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First integrated test of the superconducting magnet systems 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 a fusion plasma offering the possibility of an improved fusion power source. In this concept, a magnetic dipole (a superconducting solenoid) is magnetically levitated for several hours at the center of a 5 m diameter, 3 m tall vacuum chamber. The Floating coil (F-coil) is designed for a maximum field of 5.3 T. A Nb_3Sn conductor was selected to operate the coil when it warms from an initial temperature of below 5 K up to about 10 K at the end of the experimental run. The Levitation coil (L-coil) made from high temperature superconductor electromagnetically supports the F-coil in the center of the plasma volume. There are no electric or cryogenic feeders serving the coil through the plasma because the F-coil must operate in a levitated position. The coil is cooled by retractable feeds and inductively charged/discharged in a lower charging station (CS). The NbTi charging coil (C-coil) surrounds the CS and induces the current in the F-coil. The L-coil and C-coil have each been independently tested. This paper describes the first integrated test of the F-coil and C-coil.

Keywords: Superconducting coil; Cryostat; Levitation; Vacuum chamber; Charging station

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1. Introduction

The Levitated Dipole Experiment (LDX) is a collaborative project between Columbia University and the Massachusetts Institute of Technology to develop and investigate steady state, high beta plasma in a dipole magnetic field. The experiment is based on the superconducting solenoid levitated inside a large vacuum chamber to maximize magnetic flux expansion. Fig. 1 shows the LDX arrangement. An overview of the experiment and the magnet system [1,2] and details of magnets including F-coil [3,4], C-coil [5], and L-coil [6] have been published. This paper describes the first inductive charging of the F-coil. The floating coil (F-coil) levitates without any connection extending through the plasma volume. The F-coil is

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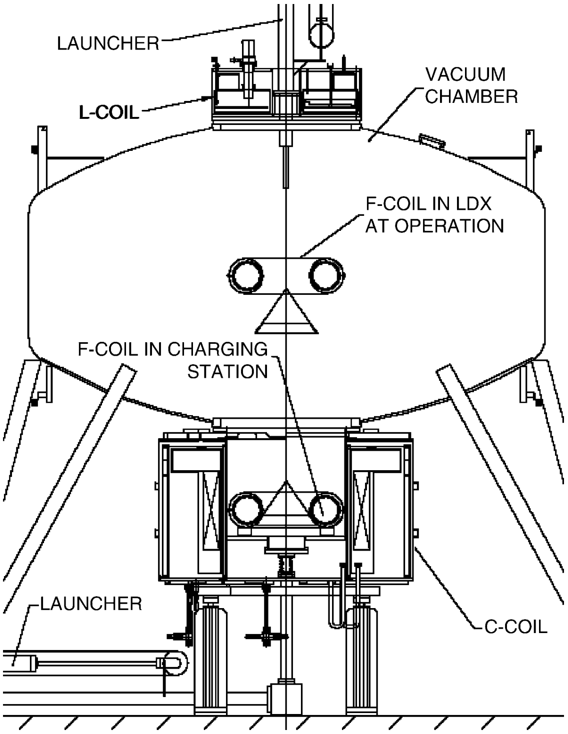

Fig. 1. LDX installation.

charged/discharged inductively when it is located in the charging station (CS) attached to the bottom of the LDX vacuum chamber. A mechanical launcher brings the F-coil to the center of the vacuum chamber and back. The F-coil remains superconductive with a near constant operating current for several hours per experimental run.

The sequence of operation is as follows. The C-coil is charged when the F-coil conductor is in the normal state. Then the F-coil is cooled below 5 K using the retractable transfer lines and it is charged inductively by the C-coil discharge. At the end of operation, the F-coil is discharged by the C-coil charge. Then F-coil is warmed by a flow of warm helium above its superconductive state. Finally, the C-coil is discharged.

The C-coil was designed, built, and tested by Efremov Institute, St. Petersburg, Russia. The critical current of the coil immersed in LHe was determined as 440 A. The C-coil stores 8 MJ of energy at an operating peak field in the winding pack of 4 T. The 8 ton C-coil with the CS in its bore was moved below the LDX vacuum chamber. The CS was bolted to the LDX vacuum chamber. Then the C-coil was centered with respect to the CS and fixed at the permanent supports. During the acceptance tests at MIT, the C-coil was energized at 0.36 A/s to 400 A without a quench.

