

Texturing of micaceous superconductor powder and fabrication of wire to preserve the texture

Peter McIntyre for the AMS Collaboration

Abstract—The superconducting magnet, cryogenics, and detector systems of the AMS experiment was fully integrated and tested in test beam at CERN during 2009. In Spring 2010 the experiment underwent thermal vacuum tests at ESTEC, where it was operated in conditions simulating those that will pertain in orbit. All elements of the superconducting magnet and cryogenics performed as designed, and equilibrium operation was attained at several values of vacuum case temperature. Details of the tests are presented. A thermal model of the overall cryogenic system was calibrated from those measurements. The model was used to predict the cryogenic lifetime of the experiment, as it would be staged on ISS, to be (28 ± 6) months.

Index Terms—high temperature superconductor, texture, powder processing, wire.

I. INTRODUCTION

THE Alpha Magnetic Spectrometer (AMS) is an experiment scheduled to be installed on the International Space Station (ISS). AMS will provide high statistics, long duration measurements of charged particle and nuclei spectra from 0.1 GeV to 3 TeV [1]. It will also measure high energy gamma rays up to 0.3 TeV with an angular resolution of 2 arc-sec.

The AMS spectrometer employs a 0.86 T superconducting dipole magnet [2], shown in Fig. 1a. The requirements of minimum fringe fields and zero total dipole moment dictated the coil configuration. A pair of field coils produces the dipole field and two sets of racetrack windings return flux symmetrically around the central bore. The windings are made using Al-stabilized NbTi/Cu conductor (Fig. 1b), maintained at 1.8 K using conduction cooling with superfluid He (SFHe).

One racetrack winding is shown in Fig. 1c. The conductor is wound and impregnated on an Al support; the completed coil is pre-stressed by winding a stainless steel wire rope around the winding, as shown in Fig. 1d.

The magnet is enclosed in a toroidal cryostat with inner diameter 1.1 m, outer diameter 2.7 m and length 0.9 m. Supporting electronics, valves and cabling are located outside of the cryostat.

II. CRYOGENIC DESIGN

The cryogenic system for the magnet contains a number of

Manuscript received 3 August 2010. This work was supported in part by the U.S. Department of Energy under Grant DE-FG03-95ER40924. P. McIntyre, is with the Department of Physics, Texas A&M University, College Station, TX (corresponding author: Peter McIntyre, phone: 979-255-5531; fax: 979-845-2590; e-mail: mcintyre@physics.tamu.edu).

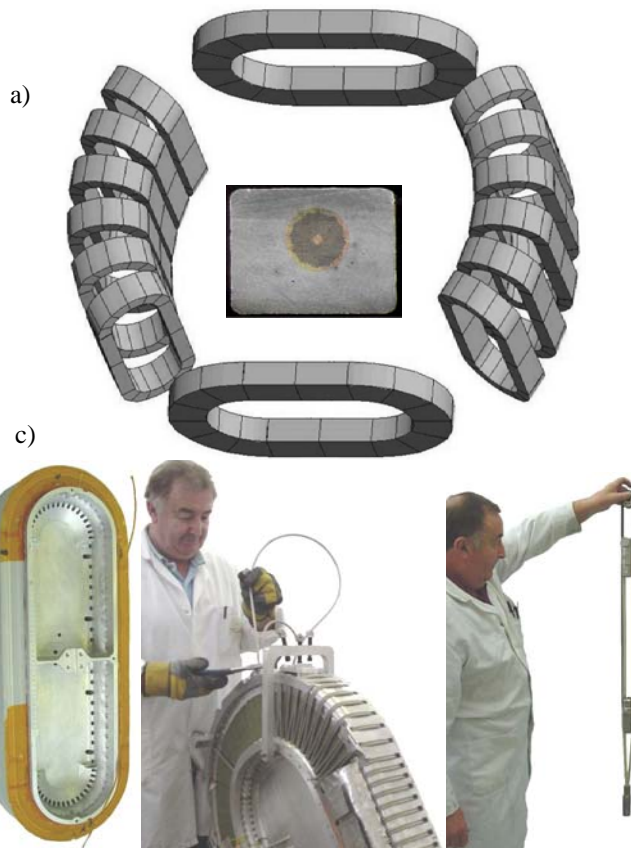


Fig. 1. a) AMS magnet windings; b) cross-section of $2 \times 1.5 \text{ mm}^2$ conductor; c) one racetrack winding; d) application of wire rope preload; e) segmented tension strap used to support cold mass.

novel features that are required to satisfy the extreme challenges of operation in the zero-g space environment [3].

