Lawrence Berkeley National Laboratory

Recent Work

Title

THE LARGE SUPERCONDUCTING SOLENOID FOR THE MINIMAG EXPERIMENT

Permalink

<https://escholarship.org/uc/item/3pv9n378>

Author

Green, Michael A.

Publication Date

1975-07-01

00004301712
Presented at the Cryogenic Engineering
Conference, Kingston, Ontario, Canada,
July 22 - 25, 1975

LBL-3677
c.1

THE LARGE SUPERCONDUCTING SOLENOID
FOR THE MINIMAG EXPERIMENT

Michael A. Green

RECEIVED
LAWRENCE
BERKELEY LABORATORY

AUG 13 1975

July 1975

LIBRARY AND
DOCUMENTS SECTION

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

For Reference

Not to be taken from this room

LBL-3677
c.1

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

-iii-

THE LARGE SUPERCONDUCTING SOLENOID
FOR THE MINIMAG EXPERIMENT*

Michael A. Green

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

July 1975

ABSTRACT

The MINIMAG experiment detects and analyzes charged and neutral particles that result from the collisions of electrons and positrons in SPEAR II. The large superconducting solenoid, which detects charged particles, must be thin from a radiation standpoint. The radiation thickness of the solenoid and its cryogenic system have been set at one-third of radiation length. As a result, the 1.5 T solenoid coil has a thickness of less than 2.0 mm. The superconductor must operate at a current density in excess of $8 \times 10^8 \text{ A/m}^2$. The solenoid, which has a diameter of about 1 m, must operate at fairly high stress ($3.3 \times 10^8 \text{ N/m}^2$) in the conductor, while the magnetic stored energy is in excess of 0.7 MJ/m. The cryogenic and refrigeration system is rather unconventional because of the stringent radiation-thickness requirements of the experiment. The magnet, its cryostat, and its refrigeration system are described in the paper. A series of experiments which lead to the full-scale magnet are also discussed.

*Work done under the auspices of the U. S. Energy Research and Development Administration.

THE LARGE SUPERCONDUCTING SOLENOID
FOR THE MINIMAG EXPERIMENT

M. A. Green
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

INTRODUCTION

The superconducting magnet described here was to be used as part of a detector for an experiment (MINIMAG) on the electron-positron storage ring and colliding-beam facility (SPEAR II) at the Stanford Linear Accelerator in California. Although the MINIMAG experiment was cancelled, the magnet development work was not. The development of superconducting magnets, such as the one described here, is vital for the advance of high-energy physics on colliding-beam machines such as DORIS in Germany, the ISR at CERN in Switzerland, and the proposed PEP machine in the United States.

The design of the MINIMAG experiment was dictated by the requirement of accurate measurement of both charged-particle and γ -ray kinematics over a large solid angle and energy range.¹ The charged-particle detector with its momentum-analyzing solenoid magnet, the magnet described here, needed to be compact to minimize the volume of the surrounding photon (γ -ray) detector. There should be a minimum amount of material between the interaction region and the γ -ray detectors. The radiation thickness of the magnet was set at one-third of a radiation length.

The detector could have occupied a space no larger than 2.3 m on either side of the interaction region in SPEAR II. Machine beam dynamics dictate that the detector solenoid magnet should have a practical length of around 2 m. The diameter of the solenoid, which could not be smaller than the diameter of the charged-particle detectors, was set at one meter. A 0.5 T conventional solenoid could have been used in this experiment; its power consumption would have been at least 1.6 MW, and its momentum resolution would have been somewhat limited. A superconducting solenoid would permit one to increase the central induction to 1.0 or 1.5 T. Thus, the power consumption would be reduced and the momentum resolution would be improved.

The MINIMAG Solenoid is described here; more detailed descriptions and calculations are found in References 2, 3, and 4. This paper concludes that the MINIMAG Solenoid design is technically feasible. The experimental work needed to prove feasibility is discussed here. Small-coil experimental results are presented as are descriptions of the full scale test coils, which were under construction at the time this paper was written.

