Completion of the Magnet and Cryogenics for the Alpha Magnetic Spectrometer and Experiments during Operation

Supplemental Proposal to the
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Supplemental funding is requested to support participation in the integration and testing of the superconducting magnet and its cryogenic systems on the Alpha Magnetic Spectrometer (AMS), shown in Figure 1. AMS is a 16 nation, 56 institute international collaboration. The entire experimental system (superconducting magnet, TRD, tracker …) was constructed in Europe and Asia (see Figure 2). The U.S. DOE participation involved electronics design and electronics components and, together with NASA, safety aspects of the magnet system. The construction of the detectors is completed. The TAMU team will join with the personnel of Space Cryomagnetics, Ltd. (SCL) and NASA to assemble and test the magnet and helium vessel, integrate all systems in the vacuum vessel, and test the magnet system with its control electronics (Figure 3).

The schedule of events for testing and integration of AMS is summarized in Table 1. After the completion of tests at SCL, the magnet system will be shipped to CERN and operated in test beam to calibrate all detector components. This requires operation of the magnet from a cryogenic ground support system that will then travel with the detector to Kennedy Space Center where the experiment will undergo complete checkout and be staged on the Space Shuttle for launch to the International Space Station (ISS).

After beam tests at CERN, the experiment will be shipped to European Space Research and Technology Centre (ESTEC), the Netherlands, for thermal-vacuum test (TVT) and electromagnetic compatibility tests (EMI). This is to ensure that the superconducting magnet will work in the hostile space environment where the temperature changes from ±65°C every 90 minutes and the magnet and cryogenics system will indeed work in vacuum. The European Space Agency (ESA) has approved these tests and will support their total costs of ~5 million euros (~$6.5 million). Figure 4 shows the thermal vacuum chamber at ESTEC (diameter 10 m, height 20 m).

Prof. McIntyre and his Texas A&M team have been asked to take on major responsibilities in the testing and integration of the superconducting magnet and its cryogenics and controls. It is appropriate to summarize here the history of the AMS effort that has built the magnet system. After the successful first shuttle flight of AMS (AMS-01) with a permanent magnet of the same size, in which the design principles and the support structure were tested in space, the construction of the more powerful superconducting magnet was approved by the DOE AMS review committee in 1999 (committee members Robert Adair, Barry Barish, Stephen Olsen, Malvin Ruderman, George Smoot, and Paul Steinhardt) and presented to and approved by HEPAP in 2001.

The superconducting magnet was designed and built under the able leadership of Prof. Hans Hofer, ETH-Zurich. The Swiss government provided much of the funding and technical devel-
Development for the magnet system. Upon the recent retirement of Prof. Hofer, the AMS Collaboration, with the assistance of NASA and Prof. A. Yamamoto of KEK, invited Prof. McIntyre of Texas A&M University as a logical successor to Prof. Hofer. Prof. McIntyre, with his accomplishments in superconducting magnet systems and his achievements in particle physics experiments, is an appropriate leader to coordinate between the European AMS magnet industries (SCL, ILK, Weka) which are responsible for building the magnet, and the scientists and engineers who are constructing the detector systems. Prof. McIntyre will oversee many of the technical aspects of magnet assembly, testing and integration. The Texas A&M team will operate the magnet in space together with SCL. The balance of the financing for the remaining work on the magnet is provided by approved commitments from Spain, Italy, Taiwan, China, NASA and DOE under the overall responsibility of MIT. The magnet system has been recently reviewed by an international committee of experts chaired by Dr. Bruce Strauss of DOE. There is no need from the AMS collaboration to request additional funds for completion of the magnet system.

The Texas A&M role in testing and integration is pivotal to reduce schedule risk in completion of AMS for launch by mid-2009. Because the Shuttle program is destined to end the following year, delays in completion could jeopardize the success of the entire $1.5 billion project. The team at SCL has done a superb job of building the magnet and cryogenics systems, but they have limited manpower and the remaining work requires parallel activity on testing the magnet, assembling and testing the He tank. The TAMU personnel will increase the man-to-task at SCL from 6 to 9, so that work can proceed in two shifts.

Figure 1. The AMS detector system, with its superconducting dipole spectrometer and detector elements.
Table 1. AMS-02 Test Schedule for 2008

<table>
<thead>
<tr>
<th>Test</th>
<th>Location</th>
<th>Duration</th>
<th>Period</th>
</tr>
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<tbody>
<tr>
<td>Beam Test</td>
<td>CERN</td>
<td>1 month</td>
<td>Aug./Sep. 2008</td>
</tr>
<tr>
<td>TVT</td>
<td>ESTEC</td>
<td>2 months</td>
<td>Sep./Nov. 2008</td>
</tr>
<tr>
<td>EMI</td>
<td>ESTEC</td>
<td>1 week</td>
<td>Dec. 2008</td>
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Figure 2. The construction of AMS was mostly done in Europe and Asia. The names of leading European physicists are included. In addition, Prof. S. C. Lee coordinates important contributions from Taiwan.
Figure 3. AMS magnet and helium cryogenics

Figure 4. ESTEC Thermal Vacuum Chamber to test the AMS spectrometer
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    - Kerry Stiff

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1. Scientific objectives of AMS

The Alpha Magnetic Spectrometer is a highly instrumented charged particle spectrometer, designed to measure the properties of high-energy charged cosmic rays [1]. AMS is scheduled to be installed on the International Space Station (ISS). It will provide high statistics, long duration measurements of charged particle and nuclei for primary energies 0.1 GeV to 3 TeV. It will also measure high energy gamma rays up to 1 TeV.

The detector has dimensions of (3 m)$^3$ and weighs ~ 7 tons. Because it must operate under solar power on ISS, it has been designed to operate with a total power budget of only 2.5 kW. The overall acceptance is 0.4 m$^2$sr. The hadron/positron rejection ratio is better than $10^6$. Heavy ion beam tests at CERN with the detector show that it will be able to measure individual heavy ions on the ISS from 0.1 GV to $\sim 1$ TV up to $Z \sim 26$.

Figure 1 shows the detector. AMS consists of the following main components (for details see Ref. 1):

- A large volume superconducting magnet and associated subsystems, detailed below;
- Transition radiation detector (TRD) which identifies extremely high velocity particles [2];
- Precision time-of-flight (TOF) system consisting of four layers of scintillator paddles [3];
- An eight layer silicon tracker system, located inside the magnet, with a total area of 6.6 m$^2$ and a measured bending coordinate resolution is 10 μm [4];
- Ring-imaging Cerenkov counter (RICH) which measures both velocity and charge of traversing particles so that cosmic ray constituents can be cleanly identified up to $Z = 26$ [5];
- A 3-D 16 radiation length sampling electromagnetic calorimeter (ECAL), a sandwich of lead and scintillating fibers, which measures the energy and direction of $e^\pm$ and $\gamma$ [6].
- A pair of CCD based Star Trackers and an onboard GPS unit to provide precise information on the orientation of the experiment and the absolute event time.

AMS will dramatically extend the knowledge of the composition, spectrum, and angular origin of primary cosmic rays. The primary scientific objectives for its observational program include a sensitive search for particle candidates for dark matter [7], a sensitive search for antimatter components of primary cosmic rays [8] (a key unanswered question in cosmology), precise measurement of the nuclide composition and spectrum of energetic cosmic rays [9], precise pointing measurement of gamma rays (by pair conversion and tracking in the spectrometer) to locate and characterize both discrete and diffuse gamma-ray sources [10], sensitive search for particle candidates for dark matter [11], and a unique capability to search for new forms of matter, such as strangelets [12].

The ultra-precision of the AMS detector enables it to measure the particles with an accuracy of (see Figure 5): coordinates to 10 μm, transit time to 100 ps, velocity to 1 part in 1000 of c. It will also simultaneously measure cosmic atomic nuclei to $\sim$TeV. Because of this unprecedented level of precision, AMS has often been referred to as the “Hubble Telescope for charged particles”.

available at the DOE Office of High Energy Physics. Some of the physics highlights are reproduced below (Figure 6 through Figure 9) and the final report is attached as Section 9.

For further details see http://ams.cern.ch/AMS/AMS.pdf. The results of the first flight on the Space Shuttle are summarized in Ref. 13, which also presents the results from the successful test flight of the first model (AMS-01) on the Space Shuttle.

Figure 5. Measurements by AMS detectors in a 196 GeV/nucleon test beam at CERN.

Figure 6. Precision study of the composition of cosmic rays as a function of energy to an accuracy of 1%. From this data one can obtain cosmic ray confinement time from the ratio of $^{10}\text{Be}$ to $^{9}\text{Be}$, and the B/C ratio to yield propagation parameters (diffusion coefficient, galactic winds …).
Figure 7. AMS search for a dark matter candidate by measuring the antiproton to proton ratio as a function of energy. Note: with the constraints provided by the 3 year WMAP data the large \((m_0, m_{1/2})\) region is accessible to AMS but not to LHC (John Ellis, private communication).

Figure 8. Sensitivity to search for antimatter by order of \(10^5\) to \(10^6\) compared to current limits above \(\sim 10\) GeV. With the theoretical estimates of the intergalactic magnetic fields, this sensitivity implies, if no antimatter is found, there is no antimatter within the edge of the observable universe (\(\sim 1000\) Mpc). (See Refs. 14.)
Figure 9. Measurement of gamma rays from $\gamma \rightarrow e^+e^-$ in the galactic plane. AMS covers an important region between space experiments and ground based experiments. Its unique properties enable AMS to extend the study of pulsars, blazars and $\gamma$ bursters.