A. Heat transfer from SFHe reservoir to magnet

The coil is refrigerated using superfluid helium (SFHe). A 2500 liter SFHe reservoir surrounds the magnet within its cryostat, and provides the entire inventory of SFHe to sustain

TABLE I. MAIN PARAMETERS OF AMS MAGNET

Central magnetic field	0.86	T
Max. fringe magnetic field @ $R=2.3 \text{ m}$	15	mT
Max. field in dipole windings	6.6	T
Max. field in racetrack windings	5.9	T
Max torque in geomagnetic field	0.27	Nm
Coil current at design field	460	A
Stored energy	5.2	MJ
Inductance	48	H

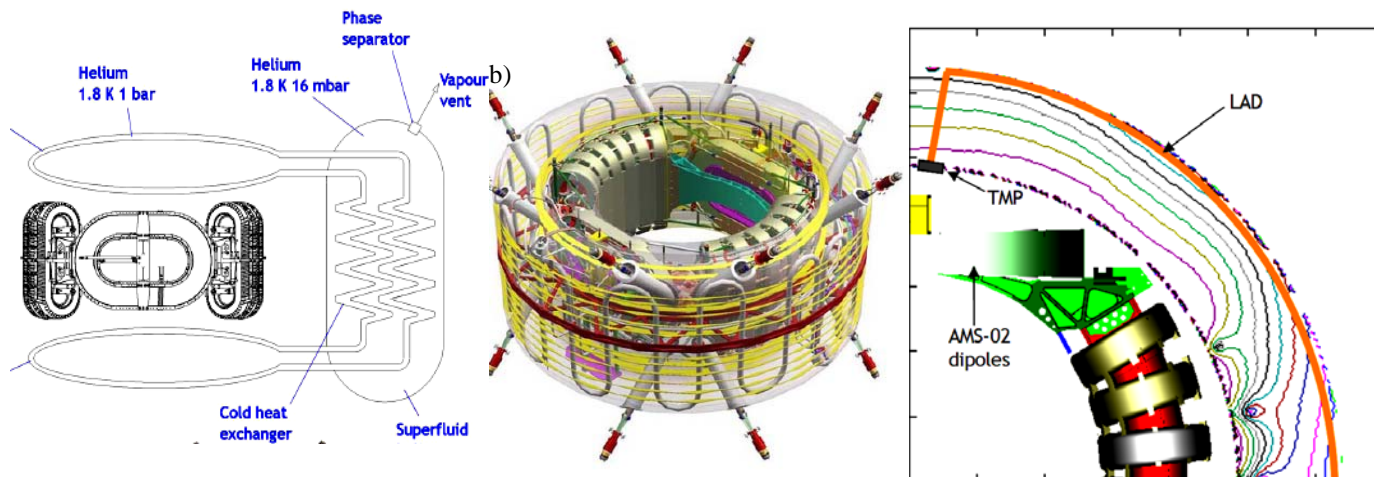


Fig. 2. a) Schematic showing SFHe transport through thermal bus bar between reservoir and magnet windings; b) cross-section showing thermomechanical pump, capillary bundle to gather SFHe, c) contours showing distribution of SFHe due to force exerted by magnetic field on diamagnetic SFHe.

the magnet for at least 3 years of AMS operation. The magnet and reservoir are supported within a tightly conformal vacuum shell. The cold mass is supported by a network of 16 tension straps as shown in Fig. 2b.

