

The Superconducting Magnet System of AMS-02 – A Particle Physics Detector to be Operated on the International Space Station

B. Blau, S.M. Harrison, H. Hofer, I.L. Horvath, S.R. Milward, J.S.H. Ross, S.C.C. Ting, J. Ulbricht, G. Viertel

Abstract--The Alpha Magnetic Spectrometer (AMS) is a particle detector designed to search for anti-matter, dark matter and the origin of cosmic rays in space. The detector will be assembled at ETH Zurich and installed on the International Space Station (ISS) in 2004. The planned duration of the experiment is 3 years. The magnetic dipole field is achieved by an arrangement of 14 superconducting coils. The magnet system consists of a pair of large Helmholtz coils together with two series of six racetrack coils, circumferentially distributed between them. This arrangement was mainly chosen to minimize the stray field outside of the magnet and to minimize the magnetic dipole moment. It generates a magnetic field of 0.87 T in the center of the magnet with a bending power of 0.78 Tm². All superconducting coils are wound from a high purity aluminium-stabilized mono-strand NbTi conductor with rectangular shape of 1.55 mm × 2.00 mm. The coils are located inside a toroidal-shaped vacuum vessel. They are indirectly cooled by superfluid helium at 1.8 K. This cooling loop is thermally connected with a 2500 l vessel for superfluid helium which serves as a cold reservoir. In order to ensure the 3 year endurance without refilling, the magnet design was optimized with respect to very low heat losses. This paper describes the main features of the AMS superconducting magnet including the manufacturing process of the conductor and the principle concept of the cryogenic system.

Index Terms--Aluminium stabilized superconductor, AMS experiment, He II, International Space Station, NbTi

I. INTRODUCTION

THE apparent absence of anti-matter in the universe is one of the great puzzles in particle and astrophysics. Balloon-based cosmic ray searches for antinuclei at altitudes up to 40 km have been carried out for more than 20 years; all such searches have been negative.

The Alpha Magnetic Spectrometer (AMS) is a space-borne particle physics experiment designed to search for charged particles outside the earth's atmosphere at a height of 430 km and to measure them with a much greater sensitivity than so far possible.

The precursor experiment AMS-01 [1] was flown on the space shuttle Discovery on flight STS-91 for 10 days in June 1998. This was primarily a test flight that enabled the AMS team to gather data on background sources, adjust operation parameters and verify the detector's performance under actual flight conditions. The data analysis of this flight is still in progress. Several results have been published to date [2]-[6]. AMS-01 had a permanent magnet (Nd₂Fe₁₄B) producing a fairly uniform field of 0.15 T.

The AMS-02 experiment will be installed on the International Space Station ISS for a period of about 3 years. The launch is scheduled for 2004. In addition to searching for dark matter and the origin of cosmic rays, a major objective of this program is to search for antinuclei using an accurate, large acceptance magnetic spectrometer. For this purpose the strength of the magnetic field is increased by a factor of six as compared to AMS-01. This high magnetic field is achieved by means of a superconducting magnet system.

II. AMS-02 DETECTOR

The AMS-02 detector will operate on the ISS at an altitude of 430 km on a 51 degree orbit. The detector assembly for the shuttle flight to the ISS is shown in Fig. 1, including the detector subsystems. The single detector components, except for the magnet system, are described elsewhere in detail [1], [7].

III. MAGNET SYSTEM

The superconducting magnet system for AMS-02 consists of a pair of large racetrack coils together with two series of six smaller racetrack coils circumferentially distributed between them, as shown in Fig. 2. The two main racetrack coils are akin to a Helmholtz pair and will be referred to as Helmholtz coils in the following. They are used to generate the majority of the transverse magnetic field. The twelve smaller racetracks are located at $\theta = \pm 60^\circ, \pm 72^\circ, \pm 84^\circ, \pm 96^\circ, \pm 108^\circ, \pm 120^\circ$. These coils are included for the following purposes:

- (a) to increase the magnitude of the overall dipole field
- (b) to reduce the magnitude of the stray field outside the magnet
- (c) to reduce the magnetic torque resulting from the interaction between the external field of the magnet system and the Earth's field.

Manuscript received September 24, 2001.

Correspondence author: B. Blau, ETH Zurich, 8093 Zurich, Switzerland, (e-mail: blau@particle.phys.ethz.ch).

