A LARGE HIGH CURRENT DENSITY SUPERCONDUCTING SOLENOID FOR THE TIME PROJECTION CHAMBER EXPERIMENT

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One of the experiments for the PEP storage rings at the Stanford Linear Accelerator Center uses a superconducting magnet to provide the magnetic field for the Time Projection Chamber detector. This magnet has an inside diameter of 2.04 m and a gap of 3.26 m. The magnet central induction is 1.5T. This magnetic induction is supplied by a thin high current density superconducting coil which is less than 0.4 radiation lengths thick. The magnet stored energy will be 10.9 MJ; the coil superconductor matrix current density will be about 7.0×10^8 Am^{-2}. The TPC magnet uses a two-phase forced flow tubular cooling system which combines many of the advantages of single-phase supercritical helium cooling with those of boiling helium bath cooling.

INTRODUCTION

The Time Projection Chamber (TPC) experiment[1] (named for the new type of particle detector which operates in a magnetic field) is typical of the large scale high energy physics experiments now being built at a number of laboratories around the world. The TPC experiment will be located in one of six long straight sections at the PEP colliding beam facility now being built at the Stanford Linear Accelerator Center (SLAC) by the Lawrence Berkeley Laboratory (LBL) and SLAC. The TPC experimental equipment, which is being built by a collaboration from five different laboratories and Universities, is 5.5 meters long, 6.6 meters wide and 7.6 meters high. The mass of the equipment is around 850 metric tons. The experiment is expected to turn on in the middle of 1980.

The TPC experiment consists of four primary parts, they are: 1) the TPC detector which is located inside a thin superconducting solenoid magnet, 2) the superconducting solenoid which is located between the TPC and two other detectors, 3) Argon calorimeters located at the ends of the TPC detector and just outside the superconducting coil, and 4) muon detectors which lie between and outside various slabs of iron, part of which form the magnet return yoke. The superconducting magnet is a solenoid which has a warm diameter of 2.04 meters and a length (between the iron poles) of 3.26 meters. The total radiation thickness between the TPC and the Argon calorimeter is about 0.67 radiation lengths. Figure 1 shows an artists conception of the TPC experiment. It shows the location of the superconducting magnet (its cryogenic vacuum vessel) in relation to the rest of the experimental apparatus.

The superconducting magnet for the TPC is the culmination of nearly three years of development effort at LBL[2,3,4,5,6,7]. The TPC magnet will be the largest intrinsically stable magnet built to date. The design of the magnet uses an integrated concept where the superconducting coil and a tubular cooling system are combined into a single package. The TPC magnet operates at current densities which are about seven times higher than that typical for magnets with the same stored magnetic energy. This is possible because the TPC magnet incorporates closely coupled secondary circuits which permit the magnet to quench safely.

The TPC magnet consists of five primary subsystems, they are: 1) the coil package, 2) the cryostat vacuum vessel and coil package support system, 3) the helium control dewar and cryogenic distribution system, 4) the power supply and quench protection system, and 5) the iron poles and return yoke. This report discusses the first four subsystems. The fifth is not discussed except that its existance is important in order that the TPC magnet work as designed.

The TPC magnet generates a nominal induction of 1.5 Tesla within a room temperature cylindrical volume bounded by the iron poles and the TPC pressure wall. The magnet field uniformity within a cylinder two meters long and two meters in diameter must be better than one part in one thousand. (This is why the iron poles are an essential part of the magnet.) The induction outside the TPC magnet coil will be less than 0.01 Tesla. The TPC magnet cryostat is 200 mm thick. The cryogenic coil package (which includes the cooling tubes) is 33 mm thick.

DESCRIPTION OF THE SYSTEM

The Coil Package. The coil package for the TPC magnet integrates the superconducting coil, the quench protection system and the helium cooling system. The TPC coil package is surrounded by vacuum and a superinsulation system. The coil package, consists of four parts which are vacuum impregnated together in epoxy. The four parts of the coil, which are shown in the cross-section in Figure 2, are as follows: 1) a thin high current density superconducting coil, 2) an 1100-0 aluminum bore tube which is 9.5 mm thick, 3) a layer of ultra pure RRR-2500 aluminum, and 4) a cooling tube system which supports the coil and carries two phase helium to cool the magnet coil.

The superconducting coil consists of about 1740 turns of copper based niobium titanium superconductor which is drawn into a monolithic conductor, which has matrix dimensions of 0.9 by 3.6 mm (the matrix is insulated by 0.05 mm of Formvar, the insulated conductor dimensions are 1.0 by 3.7 mm). The matrix consists of 1.8 parts copper to 1 part niobium titanium (45% Ti and 55% Nb) which is divided in 2200, 26μm diameter filaments. The superconductor within the matrix is twisted one twist every 40 mm. The wire was made by SUPERCON of Nadick, Massachusetts USA. It has a guaranteed critical current of 3400A at 4.2°K and 2.0T.

The physical and electrical parameters of the superconducting coil are shown in Table 1. The nominal magnet stored energy is 10.9 MJ while the current density in the matrix is 7.0×10^8 Am^{-2}. The resulting product of current density squared times stored energy is 50 times higher than normal operating practice[7,8,9]. Key elements to safe high current density operation of the TPC magnet are the conductive bore tube and the layer of ultra pure aluminum.

