Charging Magnet for the Floating Coil of LDX

A. Zhukovsky, J. Schultz, B. Smith, A. Radovinsky, D. Garnier, O. Filatov, V. Beljakov, S. Egorov, V. Kuchinsky, A Malkov, E. Bondarchouk, V. Korsunsky, V. Sytnikov

Abstract—The charging coil (C-coil) for the joint Columbia University/MIT Levitated Dipole Experiment (LDX) is under development jointly by MIT and the Efremov Institute. The NbTi superconducting C-coil serves to charge/discharge inductively the floating superconducting magnet to/from 2277 A when it is resting in the charging port at the bottom of the LDX vacuum vessel. The C-coil is designed for 3200 charge-discharge cycles. The solenoid magnet is installed in a low heat leak liquid helium cryostat with a warm bore of more than 1 m. The magnet protection system has an external dump resistor, which dissipates most of the 12 MJ stored energy during a quench.

Index Terms— inductive charging, superconducting coil, cabled conductor, cryostat, quench protection

I. INTRODUCTION

The Levitated Dipole Experiment (LDX) is a new, innovative magnetic confinement fusion experiment being designed, jointly by Columbia University and MIT, for installation at MIT [1]. The main component of the experiment is a floating superconducting coil (F-coil), which is charged/discharged inductively to/from the nominal current of 2070 A [2]. During operation the F-coil is located in a charging port (station) at the bottom of the LDX vacuum vessel. The charging coil (C-coil) is designed to charge the F-coil inductively to full current with 10% margin, i.e. to 2277 A. The C-coil is a solenoid wound with NbTi conductor and operates in a liquid helium cryostat, that surrounds the 1157 mm diameter charging station. A narrow gap between the top of the C-cryostat and the LDX vacuum vessel restricts the location of feedthroughs at the cryostat top.

The C-coil electric circuit is shown in Fig. 1. The main scenario of C-coil operation is as follows. At the beginning of the LDX working day, the C-coil is charged in 30 minutes to the full current, while the F-coil is held normal at about 20 K. The F-coil is cooled down to 5 K in about 2.5 hours, while the C-coil current is held constant. The C-coil is then discharged in half an hour, inducing full current in the F-coil. The main C-coil circuit is then opened (S1 and S2), but the quench protection dump resistor circuit remains closed. The C-coil is held at zero current when the F-coil is lifted out of the charging station in the vacuum vessel and during LDX

experiments. When the F-coil is reinstalled in the charging station, the main C-coil circuit is closed, and the C-coil is ramped up in half an hour to discharge the F-coil. The F-coil is heated above its critical temperature and the C-coil is discharged. Another scenario requires operation of the C-coil for at least 48 hours at half-current, corresponding to a mode when the F-coil is resting half-charged in the charging station between experiments. According to the main scenario, the C-coil operates at the full current for 3.5 hours per day, and the charging-discharging operation takes 2 hours per day. Considering a two day weekend, the C-coil operates 10% of the time at full current and 6% at partial current.

The C-coil is to be operated cyclically. It must be capable of providing two experimental runs in a day (full charge-discharge), 10 runs in a week, 160 runs in a year, and 1600 experimental runs, lifetime. The C-coil reacts unbalanced electromagnetic forces due to misalignments between F- and C-coil magnetic centers, which can reach ± 6 mm. The analysis of possible seismic loads showed that the magnet could be shocked with maximum seismic accelerations of 0.5 g in the horizontal and 0.35 g in the vertical direction.

To reduce the price of the C-coil it was decided to use commercially available NbTi strands. Strands with a nominal length of 500 to 3000 meters were developed and produced by the Bochwar Institute (Moscow). The C-magnet is being designed by the Efremov Institute and MIT, and will be manufactured by the Efremov Institute. The cabled conductor for the C-coil is developed and being under production by the Cable Institute (Moscow).

