The published version of this manuscript appeared in IEEE Transactions on Applied Superconductivity **20**, No. 2010 - 2014 (2010)

Integration and Testing of the Superconducting Magnet and Cryogenics for AMS

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Abstract— **The Alpha Magnetic Spectrometer is a high-resolution cosmic-ray telescope for charged-particles and photons, to be staged on the International Space Station in 2010. A central element of the spectrometer is a 0.8 T, 1 m aperture superconducting dipole magnet. The windings employ Cu-stabilized NbTi conductor and are conduction-cooled in a superfluid He cryostat. The cryogenics for the magnet employs a number of novel elements, indirect cooling using a serpentine heat pipe, thermomechanical pumping for re-cooling after quench and during current charging, capillary gathering of superfluid within the storage dewar, and a porous-plug phase separator. The magnet is designed to operate in persistent mode, with provisions for disconnect/reconnect of current leads.**

The magnet and cryogenics have been built and integrated. The AMS magnet system has been commissioned into operation and operating characteristics have been evaluated during tests at CERN. Results of the commissioning and testing are presented. Lessons for future space applications of superconducting magnets will be discussed.

***Index Terms*—superconducting, dipole, spectrometer, superfluid, space**

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 superconducting dipole magnet [2], shown in Fig. 1a. The requirement that the dipole have minimum fringe fields and near-zero total dipole moment dictates the coil configuration. a pair of field coils produces the dipole field; two sets of 6 racetrack windings return flux symmetrically around the central bore. The windings are made using Al-stabilized NbTi conductor (Fig. 1b), are maintained at 1.8 K using conduction cooling with superfluid He (SFHe), and are designed to provide a field strength of 0.86 T.

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 (Fig. 1d).

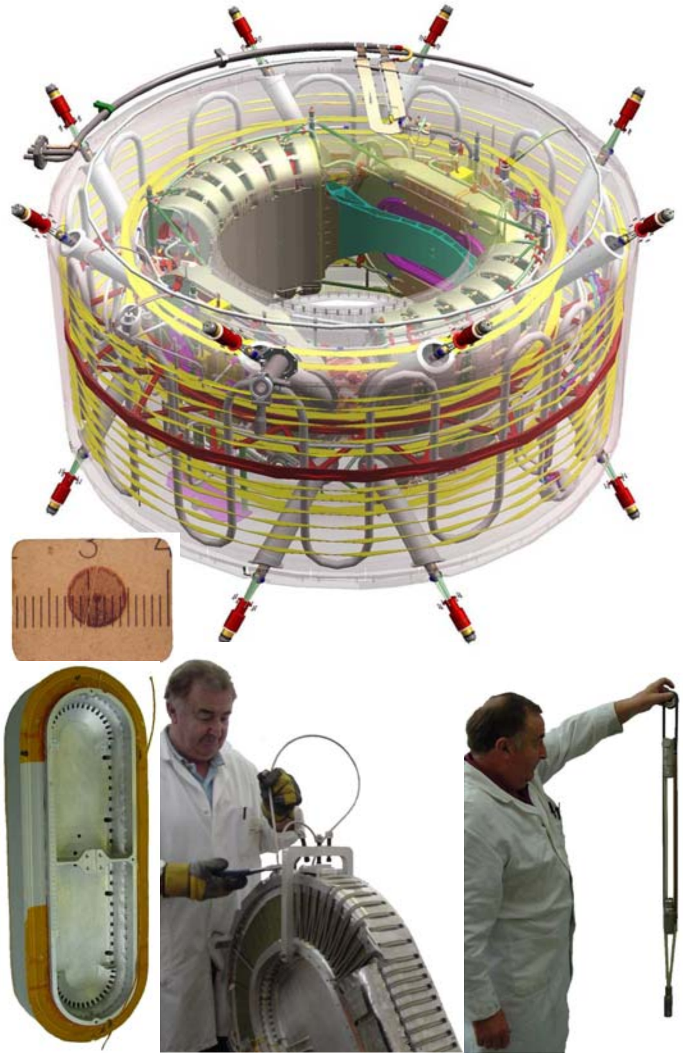

Fig. 1. a) AMS magnet and cryogenics, showing the windings and the cryostat; b) cross-section of 2x1.5 mm^2 conductor; c) one racetrack winding; d) application of wire rope preload; e) segmented tension strap used to support cold mass.

