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RETRACTABLE HELIUM TRANSFER LINES FOR THE FLOATING FUSION MAGNET

Zhukovsky A., Garnier D.T.,* Fishman V., Lations R.

MIT Plasma Science and Fusion Center 77 Massachusetts Ave., Cambridge, MA 02135, USA
* Columbia University, Department of Applied Physics and Applied Mathematics Room 210 S.W., Mudd Building, New York, NY 10027, USA

Retractable transfer lines are used to cool the Levitated Dipole Experiment superconducting Floating Coil. The lines supply and exhaust coolant to the heat exchanger of the magnet located in the vacuum chamber. When the magnet is cooled and inductively charged the lines are retracted, the magnet ports are pumped out and plugged, and the magnet is lifted for plasma experiments. When the magnet is lowered, an inlet line, pre-cooled by liquid helium, is reinserted and re-cools the magnet for the next experiment without magnet discharge. This paper describes the design and operation of the magnet's retractable cooling lines.

INTRODUCTION

The levitated dipole experiment (LDX) is a new research facility built to study the confinement and stability of plasma in a dipole magnetic field configuration [1]. A 560 kg superconducting floating toroid (F-coil) levitates in the middle of a large vacuum chamber, as shown in Figure 1A. The F-coil is magnetically supported without any connections by a levitation HTS magnet (L-coil) installed at the top of the chamber. After completion of the plasma experiments the F-coil is lowered by a launcher to a charging station, attached to the bottom of the vacuum chamber. Here the F-coil is charged/discharged inductively by a superconducting coil (C-coil) surrounding the charging station. The LDX magnet system was described in [2], the F-coil design in [3, 4], the F-coil operation in [5-7], the C-coil in [8], and the L-coil in [9].

The bottom of the charging station has inlet and outlet cooling ports, through which the retractable cryogenic transfer lines can reach the corresponding inlet and outlet ports of the F-coil. The Nb_3Sn magnet is encapsulated in a toroidal vessel pressurized with 1.2 kg of helium at room temperature to 12.5 MPa. A lead-fiberglass high heat capacity radiation shield surrounds the helium vessel. The shield is wrapped with MLI and installed in a vacuum shell. The magnet, helium gas, and radiation shield are cooled by liquid nitrogen or then helium flowing in the tube heat exchanger loops, connected to the F-coil ports. The F-coil cryostat is equipped with thermometers. The cooling ports, instrument connector, and a vacuum shell pump-out port are located at the lower part of the cryostat, facing the charging station bottom, and can be reached with retractable mating parts by personnel on the cell floor.

LDX operation is as follows. Using transfer lines inserted into the ports, the F-coil is cooled first by cold gaseous nitrogen, then by liquid nitrogen, and finally by liquid helium flowing through the coil heat exchanger. When the F-coil is still in the normal state at a helium vessel temperature above 20 K, the C-coil is charged during 25 minutes up to 420 A. When the helium vessel is cooled to 8 K the C-coil is discharged, inducing full current in the F-coil. The helium flow is terminated some time after the helium vessel reaches 4.5 K. The transfer lines are retracted, the heat exchanger is pumped-out, and the cryostat ports are plugged through the charging station ports using plug operators. The instrument connector is disconnected and the F-coil is lifted into the middle of the vacuum chamber for experiments. During the first year, the F-coil operated in a supported mode, in which three thin spokes crossed the plasma. After 1-2 hours of experiments the F-coil was lowered by the launcher to the charging station and rotated into the correct position by the rotary ring. The instrument connector was engaged and, depending on the helium vessel temperature and the test program, the F-coil could be either re-cooled or discharged by charging the C-coil. Re-cooling made possible to perform several hours of plasma experiments on a single charge of the F-coil.