Of particular interest to the Texas A&M team is the potential for precision imaging of $\gamma$-rays from gamma-ray bursters and from diffuse sources. The acceptance of AMS is comparable to that of SWIFT and GLAST, it measures $\gamma$’s with an energy resolution of 1.5% at 10 GeV and $\mu$s timing resolution with onboard GPS and a point source resolution of 10 times better than any other $\gamma$-ray instrument. By combining AMS $\gamma$-ray data with visible-light images of the same sources, it should be possible to extend the sensitivity of time-domain measurements that could test predictions of an energy dependence of the velocity of light that has been suggested in several string-related models inspired by dark energy [15].
2. Significance of AMS to advance superconducting magnet technology in space

Operating a superconducting magnet in space is a difficult challenge. Three challenges that are unique to the space environment are the extreme penalty attached to launch mass (no iron flux return), the fluid properties in zero-gravity environment (gas/liquid phase separation for cooling), and the requirement to cancel magnetic moment (no torque upon spacecraft during orbit). Over the past four decades many distinguished researchers have endeavored to develop superconducting magnets for research in space: superconducting solenoids launched on Cosmos 140 and Cosmos 213 [16], liquid helium cooling of bolometers on KKR–4 and Obzor–K [17]; and MHD generators and plasma propulsion systems [18]. None of the efforts that actually launched to space have succeeded in establishing steady-state operation of a cryogenically cooled magnet.

The most notable effort, now 20 years ago, was ASTROMAG [19], a design for a space-based spectrometer similar in objectives to AMS. In that project great effort was spent upon the difficulties of low-mass cryostable conductor [20], refrigeration and phase separation, and cancellation of magnetic moment [21].

Although much work was done to explore options for these difficult issues, no working system was developed. And so to the present day there has never been a high-field superconducting magnet of size > liter placed in stable operation in space.

Superconducting magnet technology in space will be critical to future experiments to measure charged particles and gamma rays and to manned interplanetary missions, for which a magnetic shield is required to protect astronauts from cosmic rays beyond Earth’s magnetosphere. It is also required for power generation, such as that being developed by Prof. Samim Anghaie of the Innovative Nuclear Space Power and Propulsion Institute, INSPI; University of Florida [22], by the NASA Propulsion Research Center at MSFC [23], by the Soviet Union and Russia and for electrical propulsion being developed at the Johnson Space Center Advanced Space Propulsion Laboratory under the leadership of Astronaut Dr. Franklin Chang-Diaz [24].

Section 5 presents the design of the AMS magnet. Section 6 presents the cryogenics system, which incorporates innovations in conductor, phase separation and pumping of superfluid He in zero-g, cancellation of magnetic moment, minimum-mass strategy for cryostable operation, and isolation of He inventory and recovery from quench. These innovations will provide for the first time a technology base from which future space-born experiments requiring magnetic fields can draw. They also would provide a basis for important applications of superconducting magnetic fields in space for propulsion (MHD and plasma drives) and for creating a local magnetosphere to protect astronauts during deep-space manned space flight.

Once AMS is successfully placed in operation, a series of experiments is planned to study the behavior of the magnet during quench, recovery from quench, superfluid flow in zero-g, stability of thermomechanical pumping in zero-g and restoration of pumping during quench recovery, and isolation of the coil from superfluid inventory during quench. Plans for the experiments are described in Section 8. These studies will be the only actual experience concerning these difficult issues that will be possible until future space-born magnets are flown. AMS plans to devote significant effort during the experiment’s life to these experiments, and the Texas A&M group will contribute to the planning and execution of those experiments.
3. Texas A&M group joins AMS

In December 2005, after the retirement of Prof Hans Hofter of ETH-Zurich, a delegation from the AMS experiment visited Texas A&M to invite the superconducting magnet group to join AMS in order to take over his responsibilities to coordinate between the European AMS Magnet industries (SCL, ILK, Weka) who are responsible for building the magnet and the scientists and engineers who are constructing the detector system. The Texas group was also invited to provide technical support to ensure that the magnet can be completed on time. The delegation included Prof. Samuel Ting, spokesman of AMS, Mr. Stephen Porter, Senior Project Engineer at NASA Johnson Space Center, and Mike Capell, contract manager of the magnet system.

Prof. McIntyre attended the AMS Technical Interchange Meeting (TIM) at CERN in January 2007 and began developing a detailed understanding of the status of the magnet and its cryogenics. He attended the next TIM in May and visited SCL to see the magnet and discuss plans with Stephen Harrison, SCL’s lead engineer on the project and with Trent Martin, NASA AMS Project Coordinator. He also began recruiting candidates for a technical team that could be fielded to SCL and later to CERN, ESTEC, and Kennedy Space Center (KSC) to provide engineering support for the magnet and cryogenics throughout the two years leading to launch.

Prof. McIntyre participated in a technical review of the AMS magnet effort that was held at CERN in July 2006 (review report in Section 11). It stressed the need to maintain momentum in the assembly and testing of the dipole and He tank, and cited a list of issues to be addressed.

By November 2006 the Texas A&M group succeeded in recruiting Kerry Stiff to join the group and begin the on-site Texas A&M effort at SCL. His resume is attached (Section 10). Mr. Stiff is a senior cryogenic technician with 20 years experience with cryogenics, refrigerators, and superfluid He systems. He served with SSC and with LIGO, and most recently made substantial contributions in successfully completing the superfluid cryogenic system for SNS.

It remained however to put together initial seed funding that would enable the Texas A&M group to hire Mr. Stiff while seeking supplementary funds from DOE for the project. Prof. McIntyre obtained $100,000 of gift funds from Mr. George Mitchell, and also secured a contingent commitment by Texas A&M that guaranteed Mr. Stiff’s salary for two years even if DOE did not elect to fund the project. Mr. Stiff has been hired by Texas A&M and arrived at SCL on Feb. 23, 2007. The Texas A&M group is interviewing candidates for the second technician position, and will be prepared to hire pending approval of the proposed supplemental funds.

Texas A&M proposes to field a team of three people to work full-time with the magnet and cryogenics systems: Mr. Stiff, the second technician, and a graduate student in physics. The team will work at SCL in Culham, UK for the coming year, until the magnet system is shipped to CERN for integration with the detector systems. They will work at CERN, commissioning the magnet and operating it during test beam calibrations of the detector and then participate in the critical thermal-vacuum and EMI tests at ESTEC, and finally they will work at KSC when the magnet ships there for final assembly and preparation for launch. Through that sequence of stages they will be the key persons knowledgeable about the magnet and cryogenics and its operation who stay with the experiment throughout the effort.

The addition of the Texas A&M team will ensure a two-shift operation at SCL during the crucial period (beginning now!) when the magnet must be readied for tests and the He tank must be assembled in parallel to maintain for a 12/08 delivery to KSC.
4. Superconducting magnet

Figure 10 shows the coil assembly of the superconducting dipole that forms the heart of the AMS experiment [25]. It comprises two main field windings that produce the dipole field and two arcs of return windings that constitute an active flux return. The dipole has a central field of 0.86 T and a large unobstructed inner volume (~1 m³). The magnet is designed to operate with indirect cooling by superfluid helium (1.8 K). The windings utilize aluminum-stabilized NbTi conductor which was developed to minimize the mass required for highly stabilized windings.

The superfluid He cryostat and the coil assembly are encased within a thin walled vacuum tank. The coils are separated from the helium supply so that, in the unlikely event of a quench, the immediate helium losses would be modest. As this is the first large volume, high field superconducting magnet in space, the development proceeded in two steps.

The first step was to develop and deploy a first embodiment of the experiment (AMS-01) utilizing a permanent magnet (0.15 T field) in space to ensure that:

(i) The magnet has no external dipole moment so that it cannot exert a torque on the ISS.

(ii) There is no field leakage out of the magnet so that astronauts can work safely during a nearby extra vehicular activity (EVA).

(iii) There is no iron return yoke so as to minimize weight.

AMS-01 was built using the permanent magnet, was operated successfully on the space shuttle Discovery, flight STS-91, in June 1998, and these three design concepts were validated [13].

Figure 10. Cutaway view of superconducting dipole and cryogenics in vacuum case.
AMS was then upgraded to utilize a superconducting dipole with the same magnetic field configuration as the permanent magnet model but with much higher field strength in order to extend the energy range of the measurements of particles and nuclei to the multi-TeV region. Figure 11 shows the completed coils and the field distribution for the superconducting dipole.

The superconducting magnet was built under the responsibility of ETH-Zurich. The Swiss government provided much of the funding for the initial R&D (1997-2000) and much of the technical developments in Switzerland, Germany, Spain and the UK. The three years of R&D effort was supported by ETH together with the R&D group of Oxford Instruments. This group has built a number of successful superconducting magnets, including the CLEO magnet at CORNELL, the CLAS torus at Jefferson Laboratory, and the KLOE magnet at INFN Frascati. To ensure that this group would work exclusively on the AMS magnet, ETH-Zurich, through the help of the Swiss government, has invited the R&D group of Oxford Instruments to be an independent company (Space Cryomagnetics, Ltd or SCL) supported exclusively by AMS.

The technical design of all major elements of the AMS-02 magnet and cryogenics are summarized below. The present state of development of the magnet systems was reviewed in July 2006; the review report is attached (Section 11).

**Al-stabilized NbTi conductor**

The windings of the AMS-02 dipole were made using a new, small cross-section, Al-stabilized NbTi conductor, shown in Figure 7a that was developed and fabricated by the ETH-Zurich magnet group [26]. Based on test results, this conductor reduces the quench probability by a factor of 2000 compared to conventionally stabilized wire. ETH has pioneered many of the key technologies for producing Al stabilized conductors [26,27]. Figure 7b shows the non-destructive quality control apparatus developed at ETH. It consists of an ultrasonic phased array which ensures the continuous bonding between the superconductor and the high purity Al. It also includes a laser dimension measuring system and an eddy current check for quality control. This system was used to produce Al stabilized superconducting conductor can be produced uniformly and reliably with lengths up to 2.5 km. A total of 105 km of superconducting cable was produced and wound into coils.

![Figure 11. AMS-02 dipole: completed coil assembly; b) magnetic field distribution.](image)
Each of the two larger (dipole) coils, which generate most of the useful field, has 3360 turns, and the 12 smaller (flux return) coils each have 1457 turns. The 14 coils are connected in series, with a single joint between each pair of adjacent coils. The coil current is 460 A. All of the coils have been manufactured, tested individually to design stress level, and assembled (Figure 6).

