Cryogenics: its influence on the selection of the ASTROMAG superconducting magnet coils

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ASTROMAG, a particle astrophysics experimental facility proposed for running alongside a space station, has a large superconducting magnet to analyse particles coming from deep space. Several types of magnets were investigated for use in the ASTROMAG central facility. The factors which influence the selection of the magnet coil design include: 1, the upper limit of particle momentum resolved (proportional to the integrated field) as a function of solid angle; 2, cryogenic design and its effect on cryogen lifetime for a given central facility mass; and 3, the overall cost of the magnet coils and cryostat. Four magnet types are analysed in this paper. These include a simple two-coil solenoid (the baseline design), two disc coils at the ends of the helium tank, a two-coil toroid and a thin solenoid plus bucking coil. The superfluid helium cryogenic system must have a cryogen lifetime approaching four years without refilling. (Mechanical coolers on the outer shield may be used to extend this lifetime.) The baseline magnet and cryostat mass (including the helium) is set at 2000 kg. Coils which have extended surfaces will require more helium to keep them cold. Flat surfaces require more mass in the outer vacuum vessel or a greater distance between the coils and the detectors (hence a lower integrated field). A balance must be struck between cryostat lifetime, total mass and the integrated field through the detectors. This balance tends to favour coils which are in the same vacuum vessel as the cryogen. The trade-offs are examined for the four cases given previously.

Keywords: space cryogenics; superconducting magnets; ASTROMAG; magnet coils

ASTROMAG is a particle astrophysics facility which consists of a superconducting magnet facility with two or more experiments[1]. The central facility consists of the magnet coils, the cryostat, power supplies and space station support gear which permits the experiment to be attached to and serviced by the space station.

The primary scientific objectives of ASTROMAG are to: 1, study the origin and evolution of matter in the galaxy by direct sampling of galactic material; 2, examine cosmological models by searching for antimatter and dark matter candidates; and 3, study the origin and acceleration of the relativistic particle plasma in the galaxy and its effects on the dynamics and evolution of the galaxy.

The general scientific objectives will be met by an ASTROMAG with particle detection instruments designed to make the following observations:

1 To search, with unprecedented sensitivity, for antinuclei of helium and heavier elements. The identification of any such antinuclei would imply that the universe contains domains of antimatter and would have profound cosmological implications.
2 To measure the spectra of antiprotons and positrons. These antiparticles have already been seen in cosmic rays, and they are expected as secondary products of primary cosmic ray interactions with interstellar gas; however, antiproton fluxes are higher than expected from normal models of galactic cosmic ray propagation. Further investigation of these spectra will surely improve our understanding of the origin of cosmic rays and may lead to the discovery of processes unpredictable from the basic present knowledge of elementary particle physics and cosmology.
3 To measure the isotopic composition of cosmic ray nuclei at energies of several GeV/amu (higher than reached by other means) and with previously unattained sensitivity. The few reliable measured elements show that the isotopic composition at the cosmic ray source is different from that of ambient material found in our solar system.
4 To measure the energy spectrum of cosmic ray nuclei to very high energies with unprecedented precision.

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Spectral differences between primary and secondary nuclei are indicative of galactic confinement processes and can lead to determination of source abundances of rare elements. Fine structure in the energy spectra, if observed, would revolutionize ideas about the origin of cosmic rays.

5 To measure the energy and direction of high energy gamma rays and act as a gamma ray telescope. High energy gamma rays can be measured with enough accuracy to determine the location of large gamma ray sources within our galaxy.

6 To measure the plasma surrounding the space station and study the effect of the space station on it. This experiment will increase our knowledge of plasma physics in low earth orbit.

The scientific objectives of the ASTROMAG facility require a strong superconducting magnet to generate the magnetic field which will be used to bend charged particles so that their energy charge and momentum can be resolved. The scientific capabilities of the facility depend to a high degree 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 cryostat and the experimental detectors can have a maximum diameter of ≈ 3 m. The length of the magnet and detectors must be less than 6 m.

2 The overall mass of the magnet coils, the tankage, the coolant and the cryostat should be less than 2000 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's magnetic field at a distance of less than 15 m from the magnet centre.

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 four 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 its support hardware shall withstand both launch and landing conditions for the shuttle. This means that the magnet shall be designed to withstand accelerations of $10-12g$ in any direction. The external temperature of the vacuum vessel should have a design value between 280 and 320 K. The external design pressure should be ≈ 1.0 atm*.

