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LAUNCHED VERSION OF ASTROMAG**

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VARIOUS MAGNET OPTIONS FOR A DELTA LAUNCHED VERSION OF ASTROMAG

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ABSTRACT

This Report compares various superconducting magnet options for use in a particle astrophysics experiment to be launched with a Delta rocket into a sun synchronous orbit and an earth trailing solar orbit. The goals of the experiment are to study the incidence of anti particles coming from deep space and to study populations of light nuclei (up to atomic number 8) and gammas from deep space. The proposed superconducting coils, which would be made with an aluminum stabilized niobium titanium superconductor, would be cooled using stored super fluid helium. Both a sun synchronous orbit and an earth trailing solar orbit permit one to shield the magnet and cryogen vessel behind the solar panels. This permits one to reduce the temperature of the cryostat outer vessel that increases to cryogen life time for the experiment. A number of superconducting coil and cryostat options were looked at in terms of total magnet and cryostat mass, cryogen life time, complexity and overall particle astrophysics capability for attached detectors.

BACKGROUND

ASTROMAG was originally conceived as an experiment for the space station^{1,2}. The primary scientific goals of ASTROMAG were: 1) to test cosmological models by searching for antimatter and dark matter candidates, 2) to study the origin and evolution of matter in the galaxy by sampling the nuclei in cosmic rays originating in deep space and comparing the abundance of these nuclei with the solar system, and 3) to study the origin and acceleration of relativistic particles in the galaxy and their effects on the evolution of the galaxy.

The magnetic field for bending the charged particles from space will be provided by a short superconducting solenoid magnet. The magnet will consist of two nearly identical superconducting coils on the two ends of a super fluid helium storage tank². The two coils will operate at opposite polarity so that the net magnetic dipole moment generated by the magnet system is close to zero. As a result, the magnet will not follow an earth's magnetic field line. (For the space station version of ASTROMAG, the two oppositely powered coils are good enough to prevent the superconducting magnet system from applying undue torque on the space station.) The ASTROMAG superconducting magnet system will operate at 1.8 K, with cooling provided by super fluid helium stored in the tank between the two coils. Super fluid helium is kept in the storage tank by a porous plug phase separator³.

An expendable launch vehicle configuration of ASTROMAG became desirable when the Space Station could no longer provide electric power and cooling to ASTROMAG. A decision was made to downsize ASTROMAG so that it could be launched by an Atlas IIA launch vehicle in a 500 km high, 57 degree circular orbit^{4,5}. The use of the Atlas IIA permitted one to launch a version of ASTROMAG that would have both the WiZard experiment (an anti particle experiment for measuring the spectra of electrons, positrons, anti-protons and other particles) and the LISA experiment (a heavy nuclei experiment for measuring the momentum and energy of nuclei with an atomic number from 3 to 31). The choice of a 57 degree orbit is dictated by the Atlas launch facility at the Kennedy Space Flight Center. An advantage of the 57 degree is the increased flux of particles that have an energy of less than 1 GeV per nucleon. The disadvantages of using an expendable launch vehicle such as the Atlas IIA are: 1) The mass that can be put into orbit for ASTROMAG is limited to 5200 kg or less; 2) superconducting dipole moment correction coils⁶ are needed to keep the ASTROMAG from tracking the earth's magnetic field; 3) the satellite must supply all of the power, the telemetry and cooling for the experiment (About 25 percent of the launch mass is the satellite support system.); and 4) The mass of superconducting magnet and its cryostat has to be reduced from 2280 kg for the space station version to 1590 kg for the Atlas IIA version. By changing the matrix material in conductor in the ASTROMAG superconducting coil from a copper to very pure aluminum (RRR > 1000 at zero field), the number of ampere turns in the Atlas version can be increased enough to compensate for the reduction of coil diameter⁷. (As a result, the particle resolution of the magnet was changed very little.)

