Title
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Publication Date
1987-09-01

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Presented at the 10th International Magnet Technology Conference, Boston, MA, September 21–25, 1987, and to be published in IEEE Transactions on Magnetics, MAG-24, No. 2

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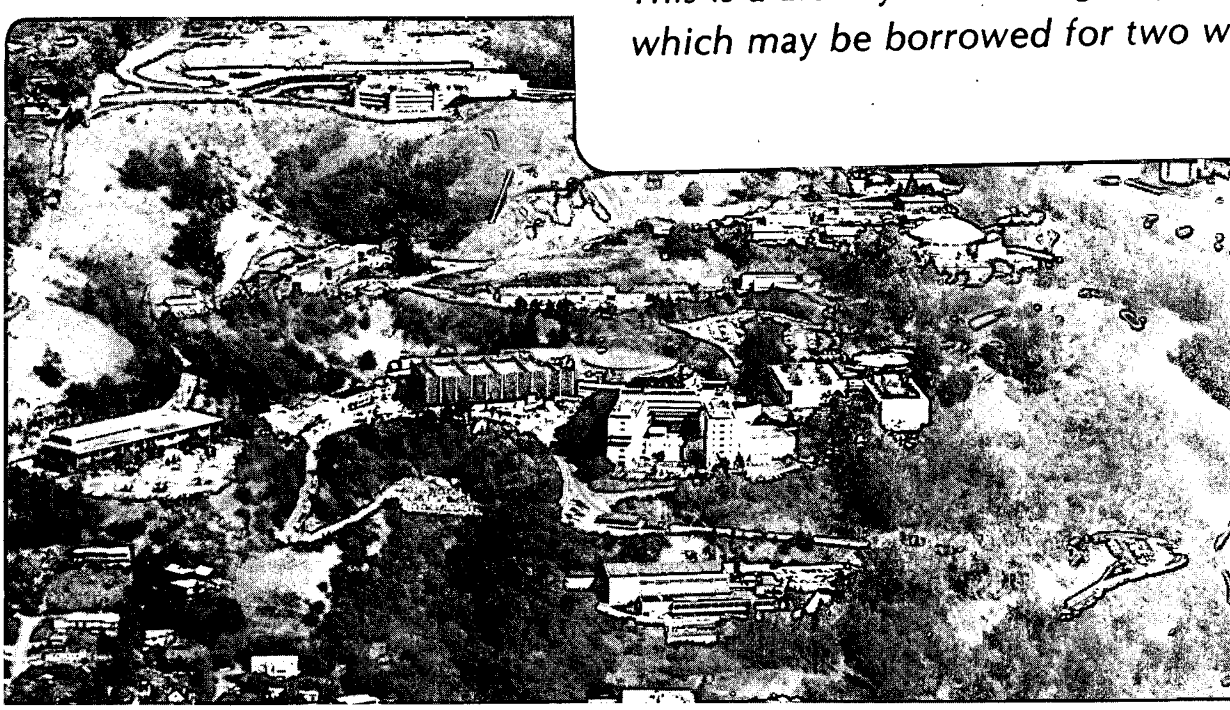
September 1987



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-23908

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THE TWO-COIL TOROID MAGNET
AN OPTION FOR ASTROMAG*

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ABSTRACT

The ASTROMAG particle astrophysics experiment for the space station requires large magnetic field integrals in order to separate high z, high energy isotopes. The two-coil toroid is a magnet configuration which can provide the desired field integral. The two-coil toroid will produce a magnetic field with zero net dipole moment which is required for operation on the space station. Magnetic fields as high as 5 T can be generated within a useful part of the experiment using this configuration. This paper presents a low mass zero mechanical moment two-coil toroid which could be launched by the space shuttle for use on the space station. The magnet design presented in this paper will be cooled using pumped helium II at about 1.8 K. The proposed cryogenic system would operate for up to 2 years on a single load of liquid helium II. The ASTROMAG cryogenic system is designed for helium resupply from the shuttle.

Introduction

The ASTROMAG experiment requires a magnetic field in order to determine the energy and momentum of charged particles of various momenta.[1] The strawman magnet configuration consists of two identical solenoidal coils which carry currents in opposing senses in order to generate a zero net dipole moment.[2] The space between the coils if filled by a spherical helium tank, the coils and the tank in a common cryostat vacuum vessel the detectors are located at the ends near the magnet coils.

