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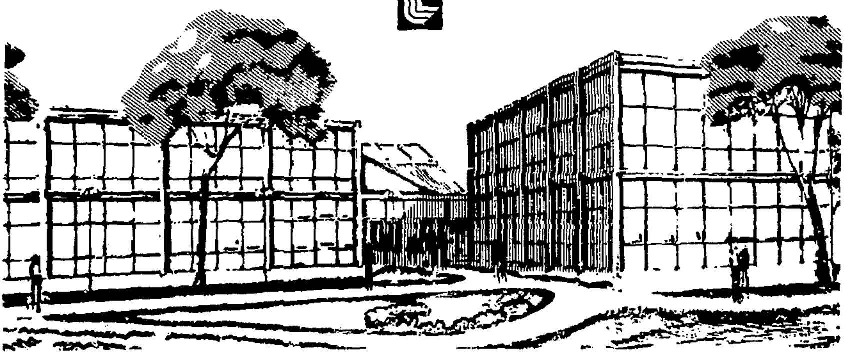

1.1-METER BORE, 8-TESLA TEST FACILITY*

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Summary

The design and fabrication of a 1.1-m bore superconducting coil for an 8-T facility at Lawrence Livermore Laboratory are discussed. This facility will provide the backing field required for testing large multifilamentary Nb_3Sn coils as part of the superconductor development program at Livermore. The magnet measures 1.85 m o.d., is 1.5 m in length, and is solenoid wound in four separate modules. Total cold weight of the assembly is 18,000 Kg. A NbTi superconductor is used throughout with a gradation of current density within the magnet to provide complete cryostatic stability.

The preliminary design of a large 3500-A multifilamentary Nb_3Sn insert magnet is also included. Together, the backing coil and insert magnets are designed to produce a 12-T central field in a 0.4-m bore. The "equal area" theory of cryostatic stability is applied in the design of both magnet systems and is discussed in detail.

A large open-mouth cryostat is used and measures 2 m in diameter and 3.7 m in length. Details of Dewar design and the refrigeration requirements are included.

Introduction

The superconducting magnet group at Lawrence Livermore Laboratory (LLL) is now engaged in a superconductor development project that will ultimately allow the construction of the large magnets required for future controlled thermonuclear reaction machines. The project began two years ago in cooperation with three U.S. firms to produce a multifilamentary Nb_3Sn superconducting material suitable for use in a 12-T magnetic field.[1] In addition to the high field requirement, the final conductor must carry a high current, 10,000 A or more, allow bending in either direction (unlike the present-day tape), withstand the mechanical strain of winding and magnetic loading, and also exhibit a current density that will allow cryostatic stabilization of the conductor. To date, short lengths of 1000-, 3500-, and 10,000-A material have been produced with variations in filament size, heat treatment, and stabilizing technique. Full characterization and optimization studies are proceeding on these conductors. A long length of 1000-A superconductor was wound into a coil and tested at design current.[2] This was the first in a series of coil tests and the results were very encouraging. It is a requirement of this development program that the materials produced operate reliably in coil shapes and sizes required for magnetic confinement in fusion research apparatus. As an initial step, we are now designing a test facility that can accomodate a variety of superconducting coils in fields up to 12 T. The facility will consist of three subsystems:

1. A NbTi backing coil capable of fields in excess of 8 T, complete with power supplies, control equipment, and protective system.
2. A Nb_3Sn insert that will boost the central field to 12 T and is complete with all accessory equipment.
3. Cryogenic equipment that includes the main cryostat for the facility, helium and liquid nitrogen (LN_2) transfer lines, additional helium recovery equipment, a 5000-ℓ helium storage Dewar, and an additional cold box.

Coil Design

The coil design described here is preliminary and is subject to minor modifications.