Heat transfer from the magnet to the reservoir is illustrated in Fig. 2a. The magnet is conduction-cooled by heat transfer from Cu foil shunts embedded in each winding. SFHe flows through two serpentine loops (thermal bus bars) to transfer heat from the windings to the reservoir efficiently. Heat produced in the coils is transferred by Gorter-Mellink conduction through the SFHe in the thermal bus bar and is dissipated by boiling to He vapor in the reservoir. During operation the reservoir contains a mixture of SFHe and He vapor. SFHe is diamagnetic, so in zero gravity SFHe will tend to regions of the reservoir with minimum magnetic field, as shown in Fig. 2c.

Two thermomechanical pumps (TMP) are used to force SFHe flow during particular times. One is used to force SFHe flow through the two current leads while they are connected to charge current in the magnet coil. A second TMP is used to force flow to re-cool the magnet after quench. A capillary bundle (LAD) is used to gather SFHe that is dispersed in the low-field regions of the reservoir and deliver it to the input of the TMPs, as shown in Fig. 2c.

Heat is removed from the reservoir by boiling liquid He. The vapor is separated at the entrance to the vapor exit channel by a phase separator plug, in which a temperature gradient blocks exit of SFHe.

The SFHe conduction-cooled cryogenics maintains the windings at operating temperature during normal operation. During a quench the thermal bus bars would go normal, limiting heat transfer to the reservoir during the quench to protect the inventory of SFHe in the reservoir from being lost.

A. Vapor-cooled heat shields and cryocoolers

The magnet and reservoir are contained within a set of four intermediate-temperature vapor-cooled shields (VCS). Each VCS is constructed as a curtain of strips of high-purity aluminum, draped to form a cylindrical curtain surrounding the cold mass. This strip segmentation was done to inhibit eddy currents from being excited during charging and quench. Each strip is secured to tubing rings at the top and bottom. VCS1

and VCS3 had rigid composite shells to provide structural spacing between the shields. A total of 130 layers of multi-layer insulation (MLI) are interspersed with the four VCS to block radiant transfer. In the as-built system there was much less space available for the MLI between VCS than was designed, and so it was necessary to remove the inner cylindrical portion of the shells and to significantly compress the MLI in order to assemble the cryostat.

The He vapor exiting the reservoir passes through the tubing rings of each VCS in turn so that its enthalpy is efficiently used to intercept ambient heat transport and maintain the shields at nominal temperatures: VCS1 @ 15 K, VCS2 @ 12 K, VCS3 @ 25 K, and VCS4 @ 70 K.

Four Stirling-cycle cryocoolers are connected symmetrically (two on top, two on bottom) to VCS4. Each cryocooler is capable of pumping 12 W of heat from 70 K to ambient temperature with 100 W of power consumption. The ambient heat load is dissipated on zenith-facing radiator panels located on the outside surface of the instrument.

III. MECHANICAL SUPPORT

The magnet plus SFHe reservoir has a mass of ~2 tons, and must be supported under static support on Earth, during launch, and in zero-g on ISS. A system of 16 support straps (Fig. 1e) support the cold mass within the vacuum case, as shown in Fig. 2b. Each strap consists of two fiberglass composite straps, a light strap sized to stabilize the load without gravitational load or inertial impulse, the a heavy strap to the additional strength needed during launch. The heavy strap decouples whenever there is no tension loading, so that it does not pose a conductive heat load once AMS is on ISS.

IV. SUPERCONDUCTING MAGNET TESTS

The superconducting magnet was integrated with its cryogenics and tested as a system during Spring and Summer 2009. The design and the results of those tests were reported previously [4]. The magnet performed to specification, and quench behavior and persistent-mode operation exceeded design expectations. It was necessary to re-build the current leads due to a materials problem in their fabrication. Once they

