Design and Fabrication of the Cryostat for the Floating Coil of the Levitated Dipole Experiment (LDX)

A. Zhukovsky[a], M. Morgan[b], D. Garnier[c], A. Radovinsky[a], B. Smith[a], J. Schultz[a], L. Myatt[d], S. Pourrahimi[e], J. Minervini[a]

Abstract-- The Levitated Dipole Experiment (LDX) is a new, innovative magnetic confinement fusion experiment being designed and installed in collaboration with Columbia University at the Massachusetts Institute of Technology (MIT). The primary objective of the experiment is to investigate the possibility of steady-state, high-beta plasma confinement with near classical transport. The main component of the experiment is a levitated cryostat with a 5.7 T Nb_3Sn superconducting magnet, housed in an Inconel high pressure helium vessel. The pressure vessel is surrounded by a large thermal mass radiation shield and an outer vacuum shell, all of which are magnetically levitated inside a much larger vacuum chamber. The cryostat, now under construction, is described in this paper. The cryostat keeps the magnet temperature between 5 and 10 K during 8 hours of levitated operation. A low heat leak support system for the helium vessel and the shield is designed to withstand impact forces of 10 g in case of a levitating failure. The helium vessel is filled to 125 atm at room temperature with 1.4 kg of helium. The helium vessel and the shield are equipped with a tube heat exchanger for initial nitrogen magnet cooling and daily helium re-cool from a high of 20-25 K back down to 5K. This cooling system uses hermetically sealed, retractable cryogenic transfer lines when the cryostat is resting in the bottom charging station of the LDX vacuum chamber. The magnet is charged and discharged inductively by an outer charging magnet.

I. INTRODUCTION

The levitated cryostat is a toroidally-shaped dewar that serves as a housing for a 5.7 T magnet. It's function is to keep the magnet temperature between 5 and 10 K during approximately 8 hours of levitated operation during which time there are no cryogenic connections to the cryostat. The cryostat is placed in a large vacuum chamber with a vacuum of 10^{-4} - 10^{-8} torr during normal operation. The cryostat is able to operate with its outside pressure ranging from vacuum to normal pressure. The magnet is wound on a stainless steel form and then it is nested in the Inconel 625 helium vessel. The helium vessel is surrounded by a lead radiation shield with a large thermal mass, which follows the concept developed in a previous levitating ring, the FM-1 of Princeton [1, 2]. The shield is covered with a thermal insulation (MLI), which is surrounded by an outer stainless steel vacuum shell. Vacuum in the space between the helium vessel and the vacuum shell is better than 10^{-5} torr. The LDX experiment and facility are described in [3] and the levitated magnet in [4]. The cryostat with a levitated cryostat mass between 545 and 585 kg, is now under construction at Ability Engineering Technology.

II. OVERVIEW

The helium vessel is initially pumped out, purged with helium gas, filled at room temperature with pure helium, and then hermetically sealed by a miniature valve located at the end of the fill line in the cryostat fill port. The maximum helium filling pressure corresponds to 125 atm at 300 K. This approach is similar to that of the previous LLNL Levitron [5]. A tube heat exchanger is used for initial magnet cooling and for nightly re-cool from intermediate temperatures. The heat exchanger is located inside the helium vessel with its vent line penetrating the vessel and thermally attached to the shield. Both ends of the heat exchanger are connected to room temperature ports in the vacuum shell. The heat exchanger is used also to warm up the magnet to 18-20 K during coil electrical discharging-charging operations.

While the cryostat is being cooled, it rests in the bottom of the LDX vacuum chamber in a special section assigned as a "charging station". Retractable inlet and outlet cryogen transfer lines are connected to the cryostat inlet and outlet ports. Cold gas and then liquid nitrogen flow through the

Manuscript received September 27, 1999.
Supported by DOE Contract DE-FG02-98ER54458.
[a]PSFC, MIT, Cambridge, MA, USA.
[b]Ability Engineering Technology, South Holland, Ill, USA
[c]Columbia University, New York, NY, USA.
[d]MTechnology, Framingham, MA, USA.
[e]SSI, Waltham, MA, USA.

heat exchanger for initial cooling of the helium vessel and the shield to about 80 K. Then the heat exchanger and transfer lines are pumped out, purged with helium gas, and the helium vessel is cooled down to 5 K by liquid helium flow. Simultaneously, the shield is cooled to about 10 K.

