THERMAL PERFORMANCE OF THE LDX 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. The floating coil (F-coil) consists of a Nb_3Sn magnet installed inside a strong vessel filled with high-pressure helium gas at room temperature. It is surrounded by a fiberglass-lead composite radiation shield and by a toroidal vacuum shell. The cryostat design provides the ability to operate the magnet for several hours of warming while suspended in the middle of the vacuum chamber without electric and cryogenic connections to the coil. For this reason the magnet is charged/discharged inductively in a lower part of the vacuum chamber. The retractable cryogenic transfer lines serve to cool down the magnet to 4.5 K before it is lifted to the operating position. The F-coil can be re-cooled multiple times while maintaining its field and current. This paper describes the thermal performance of the F-coil.

KEYWORDS: superconducting magnet, helium vessel, transfer line, charging station
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INTRODUCTION

The Levitated Dipole Experiment (LDX) is a new research facility developed and built at MIT Plasma Science and Fusion Center as part of a joint research project with Columbia University to investigate nature's way to confine high-temperature plasma [1]. The F-coil will levitate without any connections penetrating the plasma. Retractable cryogenic transfer lines cool the F-coil when it is located at the charging station (CS) attached to the bottom of the LDX vacuum chamber. The F-coil is charged/discharged inductively by a charging NbTi superconducting coil (C-coil) surrounding the CS with a small gap. The F-coil will be supported by the magnetic attraction to the levitation high-temperature superconducting coil (L-coil) installed at the top of the vacuum chamber. During the first year of plasma experiments, the F-coil is operating in a supported mode when three thin spokes connect the F-coil with a central rod of a lifting/lowering mechanism. The mechanical launcher brings the F-coil to the center of the vacuum chamber and back to the CS. An overview of the experiment and the magnet system [2], details of magnets including F-coil [3-5], C-coil [6], and L-coil [7] can be found in previous publications.

The sequence of LDX operation is the following. The C-coil helium vessel with the magnet is cooled down and filled by LHe. The F-coil is also cooled by cold GN_2, then by LN_2, and finally by LHe flowing through the cryostat heat exchanger. When the F-coil is still at a normal state (above 17 K) the C-coil is charged. When the F-coil helium vessel is cooled below 8 K the coil is charged inductively by the C-coil discharge. Cooling of the helium vessel continues until a temperature near 4.5 K is attained. After a while the He flow is terminated, retractable cryogenic transfer lines, and instrument connector are detached from the F-coil. Then the launcher lifts the F-coil to the middle of the vacuum chamber where plasma experiments are conducted. After one to two hours when the F-coil temperature is still low, it is lowered back into the CS. The instrument connector and transfer lines are engaged to the F-coil. Depending on the test program the F-coil is either re-cooled by the LHe flow for the next plasma experiments or the F-coil is discharged by the C-coil charging. In the latter case the F-coil is warmed up above 17 K by the warm GHe flow, then the C-coil is discharged.

F-COIL DESCRIPTION

The magnet was designed to carry the current up to 2070 A (1.48 MA-turns) at a peak field of 5.3 T and at the temperature below 10.8 K (the current sharing temperature). The total magnet inductance is 0.39 H and the stored energy 0.83 MJ. The magnet was wound in a stainless steel form by a pre-reacted Nb_3Sn Rutherford cable soldered into a copper channel. The impregnated winding can freely slip inside the coil form during cooling/warming and excitation. Before the coil was encapsulated into its cryostat it was tested at a helium pool boiling in a service cryostat. Without a quench the coil was energized at a current driven test up to 2200 A. After this test the 800-mm long low resistance lap joint was soldered at the coil OD to provide a persistent mode operation.

