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SUPERCONDUCTING MAGNET TECHNIQUES FOR ASTROMAG ON THE SPACE STATION

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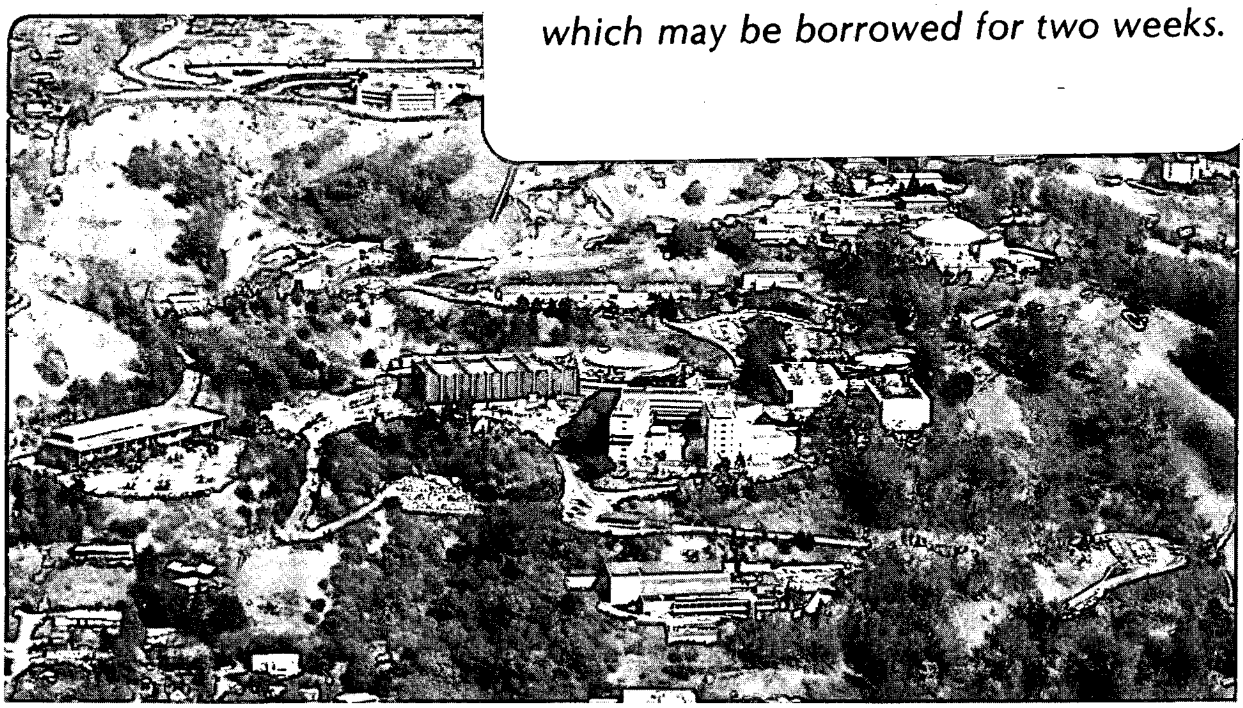

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ABSTRACT

This paper describes superconducting magnet systems which could be used as part of a Particle Astrophysics Experiment ASTROMAG on the space station. This report deals with issues of superconductor selection (should one consider the use of high critical temperature superconductor?), magnet coil and cryostat design, and the cryogenic cooling system for the superconducting magnet.

BACKGROUND

Particle astrophysics is at an important juncture in its development. Observations over the past several years have found unexpected results on the elemental and isotopic composition of cosmic ray nuclei and on the cosmic ray abundances of anti-protons and positrons. Theoretical developments have presented us with a new framework in which to understand the acceleration of these particles. Recent results and theories have raised far more questions than answers.

Over the past two years, the Particle Astrophysics team has examined how a large magnetic spectrometer outside the atmosphere for an extended period of time could address these questions. A facility consisting of a superconducting core magnet, a cryostat and associated support equipment would be used to conduct a series of experiments using a variety of detection equipment. A variety of magnet configurations have been considered. These report will discuss two of the most promising of these configurations which could be used as part of the ASTROMAG facility on the space station.

The heart of a charged particle detection and resolution system for ASTROMAG is the superconducting magnet. The scientific capabilities of the facility depend in important ways on the size, shape and placement of the magnet coils. The coil configuration strongly influences the cost and complexity of the facility.

The following constraints have been put on target magnet configurations for ASTROMAG:

1) The magnet cryostate and the experimental detectors can have a maximum diameter of about 4 meters. The length of the magnet and detectors must be less than 6 meters.

2) The overall mass of the magnet coils, the tankage, the coolant and the cryostat should be less than 4000 kg.

3) The net magnetic dipole moment must be zero so that the earth's magnetic field produces no significant torques on the space station and the field should fall to the earth magnetic field at a distance of less than 20 meters from the magnet center.

4) The coil should utilize a tested reliable superconductor with the peak field at the winding less than half of the upper critical field of the superconductor of choice.

5) The magnet will operate in the persistent mode. The magnet will have to be designed so that it can quench in a fail safe way if a normal region forms in either the magnet coil or the persistent switch.

6) The cryogenic insulation system should maintain the magnet at its design operating temperature for a period of up to two years between cryogen refills. The cryogenic system shall be in a vacuum shell so that the magnet can be launched cold.

7) The magnet and its cryostat shall operate in a shuttle environment which means the magnet and it's support hardware shall withstand both launch and landing conditions for the shuttle. This means that the magnet shall be designed to withstand accelerations of 10 to 12 g's in any direction. The mechanical resonant frequency for key components shall be greater than 35 Hz. The external temperature of the vacuum vessel should have a design value between 280 and 320 K. The external design pressure should be about 1.0 atm.

8) The magnet should be designed so that it can be charged and discharged at least four times per year.

This report examines the choice of superconductor for the magnet for ASTROMAG. The choice of superconductor is dictated in part by the choice of the cryogen used to cool the magnet. The coil and cryostat configurations are presented for a two coil HEAO type magnet and a two coil toroid magnet configuration. The cryogenic system is examined along with the coil configurations.

