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DESIGN STATUS OF SUPERCONDUCTING LARGE HELICAL DEVICE

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ABSTRACT

Large Helical Device (LHD) is a superconducting heliotron/torsatron type device. The SC coil system is composed of ℓ = 2 helical coils and 3 sets of poloidal coils with a total stored magnetic energy of 1.63 GJ. The main machine parameters, m number, ℓ number, major radius, coil minor radius, magnetic field, plasma minor radius, and plasma volume are 10, 2, 3.9 m, 0.975 m, 4 T, 0.65 m, and 30 m^3, respectively. This is an alternative toroidal device which aims at producing plasmas extrapolatable to the reactor regime. The currentless steady operation is the final goal of our LHD program, and there is no danger from the major current disruptions. 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/mm^2 with the maximum experienced magnetic field strength of 9.6 T, the refrigeration with the super-fluid helium is required. LHD has a divertor to control the steady particle recycling and to improve the confinement potentiality. The vacuum vessel has a dumbbell shaped poloidal cross-section making it possible to install the closed divertor chamber. The necessary R&D programs and detailed design are now in progress, and we start the construction of LHD from the next year. The construction of LHD will be completed in 1997.

1. Introduction

A Large Helical Device (called LHD) project is a major fusion activity of joint universities in Japan belonging to the Ministry of Education, Science and Culture. National Institute for Fusion Science was newly established in 1989 to carry out (1) the Large Helical Device project. It is also responsible for (2) computer simulation science, (3) inter-universities collaboration, (4) international collaboration, and (5) education of young scientists. The Large Helical Device project is the major part of the new institute and takes on the responsibility of the plasma physics research and reactor technology development in Japan. The construction of LHD is planned with superconducting (SC) coil systems at new Toki site, Toki city, Gifu Prefecture during the coming 7 years. The experiment will begin in 1997, April. LHD has a heliotron/torsatron configuration, 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 attaining advanced plasmas extrapolatable to the reactor regime. Straightforwardly, the objective Q value is close to 0.1. The most strong impact of our project influencing to the tokamak approach is expected to be the demonstration of the predominance of the currentless and disruption-free features of steady plasmas. Therefore, the construction of SC device is required and the adequate divertor design is also required to develop the steady particle recycling control and to establish a scenario of confinement improvement due to the edge control.

The schematic drawing of LHD is shown in Fig. 1. LHD is a superconducting heliotron/torsatron type device. The SC coil system is composed of ℓ = 2 helical coils and 3 sets of poloidal coils with a stored energy of 1.63 GJ. Major radius and minor radius is 3.9 m and 0.975 m, respectively. The maximum magnetic field strength at the plasma center is 4 T. The plasma aspect ratio is 6, and pitch number is 10. The currentless steady operation is the most predominant feature of the LHD device in comparison with tokamaks. The strongly twisted shape of the plasma which is seen in Fig. 1, indicates a typical characteristic of the helical magnetic configuration effectively increasing the potentialities of the stability and confinement of toroidal plasmas. The material of the super-conductor is NbTi, and the cooling systems are pool-boiling for helical coils and forced-flow for poloidal coils. LHD has a divertor to control the steady particle recycling and to improve the confinement potentiality. The vacuum vessel has a dumbbell shaped poloidal cross-section making it possible to install the closed divertor chamber.

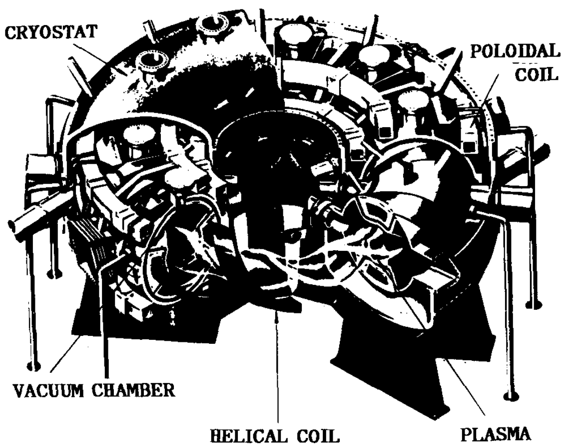

Fig. 1 Schematic Drawing of LHD

Design efforts have been concentrated on the optimization of machine parameters self-consistently satisfying the physics requirements and engineering constraints. It is physically required for LHD design to bringing out the good properties for confinement and MHD, and long confinement capability for high energy particles. The magnetic surfaces necessarily have enough distance between wall and plasma boundary, good mod-B structure, enough magnetic shear θ (up to $\sim$0.4), magnetic well (up to 1.5%) and large connection

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length of the magnetic field line for typical divertor field lines ($L \sim 3 \cdot 2\pi R$). Technically, the careful attention should be 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.