The 9.5 mm thick bore tube and layer of ultra pure aluminum are closely coupled inductively to the superconducting coil. The basic role of the aluminum is to protect the coil in the event of a magnet quench. The bore tube and the ultra pure aluminum circuit will affect the quench process in the following way:

1) The magnet bore tube and the pure aluminum causes the current to shift from the coil to itself as the quench proceeds.

2) The bore tube and aluminum will absorb a substantial amount of stored magnetic energy during the quench process.

3) Since the time constant of magnetic flux decay is long compared to the time constant for initial current decay, the transient voltages in the coil system are greatly reduced. (External quench protection systems can put large voltages on the system but, these voltages would have to be much larger if no bore tube was used.)

4) The bore tube and aluminum causes portions of the coil to go normal which would not do so by ordinary quench propagation. This phenomena is called "quench back".

5) The bore tube and pure aluminum allow effective methods of "dynamic quench protection" to be used.

The bore tube and ultra pure aluminum are "passive quench protection" elements.

TABLE 1 BASIC PARAMETERS OF THE TPC MAGNET

PHYSICAL PARAMETERS	
Vacuum vessel warm bore inside diameter	2.040 m
Vacuum vessel outside diameter (maximum)	2.440 m
Vacuum vessel length	3.840 m
Distance between the iron poles	~3.26 m
Coil diameter (cold)	2.160 m
Coil length (cold)	3.300 m
Coil package thickness (cold)	33 m
Coil package radiation thickness	0.32 Rad. len.
ELECTRICAL AND MAGNETIC PARAMETERS	
Nominal central induction	1.50 T
Induction uniformity (within a cylinder 2 m Ø by 2 m long)	≤0.001
Number of turns of superconductor*	1740
Number of turns of ultra-pure aluminum*	~710
Coil current at nominal central induction*	2270 A
Magnet coil self inductance*	4.22 H
Magnet stored energy at nominal central induction E*	10.9×10^6J
Superconductor matrix current density J*	$7.00 \times 10^8 \mathrm{Am}^{-2}$
EJ^2 product*	5.33×10^{24}

* Most probable value.

The bore tube alone will perform all of the above functions. The ultra pure aluminum layer causes the current to shift from the coil faster[10]. This makes the coil go completely normal sooner through "magnetic quench back". It also causes the magnet current to drop to low levels early and thus reducing the hot spot temperature in the coil. Low current quench protection is greatly improved. If the ultra pure aluminum is left uninuslated or its ends are shorted togther, the TPC magnet charge time increases from 0.75 hours to 2.0 hours. One can use diodes across the ultra pure aluminum coil in order to reduce the charge time. (Therefore, the charge time is no longer limited by heating in the ultra pure aluminum circuit.)

The outermost part of the coil package is the layer of squared aluminum cooling tubes. The tubes serve a dual function. They provide a flow channel for two-phase helium and they act as a support against magnetic forces in order to limit the total magnet strain during charging. (Only one out of three of the cooling tubes carries two-phase helium for magnet cooling; the other two tubes contain vacuum.)

The superconductor, bore tube, ultra pure aluminum, and cooling tube package will be vacuum impregnated in epoxy to make an integrated package. The coil layer to layer and layer to ground insulation is designed to withstand 8-10 kV. All regions of the epoxy contain glass fabric, dacron or metal. The epoxy volume is minimized and the superconductor is prestressed in order to eliminate or reduce cracking during cryogenic cooling and coil charging.

<u>The Cryostat Vacuum Enclosure and Supports</u>. Since the TPC magnet coil package is cooled by two-phase helium flowing in the tubes around the magnet, the cryostat, in the conventional sense, is eliminated. The advantages of tubular cooling over the more conventional bath cooling techniques are: 1) the cool down of the magnet is well controlled because the helium flows in a well defined path, 2) the mass and radiation thickness of the tubular cooling system is low compared to conventional inner cryostat vessels, 3) helium in direct contact with the coil is minimized, and 4) cryogenic safety is greatly enhanced because the cooling tube pressure rating is high and the ratio of liquid helium volume to free vacuum volume is minimized.

The cryostat vacuum vessel consists of an inner wall, end walls with feedthroughs, an outer wall, and a compression rod support system. The inner cryostat wall serves two primary functions which are: 1) the 11 atmosphere pressure wall and support for the TPC, and 2) a vacuum barrier for the insulating vacuum. The outer wall carries the room temperature to helium temperature supports and it serves as a place to mount drift chamber detectors as well as being a vacuum tight wall. Figure 3 shows the cross section of the coil within its vacuum enclosure.

The magnet coil package will be insulated by 50 to 100 layers of evacuated superinsulation. There will be a conduction cooled 100°K shield within the superinsulation blanket. The shield will be edge cooled by liquid nitrogen flowing in tubes. The end regions of the cryostat, where all of the penetrations are, will have liquid nitrogen cooled shields as well as superinsulation. The projected heat leak from 58 m^2 of room temperature surface is about 10 Watts.