SELECTION OF SUPERCONDUCTOR

One year ago there would have been no question about selection of superconductor for superconducting magnets in space. At that time the conductor of choice would have been niobium-titanium. The discovery of the new high critical temperature (high T_c) superconductors[1] requires one to re-evaluate this decision. The pressure for this reevaluation becomes stronger with the discovery of the yttrium-barium class of superconductors which have a zero resistance critical temperature of about 93 K.[2] These conductors could theoretically be used with liquid nitrogen as a coolant.

Table 1 compares the properties of a modern niobium titanium superconductor with the yttrium barium copper oxide 1-2-3 conductor. (The table is accurate only on the date given because there are lots of changes occurring in the high T_c superconductor field.) The important things to note are:[3] 1) The new conductor is a ceramic which is much more brittle than niobium titanium alloy. 2) There is some uncertainty as to what upper critical field is. It is felt that this is caused by the granular nature of the superconductor. 3) There is the potential for high critical current density but in bulk samples this conductor cannot carry much transport current. The current carrying performance of the superconductor at 77 K is at least one order of magnitude worse than the critical current density at 4 K given in the table. At this time, samples of yttrium barium copper oxide conductor have not been made in a form which is usable for superconducting magnets like the ASTROMAG magnet.

By looking at an ideal high T_c superconductor which can be formed in a metal matrix like niobium titanium, one can determine whether the high T_c superconductor is likely to be usable for the ASTROMAG magnet. This ideal conductor will have a critical current density which is at least 10^{10} Am^{-2}, and it will be ductile. Table 2 compares the properties of niobium titanium at 4.2 K to the properties of an ideal yttrium-barium-copper-oxide at 20 K and 77 K. From Table 2 one can see that the high T_c superconductor has more adiabatic stability. The price one pays for this is a large reduction of quench propagation velocity (by more than two orders of magnitude) and a reduction of integral of current density squared with time.[3] As a result, it appears that the high T_c superconductor is not suitable for use at current densities above the cryogenically stable limit. On earth where good nucleate boiling can occur, the cryostable current density limit is roughly the same for boiling helium or nitrogen. The cryostable current density limit goes up by a factor of 3 to 4 in liquid hydrogen or neon. For magnets designed for space use, the current density must be high in order to reduce the magnet mass. Only hydrogen or neon appear to be suitable for high current density cryo-

Table 1.

Comparison of $YBa_2Cu_3O_{7-x}$ with Nb-Ti Superconductor (September 1987)

Property	Nb-Ti	Y-Ba-Cu-O
Type of Material	Metal	Ceramic
Mechanical Properties	Ductile	Brittle
Zero Resis. Crit. Temp. (K)	9.4	~93
Max. Poss. H_{c2} at 0 K (T)	14.2	200–360
Max. Zero Resis. H_{c2} at 0 K (T)	14.2	14–30
Max. Poss. H_{c1} at 0 K (T)	0.014	0.016–0.035
Max. Critical Current Density at 4.2 K, 0 T by Magnetization (Amm^{-2})	26000	50000*
Critical Current Density at 4.2 K, 5 T by Short Sample Methods (Amm^{-2})	3750	10–100

*IBM oriented multicrystal thin film.

Table 2.

Properties of Ideal Superconductor in a RRR = 300 Copper Matrix

Type of superconductor	Nb-Ti	Y-Ba-Cu-O	Y-Ba-Cu-O
Operating temperature (K)	4.2	20.3	77.3
Superconductor T_c (K)	9.4	93	93
Matrix Resistivity (Ohm·m)	5.18×10^{-11}	5.98×10^{-11}	2.0×10^{-9}
Adiabatic Stability Dia. (μm)	5.7*	216**	863**
Dynamic Stability Dia. (μm)	103*	350**	62**
Longitudinal Quench Velocity (ms^{-1}) at $J_M = 3 \times 10^8$ Am^{-2}	~7	~0.019	~0.044
Transverse to Longitudinal Quench Velocity Ratio	0.015	0.042	0.071
Integral J^2dt to 400 K ($A^2 m^{-4} s$)	18.6×10^{16}	18.2×10^{16}	10.0×10^{16}
Matrix Current Density (Amm^{-2}) for Cryogenic Stability	72	242	56

*Based on superconductor J_c = 3750 Amm^{-2}.

**Based on superconductor J_c = 10000 Amm^{-2}.

stability. (There is a question of whether high nucleate boiling heat fluxes needed for full cryostability can be sustained in a weightless environment.)

The last factor which affects whether or not an ideal high T_c superconductor is usable is the choice of working fluids. Table 3 compares the properties of liquid helium, hydrogen and nitrogen. Helium has the lowest boiling point and two liquid phases. The superfluid phase can be phase separated from the gas by using a porous plug even in a weightless environment. Helium has a low heat of vaporization but on the other hand it has a rather high specific heat at constant pressure. Nitrogen has a high heat of vaporization and a low specific heat. Hydrogen has a high heat of vaporization and a high specific heat. One gets the most refrigeration per unit mass out of hydrogen (4630 J g^{-1}). Helium is next best (1561 J g^{-1}) and nitrogen is much lower than helium (431 J g^{-1}). Hydrogen would be the best stored cryogen to use in space except that it is extremely flammable and it's use is not allowed on either the space station or the shuttle. If one is to cool the magnet on the space station with stored liquid cryogen, helium is the cryogen of choice. (One would use conventional niobium titanium superconductor with liquid helium.)

It can be concluded that high T_c superconductor is not attractive for superconducting magnets in space unless: 1) there is a significant improvement in the ability to carry current; 2) the superconductor must be combined with a metal matrix; 3) the brittleness problem must be solved; 4) the superconductor must be used in the cryostable mode; and 5) the superconductor must be run in a liquid hydrogen bath. In short, the best superconductor to use for superconducting magnets in space will be niobium titanium cooled by liquid helium. Helium II is preferable over helium I because liquid-gas phase separation can be achieved using a porous plug and helium II can be pumped without moving parts using the fountain effect.