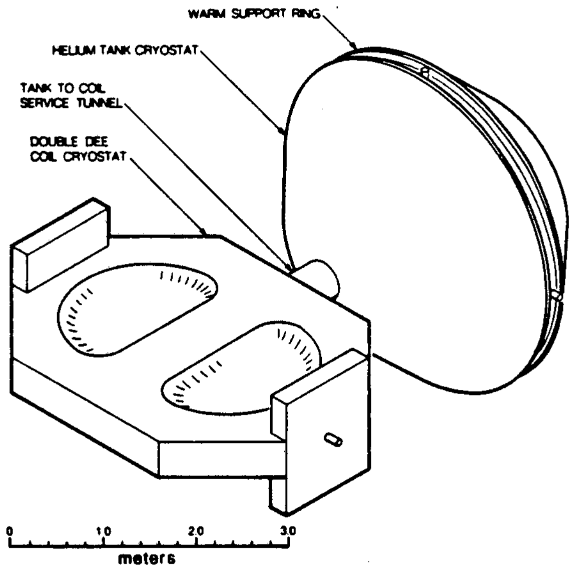
This report describes a second concept for generating magnetic field for ASTROMAG. This magnet configuration consists of two Dee shaped coils which form a two coil toroid. The two coils are located within a paddle which is connected to a spherical helium tank. (See Figure 1 for an artist conception of the two coil toroid magnet.) The physics detectors would be located on either side of the flat paddle, the particle center, the detectors, in a direction away from the tank, the particles travel toward the tank in a direction approximately parallel to the paddle surface. This report describes the two coil toroid, the magnet cryostat and the helium II cryogenic system which keeps the magnet cold for up to two years without refilling.

The Magnet Configuration

The two coil toroid shown in Figure 2 has the appearance of double rather rounded Dees. The shape of Dee is chosen so that the bending moment is the coil is zero when the coil is energized. Thus, the magnetic forces in the coils are taken up as hoop stress in the windings. The magnet parameters shown in Table 1 are for the case when each coil carries 1.6 MA and the current density in the superconductors plus matrix is 2.88×10^8 Am^{-2}. At this current density, the estimated hoop stress in the coils is 67 MPa.

*Supported by the Office of Astrophysics NASA

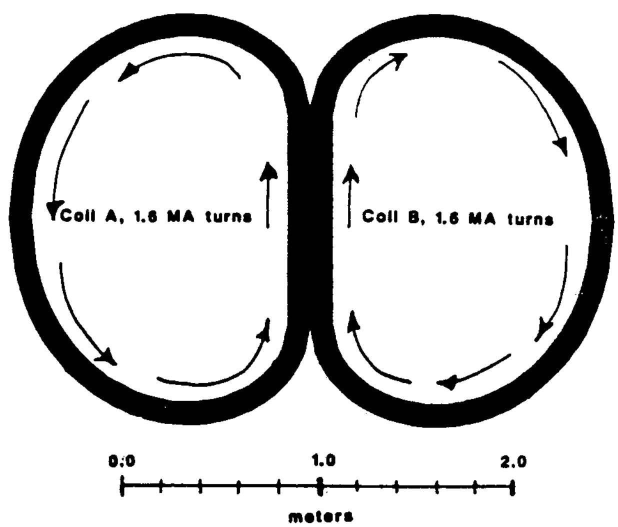
Figure 1.



ISOMETRIC VIEW OF TWO TOROID TYPE MAGNET

Figure 2.

TWO COIL TOROID MAGNET
(COIL BENDING MOMENT IS ZERO)



The field generated by the coil is highest near the straight portion of the double Dee. As one moves across the Dee the field drops off. The flux lines go in a circle through the Dee's just as they would through the Dee's of a many coil toroid. The two-coil toroid has a net magnetic dipole of moment of zero. The field falls off to the level of the earths magnetic field some 15 meters from the center of the magnet.

Table 1.

Two-Coil Toroid Magnet Parameters

Number of coils	**2**
Overall package dimensions	**3.22 x 1.97 m**
Number turns (both coils)	**3640**
Design current	**879.12 A**
Peak Field in Coil	**~7.0 T**
Coupling, Coil to Secondary	**< 0.92**
Magnet Inductance	**32.3 H**
Magnet Stored Energy	**12.5 MJ**
Current Density in Matrix	**2.88×10^{8} Am-2**
EJ^2 Limit	**1.04×10^{24} JA^2m^{-4}**
Magnet Active Cold Mass	**866 kg**
Stored energy to active cold mass ratio	**14.4 Jg^{-1}**
Magnet Coil System Mass	**1120 kg**

The two Dee coils are mounted in a frame to prevent the coils from bending at the line between the Dees when small misalignments of the two coils occur. (See Figure 3). The frame and the banding around the straight of the Dees carries the force which pushes the two coils apart. Cold mass support connections are made to this frame.