B. Blau, H. Hofer, I.L. Horvath, J. Ulbricht and G. Viertel are with the Swiss Federal Institute of Technology (ETH), 8093 Zürich, Switzerland
S.M. Harrison, S.R. Milward and J.S.H. Ross are with Space Cryomagnetics Ltd., Culham, Oxon OX14 3DB, UK
S.C.C. Ting is with the Massachusetts Institute of Technology, Cambridge, MA 02139, USA

The Helmholtz coils have a height of 1081 mm and a width of 681 mm; the winding cross section is 88 mm × 146 mm. Each racetrack coil has a height of 826 mm and a width of 306 mm; the winding cross section is 54 mm × 103 mm.

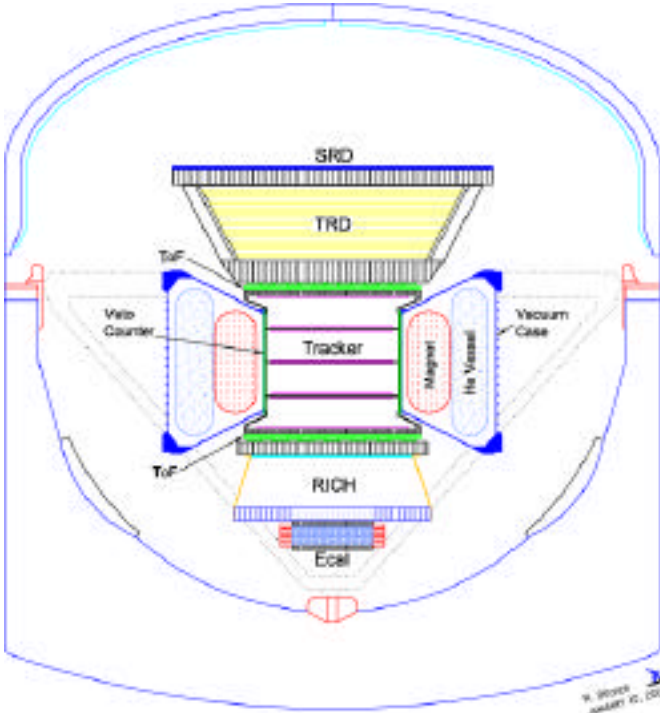


Fig. 1. The AMS-02 detector in the cargo bay of the space shuttle for the flight to ISS. The detector components are: SRD = Synchrotron Radiation Detector [8]; Tracker = Silicon Tracker; Ecal = Electromagnetic Calorimeter; TRD = Transition Radiation Detector; ToF = Time-of-Flight Scintillators; Veto Counter = Anti Coincidence Counter; RICH = Ring Imaging Cherenkov detector.

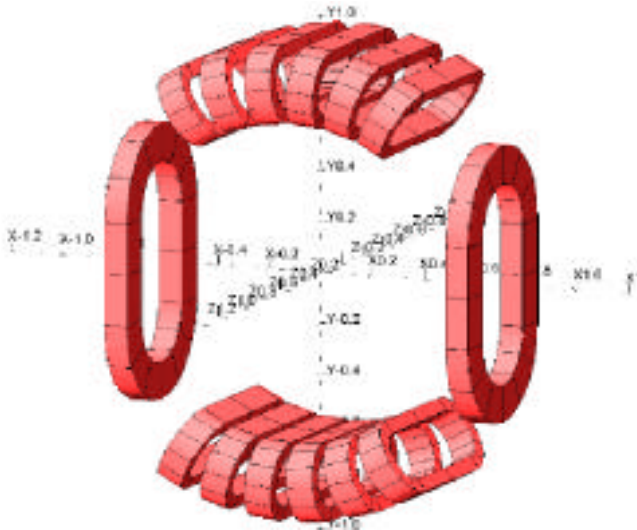


Fig. 2. AMS-02 magnet configuration producing a dipole field in x -direction. (scales in meter)

All superconducting coils are situated inside a vacuum tank and operated at 1.8 K with superfluid helium. The magnet coils and the toroidal helium storage vessel with a volume of about 2500 l are screened from heat radiation by a series of cold helium gas cooled thermal shields. An artist view of the AMS-02 magnet system including cryostat and

vacuum tank is shown in Fig. 3. The free bore of the magnet system has a diameter of 1.1 m. The outer diameter of the vacuum tank is 2.7 m and its height is 1550 mm.