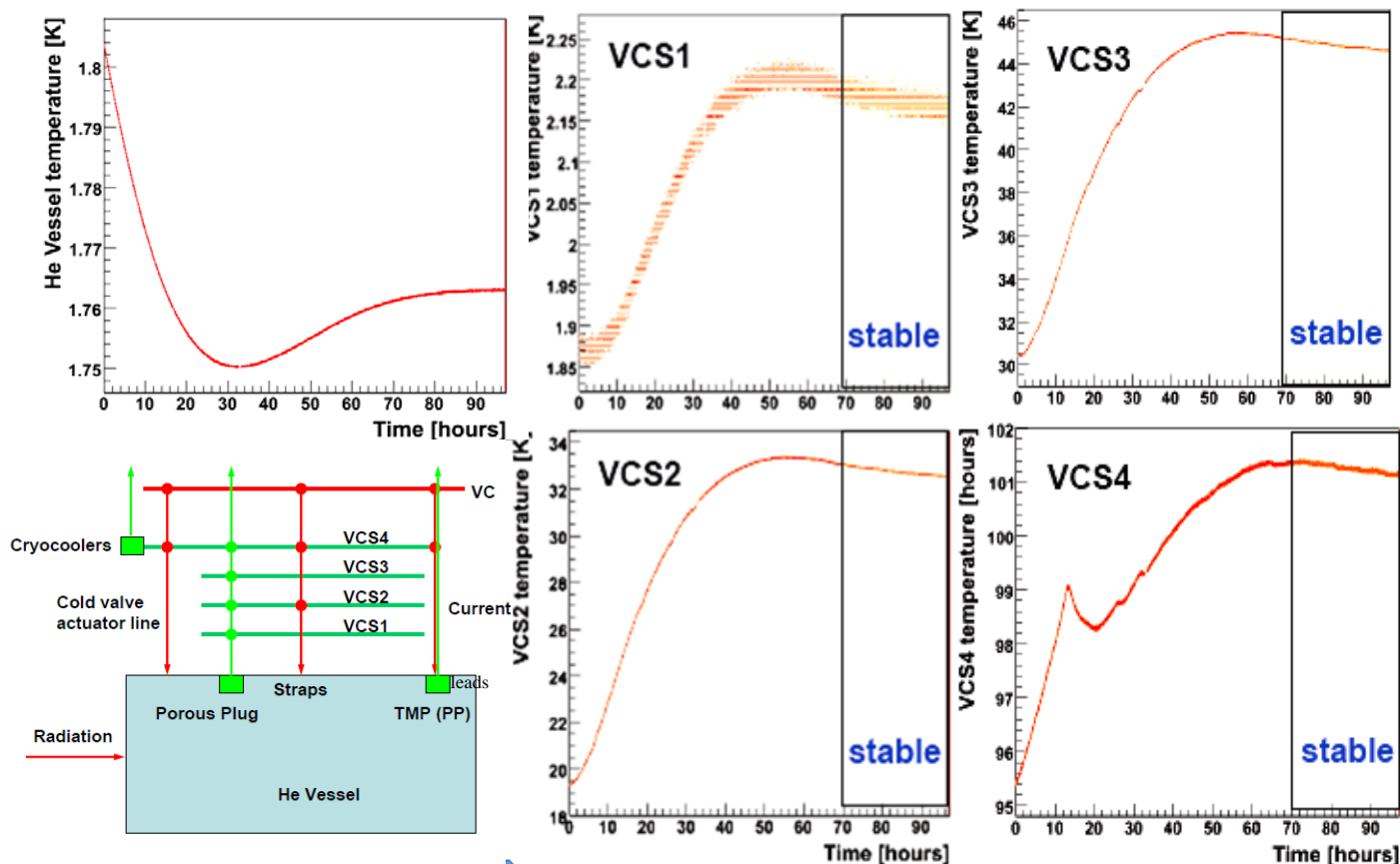


Fig. 3. a) Temperatures evolution of the He vessel and the four VCS, in the first experiment to measure heat load. The mass flow of He vapor was held constant, and the temperatures in the system evolved towards an equilibrium; b) schematic of heat flows that were accounted for in the thermal model.

rebuilt they performed to specification. The magnet was operated continuously during beam tests during Fall 2009.

I. CRYOGENIC TESTING

In Winter 2009 a first set of experiments were performed to measure the equilibrium heat load of the magnet, and to extrapolate the conditions to predict the heat for operation in the zero-g space environment on ISS and hence the operating lifetime of the SFHe inventory. The first set of measurements were made at CERN, with the vacuum case at ambient temperature, and a second set of measurements were made in the Thermal Vacuum Test facility at ESTEC, in which the vacuum case was maintained at reduced temperature.