THE SUPERCONDUCTING SOLENOID MAGNET²

A superconducting solenoid that uses conventional winding and cryogenic techniques (for example the large bubble-chamber magnets) will not meet the radiation thickness requirement of this experiment. Due to the short radiation length of copper-based superconductor composites (15 to 16 mm), a thin high-current density coil is required. In addition, for structural elements it is mandatory to use low-Z (low atomic weight) materials, which have long radiation lengths..

The Superconductor

Copper-based superconductors are used because they are available. A 1.5 T solenoid will require a conductor that is capable of carrying at least $8 \times 10^8 \text{ A/m}^2$ in the metal. (The average coil-current density may be $4 \times 10^8 \text{ A/m}^2$, provided the insulation is a low-Z material.) Superconductors that can be used with such high-current densities in the metal are available from at least three manufacturers in the United States. Table I shows the specification for a material that could be used in the MINIMAG solenoid.

A superconductor similar to the material shown in Table I was tested at the Lawrence Berkeley Laboratory in 1974. The material, which was made by Supercon (Supercon material 252E-9), could carry over $1.6 \times 10^9 \text{ A/m}^2$ in the metal at an induction of 2 T. The measured Supercon material, which has the properties close to those shown in Table I could carry over 1250 A at 4.2 K and an induction of 2 T.

The Solenoid Coil

Since the MINIMAG solenoid has an iron shield and return path, the solenoid behaves like an infinitely long solenoid magnet. Two layers of the material shown in Table I are sufficient to produce the desired maximum central induction of 1.5 T. The physical characteristics of the MINIMAG solenoid are shown in Table II. Figures 1 and 2 show the coil and its iron shield.

The superconducting magnet is divided into four coils. Each coil is 445 mm long and is wound with 810 turns on a spool, which has an overall

TABLE I.

The Characteristics of the Proposed MINIMAG
Solenoid Superconductor

Conductor diameter	1.0 mm
Critical current at 2 T and 5 K . .	> 1000 A
Number of S/C filaments	~ 3000
Copper-to-superconductor ratio . . .	1 to 1
S/C filament diameter	~ 13 μ m
Conductor twist pitch	~ 10 mm
Copper resistance ratio at 5 K . . .	> 40
Conductor radiation length	16.2 mm
Conductor diameter with insulation .	1.1 mm

TABLE II. .

The Physical Characteristics of the Magnet

Overall magnet length (including the iron).	~ 4240 mm
Overall magnet width and height	~ 2920 mm
Superconducting coil length	1840 mm
Superconducting coil diameter	1000 mm
Inside cryostat diameter	900 mm
Outside cryostat diameter	1100 mm

-9-

XBL 757-3451

Figure 1. Longitudinal cross section of the MINIMAG solenoid and it's iron return path.

XBL 757-3452

Figure 2. Lateral cross section of the MINIMAG solenoid and its iron return path.

length of 465 mm. Table III shows the expected characteristics of a 1.0 T and a 1.5 T MINIMAG solenoid.

Figure 3 shows a cross section of a magnet coil, a magnet spool, and the refrigeration tubing, and is a drawing of the large experimental coil. If the magnet coil was to withstand the magnetic hoop stress by itself, the 1.5 T magnet coil would have an average stress of about $3.3 \times 10^8 \text{ N/m}^2$ (48,000 psi). Tests at the Rutherford Laboratory in England indicate that a superconductor with copper-to-superconductor ratio of 1, should work at such a stress level.⁵ The breaking stress for Nb-Ti composite exceeds $8 \times 10^8 \text{ N/m}^2$ (116,000 psi). The stress level in the conductor will be much lower because there is an epoxy bond between the coil, the bore tube, and the Dacron cloth.