Backing Coils

The backing coils are designed to be fabricated in four sections using a NiTi superconductor that will be graded according to field strength. Four separate coils are preferred to a single unit primarily for ease of handling, flexibility in operation, and simplification of the quench protection system. Figure 1 is a schematic diagram of these coils installed in the cryostat with the first generation of Nb_3Sn inserts in the bore.

When operated at design current, the backing coils will generate a magnetic field in excess of 8 T as shown in the field plot in Fig. 2.

The backing coils are solenoid wound with a superconductor having an aspect ratio of about 3 to 1. Table 1 is a tentative specification for the three levels of maximum field. Because of the size of the cryogenic system, the bath temperature was taken at 4.6 K to allow for some overpressure. The safety factor on critical current is obtained by specifying the conductor current at 5 K, i.e., at 0.4 K above the bath temperature.

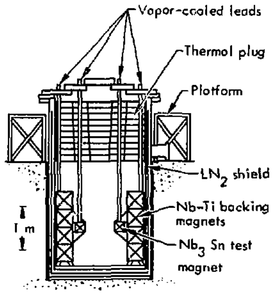
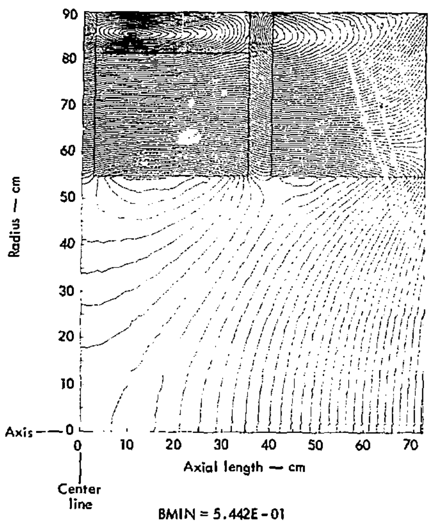


Fig. 1. Schematic diagram of high-field test facility.

*This work was performed under the auspices of the U.S. Energy Research & Development Administration, under contract No. W-7405-Eng-48.

Table 1. Conductor for backing coils.

Conductor specification	Conductor A	B	C
Maximum field (T)	8	6	3
Current at 5 K (A)	1000	1000	1000
Conductor size (mm)	2.9 × 8.1	2.9 × 8.1	2.3 × 7.0
Resistivity ratio in zero field	≥150/1	≥150/1	≥150/1
Nb-Ti filament diameter (mm)	~0.1	~0.1	~0.1
Twist pitch (mm)	~50	50	50
Insulation	Nil	Nil	Nil
Total length (ft)	30,000	130,000	38,000
Approximate weight (lb)	4.21×10^3	1.825×10^4	3.66×10^3
Total conductor weight (tonne)		11.7	



BMIN = 5.442E-01
BMAX = 8.124E+01

List of contour values follow for contours 1, 5, 10 etc.

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10	1.000E+01	55	5.500E+01
15	1.500E+01	60	6.000E+01
20	2.000E+01	65	6.500E+01
25	2.500E+01	70	7.000E+01
30	3.000E+01	75	7.500E+01
35	3.500E+01	80	8.000E+01
40	4.000E+01		

Fig. 2. Magnetic field plot of half of test facility, with backing coils only.

The stability criteria have been based on the "equal areas" theory of Ref. 3. This theory assumes that the two ends of a normal region are in the nucleate boiling regime while the normal region is in film boiling. Because of the shape of the complete heat-transfer curve, there is excess cooling capacity at the cold ends; therefore, heat flows from the normal region along the conductor to the ends. A stable condition can exist where the excess heat in the warm region just equals the excess cooling in the cold regions. If the heat generation in the wire is then slightly reduced, the nucleate boiling region propagates inward from the two ends, and the whole length returns to nucleate boiling. With a composite conductor, the conditions are not quite so simple because the joule heat generated in the copper decreases as the temperature of the conductor falls below the critical temperature for the ambient field and current density, and current begins to commutate from the copper to the superconductor.

