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William Chamberlain

March 3, 1969

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Summary

A superconducting solenoid was incorporated into a physics experiment at the LRL 184-inch cyclotron. The magnet was kept superconducting for the entire run of $5\frac{1}{2}$ months. The solenoid has a 4-1/4 in. diameter warm bore and an overall length of 3-1/2 ft. The field intensity is 60 kG. The proposed conventional solenoid which it displaced was 11 ft long.

Buried in a steel and concrete shielding wall, the solenoid was the least accessible of all components in the experiment. This condition imposed great emphasis on the reliability of the coil and cryostat structure.

The cryostat was cooled by direct evaporation of liquid helium (LHe) and liquid nitrogen (LN). The LHe supply Dewar and vacuum pump were located 25 ft from the magnet in a region accessible only with accelerator beam off. Liquid-helium automatic fill controls and LN supply Dewars were located 40 ft from the magnet in a region adjacent to the experiment control room.

The solenoid was energized continuously by the power supply--no persistent mode switch was provided.

Cryostat Specifications

In addition to flipping neutrons by virtue of their dipole moment, the magnet was designed to demonstrate that superconducting technology was ready to go to work. Design criteria for both the cryostat and its installation were selected to obtain reliability suitable to an installation of many units, even though the current installation involved only one unit.

The coil housing was designed to meet the ASME pressure-vessel code for 150-psi working pressure. Vent necks were sized for safety in the event of simultaneous loss of insulating vacuum and quench of the magnet. The magnet field energy at maximum current was 200 kJ, capable of lifting the complete cryostat and magnet to a height of 200 ft.

With 20 tons compressive force sustained by

the solenoid coil, what should be the support-structure strength and stiffness to tolerate random placement of iron shielding? Iron, placed in a high field, can only "see" about 20 kG. The proposed solenoid coil would exert the maximum force on iron if all its flux entered a 9-in. -diam pole face. This condition represents 20 kG at the pole face and results in 10 tons. If half the flux entered this pole piece, the load would be 2.5 tons. Using the concept of image poles in a semi-infinite slab of iron, the load at 5-in. distance would be only 1 ton. The design specification was selected as 2 tons at each end, the line of action being any angle away from the center through the solenoid poles.

Cryostat Construction

The main housing, seen in Fig. 1, is a rectangular flanged tube with two rectangular end caps. The three stacks are, from left to right, the electrical leads, the helium fill, and the nitrogen fill. To disassemble the unit, first remove the outer housings and LN-cooled shields from the vertical stacks and ends. The last maneuver requires tilting one of the end caps and sliding it up the remaining vent pipes. At this point, the inner vessels and supports are exposed without having opened any cold seals. All warm seals are elastomer.

At this point, it should be appreciated that in cryostat design, changing from vertical to horizontal axis is not as simple as lying down. On the other hand, we will achieve simpler arrangements. The current design was selected so that, in the event of cold-seal difficulties, we would be able to weld all joints and still get it together. Experience with cold seals has indicated that this is no longer necessary.

Figure 2 indicates the mechanical support arrangement. The tension rods are 1/4-in. -diam by 10 in. -long with a preload of 1 ton. Under maximum load, they would sustain 2 tons at 80000 psi stress. A 20° tilt of the tension rods in an axial direction enables this symmetrical system to sustain axial force. The specified load described earlier will cause a maximum coil

*Work done under the auspices of the U. S. Atomic Energy Commission.

movement of 40 mils axially or 20 mils radially. This stiff support system would be more important to the physics experiment if the magnet were a quadrupole. For this unit, the most stringent positional requirements are dictated by the 1/4-in. radial insulation between the magnet bore and the warm beam pipe. The symmetry of the system insures no change in position during cool-down. Thermal contraction only makes slight change in pretension. The tripods to which the tension rods are attached serve to extend the effective length of the tension rods, in regard to thermal isolation.

The advantage of tension-rod mounting is brought out by the fact that these tripod structures extend the 10-in. rods by only the equivalent of 4 in. at the warm end and 2.5 in. at the cold end. The biggest advantage of the tripods is provision of a convenient place to provide intermediate cooling. For example, LN cooling applied to four tripod heads, cools eight tension rods, resulting in 1/10 the heat to the helium flask. Likewise, a stream of effluent helium gas serves to cool four tripod heads and effect another order of magnitude reduction. The advantage of this last reduction is controversial. For the current test, it saved \$5000 in LHe costs, but for a refrigerator system, the saving would be negligible.

As seen in the figure, the housing has room for reservoirs above the coil. It was expected that the future trend would be away from this arrangement, allowing symmetrical shielding close to coils, but for this design, internal reservoirs appeared to be the simplest way to get the job done. Symmetrical shielding had not been specified.

Installation

Figure 3 shows the magnet installation in the process of disassembly. Note the steel shield blocks on the sides and in front. Steel and concrete on top of these completed a wall from floor to ceiling. A two-foot aisle remained for access to the vent stacks.

