High Temperature Superconducting Levitation Coil for the Levitated Dipole Experiment (LDX)

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***Abstract*—The Levitated Dipole Experiment (LDX) is an innovative approach to explore the magnetic confinement of fusion plasmas. A superconducting solenoid (floating coil) is magnetically levitated for up to 8 hours in the center of a 5-meter diameter vacuum vessel. This coil is supported by a Levitating Coil (L-Coil) on top of the vacuum vessel. In the initial machine design, this Levitating Coil was a water-cooled copper solenoid, and was the experiment's single largest load on the available water system. The main benefit of using a high temperature superconducting coil is the ability to apply more auxiliary heating power to the plasma. However, this coil will also be the first high temperature superconducting coil to be used in a US fusion program experiment. The high temperature superconducting L-Coil is a solenoid, using a two-in-hand winding of a commercially available 0.17 mm x 3.1 mm tape by American Superconductor Corporation with a critical current of 62 A at 77 K and self-field. The L-Coil will be operated at 0.9 T and 20 K. The L-Coil has a protection circuit that not only protects it against overheating in the event of quench, but also against F-Coil collision in the event of a control failure.**

***Index Terms*— fusion magnets, superconducting coil, high temperature superconductor, cryostat**

I. Introduction

The Levitated Dipole Experiment (LDX) is a new Innovative Concept fusion experiment at M.I.T., designed and constructed jointly by the Plasma Physics Laboratory of Columbia University and the M.I.T. Plasma Science and Fusion Center [1]. The primary objective of this experiment program is to investigate the possibility of steady-state, high beta operation with near-classical magnetic confinement. The most important design feature of LDX that separates it from previous levitated dipole experiments is the maximization of magnetic flux expansion. This requires a single, small, high performance Nb3Sn coil [2], using state-of-the-art conductor design [3], that is levitated within a relatively large vacuum chamber. The base-case configuration achieves levitation of a floating superconducting coil, using a disk-shaped, high-temperature superconducting Levitation Coil (L-Coil), mounted on top of a 3 m high, 5 m diameter vacuum vessel. This ring position is stable to tilt and horizontal displacements, thus reducing the control power requirements for motions in off-axis directions. A large NbTi superconducting coil (C-Coil) is used for inductive charging of the floating coil in a charging station at the bottom of the vacuum vessel [4]. The rest of the coils in the system are normal, including a set of Tilt-Slide-Rotation control coils on the side of the vacuum vessel and a Helmholtz coil pair on the top and bottom of the vessel, used for varying the compression ratio. A set of three shaping coils on the top and bottom of the vessel will be used to shape the outer flux surface when the floating coil is levitated using the bottom coil. However, they are not included during initial operations. The arrangement of the vacuum system and magnets is shown in Figure 1, including the cryostat of the L-Coil:

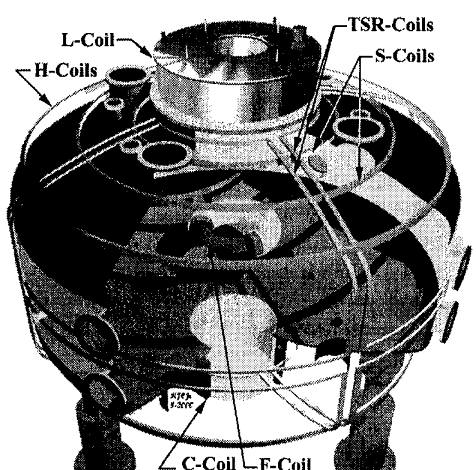

Fig. 1. LDX solid model, showing the Levitation Coil (L-Coil) on top of the vacuum vessel, suspending the Floating Coil (F-Coil). Also shown are the Charging Station on the bottom and the surrounding Charging Coil (C-Coil), 8 Tilt-Slide-Rotation saddle coils (T-S-R) coils, top and bottom Helmholtz coils (H-Coils), and 3 shaping coils (S-Coils)

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II. L- Coil Conductor

The high-temperature superconductor to be used in the Levitation Coil is a commercially available tape, provided by the American Superconductor Corporation (ASC). It is very close to being state-of-the-art in terms of having the best combination of critical properties and strength for the application. However, it was selected primarily because of its immediate availability. The tape properties are described in Table I:

TABLE I
L-COIL CONDUCTOR DESCRIPTION

Parameter	Units	Value
w_{tape}	(mm)	3.1 +/- 0.2
h_{tape}	(mm)	0.168 +/- 0.02
$t_{insulation}$	(mm)	0.10
J_{eff} (77 K, 0 T)	(kA/mm^2)	> 12
I_c (77 K, 0 T)	(A)	> 62
I_{op}	(A)	91
σ_{max} (77 K)	(MPa)	85
$\sigma_{op,peak}$ (20 K)	(MPa)	42

The conductor is a BSSCO-2223 tape, with a width and height of 3.1 mm x 0.168 mm. Available piece lengths range from 300 m to greater than 500 m. About 34 internal joints are required in the conductor, before winding. The joints, developed by ASC, are 100 mm PbSn soldered lap joints, each with a room temperature resistance of around 100 nΩ. A possible insulation system applies a 1.5 mil epoxy coating with a 1.5 kV rating to the conductor, then wraps the conductor with half-lapped glass tape, before winding. After winding, the insulation is vacuum pressure impregnated and cured with an effective total tape thickness of 0.1-0.115 mm.

III. L- Coil Winding and Cryostat

The Levitation Coil (L-Coil) is a disk magnet, consisting of a double pancake winding, internal joints, and terminations at the outer radius. The 182 A conductor consists of two 91 A tapes, wound two-in-hand. Two 3.4 km pairs of jointed superconducting tape are merged, then insulated, during the double-pancake winding of the coil. Terminations are then made at the outside of the winding. The coil is wrapped with an 0.10 mm ground insulation. The assembly is vacuum-pressure impregnated. The winding pack is sandwiched between upper and lower support plates and 9 mm copper sheets with four thin radial electric breaks used for thermal equilibration of coil surfaces, away from a single-stage cryocooler cold head. The main parameters of the L-Coil winding pack are given in Table II:

The winding pack and support plates are in a vacuum can, cooled by conduction to a cold head in contact with the top copper plate. On top of the lower vacuum box is an automatically filled liquid nitrogen reservoir that supplies all of the intermediate temperature surfaces in the cryostat, used to reduce total losses. A thermal shielding surface surrounds all structures and feedthrough lines between 20 and 80 K. There is a through-hole in the reservoir to avoid direct contact with the cryocooler. The reservoir is filled and vented with standard 3/8" inner x 3/4" outer steel bayonet tubes.

TABLE II
L-COIL WINDING PACK (WP) DESIGN PARAMETERS

Parameter	Units	Value
R_1	(mm)	331
R_2	(mm)	653
H	(mm)	6.61
npancakes		2
nlayers		564
nturns		1128
Winding		2-in-hand
$L_{conductor}$	(km)	3.4
$L_{BSSCOtape}$	(km)	6.8
I_{cond}/I_{tape}	(A)	182/91
Stored energy	(kJ)	20.4
$B_{max,\parallel}$	(T)	0.82
$B_{max,\perp}$	(T)	0.55
V_{dump}	(V)	70
$V_{crowbar}$	(V)	150

There are 16 coil support tubes, attaching the lower support plate at 20 K to the room temperature cover of the cryostat vacuum vessel. The supports are threaded into blind holes in the bottom of the top cover, then bolted to the bottoms of the cover and the lower support plate. A copper sleeve around the support tubes extends from the 80 K intermediate heat station to the floor of the nitrogen reservoir.

The power leads include a commercially available 250 A high-temperature superconducting lead-pair, intermediate heat station, and optimized 80 K to room temperature copper leads. All feedthroughs are made through the top cover of the vacuum vessel, including voltage and temperature sensor leads, fill, vent, and evacuation lines, and the cutout for the cryocooler. The cryostat cover is sealed with inner and outer O-rings. An L-Coil cryostat cutaway is shown in Figure 2.

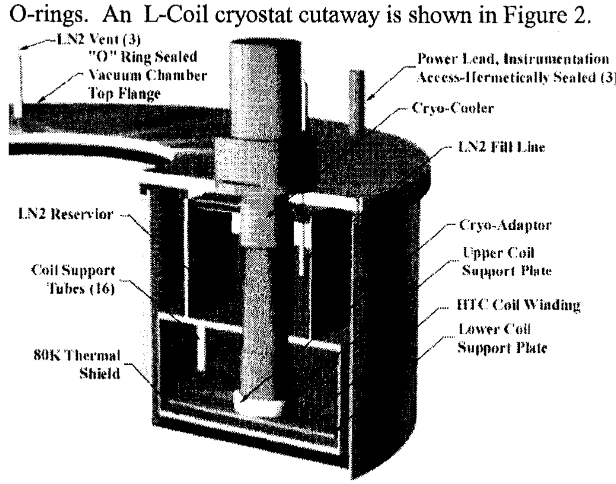

Fig. 2. Cutaway cross-section of the L-Coil cross-section with labeled components.

