QUENCH PROTECTION FOR A 2-MJ MAGNET *

J. A. Taylor, M. Alston-Garnjost, P. E. Eberhard,
G. H. Gibson, M. A. Green, B. Pardoe, M. Pripstein,
R. R. Ross, R. Smits

Lawrence Berkeley Laboratory, Berkeley, California 94720

and P. Lecomte

Deutsches Electronen Synchrotron (DESY)

Abstract

A superconducting solenoid with conductive bore tube has been used at energies up to 1.9-MJ to test various methods of quench protection. The methods all involve shifting the main coil current to the conductive bore tube and include (1) allowing the quench to evolve naturally, (2) interrupting the primary circuit while providing a varistor used as a shunt across the coil, and (3) turning the entire magnet normal by dumping a short pulse of current from a capacitor bank through the windings.

Introduction

In 1974 a group of physicists and engineers at the Lawrence Berkeley Laboratory began studying the possibility of building a superconducting solenoid which would provide approximately 1.5 T over a large usable volume, and at the same time would have walls which would not significantly absorb gamma rays so that they could be studied outside the central volume of the solenoid. Such a magnet was desirable for use in detectors being designed for colliding beam accelerators. From these studies, a design was developed which has been tested in three prototype magnets and is the basis for an 11-MJ magnet being built in conjunction with the TPC experiment at PEP.[1,2]

Figure 1 shows a partial cross section of a magnet (Coil C) based on this design. Intrinsically stable Nb-Ti conductor with a copper to superconductor ratio of 1.8 is used. This is wound on an aluminum coil form (bore tube) which acts as a shorted secondary winding during quenches. Cooling is provided by two-phase helium flowing through a tube wrapped around the magnet. This entire package is vacuum impregnated with epoxy. In operation, the magnet is surrounded by vacuum rather than the conventional LHe bath.

Tests of the first two magnets (Coils A and B) built using the conductive bore tube design have already been reported.[3,4] In December 1977 and January 1978, a larger version (Coil C) was tested. Table 1 gives some of the properties of this magnet. The maximum stored energy of the C coil is 5 times greater than that of the B coil.

Maximum Temperatures During Quenches

One of the properties studied extensively during testing of the C coil was the maximum temperature which could have developed during a quench. This can be determined if the current (I) in the coil is monitored and recorded as a function of the time (t) since the quench was initiated. The maximum possible temperature which exists in the coil is directly related to the integral $\int_0^t I^2 dt$.[5-7] This integral has been used for some time in the electronics industry to predict component failure. The temperatures indicated by this method tend to be on the high side since thermal conduction is neglected in the calculation. However, where short time intervals are involved, the error is small and the method can be a very useful tool for measuring the effectiveness of quench protection systems.

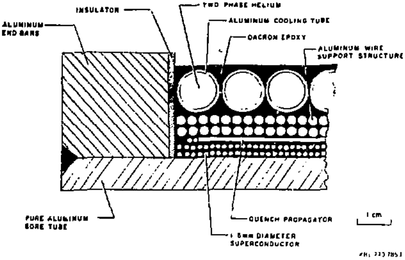


Fig. 1. Cross section of the two-meter diameter coil C solenoid.

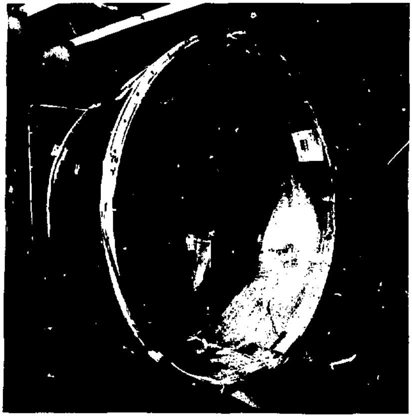
Table 1. Some coil parameters.

	Coil C Inner 1/2	Coil C Outer 1/2	Full Coil
Diameter (m)	2.0024	2.0062	2.0043
Length (m)	0.70	0.70	0.70
Cu/Sc Ratio	1.8	1.8	1.8
Wire Diameter (mm)	1.5	1.5	1.5
Inductance (H)	0.46	0.46	1.81
Max. Current (A)	1811	1767	1443
Current Density (Am^{-2}) (at Max. Current)	1.0×10^9	1.0×10^9	8.2×10^8
Max. Stored Energy (kJ)	750	710	1900

Figure 2 is a picture of the C coil. It contains 77 kg of superconductor composite. The maximum stored energy of the coil is 1.9-MJ. If this energy were uniformly distributed through only the superconductor composite during a quench, the temperature would be about 140°K. Since much of the energy of the C coil goes into the shorted secondary (the bore tube), much lower temperatures result.

