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# The Alpha Magnetic Spectrometer Superconducting Magnet

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The Alpha Magnetic Spectrometer (AMS) is designed to search for antimatter, dark matter and astrophysics observables. After the successful flight of AMS-01 aboard the Space Shuttle mission STS-91 in 1998, the AMS collaboration developed and is assembling a highly improved detector AMS-02, which will be operated on the International Space Station (ISS). The superconducting magnet consists of a pair of dipole coils and two sets of six flux return coils. This arrangement greatly reduces the magnetic stray field to minimize torque on ISS caused by interaction of the magnet field with the Earth's magnetic field. The magnet is cooled at a temperature of 1.8 K by evaporation of 2500 litres of superfluid helium. We expect an operation time in space of 3 years without refilling the helium. Of the superconducting magnet hardware, approximately 90% is complete. This paper reviews the status of the first large superconducting magnet for a space application, and the main features of the cryogenic system under micro-gravity conditions.

## 1. Introduction

The AMS experiment brings together particle physics technology and astrophysics in a way which has never before been achieved. Scientists and engineers from more than 50 institutes and research centres in 16 countries are working together to apply the methods and technologies developed in laboratories such as CERN (the European Organisation for Nuclear Research) to solving one of the mysteries of astrophysics: the apparent absence of anti-matter from the Universe.

Although balloon-based detectors have been used for more than 20 years to study cosmic rays at altitudes up to 40 km, searches for antinuclei have all been negative. AMS, however, will search for charged particles outside the Earth's atmosphere at a height of 430 km, and with a sensitivity which far exceeds anything hitherto possible. During its time on the ISS, AMS will be able to study not only anti-matter, but also dark matter, strangelets, and the origin of cosmic rays in space.

## 2. The AMS-02 Experiment

The AMS-02 experiment consists of a set of particle detectors arranged around the superconducting magnet [1]. The magnet itself has a 1.1 m diameter, ambient temperature bore in which the field is perpendicular to the axis of the detector. In this region is mounted the silicon tracker, a series of instrumented planes which are able to determine the trajectories of particles passing through. Because of the magnetic field, charged particles will follow curved paths: together with the other detectors, this will allow particles to be identified precisely and with high resolution over a wide range of energies.

## 3. Superconducting Magnet Design

The magnet system is shaped as a short, thick-walled cylinder, with the useful field generated – perpendicular to the axis – in the cylindrical bore. In principle, the requirements could be met by a simple geometry (such as a pair of Helmholtz coils), but in practice the stray field outside the magnet would then be very large. This would be unacceptable for a number of reasons. Firstly, the magnetic field could affect other parts of the AMS system, such as the electronics, leading to a requirement for shielding which would be very heavy. Secondly, the stray field could interfere with ISS systems, and could preclude EVA (extra-vehicular activity) on the ISS in the region of the experiment. Most importantly, if the stray field were large it would interact with the Earth's magnetic field, putting a torque on the ISS which would require the frequent use of thrusters for correction. The magnet has therefore been designed for minimal stray field, with a total of 14 coils (Figure 1). The two large coils provide around 70% of the useful dipole field perpendicular to the axis. The 12 smaller (flux return) coils contribute the rest of the field in the bore of the magnet, but their main function is to reduce the stray field outside the system. Table 1 lists some of the key parameters of the magnet.

The superconducting wire used for winding the coils was specially developed for AMS. It consists of filaments of niobium-titanium (NbTi) superconductor embedded in a copper matrix and co-extruded with high-purity aluminium stabilizer: it has been described in detail previously [2].

**Table 1**. Key Parameters of the AMS Magnet System

| Parameter | Value |
|---|---|
| Magnet bore | 1.115 m |
| Vacuum vessel outer diameter | 2.771 m |
| Vacuum vessel axial length | 1.566 m |
| Magnetic flux density at the centre of the bore | 0.87 T |
| Maximum magnetic flux density | 6.59 T |
| Operating current | 459.5 A |
| Inductance | 48.4 H |
| Stored magnetic energy | 5.15 MJ |
| Operating temperature | 1.8 K |
| Mass (excluding vacuum vessel) | 2300 kg |

NbTi is a low temperature superconductor and, because of the relatively high field in AMS (see Table 1), has to be cooled to a temperature of 4.0 K or less. The only cryogen which is still liquid at such a low temperature is helium, so this is the coolant which has to be used. Moreover, liquid helium itself exists in two forms: "normal" liquid helium (He I) and "superfluid" helium (He II) [3]. The transition between the two phases takes place at a temperature (slightly dependent on pressure) around 2.17 K. He II has higher density and latent heat of vaporisation than He I, so has more cooling power per unit volume. Since the magnet is ultimately cooled by the gradual boiling away of the helium, and once the helium has all vaporized the coils will warm up and no longer be operable, a useful extension in the lifetime of the system is gained by cooling with He II rather than He I. The magnet is therefore designed to operate at temperature of 1.8 K.