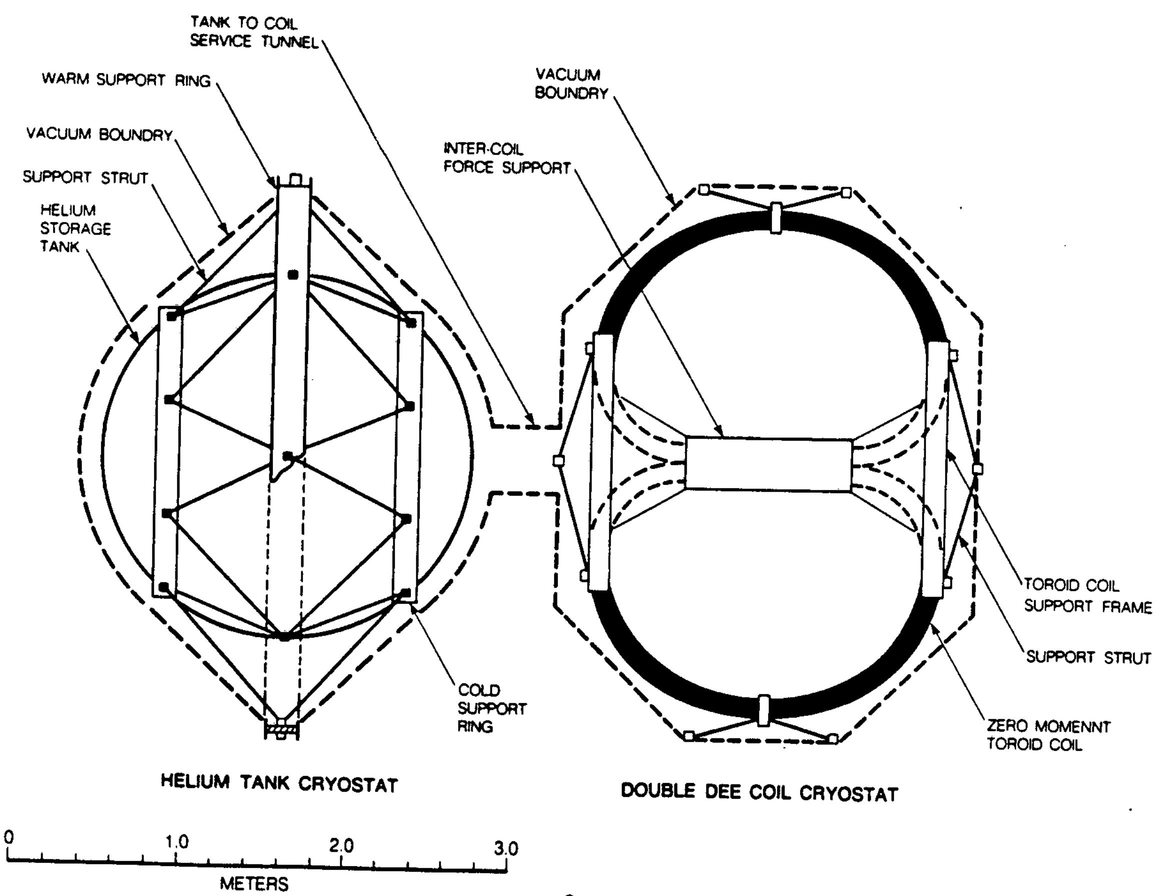
The magnet is designed to a high current density magnet in order to reduce its mass. The nominal stored energy per unit active coil mass has been set to just under 15 Jg^{-1}. This insures fail safe quenching using a shorted secondary circuit to drive the whole coil normal should either the coil or the persistent turn normal while the coil carries current.[3]

The magnet is designed so that it can be tested using helium at its normal boiling temperature of 4.22 K. In space, the magnet will operate at about 1.8 K cooled with helium II circulated through tubes which are in the Dee coil packages. The helium will be pumped through the tubes using the fountain effect.[4]

