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LARGE HIGH CURRENT DENSITY SUPERCONDUCTING SOLENOIDS FOR USE IN HIGH ENERGY PHYSICS EXPERIMENTS

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ABSTRACT

Very often the study of high energy physics in colliding beam storage-rings requires a large magnetic field volume in order to detect and analyse charged particles which are created from the collision of two particle beams. Large superconducting solenoids which are greater than 1 meter in diameter are required for this kind of physics. In many cases, interesting physics can be done outside the magnet coil, this often requires that, the amount of material in the magnet coil should be minimized. As a result these solenoids should have high current density (up to 10^9 A m^{-2}) superconducting windings. The methods commonly used to stabilize large superconducting magnets cannot be employed because of this need to minimize the amount of material in the coils.

This paper describes the Lawrence Berkeley Laboratory program for building and testing prototype solenoid magnets which are designed to operate at coil current densities in excess of 10^9 A m^{-2} with magnetic stored energies which are as high as 1.5 Megajoules per meter of solenoid length. The coils use intrinsically stable multifilament Nb-Ti superconductors. Control of the magnetic field quench is achieved by using a low resistance aluminum bore tube which is inductively coupled to the coil. The inner cryostat is replaced by a tubular cooling system which carries two phase liquid helium. The magnet coil, the cooling tubes, and aluminum bore tube are cast in epoxy to form a single unified magnet and cryogenic system which is about 2 centimeters thick. The results of the magnet coil tests are discussed in the paper.

INTRODUCTION

The electron-positron colliding beam storage ring is one of the newest tools in the study of the structure of the atom. Two new colliding beam machines are being built; PEP in the United States and PETRA in Germany. These machines, which collide 15 GeV electrons and positrons, will require a new generation of megnetic detectors to analyze the particles which result from the collision of high energy electron and positron beams.

The magnet in these detectors will be in nearly all cases a solenoid. The reasons for this are as follows: a) A solenoid gives good momentum resolution perpendicular to the beam. (The beams travel along the axis of the magnet); b) Little compensation is required because the beam travels parallel to the magnetic flux lines; c) There is little or no material between the beam interaction area and the magnetic detector (drift chambers, etc.; and d) the solenoid is simplest to build. The detector solenoid magnets are large (greater than 1 meter in diameter) so it is attractive to make them superconducting.

It is desirable to be able to do physics over a large portion of the solid angle which surrounds the colliding beam interaction zone. Furthermore, it is desirable to measure and analyze neutral as well as charged particles. Some of the neutral particles are just as well measured outside of the magnetic field. Doing physics outside as well as inside the magnets will reduce the cost of the experiment. For present generation cryogenically stable solenoids, a major problem in studies of particles passing through the magnet is its radiation thickness.

A new detector should have a minimum amount of material between the interaction region and the outside. The result is that the new generation of superconducting detector magnets will have high current density windings which cannot be cryogenically stabilized.

THE LBL DETECTOR MAGNET DEVELOPMENT PROGRAM

Two kinds of high current density detector magnets are being studied by the Lawrence Berkeley Laboratory (LBL) for use on the PEP colliding beam machine to be built by LBL and SLAC (Stanford Linear Accelerator Center) in the United States. The two kinds of detector magnets are as follows:

1) Lumped coil detectors would have thick coils (2-3 radiation lengths thick) that completely block-out particles. The space between the coils would have a very low radiation thickness[1] (0.01 to 0.03 radiation lengths.) The thin region would cover over 65 per cent of the solid angle which surrounds the interaction region.
2) Thin coil detectors would have uniformly thin coils which are 0.2 to 0.5 radiation lengths thick in a direction perpendicular to the coil. This radiation thickness would apply over 90 percent of the solid angle surrounding the interaction region.[2,3]

The use of either type of coil depends upon the physics that one wants to do and it depends upon the state of technology at the time the detector magnet design is adopted.

The diameter of detectors being considered for PEP range from 1.6m to 2.7m. In all cases the central induction is less than 2 Tesla. The detector magnets currently being studied by the LBL group are about 4.0m long, 2.0m in diameter with a central induction of 1.0 to 1.5 Tesla. These magnets are high current density magnets where cryogenic stability cannot be used.

In addition to high current density coils, major changes in the cryogenic system are contemplated by LBL in order to reduce radiation thickness and to eliminate many of the cooldown problems which plague present generation cryogenically stable coils. The LBL studies treat the magnet and cryogenic problems together.

The LBL large high current density detector magnets have the following characteristics:[4]

1) Modern intrinsically stable high current density Nb-Ti superconductor is used.
2) Quench protection is provided by a closely coupled low resistance bore tube
3) Cooling is provided by flowing two phase helium in tubes surrounding the coils and bore tube.
4) The superconductor, bore tube, and cooling tube are cast into integrated units. The entire magnet would consist of one or more of these units.