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

*1 atm = 101.325 kPa

A superconducting magnet system, which meets the scientific requirements and the constraints given above, must be made using a modern Nb–Ti superconductor cooled with superfluid helium. Superfluid helium is the coolant of choice even though the overall cryogenic performance of liquid or solid hydrogen is better. Hydrogen's flammability precludes its use on the shuttle or space station. If the ASTROMAG experiment was launched on an expendable launch vehicle, a hybrid solid hydrogen/superfluid helium cryogenic system could be considered[2].

The use of superfluid helium has a number of important advantages for cooling large superconducting magnets in space. These advantages are:

1 Temperatures of 1.4–1.8 K are easy to obtain and maintain in space. The vacuum pumping needed to obtain 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 (≈ 12 J g^{-1} or $< 1\%$).
ed 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.

It is easy to decide that the ASTROMAG magnet coils must be made from Nb–Ti cooled with superfluid helium; but it is much harder to determine with certainty the optimum configuration of the magnet coil. The magnet configuration is a function of the science which is to be performed and the overall cost of performing that science. This paper describes the process used to select a magnet configuration for ASTROMAG.

Magnet configuration selection process

An ideal magnet for ASTROMAG is a magnet which produces a maximum integral of magnetic field over distance, over the widest solid angle, with the minimum of stored energy, such that there is no material between deep space and the particle detectors. The creation of a large value of the integral of magnetic induction over distance with minimum stored magnetic energy (which is proportional to coil mass and ultimately overall mass[3]) is contrary to the notion of a large unobstructed solid angle. If you want a large unobstructed solid angle for a given stored energy, the integral of magnetic induction with distance must go down.

A number of magnet designs were compared for a given level of stored magnetic energy. The figure of merit used in the comparison was maximum detectable rigidity

(MDR) as a function of spectrometer geometrical acceptance (AΩ). For comparison purposes, the MDR must be maximized over a geometrical acceptance of ≈ 0.05 m^2 steradian. (The geometrical acceptance is proportional to the number of particles to be analysed over a given time period.) To maximize MDR, one has to increase the integral of induction (field) with distance and/or one has to improve the resolution of the detector. The isotope experiments which benefit most from increased MDR also suffer the most from material which is placed between deep space and the detectors.

During the last four years, a number of magnet designs have been studied. The designs studied have included the HEAO concept of the early 1970s[4], a Helmholtz pair of coils with a larger diameter bucking coil to generate a zero net dipole moment (the SPIRIT magnet concept of the late 1970s[5]), a two-coil toroid magnet[6], a three-disc magnet design proposed by the Fermi National Accelerator Laboratory[7], a four-coil design which produces a field with flux lines like a four leaf clover (the LUCKEY design), a thin solenoid with a bucking coil[8], two race track coils on the outside of a cylindrical helium tank[9] and disc coils at the end of a helium tank[10]. The two-coil HEAO concept has remained the baseline design because the field produces acceptable physical performance, and the coil and tankage configuration is simple and will cost the least of the different options.

The previously mentioned designs were studied with a basic coil diameter of 2.0 m and a magnet stored energy of 15 MJ at design current. The peak MDR was highest for the two-coil toroid, the three-disc design and the various configurations of the HEAO design. The thin solenoid has a nearly constant high value of MDR over a wide range of spectrometer geometrical acceptance. The three-disc design was eliminated because it was more complicated geometrically and produced a lower value of MDR than did the two-coil toroid magnet. The designs which remained after the first round of magnet selection were: 1, the two-coil HEAO (the baseline design); 2, the two disc coils at the end of the helium tank; 3, the thin solenoid with a bucking coil; and 4, the two-coil toroid magnet.

The basic HEAO magnet design shown in *Figure 1* does not produce the best physics. It does not have the highest value of MDR nor does it produce a high value of MDR over a wide range of acceptance angles. For a given stored energy, the two-coil toroid will produce almost twice the MDR. The thin solenoid with bucking coil produces a high value of MDR over a wide range of geometrical acceptance. (This feature is lacking in both the two-coil toroid and the HEAO design.) The disc coil design, which is a variation of the HEAO design, has somewhat better performance for a given stored energy.