SUPERCONDUCTING MAGNET DESIGNS STUDIED FOR PARTICLE ASTROPHYSICS EXPERIMENTS IN SPACE

Two types of superconducting magnets have been investigated for use in charged particle experiments in space:

1) The two coil solenoid has the two coils separated by about two meters and they are oppositely charged so that the net magnetic dipole moment is zero. This design will be referred to as the HEAO Type.[4,5]

2) The two coil toroid also has the property of a zero net magnetic dipole moment. These flux lines pass through these D shaped coils in a roughly circular pattern in a direction which is roughly perpendicular to the direction of the charged particles.

Table 3.

Properties of Cryogenic Working Fluids

Property	Helium	Hydrogen	Nitrogen
1 atm Boiling Temperature (K)	4.22	20.28	77.35
Triple Point Temperature (K)	—	13.80	63.3
Lamda Point Temperature (K)	2.17	—	—
Critical Temperature (K)	5.19	35.25	126.1
Critical Pressure (atm)	2.26	12.8	33.5
Liquid Density (gcm^{-3})	0.125	0.071	0.811
Heat of Vaporization (Jg^{-1})	20.8	441	198
Specific Heat (Jg^{-1} K^{-1})	5.19	14.55	1.03
Effective Refrigeration To 300 K (Jg^{-1})	1561	4630	431
Nucleate Boiling Heat Flux at 1 g(Wcm^{-2})	~1.0	9.5	19

Both types of magnet described here use niobium titanium superconductor cooled with superfluid helium at 1.8 K pumped from a spherical tank. In both cases, the superconductor is operated at a matrix plus superconductor current density of a little less than 3×10^{8} Am^{-2} with a peak induction in the coil from 6 to 7 tesla.

Figure 1 shows an isometric view of the HEAO type magnet. The coils and the helium tank are contained in the same cryogenic vacuum enclosure.[6] Figure 2 shows an isometric view of a two coil toroid.[7] The coils are separated from the helium storage tank so that the particle astrophysics can be done on both sides of the two coil toroid. The price one pays for the improved physics is more heat leak, more mass and more capital expenditure in building the two coil toroid magnet.

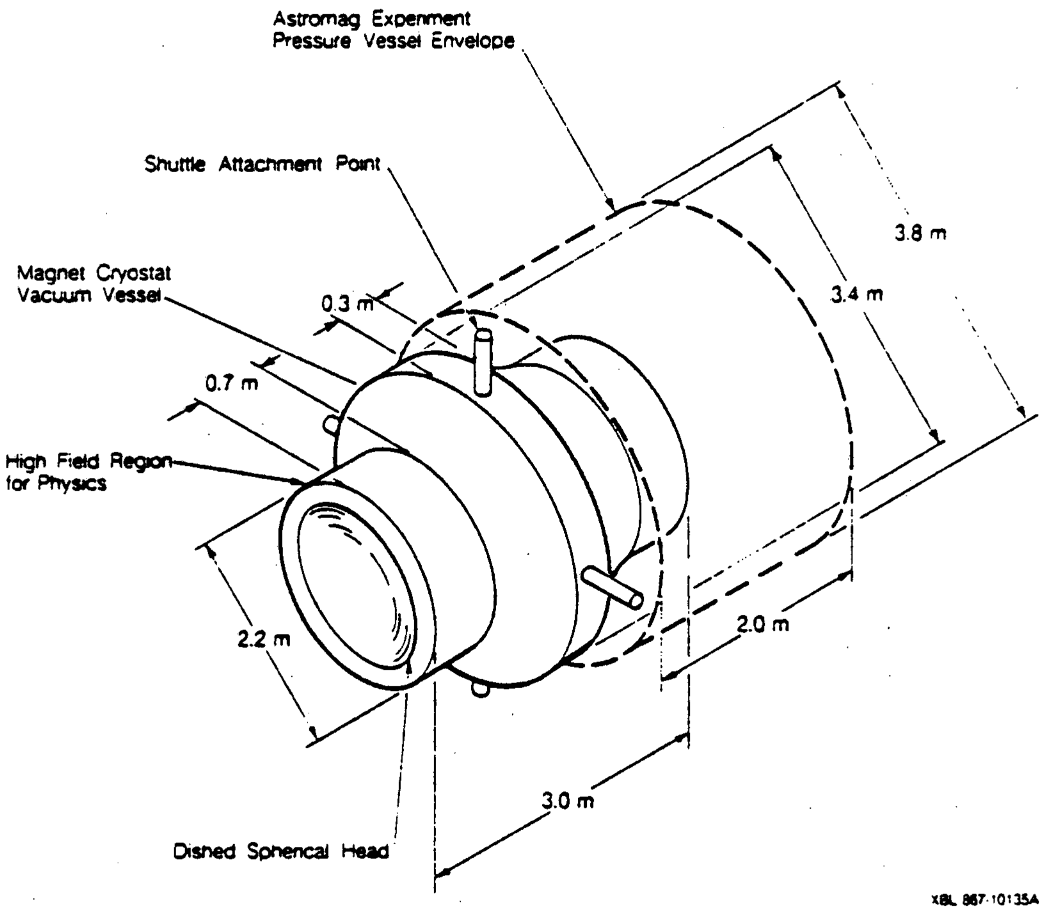
Figure 3 shows a schematic view of the inside of the magnet cryostat for the HEAO type magnet. Unlike the HEAO magnet of the early 1970's,[4] this magnet design has the coils outside of the helium tank. The coils are cooled by pumping helium from the tank through the coils and back to the tank.[8] Figure 4 shows a schematic view of the two coil toroid magnet system. The helium tank is completely separated from the two D shaped coils. (See Fig. 2 for the isometric view.) The D shaped coils, shown in Fig. 5 are designed so that the bending moment in the coils is zero when the magnet is charged. This shape permits one to minimize the mass and the coil stress. The two D shaped coils are cooled by helium pumped from the tank as in the HEAO design.

