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ASTROMAG: A SUPERCONDUCTING PARTICLE ASTROPHYSICS MAGNET FACILITY FOR THE SPACE STATION

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ABSTRACT

This paper describes a superconducting magnet system which is the heart of a particle astrophysics facility to be mounted on a portion of the proposed NASA space station. This facility will complete the studies done by the electromagnetic observatories now under development and construction by NASA. The paper outlines the selection process of the type of magnet to be used to analyze the energy and momentum of charged particles from deep space. The ASTROMAG superconducting magnet must meet all the criteria for a shuttle launch and landing, and it must meet safety standards for use in or near a manned environment such as the space station. The magnet facility must have a particle gathering aperture of at least 1 square meter steradian and the facility should be capable of resolving heavy nuclei with a total energy of 10 Tev or more.

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INTRODUCTION

Particle astrophysics stands today at a critical juncture in its development. Observations over the past several years have given unexpected results on the elemental and isotopic composition of cosmic-ray nuclei and on the cosmic-ray abundances of anti-protons and positrons. Concurrently, theoretical developments have presented us with a new framework in which to understand the acceleration of these particles. These results have raised new questions about the origins of energetic particles in astrophysical settings, sometimes deeply related to fundamental questions of cosmology and elementary particle physics. For example: What is the source of the large abundances of anti-protons observed in the cosmic radiation? Is there evidence for known or unknown particles which could account for missing mass in the universe? What is the nucleosynthetic history of this sample of non-solar system material? Answering these questions requires long space exposures of large instruments; the development of a permanently manned Space Station offers the opportunity to perform the needed experiments.

Over the past year the Particle Astrophysics Magnet Facility (ASTROMAG) Definition Team has examined how a large magnetic spectrometer outside the atmosphere for an extended period of time could address these questions. A facility, composed of a core magnet, dewar, and associated support equipment would be used to conduct a series of experiments using a variety of instrumentation. A variety of magnet and instrument configurations have been considered, and it appears to be quite feasible to construct and operate such a spectrometer facility on the Space Station. This report describes a strawman configuration for a superconducting magnet for ASTROMAG and it also describes briefly two other magnet configurations which might be attractive for the facility.

SCIENTIFIC OBJECTIVES

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 anti-matter 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.

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

- <u>Search, with unprecedented sensitivity, for anti-nuclei of helium and heavier elements</u>—The identification of any such anti-nuclei would imply that the Universe contains domains of anti-matter and would have profound cosmological implications.

- <u>Measure the spectra of anti-protons and positrons</u>—These anti-particles have already been seen in the cosmic rays, and they are expected as secondary products of primary cosmic-ray interactions with the interstellar gas; however, anti-proton 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.

- <u>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</u>—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.

- <u>Measure the energy spectrum of cosmic ray nuclei to very high energies with unprecedented precision</u>—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.

The ASTROMAG design is based on the following principles of particle detection. An incoming particle is deflected as it passes through a very strong magnetic field produced by currents in a system of coils (the magnet). The sign and magnitude of the deflection are measured by high precision particle tracking detectors. Triggering telescopes above and below the magnetic field provide information for identifying the particle. They also determine the direction of travel of the particles and provide indication to the electronics of the passage of an event to be analyzed.

THE SPECTROMETER MAGNET

The heart of the 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 in turn strongly influences the cost and complexity of the facility. A variety of coil configurations have been compared to make a preliminary evaluation of the trade-offs between capabilities and complexity.

These comparisons were based on a number of assumptions and constraints, as follows:

The dimensions and weight of the coils, dewar and stored cryogen are limited to a size which will permit simultaneous launch of the core facility and two initial experiments, with final assembly to be completed on orbit. Typical magnets considered fit in a cylindrical envelope 2-3 m in diameter by 2-4 meters in length, and have a mass less than 4500 kg.

Of this mass, no more than 1500 kg can be allocated as 'active coil mass'. That is, the mass of the coil plus any shorted secondary circuits in which the magnetic energy would be deposited should the magnet quench. Safety considerations then imply a maximum energy stored in the magnetic field in the range 15-22 MJ.[2]

The net magnetic dipole moment is required to be zero so that the interaction with the Earth's magnetic field will produce no significant torques on the Space Station. This requirement is met by employing two or more coils arranged so that the vector sum of their individual dipole moments vanishes. This configuration also causes the fringe magnetic field to decrease to the level of the Earth's field in a reasonable distance (approximately 20 meters).

The coil will utilize a proven, reliable super-conductor consisting of multifilamentary niobium-titanium in a conducting matrix. This superconductor, when operated at a temperature of 4.4 K, requires that the magnetic field strength in the superconductor be limited to a maximum of 7 Tesla. The expected magnet operating temperature will be near the lamda point, providing additional safety margin.

