The Levitated Dipole Experiment (LDX) Magnet System

Joel H. Schultz, J. Kesner, J.V. Minervini, A. Radovinsky, S. Pourrahimi, B. Smith, P. Thomas, P.W. Wang, A. Zhukovsky
Massachusetts Institute of Technology, Cambridge, MA

R.L. Myatt, MTechnology, Lincoln, MA

S. Kochan, Mechanical, Industrial & Graphic Designs, Franklin, MA

M. Mauel, D. Garnier, Columbia University

***Abstract*-- In the Levitated Dipole Experiment (LDX), a hot plasma is formed about a levitating superconducting dipole magnet in the center of a 5 m diameter vacuum vessel. The levitated magnet is suspended magnetically during an eight hour experimental run, then lowered and recooled overnight. The floating F-coil magnet consists of a layer-wound magnet with 4 sections, designed to wrap flux lines closely about the outside of the levitated cryostat. The conductor is a niobium-tin Rutherford cable, with enough stabilizer to permit passive quench protection. Lead strips are used as thermal capacitors to slow coil heating. An optimized system of bumpers and cold-mass supports reduces heat leak into the helium vessel. Airbags catch the floating coil on quenches and faults, preventing collision with the vacuum vessel.**

I. INTRODUCTION

The Plasma Physics Laboratory of Columbia University and the Plasma Science and Fusion Center of the Massachusetts Institute of Technology (M.I.T.) have designed a new Innovative Concept fusion experiment to be constructed and operated at M.I.T. The primary objective of the Levitated Dipole Experiment (LDX) is to investigate the possibility of steady-state, high beta operation with near-classical magnetic confinement.

LDX is simpler than previous internal ring devices, such as the FM-1 at Princeton [1] or the Levitron at LLNL [2], and does not include a toroidal field coil. The most important difference between LDX and previous experiments is the maximization of magnetic flux expansion. This results in a single, small coil levitated in a large vacuum chamber.

II. OVERVIEW

The principle confinement magnet of LDX, the floating coil (F-Coil) is levitated in the middle of a 5 m diameter vacuum vessel with 3 m high sidewalls.
The experiment will be located in the well-shielded experimental hall built for the TARA tandem mirror experiment. The proposed LDX experiment is shown in Figure 1.

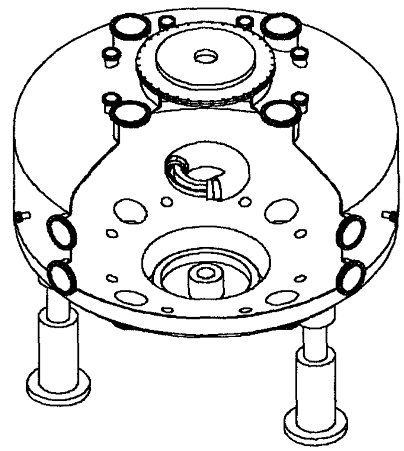

Fig. 1: LDX isometric cutaway, showing vacuum vessel, supports and flanges; a levitating coil on the top, the floating coil in the middle, and inner and outer charging coils on the bottom

The base case LDX configuration achieves levitation of a floating superconducting coil, using a single, small water-cooled levitation magnet. The ring position is stable to tilt and horizontal displacements, thus reducing the control requirements for motions in off-axis directions. A bottom superconducting coil pair is used for inductive charging of the floating coil. 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. They are not included during initial operations.

The coils in the magnet system, described above, are identified in Figure 2.

Manuscript received September 14, 1998
This work was supported by DOE Contract DE-FG02-98ER54458.

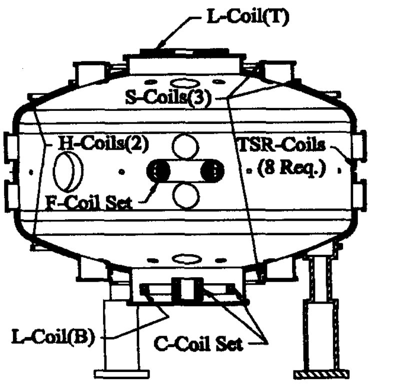

Fig. 2: LDX Coil System and Nomenclature

III. THE F-COIL

The most ambitious coil in the LDX magnet system is the floating coil (F-coil), which must provide a 4 T flux density at an "unscraped" plasma flux line, float for at least 8 hours, and survive collisions after coil quench or loss of control events. The coil/cryostat/vacuum vessel system also provides a magnetic flux expansion of 450, permitting a center/edge plasma pressure ratio of 26,000.