A further downsizing of ASTROMAG has been dictated by the desire to use a launch vehicle which is less expensive to launch. A Delta II launch vehicle was selected as a candidate less expensive launch vehicle⁸. This vehicle can be launched from the west coast of the United States as well as the Kennedy Space Flight Center in Florida. The California launch facility permits one to launch ASTROMAG into a 800 km sun synchronous circular orbit (a 98.7 degree polar orbit). Such an orbit permits the experiment to be powered by smaller solar panels and the number of low energy particles (less than 1 GeV per nucleon) is increased over the 57 degree orbit. The amount of material that can be put into a sun synchronous orbit varies from 2570 kg to 3260 kg depending on the type of Delta II launch vehicle used. The maximum size Delta II fairing is 3.05 meters (10 feet) in diameter which means that the maximum dimensions of an ASTROMAG satellite is limited to 2.79 meters in diameter and 5.73 meters long. (If a 2.44 m (8 foot) fairing with a bulge is used, the maximum diameter in the bulge region is about 2.6 meters.) For ASTROMAG, the fairing diameter is probably not an issue. The real issue is the length available for the satellite and the ASTROMAG magnet and the two experimental packages. This limitation may require both ASTROMAG experiments to share the same end of the magnet. Even under the best scenario, only one large experiment can be accommodated. The mass of the of sun synchronous orbit Delta magnet version is about 1000 kg. The reduced coil size is not compensated for by an increase in ampere turns. As a result, the particle resolution of the magnet is reduced. This reduction affects the heavy nuclei experiment negatively. The magnet in a sun synchronous can be shielded by the solar panels, which will allow the outside surface of the magnet cryostat to operate at a temperature as low as 230 K. For a given amount of super fluid helium in the cryostat, the dewar life is increased about 30 percent by reducing the dewar vacuum shell temperature to 230 K. As with the magnet system launched by an Atlas IIA, dipole moment correction coils are required.

Recent studies have centered on a Delta II launched version of ASTROMAG which is put into an earth trailing solar orbit. Under this scenario, the satellite is well outside of the earth's magnetic field (about 1.5 to 2.0 million kilometers from earth). The potential advantages of this kind of an arrangement are: 1) Large number of low energy particles are available for analysis. 2) Observation time is maximized. The life of the experiment can be extended out to beyond 3 years so the loss of collection area due to the downsizing of the experiment can be compensated for in part by increase mission time. 3) The magnet can be shielded from the sun by the solar panels. As a result of shielding the magnet and being well away from the earth, the surface temperature of the magnet cryostat can be as low as 120 K, which has the effect of increasing the dewar life time as much as a factor of 1.4 (as compared to a tank with a vacuum shell at 230 K) for a given amount of super fluid helium in the storage tank. 4) The net magnetic moment requirements are greatly relaxed for a magnet which is located well away from the earth. A single coil design may be reasonable provided the axis of

the solenoid is perpendicular to a line between the satellite and the sun. A single coil magnet will have more bending power than a two coil solenoid system, because all of the coil mass can be concentrated in the single coil instead of split between two coils. Even if a two coil zero dipole magnet is required, the superconducting dipole moment correction coils are not needed. The primary disadvantage of this type of orbit is that the satellite mass is limited to 1025 to 1290 kg depending on the version of the Delta. This has a negative effect on the size and the mass of the physics detectors and an effect on the bending power of the superconducting magnet. By necessity, only a single ended experiment can be launched into a solar orbit. The mass of the superconducting magnet, its cryostat and the helium would be in the 350 to 500 kg range.

THE DELTA LAUNCHED SUPERCONDUCTING MAGNET SYSTEMS

Table 1 compares the parameters of the space station version of ASTROMAG with the Atlas IIa version and the two Delta versions. The nominal dewar life for the space station version, the Atlas version and the low earth orbit versions of ASTROMAG are nominally 3.0 to 3.5 years. The sun orbit Delta version will have a nominal dewar life of 4.2 to 4.8 years because the outer shell temperature is 120 K over much of the outer shell. (The portion of the outer shell which is next to the particle detectors will have a temperature of about 240 K.) Studies of hybrid super fluid helium and solid hydrogen cryogenic system for the deep space version show that there is the potential to increase the helium life time out to 6.0 to 6.5 years for a superconducting magnet system with the same overall mass of 500 kg. Solid hydrogen hybrid systems have even greater potential when the cryostat vacuum shell temperature is closer to room temperature⁹. A hybrid cryogenic system is more complex and there are additional safety problems associated with it. (A cryogenic system which uses solid hydrogen for much of the cooling can only be launched by an expendable launch vehicle.)

