Title
SUPERCONDUCTING DETECTOR MAGNETS ALTERNATIVES and CHOICES

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SUPERCONDUCTING DETECTOR MAGNETS ALTERNATIVES AND CHOICES* †

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ABSTRACT

Detectors for colliding beam Experiments will require magnetic fields in order to detect and analyize charged particles. Often it is best to use a superconducting magnet to generate this field. Several kinds of superconducting magnets can potentially be used in the charged particle detectors. The solenoid appears to be the best type of superconducting magnet for this type of physics. Three kinds of superconducting solenoids can be used. The kind of solenoid magnet to be used in the experiment is dictated by the physics outside of the magnet coil. This report discusses a low current density convential solenoid and two types of high current density magnets which permits physics to be performed outside the magnet.

* Work performed under auspices of the United States Energy Research and Development Administration.

† This is Appendix A to PEP-189

SUPERCONDUCTING DETECTOR MAGNETS ALTERNATIVES AND CHOICES

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INTRODUCTION

Superconducting magnets are being considered for use in charged particle detectors in experiments for PEP and other colliding beam machines. The reasons which favor the use of superconducting magnets are as follows: 1) The central induction of the magnet can be increased. Along with the increase in central induction comes an increase in momentum resolution. 2) The power consumption and cooling water consumption are greatly reduced. As a result, the total cost of the magnet system is less, in many cases, for the superconducting magnet. 3) The high current density which is inherent in superconductors permits one to design experiments where interesting physics can be done outside the magnet coil.

a) Alternative Types of Magnets for Colliding Beam Experiments

Three types of magnets can be considered for use as detectors on PEP and other colliding beam machines. The choices include 1) the dipole, 2) the toroid, and 3) the solenoid. The three types are shown in Figure 1. All three types of magnets can be used to detect and analyze charged particles which travel perpendicular to the flux lines.

The dipole magnet is commonly used in spectrometers. It will analyze the longitudinal momentum of a particle very well. Transverse momentum

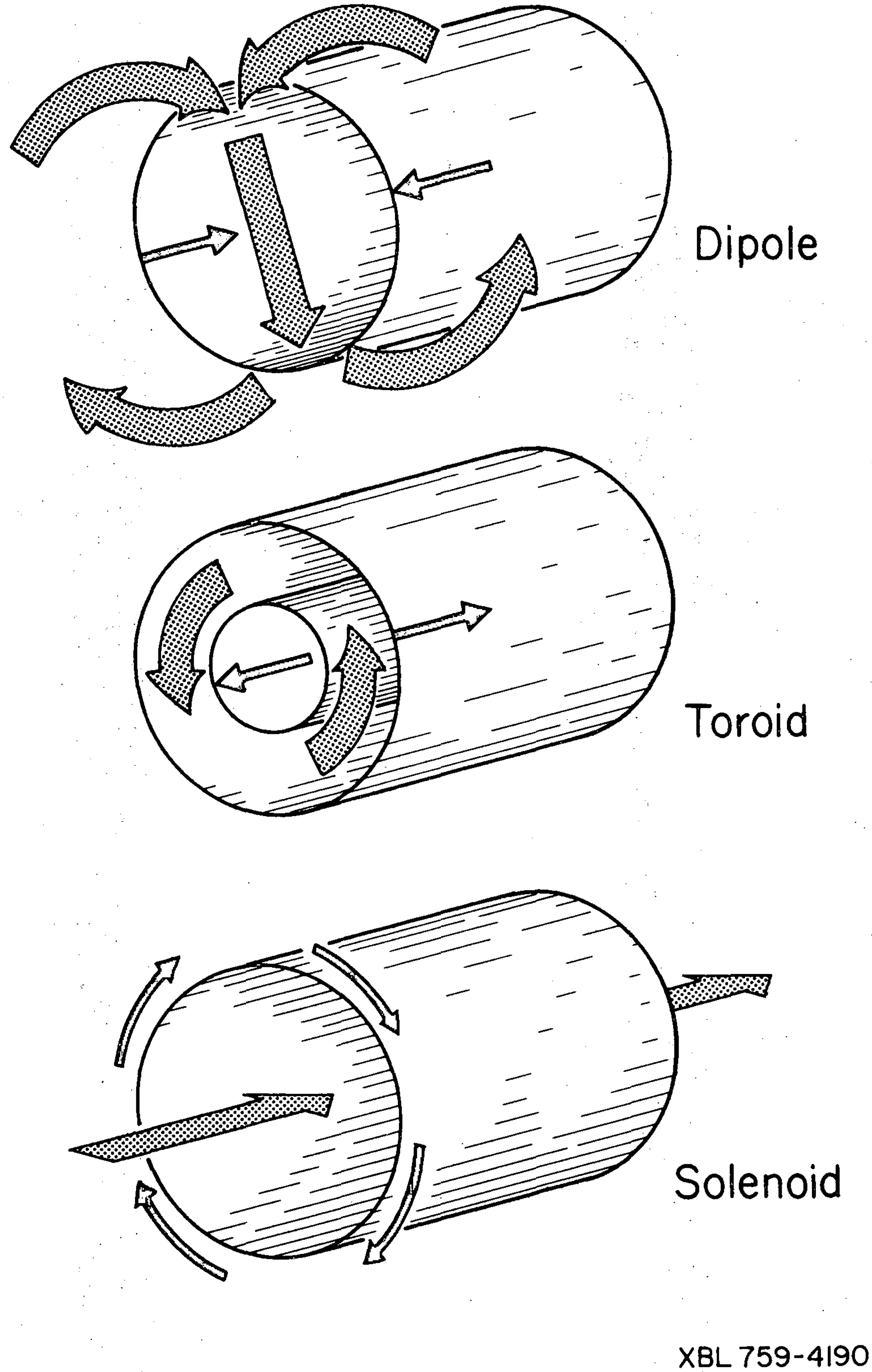

Fig. 1 Various types of Superconducting Detector Magnets

is analyzed well in one direction but not the other. The major disadvantage of the dipole is its effect on the circulating beam. A large dipole will adversly affect the orbit in any storage ring. A good system of compensating coils is needed. The experiment will be plagued with synchrotron radiation in an electron or positron machine. One should avoid magnetic fields which are transverse to the circulating beams. The final disadvantage is the difficulty encountered while building large superconducting dipole magnets. The magnetic forces encountered are large.

The toroid has, in theory, no field in the region of the beam. It offers good resolution of both transverse and longitudinal momentum. The toroid has a coil between the interaction point (collision point) of the two beams and the charged particle momentum analyzing field. This is undesirable, due to the material thickness interposed. The field in a toroid is not uniform, it varies as one over R. In addition, the toroid coil is difficult to build superconducting.

The solenoid has its field parallel to the direction of the circulating beams. The effect of the magnetic field on the beam is small therefore, only a small compensating coil will be required. There is almost no material between the collision point of the colliding beams and the momentum analyzing field. Transverse momentum is accurately resolved; longitudinal momentum is not accurately resolved. Superconducting solenoids are easy to build compared to the other types. As a result, nearly all of the proposed colliding beam experiment detectors will use solenoids which have the axis parallel to the motion of the colliding beams. Therefore, the superconducting magnets discussed from here on will be of solenoidal type.

b) Alternative Kinds of Solenoid Magnets which can be used in Colliding Beam Detectors

Once one has established that the solenoid probably is best from a physics and cost standpoint, one must ask two questions. What size is the detector? Does one want to do physics outside of the detector? In a sense, the answer to both questions is governed by the amount of money one has and the state of the art of the detectors, particularly neutral or γ detectors.

The momentum resolution of charged particles inside a solenoid improves as B_0D^2, where B_0 is the central induction of the solenoid and D is its diameter (the diameter of the detector). The minimum momentum resolved is an inverse function of B_0 and proportional to the inner tracking tube diameter. For good high momentum charged particle resoluation, one would like a large high field magnet.

Smaller magnets are less expensive than larger magnets. For a given central induction, the magnet cost will go up as D^2 or perhaps faster. For many kinds of physics, particle detection outside the magnet may be desirable. Since a typical high energy physics experiment is a compromise between various physics objectives and the money in your pocket, several kinds of solenoid magnets may be of interest.

This report will discuss superconducting solenoid magnets of three kinds: 1) the conventional low current density magnet 2) the continuous high current density thin coil magnet and 3) the high current density lumped coil magnet. The conventional solenoid will not permit a significant amount of physics to be performed outside the coil. The continuous thin coil and the lumped coil magnet will permit a considerable amount of interesting physics to be performed outside the coil. Table 1 compares the three kinds of coils in a magnet with a 0.9 m useful (warm) bore diameter and a useful length of 1.84 m Longitudinal cross section of three kinds of coils are shown in Figures 2, 3, and 4.