LBL has been studying designs using both cooper based and aluminum based multi-filament Nb-Ti superconductors. The conductor used should have small filaments (under 20 μm) and it should be twisted. AC losses are not important, but stability is. The wire should be intrinsically stable and resistant to the effects of wire motion.

The winding form or coil cannister should consist of a low resistivity material of low radiation length such as pure aluminum or magnesium. The bore tube or cannister controls the quench process permitting the high current density magnet to be run at relatively high stored energies without destruction of the magnet. The well-coupled low resistivity bore tube serves the following functions:

1) The bore tube drives the entire coil normal in a short time.
2) The bore tube absorbs most of the magnet stored energy during the quench.
3) The bore tube behaves as a shorted secondary. This reduces the magnet inductance at high rates of current change. As a result, voltage transients in the coil are greatly reduced.

The tubular cooling system takes the place of the liquid bath cryostat. Two phase helium was chosen as a cooling agent in the tubes. The reasons for choosing two phase helim are: a) The average temperature in the magnet is below 5° K and b) The mass flow of helium required for cooling the magnet is minimized. The two phase helium is delivered to the magnet from a control cryostat which is connected to a refrigerator. The advantages of the tubular cooling system over an ordinary bath cooled system are:

1) The cooldown of the magnet is well controlled because the helim flows in a well defined path.

2) The mass of the cryostat is minimized, hence its radiation thickness is also minimized.

3) The amount of liquid helium in direct contact with the coil is minimized. Helium boil-off during a quench is orderly and well controlled.

A schematic of the LBL cooling system is shown in Figure 1. The magnet is separated from a control cryostat by a 9m long flexible coaxial transfer line. The refrigerator compressor acts as a pump to circulate helium through the magnet. (A liquid helium pump could also be used.) The control dewar is used to control the magnet refrigeration process and it reduces the quality of the liquid helium entering the magnet.

THE LBL ONE METER DIAMETER THIN TEST COILS

Two one meter diameter thin test solenoids have been built by LBL. These magnets use high current density intrinsically stable superconductors (both magnets should operate at superconductor composite current densities of 10^9 A m^{-2} or more). The magnets use aluminum bore tubes to control the quench process. Both magnets employ a tubular cooling system. The primary difference between the two magnets is the superconductor used in each. The reasons for building two magents are: a) One can test the coupling between two coils operated together. An understanding of the coupling process is particularly important to the development of lumped coil detector magnets; b) One can test superconductors which have different characteristics; c) fabrication mistakes can be corrected on the second prototype; d) Reasonable cost estimates can be obtained.

The characteristics of the superconductors used in the two LBL test coils are shown in Table 1. The superconductor used in Coil A was made