Table 1
A comparison of Two Delta Magnet Versions and the Atlas Magnet Version with the Baseline Space Station Magnet for ASTROMAG

	Baseline Space Station Version Low Orbit	Atlas Free-flyer Version Low Orbit	Delta Free-flyer Version Low Orbit	Delta Free-flyer Version Sun Orbit
Cryostat OD (m)	2.120	1.820	1.550	1.300
Cryostat Length (m)	2.608	2.350	2.000	1.650
Helium Tank Volume (liters)	3440	2250	1380	760
Coil OD (m)	1.660	1.440	1.232	1.050
Coil Length (m)	0.184	0.220	0.178	0.226
Coil Thickness (m)	0.050	0.058	0.052	0.052
Coil Separation (m)	2.000	1.670	1.400	—
Number of Turns per Coil	2440	2928	2028	2544
Design Current (A)	810	800	925	900
Magnet Stored Energy (MJ)	11.0	11.6	6.4	3.6
Physics Factor##	0.987	1.000	0.700	0.712
Coil Mass (kg)	661	414	254	134
Switch & Corrector Mass (kg)	30*	22	13	5*
Helium Mass (kg)	500	327	203	110
Dewar Mass (kg)	935	724	470	230
Charging System Mass # (kg)	150**	104	-65	-25
Total Magnet Mass (kg)	2276	1591	1005	504
Magnet Weight Factor##	1.431	1.000	0.632	0.317
Overall Mass (kg)	~8500	5257	~3000	~1150

This includes the electronics.

The Atlas version has a factor of 1.000.

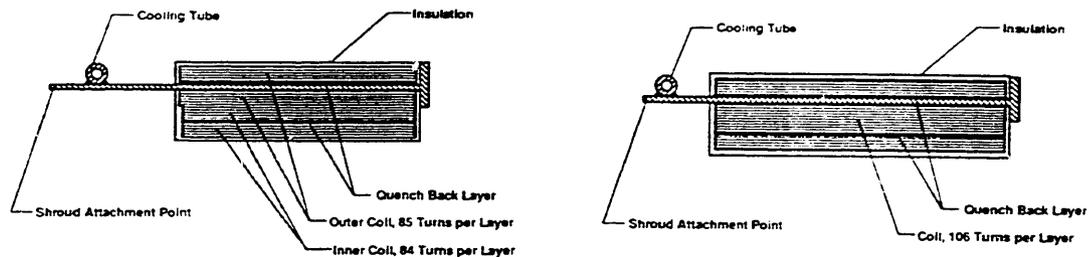
* There are no magnetic moment correction coils

** Estimated, this was not included in the space station version.

The superconducting magnet coils will be made from a superconductor with insulated matrix dimensions of 1.55 by 2.10 mm. (The projected insulation thickness will be 0.05 mm.) The primary matrix material is very pure aluminum with a RRR greater than 1000 at zero field. The ratio of aluminum to superconductor will be 3 to 1. The conductor also has 1 part copper for each part of niobium titanium. The copper based conductor (1 to 1 Cu to Nb-Ti ratio) will be co-extruded with the pure aluminum matrix. The copper based conductor is a typical multifilamentary superconductor with filament diameters which are about 25 micrometers in diameter. In both Delta launched versions of ASTROMAG, the projected magnet operating current will be about 85 percent of the superconductor critical current at along the load line (at a temperature of 4.2 K). The margin is even greater when the magnet operates at its design temperature of 1.8 K.

Figure 1 shows the coil cross-sections for both the low earth orbit version and the solar orbit versions of the ASTROMAG magnet to be launched by a Delta launch vehicle. The table below each coil cross-section describes the parameters of the magnet coil above it. The coil mass given in the tables which are a part of Figure 1, is the mass for a single coil. The low earth orbit version has two such coils whereas the solar orbit version is shown has one coil.

Figure 2 shows the low earth orbit version of a Delta launched ASTROMAG magnet. Figure 3 shows the solar orbit version. The magnet shown in Figure 2 is capable of supplying a magnetic field to detectors at each end of the cryostat. The experimental packages are not shown in Figure 2. Figure 3 shows how a single detector package can be integrated with a single magnet coil and its cryostat in the solar orbit version. The detector operates in a carbon dioxide atmosphere at a pressure of 0.1013 MPa (1 atm); the interior of the magnet cryostat is in vacuum. The temperature within the experimental package will be about 240 K. It is desirable for the rest of the magnet cryostat vacuum shell to be at 120 to 130 K. An insulated section of the vacuum shell would separate the two regions.