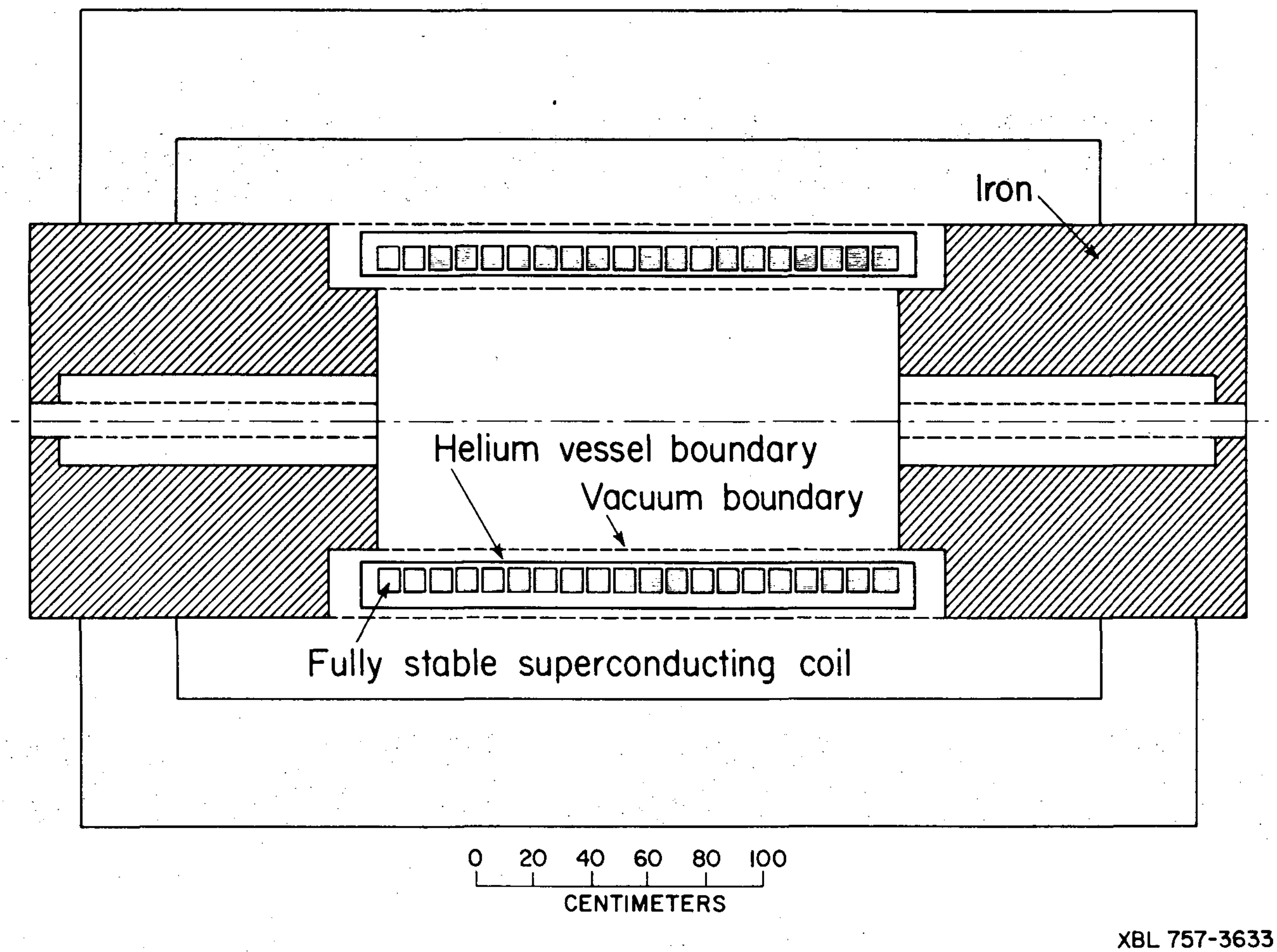

Fig. 2 Conventional Superconducting Solenoid Magnet

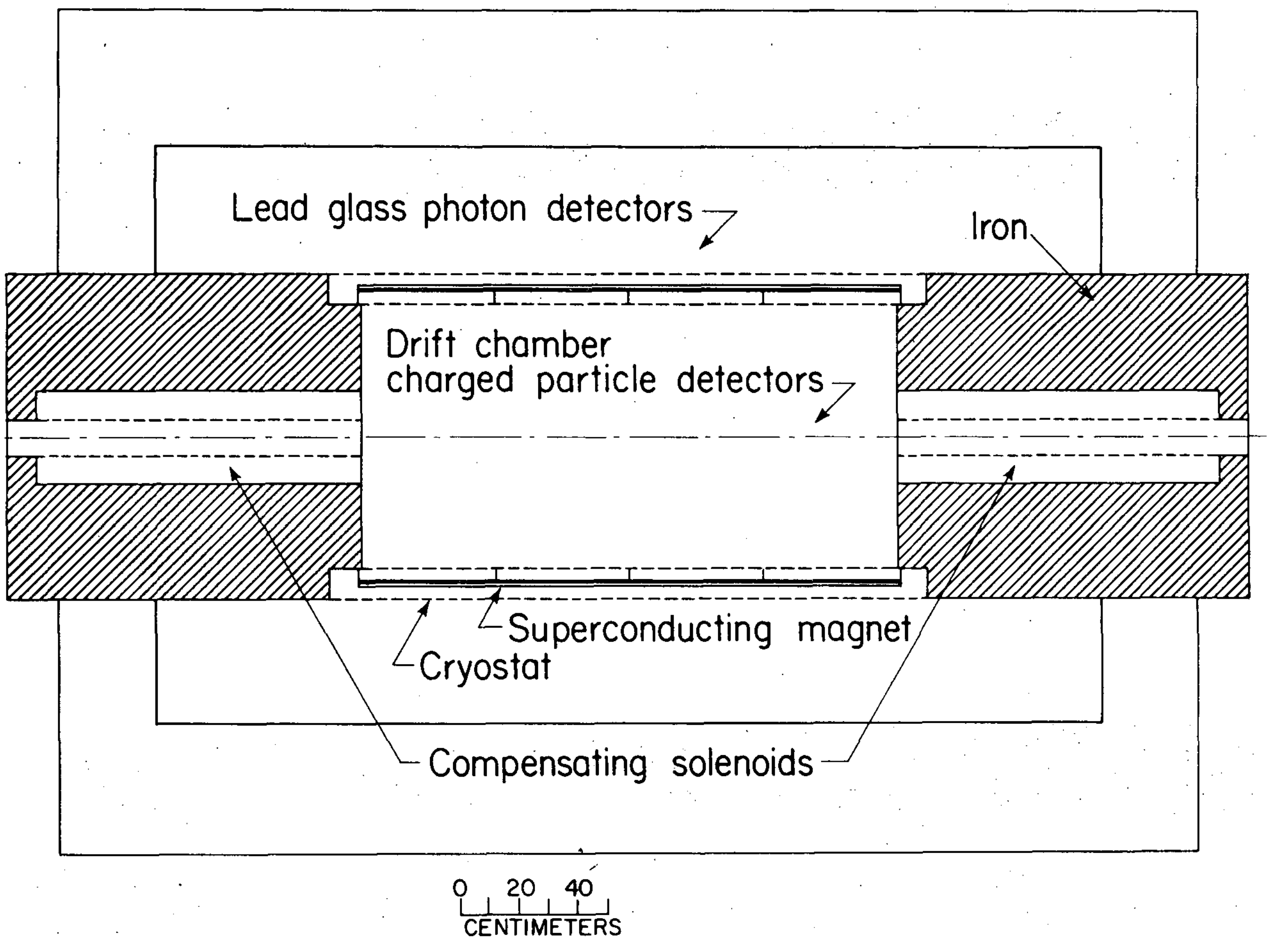

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Fig. 3 Continuous Thin Superconducting Solenoid Magnet

