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Design and construction of the LHD plasma vacuum vessel

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Abstract

In the reactor design, many components are installed in a narrow space between the superconducting coil and the plasma. In the large helical device (LHD) configuration, the plasma axis is shifted inwards relative to the centre of the two pairing helical coils, and so the space available for thermal insulation, the vacuum vessel, cooling pipes and the first wall is very narrow. The LHD plasma vacuum vessel maintains good vacuum conditions, removes heat from the plasma, and protects superconducting coils from the plasma heat. The vessel is designed to have enough rigidness for stress deformation. In the construction, to facilitate assembly with the helical coils which were completed earlier, the vacuum vessel was fabricated in sections of many small segments. Design and construction of the LHD plasma vacuum vessel is described. These technologies are also quite important to reactor design.

1. Introduction

The plasma vacuum vessel is one of the main components of the large helical device (LHD). Successful heat removal on the divertor plates is one of the important conditions for production of high quality plasmas [1,2]. From the point of view of reactor design, the installation of many components in the narrow space between the superconducting coil and the plasma is one of the key technologies [3]. In the LHD, the plasma vacuum vessel with components such as cooling pipes, the first wall, and the thermal shield is located in this narrow space.

In the LHD project, steady state operation is one of the major objectives [4,5]. For this objective, the plasma vacuum vessel maintains good vacuum conditions, removes heat from the plasma, and protects superconducting coils from the plasma heat. The construction of the vessel has been started, and many segments are patched together by welding to form a dumb-bell shaped cross section of the vacuum vessel.

2. Plasma vacuum vessel

2.1. Size and shape

Fig. 1 shows the shape of the LHD plasma vacuum vessel with the ports. The vacuum vessel, which is made of 15 mm thick stainless steel, has major radii of 3900 mm and minor radii of 1600 mm. As a result of the two grooves (each about

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1000 mm wide) provided for the helical coils, the vacuum vessel has a dumb-bell-shaped cross-section. The groove width of the large major radius side of the torus is larger (1156 mm) for the spacing of helical coil leads. There are five types of ports, with the total number being 40. The shape has been designed by using a CAD system. The vacuum vessel is designed to have enough rigidness. The vessel is made of 15 mm thick stainless steel.

2.2. Five types of ports

The plasma vacuum vessel has five types of ports: upper ports, lower ports, inner ports, outer ports, and tangential (NBI) ports. Ports and flanges will be assembled before leak testing. Their size and use are as follows.

(a) Upper and lower ports (1060×1730 mm) are used for cooling water feeds, ion cyclotron resonant frequency (ICRF) and electron cyclotron heating, gas puffing, far-infrared interferometer, etc.

(b) Outer horizontal ports (2000 mm diam) and inner horizontal ports (700×480 mm) are used for ICRF heating, LID, Thomson scattering, heavy-ion beam probes, spectroscopy, and other diagnostics.

(c) Tangential ports (940 mm diam) are used for neutral beam injection and diagnostics. The NBI heat load on the vessel wall and plasma heating efficiency have been considered in determining a NBI tangential angle of 41° and a tangential radius of 3700 mm. The inner surfaces of the ports are covered with armour tiles for protection against the divertor plasma heat.

2.3. Structural analysis

The vacuum vessel has been designed with structural analysis by finite element method (FEM). To confirm the integrity of the vacuum vessel, the stress and deformation of the vacuum vessel were evaluated by a finite element method analysis. A calculation code ANSYS Revision 5.0A was used. The stress will be that allowable for the candidate material stainless steel (SUS316L). Fig. 2 shows the analysis model of the LHD plasma vacuum vessel with ports. Since most of the vacuum vessel is symmetrically shaped, a 1/10 sector model is used for the analysis. The vacuum vessel is fixed by the supporting legs and bellows.

The vacuum vessel is designed to have enough rigidness against both inner and outer atmospheric pressure. Also it is required to have

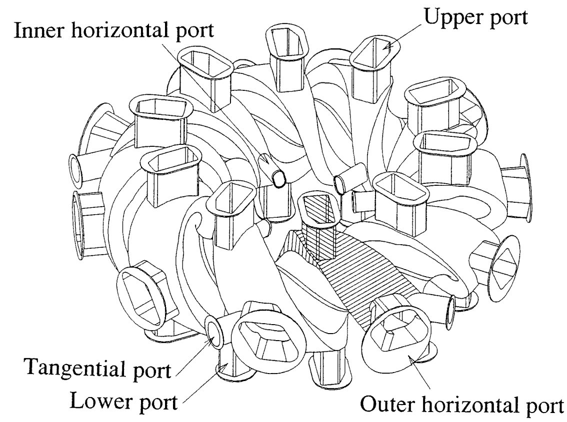


Fig. 1. Plasma vacuum vessel with five types of ports.