FREE-FLYER ALUMINUM MAGNET PARAMETERS

Number of Magnet Coils	2
Number of S/C Layers per Coil	24
Number of QB Layers per Coil	2
Number of Turns per Layer	84 or 85
Number of S/C Turns per Coil	2028
Number of QB Turns per Coil	169
Coil Outside Diameter (m)	1.232
Coil Inside Diameter (m)	1.128
Space Between the Coils (m)	1.400
Outer Coil Width (mm)	178.50
Inner Coil Width (mm)	176.40
Magnet Self Inductance (H)	15.08
6.45 MJ Design Current (A)	925.0
Coil Peak Induction (T)*	6.63
Intercoil Tensile Force (kN)*	235 #
S/C Matrix Current Density (A/sq mm)*	325
Quench Energy at 1.8 K (micro-joules)*	400
Coil Package Mass (kg)	127.2

* At the 6.45 MJ Design Coil Current
24.0 metric tons

FREE-FLYER ALUMINUM MAGNET PARAMETERS

Number of Magnet Coils	2
Number of S/C Layers per Coil	24
Number of QB Layers per Coil	2
Number of Turns per Layer	106
Number of S/C Turns per Coil	2544
Number of QB Turns per Coil	212
Coil Outside Diameter (m)	1.050
Coil Inside Diameter (m)	0.946
Coil Width (mm)	222.6
Magnet Self Inductance (H)	8.86
3.59 MJ Design Current (A)	970.0
Coil Peak Induction (T)*	6.5
S/C Matrix Current Density (A/sq mm)*	316
Quench Energy at 1.8 K (micro-joules)*	400
Coil Package Mass (kg)	134.2