The Magnet Bore Tube

The aluminum bore tube serves two functions: It is a winding form for the solenoid; and most important, it will dampen the magnet quench. The bore-tube outside diameter is 998 mm; its thickness is 6 mm. The two flanges, each 10 mm thick, are at the end of each of the four bore-tube sections and have an OD of 1024 mm and an ID of 984 mm. The spool and flanges serve as ribs which restrict the buckling of the magnet spool.

The magnet superconductor is wound under a tension of 126 N. The superconductor is prestressed to $1.6 \times 10^8 \text{ N/m}^2$ (23,000 psi). When the magnet is cooled to 5 K, the conductor prestress drops to $0.3 \times 10^8 \text{ N/m}^2$ (4,300 psi) from the difference between bore-tube and coil contractions. At room temperature the conductor prestress exerts a pressure of 5.0 bar

TABLE III.

The Electrical Characteristics of a 1.0- and 1.5-T
MINIMAG Solenoid Using a 1.1-mm-Diameter
Insulated Superconductor

	Magnet I	Magnet II
Central induction (T)	1.0	1.5
Peak induction in coil (T)	1.02	1.53
Ampere turns required	1.5×10^6	2.2×10^6
Number of turns in magnet	3240	3240
Magnet current (A)	460	700
Magnet stored energy (J)	0.6×10^6	1.3×10^6
Magnet inductance (H)	5.6	5.6
Design charge time (sec)	1200	1800
Design charge voltage (V)	2.1	2.1

-10-

XBL 757-3453

Figure 3. Magnified cross section of the experimental solenoid showing the bore tube, the superconducting coil, and the refrigeration tube.

on the surface of the bore tube. The tube thickness should be 6 mm in order to resist buckling.

Because the most important function of the magnet spool is to dampen a magnet quench, the bore tube material should have a resistivity of 3 to $8 \times 10^{-10} \Omega\text{m}$ at 5 K. Most of the magnet energy will be deposited into the bore tube during a quench. The damping thus imposed by the bore tube will reduce by a large margin the voltages developed during a quench, and will increase the quench time constant from less than 200 msec to nearly 3 sec.

The charge time of the magnet is limited by the energy dumped in the bore tube. When the magnet is charged at the design rate, up to 10 W will be dissipated in the coil bore. The ac loss in the superconductor is two orders of magnitude lower than the bore tube loss.

THE MAGNET CRYOGENIC AND REFRIGERATION SYSTEM³

The magnet will be cooled by two-phase helium flowing in a cooling tube; the helium would be supplied by a CTi Model 1400 refrigerator. The cooling tube, and the magnet coil, around which the tube is wound, are in the cryostat vacuum vessel. There is no cryostat in the conventional sense -- a conventional cryostat would be much thicker from a radiation standpoint. In addition, the unconventional cryogenic system will permit the MINIMAG solenoid to be cooled down in a relatively short time.

The Cryogenic Cooling System for the Magnet

The concept of a tubular cooling system has been demonstrated previously.^{6,7} The solenoid coil will be wrapped by a 12.0 mm-ID aluminum tube. This tube, which is nearly 250 m long, will carry the full flow of a 1400 refrigerator (about 6.2 g/sec) and has a total liquid volume of less than 40 liters. Two-phase helium was chosen as a refrigerant rather than supercritical helium because a magnet cooled by two-phase helium would operate at a lower temperature (4.6 to 5.1 K) than would a supercritical helium-cooled coil (5.1 to 5.6 K). The pressure drop under full flow of two-phase helium is less than 0.4 bar. Two tubes in parallel will further reduce pressure drop by a factor of seven. The temperature inside the magnet cooling tube should vary from 4.4 to 4.7 K, depending on the pressure. The magnet is designed to operate at 5 K, but will probably run at temperatures up to 5.5 K. The heat flows radially from the coil and bore tube to the refrigeration tubes. The estimated temperature rise from the liquid helium to the magnet bore tube is less than 0.2 K.