The floating coil (F-Coil) uses a Nb3Sn conductor in a copper channel, as shown in Figure 3.

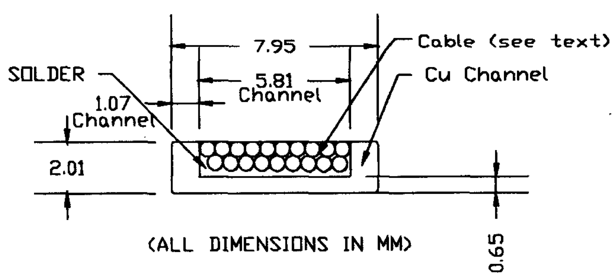

Fig. 3: F-Coil Superconductor

The superconductor is a 19 strand cable, based on the strand used in the record-breaking 13 T dipole magnet at the Lawrence Berkeley Laboratory [3]. The strand has since been improved by IGC, so that the LDX strand has a critical current density of 1100 A/mm^2 at 12 T with a +/- 3 T hysteresis loss of only 550 mJ/cc. A second advantage of this conductor is that it is 70 % noncopper. Since the copper needed for structure and protection is in the channel, copper in the strand itself is unneeded. In LDX, the conductor must operate with a peak flux density of 5.1 T and an operating temperature that rises from 4.2 to 11 K. Simulations of the temperature rise, using this advanced strand, show that the conductor should be able to remain below its current-sharing temperature for 9.5 hours.

The F-Coil in its mandrel and cryostat is shown in Figure 4. The F-Coil is a continuous winding with two joints between F1-3 and F4. It is considered as a four coil system for purposes of analysis. The winding polarity of F4 is opposite to that of F1-3. This pulls the high-field flux line close to the cryostat wall and doubles the compressibility over the best design without an "opposed-current outrigger" winding.

The F-coil is wound on a shaped aluminum mandrel. Most of the coil is layer-wound, but one end is pancake wound, so that the leads and joints are all on the outside of the F1-3 and F4 coils. The outer parts of the mandrel are bolted with washers to apply radial and axial precompression to the F-coil winding packs. The magnets are "react-and-wind" with the radii of the heat treatment and takeup spools selected to minimize the final strain on the conductor, with the cable above the conductor neutral axis. Insulation is applied during winding, followed by VPI impregnation. As a variation on the FM-1 design [1], a medium-high purity (RRR=800) aluminum sheet is applied between layers in order to reduce the peak hot spot temperature during quench by rapidly transferring current out of the F-coil and spreading the quench heat uniformly.

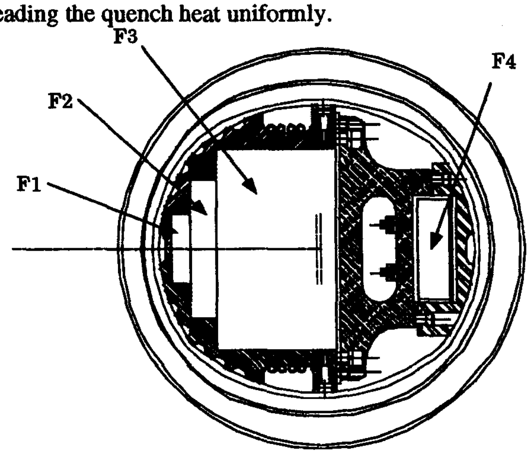

Fig. 4: F-Coils, mandrel, and cryostat

The F-coil cryostat includes a helium vessel, thermal shield, and an outer vacuum shell, as shown in Figure 4. The thermal shield follows the concept of FM-1 by retarding heat leak into the helium vessel with the use of lead strips [4] on a metal shell. Despite its high mass density, lead has the highest heat capacity of any technical solid.

The thermal shield is supported from the helium vessel by glass spheres, contained in Inconel rings. These replace the springs in the drawing. Top spheres support the shield during levitation, and bottom spheres, during charging. The spheres are free to rotate and are prevented from "rattling" by tabs, welded to the rings. This design should be much tougher against brittle deflection than the rings shown in the drawing.