The magnet was installed inside the toroidal Inconel 625 helium vessel with major and minor diameters of 762 mm and 254.5 mm respectively. The vessel was certified according to the ASME Boiler and Pressure Vessel Code for 12.5 MPa operating pressure at room temperature. At temperatures between 4.5 and 10 K when the magnet is superconducting He pressure drops to 0.13-0.35 MPa. About 1.2 kg of He mass is charged into the vessel. Only the He heat capacity provides a prolonged operation of the magnet after termination of the forced LHe flow through the heat exchanger. The high-heat capacity fiberglass-lead radiation shield surrounds the helium vessel with a radial gap of 5-mm. The shield is made of upper and lower halves by a vacuum bagging technique. 1.5-2.5 mm thick lead tiles are embedded into fiberglass and they are impregnated together by epoxy resin. Four loops of the heat exchanger copper tubes are also impregnated inside each half of the shield. All lead tiles, copper tubes and two half-shields are thermally anchored together by soldered thin copper strips. The shield is separated from the helium vessel by 16 Pyrex glass balls. The vessel and both sides of the radiation shield are covered with adhesive aluminum tape for better radiation properties. The radiation shield is wrapped by blankets of multi-layer insulation (MLI) consisting of 25-μm thick double aluminized Mylar with 0.1-mm polyester spunbonded spacers. The assembled part of the cryostat, wrapped with MLI, is installed in a stainless steel electro-polished vacuum shell, 3.2 mm thick, made of two halves. The mass of the coil is 550 kg, including 250 kg magnet, 150 kg helium vessel, 60 kg radiation shield, and 90 kg vacuum shell.

The helium vessel is supported in the vacuum shell by 24 top, bottom, and side stacks of 0.1 mm thick laminated cold rolled 316 stainless steel washers. The OD of the washers is 16 mm. Thin magnesium oxide powder was sprayed on washer surfaces before their assembly in stacks. The average amount of washers in the top, bottom, and side stacks is 215, 227, 270 washers, respectively. They are shaped and assembled in a way to keep integrity of the stack even in a case of a non-axial force. In case of a levitating failure each low heat leak support can withstand a 50 kN load. The stacks are installed in eight frames attached to the outer shell. The supports are located by three circles (top, bottom, and side). They are thermally anchored to the radiation shield by soldered copper wires.

The heat exchanger in the cryostat provides the cryogenic cooling. Two loops of 9.5 mm stainless steel tube are welded to the sides of the magnet form. Four loops with copper fins brazed to the steel tube are fixed on gussets inside the helium vessel to cool gaseous helium. The length of the heat exchanger inside the vessel is about 20 m. Outside of the vessel the tube is split for separate cooling passages in the top and bottom parts of the shield. The full length of each passage is about 15 m. The diameter of the inner loop tube is 4.8 mm and diameters of three other loops are 6.4 mm each. Downstream of the shield the tubes are united again. The heat exchanger is terminated at both inlet and outlet by female bayonets located in the lower part of the vacuum shell in the inlet and outlet ports. Special retractable inlet and outlet transfer lines with male bayonets are built and tested. The cryostat is instrumented with eight RTD Cernox thermometers epoxied to the surfaces to measure temperatures of the inlet heat exchanger tube, the helium vessel top/bottom, the shield near its ID and OD, two outlets of the shield, and the outlet transfer line. The cryostat shell has the instrument port at the lower part, which mates the retractable instrument connector. The pump-out and high-pressure fill ports are located at the top part of the vacuum shell.