The cooling circuit will be grounded electrically to the bore tube. The electrical-lead cooling gas will be fed from the main refrigeration circuit through an insulated section, which permits the leads to run at a different electrical potential (see Fig. 3). The coil, the bore tube, and the refrigeration circuit (the inner part of the cryostat) are vacuum cast in epoxy and form a single block, which is suspended from the vacuum vessel by the cryostat support system.

Since the inner cryostat consists of tubing, its pressure rating exceeds 100 bar (1450 psi). A magnet quench will not cause problems in the refrigeration circuit, because it is expected that the quench gasses can be recovered warm. The refrigeration contained within the cold helium can be stored in the refrigerator heat exchanger.

The Magnet Cryostat Vacuum Vessel and Support System

The MINIMAG solenoid will be a warm-bore magnet, which requires both inner and outer vacuum shells. Both shells are to be fabricated from aluminum. The inner shell, which sees only an outward pressure force, will have a thickness of 2.5 mm. The outer shell will be 6 mm thick because it must resist buckling, and because the preliminary design calls for no ribs, so that the radiation thickness is uniform.

The ends of the cryostat have no radiation-length restrictions (only the inner 1.75 m of the solenoid has to be thin from a radiation standpoint). The cryostat vacuum jacket will have an overall length of 2.04 m, and the end regions will contain the cryostat support system, the electrical lead feed, and the refrigeration feed-throughs. Both the magnet and the vacuum vessel will be thick in this region, from a radiation standpoint.

The support system will be a combined tension rod and compression rod support system, which is self-centering during the cooldown. The total magnet mass is estimated to be about 250 kg, but the cryogenic support system is designed to resist lateral and longitudinal forces up to 5000 N. There should be no force on the magnet except gravity force if it is

properly centered; the lateral and longitudinal force-carrying capability is needed to overcome the effects of asymmetry.

Only the ends of the cryostat will have 80 K shields and support points. The 80 K shield will cover the end region where the insulation is complicated by penetrations and support rods. The center part of the cryostat will have a multi-layer insulation (about 50 layers), which is relatively easy to apply.

The Refrigerator and It's Distribution System

The schematic of the MINIMAG magnet cooling system (Fig. 4) shows that the large superconducting solenoid and two smaller compensating solenoid magnets would be cooled by a single CTi Model 1400 refrigerator. The rated capacity of the refrigerator with two compressors and nitrogen precooling is about 70 W. The refrigerator will be connected to a 500-liter storage Dewar and to the distribution system for the MINIMAG solenoid.

The cold gas from the refrigerator will be fed to the distribution system at a pressure of 3 - 5 bar. The supercritical helium will pass into the control Dewar where it will be cooled in a heat exchanger to around 4.4 K, and then it will pass to the magnet-cooling coils through a J-T valve. Since the gas will already have been precooled, little gas (1 or 2 percent by weight) will be flashed; the two-phase stream will enter as about 99% liquid. The helium will pass through the magnets and returns to the control Dewar as at least 30% liquid, which will be used to precool the incoming helium stream. The liquid level in the control Dewar will be used to control the refrigeration system.

XBL 757-3454

Figure 4. The MINIMAG solenoid refrigeration system schematic diagram.

Since the magnets will be in series, the cooling will be positive and well defined. The cooldown of the system (an estimated 350 kg of total cold mass) should take less than 12 hr. Liquid from the 500-liter storage Dewar can be used to aid the cooldown between 25 K and 5 K and to help the system recover from emergencies (such as unexpected magnet quenches).

The estimated static heat leak for the main MINIMAG solenoid is estimated to be about 10 W plus 0.06 g/sec of flow through the electrical leads (equivalent to about 7 W of refrigeration). The dynamic load for the solenoid is estimated to be about 10 W. The two compensating solenoids would require about 6 W of refrigeration plus 0.03 g/sec of lead gas flow (equivalent to about 3.5 W of refrigeration). The transfer line and control Dewar are expected to consume an additional 9 or 10 W. The system, while charging, is expected to use about 50 W of refrigeration, but when the magnets are charged the load is expected to drop to around 40 W. The experiment was supposed to operate for at least one year. The maximum continuous operating time would have been 2000 hr, which is within the continuous operating capability of one Model 1400 refrigerator, provided it has proper purification.

