Status of the Floating Coil of the Levitated Dipole Experiment

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***Abstract*—The Levitated Dipole Experiment (LDX) is a novel concept that examines plasma compressibility as a method for stable magnetic confinement of fusion grade plasmas. The experiment uses a 0.8 m diameter ring-type dipole coil that is levitated at the center of a 5 m diameter $\times$ 3 m tall vacuum chamber to confine the plasma. This persistent mode, floating coil is wound from a prereacted Nb_3Sn conductor and encased in a toroidally shaped, constant volume helium cryostat to eliminate external connections to the coil during levitated operation. Although the peak field on the inductively charged floating coil is only 5.3 T, Nb_3Sn conductor was selected because of its higher temperature capability. The cryostat, with on-board helium supply, is designed for 6–8 hours of levitated operation as the heat leak gradually warms the coil from 5 to 10 K. The cryostat consists of three concentric shells: a sealed, high pressure Inconel helium vessel that contains the floating coil and heat exchangers that are used to recool the coil before operation, a high heat capacity fiberglass-lead radiation shield, and an outer vacuum shell. The shells are kept separated by a support system designed to withstand impact forces up to 10 g in the case of a levitation failure. The paper summarizes the manufacture and initial driven-mode test of the floating coil, and describes the design, manufacture and test of the cryostat.**

***Index Terms*—Conductor, cryostat, joint, helium vessel.**

I. Introduction

The LEVITATED Dipole Experiment (LDX) is a new concept of fusion experiment at MIT, developed jointly by the Plasma Physics Laboratory of Columbia University and the MIT Plasma Science and Fusion Center [1], [2]. The main object of LDX is to investigate the possibility of steady state, high beta operation with near-classical magnetic confinement. A relatively small dipole, magnetically levitated in the center of a large vacuum chamber, provides high magnetic flux expansion. The floating coil (F-coil) is encapsulated in a toroidal helium vessel, surrounded by a high heat capacity radiation shield and an outer vacuum shell [3]. The sealed helium vessel is filled with helium gas to 12.5 MPa at room temperature. The vessel and the shield are cooled down by liquid helium flowing through a heat exchanger. During this process the F-coil rests in a charging station at the bottom of the vacuum vessel.

A NbTi coil (C-coil) is used to charge/discharge the F-coil inductively to the nominal current of 2070 A at a peak field of 5.3 T [4]. A mechanical lifting mechanism brings the F-coil to the center of the vacuum chamber. A BSSCO-2223 levitating coil [5] and a system of control magnets set beyond the vacuum chamber provide stable levitation of the F-coil. The F-coil levitates without any connections extending through the plasma volume. The F-coil remains superconducting with nearly constant current for 6–8 hours of experiments. In the case of control loss, the F-coil is caught by a mechanism preventing collision with the chamber. Low heat leak supports of the helium vessel are designed to withstand forces of 10 g in the case of a levitating failure.

II. Magnet

A. Coil Winding

The F-coil is a solenoid with OD/ID of 764/526 mm, wound in a thin stainless steel form. A thick aluminum alloy mandrel was temporarily attached to the coil form at its sides and at the ID to keep the coil shape intact during winding and to support the coil in a liquid helium cryostat during a driven mode test. The hermetically welded coil form with the mandrel and additional sealing at the coil OD served as a vessel for vacuum-pressure impregnation (VPI) by epoxy resin. Two loops of 9.5 mm diameter stainless steel tube were welded to the top and bottom sides of the coil form. These tubes were welded to the rest of a heat exchanger located in the helium vessel with a full length of about 20 m.

The F-coil was wound and impregnated by Everson Electric Co. in Bethlehem, PA, from a pre-reacted Nb_3Sn Rutherford cable soldered in a half-hard 8 $\times$ 2 mm copper channel [6]. At the nominal operating current the maximum estimated strain in the superconductor filaments is 0.27% and the minimum critical temperature is 10.8 K. The total coil inductance is 0.4 H, which produces a stored energy of 0.9 MJ. After cooling to about 5 K by helium flow through the heat exchanger the coil is slowly heated to about 10 K over 8 hours operation without any cooling. The winding is layer wound with a single pancake at the upper side of the coil. This places both conductor ends at the coil OD allowing a solder joint. The F-coil has a single lap joint and must be charged inductively. During a driven mode test the conductor ends were temporarily soldered to the cryostat current leads.