The cryoadapter is a relatively rigid bellows allowing displacements between the cryocooler cold head and the coil, due to assembly and coefficient of expansion mismatch after cooldown, without substantially increasing thermal resistance. A more complex adapter "suspension" may have to be used in order to isolate the coil from cryocooler vibrations.

IV. DESIGN METHOD

A parametric scan of design space was performed in order to select the size and shape of the L-Coil. The scan showed that the Bi-2223 conductor was capable of providing the needed levitation force over a broad range of parameters, satisfying static allowables. A solution was recommended, using 16 pancakes, that allowed winding without any internal joints. However, this design had the disadvantages of inferior flux expansion in the plasma and considerable conductor wastage, because of the "quantization" of tape lengths. Three constraints constricted the acceptable solution space: 1) The physics requirement for a flux expansion ratio of greater than 250; 2) severe budgetary constraints, restricting the total cost of conductor and cryocooler to < $150 k; and 3) inability to remove heat from F-coil control oscillations in designs with a low fraction of critical current and a high number of pancakes.

In order to perform a parametric scan, it was necessary to develop an analytic characterization of the critical current of high temperature superconducting tapes as a function of field and temperature. Since the critical properties are a strong function of whether the field is oriented transverse to the broad surface of the tape or parallel to that surface, separate correlations were developed for transverse and parallel field. The following correlations were used. The form is similar to the equations proposed by Summers [5] for Nb3Sn. Performance dropoff with strain is very sharp for BSSCO, above a critical strain of 0.4 %, corresponding to the maximum stress of 85 MPa, listed by the vendor. Since the allowable stress is about half of the maximum, the effect of strain on critical properties was assumed to be negligible.

The effects of field and temperature on normalized critical current density are calculated by the following eight equations. The transverse and parallel field coefficients are selected to characterize the specific Bi-2223 conductor. Since the current density calculated is normalized to the critical current density of the conductor at 77 K and self-field, it is possible that these correlations have a wider application to many other BSSCO-2223 conductors, but no such claim is made here. The equations are not specifically physical and, in particular, Bc20m and Tc0m should not be interpreted as the apices of the conductor critical surface.

TABLE III
TRANSVERSE AND PARALLEL FIELD COEFFICIENTS

Parameter	Units	Transverse	Parallel
B_{c20m}	(T)	41	88.8
T_{c0m}	(K)	86	87.3
C_0		160	251
$J_{cLFnorm}$	()	7	8.6

$$b_{norm} = \frac{B + 0.0001}{B_{c2}} \tag{1}$$

$$t_{norm} = \frac{T_{op}}{T_{c0}} \tag{2}$$

Different equations were used for Bc2 for transverse and parallel field. For transverse field:

$$B_{c2} = B_{c20m}\left(1 - t_{norm}^{\ 0.3}\right) \tag{3}$$

For parallel field:

$$B_{c2} = B_{c20m}\left(1 - t_{norm}^{\ 0.5}\right)\left(1 - 0.31 t_{norm}\left(1 - 1.77\ln(t_{norm})\right)\right) \tag{4}$$

The normalized high field current density for transverse field is:

$$J_{CHF} = C_0\left(1 - t_{norm}^{\ 0.05}\right)\frac{1 - b_{norm}}{0.2 + \sqrt{b_{norm}^{\ 0.7} B_{c20m}}} \tag{5}$$

The normalized high field current density for parallel field is:

$$J_{CHF} = C_0\left(1 - t_{norm}^{\ 0.1}\right)\frac{1 - b_{norm}}{1.5 + \sqrt{b_{norm}^{\ 0.5} B_{c20m}}} \tag{6}$$

The total normalized critical current density for either transverse or parallel field is:

$$J_{norm} = \frac{1}{\dfrac{1}{J_{CLF}} + \dfrac{1}{J_{CHF}}} \tag{7}$$

The actual current density as a function of field and temperature is then:

$$J_c(B,T) = J_{norm} J_c(B_{ext} = 0, T = 77K) \tag{8}$$

Because the critical current density is normalized, it can be used to scale J_c in the superconductor or J_{eff} over the tape.