The magnet will be operated in persistent mode. The coils will be charged to their nominal operating currents using an external power source and then they will be electrically isolated to maintain the field without additional power input. The charging process will require the use of either retractable gas cooled electrical leads and/or a magnetic flux pump.

The dewar used to maintain the coils at liquid helium temperature will be designed to permit up to 2 years of operation between cryogen refills. (It is expected that the helium dewar will be resupplied with liquid helium every 12 to 16 months.) It will be housed in a vacuum shell in order to permit operation on the ground.

The shuttle launch environment places some restrictions on the design of the magnet hardware. The magnet must be designed to withstand accelerations of 10 to 12 g's in any direction. In addition, the natural resonant frequency of major components should be greater than 35 Hz. (If this requirement cannot be met, the design acceleration must go up a factor of 1.5.) The external temperature of the cryostat vacuum vessel will be regulated within the range from 240K to 320K (this temperature is set by the requirements of the physics detectors). The magnet is expected to be charged and discharged four times a year.

THE STRAWMAN MAGNET CONFIGURATION

As the basis for preliminary studies of experiments which will utilize the magnet, we have adopted a design which is technically conservative but capable of making major scientific advances in a number of areas. This strawman magnet design is illustrated in Figure 1 and Figure 2. It consists of two identical coaxial coils which carry currents in opposing senses to cancel the individual dipole moments. The space between the coils is occupied by the cryogen dewar, which also provides the mechanical structure to support the repulsive forces between the coils. This arrangement, in which the coils share a common vacuum vessel and thermal isolation system with the helium storage tank, results in a relatively simple dewar of minimum mass. The regions at the two ends of the dewar, just outside the coils, provide the volumes of high magnetic field required for experiments. This coil configuration allows the placement of experiments in regions where the field of view is nearly unobstructed by the mechanical structure of the magnet, thereby optimizing the use of the available magnetic field.

This coil configuration is well understood from previous studies.[3] The superconducting magnetic spectrometer experiment planned as part of the HEAO satellite program (and not flown, as the result of redirection of the HEAO program in 1973) employed a very similar configuration, through about 2.5 times smaller than the magnet we are considering. As a result of this similarity, coil configurations of

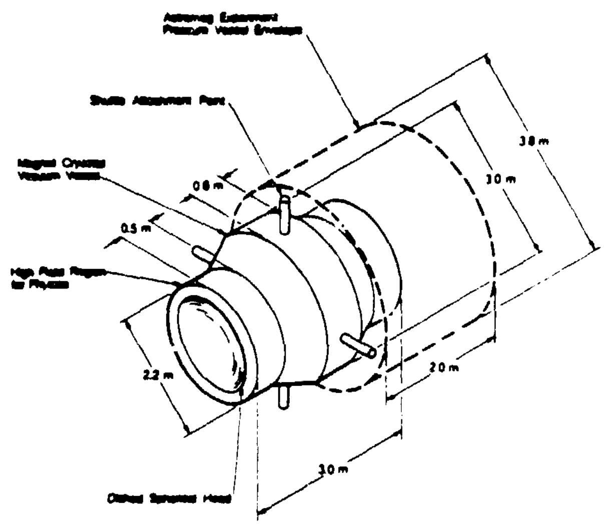


Figure 1. Isometric View of the STRAWMAN ASTROMAG Magnet with an Experiment in Place

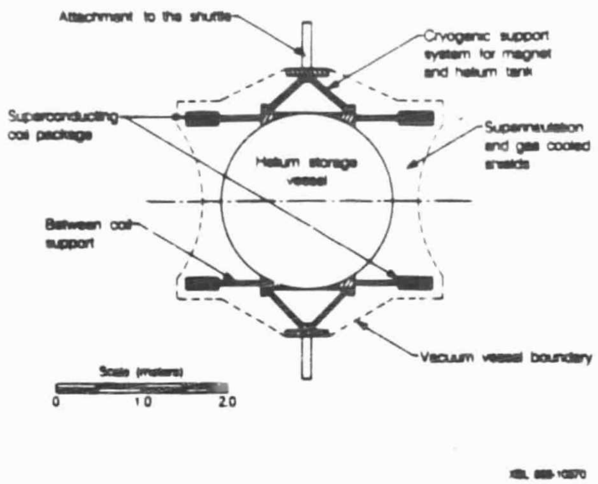


Figure 2. A Cross-Section of HEAO Type ASTROMAG Magnet

this type are commonly referred to as 'HEAO magnets'. Studies of the original HEAO magnet were carried through to the construction of a prototype coil and a thermal model dewar. These were extensively tested over a period of years and have demonstrated that the desired field strength and design lifetime can be achieved for ASTROMAG. In addition, these studies addressed a number of the technical questions related to cooling, charging, and persistent-mode operation of superconducting magnets in space. Additional experience has been gained through the continuing use of single coil superconducting magnets in balloon-borne particle astrophysics experiments and extensive ground-based magnets.