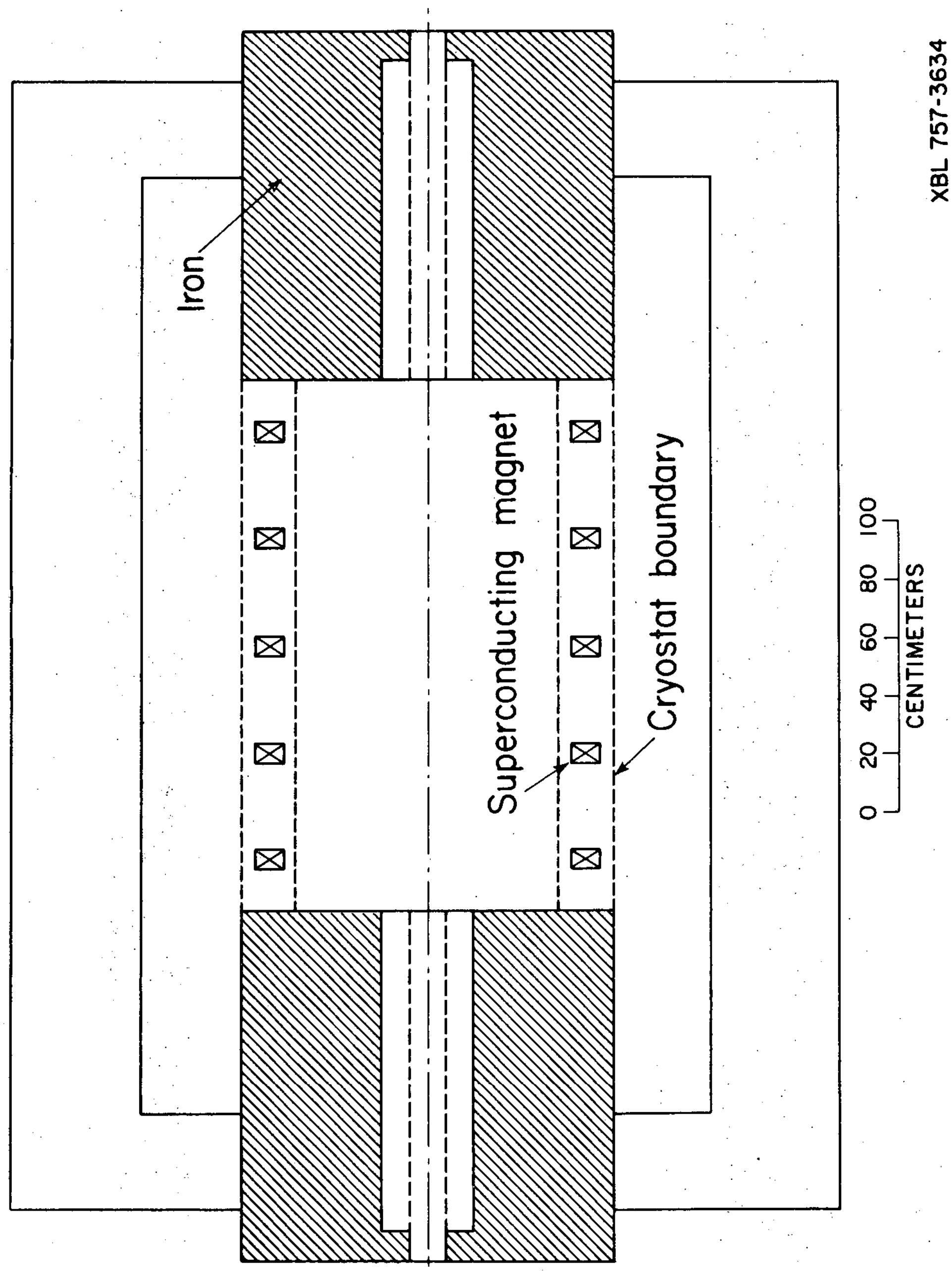


Fig. 4 Lumped High Current Density
Superconducting Solenoid Magnet

Table 1. A Comparison of the Three Kinds of Solenoid Magnets Shown in Figure 2, 3, and 4.

	Thick Conventional	Lumped Coil	Thin Coils
Central Induction (T)	1.5	1.5	1.5
Peak Induction (T) in winding	~ 1.6	> 3.0	1.53
Length Between Poles (m)	1.84	1.84	1.84
Cryostat ID (m)	0.90	0.90	0.90
Cryostate OD (m)	1.50	1.30	1.10
Current Density (Am^{-2}) in Superconductor	4×10^7	4×10^8	9×10^8
Radiation Thickness at the coils (Rad length)	2. - 3.	2. - 3.	0.2 - 0.4
Minimum Radiation Thickness (Rad lengths)	2. - 3.	0.01 - 0.05	0.2 - 0.4
Magnet Cold Mass (kg)	6.9×10^3	5×10^2	2.5×10^2
Percent of Solid Angle Usable for Physics Outside the Coil	0	50 - 55%	80 - 85%

The magnets which are compared in Table 1 and are shown in Figures 2, 3, and 4 are roughly half the size of those being proposed for PEP. The proposed PEP magnets, which are about 2 meters in diameter and 4 meters long, will have a larger percentage of usable solid angle available for physics than the magnets shown in Table 1.

It is useful to point out we have more choices available to us than there were just a few years ago. The relative merits of the three choices are discussed in the sections to come.

THE CONVENTIONAL SUPERCONDUCTING SOLENOID MAGNET

The conventional low current density superconducting solenoid has been used in high energy physics for the last eight years. Examples of this kind of magnet include: the 12 foot bubble chamber at ANL, the 15 foot bubble chamber at Fermi Lab, the Pluto magnet at DESY, the LASS magnet at SLAC, the BEBC and OMEGA magnets at CERN.

In 1965, Steckly[1] showed that if the current in a superconductor could be carried in a copper substrate without heating the superconductor to a temperature above its critical temperature, the superconductor would operate stably. The principle of cryostatic stability is used in nearly all of the large high energy physics detector magnets. This type of magnet will not quench. The current will jump from the superconductor to the copper. Since the magnet will not quench, the solenoid can be made in large sizes (over 6 meters in diameter) with faily large central inductions (up to 4 Tesla for a large sized magnet). The technology is proven and reasonably reliable.

Meaningful physics is nearly impossible outside the magnet coil because its radiation thickness is in excess of two radiation lengths in most cases. A cryostatically stable magnet is a low current density magnet. Its thick coils are massive and difficult to cool down from 300^{o} to 4^{o}K. The cryogenic system used on large conventional solenoids makes them difficult to modularize and test before final assembly. Large conventional superconducting solenoids are massive. The coil will experience large magnetic forces; the cryostats and cryogenic support systems are impressive. The large conventional solenoid is expensive to build and requires a large crew to run. However, if large diameters (greater than 2 or 3 meters) and inductions greater than 2 Teslas are required for physics reasons, there probably is no reasonable alternative to the cryostatically stable conventional solenoid magnet.

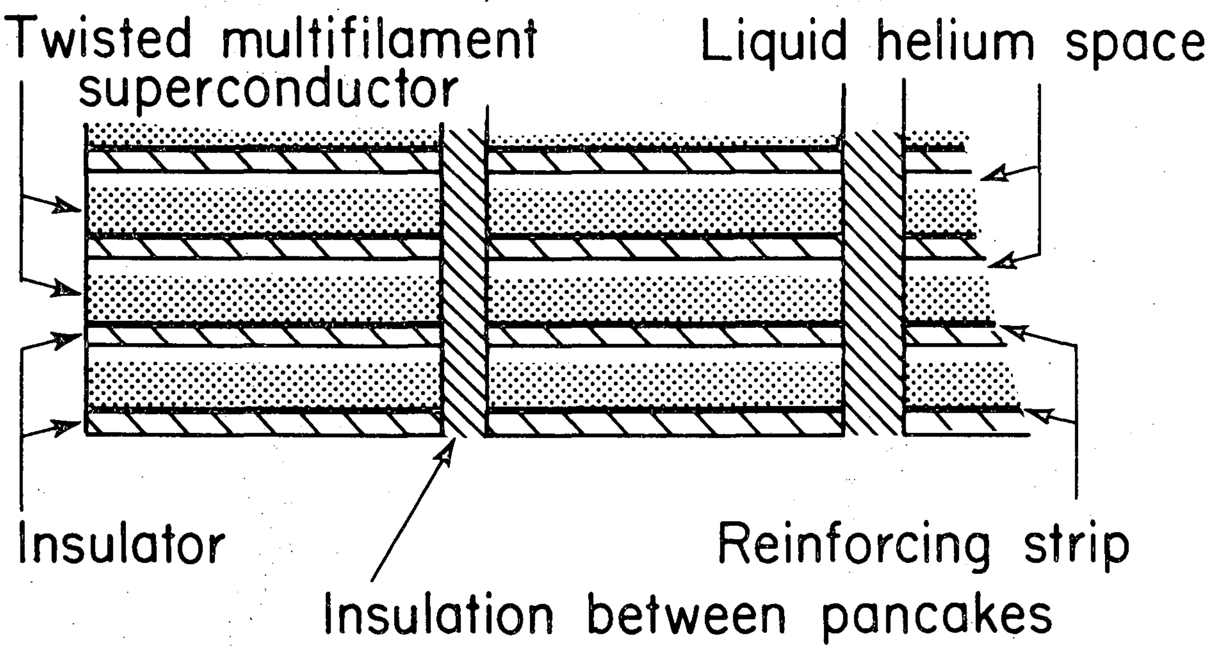
The major problem which has been encountered in most of the large solenoids built to date has been the cryogenic system. The large bubble chambers are bath cooled (Fig. 5a). (The superconductor is immersed in a bath of cold helium.) Massive bath cooled solenoids are difficult to cool down under the best of circumstances. The OMEGA magnet represents a positive step forward in large magnet cryogenics. The superconductor, which is hollow like conventional water cooled conductor, carries supercritical helium.[2] The cooldown of such a system, if properly designed, will be faster than an equivalent bath cooled magnet. The inventory of helium in contact with the magnet is reduced. However, the primary disadvantage of supercritical helium cooling is the amount of refrigeration required to obtain low enough operating temperatures. (See Fig. 5b)