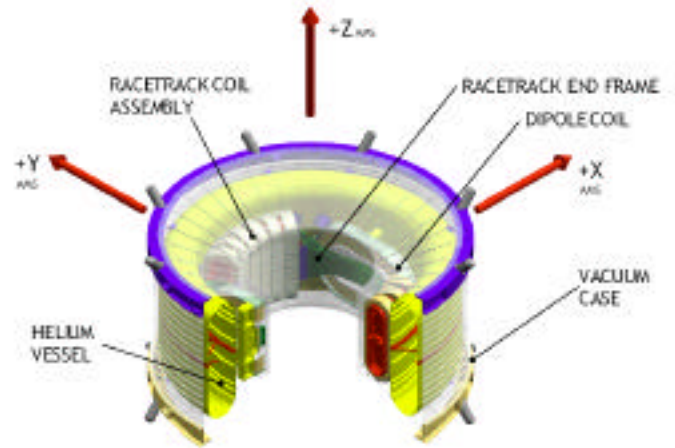


Fig. 3. 3-D artist view of the AMS-02 magnet system.

All magnets are electrically connected in series carrying a current of 459 A. The magnet system will be operated in persistent mode, using a superconducting switch. An active quench protection system has been chosen using quench heaters.

One characteristic that arises from the operation of a large Helmholtz configuration is the associated large stray field. As mentioned above, for that purpose 12 racetrack coils are incorporated into the design to reduce this field. The effect is similar to that of a conventional actively shielded magnet system: more flux is trapped within the coil system. Due to the space specific operating environment the system's overall size and mass must be compact and kept to a minimum. This constraint has important implications on the location of key components in the superconducting magnet circuit and also sensitive external electronics. For example, with the chosen magnet configuration at nominal current the maximum stray field is 15 mT at a radius of 2.3 m.

In order to withstand the large magnetic forces the coils are supported by aluminium alloy (6061-T6) machined components. The coil structure forms a circular ring with all the magnetic loads reacted internally. The inertia loads on launch, landing, etc are taken from four points on the coil structure via tension ties to the ambient temperature vacuum case.

The main parameters of the magnet system are summarized in Table I. The magnet system is designed, built and tested by Space Cryomagnetics Ltd. (UK).

IV. CONDUCTOR

All magnets are wound from the same conductor. The Helmholtz coils are constructed from 3360 turns whilst the racetrack coils have 1457 each. The conductor consists of a NbTi/Cu superconducting wire embedded in a high purity aluminium stabilizer. Aluminium has been chosen in view of the strict limit on weight.

TABLE I
MAIN PARAMETERS OF THE AMS-02 MAGNET SYSTEM

| | | |
|--|------|-----------------|
| Central magnetic field B_x | 0.87 | T |
| Dipole bending power | 0.78 | Tm ² |
| Nominal operating current | 459 | A |
| Nominal magnet inductance | 48.9 | H |
| Stored energy | 5.15 | MJ |
| Peak magnetic field on Helmholtz coils | 6.6 | T |
| Peak magnetic field on racetrack coils | 5.9 | T |
| Maximum stray field at R = 3.0 m | 3.9 | mT |
| Magnetic torque | 0.27 | Nm |

The superconducting strand, produced by Outokumpu Poricopper Oy (Finland), is a multifilamentary wire made of 552 high homogeneity NbTi filaments sheathed with a Nb barrier and embedded in a high purity copper matrix. The required minimum critical current is 400 A at 6.5 T and 4.4 K, corresponding to a j_c of 3000 A mm⁻², at 5 T and 4.2 K which is at the upper limit of present industrial capability. The strands are heat treated at the final stage to achieve a copper RRR (residual resistivity ratio) above 100. The main parameters of the strand are summarized in Table II. A total of about 55 km of superconducting strand is required for all coils. The I_c - and n -values of the strands from different billets are spot-checked at both ends of the wire upon delivery. The strand quality is completely satisfactory. All strands exceed the specification with regard to the critical current, some by as much as 12 %.

TABLE II
AMS STRAND CHARACTERISTICS

| | |
|---|----------------|
| Superconducting material | Nb 47±1 Wt% Ti |
| Strand diameter | 0.760±0.004 mm |
| (Cu+Barrier) : NbTi (nominal) | 1.15 |
| Nb : NbTi | 4 % |
| Filament diameter (nominal) | 22 μm |
| Number of filaments | 552 |
| Cu RRR | > 100 |
| I_c at 6.5 T, 4.4 K, 10 μV/m | > 400 A |
| n -value of resistive transition at 5 T | > 40 |