TABLE I. MAIN PARAMETERS OF AMS MAGNET

Central magnetic field	0.86	T
Max. fringe magnetic field @ R=2.3 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

Manuscript received 19 October 2009. This work was supported in part by the U.S. Department of Energy under Grant DE-PS02-09ER09-05.

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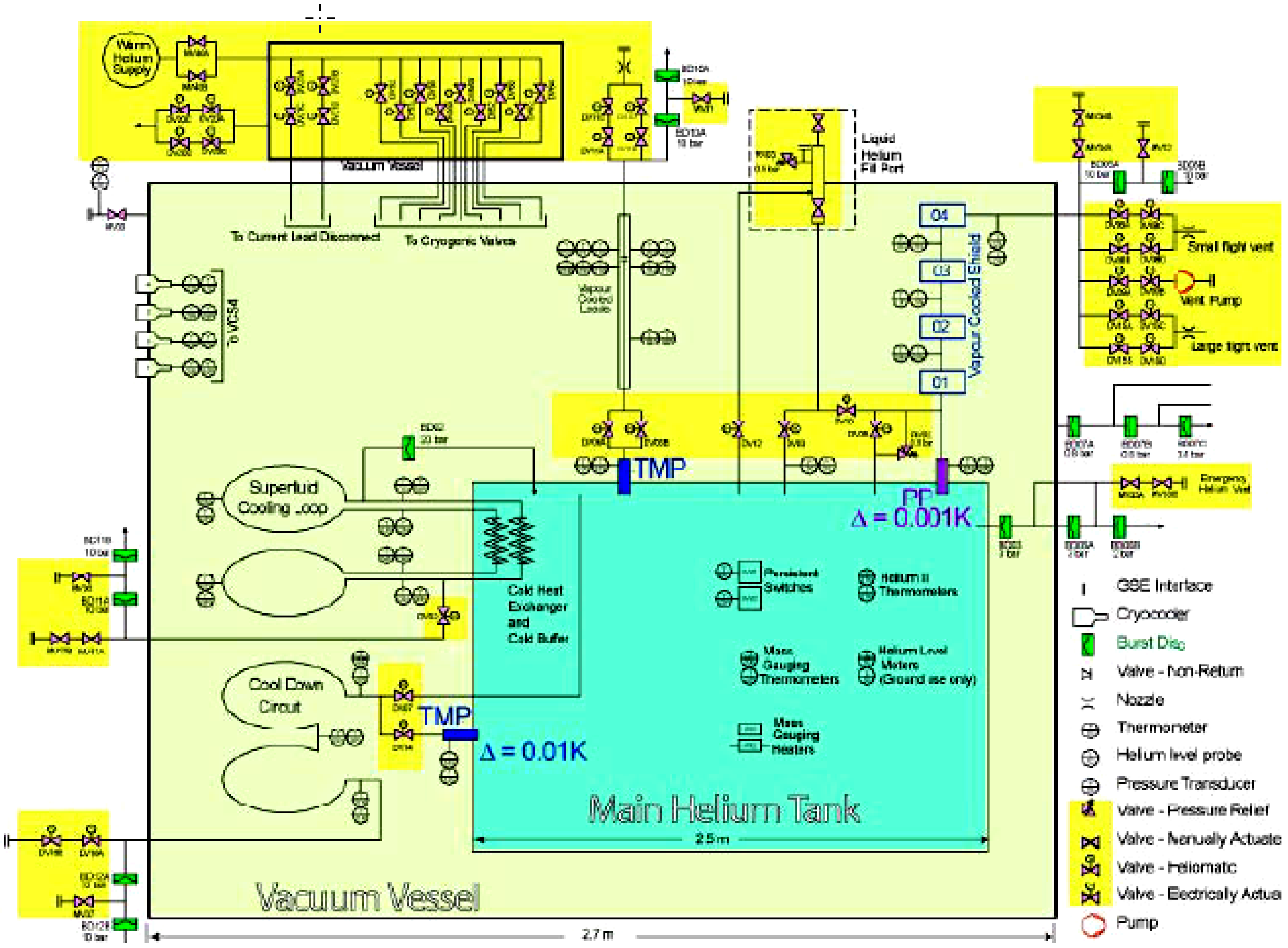


