Refrigeration System for the Atlas Experiment

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The ATLAS detector of the 27 km circumference LHC collider is of unprecedented size and complexity. The magnet configuration is based on an inner superconducting solenoid and large superconducting air-core toroids (barrel and two end-caps) each made of eight coils symmetrically arranged outside the calorimetry. The total cold mass approaches 600 tons and the stored energy is 1.7 GJ. The cryogenic infrastructure includes a 6 kW@4.5 K refrigerator, a precooling unit and distribution systems and permits flexible operation during cool-down, normal running and quench recovery. A dedicated LN_2 refrigeration system is required for the three liquid argon calorimeters (84 m^3 of LAr). Magnets and calorimeters will be individually tested prior to their definitive installation at a large scale cryogenic test area. The experiment is scheduled to be operational in 2005.

INTRODUCTION

ATLAS [1] will be one of four particle detectors designed for the exploitation of the LHC's capabilities for experiments with colliding protons and heavy ions. All of them envisage solutions with superconducting coils at 4.5 K [2]. The extent to which the ATLAS will use superconducting technology is unprecedented in complexity. This complexity is reflected in the associated helium cryogenic system. An equally complex refrigeration system is needed for the cooling of the three liquid argon calorimeters. The paper describes the cryogenic infrastructure to be installed at the LHC's collider point 1 at CERN, the refrigeration system and the operational scenarios we have studied and defined to date. The design of the ATLAS magnets and calorimeters is an international undertaking with contributions from laboratories in Europe, Japan and the USA.

THE TOROIDAL MAGNET COMPLEX AND ITS CRYOGENICS

The Barrel Toroid (BT) and the two End Cap Toroid magnets (ECT) produce a large volume toroidal magnetic field for the muon spectrometry. The BT is made of 8 rectangular coils with a length of 26 m and a height of 5 m. They are arranged around the central beam axis in the form of a cylinder with 19.5 m outer diameter [3]. The ECT's consist each of 8 rectangularly shaped coils housed in a common vacuum vessel of an outer diameter of 10.5 m. Peak field is 4 T at nominal current of 20 kA. The refrigerant flow is split in eight parallel circuits for each of the three magnet subsystems [4]. The cooling mass flow under normal operation conditions is ~600 g/s of two-phase helium for the BT magnets and ~300 g/s for each ECT circulated by means of a turbo pump backed up with a second identical one for redundancy [5]. For the BT a 5000 liter dewar and for each ECT a 1600 liter dewar provide sufficient autonomy for slow discharge in case of failure of the refrigerator. In case of fast discharge the stored energies of 1.1 GJ for the BT and 0.25 GJ for each ECT will be dumped in the cold mass of the magnets which heat up to 58 K (BT) and 53 K (ECT's) respectively.

THE SOLENOID AND ITS CRYOGENICS

The comparatively small solenoid of length 5.3 m and inner diameter of 2.4 m is designed to provide an uniform magnetic field of 2 T at 8 kA for the inner tracker. Supercritical helium from common refrigerator is sub-cooled in a control dewar (250 liter) and expanded by using a J.T. valve to provide two-phase helium (7 g/s) close to full liquid phase. The liquid helium in the dewar also serves for secure slow discharge of the magnet. The solenoid is housed in the same vacuum vessel of the liquid argon barrel calorimeter to minimise the amount of material along the particles trajectories.

THE HELIUM CRYOGENICS INFRASTRUCTURE

A dedicated helium cryogenic plant and infrastructure is proposed to be installed at CERN's LHC point 1 (see fig. 1). It mainly consists of

1) at surface level: screw compressors, He storage tanks, a recuperation and purification system
2) at underground cryogenics service cavern: cold box, precooling unit
3) at main detector cavern: distribution system, local cryogenics for the four magnet subsystems.