Note the beam pipe and back-stop cavities in the steel block. A deuterium target was placed about 2 ft in front of this block. Neutrons from the target pass through the solenoid via the beam pipe while the cyclotron beam, directed at an angle enters one of the back-stop cavities. The cyclotron beam could be alternately directed into either cavity, maintaining symmetry in the physics experiment.

Originally the LHe supply Dewar was to be placed directly above the magnet, requiring about 15 ft of transfer line. None of the roof beams had penetrations, so a slot was allowed between two beams. Initial operation indicated excess radiation through the roof slot. The slot was closed and the transfer line was brought out over the top of a shielding wall to the supply Dewar located on top of a second shielding wall. The transfer line was extended to 30 ft by this last-minute change.

Since the supply Dewar location could not be occupied with beam on, a remote-control transfer system was necessary. The control station, in all its elegance, is shown in Fig. 4. In the upper left, you see a conglomerate of cryogen level gages, vent-rate indicators, pressure gages, and regulators. On the lower right, you see a panel containing transfer cycle timers and electronics for vacuum gages. The magnet power supply and current recorder was located inside the control house. The LN supply Dewar is in the center of this picture, and to the left are nitrogen and helium cylinders for pressurizing both supply Dewars. At the very top you see the total umbilical of 16 tubes and six vacuum-gage cables. Half the tubes were required for magnehelic-style level indicators, which had pressure switches in parallel for triggering the start of LN and LHe transfer.

The rest of the tubes allowed monitoring all vent rates and prevented cold gas discharge in the physics caves except in the event of magnet quench, which discharged helium gas at the magnet through two 3/4-in. relief valves set to open at 15 psig.

The LN transfer lines used 3/8-in. aluminum tube with foam rubber insulation and a vapor separator near the point of delivery. Joints in the insulation were covered with short pieces of plastic tubing and tape. This prevented any deterioration of the foam system during the 5-1/2-month test period. One 25-ft line delivered LN to a diffusion-pump trap, and a 45-ft line delivered LN to the solenoid shield. The LHe transfer line was patterned after those used for hydrogen targets at LRL, but a multilayer wrap of nylon net and aluminized mylar was used as combination spacer system and radiation shield.

To insure availability of helium, the transfer line was designed to work with either 500-liter Dewars or 50-liter Dewars. None of the Dewars had a built-in level gage, so a magnehelic-type gage was built into the short section of transfer line, which was withdrawn when changing supply Dewars. A gas-pressure-actuated valve was designed into the bayonet joint which connected this five foot section to the 25-ft main line.

The short section was initially constructed in the same fashion as the long section, but much trouble resulted. The polyvinyl chloride vacuum housing required continuous pumping, but the end in the supply Dewar provided cryopumping which would compete with the mechanical pump, resulting in various kinds of trouble.

Thermal Oscillations

Anticipating a thermal-oscillation problem in connection with extended vent lines, we examined this problem during laboratory tests of the cryostat. We found thermal oscillation at both the lead and support coolant vents, even without extended vent lines, but extension of the vent lines aggravated the problem. In all cases, the oscilla-

tion was stopped by placing a portion of the restricting orifice close to the cryostat. Since the support coolant vent was also used for high vent rate during transfer, a remotely actuated valve was needed at the cryostat, to bypass the restriction in the normal vent line.

During the experiment run, we found the same problem associated with the supply-Dewar gas-cooled shield vent line. When this line was extended to our control station, thermal oscillation which sometimes resulted was corrected by pinching down a valve at the supply Dewar.

Having accomplished all this, we thought the thermal oscillation problem was under control. Then we suddenly became aware that what we thought were losses because of extremely lossy supply Dewars actually resulted from an extreme thermal oscillation in the short section of transfer line between Dewar and valve. The short section of transfer line was rebuilt with a hard outer cover and vacuum insulation all the way to the bottom of the Dewar. While waiting for the new transfer line, we controlled thermal oscillation by a combination of gas-bleed cooling the line and volume chamber with restriction to damp the system. Neither of these alone would do the job. When the new line was installed, the gas bleed was not necessary, but a small volume chamber was required. From this point on, the standby losses associated with the level gage and continuously installed transfer line were negligible.

Operating Data

The cryostat LN shield used 0.65 liters/h, representing a 30-W heat load. Analysis indicates 7 W was lost to supports, 3 W to vent necks, 15 W to insulation, and 5 W to nonlapping points in the insulation which were provided for assembly convenience and were tolerable by virtue of the LN shield. The reservoir held 8 liters. Our automatic-fill system delivered approximately 5 liters each 8 h. The diffusion-pump trap received 1 liter each 4 h. The LN Dewars were replaced at 3/8 full each 48 h, which indicates 2 liters/h overall consumption.

The cryostat normal helium boil-off with no current in the leads was 1/2 liter/h. With 50 A this increased by 10%, for 70 A, 20%, and 100 A, 40%. Without current, shutting off the support coolant raised boil-off 50%, and shutting off leads and support coolant brought boil-off to three times normal.