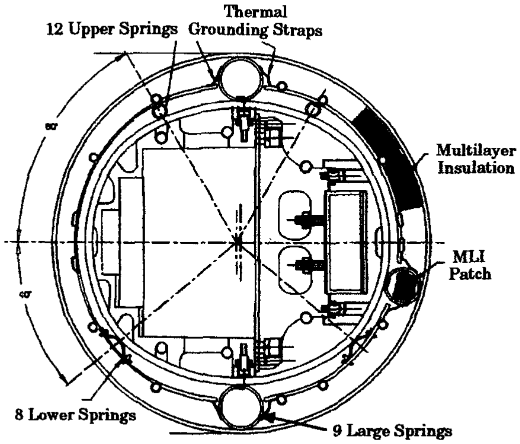

Fig. 5: Helium Vessel Supports and Thermal Insulation

The F-coil is contained by a high-pressure helium cryostat, as shown in Figure 6. The cryostat is filled with helium at 125 atmospheres through the high pressure charge line, which is then sealed off, and cooled down. This approach in which the helium seal is semipermanent is similart to that of the LLNL Levitron [2]. Pressure relief is not needed either after quench or between experimental runs. This is expected to greatly reduce the operating costs of the experiment. Overnight, between experimental runs, the F-coil and its helium are recooled through heat exchangers with welded penetrations through the helium vessel. Liquid helium is circulated through the helium exchangers, then drained before operation. Rollers in the charging station floor are used to align the heat exchanger check valve with the fill-line.

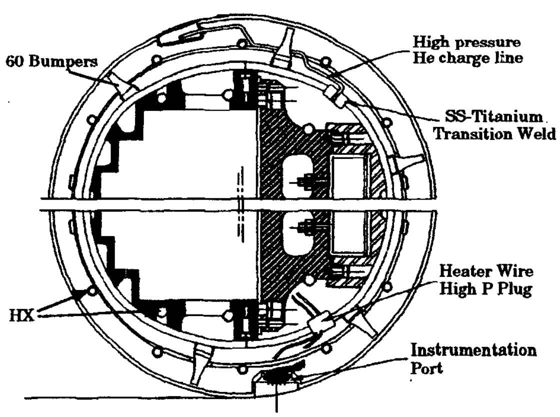

Fig. 6: Cryostat, bumpers, charge line, and feedthroughs

A system of bumpers is used to protect the F-coil during collision, as shown in Figure 6. The bumpers are separated from the vacuum shell by enough space to permit cooldown and tolerances without contact. Radiation to the bumpers is comparable to the total heat leak through mylar superinsulation. The bumpers are now a shallow-angle puck sandwiched between dozens of shim stock disks. The disks are pinned through their center by a triangular rod. When used as a gravity support of the vacuum shell, the large number of contact resistances minimizes heat leaks. When disengaged, the heat leak is reduced to radiation losses. The puck is centrally drilled through its x-and-y axis, allowing a sliding connection to the radiation shield. This configuration should be much stronger against off-normal loads than the tapered bumpers shown in Figure 6.

On quench or loss of control, a system of dual-pressure air bags is deployed from the floor and along the sidewalls, as shown in Figure 7. Top collisions are avoided by a redundant switch, interrupting current to the levitating coil. A dual-pressure system is used in order to speed deployment and linearize the deceleration after impact. The airbag material is a lightweight, untearable sail-cloth, such as teflon-coated kevlar. To avoid outgassing, the airbag trough is covered by a thin metal foil seal. Medium vacuum is maintained in the troughs through individual vacuum pumps. The disposable metal foil is torn by the expanding airbags and is manually replaced by a new foil seal.

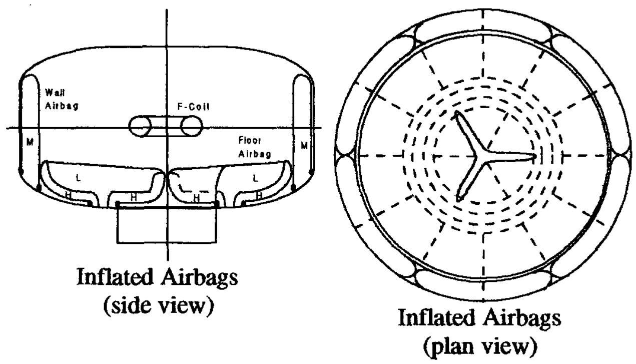

Fig. 7: Fully deployed airbag coil catcher system

IV. THE C-COILS

The F-coils depend entirely upon inductive charging through a charging station at the bottom of the vacuum vessel. This allows the elimination of current leads in the F-coils. At 2,000 A, the use of detachable current leads would be a major feasibility problem. A more traditional low current design would probably have made protection infeasible for an 800 kJ coil, as well as increasing the number of joints needed, proportionally with the current decrease.