Cryostats for the Two Coil Toroid Magnet

The two coil toroid magnet design has the two coil toroid separated from the helium tank in order to insure that physics can be done on both sides of the toroid coil pair. (See Figure 3). As a result, two separate cryostats are proposed. The two coils of the toroid with its support frame is in one cryogenic vacuum vessel. The helium storage tank with its valves and porous plugs is in the other cryostat along with the superconducting switch. The gas cooled electrical leads would be in the cryostat with the switch. The two cryostats are interconnected by a service tunnel

Figure 3. Two coil toroid cryostat system.



which contains the superconducting leads to the coils, the helium flow circuit for the coils, and the shield gas circuits which are interconnected between the two cryostats. The service tunnel does not carry force between the two cryostats. Each cryostat is separately supported to the space shuttle.

The magnet coil cryostat is flat so that the physics detectors can be mounted close to the coil surface in order to maximize the integrated field along cosmic ray tracks which pass through the detector which are mounted close to the coil. The cold mass supports are connected to the coil frame where the field is low (see Figures 3) so that the cold mass supports do not interfere with the particle. Tracks in a region where the heavy nuclei physics is best. The shields are mounted around the coils and the vacuum vessel is designed so that the space inside the Dee is either open or a plastized sail cloth membrane is put across the inside of the Dee such that the vacuum forces are minimized.

The 1.8 K helium storage tank is a sphere which has an outside diameter of 2.2 m. Since the super conducting coil is indirectly cooled by helium from the tank, the tank thickness is determined by the 1 atm external pressure on the tank when the tank is vacuum leak checked. The proposed tank cold mass support system, shown in Figure 3, is multiple failure safe with thirty two separate support bands. The space inside the support bands, under the outer support rings will contain the thermal intercepts for the support bands, the shields, the persistent switch and the retractable gas cooled leads.

The Two-Coil Toroid Magnet Cryogenic System

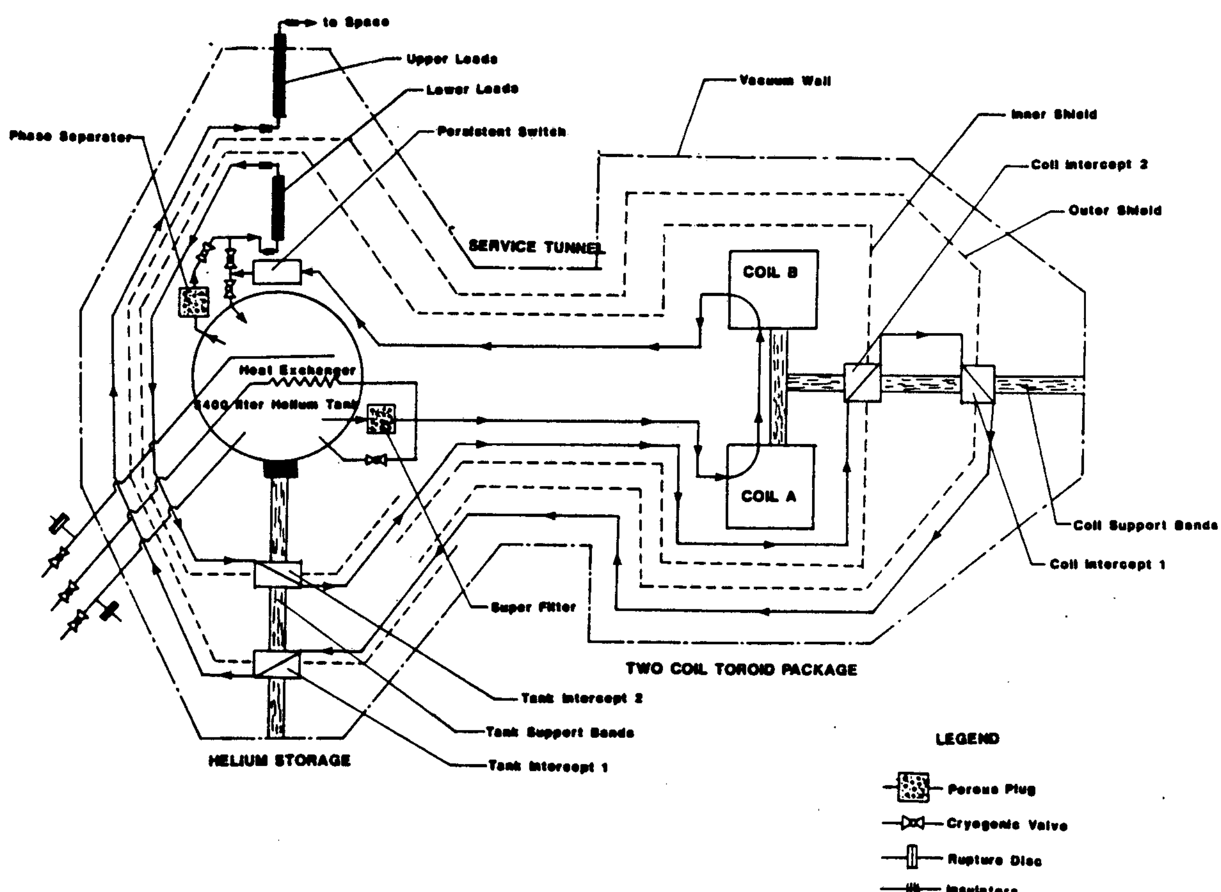
Figure 4 is a schematic diagram of the two coil toroid cryogenic system. Cold valves, cold burst discs and cross-over plumbing associated with ground operations and shuttle safety operations have been omitted in part. Figure 4 shows two distinct flow circuits in their modes of operation while the magnet is at 1.8 K in a space environment.