Figure 3 shows the heat-generation curve for the 8-T conductor operating at 1000 A and also shows a typical heat-transfer curve for bare copper. The joule heating has been adjusted to give equal areas; this results in a limiting heat-transfer rate, $q = 0.27\ W/cm^2$. The heat-generation curve can be calculated fairly accurately. It is more difficult to predict the heat-transfer curve, which depends upon many factors such as conductor surface conditions, conductor insulation, surface orientation, and cooling-channel dimensions. The small temperature margin available at 8 T makes these factors more critical than at lower fields. Although a layer of conventional enamel insulation on the conductor can improve some of the heat-transfer characteristics,[4] the temperature drop through the insulation would be prohibitive at 8 T.

Because the preceding heat-transfer calculations do not take into account conduction to a neighboring turn of cold superconductor, they are probably somewhat pessimistic. On the other hand, because the cooling channels are relatively long (35 cm) and have a radial depth of only 1.6 mm, if a large portion of a section were to go into film boiling, the coil would probably quench. The design is thus a reasonable compromise.

Although the conductor shape and amount of stabilizer have been largely controlled by stability considerations, the resulting protection characteristics seem to be acceptable. The total stored energy of the backing coil is 60 MJ. If the coil is quenched, the initiation will be detected, and the four sections will be discharged into four independent circuits. Under these conditions, the quench parameters will be:

Maximum voltage per section	320 V
Maximum temperature rise	300 K
Discharge time constant	90 s

Each section of the backing coil will be wound on its own stainless-steel former, which will be complete with side flanges. The formers will be designed to prevent the application of the entire axial force of the end coils to the center windings. Bracing between the Nb_3Sn insert and the backing coils will withstand asymmetric loading caused by construction tolerances and possible fault conditions.

Fault conditions have not yet been fully analyzed, but computer codes exist to do this. In assessing the order of magnitude of the problem, we have estimated that the out-of-balance axial force caused by the current falling to 90% of the full value in one of the inner backing coil sections is 30 tonne, which is not excessive.

Nb_3Sn Coils

The Nb_3Sn coil has been provisionally split into three concentric sections, each on its own form. Besides having most of the advantages outlined for the backing coil, this division offers the following added advantages:

1. These sections can be examined in more detail. Sections can be modified or changed more easily.

2. Alternative materials can be tested under coil conditions at a fraction of the cost of a whole coil set.

The Nb_3Sn coil design is based on the AIRCO* 3500-A conductor with added copper stabilizer. A high current density is desirable in this winding because any increase in coil diameter will increase the size and cost of the outer coil. The inner diameter has a lower limit imposed by the strain characteristics of the Nb_3Sn. The "equal area" stability theory is used again and, as shown on Fig. 4, requires a $q \simeq 0.35\ W/cm^2$. This is larger than the q of 0.27 W/cm^2 chosen for the NbTi coils; however, the increased magnetoresistivity and higher conductor current both make it more difficult to achieve with a similar overall current density.

The proposed conductor (Fig. 5a) has copper, in which cooling channels have been machined, soldered to one wide face of the conductor. All four sides of the cooling channels and 50% of the external surface are available for cooling. With 1-mm-thick insulating "buttons" similar to those used in the Baseball experiment between turns in the layer, and 1.6-mm-thick cooling channels between layers, the overall current density is 2650 A/cm^2. Splitting the coil into three sections, each with its own former, further reduces the effective current density.

One of the advantages claimed for the conductor configuration in Fig. 5b is that the quadrant in which all the superconductors are embedded can be kept on the inside of the bend radius in the two planes of bending in a yin-yang geometry. This has the effect of moving the neutral axis of bending outwards in both planes so that the tensile strain on the superconducting filaments is reduced and the compressive strain is increased. Because the magnetic load is always tensile along the conductor direction, such a configuration reduces the net tensile stress in the conductor. This is desirable because the Nb_3Sn filaments are believed to be less susceptible to damage when subjected to compressive rather than to tensile strain.

