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Review of SC magnet technologies developed in LHD project

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Abstract

The Large Helical Device (LHD) is a heliotron-type toroidal fusion experimental device which will provide useful and reliable data sets for high temperature plasmas with an equivalent Q value of 0.1–0.35. One of the crucial tasks of LHD is to demonstrate steady-state operations by taking the advantage of currentless plasmas. In this respect, the coil systems are fully superconducting (SC); consisting of a pair of helical coils, three pairs of poloidal coils and nine bus-lines, all of which are presently in the final stage of assembly. The helical coils and the Outer Vertical (OV) poloidal coils are the world largest SC coils among the existing fusion devices. The flexible SC bus-lines are one of the innovative components newly applied through this project. The technological development of the SC magnets took key roles in LHD.

1. Introduction

The project of the Large Helical Device (LHD) is now executing the final year program of its 8 year construction schedule. The engineering research and development for LHD have almost been completed, and we have now accomplished more than 95% of the tough and long construction schedule. The main objectives and target plasma parameters of LHD are: (1) confinement studies and demonstration of high temperature helical plasmas, with an average electron density and ion temperature of $n \sim 10^{20}$ m^{-3} and $T = 3–4$ keV, or with $n \sim 2 \times 10^{19}$ m^{-3} and the central ion temperature $T(0) \sim 10$ keV, both under input heating power of >20 MW, (2) MHD studies on high beta plasmas of $\langle\beta\rangle$ (plasma pressure/magnetic pressure) $\geqslant 5\%$, (3) studies on confinement improvement and steady-state experiments using divertors, and (4) development on physics and technologies required for realizing fusion reactors [1]. In this connection, LHD is expected to provide useful and reliable data sets making it possible to project a fusion reactor precisely.

One of the major goals of the LHD project is to demonstrate the high potentiality of a heliotron-type device by producing currentless steady-state plasmas with sufficiently large Lawson parameters without a major disruption that would terminate a discharge in tokamaks causing severe damage to the plasma facing materials. In this respect, LHD was determined to become the world first fully superconducting (SC) fusion device which strongly depends on SC and cryogenic technologies [2]. A schematic view and the major specifications of LHD are shown in Fig. 1 and Table 1. The coil system consists of a pair of helical coils, three pairs of poloidal coils and nine bus-lines, which are all presently in the final stage of assembly aiming at the first plasma operation scheduled at the end of March, 1998. It should be noted that both the helical coils and the Outer Vertical (OV) poloidal coils are the world largest SC coils among the existing fusion devices.

The design basis of the LHD SC coil system has been focused on ensuring high reliability and safety in a long term as a fusion device. However, many components had been the first experiences in the field of SC engineering. In this paper, the SC magnet technologies developed for LHD in NIFS are reviewed.

2. Helical coils

The two helical coils have the major radius of 3.9 m and the average minor radius of 0.975 m with a poloidal pole number of 2 and a toroidal pitch number 10. The overall coil current reaches up to 7.8 MA in the Phase II

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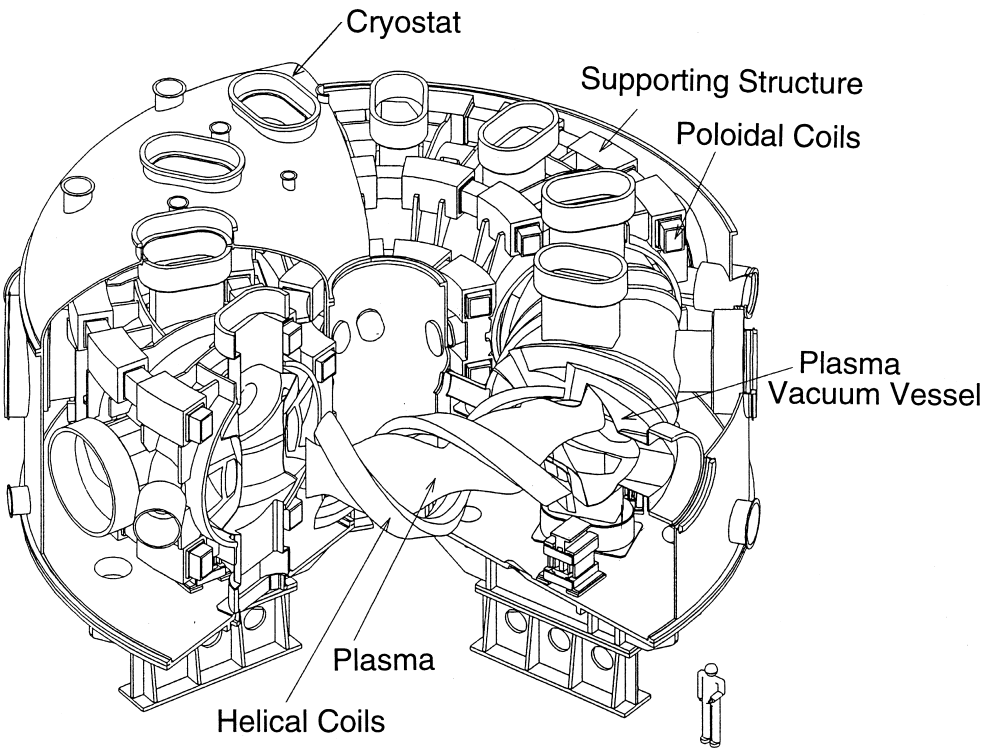

