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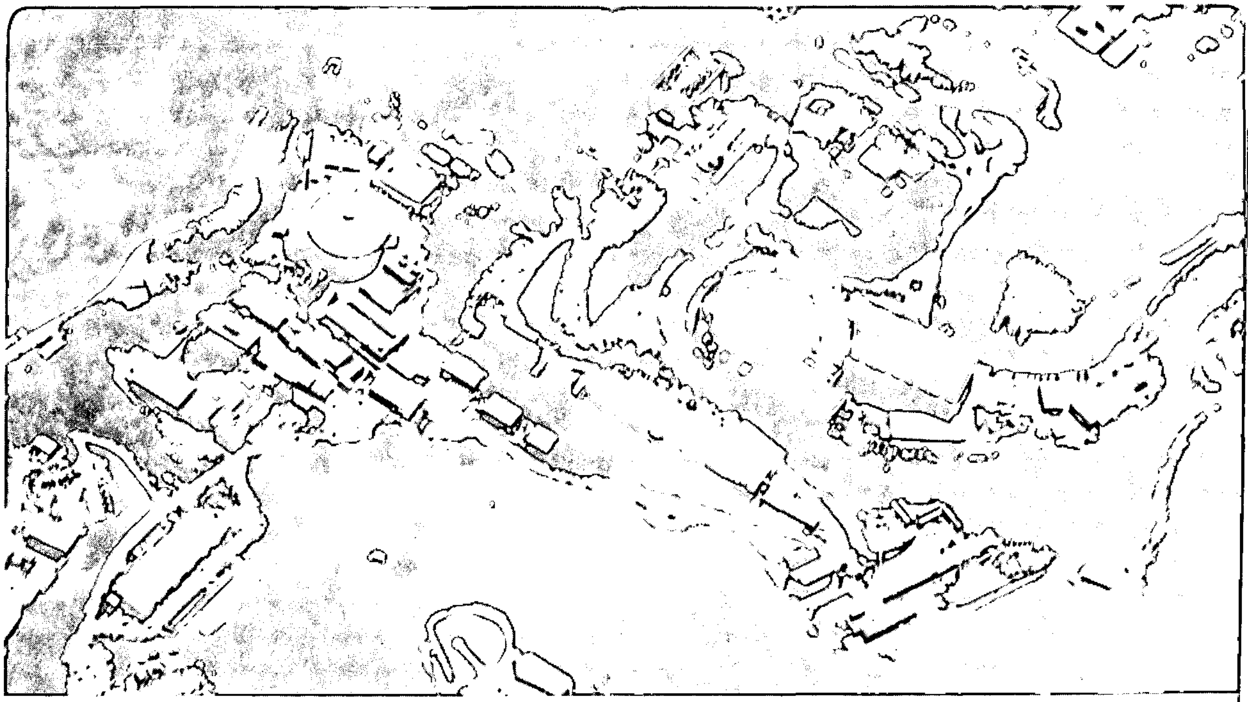

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DISCLAIMER

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ASTROMAG-034

THE ASTROMAG SUPERCONDUCTING MAGNET FACILITY CONFIGURED FOR A FREE FLYING SATELLITE

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ABSTRACT

ASTROMAG is a particle astrophysics facility that was originally configured for the Space Station. The heart of the ASTROMAG facility is a large superconducting magnet which is cooled using superfluid helium. The task of resizing the facility so that it will fly in a satellite in a high angle of inclination orbit is driven by the launch weight capability of the launch rocket and the desire to be able to do nearly the same physics as the Space Station version of ASTROMAG. In order to reduce the launch weight, the magnet and its cryogenic system had to be downsized, yet the integrated field generated by the magnet in the particle detectors has to match the Space Station version of the magnet. The use of aluminum matrix superconductor and oriented composite materials in the magnet insulation permits one to achieve this goal. The net magnetic dipole moment from the ASTROMAG magnet must be small to minimize the torque due to interaction with the earth's magnetic field. The ASTROMAG magnet consists of identical two coils 1.67 meters apart. The two coils are connected in series in persistent mode. Each coil is designed to carry 2.34 million ampere turns. Both coils are mounted on the same magnetic axis and they operate at opposite polarity. This reduces the dipole moment by a factor of more than 1000. This is tolerable for the Space Station version of the magnet. A magnet operating on a free flying satellite requires additional compensation. This report presents the magnet parameters of a free flying version of ASTROMAG and the parameters of the space cryogenic system for the magnet.

INTRODUCTION

Moving ASTROMAG[1] from the Space Station[2] to a satellite launched by an expendable launch vehicle became desirable as the Space Station reconfiguration decreased the resources which could be used by ASTROMAG. The primary scientific goals of ASTROMAG are: to test cosmological models by searching for antimatter and dark matter candidates; to study the origin and evolution of matter in the galaxy by direct sampling of galactic material and comparing it with solar systems and universal abundance: and to study the origin and acceleration of relativistic particle plasma in the galaxy and its effects on the dynamics and evolution of the galaxy.

For a free-flying ASTROMAG there are two instruments: LISA (Large Isotope Spectrometer for ASTROMAG) for which J. F. Ormes (Goddard Space Flight Center) is Principal Investigator and WiZard for which R. L. Golden (New Mexico State University) is Principal Investigators and P. Picozza (U. di Roma) heads the Italian half of the collaboration. WiZard will measure the spectra of electrons, positrons, antiprotons, and other low-Z cosmic ray components. Significant emphasis is on a high-statistics search for anti-helium. LISA will measure the isotopic composition of the cosmic rays for higher-Z elements ($3 < Z < 31$) as well as search for antinuclei. The separation of isotopes is difficult and requires high resolving power. ASTROMAG will provide accurate measurements of the high-energy spectra of cosmic ray nuclei, antiprotons, electrons and positrons. Figure 1 shows the ASTROMAG satellite.

