

Operation of the Levitated Dipole Experiment Floating Coil

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Abstract—The Levitated Dipole Experiment (LDX) is an innovative facility to study plasma confinement in a dipole magnetic field, created by a superconducting solenoid (floating coil), which is magnetically levitated in the center of a 5 m diameter by 3 m tall vacuum chamber. This persistent mode, floating coil (F-coil) consists of a Nb3Sn magnet installed inside a high-pressure vessel filled with 12.5 MPa helium gas at room temperature. It is surrounded by a high heat capacity fiberglass-lead composite radiation shield and by a toroidal vacuum shell. The built-in tube heat exchanger serves to cool the magnet, the helium vessel, and the thermal shield. When positioned at the lower part of the vacuum chamber the F-coil is cooled by retractable cryogenic transfer lines to about 4.5 K and it is charged inductively by the charging coil installed outside of the vacuum chamber. Then the helium flow is interrupted, the heat exchanger is pumped out, retractable lines are disengaged from F-coil ports, the ports are plugged, and the F-coil is lifted to the middle of the chamber to initiate and study plasmas. After several hours and just before the F-coil warms up to about 10 K it is lowered down for the next re-cooling or for discharging. This paper describes the F-coil cooling system and inductive charging system operation and performance.

Index Terms—charging station, heat exchanger, magnet, transfer line

I. INTRODUCTION

THE Levitated Dipole Experiment (LDX) is a newly completed research facility designed to test plasma confinement in a dipole field [1]. The floating coil (F-coil) will be supported in the middle of the LDX vacuum chamber without mechanical connections by the magnetic attraction to a HTS levitation coil (L-coil). During the first year of plasma tests the F-coil was operated in a supported mode connected with the central rod of a lifting mechanism. When the F-coil is located at the charging station attached to the LDX bottom it can be charged inductively by the charging coil (C-coil), which surrounds the charging station with a small gap. Retractable cryogenic transfer lines and instrument connector are disengaged from the F-coil before it is lifted into the middle of the LDX for plasma experiments. Description of the LDX magnet system can be found in [2], the F-coil in [3]-[5],

the C-coil in [6], and the L-coil in [7].

The F-coil is the persistent mode superconducting magnet designed for 2070 A current at the peak field 5.3 T and the temperature below 10.8 K. Before one low-resistance joint was made the coil was tested at the current driven mode in boiling helium at up to 2200 A without quenching. The magnet is installed in the high-pressure Inconel-625 toroidal helium vessel. It is filled at room temperature by 1.2 kg of high-pressure helium. At the magnet operating temperature 4.5-10 K the helium pressure drops to 0.13-0.35 MPa. The fiberglass-lead radiation shield is separated from the helium vessel by 16 glass balls with a 5-mm gap. Multilayer insulation covers the shield. The toroidal stainless steel shell protects all the design and creates a vacuum space around the helium vessel. The full mass of the coil is 550 kg (400 kg - cold mass, 60 kg - radiation shield, 90 kg - vacuum shell). LN₂ or LHe flow running through loops of the tube heat exchanger cools the magnet, helium vessel, and shield. Retractable transfer lines enter the heat exchanger ports to provide cryostat cooling. The low heat leak helium vessel support system is design to withstand 50 kN of a load in a case of levitating failure. It consists of 24 stacks of 0.1 mm thick washers of laminated cold rolled 316 stainless steel arranged along the top, bottom, and side. The stacks are installed in 8 frames between the helium vessel and the shell. The cryostat is instrumented with thermometers installed outside of the helium vessel, on the shield, on inlet and outlet tubes of the heat exchanger.

II. F-COIL OPERATION

A. Operating Scenario and System

F-coil cooling by the cryogen flow through the transfer lines and their connection/disconnection with F-coil ports must not spoil the LDX vacuum (10^{-6} - 10^{-8} Torr). The F-coil ports must be sealed when the coil is lifted into the LDX chamber. Fig. 1 shows the F-coil operating system, which satisfies the requirements. Guard tubes engage in the F-coil ports and hermetically seal the space around the transfer lines from the surrounding vacuum in the charging station. The vacuum guard tubes are connected through charging station ports, and can be pumped out, pressurized, and purged by GHe. The vacuum tubes can be moved vertically within these ports to connect to the F-coil.

