Cryogenic Design of the ATLAS Thin Superconducting Solenoid Magnet

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Cryogenic characteristics of a thin superconducting solenoid magnet has been studied for a high energy particle-detector, ATLAS, in the Large Hadron Collider (LHC) project at CERN. The thin solenoid wound with aluminum stabilized superconductor is indirectly cooled by forced flow of two-phase helium in serpentine cooling tube on the outer support cylinder of the coil. This report describe a cryogenic design of the thin solenoid magnet and its cooling system.

INTRODUCTION

A thin superconducting solenoid magnet is planned to be developed for the ATLAS detector which is one of major particle detector systems in the Large Hadron Collider (LHC) project at CERN [1, 2]. It is designed to provide a central magnetic field of 2T in a warm-bore volume of 2.3 m in diameter and 5.6 m in length for precise momentum measurement of secondary particles produced in 14 GeV proton-proton head-on collisions in the LHC accelerator. Since the solenoid is required to be as thin (and transparent) as possible in terms of radiation length for particles to traverse the solenoid magnet wall with minimum interaction. The solenoid coil is wound with aluminum stabilized superconductor on inner surface of an outer support cylinder, and is cooled indirectly by using two-phase helium flow in serpentine cooling pipe welded on outer surface of a coil support cylinder. The resource cryogen is supplied by a common large refrigerator for whole ATLAS detector magnet system consisting of toroidal magnets and a solenoid magnet [3,4,5].This report describes a cryogenic design of the ATLAS solenoid and associated interface to the expected common refrigerator system for the ATLAS superconducting magnet system.

SOLENOID COIL AND CRYOSTAT

The solenoid coil consists of a single layer-coil wound with aluminum-stabilized superconductor and an outer support cylinder as shown in Fig. 1. The coil is directly wound inside the support cylinder made of high-strength aluminum alloy. A total cold-mass thickness of 43 mm resulting in a cold mass of 5 tons has been determined with an optimization of E/M (stored energy / cold mass) ratio of 8.4 kJ/kg [6]. It enables to absorb a full stored energy of 42 MJ into the cold mass with an averaged coil temperature rise of about 80 K, in case of quench. The temperature rise may be homogenized with fast thermal propagation given by axial pure-aluminum strips placed on inner coil surface [6]. Major coil design parameters are summarized in Table 1.

Fig. 2 shows an isometric view of the coil structure. A cooling pipe with an inner diameter of 18 mm is welded to the outer surface of the outer support cylinder. The single serpentine path has 24 axial passes with a circumferencial pitch of 33 cm. The cold mass is supported by 12 triangle-supports made of glass fiber reinforced plastic (GFRP) at each axial end of the coil structure. The triangle supports are designed to provide combined functions in supporting against the expected maximum load within 3 G. A coil end is axially fixed by the support and the other end is axially free to allow axial thermal shrinkage according to the coil cool-down. The radial shrinkage may be allowed by radial tilting of all triangle supports.

Table 1. Design parameters of the ATLAS solenoid.

Coil Inner Radius	1.218 m
Coil Half Length	2.65 m
Central Field	2.0 T
Peak Field	2.6 T
Nominal Current	8,000 A
Stored Energy	42 MJ
E/M Ratio	8.4 kJ/kg

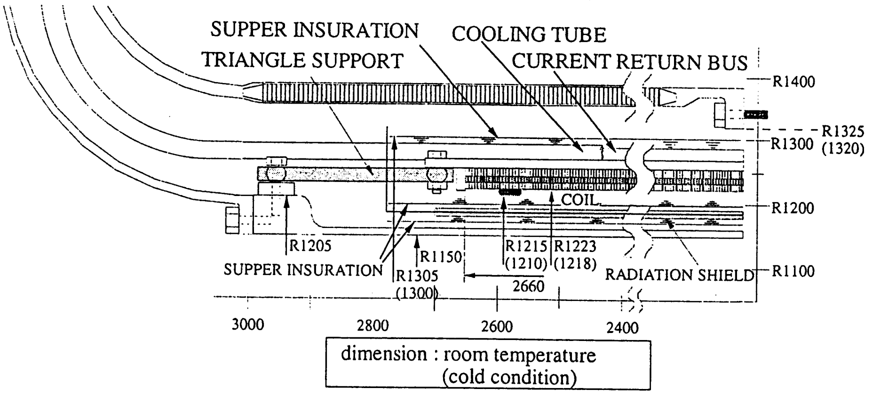

Fig. 1. Cross section of the axial end of the ATLAS solenoid coil and cryostat.

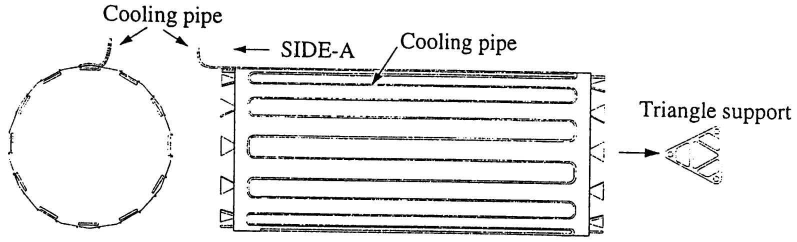

Fig. 2. An isometric view of the cooling tube and the coil support scheme.