The TPC coil package, which operates at 4.6°K, is supported to the room temperature outer wall through a system of 16 fiberglass-epoxy compression rods. The support system is shown in Figure 4, which shows the North end of the TPC magnet with its end vacuum wall peeled away. There are two types of support rods and support rod fixtures. There are radial support rods at four places (at 1,5,7 and 11 o'clock) at each end. In addition, there are antirotation rods located in two places (at 3 and 9 o'clock) which prevent rotation of the coil within the cryostat vessel. (Radial compression rods alone are unstable.) The fiberglass epoxy rods are hollow with a 25.4 mm outside diameter and 3.2 mm thick walls. (The hollow rods resist buckling better than solid rods of the same cross sectional area.) Since the coil and cryostat are thin compared to their diameter, six rod fixtures are needed at each end to reduce ring deflection while the support system is loaded. The supports are designed to carry a longitudinal load of 2×10^5 N and a radial load of 1×10^5 N. The expected heat leak from 300K to 4K through the support rods will be under 10 Watts.

All services to the magnet will pass through the north wall of cryostat at clock positions (while facing south) of 3, 7 and 11 o'clock (see Figure 4). Vacuum services to the cryostat will be at the three o'clock position. They include pumping by a cryoadsorbtion pump (backed with mechanical pump), and a rupture disk. Unlike conventional superconducting magnets of this size, the helium inventory is small (about 80 liter). Therefore, the ratio of free vacuum volume to liquid helium volume is about 30. This is very favorable from a safety standpoint (particularly when one considers that the rupture pressure for the cooling tubes exceeds 100 atm).

The liquid helium and liquid nitrogen (for the shields) will be fed into the magnet at the seven o'clock position. Helium and nitrogen entering the magnet vacuum enclosure is separated from the helium and nitrogen leaving the enclosure by the use of separate transfer lines to be described later. The gas cooled electrical leads for the magnet will enter at the eleven o'clock position (see Figure 4). The 2700A gas cooled leads are entirely enclosed in the cryostat vacuum. Plug-in cable connectors which are designed to be free of condensed water and ice will be connected to the outside of the cryostat. (Water in the region of the TPC wireing must be avoided.) Miscellaneous instrumentation wires and wiers for carrying short current pulses will be located where convenient in 3, 7 and 11 o'clock positions. External magnet supports will be located at 1, 3, 5, 7, 9 and 11 o'clock at each end of the cryostat. They will carry the magnetic and gravitational forces from the cryostat to the iron return yoke.

The Control Dewar and Cryogenic Distribution System. The TPC magnet cryogenic system can be divided into two distinct parts which are separated by about 15 meters of semi-flexible helium transfer line. The first part is the magnet itself with its cooling rube. Since the TPC experiment is located behind a radiation shield, there is no access to the cryostat. So the magnet cryogenics will be designed for transient pressures as high as 100 atm. (The normal operating pressure within the TPC magnet cooling tube is typically less than 1.5 atm.) The second part of the cryogenic system is the control dewar and conditioner system which separates the refrigerator and its compressors from the load (the magnet coil). The cooling tube within the magnet coil package was described previously, so this section talks about the external cryogenic system.

The role of the control dewar system is as follows: 1) it separates the refrigerator from the load with a buffer volume of about 200 liters of liquid helium, 2) it contains the valves for controlling the cool down process, and 3) it contains a heat exchanger which reduces the input quality (defined in the steam sense, where low quality means more liquid and less gas) of two phase helium to the magnet. (Reduced quality helium means reduced system pressure drop and additional safety margin.)

Two-phase helium is pumped from the control dewar to the magnet cooling tube by either the refrigerator compressor or a liquid helium pump. The TPC magnet cryogenic system can use either method of pumping so that redundant operation can be achieved.

The reciprocating helium pump built at LBL is designed to pump to 17 gs^{-1} of liquid helium at differential pressure as high at 4 atm. (The flow system requires 12 gs^{-1}.) The helium pump is a positive displacement bellows pump which is driven by a torque and speed controlled motor drive. The pumped helium is heat exchanged with boiling helium in the control dewar to remove the pump work thus providing sub-cooled helium to be transferred over to the magnet coil package.

When the refrigerator compressor is used to pump the two-phase liquid, a helium flow of up to 12 gs^{-1} is supplied from the refrigerator J-T circuit. The J-T circuit flow is expanded to a pressure of about 4 atm and the helium is cooled through a heat exchanger by the boiling bath in the control dewar. The flow is expanded again to the operating pressure of the coil package cooling tube. This provides two-phase helium which is nearly all liquid.

Table 2 presents the expected cryogenic cooling system operating parameters. The TPC magnet will be cooled by a 200W refrigerator which will be located adjacent to the control dewar outside the radiation shielding. The refrigerator will be supplied by compressed helium from a central compressor house located about 600 m away. The magnet cryogenic system will have cold mass of about 1800 kg. All of this mass is coupled to the cooling tube. When cold helium is pumped into the system at the rate of 12 gs^{-1} from the conditioner and the refrigerator, the cool down time is expected to be 24 to 36 hours, depending on whether liquid helium (about 400ℓ) is used to assist the refrigerator when the magnet temperature drops to 30°K and below.