CHARGING STATION AND COOLING SYSTEM OPERATION

The CS cylinder, about 1 m tall and 1.2 m in diameter, is attached to the bottom of the LDX vacuum chamber. The F-coil is serviced and remains within the CS excluding the times of operation in the middle of the LDX vacuum vessel. The bottom of CS has flanges for plasma diagnostics, feeds for the F-coil, and a central flange for the launcher. When the F-coil is resting in the CS it is supported and centered by a rotating ring. When the ports in the bottom of the F-coil are aligned to the ports in the CS a stopper fixes the azimuthal position of the coil. The inlet and outlet transfer lines and the instrument connector can be engaged into the corresponding F-coil ports. The bottom of the F-coil is also equipped with an extra pump-out port with a plug, which can be removed by a plug operator attached to the bottom of the CS. This vacuum port serves to pump the F-coil by the LDX pump-out system when the F-coil port is open. Connecting-disconnecting the retractable cryogenic transfer lines with the F-coil ports does not spoil the high vacuum in the CS (10^{-6}-10^{-8} Torr). No leaks from the F-coil ports are permitted during cooling of the F-coil. During operation in the middle of the LDX chamber the inlet and outlet ports must be plugged for the same reason. The design developed to fulfill these requirements is schematically shown in FIGURE 1.

Both retractable transfer lines are separated from the vacuum chamber volume by

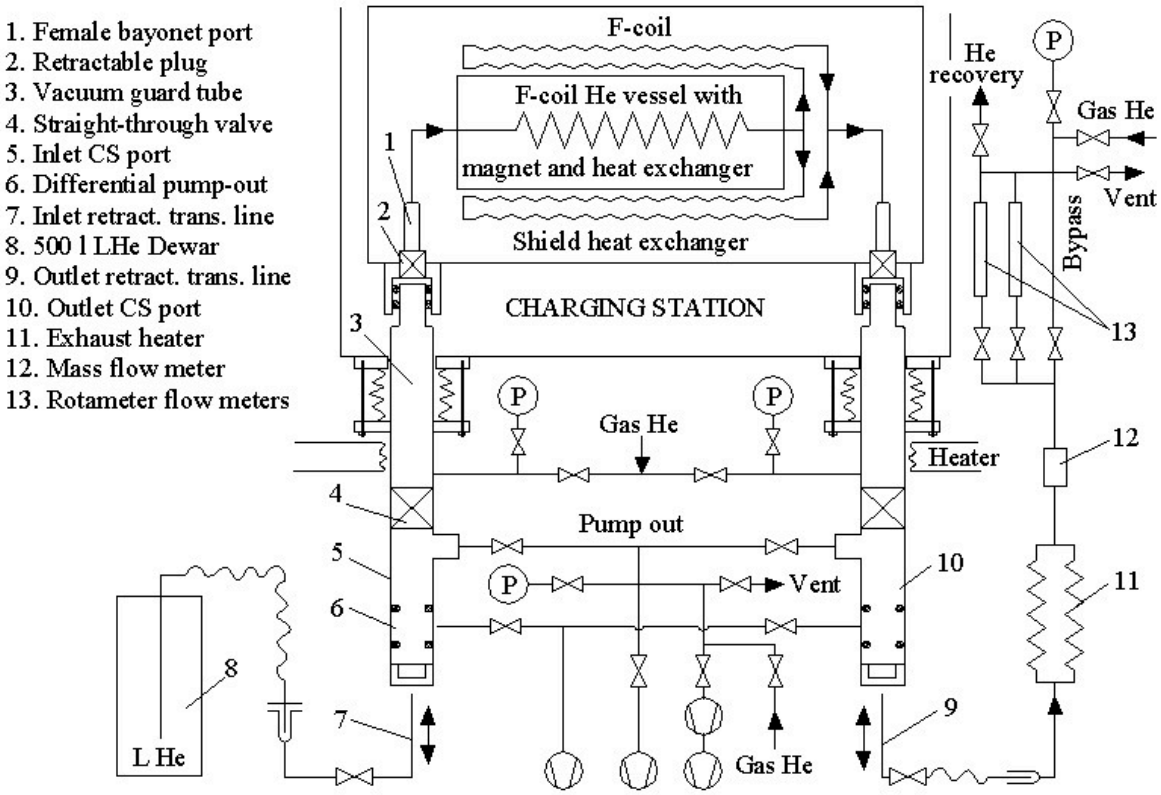

FIGURE 1. F-coil cooling, pumping out, and purging system (schematic). Transfer lines are retracted.