Table 4 compares the two types of superconducting magnets for ASTROMAG. The current density in the winding and the mass of the windings is limited by quench protection considerations. If one wants to quench the magnet in a fail safe way,[9] the stored energy per unit active coil mass should be limited to a maximum value of about 15 J g^{-1}. Thus, the coil final temperature after quenching is just above 100 K. The whole coil is driven normal during the quench through heating from a secondary circuit by currents induced in the circuit during the process of the coil going normal. A properly designed high current density magnet with a secondary circuit should need no external quench protection nor should the temperature at the hot spot exceed 400 K. By proper design, the persistent switch can also be protected by the passive quench protection system.

From Table 4 one can see that the stored energy of HEAO system is higher than for the two coil toroid. The stored energy was selected so that the overall mass of the two types of magnets is about the same. The two coil toroid has a total of 3.2 MA turns whereas the HEAO type design has about 4.8 MA turns. The two coil toroid will perform somewhat better, from a particle resolution standpoint, than will the HEAO type. The cold mass of any given design is approximately proportional to the stored energy. Both

Figure 1.

ISOMETRIC VIEW OF HEAO TYPE MAGNET



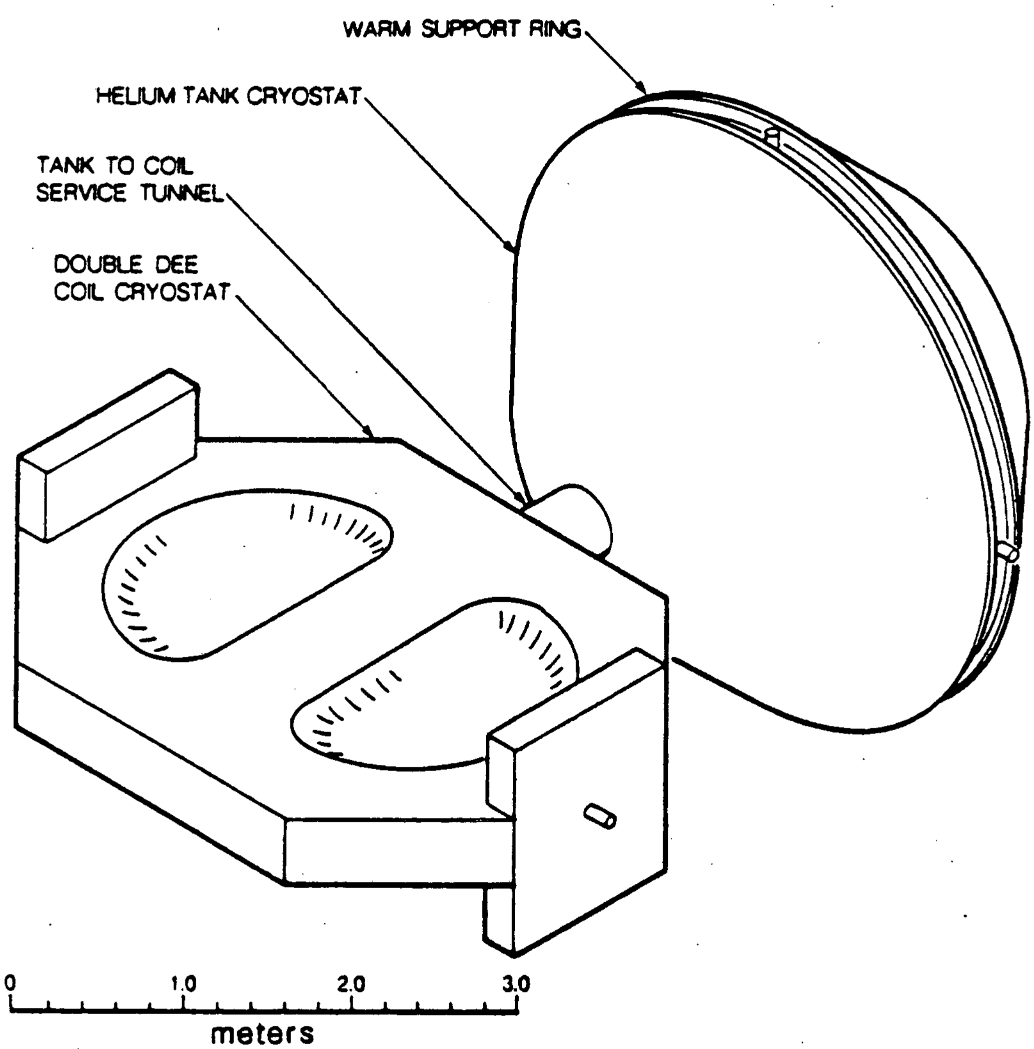


Figure 2.

ISOMETRIC VIEW OF TWO TOROID TYPE MAGNET

Figure 3.

