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Testing and Final Construction of the Superconducting Magnet for the Alpha Magnetic Spectrometer

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***Abstract*—The Alpha Magnetic Spectrometer (AMS) is a particle physics experiment based on the International Space Station (ISS). At the heart of the detector is a large superconducting magnet, cooled to a temperature of 1.8 K by superfluid helium. The magnet and cryogenic system have been designed and built by Scientific Magnetics (formerly Space Cryomagnetics) of Culham, England. This paper describes the results from magnet testing, and the final assembly of the magnet and flight cryostat.**

***Index Terms*—Cryogenics, space technology, superconducting magnets.**

I. Introduction

THE AMS experiment will examine the fundamental physics of the universe, in particular through the search for antimatter and dark matter. Following a successful precursor mission [1] on the 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. This version—AMS-02—will be launched to the International Space Station (ISS) before the retirement of the Shuttle fleet in 2010.

The magnet was completed in 2007, and tested in a specially-constructed test cryostat later in the same year.

II. The AMS Experiment

The AMS collaboration includes over 500 physicists from more than 50 institutes in 15 countries. Its objective is to study cosmic rays outside the Earth's atmosphere.

The experiment consists of a number of particle detectors clustered around the magnet, including a multiple-plane silicon tracker mounted in the cylindrical bore. The magnet generates a field perpendicular to the axis of the experiment, to give maximum resolution of particles passing through the tracker.

III. The AMS Superconducting Magnet

Many details of the design of the magnet have already been published [2], [3], as have results from the testing of the individual coils [4].

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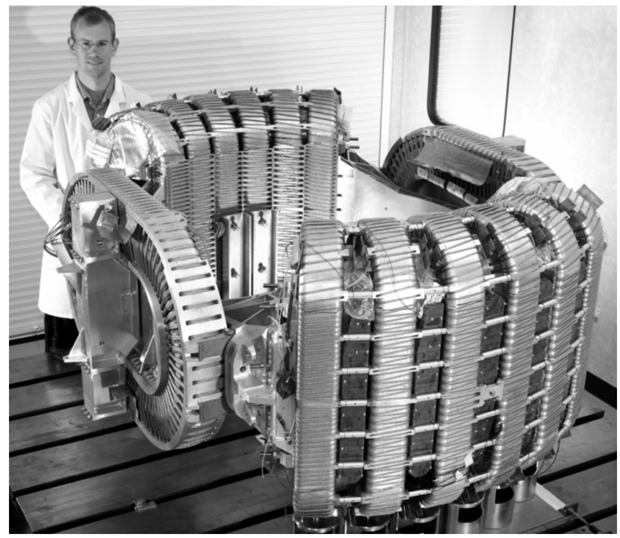

Fig. 1. Completed assembly of the AMS magnet coils before testing. The larger coils—which generate most of the useful field—are referred to as "dipoles". The two banks of 6 smaller shielding coils are called "racetracks".

Fig. 1 shows the magnet shortly after assembly of all the coils. This arrangement results in a dipole field perpendicular to the bore tube, with very low field outside the outer diameter of the vacuum vessel. The low stray field is of great importance: not only does it prevent interference with systems on the ISS, but it also reduces the interaction between AMS and the Earth's magnetic field which would otherwise impose an unacceptable torque on the space station.

IV. Test Facility

A. Design

In flight, the AMS magnet will not be in the helium vessel, but will be indirectly cooled using a system of pressurized superfluid helium-filled heat pipes [3]. This arrangement was reproduced for the test facility, except that the heat pipes were open to the helium vessel instead of being connected via a heat exchanger. Pressurization of the helium (to suppress boiling in the pipes which would otherwise disrupt the heat transfer) relied on hydrostatics, as the helium vessel was mounted above the magnet.