A new Fortran code, LEVITATOR, was written by the author for designing superconducting levitation magnets. The code requires a conductor description and varies R1, R2, and the number of pancakes. The outputs include transverse and parallel field, stored energy, DC losses, pulsed losses, and conductor cost. The dump voltage V_{dump} needed to protect the coil and the crowbar voltage $V_{crowba}r$ needed to prevent the floating coil from colliding with the vacuum vessel upper flange are also calculated. Eq. 1-8 are used to calculate the fraction of critical current. A few key results of a LEVITATOR run are shown in Figures 3a,b,c,d.

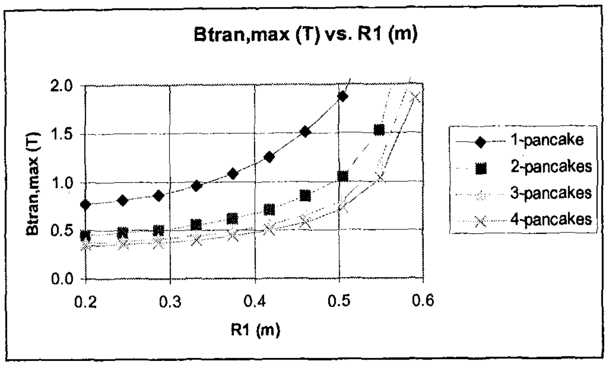

Fig. 3a Btran,max (T) vs. R1 (m); 1, 2, 3, and 4 pancakes

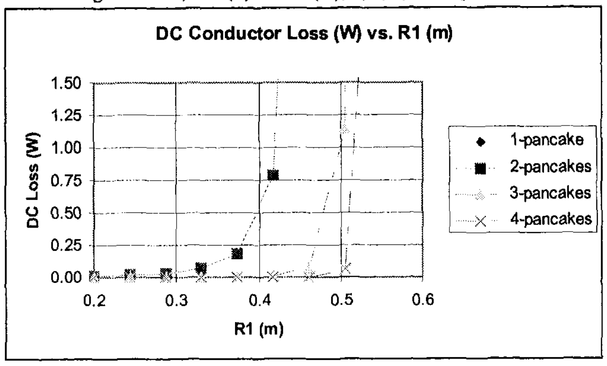

Fig. 3b DC Losses (W) vs. R1 (m), 1, 2, 3, and 4 pancakes

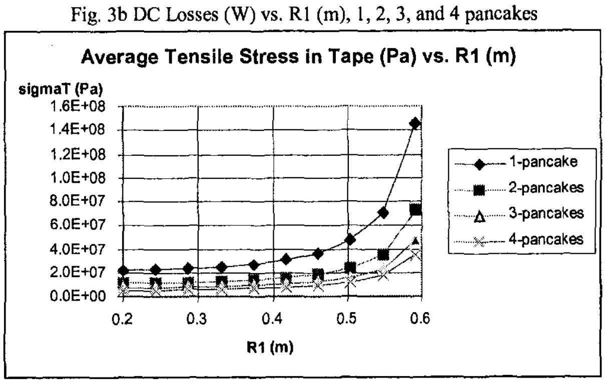

Fig. 3c Average Conductor Hoop Tension Stress (Pa) vs. R1(m), npancakes

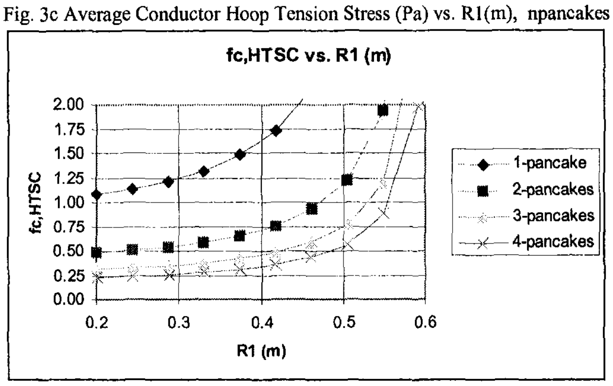

Fig. 3d Fraction of Critical Current vs. R1 (m); npancakes

Early studies show that the coil performance always improved as the outer radius increased to 0.635 m, the maximum allowed by upper flange bolt clearance, so this was subsequently held constant.