Fig. 2. Schematic layout of AMS cryogenic system.

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.

I. CRYOGENIC DESIGN

The cryogenic system to maintain superconducting operation contains a number of 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 the magnet for the duration of AMS lifetime. 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. 1.

The magnet is conduction-cooled by heat transfer from Cu foils embedded in each winding. SFHe flows through two serpentine loops 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 serpentine loops and is dissipated by boiling to He vapor in the reservoir. During operation the reservoir contains a mixture of SFHe and He vapor. Helium is diamagnetic, so in zero gravity SFHe will congregate in regions of the reservoir with minimum magnetic field (see Fig. 3).

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 dispersed SFHe in the low-field regions of the reservoir and deliver it to the input of the TMPs (Fig. 3).

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 serpentine loops would go normal, strongly limiting heat transfer to the reservoir during the quench to protect the precious inventory of SFHe in the reservoir from being lost.

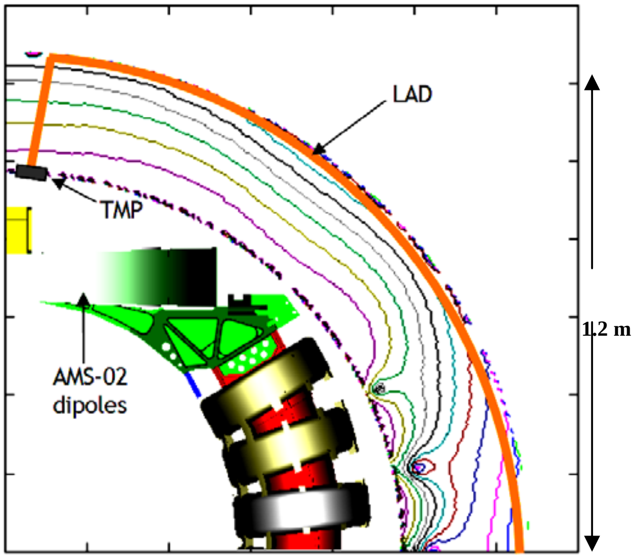


Fig. 3. Cross-section of magnet and reservoir showing thermomechanical pump, capillary bundle to gather SFHe, and distribution of SFHe inside.

B. Vapor-cooled heat shields and cryocoolers

The magnet and reservoir are contained within a set of four intermediate-temperature heat shields. He vapor exiting the reservoir is heat-sinked to each shield in turn so that its enthalpy is efficiently used to intercept ambient heat transport and maintain the shields at nominal temperatures of 5K, 12 K, 25 K and 70 K. Four Stirling-cycle cryocoolers are connected symmetrically around the 70 K shield. Each cryocooler is capable of pumping 12 W of heat from 70 K to ambient temperature with 100 W power consumption. The ambient heat load is dissipated on zenith-facing radiator panels located on the outside surface of the instrument.