Based on the thermal budget of the magnets (see table 1) we presently foresee a refrigerator of 6 kW@4.5K and a compressor flow of 500 g/s (1-20 bar). Detailed studies are envisaged taking various scenarios into account such as precooling, baseline operation, recovery from fast discharge, permitting an optimisation of the thermodynamic cycle. The thermal budget of the four magnets is 2550 W of isothermal refrigeration at 4.5 K, 10.3 g/s of liquefaction for cooling of four pairs of current leads, and 10600 W for the thermal shields (feed 40 K, return 80 K). For the cooling of the magnets from 300 to 100 K, a dedicated precooling unit with a LN_2/He heat exchanger will be installed. The 23 m^3/d of LN_2 required during cool down is supplied from two 50 m^3 storage tanks at the surface and the helium mass flow is withdrawn from the compressor/refrigerator circuit.

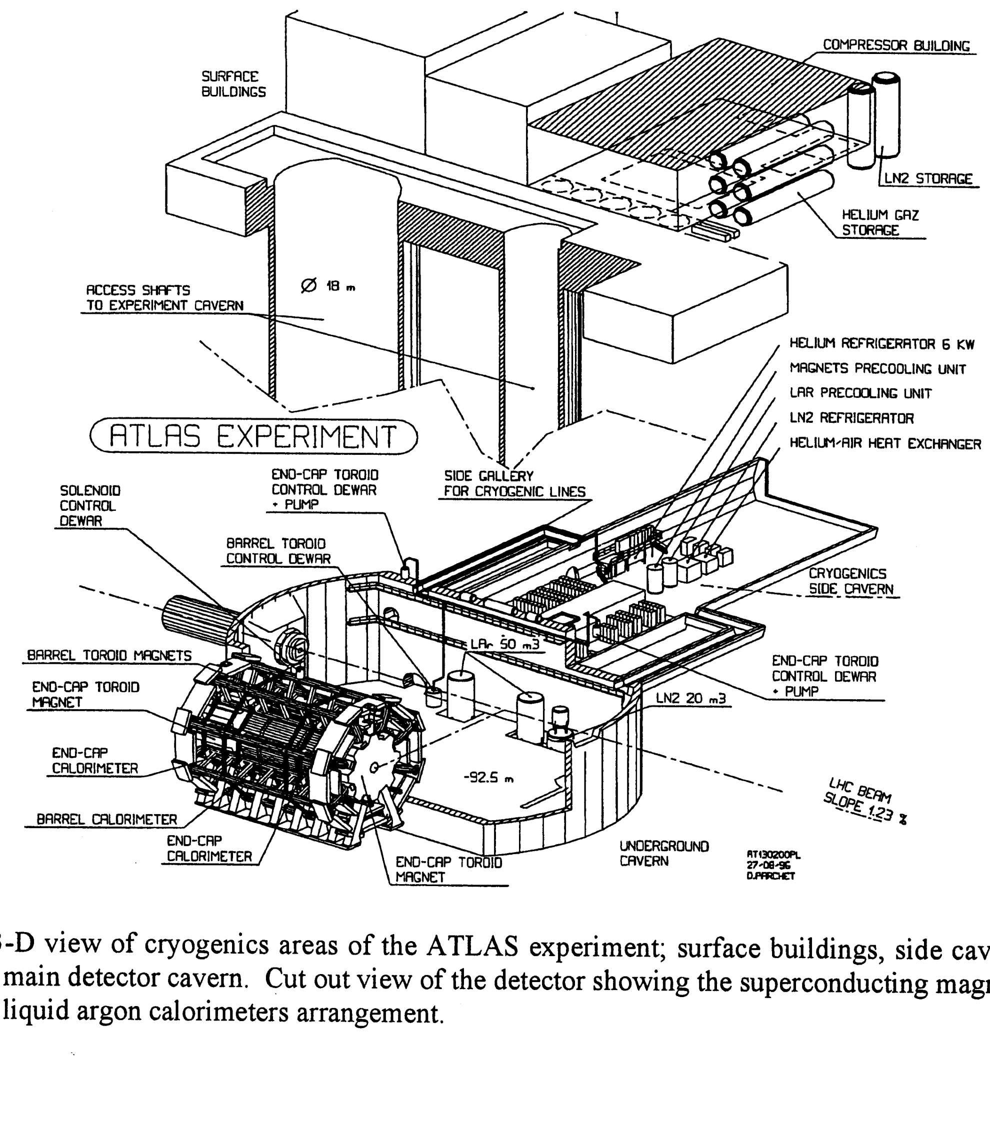

Figure 1 3-D view of cryogenics areas of the ATLAS experiment; surface buildings, side cavern and main detector cavern. Cut out view of the detector showing the superconducting magnets and liquid argon calorimeters arrangement.

Table 1: Cryogenics parameters for the refrigeration systems of the ATLAS magnets and calorimeters. BT = Barrel Toroid Magnets, ECT = End Cap Toroid Magnet, ECC = End Cap Calorimeter.

Helium Cryogenics						Argon Calorimeter Cryogenics				
Baseline operation Conditions										
		BT	2 ECT	Solenoid	Total			Barrel	2 ECC	Total
Liquid volume	m^3				15	Liquid volume	m^3	44	40	84
Cold mass	tons	350	214	5.5	570	Cold mass	tons	130	440	570
