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Author

Green, M.A.

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M. A. Green, J. M. DeOlivares, G. Tarle, P. B. Price,
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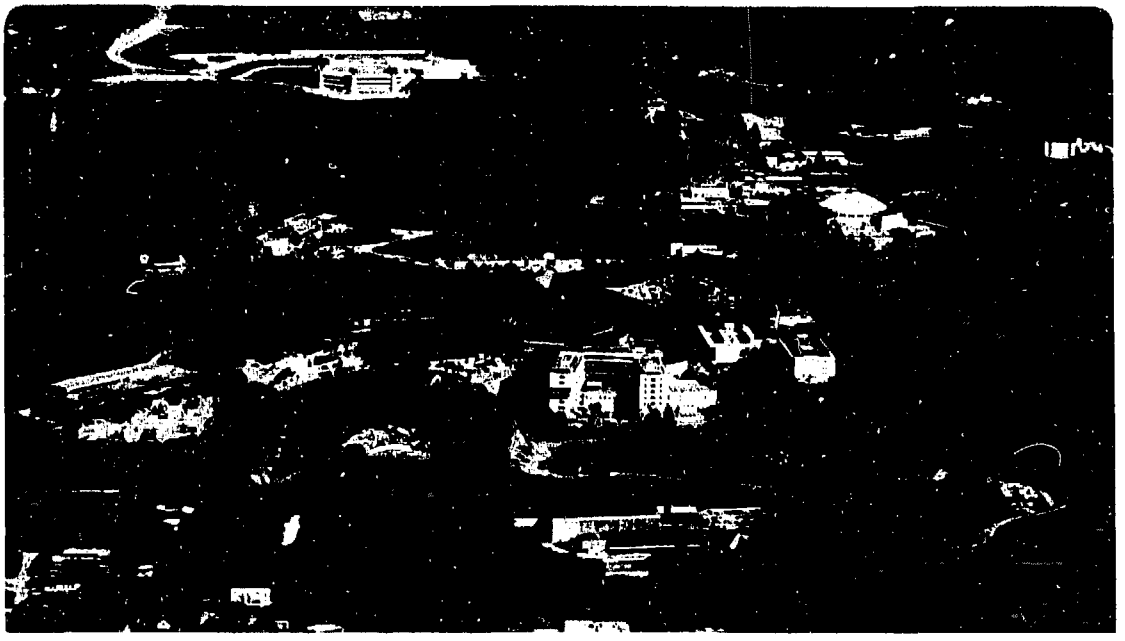
August 1979



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MASTER

A SUPERCONDUCTING MAGNET SYSTEM FOR THE SPIRIT COSMIC RAY SPACE TELESCOPE

M.A. Green and J.M. DeOlivares

Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

G. Tarle, P.B. Price and E.K. Shirk

Department of Physics
University of California
Berkeley, CA 94720

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ABSTRACT

The SPIRIT (A Superconducting Passive Iron Isotope Telescope) experiment requires a large volume ($1m^3$) of 2T field in order to achieve enough resolution to study heavy primary cosmic rays. It is proposed that the SPIRIT superconducting magnet system and its experimental package would be used in one of the space shuttles. The superconducting magnet design is based on Lawrence Berkeley Laboratory thin high current density solenoid technology.

The superconducting magnet system consists of a number of coils which generate a 2T induction within the experiment, and at the same time allow free access to the package by cosmic rays. The superconducting magnet system uses high current density conductor which is protected by a shorted secondary circuit. The magnet coils are to be cooled by pumped two phase helium which is circulated through tubes. Refrigeration is supplied from a large liquid helium dewar.

INTRODUCTION

The identity of the source of the cosmic radiation is one of the oldest and most interesting unanswered questions of 20th century physics. While it has become increasingly clear that these energetic particles owe their existence to some of the most violent processes that occur in our galaxy (e.g. supernovae), a detailed understanding of the cosmic ray source and the conditions of galactic propagation has not been achieved. Of particular interest in this regard is the isotopic composition of the cosmic radiation since nuclear abundance anomalies would provide the most exciting clues as to their nuclear origin. The iron isotopes provide the most fruitful candidates for such a study since they are both abundant and are least modified by galactic transport. To date the most accurate isotopic studies of the iron group cosmic rays[1] have ruled out large deviations from solar system source composition. In order to achieve a convincing separation of the isotopes of iron it is necessary to design an instrument which can collect over 10^4 iron nuclei and achieve a mass resolution of $\sigma \lesssim 0.15$ amu.

