Engineering Status of the Superconducting End Cap Toroid Magnets for the ATLAS Experiment at LHC

D E Baynham, J Butterworth, F S Carr, M J D Courthold, D A Cragg, C J Densham, D Evans, E Holtom, J Rochford, D Sole, E F Towndrow, G P Warner,
CLRC, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK

Abstract —**The ATLAS experiment at LHC, CERN will utilise a large, superconducting, air-cored toroid magnet system for precision muon measurements. The magnet system will consist of a long barrel and two end-cap toroids. Each end-cap toroid will contain eight racetrack coils mounted as a single cold mass in cryostat vessel of ~10m diameter. The project has now moved from the design/specification stage into the fabrication phase. This paper presents the engineering status of the cold masses and vacuum vessels that are under fabrication in industry. Final designs of cold mass supports, cryogenic systems and control/protection systems are presented. Planning for toroid integration, test and installation is described.**

I. Introduction

The ATLAS muon spectrometer is based on a superconducting toroid magnet system [1] consisting of a long Barrel Toroid (BT) and two inserted End Cap Toroids (ECT's). The Rutherford Appleton Laboratory is responsible for the engineering design and management of the End Cap Toroid Magnets under a collaboration agreement with CERN/ATLAS. The major features of the End Cap Toroid are shown in Fig 1.

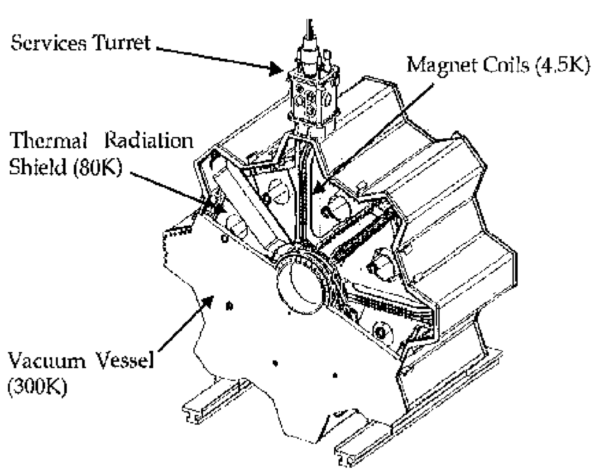

Fig 1. End Cap Toroid

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TABLE I
TOROID MAJOR PARAMETERS

Overall Dimensions		
Inner diameter	m	1.65
Outer diameter	m	10.7
Axial length	m	5
Windings		
Number of coils		8
Turns / coil		116
Operating current	kA	20
Total Ampere turns	MAt	22
Stored energy / End Cap	MJ	250
Weights		
Cold Mass	tonnes	160
Total / End Cap (excl. shielding)	tonnes	239

The design is based on eight superconducting, racetrack type coils assembled as a single cold mass. The cold mass and radiation shields are installed in the large, castellated, aluminium alloy vacuum vessel. Services are provided through a single turret and the ECT will be mounted on the main rail structure of ATLAS to allow movement for access to the inner part of the experiment. The major parameters of the ECT are given in Table 1.

The design concepts have been reported elsewhere [2]. In this paper we focus on the transfer of the definition designs of cold mass and vacuum vessels to industry and present final designs of the other toroid components. All major toroid components will be fabricated in industry and supplied to CERN for final integration and test before transfer to the ATLAS experimental area. Planning for integration is well advanced and the concepts and infrastructure are described in section IV.

II. Cold Mass

A. General Concept

The concept of the cold mass is shown in Fig 2. The cold mass consists of eight superconducting coil modules and eight keystone box modules. The keystone box modules are the structural elements that maintain the toroid shape under gravitational loads. The magnetic forces are reacted in the inner radius through a stiff arch. The coils will be

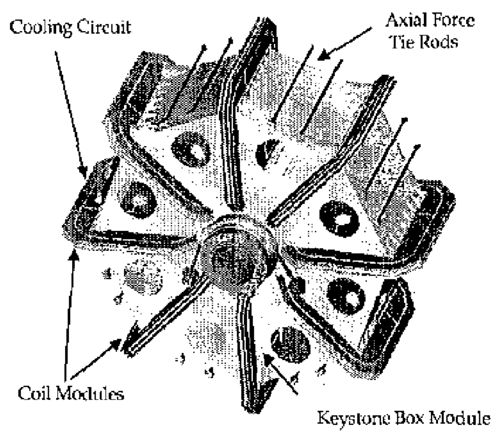

Fig 2. Cold Mass Concept

indirectly cooled by pumped circulation of helium. Each coil and keystone box module will have its own fully integrated cooling circuits attached.