Figure 12. Al-stabilized NbTi conductor used in the AMS-02 dipole: a) conductor dimensions and photograph of cross-section; b) phased-array ultrasound system to assure uniform bonding.
**Quench protection**

Design of the AMS dipole had to accommodate several unusual constraints arising from the requirement for operation in space. Cryogenic cooling is provided by conduction through copper heat shunts to a serpentine tube containing superfluid helium (see Figure 8), so that if the magnet quenches the inventory of liquid helium that is vaporized and lost is kept to a minimum. The Al-stabilized conductor is sufficiently conductive that the coils are very stable. If a quench does occur in a winding, the heat generated is conducted throughout that winding so quickly that peak temperatures are not hazardous. Because all 14 windings are connected in series there is no danger of magnetically induced stresses causing damage. However, the coils are only thermally connected to one another through the cooling serpentine, so that a quench in one winding would not couple to other winding and the entire stored energy of the magnet (5 MJ) could be dissipated as heat in that winding.

In order to prevent that, each winding is constantly monitored by a quench detection system and each winding is equipped with multiple quench heaters (see Figure 14). If the onset of a quench is detected in any winding, all quench heaters are powered to force quench everywhere in the coil. The operation of the quench detection system and the quench heaters is an important part of the testing and qualification procedure for the magnet coil.

![Figure 13](image13.png)

Figure 13. Isometric view of dipole showing provisions for current leads, joints, and conductive cooling serpentine.
Mechanical support system

The mechanical loads on the system are either magnetic or inertial. Magnetic loads apply whenever the magnet is charged, and can be between or within coils. Significant inertial loads are applied during launch, re-entry and landing of the space shuttle, but because the magnet will not be charged during launch or landing, magnetic and inertial loads are never superimposed.

In general, the magnetic loads are much greater than the inertial loads. All magnetic loads are reacted within the structure of the coil set, and none are transmitted to the vacuum tank or other parts of the AMS system. These loads are resisted by components made from high strength aerospace grade aluminum alloy, chiefly 6061-T6. Each coil is subject to internal forces as a result of its own magnetic field. In general, these are burst forces, trying to expand the racetrack-shaped coil into a ring. These loads are in the plane of the coil, and are resisted by the former on
which the coil was wound. In addition, each coil is attracted or repelled by all the other coils in the magnet. This leads to a relatively complicated load system on some of the coils, with forces perpendicular to the plane of the coil.

The magnetic loads are quite large: the two dipole coils feel a net attraction of around 250 tons. During individual coil testing, each coil is charged until some part of the winding is subject to the same force it will experience in flight. The cold (1.8K) mass of the magnet is more than 2,000 kg. This has to be supported from the experiment structure (in particular the vacuum tank), which is at ambient temperature (~270→40 K).

A total of 16 straps support the magnet from the vacuum tank (Figure 15). The support straps must carry the load without conducting significant heat across the large temperature gradient. During normal operation on the ground, inertial loads are relatively small: once on orbit they disappear altogether. At these times, the function of the straps is only to position the magnet correctly within the vacuum tank. During launch and landing, however, inertial loads and vibration become very significant. Now the straps have to resist large forces, and also require high stiffness to prevent low frequency resonance which could lead to mechanical damage.

The straps have been designed to satisfy both requirements. Each strap consists of a pair of composite bands connected in parallel, as shown in Figure 15. One band is thin, with low stiffness and strength and low heat conductance (less than 3 mW per support), and is permanently connected between the cold mass and the vacuum tank. The other band is much thicker and stronger, but possesses a passive disconnect feature. During normal operations on the ground or in space, only the low-stiffness band is engaged, and the heat conduction is very low. During launch, the high-stiffness band engages as well. The conducted heat load is much higher but because the launch takes only a few minutes the effect on the overall endurance of the system is not significant. This configuration has been tested under vibration loads at the SERMS laboratory, Terni, Italy, confirming the structural modeling.

**Vacuum shell**

The vacuum case is ~3m in diameter and 3mm thick. Two cases were built. One for tests, one for flight. The test model of the vacuum vessel of the cryostat has been completed (Figure 16) and has been tested in Terni, Italy.

![Figure 16. Vacuum vessel of the cryostat, transported for vibration testing and thermal cycling.](image)
5. Cryogenic Systems

The cooling of terrestrial superconducting magnets using liquid helium is a well-established technology, but there is little experience of helium cryogenics in space. Apart from a few small-scale experiments, the only major missions involving liquid helium have been the Infrared Astronomical Satellite (IRAS) [28], the Cosmic Background Explorer (COBE) [29], the Infrared Space Observatory (ISO) [30] and the Superfluid Helium On-Orbit Transfer demonstration (SHOOT) [31].

The cryogenic system for the AMS magnet combines technologies from terrestrial magnet cryogenics and space cryogenics to meet the particular challenges of the space shuttle launch and the environment of the ISS [32]. It maintains the magnet at a temperature of 1.8 K, under all operating conditions, for the duration of the experiment. It therefore has to be able to store enough helium to last the entire mission, to transfer any heat from the cold components to the helium, to allow the magnet to be charged and discharged safely from the external power supply, and to re-cool the magnet after a quench. On the ground, it also has to control the cool down of the magnet from ambient temperature.

Figure 12 shows the elements of the AMS-02 cryogenics system, including the passive phase separator (PP), which removes the gaseous He which is then used to cool the 4 vapor cooled shields; the two thermo-mechanical pumps (TMP), one to cool down the magnet in the unlikely event of a quench and the other to cool down the current leads during magnet charging and discharging; the helium-gas-pressure-activated cold valves which operate at 1.8 K; the warm valves outside the vacuum tank which operate at ambient temperature but with cold He gas flowing through them; and the burst disks (0.8, 3, 10 and 20 bar) for safety. The valves are implemented redundantly in parallel (for example DV06A, B), in series (DV16A, B) or both (DV15A, B, C, D), so that a valve failure could not cause an overpressure condition or loss of the liquid helium inventory.

The AMS magnet is cooled by superfluid helium. There are two main reasons for this. Firstly, the specific latent heat and density of superfluid helium are both higher than in normal liquid helium. Since the amount of cryogen that can be carried is limited by the size of the helium vessel, this gives a useful endurance benefit (there is a greater mass of helium, and each kilogram has a higher cooling capability). 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 the superfluid state, however, the very high thermal conductivity makes it impossible for the helium to support large temperature gradients, so the system remains isothermal. Also the super fluidity is used to great advantage, both to gather the superfluid within the He tank to the pump inlet (no gravity!) and to pump it through the serpentine heat exchanger during cool-down using the thermomechical pumping.

Superfluid helium is obtained by reducing the pressure above a vessel of normal liquid helium. The boiling point of helium at atmospheric pressure is 4.2 K, and this can be reduced to 1.8 K if the absolute pressure is reduced to 16 mbar. On the ground, this pressure reduction is achieved using large vacuum pumps to remove helium vapor. Once on orbit, the vacuum of space itself is used as a pump, and the low temperature can be achieved simply by venting the helium vessel to space.
Figure 17. AMS-02 cryogenics system.
**Helium vessel**

The helium vessel is a toroidal tank, with inner and outer diameters of 1.9 m and 2.6 m, height 1.2 m and volume 2500 liters. It is a fully welded construction of aluminum alloy 5083-H321. For maximum strength and minimum weight, both cylinders are ribbed and they are joined together by cross-bracing at the mid-plane.

The sixteen support straps have to pass through the volume occupied by the helium vessel as they support the coils from the outer cylinder of the enclosing vacuum tank. Because a high heat load would result if the straps came into contact with the helium itself, the vessel is equipped with 16 tubes which pass completely through it. These allow the straps to pass through the vessel while remaining in vacuum.

Figure 18 shows the lower half of the He tank, after welding of the assembly.

![Figure 18. He cryostat lower half, with serpentine heat exchanger coils in place, after assembly welding in Switzerland.](image)

**Phase separation**

There is a small amount of heat that is not intercepted on the support straps and refrigerated by the cryocoolers and also a small amount that is generated by electronics at He temperature. That remnant heat is transferred to the superfluid helium in the 2500 liter He tank, which is the ultimate low temperature heat sink for the system where the heat is dissipated by boiling normal helium that is in equilibrium with the superfluid in the He tank. For efficient use of the helium, the gas which is generated has to be separated from the liquid and used to remove heat from other parts of the system. On the ground, phase separation can be achieved simply by placing the vapor vent at the highest point in the vessel: gravity will then ensure that the liquid remains at the bottom and the vapor is released from the top. In space this approach clearly will not work, so the system uses a special zero-gravity passive phase separator (PP) [33] 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. In flight, a slight (~30 mK) temperature difference is maintained between the two faces of the plug.

The separator takes advantage of the thermo-mechanical effect [34] that superfluid He liquid moves from cold regions to hot regions, thus the He gas can be removed and the superfluid He liquid retained as shown in Figure 19. The phase separator for AMS has been tested [35] and will soon be welded into the helium vessel.

**Vapor cooled shields (VCS)**

A series of four concentric shields completely encloses the magnet and helium vessel. By cooling these shields with the vapor from the helium vessel (separated by the phase separator, PP), the heat leak into the coldest parts of the system is dramatically reduced, and thus the lifetime of the experiment increased. The vapor flows through pipes connected to the shields, removing radiated heat as well as intercepting conducted heat from the support straps and other components. The design of the shields is particularly challenging, as there is very little space available for them.
Figure 20. One of the four vapor cooled shields.

To maximize the useful field in the bore of the magnet system, the coils have to be large, and also as close as possible to the inner surface of the vacuum tank. Likewise, the helium vessel has to be large to be able to carry the maximum volume of superfluid helium.

Two of the shields are rigid, consisting of variable-thickness aluminum honeycomb with fiberglass skins. These are designed for minimum thickness while retaining sufficient strength to withstand launch and landing loads. The other two shields are flexible, made from thin sheets of soft aluminum. Figure 20 shows one of the completed (honeycomb) shields.

**Cryocoolers**

Cryocooler technology has made great progress in recent years but, for fundamental thermodynamic reasons, coolers capable of reaching temperatures approaching 1.8 K require extremely large amounts of power at ambient temperature to be able to provide significant cooling. This power is not available on the ISS, so it is not feasible to provide mechanical cooling to the magnet itself.

