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The Superconducting Magnet of AMS-02

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The Alpha Magnetic Spectrometer (AMS) is a particle physics detector designed to search for anti-matter, dark matter and the origin of cosmic rays in space. The detector will be installed on the International Space Station (ISS). 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. It generates a magnetic field of 0.87 T in the center of the magnet with a bending power of 0.78 Tm^2.
All superconducting coils are indirectly cooled by pressurized 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 and the principle concept of the cryogenic system.

1. 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 in [2]-[6]. AMS-01 had a permanent magnet ($Nd_2Fe_{14}B$) 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 2005. 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.

2. 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

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for the magnet system, are described elsewhere in detail [1], [7].

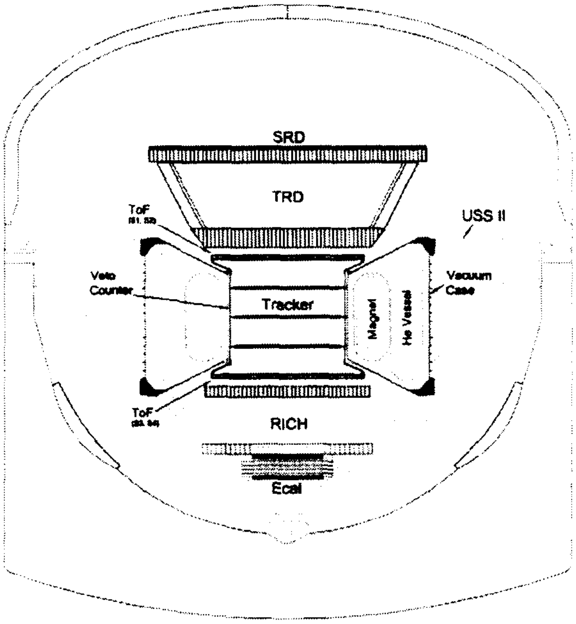

Figure 1. The AMS-02 detector in the cargo bay of the space shuttle for the flight to ISS. The detector components are: SRD = Synchrotron Radiation Detector [8]; Tracker = Silicon Tracker; Ecal = Electromagnetic Calorimeter; TRD = Transition Radiation Detector; ToF = Time-of-Flight Scintillators; Veto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

3. Magnet system

The superconducting magnet system for AMS-02 consists of a pair of large racetrack shaped 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 $\theta = \pm 60°, \pm 72°, \pm 84°, \pm 96°, \pm 108°, \pm 120°$. These coils are included for the following purposes:

1. to increase the magnitude of the overall dipole field
2. to reduce the magnitude of the stray field outside the magnet
3. to reduce the magnetic torque resulting from the interaction between the external field of the magnet system and the Earth's field.

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.

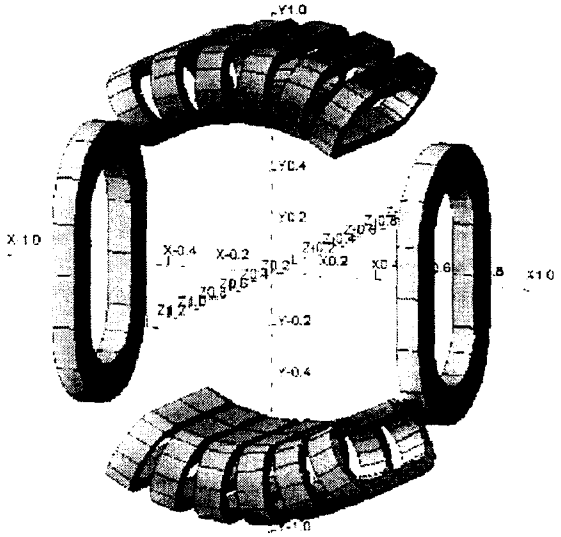

Figure 2. AMS-02 magnet configuration producing a dipole field in x-direction. (scales in meter)

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.

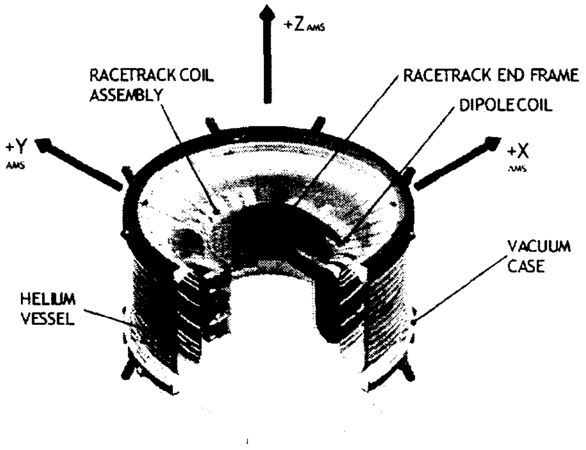

Figure 3. 3-D artist view of the AMS-02 magnet system.