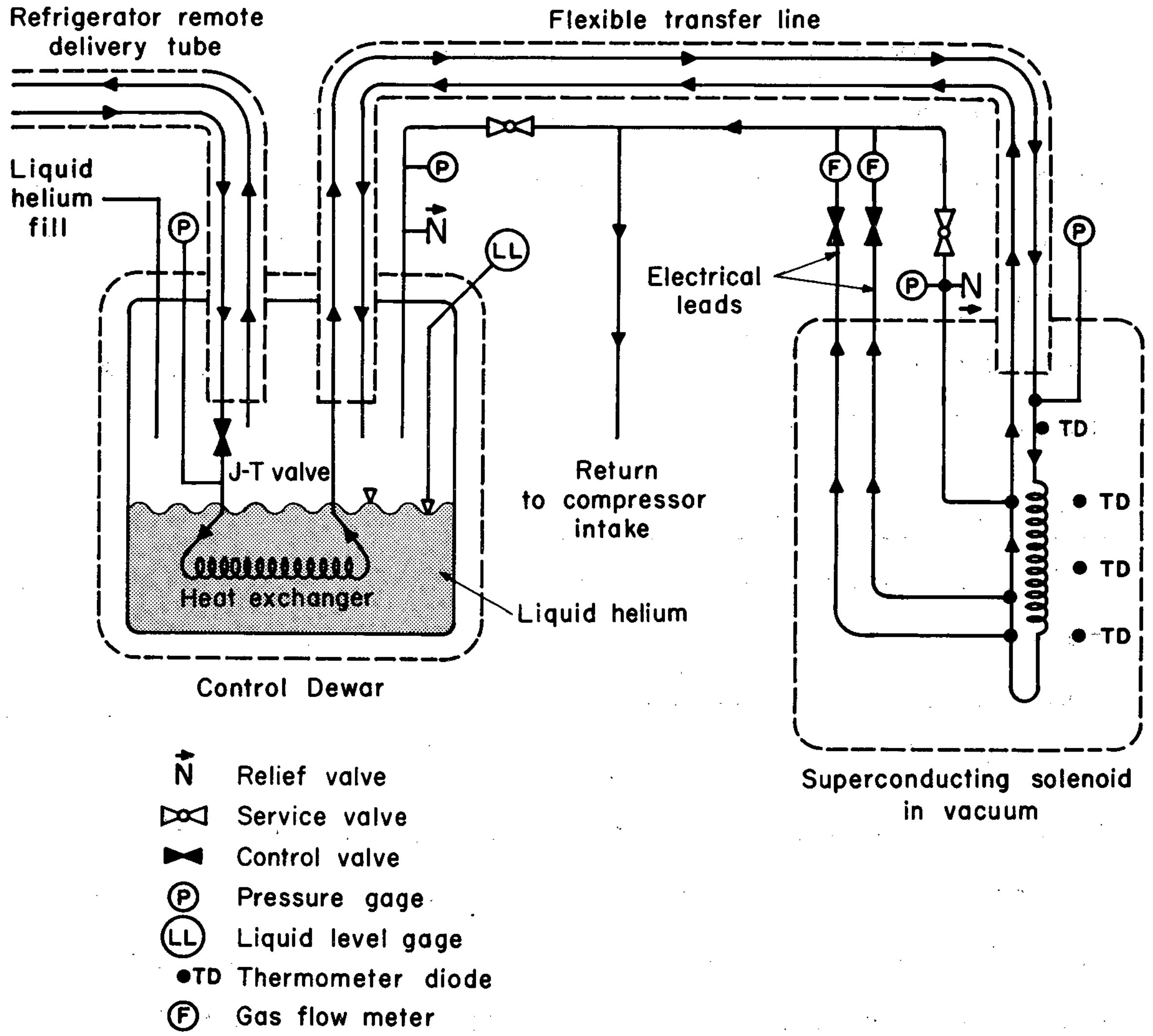

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Figure 1 A schematic of the tubular cooling refrigeration system used for the LBL this coil tests.

TABLE 1.

THE SUPERCONDUCTOR CHARACTERISTICS FOR THE A AND B MAGNETS

	A Coil	B Coil
Manufacturer	MCA	Supercon
Insulated Matrix Diameter (mm)	1.09	1.10
Bare Matrix Diameter (mm)	0.99	1.00
Copper to Superconductor Ratio	1.8	1.0
Number of Filaments	2300	2700
Filament Diameter (μm)	12.3	13.6
Filament Twist Pitch (mm)	~10	~10
Critical Current @ 4.2 K & 2 T (A) (defined as 10^{-14} Ωm resistivity)	900	1360
Critical current density @ 4.2 K and 2 T (Am^{-2})	1.17×10^9	1.73×10^9

by Magnetic Corporation of America (MCA); the B coil superconductor was made by Supercon Incorporated. Both superconductors are state of the art conductors. Both superconductors were supplied to LBL with a formvar insulation which is 0.05 mm thick. LBL inspected, etch tested, and measured the resistivity of the conductor as a function of the induction and current.[5] Samples of the superconductor were wound onto an oval solenoid which permitted the conductor to be tested at high current densities (greater than 10^9 Am^{-2}) and at high tensile stresses (up to 4 x 10^8 Nm^{-2}) due to the magnetic field.[6]

The superconductor was wound on bore tubes fabricated from 6.35 mm (¼ inch) thick 1100 aluminum plate. The bore tube material has a resistivity of 1.8 x 10^{-9} Ωm at 50° K and below. After the bore tube was rolled up and welded, it was annealed. Two layers of superconductor were wound on the bore tube under a tension of 130 N. This pre-stresses the superconductor so that the thermal contraction coefficient of the superconductor and the bore tube are matched. Insulation between the bore tube and the superconductor and insulation between superconductor layers consist of 0.35 mm of impregnated glass tape (Glass was substituted for dacron at a cost of 0.01 radiation lengths of radiation thickness.) An aluminum cooling tube which is 117 meters long with an outside diameter of 12.7 mm was wound on the superconductor glass composite. The voids between the tubes were filled with polyester braids. The whole assembly was vacuum cast in epoxy to form a single unified magnet.[7] A detailed crosssection is shown in Figure 2. A photograph of a finished coil (Coil B) is shown in Figure 3. Table 2 shows the physical and electrical properties of the two LBL test solenoids. The weight of each of the magnets is 81 kg. The radiation thickness of each magnet is 0.23 to 0.27 (average 0.24) radiation lengths.