The parameters for a strawman HEAO type coil, which has a projected cold mass of 2800 kg, (including liquid helium) is shown in Table 1. The proposed superconducting coils are to be cooled by circulated two-phase helium using a low mass flow helium pump as a circulator. The tensile force between the coil is to be carried by MP-35N tension rods which isolate the coils thermally from the spherical helium storage tank. This arrangement permits the coils to recover from a quench in space using the sensible heat in the helium as well as the latent heat.

The magnet must be designed to quench in a fail safe way. The designs studied assume that both coils can be driven normal by quench back from a shorted secondary circuit.[4] All of the stored magnetic energy will end up in the coil packages (which would be thermally isolated from the tank). In order to achieve fail safe quenching, the stored energy per unit mass is limited to no more than 15 J per gram of active coil mass.

When the magnet is operating in space in persistent mode, the boil off gas is used to cool the lower electrical leads, the cryostat shields and the intercepts on the cold mass supports. During charging the gas-cooled leads are engaged and all of the gas flow passes through the shields and the leads. The charging and discharging of the magnet four times a year is expected to consume 50 to 70 liters of helium. The overall mass of the magnet and cryostat with parameters given in Table 1 is expected to be about 4200 kg.

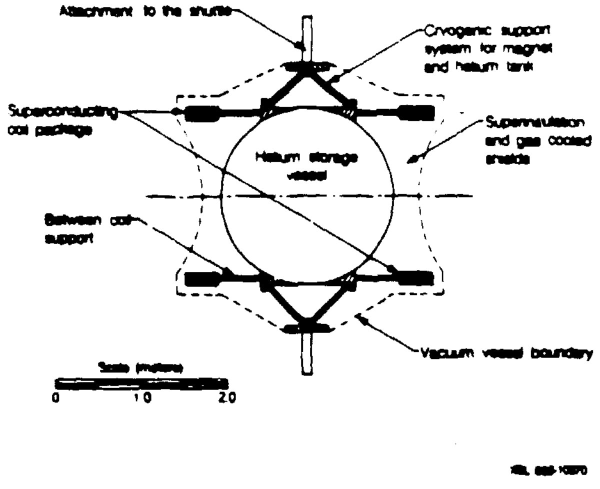
HEAO MAGNET PARAMETERS

Number of coils	2
Coil outside diameter	2.0 m
Coil separation	2.2 m
Number turns	6400
Design current	754.06 A
Peak field in coil	6.25 T
Coupling between coil and secondary	> 0.9[illegible]
Magnet inductance	66.9 H
Magnet stored energy	19.0 MJ
Current density in s/c plus matrix	2.985×10^{8} A m^{-2}
EJ^2 limit	1.69×10^{24} J A^2 m^{-4}
Magnet coil cold mass	1500 kg
Magnet active cold mass	1300 kg
Stored energy to active cold mass ratio	14.6 J g^{-1}

In general, the technology required to produce the magnet system is well developed and does not involve major advances beyond the present state of the art. However, multiple options and alternatives are available in several areas of the design and operation of this device, and detailed studies are planned to evaluate the various trade-offs and to further optimize the HEAO-type magnet for astrophysical experiments. The relationship between stored magnetic energy and active coil mass will be investigated in order to provide the maximum particle resolution within the bounds set by weight and safety considerations. The shape and thickness of the dewar and outer vacuum shell in the region outside the surfaces of the coils will be studied in an effort to minimize the distance between the coils and the active area of the trajectory detectors in order to optimize the use of the regions of highest magnetic field strength. Alternative techniques for providing cooling to the coils--immersion in the liquid helium, conductive cooling without immersion, helium pumping to isolated coils--will be investigated, as will their implications for dewar mass, for retention of the cryogen in the case of a quench, for the need to develop pump technology, and the choice between the use of normal or super fluid helium. Techniques for charging the coils and switching into the persistent mode involving retractable a electrical leads or a magnetic flux pump will be studied.