TABLE 2 TPC MAGNET COOLING SYSTEM PARAMETERS

Number of cooling tube turns	192
Number of active turns	64
Cooling tube flow length (active tube)	440 m
Cooling tube flow area	1.8×10^{-4} m^2
Cooling circuit design mass flow	12 gs^{-1}
Peak magnet operating temperature	4.8 K
Estimated cooling circuit pressure drop	∿0.3 atm*
Estimated refrigeration during D.C. operation	∿30 W
Estimated refrigeration during magnet charging	∿80 W**
Estimated gas flow through the electrical leads	0.2 - 0.25 gs^{-1}#
Magnet cooldown time	≤36 hours

* Does not include a 0.2 atm possible "garden hose" oscillation.

** 50W of refrigeration is required to overcome heating in the bore tube due to currents induced by charging.

\# Lead gas flow is not included in the refrigeration estimate.

Figure 5 shows a simplified schematic of the helium cooling system. The first part of Figure 5 shows a method for fast magnet cool down using the conditioner to precool helium gas from the compressors to 80°K. This gas cools the magnet to 100K quickly. Then the helium refrigerator continues the cool down to 4°K. The second part of Figure 5 shows operation of the magnet while it is cold. The conditioner and control dewar system is designed for rapid cool down. However, if a controlled cool down rate is required, the cryogenic cooling system permits this kind of operation.

The control dewar and conditioner, which are located outside the radiation shielding wall, is connected to the magnet, which is buried inside the iron of the TPC experiment, by two 15 meter long nitrogen shielded semiflexible transfer lines. (They can be bent over a 1 meter radius of curvature when they are warm.) The transfer lines carry both liquid nitrogen (which is circulated by a nitrogen pump located in the conditioner dewar), and liquid helium. The liquid nitrogen, which is used to cool nitrogen shields inside the TPC magnet cryostat, also cools shields inside of the transfer line. The projected heat load for 30 meters of transfer line is expected to be less than 5 Watts.

The cryogenic cooling system to be used on the TPC magnet has been tested on three LBL tubular cooled solenoid magnets. The cooling system operated successfully with low pressure drops across the cooling tube. However, the LBL test coils were tested with the solenoid axis vertical (hence the axis of the cooling tube helix is also vertical). The TPC magnet will have a horizontal axis. The helium in the cooling tube will have to flow up and down as it travels through the cooling tube. Such two-phase helium flows can be subject to "slug-plug" flow oscillations (the so called "Garden Hose" effect).

LBL has tested this effect in a one meter diameter cryogenic test coil which has up and down motion similar to that expected in the TPC magnet. Garden hose oscillations of 0.2 atm peak to valley were observed. These oscillations had period of about 30 seconds and appeared to involve the refrigerator as well as the tube coil. As the pressure in the tube was increased, the amplitude of the oscillations was reduced. When the pressure in the tube reached the critical pressure the oscillations stopped. The LBL measurements showed that the temperature in the tube tracked the pressure (a 0.2 atm pressure excursion was accompanied by a 0.2°K temperature excursion). The garden hose oscillation does not appear to be a problem for the TPC magnet. More experimental work will be done in the coming months.

Power Supply and Quench Protection System. The TPC magnet will normally operate at a current of 2270A to produce 1.5T central induction. Operation at 1.65T central induction is being considered. Therefore, the rated current for the power supply has been set at 3000A. The voltage drop across the electrical leads and SCR switches is around 5 volts. The charging voltage approaches 3.7 volts when the magnet charge time is 0.75 hours. Therefore, the power supply rated voltage has been set at 10 volts. A six phase primary regulated supply with a low pass filter will be used.

Quench protection for the TPC magnet consists for four distinct elements. They are: 1) the 9.5 mm thick 1100-0 aluminum bore tube, 2) the layer of ultra pure aluminum, which has an average thickness of 1.6 mm, 3) an SCR circuit breaker, with a varistor resistor across the coil, and 4) a capacitor bank which discharges into the magnet coil center tap to drive the coil normal. The first two quench protection elements are passive; the last two elements require the quench to be detected quickly. It is hoped that bore tube plus the ultra pure aluminum is sufficient to protect the TPC coil in a fail safe way. The two dynamic quench protection elements are added as additional insurance. Figure 6 shows the quench protection system for the TPC magnet.

The varistor resistor is a non-linear resistor that has a voltage drop which is proportional to the current to ~ 0.2 power. The presence of the aluminum secondary circuits greatly enhances the performance of the varistor as a quench protection element.[11] When the varistor is put into the magnet coil circuit by opening the SCR switch from the power supply, the current in the coil circuit drops over three orders of magnitude in 5 to 10 ms. Most of the current which is in the coil will be transferred to the ultra pure aluminum. After around 200 ms, the current in the coil circuit rises back to around 3 percent of its starting value. (The ultra pure aluminum resistance increases as energy is deposited into it. Therefore, some of the current in the circuit is shifted back to the coil.) The varistors to be used in the TPC magnet have a voltage drop of 4000 V at a current of 2300A.

