

Cryogenic System for a Large Superconducting Magnet in Space

Stephen M. Harrison, Erich Ettliger, Gunter Kaiser, Bertrand Blau, Hans Hofer, Istvan L. Horvath, Samuel C. C. Ting, Jürgen Ulbricht and Gert Viertel

Abstract—The Alpha Magnetic Spectrometer (AMS) is a particle physics experiment for use on the International Space Station (ISS). At the heart of the detector will be a large superconducting magnet cooled to a temperature of 1.8 K by 2500 litres of superfluid helium. The magnet and cryogenic system are currently under construction by Space Cryomagnetics Ltd of Culham, England. This paper describes the cryogenic system for the magnet, designed for the unusual challenges of operating a superconducting system in space. Results from experiments demonstrating some of the new techniques and devices developed for the magnet cryogenics are also presented.

Index Terms—Cryogenics, space technology, superconducting magnets, superfluid helium.

I. INTRODUCTION

THE AMS experiment is designed to examine the fundamental physics of the universe, particularly 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.

Although there have been a number of cryogenic helium space missions, AMS will be the first large superconducting magnet to be used in space. The designers have therefore been presented with a number of unique challenges, especially with regard to the cryogenic system required to keep the magnet cold, operational and safe.

II. MAGNET

The magnet consists of fourteen coils connected in series

Manuscript received August 5, 2002.

S. M. Harrison is with Space Cryomagnetics Ltd, E1 Culham Science Centre, Abingdon, England (telephone: +44-1235-463964; fax: +44-1235-463638; e-mail: info@spacecryo.co.uk).

E. Ettliger is with Linde AG, Dr.-Carl-von-Linde-Strasse 6-14, 82049 Hoellriegels kreuth, Germany.

G. Kaiser is with the Institute for Air Conditioning and Refrigeration, Bertolt-Brecht-Allee 20, 01309 Dresden, Germany.

B. Blau, H. Hofer, I. L. Horvath, J. Ulbricht and G. Viertel are with the Eidgenössische Technische Hochschule Zurich.

S. C. C. Ting is with the Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

(Fig. 1). The two larger coils provide the majority of the field



Fig. 1. Arrangement of the AMS magnet coils. The larger coils generate most of the transverse field: the smaller coils constrain the return flux.

- perpendicular to the axis of the detector - useful for deflecting the incoming particles. The other twelve coils contribute a small amount to this perpendicular field, but their main function is to reduce the stray field from the larger coils [1]. Table 1 lists the main parameters of the magnet system, and Fig. 2 shows the layout of the coils, helium vessel and vacuum case.

III. SPACE CRYOGENICS

To date, there have been four large liquid helium payloads launched into orbit. These are the Infrared Astronomical Satellite (IRAS), the Cosmic Background Explorer (COBE) [2] and the Superfluid Helium On-Orbit Transfer (SHOOT) demonstration [3] – launched by NASA – and the Infrared Space Observatory (ISO) launched by the European Space

TABLE I
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	3 years
total mass ^a	2300 kg

^aExcludes the vacuum case, which forms a part of the experiment support structure.

Agency (ESA). Of these, IRAS, COBE and ISO were all infrared telescopes, and SHOOT was an experiment to demonstrate the technology of superfluid helium transfer in zero gravity.

The cryogenic system for AMS draws on the techniques developed for all these systems, but having a superconducting magnet introduces some new features. These include leads capable of transferring the operating current of almost 460 A from the ambient temperature power supply to the magnet at 1.8 K, the wide range of heat loads in normal operation due to charging and discharging the magnet, and the requirement to cool the persistent switch which allows the magnet to operate without an external power supply. It is also necessary to consider the effect of the magnetic field on other parts of the system such as thermometers, cryocoolers and even the helium itself.

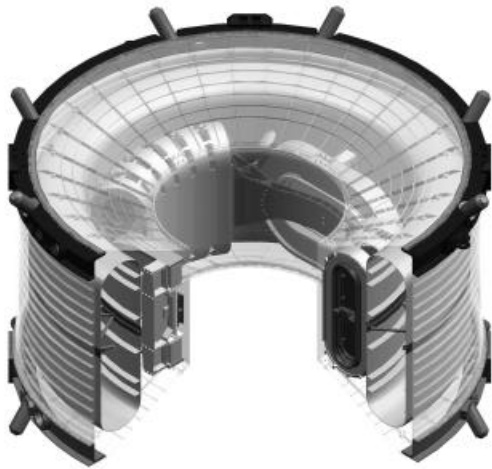


Fig.2. Arrangement of the AMS magnet showing the helium tank and magnet coils inside the vacuum case.