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The main scenario of LDX operation is followings. The C- and F-coils are initially cooled by N₂ and subsequently by LHe. The C-coil magnet is cooled by pool boiling. The F-coil is cooled by the forced flow of a cryogen through the heat exchanger. The C-coil is charged in about 25 minutes to the maximum current (420 A), when the F-coil is still in the normal state (above 17 K), which corresponds to the helium vessel temperature above 20 K. When the temperature drops below 8 K the C-coil is discharged inducing the full current to the F-coil. After the helium vessel reached 4.5 K it is cooling further during 20-30 minutes. Then the LHe flow is terminated, the transfer lines are retracted, the heat exchanger is pumped, and its ports are plugged by plug operators. The instrument connector is then detached and the vacuum guard tubes are retracted from the F-coil ports. The C-coil is open circuited and held at zero current (the quench protection dump resistor circuit remains closed) when the F-coil is lifted out of the charging station and during LDX plasma experiments. After 1-2 hours the F-coil is lowered back to the charging station and is rotated on a rotary ring to a position where a stopper fixes it. The guard tubes and the instrument connector are then engaged into the cryostat ports. Depending on the program the F-coil can be re-cooled by LHe flow through the transfer lines, or the C-coil can be ramped up (the main charging circuit is closed) to discharge the F-coil. Then the F-coil is warmed up by a He flow (above 20 K), so that the C-coil can be safely discharged.

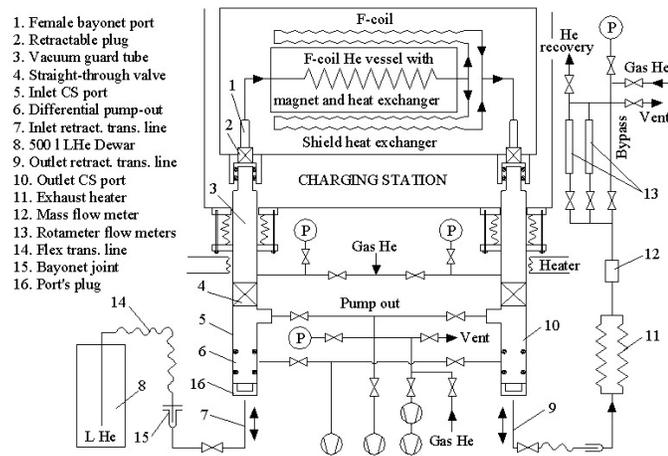


Fig. 1. F-coil operating system (schematic). Transfer lines are retracted. Vacuum guard tubes are engaged into F-coil ports.

B. F-coil cool down

The cool-down charts for F-coil are shown in Fig. 2. Initially the F-coil was cooled by a cold GN₂ flow. Due to a large pressure drop in its long heat exchanger and a limitation of the pressure in the inlet for the transfer line seals, the initial flow rate of N₂ corresponded only to 4.2 l/h at 0.27 MPa. Thereafter LN₂ was supplied with the flow rate of about 6.3 l/h at 0.21 MPa. All the time bottom of the helium vessel was cooler than the top because the vessel is cooled by the natural convection of GHe. It takes about 76 hours to cool the helium

vessel and magnet to about 85 K. Below 85 K the cryostat was cooled by LHe. The usual time for cooling the helium vessel from 85 K to 4.3 - 4.6 K was 5 - 6 hours while