The design of the coils is shown in Fig 3. A coil consists of a center plate with a double pancake winding mounted on each side. The outer plates with their cooling circuits complete the sandwich structure.

The coil structure is completed by the clamp bars and the support channel which is integrated with the coil at the impregnation stage. The bars are secured to the structure through large shear bolts, which are designed to support the magnetic forces if the internal resin bonds should fail.

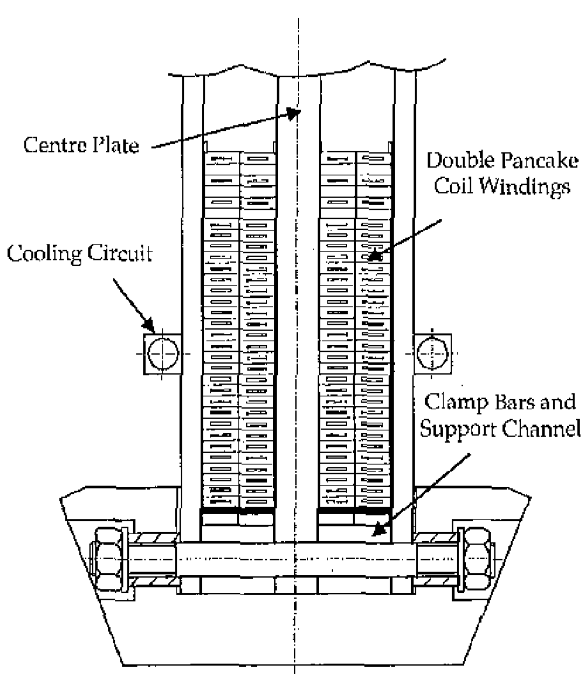

Fig 3. Coil section including support channel

TABLE II
CONDUCTOR PARAMETERS

Operating current		kA	20
Operating field (peak)		T	4.13
Design current (4.2K, 5T)		kA	60
Cable (Rutherford type) number of strands			40
	strand diameter	mm	1.3
Aluminium stabiliser	width	mm	41
section	thickness	mm	12
RRR Zero field			800
Total conductor length		km	25.6

B. Conductor

The conductor is based on a Rutherford Cable clad with a high purity aluminium jacket by co-extrusion. The major conductor parameters are shown in Table II. Coil fabrication as double pancakes requires conductor delivery in piece lengths of 820m. Conductor fabrication will be from two sources, VacuumSchmelze (G) and a partnership of EMI (I) and ACS (CH). The supply from EMI/ACS consortium is coordinated by the institutes LASA (I) and ETH (CH). Each supplier will deliver 16 lengths of ~820m. Qualification lengths have been produced and first production lengths have been delivered. The qualification and production lengths meet the technical specification. Conductor production is due for completion in mid 2000 which is on schedule for the coil fabrication programme.

C. Cold Mass Mechanical Analysis

The overall cold mass structure, Fig 2, has been analysed when subjected to the major loads, gravitational, magnet and seismic (0.15g). The global stresses are well within the design values for the structural aluminium alloy type 5083. The maximum deflection under all combined loads is <3mm and a buckling factor ~10 has been computed. The local stresses within the coil matrix have been evaluated using detailed models. This analysis shows distributed tensile stresses at the coil former interface <5MPa due to combined thermal and magnetic loads. Regions of higher local stress due to differential thermal contraction can occur at localised areas of pure resin and at orthogonal interfaces between laminate insulation layers.

The localised areas of pure resin (~1mm scale) are unavoidable in such a large coil. We have therefore developed an epoxy resin system with high toughness at 4.5K [3] to minimise the risk of crack initiation in such areas. The local stresses at laminated interface will be greatly reduced by using material with high glass content (65% by volume) at the critical interfaces.