IV. AMS MAGNET CRYOGENIC SYSTEM

The purpose of the cryogenic system is to keep the magnet coils superconducting under all operating conditions while maximising the lifetime of the experiment. It must also allow the magnet to be re-cooled and operated again following a quench in space. The system will be launched cold, carrying sufficient liquid helium to last for the entire mission.

A. Helium Management and Endurance

The AMS magnet is cooled using superfluid – rather than normal liquid – helium. This is decided by two important factors. Firstly, the specific latent heat and density of superfluid helium are both higher than for normal liquid. Since the amount of cryogen which can be carried is limited by the available volume for the helium tank this gives a useful endurance benefit. Secondly, in zero gravity there can be no convection currents. In normal liquid helium this can result in thermal stratification, making it difficult to ensure that all parts of the system are fully cold. In superfluid, however, the

very high thermal conductivity ensures that the helium remains isothermal.

As in all helium cryogenic systems, the key to maximising the endurance is to keep the heat leak to the liquid to a minimum while using the entire enthalpy of the boiled off vapour to remove incoming heat at the highest possible temperature. To achieve this, it is necessary to separate the liquid and vapour phases, and constrain the vapour to flow through a series of radiation shields before venting it to the vacuum of space.

1) Phase Separation

The superfluid helium is stored in a 2500 litre toroidal vessel. This is a fully-welded, aluminium alloy structure, currently under construction in Switzerland. Welded into the top of the vessel is a zero-gravity phase separator, developed by Linde in Germany. The phase separator is similar in construction to that used on ISO, consisting of a porous plug of sintered stainless steel in a steel housing. With careful design and testing, the porous plug can work as a phase separator even in the absence of gravity [4]. Instead of buoyancy, it uses the thermo-mechanical effect [5] to separate the liquid from the vapour.

2) Vapour Cooled Shields

To obtain the maximum magnetic field, the gap between the coils and the vacuum case has to be as small as possible: this leaves very little room for the shields and superinsulation, especially on the magnet bore, and has made the design of the shields particularly challenging.

The helium vapour, separated by the porous plug, flows through four concentric shields at successively higher temperatures, removing radiated heat as well as intercepting conducted heat from support straps and other components.

Two of the shields are of a rigid composite honeycomb structure, designed for minimum thickness while retaining sufficient strength to withstand the loads associated with a Space Shuttle launch and landing. The other two shields are flexible, made from sheets of soft aluminium: this makes for slightly less than ideal thermal performance but it does allow the shields to be very thin, which is vital for optimising the magnetic field.

3) Cryocoolers

To extend the helium lifetime, four Stirling cycle cryocoolers are connected to the outer shield. The coolers are qualified and tested by a team at NASA Goddard Space Flight Center, and are expected to remove a total of approximately 12 W at around 68 K. One of the initial concerns over the cryocoolers was whether their operation or performance would be compromised by the presence of the magnetic field. However, recent testing carried out by NASA [6] has demonstrated that the cryocoolers can be operated without problems or degradation in the stray field generated by the magnet.

4) Mass Gauging

In zero gravity there is no clearly defined liquid level, so conventional helium level probes cannot be used. Instead, a

calorimetric method is used to determine the mass of helium in the tank. Detailed analysis of the technique has been published [7] but the principle is simple. A heat pulse is applied to the helium while the temperature is monitored some distance away in the tank by an accurate thermometer. Because of the high thermal conductivity of the superfluid, the helium in the tank is isothermal. The heat pulse is therefore manifest not by local boiling of helium but by a small rise in the temperature of the entire helium bath, measured by the thermometer. Knowing the energy dissipated by the heater and the temperature rise in the bath, the mass of helium can be deduced.

The mass gauging system for the AMS magnet is similar to the one used on ISO and is being developed by Linde in Germany. The performance depends most strongly on the accuracy of the temperature measurement, and is therefore limited by the space qualified electronics.

B. Steady State Cooling System

The requirement that it should be possible to re-cool the magnet after a quench on orbit effectively precludes mounting the coils inside the helium vessel. It is therefore necessary to cool the coils by conduction to the superfluid helium in the tank. The ideal conductor would have very high thermal conductivity at very low temperatures (to remove steady state and charging heat loads from the coils) but very low conductivity at higher temperatures (to avoid transferring heat too quickly to the superfluid tank following a quench). Fortunately, helium itself satisfies these requirements, having extremely high thermal conductivity in the superfluid state below 2.17 K, but relatively low conductivity above this temperature.