II. CONDUCTOR

The conductor and C-coil are designed with the following criteria. The maximum hot spot temperature after a quench shall be below 150 K, and the maximum voltage developed during a C-coil quench is 3 kV. The conductor operating
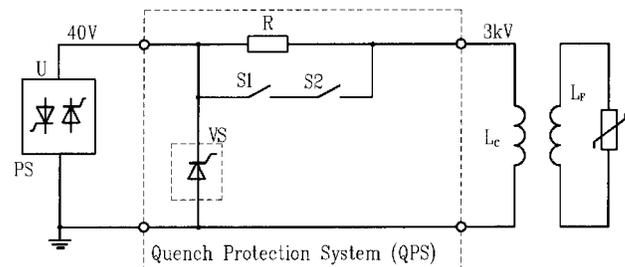
Fig. 1. Main electric power circuit scheme. L_C – C-coil; L_F – F-coil; PS – power supply; R=5.7 Ohm – dump resistor; S_1 – main controllable electronic switch of IGCT type; S_2 – main controllable mechanical switch; VS – thyristor switch.

current is limited to $0.4\ I_C$, where I_C is the conductor critical current at the maximum field and operating temperature, in order to eliminate training after installation at MIT. For the same reason the conductor strain is limited to 0.1 to 0.2%.

The stress in the conductor is limited to 70% of the allowable yield stress. The strains are much smaller than usually allowable 0.4 to 0.5% strains in epoxy impregnated solenoids, steady-state working at the operating current up to 90 to 95% of the critical current.

The available NbTi strands have the following specification: outer diameter 0.85 mm; filament diameter 10 µm; number of filaments 2970, Cu/nonCu = 1.38, RRR > 100. Two conductor options with these strands were investigated (see Fig. 2). The option A conductor is the cable-in-channel type. It contains three NbTi strands twisted in a triplet and soldered into the groove of a rectangular channel made of oxygen-free copper. The minimal technological cross section of the copper channel is slightly higher than the specified design criteria. The conductor B option is a solder-impregnated compacted cable containing three superconducting strands co-twisted with six 0.85 mm copper wires around one central 1.5 mm copper wire at a twist pitch of 35 mm. All copper wires are made of oxygen-free pure copper. The test samples were manufactured by the Cable Institute and tested by the Efremov Institute. The central 1.5 mm diameter wire is flattened and compacted during cable forming after the solder bathing. The used solder (29-31% Sn; 1.5-2.0% Sb; Pb- the rest) has a melting temperature interval from 185 to 250 °C. The conductor is insulated by a half overlapped 0.05 mm thick Kapton tape,

Option A
Cu/NbTi ratio is 9.7

Option B
Cu/NbTi ratio is 8.6

1 – superconducting strand; 2 – copper channel; 3 – turn insulation
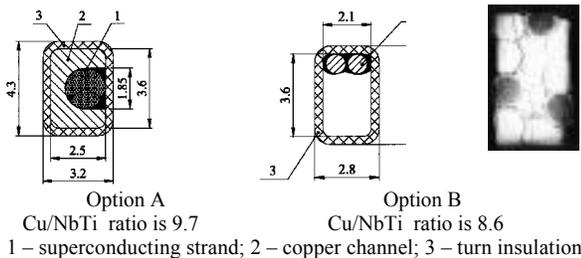
Fig. 2. Cross section of considered conductors.
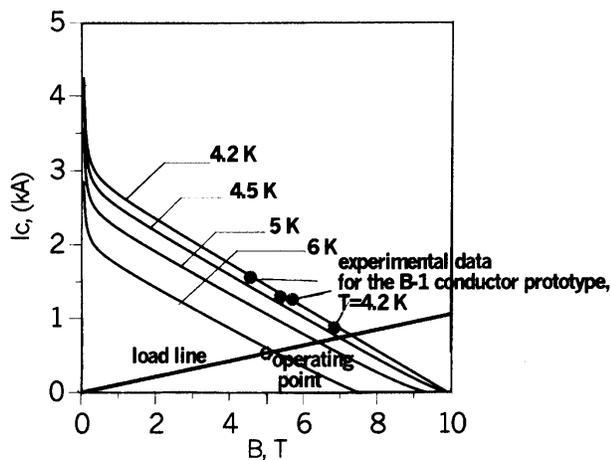
Fig. 3. Critical current of the cabled conductor (I_C) versus magnetic field flux density (B).