---

*Work supported by the General Science and Basic Research Division, U. S. Department of Energy under contract W-7405-ENG-48.



CBB 776-6029

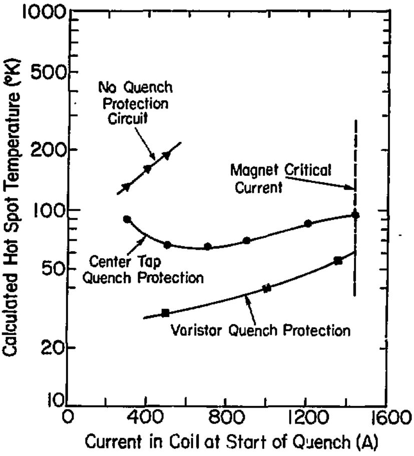
Fig. 2. Two-meter diameter coil C solenoid in preparation for testing.

Without some provision for controlling a quench, the energy of a magnet can produce non-uniform heating. If a major portion of the stored energy ends up as heat in a small volume, destructive temperatures are produced. To prevent these high temperatures, either the energy must be routed to some alternate heat sink or it must be spread over a larger volume. The ideal situation for the latter solution would be a uniform distribution over the entire volume. The goal of the protection systems for the C coil is to distribute the heating over a larger volume and in a more uniform fashion than would result with no quench protection.

Three methods of quench protection were studied during the tests of the C coil; results are shown in Fig. 3, each method will be discussed in a section of this paper. The methods of protection studied were (1) internal protection provided by the conductive bore tube design, (2) interrupting the current in the main magnet circuit while providing a varistor as a shunt across the coil, and (3) dumping a short pulse of current from a capacitor back through the windings. Over 130 quenches have been recorded and studied on this magnet.

Protection Based on the Bore Tube Design

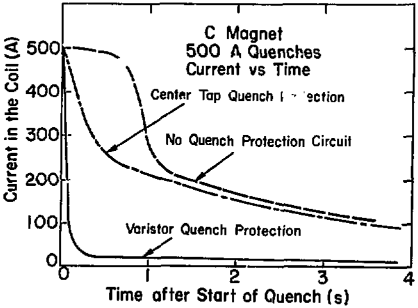
Protection due to the conducting bore tube occurs when the resistance of the coil circuit grows large enough to cause the current to decay with a time-constant comparable to that of the aluminum bore tube. When this occurs, currents circulate in the bore tube and dissipate part of the magnet's energy there. Eventually heat from the bore tube is transferred to the superconductor and turns the entire coil normal.[8]



XBL 786-9289

Fig. 3. Maximum temperatures computed for the three protection methods.

In the A and B coils, this mechanism was sufficient to protect the coils with no further circuitry. In the C coil, as well, current is shared between bore tube and magnet windings at the time of a quench. A plot of current vs time for a 500 A quench is shown in Fig. 4. With 500 amps in the coil (2 layers) the hot spot temperature during a quench reached 200°K (computed from $\int I^2 dt$). This was at an early stage of the test, and it was decided not to risk higher temperatures at that time. Based on our experience with the A and B coils, it is expected that this inherent protection would become more effective at higher currents. It is unknown whether it is adequate by itself to protect the coil at its maximum stored energy.



XBL 786-9279

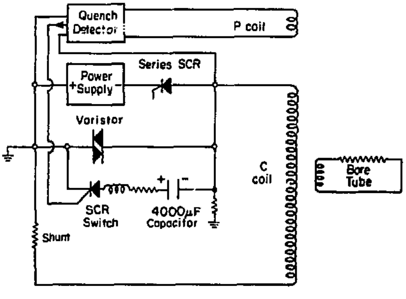
Fig. 4. Magnet current decay for the three protection methods.

Added Protection by Switch and Varistor

The most effective protection system tested used a Silicon Controlled Rectifier (SCR) as a switch in the main coil circuit. A varistor was provided across the coil as a shunt. The circuit is shown in Fig. 5. The varistor is a device which changes its resistance in such a way that it tries to maintain a constant voltage drop. In order to switch off the current in the main coil circuit when a quench is detected, the SCR in the capacitor dumping section turns on and discharges the capacitor. This momentarily provides an alternative power source for the magnet; the current through the series SCR goes to 0. This permits the series SCR to switch off, thus opening the main circuit. When the capacitor has discharged, the magnet's current must now flow through the varistor. The varistor maintains the voltage across the coil at (or less than) 1800 V. Thus, it adds enough resistance to cause the magnet circuit to have a very short time constant. This in turn causes almost all of the energy of the magnet to shift to the bore tube. At the same time the main coil turns resistive due to $\dot{B}$ effect.