However, the heat load to the 1.8 K parts of the system can be reduced significantly if heat is removed at a higher temperature. For this reason, four Stirling cycle coolers are connected to
the outer vapor cooled shield. The cryocoolers are qualified and tested (see Figure 21) by a team at NASA Goddard Space Flight Center, and are expected to remove a total of about 12 W at 68 K. This should be sufficient to reduce the rate of consumption of superfluid helium by a factor of four. A high (~92%) efficiency power supply to drive, control and monitor the coolers has been developed. One of the initial concerns over the cryocoolers was whether their performance might be compromised by the presence of the magnetic field. However, testing carried out by NASA at MIT [36] has demonstrated that the cryocoolers can be operated without problems or degradation in the stray field generated by the magnet in the locations where they are installed.

In nominal operation, each cooler consumes 100 W, which, along with the heat removed from the cryogenic system, is conducted using a dual redundant capillary pumped loop to a quarter panel zenith facing radiator on the top of the experiment (see Figure 10).

![Figure 21. Vibration test of Cryocooler at NASA-GSFC.](image)

**Coil cooling system**

The most obvious feature about the cooling system is that the coils are dry; they are not mounted inside the helium vessel, see Figure 11. There are two reasons for this. Firstly, if the coils were inside the helium space, the geometry of the vessel itself would become very complicated, and this would add considerable mass. Secondly, and more importantly, it must be possible to recover from a magnet quench in space (however unlikely this may be) by re-cooling the magnet using the onboard helium. If a magnet immersed in helium quenches, the heat transfer is so rapid that the helium quickly pressurizes and is lost through the vessel pressure relief devices.

If the coils cannot be physically inside the helium vessel, they must be cooled instead by conduction to the superfluid helium. 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 much lower conductivity at higher temperatures (to avoid transferring heat too quickly to the superfluid following a quench). Helium itself fulfils both these requirements, having extremely high thermal conductivity below 2.17 K but relatively low conductivity above this temperature.

Each coil is connected at two positions to a thermal bus bar which consists of a copper pipe filled with superfluid helium. Figure 22 shows the thermal bus bar soldered to the copper heat
transfer foils that are embedded within each epoxy-impregnated winding. The helium in the serpentine is at a pressure of ~ 1 bar so that it is supercooled and boiling is suppressed. Part of the thermal bus bar is inside the main superfluid helium vessel and so acts as a heat exchanger (see Figure 14). Heat radiated to (or generated in) the coils is transferred by Gorter-Mellink conduction (the heat transfer mechanism in superfluid helium) through the superfluid helium in the thermal bus bar and is dissipated by boiling the helium in the vessel.

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. The flow of heat around the thermal bus bar utilizes Gorter-Mellink conduction. The methodology used in the system design was based on that developed by Mord and Snyder [37] and adapted for the AMS geometry.

Figure 22. Thermal bus bar installed on the copper heat transfer foils of the magnet windings.

**Current leads**

The magnet can be operated at currents up to 459.5 A. It is equipped with persistent switches which, when closed, form a superconducting link across the terminals of the magnet. This allows it to continue to operate, once charged, in persistent mode without connection to the external power supply. The leads, which supply current from the power supply to the magnet, are therefore only used for charging or discharging: since the magnet will mostly be operated at a constant field, the leads will be used only rarely.

For this reason the leads are designed for minimum heat leak when they are carrying no current. This makes them less efficient during charging but, because their overall duty cycle is very small, results in total in much reduced helium consumption. To achieve this, the cross section of the leads is relatively small. When the magnet field is constant and the leads carry no current, the conducted heat load is therefore minimized. During charging, the leads generate a substantial amount of Ohmic heating because their resistance is rather high. This heat can only be removed by helium from the superfluid helium vessel. However, the vessel itself operates at a pressure of just 16 mbar, which is not high enough to ensure a sufficient flow of helium.
A thermo-mechanical pump (TMP) is therefore mounted in the superfluid helium vessel. The TMP is used to pump helium from the vessel through the current leads to provide cooling when required (see Figure 17). The TMP operates like the passive phase separator but in reverse. A small heater is used to induce a slight temperature difference across the TMP, but with the warmer side towards the current leads and the cooler side towards the He vessel, causing sufficient He to be pumped out to cool the leads. TMP technology in space was first demonstrated by NASA in the SHOOT demonstration but the TMP for AMS differs in details of its operation, and is developed by the Institut für Luft und Kältetechnik (ILK), Dresden, Germany [38].

A further reduction in the heat conducted by the current leads when the magnetic field is constant (no current through the leads) is given by a disconnect feature near the warm end of the leads. This device provides a complete thermal and electrical break in the leads when the persistent switch is closed.

**Cryomagnet avionics**

The electronics to power, monitor and control the magnet is housed primarily inside the Cryomagnet Avionics Box (CAB), which has been built by CRISA, EADS, Madrid. As illustrated in Figure 23:

a) the cryomagnet current source (CCS) and precision shunt, used to charge the magnet;

b) the dump diode arrays mounted on the port and starboard USS (CDDP and CDDS), which dissipate the energy stored in the magnet when it is ramping down;

c) the cryomagnet self-protection (CSP), used to detect and protect the magnet in case of a quench or the extended loss of power or communications;

d) the dual redundant uninterruptible power supplies (UPS), which power the self protection functions;

e) the cryomagnet controller and signal conditioner (CCSC), which gather the monitoring data and forwards it to the four-fold redundant main computer (JMDC) and receives and executes commands from the JMDC;

f) the power switch module, which activates valves and heaters as directed by the CCSC;

g) the cryocooler electronics box (CCEB).

Figure 23 also shows the major electrical features of the magnet which include the superconducting coils with a load of zero ohms and an inductance of 48 H, the persistent switch and mechanical disconnecting current leads, the quench heaters, warm and cryogenic valves and associated temperature, pressure and voltage sensors. Additional sensors are located within the CAB itself.

Operationally, the magnet will be launched cold but at zero field and charged only after installation on the ISS. Charged or not, the CCSC will continuously monitor the magnet state and relay these readings through the AMS CAN bus housekeeping network to the JMDC. Altogether about 150 values are monitored including 23 prime and 23 redundant cryogenic temperature measurements based on CERNOX sensors, which cover ranges from 1.4 to 400 K with accuracies down to 1 mK.
These exacting measurements allow the proper functioning of the cryogenics and magnet to be accurately controlled. The information will then flow through the NASA air-to-ground links to the POCC, the AMS ground operations center. Commands follow the reverse path to reach the CCSC, which then initiates the appropriate action within the CAB and the magnet.

The magnet is charged by the CCS. After various checks to ensure, for example, that the magnet coils are superconducting, the complete charging operation consists of five phases: preparation, output voltage limited charging, power limited charging, current limited charging and disconnection. To prepare the magnet for charging, the current leads are cooled by He vapor generated by the differentially heating the associated TMP, the superconducting persistent switch is “opened” by heating it into the normal state and the current leads are mechanically connected. The CCS then draws power directly from the ISS 120 VDC “A” feed and it is converted to a maximum of 10 VDC using six DC-DC converters in parallel. The resulting current flows through the precision shunt to the current leads and serially through all the magnet coils and back. In the third phase the power drawn from the ISS is limited to 1875 W and the current in the coils continues to increase while the output voltage drops. Then the target coil current of 459.5 A, as monitored by the precision shunt, is smoothly approached. After the target current is reached the persistent switch is allowed to cool and it again becomes superconducting and the current is trapped within the closed circuit of the magnet coils plus switch. Then the current leads are disconnected and no longer need to be cooled by the TMP and the CCS is shutdown. In total the charging process is estimated to take less than 2 hours.

Ramping down the magnet current is less complicated. The CCS remains powered off and disconnected, the current leads are cooled and connected and the persistent switch is again driven open. The current in the magnet coils then flows through the dump diodes (CDD-P,-S) which are mounted directly on the Unique Support Structure (USS) and the stored magnetic energy is converted into heat dissipated by these diodes. To dissipate the 5 MJ stored in the magnet is estimated to take less than 1.5 hours.
The CSP has two overlapping functions: to detect and protect the magnet should a quench occur and to automatically ramp down the magnet after a fixed delay should either power or communication to the experiment be interrupted. An uncontrolled quench, though unlikely, could damage the magnet. If the onset of a quench is detected, as indicated by a voltage drop anywhere over the coils or persistent switch, a fast pulse of energy is required to fire the quench heaters wound within each coil and dissipate the stored magnetic energy evenly over the cold mass. As the power level required is never available from the ISS, this energy is drained directly from the UPS to the quench heaters. If, during a charge or discharge operation, the current leads start to overheat, they can also be damaged quite rapidly, so current lead temperature sensors are also tied into the quench heater trigger.

It should be stressed that, owing to the advanced properties of the AMS superconductor and the cryogenics design, none of these conditions, including a spontaneous magnet quench, is anticipated to occur on orbit. However, should it ever happen, this design ensures that the magnet will not be damaged and that, after re-cooling, it can be recharged and the mission can proceed successfully. In any case, no hazard will be presented.

When charged, the magnet current would continue to circulate indefinitely, even if the experiment was powered down or the command path to the experiment was broken. To obviate concerns arising from this when attached to the ISS, the CSP also contains an auto ramp down timer. In the event that no external communication is received for 8 hours the CSP initiates the ramp down sequence, while continuing to monitor and protect against a quench. Consequently, even in the event that power or communication to AMS is interrupted, after 8+1.5 hours the magnet is guaranteed to be at zero field. A critical element of the magnet avionics is then the Unin-
interruptible Power Supply (UPS), which provides the power to the CSP and through the CSP to the quench heaters, in the unlikely event of a quench. After an extensive investigation of capacitors and battery technologies it was determined that only the highest quality Lithium-Ion cells would fulfill the requirements of energy density, thermal operating range and rate of discharge, as well as reliable and safe operation on orbit. These cells were produced by Yardney/Lithion. They are based on the mechanical design space proven in the Mars Lander and Exploration Rover programs and the cell chemistry used in the B-2 Bomber upgrade. In addition they are supplied with a Battery Management Systems (BMS) adapted for the AMS-02 requirements from a space qualified system developed for JPL. The BMS ensures that the eight cell battery is neither over charged nor over discharged, both of which could reduce the battery capabilities, though with the implemented mechanics and chemistry neither condition would be a hazard. However, as even the highest reliability batteries may not perform at full capacity at end of life, two UPS (cell pack plus BMS) will be installed on AMS-02. Either is sufficient to meet the requirements.
6. Testing and integration of the magnet and cryogenics on AMS

Texas A&M proposes to field a team of three people who will be dedicated to the above program of effort throughout the whole sequence, at SCL, then at CERN, then at ESTEC, and finally at KSC. The on-site team leader is Kerry Stiff, a senior cryogenic technologist with 20 years experience in all aspects of cryogenics and magnet technology pertinent to the work in hand. A junior technician with cryogenics and controls experience will work under his direction. A physics graduate student in physics from Texas A&M will do his thesis research on the testing and integration of the AMS experiment and the cryogenics experiments planned during AMS operation in space. Prof. Peter McIntyre will provide scientific and technical leadership of the team, and he plans to spend two month-long working trips during the coming year with the on-site effort. The Texas A&M group in College Station will provide backup support as necessary.

