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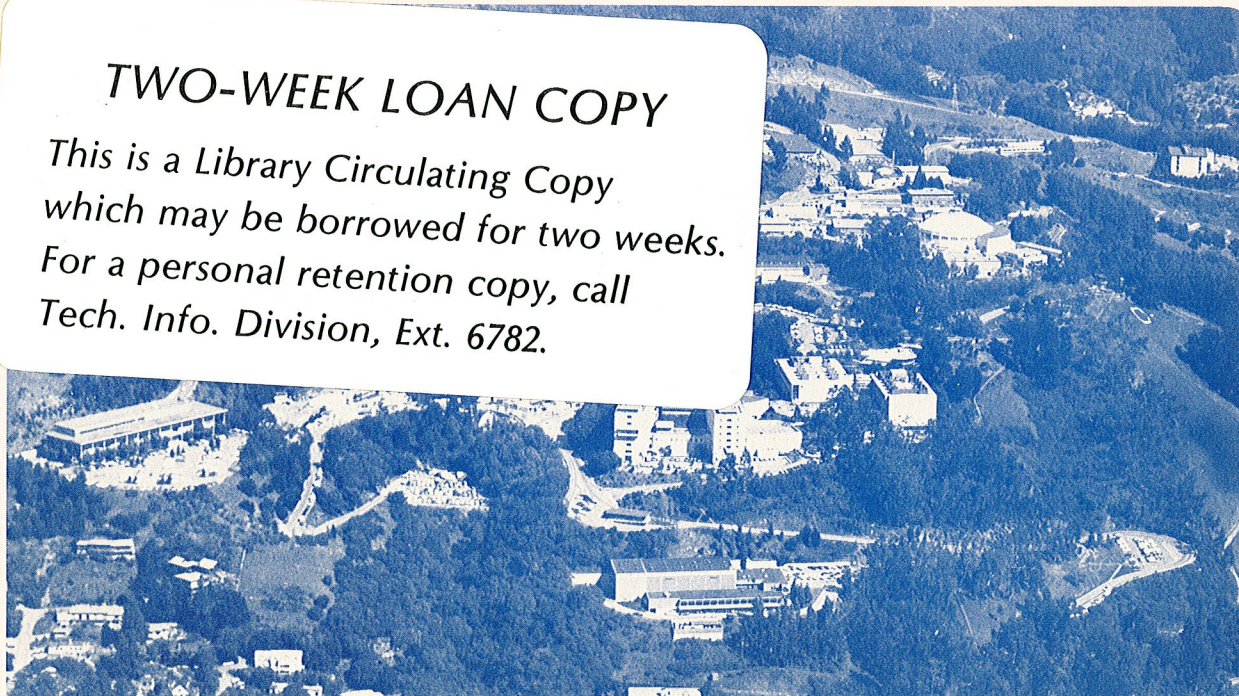
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A 2 MEG-AMPERE PROTOTYPE LEVITATED COIL FOR MULTIPOLE FUSION

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Abstract

This paper describes a proposed prototype levitated superconducting coil which carries 2 million ampere turns. The coils major diameter is 1.0 meter and it occupies a cross-section which is about 0.2 meter minor diameter. The prototype coil will carry four times the current of the largest such magnet built to date. As a result, the peak induction in the coil is about 8 T and the stored magnetic energy will be around 3 MJ. The paper describes the proposed Nb₃Sn superconductor, the quench protection system which is based on the LBL shorted secondary concept, the isochoric refrigeration storage system which stores about 5 kJ of refrigeration between 4.5°K and 7°K, and the persistent switch.

Introduction

This paper describes a technology validation coil which leads up to two meter diameter 2 megampere levitated rings which are part of a proposed multipole fusion device. The concept of levitated superconducting rings is not new. A number of such rings have been built at Princeton,^{1,2} Culham,³ Livermore,⁴ and elsewhere.⁵ The work described here was proposed by TRW^{6,7} and funded by EPRI.⁸ Many of the concepts developed here were developed on the earlier rings.

A levitated ring does not have the normal refrigeration and power supply services attached to it. As a result, low temperature refrigeration must be stored in the levitated ring. The ring is powered by persistent currents which decay with a very long time constant. The technology validation ring would have the following general characteristics: 1) the major diameter would be 1.0 m; 2) the coil cross-section would fit into a circle which is 0.2 m in diameter; 3) the coil would carry 2 million ampere turns in the persistent mode; 4) the ring should be capable of running at least 1 hour without helium refrigeration; and 5) the coil shall quench safely without external quench protection. The coil current decay time constant should be long early in the quench process.

The technology validation ring proposed here carries 4 times the current carried by the largest levitated ring built to date.⁹ In order to meet the desired design criteria the proposed coil would have the following characteristics:

1. Multifilamentary Nb₃Sn in a bronze matrix would be used as the superconductor of choice.
2. A passive isochoric refrigeration system capable of storing 5000 J between 4.5 and 7.0°K would be used.
3. A shorted secondary winding would be used for passive quench protection.