For electrical and thermal stabilization the strand is enclosed in a rectangular high purity aluminium sheath with the dimensions

$$2.00 \pm 0.03 \text{ mm} \times 1.546 \pm 0.025 \text{ mm}.$$

The strand was embedded in the high purity aluminium by a co-extrusion process using a continuous rotary extrusion machine from Holton Machinery Ltd. (UK). The high purity aluminium is fed into the machine as a 5 mm diameter rod. Before the wire enters the extrusion chamber along a horizontal path it is mechanically cleaned and pre-heated under a non-oxidizing gaseous atmosphere. The preheating of the strand before extrusion have been selected to achieve the minimum degradation in the current carrying capacity of the conductor and to assure the best quality of bonding between the aluminium and the strand surface. The co-extrusion process requires heating the aluminium up to 470 °C. The extrusion speed is typically 35 m/min. The nominal time any segment of the strand is exposed to a temperature in excess of 400 °C during the extrusion process is estimated to be less

than 1 s. As a standard quality assurance procedure the I_c -value of the extruded conductor is spot-checked on samples taken from each conductor length. An I_c of 424 A at 6.5 T and 4.4 K was found on average. The production of the conductor has been successfully completed within the strict tolerances required. An enlarged cross section of the AMS conductor is shown in Fig. 4.

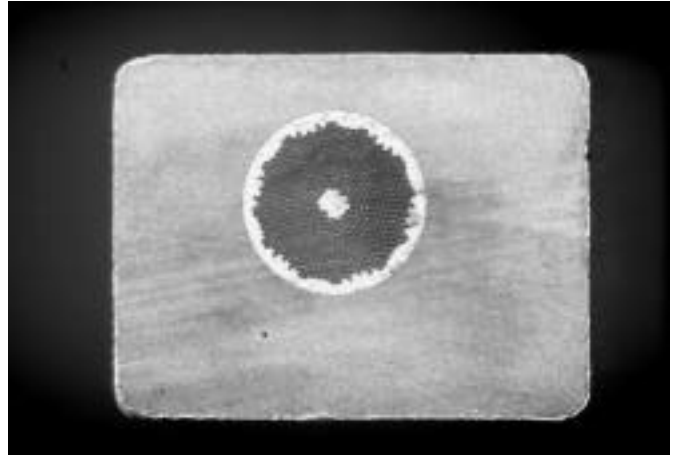


Fig. 4. Enlarged cross section of the AMS conductor with dimensions: 2.00 mm × 1.55 mm.

A maximum impurity of 20 ppm and a minimum RRR of 1000 at zero field has been specified for the aluminium sheathing. The RRR was spot-checked on samples taken from each extruded conductor. All samples showed RRR values greater than 1000. The good bonding between the aluminium and the strand has been checked and confirmed with a conventional ultrasonic imaging system.

V. CRYOGENIC CONCEPT

The AMS magnet uses low temperature superconductor, as this is the only way to generate the required field over the specified volume within the mass and power constraints of launch on the Space Shuttle and operation on the ISS.

The coils therefore have to be cooled to very low temperatures. Cryocoolers are available which refrigerate to temperatures in this range, but unfortunately both the Carnot efficiency and the Coefficient of Performance become very small at temperatures as low as 4 K. This means that the electrical power required to keep the magnet cold enough to be superconducting would be very large: certainly much too large for the limited power budget available to the experiment on the ISS. The only remaining option is to cool the coils with liquid helium.

A. Past Cryogenic Helium Missions

There have been four major liquid helium-cooled payloads launched in the past: the Infrared Astronomical Satellite (IRAS) in 1983, the Cosmic Background Explorer (COBE) in 1989, the Superfluid Helium On-Orbit Transfer Flight Demonstration (SHOOT) in 1993 and the Infrared Space Observatory (ISO) in 1995. The volume of helium launched in these experiments ranged from about 400 liters to as much as 2300 liters. Between them, these missions have demon-

strated most of the technologies required to cool a superconducting magnet in orbit. These include phase separation in zero gravity [9], calorimetric techniques (mass gauging) for determining liquid inventory [10] and thermomechanical pumps for transferring superfluid helium [11].

B. Special Features of Space Cryogenics for Magnets

A superconducting magnet – particularly one which is as state-of-the-art as the AMS magnet – poses a range of additional challenges to the cryogenic system.

1) Heat Load

The heat load to the helium can vary by an order of magnitude. When the magnet is being charged, additional power is dissipated in heating the persistent switches, in AC losses in the superconductor, and in eddy current heating in the structure which supports the coils. When all of these mechanisms are taken into account, the heat load during charging is currently estimated to be about 30 times greater than during steady state operation.

2) Current Supply

During charging the operating current has to be transferred into and out of the magnet system. Power leads are required which will carry this current without conducting excessive heat energy into the helium. Because the magnet will spend most of the time operating persistently, with no current flowing in the leads, the zero current operation of the leads is particularly important.