The levitated magnet is charged inductively when in the charging station. After all LDX systems are ready for plasma experiments, the outer transfer lines and instrumentation connection to the cryostat are retracted. A mechanical system lifts the cryostat to a working position inside the vacuum chamber, roughly 1.5 m from the chamber bottom. Levitation magnets outside the vacuum chamber are energized to electro-magnetically support and control the position of the floating magnet and the cryostat. The mechanical system is then retracted for plasma operation. When the experiments are finished (in 8 hours or less), the mechanical system lowers the cryostat to the charging station. Rollers in the charging station floor are used to align vacuum shell ports with corresponding ports in the floor. The cryostat is fixed on this position in the charging station by a positioner pin which is locked in a mating hole of the cryostat bottom. A retractable instrumentation connector is connected to a mating connector in the cryostat to monitor helium vessel and shield temperatures. The retractable vacuum tubes and transfer lines are then connected to the cryostat heat exchanger inlet and outlet ports, and the liquid helium re-cooling (or coil discharging) cycle begins if it is necessary.

In the case of a magnet quench or a control failure during the levitation mode, the cryostat will crash downward and/or to the side. A special system serves to catch the cryostat and protect it from a rigid impact with the vacuum chamber walls. A low heat leak support system of the helium vessel and the shield is designed to withstand impact forces of 10 g. It consists of glass ball supports located between the helium vessel and the shield. Stacks of thin Inconel shims are used as supports and side bumpers between the helium vessel and the vacuum shell. These supports are designed to hold the weight of supporting parts and to maintain the gaps between the cryostat shells as well as withstand the impact forces of 10 g. Special supports prevent rotation of the vacuum shell with respect to the helium vessel.

III. HELIUM VESSEL

The helium vessel cross section (half of torus) is shown in Fig. 1. Main dimensions of the cryostat torus are ID = 448 mm; OD = 1120 mm; minor od about 348 mm. The helium vessel is a round cross section toroid with a major diameter of 782 mm and a minor outer wall diameter of 274 mm. The vessel contains a sealed volume of about 76 liters, filled with helium, which serves as a cooling reservoir during magnet operation. The vessel is under high pressure at room temperature and it is designed, and will be certified according to the ASME Boiler and Pressure Vessel Code. Pressure relief is not needed either after quench or at room temperature storage. The vessel has three penetrations: inlet and outlet of the heat exchanger at bottom ports and a helium fill tube at the top port. The fill line is provided with a burst disk to avoid an accidental overpressure of the vessel. Top and bottom vessel halves are made of pipe half-elbows with four halves welded to form a half torus. The cold formed Inconel 625 half-elbows used for the vessel are made from 10 IPS Schedule 40 pipe elbows with a major radius of 15” (381 mm), nominal outer diameter of the pipe 10 3/4” (OR = 136.5 mm), and wall thickness 0.365” (9.27 mm). The helium vessel welded from standard prefabricated elbows is significantly less expensive than a vessel made by any other technology.

The vessel wall thickness should be minimized to reduce the levitating mass. For the minimum allowable weld (and wall) thickness the Pressure Vessel Code requires full radiographic inspection of vessel wall welds, which can be done for vessel halves. The magnet of about 265 kg is installed into the bottom shell, then covered with the top shell (with adequate magnet supports). Two final equatorial top-to-bottom welds form the final closure seams of the hermetic helium vessel. For the final vessel closure seams the ultrasonic examination may be substituted for radiography, which is otherwise impossible in our design. The vessel mass with the magnet is in the range between 395 and 435 kg depending on a final vessel wall thickness, which we will try to machine to the allowable minimum.

