Status of the Superconducting Magnet for the Alpha Magnetic Spectrometer

Stephen Harrison, Steve Milward, Robin Stafford Allen, Richard McMahon, Hans Hofer, Jürgen Ulbricht, Gert Viertel, and Samuel C. C. Ting

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 are currently under construction by Space Cryomagnetics Ltd of Culham, England. This paper describes the current status of the design and manufacture of the magnet system— including test results from the fourteen superconducting coils— and outlines the remaining work required to complete the project.

Index Terms—Superconducting magnets, Space technology, Cryogenics.

I. 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 [1] 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 design of the magnet system is virtually complete, and much of the hardware has been assembled and tested.

II. THE AMS EXPERIMENT

AMS is an international project, involving approximately 500 physicists from more than 50 institutes, based in 15 countries. The experiment comprises a series of particle detectors clustered around the magnet (Fig. 1), 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 [1].

Fig. 1. Exploded view of the AMS experiment, showing the different particle detectors arranged around the superconducting magnet.

III. THE AMS SUPERCONDUCTING MAGNET DESIGN

Some details of the design have already been published [2].

A. Magnetic Design

The magnet is toroidal in shape, with a warm bore of just over 1.1 m (Table I). The arrangement of the coils (Fig. 2) 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 avoid 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.

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S. Harrison, S. Milward, R. Stafford Allen and R. McMahon are with Space Cryomagnetics Ltd, E1 Culham Science Centre, Abingdon OX14 3DB, UK (phone: +44-1865-409200; fax: +44-1865-409222; e-mail: stephenharrison@spacecryo.co.uk).

H. Hofer, J. Ulbricht and G. Viertel are with the Eidgenössische Technische Hochschule (ETH), CH-8093 Zurich, Switzerland.

S. C. C. Ting is with the Massachusetts Institute of Technology, 51 Vassar Street, Cambridge, MA 02139-4307 USA.
B. Cryogenic Design

The cryogenic design has been described in detail previously [3].

The magnet is cooled by conduction to a vessel containing 2500 litres of superfluid helium at 1.8 K. It will be launched cold, with the vessel full. The helium will boil off throughout the lifetime of the experiment: once it has all gone, the magnet will no longer be operable. Surrounding the magnet and helium vessel are a series of four vapour-cooled shields: the outermost of these is also cooled by four Stirling-cycle coolers.

C. Mechanical Design

The mechanical loads are either magnetic or inertial. Magnetic loads are all reacted internally by the magnet structure, but the inertial loads have to be transmitted to the vacuum vessel by a system of composite straps. The straps are of a complicated design (to ensure minimal heat load between the vacuum vessel and the magnet at 1.8 K) and have therefore been subject to particular scrutiny and safety testing.

IV. MANUFACTURING STATUS

A. Structural Test Article

It is usual practice with space hardware to manufacture two identical systems. One of these will be for qualification, and will undergo mechanical and vibration testing to levels greater than those expected in service: the other will be tested to a less severe level and will be used for flight.

In the case of the AMS magnet, a full scale replica of the whole system would be prohibitively expensive and take far too long to be practical. Instead, a Structural Test Article (STA) is under construction for mechanical and cryogenic characterisation and testing. The STA is identical to the flight system in virtually all respects, except that the coils have been replaced by a mass dummy in the form of a specially-machined aluminium ring (Fig. 3). But two sets of radiation shields, helium vessels, valves, vacuum vessels, etc., are required: one for the flight system and one for the STA.

B. Coils and Support Structure

All 14 of the superconducting coils have been manufactured and tested, and most of the major items of support structure have been completed. Work is now proceeding to connect all these items into their flight configuration (Fig. 4).

C. Helium Vessel

The 2500 litres of superfluid helium is carried in an annular
vessel, consisting of inner and outer cylinders with hemispherical closures. Structural strength and rigidity is given by an aluminium stiffening ring which joins the two cylinders at the equator. All parts of the vessel are fabricated from aluminium alloy 5083: for weight optimisation the cylinders are ribbed, and all joints are welded (Fig. 5).

**D. Radiation Shields**

The radiation shields are manufactured from aluminium honeycomb with fibreglass skins, for high stiffness and minimum weight. Because the space available between the magnet and the inside of the vacuum vessel is restricted, the profile of the shields is complex, and the honeycomb panels have variable thickness. Two of the shields are now complete (Fig. 6) and ready to assemble once the coils and helium vessel have been put together.

**E. Vacuum Vessel**

The vacuum vessel is being produced in the USA on behalf of NASA. The identical vessels for both the STA and flight systems will be completed towards the end of 2004.

