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Abstract --- A prototype thin superconducting solenoid magnet has been developed to verify technical feasibility of an advanced thin superconducting solenoid magnet with a magnetic field of 2 T in a cylindrical volume of 3.4 m ϕ x 9 m and with a transparency of 1.2 radiation length (X_0). The magnet is required to have a stored energy / effective cold mass (E/M) ratio of 7.5 kJ/kg. The technical goal has been successfully achieved with realizing E/M=9.6kJ/kg as a result of the prototype R&D. The prototype development and test results are presented.

I. INTRODUCTION

A prototype thin superconducting solenoid magnet was developed to verify technical feasibility of the SDC thin superconducting solenoid magnet, which was planned to be built in the SSC project [1]-[2]. The SDC solenoid was required to provide 2 T in a room temperature bore of 3.4 m ϕ x 8.8 m with an overall magnet-wall transparency of 1.2 radiation length (X_0) in the transverse (radial) direction. The net coil transparency should be 1 X_0 or less. In terms of electromagnetic force, the SDC solenoid was required to sustain under a radially internal pressure of 1.6 MPa and an axial compression of 13 MN because of iron yoke locating far (0.6m) from the coil end. To meet those requirements, the following technical advances have been intended.

E/M ratio of 7.5 kJ/kg: A ratio of stored energy of the magnet to the effective cold mass was considered [3]. A ratio of 7.5 kJ/kg extended from the ~5 kJ/kg in existing thin solenoids was taken with allowing the averaged coil temperature rise up to 75 K, even in case of full energy dump into the coil. It is simply explained by using enthalpy, H, as follows[2]:

$$E/M = H(T1) - H(T2) = \sim H(75 K) = 7.5 \text{ kJ/kg.}$$

Strong aluminum stabilized superconductor: Strong conductor with a yield strength $\sigma_{0.2}$ of >70 MPa at 4.2 K has

been required. In combination of hoop stress, σ_ϕ and axial stress, σ_z , the maximum shearing stress 2τ induced inside the material itself was considered. With assuming elastic condition, $\sigma_{0.2}$ should be larger than 2τ in the conductor as follows;

$$\sigma_{0.2} > 70 \text{ MPa} > 2\tau (= \sigma_\phi - \sigma_z = 57 \text{ MPa})$$

Development of reinforced aluminum stabilizer has been successfully made by adding Zn (200ppm) as controlled impurity into 5N pure aluminum in combination with area-reduction of 10 - 20 % in cold work [2], [4].

Fast Quench Propagation: Reliable and fast quench propagation with homogeneous energy dump is important in order to eliminate excessive temperature after quench. It has been realized by using a technique of "pure-aluminum strip quench propagator" to enhance relative, transverse quench velocity up to a level of 10^{-1} and the peak temperature in the coil may be suppressed below 100 K. The concept is understood by using a simple relation of relative transverse quench velocity (v) and thermal conductivity (k), as follows:

$$v_z / v_\phi = \{ k_z / k_\phi \}^{1/2} \geq 10^{-1}.$$

Isogrid/Honeycomb Vacuum Vessel: This approach has been very effective to save wall thickness of outer vacuum vessel by a factor 2 - 4 depending on the design condition. R&D for large scale fabrication has been successfully made.

The prototype magnet design was optimized with a full diameter of 3.84 m and with an axial length of 1.9 m at 1/4 length of the detector solenoid. The maximum current was determined to be extended up to 12,000 A, corresponding to 150 % of the operational current of the detector solenoid. It has enabled to realize more than equivalent than the technical goals described above and to verify the detector solenoid feasibility. Major parameters of the prototype magnet are summarized in Table I in comparison with design parameters of the detector solenoid.