HEAO TYPE MAGNET CRYOSTAT SYSTEM

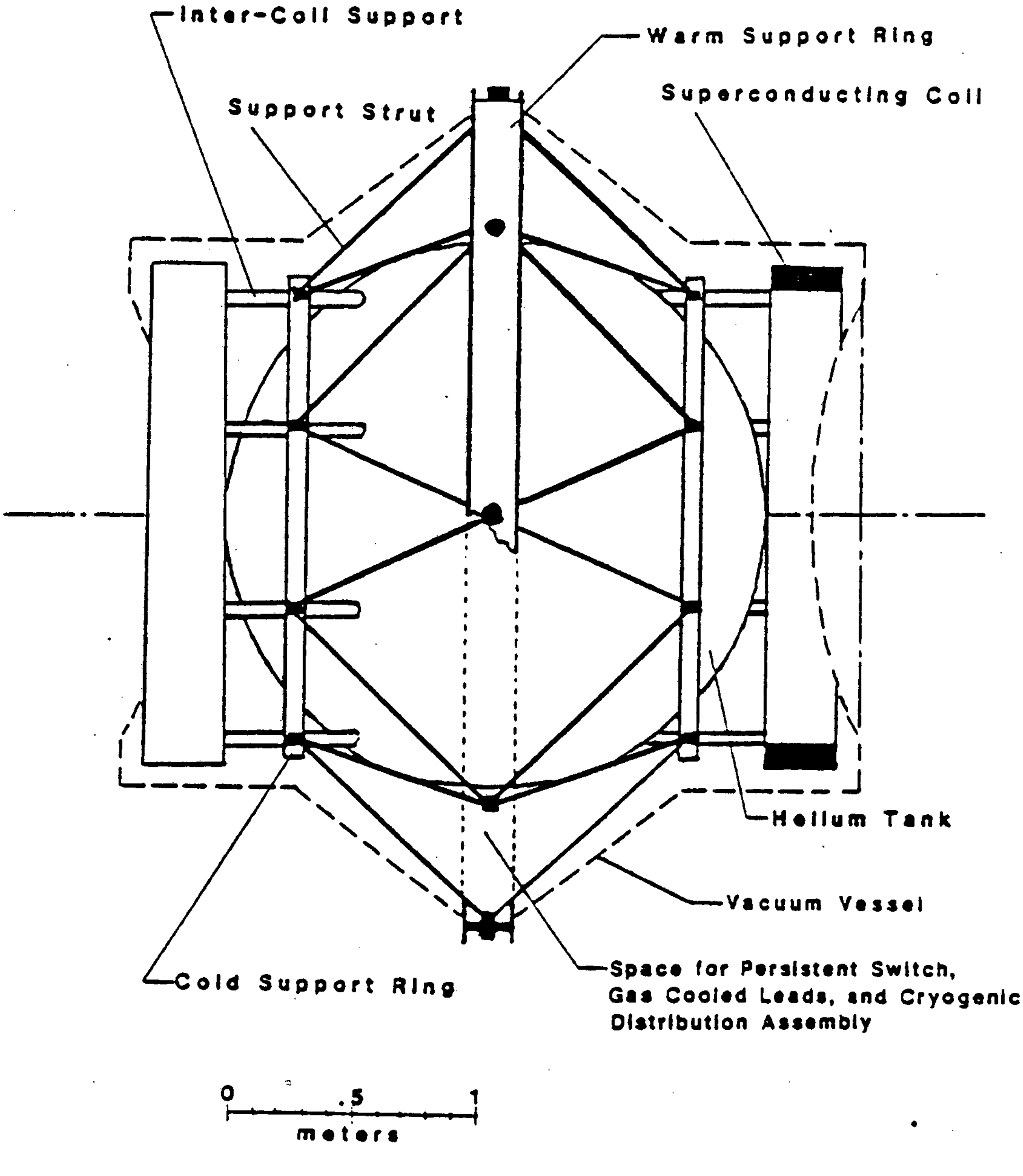


Figure 4.
TWO COIL TOROID CRYOSTAT SYSTEM

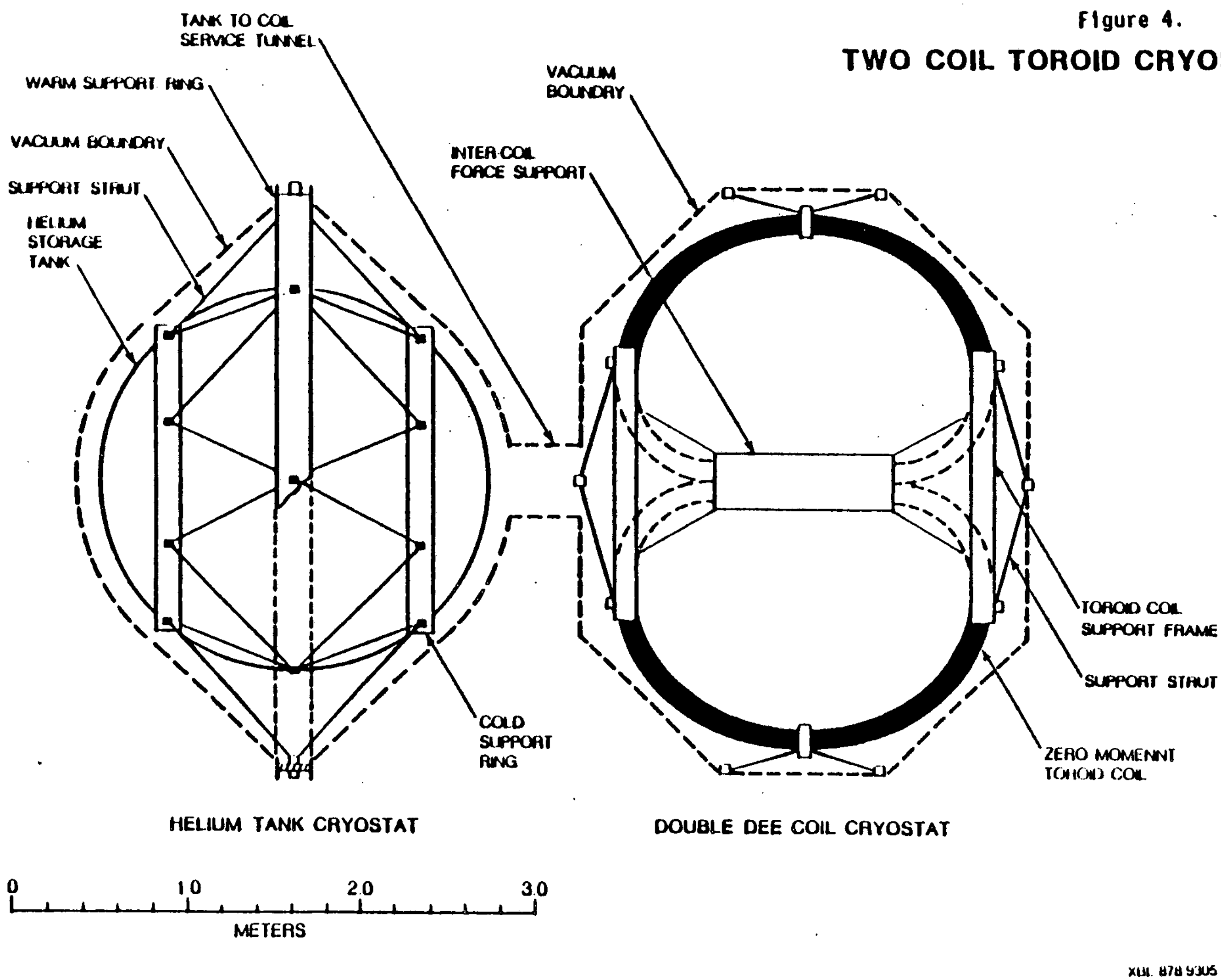


Figure 5.