Three important developments have made the design of such an instrument possible: 1) With considerable impetus from the new generation of accelerators, magnet and cryogenic technology has reached the stage where very large volumes can be filled with uniform fields in excess of 2T. 2) A track recording plastic detector made of CR-39 has been developed[2] that is sensitive to minimum-ionizing particles of the so-called very heavy group ($20 \leq Z \leq 30$), has very good charge resolution, yields etched tracks of very high optical quality, and can be made in films thin enough that multiple Coulomb scattering can be neglected. 3) The advent of the space shuttle will make it possible to lift payloads weighing many tons into orbit for periods of several weeks.

One of us (G.T.) has conceived of an instrument (SPIRIT) which capitalizes on these recent developments and can achieve the required collecting power and resolution in a 10-day shuttle flight using only passive components. A three-tiered passive hodoscope consisting of track-recording plastic with a thin (60 μm) central layer will record the trajectories of cosmic ray particles through a magnetic field with an average strength of 2T. These particles will be traced to their end of range in a stack of CR-39 where their charge will be determined by measurements of etched cone length. The measurement of magnetic rigidity in combination with the measurement of range will be used to determine particle mass.

In this paper we shall discuss the design of the superconducting magnet and cryostat systems. To achieve the resolution and collecting power necessary to meet the experimental objectives we need a superconducting magnet with an average field of 1.5 to 2 Tesla over a $1m^3$ volume. Spatial gradients need to be kept below $4Tm^{-1}$ so that shifts in detector orientation expected during flight will not result in a degradation of resolution. The whole apparatus must be contained in the space shuttle orbiter cargo bay which has a dynamic envelope diameter of 4.57m.

THE SUPERCONDUCTING MAGNET

In order to achieve the resolution and collecting power necessary to meet the experimental objectives of SPIRIT, a superconducting magnet with an average field of 2T over volume of $1m^3$ is needed. The $1m^3$ volume must be clearly accessible to cosmic radiation entering from a polar angle from 0 to about 45° (see Figure 1). The proposed magnet consists of six coils. The four inner coils generate a uniform high field over the $1m^3$ control volume. The two outer coils will generate a smaller field over a larger volume so that the entire assembly will have a zero net dipole moment, which results in a negligible distant field.

The design of the SPIRIT magnet system is similar in concept to the high current density type of magnet which has been under development for the last four years at LBL.[3,4,5] This development work has come to fruition with the construction of the 2m diameter, 3.3m long TPC thin solenoid which is designed to operate at a current density of $7 \times 10^8 Am^{-2}$ and at a stored energy of greater than 10 MJ[5]. This design concept used in the TPC solenoid is particularly applicable for use in space.

The SPIRIT magnet has the following characteristics: 1) intrinsically stable high current density superconductor is used, 2) quench protection is based on the use of LBL shorted secondary concept, 3) cooling of the superconducting magnet is done with pumped two phase helium, and 4) the magnet coil, the shorted secondary and the cooling system are integrated into a single package which is contained within a single cryostat vacuum vessel.

Large currents are required in the four inner coils in order to generate the 2T induction over the volume of the experiment and meet the requirement for clearly accessible solid angle. As a result, peak inductions within the superconductor will approach 8T. Therefore, it is proposed that the four inner coils be wound with prereacted multifilamentary Nb_3Sn. The two outer coils, which carry lower currents would use multifilamentary Nb-Ti conductor. Electrically the six coils are connected in series; the loop is closed by a persistent switch. The SPIRIT magnet would operate in the persistent mode for the entire 10 days of the shuttle flight.