The use of a varistor as a quench protection element requires that the quench be detected quickly and that the varistor be switched into the magnet circuit quickly. The higher the current density in coil the more important fast detection and swtiching become. LBL has developed quench detection circuitry which dtects the presence of a normal region in the coil within 5 ms (at the design current of the coil).

The second dynamic quench protection system discharges a capacitor into the center tap of the TPC coil. This causes a current pulse to flow down one layer while a negative current pulse flows down the other layer. These current pulses drive the entire coil normal within 2 or 3 ms of firing the capacitor bank. Since the two current layers are closely coupled, it takes relatively little energy, compared to the stored energy of the coil, to put large current pulses in the coil. The coil is driven normal by large changes in magnetic flux caused by a current redistribution within the coil, or it is driven normal by having one of the coil layers exceed the critical current limit for the superconductor in that layer. A capacitor bank which has a capacitance of 4500μF supplies the current pulse. The presence of a conductive bore tube appears to enhance the performance of this method of quench protection.

The cable from the power supply and quench protection system will momentarily be operating at 4000 V. The voltage to ground limit within the magnet and the connecting electrical circuitry should be at least 8000 V.

The two active quench protection elements described here have been tested on the LBL two-meter diameter test solenoid magnet. A detailed report of these tests will be presented later.[12] The two meter diameter test coil was quenched many times by inducing a quench with a small quench coil. The magnet was tested up to its critical current. There was no evidence of training. Both active quench protection schemes were tested at the full stored energy (1.9×10^6J) and matrix current density (8.2×10^8 Am^{-2}) in the coil. Both quench protection methods appeared to work very well.

The quench (induced by a small quench coil) was detected by the quench detection system in times as short as 2 ms (we found that quenches could be detected when as little as 45 cm of superconducting wire had turned normal). At high currents either quench protection system drove the magnet entirely normal in less than 5 ms. The varistor quench protection system was most effective because the current in the coil circuit was driven down to only a few percent of its starting value which resulted in low hot spot temperatures. Either quench protection system resulted in less than 100°K at the hottest spot. The LBL test demonstrate that high current density large coils can be quenched safely.

CONCLUSION

The TPC magnet uses a new type of superconducting magnet technology to obtain a low mass low radiation thickness system. The TPC magnet is designed to quench safely even though the magnet stored energy and current density are much higher than is normal for magnets built with more conventional technology. The cooling system is integrated with the coil to create a system which can be cooled down quickly and operated in a safe way.

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REFERENCES

1. "A Proposal for a PEP Facility Based on the Time Projection Chamber", PEP-4, December 1976.

2. M.A. Green, "The Large Superconducting Solenoid for the Minimag Experiment", Advances in Cryogenic Engineering 21, pg. 24, 1975; and LBL-3677, July 1975.

3. M.A. Green et al, "Large High Current Density Superconducting Solenoids for Use in High Energy Physics Experiments", Proceedings of the 6th International Cryogenic Engineering Conference, Grenoble, France, May 1976, and LBL-4824.

4. P.H. Eberhard et al, "Tests on Large Diameter Superconducting Solenoids Designed for Colliding Beam Accelerators", IEEE Transaction on Magnetics MAG-13, (1), pg. 78, January 1977 and LBL-5364.

5. M.A. Green, "Large Diameter Thin Solenoid Magnets", Cryogenics, pg. 17, January 1977, and LBL-5515.

6. M.A. Green, "Large Superconducting Detector Magnets with Ultra Thin Coils for Use in High Energy Accelerators and Storage Rings", to be published in the Proceedings of the 6th International Conference on Magnet Technology, Bratislava, Czeckoslovakia, August 1977, and LBL-6717.

7. P.H. Eberhard et al, "Quenches in Large Superconducting Magnets", to be published in the Proceedings of the 6th International Conference on Magnet Technology, Bratislava, Czeckoslavakia, August 1977, and LBL-6718.

8. P.H. Eberhard et al, "Quench Protection for Superconducting Magnets with a Conductive Bore Tube", LBL-6444, May 1977.

9. P.H. Eberhard et al, "A Burnout Safety Condition for Superconducting Magnets and Its Applications", to be published in Nuclear Instruments and Methods, LBL-7272, February 1978.

10. M.A. Green, "PEP-4 Experiment, Thin Superconducting Coil, the Use of Ultra Pure Aluminum in the Coil", LBL internal Engineering Note M5116, December 1977.

11. M.A. Green, "The Role of the Conductive Bore Tube in the Varistor Method of Quench Protection", LBL internal Engineering Note M5191, April 1978.

12. J.D. Taylor et al, "Quench Protection Studies on a 2 MJ Magnet", submitted to 1978 Applied Superconductivity Conference in Pittsburgh, Pennsylvania, USA, September 1978.