LHD has been designed for past four years by Design Group organized inter-universities in Japan [1,2,3] and was succeeded to the newly established National Institute for Fusion Science last year. The activity was accelerated by the new institute [4,5,6,7]. At present, necessary R & D program is in progress at new site. This paper deals with the engineering and technical aspects of LHD and related physics design considerations.

2. Specifications and General Design Characteristics of LHD

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/m^{3}sec), (2) to produce a high beta value of 5%, and (3) to attain a quasi-steady state operation using the helical divertor. Parameter regime of the LHD plasmas expected is shown in Fig. 2 using the $n\tau T$ and T coordinates. In this figure, the regime obtained by the present day large tokamaks is also shown. Since the target regime is close to the tokamak data points, the LHD experiment is expected to produce new data sets necessary to investigate currentless toroidal plasmas, which are not attainable by tokamak approach. It will contribute to develop a toroidal magnetic fusion research and is expected effective to establish a comprehensive and alternative way of tokamaks. The specifications of LHD are listed in Table 1. In Fig. 3, the coil stored energy and maximum magnetic field are shown for typical superconducting devices. The values of LHD are 1.63 GJ and 9.6 T, respectively. Since the conductor material is NbTi, the operation condition is beyond of the stability limit at 4.2K LHe. Therefore, to get a high current density of 53.3 A/mm^2 at 9.6 T, we decided to use super fluid helium cooling system. This decision requires more efforts on the research and development for completing the LHD engineering design. However, it is expected to add a new technical innovation to our technology development. As is shown in Table 1, the experimental scenario is divided into two phases (I and II). This scenario is effective to reduce the load of the engineering developments and budget program. The coil aspect-ratio was recently reduced from 4.17 to 4 to improve MHD features. The value of γ_c ($=m/2 \cdot a/R$) was increased from 1.20 to 1.25 with a small reduction of the major radius (R=4.0 m to 3.9 m). In this optimization, the plasma volume was kept almost constant. It is also found that the slight pitch modulation of helical coils ($\alpha = 0.1$) is desirable for providing a clear separatrix configuration outside of the outermost closed magnetic surface.

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 changing rate of the magnetic field 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 phase II of D-D plasma, the maximum shot per year is supposed 5,000 and total neutron irradiation estimated is 2.4×10^{17} n/shot. Reacting plasma experiments with tritium is not included in this project.

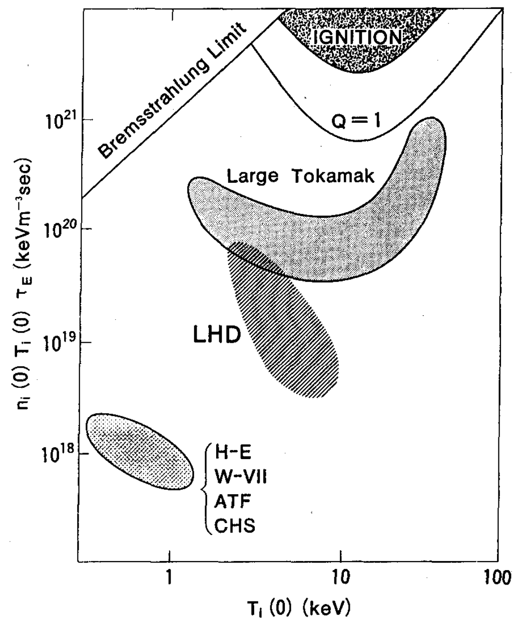


Fig. 2 Parameter Regime of the LHD Plasmas Expected

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	4.2 K	1.8 K
POLOIDAL COIL CURRENT	STEADY	REAL TIME
INNER VERTICAL	-4.3 MA	←
INNER SHAPING	-4.4 MA	←
OUTER VERTICAL	4.9 MA	←
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
$D^\circ \rightarrow D^+$	-----	PRACTICE
NEUTRON YIELD	-----	2.4×10^{17} n/shot
COIL ENERGY	0.9 GJ	1.6 GJ
REFRIGERATION POWER	5∼7 kW	10∼15 kW

From the engineering viewpoint, much attention has been integrated into the following issues;(1) superconducting helical coils, (2) superconducting poloidal coils, (3) vacuum vessel with divertor, (4) power supply and coil protection circuit, (5) control system, (6) refrigeration system, (7) heating system, and (8) diagnostic system. In this paper, we report the results of these technical developments except (7) and (8). A bird's-eye view of the main experimental building and the poloidal cross-section of LHD are shown in Fig.