Cold mass shield	tons	25	45	0.5	71	Isoth.load 89 K	kW			19.1
Stored energy	GJ	1.1	0.5	0.04	1.7					
Load 40 to 80K	kW	6.3	4.02	0.28	10.6	LN_2 refrigerant flow			m^3/d	14
Load 4.5 K	kW	1.24	1.22	0.09	2.55					
Current leads	g/s	3	6	1.3	10.3					
Total equiv. 4.5 K	kW	2.03	2.13	0.24	4.50					
Refrigerator (with contingency)@4.5 equiv.				kW	6	LN_2 refrigerator			kW	25
Compressor mass flow (1-20 bar)				g/s	500					
Cool down operation conditions										
Time 300/100 K (pre-cooling unit)				days	28	Time 300 K/89 K (He/LN_2 pre-cooler) (ΔT max = 40K) total			days	40
Time 100/4.5 K (refrigerator)				days	12					
(ΔT max = 40K) total				days	40					
Average cool-down power				kW	43					
He mass flow pre-cooling unit (300-100 K)				g/s	220					
LN_2 consumption				m^3/d	23					

HELIUM DISTRIBUTION SYSTEM

The refrigerants are distributed via a low loss transfer line system linking the precooler unit and the refrigerator of the side cavern to the cryogenics equipment of the main cavern. Our modular design of connecting the magnet subsystem as shown in fig.2 permits operational flexibility in cool down, baseline running and recovery modes. Feed and return flows of any defined temperature level at baseline load (supercritical He at 4.5 K, shield cooling 40/80K) form a closed circuit via a bypass at the end of the transfer line. For the precooling we foresee an independent line following the same principle. For reasons of thermodynamic optimisation, the enthalpy of the cold return gas is utilised in the refrigerator and/or the precooler (no heaters will be installed for warming up the helium gas flows).