TWO COIL TOROID MAGNET
(COIL BENDING MOMENT IS ZERO)

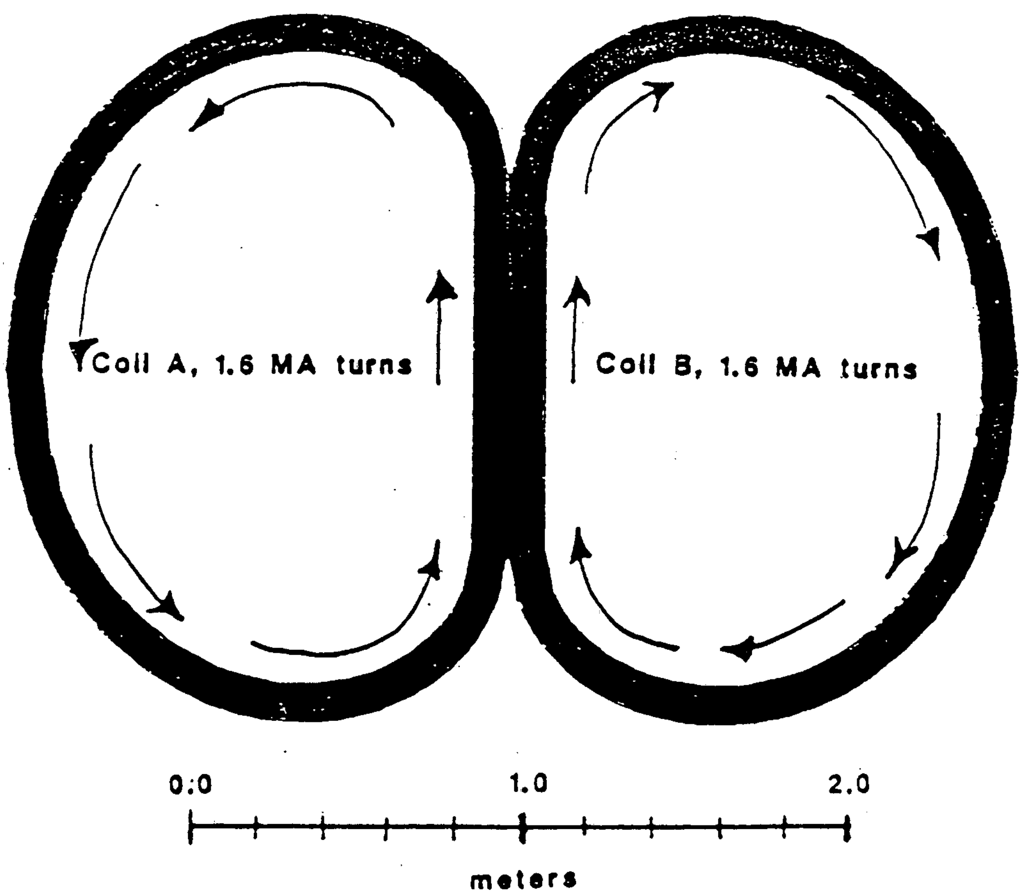


Table 4.

Comparison of the HEAO and Two Coil Toroid Types of Astromag Magnets

	HEAO	Toroid
Coil shape	Circle	Double Dee
Number of coils	2	2
Distance between coils (m)	2.2	0.065
Coil package dimension (m)	2.05	3.22 x 1.97
Number of turns	6400	3640
Design current (A)	754.1	879.1
Peak Induction in coil (T)	~6.3	~7.0
Force between coils (N)	4.4×10^5	3.4×10^6
Magnet Inductance (H)	66.9	32.3
Magnet stored energy (MJ)	19.0	12.5
Matrix Current Density (Am^{-2})	2.99×10^8	2.88×10^8
EJ^2 Limit ($JA^2\ m^{-4}$)	1.69×10^{24}	1.04×10^{24}
Magnet charge time (hr)	3.0	2.4
Overall cold mass (kg)	2650	2200
Overall magnet mass (kg)	3700	3850

magnets include about 700 kg of superfluid helium in the cold mass estimate.

Both magnet types shown in Table 4 use similar multi-filamentary niobium titanium. The superconductor is in a copper matrix with a copper to superconductor ratio of about 2 to 1. The filament diameter in both cases is less than 30 microns. The matrix resistivity at 1.8 K is designed to be about 10^{-9} ohm meters. The niobium titanium critical current density is set at 2500 A mm^{-2} at 4.2 K and 5 T. Reducing the temperature to 1.8 K improves critical current density. The niobium titanium superconductor proposed for both types of magnets is entirely within the state of the art. At design current and temperature, the magnet will be operating at less than 50 percent of its critical current.

THE SUPERFLUID HELIUM COOLING SYSTEM

Superfluid helium is the stored cryogen of choice for superconducting magnets in space as it is for various low noise squib detectors and various short wavelength rf detectors. The use of super fluid helium for cooling has a number of important advantages for cooling large superconducting magnets in space. These advantages are:

1) Temperatures of 1.4 to 1.8 K are easy to obtain and maintain in space. The vacuum pumping needed to get superfluid helium is free.

2) The liquid density is higher for superfluid helium than helium at its 1 atm boiling temperature of 4.2 K. The tanks can be made somewhat smaller per unit helium mass.

3) Superfluid helium has a higher heat of vaporization. There is little difference in available total refrigeration between superfluid helium and helium at 4.2 K (about 12 J g^{-1} or less than one percent).

4) Complete gas-liquid phase separation can be obtained in a weightless environment using a porous plug. Taking only helium gas into the leads and shields will reduce overall helium consumption.

