the coil is raised according to increasing of ramp rate. At a ramping rate of 1600A/m, the maximum temperature was raised to 6.7K at the coil upper part. From the correlation of coil voltage during excitation and ramp rate, an inductance was also calculated to be 0.3H.

A set of heater quench tests were carried out to understand the quench behavior such as quench threshold energies and peak temperatures. The highest current for the heater quench test was 900A. In this test, the current decayed within 1.3 seconds. This result was consistent with the quench simulation shown in Fig. 3. Since the correlation between the enthalpy of aluminum and a 65K of measured average temperature, it was agreeable that a 6kJ/kg enthalpy was dumped into the coil. A summary of heater quench test is given in table 4.

5. SUMMARY

TABLE 4. Summary of the heater quench test

Current	Location	Input energy	T(Peak)	T(Average)
600	Center	7.9W - 1.44sec	61K	50K
800	Center	5.1W - 1.34sec	76K	60K
900	Center	3.5W - 1.40sec	88K	65K
600	End	6.5W - 1.20sec	74K	52K
800	End	4.0W - 1.44sec	84K	61K

Fig. 7. Comparison table of E/M ratio with others solenoid magnet.

The WASA superconducting solenoid magnet has to be as thin as possible and still allowing a safe and stable operation. It includes an aluminum stabilized coil with a conduction cooling and a corrugated structure on the outer cryostat wall. From the successful excitation test, the performance of the magnet has been verified. The current reached 900A where the total stored energy was safety dumped into the coil after a heater induced quench. As the result, the transparency of 0.18X₀ has been achieved with an E/M ratio of 6kJ/kg. The E/M ratio comparison with other solenoid magnets for high energy physics experiments is shown in Fig. 7 [8].

The WASA magnet is now in the process of the final assembly. After completion, the final test is planned, and the magnet will be installed into the WASA detector system.

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REFERENCES

- [1] Calen et al, Proposal for a detector at CELSIUS from the WASA collaboration, PAC proposal, TSL, 1987.
- [2] A. Yamamoto et al, Conceptual design of thin superconducting solenoid for particle astrophysics, IEEE Trans. MAG, 1988, p. 1421.
- [3] Y. Makida et al, Performance of a thin superconducting solenoid for particle astrophysics. Adv. Cryog. Eng. 1991, p. 401.
- [4] M. Wilson, Superconducting Magnet, Oxford Univ. press. 1983.
- [5] R. Ruber et. al., Calculation on the New Yoke Design, WASA memo, 1992.
- [6] R. Ruber et. al., The Design of a Superconducting Solenoid for WASA, WASA report, 1993.
- [7] R. Ruber et. al., Superconducting Solenoid Test, December 1994, WASA memo, 1995.
- [8] Particle Data Group, Review of particle properties, Phys. 1, Rev. D, Vol 50, No. 3, 1994, p.1265 -1266.