4(a) and (b). Outer diameter of LHD is ~13 m. The total weight is ~1,500 ton, of which helium cooled weight is 850 ton (helical coils: 140 ton, poloidal coils: 120 ton, and support structure:590 ton). 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 closed divertor operation.

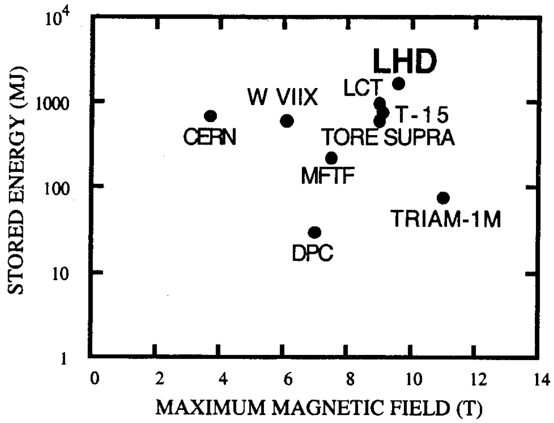


Fig. 3 Coil Stored Energy and Maximum Magnetic Field of LHD and Existing SC Devices

The radial-build is shown in Fig. 5. Between plasma and helical coil, coil casing (45 mm), super-insulation, thermal insulation gap (50 mm), LN_2 shield, vacuum chamber (15 mm), first wall (40 mm), and divertor area are installed in high spatial resolution. The tightest place locates 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 80 ports are installed to the vacuum vessel. The biggest one with a lozenge shape is located on the outer equatorial plane. The total value of the port area is ~20 m^2, which accounts for ~10% of the total chamber surface. The baking temperature of the vacuum vessel is about 100℃, and that of the divertor carbon tile is 350℃. The expected heat flux on the divertor plate is 1 kW/cm^2 for 5 sec and 30 MW heating power. This criterion is thought to compose an engineering R & D experiment for the tokamak engineering reactor program. The cooling water pipes of the vacuum vessel are fabricated to the inner surface (plasma side) keeping the feasibility for the necessary maintenance, because the damage due to runaway burst is suppressed at a sufficiently low level in SC helical system.

The current density of the coil package is an important parameter to improve the physics properties of LHD, especially to increase the boundary shear and to supply enough room for divertor. The current density is 40 A/mm^2 for 3 T operation (phase Ⅰ, 4.2K), 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. The material of the superconductor is NbTi and cooling systems are pool-boiling for helical coils and forced-flow cooling for poloidal coils. 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 γ_c from 1.1 to 1.4 is available by changing the coil current in each layer, we may attain the various operation regime, i.e., well or hill, shift of axis, and high shear or low shear.

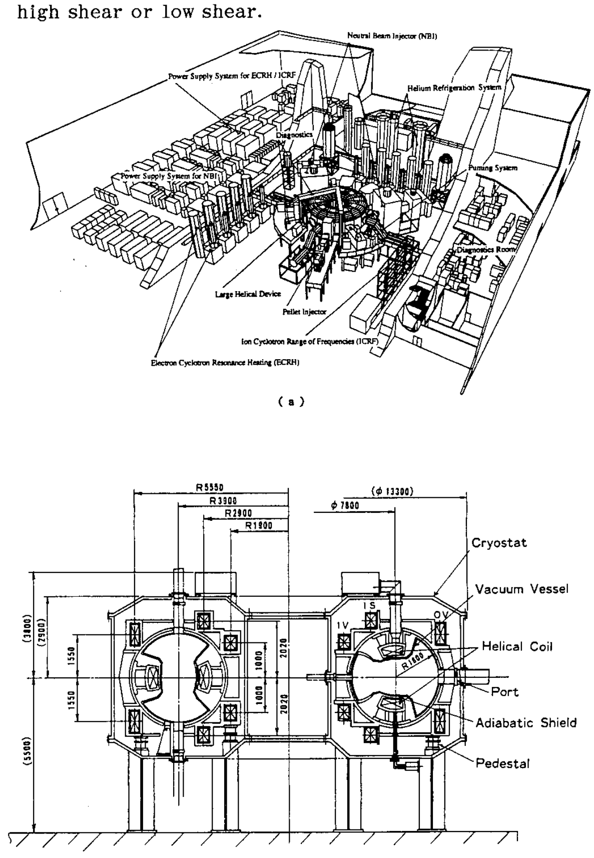


Fig. 4 (a) A Bird's-Eye View of the Main Experimental Building, (b) The Poloidal Cross-section of LHD