Fig. 2 shows the two cooling systems schematically. In both cases, the magnet is indirectly cooled to 1.8 K in vacuum. Cooling in the flight system should be more effective than in the test facility, as the pressure in the heat pipe will be greater. This will allow a larger temperature gradient between the coils

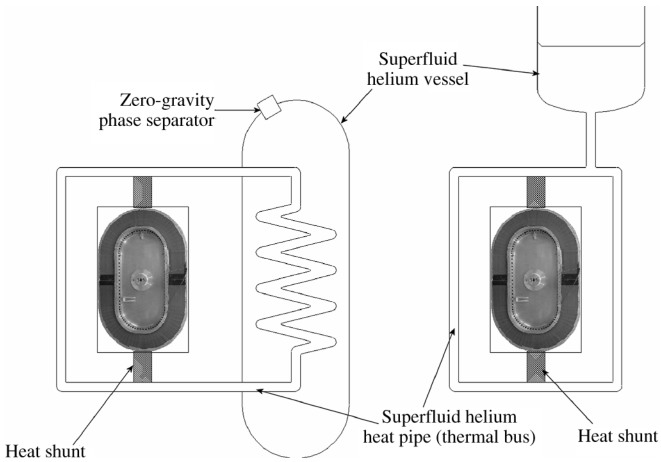

Fig. 2. Cooling arrangements for flight (left) and test (right), showing one coil to represent the whole magnet. In the flight system, heat is removed from the coils through heat shunts (strips of conductive metal connected to the coils), then transferred through the superfluid helium heat pipe to a heat exchanger where it is dissipated by boiling the stored liquid in the helium vessel. In the test arrangement, the heat pipe is connected directly to a header tank mounted above the magnet.

TABLE I
KEY MAGNET PARAMETERS IN THE TEST

Parameter	Value
Magnet bore	1.115 m
Central magnetic flux density	0.78 T
Maximum magnetic flux density	5.89 T
Maximum operating current	411 A
Stored magnetic energy	4.1 MJ
Inductance	48.4 H
Operating temperature	1.7-1.9 K

and the helium vessel, as the upper temperature in the heat pipe will be the lambda point, not the local boiling point.

B. Hardware

The test facility was engineered and designed by Scientific Magnetics. The liquid vessels, current leads, and much of the pipework were recycled from the test rig used for testing the individual coils. The large vessels and radiation shields surrounding the magnet itself, however, were contributed to the AMS project by the Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing. Manufacturing was undertaken by the Lanzhou Vacuum Equipment Company, then the components were shipped to Culham for integration with the rest of the test facility. Once assembly of the test cryostat was complete, the magnet was installed and all the plumbing and electrical connections made (Table I).

Fig. 3 shows the magnet suspended within the inner vacuum case (IVC). This is surrounded by two aluminum radiation shields connected to vessels in the upper part of the cryostat at 4.2 K and 77 K respectively (see Fig. 4).