retractable vacuum guard tubes, which hermetically seal the spaces between the bottom of the CS and the cryostat inlet and outlet ports. The guard tube permits connection and retraction of the transfer line without contamination of the external vacuum in the vacuum chamber. After the F-coil helium vessel is cooled, the LHe supply and exhaust valves are closed, the transfer lines are retracted, and the heat exchanger is pumped out to about 0.1 Torr using both inlet and outlet ports. This prevents any heat leak by convection (through a column of He gas in the heat exchanger) between the room temperature vacuum vessel, cold helium vessel, and the shield. The inlet and outlet cryostat ports are then plugged and sealed using a plug operator. The vacuum tubes are pumped out to about 10^{-5} Torr and disconnected by vacuum valves from the outer system. The retractable vacuum tubes are allowed to be moved from the cryostat by the linear-motion bellows. After disconnecting the instrument connector, the charged F-coil is ready to be lifted into the middle of the LDX for plasma experiments.

When transfer lines or plug operators are inserted or withdrawn from the CS ports, the straight-through valves are closed, the ports below valves are pressurized by $1.4x10^{5}$ Pa He gas, and they are purged to prevent air contamination. The operation is analogous to a docking system in space. It includes several steps of pumping, pressurizing and purging both CS ports with He gas. During this operation the C-coil is discharged and personnel are permitted to work below the CS. Care must be exercised to avoid an operational error, which can cause contamination the port and plug the cryostat cooling tubes with ice. After plasma experiments are completed, the floating coil is brought back down to the bottom of the CS. There are several scenarios for operation depending on the experimental program. If the helium vessel temperature is below 11 K, the F-coil can be re-cooled for continuing plasma experiments, the plugs will be removed from the F-ports and the outlet line engaged. The inlet transfer line must be pre-cooled by the LHe flow before insertion into the CS port. No moisture or ice can be left at the male bayonet before insertion because they can cause plugging of the heat exchanger. The transfer line should be inserted into the F-coil port fast to avoid excessive heating of the magnet at the beginning of helium transfer, which can cause the F-coil to quench.

If the F-coil is to be discharged all preparations for the discharge of the C-coil must be made beforehand. Operators can not work below the CS in the elevated magnetic field that is present when the C-coil is charged above 50 A. Our experience has shown that the C-coil can be discharged if the F-coil helium vessel temperature is above 20 K. At this temperature the F-coil is in the normal state. If the vessel is above 13 K when the F-coil is lowered into the CS, it should be discharged immediately to prevent the F-coil (and then the C-coil) from quenching. The usual discharge from the full current is about 23 minutes. After the F-coil has been discharged, we wait until the helium vessel is warmed to above 20 K and then discharge the C-coil. If the vessel temperature is below 13 K we can shorten the delay time until the C-coil can be discharged by warming the F-coil with a flow of warm He gas. In this case the plugs must be removed from the F-coil. During the subsequent time interval (which can be a night, a weekend, or some other period of time) the magnet remains in the CS, where it warms and it must be re-cooled before recharging. For recharging the vacuum guard tubes are moved up and seal the cryostat ports, the plugs in the F-coil are removed, the transfer lines are inserted into the ports, and the cryostat is cooled down.