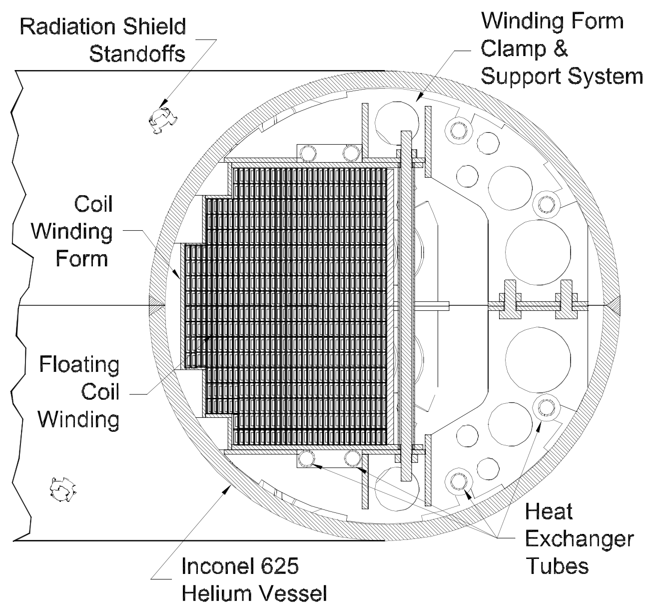

Fig.1. Helium vessel cross section.

Ten radial gussets, each of two halves, provide the magnet support inside the cryostat. The magnet is clamped between two gusset halves by threaded rods with nuts. The heat exchanger in the vessel is a 3/8” stainless steel tube about 20 m long. The tube makes four circumferential loops at the top and four loops at the bottom of the vessel. About half of tube length is brazed to the magnet form wall. The other half has copper fins brazed to the steel tube to increase heat transfer to helium gas in the vessel. The helium vessel in the cryostat is surrounded by a high vacuum (residual gas is helium), better than 10^{-5} torr. During LDX experiments the vessel temperature will be cycling between 5 and 25 K as the helium pressure cycles between 1.4 and 10.0 atm, once per day. The operating temperature of the magnet is 5 - 10 K with helium pressure in the vessel 1.4 - 3.5 atm. The helium vessel is wrapped with an aluminum adhesive tape for a better reflection.

IV. CRYOSTAT

The cryostat cross section is shown in Fig. 2. The radiation shield is a torus with a clearance of 5 mm to the helium vessel. It is a multi-layer structure of stainless steel (or Monel), copper, and lead, bonded together and then covered at both inner and outer sides with an aluminum adhesive tape for a better emissivity. The shield consists of two halves, firmly connected at their inner and outer equatorial circles. The shield is supported by six 10 mm diameter glass balls installed at the top and 6 balls at the bottom of the helium vessel inner part. The shield outer part is supported by the vacuum shell support system. Two shield halves are cooled by two parallel loops of 1/4” flattened copper tubes soldered to the shield structure. The mass of 2 mm thick lead of the shield is about 50 kg and the full mass of the shield is close to 60 kg to provide the required thermal mass and operation time between re-cooling. Technological models of the shield are under consideration now. The shield design will be finalized after thermal cycling and completion of load tests to be performed on models.