Launching ASTROMAG with an expendable launch vehicle such as an Atlas IIa has both advantages and disadvantages compared to the Space Station version of the experiment. The primary disadvantage is the weight limitations imposed by the Atlas IIa rocket system. The mass of ASTROMAG must be reduced from about 8000 kg to about 5000 kg overall. The 5000 kg includes the satellite with its attitude control system, the power system, and heat rejection system. As a result, the mass of the LISA instrument, the WiZard instrument and the superconducting magnet have had to be reduced. The advantage of the use of an expendable launch vehicle is that ASTROMAG is no longer limited by the angle of inclination of the Space Station orbit (28 degrees). By increasing the angle of orbit inclination to 45 degrees or above, the number of lower energy (below 1 GeV per nucleon) particles can be greatly increased. In the lower energy ranges, this more than makes up for the decrease of detector collection area which comes from reducing the mass of the facility. Since at the present time the Atlas IIa can only be launched from the Kennedy Space Flight Center (KSC), the selected angle of inclination for ASTROMAG is 57 degrees (the maximum angle of inclination for a space craft launched from KSC).

The Atlas IIa can launch a satellite with a mass up to 5808 kg (12800 lbs) in a 500 km (300 mile) orbit at an inclination of 57 degrees. The projected mass for the satellite and ASTROMAG is 5000 kg. The magnet, its cryogenic system and its power system will weigh about 1600 kg; the LISA instrument about 900 kg; and the WiZard instrument about 1200 kg. The satellite with its attitude control system, solar panels, communication system and heat rejection system will have a mass of about 1300 kg. The largest cuts in the mass occurred in the two instruments. Scientically the integrated magnetic field must be as large as possible, so the magnet was cut least.

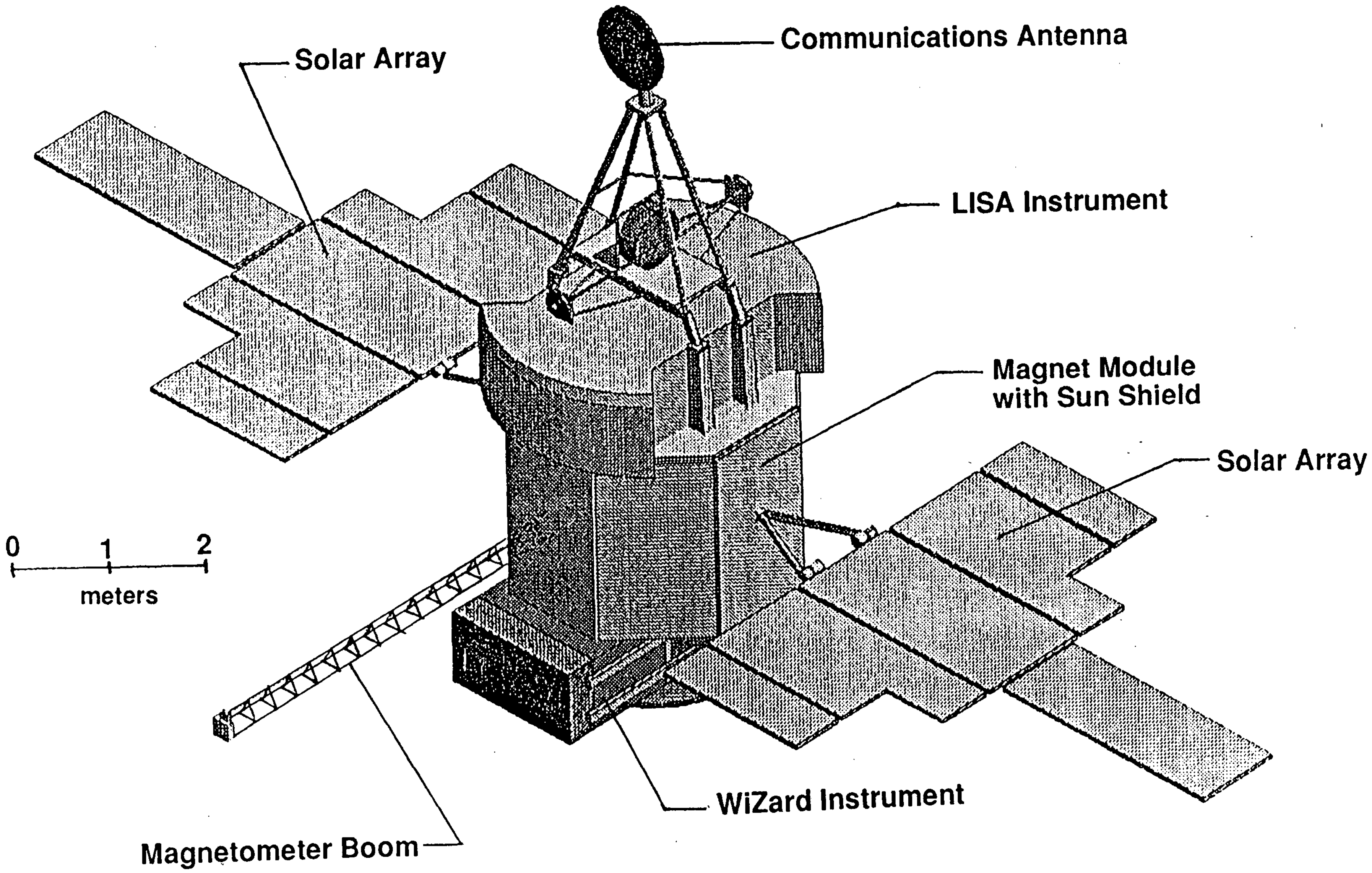


Figure 1 The ASTROMAG Free-flyer Satellite in the Deployed Position

THE EXPENDABLE VEHICLE ASTROMAG MAGNET SYSTEM

When ASTROMAG moved from the Space Station to a free-flyer, a number of the design assumptions changed. The design assumptions for the free-flyer version of the ASTROMAG magnet are as follows:

1. The diameter of the magnet, its cryostat, the satellite and the two instruments is limited by the 14 foot (4.27 meters) shroud diameter of the Atlas IIa. The mass of the satellite, the magnet and its dewar, the magnet charging systems, the WiZard , and the LISA is limited to a maximum of 5808 kg (12800 lbs). The magnet, its cryostat and its charging system represent about a third of the overall mass.