The Texas A&M team will have two key responsibilities to ensure that the magnetic spectrometer will be delivered to KSC by the end of 2008. First, they will augment the professional team at SCL for the coming year, during which two key patterns of activity must be carried forward in parallel: testing of the superconducting magnet (Figure 24), and assembly and testing of the superfluid helium tank and its associated subsystems (Figure 25). There is not enough time to schedule those activities in series and meet the December 2008 launch window for the Shuttle program. While SCL has done an excellent job of designing and building the components for both systems, it does not have adequate expert manpower to support the two coming patterns of activity in parallel. The Texas team will live and work at SCL, taking whatever roles the SCL team requests of them, to provide the necessary extra skilled effort.

Second, after becoming intimately familiar with all systems in the superconducting magnet and its cryogenics during the work at SCL, the Texas team will travel with the system to CERN and to bring the magnet and cryogenics into operation in the test beam and then to ESTEC. The contract with SCL calls for minimum involvement of SCL personnel at CERN, at ESTEC or at KSC. The Texas team will provide that continuity, at CERN, at ESTEC and then at KSC.

In addition, the Texas A&M team will work with AMS management to plan and execute cryogenic experiments during AMS operation on ISS. AMS will be the first-ever instrument that operates a large superconducting magnet in space for years of duration. AMS plans to conduct experiments in the host of operational modes that are required for its operation: charging and discharge, quench detection, quench initiation, quench recovery, gathering and pumping of superfluid helium, indirect cooling, and phase separation of He vapor from superfluid liquid. The Texas A&M team will collaborate with colleagues in AMS who designed and built the superconducting magnet and its cryogenics to plan and execute those tests in a way that yields maximum information pertinent to future applications of superconducting magnets in space.

Those experiments take on a significant urgency with the growing importance of space-based superconducting magnet technology for future high energy experiments in space, and for magnetic shielding of astronauts and advanced propulsion using plasma and MHD technology. The space radiation environment beyond Earth’s magnetosphere poses an ultimate challenge: the cumulative dose to astronauts for a multi-year mission would be lethal unless effective shielding could be provided. The only technically feasible way to provide that shielding would be to provide the spacecraft with its own ‘magnetosphere’ in the form a large superconducting toroid.
AMS physicists developed a conceptual design for such a toroid that grew from what they learned in designing the AMS systems. The Texas team has further developed that design to a stage where its technical feasibility is firming up so that serious technical development could begin in the coming years. The Texas A&M team plans to mature this technology for use in space.

A 3-year funding program is proposed, in which the first two years would anchor the completion and integration of the magnet/cryogenics systems in AMS, and the following year would carry through launching to ISS, commissioning AMS into operation, and conducting cryogenic experiments.

Time is of the essence. SCL is fitting out the magnet for installation in its test dewar. Tests will be conducted by summer. The helium tank is being assembled one stage at a time. The window of time in which additional skilled technologists are needed has now begun. A funding decision is requested as soon as possible. Significant delay after that time could jeopardize the ability of AMS to maintain the schedule needed to match NASA launch windows in the end game of the Shuttle program.
7. Experiments with AMS magnet/cryogenics to optimize magnetic shields for manned exploration

**Study of the magnet cryogenics in space**

The properties of superfluid helium are critical to implementing superconducting magnets. Further research is required to fully understand the behavior of superfluid helium in a strong magnetic field when under zero gravity. The superfluid helium near a superconducting magnet is always subject to three forces. First, the property of film flow causes it to flow over and coat all surfaces with which it comes in contact. Second, thermal gradients give rise to pressure gradients. Third, because helium is weakly diamagnetic it is weakly repelled by the magnetic field.

On the ground, these three effects are overwhelmed by the effect of gravity. In space, under zero-g, the detailed behavior of superfluid He must be more thoroughly understood. For example Figure 20 shows stratification by thermal gradient in cooling lines. The provisions for phase separation, gathering of superfluid within the He tank, and isolation of the He inventory during quench were designed with the above forces in mind, and extensive tests have been done in the Earth-bound lab to validate the designs. It will be important to plan and execute a set of experiments once AMS is operating on ISS to measure superfluid flow both in and out of equilibrium.

**Study of quench recovery procedures in space**

The AMS-02 aluminum stabilized superconducting cable essentially eliminates the possibility of an unforced quench. However, as an important prerequisite to the use of superconducting cryomagnets on long duration manned space flights, it is important to be able to study the method of recovering from a quench. A quench test in space will yield critical information on:

(i) The behavior of the cryogenic system during and after the quench;
(ii) Heat transfer from the magnet to the He with large temperature differentials under zero-g;
(iii) The effectiveness and duration of the procedure for re-cooling the magnet.

![Figure 26. Heat transport in He vapor: a) mixing on the ground; b) stratification in zero gravity.](image)
Figure 27. (a) Typical superconducting magnet coil venting all of its superfluid helium during a quench. (b) Coil temperature and liquid superfluid helium level during a test quench of an indirectly cooled AMS-02 coil. A negligible amount of helium is vented.

To study in detail the thermal transport properties of superfluid and vapor phase helium, a quench should be induced in the AMS-02 magnet. During a quench a segment of the magnet coil ceases to be superconducting and becomes resistive. The energy contained in the magnet is then rapidly dissipated as the field and current decay. In a typical superconducting magnet the coils are immersed in superfluid helium which is quickly vaporized during a quench, as shown in Figure 27a.

In contrast the AMS-02 magnet, and the magnets proposed above for radiation shielding, are indirectly cooled so that the helium is not vaporized during a quench. Figure 27b shows the effect on the ground of a quench of one AMS-02 coil on the superfluid helium level. Despite a sharp ~60 K rise in the coil temperature the helium level is barely affected. Although a spontaneous quench is unlikely with an Al-stabilized conductor, to ensure that it is possible to recover from a quench, it is proposed to induce one near the end of the experiment. Equally important, an induced quench would yield valuable data on the thermal system of the AMS-02 magnet. After a quench the magnet coil temperature raises quickly from 1.8 K and this heat is radiated to the surrounding helium tank. Within the contained superfluid helium, as indicated in Figure 26a, on the ground this induces both internal convection (which is peculiar to superfluid helium and gives it its enormous effective thermal conductivity) and natural convection due to the force of gravity (warmer low density fluid rises and is replaced by cooler high density fluid). In space, the natural convection disappears and only the internal convection is present (Figure 26b). Inducing a quench is the only means to examine the effectiveness of the thermal design during this transition.
9. Facilities

The Accelerator Research Lab has built up a substantial body of equipment and facilities that support the full array of tasks required in building superconducting magnets:

- Class 1000 clean room for coil winding,
- Winding fixtures for 1 m coils and for 4 m coils;
- System for removing starch sizing from insulated cable and replacing it with palmitic acid;
- Complete tooling for reaction heat treatment of coil assemblies;
- Zone-regulated furnace capable of heat-treating up to 3 m long magnets up to 900°C;
- Vacuum impregnation system capable of epoxy impregnating coils up to 3 m long;
- EDM machining system with CAD/CAM capability, used to fabricate parts with extreme precision;
- Laser-welding and drilling system, used to weld expansion bladders and laminar springs,
- Fixturing for coil handling and magnet assembly;
- Hydraulic presses for assembly of flux return cores and for preload of coil assemblies during welding;
- Preload system in which a magnet is heated above melt point of Wood’s metal, expansion bladders are filled with metal and hydraulically preloaded, and the magnet is cooled while maintaining pressure on the bladders.

We also have all the ingredients for a full capability for a vertical test stand and associated liquid helium cryogenics, but it awaits the happy day when we have any shred of spare manpower with which to commission it.
10. **Key Personnel**

*Peter McIntyre* holds the Mitchell/Heep Chair in Experimental Physics at Texas A&M University, and has led the development of the block-coil design to date. In the past he has authored the concepts of proton-antiproton colliding beams, invented depressed-collector techniques for electron cooling, co-authored the superferric design of the SSC, and developed cathode technology for high-power microwave tubes. Prof. McIntyre is now also contributing to an industry effort towards new manufacturing technology for high-performance internal-tin Nb$_3$Sn superconducting wire.

*Al McInturff* is a senior accelerator physicist, with 40 years of experience in superconductor development and the design, fabrication, and testing of superconducting magnets. Dr. McInturff has contributed to every facet of superconducting technology, strand development, PIT process in Nb$_3$Sn, development of the successful Tevatron magnets, development and testing of the SSC dipoles, and most recently the pattern of successful developments of Nb$_3$Sn dipoles at LBNL.

*Kerry Stiff* is a senior cryogenic technician with 20 years experience with cryogenics, refrigerators, and superfluid He systems. He served with SSC and with LIGO, and most recently contributed to the successful completion of the superfluid cryogenic system for SNS.

*Akhdiyor Sattarov* was trained as a nuclear theorist, and has been working for the past 5 years in the calculational physics of superconducting magnets and particle accelerators. He performs finite element calculations of the magnetic fields, the mechanical stress, and the quench propagation in the magnets, and also beam optics and dynamics in accelerators. He has developed techniques by which to do constrained quadratic optimization of the dipole designs.

*Tim Elliott* is a senior technician, with 20 years experience in a wide range of technologies. He contributes to the mechanical designs of both magnets and fixtures, electrical controls and DAQ. He operates our high vacuum systems and hydraulic systems. He is also our EDM machinist, and has developed the CAD/CAM links by which we are able to make parts efficiently.