To save material to be used in the cryostat, the coil is installed into a common vacuum vessel with another cold detector component, Liquid-Argon Calorimeter (LAr-Cal) and its cryostat. No outer radiation shield is provided because of the inner wall of the Liquid-Argon calorimeter cryostat which may provide a thermal boundary at 80 K. The inner radiation shield is provided for an intercept against thermal radiation from the inner vacuum warm bore tube. As shown in Fig. 3, the cryogen lines and the superconducting leads of the solenoid extend through other detectors in an 10 m long chimney to a control dewar, which is located outside top of the muon detector at the axial detector-center. The control dewar provides optimized cryogen flow into the solenoid magnet in various cooling modes, and supplies cold gas flow to current leads passing through the control dewar.

CRYOGENIC DESIGN

Thermal loads

In a steady state, the net thermal load into the ATLAS solenoid magnet is estimated to be about 50 W at 4.2 K and about 450 W at a radiation shield temperature of 60 - 80 K. An eddy current loss of about 20 W in the support cylinder is additionally required during a magnet charging/discharging period of 20 min., and a cold helium gas flow of 1 g/s is required for a set pair of current leads during the solenoid excitation. For a purpose of liquid helium level control, a heater of about 10 W may be consumed in the control dewar. As a result, a total thermal load of 100 W including a contingency of 20W is considered in the coil and the control dewar at 4.2 K. A summary of the thermal load is given in Table 2.

Table 2. Thermal load of the ATLAS thin solenoid.

		4.2 K	80 K	Lhe
Radiation	(coil)	10 W	50 W	
	(chim. & C/D)	5	50	
Conduction	(coil)	5	50	
	(chim. & C/D)	30	250	
Eddy current loss	(coil)	20		
Control heater	(C/D)	10		
Current leads	(C/D)			1 g/s
Contingency		20	100	0.2g/s
		100 W	500 W	1.2 g/s (40 l/h)

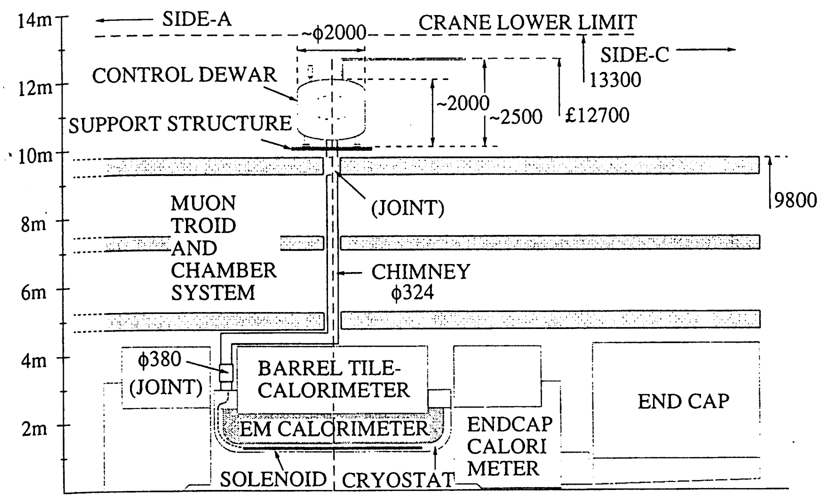

Fig. 3. A cross sectional layout of solenoid, chminey and control dewar in the ATLAS detector.

Cooling scheme and parameters

Figure 4 shows a planned schematic flow diagram for the ATLAS solenoid cooling system. Table 3. gives major cooling characteristics for the solenoid. The helium gas as cryogen resource is given by a common large refrigerator and a pre-cooler system for the ATLAS magnet system at CERN [4]. The solenoid is pre-cooled by using a cold helium gas flow of about 20 g/s, supplied by the pre-cooler under safety constraints given in Table 3 to eliminate excessive thermal stress during a transient pre-cooling period. Depending on the operational condition, warm helium gas may be mixed with the cold gas, as an optional mode, to ensure the temperature control of the cold gas. In a steady state operation at 4.4 K, the two phase helium flow is supplied to keep the coil temperature at about 4.5 K(<5 K). The supercritical helium from the common refrigerator is expanded by using a J-T valve and sub-cooled in the control dewar to provide two phase helium close to full liquid helium phase (helium quality of X=0) through this process. The two-phase helium is supplied into the serpentine cooling path in the solenoid magnet and is returned back to the control dewar with keeping two-phase condition (at X< 0.8). The helium mass flow rate in the cooling path is about 7 g/s with a helium quality factor changing of about 0.4 (from 0.2 to 0.6) in the net coil part and of about 2 x 0.2 in the chimney part. The inner radiation shield is cooled by gas helium flow, with an intermediate temperature of 60 - 80 K, provided by the common refrigerator. The outlet gas from the current leads may be transferred either to (i) a low pressure line returning to the compressor, (ii) a gas recovery line at atmospheric pressure, or (iii) a direct vent line, depending on safety conditions of the current leads.