2. The magnet coil must use a stable, reliable superconductor which can carry the full magnet current at 4.2 K at a peak induction in the coil of 7.5 tesla. The superconductor of choice is niobium titanium with a pure aluminum matrix.[4] The operating temperature for the coils is 1.8 K.

3. The net magnetic dipole moment of the ASTROMAG magnet must be less than 1 part in 100000 of a single magnet coil 1.4 meters in diameter carrying 2.34 million ampere turns. The ASTROMAG magnet consists of two identical coils which are powered to opposite polarity. In addition an orthogonal set of superconducting magnetic moment correction coils must be provided in order to achieve the required net dipole moment.[5]

4. The magnet must operate in the persistent mode. The magnet need only be charged once at the start of the two year mission. The magnet stored energy loss must be less than one percent per year while it is operating in the persistent mode. The magnet must quench in a fail-safe way if a normal region forms in either magnet coil or the persistent switch.

5. The magnet cryogenic system should maintain the magnet coils at their design operating temperature for a minimum period of two years.
   The magnet will be launched uncharged and with a full superfluid helium tank

6. The magnet and its cryostat should be designed to withstand the launch environment of the Atlas IIa rocket. The specified accelerations are lower than for the shuttle because a landing of the payload is not required. The launch g forces are primarily in the fore and aft direction which simplifies the cold mass support system. The mechanical resonant frequency for the key magnet components is still 25 Hz or greater.

The use of an expendable launch vehicle dictates that the mass of the magnet coil must be reduced without sacrificing integrated field. Changing the coil from a copper-based superconducting coil to an aluminum matrix superconducting coil permits one to reduce the coil mass without reducing the performance of the coil.[4,6]

Figure 2 and its table show a reduced mass, reduced size aluminum matrix ASTROMAG magnet coil. The stored magnetic energy and the integrated field in the ASTROMAG experiment is nearly the same as the phase A version of the Space Station ASTROMAG magnet.[2] The mass of the coils has been reduced to about 65 percent of the mass of the Space Station version of the ASTROMAG magnet coils. The overall mass of the two coils, the persistent switch, the dewar, helium in the dewar, the charging leads, and the magnet charging system is 70 to 75 percent of the Phase A mass for the Space Station version of ASTROMAG.[3] The expected dewar life time for the expendable launch vehicle version of the ASTROMAG magnet is about the same as the Space Station version of the ASTROMAG magnet (3 to 4 years).

Figure 3 shows the reduced mass ASTROMAG dewar and the coils. The coil outer diameter was reduced from 1.66 meters to 1.45 meters. The spacing between the coils was reduced from 2.0 meters to 1.67 meters. The estimated overall dimensions of the reduced mass magnet cryostat are 1.82 meters in diameter by 2.35 meters long. (The Space Station magnet cryostat had an overall diameter of 2.12 meters and an overall length 2.61 meters.) The superfluid helium tank between the two coils will hold up to 325 kg superfluid helium (compared to 500 kg for the Space Station version). Figure 3 shows the proposed locations for the persistent switch, the gas cooled leads, and the three orthoganal sets of magnetic moment correction coils.[7]

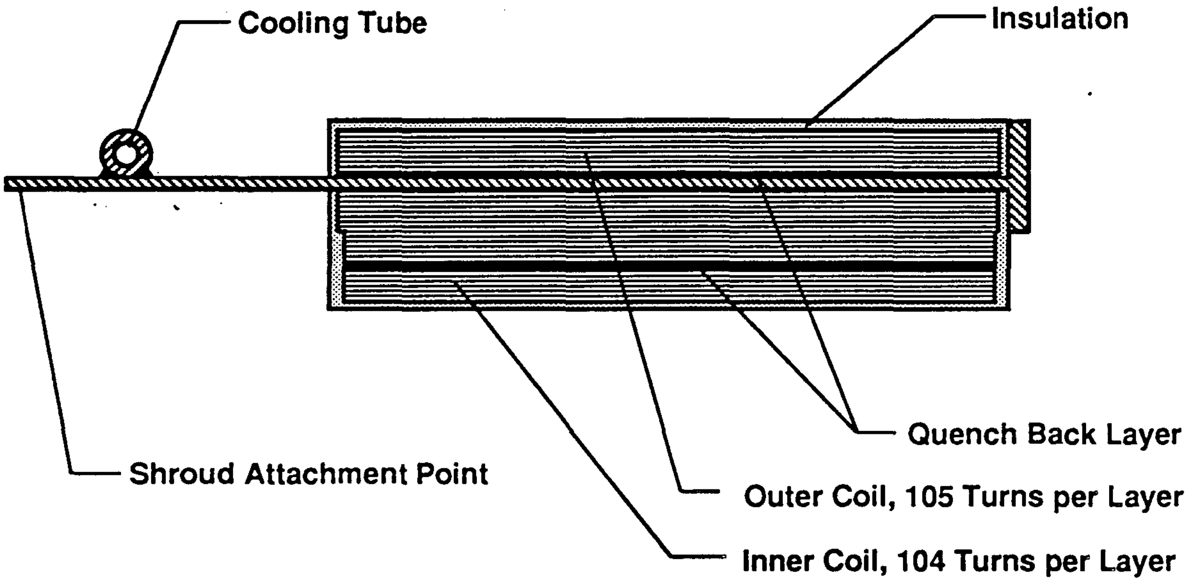
The changes in the overall design and operating requirements for the freeflyer design ASTROMAG suggest that the coils, the cryogenic system and the charging system can be simplified without a loss of required magnet function.

1. The overall design aim is to simplify the ASTROMAG magnet and its cryogenic system so that more elements are passive The dewar control valves, the gas cooled leads, the persistent switch, the trim coils, and most of the plumbing should be located in the region around the helium tank halfway between the two coils. This region has the lowest magnetic induction (0.35 to 0.55 T) and it is far from the experiments and the cryostat cold mass supports. Ferromagnetic material in this region will have a minimal effect on the quality of the magnetic field in the LISA and WIZARD experiments.