Coil Design Criteria

The general parameters require that the coil be intrinsically stable with a shorted secondary winding. In general, the following conditions must be met for safe operation.

$$\epsilon EJ^2 < 10^{+23} \quad (1)$$

Where E is the magnet stored energy (in Joules); J is the superconductor matrix current density; and ϵ is one minus the coupling coefficient. ϵ is defined as follows:

$$\epsilon = 1 - \frac{M_{12}}{L_1 L_2} \quad (1a)$$

Where L₁ is the coil inductance; L₂ is the shorted secondary circuit inductance and M₁₂ is the mutual inductance between the coil and the shorted secondary.

Once the criteria given in Equation 1 has been met, other criteria come into play. They are, the peak induction in the coil, the maximum coil operating temperature (as judged from looking at the current density in the conductor and the peak field in the coil), and whether or not the superconductor can be operated at low enough current density to permit pure copper to be added to the matrix. (It should be noted that if ϵ is small enough, copper is not needed in the superconductor matrix at all. The addition of copper will reduce the voltages developed in the coil during a quench. In all cases, it is desirable to minimize ϵ). The last design consideration is whether or not the coil design can be scaled to a diameter of 2 meters or more.

A number of different coil designs were considered. The designs were checked for the peak induction in the winding, the ϵEJ^2 limit and whether ϵ is small enough to permit the coil to be wound with a pure bronze matrix conductor. The design chosen is shown in Figure 1. The ϵEJ^2 limit is well below $10^{23} \text{JA}^2 \text{m}^{-4}$ so the magnet should be safe from a quench standpoint. ϵ is small enough that the design is directly scalable to a two meter diameter coil (see Table 1).

The test coil is to be built in six layers wound on a copper mandrel. The first, third and fifth layers consist of multifilamentary Nb₃Sn conductors which is insulated with epoxy and layer wound with fiber glass between the layers. The fiberglass between the conductors is vacuum impregnated with epoxy. The second and fourth layers consist of round ultra pure aluminum (RRR = 2500 at 4.2K and 0T) which is cast in low melting temperature solder. The aluminum forms the

Table 1: Electrical Parameters for the Proposed Validation Coil and a Two Meter Diameter Coil of the Same Design.

		Test Coil	Final Magnet
Major Diameter	(m)	1.000	2.000
Total Current	(A)	2.000×10^6	2.000×10^6
Number of Turns		2106	2106
Design Current	(A)	949.7	949.7
Superconductor Matrix Current Density J	(Am^{-2})	3.957×10^8	3.957×10^8
Peak Induction in the Coil	(T)	8.007	7.275
Coil Inductance L_1	(H)	6.372	16.714
Secondary Circuit Inductance L_2	(H)	1.561×10^{-6}	4.021×10^{-6}
Mutual Inductance Between the Coil and the Secondary M_{12}	(H)	3.081×10^{-3}	8.049×10^{-3}
Coupling Coefficient ϵ		0.0458	0.0360
Stored Energy E	(J)	2.874×10^6	7.537×10^6
EJ^2 Limit	($\text{JA}^2 \text{m}^{-4}$)	4.499×10^{23}	11.801×10^{23}
ϵEJ^2	($\text{JA}^2 \text{m}^{-4}$)	0.206×10^{23}	0.425×10^{23}

shorted secondary circuit. The sixth layer is the isochoric cooling circuit which stores about 5000 J of refrigeration between 4.5 and 7.0K. This layer also contains cooling tubes which permits the magnet coil to be cooled down with a refrigerator.