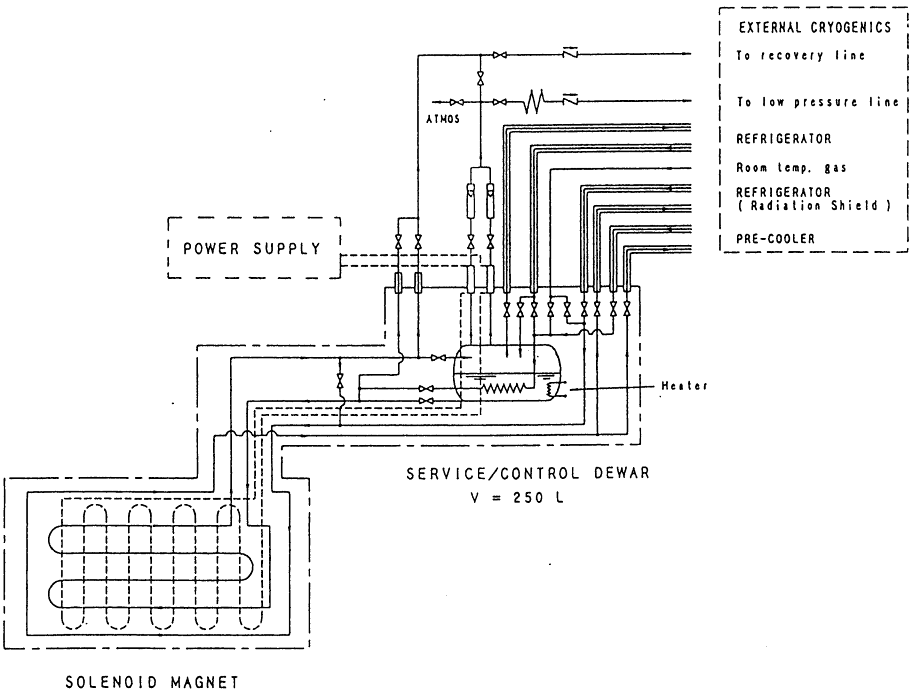

Fig. 4. Schematic flow diagram for the ATLAS solenoid cryogenic system.

Table 3. Design parameters required for the ATLAS solenoid cryogenic system.

Cool-down		
Cold mass	(coil)	5 tons
	(chimney & control-dewar)	1 tons
Cooling speed		<3 K/h
dT (T-coil - T-gas)		<40 K
dT (T-He-in - T-He-out)		<30 K
He-gas mass flow rate		20-30 g/s
Supplied helium pressure		>1 MPa
Steady State (during excitati)		
Heat load at 4.2 K		80 W + 40 l/h
Two-phase helium flow rate		7 g/s
dX	(coil)	0.4
dX	(chimney & control dewar)	<2 x 0.2
Magnet charging/discharging		
Heat load at 4.2 K		100-160 W + 40 l/h
Two-phase helium flow rate		6-10 g/s
Quench Recovery		
Energy Dump into the coil		21 MJ (50 %)
Recovery time		4 hr.
Helium flow rate		20 g/s
Required LHe		3,000 l

When the magnet quenches, the solenoid system is immediately disconnected from the common refrigerator system to minimize a disturbance to the refrigerator, and is re-cooled down according to a quench recovery sequence. In case of a refrigerator problem during the magnet excitation, the solenoid magnet is to be de-energized under a controlled slow-discharge, with eliminating a quench by using remaining liquid helium (~2 kg) in the cooling path in the coil and by using own enthalpy in the cold mass below the critical temperature. The current lead gas flow may be maintained during the discharge by using liquid helium in the control dewar.

SUMMARY

A conceptual design study of a cryogenic system for the ATLAS thin superconducting solenoid magnet has been made. The solenoid provides a central magnetic field of 2 T in a warm bore diameter of 2.3 m and an axial length of 5.6 m. The solenoid with a cold mass of 5 tons is indirectly cooled by using forced flow of two phase helium. passing through a serpentine cooling tube welded on the outer surface of the coil support cylinder. Resource cryogen is supplied by a common large refrigerator system to be provided by CERN, and the operational conditions of the cryogen may be optimized by using a control dewar dedicated to the solenoid system. The helium mass flow rate of < 10 g/s is required to keep the steady operational condition in the magnet excitation with keeping quality factor of X << 1 in the coil, and it may include a redundancy to enable the magnet to be discharged without quench by using remaining liquid the cooling parth and by using own enthalpy below the critical temperature.

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