In each of these measurements the mass flow of He vapor passing up through the VCS sequence was throttled to a constant value, and the temperature vs. time was measured on the He vessel and on each of the VCS. The data from the first such experiment at CERN is given in Fig. 3a. As expected, the temperatures tend toward equilibrium values. By determining those equilibrium values we can construct a thermal model of the entire cryogenic system, shown in overview in Fig. 3b.

This experiment was done with the vacuum case held at three values of ambient temperature: ~ 300 K at CERN, and 242 K and 261 K at ESTEC. With those three sets of data we were able to make a constrained fit to all parameters in the thermal model and obtain the heat load contributions from the several paths.

Several unexpected heat loads were encountered. A total of nine cold valves are provided to control the several modes of operation of the cryogenics for cooldown, magnetic charging, quench, and recovery. Each of these valves is controlled pneumatically: when the valve is to be actuated pressurized He gas must be connected to a ~ 9 m-long tube that connects from the ambient-temperature gas supply to the 1.8K-temperature valve. We observed thermo-acoustic oscillations on these lines whenever they were actuated, accompanied by heat transfer. The oscillations were studied in a separate mock-up; the pressure and temperature oscillations are shown in Fig. 4. The heat transfer was measured to be 100 mW whenever a valve was actuated.

A second anomalous heat load was discovered during the tests at ESTEC: there is a thermal conductance located in the lead disconnect assembly, which appears to conduct heat from the cold side of the disconnected lead to VCS4. One of the cold valves (DV6) can be used to connect a flow of He boil-off vapor through a line that is sunk to the lead assembly; this has the purpose of intercepting the heat that is generated during charging of the magnet when the leads are connected and current is passing through the leads. We controlled that flow to measure the heat that is conducted to the cold mass from the short on the leads, as shown in Fig. 5. At the beginning of the time trace, the DV6 is opened to intercept the heat load from the short at the disconnect. After 30 m DV6 is opened. From the slope break in dT/dt we can calculate that a heat load of 220 mW is being conducted at this short (including 100 mW due to the open valve DV6).

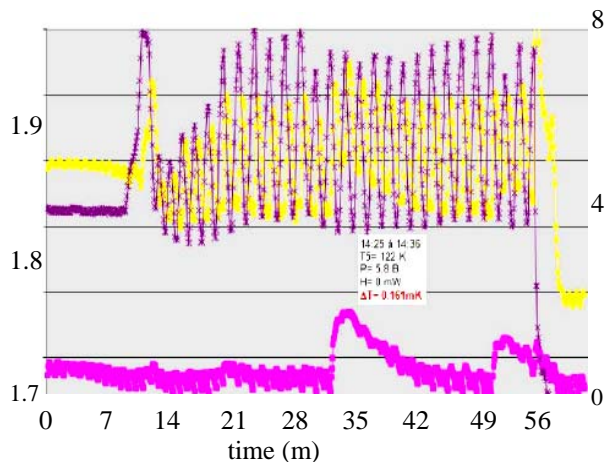


Fig. 4. Thermo-acoustin oscillations observed on a He vapor control line leading to a cold valve.

TABLE 2. HEAT LOAD CONTRIBUTIONS UNDER 3 CONDITIONS

	Room	TVT(242K)	ISS(250K)
Radiation	120mW	20mW	(20mW)
Straps (+ ...)	260mW	130mW	(130mW)
Cryocoolers (eff)	0mW	70mW	(0mW)
Current Leads	240mW	160mW	(10mW)
Actuation lines	100mW	100mW	(0mW)
Instrumentation	20mW	10mW	(2mW)
Total	720mW	490mW	(160mW)