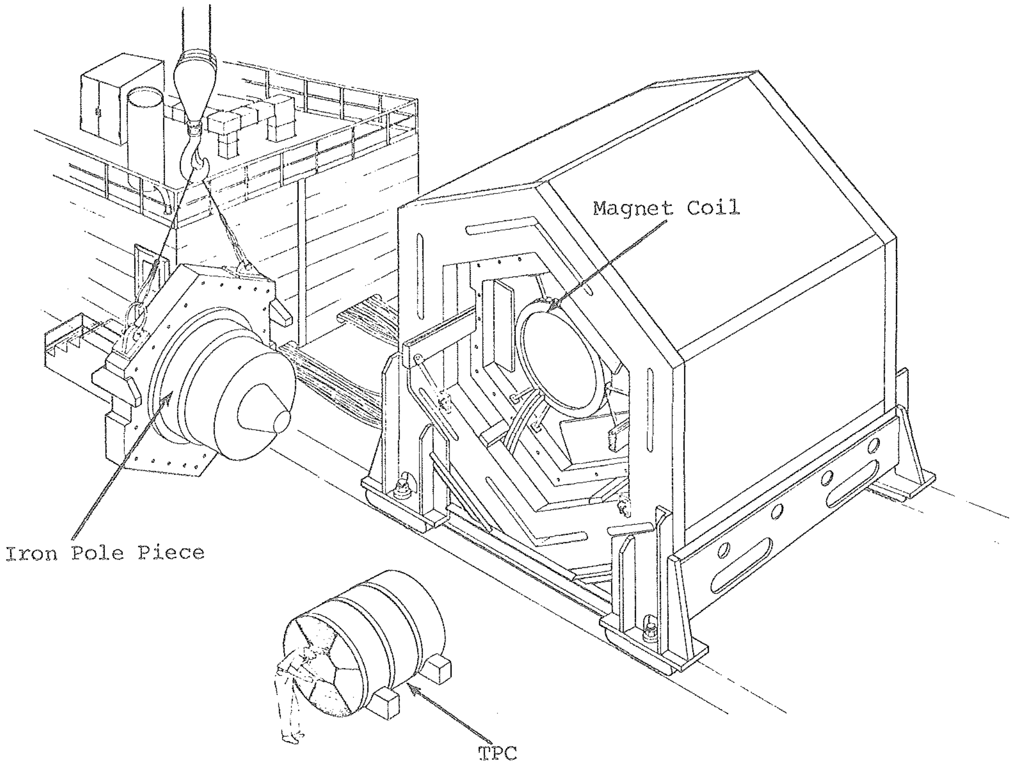

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FIGURE 1 An Artists Conception of the TPC Experiment with the Pole Piece and TPC Removed (the Man Stands Next to the TPC)

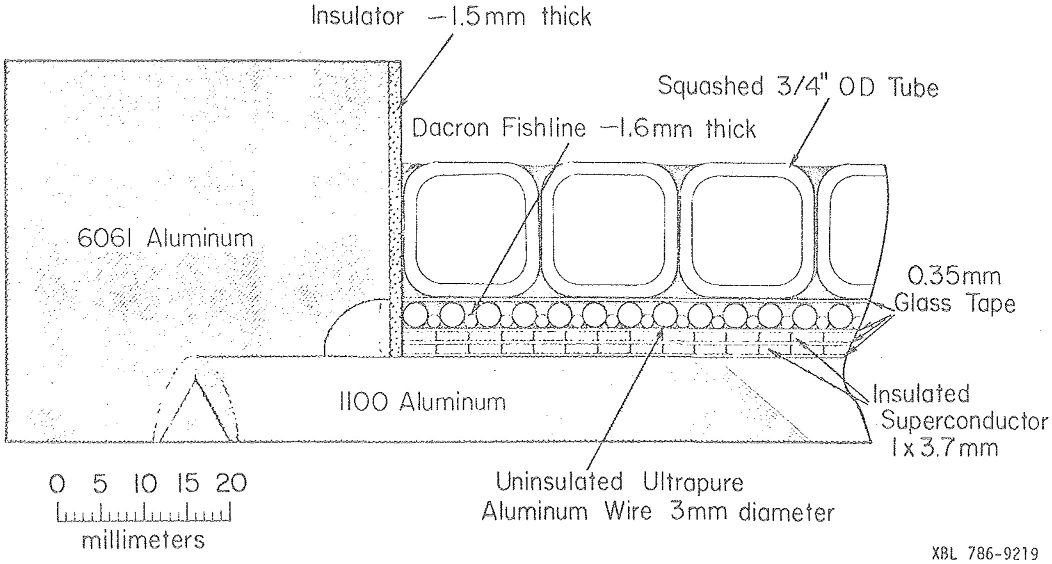

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FIGURE 2 A Cross-Section View of the Magnet Coil Package