Large conventional bubble chamber solenoids have been major users of superconducting magnet technology. Large magnets of this type will continue to be built. Physics experiments which require some of the particle detection to occur outside of the magnet winding cannot use conventional low current density superconducting magnets. The other alternatives are discussed in the next two sections.

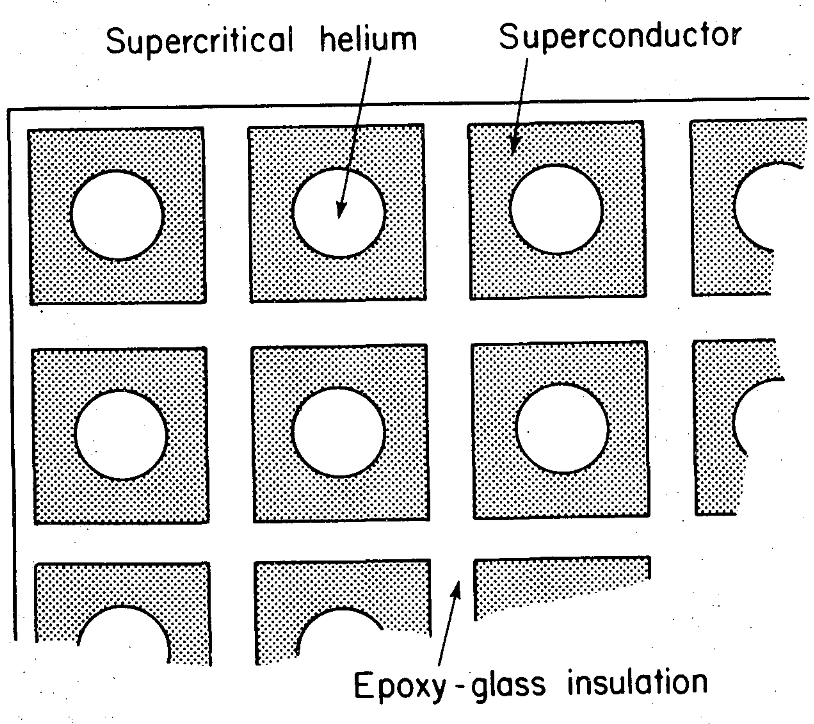
THE THIN HIGH CURRENT DENSITY SOLENOID MAGNET

The thin high current density solenoid magnet has a low radiation thickness over its entire surface. In PEP, the magnet will permit physics to be performed at about 90% of the solid angle outside the coil. The magnetic induction outside the coil will be quite low if the central induction is kept below 1.8 Tesla and if the iron return yoke is properly designed. When the induction outside the coil is low, photomultiplier tubes and other sensitive electronics may be used in that region. The thin solenoid can be easily

Fig. 5 Conventional Cryogenically Stabilized Coil Configuration



a. Bubble Chamber Coil Configuration



b. Tubular Supercritical Helium Cooled Coil Configuration (like the OMEGA magnet coil) modularized so that individual magnet sections can be tested separately. The coil mass is low; the cooldown from 300 to 4K is relatively easy.

The thin solenoid is not without its disadvantages: The magnet must operate at very high current densities. As a result, large magnetic stresses and high stored energy per unit mass can occur. The magnet will quench if any of the superconductor goes normal. A practical upper central induction limit is just over 2.0 Tesla. Large diameter coils, which are stress limited, will have a lower central induction. Small high current density solenoids have been built and operated successfully in experiments. However, large high current density solenoids have not yet been proven.

Engineering studies on the thin solenoid show that the concept is technically feasible.[3] Preliminary experimental tests on small magnets have been very encouraging. The remainder of this section will discuss the following; the design characteristics of thin solenoid magnets, the scaling laws for thin magnets, and the LBL test program for thin magnets.

a) The Design Characteristics for Thin Solenoid Magnets

The thin (low radiation thickness) solenoid should have the following characteristics: 1) It must have uniform radiation thickness (normal to the magnet coil) over the full length of the coil. 2) The cryogenic system should be designed for ease of cooldown and simplicity of construction in the thin region of the magnet. 3) The coil should be built in moduals which can be tested individually. A thin solenoid which meets the above criteria was designed in conjunction with the MINIMAG experiment.[4]

The MINIMAG solenoid was designed so that it could be modularized. The major stress, stored energy, and quench problems were studied. The tubular cooling system permits rapid cooldown and positive cooling consistent with the low radiation thickness requirements of the experiment. The thin solenoid consists of four primary parts; the solenoid bore tube, the superconducting coil, the refrigeration cooling tube, and the cryostat vacuum vessel. (See Fig. 6)

The solenoid bore tube serves as a winding form for the coil, but its most important function is an electrical one. It slows down the quench process (the process of going normal and dumping the magnet stored energy), and it serves as a thermal sink for most of the magnet stored energy during a quench. The superconducting coil is wound with intrinsicially stable (twisted fine filamented) superconductor which is operated at 80% of its critical current or less.

The thin solenoid would not have cryostat in the conventional sense. The inner cryostat vessel is replaced by a coil of aluminum refrigeration tubes which carries flowing two-phase helium. The refrigeration tube forms an integral part of the superconducting magnet. The magnet bore tube, the superconducting windings and refrigeration tube are vacuum impregnated forming a single structure which is suspended inside the vacuum enclosure. The ends of the thin magnet may be thick from a radiation standpoint. Therefore, all of the cryostat support functions, refrigeration feeds and current leads would be in that region.

The superconducting coil is designed to carry all of the magnetic stresses put into the system at its peak field. However, we expect that the aluminum bore tube will help support the magnetic stresses in the system, which gives an additional margin of safety.

The thin magnet design proposed for MINIMAG attempted to combine the cryogenic system and superconducting magnet into a single integrated system. Thus, one can avoid the kinds of cryogenic problems which have been common on the large bubble chamber magnets. Since the magnet is not cryostatically stable, the liquid helium inventory in contact with the magnet can be reduced.