2 The magnet charge time can be increased to six hours or longer. Because the magnet is charged only once during the two year mission, the charge time is not an important issue. When the magnet charge time is greater than six hours, there is no need for cold diodes either across the persistent switch or in the pure aluminum magnet quench back circuit.

3. The magnet coils and the persistent switch can be cooled by conduction to the the superfluid helium tank during all phases of magnet operation. During normal operation of the magnet, there are no dewar life time consequences from conduction cooling. When the magnet is charged or discharged, heat is added to the helium in the tank instead of to the gas flowing out through the gas cooled leads. The temperature and pressure in the main helium dewar is increased but the helium in the tank remains in the superfluid state except when the tank is nearly empty.

Figure 2 A Cross-section of the ASTROMAG Free-flyer Superconducting Coil with the Aluminum Quench Back Circuit (The attached table shows the magnet parameters.)

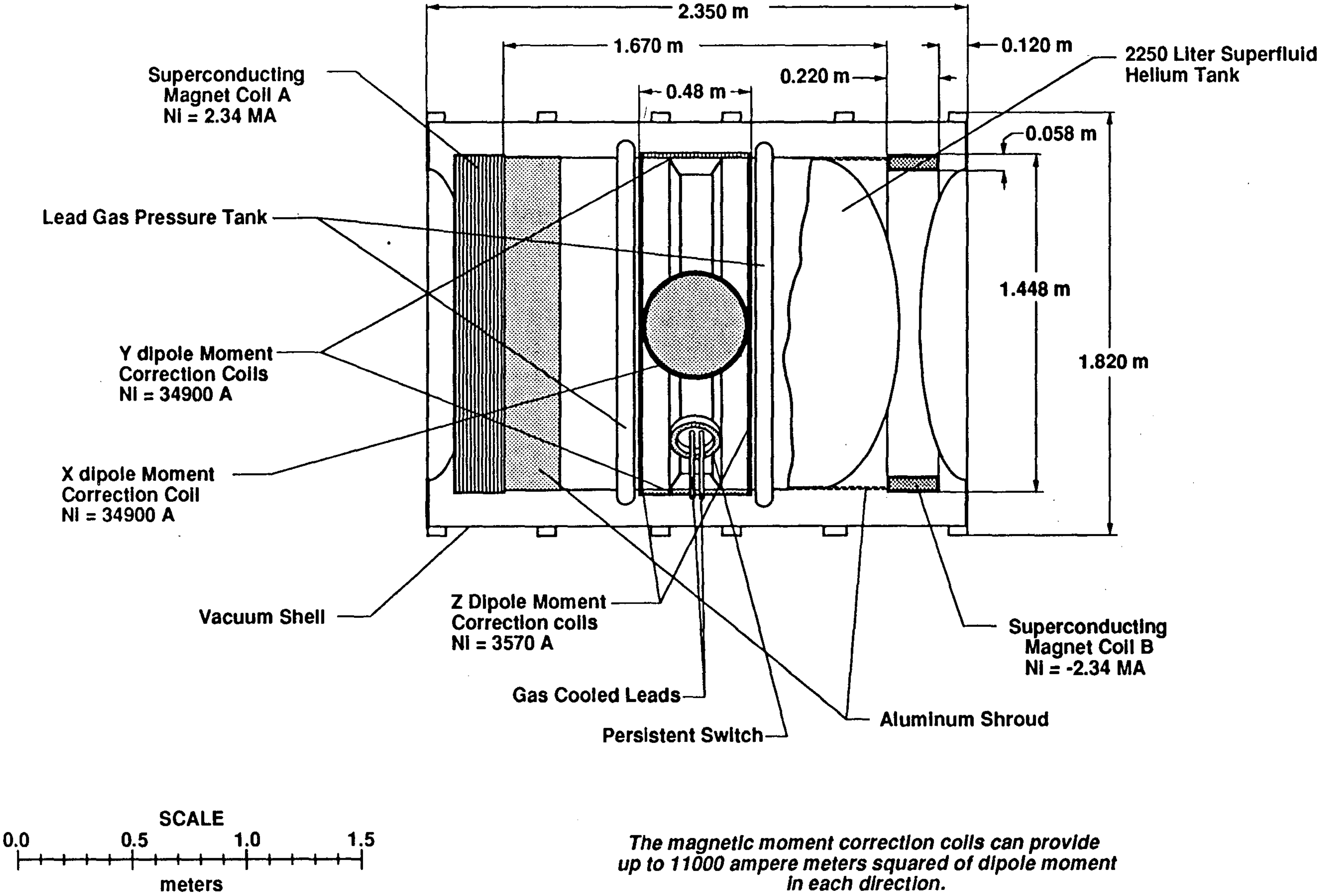


FREE-FLYER ALUMINUM MAGNET PARAMETERS

Number of Magnet Coils	2
Number of S/C Layers per Coil	28
Number of QB Layers per Coil	2
Number of Turns per Layer	104 or 105
Number of S/C Turns per Coil	2928
Number pf QB Turns per Coil	209
Coil Outside Diameter (m)	1.44
Coil Inside Diameter (m)	1.32
Space Between the Coils (m)	1.67
Outer Coil Width (mm)	220.50
Inner Coil Width (mm)	218.40
Magnet Self Inductance (H)	36.14
11.57 MJ Design Current (A)	800.0
Coil Peak Induction (T)*	6.54
Intercoil Tensile Force (kN)*	345 #
S/C Matrix Current Density (A/ sq mm)*	281
Quench Energy at 1.8 K (micro-joules)*	503
Coil Package Mass (kg)	206.9

* At the 11.57 MJ Design Coil Current

35.2 metric tons



The magnetic moment correction coils can provide up to 11000 ampere meters squared of dipole moment in each direction.

Figure 3 The ASTROMAG Free-flyer Magnets Configuration Showing the Coils, the Cryostat, The Persistent Switch, the Leads and the Magnetic Moment Correction Coils

4. An alternative method of supplying cold helium to the gas cooled leads to a superfluid helium pump is a small 25 to 30 liter helium tank which can be pressurized using a heater. The pressure tank stores enough helium for one charge and one discharge of the magnet. The small tank can be cooled by conduction to the main helium tank and it can be charged with helium initially by adding helium gas under pressure.