The full mass of the coil is about 230 kg. Uniform absorption of the stored energy by the coil mass would cause temperature rise of less than 50 K. In the event of nonuniform

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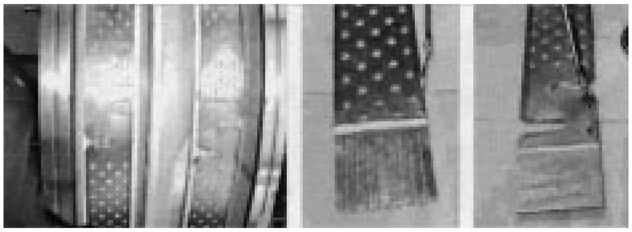

Fig. 1. The coil is wound in the form. The central turns and tails are tightened between two outer copper rings. Soldered area, stress relief slots, and perforations are seen as well as fingers and stress relief of the joint.

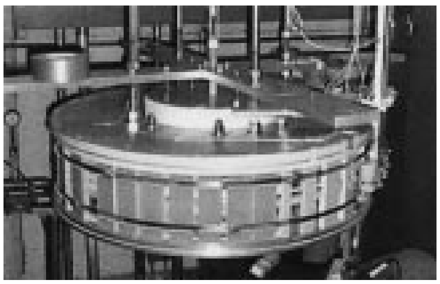

Fig. 2. The coil is ready for a current driven test.

quenching a much higher peak temperature up to 460 K was estimated. Quench propagating copper rings (annealed after machining, 1 mm thick, OFHC, RRR $= 80$) are installed in the coil to prevent local over-heating. In a quench event the rings generate eddy currents and a hot zone spreads rapidly through the winding. One ring is located between the two first layers to provide good integrity with the surrounding winding. Two outer rings are installed at both sides of the coil, leaving the central section for the final conductor joint. These rings are tightened to the coil by fiberglass bandages, which serve also as thermal isolation from surrounding helium during quench for fast heating of the coil. Calculations show that the quench protection rings equalize the temperature in the coil cross section and bring the worst case peak temperature down below 180 K.

A successful technique was developed for soldering a strong low resistance copper ring joint. Copper strips were wrapped under tension around the winding. Each ring was completed by soldering an overlapped joint *in situ*. A short path for melted solder flow and flexibility in the strip fingers permitted a solder joint without voids. During VPI, epoxy resin fills 6% of the perforated ring surface, improving the bonding to the winding (Fig. 1). The coil was impregnated by epoxy resin CTD-101K with a special mix and cure schedule at a maximum temperature of 110 C. This procedure was developed to keep the curing temperature below 118 C, the melting point of the solder used for the copper rings. Both ends of the coil were protected against bonding with resin. They were temporarily pancake wound in the central part of the coil OD between the copper rings.

B. Driven Current Test

Two lengths of Nb_3Sn conductor were prepared for fabrication into test joints. Flexible NbTi cables were soldered to the ends of these conductors for connection with the cryostat current leads. Two test joints (25 and 50 cm long) were made. A T-shaped copper heater block with an imbedded heater was used to solder a 160 mm long arc of conductor. The base of the T was machined with a radius close to the coil outer radius. A 0.1 mm 52In–48Sn solder foil was placed between the conductors. The base of the T section was pressed against the top conductor. Solder melting was visually controlled at about 120 C. Movement of the heating block allowed soldering along the full length. Each soldering plane was rotated to lie horizontally. Wires were soldered on for voltage measurements. Both test joints were supported in the axial direction by G10 plates with precision-machined slots (Fig. 2). Hoop stresses in the unimpregnated turns and the joints were taken by two steel hose clamps, tightened to the outer surface of G10 plates around the coil with a measured torque in the clamp locks.

The mandrel with the F-coil hung on four long stainless steel tubes, fixed to the cryostat cover. The test stand was equipped with quench detection and protection systems. The test was instrumented by Hall probes for measurement of the axial magnetic field in the coil bore, thermometers fixed at the mandrel and coil, and a helium level meter. Initially the coil was cooled down by liquid nitrogen to 78 K at differential temperatures less than 50 K. Later during a slow cooling by liquid helium the coil reached a superconductive state at about 17 K, indicated by a 1 A probe current.