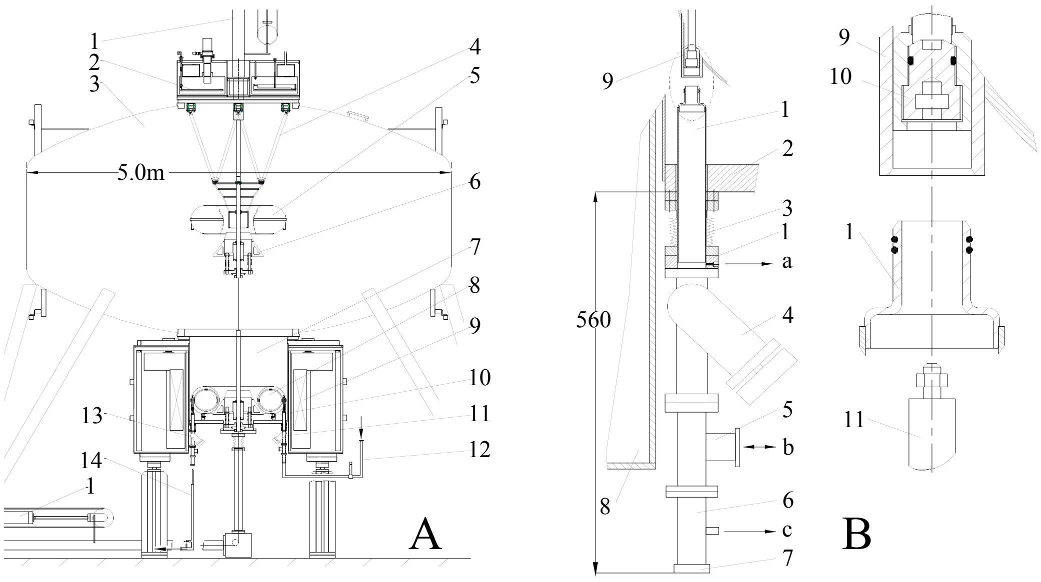

Figure 1 A LDX facility 1 – launcher, 2 – L-coil, 3 – vacuum chamber, 4 – upper limiter, 5 – F-coil during LDX operation, 6 – launcher-catcher, 7 – charging station, 8 – F-coil in the charging station, 9 – C-coil, 10 – rotary ring, 11 – charging station inlet port, 12 – inlet transfer line (inserted), 13 – charging station outlet port, 14 – outlet transfer line (retracted). B - Coolant port 1 – guard tube (shown retracted), 2 – charging station, 3 – linear motion bellows, 4 – 35 mm straight-through valve, 5 – T-fitting, 6 – differential pumping seal, 7 – compression seal, 8 – C-coil, 9 – F-coil port, 10 – F-coil port plug, 11 – plug operator tip, a – to pressure gauge, b- pump out & purge, c – differential pump out

DESIGN

The design of the cooling lines for the F-coil has to satisfy several requirements. F-coil cooling and the connection/disconnection of the transfer lines must not spoil high vacuum (10^{-4}-10^{-6} Pa) in the LDX vacuum chamber. The F-coil heat exchanger must be pumped out after cooling flow termination to decrease the heat leak to the magnet from the supply and exhaust tubes. F-coil ports must be sealed before the coil is lifted in order not to spoil the LDX vacuum. A very small space is available for the F-coil bayonets between the radiation shield and the vacuum shell, and also outside the vacuum shell, due to the short distance to the plasma. Transfer lines have vertical bayonets with the cold side above the warm side. This orientation of the cryogenic bayonet causes increased convection of gas in the bayonet gap due to gravity. The strong free convection causes freezing of the warm side rubber O-ring seal and bayonet leak. Gas stratification limits the convection and provides reliable operation of bayonet seals at the downward direction of the flow.

The charging station port is shown in Figure 1B. Vacuum guard tubes inserted and sealed by double O-rings in the helium vessel ports separate the LDX vacuum from the space around the transfer lines. Flanges connect the guard tubes with linear motion bellows at the bottom of the charging station. The bellows provide 25 mm of vertical movement of the guard tubes to engage/disengage them in the ports. The guard tube flange has holes for electric heaters and for pressure measurements. When the transfer line with 890-mm retractable length is removed from the port this leaves only a 75-mm gap to the cell floor.