The size of the main experimental room is ^{w}45m×^{l}75m×^{h}40m. To shield the neutrons of phase Ⅱ experiments, the required thicknesses of the wall and roof are 2 m and 1.3 m, respectively. All of the cables, pipes, and beam lines of the experimental room are guided into underground room and re-arranged in the common pit to reduce the neutron streaming. Around the main experimental room, power supplies of coils and heating system, refrigeration systems, cooling water system, diagnostic system, and control system are rationally distributed. The total area of the building is $\sim$20,000 m^2.

Construction schedule from now is shown in Table 2. Next year, we start the constructions of inner vertical field coil, fabrication machine, and cryostat. Fabrication machine is shown in Fig. 6. It will be completed in 1993, and immediately after the completion, we start to manufacture 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 technical preparation is now being developed by the R & D model of the vacuum vessel.

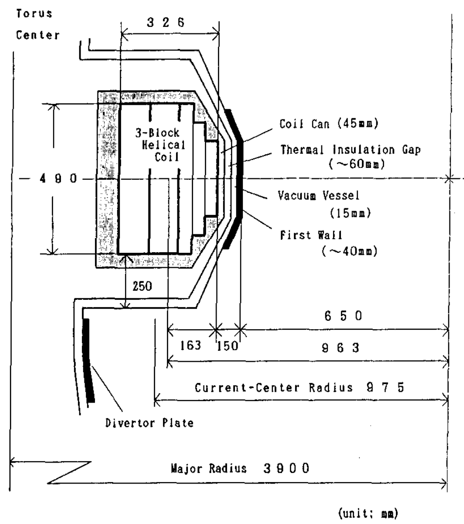
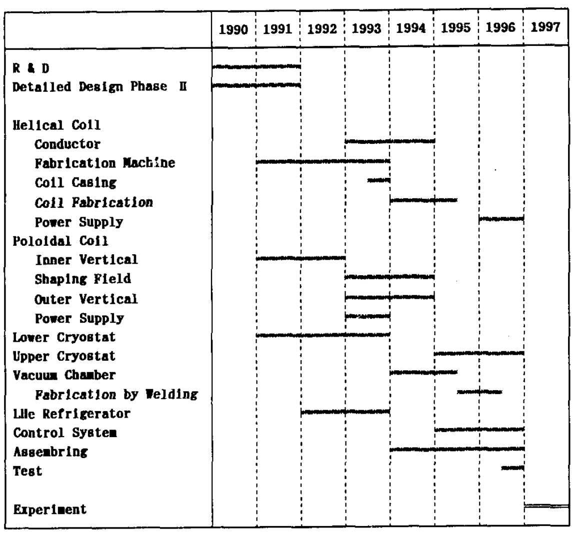


Fig. 5 Schematic Drawing of Radial-Build

Table 2 Construction Schedule of LHD



3. Conductor Development of the Helical Coil

The most urgent subject to be solved in a superconducting coil design is to develop a viable superconductor. From the point of view of large magnetic force ($\sim$1,000 ton/m) and torsional angle (Max$\sim$50°/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. 7, two types of cross-sections of the newly developed conductors are shown. Specifications of each conductor are shown in the figure. One is 30 kA class conductor, which has transpose structure type. Another is 20 kA class conductor, which has multi-layer distribution type. The overall current density is both $\sim$55 A/mm^2 which satisfies the design condition. The diameter of strand is 1$\sim$1.5 mm and Cu/SC ratio in strand is 1.0. In Fig. 8, the characteristic load curve is shown for 30 kA class conductor. The critical current of conductor is 55 kA for 4.2 K and 70 kA for 1.8 K. This figure shows that our design is close to the full stability limit of the pool boiling type NbTi conductor. 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. Therefore, 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. 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)[8]. The necessary data base for the coil fabrication has been already obtained.

