Contribution of Superconducting Large Helical Device to Fusion Technology

超伝導大型ヘリカル装置の核融合炉工学への寄与について

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ABSTRACT

Large Helical Device (LHD) is a superconducting heliotron type device for advanced fusion experiments. The SC coil system is composed of a pair of helical coils and 3 sets of poloidal coils with a total stored magnetic energy of 1.63 GJ, which will be the world maximum. The main machine parameters, major radius (R_0), coil minor radius (a_0), magnetic field, plasma minor radius (a_p), and plasma volume are 3.9 m, 0.975 m, 4 T, 0.65 m, and 30 m³, respectively. The material of the super-conductor is NbTi, and the cooling systems are pool-boiling for helical coils and forced-flow for poloidal coils. Since the current density of the helical coils is as high as 53.3 A/mm² with the maximum experienced magnetic field strength of 9.6 T, the refrigeration with the super-fluid helium is required. LHD is expected to demonstrate the viability of the helical magnetic configuration extrapolatable to the fusion reactor. The major contributions to fusion technology area are seen in the superconductivity research and development. The necessary R & D programs, detailed design, and construction of parts are now in progress. The construction will be completed in 1997.

Keywords: Large Helical Device, Nuclear Fusion, Plasma Physics, Fusion Technology

1. Introduction

Large Helical Device (called LHD) is a superconducting heliotron type device, of which construction schedule is made as the 7 years project.¹⁻³ This year is the second year of the project, and we have started the construction of the lower cryostat, helical coil fabrication machine and one of the smallest poloidal coils. A Large Helical Device project is established to concentrate a major fusion activity of universities into only one and new institute, National Institute for Fusion Science in Japan, which belongs to the Ministry of Education, Science and Culture. The construction of LHD contributes a lot to the superconducting (SC) coil systems development. The new site is Toki City, Gifu Prefecture. The experiment will begin in 1997, April.

LHD has a magnetic configuration with medium magnetic rotational transform and strong shear, and is regarded to mark a principal milestone in the alternative magnetic fusion approach. Due to the physics understanding of toroidal currentless plasma, LHD is expected to demonstrate the potentiality of the helical configuration by attaining

Fig.1. Objective Parameter range of LHD.

advanced plasmas extrapolatable to the reactor regime. The objective parameter range is shown in Fig. 1 with the obtained parameter ranges of large tokamaks and existing helical devices. The construction of SC device is required to develop the steady state plasma operation.

The major missions of LHD are; (1) to study on transport for wide-ranged plasma parameters ($T(0) \lesssim 10$ keV, and $n \tau T = 2 \sim 10 \times 10^{19}$ keV/m³sec), (2) to produce a high beta value (β) of 5%, and (3) to attain a quasi-steady state operation.⁴⁻⁵ $T(0)$, n , τ , and β are central temperature, density, confinement time, and ratio of plasma energy versus magnetic pressure, respectively. The specifications of LHD are listed in Table 1. Expected

plasma performance of Fig. 1 is considered as a necessary step to extrapolate our future experimental results to the fusion reacting plasma conditions. The coil energy versus magnetic field strength of existing superconducting fusion devices are shown in Fig. 2. LHD will be the largest one. As is shown in Table 1, the experimental scenario is divided into two phases (I and II). In the phase I, magnetic field is limited at the maximum of 3 T. Hydrogen neutral beam is used for detailed physics experiment. In the phase II experiment, magnetic field is raised to the 4 T with super fluid He II and parameters will be improved. This construction scenario is effective to reduce the load of the engineering developments and budget program.

Table 1. Specifications of LHD.

	PHASE I	PHASE II
MAJOR RADIUS	3.9 m	←
COIL MINOR RADIUS	0.975 m	←
AVERAGED PLASMA RADIUS	0.5~0.65 m	←
PLASMA ASPECT RATIO	6~7	←
ℓ	2	←
m	10	←
$\gamma_c = m/2 \cdot a_c/R$ (PITCH PARAM.)	1.25	←
α (PITCH MODULATION FACTOR)	0.1	←
MAGNETIC FIELD		
CENTER	3 T	4 T
COIL SURFACE	7.2 T	9.6 T
HELICAL COIL CURRENT	5.85 MA	7.8 MA
COIL CURRENT DENSITY	40 A/mm ²	53.3 A/mm ²
NUMBER OF LAYER	3	←
LHe TEMPERATURE	4.4 K	1.8 K
POLOIDAL COIL CURRENT	STEADY	REAL TIME
INNER VERTICAL	5.0 MA	←
INNER SHAPING	-4.5 MA	←
OUTER VERTICAL	-4.5 MA	←
LHe TEMPERATURE	4.5 K	4.5 K
PLASMA VOLUME	20~30 m ³	←
ROTATIONAL TRANSFORM		
CENTER	< 0.5	←
BOUNDARY	~1	←
HELICAL RIPPLE AT SURFACE	0.2	←
PLASMA DURATION	10 sec	←
REPETITION TIME	5 min	←
HEATING POWER		
ECRH	10 MW	←
NBI	15 MW	20 MW
ICRF	3 MW	9 MW
STEADY	-----	3 MW
D ^o → D ⁺	-----	PRACTICE
NEUTRON YIELD	-----	2.4X10 ¹⁷ n/shot
COIL ENERGY	0.9 GJ	1.6 GJ
REFRIGERATION POWER	5~7 kW	10~15 kW