When the liquid helium level increased above the coil midplane and covered the coil current leads the magnet was charged; first, to 1500 A at a ramp rate of 12.5 A/s, and then discharged to 1000 A. Then the current was increased in two steps up to 2200 A. At that time liquid helium covered the coil. After a flat top, the coil was fully discharged at 12.5 A/s. The maximum test current was 6.3% higher than the coil operating current. Later the coil was charged again to 2200 A and fast charged-discharged at 12.5 A/s to 1500 A several times. In the last discharge, the current was manually damped at 500 A. The coil did not quench at any time.

Field measurements in the coil bore agreed well with calculations. Resistances of the test joints were measured at 2200 A. They were about 2.3 nΩ and 4.6 nΩ for 50 cm and 25 cm length respectively. The measured coil RR of 6.95 (resistances at room temperature/78 K) is a typical figure for stabilizing copper. No damage was found when the coil was examined. The torque in the stainless steel hose clamp locks was the same as before the test. This confirmed that there was no plastic deformation in the coil structure after energizing.

C. Coil Joint and Outer Bandage

The technique and devices used for making the test joints were also used for the final joint production. When the dry run was completed, the overlapped joint was located in the midplane of the coil and the winding including the joint looked as an uninterrupted spiral. The overlapped joint length is about 800 mm. All voltage taps used in the coil test were removed and the conductor was insulated by Kapton tape and epoxy. The extra length of conductor was cut off. Exposed conductor was wrapped with Kapton tape and put into glass sleeves. The part of conductor used for the joint was cleaned of its insulation and washed with ethanol. Five turns were made around the impregnated part of the coil to fill the gap between the impregnated coil sides and the copper protection rings. The middle turn was used

Fig. 3. A Nomex string is wet wound above the insulated joint. G10 ramps, long side arches and side plates are installed for joint support.

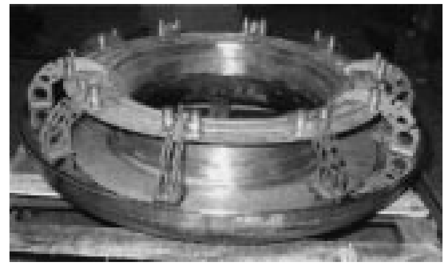

Fig. 4. Support frames adjusted to the dummy coil form and to the lower half-vessel. The top of each frame has two cylinders with Inconel 625 springs providing 450 kg compression to the coil inside the helium vessel after the final closure.

for the joint. Both ends of the conductor were filed to maintain smooth slopes of 20 mm long (slope 1 : 10), which eliminate steps and shear stresses at the joint ends. Various G10 spacers were used to support the final turns and the overlapped joint.

Two stainless steel wires with tensioning screws were soldered to both sides of the conductors' ends to make a tense winding. The joint was soldered with a small application of flux, then cleaned. The stainless steel wires were unsoldered from the conductor. The joint was wrapped with Kapton and glass tapes located below the joint in advance. The stainless steel coil form and both sides of the coil were carefully sprayed with a release agent to protect them against epoxy bonding and to seal circular gaps between the coil and coil form. Then all G10 spacers were removed and the assembly was step by step painted with a low viscosity epoxy resin. During these processes the coil was slowly and periodically rotated. Three layers of a flat Nomex string were wound above the joint (Fig. 3). G10 side spacers were installed on both sides of the joint. Several layers of a wide glass tape were wound on the top of the joint and adjacent parts of the spacers. Then the wet glass tape was covered with a Tedlar film that is not adhesive to resin. All windings were made with hand tension. On top of the Tedlar film an elastic rubber hose was wound around the fiberglass area to cure the resin under compression. After room temperature curing, all extra coil wraps were removed. The quality of the impregnated fiberglass bandage appears to be excellent. The anti-rotation coil-to-form supports were installed on the coil form with a gap to the coil surface to allow coil expansion under electromagnetic loads. Then the mandrel was removed from the coil.