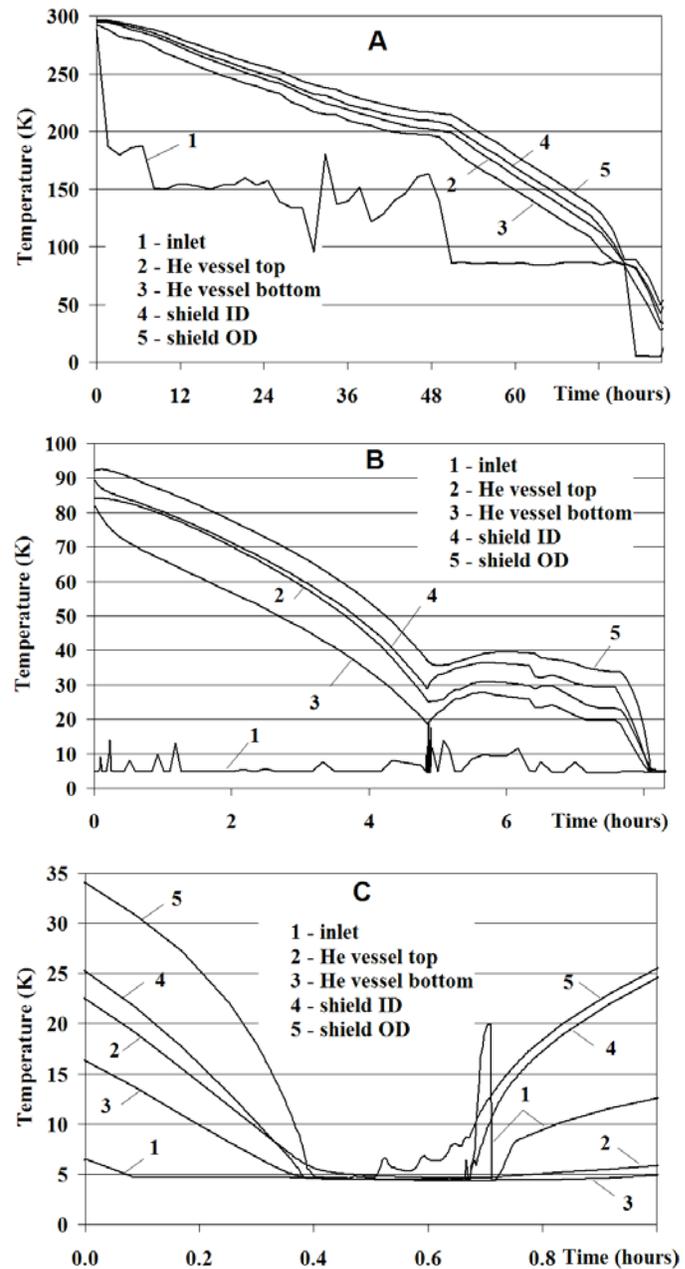


Fig. 2. F-coil initial cool-down. A) From room temperature by nitrogen flow. B) From 85K by liquid helium flow. C) Last stage of cooling and LHe flow termination.

maintaining 0.17 MPa pressure in the Dewar (the maximum pressure before the relief valve open). In Fig. 2B the time of cooling is about 2.5 hours longer because of an decrease in the cooling intensity due to the preparation of the C-coil for charging, which can be done when the F-coil is above 20 K. The flow rate of LHe during the waiting period was about 7 l/h. The usual consumption of LHe for non-interrupted cooling was about 110 liters at the average flow rate of about 25 l/h, changing from 8 l/h at the beginning to 45 l/h at the end. At the very end of cooling the pressure in the Dewar was

decreased by steps to 0.12 MPa to control the flow and to decrease the inlet helium temperature (see Fig. 2C). Finally the helium vessel minimum temperature reached about 4.3 K and the LHe flow was terminated. At this time the full consumption of LHe was about 140 l. Just after flow termination the cryostat inlet temperature jumped to 20-35 K. The heat exchanger was pumped out and the temperature dropped. After we got some experience the time between flow termination and F-coil lifting shrinks to 12 minutes.