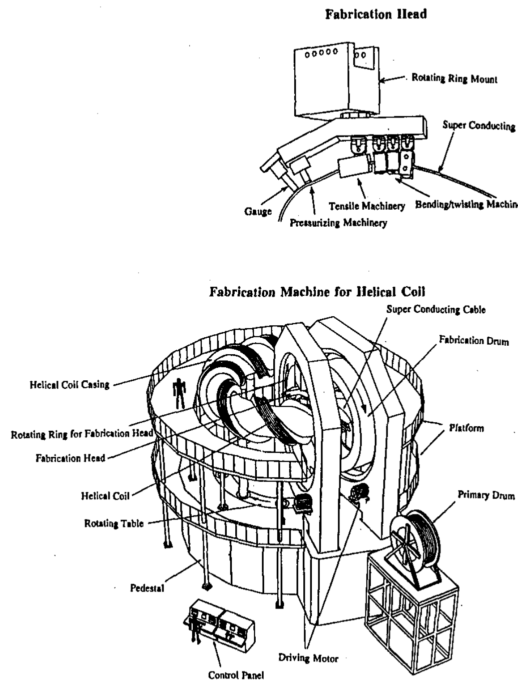
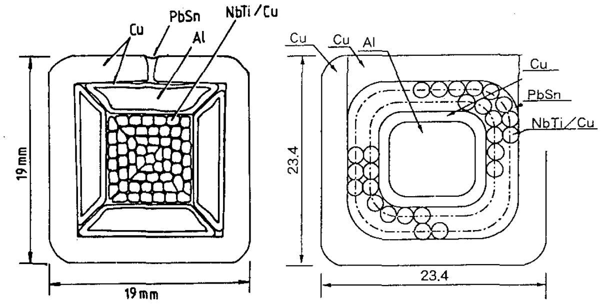


Fig. 6 A Bird's-Eye View of Fabrication Machine and Fabrication Head



NOMINAL CURRENT	20 kA	NOMINAL CURRENT	30 kA
CRITICAL CURRENT(8T,4.2K)	34.7 kA	CRITICAL CURRENT(8T,4.2K)	60.0 kA
OVERALL CURRENT DENSITY	55.4 A/mm^2	OVERALL CURRENT DENSITY	55 A/mm^2
SIZE	19.0 X 19.0 mm X mm	SIZE	23.4 X 23.4 mm X mm
NUMBER OF STRAND	58	NUMBER OF STRAND	80
DIAMETER OF STRAND	1.22 mm	DIAMETER OF STRAND	1.5 mm
Cu/SC RATIO IN STRAND	1.0	Cu/SC RATIO IN STRAND	1.0
Al CROSS SECTION	83.0 mm^2	Al CROSS SECTION	105.2 mm^2

Fig. 7 Cross-sections of Newly Developed Conductor

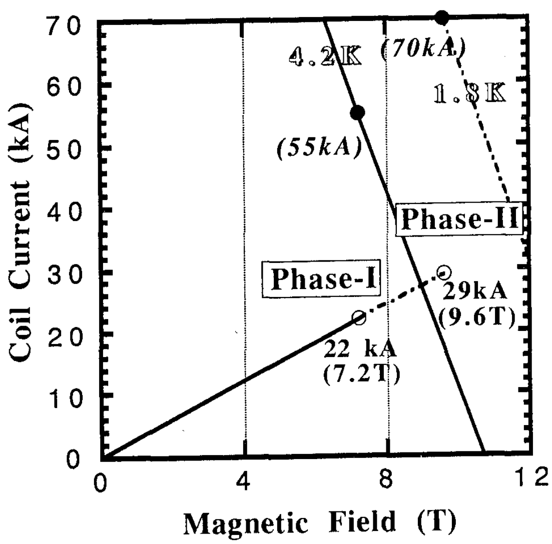


Fig. 8 Characteristics of Helical Coil Conductor

4. Mechanical Analyses of the Helical Coil and Vacuum Vessel

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 idea. In Fig. 9, 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/mm^2. The stress level of the shell support is about 20 kgr/mm^2. 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.