In phase II experiment, the magnetic field is raised up to B=4 T, and heating power is also increased. In addition, we apply the real time vertical coil current control for the high β experiment. The maximum field changing rate in time is 0.04 T/sec for helical coil and 0.5 T/sec for poloidal coil. These values are 10 times smaller than those of the same sized tokamak device. In the phase II experiment, the maximum shot number of D-D plasma production per year is supposed 1,000 and total neutron irradiation estimated is 2.4×10^{17} n/shot. Reacting plasma experiments

with tritium is not included in this project.

Since LHD is a physics experimental device, design efforts have been concentrated on the optimization of machine parameters self-consistently satisfying the physics requirements and engineering constraints.^{7,8} There are four major physics criteria for the LHD designing tasks, i.e.,

- (1) r_{Lc} (the inner most minor radius where loss cone of the high energy particle exists) $\geq 1/3a_p$
- (2) η_n (heating efficiency) $\geq 70\%$
- (3) $\beta \geq 5\%$

Fig.2. The Magnetic Field Strength and Stored Energy of the Existing Superconducting Fusion Experimental Device.

Fig.3. Results of Physics Optimization.
m: Pitch number of Helical Coil
 γ_c : Pitch Parameter ($=m/2 \cdot a_c/R_c$)

(4) $w_d \geq 3\text{cm}$ (distance between plasma boundary and first wall)

The results is shown in Fig. 3. There are three limiting lines i.e., stability and equilibrium β (3), and available distance between plasma and wall (4). These criterion requires several important engineering developments. Technically, careful attentions should have been paid to the current density of the coils, stress level of support structure, toughness of vacuum vessel, selection of plasma facing material, and fabrication scenario.

2. Engineering Aspects of LHD

The helical coil is designed using pool boiling type conductors with enough amount of Al and Cu as a stabilizer. The experienced magnetic field at the conductor is 7.2T (central field 3T, so called phase I) and 9.6T (4T, phase II). This is the major reason that the temperature of the coil is planned to decrease from 4.4K to 1.8K in the phase II experiment using super fluid He II. The coil is fully stabilized at the phase I experiment, and will be dynamically stabilized at the phase II experiment. The maximum overall current density is 53.3A/mm^2 . The poloidal coil is cooled by forced flow of supercritical helium. Both of a cable-in-conduit and a hollow type are under development now. Inlet and outlet temperatures of the coolant is 4.5K and 4.8K, respectively. Magnetomotive force of the three sets of poloidal coils (IV, IS, and OV) are 5.0MA, 4.5MA, and 4.5MA, respectively. To construct the superconducting coil system, developments of superconductor rated 30kA, electromagnetic force support among coils, good thermal insulation between coil vessel and plasma vacuum vessel etc., are necessary. At the new Toki site,

experimental building and equipments for applied superconductivity, cryogenics and vacuum technology have been completed last year and are made use of for the engineering R & D tests, in which the facilities of superconductivity test stand including 200l/h helium liquifier with supercritical helium generation capability, 1000 ton cryogenic mechanical test machine, 9T superconducting split coils with 75kA DC current supply for conductor development, and four superconducting R & D coils. The bird eye view of the new experimental room and facilities is shown in Fig. 4. The R & D subjects now under tests are summarized in Table 2.

Table 2. R & D Subjects.

