Testing the coils of the superconducting magnet for the Alpha Magnetic Spectrometer

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The Alpha Magnetic Spectrometer (AMS) is a particle physics experiment for use on the International Space Station (ISS). At the heart of the detector is a large superconducting magnet system cooled to a temperature of 1.8 K by 2500 litres of superfluid helium: both the magnet and cryogenic system are currently under construction by Space Cryomagnetics Ltd of Culham, England. The magnet consists of 14 superconducting coils arranged around the 1 m diameter warm bore. Each coil is tested under flight-like cryogenic conditions before assembly into the final configuration. This paper describes the design of the testing facility, and the results from the coil tests.

INTRODUCTION

The AMS experiment is designed to examine the fundamental physics of the universe, in particular through the search for antimatter and dark matter. Following a successful precursor mission on the US Space Shuttle (STS-91) the AMS collaboration decided to increase the sensitivity of the detector by upgrading the original permanent magnet arrangement to a superconducting system.

THE AMS MAGNET

The magnet consists of 14 coils arranged around the 1 m diameter ambient temperature bore (Figure 1). The two larger "dipole" coils generate magnetic field perpendicular to the axis of the bore which is useful for resolving incoming charged particles. The remaining twelve "racetrack" coils constrain the return flux to reduce the stray field from the magnet. This is vital for operation in space; otherwise the field from AMS would interact with the Earth's magnetic field to put a significant torque on the ISS [1]. A list of the principle magnet parameters is given in Table 1.

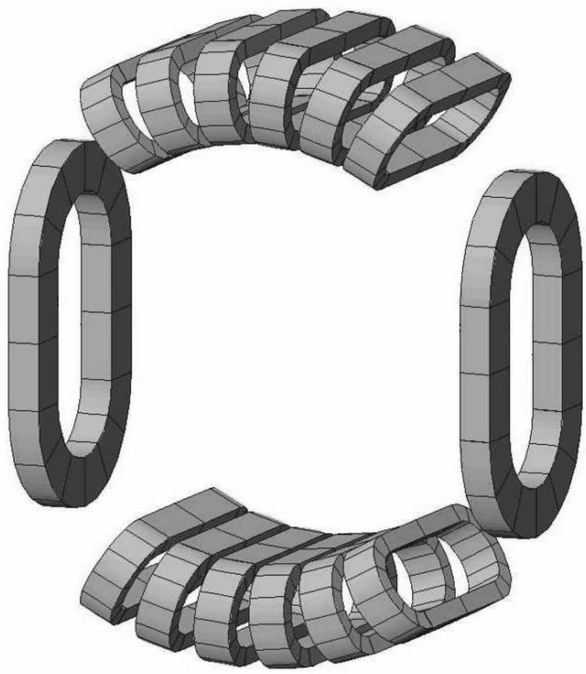

Figure 1 Layout of the AMS Magnet Coils

CRYOGENIC SYSTEM

The experiment will be launched fully cold with an inventory of 2500 litres of superfluid helium. The helium gradually boils away throughout the mission, and the experiment will end when it finally runs out.

One of the most important features of the cryogenic system is that the coils are not located inside the helium tank. This feature means that the magnet is able to quench in space without losing all of its helium inventory, and so can be re-cooled and operated again without requiring another mission to refill the helium vessel. The costs of a launch are so high that, no matter how unlikely a magnet quench may be, it is necessary to provide this fallback position.

For this reason, each coil is suspended inside the vacuum space, with copper heat shunts for removing heat from the winding. The heat shunts are connected in a number of positions to a thermal bus bar, which simply consists of a copper pipe filled with superfluid helium. Internal conduction inside the pipe is sufficient to transfer the heat away from the coils to the helium vessel.

Details of the design of the magnet cryogenic system have been published previously [2].

Table 1 Key magnet parameters

Parameter	Value
Magnet bore	1.115 m
Outer diameter of vacuum case	2.771 m
Length of vacuum case	1.566 m
Central magnetic flux density	0.87 T
Maximum magnetic flux density	6.59 T
Maximum operating current	459.5 A
Stored magnetic energy	5.15 MJ
Inductance	48.4 H
Operating temperature	1.8 K
Target endurance on orbit	3 years
Total mass (excluding vacuum case)	2300 kg

COIL TESTING REQUIREMENTS

The AMS magnet coils will all be tested individually before assembly into the flight configuration. It is advantageous to be aware of any potential problem at the earliest possible stage, and the cost of rectifying a problem after the magnet has been assembled could be prohibitive.