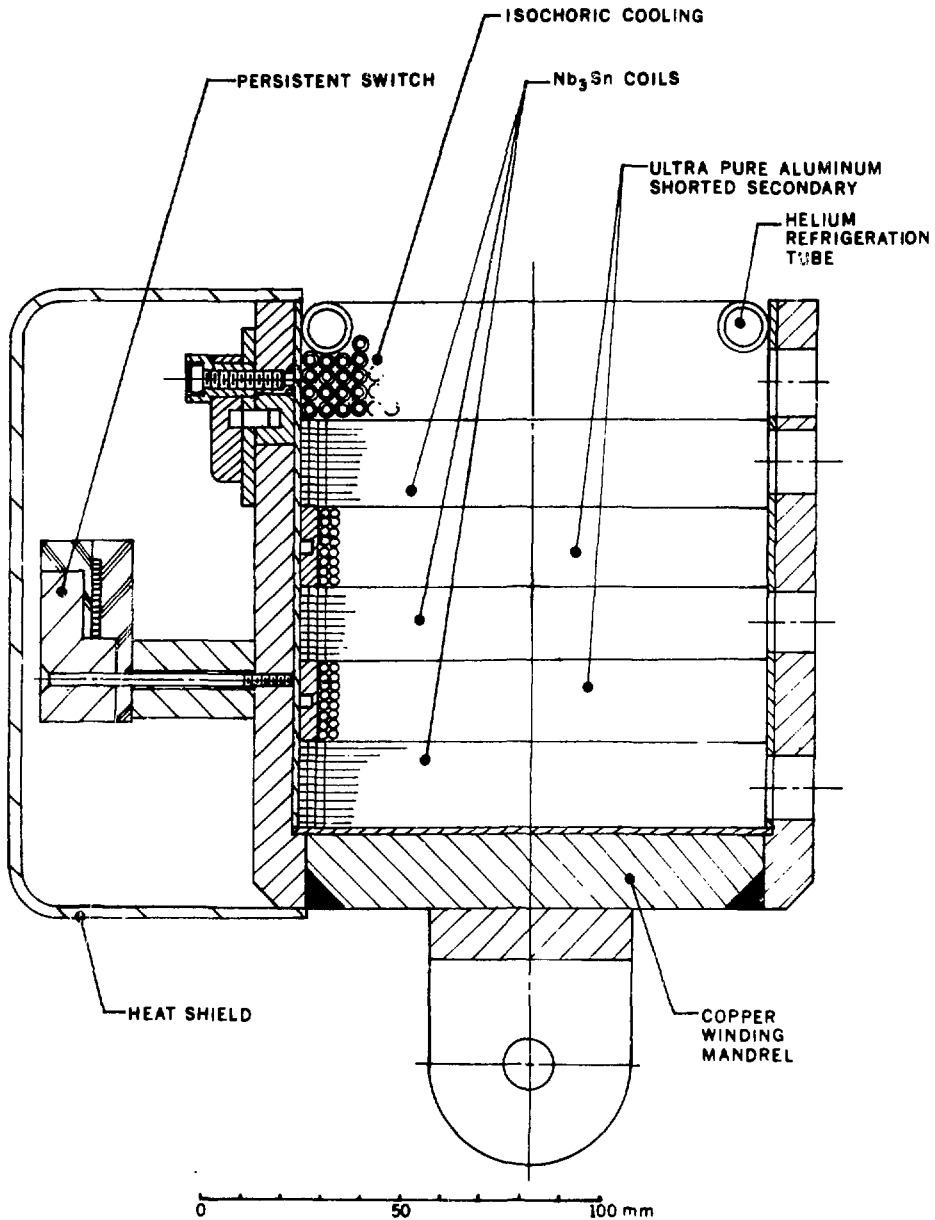
The copper conductor was proposed for the technology validation coil was based on information from Airco.¹⁰ The superconductor is pre-reacted multifilamentary Nb_3Sn which has matrix dimensions of $1.2 \times 2.0 \text{mm}$. The ratio of unreacted bronze to niobium is assumed to be about 2.8. It is expected that there would be around 30,000, 4 micron diameter filaments which are twisted about one twist every 50mm. (If the superconductor has copper in it, the unreacted ratios are 2.8 bronze, 1 niobium and 0.6 copper.) The critical current capacity at 4.2°K should be greater than 1100A in a 10 T field. About 6500m of conductor is required. A current of 950A is required at 8.0T and 7.0K.

The shorted secondary quench concept has been used in the LBL thin solenoid program.¹¹⁻¹³ The largest of the LBL thin solenoids designed for a high physics experiment at the Stanford linear accelerator uses ultra pure aluminum as part of the passive shorted secondary quench protection system.¹⁴ The shorted secondary circuit serves the following functions provided it is well coupled to the coil circuit; 1) the shorted secondary will absorb a substantial amount of the stored magnetic energy during a quench; 2) since current is shifted out of the coil, the hot spot

temperature in the coil is reduced; 3) the secondary circuit extends the current decay time constants. (The solder is particularly helpful in this respect). This reduces the voltages developed in the coil; 4) the shorted secondary circuit initiates "quench back" which drives the entire coil normal quickly.¹⁵ Aluminum was chosen for its low magneto-resistance. The low melting temperature solder extends the time it takes for the temperature of the secondary circuit to reach 25°K. In a full scale levitated coil experiment, this permits a system of catchers to be activated.

The isochoric cooling system for the technology validation ring is quite different from the designs used at Livermore and Princeton. The proposed isochoric cooling system consists of stainless steel tubes charged with room temperature helium at a pressure of $3.6 \times 10^7 \text{ Nm}^{-2}$ (5240 psi). The stainless steel tubes would have a wall thickness which is about one-tenth of the tube diameter. The average density of the helium in the tubes is around 50 kg m^{-3} . The helium stores about 5kJ of thermal energy between 4.5K and 7.0K. The coil and its structure will store less than 700J over the same temperature range. The stainless steel tube is cast in a low melting point solder to insure good thermal contact. The cooling tubes, which are attached to the refrigerator, are in the corners of the isochoric cooling region (see Figure 1).