II. CHARGING THE MAGNET AND QUENCH PROTECTION

The magnet is charged by connecting an external power supply through a pair of current leads. Each lead incorporates an actuated mechanical break which can be opened to give a vacuum gap of ~2 mm when not in use. A TMP is used to pump a flow of SFHe through the leads during charging of the magnet. Once the magnet reaches operating current, a persistent switch is closed to provide persistent loop current, the external supply is ramped down, the mechanical breaks are opened, and finally the TMP is turned off.

Fig. 4 shows the circuitry used to charge the magnet, place it in persistent mode, and protect it in the event of a spontaneous quench. The quench detection system works by comparing the voltage drops across pairs of windings that have the same inductance, specifically by comparing the voltage drops across the two dipoles and by comparing the drops across 4 sets of 3 racetrack (flux return) coils. This is effective when the magnet is ramped and also when it is operating in persistent mode.

In the event that a quench initiation is detected, a network of quench heaters is fired to drive segments of every winding to normal state so that the magnetic energy will be evenly distributed and no location can overheat.

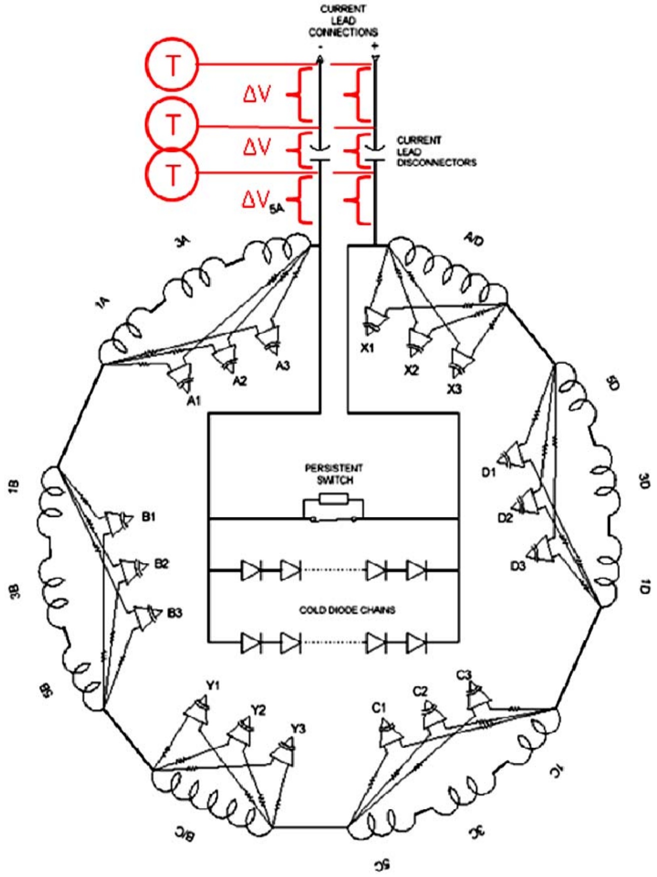


Fig. 4. Circuitry for persistent switch and quench protection.

III. TESTING OF THE MAGNET AND CRYOGENICS

The AMS magnet was integrated with its cryostat and the main operations were tested in Spring and Summer 2009. These tests revealed several problems that required repair or modifications.

A. Cooldown and cryogenic operation

The magnet and cryostat were cooled using a specially designed cryogenic support system which included a master dewar in which LHe can be transferred and precooled to SFHe by vacuum pumping, and liquid and gas valve boxes to control the several modes of flow and pumping on the AMS cryostat.

For cooldown from ambient to 100 K, a closed-circuit flow of He gas was passed through a liquid nitrogen (LN_2) heat exchanger and through the reservoir. The cooldown was controlled at a slow rate ~15 K/day down to 100 K in order to limit differential strain in structures. After that the system was cooled by injecting LHe until liquid accumulated in the reservoir. The process succeeded without problems.