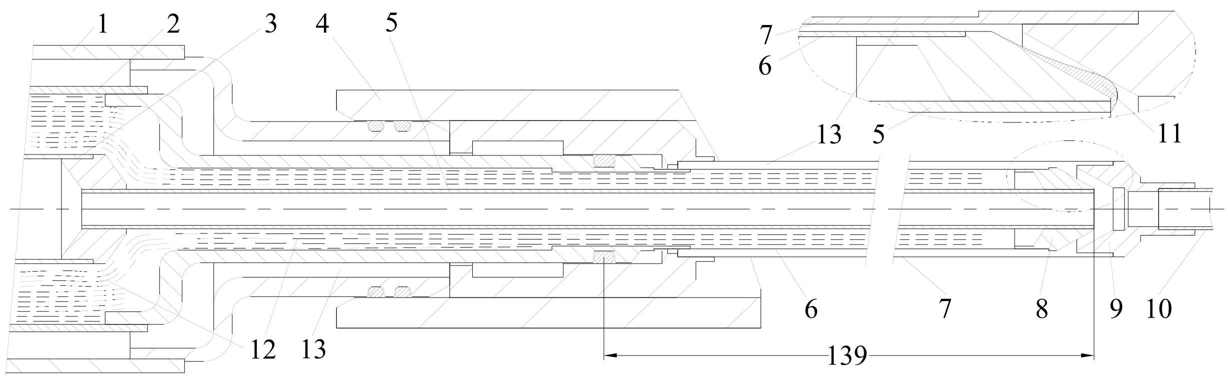

Figure 2 Transfer line bayonet joint. 1 – vacuum guard tube, 2 – vacuum jacket 28.6x0.9 mm, 3 – helium tube 9.53x0.7 mm, 4 – F-coil port, 5 –male part helium tube 4.76x0.4 mm, 6 – male part vacuum jacket 9.53x0.15 mm, 7 – female part tube 10.6x0.25 mm, 8 – male part tip, 9 - female part seat, 10 – F-coil heat exchanger tube, 11 - indium coating, 12 - MLI, 13 - vacuum

The bayonet joint for the F-coil is shown in Figure 2. The tip of the male part and the mating female seat are 60^{o} lapped cones. The radial gap in the bayonet joint is 0.29 mm with the 125 mm height. During operation the cone seal has to keep the vacuum in this gap. The calculated heat leak in the bayonet structure from the 4 K tip to the room temperature O-ring seal is 0.3 W. Nine half overlapped layers of DAM MLI tapes are spirally wrapped around the helium tube. The male part is attached to the transfer line with 18 layers of the same MLI tape wrapped in 3 mm annular space around the helium tube. 20 layers of a non-outgassing, inorganic, non-flammable MLI tape are wrapped on top of it. The non-flammable MLI protects the Mylar tape against damage during jacket welding. Both transfer lines have manual valves and standard female bayonets for connection to the cryogen supply at the inlet and the gas exhaust at the outlet.

OPERATION

The cryogenic transfer system was first tested in atmosphere without the guard tube, using the test cryostat with a bottom supply and the transfer line prototype with the bayonet described above. A thermocouple measured the temperature near the transfer line bayonet O-ring. It was discovered that for reliable sealing the male bayonet cone must be pressed firmly into the female bayonet seat. With weak compression the O-ring temperature dropped with time, the rubber lost elasticity, and the cold gas ran to the surrounding atmosphere. During the first long successful liquid nitrogen transfer, the O-ring temperature drop was about 3.3 K with respect to the initial room temperature and 3.6 K during liquid helium transfer. A springy support at the transfer line bottom applied pressure to the bayonet joint. After the test a modified transfer line was made, according to the design described above. The temperature drop near the O-ring during liquid nitrogen transfer for this, approved for the operation transfer line, was about 0.5 K, demonstrating a small heat leak to the bayonet tip. The test showed that in our design the free convection in the gap was suppressed when it was sealed, even without initial pump-out of the gap.

During initial operation of the LDX cryogenic system we discover that the vacuum in the space between the guard tube and the transfer line was occasionally spoiled slowly. After a while, the guard tube seal began leaking into the LDX chamber. This leak usually happened at the inlet after the nitrogen gas cooling was changed to liquid or the last one was replaced by liquid helium cooling. In these cases vacuum in the joint gap was broken by the gas penetrating through the imperfect stainless steel-to-steel cone seal, causing the strong convection in the gap. Finally, the rubber of the bayonet seal was frozen and cold gas penetrated into the vacuum space inside the guard tube. When the temperature of the rubber O-rings of the guard tube seal dropped sufficiently, cold gas penetrated into the LDX chamber with a rate that increased with time, spoiling the vacuum in the experimental volume.