RADIATION THICKNESS OF THE MINIMAG SOLENOID⁴

A conventional version of the MINIMAG solenoid would be one-third of a radiation length thick. Most of the radiation thickness (over 90%) is an aluminum conductor coil 30 mm thick. The superconducting version of the MINIMAG solenoid is also one-third of a radiation length thick, the

TABLE IV.

The Average Radiation Thickness of Various
Components in the MINIMAG Solenoid

Component	Radiation Thickness (Radiation Lengths)
Inner vacuum vessel	0.028
Inner superinsulation	0.008
Magnet bore tube	0.067
Superconductor	0.101
Refrigeration tubes & helium	0.030
Dacron and epoxy filler	0.009
Outer superinsulation	0.008
Outer vacuum vessel	0.067
Total Thickness	0.318

thickness being quite uniform at 0.32 ± 0.02 radiation lengths. Table IV shows a breakdown of the radiation thickness of the various parts of the MINIMAG solenoid.

EXPERIMENTAL MAGNETS

Proving the feasibility of the MINIMAG concept requires three stages of experimental work: In the first two stages, a small round solenoid and a small oval solenoid were completed before the MINIMAG experiment was cancelled. The third stage of the experiment, which will be completed in the fall of 1975, consists of two large solenoids, which operate under conditions similar to those in the MINIMAG experiment.

The Small Round Solenoid⁸

The round solenoid was wound with a rectangular superconductor (0.7 mm by 1.4 mm) made by Supercon (Supercon 252-E10). This conductor, which has 3045 filaments in a copper matrix (one part copper to one part Nb-Ti), will carry 1.5×10^9 A/m² at 2 T and 4.2 K. The conductor was wound in four layers on a round form, which has a center tap between the 2nd and 3rd layers. There are 113 turns on the first two layers and 114 turns on the outer two layers. The coil is about 100 mm long with a bore diameter of about 60 mm.

We tested the outer two layers at a temperature of 4.2 K. The magnet quenched at 1420 A (1.45×10^9 A/m² in the conductor which is on the 10^{-14} Ω m resistance line). There was no charge rate sensitivity or training

in the coil. The peak induction in the conductor was 1.78 T; the coil central induction was 1.66 T.

All four layers were tested at two temperatures, 4.2 K and 4.6 K. The magnet quenched at 1130 A (1.15×10^9 A/m²) and 1080 A (1.10×10^9 A/m²), respectively. There was no training or charge rate sensitivity. The peak induction reached 2.83 T in the winding. The round solenoid test proved that modern multifilament superconductors can be made to operate at very high current densities in a magnet.

The Oval Solenoid⁹

The oval solenoid, which was wound with the same superconductor as the round solenoid, was designed to subject the superconductor to very high tensile stresses while the conductor is running at high current densities in a magnetic field (see Fig. 5). The oval solenoid form has variable radii of curvature: The largest radius is 500 mm; the smallest, 33 mm. The stress in the conductor is determined by the largest radius of curvature assumed by the conductor. It should be noted that this largest radius is reduced as the conductor is strained. (The conductor pulled away from the winding form during the test.)

The superconductor in the coil was stressed as current was put into the coil; the peak current was 1300 A (1.33×10^9 A/m). At that current the stress in the conductor was at least 3.7×10^8 N/m² (57000 psi), while the peak induction was 1.84 T. In later tests, the coil was impregnated with wax, which did little to strengthen the coil, and prevented good cooling. The motion of the conductor as it was stressed caused the

CBB 753-1874

Figure 5. The test oval solenoid.

coil to train between 70 and 95 percent of the coil's critical current. The test showed that superconductors can be operated at high stress levels and high current densities simultaneously. The tests also showed that the superconductor should be held firmly by the epoxy to prevent wire motion.