Once the reservoir was filled with LHe, a vacuum was pumped on the vapor head in the reservoir to create SFHe, and the system was cooled down and warmed up. Heat-exchanged neon flow was used to break the insulating vacuum during the final warm up to prevent any possibility of creating an inversion that would limit heat transport. Finally liquid helium in the master dewar was pumped to subcool the liquid He to ~3 K in the master dewar, and the liquid was transferred to the AMS reservoir. This operation will be important to 'top off'

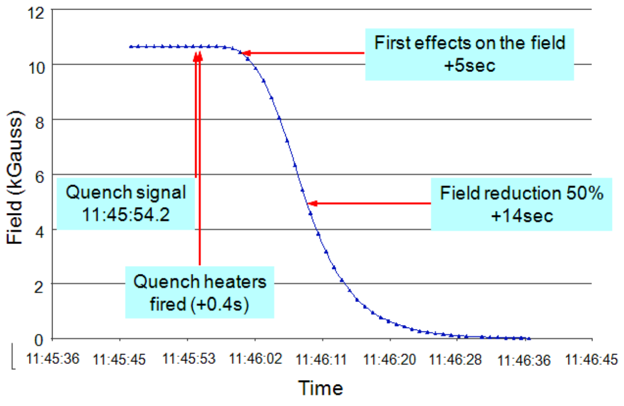


Fig. 5. Field decay following initiation of quench.

the reservoir with SFHe prior to launch.

Below 100 K the cryocoolers were used to intercept heat at 70 K and return it to ambient temperature. The system worked as designed.

B. *Excitation of the magnet*

The lead assemblies were checked by ramping current to half the design value with the persistent switch in persistent mode. It was immediately clear that the lead resistances were much higher than they had been when installed. The negative lead exhibited a cold resistance of 2.2 mΩ, far larger than the design value. The resistance was non-linear and fluctuating, indicating an intermittent connection within the lead structure.

Disassembling the leads revealed that, by error, dissimilar metals had been used in the succession of blocks, bolts, and nuts, and an unfortunate choice of Woods' metal to bond the joints between elements. The structure was re-worked to achieve full bonding without the potential for opening under warm-cold cycles. After these repairs both joints had a measured resistance of 0.6 mΩ, the design value. Both were cold-cycled 10 times and exhibited stable behavior.

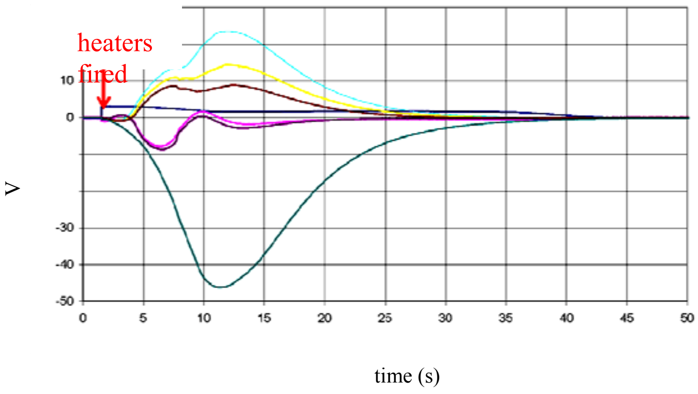
C. *Field decay in persistent mode and field mapping*

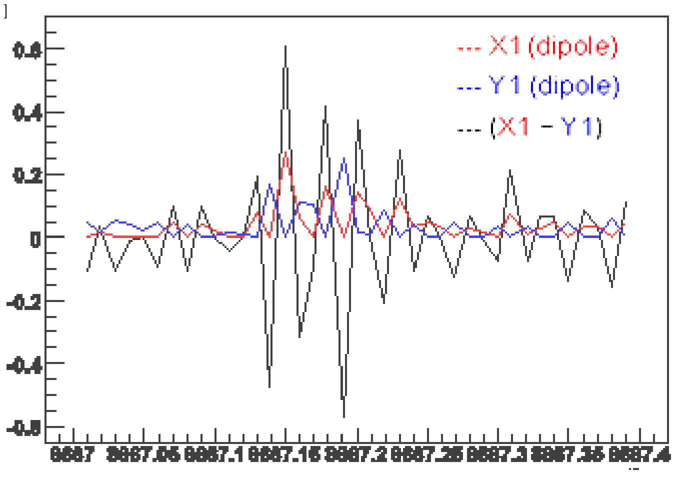
Studies of field decay and field mapping were conducted at half-field (230 A coil current) because of the quench protection difficulties discussed below. Field decay rate in persistent mode was observed to have a decay lifetime of 100 years, consistent with design resistance in the persistent joint. The field map was consistent with the calculated fields in the magnet design.