We have taken advantage of this factor to reduce the insert bore to 40 cm and, as shown on the field plot in Fig. 6, the full field of 12 T should be obtainable with the 2650-A/cm^2 current density mentioned above. The actual strains and the degradation they cause are now being checked on short samples, and the results will be known before the conductor is

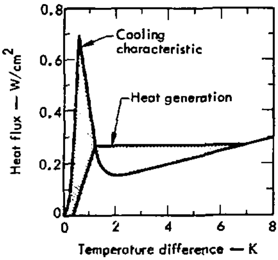


Fig. 3. "Equal areas" criterion for 8-T Nb-Ti conductor (origin = 4.6 K, T_c = 5.8 K).

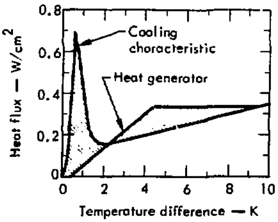


Fig. 4. "Equal areas" criterion for 12-T Nb_3Sn conductor (origin = 4.6 K, T_c = 9 K).

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research and Development Administration to the exclusion of others that may be suitable.

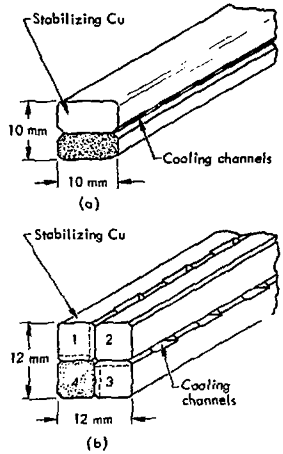


Fig. 5. Conductor configurations.

fabricated. Samples of 3500-A conductor have been made specifically for this purpose because the small quantity of conductor made previously was used for critical current measurements.

The maximum hoop stress of about 20×10^3 psi will occur in the outermost of the three coil sections. Young's modulus, measured at room temperature, is approximately 20×10^6 psi. Thus, the strain of about 0.1% is small compared with that caused by bending. To minimize compression of the inner layers, minimum tension will be used during winding. Minimal compression is advisable for two reasons: compression caused by bending is already high and may be a limiting factor; and any compression of the inner layers as a result of tension in the outer layers increases the tensile load on the outer layer when the coil is energized.

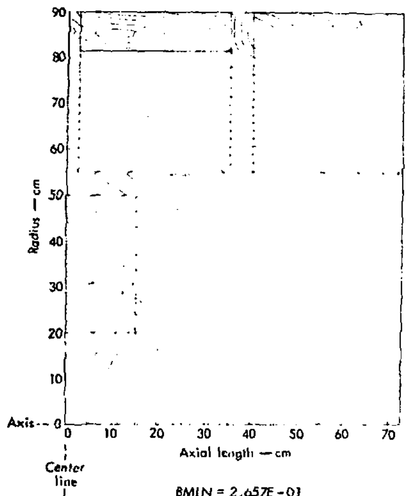
Joints in Superconductors

A problem to be overcome in all large superconducting coils is that of joints between conductor lengths. The maximum conductor length is determined by the capabilities of the fabrication plant, which usually limits the piece weight to not more than 600 lb. The NbTi conductor for the backing coil will, therefore, be supplied by 300 to 600 separate lengths.

Many of the joints must be situated in the coil winding. Considerable cost savings can be made by joining the conductor at any point rather than by trying to control the conductor length so that the joints are positioned at predetermined points.

Preliminary results of the development work carried out jointly by LLL and the Battelle Columbus Laboratories on explosive joining techniques look promising, and we propose to use this technique for the backing coil.