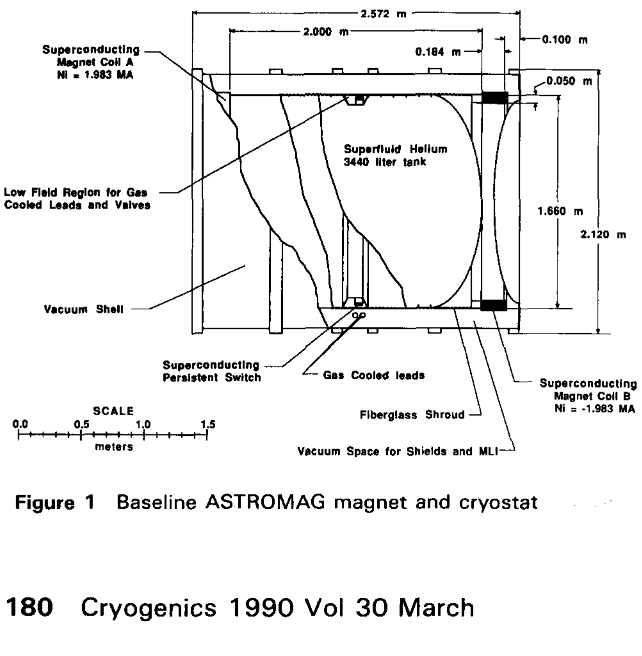


Figure 1 Baseline ASTROMAG magnet and cryostat

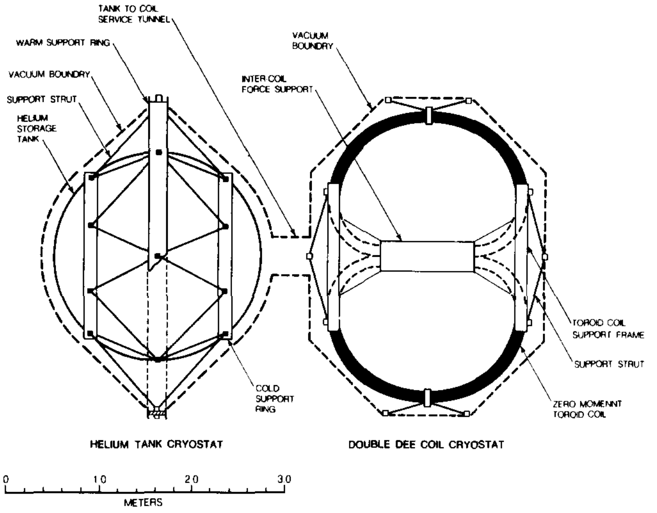


Figure 2 Two-coil toroid magnet and helium tank

Two-coil toroid

The two-coil toroid shown in *Figure 2* has the appearance of a double, rather rounded 'D'. The net dipole moment of the magnet shown in *Figure 2* is zero. The magnetic field falls off to 3 G in ≈ 10 m. The shape of each D was chosen so that the bending moment is zero in the coils when they are energized; thus, the magnetic forces are taken up in loop forces in the coils. This reduces the coil mass to a minimum. Each coil carries 1.6 MA with a peak field of ≈ 7.0 T. The coils shown in *Figure 2* will store an energy of 12.5 MJ at design current.

The two-coil toroid shown in *Figure 2* has the coils separated from the helium storage tank so that both sides of the double D can be used to add to the overall performance. Two separate cryostats are proposed. The coils would be cooled with superfluid helium circulated by a fountain effect pump from the storage tank. Shield cooling gas is carried from the tank shields to the shields for the coil package.

When the current in each coil is 1.6 MA, the peak MDR is roughly 1.7 times that of the baseline HEAO coil system (stored energy 11 MJ) shown in *Figure 1*. The mass of the coil and its cryostat would be ≈ 4000 kg. To meet the weight and cryostat life constraints of ASTROMAG, the magnet size had to be reduced to 65% of the size shown in *Figure 2*. The magnet stored energy had to be cut to 5 MJ at design current (≈ 880 A). As a result, the peak MDR is only 10–15% higher than the baseline magnet system shown in *Figure 1*. The magnet and its cryostat are more costly and complex. As a result, the double D magnet was dropped from consideration for ASTROMAG.