3) Magnet Quench

However unlikely, it is required that the magnet should be capable of recovering from a quench in space, re-cooling and running again. It is therefore necessary to ensure that the helium enthalpy - as well as the latent heat of vaporization - can be used for re-cooling. The coils therefore are mounted outside the helium vessel. Following a quench, helium from the vessel is pumped around a cooling circuit connected to the coils and vented into space. Because the vessel operates at a rather low absolute pressure, the helium has to be pumped around the cooling circuit. A thermo-mechanical pump is under development for this duty. It is anticipated that the magnet could be operational again within 3 days after a quench.

4) Cryogenic Safety

With a volume of 2500 liters, the AMS magnet will contain by far the largest inventory of helium ever launched by Space Shuttle. A special development program has been carried out to evaluate the safety implications [12].

5) Orbit

IRAS, COBE and ISO were all positioned in relatively shaded orbits. This kept the shell temperatures of the cryostats low and minimised the rate of helium consumption. AMS will be installed on the ISS, with an ambient temperature averaging close to 280 K.

C. The AMS Magnet Cryogenic System

The magnet will be launched cold, with its 2500 liter helium tank filled with superfluid helium (He II) at a temperature of about 1.8 K. The superfluid – rather than normal liquid – state is preferred because it virtually eliminates

thermal stratification in the system and it allows the existing technologies described above (phase separation, mass gauging, thermomechanical pumps) to be used with minimal additional development. Superfluid also has a higher density and specific heat capacity than normal liquid helium: since the helium inventory is limited by the available volume, this also gives useful additional endurance to the system.

Once on orbit, phase separation of the helium will be achieved using a porous plug. The vapor will cool four concentric radiation shields before being vented to space. The outermost shield will also be cooled by four Stirling cycle coolers to reduce the cryogenic heat load.

VI. SUMMARY

The construction of the AMS-02 magnet system is in progress. The launch and the installation of the AMS-02 detector on the ISS is scheduled for October 2004. The production of a novel aluminium stabilized NbTi wire with very tight dimensional tolerances has been completed successfully. The production of the coils has been started.

VII. ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to H. Marti of Marti Supratec AG for his many important contributions to the successful fabrication of the conductor. J. Neuenschwander and G. Roessler of EMPA, Switzerland are kindly acknowledged for performing the ultrasonic bonding tests. The authors also like to thank M. Okle for his valuable assistance during all phases of the conductor development program.

VIII. REFERENCES

- [1] G. M. Viertel, M. Capell, "The ALPHA Magnetic Spectrometer," *Nucl. Instr. and Meth. in Phys. Res. A*, vol. 419, pp. 295-299, 1998.
- [2] AMS Collaboration, "Search for antihelium in cosmic rays," *Phys. Lett. B*, vol. 461, pp. 387-396, Sept. 1999.
- [3] AMS Collaboration, "Protons in near earth orbit," *Phys. Lett. B*, vol. 472, pp. 215-226, Jan. 2000.
- [4] AMS Collaboration, "Leptons in near earth orbit," *Phys. Lett. B*, vol. 484, pp. 215-226, June 2000.
- [5] AMS Collaboration, "Cosmic protons," *Phys. Lett. B*, vol. 490, pp. 27-35, Sept. 2000.
- [6] AMS Collaboration, "Helium in near earth orbit," *Phys. Lett. B*, vol. 494, pp. 193-202, Nov. 2000.
- [7] B. Blau et al, "Status of AMS02 detectors and the superconducting magnet," *Gravitation & Cosmology*, vol. 5, Supplement, pp. 1-10, 2000.
- [8] H. Hofer, M. Pohl, "Charge determination of high-energy electrons and nuclei by synchrotron radiation with AMS," *Nucl. Instr. Meth. A*, vol. 416, pp. 59-63, 1998.
- [9] S. Volz, M. DiPirro, S. Castles, M. Rhee and M. Ryschkewitsch, "Cryogenic on-orbit performance of the NASA Cosmic Background Explorer (COBE)," *SPIE Vol. 1340 Cryogenic Optical Systems and Instruments IV* (1990).
- [10] M. DiPirro, R. Boyle, O. Figueroa, D. Lindauer, D. McHugh and P. Shirron, "The SHOOT cryogenic system," in *Superfluid Helium Heat Transfer*, presented at AIAA/ASME thermophysics and heat transfer conference, June 18-20 1990.
- [11] M. DiPirro and R. Boyle, "Lab tests of a thermomechanical pump for SHOOT," *Advances in Cryogenic Engineering* 33, p. 487 (1988).
- [12] S. Harrison, "Loss of vacuum experiments on a superfluid helium vessel," submitted for publication in *IEEE Trans. Appl. Superconduct.* [Proc. of 17th Int. Conf. on Magnet Technology, Sept. 2001, Geneva, Switzerland]