*Nick Diaczenko* is a senior machinist and technician, with extensive experience in the fabrication of precision equipment of all kinds. Nick developed our laminar spring, machined many of the parts in our magnet assembly, and developed the demanding weld techniques for the hoop plates, the body welds, and the high-pressure bladders.

*Ray Blackburn* is our CAD designer. He has designed all of the piece parts and assemblies for the dipoles described above. He took the lead in developing our systems for cable cleaning and spray application of palmitic acid. He is building the support coffin that will hold the coil assembly during reaction bake.

*Andrew Jaisle* is a senior technician, who participated in the magnet R&D team at Brookhaven, then ran the model magnet fabrication facility at SSC. Andrew worked with us for two years earlier, then returned to the Dallas area for personal reasons. He has elected to return to the group, and is taking leadership straightaway in the completion of the furnace lift fixture and the modifications of the impregnation system.

In addition we have four graduate students – two in their third year (Joong Byeon and Nathaniel Pogue) and one in his first year (Eddie Holik). Two undergraduate students (Chris English and Aaron Collier) participate in the research. All of these students are academically strong and well motivated.
Peter McIntyre
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DATE OF BIRTH: September 26, 1947
EDUCATION: A.B. Honors, Physics, Univ. of Chicago, 1967
M.S. Physics, University of Chicago, 1968
Ph.D. Physics, University of Chicago, 1973

Peter Mastin McIntyre is Mitchell-Heep Professor of Experimental Physics at Texas A&M University and President of Accelerator Technology Corp.

Dr. McIntyre is an A.P. Sloan Foundation fellow, and is listed in Who's Who in America. In 1980 he was awarded an IR100 award for the invention of a technique for high-efficiency collection of intense electron beams. Dr. McIntyre was among the first to propose the construction of the Superconducting Super Collider and was a co-author of the Texas SSC site proposal. In 2001 he was elected a Fellow of the American Physical Society.

High energy physics. Prof. McIntyre is a founding collaborator in the CDF experiment at Fermilab. The CDF team is studying 2 TeV proton-antiproton collisions and in 1995 discovered the top quark. He is currently participating in the search for signals of supersymmetry in CDF.

Accelerator technology. Prof. McIntyre has developed several new technologies for superconducting magnets, including low-field superferri dipoles for hadron colliders, stress management for ultra-high-field dipoles, a 4 Tesla whole-body solenoid for functional brain imaging, a 400 MHz self-shielded solenoid for MR spectroscopy, a superconducting dipole for MR well logging, and a structured cable using the new high-temperature superconductors. He is currently developing a 12-16 Tesla Nb3Sn collider dipole which incorporates stress management, conductor optimization, and hydraulic preload. He authored a concept for a Tevatron Tripler, a possible upgrade of the Tevatron colliding beams facility at Fermilab.

Most recently Prof. McIntyre has extended the high-field magnet technology to accommodate hybrid coils in which Bi-2212 inner windings are used in the highest-field regions and Nb3Sn windings are used in the lower-field regions. This makes it possible to extend to 25 Tesla dipole field, opening the possibility of a Tripler upgrade to the Large Hadron Collider at CERN. He also applied his structured-cable design to a Nb3Sn quadrupole for the high-radiation, high-heat requirements of the intersection regions at LHC and at the International Linac Collider. He devised a levitated-pole dipole for the difficult design of the dipole used to separate the beams on each side of the intersection region. He has devised a getter/electrode assembly capable of killing the electron cloud effect in the arc dipoles of LHC, an effect that threatens otherwise to limit the luminosity of the collider.

Materials science. Prof. McIntyre is developing new manufacturing technology for high-performance Nb3Sn superconducting wire that will be essential in the superconducting magnets for future hadron colliders and also for extending the performance of NMR spectroscopy for structural biology and materials science. He is developing techniques for hollow extrusion of subelement billets, continuous wrapping of Ta diffusion barrier and stabilizer Cu onto drawn subelement, and continuous restacking of multi-filament assemblies. He has also developed a
technique for zero-defect removal of supermicron particles from the precursor powders used in powder-in-tube fabrication Nb3Sn superconductor. Prof. McIntyre is beginning the development of a technique for synthesis of high-performance MbB2 superconducting powder using an rf plasma torch process.

**Applied physics.** In 1987 Prof. McIntyre founded Accelerator Technology Corporation (ATC) to commercialize products using the new technologies emerging from high-energy research. ATC manufactures a structured cable using Bi-2212 superconductor, a family of silicon devices for electronic sequencing of DNA, and a high-efficiency, high-throughput electron beam system for disinfestation of foods and treatment of organic contaminants in water.

Prof. McIntyre is developing a design for accelerator-driven thorium-cycle nuclear fission power, in which proton beams from a flux-coupled isochronous cyclotron stack are used to drive the transmutation of thorium to produce ~GW electric power. The technology has the benefits that there is abundant fuel (enough to run the Earth’s energy needs for a thousand years), it eats its own waste, it cannot melt down, and it produces almost no bomb-grade isotopes. In a collateral development Prof. McIntyre invented and is currently developing a new technique for fabricating SiC-reinforced steel tubes for use as fuel rod cladding in Generation-IV fission power reactors. The same technique has potential for applications to smart materials.

Prof. McIntyre is applying his high-field superconducting magnet technology for two other applications: a 30 T solenoid to extend the reach of structural biology for proteins, and a 10 Tm shield toroid to protect astronauts from cosmic radiation on missions to the Moon and Mars.

Prof. McIntyre is beginning the development of two additional applications of the high-field magnet technology: high-field MR solenoids for structural biology, and magnetic shielding of manned spacecraft to protect astronauts from cosmic rays.

**Undergraduate education.** Prof. McIntyre has led the development of Visual Physics, a reform of first-year physics at Texas A&M University. VP encompasses integration of lecture and interactive problem-solving, highly visual laboratory experiments, and instruction in technical writing using lab reports as writing assignments.

**Recent Publications (52 during 2005-6)**

459. Test results of a Nb3Sn wind/react block dipole. (with A. McInturff et al.), ibid.
458. Fabrication process development with ‘dirty’ MgB2. (with T. Elliott and A. Sattarov), ibid.
455. Recent developments on Nb3Sn dipole technology at Texas A&M. (with T. Elliott et al.), ibid.
454. On the feasibility of a Tripler upgrade for the LHC (with A. Sattarov), ibid.
451. Observation of \( B_s^0 \rightarrow \bar{B}_s^0 \) oscillations. (with A. Abulencia et al.), Phys. Rev. Lett. 97, 242003 (2006).
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Experience, Expertise

- Helium liquefaction / refrigeration
- High purity gas systems, Installation, Certification, Maintenance
- Gas processing, Cryogenics, Adsorbents, Membranes, Getters,
- High vacuum techniques, leak detection, residual gas analysis
- Trace gas analysis, Gas chromatography, Spectroscopy
- Instrumentation, Process Control, PLCs
- Operations, Management, Personnel Training
- Field service, Operation, Maintenance
- Start-up and commissioning, Documentation

Career Highlights

- Operated and maintained superfluid helium cryogenic system at SNS.
- Leak detection, instrument check out and start up of three 4kW-helium liquefier systems at the Superconducting Super Collider.
- Start-up and performance testing of cryogenic systems for a new superconducting particle accelerator in New Delhi, India.
- Supervised construction, start up, operation and maintenance of cryogenic plants throughout the western hemisphere and Asia.
- Leak detection, vacuum conditioning and residual gas analysis to establish the world’s largest ultra high vacuum systems at gravitational wave observatories in Louisiana and Washington State.
- Particle analysis, gas analysis, leak detection and certification documentation necessary to commission new wafer fabrication plant for a major semiconductor manufacturer.
- Planned and supervised repair and upgrade of a gasoline production, helium purification and helium liquefier plant.
- Designed, assembled and commissioned control system for a natural gas processing plant on the Navajo Indian Reservation.

Positions Held


2003-2005: Nathaniel Energy Corp, Englewood, CO   Helium Operations Manager   Responsible for operations at natural gas processing/helium extraction, purification and liquefaction plant at Keyes OK. Supervised staff of ten employees including scheduling, personnel training and mentoring and performance reviews. Supervised overhaul of gasoline production unit and gas dehydrators. Planned and supervised disassembly of cryogenic helium purifier and liquefier including replacement of heat exchanger and adsorbers. Rebuilt expansion turbines and reciprocating expansion engines on location. Acted as liaison between Company, primary contractors, and vendors. Instituted a program for identifying and controlling process gas losses. Increased plant production by 25 percent while reducing cryogen consumption by 25 percent.

1997-2002: Caltech/MIT LIGO Project, Pasadena, CA   Vacuum Specialist   Technical liaison with prime contractor responsible for certification of vacuum system leak integrity, cleanliness and dimensional tolerances. Specified, purchased and assembled instrumentation to control beam tube temperatures, power supply variables and
vacuum pump parameters for bake out and conditioning of world's largest deep vacuum systems consisting of ten
miles of fifty inch diameter beam tube, dozens of vacuum vessels fifteen feet high and eight feet in diameter, hun-
dreds of flanges and hundreds of miles of weld. Installed and operated equipment necessary to heat beam tube and
associated vessels to a temperature of one hundred fifty degrees Centigrade for six weeks while pumping with
cryopumps and turbo pumps. Installed, calibrated, operated and interpreted data from five Balzers quadruple resid-
ual gas analyzers. Established and outfitted mechanical and vacuum laboratories. Purchased tools and instruments.
Assembled and configured vacuum pumping, analytical and control equipment.

1995-1997: Independent Contractor  Performed start up and performance testing of cryogenic systems for a new
superconducting heavy ion accelerator for the Nuclear Science Center, New Delhi, India. Furnished technical sup-
port for a new superconducting linear accelerator at the Tata Institute for Fundamental Research in Mumbai, India.
Dismantled and shipped one helium liquefier for Applied Cryogenics Technology. Supervised dismantling, docu-
mentation and shipment of three large helium refrigerators for the Texas National Research Laboratory Commission.
Provided Technical support for several customers.