TABLE I shows the basic parameters of the six coils. The placement of the coils in the magnet is shown in Figure 1. There are three types of coils (there are two coils of each type). The four inner coils carry over 11 million amperes in order to generate 2T over the experimental volume of

TABLE I THE BASIC PARAMETERS OF THE THREE TYPES OF COILS PROPOSED FOR THE SPIRIT SUPERCONDUCTING MAGNET SYSTEM

	Coils 1A & 1B**	Coils 2A & 2B*	Coils 3A & 3B**
Inside diameter (m)	0.800	1.100	1.892
Outside diameter (m)	1.100	1.400	2.292
Distance from center (m)	0.600	0.750	1.250
Coil package length (m)	0.400	0.250	0.200
Coil package total current (A)	2.484×10^6	3.096×10^6	-1.620×10^6
Number of turns	2760	3440	1800
Current per turn (A)	900	900	-900
Peak induction in the coil package (T)	~8.2	~7.2	~4.0
Superconductor type	Nb_3Sn	Nb_3Sn	Nb-Ti

* The inner coils which produce the 2T field within the experimental volume.

** The outer coil which cancel the dipole moment generated by the inner coils. The net dipole moment must be zero.

$1m^3$. As a result, the use of Nb_3Sn conductor is proposed. If one reduces the average induction in the experimental region from 2T to 1.5T, the current in the inner coils is reduced to 8.2 million amperes. The peak induction in the coil is reduced to 6.0T which permits Nb-Ti conductor to be used instead of Nb_3Sn.

TABLE II presents the electrical parameters of the six coil magnet system shown in Figure 1. The proposed SPIRIT magnet has an inductance of 85.1H. When the central induction is 2T, the magnetic energy stored in the coil system is just over 34MJ. It is proposed that the coil superconductor be operated at a current density of $3 \times 10^8 Am^{-2}$. The proposed conductor current density is about six times higher than the conductor current density normally used in a magnet with a 34MJ stored energy. This is necessary in order to reduce the mass of the magnet system. TABLE III presents the parameters for the superconductor proposed for use in the SPIRIT magnet.

The proposed operating current density and high stored energy result in a high EJ^2 product; (E is stored energy, J is superconductor matrix current density). Thus, we propose that a well coupled secondary circuit made from very pure aluminum be used for quench protection. The shorted secondary quench protection system is used on the 2m diameter TPC solenoid which has an EJ^2 product of $5.4 \times 10^{24} JA^2m^{-4}$. The shorted secondary concept affects the quench process in the following ways:

1) The shorted secondary causes the coil current to shift from the coil to the secondary circuit. As a result, there is less current in the coil to contribute to the conductor hot spot.

2) The shorted secondary circuit absorbs a substantial amount of the magnet stored energy. In the proposed magnet system, the shorted secondaries are expected to absorb about 70 percent of the magnetic

TABLE II THE ELECTRICAL PARAMETERS FOR THE SPIRIT SUPERCONDUCTING MAGNET SYSTEM (THE SIX COILS HOOKED IN SERIES)

Integrated average induction within the experiment	2.0T
The experimental volume	~ $1.0m^3$
Magnet system design current	900A
Magnet system self inductance	86.2H
Magnet system stored energy at its design current E	$34.3 \times 10^6 J$
Current density in the superconductor Matrix J	$3 \times 10^8 Am^{-2}$
EJ^2 product at the design current	$3.1 \times 10^{24} JA^2m^{-4}$

TABLE III PROPERTIES OF THE SUPERCONDUCTOR PROPOSED FOR THE SPIRIT SUPERCONDUCTING MAGNET SYSTEM

	Nb_3Sn*	Nb-Ti**
Uninsulated matrix dimensions (mm)	3 x 1	3 x 1
Insulated matrix dimensions (mm)	3.1 x 1.1	3.1 x 1.1
Insulation type	epoxy	formvar
Copper to superconductor ratio	~1 to 1	~1.8 x 1
Bronze to unreacted Nb ratio	~2.8 to 1	DNA#
Number of filaments	>30,000	~2,000
Filament diameter (μm)	~4	~25
Twist pitch (mm)	~50	~50
Average matrix resistivity at 4.2K (Ωm)	$\sim 10^{-9}$	$\sim 2 \times 10^{-10}$
Current capacity at 4.2K (A)		
at 5 Tesla	3,900	1,600
at 10 Tesla	1,100	--

* The multifilamentary Nb_3Sn is proposed for the four inner coils 1A, 1B, 2A and 2B. This conductor has some copper in the matrix.