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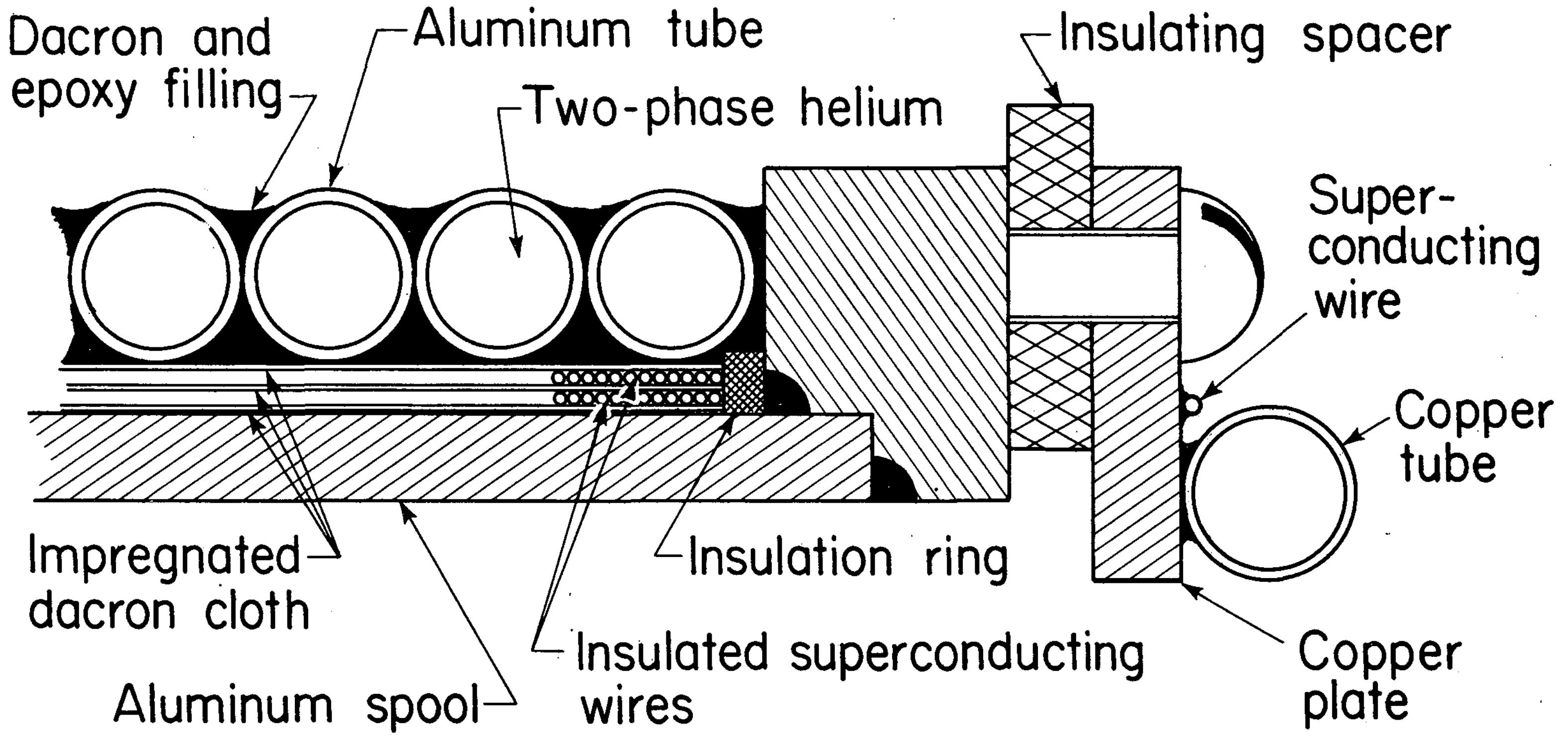

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Figure 2 The LBL one meter diameter thin coil cross-section.