TYPE	COOLING	SPECIFICATIONS
(1)HELICAL $\ell=2, m=16$	POOL	$R=0.3\text{m}$, $a_c=0.063\text{m}$ $B=2.0\text{T}$, $I=0.775\text{kA}$
(2)HELICAL $\ell=1, m=3$	POOL	$R=0.8\text{m}$, $a_c=0.2\text{m}$ $B=3.0\text{T}$, $I=8.93\text{kA}$
(3)HELICAL $\ell=1, m=4$	FORCED-FLOW	$R=0.9\text{m}$, $a_c=0.25\text{m}$ $B=2.77\text{T}$, $I=8.08\text{kA}$
(4)TWO DOUBLE PANCAKES	FORCED-FLOW	$R=0.82\text{m}$ $B=2.76\text{T}$, $I=25\text{kA}$
(5)S-SHAPED MODULE	POOL	$R=1.4\text{m}$ $B=7.5\text{T}$, $I=20\text{kA}$

3. Results of LHD Engineering Design

Since LHD is a total engineering system, from the engineering viewpoint, much attention has been integrated into the following issues;(1) superconducting helical coils, (2) superconducting poloidal coils, (3) vacuum vessel, (4) power supply and coil protection

circuit, (5) control system, (6) refrigeration system, (7) heating system, and (8) diagnostic system. A bird's-eye view of the main experimental building and the poloidal cross-section of LHD are shown in Fig. 5 and Fig. 6.

Outer diameter of LHD is ~ 13 m. The total weight is $\sim 1,500$ ton, of which helium cooled weight is 850 ton (helical coils: 140 ton, poloidal coils: 120 ton, and support structure: 590 ton).

Fig.4. Bird Eye View of the SC R & D Building.

Fig.5. A Bird's-Eye View of the Main Experimental Building.

Helical coils, poloidal coils and supporting structure are put together in the toroidal cryostat. A vacuum vessel with a dumbbell shape is installed between helical coils and plasmas. The complicated three dimensional shape is required to supply a sufficient room for the plasma boundary. The tightest place is located at toroidally inside portion along the helical coils. At least 5 cm is necessary for the adiabatic shielding. Super insulation and LN_2 shield are installed among this space. Since the deformation brought during cooling down phase is about 2 cm in major radius direction, we have designed adiabatic supporting pedestals which have a sliding structure. More than 40 ports are installed to the vacuum vessel, of which schematic drawing is shown in Fig. 6. The biggest one with a lozenge shape is located on the outer equatorial plane. The total value of the port area is $\sim 20\text{ m}^2$, which accounts for $\sim 10\%$ of the total chamber surface. The baking temperature of the vacuum vessel is about 100°C , and that of the inside carbon tile is 350°C . The expected heat flux is 1 kW/cm^2 for 5 sec and 30 MW heating power.

In Fig. 7, the poloidal cross-sections of the helical coil, coil can, LN_2 shield, and vacuum chamber are shown. After the detailed physics optimization, the shape of the vacuum chamber is made by a part of circle to get an enough room between the plasma boundary and the first wall. The current density of the coil package is an important parameter to improve the physics properties of LHD, especially to increase the boundary magnetic shear and to supply enough room between the coil and plasma. Therefore, as was explained, the current density is 40 A/mm^2 for 3 T operation (phase I, 4.4K), and is increased to 53.3 A/mm^2 for 4 T operation (phase II, 1.8K). These values are much larger than the value attained with the normal copper conductor. Since there are no dangers from the major current disruption, the AC loss, and repetitive mechanical fatigue problems, the helical steady device has an advantage to pursue the engineering design and to build up the practical construction scenario. Unlike a normal conducting coil device, LHD is also free from the thermal stress. Therefore, we could apply the stiff support structure concept to sustain a severe magnetic force exceeding several tens of thousand tons. To increase the dynamic range of the magnetic surface properties, the helical coils are divided into 3 layers, and independently connected to the power supply. Since a wide range of the helical coil pitch parameter γ_c of Fig. 3 from 1.1 to 1.4 is available by changing the coil current in

each layer, we may attain the various operation regime and magnetic parameters, i.e., well or hill, shift of axis, and high shear or low shear.

Fig.6. The Poloidal Cross-section of LHD.

Fig.7. The Cross-section of Helical Coils.

Fig.8. The Cross-section of the Newly Developed Conductor.

4. Conductor Development

The most urgent subject to be solved in a superconducting coil design is to develop a viable superconductor.^{9, 10} From the point of view of large magnetic force ($\sim 1,000$ ton/m) and torsional angle ($\text{Max} \sim 50^\circ / \text{m}$), NbTi conductor was selected as a base material. Since the maximum field of the conductor exceeds 9 T, specifications of the NbTi conductor required for LHD are close to the limiting criterion. We are developing several candidates of the conductor, in which aluminum is added for the improved stabilization. In Fig. 8 and Table 3, the cross-sections of the major candidates of conductors and the specifications are shown. The location and amount of aluminum, distribution of NbTi strands are different in each design. Since the resistivity of the each strand is zero, it is necessary to study on the uniformity of the current distribution between strands. We have investigated uniform distribution type, multi-layer distribution type, and transpose structure type. The stability property of conductors has been already confirmed, and no difference of the conductor capability due to the aluminum stabilizer location has been observed. The typical data obtained for the

Table 3. Specifications of Helical Conductor.