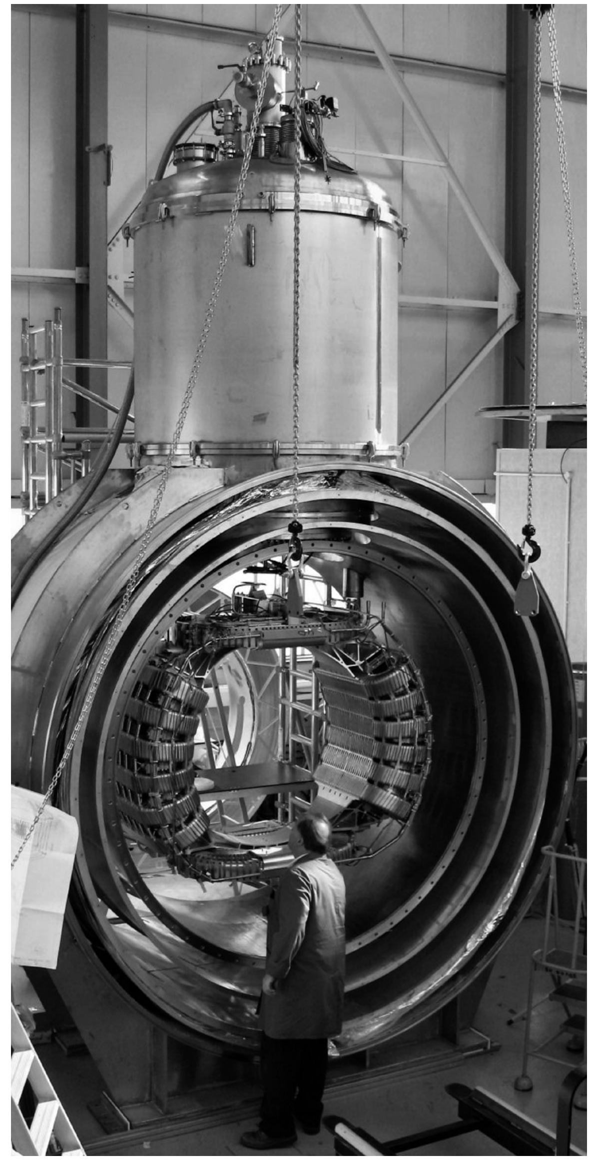

Fig. 3. The AMS magnet during installation in the test facility, before assembly of the vessel and radiation shield end caps.

V. Operation of the Test Facility

A. Cooling the Magnet

To cool the magnet from room temperature, it was surrounded by a helium atmosphere in the IVC which was itself cooled by a liquid nitrogen thermosiphon arrangement. The helium therefore acted as an exchange gas, providing very even cooling to the coils. In a large, multiple coil magnet such as AMS, it is important not to generate excessive thermal stresses due to large temperature gradients. Fig. 5 shows the temperatures of the coils as the magnet was cooled to 85 K.

The IVC was then evacuated and the magnet was cooled down by transferring liquid helium into the test rig vessels. During single coil testing, liquid helium had been transferred directly into the IVC, which was thermodynamically much more efficient. However, with the higher voltages expected

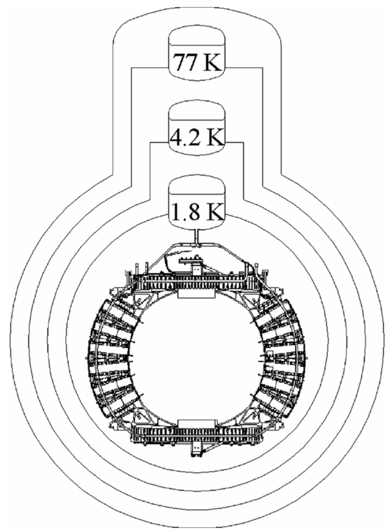

Fig. 4. Schematic diagram of the magnet test facility showing the shields linked to the vessels at 4.2 K and 77 K.

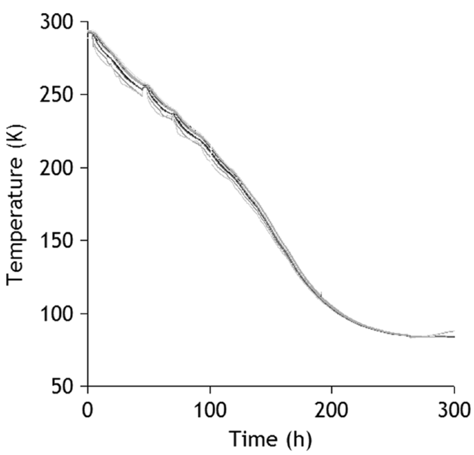

Fig. 5. Magnet coil temperatures during initial cool down. As in the other figures, the timescale is the elapsed time since the start of cooling.

during magnet testing, the risk of breakdown due to contamination of the IVC with low pressure helium was deemed too great to use this technique.