Thin solenoid

The thin solenoid option, proposed by Yamamoto *et al.*[8] is shown in *Figure 3*. This magnet consists of a 1.3 m

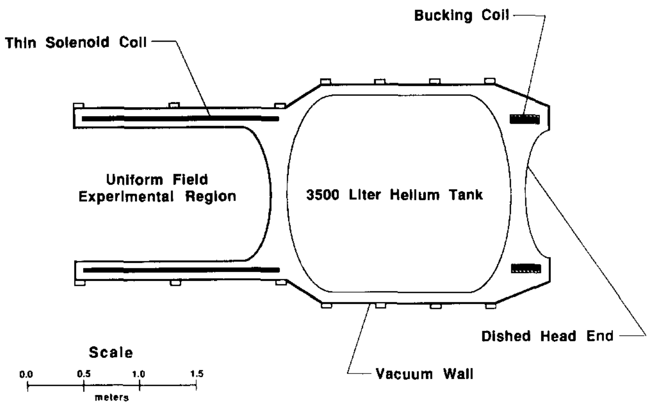


Figure 3 Thin solenoid plus bucking coil

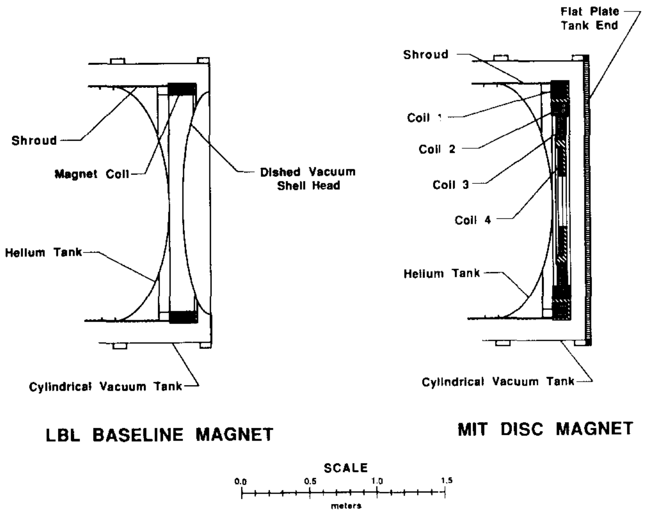


Figure 4 Baseline and MIT disc magnets

diameter thin solenoid which is 1.7 m long. The bucking coil diameter is also 1.3 m; its length is just over 250 mm. The helium tank is between the coils. The coils are cooled by conduction from a tube which contains superfluid helium pumped from the storage tank.

Both coils would be wound using a pure alumnium matrix superconductor, which has within it a copper matrix Nb−Ti superconductor. The magnetic forces are carried by the copper matrix superconductor and by a hard aluminium outer support shell. According to the proposed design, the stored energy is ≈6.6 MJ[11]. The thin solenoid carries ≈2.3 MA; the bucking solenoid carries the same current with the opposite polarity. Its average diameter is the same as the thin solenoid so that the net magnetic dipole moment is zero.

Physical performance can be achieved inside the thin solenoid where the field is relatively uniform with an average induction of 1.1 T. The integral of induction over the distance inside the thin solenoid is comparable to the baseline case near the end of the cryostat. The lever arm for particle resolution is shorter, so for a given detector resolution, the MDR is a little smaller than for the baseline case. The MDR as a function of available solid angle is large. This means that a lot of particles will experience a large amount of bending. Physical interactions experienced at the bucking coil end of the experiment are comparable to those in the baseline case. (The peak MDR is the same to within 10%.)

A case can be made for the number of events which can be analysed by a thin solenoid with detectors inside. The disadvantage of the thin solenoid is that there is ≈ 0.25 radiation lengths of material between deep space and the detectors. Isotope physics, an antihelium search and gamma ray searches are badly affected by the extra material. The search for antiprotons is not, however, badly affected by the extra material. As a result, a Japanese group is building a thin solenoid detector for an antiproton balloon experiment[12].

The thin solenoid shown in *Figure 3* has an estimated mass of ≈2200 kg. The surface area of the cryostat is larger than that for the baseline case. As a result, the cryostat lifetime is expected to be substantially less than four years.

Disc coils at the end of the helium tank

The disc magnet proposed by MIT is a variation of the baseline magnet shown in *Figure 1*. As with the baseline magnet (and all of the other magnets described here) the coils are located outside of the helium tank. To maximize the integral of induction over distance (and hence MDR), the coil must be located as close to the particle detectors as possible. In the baseline design, the tank has a concave end so that the thickness of the material at the end of the cryostat can be minimized. The space from the coil to the outside wall includes the superinsulation and shields as well as the cryostat vacuum wall. Studies of this problem suggest that the minimum distance from magnet coil to the outside of the cryostat vacuum wall can be ≈ 80 mm without substantially decreasing the helium dewar lifetime.