* At the 3.59 MJ Design Coil Current

a) The Low Earth Orbit Version

b) The Solar Orbit Version

Figure 1 Coil Cross-sections for Delta Launched Versions of ASTROMAG

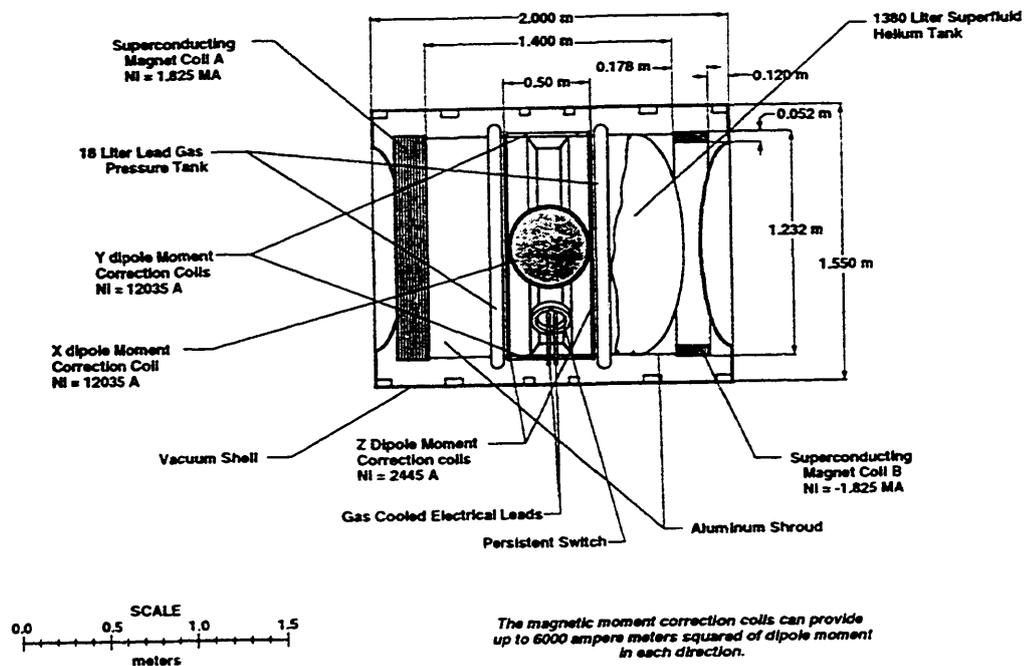


Figure 2 A Low Earth Orbit Delta Launched Version of the ASTROMAG Magnet

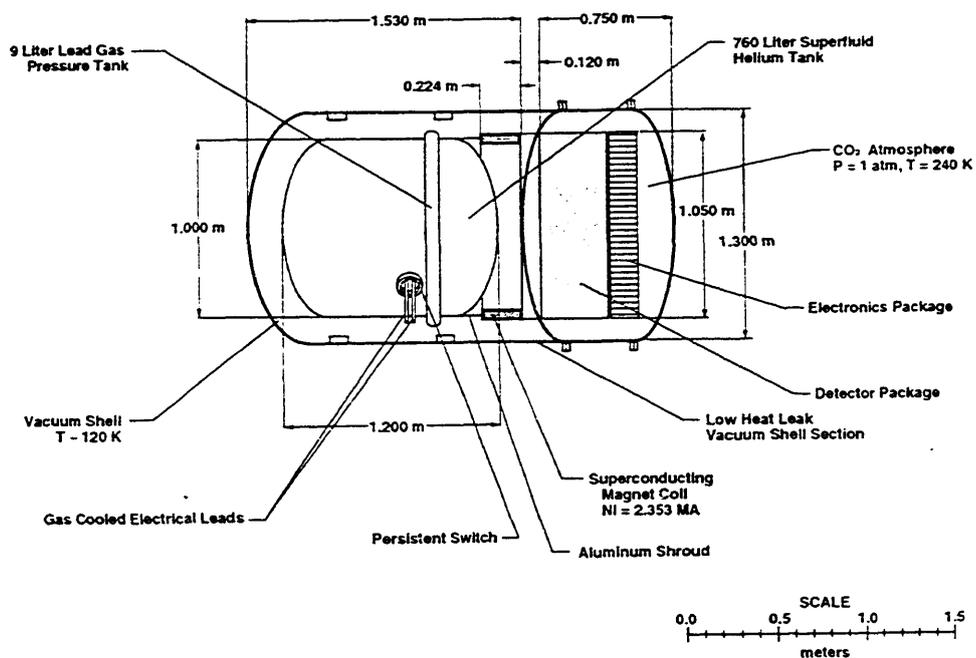


Figure 3 A Solar Orbit Delta Launched Version of the ASTROMAG Magnet

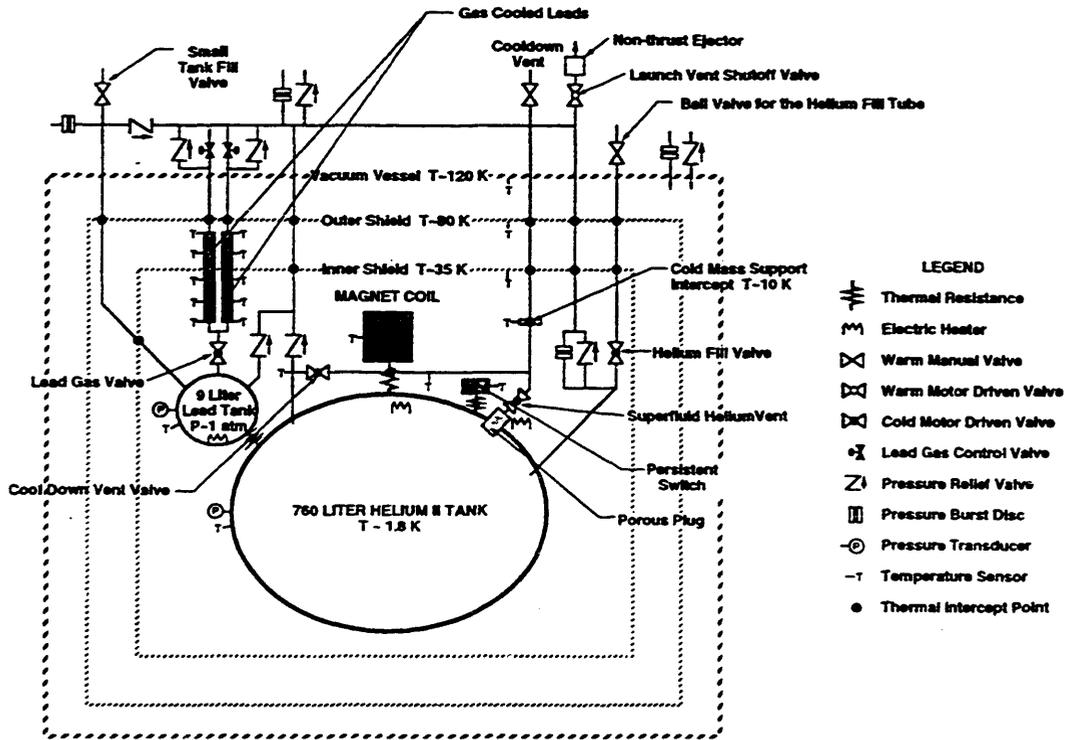


Figure 4 The 1.8 K Cooling System for the Solar Orbit Version of the ASTROMAG Magnet