with a total thickness of 0.1 mm. A 10 µm S-glass fiber braid of 0.25 mm total thickness is applied over Kapton.

Option B promises to reduce the mass and dimensions of the coil due to a lower content of copper in comparison with option A. The production process of the B conductor is also simpler and delivery time is shorter compared with the A type. Mechanical and electrical tests of B prototype conductors demonstrated properties adequate for the C-coil requirements. The critical current data for the B samples are shown in Fig. 3 with the magnet loading line and critical current characteristics established as 75% of the sum of the nominal I_C of three superconducting strands in virgin state before cabling and compaction. The "n-factor" of the conductor samples is close to 16. The measured RRR is about 118 at 10 K in the zero background field. Tensile tests are performed for the cabled conductor samples at room temperature (RT) and at 77 K. At 77 K the tests are made before and after 16,000 cycles of tension loading (0-85 MPa) relevant to the C-coil conductor operating conditions. The averaged results of the tests are following (RT/77): the Young's modulus 76/85 GPa, the yield stress 209/267 MPa, ultimate strength 314/405 MPa, and elongation 4.0/4.8%. Due to these results the B conductor was selected for the coil.

III. WINDING PACK

A pancake winding was considered as an option. It was rejected due to the high level of a pre-stress needed to provide mechanical integrity after cool-down and under loading. A C-coil configuration with a stainless steel or fiberglass mandrel has been considered and also rejected due to the results of stress analysis. The coil was finally designed as a layer winding with a lateral position of the layer-to-layer joints outside the outer cylindrical surface of the coil. A mandrel-free vacuum-pressure impregnated self-supporting winding was chosen. No coil reinforcement was used. The winding pack (WP) is designed with a height of 750 mm, and inner and outer diameters of 1300 and 1600 mm. The C-coil parameters at the operating current of 526 A are shown in Table I.

The total conductor length is 37.5 km with a mass of about 2510 kg. The full mass of WP with insulation is about 2750 kg. The conductor will be delivered in batches of different length, each of which will be sufficient for continuous winding of one, two or three layers. The exact number of conductor joints in the coil (about 36) will be determined and minimized after conductor production.

TABLE I
C-COIL WINDING PACK DESIGN PARAMETERS

Parameter	Value
WP mean current density, A/mm^2	39.3
Number of layers	50
Number of turns in a layer	165
Total number of turns	8250
Length of conductor in a layer, m	700-900
Winding density, turns/m^2	7.4 10^4
Stored energy, MJ	12.2
C-coil self inductance, H	88.85
F-coil self inductance, H	0.3886
Mutual inductance of C- and F-coils, H	1.688
Energy transferred to F-coil, MJ	1.0073
Maximum magnetic field in the WP, T	4.92
C-coil protection dump time constant, s	<17.2

The coil is wound on a demountable mandrel with a cylindrical hub and two flanges. After winding the coil is vacuum-pressure impregnated with epoxy resin Araldite-745 at a low pressure below 0.0013 MPa and a high pressure of

0.8 MPa. The free-standing coil is made by removing the mandrel after the epoxy is cured. The soldered praying-hands joints 0.6 m long are located around the WP. The final selection of the joint configuration will be made after prototype joint testing. The expected contact resistance of one joint is no more than 2×10^{-8} Ohm.