Fig. 1. A schematic view of LHD.

operation condition (the central toroidal field: 4 T) with a stored magnetic energy of 1.6 GJ. A cross-sectional view of the helical coil is illustrated in Fig. 2 and the major specifications are listed in Table 2.

For the windings of the helical coils (450 turns for each, divided into three blocks), we have adopted pool-cooled composite-type superconductors with NbTi/Cu compacted strands and copper and pure aluminum stabilizers, by considering the following points: mechanical flexibility required for the on-site winding into three-dimensional helical shapes with high accuracy, high current density up to 53 A/mm^2 inside the winding package, requirement for small error field caused by joints, and less requirement on the AC loss due to the low alternating field in the coils except in emergency discharges. Since the conductors are not able to withstand the large electromagnetic force by themselves, they are designed to be packed into thick stainless steel cases (“HC cans”) which are also used as a bath of liquid helium and a bobbin for winding. The conductor has a cross-section of 12.5×18.0 mm^2 and the nominal current is set at 13.0 kA for the Phase I condition (3 T operation) in which the coil is immersed in liquid helium of 4.4 K and the maximum field on the conductor reaches 6.9 T. In Phase II, the windings will be further cooled down to 1.8 K using superfluid helium and the nominal current will be 17.3 kA at 9.2 T. One of the important outcomes of the SC R&D in NIFS is the development of this superconductor [3] which is expected to be sufficiently stable to ensure the reliable operations of the helical coils with such large amount of stored energy. A Cu–2% Ni clad was adopted around the pure aluminum stabilizer to reduce the “Hall current” generation and to sustain the high conductivity of the pure aluminum up to the high magnetic field [4]. The total length of the fabricated conductors reached up to 36 km, of which unit length was around 1 km. Before being delivered to the on-site winding process, short samples of 2 m long were prepared out of a terminal of

Table 1
Major specifications of LHD (the figures in the brackets show the values in Phase II)

Major radius	3.9 m
Averaged plasma minor radius	0.5–0.65 m
Plasma volume	20–30 m^3
Toroidal magnetic field	3 (4) T
Field period	10
Plasma heating power	40 MW
Coil stored energy	0.9 (1.6) GJ
Cold mass	820 tons
Total weight	1500 tons
Refrigeration power	10 (15) kW