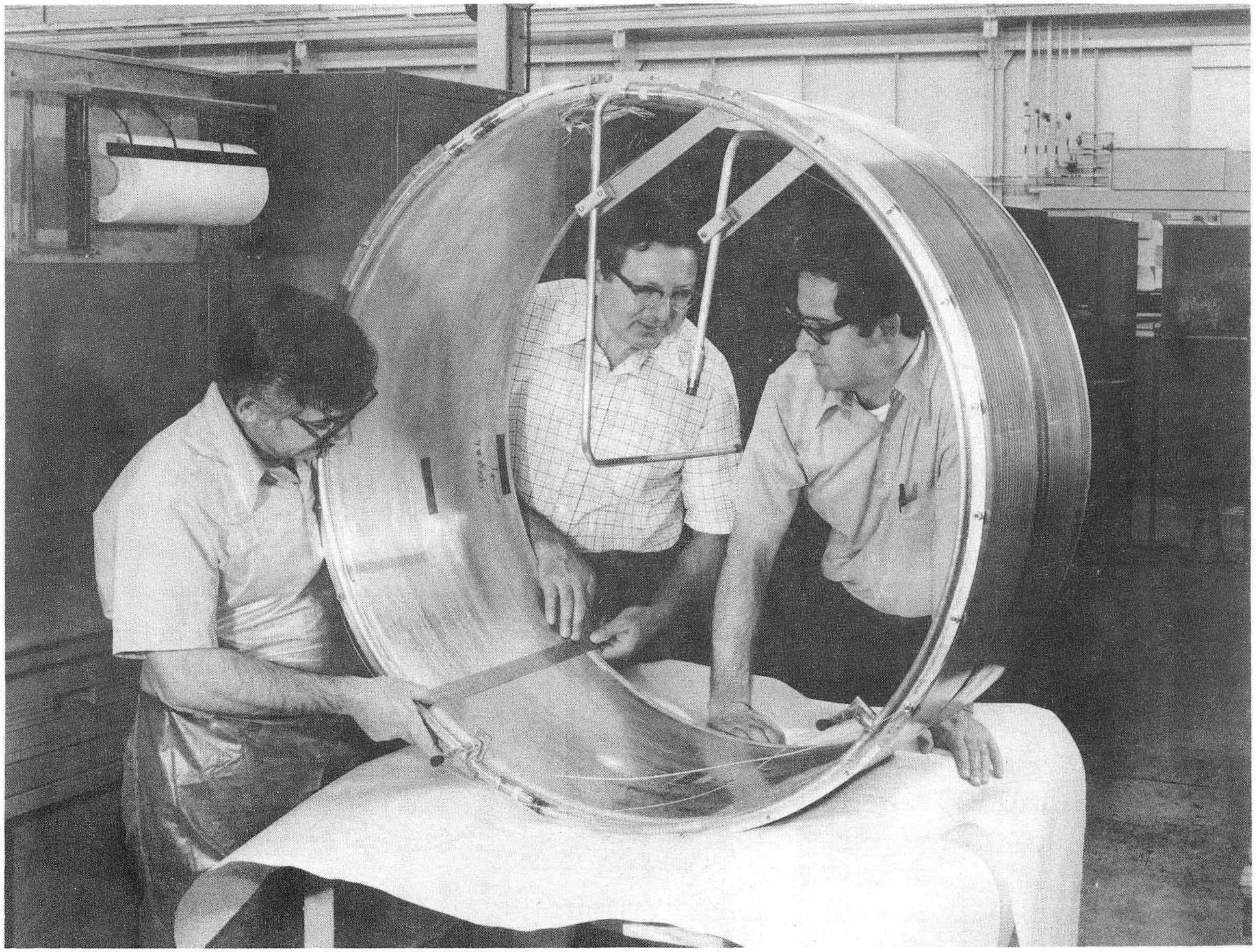

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Figure 3 One of the LBL thin coil solenoid magnets (the B coil)

TABLE 2

THE PHYSICAL AND ELECTRICAL CHARACTERISTICS OF THE TWO LBL TEST COILS

	A Coil	B Coil
Magnet Inside Diameter (mm)	1021.	1021.
Magnet Outside Diameter (mm)	1070.	1070.
Average Coil Diameter (mm)	1035.	1035.
Magnet Overall Length (mm)	500.	500.
Coil Length (mm)	461.	464.
Number of Turns	835	832
Critical Current @ 5° K (A)	910.	1160.
Design Current (A)	700	880
Design Matrix Current Density (Am^{-2})	0.91×10^9	1.12×10^9
Central Induction at Design Current (T)	0.65	0.77
Peak Induction at Design Current (T)	1.11	1.40
Magnet Inductance (H)	0.75	0.74
Magnet Stored Energy at Design Current (J)	1.83×10^5	2.88×10^5

The solenoids are instrumented with strain gages on the bore tube.[8] (There are 2 gages on coil A and there are 4 gages on coil B.) Each solenoid has three silicon diode thermometers attached to the bore tube.[9] The A coil has one small coil at one end for inducing quenches; the B coil has four small coils for inducing quenches. (There is one quench coil at each end and two coils in the center of the magnet.) The A magnet has one dB/dt measuring coil wound around it. The B magnet has two such coils (one is between the cooling tube and the superconductor; the other is wound outside of the cooling tubes.) Other instrumentation such as pressure taps, thermometers on the refrigeration circuitry and magnetic field measuring coils are also included. Coils for inducing quench through the bore tube were also installed as was a heater mounted against the bore tube.