** The multifilamentary Nb-Ti is proposed for the two outer coils 3A and 3B.

DNA means "does not apply".

energy; (this energy will be shared by all of the coils, not just the one that went normal).

3) The shorted secondary will cause "quench back" in the other coils when one of the six coils turns normal through ordinary quench propagation. Quench back is a key element in the protection of thin high current density solenoids which have been built at LBL.

The shorted secondary circuit would be insulated from the superconductor. It is desirable that inductive coupling between the coil and the secondary circuit be maximized. We propose that the shorted secondary circuit be made from ultra pure aluminum (0.99999 pure or better) which has a residul resistance ratio at 4.2K and 0T of about 2000. Aluminum has a much lower magnet resistance at 8T than copper. It also has one third the density. At full field, one can expect the shorted secondary circuit to have a RRR > 300. As a result, the shorted secondary circuit is expected to have a time constant in excess of 30 seconds. If the coupling between the coil and the shorted secondary circuits is good enough, effective shifting of the coil current will occur.

The proposed coils will have the superconductor, shorted secondary and a forced flow tubular cooling system combined into an integrated package, the proposed superconducting coils are designed to be well insulated with insulation to ground good to 10kV or more. Therefore, we propose that the superconductor, shorted secondary and cooling system be cast in epoxy resin. This technique has been used successfully in the TPC solenoid and three 1 and 2 meter diameter test coils.[6] Figure 2 shows a proposed arrangement of superconductor, shorted secondary circuit, cooling tube, and mechanical support inside of the two inner coils.

The shield coils not only effectively eliminate magnet moment, but they also greatly reduce stray magnetic field in the shuttle bay. It is

proposed that the superconducting magnet be located at the rear of the space shuttle bay. The expected stray magnetic induction in a region normally housing astronauts is expected to be around 10^{-4}T.

It is proposed that coil 1 and 2 (in each half) be attached directly (see Figure 2). A compressive force 7.7×10^5N (77 metric tons) is expected between the two halves (between coils 1A, 2A, 3A and coils 1B, 2B, 3B). We propose to carry this force with cold column struts between coil 1A, 2A and coil 1B and 2B. The columns are arranged so that there is full access of the cosmic rays to the experiment. A tensile force of 5.8×10^6N (580 tons) is expected between each of the two outer coils and their companion inner coils. We propose to carry this force with a continuous web of metal between the outer and inner coils. The six coils are expected to act as a rigid frame which will have a cold mass of about 4000kg (the helium tanks and the coil cryogenics will attach directly to this frame).

THE CRYOSTAT AND CRYOGENIC COOLING SYSTEM

The proposed superconducting magnet coils will be cooled using two phase helium pumped through tubes in the coil package (see Figure 3). We plan to circulate the two phase helium from a separate helium storage tank located at the end of the experiment (see Figure 1). Forced tubular cooling offers a number of advantages over the more conventional bath cooled systems:[7]

1) Tubular cooled systems can be cooled easily from room temperature by a refrigerator which is external to the cryostat system.

2) Only a small fraction of the liquid helium is in direct thermal contact with the superconductor at any one time during a quench. The tubular cooling system can contain the pressure rise due to this small amount of helium. Helium boil off during a quench is orderly and well controlled.

3) In conventional systems, diamagnetic repulsion of the helium in a weightless environment would result in a loss of liquid cooling capacity.[8] Tubular cooled coils would contain two phase helium which is in direct contact with the coil at all times.

4) The design of the cryostat is simplified. Many of tne cryogenic safety problems found in conventional bath systems are eliminated.

The forced two phase tubular cooling system requires a helium pump to circulate the helium from the helium storage tank located at the end of the magnet. The entry to the pump is located near the zero field point in the tank. As a result, diamagnetic repulsion insures that liquid helium will always be delivered to the pump entry.[9] The pump proposed is similar to a reciprocating bellows type pump which has been under development at the Lawrence Berkeley Laboratory.[7] We propose that the pump be able to pump $1.0 gs^{-1}$ across a pressure rise of $2 \times 10^4 Pa$ (0.2 bar). It is expected that such a pump will require about 1 to 1.5W of refrigeration to operate. (The pump will boil off 1.4-2 liters per hour of liquid helium from the tank.)