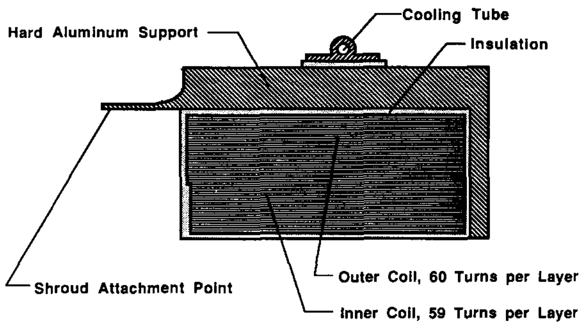
The disc coil design proposed by MIT[10] has four pancake coils which have different thicknesses to ensure that the coil peak field is no more than 7.0 T. The inner radius of the innermost coil (coil No. 4) is 190 mm. The outer radius of the outermost coil (coil No. 1) is 850 mm. The four coils form a disc across the end of the helium tank (see *Figure 4*). The MIT disc coil design has a total current for the four coils of ≈4.1 MA (compared to 2.0 MA for the baseline coil). The MIT coil has a stored energy of 20.8 MJ (compared to 11.0 MJ for the baseline coil) and the integrated induction over distance (and hence potential MDR at a given distance from the coil with given detector resolution) is ≈65% larger than for the baseline case.

A comparison of the two designs shows that there are some important differences which must be considered when evaluating the disc design over the baseline design[13]. The differences which had to be resolved were: 1, the mass of the two types of coil; 2, the thickness of the flat plate which forms the end of the cryostat; and 3, the mechanical bending moments which are put into the shroud when it carries the intercoil force. (This force is a tensile force due to the fact that the two coils have opposite polarity.)

The moments generated by the intercoil forces can be reduced or eliminated by moving the inner coils (coil Nos 2, 3 and 4) with respect to the outer coils so that the net force in these coils along the magnet axis is zero[14]. The total axial tensile force applied to the intercoil shroud is unchanged by moving the inner coils with respect to the outer coils. (The required changes in position are only a few millimetres.)

The flat plate which forms the end of the cryostat can be made into a honeycomb structure. As a result, for a given dewar end plate mass, the particle detectors are moved out by 25 – 40 mm. This reduces the peak MDR by a few per cent. The thinnest honeycomb plates can be made from titanium. A titanium vacuum shell (or one where part of the shell is made from titanium) does impact the cryostat cost, but the effect is not large.

The disc coils shown in *Figure 4* have a much larger cross-sectional area than does the baseline case (338 cm^2 *versus* 92 cm^2). A copper based superconducting coil similar to the baseline case would have a mass of 817 kg per coil, compared to 310 kg for a single baseline coil. To reduce the coil mass, the copper based superconductor would have to be replaced with an aluminium based superconductor and the Nb – Ti superconductor would have to be graded within the aluminium stabilizer to further reduce mass. The resulting minimum mass coil would be 520 kg. This mass is still too high to stay within the overall coil (two coils), tankage, helium, insulation and vacuum shell mass of 2000 kg. If a disc coil cryostat is to have an overall mass and lifetime similar to the baseline case, the magnet stored energy would have to be reduced to 12.4 MJ. As a result, the disc coil MDR is only 18% larger than the baseline case.



ALUMINIUM BASELINE MAGNET PARAMETERS

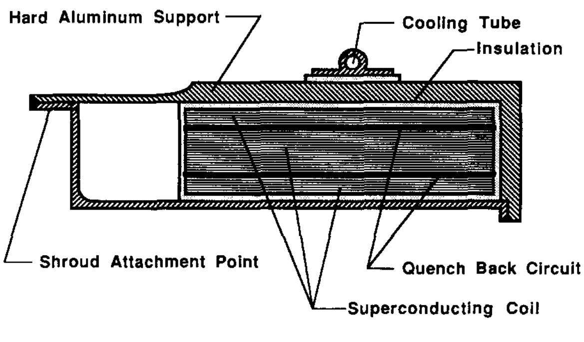
Number of Magnet Coils	2
Number of S/C Layers per Coil	42
Number of Turns per Layer	59 or 60
Number of S/C turns per Coil	2500
Coil Outside Diameter (m)	1.66
Coil Inside Diameter (m)	1.50
Space Between the Coils (m)	2.00
Outer Coil Width (mm)	186.00
Inner Coil Width (mm)	182.90
Magnet Self Inductance (H)	32.36
13.82 MJ Design Current (A)	925.87
Coil Peak Induction (T)*	6.97
Intercoil Tensile Force (kN)*	319#
S/C Matrix Current Density (A/ sq mm)*	213
Quench Energy at 1.8 K (micro-joules)*	948