5. The retractable part of the main magnet coil leads need not be gas cooled.[8] This means that the gas cooled portion of the leads will always start out at liquid helium temperature before the leads are connected. As a result, the gas cooled leads do not have to be precooled before they can carry magnet current. The elimination of a pre-cooling step will improve the overall efficiency of the magnet charging system. The leads themselves are simplified.

6. Magnetic moment trim coil leads do not have to be gas cooled.[5] These leads can be made from a low thermal conductivity material which has staged cooling to the gas cooled shields. The charge and discharge time for the trim coils can be short (less than 30 seconds) so there is no need to have active lead cooling during charging and discharging of the trim coils. When the trim coils are not being charged or discharged, they can operate in the persistent mode.

SWITCHES, TRIM COILS AND PLUMBING IN THE LOW FIELD REGION BETWEEN THE COILS

Figure 4 shows a contour map of lines of constant magnetic induction for the coil and cryostat assembly shown in Figure 3. The origin in Fig. 4 ($R = 0$ and $Z = 0$) is on the common axis for the two coils and exactly between the two coils. Each of the two identical coils carries 2.34 million ampere turns. The two coils are powered in opposition so that the net magnetic dipole moment is zero. The primary field shape is an axially symmetric quadrupole. If one looks at the region between the surface of the helium tank ($R = 0.7$ meters) and the cryostat vacuum shell boundary ($R = 0.9$ meters) one sees that the lowest magnetic induction occurs in the region halfway between the two coils (around $Z = 0$). The absolute value of the magnetic induction in a cylindrical region from $R = 0.7$ meters to $R = 0.9$ meters and from $Z = -0.25$ meters to $Z = +0.25$ meters will be from 0.38 T to 0.52 T. The primary direction of the magnetic flux lines is radial. This is the region between the helium tank and the vacuum shell with the lowest magnetic induction.

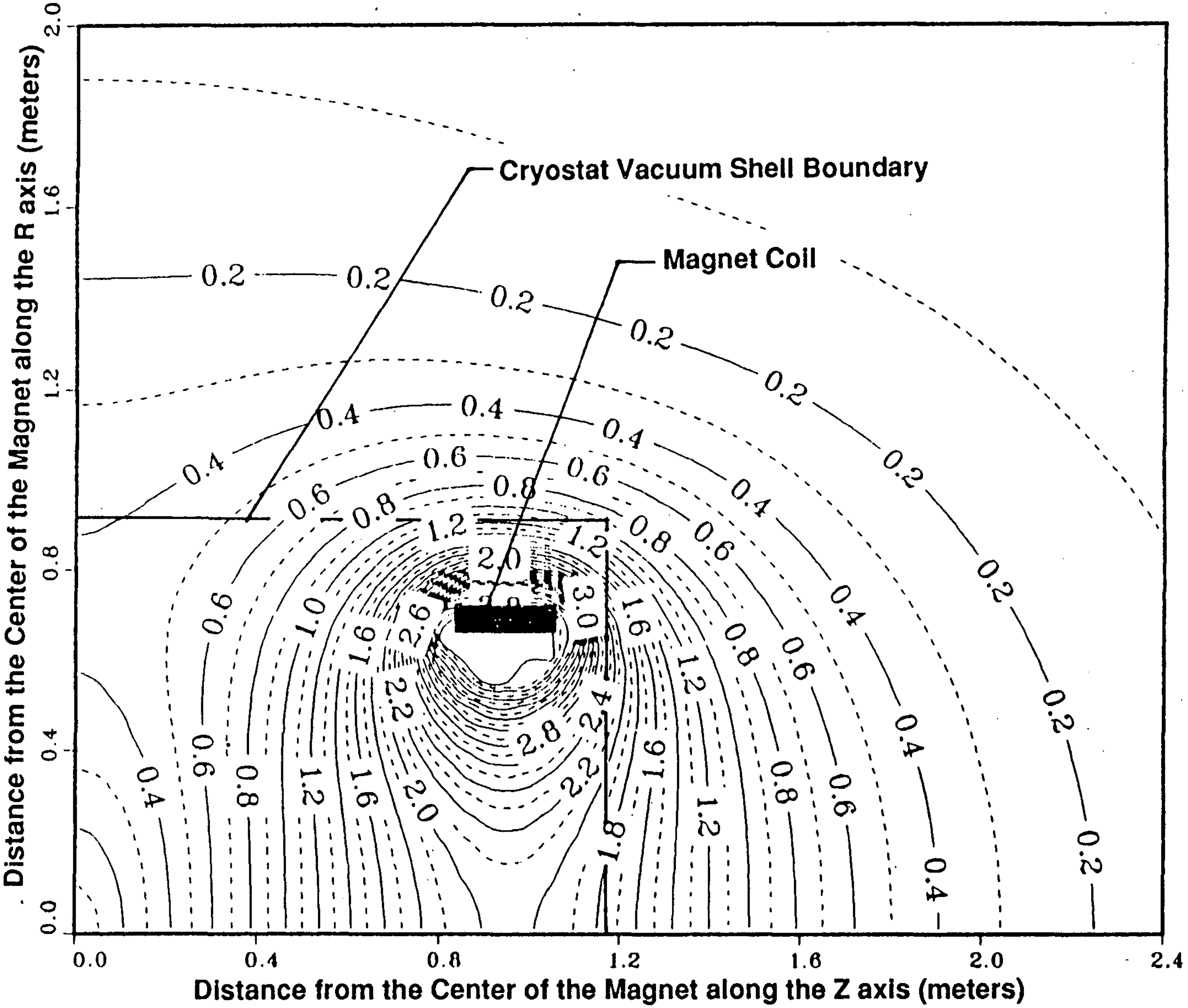


Figure 4 A Magnetic Induction Map for a quarter Section of the ASTROMAG Magnet (Lines of constant magnetic induction versus R and Z from the magnet center are shown. The contour Interval is 0.1 tesla. Contours above 4 tesla are left out.)