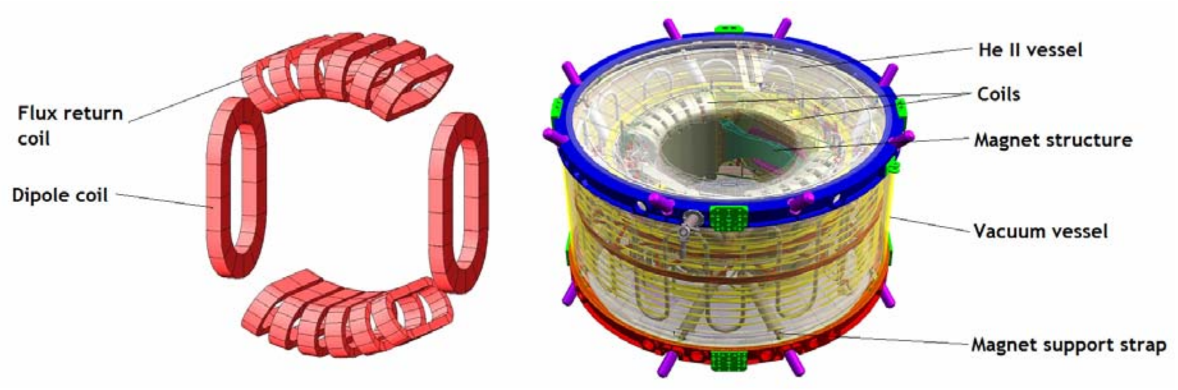

**Figure 1.** Diagrams of the superconducting coil arrangement and of the coils assembled into the final magnet system.

He II has a number of unusual properties which can be useful for operation in zero gravity. Chief among these are its anomalously high thermal conductivity, and the thermo-calorific effect. The thermal conductivity is a result of a special heat transport mechanism within the He II [3]. It means that, while the helium is in the superfluid state, heat can be transported with very small temperature gradients (much smaller than could be achieved through solid copper, for example). As a result, the entire 2500 litre helium vessel is essentially isothermal, whereas if He I were used relatively large thermal gradients could be set up. Another feature which comes directly from the use of He II is that the magnet can be cooled by conduction, rather than by being immersed in a bath of liquid helium. The small amounts of heat incident on and generated in the magnet coils are removed by conduction through thermal bus bars - consisting of pipes filled with He II - to be dissipated by boiling in the large helium vessel. One of the advantages of conduction cooling is that the magnet can be closer to the tracker in the bore (since there is no inner wall of the helium vessel in between) which gives a higher useful field. Another is that, following a quench (a sudden transition of the wire from superconducting to resistive, leading to rapid warming of the magnet to between 60 and 70 K) the magnet does not dissipate large amounts of heat in the helium. Although a magnet quench on orbit is extremely unlikely, this feature means that it will be possible to re-cool the magnet and operate it again: if the coils were bath-cooled a quench would lead to rapid pressurization and venting of the helium, with no possibility of re-cooling [4].

The thermo-calorific effect in He II is a well-known phenomenon in which temperature gradients in the helium lead to pressure gradients. The general effect is that the He II is attracted towards warm surfaces in preference to cold ones. This has obvious benefits when the helium is being used as a cooling medium, but can also be used in the design of a zero-gravity phase separator [5] to ensure that only vapour escapes from the helium vessel, and not liquid. In AMS, the thermo-calorific effect is also used to drive a He II pump for cooling the electrical feedthroughs carrying the current into the magnet [6].

Most superconducting magnets are installed either in hospitals (MRI scanners) or laboratories, and are not subject to the loads and vibrations encountered during a space mission. The AMS magnet has therefore been designed with more attention than most to the mechanical engineering requirements. The mechanical loads are all either magnetic or inertial. The magnetic loads are all reacted internally by the magnet structure, but the inertial loads have to be transmitted to the vacuum vessel by a system of composite straps (Figure 1). The strap design is fairly complicated to minimize heat conduction between the ambient temperature vacuum vessel and the magnet at 1.8 K: the straps have therefore been subject to particular scrutiny and testing during space qualification.

## 4. Magnet Status (July 2005)

Figure 2 shows pictures of the coils, helium vessel, and vacuum vessel during manufacture.

**Figure 2.** Photographs of the assembled magnet coils, the lower half of a helium vessel, and the vacuum vessel during manufacture in England, Switzerland and the USA.

The magnet coils are complete, and each was tested individually at 1.8 K before being assembled together. The next operation on the magnet will be a full-scale test to full field at 1.8 K. The helium vessel is being manufactured in Switzerland, after which it will undergo leak testing at 1.8 K in a specially-constructed facility in England. The vacuum vessel has been designed and manufactured in the USA on behalf of NASA: this item is also now complete and final preparations are being made for it to be shipped to England for the final integration of the magnet system.

Once the magnet has been completed and tested, it will be delivered to CERN where the detectors will be installed. Finally, the fully-assembled experiment will be transported to Kennedy Space Center for final preparation and launch on the Space Shuttle.

## References

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