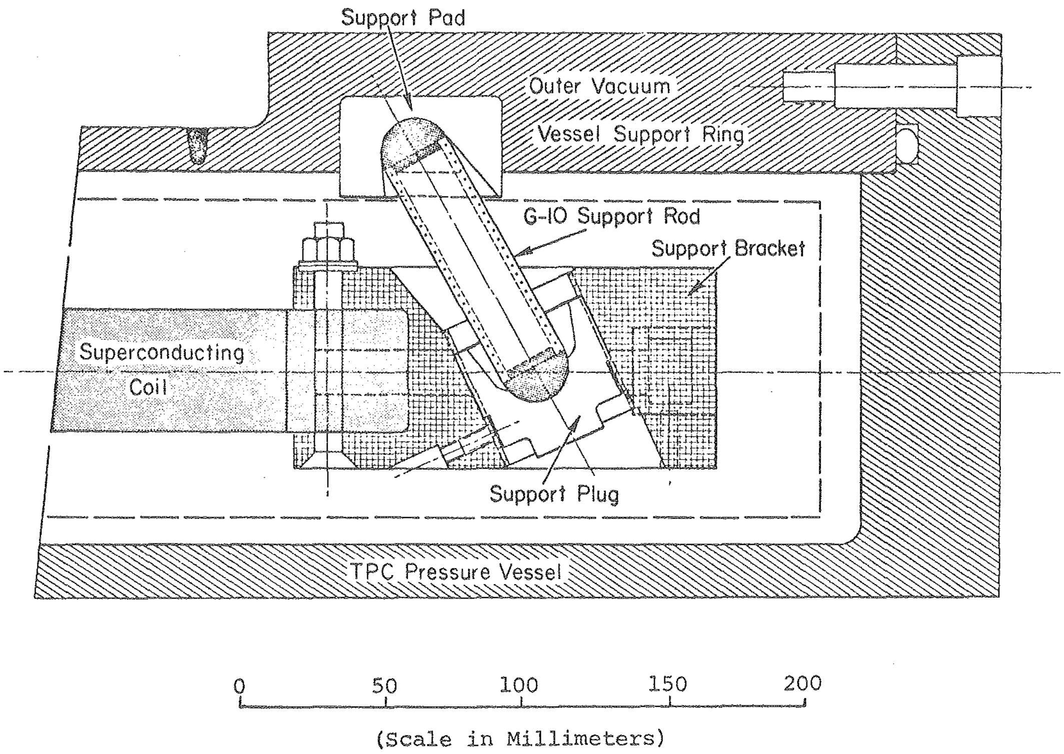

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FIGURE 3 A Cross-Section View of the End of the TPC Magnet Cryostat Showing the Superconducting Coil Package and Compression Rod Support System