All coils are electrically connected in series carrying a current of 459 A. The total inductance is 48.9 H. The magnet system will be operated in the so-called persistent mode, using a superconducting switch. This mode utilizes a unique phenomenon of superconductors, namely to conduct a constant electrical current without any energy dissipation. This implies that, once a constant current is established in a completely superconducting loop, it will continue to flow forever without any measurable attenuation. To operate the magnet, the current will be first ramped up to the nominal value by means of a power supply. Then, when steady state conditions are reached, the power supply will be bypassed with the superconducting switch. Now the current loop is completely superconducting and the power supply can be disconnected.

In case any small section of one of the superconducting magnets is heated locally above its critical temperature and, consequently, becomes suddenly normal conducting, an undesired phenomenon called a quench occurs. The quench spreads rapidly through the entity of the magnets and all stored magnetic energy is converted into heat in a very short period of time. In order to prevent the magnet in such a case from any potential damage due to excessive heating, 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 1. The magnet system is designed, built and tested by Space Cryomagnetics Ltd. (UK). To date, 8 racetrack coils have been completed. Presently, the first coil is cooled down to 1.8 K for cold tests, such as charging to full current and quench tests. Recently, a contract for developing and building the magnet current source as well as the complete control and signal conditioning electronics for the cryogenic system and the quench protection system has been placed with ASTRIUM Crisa (Spain).

Table 1
Main parameters of the AMS-02 magnet system.

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

Table 2
AMS strand characteristics.

Strand diameter (mm)	0.760 ±0.004
(Cu+Barrier):NbTi(nominal)	1.15
Nb:NbTi (%)	4
Filament diameter, nominal (μm)	22
Number of filaments	552
I_c at 6.5 T, 4.4 K, 10 μV/m (A)	$>$ 400

4. Conductor

All magnets are wound from the same kind of 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.

The superconducting strand, produced by Outokumpu Poricopper Oy (Finland), is a multifilamentary wire made of 552 high homogeneity NbTi filaments ($\o \approx 22$ μm) sheathed with a Nb barrier and embedded in a high purity copper matrix. The required minimum critical current (I_c) is 400 A at 6.5 T and 4.4 K, corresponding to a critical current density jc of 3000 Amm^{-2}, at 5 T and 4.2 K which is at the upper limit of present industrial capability. The main parameters of the strand are summarized in Table 2. A total of about 55 km of superconducting strand is required for all coils. The I_c-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 %.

For electrical and thermal stabilization the strand is enclosed in a rectangular high purity aluminium sheath with the dimensions 2.00±0.03 mm × 1.546 ± 0.025 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.

A maximum impurity of 20 ppm has been specified for the aluminium sheathing. The purity was spot-checked on samples taken from each extruded conductor. The good bonding between the aluminium and the strand has been checked and confirmed with a conventional ultrasonic imaging system.

5. Cryogenic concept

5.1. Selection of cooling method

The AMS magnet is made of a low temperature superconductor, as this is the only way to

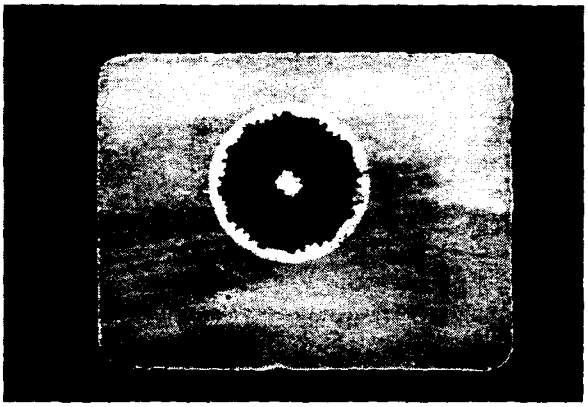

Figure 4. Enlarged cross section of the AMS conductor with dimensions: 2.00 mm × 1.55 mm

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. Although, in principle, it would be possible to wind the magnet from high temperature superconductor (HTS), in practice HTS technology is not yet sufficiently developed for such a demanding application. The coils therefore have to be cooled below 10 K. 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 such low temperatures. 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 which has been brought along from ground.

5.2. Past cryogenic helium missions

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 demonstrated 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]

5.3. 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.

5.3.1. 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.

5.3.2. Current supply

During charging the operating current has to be transferred into and out of the magnet system. Current 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.

5.3.3. Magnet quench

However unlikely, it is a 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.

5.3.4. 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].

5.3.5. Orbit

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

6. 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 porous plug technology and the adaptation of this technology to the AMS requirements have been successfully developed and demonstrated by *Linde* AG (Germany).

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. These cryocoolers with a cooling power of 8 W each at 77 K (input power: 150 W) have been built in the US and tested, space qualified and adopted to AMS requirements by NASA Goddard (USA).