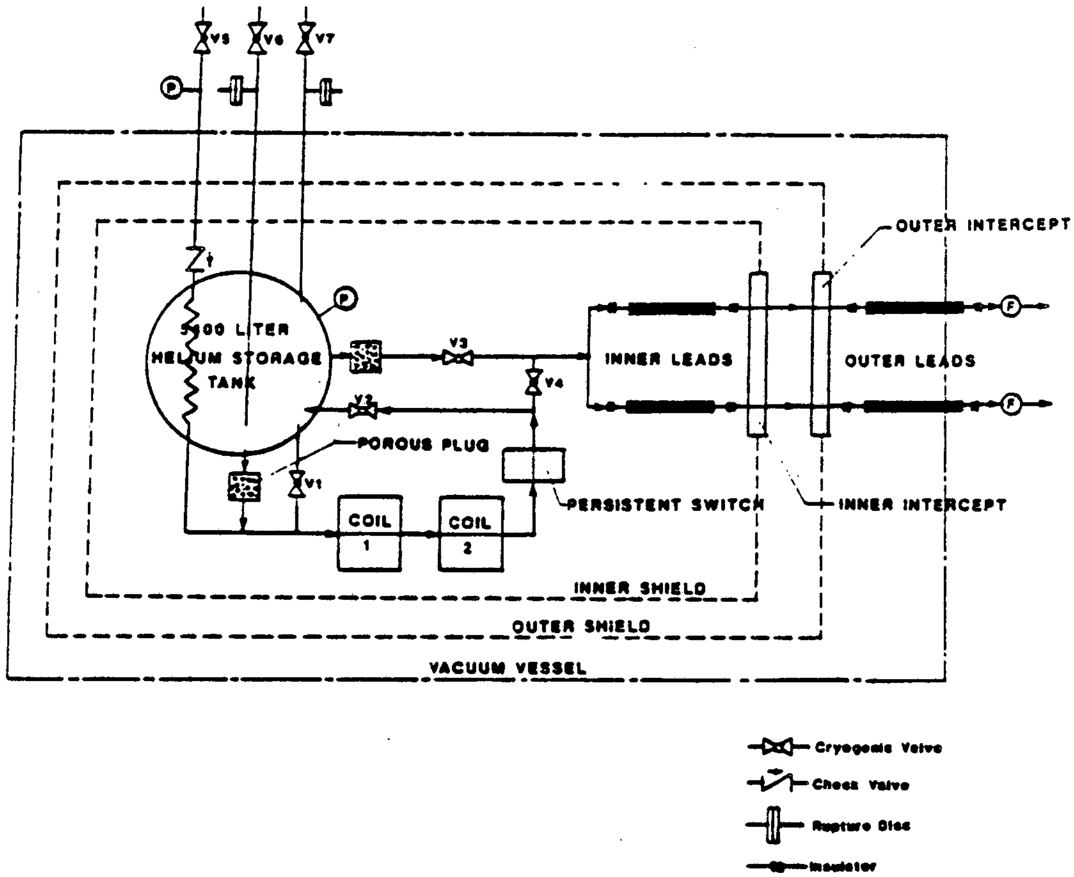
5) Superfluid helium can be pumped through the magnet coils using the fountain effect. There are no moving parts in the pump and the heat needed to drive the pump is supplied by heat leaks into the system.

6) The critical current density in the superconductor is higher at 1.8 K than it is at 4.2 K. There is an additional margin when operating at 1.8 K or one can increase the magnetic induction at the superconductor.

Figure 6 is a schematic diagram of the cryogenic system for the HEAO version of the ASTROMAG superconducting magnet.[8] Some of the cold valves, cold burst discs and the crossover

Figure 6.

ASTROMAG CRYOGENIC SYSTEM SCHEMATIC



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plumbing associated with ground operations and shuttle safety requirements have been omitted to provide a clear picture of the basic cryogenic system. Figure 6 shows one of the methods being investigated for circulating superfluid helium through the superconducting coils and the persistent switch using a thermomechanical effect pump.[10] An alternate superfluid helium pump is illustrated in Fig. 7. This method developed and tested by Hofmann[11] uses multiple heat exchangers and can pump up to 3 gs^{-1} using the fountain effect. The Hofmann pump is driven by heat deposited on the piece to be cooled. Figure 6 also shows how the boil-off gas can be used to cool the retractable gas-cooled electrical leads, the radiation shields and cold mass support heat intercepts. The two coil toroid cryogenic system is more complicated than the system shown in Fig. 6. Two sets of shields and intercepts are in series in place of the single set of shields and intercepts shown in Fig. 6.