C. F-coil performance

Testing of the F-coil began on July 2004 by discharging the C-coil at gradually increased current of 100A, 250A, 300A, and finally at 400A on July 2005. The last charge is close to the maximum operating C-coil current of 420A. The F-coil was charged, respectively, to 430A, 1080A, 1290A, and finally to 1730A. The first plasma experiments with F-coil began in August 2004. Quench analysis studies have indicated that at currents below 1300 A the stresses in the F-coil are much lower than the allowable level. To prolong the time of the plasma experiments the tests at these low currents were continued until the F-coil quenched. During a few tests the F-coil quench temperatures were measured when the coil was in the charging station (Fig. 3). The maximum F-coil operating time during warming before a quench was seen to depend on degree of GHe cooling and a level of vacuum in the cryostat. For a 1290A charge the time was 2.7 h, which permitted plasma experiments during about 2.5 hours. Fig. 4 indicates that the coil warming rates for an uncharged coil are very similar to the rates for the charged and quenching coil. Soon after flow termination the top/bottom vessel temperatures increased almost linearly until 11-12 K, after which the warming rate increased. Shortly after this time the coil quenched and the shield temperature reached the maximum (51-55 K in Fig. 3 and 50 K in Fig. 4). The quench temperatures at the vessel bottom were 16.2, 14.4, 13.8 K for currents 430, 1080, and 1290 A, respectively. The after quench helium vessel temperatures increased from 28-30 K at 430 A to 40-42 K at 1290 A. In a good agreement with the energy dissipated at the quench the corresponding temperatures at zero current were 27-30 K. Repeatable quenches at the currents below 70% of the nominal current didn't change the F-coil performance.

The permitted baking temperature for the F-coil was limited to 90-95 C because of the use of a low temperature solder. In spite of a long period of baking and pumping, a significant out-gassing in the cryostat vacuum space was observed. After several months of operation the problem was partially solved by activating a port in the lower part of the F-coil cryostat, which permitted the cryostat to be pumped by the LDX vacuum system when it was resting in the charging station. The F-coil vacuum port was plugged during LHe cooling, during plasma experiments, and during periods of high pressure in the LDX vacuum chamber.

Figures 3 and 4 show warming processes after a long period of out-gassing and, correspondingly, initial poor vacuum in

the cryostat. Fig. 5 shows the F-coil warming rate at a better initial vacuum due to LDX pumping until the beginning of LHe cooling. The explanation of the cryostat thermal behavior is the following: The maximum temperature observed in the

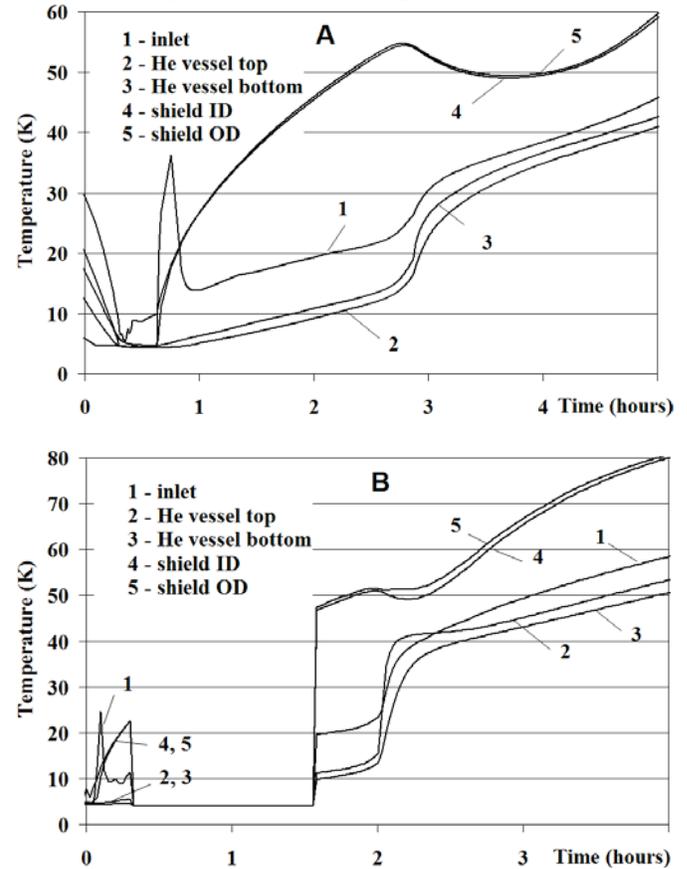


Fig. 3. F-coil quenches during warming after termination of cooling. A) 430 A charge. B) 1290 A. The charts interrupted when the F-coil moved out of the charging station for the plasma experiments.