A 2500 liter helium tank can be built into the end of the coil as shown in Figure 1. The coils and tank would be thermally isolated with fiberglass epoxy spacers. The coils and tank would be insulated with a combination of superinsulation and shields which use the helium boil off from the tank. A total heat leak of 2-3W is expected into the 4K region. We expect the helium boil off rate to be 5-6 liters per hour. The total helium inventory in the tank should be enough for about 20 days. (The expected mission time is 10 days.)

CONCLUSIONS

The proposed SPIRIT superconducting magnet system appears to be within the state of the art. A coil system which uses multiflamentary Nb_3Sn and Nb-Ti is similar to the proposed fusion magnets. Forced two phase cooling and quench protection using shorted secondary circuits has been demonstrated at LBL. Forced cooled high current density superconducting coils are well suited to space application. The development of this technology and the space shuttle make possible the study of some of the fundamental physics which occurs in deep space.

ACKNOWLEDGMENTS

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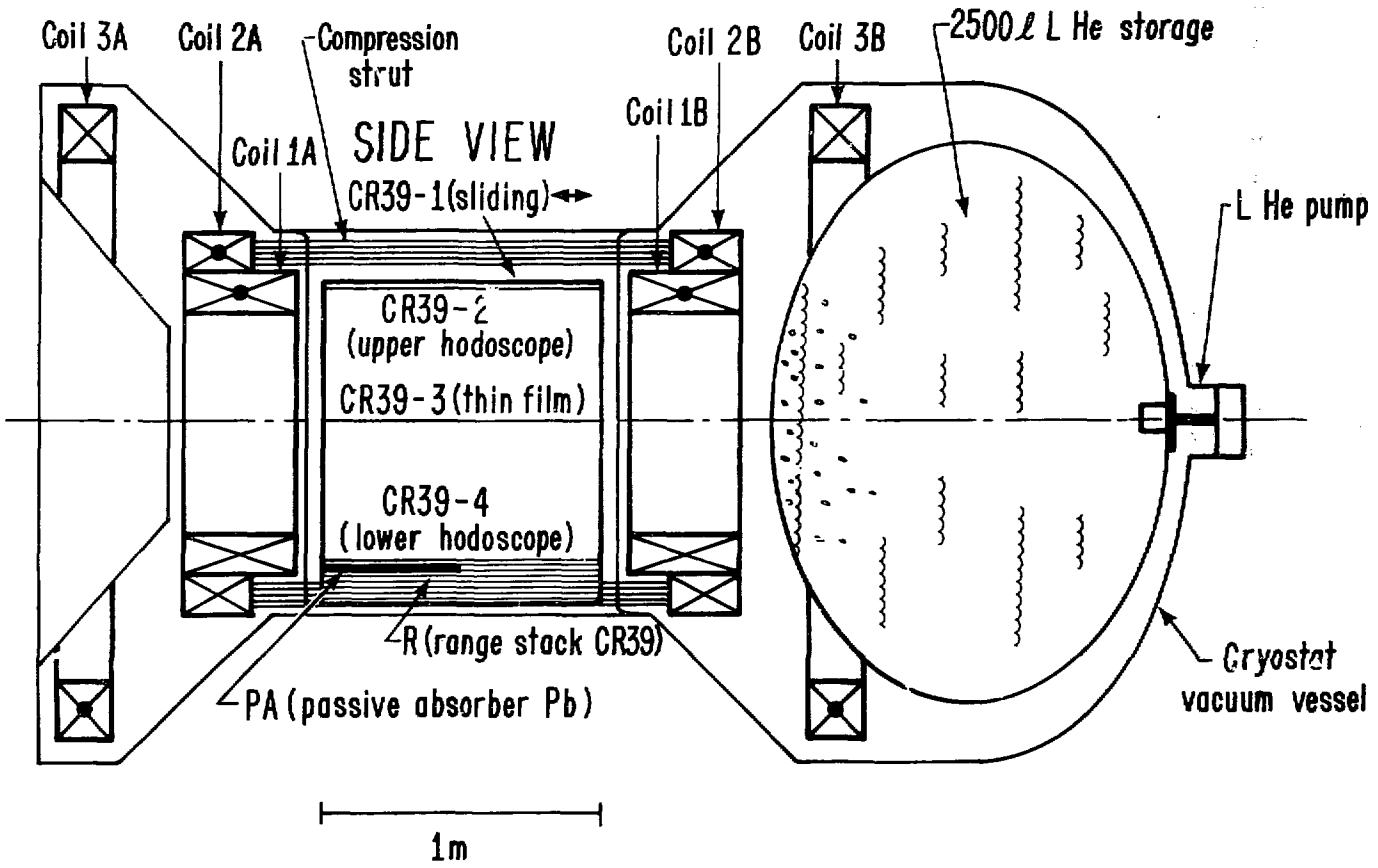
LIST OF FIGURES