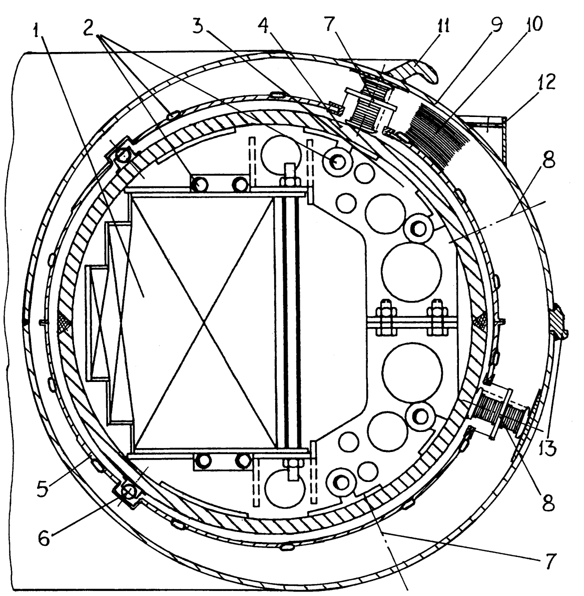

Fig. 2. Cryostat cross section schematic.
1 – magnet; 2 – heat exchanger; 3 - gusset; 4 – helium vessel; 5 – radiation shield; 6 – glass ball shield support; 7 – vacuum shell and shield support; 8 – side bumper; 9 – vacuum shell; 10 – MLI; 11 – lifting disk; 12 – laser beam control structure; 13 – vacuum shell ring.

The 3.2 mm thick 316L stainless steel vacuum shell of the cryostat is close to a circular cross section torus which creates a crescent shaped gap around the shield. The gap is filled with MLI. Two halves of the shell are made by computerized metal spinning to meet cryostat tolerances. The shells are welded to the equatorial reinforcement outer ring at the OD, and at the ID they are welded together. The support ring is strong enough to survive a cryostat side collision and not cause a plastic deformation of the vacuum vessel. The 316L shell is welded with weld rod ER 310 to avoid influence of magnetization of the stainless steel welds on the field uniformity in the plasma surrounding the cryostat. This material provides a magnetic permeability of welds of 1.02-1.05 at room temperature, which is acceptable for the plasma experiments. A circular lifting disk is welded to the upper part of the cryostat. The outer surface of the cryostat has brackets for a metal ring, which will be installed, when the cryostat is delivered to MIT. The ring will be machined after cryostat assembly with respect to the magnetic axis and equatorial plane of the magnet to provide datum surfaces for a laser position and tilt control system. A plasma limiter can be attached later to the outer equatorial perimeter of the vacuum shell. The limiter protects the cryostat surface against contact with the hot plasma. The OD of the ring is 1140 mm and the radial cryostat OD-to-charging station wall clearance is about 3 mm. The equatorial ring and the lifting disk are used for the final cryostat balancing around the vertical axis by removing some material.

The cryostat outer surface is made with the objective of a minimum emissivity of 0.7 at 300 - 360 K to irradiate energy to the room temperature LDX vacuum chamber wall between plasma shots. The maximum temperature of the outer cryostat wall during plasma operation increases from room temperature to 350 K after a couple of hours. The final method for covering the cryostat surface with a high emissivity film is not yet determined. Possible candidates include a flame sprayed chrome oxide coating or a plasma sprayed coating of 13% titanium dioxide - 87% aluminum oxide, which provides emissivity greater than 0.75 at 10 μm wavelength.

The helium vessel - vacuum shell support system carries the helium vessel and the shield weight (about 500 kg) with the cryostat resting in the charging station or hanging on a lifting device. It carries mostly only the vacuum shell weight during the levitation mode (82 kg app.). Supports are designed to withstand impact forces of 10 g at any angle without functional damage of the cryostat. The system consists of 10 top and 10 bottom supports and two rows of 10 side bumpers. The neighboring rows of support/bumpers are located in chess-board order around the vessel. Cryogenic supports of fiberglass (G-10) are usually better thermal insulators than the metal shim stacks. In the LDX application the support normal pressure is low but the support must survive very high occasional pressures (10 g shocks) accompanied by a short time high heat leak without mechanical failure. In this case thin hard metal shim stacks provide the lowest normal operating heat leak [6].