F-COIL CRYOGENIC PERFORMANCE

We observed the cryogenic performance of the F-coil depends on the quality of the F-coil vacuum. During interruptions of pumping of the F-coil, significant out-gassing occurred. Since the F-coil contains epoxy resin and low temperature solder, the magnet and radiation shield could not be baked at high temperature. The F-coil was warmed up to 90-95 ^oC by hot GN_2 flowing through the heat exchanger from the outlet, and pumped for one week. Several times the vacuum space was purged by hot GN_2. After this treatment the out-gassing into the vacuum space decreased but was still substantial. The first N_2 and LHe cooling of the coil was performed at the room conditions. During LN_2 cooling cold spots were detected in places where several top and bottom helium vessel supports contact the outer shell. All other outer surface including vicinity to the side supports was close to the room temperature. A low thermal resistance of several laminated supports could be caused by their excessive axial compression during assembly of two halves of the shell. After preliminary cooldown the coil was installed into the LDX CS where it operated in 10^{-5}-10^{-7} Torr vacuum. Due to a big pressure drop in the long heat exchanger and limitation of the pressure in the inlet transfer line seals the initial flow rate of nitrogen cold gas at 0.27 MPa corresponded only to 4.2 l/h. When helium vessel temperature dropped below 200 K LN_2 was supplied with the flow rate of about 6.3 l/h at 0.21 MPa. The temperature of the vessel bottom was always lower than at the top because the vessel is cooled by natural convection of GHe inside the vessel. The full time of cooling the 400-kg cold mass to 80 K was about 76 hours. LHe cooled the cryostat after purging and pumping out the heat exchanger. Usual time of helium vessel cooling from 80 K to 4.4 K was 5-6 hours at 0.17 MPa pressure in the supply Dewar (maximum pressure before the relief valve open). Usage of LHe was about 110 l 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.

The first charges of the F-coil were performed in July 2004 by discharging the C-coil from 100 A and 250 A, which corresponded to charging the F-coil to 430 A and 1080 A respectively. Gradually respective currents in the C- and F-coils were increased to 300 A

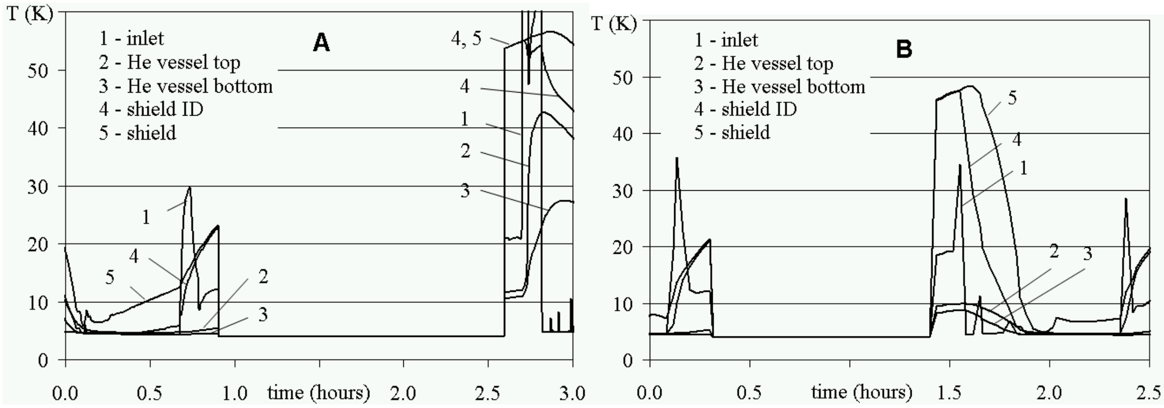

FIGURE 2. F-coil temperature history during plasma experiments. Interruptions in temperature charts approximately correspond to coil operation outside CS. A) Unsuccessful attempt to re-cool the F-coil after plasma tests. Quench at 1290 A after supply of LHe into not properly pre-cooled transfer line when the inlet tube temperature jumped to 182 K due to a "bubble" of warm gas. Shortly after the quench the coil was re-cooled for the next charge. B) Successful re-cooling of the coil at 1730 A after plasma experiments.

and 1290 A, and finally to 400 A and 1730 A (1.2 MA-turns). The last charge is close to the maximum operating current of the C-coil (about 420 A). When the helium vessel temperature dropped to 6-9 K the C-coil was discharged, inducing the current in the F-coil. This took 17-23 minutes. Then before termination of the He flow, the coil was cooled additionally for about 30 minutes with a step-wise decrease of the He pressure (to 0.12 MPa), temperature, and flow rate to complete the cooling of GHe in the helium vessel to the minimal temperature. By this time the full consumption of LHe was about 140 liters.