Most of the critical performance parameters, including peak transverse and parallel field, DC losses, both in the superconductor and in the joints, tensile and Tresca stress, and fraction of critical current density improve by decreasing the inner radius R1 and increasing the number of pancakes. The design space can be limited "to the left" by the design allowables listed in Table IV:

TABLE IV: L-COIL DESIGN ALLOWABLES

Parameter	Units	Variable
$f_c(B,T)$		< 0.7
n in-hand		<= 3 (2)
t_{ins}	(mm)	>= 0.1
ε	(%)	< 0.3
σ_{Tresca}	(MPa)	< 45

The fraction of critical current constraint of fc<0.7 restricts the inner radius to less than 0.37 m for a 2 pancake design. We are prevented from just winding to the lowest radius that allows clearance of the F-coil lifting mechanisms by the results shown in Figures 4a,b,c,d.

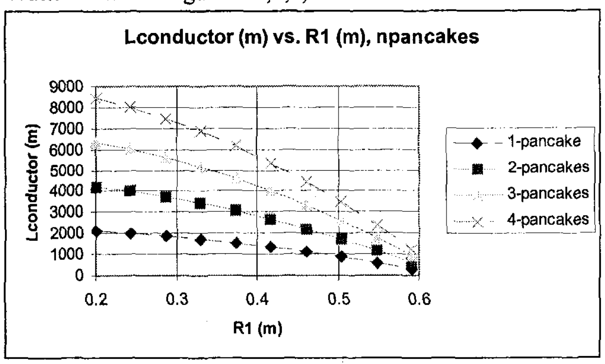

Fig. 4a Lconductor (m) vs. R1(m), 1,2,3, and 4 pancakes

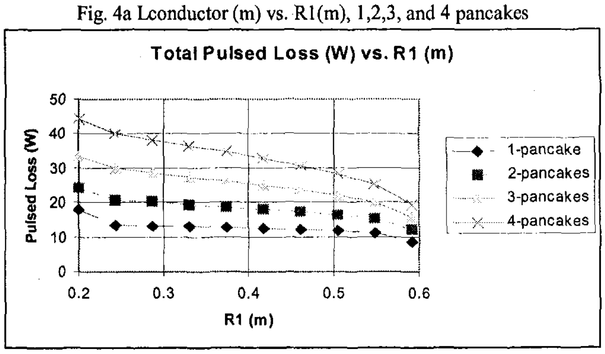

Fig. 4b. Total Transverse & Parallel Pulsed Field Loss (W) vs. R1(m)

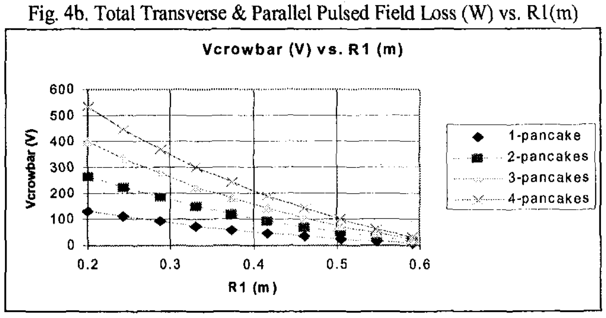

Fig. 4c Vcrowbar (V) vs. R1(m) for a 1.5 s crowbar time

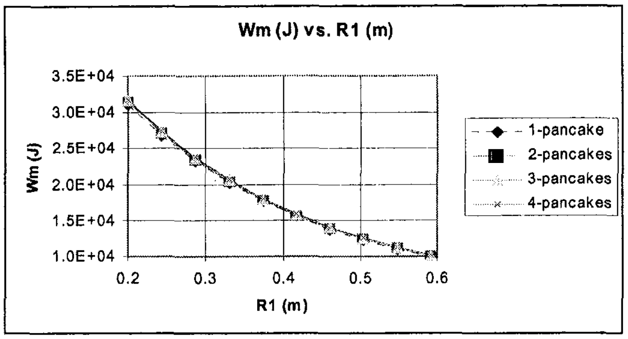

Fig. 4d Wm,self (J) vs. R1(m)

The length of superconductor, pulsed losses, stored energy, dump and crowbar voltage all increase as R1 decreases and all but stored energy increase with the number of pancakes. Very low radius designs that improve flux expansion may have prohibitively high pulsed losses. The cost goal of $150 k is met at the reference design value of R1=0.331 m and 2 pancakes.