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**V. TESTING AND QUALIFICATION**

As well as the tests carried out on the magnet itself, and the qualification of the system for flight using the STA, a great deal of testing is being carried out at component and sub-assembly level. The scope ranges from vibration tests on safety-critical items (such as burst discs) to detailed cryogenic and charging tests on individual coils.

**A. Coil Tests**

Each of the fourteen magnet coils has been tested individually (Table II): some results from the flux return coil tests have been reported previously [4]. In each case, the coil was cooled down to 1.8 K in vacuum and charged to the maximum allowable current. Care was required in selecting the maximum current for the test: without the influence of the other 13 coils, the pattern of magnetic field and forces within the test coil was different. The maximum current for any coil was therefore defined as that current at which some part of the coil experiences the same load as that to which it will be subjected during flight. To keep weight to a minimum, there is very little margin in the mechanical structure so, if the current is increased beyond this limit, some part of the coil will actually be overstressed. The maximum current allowed in the large coils (which generate the dipole field) was 335 A, while some of the flux return coils were charged to 600 A. These figures can be compared with the design current for the fully-assembled magnet of 459.5 A.

As well as the maximum current test, all the coils were quenched deliberately using film heaters, and then re-charged.

**B. Strap Tests**

The straps suspend the cold mass of the coils and helium vessel from the structural parts of the vacuum vessel. The rate of change of load with deflection of each strap may have any

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**TABLE II**

<table>
<thead>
<tr>
<th>Coil</th>
<th>Maximum allowable current</th>
<th>Number of training quenches</th>
<th>Stable current achieved</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>600 A</td>
<td>3</td>
<td>600 A</td>
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<tr>
<td>2</td>
<td>600 A</td>
<td>1</td>
<td>600 A</td>
</tr>
<tr>
<td>3</td>
<td>562 A</td>
<td>0</td>
<td>562 A</td>
</tr>
<tr>
<td>4</td>
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<td>3</td>
<td>600 A</td>
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<td>0</td>
<td>335 A</td>
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<td>14</td>
<td>335 A</td>
<td>0</td>
<td>335 A</td>
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</tbody>
</table>

Coils 13 and 14 are the larger coils generating most of the dipole field. All coils reached their target current and will be used in the flight system.

Coil testing has also been useful for testing other systems in the background field, such as electrically-actuated valves.

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**Fig. 5.** The central ring of the helium vessel. Under the watchful eye of a specialist from NASA, welding operations are carried out by the vessel fabricator, Bieri Engineering in Winterthur, Switzerland.

**Fig. 6.** One of the vapour-cooled shields. The shield is constructed from aluminium honeycomb with fibreglass skins: it will later be covered with high-purity aluminium for heat conduction.
of three different values, depending on the applied load and the thermal conditions (whether the magnet is cold or warm). With 16 straps acting together, the analysis of the system dynamics during launch is immensely complicated: it has therefore been of particular importance to test the straps thoroughly so that the algorithms used for modelling their behaviour are as accurate as possible.

The straps have been tested to failure in tension at ambient and cryogenic temperatures, they have been tested for fatigue, and tested dynamically (Fig. 7). All tests have been passed successfully.

C. Component Level Testing

In addition to these tests on large pieces of hardware, a range of tests has been carried out on smaller components, such as burst discs, valves, cryocoolers, electronics, sensors, and heat exchangers. The tests include functional qualification (checking that the component operates according to specification), vibration testing, thermal testing, and superfluid helium leak testing. A few critical components have been subjected to vibration tests at temperatures as low as 10 K.

VI. Future Work

With all of the major components of the magnet system either complete or in manufacture, most of the remaining work consists of continuing tests on components and larger assemblies, in parallel with the assembly of the STA and flight system. A large cryogenic station is also currently being designed, so that the system can be operated at the Kennedy Space Center [5].

A. Magnet Test

Once all 14 coils have been put together into the full magnet configuration, this assembly will be tested to ensure the correct operation of all coils and support structure. Only after this test is complete will assembly into the flight cryostat begin. The cryostat used for testing individual coils is being modified to accept the complete magnet.

B. Helium Vessel Test

It is vital for the reliability of the system that the helium vessel should be fully leak tight. A special test cryostat has been built (Fig. 8) which will allow the completed helium vessel to be mounted with its axis horizontal, and filled with liquid helium. The pressure of the helium will then be reduced by pumping to generate superfluid. Because this process will leave the vessel less than half full, the cryostat is designed to rotate slowly about the horizontal axis. This will ensure that every part of each weld is in contact with the superfluid and can be guaranteed leak proof.

VII. Conclusions

The AMS magnet will be the first large superconducting magnet in space and, as such, presents a number of unique challenges. Good progress continues to be made with the construction of the system, with all 14 coils having been successfully completed and tested.

REFERENCES