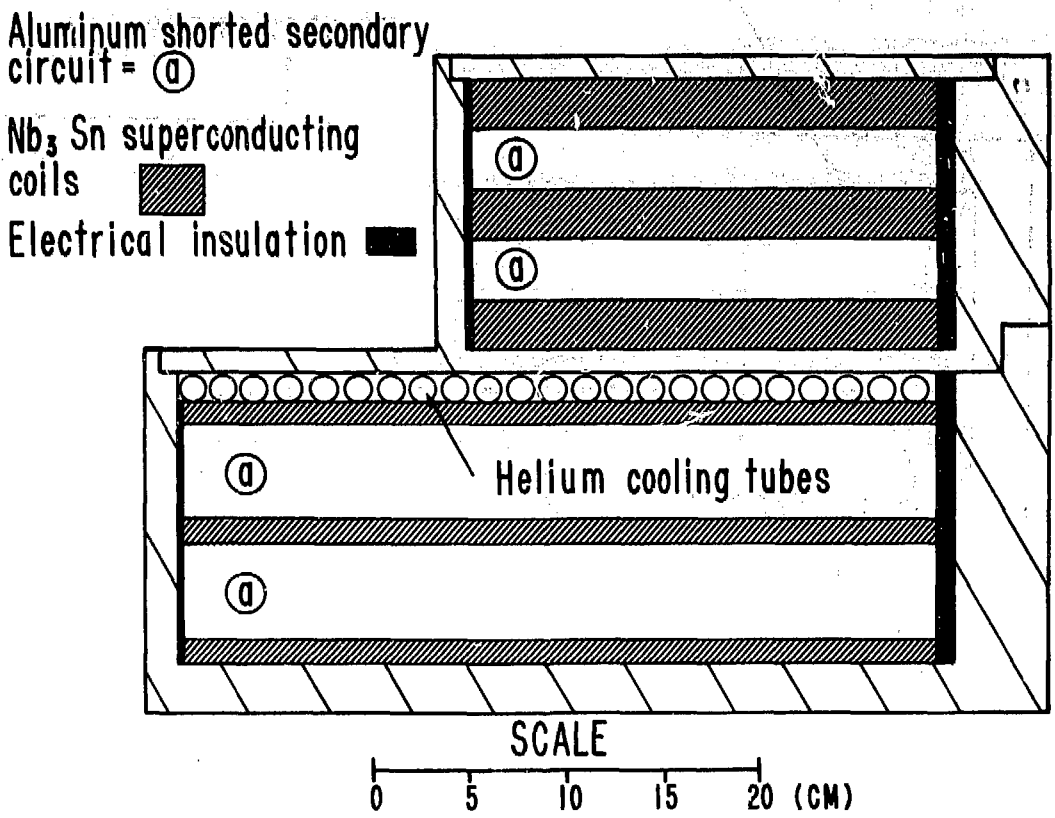
Figure 1 — A Cross-Section View of the SPIRIT Experiment Showing the Six Coil Superconducting Magnet System

Figure 2 — A Cross-Section of the Proposed Inner Coils (Coils 1 and 2) for the SPIRIT Magnet