The first plasma experiments in LDX started in August 2004. Estimate of stresses in the magnet during quenches showed that at currents below 1300 A they are below the allowable level. To maximize the time of these plasma experiments the tests were permitted to continue until the F-coil quenched during warming. (F-coil quenches should be avoided at higher currents.) The maximum time of operation between cooling flow termination and quench depends on degree of GHe cooling in the helium vessel and level of vacuum in the cryostat. At the 1290-A F-coil charge this time reached 2 hours 42 min and it provided 2.0-2.5 hours of plasma experiments, during which time 20-30 plasma shots were performed. After the quench, the coil was lowered to the CS and cooled down for the next plasma experiment or allowed to warm until the next day. The usual experimental session consisted of a two-day run, which permitted 3-4 charges of the F-coil. The temperature history of the F-coil before and after plasma experiments is shown in FIGURE 2. Every time after termination of the LHe flow the cryostat inlet tube temperature increased sharply to 30-35 K. The heat exchanger was pumped and the temperature dropped immediately. Helium vessel temperatures increased approximately linearly during 2.0-2.5 hours of the magnet warming. The bottom/top quench temperatures were 14.4/16.6 K for a 1080A charge, and 13.8/15.9K for a 1290A charge. The after-quench temperature stabilized at 35-40 K.

On December 10, 2004 during experiments with plasma using a reversed current in shaping coils external to the LDX vacuum chamber, the F-coil supports buckled and the coil tilted. At a 90-degree tilt, reached in 3.5 seconds, the coil struck and bent the 48-mm heavy wall lifting tube. The coil tilt and blow with 3.7 kJ energy, equivalent of dropping the coil from a height of 0.67 m. After rocking near the vertical position, the coil returned back to the horizontal position and quenched in about 2.5 minutes after this return. During the event the three support spokes were bent/unbent but they survived the event without a

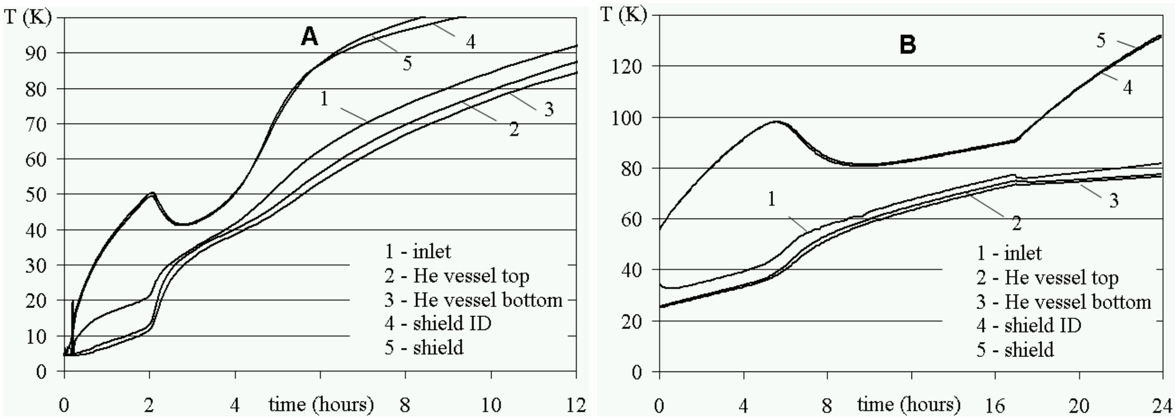

FIGURE 3. F-coil warming history without a magnet quench. The coil heat exchanger is pumped out and plugged. A) Warming at a poor insulating vacuum, after the coil tilt, December 21, 2004. B) Warming at a better vacuum when the cryostat vacuum space was pumped out by LDX (about 10^{-6} Torr) until LHe cooling started (about 12 hours before zero time in the chart), on July 1, 2005. The helium vessel was warmed up above 20 K to discharge the C-coil after plasma experiments. At about 18 hours the cryostat was pumped out again by LDX (see changes of chart slopes).