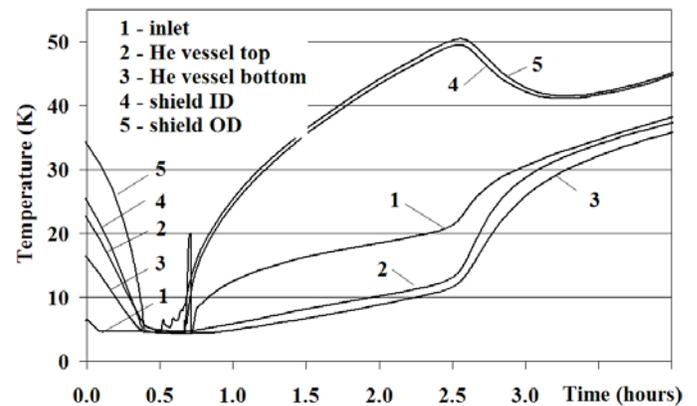


Fig. 4. F-coil warming after termination of the cooling flow at no current in the coil and poor initial insulating vacuum in the cryostat.

shield chart and simultaneous sharp warming of the helium vessel in poor vacuum conditions result from the presence of gases that evaporate from the outer parts of the laminated supports and from outer layers of MLI. These gases are cryopumped and condense on the cold surfaces of helium

vessel and cold end of the supports (between the helium vessel and the shield) resulting in an increase of thermal conduction. The heat leak to the shield decreases mostly due to improved thermal resistance of outer parts of supports after evaporation of condensed gases. The heat leak from the shield to the

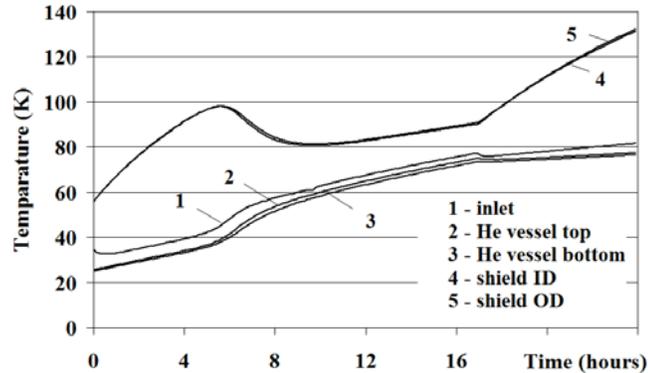


Fig. 5 F-coil warming at a better initial vacuum in the cryostat

helium vessel increases due to degradation of thermal performance of the support coldest parts. Finally the heat leak from the cryostat shell to the shield dropped below the heat leak from the shield to the helium vessel, which caused the temporary temperature maximum of the shield. With a poor vacuum the maximum temperature of the shield reaches 50 K (Fig. 3, 4). A better vacuum in the cryostat permits a higher maximum temperature, which is close to 100 K in Fig. 5. The sharp change in the temperature charts in Fig. 5 corresponds to the time when the F-coil pump port was reopened to the LDX vacuum. The differential shield-helium vessel temperature subsequently increased from 15 K to 50 K and later to 80 K due to the recovery of insulating properties of the laminated supports at the additional improvement of the vacuum in the cryostat.