The C-coil WP with conductor joints and clamp structure is shown in Fig. 4. The clamp structure consists of the pre-load structure formed by 12 separate units and upper and
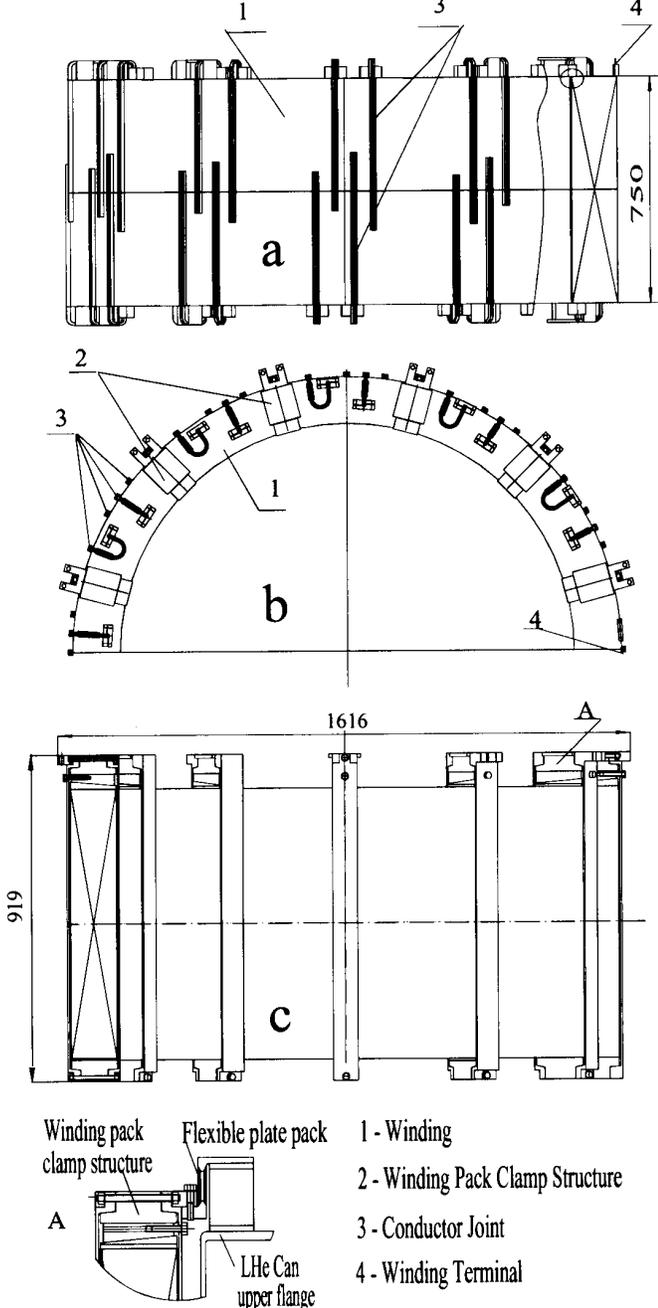
Fig. 4. Winding pack (WP)
a – WP with conductor joints and terminals (side view); b – WP with clamps (top view); c – WP with clamps (side view); A – WP clamp structure connected with liquid helium can.

lower fixing hardware. Each unit has lower and upper beams, outer and inner tie-plates, a wedge key and two stud bolts. All the parts of the pre-load structure are made of a strong aluminum alloy. The upper fixing parts are welded to the

upper flange of the helium can. The WP is hung on the upper flange with flexible stainless steel plate packs bolted to the upper beams. Lower beams are fixed in the lower fixing parts to provide support for horizontal forces applied to the WP, but allowing vertical and radial displacements due to differential thermal contractions of various parts. The clamp structures are electrically insulated from the WP by 1.5 mm thick fiberglass plates.