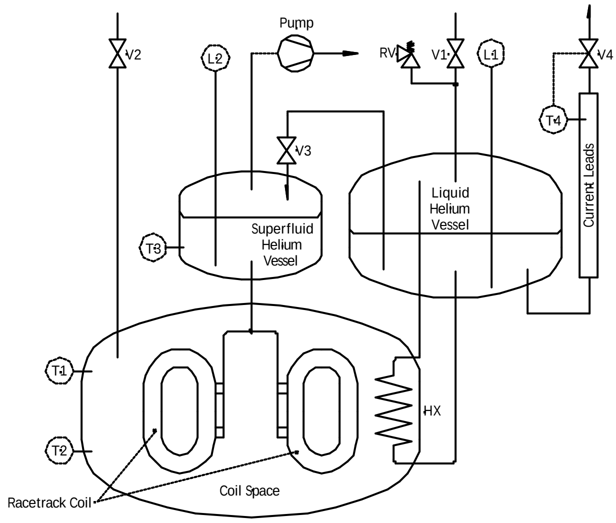

Figure 2 Schematic diagram of the coil test facility

To obtain the most benefit from the experiments, the coils need to be tested in conditions similar to flight. This means that the mechanical and cryogenic environments should be modelled as closely as possible (although, unfortunately, zero-gravity is not feasible).

The mechanical loadings on the coils are very different when they are charged individually, compared with the forces generated when the adjacent coils are present. In particular, the forces on the racetrack coils are much lower when tested singly than they are when the fully-assembled magnet is charged to the same current, but the forces on the dipole coils are higher during the single coil test. It is most important not to overload any parts of the coils during testing, so all are charged until some part of the winding experiences the same load that it will see in the full magnet assembly. During single coil testing, the racetrack coils are charged to currents higher than the nominal magnet current (four to 562 A, and eight to 600 A), but the dipole coils can only be operated at 335 A.

To make the test cryogenically representative of the flight system, the coil is mounted in vacuum, with its heat shunts connected to a pipe filled with superfluid helium. Figure 2 is a schematic diagram of the arrangement. (The liquid nitrogen shield and outer vacuum case have been omitted for clarity.)

TEST PROCEDURE AND RESULTS

The test facility is large enough to accept either two racetrack coils simultaneously (as in Figure 2) or a single dipole coil. Although this allows two racetrack coils to be cooled down together – saving a considerable amount of time – the coils have to be energised separately because of the large forces which would otherwise exist between them.

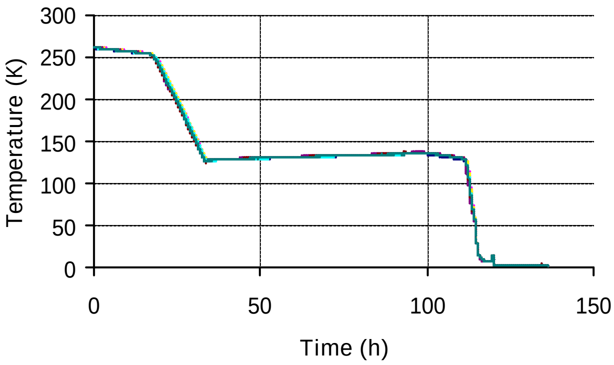

Figure 3 Racetrack coil cool down

Figure 4 The last two racetrack coils with the test facility

Cool down

Cooling the coils to their operating temperature of 1.8 K in vacuum is a necessarily complicated process. The objectives are to cool the coils as quickly as possible, while minimising the consumption of liquid helium, and avoiding large thermal gradients at temperatures above 100 K (which could damage the coils by differential thermal contraction).

First the coil space vessel is filled, through valve V2, with helium at ambient temperature as an exchange gas. The liquid helium vessel is then filled with liquid nitrogen, filling heat exchanger HX and setting up convection in the coil space which cools the coils. Once below about 120 K, the liquid nitrogen is removed and the coils are cooled directly by transferring liquid helium into the coil space until the temperature drops to about 10 K. Then the coil space is evacuated, and the liquid helium vessel filled with liquid helium at about 4.5 K. Once this vessel is full, some of the helium is transferred through valve V3 to fill the superfluid helium vessel. Finally, the helium in this vessel is pumped down to 16 mbar or less to reduce the temperature below 1.8 K. This helium fills the pipe connected to the heat shunts on the coils, and thus the coils are cooled to 1.8 K in the vacuum of the coil space vessel.