After a number of tests at low current (<100 A) at 4.2 K, the 1.8 K helium vessel was pumped down using a 1000 m^3/hr Roots pump to generate superfluid helium in the magnet cooling channels (Fig. 6). From this time on, the magnet was surrounded by vacuum and cooled by conduction to the superfluid-filled heat pipe. The only differences from the flight cooling arrangement were the presence of gravity, and that the helium in the cooling channel was at a lower pressure.

B. Charging the Magnet

The first charge was to 230 A, being 50% of the design current. The effects of eddy currents were observed as heating in all the coils: these were ramp rate dependent and decayed rapidly when the current was held steady.

After maintaining 230 A for 15 minutes the magnet was deliberately quenched by powering a set of heaters mounted on the structure of one of the dipole coils. The subsequent quenching

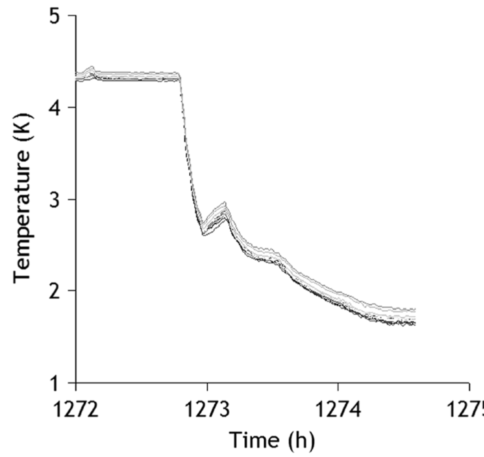

Fig. 6. Magnet coil temperatures while pumping down to 1.8 K. The interruption in the cooling at 1273 hours was due to refilling the helium vessel with liquid at 4.2 K.

of this coil generated a voltage imbalance with the other dipole. The quench protection system correctly interpreted this as a quench, and powered quench heaters on all the other coils to ensure even distribution of the stored energy throughout the magnet. The maximum temperature measured in a dipole coil was 56 K, and in a racetrack was 55 K.

The magnet was re-cooled and re-charged several times during the testing program. It quenched spontaneously on three occasions, once at 298 A and then later twice close to 410 A, which is 90% of the original design current.

The root cause for this apparent limit on the current has been difficult to establish. Fig. 7 shows the coil temperatures measured before the first quench at 410 A (plots from the second quench at this current were almost identical). When the current was around 300 A, both the dipole coils began to warm up: the magnet quenched when the temperatures reached about 2.4 K. Although the magnet itself should still have had some temperature margin, it is likely that the quench coincided with the transition from superfluid to normal helium in the cooling pipe, and a subsequent reduction in the heat transfer capacity.

Of more interest is the reason for the rise in the temperature of the coils. The dipoles appear to have been the source of the heating, with the other 12 coils warming up due to thermal coupling through the cooling circuit. Further testing showed that the warming was strongly dependent on the ramp rate: there may also have been some effect depending on whether the magnet was being charged rather than discharged, and there was limited evidence of an onset current, above which the effect first became apparent.

It has not yet been possible to determine why the dipole coils experienced this temperature rise. Detailed modeling of the cooling circuit has eliminated the cryogenic system as a possible culprit. A weak short between turns could, in principle, give rise to similar effects, but it is unlikely that this would arise identically in both dipole coils, and there was no evidence of shorted turns during manufacture or when the coils were tested individually.

In further testing, the magnet was charged on several occasions to currents around 400 A without incident. At low sweep

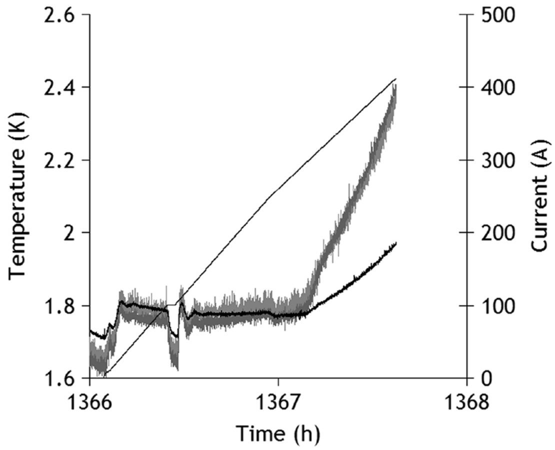

Fig. 7. Magnet coil temperatures before the first quench at 411 A. The straight line is the current: the others are temperatures. The trace which remains below 2 K before the quench is the average temperature measured on all the racetracks. The other lines are the two dipole temperatures, which are almost indistinguishable.