THE TESTS OF THE LBL A COIL

The LBL A magnet was tested for the first time in November of 1975. Further testing occured in March of 1976. Between the first and second test, the refrigeration system was modified to the system shown in Figure 1. The data acquisition and data analysis system was also changed. A future paper will be devoted to describing the LBL computerized data analysis system. The purposes of the two tests of the A coil are as follows:

1. The two phase cooling system was tested to prove its feasibility for cooling large superconducting solenoids.
2. The quench protection role of the bore tube was tested. The test measured the dynamics of magnet quenching.

3. The structural integrity of the coil, its bore tube and the cooling system was tested.

The A coil was cooled down using the LBL CTi Model 1200 refrigerator. This machine will, on a good day, produce about 15 to 20 W of refrigeration at 4.5° K. (This capacity is about half of its rated capacity when it was new. The reduction of refrigeration capacity is due to heat exchanger fouling and reduced capacity of the compressor system.) The control dewar, heat exchanger, and magnet were cooled from room temperature to 60° K in about 8 hours. Liquid helium was added to the control dewar in order to complete the cooldown down to 4.8° K. The mass flow through the J-T circuit of the LBL refrigerator is 1.5 to 2.0 gs^{-1}. Figure 4 shows the theoretical and measured pressure drop across 117 m of magnet cooling tube as a function of the average temperature in the magnet. Once the magnet was cooled to below 5.0° K, two phase flow was established in the magnet. The magnet operated between 4.6 and 5.0° K. (There was some uncertainty because the silicon diode thermometer seemed to be reading about 0.2 to 0.4° K high. This could be due to heat conduction down the leads or due to the 25 μW of heat diapated in each diode.) The tubular cooling system performed well despite the fact that the total system refrigeration requirements exceeded the capacity of the LBL cold box by 10 to 15 watts. Liquid helium added to the control dewar made up for the deficiency in refrigeration.

Electrical tests confirmed theoretical calculations of coil inductance between the coil and the bore tube. A field map was made inside the coil and it confirmed theoretical calculations. The characteristics of the quench inducing coil were measured.[10] Time constants of the coil and bore tube were measured confirming theoretical calculations.