D. Cold Mass Fabrication Status

The cold mass specification was completed at the end of 1998. The contract for cold mass fabrication, delivery and assembly at CERN was placed by NIKHEF (NL) under an In-Kind agreement with ATLAS in February 1999. The cold mass fabrication will be carried out by HMA Power Systems in the Netherlands.

The cold mass reference design has been translated into the manufacturing design by HMA. The coil winding and impregnation process will be qualified by the fabrication of a dummy coil. The cold mass will be fully assembled at the manufacturers works before shipment to CERN. The aim is to transport each cold mass as two half units in order to minimise reassembly effort at CERN. The first cold mass is scheduled for delivery to CERN in December 2001.

III. CRYOSTAT

A. *Vacuum Vessel Design*

The vacuum vessel design concept is shown in Fig 1. The castellated outer shell of the vacuum vessel will be formed from 40mm aluminium alloy plate using a brake-pressing technique. The end plates will be fabricated from 75mm stock plate and braced internally by 8 stay-tubes to reduce deflections and stresses. The vessel will be fabricated as two half-vessel modules, which are the largest units transportable to CERN. Each vessel will be fully assembled and tested in industry before transport to CERN. These tests will include all dimensional checking and full vacuum testing with temporary sealing at the joint lines between the half vessels. After delivery to CERN the half-vessel joint lines will be weld sealed for final operation. All other seals i.e. end plate to outer shell, centre tube and stay tubes will be made by double 'O' rings.

B. *Vacuum Vessel Fabrication Status*

Vessel design and specifications were completed at the end of 1998. The contract for vessel fabrication, delivery and assembly at CERN was placed by NIKHEF under an In-Kind agreement with ATLAS in February 1999. The vessels will be fabricated by Schelde EXOTECH in the Netherlands.

The vessel reference design has been translated into the manufacturing design by Schelde EXOTECH, and the fabrication procedure approved. Materials procurement and fabrication are underway. The first vessel is scheduled to be delivered to CERN in December 2000.

C. *Cold Mass Supports*

The cold mass is supported from saddles mounted on the centre bore tube of the cryostat by 4 stainless steel tie rods. This will allow accurate alignment of the cold mass with the cryostat bore tube and the beam.

The interaction of the BT and ECT fields generates an axial force of 300 tonnes on each ECT. This force will be transferred to the vacuum vessel by 16 axial tie bars as shown in Fig 2. The axial loads will be reacted through brackets to the cryostat of the Barrel Toroid.

D. *Thermal Radiation Shields*

The thermal shields will consist of the following main elements; a large outer shell which is castellated in the profile of the vacuum vessel; two end plate shields; a centre tube shield and 8 stay tube shields. The main shields will be fabricated from aluminium alloy plate of 20mm thickness and cooled by circulation of helium gas in pipes welded to the shield. The shield coolant will be fed from a series of main manifolds for the primary elements. Gas flow over the shield surface will be distributed through parallel circuits with the sharing controlled by restrictors.
The shields are designed as modular elements with the size dictated by transport limitations and installation criteria. The outer shell will be fabricated and delivered as 4 large modules complete with coolant manifolds and internal circuits. The end shields will be delivered as half plate units. During integration at CERN the large modules will be connected mechanically and the coolant manifolds completed - the final assembly of the full shield will require less than 20 on site welds.

Shield design and specification is complete and approved. Shield fabrication will commence in early 2000 for delivery to CERN in early 2001.

E. *Services Turret*

All services to the toroid coils, cryogenics, electrical, vacuum and control will be connected through a single services turret mounted on top of the vacuum vessel as shown in Fig 4. The design of the services turret is complete. It's installation will form part of the final toroid integration process.

IV. TOROID INTEGRATION, TEST AND INSTALLATION

The integration of the manufactured components into the final toroid will take place at CERN. A full study of the integration process has been made taking into account the modular delivery of components, the existing infrastructures