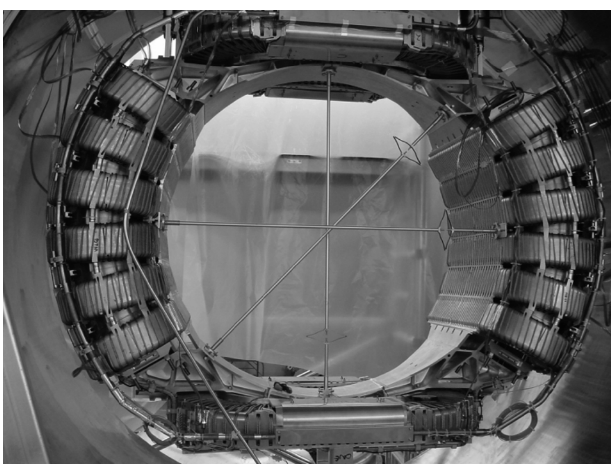

Fig. 8. Extensometers (three rods) mounted across the bore of the magnet before testing.

rates, the heating in the dipoles was dramatically reduced, and this leaves open the possibility that the magnet may be charged to higher fields in the flight cryostat.

C. Deflections of the Magnet Structure

To determine elastic movements of the structure under magnetic loads a system of extensometers was developed [5] which directly measured the distance across the bore of the magnet as it was charged (Fig. 8).

Peak deflections of around 1.5 mm were measured across the bore. These were slightly less than predicted from finite element analysis, and confirmed the integrity of the magnet structure.

VI. Current Status

The magnet testing program was completed in December 2007. The magnet was then removed from the test facility and

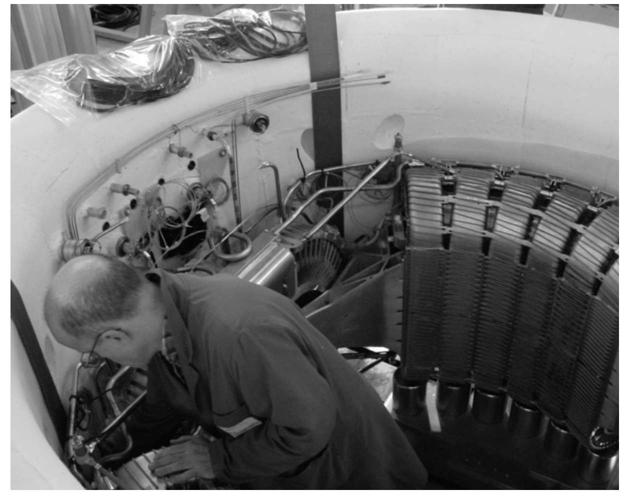

Fig. 9. The magnet being fitted into the bore of the helium vessel.

fitted into the bore of the helium vessel (Fig. 9). The cryogenic plumbing is complete, and the application of the superinsulation and radiation shields is well under way, in preparation for installing the system in the flight vacuum vessel.

VII. Conclusions

The AMS magnet has been tested at 90% of its design field in a test cryostat which reproduces as closely as possible conditions on orbit. Operations at higher fields were not possible because of heating in the dipole coils which is not fully understood. This heating is strongly dependent on the sweep rate so, by charging more slowly, higher fields may still be achievable in the flight cryostat if desired. The mechanical stability of the magnet was measured and confirmed during the testing. Integration of the magnet in the flight cryostat is proceeding.

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