A thermal analysis was done using the Sinda code. This analysis shows the importance of



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Figure 1. A cross-section of the proposed technology validation ring.

winding the coil on a mandrel which conducts heatwell. The mandrel carries heat radiated to the coil package surface to the isochoric cooling system, thus reducing the temperature in the coil. The thermal analysis showed that most of the 5000J capacity of the isochoric cooling system is available for cooling the magnet coils. From the thermal analysis, it is believed that the technology validation coil can remain superconducting (while carrying 2 million ampere turns) for at least one hour provided the heat leak

through the superinsulation to the coil averages less than 1 watt.

A stress analysis was done using the SASS program. Hoop strains of less than 0.2 percent were calculated in the worst case. The stress analysis produced no particular surprises. However, it appears that the stress level will be higher in the 2 meter diameter full scale coil. Measurements of strain in the test coil will show if the test coil design is truly scalable to the two meter diameter.

Persistent Switch Design

In general, the technology validation ring superconducting persistent switch must meet the following design criteria.

1. The switch must be capable of carrying the full design current of the superconducting magnet coil without going normal. The switch should be capable of superconducting operation at a temperature of about 1.0K above the operating temperature of the superconducting coil.
2. The switch inductance must be low, therefore the switch should be wound in a non-inductive way.
3. One should be able to operate the switch in the open position with current flowing to the coil from external leads without driving the superconducting magnet normal.
4. Accidental switch opening at full magnet current should not burn the switch out, nor should the voltage across the magnet exceed 2000V.

The proposed persistent switch is required to operate at 1000A at a temperature of 10.0K. The magnet inductance will be 6.37H while the switch inductance is less than 10mH. The peak magnetic induction in the region of the switch is expected to be less than 5.0 Tesla.

It is proposed that the persistent switch be made from an all bronze version of the conductor proposed for the technology validation ring. At 20°K the resistivity of the depleted bronze material which makes up the matrix is about 7×10^{-8} ohm meters. For a 2 ohm switch about 50 meters of bronze matrix conductor is needed to make the persistent switch. This is about 16 turns of conductor wound in a bifilar fashion around an aluminum mandrel which has an inside winding diameter of about one meter. The resistance of the switch when it is closed is expected to be about 2×10^{-9} ohm. A cross-section of the switch is shown in Figure 2.

The reason one can use the small switch shown in Figure 2 is that the superconducting magnet coil and the switch are both protected by the magnet shorted secondary circuit. If the switch should become normal, it is as if a 2 ohm resistor is put across the leads of the coil. With 2 ohms across the coil, the primary circuit time constant is 3.2 seconds; the shorted secondary circuit time constant is 60 seconds (based on RRR = 1000 and an aluminum packing fraction of 65 percent in the shorted secondary in the coil). As a result, the current in the coil and the switch drops to about 5 percent of its starting value in about 150ms. The persistent switch temperature will end up below 200K when the coil current has completely decayed.

The persistent switch is thermally insulated from the coil by NEMA - G-10 spacers. These spacers permit the heaters to open the switch without large heat fluxes to the coil. The heaters (Soldering iron heaters will be put in the switch mandrel) should keep the switch open with less than 5 watts of heating. The persistent switch will not have its own isochoric cooling system. Therefore, one must thermally shield the switch from incoming radiant heat transfer.

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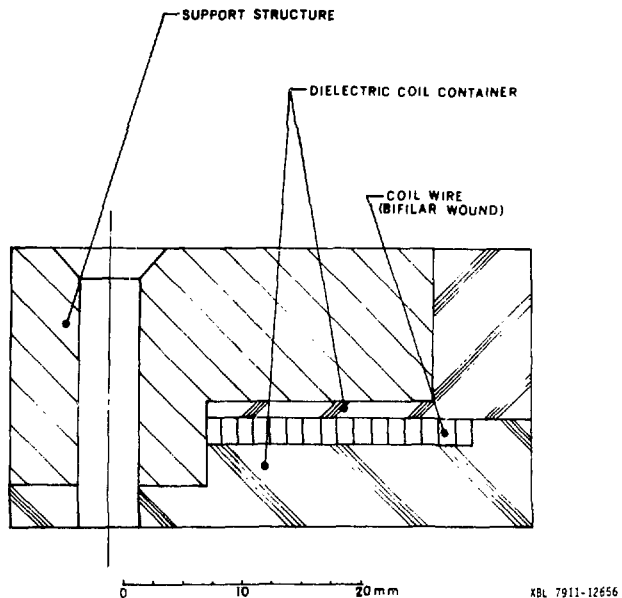


Figure 2. A cross-section of the persistent switch.

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