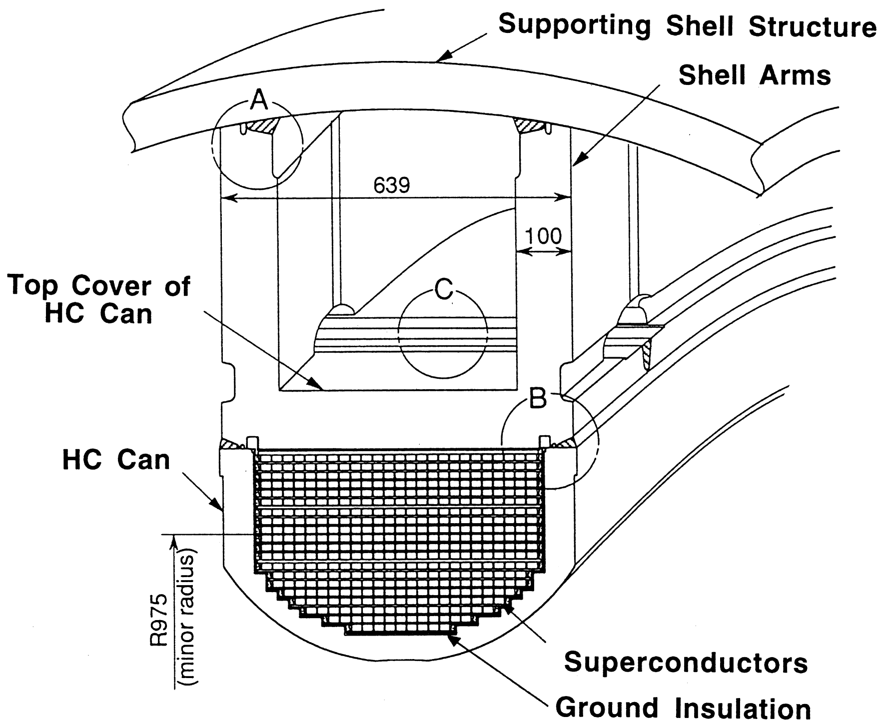

Fig. 2. A schematic cross-sectional view of the helical coil with supporting structures. In the figure, the welding sections are indicated; A: between the shell arm and the supporting shell, B: between the HC can and its top cover, and C: the joint of the top cover.

Table 2
Major specifications of the helical and poloidal coils (in Phase II)

	Helical coils	IV coils	IS coils	OV coils
SC material	NbTi/Cu	NbTi/Cu	NbTi/Cu	NbTi/Cu
Conductor type	Al-stabilized composite	CICC	CICC	CICC
Cooling method	Pool-boiling	Forced-flow	Forced-flow	Forced-flow
Major radius	3.9 m	1.8 m	2.82 m	5.55 m
Weight (per coil)	120 tons	16 tons	25 tons	50 tons
Maximum field	9.2 T	6.5 T	5.4 T	5.0 T
Stored energy	1.6 GJ	0.16 GJ	0.22 GJ	0.61 GJ
Nominal current	17.3 kA	20.8 kA	21.6 kA	31.3 kA
Current density	53.0 A/mm^2	29.8 A/mm^2	31.5 A/mm^2	33.0 A/mm^2
Total current	7.8 MA	5.0 MA	− 4.5 MA	− 4.5 MA

each lot of the fabricated conductors and were inspected about their superconductivity properties [5] using the superconductor test facilities of NIFS equipped with a 9 T split coil, 100 kA current leads and 75 kA DC power supplies [6]. The critical current and the recovery current of all the 38 lots were measured to satisfy the required specifications of 22 kA and 13 kA, respectively, at the bias field of 7 T.

The development of a numerically controlled winding machine (with 13 NC driving axes) was one of the technological breakthroughs for realizing the three-dimensional helical windings with a required high positional accuracy of 2 mm. The shaping errors with in-plane and out-plane bending as well as twisting of the conductors were reduced less than 15% after many try and errors, which has improved the final positional accuracy of the windings [7].

The conductors have been wound from the bottom of the HC cans in 20 layers divided by GFRP spacers of 3.5 mm thickness (between layers) and 6 mm (between blocks) which have been newly developed for LHD with a high Young's modulus of up to 30 GPa [8]. The exposure rate of the conductors was determined by optimizing the expected mechanical stress on the layer-to-layer spacers (to be less than 100 MPa) and the expected recovery current (to be higher than the nominal current of 13.0 kA in Phase I) [9]. The mechanical rigidity of the winding package was experimentally investigated by preparing coil package samples of 6 layers × 6 turns which were examined in liquid helium using 10 MN cryogenic mechanical testing machine [10].

In three-dimensional helical coils, it is rather difficult to apply tension to their windings, which is generally effective to reduce residual gaps between conductors in cylindrical and/or D-shaped coils. Therefore, we have developed a special technique in LHD, i.e., first placing the conductors at slightly deviated positions with shorter longitudinal paths and later shifting them to the final positions with longer paths, hence there appearing tension along the conductors without deforming the shapes given by the winding machine beforehand [11]. The resulted tension was estimated to be 30–50 MPa with a 5 mm shift of the conductors.

The final positions of the conductors were measured by scanning the conductor surface with a laser-distance meter from the top of the HC can. Using the measured data, the layer-to-layer spacers were machined by an NC planer so that they fitted precisely to the profile of the layer beneath with filling reinforced epoxy. Using these techniques, the maximum deviation of the conductor positions relative to the HC can was kept within ±0.5 mm [12]. It should also be noted that the difference between the average minor radii of the two helical coils was less than 0.2 mm.