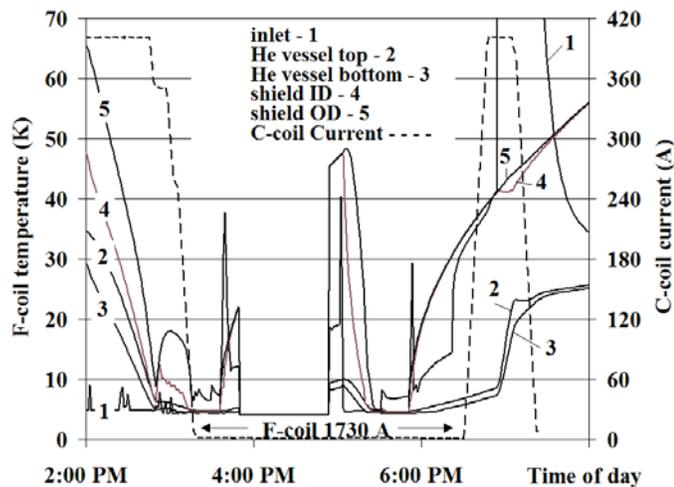


Fig. 6. C-coil is charged to 400 A and discharged inductively charging the F-coil to 1730 A. F-coil is re-cooled after plasma operation in LDX, discharged, and finally warmed up by gas He flow above 20 K for safely discharge of the C-coil.

In fig. 6 the F-coil temperature history is combined with the current history for C- and F-coils. The C-coil was charged to 400 A, when the F-coil helium vessel was above 30 K. When the helium vessel temperature dropped below 8 K the C-coil was fully discharged, which inductively charged the F-coil to 1730 A. (The current in the F-coil was calculated by using Hall probe measurements.) The helium flow was then terminated and the F-coil was lifted into the middle of the LDX vessel for plasma experiments. After returning into the charging station (when the helium vessel was below 10 K) the charged F-coil was re-cooled by LHe flow without quenching. The F-coil was then discharged by recharging the C-coil to 400 A (exactly as in the initial charge), indicating that no degradation of the current had occurred after during 4 hours of F-coil operation at 1730 A. Next, the F-coil helium vessel was warmed to above 20 K by the room temperature helium flow and the C-coil was discharged.

III. CONCLUSION

During about of one year of the supported mode experiments the C- and F-coils of the LDX reliably operated at currents up to near the nominal current. The F-coil has been charged to near the maximum operating current and re-cooled without quenching. Our experiments confirmed the possibility of multi-hour sessions of plasma tests after a single inductive charging of the F-coil. No current degradation was determined during several hours of F-coil operation. The LDX is presently being prepared for the levitated mode operation.

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REFERENCES

- [1] J. Kesner, L. Bromberg, D. Garnier, M. Mauel, Plasma confinement in a magnet dipole, *17th IAEA Fusion Energy Conf.*, Paper IAEA-F1-CN-69-1CP/OS, Yokohama, Japan, 1998.
- [2] Schultz at al, The Levitated Dipole Experiment magnet system, *IEEE Trans. Appl. Supercond.*, vol. 9, No. 2, pp. 378-381, June 1999.
- [3] A. Zhukovsky at al, Design and fabrication of the cryostat for the floating coil of the LDX, *IEEE Trans. Appl. Supercond.*, vol. 10, No.1, pp. 1522-1525, March, 2000.
- [4] A. Zhukovsky at al, Status of the Floating Coil of the Levitated Dipole Experiment, *IEEE Trans. Appl. Superconductivity*, vol 12, pp. 666-669, 2002.
- [5] A. Zhukovsky at al, First integrated test of the superconducting magnet system for the Levitated Dipole Experiment (LDX), in *Fusion Engineering and Design*, to be published.
- [6] A. Zhukovsky at al, Charging magnet for the F-coil of LDX, *IEEE Trans. Appl. Supercond.*, Vol. 11, No. 1, pp. 1873-1876, March 2001.

- [7] P. C. Michael et al, Performance of the conduction-cooled LDX levitation coil, *Adv. in Cryo. Eng.*, vol. 49, pp. 701-710 2004.