OTHER MAGNET CONFIGURATIONS

In an effort to optimize the physics capability of the ASTROMAG facility, a number of magnet configurations have been studied in addition to the HEAO-type magnet which is, at this time, regarded as the baseline configuration. For purposes of comparing different coil configurations, we have used as a figure of merit the maximum detectable rigidity (MDR) above which the spectrometer has a geometrical acceptance of approximately 0.1 m^2 steradian, assuming an arrangement of trajectory detectors similar to that used for the HEAO-type magnet. In order to achieve a higher MDR, one has to increase the integral of field with distance and/or



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The three-coil disk magnet consists of a central flat disk coil and two conical end disks. The version shown in Figure 3 has disks with an outside diameter of 2.4 meters and an inside diameter of 0.9 meters. The end coils are conical in shape to optimize the support of the magnetic forces. The two end coils carry a current of opposite polarity from the center coil, with the three coil set having no net magnetic moment. The helium storage tank is at the end of the coil package. Helium can be in direct contact with the coils provided the helium tank also runs down the center of the disks. The trajectory detectors would be located between the disks. The field between the disks is relatively uniform in magnitude (compared to the HEAO magnet), and its direction is approximately radial. This system is under active design study at FERMILAB.

The second alternate design is a two-coil approximation to a toroid magnet. This configuration consists of two side-by-side coils which carry currents of opposite polarity so that the net magnetic dipole moment is zero. The resulting magnetic field is approximately toroidal, falling off as 1/r (r = radial distance from center) in the mid-plane of the coils. The trajectory detectors are located on either side of the two coils so that the coil axis pass through the detector stack in a direction parallel to the detector planes. The configuration shown in Figure 4 has two circular coils with an outside diameter of 1.9 meters. (Configurations employing D-shaped are also being considered.) The helium tank is remote from the coils, and it is likely that the liquid helium must be pumped through tubes attached to the coils. This design is actively being studied by INFN in Frascati, Italy and by ANSALDO company in Genoa, Italy.

The major advantage provided by either the disk coil design or the toroid coil design is that they may be able to provide appreciably greater MDR than the basic HEAO design, for a given stored magnetic energy in the field. However, both the toroid and the disk designs have some distinct disadvantages relative to the basic HEAO design. These disadvantages are: 1) Both magnets produce magnetic force patterns which will require extra mass for supporting members; 2) Both magnets will have large and relatively flat surfaces to carry vacuum loads; 3) Both cryostats will have large surface-to-volume ratios resulting in increased heat leak; 4) Both types of magnet may require cryogen tankage which is some distance from the coil; 5) For a given stored magnetic energy, the disk and toroid magnets will be more massive than the HEAO-type magnet; and 6) Both types of magnet are expected to be more expensive than the HEAO magnet.

Both the disk and the two-coil toroid concepts are being studied to evaluate the trade-off between improved resolution and increased weight and costs. On the basis of preliminary design studies of all of the magnet concepts we will be able to select one magnet type. Continuing studies will then focus on the further refinement of that single design.

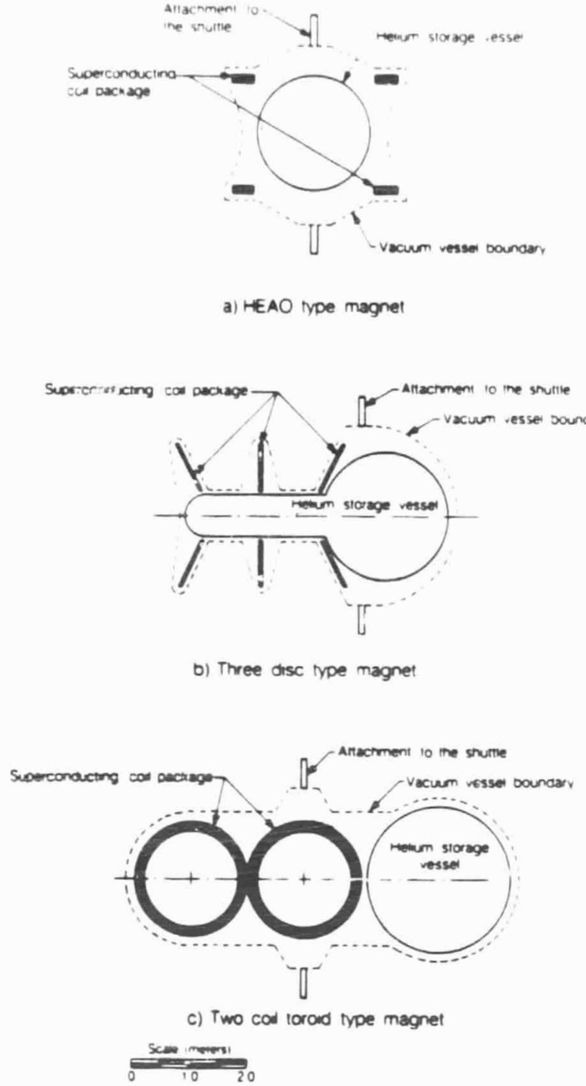

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Figure 3. A Comparison of Three Types of ASTROMAG Magnets

Acknowledgments

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