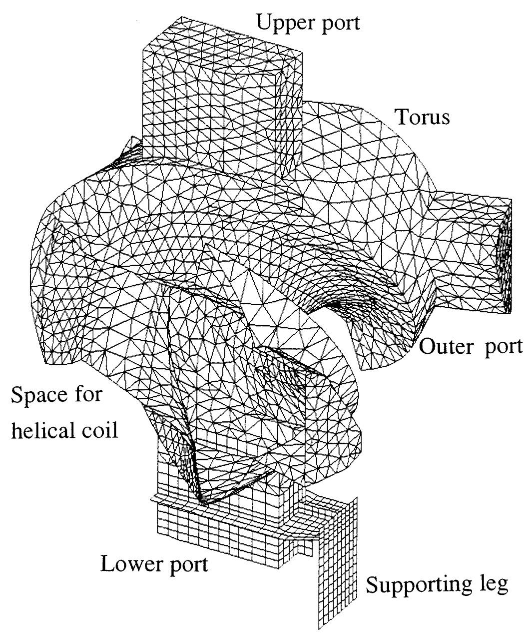
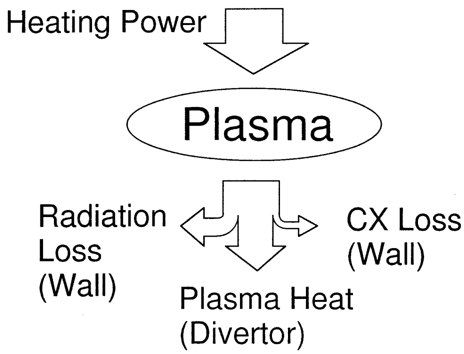


Fig. 2. The analytical model of the LHD plasma vacuum vessel with ports and supporting leg.



Heating Power	ECH	10 MW	(10s)
		3 MW	(cw)
	NBI	20 MW	(10s)
	ICRF	9 MW	(10s)

			Total
Max. Heat load on the Divertor Plates	5 MW/m^2	(10s)	20 MW
	10 MW/m^2	(5s)	>30 MW
	0.75 MW/m^2	(cw)	3 MW
Max. Heat Load on the First Wall	0.2 MW/m^2	(10s)	20 MW
	0.015 MW/m^2	(cw)	3 MW

Fig. 3. Heat loads on the plasma vacuum vessel.

enough rigidness against thermal stress due to causing baking and plasma radiation.

Under baking, when the temperature changes from 293 to 373 K, the maximum displacement (6 mm) appears at the outer port. Most of this displacement is symmetrical. The maximum stress (69.6 MPa) is found at the joint of the port and the torus. It is less than the allowable value. Enough rigidness of the vacuum vessel against both inner and outer atmospheric pressure (maximum stress of 58.5 MPa), and thermal stress due to baking and plasma radiation was confirmed.

3. Radial build between coil and plasma

3.1. Heat flux in the vacuum vessel

Fig. 3 shows the heating power and maximum heat load on the divertor plates and the first wall for several scenarios. The total area of the vacuum vessel is 428 m^2 (torus shape: 101 m^2, side plates for HC space: 99 m^2, bottom plates for HC space: 100 m^2, and ports: 128 m^2). The total area of the divertor plates is 32 m^2 (0.16 $\times$ 200 m). The production of steady-state plasmas with duration >3600 s and a total input power Q of 3 MW is planned for LHD. It is assumed that half of this power will eventually be carried to the divertor plates by the particle flux, while the other half will be carried to the wall of the vacuum vessel by radiation from the plasma [6].Thus, the vacuum vesselis designed to remove heat from the plasma and to protect the superconducting coils, in addition to providing good vacuum conditions. This total heat flux in the vacuum vessel is 1.5 MW (1.5 W cm^{-2} on the vessel wall at the radial build). For the case of pulse operation (20 MW, 10 s, 5 min interval operation), the maximum total heat flux is equivalent to 666 kW at steady state operation. Thus, the heat flux on the vessel wall is 333 kW (0.3 W cm^{-2} on the vessel wall).

3.2. Radial build between superconducting coil and plasma

In the LHD configuration, the plasma axis is shifted inwards relative to the centre of the two pairing helical coils. Thus, the distance between the coil centre and the edge plasma is as small as 328 mm on the small major radius side of the torus. Within this narrow space, many components must be installed such as the super conducting helical coil, its coil can, the thermal shield, the vacuum gap, the vacuum vessel, and the first wall as shown in Fig. 4. Effective edge plasma control by the divertor requires a space >15 mm between the plasma and the first wall.

3.3. First wall and cooling system

The temperature of the vacuum vessel must be <343 K to limit the temperature of the thermal shielding plates, which are located on the coil side of the vacuum vessel, to 80 K. The wall cooling system of the plasma vacuum vessel is located in the narrow space (<25 mm) between the plasma and the vessel on the small major radius side of the torus (radial build).