The basic plumbing for the cryostat, the main magnet persistent switch, the magnetic dipole moment trim coils and the persistent switches for the trim coils are located in a region of low magnetic field. This minimizes the effect of these elements on the magnetic field in the experiments and it also minimizes the effect of the magnetic field generated by the coils on the elements themselves. The cold helium control valves are most affected by the magnetic field. For example, the cold helium valves for the SHOOT experiment are motor operated.[9] Operation of SHOOT valves in a 0.5 tesla magnetic induction may not be possible without additional magnetic shielding for the motor unit. The presence of ferromagnetic material in either type of valve can affect the field quality in the experiments and it can affect the net dipole moment of the magnet system. Therefore it is desirable to minimize the number of cold valves and to place them symmetrically in a ring around the center of the helium tank (at $Z = 0$). Figure 5 shows a cryogenic circuit diagram which eliminates the unneeded cold valves and yet meets NASA safety standards.

The main persistent switch is located in a low field region in order to maximize the operating margin of the switch. The persistent switch can be cooled by conduction to the helium tank during all phases of its operation. When the switch is cold and operating in the persistent mode, its temperature should be around 2.0 K. The temperature at which the switch becomes normal depends on the current passing through the switch. At the full magnet current of 800 amperes, the switch should not turn normal until its temperature is above 7.0 K. The estimated mass for a persistent switch which has an open resistance of 1.25 ohms at 10 K is just over 10 kilograms.

The trim coils should also be located in the low field region of the magnet. This location has three advantages:

1) The inductive coupling of the individual trim coils to the main magnet coil is minimized. When each pair of magnetic trim coils is correctly hooked up, the inductive coupling to the main magnet coils should be zero.[5,7]

2) The interaction forces between the trim coils and the main magnet should be minimized. At the maximum design trim coil current of 15 amperes in Z magnetic moment correction coils, a longitudinal force of 15.7 kN (1.6 metric tons). This force will act in a direction along the cylindrical surface of the helium tank. The X-Y coils will produce a smaller net force (about 2 kN) in a direction perpendicular to the cylindrical tank surface.[7]

3) the operating temperature margin for the trim coils will be maximized in the low field region. (The trim coils should carry their full design current at a temperature of 6.5 K.) The trim coils and their persistent switches, which operate at 2 K, can be cooled by conduction to the helium tank.

The physical location of the three trim coil pairs and the main coil persistent switch is shown in Figure 3.