The superconductors are connected between the layers at both terminals of a conductor located at peripheries inside the "HC cans". A soldered lap joint was adopted because of its simplicity for pool-cooled superconductors. Since the reduction of heat generation is extremely important within the helical coil with its tight channels, we have developed a special technique which has effectively reduced the joint resistance without spoiling the mechanical rigidity of the conductors [5]. A joint piece of ~ 400 mm long connects the two conductors by 20 SC strands through thin solder layers. The joint resistance has been experimentally measured with short samples and was confirmed to be sufficiently low, such as less than 0.7 nW/joint with a transport current of 17.3 kA. Bubbles of gas helium generated by the joint resistance and by other heat input such as radiation and conduction from the surrounding structures are extracted from the "HC cans" through the channels distributed at the corner sections of each layer in the helical coil package.

After the completion of winding of all the 900 turn conductors into the "HC cans", the top covers with "shell-arms" were placed onto the windings with welding (see Fig. 2) [13]. Then the "shell-arms" were welded to the outer torus-shaped shell structure which finally supports the large electromagnetic force on the helical coils. Both the "HC cans" and the supporting structure are made of austenitic stainless steel SUS316 (total weight: 550 tons, thickness: up to 100 mm) not only because it is fully austenitic and naturally non-magnetic but also there are enough 4 K data concerning its mechanical properties. The carbon and nitrogen contents are increased by optimizing the tensile yield strength at 4 K as well as the properties during hot pressing and electron beam welding. The shell structure was built from 20 fan-shaped parts which were welded together on-site. Since LHD is a currentless steady-state device, it is an advantage that there is no one-turn electrical break around a torus unlike tokamaks. A finite element numerical analysis was carried out using shell and solid element models to examine the expected deformation of the structure due to the electromagnetic force in 4 T operation modes. By adding vertical ribs to the shell structure, the local deformation can be kept less than the specified value of 3.4 mm. The coils needed to be positioned with an accuracy of <2 mm and thus the supporting structure was assembled with an overall accuracy of <5 mm prior to the coil setting [14].

The design and practical techniques of thick stainless steel welding with such high accuracy has been another crucial issue for constructing LHD. The fracture toughness of such welding sections was experimentally investigated at 4 K using a 10 MN cryogenic mechanical testing machine [15]. The assembly of the supporting structures and the helical coils has been successfully completed. Partial penetration welding was used to reduce the deformation caused by welding [13,14]. This work has been performed by devoted efforts of excellent welders with highly trained skills. The total cryogenic mass including the poloidal coils is about 820 tons and is supported by ten adiabatic posts.

3. Poloidal coils

The poloidal coil system of LHD consists of three pairs of circular solenoids; Inner Vertical (IV), Inner Shaping (IS) and Outer Vertical (OV) coils, which have the maximum coil currents of 5, −4.5 and −4.5 MA, respectively, and the average radii of 1.80, 2.82 and 5.55 m, respectively. The poloidal coils have NbTi/Cu cable-in-conduit conductors with forced-flow cooling by taking the advantage of their low AC loss characteristics because the poloidal coils are planned to be operated in AC modes for physics experiments.

The main parameters of the poloidal coils are listed in Table 2. Each coil consists of eight double-pancakes, and supercritical helium of 4.5 K, 1 MPa is supplied to each pancake in parallel from the inner (high field side) turns to the outer turns with a mass flow rate of 5 g/s. A plan view of the IV coil is shown in Fig. 3. The conductor consists of a cable with 486 strands and a conduit