D. *Quench studies*

We evaluated the quench protection system by ramping the magnet to 230 A (half design current, safe even if quench heaters did not work) and using an external voltage to induce a quench signal on one pair of voltage taps artificially. Fig. 5 shows the observed decay of the magnetic field following initiation of a quench at 230 A coil current.

Fig. 6 shows the voltages across the succession of windings and across the power supply. The pattern of inductive and resistive transients was exactly as expected. The windings reach an asymptotic final temperature of 50 K, as indicated by thermometry mounted on the coil case.





ance driven from cryocooler motors.

Our adiabatic calculations for the AMS conductor at the measured MIITS value of 0.34 MA^2s yields a hot spot adiabatic temperature of 150 K. A worst-case estimate of hot-spot temperature for a quench from full field can be obtained by not assuming any benefit from quenchback in which the magnetic field depresses the local critical current in the high-field regions of the windings so that quench progresses faster once initiated. This worst case estimate would be 300 K. In the AMS field geometry we would expect significant benefit from quenchback, so the actual temperature from a full-field quench should be considerably less.

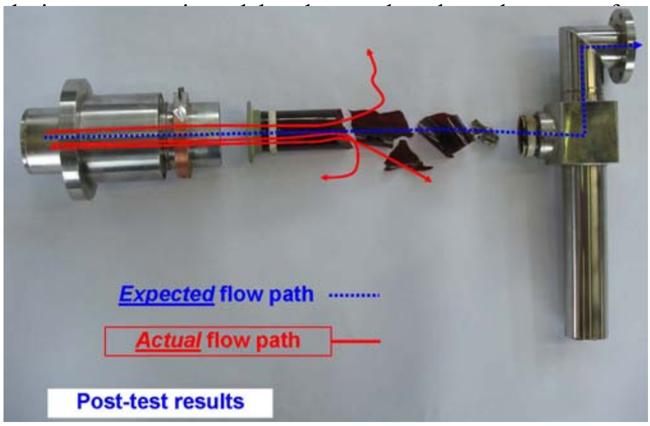
We then evaluated the stability of the quench detection system. After a 12-hour period of persistent operation at 230 A, there was a spontaneous quench. It was found that there was spurious noise on the voltage tap pairs, shown in Fig. 7. The noise had ~50 Hz dominant component, and the phases of the noise signals on the taps suggested that it was of physical origin in the magnet and not merely ambient noise pickup.

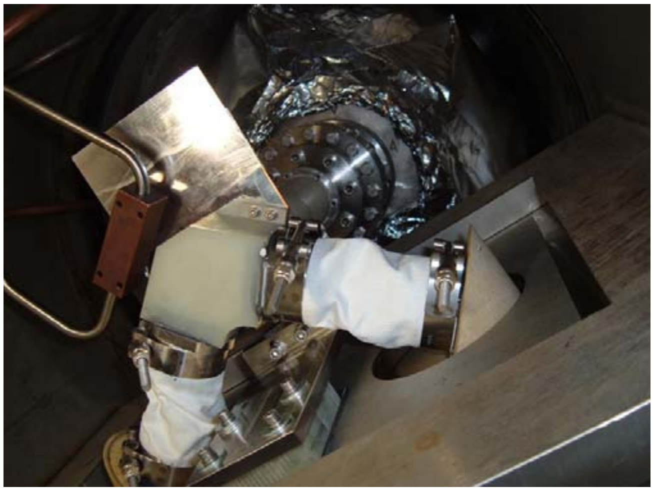
Further investigation revealed that the noise was due to a (small) 50 Hz vibration produced by the cryocooler motors. The vibration was coupled through the tension straps to the magnet structure; unfortunately there is a nearby acoustic resonance of the structural frame that produces an antisymmetric breathing-mode vibration of the two main dipole windings. That vibration produces a modulation in the field that inductively drives difference signals on the appropriate one of the quench detection signals.