Each support/ bumper consists of two stacks of hard Inconel X-750 disks attached to both sides of a plate, which is then connected with the shield. The 14 mm diameter disks are about 0.1 mm thick and sand blasted on both sides. The mechanical analysis indicates that a 50 mm diameter pad, welded to the inside of the vacuum shell opposite to the side bumper is required to prevent shell damage at a collision force of about 37 KN per bumper, which is 75% of the full 10 g load. Smaller reinforcement pads are welded opposite the top and bottom supports. Due to a structural differential contraction there is a 1.6 - 2.0 mm gap between the bumpers and vacuum shell at operating temperatures. Top and bottom supports are thermally anchored to the shield for heat interception. The design provides a very low heat leak to the cryostat cold parts at low levitating and resting loads. The average heat leak to the helium vessel (8.0 K) from the vacuum shell (320 K) through the support system at a shield temperature of 45 K is estimated as 0.27 W. To the shield for the same temperatures it is about 2.7 W.

Four RTD cernox thermometers are epoxied to the outer surface of the helium vessel and four to the shield for temperature control when the cryostat is resting in the charging station. During initial cooling if the temperature of the He vessel/shield is above 140 K, a differential temperature between the cold nitrogen inlet and the helium vessel/shield shall be below 50 K. This constraint is required to avoid large thermal stresses in the heat exchanger and its interface with cryostat parts, especially with the shield.

The estimated cryostat thermal performance is shown in Fig.3. The cryostat warming process is considered from an initial helium vessel temperature of 5 K, shield temperature of 10 K, and for a gradual change of vacuum shell temperature from 300 to 350. In about 9 hours the magnet and helium vessel temperature reaches 10 K and the shield temperature increases to 73 K. 10 K is the maximum working temperature of the magnet after which it should be discharged inductively or re-cooled by LHe flow through the heat exchanger.

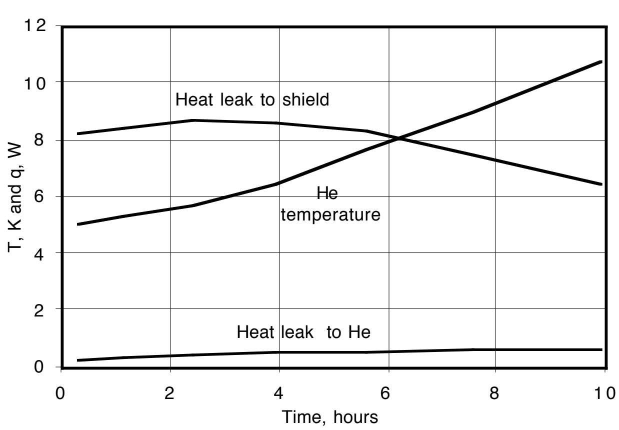

Fig. 3. Helium vessel and magnet temperature and heat leak in the cryostat.

V. Conclusions

A design of the levitating cryostat of about 550 kg for the floating magnet of the LDX has been described. The cryostat should provide close to a 9 hour period of magnet operation without external cooling. The low heat leak cryostat support system is designed to withstand up to 10 g crash-collision load. The helium vessel and cryostat parts are now under fabrication. According to the schedule the helium vessel with the enclosed magnet will be assembled and certified as an ASME Pressure Vessel in spring of 2000. The cryostat should be finished in fabrication and operational in summer of 2000.

REFERENCES

[1] J. File at al, “Operation of a levitated superconducting ring in a plasma physics experimental device”, Journal of Applied Physics, Vol. 42, No. 1, p.6, January 1971.
[2] G.D. Martin and J.W. Willard, “Lead shield dewar development”, IEEE Trans. on Nuclear Science, NS-18, pp. 273-276, 1971.
[3] J. Kesner at al, “Plasma Confinement in a Magnet Dipole“, 17th IAEA Fusion Energy Conf., Paper IAEA-F1-CN-69-1CP/OS, Yokohama, Japan, 1998.
[4] J.H. Schultz at al, “The Levitated Dipole Experiment (LDX) Magnet System“, IEEE Trans on Appl. Supercond., Vol. 9, No.2. pp.378-381, June 1999.
[5] C.E. Taylor and T. Duffy , “Coils for Superconducting Levitron”, Proc. of Symp. on Probs of Fusion Research, pp. A5(1-7), January 1970.
[6] R.P. Mikesell and R.B. Scott, Journal Research NBS, 57, No. 6, pp. 371-378, 1956.