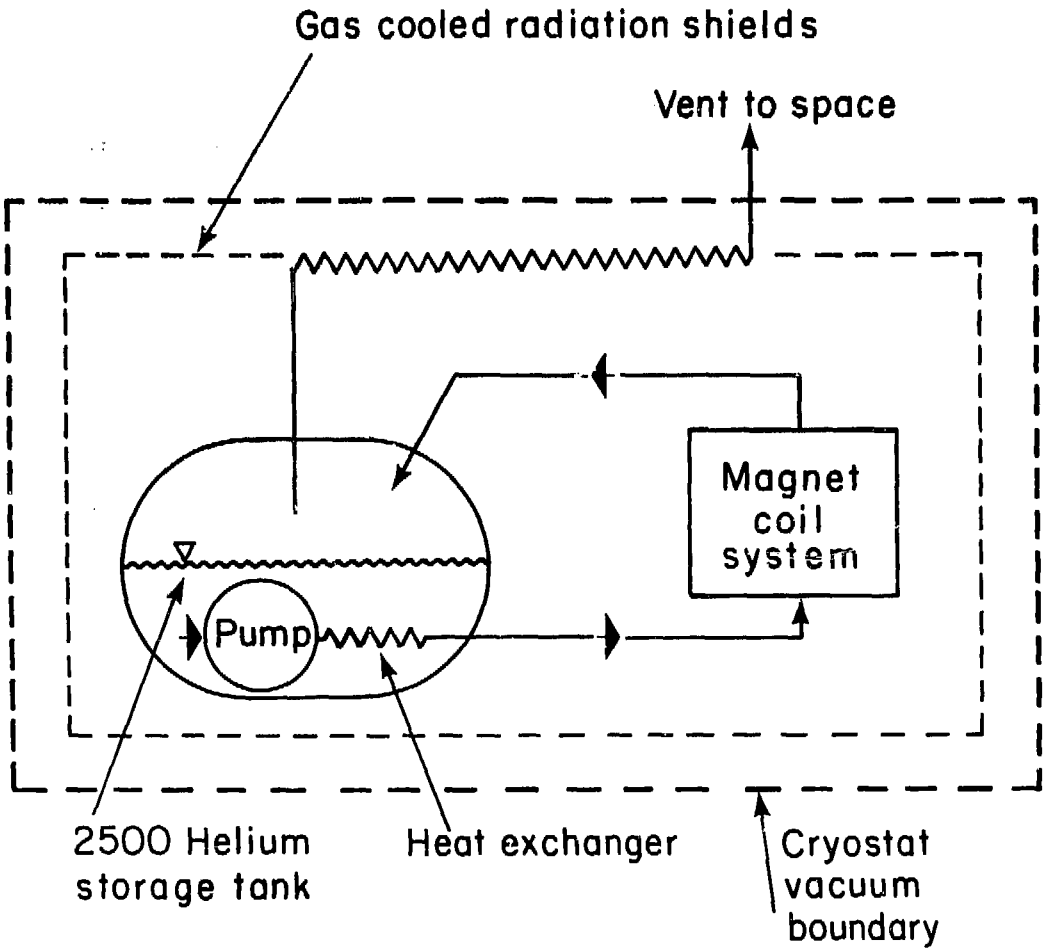
Figure 3 — A Simplified Schematic Diagram of the SPIRIT Magnet Helium Tank and Distribution System


Coil 3A
Coil 2A
Compression strut
Coil 2B
Coil 3B
2500 ℓ L He storage
Coil 1B
Coil 1A
SIDE VIEW
CR39-1(sliding)
L He pump
CR39-2
(upper hodoscope)
CR39-3(thin film)
CR39-4
(lower hodoscope)
R(range stack CR39)
PA(passive absorber Pb)
Cryostat vacuum vessel
1m

XBL 795-697A


Aluminum shorted secondary circuit = ⓐ
Nb3 Sn superconducting coils
Electrical insulation
ⓐ
ⓐ
ⓐ
ⓐ
Helium cooling tubes
SCALE
0 5 10 15 20 (CM)

XBL 797-2237


Gas cooled radiation shields
Vent to space
Magnet coil system
Pump
2500 Helium storage tank
Heat exchanger
Cryostat vacuum boundary

XBL 797-2236