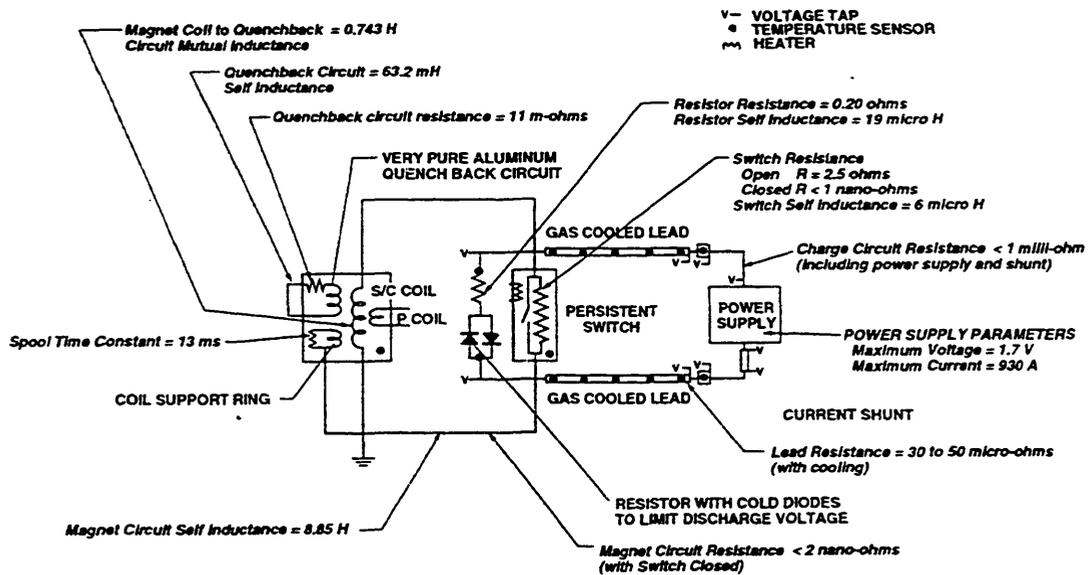


Figure 5 An Electrical Circuit Diagram for the Solar Orbit Version of a Delta Launched of the ASTROMAG Superconducting Magnet

Figure 4 shows the super fluid helium cooling system for the solar orbit version of a Delta launched ASTROMAG. The cryostat vacuum shell, which is in the shadow of the solar panels, is expected to be at 120 to 130 K (except the end where the detectors are located which is at 230 K). Two shields are shown in Figure 4. These shields are cooled by the boil off from the helium dewar. The magnet coil and the persistent switch are cooled from the super fluid helium tank by conduction. Gas needed to cool the retractable gas cooled leads which supply current to the magnet during charging at the beginning of the mission (The magnet is charged once and is kept charged for the rest of the mission.) is supplied from the 9 liter tank which is pressurized by heating the helium. The separate helium tank is filled under pressure as the main storage tank is cooled down from room temperature. The boil off from the 760 liter helium II tank passes through a porous plug super fluid helium phase separator.

Figure 5 shows the power supply, persistent switch and the single superconducting coil which produces the magnetic field for the solar orbit version of ASTROMAG. Figure 5 shows key values of inductance, resistance and voltage in the superconducting magnet electrical system. The charge rate for power supply system shown in Figure 5 can be optimized to minimize the total amount of helium boil off during a charge¹⁰. This optimization will be carried a step further to minimize the total mass of helium boiled off during a charge, the mass of solar panels and the mass of backup batteries.

CONCLUSION

ASTROMAG magnets suitable for launch by a Delta rocket can be designed and built for either an 800 km sun synchronous orbit or an earth trailing orbit around the sun. The magnets for both orbits can benefit from having the outer vacuum shell operate at a temperature below room temperature. The dewar life in both cases will be sufficiently long to allow the required particle astrophysics data to be taken. In both cases the cryogenic system is straight forward and similar to helium dewars which have already been put into orbit.

ACKNOWLEDGMENTS

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