Helium II is circulated through the coils and the persistent switch using a thermomechanical (fountain effect) Helium II pump.[5] The pump shown in the schematic is the simplest form of the thermomechanical pump. If the flow through the flow circuit is not adequate (the flow must be at least 0.1 gs^{-1} when the magnet is in persistent mode, and it must be greater than 1 gs^{-1} when the magnet is being charged on discharged), a Hofmann type thermomechanical pump can be used. This type of pump, which has four heat exchangers built into it, can pump helium II at rates of 2 gs^{-1} or more.[6]

The second flow circuit shown in Figure 4 carries the helium gas, which has been phase separated from the liquid by a porous plug through the gas cooled leads, the shields and the cold mass intercepts for the cryostats. The cooled leads located within the vacuum vessel are divided into two parts.[7] The low temperature part is connected to the persistent switch. The high temperature part of the leads is retracted away from the low temperature part of the leads when the magnet is operating in the persistent mode. In the flow circuit, the cold mass support intercepts for both cryostats and the shields for both cryostats is

Figure 4.

ASTROMAG TWO COIL TOROID HELIUM II CRYOGENIC SYSTEM



between the cold and warm parts of the gas cooled leads. The helium gas in the shields and intercepts will intercept about 6 watts entering the cryostats from the outside vacuum vessels by radiation and conduction down the cold mass supports. In addition, the gas flow also intercepts heat entering the leads and heat generated by resistive heating when the leads are engaged and carrying current.

The projected cold mass for the two-coil toroid magnet system is 2200 kg including 700 kg of helium. The radiant heat transfer area for the outer shield is estimated to be between 30 and 35 m^2. Using these figures, calculation of helium boil off at 1.8 K was made. The estimated boil off is 0.26 liters per hour which comes out to 342 kg yr^{-1}. When the magnet is charged or discharged about 1 kg of helium is used to cool the magnet coils, the switch and the leads. If the magnet is charged and discharged four times a year, the total annual helium usage is estimated to be 354 kg, which means that the projected cryostat lifetime is about 2 years. This is almost the same as for the strawman magnet configuration.

Concluding Comments

The two coil toroid magnet system presented here has parameters which are similar to the strawman HEAO configuration for the ASTROMAG magnet. The over all mass is estimated to be about 3800 kg which is 100 kg larger than the estimated mass for the strawman configuration. The active mass of the superconducting coil is 23 percent of the total mass as compared to 39 percent for the strawman configuration. The total cold mass for the two coil toroid (excluding helium) is 39 percent of the total mass as compared to 53 percent for the HEAO configuration. The cryostat for the two coil toroid is more complicated than the HEAO magnet type cryostat. This complication and the added cost associated with it must be weighed against the projected improvement in the momentum resolution that is expected for the two coil toroid magnet system and its associated detectors.

ACKNOWLEDGEMENTS

The authors wish to thank R. L. Golden J. F. Ormes, and M. E. Weidenback for their helpful comments concerning the physics potential of the two coil toroid system as compared to the simplier HEAO type coil system. The authors thank the research division Ansaldo Company in Genova Italy for their contributions to the study. This work was performed under the auspices of the Office of Astrophysics of NASA, the Goddard Space Flight Center, INFN Frascati, Italy, and work supported by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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