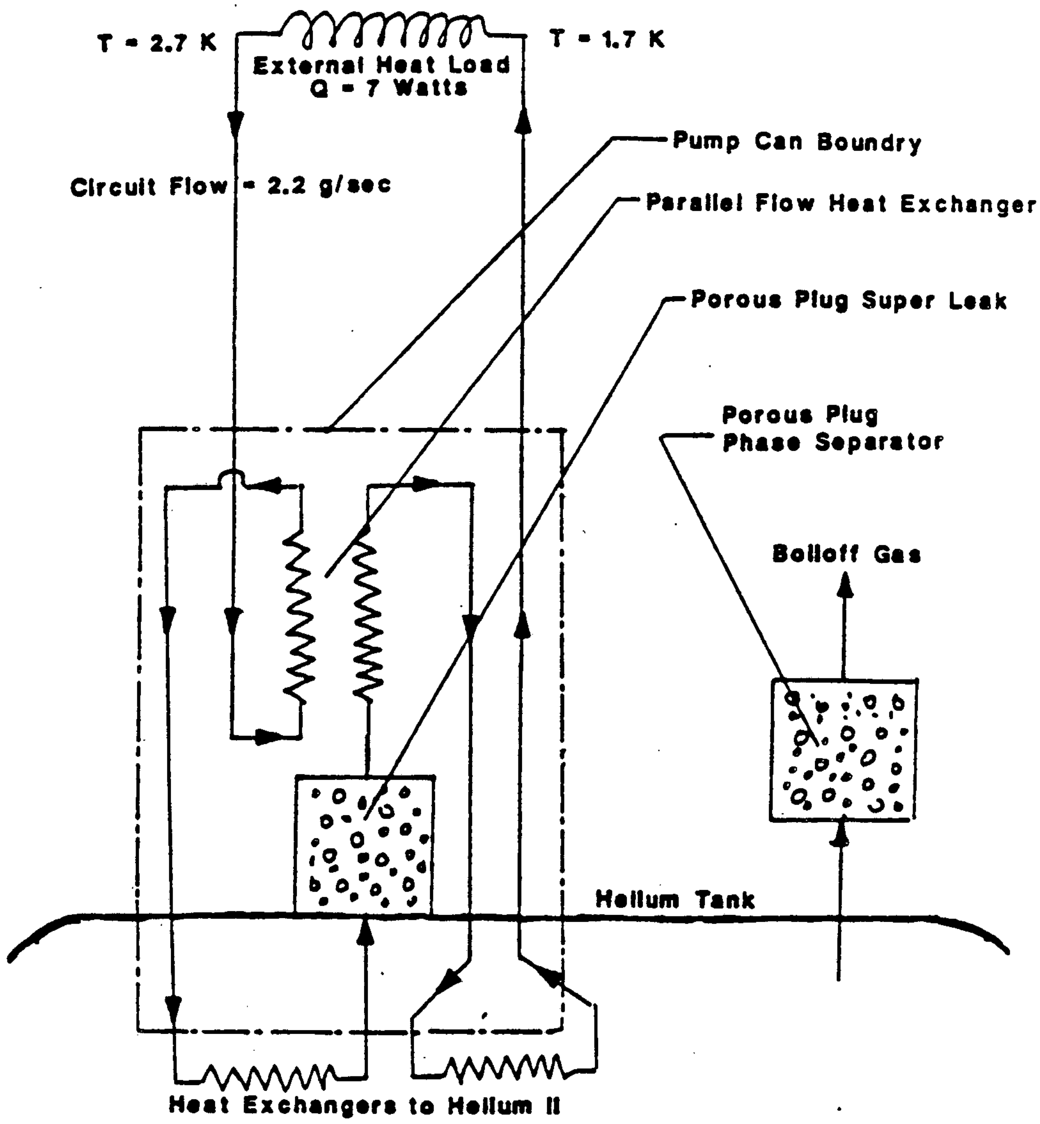
The two shield concept shown in Fig. 6 is similar to the HEAO cryostat[4] of the early 70's except that the gas cooled leads are at both ends of the shield gas flow circuit. The gas cooled lead will disconnect in the middle. The proposed leads are enhanced heat transfer leads which can be operated at any orientation in a vacuum.[12] The shields and intercepts will be between the two sets of leads which are connected only charging or discharging the magnet. When the leads are connected together and operating, the shields and intercepts will run colder than normal. As a result, some of the refrigeration lost during the charging or discharging of the magnet will be recovered. Table 5 compares the heat loads and helium boiloff rates for both types of magnets with the leads retracted and while the magnet is being charged or discharged. In both cases the estimated lifetime of a full tank of helium is around 2 years. The addition of a third shield cooled by a nitrogen temperature refrigerator can increase the useful life of the ASTROMAG cryostat to about 3-1/2 years.

The cryogenic system shown in Fig. 6 is designed so that the magnet coils can be cooled down, from the storage tank, in the event of a quench. About 75 kg of helium is required to recover from a 19 MJ quench. (Recovery from a 12.5 MJ quench will require about 55 kg of helium.) The coils, persistent switch and the tank can be cooled down from using liquid helium pumped from a large external storage tank.

Table 6 compares the mass of various components in the HEAO and two-coil toroid versions of ASTROMAG. The cold mass for the HEAO version of ASTROMAG is larger than for the two coil toroid version (2650 kg versus 2200 kg, which includes 700 kg of superfluid helium in the tank when it has about 15 percent ullage.) Much of the difference in the cold mass is reflected in the difference of the stored magnetic energy in the two systems. The two-coil toroid has more of its mass at temperatures above 4 K. The surface area of the two cryo-

Figure 7.

HOFMANN FOUNTAIN EFFECT PUMP FLOW CIRCUIT



SUPERFLUID HELIUM AT 1.7 K

Table 5.

Comparison of the Heat Leaks for the HEAO and Two Coil TOROID Types of ASTROMAG Magnets

	Heat Leak (W)			
	HEAO		TWO-COIL TOROID	
	Leads Detached	Leads Attached	Leads Detached	Lead Attached
Support Bands	0.10	0.10	0.08	0.08
Radiation	0.08	0.08	0.11	0.11
Electrical Leads	0.04	0.80	0.04	0.94
Presistent Switch	—	0.90	—	1.00
Charging Heating	—	1.00	—	1.00
Miscellaneous	0.02	0.02	0.02	0.02
Total Heat Load (W)	0.24	2.90	0.25	3.15
Helium Boil of Rate (gs^{-1})	0.0104	0.1310	0.0108	0.1414
Charge Time (hr)	3.0		2.4	
Annual Helium Useage (kg)	339		352	

Table 6.

A Comparison of the Mass of Various Components of the HEAO and Two Coil Toroid Types of ASTROMAG Magnets

	Mass (kg)	
	HEAO Magnet	Two-Coil Toroid Magnet
Superconducting Coils	1500	1120
Persistent Switch	80	80
Helium Tank	370	300
Liquid Helium	700	700
TOTAL COLD MASS	2650	2200
Shields and Insulation	200	300
Vacuum Vessel	850	1350
TOTAL MAGNET MASS	3700	3850

stats for the two-coil toroid magnet system is larger than it is for the single HEAO magnet cryostat.

CONCLUDING COMMENTS

Superconducting magnets for particle astrophysics experiments in space will use niobium titanium superconductor cooled by superfluid helium at about 1.8 K. The two coil toroid magnet appears to be a little better than the HEAO design from a physics standpoint despite the lower stored energy associated with the two coil toroid. Much of the improved physics associated with the two coil toroid is based on being able to use both sides of the toroidal coils. This requires the magnet coil cryostat be separated from the helium storage tank cryostat. As a result, the proposed two coil toroid magnet system will cost nearly twice as much as the simpler HEAO type magnet which has it's coils located within the same cryostat as the helium storage tank. There is a clear trade off between improved particle resolution and the cost of the detector magnet.

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