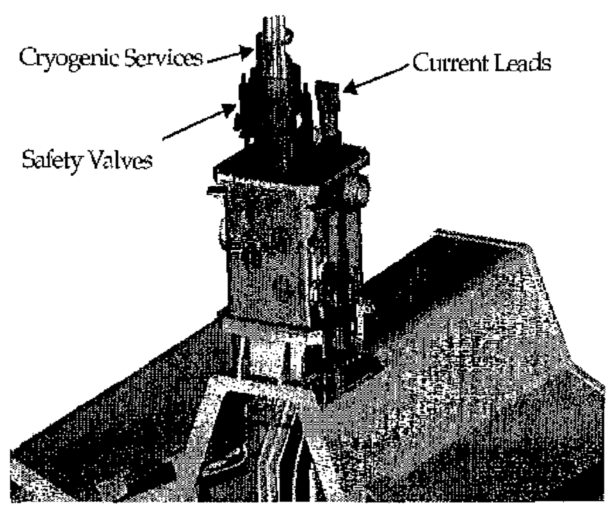

Fig 4. Services Turret

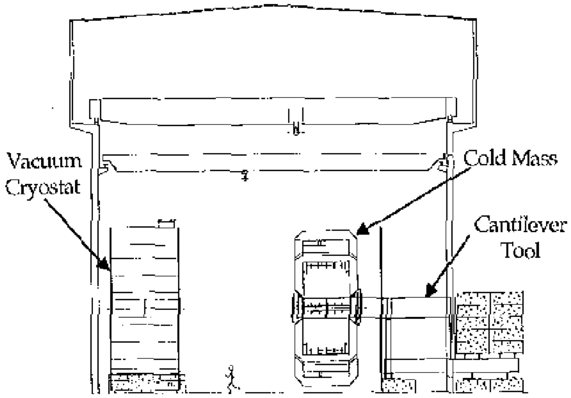

Fig 5. Integration arrangement in assembly building

at CERN (building access, crane facilities etc) and the integration tooling which will be required. After delivery, the vacuum vessel and cold mass modules will undergo an acceptance assembly at CERN by the manufacturers.

Integration will involve the moving, turning and assembly of large objects >10m diameter and with large masses >150 tonnes. The basic steps will be as follows:

(i) after completion of the vacuum vessel on-site tests the superinsulation and thermal radiation shields will be installed in the outer vacuum shell to form the outer cryostat wall.

(ii) during final assembly of the cold mass at CERN the vacuum vessel bore tube and cold mass supports will be integrated with the cold mass.

(iii) for integration of the cold mass assembly into the vacuum vessel the cold mass will be mounted on a large cantilever beam as shown in Fig 5.

(iv) final closure of the cryostat will require mounting of the services turret, the end plate thermal radiation shields and the cryostat end plates. When these processes have been completed the loads will be transferred from the cantilever beam to the vessel rail structure. After final integration tests the toroid will be transferred to a test position where a full cool-down and powering tests will be made before transfer to the ATLAS cavern for installation.

V. CRYOGENIC SYSTEMS

The ECT's will be cooled from central ATLAS refrigeration plant operating in two modes; 300K-100K cool down using a liquid nitrogen pre-cooler; 100K-4K cool down and 4K operation using a helium refrigerator. The local cryogenic interfaces between plant and toroid (transfer lines, storage dewars and valve controls) are currently under review as part of a general integration of ATLAS magnet cryogenic services. The internal cryogenic system of the ECT's is fully defined in terms of operating parameters and pipe layouts to deliver coolant to the cold masses and thermal shields. The behaviour of the coolant in the cold mass cooling circuits under quench conditions has been modelled. This simulation combined the heat input derived from quench analysis with the coolant modelling code GANDALF (developed for CICC analysis) to determine maximum pressures and mass flows during the quench transient. The simulation showed that the majority of coolant will be ejected by the early part of the heating transient and the pressure rise should not exceed ~1 bar during the quench transient.

VI. SAFETY SYSTEMS

The safety system requirements for the ECT's have been fully defined and the levels of redundancy analysed. The present emphasis is on the integration of ECT requirements within the overall ATLAS magnet safety system framework. In such a large magnet system the detection of earth leakage currents is a critical safety requirement. In this context a novel system is being developed which will allow the highly sensitive detection of earth leakage currents by application of low frequency ac signals.

VII. STATUS AND CONCLUSIONS

The fabrication phase is now under way for the major long delivery components; conductors, cold masses and vacuum vessels. All other cryostat internal components are specified and ready to move to the manufacturing phase. The final integration process and infrastructure requirements are defined. Surface tests are scheduled for 2003 in preparation for installation at the end of 2004.

ACKNOWLEDGMENT

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