This protection uses the same effect as the protection given by the bore tube alone (the shift of current to the bore tube). The SCR and varistor make the phenomenon much more effective by causing the current to shift more quickly. Only a small part of the energy is dissipated in the varistor. The protection works by distributing the energy of the quench over a larger volume rather than in a local hot spot.

The major disadvantage of this technique lies in the high voltages developed across the magnet leads. When the C coil is operating near its maximum current, these voltages are over 1000 V for almost a second and over 600 V for 2 sec. Since the magnet operates in a vacuum, instead of a helium bath, insulation of these voltages is simplified. However, as the bore tube warms up during a quench, materials which have cryopumped onto its surface are released and the vacuum deteriorates. The electrical insulation of a 10^{-2} to 10^{-3} Torr vacuum is very poor; much worse than at atmospheric pressure.[9] Thus, in the time during a quench when the vacuum becomes worse, the remaining high voltage is more likely to arc over if no insulation other than vacuum is used.



XBL 789-2871

Fig. 5. Circuit schematic with series SCR switch and varistor for protection.

Additional Protection Due to a Current Pulse

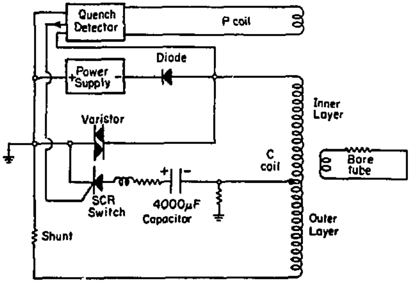
Although the current pulse protection (called Center Tap Protection on Figs. 3 and 4) is less effective, it is quite adequate. The voltages involved are lower and do not persist over a long period. A circuit diagram is shown in Fig. 6.

Note that the C coil was wound with a current lead (center tap) attached between the two layers of windings so that is could be run as either a single layer or a double layer coil. This center tap lead is attached to the protection circuit.

The SCR switch of the protection circuit is normally open and the capacitor bank remains charged (charging circuit is not shown). When a quench is detected, a trigger pulse is sent to the gate of the SCR and the capacitor discharges. During the discharge, current flow increases in the outer layer of windings and decreases in the inner layer of windings. The result is a large field change in either layer, but little change in the flux seen by the two layers in series. If the two layers are closely coupled, the inductance at the center tap is very low (less than 50 µH for the C coil). This effect could work without the bore tube. The change in flux between the two layers produced $\dot{B}$ heating which turns the conductor normal.

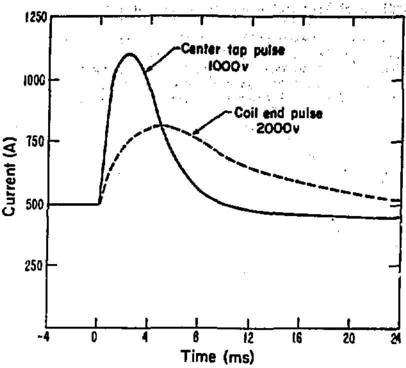
It is possible to get the large dI/dt with moderate voltages. The limiting factors are the dI/dt and the maximum I which are not harmful to the SCR. This is controlled by an inductor and resistor in the protection circuit.

Figure 7 shows a plot of the current through the outer half of the coil. The current rises rapidly, reaching a level near maximum after about 0.3 msec. This current level is maintained for about 2 msec then decays with a time constant of $\sim$3 msec. The voltage at the center tap is elevated only until both halves turn normal. As a result of the current pulse and the resulting $\dot{B}$ the superconductor is turned normal in the outer half of the coil during the same msec in which the quench was detected. The inner half may also turn normal at that time, but does not remain normal since the current flowing in that half of the coil is low. Later it does turn normal, largely due to heating from the outer layer. This



XBL 789-2872

Fig. 6. Circuit schematic with protection by current pulse on center tap.

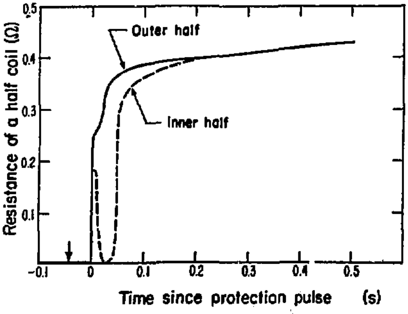


XBL 789-2874

Fig. 7. Current in outer half coil during protection pulse.

time varies from 35 msec for 500 A down to $\sim$2msec at maximum current. Figure 8 shows a plot of the resistance of each half of the coil as a function of time. The effectiveness of this method is decreased if the leads to the inner and outer halves of the coil are reversed so that current increases in the inner half and decreases in the outer half; an explanation of this will be given in a future paper.