	KISO-4B	Design-M
Superconductor	NbTi	←
Nominal current	21 kA	←
Overall current density	58 A/mm ²	←
Size	19.0 mm X 19.0 mm	←
Surface treatment	Copper oxide	←
Critical current (8T*, 4.2K)	43 kA	38 kA
Critical current density of NbTi (8T*, 4.2K)	1100 A/mm ²	1070 A/mm ²
Number of strands	84	58
Diameter of strand	1.05 mm	1.22 mm
Cu/SC ratio in strand	0.9	1.0
Diameter of filament	28.5 μ m	25 μ m
Number of filaments	726	1213
Twist pitch of filament	20 mm	17.0 mm
Twist direction of filament	inner Right/Right outer Right/Left	Left for all layers
Twist pitch of cable	inner 232 mm outer 254 mm	127 mm for all layers
Twist direction	inner Right/Left outer Right/Right	Right for all layers
Cross section		
Total	361.0 mm ² (100%)	361.0 mm ² (100%)
Al	83.4 mm ² (23%)	83.0 mm ² (23%)
NbTi	38.9 mm ² (10%)	36.1 mm ² (10%)
Cu	216.9 mm ² (60%)	223.8 mm ² (62%)
PbSn	25.6 mm ² (7%)	18.1 mm ² (5%)

* Include the conductor self-field

critical current of helical coil conductor are shown in Fig. 9. Anisotropic current distribution has not been observed. The most important result of this conductor R & D is that we have confirmed that our design technique based on the existing empirical stability scaling of the pool-boiling conductor is sufficiently applicable. Feasibility research of the coil fabrication is investigated from three kinds of the practical R & D small model coils ($R \sim 1$ m, $B \sim 2$ T, $m = 3 \sim 4$). The necessary data base for the coil fabrication has been already obtained.

Fig.9. The Value of the Deformation of the Structural Shell and Top Half of the Helical Coil Casing.

Table 4. Construction Schedule of LHD.

	1990	1991	1992	1993	1994	1995	1996	1997
R & D								
Detailed Design Phase II								
Helical Coil								
Conductor								
Fabrication Machine								
Coil Casing								
Coil Fabrication								
Power Supply								
Poloidal Coil								
Inner Vertical								
Shaping Field								
Outer Vertical								
Power Supply								
Lower Cryostat								
Upper Cryostat								
Vacuum Chamber								
Fabrication by Welding								
LHe Refrigerator								
Control System								
Assembling								
Test								
Experiment								

Table.5 Contribution of LHD to Fusion Technology.

5. Mechanical Analyses of the Helical Coil

In helical systems, the error field due to a mechanical deformation of helical/poloidal coils is very dangerous for the magnetic field configuration. The deformation and the stress/strain of helical coils and support structures have been analyzed with a finite element method (FEM) code. The critical issues for designing support structure are to develop a reasonable structural design which ascertains the necessary and high accuracy of the helical coils ($\sim \pm 2$ mm), because the stress level and the degree of the deformation strongly depend on the structural design concept. In Fig. 10, the typical results with the FEM code are presented for the top half casing of the helical coils and the structural shell, where the averaged thicknesses of the helical coil casing and structural shell are 50 mm and 100 mm, respectively. Spatial restrictions by ports are taken into account of the calculation. The maximum stress appears on the inside surface of the helical coil casing and reached to ~ 35 kgr/mm². The stress level of the shell support is about 20 kgr/mm². These values are sufficiently accepted by the structural material of the stainless steel. The deformation of the helical coils and shell is suppressed within 2 mm, and this calculation gives the consistent supporting design.

6. Construction Schedule

Construction schedule from now is shown in Table 4. This year, we have started the constructions of inner vertical field coil, fabrication machine, and cryostat. It will be completed in 1993, and immediately after the completion, we start manufacturing the helical coils with it in Toki site. It takes one year and half. The vacuum vessel is assembled after the coil fabrication is completed. It takes about one year. The necessary technique is now being developed by the R & D model of the vacuum vessel, i.e., forming of stainless parts, assembling and welding.

7. Concluding

In this paper, we briefly summarized the objectives and present construction-status of LHD. The possible contributions of LHD to the fusion research are also expressed. These are simply summarized in Table 5. We wish that our activities contribute a lot to the developments of superconductivity.

Fig.10. The Typical Data Obtained for the Critical Current of the Helical Coil Conductor.

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