The losses in the winding pack due to pulsed position control loads turned out to be the key feasibility issue in the design. The cryogenic losses are summarized in Table V:

TABLE V: CRYOGENIC LOSSES

Parameter	Units	20 K	80 K
DC $Loss_{tape}$	(W)	0.0636	
DC $Loss_{joints}$	(W)	0.016	
Lead Loss	(W)	0.73	16.4
Gravity Supports	(W)	0.059	0.85
Feedthroughs	(W)	0.04	0.7
Radiation Losses	(W)	0.38	5.11
Pulsed Losses	(W)	20	
Total Losses	(W)	21.2	23.1

The losses at 80 K are dominated by lead losses, while the losses at 20 K are dominated by the pulsed losses, due to F-Coil position control.

L-Coil operation has a steady-state and two cyclic components. It has a nominal operating current of 182 A that remains constant over 8 hours, during levitation. The system requirements for LDX and the L-Coil are that they must be capable of providing two experimental runs in one day, 10 runs/week, 160 runs/year, and 1600 runs, lifetime. The L-Coil also has cyclic requirements for controlling the floating F-Coil. The F-Coil is assumed to have maximum displacements of +/- 1 mm with a characteristic frequency of 1.0 Hz. The vertical control transform for the L-Coil is 485 A/m. Therefore, the coil must sustain the losses from a 1.0 A x 1 Hz minor oscillation in the winding. The loss mechanisms analysed include the hysteresis loss of the BSSCO tape, circulating currents between the hands of the two-in-hand winding, and eddy currents in the copper sheets. The total pulsed losses due to minor cycling are estimated to equal 20 W and are far and away the highest losses in the system. Since there is still a significant amount of uncertainty in characterizing the F-coil controllability and the pulsed losses in the 2-in-hand tape, conductor and control characterization are an important part of the LDX program. In particular, the lifting mechanism is designed to permit plasma operation in a mechanically supported position and control can be established during gradual removal of the lifter.

It was decided to increase crycooler capacity to 30 W at 20 K and use a nitrogen reservoir, instead of a two-stage cryocooler, because the height and weight of the assembly would be reduced, along with the cost of the system. This also permits the addition of a second cryocooler, if losses are higher than expected. Finite element analysis indicated that the thermal conduction temperature rise in the coil can be held to 5 K up to a load of 100 W.

An innovative technique to reduce radiation and gas conduction loads, which was also selected for the LDX Charging Coil [4], is the use of low emissivity "crystalline" aluminum coatings on metal substrate sheets, instead of conventional MLI. All 80 K surfaces are covered by thin metal sheets with 1–3 μm coatings of vacuum deposited crystalline aluminum. Emissivities of less than 0.003 at 4 K and 0.01 at 80 K have been achieved [6]. Since the aluminum coating is crystalline, without grain boundaries, it has extremely low outgassing, if applied directly to the vessel wall. Cryoadsorption panels with a charcoal adsorbent will be installed on the liquid nitrogen tank to maintain 10^{-7} torr operating vacuum in the vacuum vessel. As shown in Table VI, this performance level is not important to the L-Coil design. However, the coated sheets are inexpensive and were selected as part of a systematic effort to improve all aspects of fusion magnet performance. Low emissivity coatings should be particularly useful for high surface area and ultralow loss applications, such as Heavy Ion Fusion Drivers and Levitated Dipole F-Coils.

A quench protection system serves to protect the superconducting C-coil and the power supply in case of quench or a power supply failure. The L-Coil is charged and discharged by a two-quadrant 200 A x +/- 10 V power supply, supplemented by an electronic switch and a 150 V/0.75 Ω crowbar/dump resistor. A 1.3 s dump time is adequate for thermal protection, but the more stringent 0.6 s crowbar time is used with a single switch to avoid complexity.

V. CONCLUSIONS

The LDX Levitation-Coil will be the first high temperature superconducting coil to be used in a fusion physics experiment.

A new code was written based on a correlation of BSSCO-2223 properties as a function of field and temperature. Parametric studies permitted the conceptual design of a disk solenoid that satisfies allowables, suspends a floating cryostat in the middle of a 3 m high cryostat, and permits the physics goal of high dipole flux expansion.

Thermal losses are dominated by pulsed losses due to position control limit cycling. Loss contingency is managed by the use of a large cryooler, an 80 K reservoir, and finite element analysis, confirming the possibility of further upgrade.

The LDX project is using a new technique for radiation and gas conduction loss reduction that should improve the feasibility of other fusion magnets.

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