Protection by this method is due to spreading the heating, during a quench, more uniformly through the magnet. In the C coil, the bore tube also takes a large portion of the heating. This is due to the shift of current from the winding to bore tube as the time constant of the windings becomes shorter. The fraction of energy taken by the bore tube is about 60% at 500 A and 75% at 1400 A.



XBL 789-2873

Fig. 8. Coil resistance with center tap current pulse protection. Initial current is 500 A.

Variations on the Current Pulse Method. In the C coil, the conducting bore tube permits an additional method of using current pulse protection. In this version, the protection current pulse is applied to the same leads as the power supply (the power-supply is isolated by a diode). The bore tube, acting as to see a relatively low inductance, though not so low as that seen at the center tap. Therefore, it is possible to use these pulses to turn the coil normal. However, higher voltages are required to give the same protection. Figure 7 compares the current through the magnet for the center tap and end connection wiring, as a function of time. The rise and decay times are much *slower for the end wiring and maximum current is lower.* These curves were done with 2000 V on the capacitor for the end protection case and 1000 V on the capacitor for the center tap protection case. This full voltage does not appear at the leads of the magnet due to the resistor and inductor of the protection circuit.

Possible Use in Other Magnet Designs

Quench protection through the use of a current pulse at the center tap of a magnet appears to be usable in magnets which do not have a conducting bore tube. The two halves of the coil would need to be closely coupled inductively so as to permit a rapid increase of current at the center tap without excessive voltages. Quench detection must be both quick and reliable for optimum operation. Seven hundred joules of stored energy will heat 1 cm^3 to 300°K. Total mass of the conductor would have to meet this criteria with some reserve for heating prior to the coil being turned fully resistive.

It should be clearly stated that our tests thus far have only been done with a conducting bore tube. We expect to test non-shorted secondary type magnets at a future time.

Conclusions

Both the series SCR with varistor and the current pulse on the center tap provide adequate protection for magnets with a shorted secondary winding in the 2 MJ size range. Both methods will be available for protection of the TPC magnet and a redundant system of quench detection and protection will be used to insure reliable operation.

Acknowledgments

Many people have participated in the construction of the C coil and its testing. We would particularly recognize the efforts of Paul Miller who oversaw construction of the coil in the shops, and along with Chuck Covey and Harold Van Slyke prepared the test setup and operated the refrigeration system during the test. In addition, a number of other laboratory employees have also contributed to the successful completion of these tests. It is all too easy to over-look their work as part of the every day routine at a large laboratory. The success of this project is in large measure due to their interest and spirit of cooperation.

References and Footnotes

1. A. R. Clark, et al., "A Proposal for a PEP Facility Based on the Time Projection Chamber," PEP-4 (1976).

2. M. A. Green, et al., "A Magnet System for the Time Projection Chamber at PEP," this proceedings, Rept. LBL-7577 (1978).

3. M. A. Green, "The Development of Large High Current Density Superconducting Solenoid Magnets for Use in High Energy Physics Experiments," Doctoral Dissertation, Rept. LBL-5350.

4. M. A. Green, "Large Diameter Thin Superconducting Solenoid Magnets," Cryogenics, p. 17 (1977).

5. P. H. Eberhard, et al., "Quenches in Large Superconducting Magnets," Proc. 6th Intern. Conf. on Magnet Technology, Rept. LBL-6718 (1977).

6. P. H. Eberhard, et al., "A Burnout Safety Condition for Superconducting Magnets and Some of Its Applications," Rept. LBL-7272 (1968).

7. For a similar but not identical derivation see: B. J. Maddock and G. B. James, "Protection and Stabilization of Large Superconducting Coils," Proc. IEEE 115(4), 543 (1968).

8. P. H. Eberhard, et al., "Tests on Large Diameter Superconducting Solenoids Designed for Colliding Beam Accelerators," IEEE Transactions on Magnetics, MAG-13(1), 78 (1977).

9. This effect is known as "Townsend's Breakdown Condition" or "Paschen's Law." For example see: A. Von Hippel, "Dielectrics" Handbook of Physics, Condon and Odishaw, eds. (McGraw-Hill Book Co., 1967), 2nd edition, p. 4-122.