As described previously, one of the critical issues of the vacuum vessel design is that the gap between helical coil and plasma is limited, especially on the inboard side of the torus. The distance between the helical coil and first wall including coil casing must be less than 15 cm to take the enough distance between the first wall and plasma and to avoid the severe plasma wall interaction. This means that an accurate fabrication and assembly of the vessel ($\sim\pm 5$ mm) are required. We have considered two types of loading on the vessel, atmospheric and magnetic ones. The latter is produced when the poloidal fields are changed in time or bootstrap current disappears in a short period. The FEM was also adopted to evaluate the stress level and deformation of the vacuum vessel.

The most severe stress due to the atmospheric force appears near the largest port on the equatorial plane. It is close to the value of 15 kgr/mm^2. The magnetic loading appears when a large eddy current is induced by a sudden d'op of the induced plasma current. The design criterion is based on the condition to withstand the magnetic loading due to 150 kA/1 msec current disruption. In the high $n\tau T$ plasma production, in which the bootstrap current becomes maximum and is flowing in the direction to increase the vacuum rotational transform angle, the direction of the magnetic force is outward which is the same as the atmospheric force. It is concluded from the FEM analysis that the thickness of 15 mm is sufficient for the vacuum vessel to satisfy the design criterion and this is close to the limiting thickness for fabricating the vacuum vessel reliably after completing the helical coil fabrication.

5. R & D Programs

Necessary R & D programs for developing SC helical device have been already started from 3 years ago. They are listed in Table 3. To increase the cost performance of the research programs, R & D items are separated and developed individually according to major subjects. Device (1) is the first superconducting helical coil being planned to find out the engineering requirements for developing SC helical coil system. We have already completed the necessary tests. The maximum current obtained was close to the critical current of the NbTi conductor. For machine fabrication and stability test, (2) and (3) were made and now we are preparing to start the cooling down test. One is pool boiling type, and another is CIC forced-flow cooling type. Soon, the investigations on the necessary developing items related with stability, magnetic force analysis, quench test etc. will start. Since the size of these devices are $\sim 1/4$ of LHD and magnetic field strength is $\sim 1/2$, the prototype of coil fabrication machine was designed and used in the practical fabrication. The required technology development to weld the coil casing without large deformation was also attained. Since the magnetic force on (2) and (3) is smaller than the real value, we made the device (5) to explore the stress analysis and to accumulate the necessary data for the optimization of the insulation material, gap structure, and conductor toughness, etc. To develop forced-flow type poloidal coil, the device (4) was build. The CIC cable was developed and used to fabricate proto-type R & D device of the poloidal coils.

The first building in Toki site is planned for SC development, and will be completed in October, 1990. Necessary equipments, stress analysis device (1000 ton), 75 kA power supply, 200 ℓ/hr LHe refrigerator etc. are now ready for pursuing the final goal of our SC R & D program.

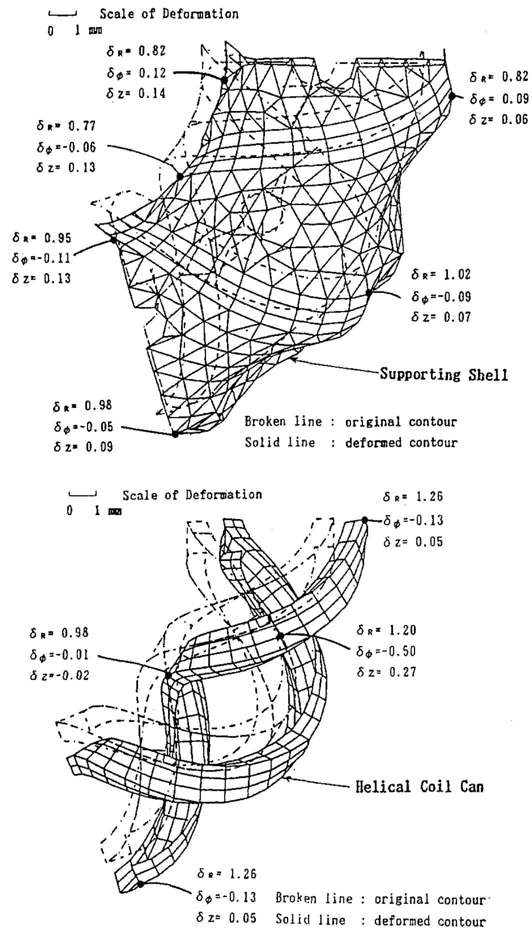


Fig. 9 Deformation of the Structural Shell and Top Half of the Helical Coil Casing

Table 3 R & D Devices

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

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