To eliminate the seal failures, the axial compression of the transfer line nose to the female seat was increased until it was close to the male bayonet buckling force. Electric heaters were inserted into holes in the guard tube flanges to warm O-rings. The flange temperature was maintained at about 45^{O} C. The heaters were ineffective due to their long distance (220 mm) to the O-rings. These measures reduced the number of sealing failures but did not eliminate them. After each failure, it was necessary to interrupt F-coil cooling, remove the transfer line, plug the F-coil port, change the transfer line O-ring, and re-cool with no guarantee of success. A solution to the problem was ultimately found in tinning the male conical tip with indium. The tinning of the tip was made in the downward orientation, where melted indium created a spherical-like surface under gravity and surface tension (see Fig. 2). The indium plating covered all the small and micro scratches of the cone surface, which were the likely causes for progressive leaking in the bayonet seal. Indium keeps its elasticity even at helium temperatures and also seals scratches at the seat surface. At the applied force, the "sphere-to-cone" seal in the bayonet provides a much higher contact pressure in the seal than in the cone-to-cone seal. For reliable operation, the tinned surface needed to be re-tinned to restore the surface shape after several insertions/retractions (4-6 cycles). Our practice was to re-tin the bayonet tip at the beginning of each experimental day, when the transfer line was removed from the F-coil port.

Another operational problem was that sometimes during insertion/retraction of transfer lines, ice plug formations partially or fully prevented the circulation of helium in the system. The ice plugs formed in spite of the charging station port was purged by counter-flow room temperature helium gas every time when the 28.6 mm diameter compression fitting was briefly open to the atmosphere. Most of the ice plugs appeared at the inlet of the F-coil heat exchanger. F-coil operation was interrupted until the next morning, when the ice plug disappeared. The heat exchanger was purged with counter flow of helium gas. Depending on the F-coil temperature, the liquid nitrogen or liquid helium cooling could be continued. The problem was overcome by increasing the pressure of purge helium gas from 1.2 to 1.35 bars. The higher pressure provided a reliable seal of the hole open to the atmosphere against the penetration of air inside the charging station port, then into the F-coil heat exchanger.

The upward flow and low heat load transfer line reliably operated at the maximum pressure of up to 2.7 and 1.6 bar in liquid nitrogen and helium supply lines respectively. The indium cover hermetically bonded the male part to the female seat. During every retraction a specific sound accompanying the rotation of the transfer line confirmed this bonding. During operation the vacuum around the transfer line (and likely in the bayonet gap) was 5-10 Pa even when the pump-out line was closed. The heat to the bayonet was supplied only by the thermal conduction through the structure.

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REFERENCES

1. Kesner J., Bromberg L., Garnier D.T., Mauel M., Plasma confinement in a magnet dipole, 17th IAEA Fusion Energy Conf., Yokohama, Japan (1998), Paper IAEA-F1-CN-69-1CP/OS
2. Garnier D.T.., at al, Design and initial operation of the LDX facility, Fusion Engineering and Design, (2006), to be published
3. Zhukovsky A., at al, Design and fabrication of the cryostat for the floating coil of the LDX, IEEE Trans. App. Supercond., (2000), 10, No.1, 1522-1525
4. Zhukovsky A., at al, Status of the floating coil of the LDX, IEEE Trans. App. Supercond., (2002), 12, 666-669
5. Zhukovsky A., at al, First integrated test of the superconducting magnet system for the Levitated Dipole Experiment (LDX), Fusion Engineering and Design, (2005), 75-79, Part B, 29-32

6. Zhukovsky A., Garnier D.T., Radovinsky A., Thermal performance of the LDX F-coil, Adv. in Cryo. Eng., (2006), 51, 78-85
7. Zhukovsky A., Garnier D.T., Operation of the Levitated Dipole Experiment floating coil, IEEE Trans. App. Superconductivity, (2006), 16, 898-901
8. Zhukovsky A., at al, Charging magnet for the F-coil of LDX, IEEE Trans. App. Superconductivity, (2001), 11, 1873-1876
9. Michael P., at al, Performance of the conduction-cooled LDX levitation coil, Adv. in Cryo. Eng., (2004), 49, 701-710