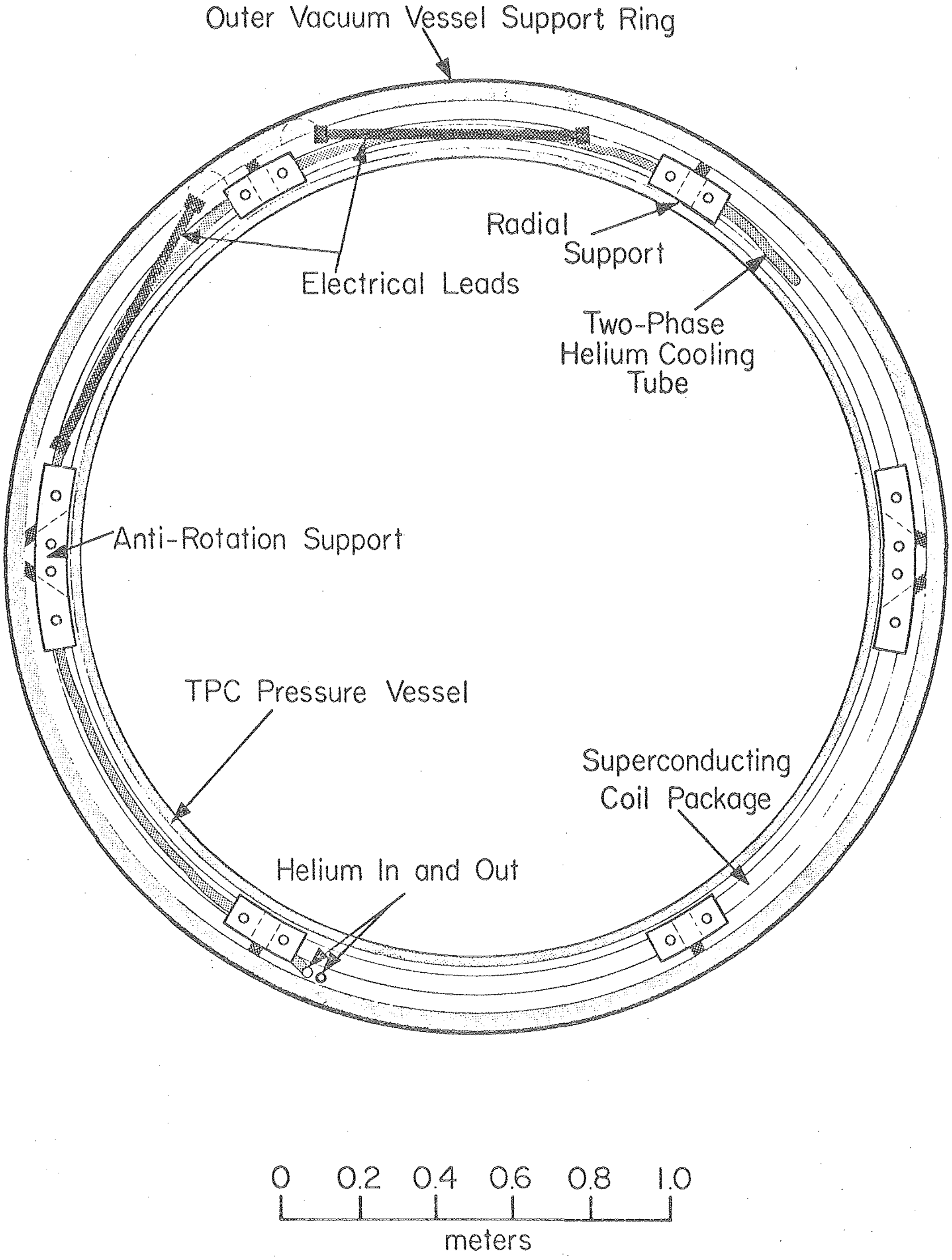

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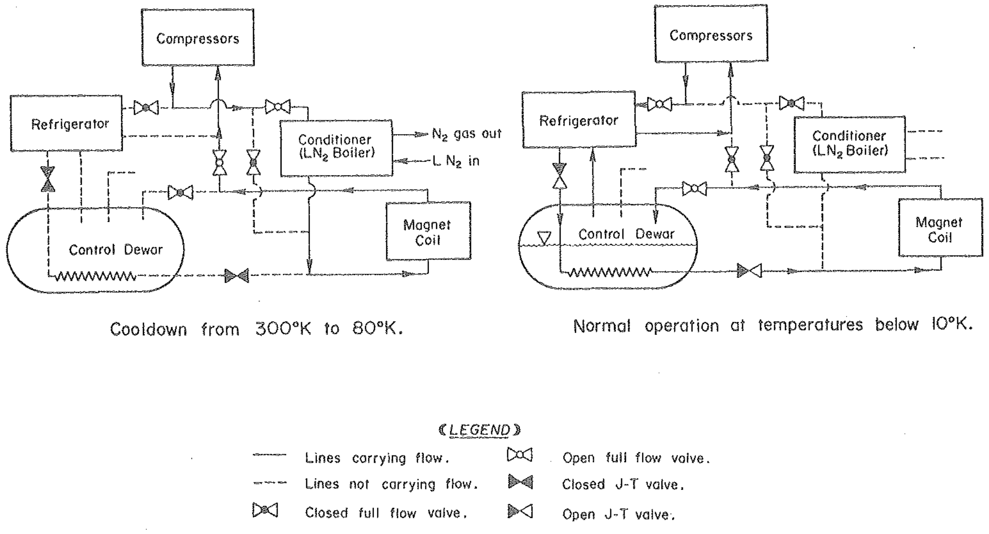
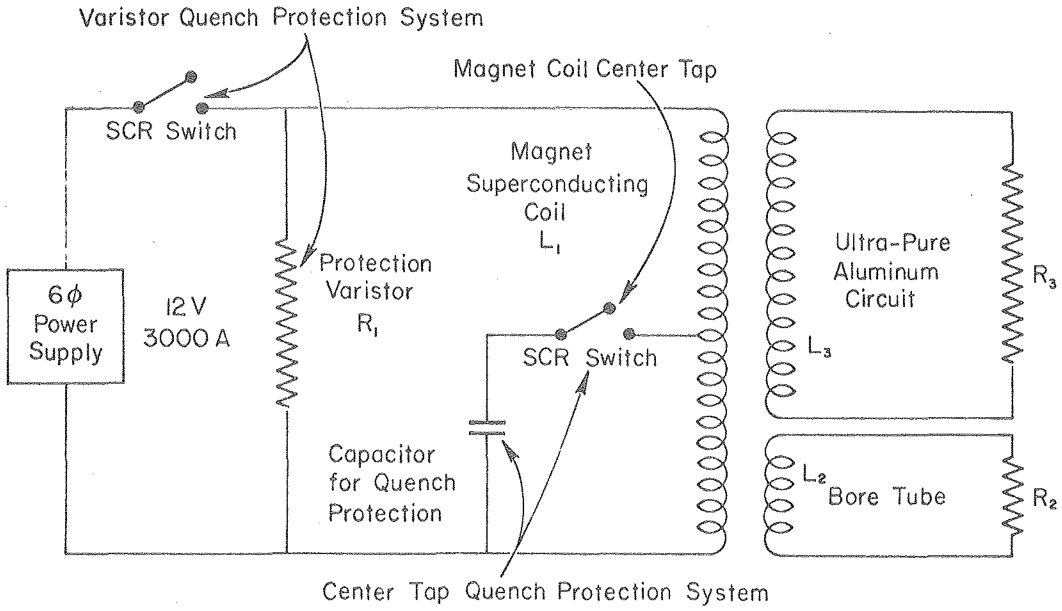
FIGURE 4 A Cut Away End View of the TPC Magnet Cryostat Showing the Location of Supports, Electrical Leads the Coil Package and Inner and Outer Vacuum Cans



Cooldown from 300°K to 80°K.

Normal operation at temperatures below 10°K.

FIGURE 5 A Simplified Schematic Diagram of the Magnet Cooling System. Helium Flow During Cool Down and Normal Operation is Shwon



XBL 786-9253

FIGURE 6 A Simplified Schematic Diagram of the Magnet Power Supply and Quench Protection Systems

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