An extensive series of trade studies established that the combination of a tall inner coil and a short outer coil, surrounding the F-coil, was the optimal design solution. A superconducting coil was selected, because it was less expensive than a normal coil. In order to stay within available power and water supply limits, the best normal coil option was ten times larger than the pool-boiling NbTi coil design selected. Since the coil can be ramped slowly and dumped reliably, it is not designed to be cryostable. The overall current density of the C-coil winding packs are 14 kA/cm^2 at a maximum flux density of 3.9 T. A superconducting bus connects the inner and outer coils in order to reduce the helium loss to that through one pair of 750 A leads.

V. THE T-S-R-COILS

A set of eight normal coils are arrayed about the vacuum vessel, in order to control tilt, slide, and rotation of the F-coil cryostat, as shown in Figure 8. Each coil generates both vertical and radial field. Eight independent power supplies are used, so that currents through the coils can be combined algebraically to give nearly-orthogonal control fields against five degrees of freedom (slide in the X-Y direction, X-Y tilt about the Z-axis, and rotation). Tilt and slide forces can be easily predicted from the external field gradients. Rotation is due to vertical and toroidal asymmetries in the winding and perhaps to plasma momentum. LDX would be the first levitated ring experiment to attempt to eliminate coil rotation with an active control system.

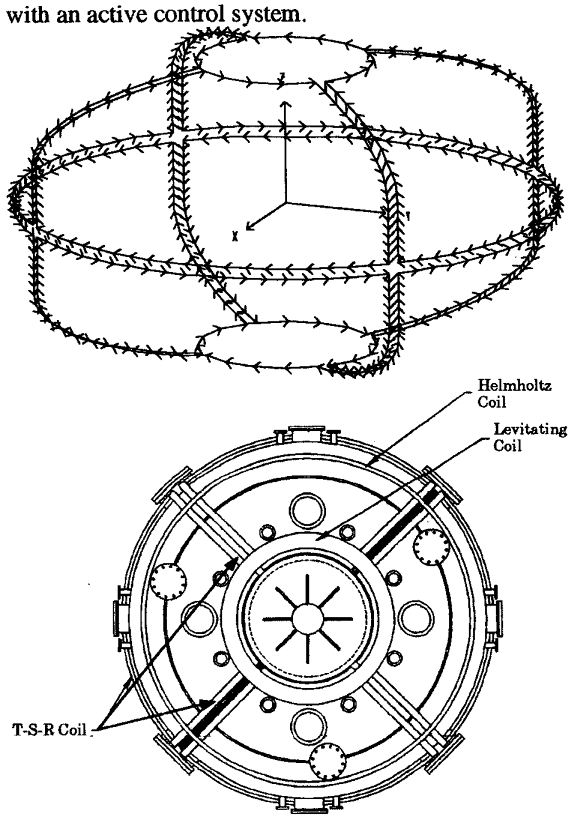

Fig. 8: T-S-R geometry & Vacuum Vessel Plan View

The cryostat position is detected by a redundant laser and Position-Sensitive Diode (PSD) system. A hook within the high-field flux surface is used both as an optical surface and a lifting fixture for removing the cryostat from the charging station. A scratch at the 45 degree surface of the cryostat can be used as a reflective position sensor for both vertical and radial position. Rotation measurement is achieved by using a linear array based detector to read a bar code on the cryostat outer wall.

VI. CONCLUSIONS

The conceptual design has been completed for a levitated dipole experiment with moderate field and very high flux expansion.

An 8 hour levitation time has been designed through the use of advanced superconductors, a lead thermal shield, and compact, low heat-leak supports.

Simplified operations are achieved by using a sealed helium vessel.

Steady-state support in a large vacuum vessel requires only modest external coil power. Protection design is achieved with a combination of "tightly-tailored" airbags and robust bumpers. Thermal protection is achieved by internal dump, enhanced by high-purity aluminum, interlayer sheets.

Modern laser optics can be used to provide redundant control and protection, as well as to detect and suppress rotation.

VII. ACKNOWLEDGMENTS

We would like to thank John Schmidt, Bruce Montgomery, Dave Gwinn, and Joe Smith for helpful discussions. We would like to thank the late Jim Sinnis, Peter Bonanos, Phil Heitzenroeder, John Schmidt, , and Joe File for discussion of the Princeton FM-1 design.

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