Figure 3 shows a typical cool down profile for one of the racetrack coils. The gentle cooling for the first 20 hours was simply a result of filling the radiation shield of the test rig with liquid nitrogen. The more rapid cooling between 20 and 30 hours was achieved by cooling the heat exchanger with liquid nitrogen transferred into the liquid helium vessel, as described above. About 70 hours later (the delay was due to a holiday period) helium was applied directly to the coil space: this corresponds to the rapid cool down from 130 to 10 K. Finally, liquid helium was transferred into the helium vessel and pumped down. Note that Figure 3 actually consists of the traces of 7 temperature sensors located at various positions on the surface of the coil: cooling was so evenly distributed that the coil was virtually isothermal.

Energisation
The coil is charged from an external power supply through vapour-cooled current leads. The changing current causes eddy currents to flow in the aluminium coil former (see Figure 4), and the warming effect of these can be seen from the thermometry to be a strong function of the current sweep rate. This warming effect will not be a problem for charging the magnet in orbit since the current sweep rate is much lower for the full magnet than for a single coil.

Training behaviour
Some of the racetrack coils have experienced training quenches at currents between the nominal magnet current (459.5 A) and the test current (either 562 or 600 A). Where such quenches have occurred, the coil has been re-cooled and re-charged. All twelve racetrack coils have been successfully charged to the maximum test current: in the worst case four training quenches were needed, but six of the coils required no training at all. None of the coils has quenched below the magnet operating current of 459.5 A.

Quench testing
The AMS magnet uses an electronic protection system to ensure that, in the event of a quench of the fully-assembled magnet, the stored energy is distributed evenly among the 14 coils. Each coil is therefore equipped with two heaters which can be powered externally to initiate a quench. One of the objectives of the tests was to check the operation of the heaters, and to measure the energy required to force a quench. Each coil – regardless of its training history - has therefore been deliberately quenched from the magnet operating current of 459.5 A, then re-cooled and re-energised.

Quench heater pulses with a power of 200 W were applied to the coils for periods increasing in increments of 10 ms. Although there was some scatter in the results from different coils, most of the racetracks required a pulse lasting 90 ms to initiate a quench. This means that the energy to quench is 18 J, so the coils are very stable.

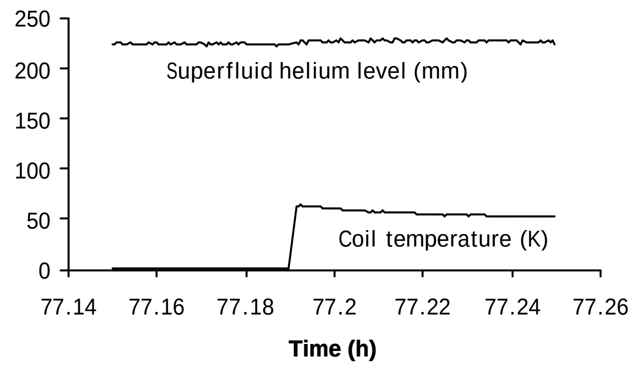

Figure 5 Temperature and level in a quench

It is of particular importance to AMS that a magnet quench does not lead to rapid loss of the helium inventory, because it is a requirement of the system that it should be possible to re-cool and energise it in space without the option of re-filling with liquid helium. Figure 5 shows how this has been achieved with the present design of indirectly-cooled coils: the level of the superfluid helium in the vessel remains almost constant, even though the temperature of the coil itself approaches 60 K.

CONCLUSIONS
A special test facility has been designed and constructed which allows the AMS superconducting magnet coils to be tested individually in a cryogenic environment which approximates to conditions on the International Space Station. The twelve racetrack (flux return) coils have been tested at currents exceeding the assembled magnet current, to simulate the mechanical loadings in service. Quench testing has also been performed on each coil to check the operation of the quench heaters and the stability of the coils. All tests have been successful, and the coils are now being assembled into the flight configuration.

REFERENCES

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2. Harrison, S.M., Ettlinger, E., *et al.*, Cryogenic system for a large superconducting magnet in space, IEEE Transactions on Applied Superconductivity (2003) 13 1381-1384