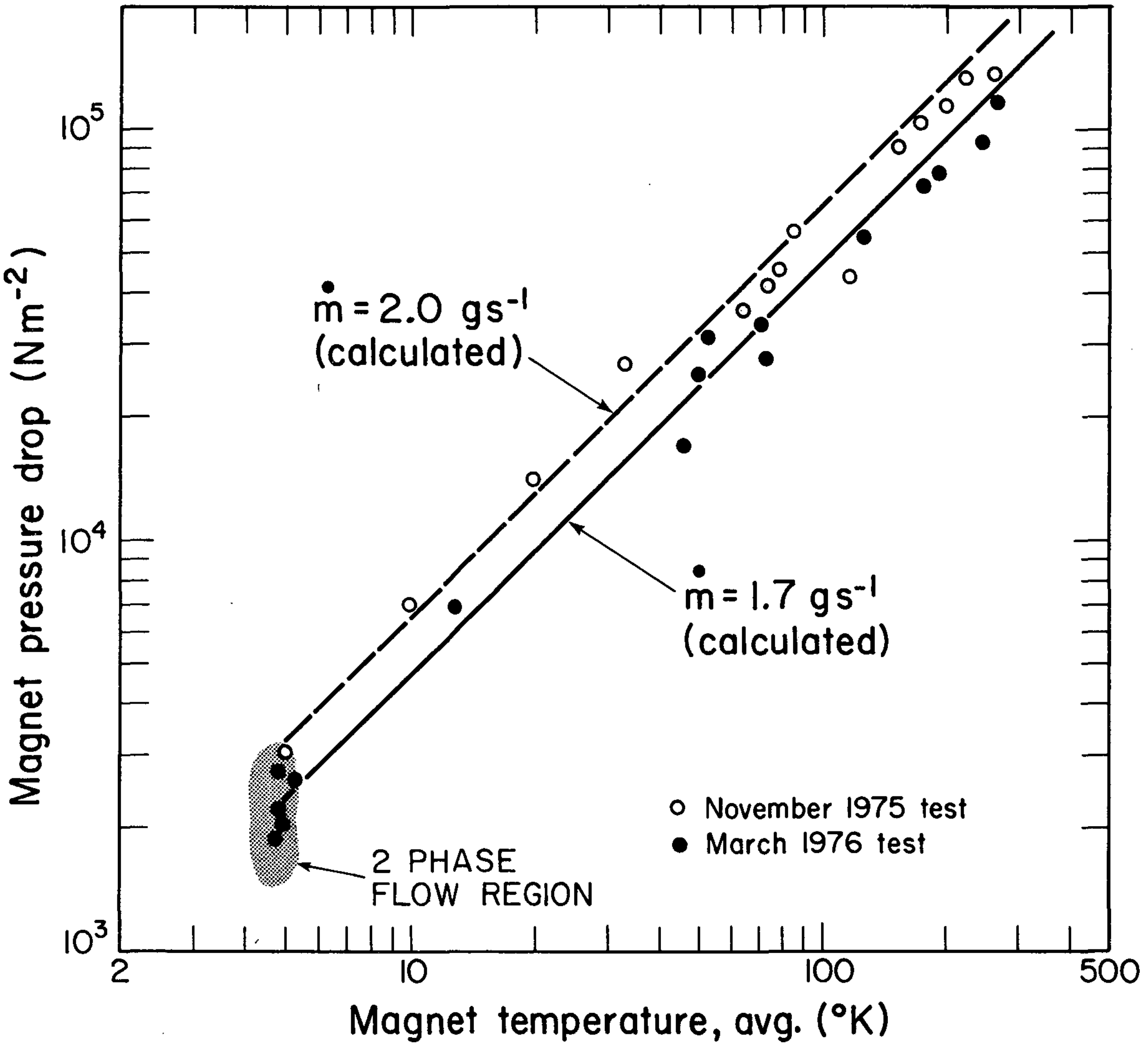

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Figure 4 Pressure drop across the 117 m long magnet cooling tube verses the magnet temperature (a comparison of calculation and measurements.)

Quench tests of the coil were made in graduated steps. Quenches were induced at low currents before induced quenches were tried at higher currents. It was established that a quench should do no damage to the coil at the next current level before the next quench was tried. The object of this procedure was to get as much data about the coil as possible.[11]

The quench test demonstrated that most of the magnet stored energy ends up in the magnet bore tube. The bore tube caused the whole magnet to go normal long before the quench fully propagated by normal means. Figure 5 shows I/Io, where Io is the starting current, as a function of time for quenches in the A coil at Io = 100, 300, 500 and 700 A. The I/Io curve makes a sharp break; that is the point where the whole coil suddenly goes normal. The shift of part of the magnet current from the coil to the bore tube generates enough heat to drive the entire coil normal. The bore tube worked entirely as expected. The magnet can be safely quenched even when the superconducting composite is carrying current densities in excess of 10^9 A m^{-2}.

Measurement of strain in the bore tube during the first test of the coil showed that the coil, bore tube and cooling tube behaved as a single unit. During the second test, it became clear from the strain gage measurements that a portion of the magnet coil separated from the bore tube as the magnet was charged. This is due to failure of an epoxy joint between the two. During the second test, training of the coil was observed. Spontaneous quenches occurred at 597, 654, 696, 733 and 773 A; the training was progressive. Once 700 A had been exceeded, the magnet charged to 700 A without difficulty. The A coil has been