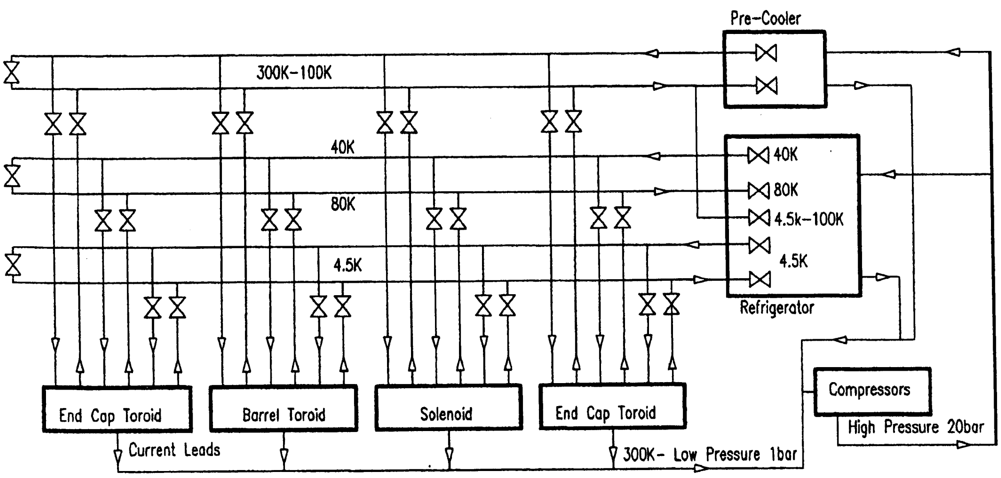

Figure 2 Helium Distribution System for the ATLAS Magnets.

FUNCTIONING

The normal cool down procedure foresees all magnet subsystem cooled in parallel from ambient to ~100 K by means of the LN_2 precooler unit (limits on magnets: temperature gradients of 40 K and 2.5 K/h). From ~100 K to 4.5 K the refrigerator's J.T. flow will be used. However, sequential cooling of the magnets can be carried out. In both cases the total cool down time will be ~40 days.

The modular design of the He distribution system permits the magnet subsystem to be run under different conditions if required. For example, one magnet could be in cool down mode from ambient while the remaining are already operating at 4.5 K. In another configuration one or more magnet(s) may be in quench recovery mode while the others are kept cold. Recovery time for any quenched magnet subsystem will not exceed four days. Various post-quench situations will be studied and optimal solutions investigated for different operational scenarios.

THE LAR CALORIMETERS AND REFRIGERATION SYSTEM

The three liquid argon calorimeters, with a total liquid inventory of 84 m^3 are: the barrel electromagnetic calorimeter (dimensions of vessel 4.5 m o.d., length 6.8 m) and the two end cap (both electromagnetic and hadronic) calorimeters 4.5 m o.d., length 3.3 m. The equipment of the dedicated LAr refrigeration system are located at

1) floor level: nitrogen compressor (for the LN_2) refrigerator, LN_2 storage tanks, helium compressor
2) the underground cryogenics service cavern: LN_2 refrigerator (25 kW), precooling unit (He/LN_2)
3) the main cavern: 2 LAr storage tanks each 50 m^3, LN_2 buffer tank of 20 m^3, local auxiliary cryogenics.

Precooling of the calorimeters from ambient temperature to 89 K in 40 days uses He/LN_2 heat exchange. Helium at 1-3 bar is circulated with a compressor. At operational temperatures, the calorimeters are purged and filled with LAr delivered by truck from the surface area. Internal cooling of the LAr is done either directly with LN_2 or indirectly with an intermediate LAr circuit (design decision pending) in horizontally heat exchanger tubes. The LN_2 refrigerator provides the cooling for all operational modes (cool down, normal operation at 89 K) of the detectors. The 20 m^3 of LN_2 in the main cavern is designed to give more than a day of autonomy in case of failure of the LN_2 refrigerator. An additional back-up utilises the LN_2 (2 x 50 m^3) from the tanks at the surface level. If necessary, the complete liquid inventory of any or all cryostats can be drained into the 100 m^3 LAr storage tanks near to the detector in the main cavern.

THE ATLAS TEST FACILITY HALL

All the cryogenic components must be tested prior to their final installation in the underground cavern. This will be carried out in a large experimental hall with 10.000 m^2 of surface area which will be transformed into a cryogenics test facility permitting individual tests of BT and ECT magnets and the three liquid argon calorimeters. Four test stands will be required for the BT magnets which will be operated in parallel. Helium precooling units both for the magnets and calorimeters will be provided. A helium cryoplant already existing at CERN with a capacity of 1200 W@4.5 K will be used. The stringent schedule, especially the arrival of a pre-series prototype barrel magnet coil with approximately 1/3 of the length of the final magnets requires this test facility to be available in 1999, well before the start of delivery of the series magnets planned for 2001.

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