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TABLE 1.
Main parameters of the SDC prototype and detector solenoid

		Prototype	Detector
Dimensions:		(progress)	(design)
Cryostat	Inner radius	1.7 m	
	Outer radius	2.06 m	2.05 m
	Half length	1.2 m	
Coil	Mean radius	1.84 m	
	Half length	0.95 m	4.17 m
Electrical:			
Central field		1.5 T	2.0 T
Peak field in coil		3.8 T	2.8 T
Current		12,000 A	8,000 A
Iop/Ic on load-line at 4.2 K		75 %	50 %
Inductance		0.62 H	4.6 H
Stored energy		45 MJ	146 MJ
E/M ratio		9.6 kJ/kg	7.3 kJ/kg
Mechanical:			
Hoop stress in coil		48 MPa	42
Axial stress in coil		18 MPa	15
Coil weight		4.6 ton	20 ton

II. FABRICATION OF THE PROTOTYPE SOLENOID

The prototype magnet was developed in a joint effort between Japan and the U.S. The superconducting coil was developed by KEK in cooperation with Toshiba [5]. The "isogrid" vacuum vessel was developed by Fermilab and SSCL in cooperation with PS Associates and Armro Fabricating Corp [6]. A complementary effort to study feasibility of a brazed Al-honeycomb vessel was carried out by KEK in cooperation with IHI [7].

Fig. 1 shows a cross section of the axial end of the coil and cryostat. The aluminum stabilized superconductor was wound on inner surface of the outer support cylinder made of high strength aluminum alloy (A5083) by using inner winding technique. The coil is surrounded by LN2 radiation shield and installed into the vacuum vessel. The outer vacuum vessel was fabricated by using "isogrid shell". Fig. 2 shows a cross section of the coil made in practice winding. The inter-turn insulation of 0.2mm was made by using B-staged epoxy/glass/Upilex tape. The ground insulation 0.2mm was made by using glass-fiber-reinforced plastic(GFRP) and glued directly to inner surface of the

Fig. 1. Cross section of axial end of the prototype solenoid.

Fig. 2. Cross section of the coil.

support cylinder. The pure aluminum strip quench propagator with a thickness of 1 mm was placed on inner surface of the coil. The coil was cured at 130 degree C for a duration of 10 hours. Fig. 3 shows the prototype coil completed. The pure aluminum strips is seen on inner surface of the coil, and the cooling tube of forced flow of 2φ helium is seen outside the support cylinder. Fig. 4. shows the prototype solenoid magnet prepared to be tested in an experimental hall at KEK.

Fig. 3. The prototype coil completed.

Fig. 4. Prototype magnet prepared for the tests.

TABLE II.
CRYOGENIC CHARACTERISTICS IN STEADY STATE

2-phase He mass flow in the cooling tube	6 - 7 g/s
He gas flow through current leads (0 A)	0.17 g/s
Inlet pressure	0.13 MPa abs.
Pressure drop across cooling tube	0.15 kPa
Inlet quality	0.3
Outlet quality	0.6
Thermal load in magnet	20 W
Thermal load in transfer-lines(100m)	50 W
Coil temperature (@T-He=4.5 K)	4.6 - 4.7 K

III. PERFORMANCE TESTS

The first general performance test have been carried out at KEK in early 1994. The second test was carried after a period of six months including another thermal cycling.

A. Cooling and Cryogenic Characteristics

The magnet was cooled-down by using a helium refrigerator with a helium mass flow rate of 20 g/s and with a cooling speed of 3 K/hr. The temperature difference in the coil was kept to be < 40 K. The magnet was cooled down to 4.2 K during 4 days. The cryogenic characteristics in steady state at 4.6-4.7K are summarized in Table II and in [8].

B. Excitation and mechanical characteristics

Normal excitation tests successfully reached to the maximum current of 12,000 A corresponding to 150 % of the nominal excitation compared with the detector solenoid design as shown in Fig. 5. An E/M ratio of 9.6 kJ/kg was realized at 12,000 A in steady state. The mechanical stability of aluminum stabilized superconductor was evaluated by using strain gauges placed on outer surface of the outer support cylinder. Fig. 6 shows excitation dependence on the hoop strain according to repeated excitation cycle from 0 A to 8,000 A and to 12,000 A in several steps. An integrated

Fig. 5. Excitation up to 12,000 A along the I_c load line.