The thermal model was adjusted to include the above sources of heat load during the several modes of test, and a constrained fit to its parameters was then performed to describe consistently the temperature profiles observed at the three values of case temperature studied. The analysis of the several contributions to the heat budget are summarized in Table 2. The first column describes the contributions to the 720 mW observed during testing at CERN with the vacuum cas at room temperature. The second column describes the contributions to the 490 mW observed during the TVT test with the case at 242 K. The last column uses the thermal model to then estimate the heat load that would be present during zero-g operation on ISS. The estimate accounts for the release of the heavy support straps, the full function of the four cryocoolers, operation of DS6 to intercept the heat load from the lead short, and case temperature appropriate to ISS operation. The aggregate heat load of 160 mW would correspond to a cryogen lifetime of (20 ± 4) months for operation of AMS on ISS. The original design objective was 3 years, based upon the projected duration of ISS operation after AMS was installed.

II. CONCLUSIONS

The decade of effort to build and test the superconducting magnet and cryogenics for AMS was successful: all systems worked as designed, several anomalous heat loads were identified and resulted in an estimated cryogen lifetime about half of

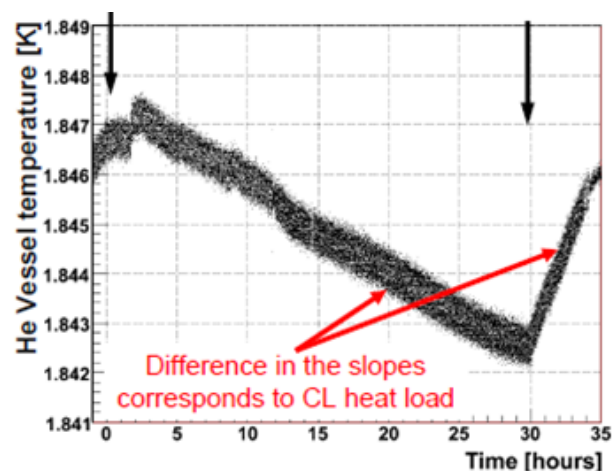


Fig. 5. Measurement of heat load from thermal short on lead disconnect.

3 year objective. Since improved cryocoolers have been developed and space-qualified and are now available, the lifetime could be restored to approximately the design value by replacing the original cryocoolers by current-technology ones.

However NASA announced in Spring 2010 that it commits to operated ISS for at least another 10 years and possibly longer. In view of that much longer operating life, the AMS collaboration elected to replace the superconducting magnet and its cryogenics with the 0.12 T permanent magnet version in which the experiment flew in AMS-01. By re-configuring its Si tracking system, it is possible to recover most of the impact of the lower magnetic field, and AMS will be able to run as long as ISS is in orbit.

The technical effort on the magnet and cryogenics has been a dramatic success:

- Gathering and thermo-mechanical pumping SFHe in a large vessel in zero-g works.
- SFHe heat pipe cooling of a large, distributed dry-coil magnet works.
- Controlling quench, limiting loss of He inventory, recovering works.

This success lays a solid basis for a next generation of magnetic and cryogenics space.

ACKNOWLEDGEMENTS

AMS is a collaboration of 16 nations and 500 physicists, and gratefully acknowledges support in the magnet and cryogenics efforts from DOE, NASA, CERN, ETH, ESA, and INFN. A special debt of thanks are due to the technical staff at CERN and at ESTEC for their support to the cryogenics effort.

REFERENCES

- [1] J. Alcaraz *et al.*, "The Alpha Magnetic Spectrometer (AMS)", *Nucl. Instr. and Meth. in Phys. Res.*, vol. A478, 1-2, pp 119-122, 2002.
- [2] B. Blau *et al.*, "The superconducting magnet system of the alpha magnetic spectrometer AMS-02", *Nucl. Instr. and Meth. in Phys. Res.*, vol. A518, 1-2, pp 139-142, 2004.
- [3] S.M. Harrison *et al.*, "Cryogenic system for a large superconducting magnet in space", *IEEE Trans. Appl. Superconductivity*, vol. 13, 2, pp 1381-1384, 2003.
- [4] P. McIntyre, 'Integration and Testing of the Superconducting Magnet and Cryogenics for AMS', Proc. MT-21 Conf., Hefei, Oct. 18-23, 2010.