When the magnet is being charged, the normal conducting current leads require an increased amount of cooling power. This will be achieved by pumping an enhanced flow of cold helium through the leads. Since the use of conventional helium pumps is not advisable in a strong magnetic field the use of a thermomechanical pump is foreseen. The principle of this pump is based on the superfluid phenomenon of the so-called fountain effect. The pump has been developed successfully by ILK Dresden (Germany) with the support of Linde AG and will be built by ILK Dresden.

The magnet coils are cooled indirectly by heat conduction. The coils are connected with the 2500 l superfluid helium tank via pipes containing pressurized superfluid helium. The use of superfluid helium for heat transport is particularly advantageous as the heat conductivity of superfluid helium is exceptionally high, much higher than of any other material. The feasibility of this cooling concept could be proved recently by Space Cryomagnetics Ltd.

A preliminary cryogenic schematic is presented in Fig. 5.

7. Conclusion

The construction of the AMS-02 magnet system is in progress. About half of the coils have been produced to date. The launch and the installation of the AMS-02 detector on the ISS is scheduled for 2005. The production of a novel aluminium stabilized NbTi wire with very tight dimensional tolerances has been completed successfully. The development and the production of the special components of the superfluid helium system (1.8 K) is in good progress.

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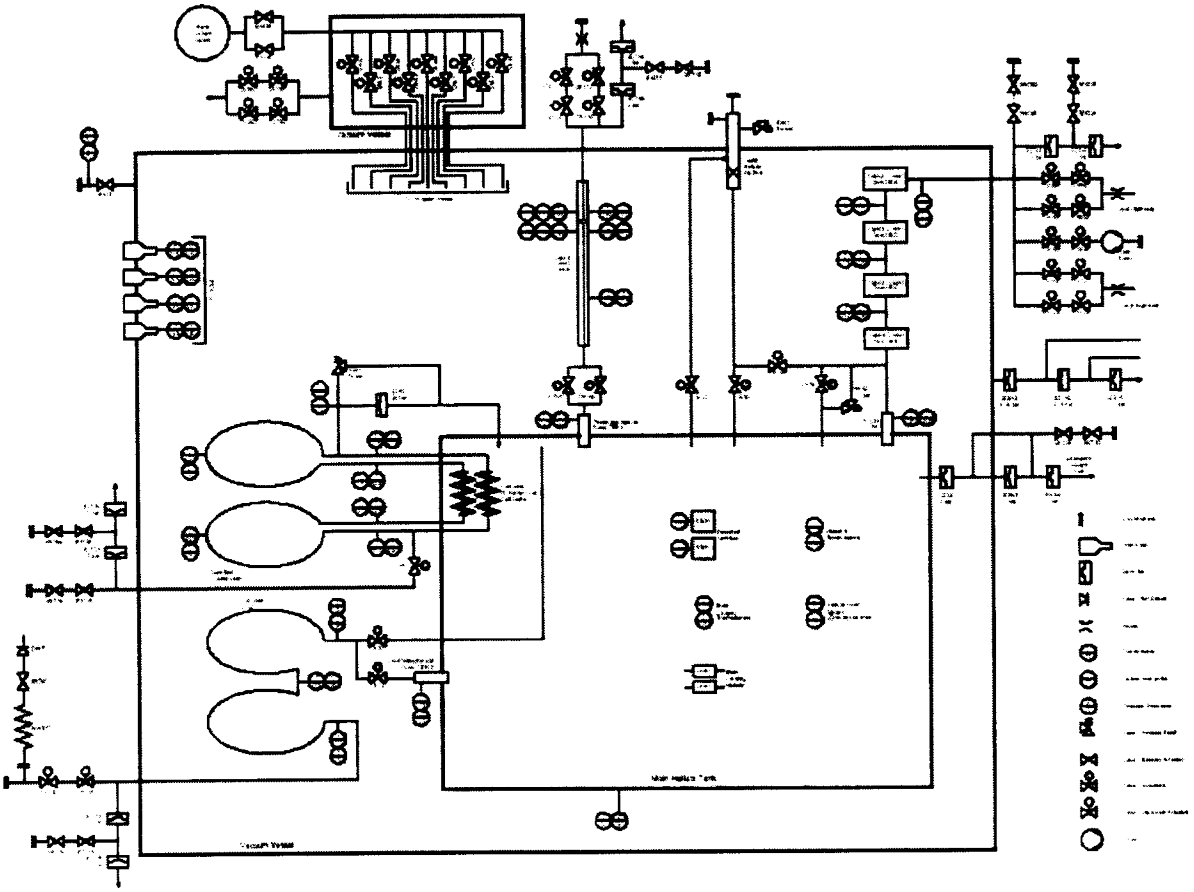

Figure 5. The preliminary cryogenic schematic of AMS-02

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