2. Floating coil and charging station

The F-coil (OD/ID of 764/526 mm, 720 turns) was wound at Everson Electric Co. (now Everson-Tesla) on a stainless steel form using about 1500 m of pre-reacted Nb_3Sn Rutherford cable soldered into a copper channel. Three copper rings are built into the coil and epoxy impregnated with the winding for a more uniform heating of the coil during a quench. After manufacturing, the coil was tested during a current driven test at MIT in a liquid helium cryostat. The coil was charged at 12.5 A/s to 2200 A without a quench. Then the 800 mm long lap joint was fabricated at the coil OD. An epoxy impregnated fiberglass tape reinforced the coil and the joint.

The finished coil was then transferred to Ability Engineering, where its cryostat was manufactured. The coil is installed inside of a toroidal, Inconel 625 helium vessel. The vessel is designed to store about 1.2 kg of helium at room temperature and 12.5 MPa to supplement the magnet's heat capacity during operation between 5 and 10 K, at which the helium pressure drops to 0.14–0.35 MPa. A high heat capacity fibreglass–lead composite radiation shield surrounds the helium vessel with about a 5 mm gap. Eight 12 mm Pyrex glass balls support the shield at the vessel. The shield is wrapped with a multi-layer insulation. Then the magnet and shield assembly is installed in a vacuum shell made of two halves. The helium vessel is supported in the vacuum shell by 8 sets of top, bottom, and side supports comprised of 0.1 mm thick laminated cold rolled steel washers. Installed in eight frames the stacks are thermally anchored to the shield, and designed to withstand an impact load of 50 kN each in case of levitating failure. The full mass of the F-coil is 550 kg (400 kg, helium vessel with magnet; 60 kg, shield; 90 kg, vacuum shell). A tube heat exchanger serves to cool first the coil, then the He gas in the vessel, and finally the shield. The heat exchanger inlet and outlet ports as well as the instrument connector are located at the bottom of the cryostat. The pump-out port and the high-pressure helium fill port are installed in the upper part of the cryostat. Eight Cernox RTD thermometers measure temperatures of the helium vessel wall, radiation shield, and heat exchanger inlet and outlet.

The F-coil charging station (CS) was also made at Ability Engineering. It is a 1157 mm diameter, about 1 m tall steel cylinder bolted to the bottom flange of the LDX chamber. The CS bottom plate has holes for F-coil feedthroughs, the launcher, for diagnostics. A rotating ring supports and centers the F-coil inside of the CS. A CS stopper limits the azimuthal rotation of the F-coil. Once the F-coil is aligned, the transfer lines and the instrument connector are engaged into the F-coil ports from below the CS. The support ring is installed on four load cells to measure vertical forces between F- and C-coils during charging. Four other load cells measure horizontal forces. An intricate system of retractable guard tubes, pump-out ports, valves and pumping lines is built below the CS. This system is used for connecting and retracting the helium transfer lines without spoiling vacuum in the LDX chamber, pumping out, and plugging the F-coil heat exchanger before launch, and for other operations.

3. Inductive charging of the F-coil

The F-coil was cooled several times outside of the vacuum chamber by liquid nitrogen and then by liquid helium. These cryogenic tests indicated that the F-coil top and bottom supports were the sources of an excessive heat load. Cold spots were detected at the shell surface near the supports, particularly, the ones near the top. We believe that this heat conducts through the laminated stacks due to an excessive vertical compression of top and bottom supports which occured during assembly and consecutive welding of the shell halves. No other cold spots were found on the shell surface including areas near side supports. Cooling of the helium vessel by LN2 flow to about 80 K took 100–120 h. Cooling by LHe to about 4.5 K took 6.3 h at a LHe consumption of 110 l. At the end of cooling, the minimum helium vessel temperature was maintained 4.4–4.7 K at a LHe flow rate of about 40 l/h. The bottom of the helium vessel was always colder than its top.

After these cryogenic tests the F-coil was installed inside the CS of LDX. All mechanisms of the CS were checked and adjusted. The LDX vacuum chamber was pumped out to about 6×10^{-3} Pa. The F-coil was cooled by a flow of LN2 and then by LHe through the heat exchanger. Simultaneously the C-coil was cooled down and filled with LHe. The C-coil quench detection system was calibrated during several ramps at currents below 50 A. When the temperature of the F-coil helium vessel was close to 30–35 K, the C-coil was charged to 100 A. When the temperature of the helium vessel dropped to 4.6–5.7 K we began to discharge the C-coil charging the F-coil finally to about 430 A. About 20 min after charging of the F-coil LHe cooling was terminated and the coil was left to warm through its heat leak. The F-coil quenched 2 h 15 min after termination of cooling. The full consumption of LHe was 133 l.