The joining problem also exists for Nb_3Sn conductors in general and, in particular, for the insert for this test facility. The present estimate is that the conductor can be supplied in seven lengths, meaning two joints in each of the three sections. The higher current and the brittle nature of the finished conductor add to the difficulties of making satisfactory joints for a Nb_3Sn winding. The explosive technique might, however, again offer a satisfactory solution. Because the conductor is cryostatically stabilized, a joint carried out on the reacted material might be satisfactory. The other possibility is to join the material explosively prior to reacting. We propose to explore both possibilities for this project.



BMIN = 2.657E - 01
BMAX = 1.178E - 02

List of contours

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3	1.200E + 01	18	7.200E + 01
4	1.600E + 01	19	7.600E + 01
5	2.000E + 01	20	8.000E + 01
6	2.400E + 01	21	8.400E - 01
7	2.800E + 01	22	8.800E - 01
8	3.200E + 01	23	9.200E + 01
9	3.600E + 01	24	9.600E + 01
10	4.000E + 01	25	1.000E + 02
11	4.400E + 01	26	1.040E 02
12	4.800E + 01	27	1.080E + 02
13	5.200E + 01	28	1.120E + 02
14	5.600E + 01	29	1.160E + 02
15	6.000E + 01		

Fig. 6. Magnetic field plot of half of the test facility, with Nb-Ti backing coils and Nb_3Sn insert coils.

Cryostat

The cryostat that insulates the magnet system in its liquid helium (LHe) environment is a double-walled, stainless-steel vessel 2.1 m in diameter and 3.2 m long. It is open to the full internal diameter at the top, thereby allowing the magnet system to be completely assembled prior to being lowered into the cryostat. Both a LN_2-cooled heat shield and "super insulation" are used to vacuum insulate the walls and bottom of the cryostat. The 0.7-m-thick insulating plug suspended from the cover plate is a laminated assembly of foam plastic and heat shields.

The cryostat is designed to fit the existing pit in the floor of the cryogenic laboratory.

Heat Loads

The heat load on the system is comprised of radiation and conduction into the cryostat and joule heating of the current leads and normal joints in the superconductor. Table 2 is a tabulation of the calculated values. It has been our experience that our predicted values are generally higher than those measured on cryogenic apparatus; therefore, no contingency factors are included.

The figures in Table 2 represent the maximum heat load on the system when both magnets are operating at full design currents of 3500 A on the Nb_3Sn magnet and 1000 A for the NbTi magnet. Under these conditions, the LHe boil-off rate is 80 ℓ/h. When the system is not operating but is sustained at LHe temperature with the liquid level below the bottom of the current leads, the heat load should be about 30 W (or a boil-off rate of ~43 ℓ/h).

Table 2. Calculated heat loads on the cryogenic system.

Source	Heat load (W)
Radiation (through Dewars)	2
Conduction (inner shell)	13
Conduction (top plug)	11
Current leads (Nb-Ti magnet)	5
Current leads (Nb_3Sn magnet)	20
Normal joints	4
Instrumentation leads	1
Total:	56

Refrigeration System

The refrigerator/liquefier must function in three distinct modes to fulfill the requirements of the magnet system.

1. It must first cool the 18,000 kg of superconducting magnets and structure from room temperature to the operating temperature of 4.6 K.

2. It must supply LHe or refrigeration at operating temperature and at a rate to compensate for the maximum heat load with a reasonable reserve capacity.

3. It must be equipped with the necessary heater and valves required to warm the system back to room temperature.

To meet these requirements, we have specified a simple, Claude-cycle, helium refrigerator with LN_2 precooling and a single turbine expander equipped with gas bearings of the BOC design. This system is capable of 100 ℓ/h of LHe or 320 W of refrigeration at 4.6 K. It has the added advantage of greatly increased refrigeration capacity at increased temperature, in this case 2.4 kW at 40 K. This capability is a necessity in cooling a large mass.

A 5000-ℓ LHe storage Dewar is included as part of the refrigeration system. Its primary purpose is that of a thermal flywheel; however, it also serves as an efficient means of storing the LHe from the test facility cryostat when the system must be raised to room temperature.

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