III. Helium Vessel

The design of the helium vessel is given in [3]. This section is an updated report of the production and test of the helium vessel at Ability Engineering in South Holland, IL. The vessel is filled with helium at room temperature at 12.5 MPa. This stores about 1.4 kg of helium with a high heat capacity at magnet operating temperature. Due to the high filling pressure the vessel was manufactured, tested, and certified according to the ASME Boiler and Pressure Vessel Code. Cold formed pre-fabricated Inconel 625 half-elbows with about 9.8 mm thick walls were used to weld the torus with major and minor inner diameters of 762 mm and 254.5 mm correspondingly. Inconel 625 was chosen as a strong, ductile, Code approved alloy, which does not need a heat treatment after welding. The elbow material was annealed then air cooled and certified for a tensile strength of 900 MPa and a yield strength of 460 MPa. The alloy and its welds are almost nonmagnetic and have low susceptibility at temperatures below 6 K [7].

Four half elbows were welded together to make each half of the torus. Special measures were taken to avoid deformations due to welding. Two feed tubes were welded into the lower half for the heat exchanger and one into the top half for helium filling. Both halves were fully inspected by X-rays. The minimal thickness of the vessel walls and welds varies from 8.8 mm at the torus ID to 7.0 mm at the OD to keep primary membrane stresses below 236 MPa (Code allowable). The outer surfaces of both halves (between the OD and vertical plane) were machined to reduce their weight from 182 kg to 150 kg. The wall thickness remained above 7 mm, as measured by an ultrasonic micrometer.

The magnet is supported inside the vessel by 10 steel frames. They also support the four loops of the finned tube heat exchanger hanging in the helium space. The frames were sized using a dummy coil form (Fig. 4). The datum surface was machined inside the bottom of the lower half. A flat ring with square holes to hold the bottom of each frame was fixed to the datum surface to prevent the rotation of the magnet inside the vessel. Before welding into the lower half-vessel the heat exchanger tube was thermally shocked twice by liquid nitrogen flowing consecutively from both sides. The heat exchanger was leak checked inside the temporary sealed helium vessel. The leak in vacuum was below 10^{-9} cm^3/s at 12.5 MPa inner pressure.

A closing weld technique was developed and practiced on dummy elbows and the coil form. The full penetration welds required by the Code threatened to damage the inner part of the impregnated coil set 10 mm from the melted metal. A shielding steel tape was fixed between the helium vessel and inner diameter of the coil form. The shield reduced the coil form temperature from 77 to 34 C for the first weld pass and from 113 to 47 C for the second.

After helium vessel closure, the final equatorial welds are ultrasonically inspected. The wall and weld thickness around the helium vessel ID varies from 9.8 mm to 11.8 mm (the last figure for welds). The inner wall was carefully ground to bring the ID to the designed 487.8 mm at the wall and the weld thickness not less than 9.2 mm. Strain gauges were temporarily installed at central welds to monitor deformation during a pressure test. The pneumatic test was performed with helium at room temperature. The test pressure was 13.8 MPa. The test pressure must be

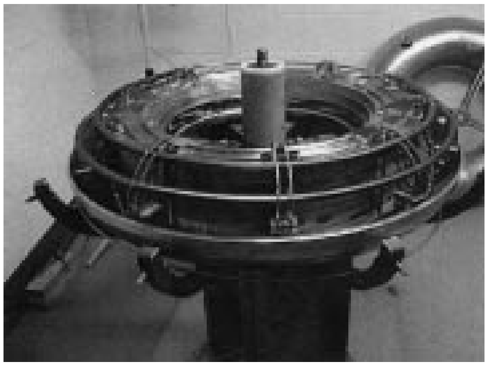

Fig. 5. The lower half-vessel installed in the cryostat assembly apparatus. The upper half-vessel is seen behind. The magnet with the heat exchanger is installed in the lower half-vessel.

10% higher than the maximum working pressure. No leak was detected. The maximum measured vertical strain at the vessel ID was 0.096%, which is only 12.5% lower than its calculated value of 0.11%. A good correspondence between these values gives us confidence that the maximum operating stress at room temperature in the inner diameter wall will be from 76 to 87% of the allowable. A helium leak detector test was made at the working helium pressure in the vessel, when it was placed into the cryostat vacuum shell, sealed and pumped out. A leak was below 10^{-9} cm^3/s. The helium vessel is certified by a stamp according to the ASME Code.