The reservoir capacity was 10 liters, and the space around the coil was 20 liters. During magnet operation, the boil-off rate of 0.6 liters/h required an 8 liter fill each 13 h. On standby, with zero current, the fill period would be 16 h, but when the magnet was to be off for some time, we would let the level drop below the coil and trigger a fill each 48 h. The maximum hold time from full to empty was 60 h.

After correcting the thermal-oscillation

problem, we found that 500-liter supply Dewar loss rates were two to four times the specified 1% per day, which comes to 0.4 to 0.8 liters/h. The transfer losses ran from 20 to 67%, depending upon the quantity transferred. In spite of a slow 10-min line cooldown, which used 1/2 liter, the system did not transfer well until some additional time had elapsed. The small 8-liter transfers during operation were therefore inefficient. Under these circumstances total losses ran as high as 1.4 to 1.8 liters/h, depending on supply Dewar quality. On standby, the 24-liter transfers brought overall losses down to 1 to 1.4 liters/h. Poor performance of the transfer line is attributed to porous polyvinyl chloride vacuum housing in conjunction with insufficient ventilations in the mylar wrap, as well as poor venting at the delivery end, which prevented operation at higher flow rates. With improved transfer we would have operated three weeks on a 500-liter supply Dewar, which would correspond to 1 liter/h. As it was, we achieved two weeks on a Dewar, corresponding to 2 liters/h. During the period when the severe thermal oscillation remained undetected, the loss rate was 3 liters/h, requiring a 500-liter Dewar each week.

Cool-Down Data

The total weight of the cryostat and magnet was 700 lb. The coil wire weighed 175 lb. A total of 400 lb had to be cooled to LHe temperature. It was cooled to 77°K with 150 liters of LN, and then to 4.2°K with 65 liters of LHe. Each step required 3 h and 2-1/2 times the theoretical minimum of cryogen. What is the break-even time for letting the magnet warm up during standby operation? If we had a zero-loss transfer and supply Dewar, this would be 5 days, and under actual conditions it was 2-1/2 days, but for this test, the magnet was maintained in the cold condition so that our test would more nearly correspond to the expected cold periods to be encountered in future installations.

Quench History

In Vertical Test Dewar

Quench 1. After 20 min at 100 A, the magnet was charged slowly at 0.5 A/min to 111 A (66 kG). At this point it quenched.

Quench 2. It was charged to 100 A in 16 min, held 3 min, discharged in 9 min, held 3 min, charged in reverse polarity to 93 A in 15 min. At this point it quenched.

Quench 3. Without changing polarity from the previous quench, the coil was charged at the same rate used previously. The coil quenched at 80 A. This quench was startling. It was decided that the future charging voltage would be 2 V instead of 5 V.

As a test, the quench-2 sequence was repeated except for 36-min charge to 100 A. No quench occurred.

In Horizontal Warm-Bore Cryostat

Quench 4. During a physics run, after several

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In Horizontal Warm-Bore Cryostat

Quench 4. During a physics run, after several

hours at 70 A, the magnet was discharged in 7 min, polarity was switched rapidly, the magnet was charged in 21 min to 68 A. At this point it quenched.

Quench 5. After the end of the run, the magnet was charged in 14.5 min to 108 A. At this point it quenched.

After the last quench, it was concluded that there had been no deterioration of the magnet during 5-1/2 months of use, and the convenient 5-V charge rate was not the cause of quenching below 100 A. The low-current quenching was believed to be caused by a combination of heat from the discharge and effect of polarity reversal, but since quench 3 had neither of these, we really don't know.

Operating Schedule

The test extended over 24-1/2 weeks from July 28, 1968 to January 15, 1969. The periods of magnet use can be broken into three parts:

1. A week of trial run during which the coil was energized at 50 A for full test time, which amounted to about 50% elapsed time.

2. A month of use in which the coil was energized at 50 A during 100% of the experiment run time, which was approximately 60% of the elapsed time during this month.

3. A month of use in which the coil was energized at 64 and 70 A during 67% of the experiment operating time, which was approximately 75% of the elapsed time in this period. During this period the coil was periodically reversed in polarity, running 1/3 of the time in each polarity and 1/3 of the time off.

Conclusion

Based on the contents of this paper, one might conclude that the operation of a superconducting magnet is primarily a problem in cryogenics rather than electromagnetism, and for cryogenics, it is primarily a problem in refrigeration transport. This is most probably true, and will continue to be true when magnets are properly constructed, but it should be noted that this was a simple solenoid which avoided the difficulties of dipoles and quadrupoles. Also, note that the experience has been related by a cryogenics engineer.

Fig. 1. Cryostat with solenoid installed.

XBL 684-565

Fig. 2. Mechanical supports. Only one end is shown. A longitudinal member, not shown, is attached to each LN system support point and to each He-gas-cooled terminal, forming a system of tripods.

Fig. 3. Cryostat installed with top shielding removed.

Fig. 4. Cryostat control station.

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