It was not possible to eliminate the vibration-driven signal without access to the internal connections within the cryostat, and there is no time to re-open the entire cryostat within the critical path timeline towards preparation for launch. We were able to de-sensitize the quench protection circuits to the resonant signal by inserting a low-pass filter with time constant 220 ms. The spurious signal from the acoustic resonance is thereby attenuated while maintaining the sensitivity necessary for detection of the (much slower) signals from quench initiation.

E. Burst disk protection

A sequence of burst disks protects the cryostat from overpressure conditions in the event that the pressure in the SFHe reservoir rises. The most serious such event would if the insulating vacuum were to be vented to air during the lift-up to orbit in the Space Shuttle bay. A rupture disk (burst pressure 3 bard) connects from the SFHe reservoir to a vent tube located in the insulating vacuum space. This tube connects to two rupture disks (burst pressure 1 bard) located on the wall of the vacuum vessel, as shown in Fig. 8a. The Kapton tube was arranged in a folded configuration (much as an umbrella is folded), with the assumption that the folds would open to provide full conductance for He flow in the event of rupture. The [illegible] by conduction along the tube to a minimum and also to block radiation through its aperture.





connecting tube and flexible astronaut sleeves connecting to outer disks.

We tested the rupture disk assembly under circumstances designed to simulate the flow of liquid and vapor that would be produced by a quench. The folded Kapton tube shattered under the shock wave of exiting liquid and vapor (Fig. 8a).

The rupture disk assembly was re-designed to use a thin-wall G-10 tube connecting to a Tee-connector which is heat sinked at 70 K, then connected to the ambient-temperature rupture disks using flexible fabric tubes of the material from which astronaut suits are made (Fig. 8b). In addition an Al foil baffle disk was installed in the T-connector, scored with radial slits so that the flaps open in event of rupture. The baffle disk intercepts heat radiation at 70 K temperature to prevent heat transport to the SFHe reservoir.

The new configuration was successfully tested multiple times and qualified for the requirements of the mission.

F. Heat load and cryogen lifetime

The target heat load for the entire AMS cryostat is <100 mW, which would correspond to a few-year lifetime for operation of the spectrometer in orbit. The heat load is dominated by thermal radiation leaking through the vapour-cooled shields. Additional heat sources include conductive heat load in the plumbing; heat conducted down the 16 support straps; and heat conducted down the instrumentation wiring. In initial testing efforts were made to measure the operating heat load, although the system was not adequately instrumented during those tests for a careful measurement. The estimated heat load in standalone testing of the assembled magnet and cryostat was ~1 W much larger than the design target.

Considerable effort has been made to determine the origins of the additional heat. The following sources were identified and remediated:

- Radiant heat transfer up the Kapton tube (testing was done with the original rupture disk assembly – eliminated by the Al baffle and heat-sinked Tee described above;
- Radiant heat in the holes in the superinsulation blanket at the openings for the support straps – eliminated by fitting blanket segments in the openings.

Standalone testing also presents several heat loads that will not be present during operation in orbit (where vacuum surrounds the vacuum tank):

- convective and/or thermo-acoustic oscillation loads in the cold valve activation lines and in the fill lines and current lead cooling line – these lines will be evacuated in space.
- the activation line for one cold valve which was kept open (DV05) to pump the vacuum of the reservoir – this will be closed for operation in space.