The mechanical analysis of the WP and clamp structure is performed for the following cases: pre-loading the tie-plates, cooling from RT to 4 K, loading by electromagnetic forces plus full seismic loads (at the full C-coil current and at half-current in C- and F-coils), and transportation loads under 2 g accelerations. The pre-compression of 0.85 MN at RT is chosen to avoid sliding of the winding in the clamp plates under simultaneous unbalanced magnet and horizontal seismic loads. After cooling, the pre-loading increases to 0.93 MN. The results showed that the maximum stress intensity in conductor copper is 114 MPa. The maximum electromagnetic loads are the source of hoop stresses in the winding of up to 84 MPa and hoop elastic strains up to 0.12%. Very low shear stresses are developed in the winding. There is no tendency for conductor layer separation due to the compressive nature of radial stresses.

The cryostat is shown in Fig. 5. The C-coil is fixed inside the liquid helium "mushroom" shaped vessel with a helium volume above the coil sufficient to work without helium re-filling for several days. The helium vessel is supported by a structure consisting of 16 inclined thin wall G-10CR tubes embedded at the ends into stainless steel fittings. The fittings are attached at one tube end to the outer wall of the helium vessel and at the other end to the stainless steel basic ring. The basic ring is supported by four columns consisting of flexible plate packs, in-vessel basic columns and outer columns, connected to the C-coil stand. The support system of the cold mass is designed to withstand the most severe combinations of electromagnetic and seismic loads.

VI. CRYOSTAT

The 80 K thermal shield around the helium vessel consists of outer and inner stainless steel liquid nitrogen vessels. The basic support ring and some other supporting elements are cooled by liquid nitrogen.
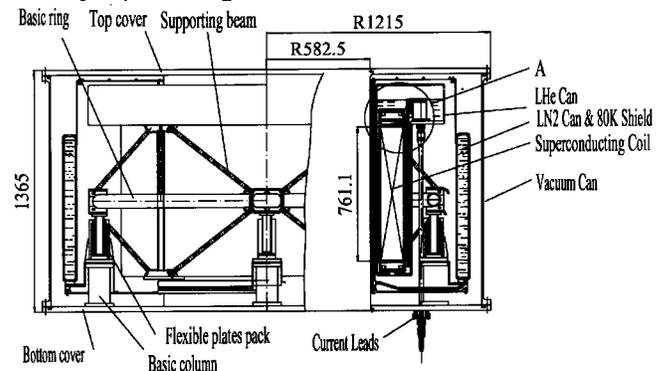
Fig. 5. C-coil cryostat.

The nitrogen vessels are filled by liquid nitrogen automatically. The vacuum can surrounds the thermal shield. The bottom position of all electric, instrumentation, and cryogenic feedthroughs is dictated by the restricted space at

the C-cryostat top. The cryostat has two liquid helium supplies: one to the helium vessel bottom for the initial cooling and the other to the vapor volume at the helium vessel top for the regular helium refilling.

At the initial stage of the design, HTS current leads were considered to limit the heat leak and to minimize liquid helium consumption during C-coil operation. Such leads cannot work at a substantial magnetic field and should be placed at a relatively long distance from the main C-coil cryostat (at the radius of 2.5 m). This placement of the HTS current leads in a separate cryostat with long superconducting connecting leads eliminated their advantages in comparison with traditional gas-cooled copper leads. Finally, the HTS current leads were rejected. Helium vapor is vented downward from the cryostat through the gas-cooled leads in the normal operation. The current lead design will be optimized after full-scale tests. The preliminary estimation of a heat supplied to liquid helium due to the current leads is 0.76 W at 530 A and 0.18 W at zero current.

To reduce the radiation heat load, all the surfaces of the vessels and thermal shields of the cryostat are covered with thin steel tapes coated by a highly reflective 1 to 3 µm aluminum layer. A special surface treatment will be used in which evaporated crystalline aluminum on a metal substrate results in a surface with extremely low emissivity [3]. The emissivity factor for such surfaces at temperatures of 80 to 4 K is less than 0.004. The estimated radiation heat leak to the helium vessel is about 0.11 W. Cryoadsorption panels with a charcoal adsorbent will be installed on the liquid nitrogen vessel to maintain 10^{-7} torr operating vacuum in the cryostat. This vacuum is associated with a residual gas heat leak to the 4 K level of about 0.02 W.