Fig. 2 shows the temperature history of the F-coil during its second charging to about 1080 A (corresponding to 7.8 MA-turn) and subsequent quenching after about 2 h of warming. The inlet temperature showed a sharp jump after the He supply was shut-off. Then it dropped just after the heat exchanger was pumped out. The quench occurred at top/bottom temperatures of 16.7/14.5 K. The maximum top/bottom helium vessel temperatures after the quench reached 38/34 K. Fig. 3 shows the time histories of currents in the C- and F-coils during inductive charging. The F-coil current calculations are based on calculations of the mutual inductance between C- and F-coils and Hall probe measurements.

Next, the F-coil was re-cooled and the C-coil re-energized to 250 A. The F-coil was charged again and

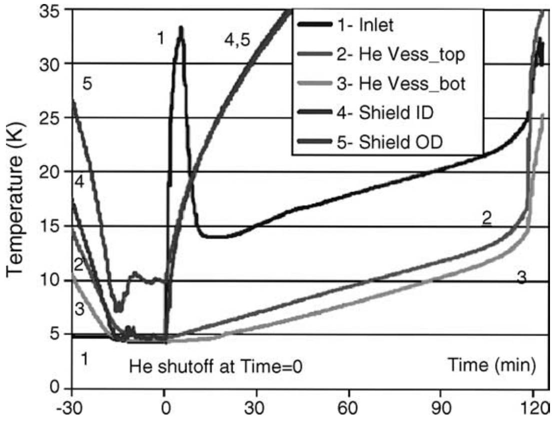

Fig. 2. Temperatures of the F-coil charged to about 1080 A and warmed till quench.

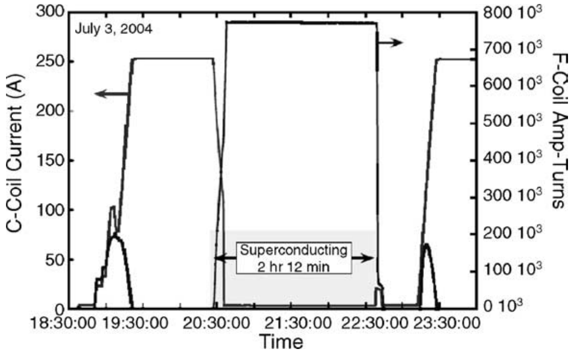

Fig. 3. F-coil inductive charge to about 1080 A.

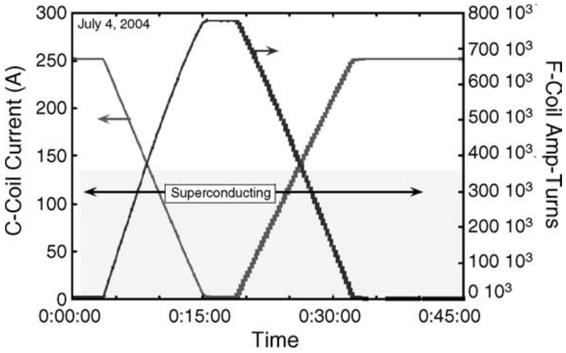

Fig. 4. F-coil inductive charge/discharge test.

discharged after 5 min of flat top current (see Fig. 4). The C-coil was re-charged inductively to exactly the same 250 A indicating negligible internal current dissipation in the F-coil. Finally, the F-coil helium vessel was warmed by a room temperature He flow to above 20 K and the C-coil was discharged.

4. Conclusions

The F-coil was inductively charged to about 60% of the peak charge. This is the F-coil current that will be used during the first plasma experiments with the coil is mechanically supported in LDX. The F-coil provides a nearly constant field for about 2 h allowing studying the quasi-steady dipole-confined plasma. Operation of the C-coil in the presence of the F-coil verified our design of the C-coil quench detection diagnostics and proved that the F-coil was properly centered within the C-coil since the measured magnetic forces were small. Future improvements are expected to provide a longer period of F-coil superconducting operation. The C-coil appears to be re-charged by the F-coil with negligible loss of current.

Acknowledgments

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