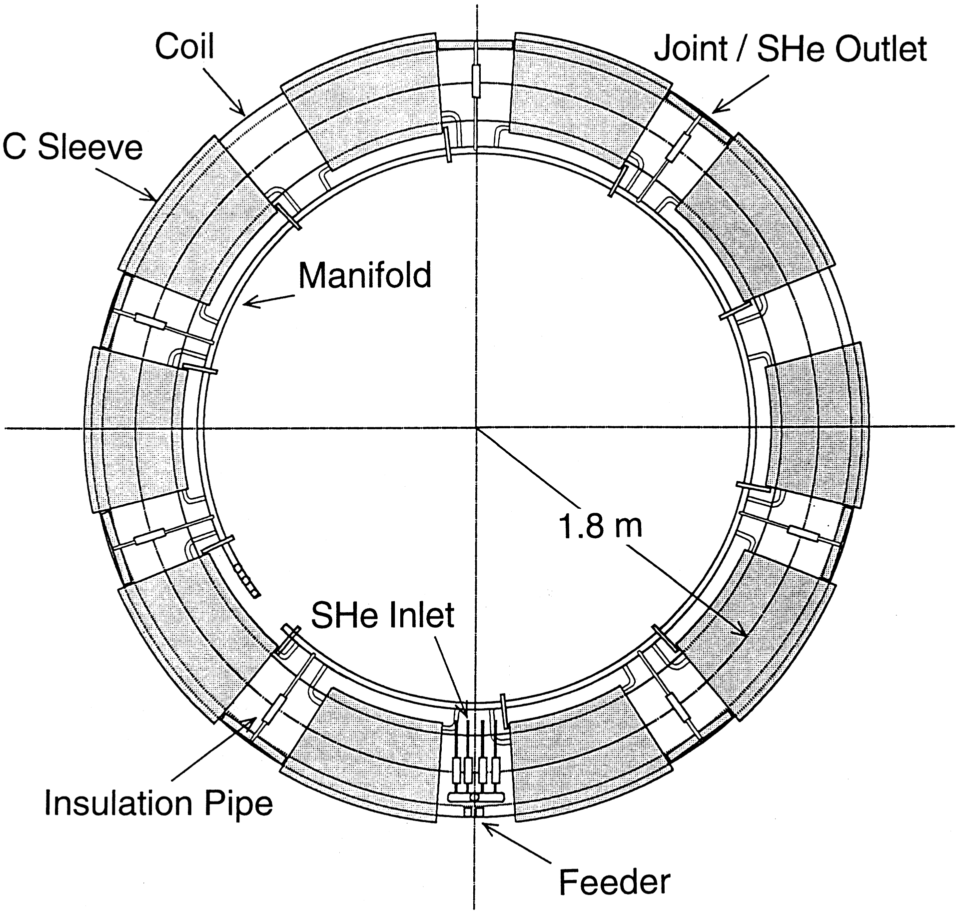

Fig. 3. A plan view of the IV poloidal coil.

of rectangular cross-section with a thickness of 3 mm (for IV and IS) or 3.5 mm (for OV). The nominal currents for the Phase II operation are set at 20.8, 21.6 and 31.3 kA, for IV, IS and OV, respectively. The void fraction inside the conduit is designed to be 0.38, based on an optimization work taking into account strand movements and inter-strand coupling losses. According to the results obtained with former R&D coils [16], the strand surface is not coated in order to keep uniform current distribution among strands and high heat transfer characteristics from strands to supercritical helium, which both ensure high cryogenic stability. The critical current is designed to be three times higher than the operating current according to the R&D results with respect to stability margins [17].

The double-pancakes were wound using a special winding machine. First, a half length of a conductor was paid out from the bobbin, and the winding started from the middle of the conductor. The conductor was wrapped with 0.5 mm thick impregnated glass epoxy tapes. After the winding of the lower pancake, the remaining half conductor was wound onto it with a 0.8 mm thick insulation in between. A double-pancake was then molded in a furnace. To minimize the error field, the pancakes kept the positional tolerances of 2 mm for the inner and outer diameters and 1 mm for the height after the molding. The eight double-pancakes were then stacked together with layer insulation and molded to form a coil.

The joints between the double-pancakes of the poloidal coils have adopted another new technique. A solid state bonding of NbTi filaments was applied for the first time to such large cables [18]. It should be noted that the required space for this joint is very small; 37 mm wide, 50 mm high and 60 mm long, which is preferable also from the viewpoint of reducing the error field. The performance of this type of joint was experimentally confirmed with short sample tests, which showed that the joints remained superconducting up to the nominal operation points.

The poloidal coils were finally covered with ten (for IV and IS) or 20 (for OV) stainless steel "PC sleeves" of

40 mm thickness which are distributed toroidally. Then the coils were stiffly fixed to the supporting shell with a symmetrical positional accuracy of 0.5 mm in all directions, which is quite important to guarantee the generation of fine magnetic surfaces.