The coil cooling scheme, based on this principle, is shown schematically in Fig. 3. Each coil is connected at two positions to a thermal bus bar which consists of a copper pipe filled with superfluid helium. Part of the thermal bus bar is inside the main superfluid helium tank and so acts as a heat exchanger. Heat radiated to (or generated in) the coils is transferred by Gorter-Mellink conduction through the superfluid helium in the thermal bus bar and dissipated by boiling the helium in the tank. The bus bar circuit has to operate above the saturation pressure to suppress any boiling at the surfaces where heat is removed, so some means of external pressurisation is needed.

The copper pipe forms a sealed circuit, filled with helium while the magnet is being cooled down, but there is no net flow through it. Similar schemes have been proposed in the past [8] incorporating a thermo-mechanical pump (TMP) to induce a flow round the cooling circuit to improve the heat transfer. Typically, the power for the TMP is simply the heat load of the magnet. For the AMS magnet, although such schemes were analysed, there was no clear benefit to set against the added complexity and development effort required.

Analysis of the flow of heat around the thermal bus bar

requires the solution of the non-linear differential equation describing Gorter-Mellink conduction. The methodology used in this case was based on that developed by Mord and Snyder [8] and adapted for the AMS magnet geometry.

C. Current Supply

The magnet can be operated at currents up to 459.5 A. It is equipped with persistent switches allowing it to continue to operate, once charged, without connection to the external power supply. The leads, which supply current from the power supply to the magnet, are therefore only rarely used.

For this reason, the leads are designed for minimum heat leak at zero current, making them rather inefficient during charging. This is achieved by making the cross-section of the leads relatively small. When the magnet field is constant and the leads carry no current, the conducted heat load is therefore minimised. During charging, the leads generate a substantial amount of Joule heating which can only be removed by forced cooling with helium from the superfluid

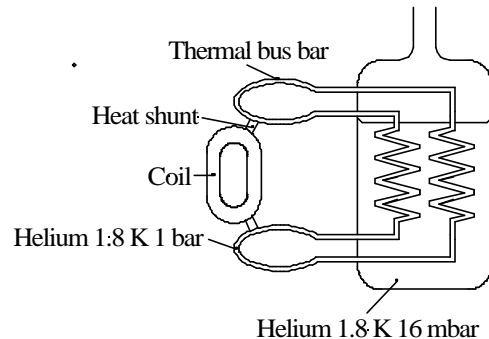


Fig.3 Schematic diagram of the superfluid-filled thermal bus bar cooling arrangement.

tank. However, the tank itself operates at a pressure of just 16 mbar, which is almost certainly not high enough to ensure a sufficient flow of helium.

A thermo-mechanical pump (TMP) is therefore connected to the superfluid helium tank. The TMP is used to pump helium from the tank through the current leads to provide cooling when required. TMP technology in space was first demonstrated by NASA in 1993 [3] but the TMP for the AMS magnet is being developed independently by the Institute for Air Conditioning and Refrigeration (ILK) in Dresden, Germany [9].

A further improvement in the current leads thermal performance is given by a disconnect feature towards the warm end of the leads. This device, at present under development, provides a complete thermal and electrical break in the leads when the persistent switch is closed.

D. Cryogenic Safety

As with any cryogenic system, safety of equipment and personnel is the first priority. As the AMS magnet will be launched on the Space Shuttle, safety has to be assured in ground handling operations, during launch, and on orbit. All

cryogenic volumes, as well as the vacuum case, are protected by burst discs to prevent excessive pressures building up in any fault conditions. Some of the discs have to operate at temperatures below 2 K, and these are the subject of a special development and testing programme.

In addition, extra protection is provided to mitigate the effect of a catastrophic loss of vacuum. This could be caused, during ground handling, by a serious rupture of the vacuum case. To slow down the rate of pressurisation and venting of the helium, a thin (3 mm) layer of lightweight cryogenic insulation is applied to the outside surface of the helium vessel. Carefully constructed experiments [10] have shown that this insulation can reduce the heat flux to the superfluid helium by a factor of 8 following a sudden, total loss of vacuum.

E. Valves

The cryogenic valves have also been developed specially for the AMS magnet by Weka in Switzerland. Previous superfluid helium space missions have used valves actuated either by stepper motors or by solenoids. The AMS valves have to be operated in magnetic fields up to 2 T so electrical actuation is not ideal. Instead, the valves are actuated by pressure from an external supply of warm helium gas. Under normal operation, the valves are held closed by springs, so the actuators are only used when the valves have to be opened during cool down, filling, or charging operations. This means that the only connections between each valve and the vacuum case are a capillary tube to supply the actuating gas and instrumentation wires for monitoring the valve position.