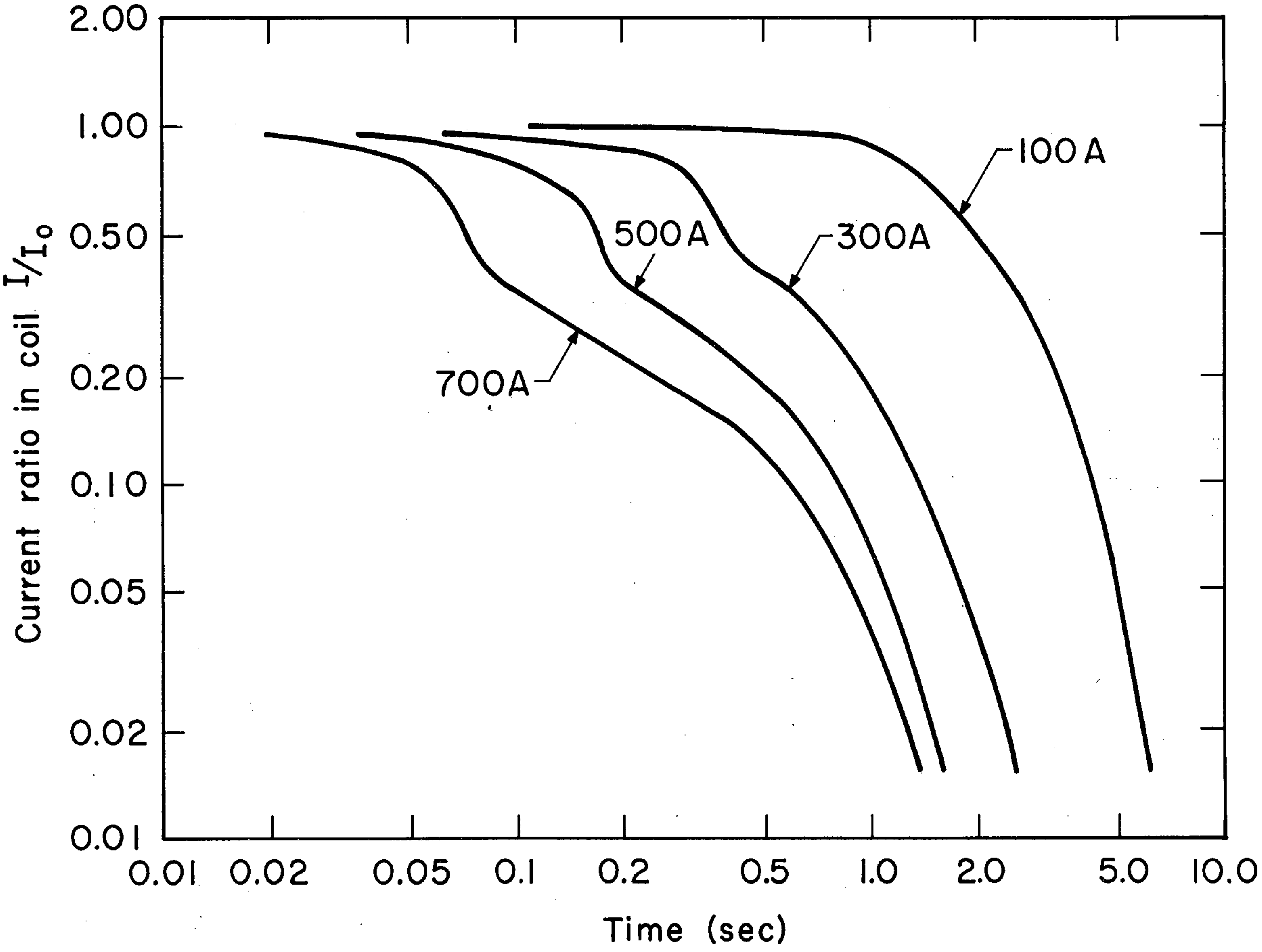

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Figure 5 The ratio of the coil current to the initial coil current as function of time since the start of the quench for initial currents of 100, 300, 500 and 700 A.

charged to about 85 percent of its critical current at 4.8° K. The coil probably could have been trained further. The tubular cooling system and the bore tube behaved as expected. However, future LBL coils will have to be redesigned in order to eliminate the problems due to epoxy breakage between the coil and the bore tube.

FUTURE LBL TESTS

The B coil one meter diameter solenoid will be tested in the late spring of 1976. The interaction between the A and B coils will also be tested. The next generation of PEP detector prototype coils will include a 2 meter diameter solenoid. It is expected that some new design concepts will be employed in future test coils.

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REFERENCES

1. F. Lobkowitz et al., "General Users' Magnet Design for PEP", published in the 1975 PEP Summer Study Proceedings, pp. 46-75.
2. A. Barbaro-Galtieri et al., "Report of the General Purpose Detector Group", published in the 1975 PEP Summer Study Proceedings, pp. 108-115.
3. M. Alston-Garnjost et al., "A Proposal to Simultaneously Measure Charged Particles and Gamma Rays Over a Large Solid Angle at SPEAR II", a Lawrence Berkeley Laboratory Proposal, October 1974.
4. M.A. Green, "The Large Superconducting Solenoid for the MINIMAG Experiment" To be published in Advances in Cryogenic Engineering, LBL-3677, July 1975.
5. M.A. Green, J.D. Taylor, P.H. Eberhard, "PEP Detector Development, Large Superconducting Test Solenoid, Superconductor Tests", Lawrence Berkeley Laboratory Engineering Note M 4885, January 1976.
6. P.H. Eberhard, M.A. Green, J.D. Taylor, "MINIMAG Experiment, Large Superconducting Solenoid Magnet, The Oval Solenoid Test", Lawrence Berkeley Laboratory Engineering Note M4843, UCID 3759, July 1975.
7. M.A. Green, J.D. Taylor, "PEP Detector Development, Large Superconducting Test Solenoid, Construction of the A Coil", Lawrence Berkeley Laboratory Engineering Note M 4886, December 1975.
8. M.A. Green, J. Gunn, "PEP Detector Development, Large Thin Coil Solenoid Test, Strain Gage Selection and Placement", Lawrence Berkeley Laboratory Engineering Note M 4890, January 1976.
9. E. Groves, private communication on the calibration of Lakeshore Cryotronics Silicon Diode Thermometers.

10. P.H. Eberhard, J.D. Taylor, "A Technique to Induce Quenches", Lawrence Berkeley Laboratory Physics Note 816, February 1976.

11. P.H. Eberhard, "A Cautious Method for Testing Superconducting Magnets", Lawrence Berkeley Laboratory Physics Note 812, December 1975.

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