* At the 13.87 MJ Design Coil Current
\# 32.6 metric tons

Figure 6 Aluminium baseline superconducting coil

Aluminium *versus* copper matrix superconductor in the ASTROMAG coil

The baseline magnet coils shown in *Figure 1* are shown in more detail in *Figure 5* with its adjacent table. Copper based superconducting coils can be built to employ quenchback as a quench protection method. Coils which employ quenchback as a quench protection method have shorted secondary circuits which heat other parts of the coil (or the second coil in a two-coil system), driving them normal before the normal zone would propagate into that region.



COPPER BASELINE MAGNET PARAMETERS

Number of Magnet Coils	2
Number of S/C Layers per Coil	34
Number of QB Layers per Coil	4
Number of Turns per Layer	72
Number of S/C turns per Coil	2448
Number of QB turns per coil	288
Coil Outside Diameter (m)	1.66
Coil Inside Diameter (m)	1.56
Space Between the Coils (m)	2.00
Coil Width (mm)	184.00
Magnet Self Inductance (H)	33.52
11 MJ Design Current (A)	810.09
Coil Peak Induction (T)*	6.74
Intercoil Tensile Force (kN)*	251#
S/C Matrix Current Density (A/ sq mm)*	405
Quench Energy at 1.8 K (micro-joules)	9.6

* At the 11 MJ Design Coil Current
\# 25.6 metric tons

Figure 5 Copper baseline superconducting coil

The major disadvantage of the copper based superconducting coil is the low energy needed to drive the magnet normal. If one uses minimum propagation zone[16] (MPZ) arguments, one can state the case that coils made with low resistivity aluminium would require about two orders of magnitude more energy to drive them normal[17]. The study described in Reference 17 suggests that there may be other advantages to a coil made with an aluminium matrix superconductor which is similar to the baseline magnet shown in *Figure 1*. The results of an aluminium coil design study are shown in *Figure 6* with its adjacent table. The results are as follows:

1 The number of ampere turns in the magnet can be increased by ≈ 17% without sacrificing the operating margin. (The coil design current is 92% of the superconductor critical current along the load line at a temperature of 4.2 K.)
2 The energy needed to initiate a quench is 100 times larger with the pure aluminium design.
3 The quench decay time for the magnet is expected to increase by a factor of two. As a result the energy dumped into the helium tank from the coil quench is reduced and the eddy current forces on the shields are lower.
4 The overall coil current density is lower when the energy per unit coil mass is increased.

The pure aluminium baseline coil is expected to produce about the same maximum MDR as the disc coil. There are some areas which are not well understood in non-cryostable aluminium matrix coils which have the aspect ratio of the coil shown in *Figure 6*. The problem areas which requires further study are:

1 Pure aluminium has no strength. The magnetic forces must be shared between the copper based superconductor inside the aluminium stabilizer and the hard aluminium support bobbin which has been shrunk to fit the outside of the coil.
2 Quench propagation is well understood in thin solenoids using a pure aluminium conductor, but is not well understood in coils which have an aspect ratio similar to the one shown in *Figure 6*. Quenchback and quench propagators similar to those proposed by Yamamoto[18] may help protect the aluminium matrix superconducting coil. Further study will solve both the structural and quench protection problems in coils of this type.

Conclusions

The ASTROMAG magnet will be of the HEAO type (see *Figure 2*) or the modified disc HEAO type (see *Figure 4*). The two-coil toroid and thin solenoid coils offer no clear cut physical performance advantages over the simpler HEAO design when they are built so that the magnet facility has a mass of 2000 kg and an overall helium storage life approaching four years.

The modified disc type HEAO coil is still a contender, but its advantages (in terms of MDR) are greatly lessened when compared on the basis of equal coil mass and when both the baseline HEAO and the disc HEAO designs use aluminium based superconductors. (There is then almost no advantage.) The use of an aluminium based superconductor improves the performance of the baseline design more than it does the disc coil design. (The larger aluminium based coil magnet has less of its stored energy around the coils.)

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