IV. Cryostat

The high heat capacity fiberglass-lead radiation shield of the helium vessel is now being fabricated by a vacuum bagging technique, that is routinely used for boat construction. Several dummy shields had been built before the following procedure was developed. First, a precisely shaped mold was made for two identical half-shields. The base of the half-shield was made of three fiberglass layers over aluminum foil. The layers were wetted with epoxy resin and vacuum bagged on the waxed mold. The toroidal half-shield was carefully separated from the mold, cleaned, and then placed back. Four loops of the heat exchanger tube were bonded by epoxy resin to the base surface. Holes were made for the shield and helium vessel supports and for tube penetrations. Sand blasted lead plates with soldered copper strips were adjusted to the ground surface. The strips serve as heat sinks from lead to copper tubes during cryostat cooling. The strips were soldered to the tube with low temperature solder. All metal support components were installed into holes in the base. The base, lead surfaces facing to, and other metal parts were wetted with resin and strongly fixed to the base by vacuum bagging. All tube-lead and lead-lead gaps were filled with a dense resin with a glass powder filler. After epoxy curing and cleaning the final three layers of fiberglass were vacuum bagged on top of the shield. The two half-shields will be tied together in the final cryostat assembly. 12 mm Pyrex glass balls support the shield 5 mm off the helium vessel. 16 balls are fixed in four circles around the vessel. The heat exchanger tubes are brazed to the exhaust tube of the helium vessel and to the outer cryostat ports.

The radiation shield will be covered by multi-layer insulation. The chosen MLI system was developed and tested in Fermilab for SSC [7]. It is double aluminized 25 μ thick Mylar (DAM) of with polyester spunbonded 0.1 mm spacers. The layer density is about 36 DAM/cm.

The helium vessel is supported in the vacuum shell by specially shaped stacks of 30% cold rolled 316L stainless steel laminations. 7200 sand blasted rings and disks 0.1 mm thick were made. They are being assembled in 24 stacks. The supports will be installed into 8 frames by three rows around the outer surface of the helium vessel. These low heat leak supports are thermally anchored to the shield. Each support is designed to withstand a load of 50 kN. The cryostat assembly is performed using the assembly fixture as shown in Fig. 5. It has a central hydraulic jack to easily raise and lower the helium vessel onto the vacuum vessel and a space frame to support the lower half of the vacuum shell. Two halves of the vacuum shell are 3.2 mm thick. They were made by spinning 316L stainless steel sheets. The edges of the half-shells were machined and adjusted to each other and to circular slots in the equatorial reinforcement outer ring. Both half-shells were electro-polished.

V. Conclusion

The floating coil has been tested and installed in the high-pressure helium vessel. The cryostat is now being fabricated at Ability Engineering. The assembly is supposed to be finished this year.

References

[1] J. Kesner, L. Bromberg, D. Garnier, and M. Mauel, "Plasma confinement in a magnet dipole," in *17th IAEA Fusion Energy Conf.*, Yokohama, Japan, 1998, Paper IAEA-F1-CN-69-1CP/OS.

[2] J. Schultz *et al.*, "The levitated dipole experiment magnet system," *IEEE Trans. Appl. Supercond.*, vol. 9, no. 2, pp. 378–381, June 1999.

[3] A. Zhukovsky *et 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, Mar. 2000.

[4] A. Zhukovsky *et al.*, "Charging magnet for the F-coil of LDX," *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, pp. 1873–1876, Mar. 2001.

[5] J. Schultz *et al.*, "High temperature superconducting levitation coil for the Levitated Dipole Experiment (LDX)," *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, pp. 2004–2009, Mar. 2001.

[6] B. Smith *et al.*, "Design, fabrication and test of the react and wind, Nb_3Sn, LDX floating coil conductor," *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, pp. 1869–1872, Mar. 2001.

[7] I. B. Goldberg *et al.*, "Magnetic susceptibility of Inconel alloys 718, 625 and 600 at cryogenic temperatures," in *Adv. in Cryogenic Engineering*. New York: Plenum Press, 1990, vol. 36A, pp. 755–762.

[8] J. D. Gonczy *et al.*, "Thermal performance of MLI system for the SSC," in *Adv. in Cryogenic Engineering*. New York: Plenum Press, 1990, vol. 35, p. 497.