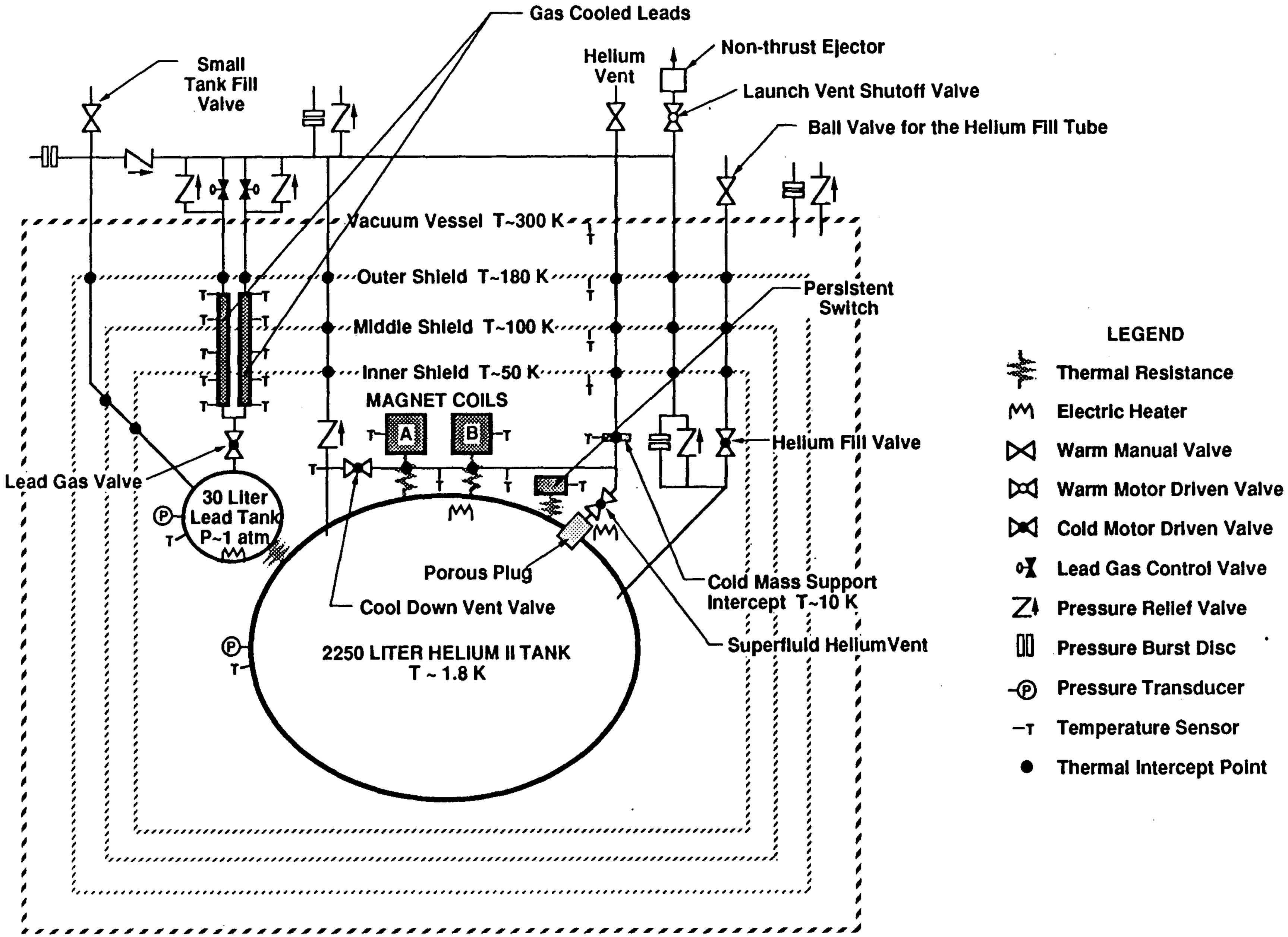


Figure 5 The Free-flyer ASTROMAG Magnet 1.8 K Cryogenic System

THE MAGNET CHARGING SYSTEM AND THE QUENCH PROTECTION SYSTEM

Simplification of the magnet and its charging system will improve the reliability of the ASTROMAG magnet. Since the ASTROMAG magnet is charged only once or twice during its operating life in space, the time needed to charge the magnet to its full operating field is not an important factor in the ASTROMAG. There is a tradeoff between the total amount of helium needed to keep the gas cooled leads cold and the helium boiled away to remove the heat generated within the persistent switch and the coils during the charging. The heat generated in the persistent switch is proportional to the charge rate squared and inversely proportional to the switch open circuit resistance. The heat generated within the coils during charging is proportional to the charge rate squared. The helium needed to cool the coils and the switch is proportional to the thermal energy generated within them. The helium needed to cool the 800 ampere gas cooled leads is proportional to the charging time.

The open circuit resistance of the persistent switch is controlled by the maximum allowable voltage across the magnet when the switch turns normal at full current unless there are cold diodes and a resistor in parallel with the switch. In order to eliminate these diodes, the switch open circuit resistance should be between 1.2 and 1.5 ohms.

Figure 6 shows the electrical circuit diagram for the magnet and its charging circuit. The power supply shown in Fig. 6 sized for a six hour charge time. At full current while charging, the power supply will deliver 1720 W. About 1200 W of this power will come directly from the satellite solar cells; the remainder will come from a battery system needed to insure that the experiments are powered when the ASTROMAG satellite is in the earth's shadow.

COLD HELIUM SUPPLY TO THE MAGNET GAS COOLED ELECTRICAL LEADS

The Space Station version of the ASTROMAG experiment had to be charged and discharged four times a year. The gas needed to charge and discharge the magnet became significant, so it was desirable to minimize the heat put into the superfluid helium tank and the amount of gas needed to cool the leads. In order to achieve minimum helium usage while charging, a superfluid helium pump similar to the one built by Hofmann[10] was proposed. The Hofmann flow loop could pump up to 2 grams per second over a pressure rise of 0.5 atm. The pressure required to operate gas cooled leads discharging into space is about 0.1 atm.

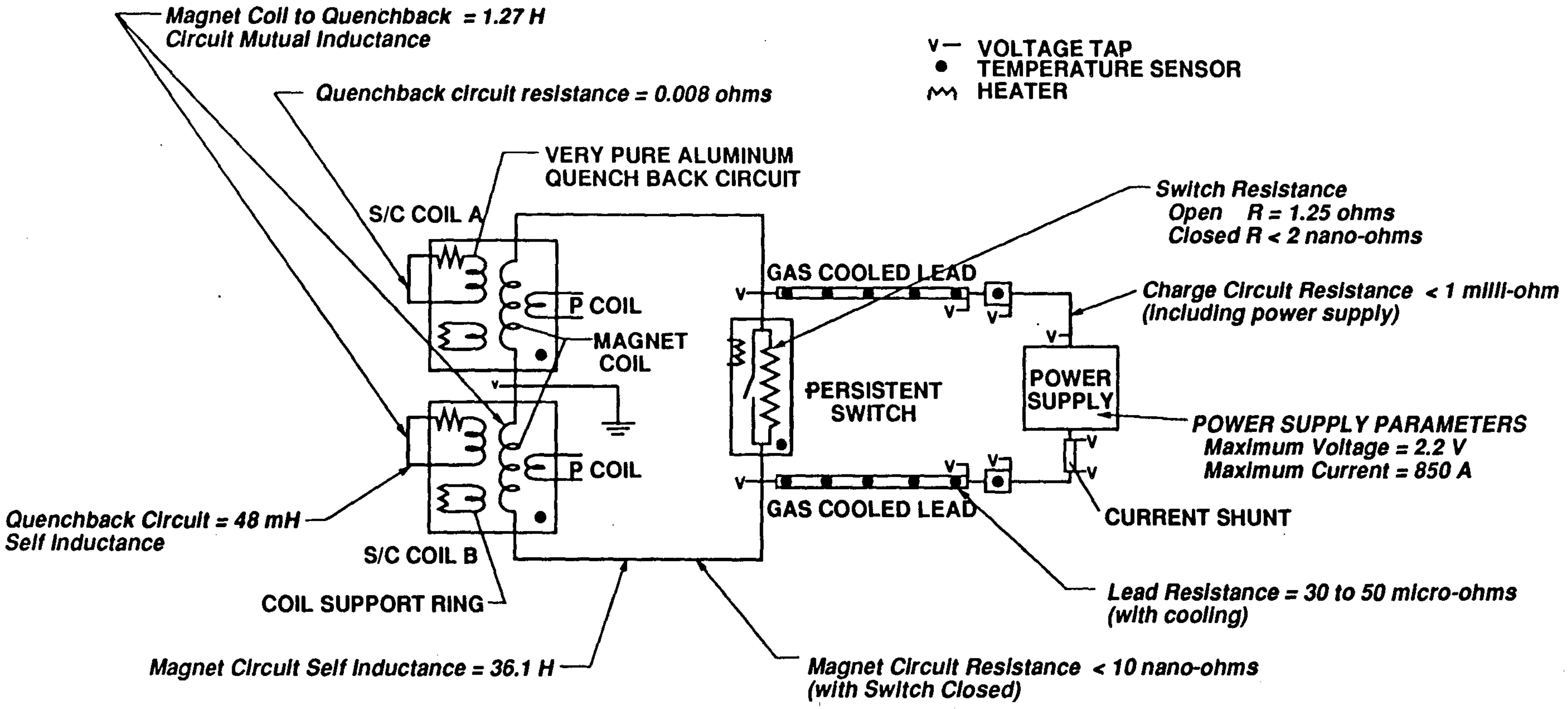


Figure 6 The Electrical Circuit Diagram for the ASTROMAG superconducting Magnet with Quench Back Circuits