V. TEST RESULTS

An extensive testing programme is under way, both at a component level (items such as valves and persistent switches) and at a system level to prove the concepts and hardware developed for the AMS magnet cryogenic system.

A. Steady State Cooling System

A full-scale replica of the superfluid thermal bus bar system outlined above was designed and constructed by Space Cryomagnetics Ltd. The replica consisted of a thermal bus bar in the form of a 20 m long sealed copper pipe with a 15 mm bore. Part of the pipe was inside a 200 litre helium vessel to provide a cold heat exchanger: the rest was in the vacuum space.

The copper pipe was connected to an external, clean supply of helium. The vessel was cooled down and filled with liquid helium which was then further cooled to 1.8 K by pumping. Helium was drawn into the copper pipe due to the cooling, but the pressure in this circuit was maintained at around 1 bar. Eventually, the vessel contained boiling superfluid helium at 1.8 K and 16 mbar, but the pipe was filled with supercooled helium at 1.8 K and 1 bar.

Heaters on the part of the thermal bus bar outside the

helium vessel were then used to simulate the heat load due to the magnet coils being charged. Up to 6 W could be generated by the heaters and transferred through the thermal bus bar to be dissipated in the vessel of boiling helium. If more power was generated in the heaters, the thermal bus bar was unable to transfer all the heat and temperatures within it began to rise rapidly.

B. Loss of Vacuum Experiments

A series of experiments has been carried out to investigate the results of catastrophic loss of vacuum on a vessel filled with superfluid helium. Work continues to determine the effect of a relatively slow leak of air into the vacuum space.

C. Coil Testing

Each of the AMS magnet coils will be tested individually before the system is assembled. A facility has been designed and built by Space Cryomagnetics Ltd which allows a single coil to be tested in a configuration identical to the full system: mounted in vacuum and cooled by conduction to a superfluid helium-filled, thermal bus bar. So far, just the first coil has been tested. With this arrangement, the coil was cooled to 1.6 K and charged to the full operating current.

VI. FUTURE PLANNED TESTS

Further testing of various components of the system is planned, including cold (4 to 10 K) vibration testing of cryogenic valves and persistent switches.

VII. CONCLUSIONS

Progress continues to be made in the design, testing and manufacturing of the AMS superconducting magnet and cryogenic system. In particular, the use of superfluid helium in a thermal bus bar configuration has been demonstrated on a scale appropriate for cooling a 3 m diameter magnet system. Testing and qualification of many parts of the system is yielding encouraging results.

REFERENCES

- [1] B. Blau, S. M. Harrison *et al.*, "The superconducting magnet system of AMS-02 – a particle physics detector to be operated on the International Space Station," *Proceedings of the 17th International Magnet Technology Conference*, to be published.
- [2] S. M. Volz *et al.*, "Cryogenic on-orbit performance of the NASA Cosmic Background Explorer (COBE)," *SPIE Vol. 1340 Cryogenic Optical Systems and Instruments IV*, pp. 268–279, 1990.
- [3] M. J. DiPirro, P. J. Shirron and J. G. Tuttle, "The transfer of superfluid helium in space," *Cryogenics Vol. 34 ICEC supplement*, pp. 267–272, 1994.
- [4] A. Nakano, D. Petrac and C. Paine, "He II liquid/vapour phase separator for large dynamic range operation," *Cryogenics Vol. 36*, pp. 823–827, 1996.
- [5] A. Kent, *Experimental low-temperature physics*. Macmillan, 1993, pp. 54–57.

- [6] S. Breon *et al.*, "Operation of a Sunpower M87 cryocooler in a magnetic field," *Proceedings of the 12th International Cryocooler Conference*, to be published.
- [7] M. J. DiPirro, P. J. Shirron and J. G. Tuttle, "Mass gauging and thermometry on the superfluid helium on-orbit transfer flight demonstration," *Advances in Cryogenic Engineering Vol. 39*, pp. 129–136, 1994.
- [8] A. J. Mord and H. A. Snyder, "Self-driven cooling loop for a large superconducting magnet in space," *Cryogenics Vol. 32*, pp. 205–211, 1992.
- [9] G. Kaiser *et al.*, "Thermo-mechanical superfluid helium pumps for Alpha Magnetic Spectrometer (AMS-02) mission," *Proceedings of the 19th International Cryogenic Engineering Conference*, to be published.
- [10] S. M. Harrison, "Loss of vacuum experiments on a superfluid helium vessel," *Proceedings of the 17th International Magnet Technology Conference*, to be published.