The Large Solenoids

Two full-scale MINIMAG-type coils are under construction. Each solenoid coil is 1.03 m in diameter and 0.5 m long and corresponds to one of the four coils in the MINIMAG solenoid. The two large test coils will permit us to test the superconductor under the stored energy and cooling conditions present in the full MINIMAG solenoid. They will be tested separately, then together.

Each of the two large solenoids is wound with a different superconductor. Each superconductor is 1.0 mm in diameter and has 0.05 mm thick Formvar insulation. Each conductor should carry over 1000 A at 2 T and 4.2 K. The first coil to be tested will be wound with an MCA conductor that has 2300 filaments twisted in a copper matrix. (The copper-to-superconductor ratio is 1.8 to 1.) The second coil will be wound with Supercon material which has 2700 filaments twisted in a copper matrix. (The copper-to-superconductor ratio is 1 to 1.) Testing with two kinds of superconductors permits us to evaluate their performance under conditions of high current densities and at full stored energy.

SUMMARY

A superconducting MINIMAG solenoid can be built so that it is less than one-third of a radiation length thick. The 1.5 T magnet will approach a number of technical limits. The stress problems and quench problems are solvable. The magnet is designed to operate well below its critical current at a temperature of 5 K. Because the magnet is not cryogenically stable like the large bubble-chamber magnets, the intrinsic stability of the twisted fine filamented superconductor is needed to insure that the magnet will operate stably. Preliminary tests are encouraging. Full scale tests which will accurately model the large MINIMAG solenoid will be finished in the fall of 1975.

REFERENCES

1. M. Alston-Garnjost, A. Barbaro-Galtieri, O. Dahl, P. Eberhard, R. Kenney, A. Litke, G. Lynch, T. Mast, D. Miller, J. Nelson, S. Parker, M. Pripstein, R. Ross, B. Sadoulet, F. Solmitz, M. Stevenson, and D. Young, "A Proposal to Simultaneously Measure Charged Particles and Gamma Rays over a Large Solid Angle at SPEAR II," Lawrence Berkeley Laboratory Proposal, October 15, 1974.
2. M.A. Green, "MINIMAG Experiment, Large Superconducting Solenoid Magnet; A Description of the Magnet and It's Conductor," Lawrence Berkeley Laboratory Engineering Note M4833, UCID 3753, May 1975.
3. M.A. Green, "MINIMAG Experiment, Large Superconducting Solenoid Magnet, The Cryogenic System," Lawrence Berkeley Laboratory Engineering Note M4834, UCID 3754, June 1975.
4. M.A. Green, "MINIMAG Experiment, Large Superconducting Solenoid Magnet, The Radiation Thickness of the Magnet and Its Cryostat," Lawrence Berkeley Laboratory Engineering Note M4835, UCID 3755, March 1975.
5. Materials for Use in Superconducting Magnet Construction (a report of the GESSS Collaboration) GESSS-3, April 1974.
6. M.A. Green, "Cooling Intrinsically Stable Superconducting Magnets with Supercritical Helium," pp. 669, IEEE Transaction on Nuclear Science, NS-18, June 1971.
7. CERN Courier, "Villigen Superconducting Muon Channel Begin Operation," A Description of the Swiss Institute for Nuclear Research -- Super-critical Helium-cooled Solenoid) 15 (2): 36 (1975).

8. M.A. Green and J.D. Taylor, "MINIMAG Experiment, Large Superconducting Solenoid Magnet, The First Small Experimental Magnet," Lawrence Berkeley Laboratory Engineering Note M4836, UCID 3756, July 1975.
9. P.H. Eberhard, M.A. Green, and J.D. Taylor, "MINIMAG Experiment, Large Superconducting Solenoid Magnet, The Oval Solenoid Test," Lawrence Berkeley Laboratory Engineering Note M4843, UCID 3759, July 1975.

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720