1994-1995: Air Liquide Corp. Houston, TX  Project Engineer  Responsible for leak detection, particle analysis
and gas analysis necessary to commission gas distribution system for a major semiconductor fab. Performed docu-
mentation, specified and ordered equipment and expendable supplies, trained customer personnel. Performed trace
gas analysis, leak detection and particle analysis necessary to recommission an optical imaging devices fab after a
fire. Performed gas analysis and trouble shooting for several customers. Contributed to financial and technical prop-
osals for gas distribution systems for one new semiconductor wafer fab and for substantial upgrades to an older fab.

1992-1994: Universities Research Association Dallas, TX  Senior Technical Aide  Performed leak testing, instru-
ment check out and performance testing and debugging of large helium refrigerators and associated superconduct-
ing magnet test stands for Accelerator Systems String Test facility and Magnet Test Laboratory. Led operating crew
during magnet testing. Trained operators and maintenance personnel. Disassembled and relocated refrigerator for
magnet spool piece test laboratory. Developed process and residual gas analytical techniques.

1991-1992: Independent Contractor  Performed start up and commissioning of control, analytical and vacuum sys-
tems associated with natural gas/helium separation pilot plant employing new coal based carbon adsorbent for Ni-
trotec, Inc. Installed instrumentation upgrades and performed maintenance at an old carbon dioxide plant for the
BOC Group. Provided contract maintenance, plant start up and technical services for SERH Inc., AFG Energies,
Inc. and others.

to commission three helium liquefiers, two helium extraction and purification plants, one nitrogen liquefier and an
argon extraction and liquefaction plant. Developed, assembled and operated trace gas analyzers for process and
control and quality assurance. Performed plant maintenance and documentation at these facilities and several air
separation plants.

1979-1980  Turbitrol Inc. Doraville, GA  Field Service Engineer  Responsible for instrument start up of two large
waste water plants. Performed service and plant upgrades for numerous customers. Installed telemetering, and con-
trol instrumentation for remote well, pumping and storage facilities. Developed process water analyzers. Performed
field and test bench electronic servicing to the component level.

1978-1979  Spartan Mechanical Contractors Atlanta, GA  Instrument Technician  Installed new equipment and
performed maintenance for several customers.

1976-1978  Air Products and Chemicals Allentown, PA  Instrument Technician  Control system commissioning of
three large air separation plants and three small nitrogen plants. Designed gas analyzers, developed gas analysis and
sampling techniques for high purity argon certification. Performed bench overhaul, repair and upgrades of gas ana-
lyzers. Supervised maintenance outages of cryogenic plants across south east United States and South America.
Performed emergency maintenance of air separation plants across the western hemisphere.

1972-1976  Navajo Refined Helium Inc. Bethlehem PA  Instrument Technician  Participated in dismantling and
relocation Bureau of Mines helium plant at Shiprock, NM. Fabricated and installed equipment for major renovation
of equipment as directed by Air Products, Inc. Designed, assembled and de-bugged the control system for a helium
extraction and purification plant. Designed, fabricated and commissioned telemetering system for natural gas well
control and flow metering. Set up quality assurance lab. Trained and supervised plant operators who had poor
communications skills.

Review panel: Barry Barish, (Cal Tech), chair; Elliott Bloom (SLAC); James Cronin (Univ. of Chicago); Steve Olsen (Univ. of Hawaii); George Smoot (LBNL); Paul Steinhardt (Princeton); Trevor Weekes (Harvard College Observatory)

Chairman’s Report
This is a summary report of the AMS review made by the chair, Barry Barish. I try in this letter to capture what I believe were the main points that came out during the review, both in the presentations and discussions with the AMS collaboration, in the executive session that followed and in the conclusions expressed by individual reviewers. Finally, I should comment that we delayed submitting our individual letters until we could individually do some follow-up work after the review on some issues that were raised during the review. I also include here some of the main points that were reported from those post-review inquiries.

Overall Conclusions
The AMS experiment is designed to perform precision measurements of unprecedented sensitivity of the primary cosmic ray spectrum using both particle identification and precision momentum measurement with a large aperture superconducting magnet. Such cosmic ray measurements will provide very important new information on cosmic rays astrophysics and on various high energy phenomena. Such measurements will lead to important new understanding of the nature of our galaxy. There is also the exciting possibility that AMS could make some fundamental new discoveries.

All committee members were extremely impressed by the powerful detector that has been developed for AMS and also by the considerable strength of the AMS international collaboration. The committee members found that there is a strong scientific case for deploying AMS, with the exception of one member, who had reservations both regarding the science and the approach of the collaboration.

The Science of AMS
1. Cosmic Ray Physics
The sensitivity of the instrument will be well beyond that of any previous instrument put in space to study high energy cosmic rays. Putting such a powerful new instrument in space gives strong justification on rather general grounds, because of what we can anticipate it will contribute to cosmic ray physics, due to its ability to make a whole variety of new quantitative measurements. It can be expected that such new data will have a large impact on the field.

AMS will make high statistics measurements of the momentum distribution of protons and heavier nuclei up to ~ 1000 GeV. On the low energy side, they have already observed effects of the geomagnetic cutoff in AMS-1 and now can extend this measurement to near the knee in the cosmic ray spectrum. They also could shed light on the secondary to primary flux, which is observed to be dropping with energy at low energy and they can extend this measurement to much higher energy. Detailed measurements of the isotopic composition are especially important in that they will give insight into the scales of propagation times of charged particles in the galaxy and, in turn, information on galactic magnetic fields. Finally, a more detailed knowledge of the
properties of the primary cosmic ray flux is needed to model neutrino fluxes and such information can significantly reduce the uncertainty in the flux.

The particle separation in AMS will also enable them to do measurements of positrons up to about 100 GeV, well beyond that available from balloon experiments. We know how cosmic-ray positrons are produced, which is mostly through p-p interactions in interstellar space. The goal of these measurements will be to compare the intensity and spectrum measured in AMS with the expected production rate. This comparison can help us understand how the energy spectrum is deformed by diffusion or radiative energy losses in the galaxy.

The physics questions for antiprotons are quite complementary. They are also produced mostly in p-p collisions, but in this case the only significant loss mechanism is diffusion. The astrophysics of positron and antiproton observations is quite significant, and may well be the most important contribution of AMS to cosmic rays physics, independent of the possible discovery potential in these measurements.

2. Prospects for Discovery Physics

The original motivation for AMS was to search for antimatter in the Universe. One of the major goals remains to set an improved experimental constraint on antimatter. The idea is that the baryon asymmetry in the early universe caused non-uniformities, where there are regions of the universe dominated by matter and others dominated by antimatter.

This appears unlikely, as both theory and experiment (e.g. WMAP) have constrained these possibilities and now it seems difficult to make a consistent picture where matter and antimatter have stayed unmixed in separate regions. Although the probability of discovery of antimatter appears unlikely, improved experimental limits are of value themselves.

A second and more promising discovery goal that was presented to us was the searches for dark matter. The signature being sought are excesses in the antiparticle (positrons, antiprotons, etc) spectra resulting from dark matter particle annihilations. Hints of excesses that have been reported and AMS will provide much more precise data. Even with much better data, the interpretation will be challenging due to uncertainties in the production models from normal processes. It is worth noting, however, that AMS will provide comprehensive cosmic ray data that will help better constrain these models.

Lastly, we were presented with the prospects for detecting strangelets, a new form of strange quark matter conjectured by Ed Witten in 1984. The existence of hadronic states with more than three quarks is allowed in QCD and ultra-dense matter, like that found in neutron stars, might form such matter. Although limits have been set on strangelets from accelerators, strangelets with A>8 cannot be made by coalescence at accelerators the question of the existence of strange quark matter require a different approach like using astrophysics searches. The idea is that there will be a substantial flux of strangelets in the cosmic radiation due to binary collisions of strange stars.

AMS will measure charge, mass, and momentum and can search for strange quark matter by looking for anomalously low mass/charge or A/Z. This search was already tried in AMS-01 and two possible candidate events were found, but the limited statistics and resolution did not rule out that they were background events, so this result was not published. AMS-02 will provide a much more sensitive search.
The strangelet search appears to be the most promising discovery channel that has been conjectured from known physics. Of course, discoveries of unanticipated phenomena remain an important possibility, resulting from putting a new very sensitive instrument with such powerful capability into space.

3. PAMELA Mission

The committee noted and several committee members expressed concern that some of the “cream would be skimmed off the top” of AMS-02 by the PAMELA mission, which was launched in July 2006. We could not fully analyze the capabilities of PAMELA, but it is a significant step beyond AMS-01. However, it has no where near the promised sensitivity of AMS-02, which has about 200 times greater sensitivity and has other important capabilities (e.g. transition radiation detectors) not employed on PAMELA as launched. Nevertheless, some initial discovery potential lies with PAMELA, even though it can be argued that AMS-02 will be even more justified if PAMELA demonstrates early some of the rich science that will be seen by AMS-02.

Progress on Fabrication of the Detector

AMS is designed to be a powerful new instrument in space. It is based on a large aperture superconducting magnet instrumented to be a precision experiment with very good background rejection. The goals are to separate anti-helium from helium to 1 part in 1010, to separate positrons from protons to 1 part in 106 and to measure spectra to 1% accuracy. To accomplish these goals, AMS has large bending power of BL2 = 8000 Gm2 using the first superconducting magnet designed to be put in space, has minimal material in the particle paths and makes repetitive measurements of momentum and velocity. This combination makes a powerful instrument with time resolution of \( \Delta t = 100 \) ps, spatial resolution of \( \Delta x = 10 \) \( \mu \)m, and measurements of velocity with accuracy of \( \Delta v/v = 0.001 \). Progress in building and assembling AMS-02 has been excellent. We heard reports on all the subsystems:

The superconducting magnet has been the responsibility of Switzerland. It has been especially engineered for space with a new type of superconducting cable that eliminates quenches, and numerous other innovations to prepare the first superconducting magnet for space. It recently passed a system review performed by the DOE (July 2006) and chaired by Bruce Strauss. It appears on track for a final readiness review before launch.