An alternative method of providing cold gas to the gas cooled leads is illustrated in Figure 5. This method is adequate if the magnet is to be charged and discharged only once during the life of the ASTROMAG satellite. The 800 ampere gas cooled leads use helium at the rate of 90 to 95 milligrams per second when the leads are operating at full design current. At low currents, 65 to 70 milligrams per second of gas flow is required. About 1.8 kilograms of helium is required for each six hour magnet charge or discharge. A small helium storage tank, which can be pressurized by adding heat can be used to supply both the gas and the pressure needed to operate the gas cooled leads for the ASTROMAG magnet. The small storage tank (about 30 liters for one charge and discharge) is cooled from the main helium tank by conduction. The thermal connection to the main helium tank should permit the small storage tank to operate at 3.8 K while less than 1 watt is transferred to the main helium storage tank. The remainder of the heat put into the small tank keeps the tank pressure up while helium flows from the tank up through the gas cooled leads. The small storage tank can be filled from a source of high pressure helium gas through a capillary tube (which has been thermally staged to the gas cooled shields) after the main helium storage tank is cold and filled with superfluid helium. The location of this storage tank and the gas cooled electrical leads is illustrated in Figure 3.

The gas cooled leads do not care if the helium enters them as a gas or as a liquid.[8] The control of the gas flow through each of the leads is done by using a control valve at the room temperature end of the lead. The gas flow is controlled either from the temperature of the lead near the room temperature end or by the total resistance of the lead (as measured by the lead voltage drop divided by the current). The resistance of the gas cooled lead is proportional to the temperature of the lead, one quarter of a lead length from the room temperature end of the lead.

THE GAS COOLED LEADS AND OTHER LEADS

The gas cooled leads can be simplified by moving the lead disconnect point from near the cold end of the lead to the room temperature end of the gas cooled portion of the lead. There are three reasons why this is desirable:

1. The gas cooled portion of the lead can be stationary. The lead can be plumbed into its helium flow circuit without moving seals or movement of the helium plumbing. The leads themselves are simpler, and there are a number of different options for the type of superconductor which can be used on the lower part of the gas cooled leads. The gas cooled leads themselves can be made from 6061 aluminum.[11,12] The retractable part of the lead can be made from copper.

2. The gas cooled lead leads do not have to precooled before they can be used to carry the magnet current. This is particularly advantageous when the magnet is being discharged at its full design current of 800 amperes. The gas cooled leads start out at 2.0 K.

3. Since the gas cooled leads are connected and disconnected at the room temperature end of the leads, the drive system for connecting and disconnecting the leads is also entirely at room temperature.

Moving the lead retraction point from the lower end of the gas cooled lead to the upper end increases the voltage drop across the joint between the two parts of the lead. This increases the helium flow required to cool the lead. On the other hand, the eliminating the need for lead precooling will reduce the overall amount of helium needed to cool the gas cooled leads.

The electrical leads needed to operate the valve motors and the magnetic moment trim coils do not have to be gas cooled. These leads do not carry current for a long period of time and they can be cooled by attaching them to the shields and the shield gas cooling system. The trim coils can be charged to their full current of 15 amperes in about 30 seconds. The cryogenic motor operated valves will operate for only a few seconds. The lead current density can be increased; much of the i^2R energy can be stored in the leads and released to the shields later. The trim coils and the cryogenic motor operated valve do not operate very frequently. The effect of valve operation and trim coil charging and discharging on dewar life is expected to be minimal.

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REFERENCES

1. M. A. Green, G. F. Smoot, R. L. Golden, et. al, IEEE Transactions on Magnetics, MAG-23, p. 1240, 1987.

2. "ASTROMAG Phase A Study Final Report by the Advanced Missions and Analysis Office, Code 402, NASA, Goddard Space Flight Center, Greenbelt, MD. 20771, 21 December 1989.

3. "ASTROMAG Free-flyer Study Report" , NASA, Goddard Space Flight Center, Greenbelt, MD. 20771, March 1991.

4. M. A. Green, "Evolution of the HEAO Magnet Design to Improve the Physics of ASTROMAG", LBL ASTROMAG Note-030, LBID-1685, November 1990.

5. M. A. Green, "The Design of Superconducting Magnetic Dipole Moment Correction Coils for ASTROMAG", LBL ASTROMAG Note-018A, LBID-1550, October 1989.

6. M. A. Green, IEEE Transactions on Magnetics, MAG-27, p. 2260, 1991.

7. M. A. Green, "Reduced Size Trim Coils for the Free-flyer version of ASTROMAG", Lawrence Berkeley Lab ASTROMAG Note-032, May 1991.

8. M. A. Green, P. L. Andrews, C. T. Day, et al., "Preliminary Test of the LBL Tampax Leads Operating at Angles Near Horizontal", LBL Engineering Note M5524B, May 1980.

9. M. J. DiPirro and P. Kittel, Advances In Cryogenic Engineering **33**, p 893, Plenum Press, New York, 1987.

10. A. Hofmann, A. Khalil, H. P. Kramer, et al., Advances In Cryogenic Engineering **33**, p 471, Plenum Press, New York, 1987.

11. M. A. Green, "Retractable Gas Cooled Leads for the LBL ASTROMAG Lead Experiment", LBL ASTROMAG Note-023, November 1989.

12. M. A. Green, H. Aguiar, M. J. Bensadoun, et al., "Measurements of Retractable 6061 Aluminum Gas Cooled Leads in a Vacuum," presented at the Cryogenics Engineering Conference, Huntsville, Alabama, June 11-14, 1991.

FIGURE CAPTIONS

Figure 1	The ASTROMAG Free-flyer Satellite in the Deployed Position
Figure 2	A Cross-section of the ASTROMAG Free-flyer Superconducting Coil with the Aluminum Quench Back Circuit (The attached table shows the magnet parameters.)
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