Careful measurement and optimization of heat load will be a priority during the next testing of the system, with the goal of reaching the 100 mW target.

IV. CONCLUSIONS

The AMS experiment is undergoing final assembly at CERN. The magnet and cryogenics will then be tested to full-field operation. Issues of quench protection and heat load will be evaluated to determine the effect of the improvements discussed above. Then the spectrometer will be operated in a test beam to calibrate the performance of its detector systems.

The spectrometer will then be transported to the environmental test facility at the European Space Research and Technology Centre (ESTEC) where it will be evaluated under the simulated temperature and vacuum conditions of orbit. Finally it will be transported to the Kennedy Space Center, ‘topped up’ with SFHe, and installed in the bay of the Space Shuttle. AMS is scheduled to launch on the last flight of the Space Shuttle on July 29, 2010.

AMS will be the largest superconducting magnet ever operated in space. Together with the balloon-borne Bess-Polar spectrometer [4], its operation should provide a substantial new foundation of technology for use in future applications of large superconducting magnets and cryogenic systems in space.

ACKNOWLEDGMENTS

The construction of AMS-02 is an undertaking of many individuals and organizations. Prof. Samuel C.C. Ting (MIT) conceived the AMS experiment and has provided the scientific leadership of the entire enterprise. The support of the National Aeronautics and Space Administration (NASA) and the U.S. Dept. of Energy (DOE) has been vital in the inception, development and fabrication of the experiment. The interest and support of Daniel S. Goldin (NASA), John O'Fallon, Peter Rosen and P.K. Williams (DOE), and of our NASA Mission Management team Douglas P. Blanchard, Kenneth Bollweg, Trent Martin, Mark J. Sistilli, and of Susan Breon, GSFC-NASA is gratefully appreciated. It is a pleasure to acknowledge the support of the space agencies from Germany (DLR), Italy (ASI), France (CNES), Spain (CDTI) and China (CALT) and Taiwan (CSIST).

The support of INFN (Italy), IN2P3 (France), CIEMAT and CICYT (Spain), LIP (Portugal), CHEP (Korea), the Chinese Academy of Sciences, the National Natural Science Foundation and the Ministry of Science and Technology of China, Academia Sinica (Taiwan), NSF, M.I.T., ETH-Zűrich, the University of Geneva, National Central University and National Cheng Kung University (Taiwan), Moscow State University, SEU (Nanjing), Shanghai Jiao Tong University, RWTH-Aachen, the University of Turku, the University of Technology of Helsinki, and Texas A&M University is gratefully acknowledged. The support of George P. Mitchell is gratefully acknowledged.

We are also grateful for the strong support and interest shown from the private sector, including E. Ettlinger of Linde, R. Herzog of ILK, J. Ross, S. Milward and S. Harrision of Scientific Magnetics, M. Molina of CGS, Milan, F. Petroni of CAEN, A. Poseda of CRISA, Ing. A. Pontetti of G&A Engineering, E.A. Werner and J. Krieger of ISATEC, and H. Bieri, Bieri Engineeering.

The integration and testing of the magnet and cryogenics has required an immense effort over the past two years. The team who have accomplished this work include R. Anderson, A. Bassila, R. Battiston, R. Becker, R. Blackburn, M. Capell, J. Colvin, C. Gargiulo, V. Datskov, T. Elliott, M. Gallilee, W. Hungerford, R. Klimas, V. Kousenko, A. Lebedev, A. McInturff, F. Pellegrino, D. Schinzel, A. Siemko, R. Stafford, K. Stiff, M. Vergain, Y. Yang, and J. Zeigler. It is a pleasure to acknowledge support for the integration and testing effort from CERN, DOE, NASA, and ESA.

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