The operating scenario of the C-coil, for which current is supplied to the coil for only about 13% of the week, causes the low weekly consumption of liquid helium shown in Table II. The 150 liters of the liquid helium volume above the C-coil limits the need to refill the cryostat with liquid helium to twice a week with five days of operation. In this case, the liquid helium losses associated with helium transfer will be limited. The average usage of liquid helium close to 30 liters per day (0.9 W) is a very good rate for a cryostat with about 2.5 m outer diameter and a 1.2 m warm bore.

V. QUENCH PROTECTION SYSTEM

A quench protection system (QPS) serves to protect the

TABLE II
Weekly liquid helium consumption in liters

Parameter	Value
Resistive losses in joints	10
Conductor AC losses	6
Heat supply through current leads	61
Radiation heat leak from the shield	31
Heat leak through the support system	52
Heat leak through fill and vent helium lines	26
Heat leak due to instrumentation wires	8
Other heat leaks	3
Total, liters per week	197

superconducting C-coil and the power supply in case of quench or a power supply failure (see Fig. 1). The four-quadrant 40 V and 600 A power supply is used for the charge/discharge of the C-coil. During the time when the F-

coil is out of the charging station, the C–coil protection circuit must be open. To protect the C-coil from damage during a quench, the QPS shall provide a fast discharge through the dump resistor. At the maximum terminal voltage of C-coil of 3 kV the dump resistor shall be 5.7 Ohm. The QPS is connected to the C-coil by high voltage cables. The QPS starts to operate in 100 ms after the signal "quench" is received from the quench detection system. The detection system monitors the normal zone resistive voltage in the magnet. The system generates a signal for the QPS if the voltage reaches a threshold value. The resistive voltages of the current leads are also monitored and the QPS sends a signal to dump the C-coil in case of excessive voltage due to overheating of a lead. When operation "quench" starts, the thyristor switch is closed. After several milliseconds of time delay, the main electronic and mechanical switches receive the signal to open. The electronic switch opens first due to its significantly shorter response time versus mechanical switch, which normally opens at zero current. The mechanical switch provides the visible break, and can also operate at full current in case of electronic switch failure. Two independent types of switches in series are used to increase the reliability of the QPS.

VI. CONCLUSION

The low helium-consumption C-coil is under development for the inductive charging/discharging of the floating coil of LDX. The paper describes present status of research and design phases of the project. The C-coil will be assembled into its cryostat with all instrumentation and tested with the quench protection system under operating conditions at the Efremov Institute Cryogenic Test Facility [4]. After the test, the cryostat will be equipped with transport supports and shipped from St. Petersburg to Boston. Removable transport supports of the helium vessel and shield withstand the transport loads with maximum accelerations up to 2 g. The C-cryostat should be installed at the MIT LDX facility in the spring of 2001.

REFERENCES

[1] J. Schultz at al, "The Levitated Dipole Experiment (LDX) Magnet System", *IEEE Trans. on Appl. Supercond.*, Vol. 9, No. 2, pp.378-381, June 1999.
[2] A. Zhukovsky at al, "Design and Fabrication of the Cryostat for the Floating Coil of the LDX", *IEEE Trans. on Appl. Supercond.*, Vol. 10, No.1, pp. 1522-1525, March, 2000.
[3] M.P. Larin, Soviet Physics, *J. of Technical Physics*, 50, p. 1955, 1980.
[4] V.A. Glukhikh, O.G. Filatov at al, "Cryogenic Test Facility of the D.V. Efremov Institute", *IEEE Trans. on Appl. Supercond.*, Vol. 10, No. 1, pp. 1564-1567, March, 2000.