crack and only a 4-cm long dent about 1-mm deep was left on the surface of the cryostat. Subsequently the performance of the F-coil was tested and it appeared to be unaffected by the tilting event. After the launcher was repaired the plasma experiments continued. The tilting event served as an indication that the cryostat and magnet support systems could survive severe shocks during levitation failures.

After 6 months of operation we measured the vacuum in the F-coil vacuum space, and determined that it was 15 Torr. The pressure had increased from 10^{-5} Torr due to continued out-gassing of fiberglass, MLI, and laminated supports during this period of time. The measurement indicated that cryogenic operation of the coil was accompanied by cryopumping and condensing of gases on the cold surfaces of the shield, supports, and helium vessel. To reduce the pressure rise within the cryostat vacuum space a port was installed to enable pumping of the coil by the LDX vacuum chamber pumping system. This port was plugged when the temperature inside the cryostat was below 75 K to avoid cryopumping the LDX chamber. The vacuum conditions in the insulating space of the coil can explain the thermal behavior during cryostat warming. Typical coil warming processes are shown in FIGURE 3. After termination of cooling, the helium vessel temperature increased linearly to about 11-12 K, after which it increased more rapidly. The rate is almost the same for the charged and non-charged coil. In FIGURE 3A the temperature charts look like the after-quench warming, when the quench took place several minutes after the increase rate of warming. Close to this time the shield temperature had reached its maximum (about 50K for a poor vacuum and about 100K for a better vacuum). At this temperature condensed gases begin evaporating from the outer parts of the laminated supports and outer layers of MLI. The support (and MLI) thermal resistance increased and the heat leak to the shield decreased. Vapor condensed on colder parts of supports and helium vessel. The heat leak from the shield to vessel thus increased mostly due to degradation of thermal performance of the colder parts of supports.

Finally the heat leak from the cryostat shell to the shield dropped below the heat leak from the shield to helium vessel, which caused the temperature maximum shown in FIG 3. After a relatively short cooling (during about 40 minutes for a poor vacuum and 3.5 hours for a better vacuum) the shield temperatures reached the minimum and again began increasing. All temperature slopes became nearly steady state. The outer shell-to-shield heat leak prevailed over the shield-to-helium vessel heat leak. Insulating vacuum in the cryostat degraded due to decreasing of cryopumping during warming. The better is the insulating vacuum at room temperature, the less gases are cryopumped on the cold surfaces during the cryostat cooling, the slower are the changes of the temperature in the cryostat during its warming, and the higher is the maximum shield temperature as well as the shield-to-helium vessel differential temperature. The maximum of the temperature of the shield is a sign of a degraded vacuum in the cryostat. When 30 hours later the pump-out port was opened again the temperature slopes sharply changed. The differential shield-to-helium vessel temperature increased from about 15 K to 50 K and then to 80 K. The proper explanation of this behavior is an improved thermal performance of the laminated supports during good vacuum conditions, when their insulating properties are recovered.

SUMMARY

The LDX F-coil has operated successfully for one year, and it has facilitated plasma experiments without electrical and cryogenic connections that disturb confined plasma. We have demonstrated re-cooling of the F-coil without quenching when it was charged to near the maximum operating current. This result opens the way for repeatable multi-hour plasma experiments without current degradation after a single F-coil inductive charge. The permanent out-gassing in the cryostat vacuum space requires a repeated pumping to prevent degradation of the thermal performance of the laminated supports. The LDX is presently being prepared for the F-coil levitation.

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