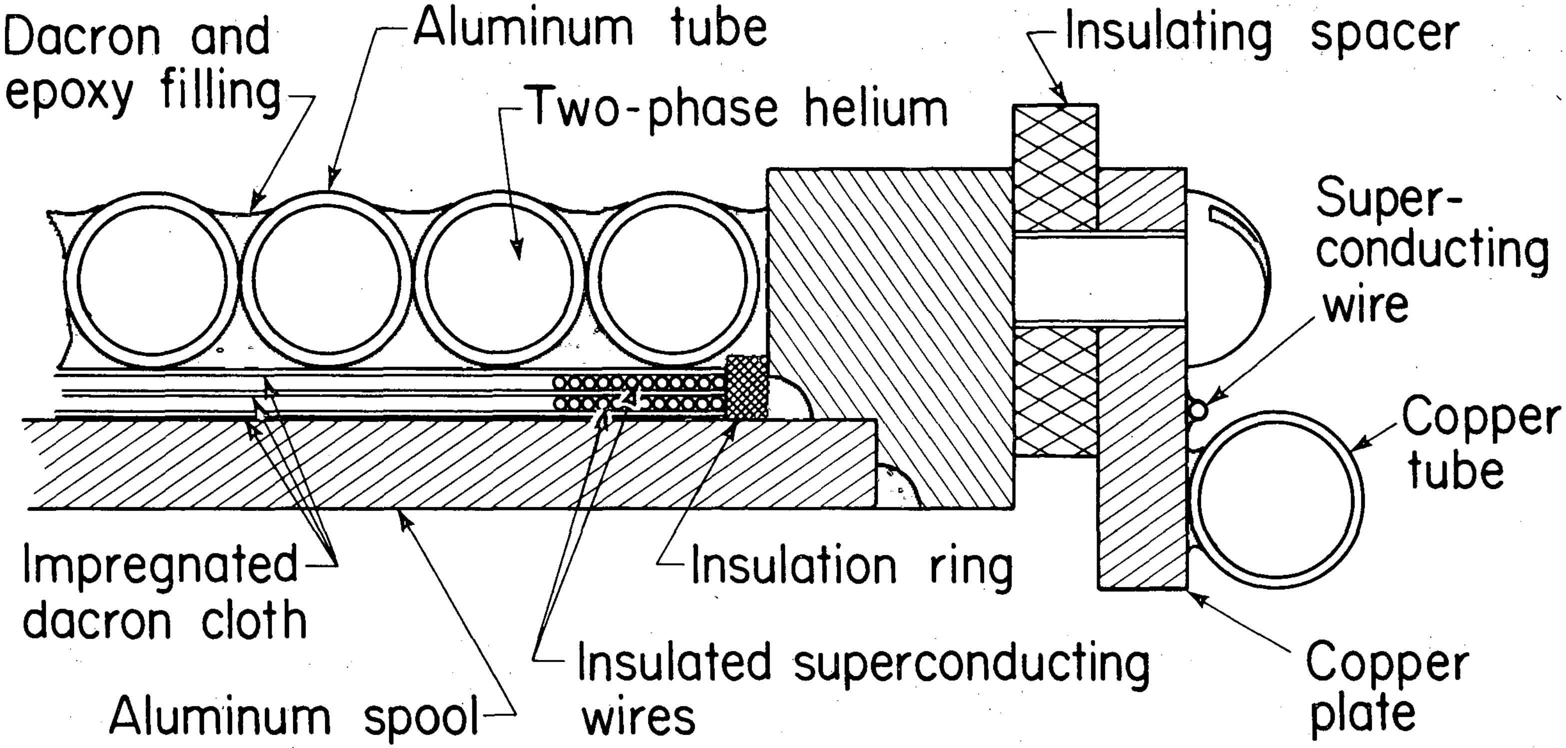


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Fig. 6 The MINIMAG Thin Coil cross section

Most of the helium in the system is out of direct contact with the magnet. The tubular cooling system also permits a positive well controlled cooldown process. The cooldown of a "MINIMAG type" thin solenoid should proceed much faster than a comparable low current density magnet.

b) Scaling Laws for Thin Magnets

Thin coils must operate at lower central inductions as the magnet diameter increases. There are two primary reasons for this; the stored energy per unit coil mass should be less than 25-30 Jg^{-1}. The maximum stress in the conductor (the magnet coil is assumed to carry all of the magnetic stress) should be less than 5×10^8 Nm^{-2} (72300 psi). Keeping the preceeding limitations in mind one may apply the following scaling law to thin coil construction;

$$\Gamma = B_o^2 D^{3/2}$$

when

$$B_o \leq B_{max}$$

$$E_o \leq E_{max}$$

where

$$B_o \approx \frac{\mu_o NI}{L}$$

$$E_o \approx \frac{\pi D^2 B_o^2}{8 \mu_o}$$

We define the preceeding symbols as follows: B_o is the central induction (T); D is the coil diameter (m); L is the coil length between poles (m); E_o is the coil stored energy per unit length ($J\,m^{-1}$); μ_o is the permeability of air ($\mu_o = 4\pi \times 10^{-7}$). NI is the ampere turns in the magnet; Γ is the scaling constant for thin solenoids; B_{max} is the maximum central induction for the magnet; E_{max} is the maximum stored energy per unit length. Γ, B_{max} and

E_{max} are functions of coil radiation thickness. In addition, the maximum practical coil diameter D_{max} is also a function of radiation thickness. Table 2 presents estimated values of Γ, B_{max}, E_{max}, and D_{max} for thin superconducting solenoids of various radiation thickness.

Table 2. Design Parameter Constants for Various Thin Solenoid Magnets

	Thick	Moderately Thick	Medium	Thin	Ultra* Thin
Radiation Thickness (Radiation Lengths)	0.48	0.40	0.32	0.25	0.18
Scaling Constant Γ	8	6	4	2	2
B_{max} (T)	2.0	2.0	1.6	1.2	1.2
E_{max} (Jm^{-1})	2×10^6	1.5×10^6	1×10^6	0.5×10^6	0.5×10^6
D_{max} (m)	~3	~3	~2.5	~2	~2

* Based on the use of magnesium magnet and cryostat parts.

The four magnets shown in Table 2 which have radiation thickness of 0.48, 0.40, 0.32, and 0.25 radiation lengths are assumed to have aluminum bore tubes and cryostats. The "ultra thin solenoid" is assumed to have a magnesium bore tube and cryostat. A radiation thickness of 0.18 radiation lengths is judged to be very close to a lower limit for thin coil technology. A magnet which has a radiation thickness of 0.18 radiation lengths will cost 30-50% more than the same magnet when it has a radiation thickness of 0.25 radiation lengths. Table 3 shows a breakdown of radiation thickness of the magnets shown in Table 2.

Table 3. The Radiation Thickness of Various Components of Low Radiation Thickness Solenoids

a) 1 meter diameter solenoid

radiation thickness (radiation lengths)

Component	Thick	Moderately Thick	Medium	Thin	Ultra* Thin
S/C coil	0.20	0.15	0.10	0.05	0.05
Bore tube	0.13	0.10	0.07	0.05	0.03
Cooling tubes	0.04	0.04	0.04	0.04	0.03
Cryostat	0.11	0.11	0.11	0.11	0.07
TOTAL	0.48	0.40	0.32	0.25	0.18
Central Induction (T)	2.00	2.00	1.60	1.20	1.20