The Transition Radiation Detector (TRD) is designed to give a p/e+ rejection of greater than 102 up to 250 GeV. That goal appears well in hand as demonstrated in a beam test at CERN yielding a rejection of better than 102 over the entire range, and in fact a rejection of about 103 below 150 GeV. The time-of-flight system measures the time of relativistic particles to ~ 100 picoseconds. An elaborate veto system with improved electronics and light collection system over AMS-01 has measured inefficiency for minimum ionizing particles of better than 10-4. Production is complete on the large silicon tracker – 8 planes, 6.6 m2. The ring imaging Cerenkov counter has almost 11K channels and we were shown impressive performance tests from a test beam of E=158 GeV/n. The electromagnetic calorimeter makes 3 dimensional, 16 X0 measurements of the direction & energy of gamma rays and electrons and again we were shown measurements reaching the resolution goals in energy and angle. Finally, the electronics, developed in Taiwan, also appears to be well advanced. It is based on accelerator detector technologies and is ~ 10 times faster than commercial space electronics.
Overall, the committee members were uniformly impressed with the ambitious technical design and the actual realization of the detector. This impressive detector has been carefully developed with special care to achieve the technical goals. It is within a few months of being ready to begin the final integration phase.

**Readiness for Deployment**

AMS-01 was a very important and successful demonstration mission. It successfully used much of the AMS-02 technologies in space and successfully exploited the considerable cosmic ray science.

The AMS-02 detector subsystems are now almost completed and the next big step will be the integration phase preparing for launch. Integration of the detector subsystems has been proceeding at CERN and the next big step will be the full integration. CERN and ESA have been providing AMS with strong logistic support during the period 2006-2008 to assemble the detector, to calibrate the detector in a test beam and to ensure the temperature of the detector is controlled to 1°C. We were told that ESA will provide a 45 day Thermal-Vacuum test at Noordwijk. Serious integration of the full instrument system is scheduled to begin soon - early 2007 - with the goal of shipping a flight ready payload to Kennedy Space Port in late 2008. Pending completion of integration, test, and calibrations leading to a strong Flight Readiness Review result, the Agencies (NASA with DOE concurrence) should plan in 2008 to manifest AMS for a Shuttle flight to deployment on ISS.

The results presented for the subsystems (most of them) indicated reasonable expectation for meeting the science and launch requirements. Integration is still a key episode in that it is only then that full compatibility, performance, and schedule can be confidently predicted. In space based experiments, it is not uncommon to discover problems late in environmental testing, or to find that important components have fatal problems in the space environment from vendors and/or other missions. However, as the AMS collaboration controls the instrument readiness aspects of the mission (vs. NASA control of safety), they may be somewhat mitigated compared to other recent missions. The costs of this final integration step were also a concern to some committee members. It is certainly not small and it is not clear at this time how much resources will be required and how they will be paid.

**AMS Role in International Collaboration on Major Scientific Projects.**

The role of AMS in the area of international collaboration on major scientific projects is truly outstanding. When the AMS-02 detector is integrated, it will bring together the efforts of many nations and groups across the globe. In fact, this experiment has crystallized its collaboration around the international contributions to the space station itself. There have been very large contributions to AMS coming from Italy, China, France, Taiwan, and the US, with significant contributions by five other countries, and some contribution from six others. The committee particularly noted the uniqueness of having Taiwan and the PRC together on AMS. It was emphasized by Professor Shih-Chang Lee in his presentation that they agree on the importance of having AMS-02 on the ISS. The national governments of the participants, through their ministries of science, have regularly reviewed and expressed enthusiasm for the project.

The Review Committee heard representative scientists from nearly all of the participating nations. One had to be impressed by how each group is making an important contribution to the whole and how the disparate groups have been coordinated to work together smoothly and effi-
ciently with one another. Indicative of the cooperation was the fact that a single presenter described to the Review Committee As one reviewer commented, “In addition to what it accomplishes scientifically, the AMS project is sure to be viewed as a model for international collaboration in science.”

The total project is clearly well managed by Professor Ting. In general, the committee had only praise and some wonder of this effort. One committee member however, felt that the structure of the overall project management, beyond the leadership of S. Ting has not been made clear.

**FINAL REMARKS**

AMS-02 is poised to soon begin its final integration phase. The very strong AMS collaboration has carried out a very successful demonstration mission, AMS-01, and has done a magnificent job of designing and building a state of the art device for deployment on the space station. The science potential of AMS-02 is very broad, including a wide variety of measurements fundamental to understanding high energy cosmic rays and their origins. In addition, such a sensitive detector may well make some fundamental discoveries. The collaboration is exceptionally strong and is made from an international team with cohesion and outstanding technical skills. The leadership and management of AMS is effective and dedicated. In the opinion of this review committee, the AMS mission is ready for the next step and plans should be made to place it onto the space station, in order for it to carry out its promising science.
Executive Summary

Introduction

The AMS02 experiment is scheduled to be transported to the International Space Station sometime prior to 2010. This will be the largest experiment on the Space Station and NASA is following its progress with detailed design and construction reviews including ground operations to ensure that the experiment will have a safe, reliable and timely operation.

The first AMS experiment used a permanent magnet with a performance parameter, $BL^2$ of 0.14 Tm². The new experiment proposes to use a superconducting magnet with a performance parameter about six times higher, 0.86 Tm². The magnet consists of two race track Helmholtz coils with twelve race tracks placed in a toroidal like pattern to actively shield stray magnetic flux. The maximum field in the active area is 0.86 T with a peak field in the coils of 6.6 T. The coils operate at 60% of short sample current.

Space flight requirements and conditions have clearly dominated the design of the magnet system including reliability, weight and operation in zero gravity. Longevity on the space platform is also a consideration requiring low total heat leak. To meet these criteria the coil has been designed with relatively low transport current yielding a quite high inductance. The coils are operated in the persistent current mode with the power supply disconnected. A unique forced flow of superfluid helium is used to cool the magnet system.

The two main dipole coils and the twelve flux return coils have been constructed. Each has been individually tested in liquid helium. Some training was observed. The next phase of the magnet construction project is functional testing of the flight magnet assembly in a test cryostat at the Culham, UK, shops of Scientific Magnetics. A test program is planned using a modified superfluid helium cooling scheme. Upon successful testing the magnet will then be assembled into the flight cryostat.

Review charge

At the request of Professor Ting and Dr. Robin Staffin a review of the plans for the testing of the AMS-02 magnet system was held at CERN on Tuesday, July 25. The charge given for the review was:

The magnet for the AMS project is being assembled at Space Cryomagnetics Ltd. (aka Scientific Magnetics) in a test cryostat and then will be shipped to CERN for final assembly into the flight cryostat. You are being asked to review all technical areas of this portion of the project as well as its schedule and management aspects. In particular, please address the following questions in your assessment.

1. Comment on the detailed technical plans of the design teams for assembly and testing of the cryostats and magnet systems
2. Comment on the adequacy of human and other resources planned for the final stages of this project.

3. An experienced review committee was assembled and the members and short backgrounds of each are listed in Appendix A.

4. A technical presentation was made by Robin Stafford-Allen and Steve Milward of Scientific Magnetics. The technical presentations gave a general design overview and a top level test program. A detailed question and answer session followed.

Findings

While the overall design has been extensively reviewed the committee was concerned about two issues. Both had to do with the system for the removable leads and the ability to safely discharge the magnet in the case of a quench. After the magnet is put into the persistent current mode the leads are disconnected by a pneumatic actuator. Concern was expressed regarding the reliability of the actuator as well as the source of high pressure gas for that device.

The Scientific Magnetics staff gave a summary of testing of the individual coils of the AMS02 system. Each of the coils was tested to 10% above the nominal stress expected in their space environment. It was stated that some of the coils trained (required several quenches) to reach that level. In operation the flux-return coils are operated in a toroidal like configuration and will have major bending stresses along the outside leg. Given this data the committee felt that the plans for only one cooldown cycle during operation in the test cryostat was not adequate.

Data presented to the review committee indicated signal noise in the control voltage leads during prior testing. This might lead to false quench signals and would possibly affect the overall helium usage if not corrected.

Comments

The committee was pleased that NASA JSC is providing a project engineer, Ken Bollweg, to follow the final testing and commissioning of AMS02. In addition to minimize the potential pitfalls of technology transfer they are sending their own welder to fabricate the final welds on the final cryostat.

Due to the fact that only an outline for the next stages of testing were provided to the committee it was difficult to ascertain if the test plan included all of the individual items that members of the committee would have expected. For example it was not clear if high voltage (hi-pot) testing was part of the test protocol. In addition the committee would have liked to see more detail regarding the test plans for the cooling system including specific tests for penetrations and feed-through. The Action Items and Recommendations that follow reflect these concerns.

In summary the AMS-02 magnet system is well advanced. Attention to detail during the next phase of assembly and testing is mandatory for success.
Action Items and Recommendations from the Magnet Testing and Integration Review:

1. Make measurement of the amount of helium that is used during a quench and recharge a test objective.

2. Show how the plans are to control signal noise on the Cryomagnet Self-Protection System to prevent false quench signals.

3. Review and provide to the next review committee your design choices for the disconnect system for the current leads. In particular answer the following questions: What is the heat leak through the current leads if they are not disconnected, and why did the project choose to disconnect the current leads? Please provide the entire test data to date and that expected from the coming test program regarding the current leads including the reliability of the disconnect assembly.

4. Add at least one additional thermal cycle to the magnet testing in the MATF. For example: Step 7B – Warm the magnet system to room temperature and re-cool to 1.8K.

5. Show how the resistance of the inter-coil joints is planned to be measured in the coming test program? (This question is related to magnet decay).

6. Consider adding redundancy to the warm helium system that would incorporate two gas supply tanks.

7. Present plans to measure the expected endurance on the system before flight.

8. Add high-pot testing to the MATF.

9. Consider the American Vacuum Society (AVS 2.1) standard or the equivalent for leak testing.

10. Provide test plans for verifying all superfluid liquid helium feed-throughs and in particular the electrical feed-throughs.

11. Perform a Test Readiness Review with a committee of independent experts. Experts must have access to full test plan.
14. References

16 O.P. Anashkin et al., ‘Testings of the 20 kOe superconducting magnet during Earth satellite flight’, Kosmicheskie Issledovanija 7, 5, 1969
17 Kosmicheskie Issledovanija 12, 6 (1974).
18 NERVA, SEVER-M, PAMIR, PRIKASPY.