The cool-down and excitation test of one of the IV coils (IV-L) was a highlight of the poloidal coil R&D. The test facilities in NIFS were fully used to perform this big test [19]. Although we first had so many difficulties, the coil was finally cooled in 250 h. Uniform temperature distribution was confirmed by keeping the temperature difference between the coil inlet and the outlet to be always less than 50 K. Then the coil was successfully energized up to the specified current of 20.8 kA without a coil quench [20]. The hydraulic characteristics of the conductors during the cool-down as well as the excitations were investigated [21], which showed good agreement with the previous results obtained with R&D coils.

4. Superconducting bus-lines

Since it is extremely essential to reduce the error field in the helical system, the current leads for the SC coils of LHD were decided to be located far from the cryostat. In this connection, a superconducting bus-line system has been adopted under careful designs and intense R&D [22]. It should be noted that this is one of the innovative components newly applied to a fusion device through the LHD project.

Fig. 4 shows a schematic view of the layout of the SC bus-lines. Nine sets of bus-lines (six of them for the helical coils and three for the poloidal coils) with lengths 45.7–58.0 m have been installed to connect the SC coils of LHD with a current lead cryostat located near the DC power supplies. One of the important features of the LHD SC bus-lines is that they are mechanically flexible, which was determined to be suitable for facilitating the installation of bus-lines in the basement of the LHD experimental hall. The minimum bending radius is restricted to be >1.5 m.

An aluminum stabilized NbTi/Cu compacted strand cable was developed to satisfy the cryostable condition with a nominal current of 32 kA at 1 T. A pair of SC cables were electrically insulated and installed in the innermost part of a cryogenic transfer line consisting of five-layered corrugated tubes (outer diameter: 220 mm). The cables are cooled by two-phase helium of 4.2 K with a mass flow rate of 12 g/s for each line.

The SC current feeder system especially requires high reliability and safety exceeding that of SC coils, because the stored magnetic energy of the coils must be extracted through bus-lines and current leads when a coil quenches. In this connection, the breakdown voltage of the bus-lines are designed to be higher than that of the SC coils and it is 5 kV in DC mode under the environment of 80 K gas helium. The heat loads into the 80 and 4.2 K levels of the corrugated tubes are estimated to be 3 W/m (total 2.12 kW) and 0.3 W/m (total 1.02 kW), respectively. The SC current feeder system is designed to maintain its rated capacities even with a failure of the refrigerator/liquefier system while extracting the coil energy. An R&D bus-line of 20 m length has been fabricated and successfully tested. The conductors have been confirmed to be cryostable with a nominal operation [22].

5. Conclusions

The construction of LHD has successfully reached the final stage. The SC helical coils, poloidal coils and bus-lines have been successfully completed based on the technological development with intensive R&D. The SC coil system, covered by an outer cryostat, will be cooled and excited using a 10 kW refrigerator/liquefier and DC

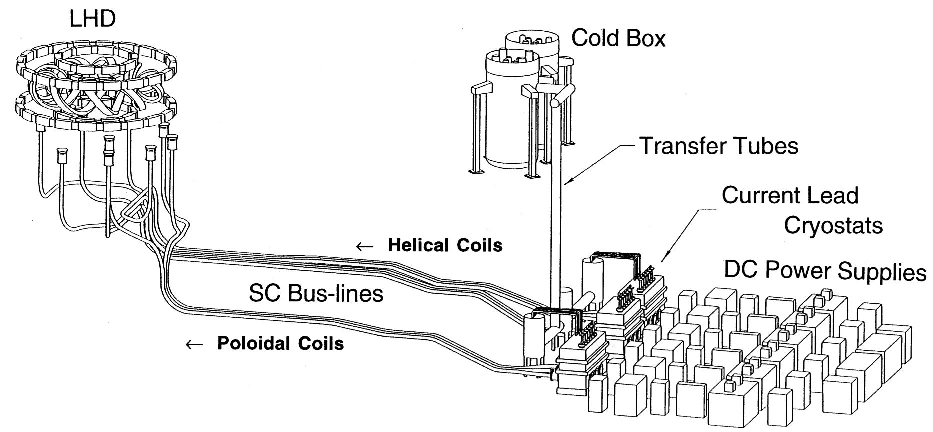

Fig. 4. A bird's-eye view of the SC current feeder system.

power supplies which were also carefully designed and constructed as are described elsewhere. Through the LHD project, we have obtained many SC magnet technologies which should be useful and necessary for constructing future fusion reactors.

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