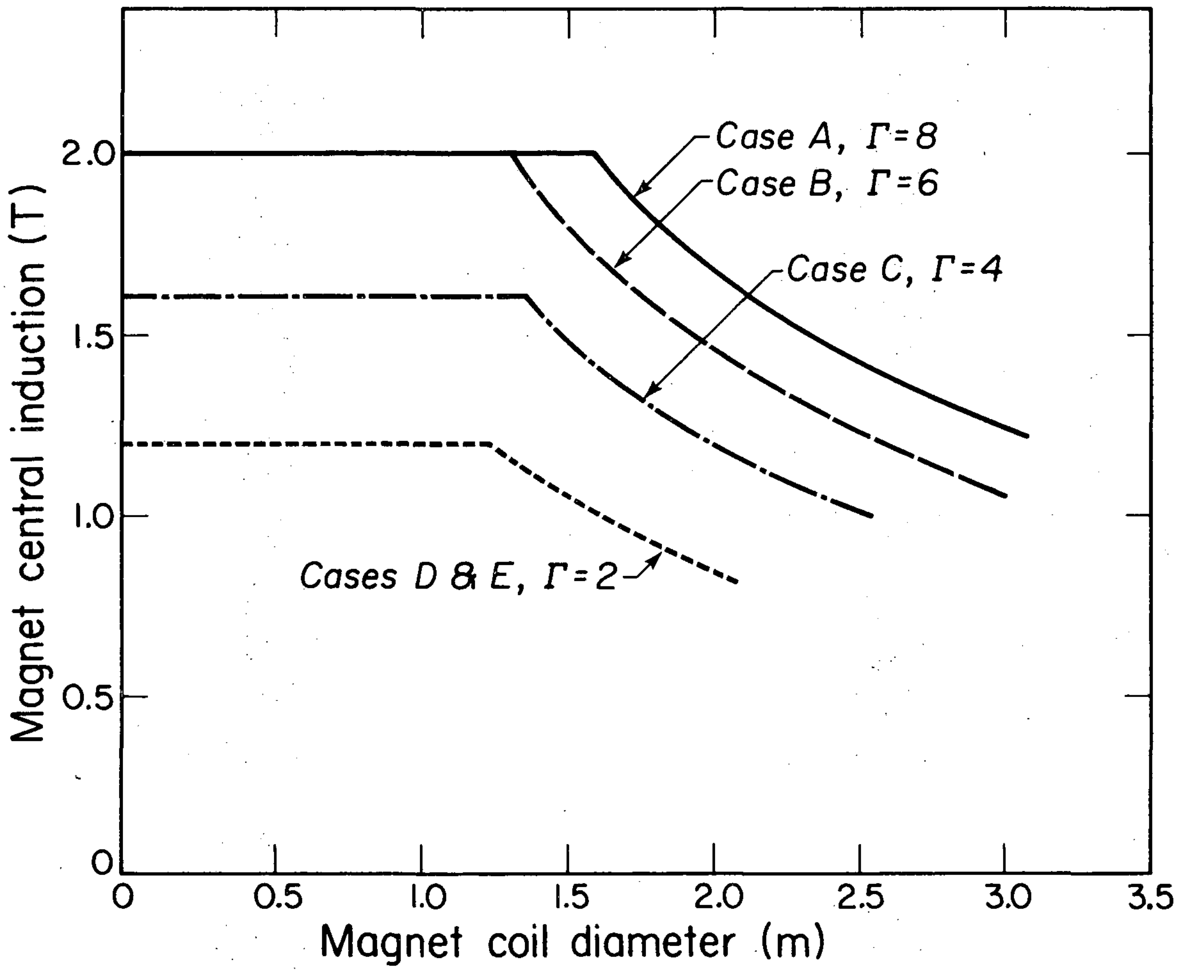
b) 2 meter diameter solenoid

radiation thickness (radiation lengths)

Component	Thick	Moderately Thick	Medium	Thin	Ultra* Thin
S/C coil	0.15	0.11	0.07	0.03	0.03
Bore tube	0.14	0.10	0.06	0.04	0.03
Cooling tubes	0.04	0.04	0.04	0.03	0.02
Cryostat	0.15	0.15	0.15	0.15	0.10
TOTAL	0.48	0.40	0.32	0.25	0.18
Central Induction (T)	1.68	1.46	1.18	0.84	0.84

*Based on the use of magnesium magnet and cryostat parts

Fig. 7 Scaling of Thin Solenoids Control Induction Versus Magnet Coil Diameter



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Case A 0.48 Radiation lengths thick

Case B 0.40 Radiation lengths thick

Case C 0.32 Radiation lengths thick

Case D 0.25 Radiation lengths thick

Case E 0.18 Radiation lengths thick

0 0 0 0 4 4 0 8 3 9 8

Figure 9 shows a plot of the thin magnet central induction B_o, Vs the magnet diameter D for magnet with radiation thickness of 0.48, 0.4, 0.32, and 0.25 and 0.18 radiation lengths. Figure 7 uses the Γ, B_{max}, E_{max}, and D_{max}, given in Table 2. These values are our "best guess" at this time. They are based on limited experimental data. An experimental program now under way at Lawrence Berkeley Laboratory will determine much more accurately the values of Γ, B_{max}, E_{max}, and D_{max}.

c) The LBL Experimental Test Program for Thin Magnets

The experimental program is built around the testing of two 1.03 m diameter MINIMAG type prototype coils. These coils have a radiation thickness of 0.24 radiation lengths. The two coils will use different Niohium-Titanium superconductors. One coil will use a 1.8 to 1 copper to superconductor ratio conductor, the other coil will use a 1 to 1 copper to superconductor ratio conductor. Both conductors are 1.0 mm in diameter (the bare diameter before a layer 0.05 mm thick formvar is applied). Both conductors have over 2000 filaments and they are twisted at the rate of one turn per centimeter. The filament diameter in both conductors is under 15 μm. Both conductors are modern intrinsically stable conductors.

The two different conductors are wound on two 6.35 mm (1/4 inch) thick 1100 series aluminum alloy tubes which are 1030 mm in diameter and 500 mm long (including end flanges). (See Fig. 8) The bore tube is expected to play an important role in controlling the superconducting magnet quench. The superconducting coil has a layer of 12.7 mm OD (1/2 inch OD) aluminum tube wound around it. This tube will carry two-phase liquid helium as a coolant for the superconducting magnet. (See Fig. 9)

The two superconductors have been tested at high current densities ($> 1.2 \times 10^9$ A m^{-2}) and high magnetic stresses ($> 4 \times 10^8$ N m^{-2}) in small

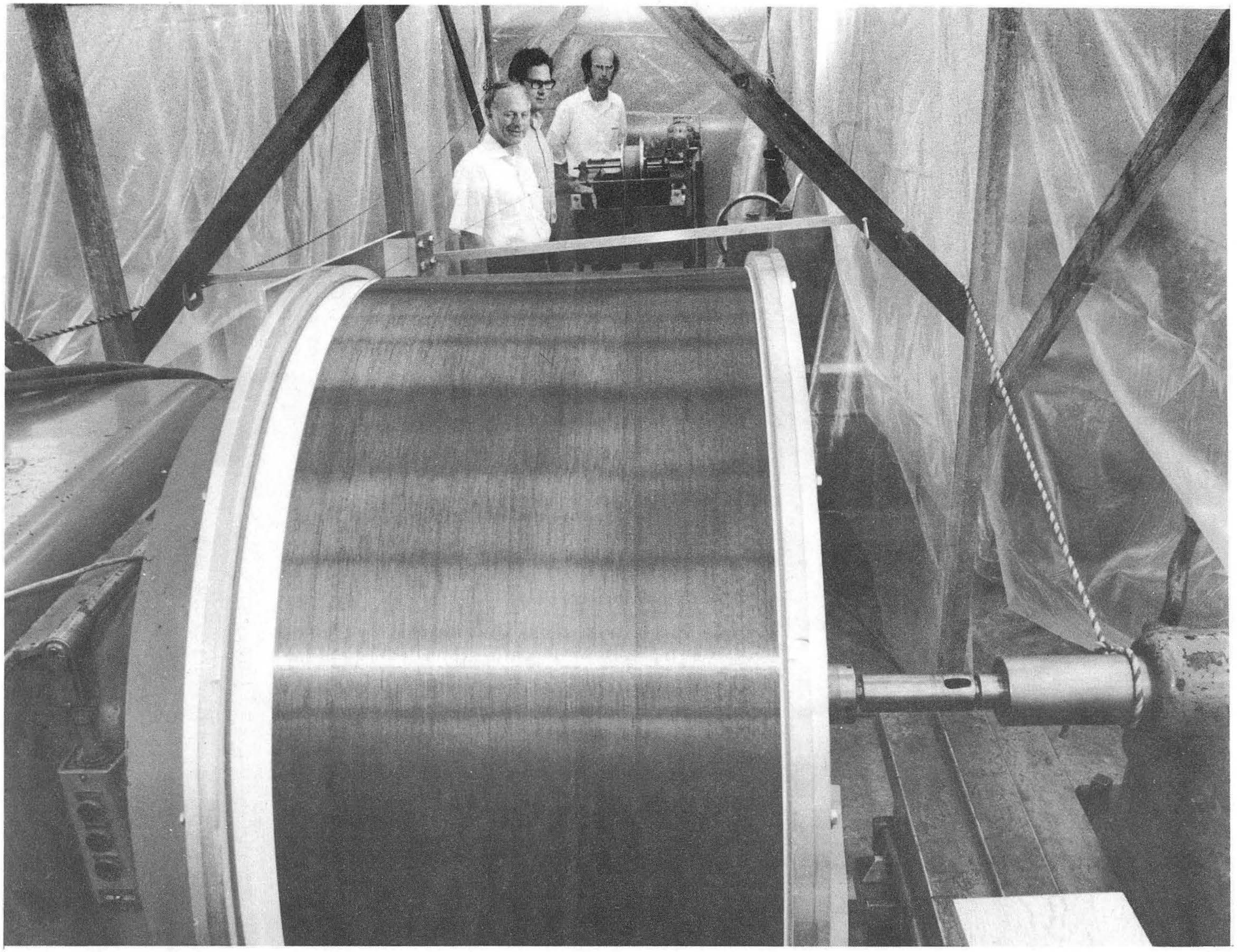

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Fig. 8 MINIMAG Test Solenoid, the winding of the first Superconductor layer