Fig. 6. Squared excitation as a function of hoop strain.

hoop strain of 1,090 micro-strains (point A) was measured at 12,000 A and a permanent elongation of 210 micro-strains was observed after discharging to 0 A (point B). Fig. 7 shows stress strain curve of the aluminum stabilized superconductor (measured at 77 K) and overwritten excitation dependence of the measured strain gauge on the outer support cylinder. It has been understood that aluminum stabilized superconductor was slightly yielded according to the excitation up to a strain level of 0.11% and linearly back to a negative value at 0 A. As a result of permanent elongation during excitation, a compressive prestress was generated inside the conductor at 0 A. It has remained in further excitations, and helped to keep elastic condition in further excitation up to 12,000 A.

In the second performance test, the magnet was excited up to 11,600 A and it was confirmed that the prestress was remaining and the coil was remaining in elastic condition.

A general superconductor performance in terms of critical current versus critical temperature was measured by stopping helium mass flow and by raising the coil temperature with keeping the current. As a typical result at $I = 10,000$ A, the magnet quenched at 6.35 K and the expected superconductor performance was verified.

Fig. 7. Stress-strain curve of the Al stabilized superconductor and overwritten strain gauge characteristics up to 12,000 A.

TABLE III.
SUMMARY OF HEATER QUENCH TESTS

Current	Location	Q. Energy	V _{q-z}	T-peak
R _d =0.025 ohm:				
5,000 A	Center	7.8-6.8 J	m/s	44 K
8,000	Center	3.4-1.5	0.2	57
10,000	Center	2.4-1.8	0.5	63
11,250	Center	1.8-1.5	0.9	73
5,000	End	3.4-2.3	0.14	49
8,000	End	2.2-1.5	0.4	55
10,000	End	1.4-1.2	0.5	74
R _d =0 ohm				
8,000	Center	4.4-2.8		72
11,600	Center	1.5-1.3		95

C. Heater Quench Test

A series of heater quench test was carried out to evaluate quench energy, quench velocity and peak temperature after the quench. A summary is given in Table III. The stored energy was partially extracted to a dump resistor of 0.025 ohm and diode (20 V) in most cases. The highest energy dump test was carried out at 11,600 A, and about 90 % of stored energy corresponding to $E/M > 8$ kJ/kg was dumped into the coil. Fig. 8 shows decay current and temperatures inside the coil and outside the support cylinder. A calculation by using QUENCH code was also shown [9]. The measured result of the coil peak temperature is reasonably consistent with the calculation. On the other hand, the fraction of the energy dump in the support cylinder was much smaller than that expected, and the net energy dump ratio to the coil mass, excluding the support cylinder, was > 10 kJ/kg. More analysis is being carried out.

V. SUMMARY

The SDC prototype magnet was successfully excited up to the maximum current of 12,000 A with keeping a mechanical stability. The integrated hoop strain of 0.1 % and a permanent elongation within a level of 0.02% under the maximum share stress of 66 MPa in the conductor. In further excitation, the magnet has shown elastic characteristics,

Fig. 8. Coil temperature after quench at 11,600 A.

Fig. 9. E/M ratio achieved in the SDC prototype in comparison with other detector solenoids.

even after a period of six months and a thermal cycling.

The E/M ratio of 9.6 kJ/kg was successfully realized in the full excitation. The E/M ratio of > 8 kJ/kg was safely dumped into the coil without excessive temperature rise beyond 100 K. Fig. 9 shows the E/M ratio achieved in the SDC prototype solenoid in comparison with other thin solenoids used in various high-energy physics laboratories[3]. The successful achievement in the SDC prototype solenoid has verified a possible magnet design with $E/M > 8$ kJ/kg in the practical application, and feasibility of the magnet with $E/M > 10$ kJ/kg in future applications.

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