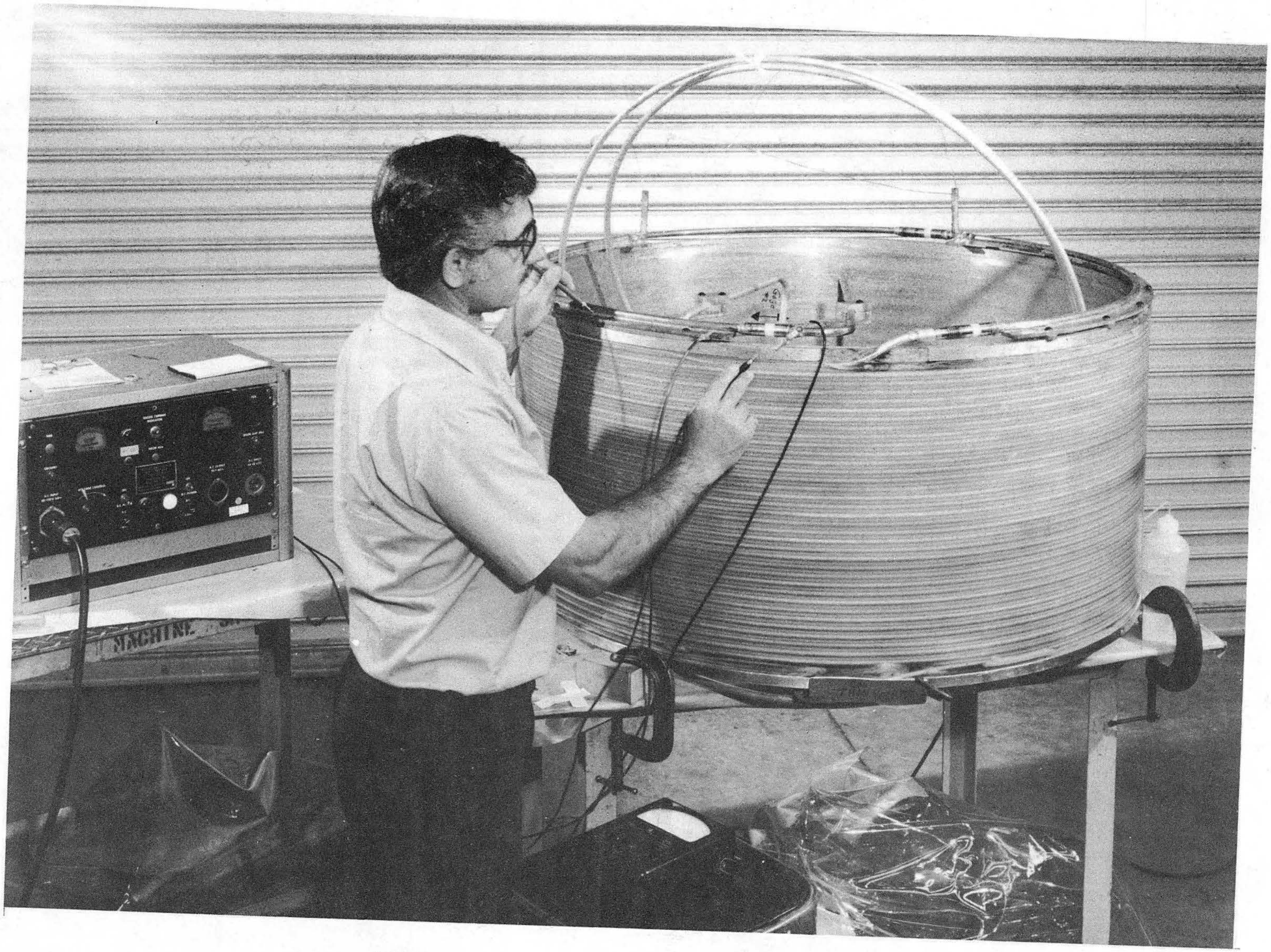

Fig. 9 MINIMAG Test Solenoid, Voltage Test on the Solenoid CBB 7510-7785

oval solenoid tests. The large solenoids will test the conductor under conditions of high current density, high magnetic stress, and high stored energy. We expect to be able to determine experimentally the magnet scaling factors Γ, B_{max} and E_{max}. Thus, we expect to prove that high current density superconducting coil technology can be applied to relatively large (1 - 3 m in diameter) magnets with central inductions from 0.8 to 1.8 Tesla.

THE LUMPED HIGH CURRENT DENSITY SOLENOID MAGNET

The lumped solenoid has a non-uniform radiation thickness over its length. The supports between coils are also thick from a radiation standpoint (see Fig. 4b). The radiation thickness is 0.01 - 0.06 radiation lengths in the thin regions of the magnet; the radiation thickness at the coils and support members will typically exceed two radiation lengths. The regions of very low radiation thickness are useful for certain kinds of physics. (i.e., the accurate measurement of the momentum of high momentum charged particles and low energy gamma rays.) Like the thin continuous solenoid, the lumped magnet is easily modularized so that individual magnet sections can be tested separately. The coil mass is not as low as the continuous solenoid, but it remains low enough so that the cooldown of the magnet from 300^{o}K to 4^{o}K is relatively easy.

The lumped solenoid must operate at relatively high current densities in the conductor. As a result the magnet will quench if any of the superconductor goes normal. The quench process must be understood and dealt with. Since the magnet must be designed with the quench process in mind, the central induction of the lumped high current density solenoid should be no higher than 2.0 to 2.5 Tesla. Large diameter lumped coils will be stress limited, so they would be operated at a central induction below 2.0 Tesla.

Numerous small magnets have been operated at the current densities proposed for the lumped solenoid (about 4×10^{8} A m^{-2}). Large lumped coil type magnets ($\sim$2 m in diameter) which is similar to the lumped solenoid coils, have been built by NASA[5] and by the high energy physics laboratory at Stanford University.[6] Both magnets have been operated reliably. The lumped coil concept is, in a sense, more proven than the thin continuous solenoid concept.

Preliminary engineering studies on a lumped coil detector indicate the magnet concept is technically feasible. Successful thin coil tests are encouraging for the thick lumped magnets as well. These magnets are not driven to as high current density as the thin coils are. Successful completion of the large thin coil tests will improve our knowledge of the lumped coil system and will verify the technical feasibility of the concept and will provide reasonable experimental determination of magnet scaling factors.

a) The Design Characteristics of Large Lumped Solenoid Magnets

The lumped solenoid will have the following characteristics: 1) the holes or very thin regions of the magnet or magnet cryostat should be as large as possible. 2) The cryogenic system should be designed for ease of cooldown and simplicity of construction. 3) The coil should be easy to test in modules. Preliminary designs for a proposed CERN experiment[7] indicate that the preceeding criteria can be met in a lumped solenoid system.

A lumped solenoid should be easy to modularize. The modules may or may not be identical in physical shape, but they must contain the same number of ampere turns of conductor. The solutions to stress, stored energy and quench problems, which were applied in the MINIMAG thin solenoid studies may be used for the lumped magnet system. The use of the tubular cooling system, which is an important part of the MINIMAG concept and has been successfully employed at SIN,[8] can be used to advantage in the lumped coil system.

The lumped solenoid magnet consists of four primary parts; the lumped coil bore tubes, the superconducting windings, the tubular cooling systems, and the cryostat vacuum vessels. (See Fig. 10)

The solenoid bore tube serves the same function in the lumped coil solenoid as it does in the thin coil solenoid. In both cases, the coil bore tube controls the magnet quench process. The lumped coils are not as well coupled inductively to the bore tube as the thin coils. (98% coupling is possible in the thin coil system; 90% coupling should be possible in the lumped coil magnet.) Like the thin solenoid, the lumped coil solenoid should be wound with intrinsically stable superconductors. The conductor is operated at a lower current density than in the thin continuous coil case. The primary reason for this is that peak induction in the conductor can be twice the central induction of the magnet. (In a thin solenoid, there is less than a 5% difference between the peak and central inductions.) The superconductor in the lumped solenoid would be operated at 75% of its critical current or less.

Like the thin solenoid, the lumped solenoid should use a tubular cooling system using two phase helium. The refrigeration tubes, the bore tube and superconducting coil form an integrated package. The lumped coils are assembled together with cold force carrying members. The structure, which is mostly holes, is nearly in force equilibrium. The support system which suspends the lumped coil structure to the room temperature outside world is designed to carry gravitational forces and those magnetic forces which are generated by asymetric currents in the system.

Two kinds of cryogenic vacuum can be considered for the lumped solenoid system; the continuous uniform cryostat and the thin window cryostat. The continuous sryostat is less expensive than the thin window cryostat but its radiation thickness is a factor of 3 to 5 greater.

In order to minimize radiation thickness, the continuous cryostat would have to be made of magnesium or magnesium alloy. The thickest part of the

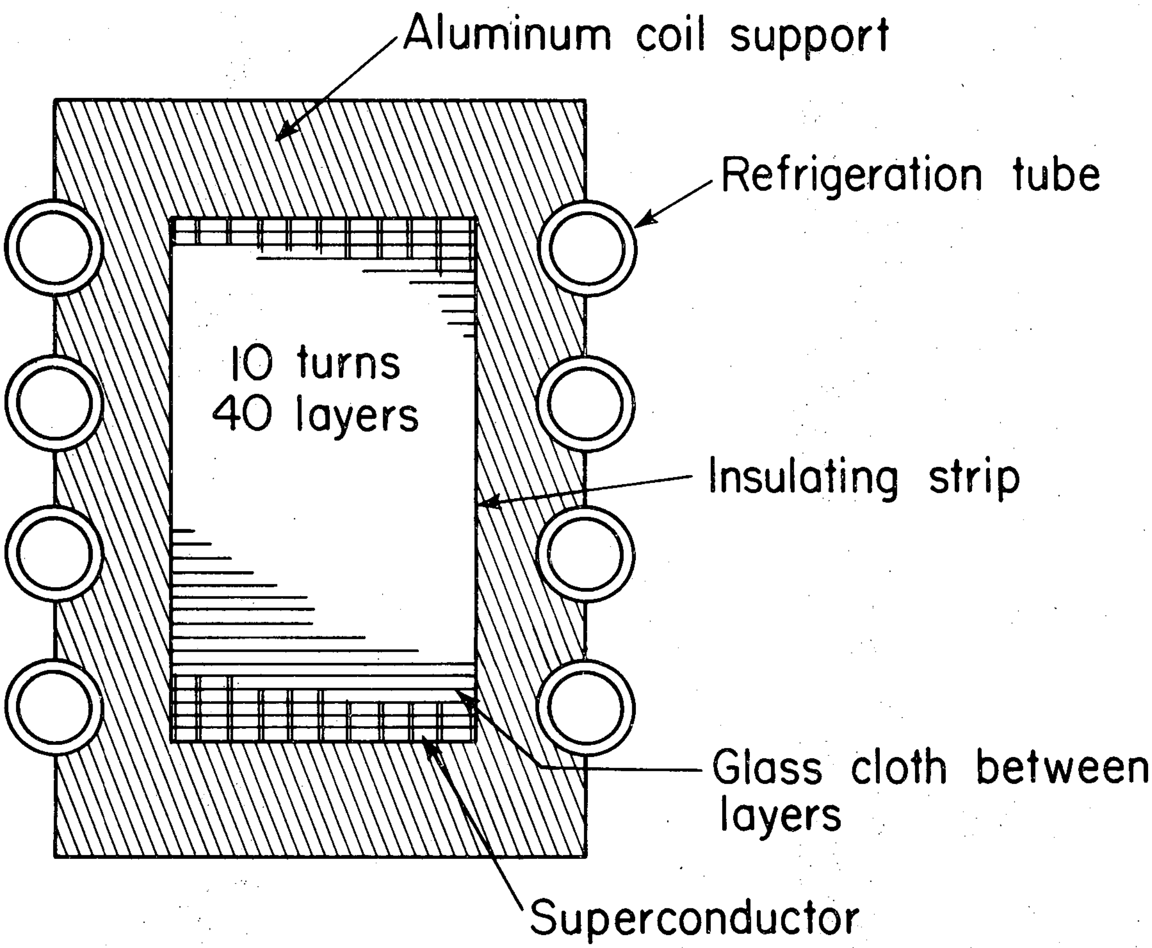

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Fig. 10 A coil cross-section for one coil of a lumped coil Superconducting Magnet cryostat is the outer vacuum can. This thickness is needed to resist buckling due to vacuum loading. Proper mechanical design will result in radiation thicknesses between the coils, of 0.05 to 0.07 radiation lengths.

If the physics of the experiment requires less than 0.05 radiation lengths of material in the thin regions of the magnet, the thin window cryostat should be considered. A thin window cryostat can have a radiation thickness as low as 0.01 radiation lengths. It can be built with either aluminum foil or Mylar windows. Both kinds of windows will be quite fragile. Both will require either plastic foam or a screen to protect the windows from damage. A cryostat without windows, the cryostat vacuum vessel closely surrounds the coils and stuts, has been suggested. The cost of such a cryostat plus maintenance problems associated with such a system rule it out. In addition, there is little physics advantage which can be gained by reducing the minimum radiation thickness from 0.01 radiation lengths to zero.

The thin solenoid tests which will soon be conducted at Berkeley will answer many technical questions which the lumped solenoid poses. The cooling system is essentially the same for the two systems. In some way, the lumped solenoid design is conservative compared to the continuous thin solenoid design. Therefore, a successful 1 meter diameter thin solenoid test will advance the cause of the lumped solenoid as well.

b) Scaling Laws for Lumped Magnets

There are two primary criteria which determine the size of the lumped coils in a lumped coil magnet system. They are; stored energy per unit coil mass and magnetic stress. To the first order, the stored energy per unit mass and magnetic stress go together. As a result, the scaling law given here will be based on stored energy per unit coil mass alone. The coil in this case includes the superconductor and the bore tube. Each is treated separately.

The current density in the superconductor (the Nb-Ti alone) is a function of the local temperature, induction and stress. The current density in the overall matrix (copper, other normal metals and superconductors) is a function of the stored energy. The stored energy for a lumped coil magnet with iron on return path and a central induction $B_o < 1.8$ T is to the first order:

$$E \quad \frac{\pi D^2 L B_o^2}{8 \mu_o}$$

The stored energy per unit superconductor matrix mass is:

$$K_{SC} = \frac{E}{M_{SC}}$$

The stored energy per unit aluminum bore tube mass is:

$$K_{bore} = \frac{E}{M_{bore}}$$

where the symbols are defined as follows: E is the magnet stored energy (J); D is the magnet coil diameter (m) at the center of the windings; L is the magnet length between pole tips (m); B_o is the central induction of the magnet (T); M_{SC} is the total superconductor matrix mass (g), which include the Nb-Ti and all normal metals in the matrix; M_{bore} is the bore tube mass; and μ_o is the permeability of air $\mu_o = 4\pi \times 10^{-7}$.

If the lumped coil magnet is divided into N coil packages, the following empirical values of stored energy per unit mass apply;

$$K_{SC} = \frac{100}{N} \quad (Jg^{-1})$$

when $4 \leq N \leq 8$

$$K_{SC} = 12.5 \quad (Jg^{-1})$$

when $N > 8$

$$K_{SC} = 25 \quad (Jg^{-1})$$

when $N < 4$

In general the aluminum bore tube should be designed so that $K_{bore} \approx 10 \ Jg^{-1}$. Magnetic stress only becomes a problem when K_{SC} is greater than 20 Jg^{-1}. The only further restriction on the design is that the superconductor operating current be less than 75% of the superconductor critical current at the peak induction in the coil.

The resulting scaling is as follows: 1) For a given central induction the solid angle lost due to the coils and their supports is a constant. 2) The solid angle lost goes as I/D if you allow B_o to go down as $D^{-1/2}$. Both of the preceeding statements assume that the thickness of the superconducting coil package and its cryostat remain constant as D changes. Scaling probably does not apply when D is greater than 3 meters.

The scaling laws given here for lumped coil systems are approximate. Better scaling laws will result from the series of experiments now going on at LBL. It is suggested that reference 10 be consulted for further information on the lumped coil magnet system.

SUMMARY

Two basic types of detectors can be considered for use on PEP and other intersecting storage ring devices. Both will utilize solenoidal fields with flux paths parallel to the direction of the beams. One type, the conventional superconducting solenoid, permits physics to be performed only inside the coil in the magnetic field. The second type based on high current density technology permits physics to be performed both inside and outside the magnet coil.

Two kinds of high current density magnets can be considered. One is based on a continuous then coil of uniform radiation thickness; the second is based on lumped coils which have regions of high radiation thickness and regions of near zero radiation thickness. For many experiments the high density magnets could result in substantial cost savings in both capital and operating funds. The central induction of such magnets is 2 Tesla or less, and the maximum practical diameter is 2 to 3 meters.

Each of the two types high current density magnets has advantages for some kinds of experiments. If high central inductions and/or large field volumes are required, there is probably no practical alternative at this time to the conventional low current density superconducting solenoid. Since the performance parameters of the high current density magnets are not fully understood, experimental work now under way at LBL will establish the practical limits of operation for magnets using high current density intrinsically stable superconductor.

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