Fig. 5 shows the radial build. The water feeds for wall cooling, which are located on the plasma side of the vacuum vessel, have a U-shaped cross

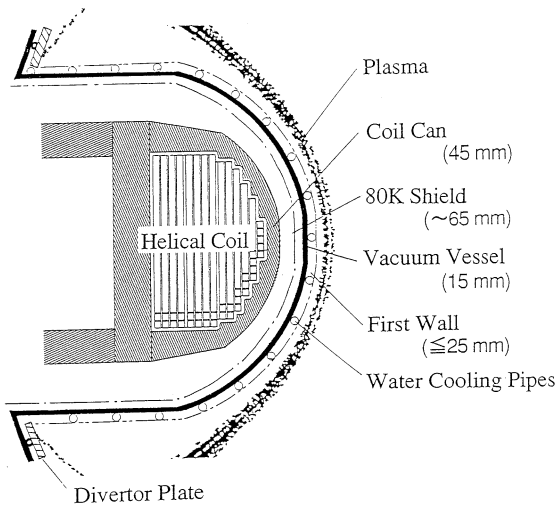


Fig. 4. Radial build between helical coil and vacuum vessel.

section (10 × 28 mm, 2 mm thick stainless steel) and are welded to the vacuum vessel wall. The water pass intervals are 80 mm on the small major radius side of the torus, and 200–250 mm on other parts. The first wall is made of 10 mm thick stainless steel plate which is covered by 0.5 mm thick copper plate on one side. The size of the plates depends on the part, the largest one is

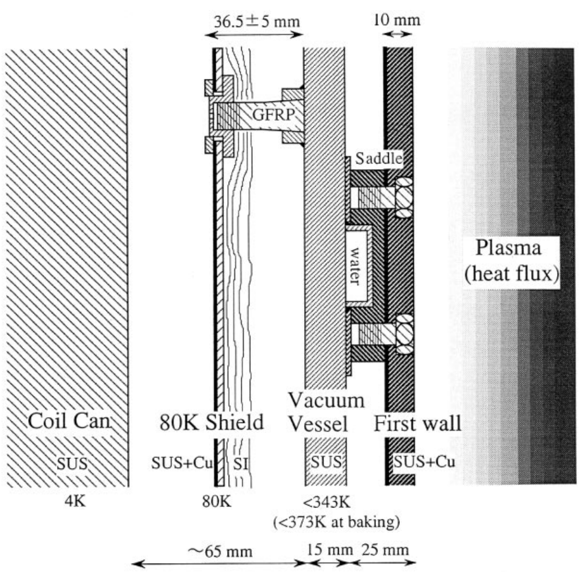


Fig. 5. Components between the coil can and the plasma in the radial build.

Table 1
Number of segments without ports

Part of vessel	Total	Full sector	Half sector
Torus shape	60	6	15
Side plates for HC space	240	24	(3+12)
Bottom plates for HC space	120	12	6
Total	420	42	21

about 250 × 400 mm. The plates are mechanically fixed to the water pass by using a saddle on the vessel wall and bolts.

3.4. Thermal insulation for superconducting coils

The thermal shield for the superconducting coil has been located on the coil side of the vacuum vessel. These plates are made of stainless steel and are supported from the vacuum vessel with 5180 glass-fibre-reinforced plastic (GFRP) legs. Total heat from the vacuum vessel to the shield plate is 6 kW when the vacuum vessel is 343 K. The thermal shielding plate is cooled under 80 K by helium gas using cooling pipes on the shielding plate. The vacuum vessel temperature is required to be < 343 K to keep the shield temperature low. On the small major radius side of the torus (radial build), the thermal shielding system is located in the narrow space (< 38.5 mm) between the helical coil and the vacuum vessel.

4. Construction of the vacuum vessel

4.1. Patched together into a helical shape

To form a complete shape of the vacuum vessel, many segments (each about 1 × 1 m) are prepared by press forming, and patched together by welding. Table 1 shows the number of segments. To facilitate assembly with the helical coils, which were completed earlier, the vacuum vessel was fabricated in two different kinds of sections: half-sector units (torus parts and side plates for HC space), corresponding to the spherical ends of the

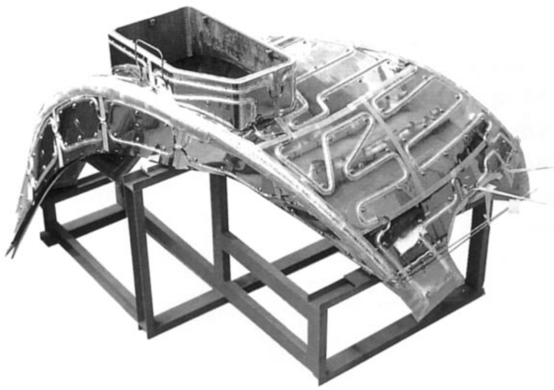


Fig. 6. Half sector unit of torus shape and side plates for helical coil space. The surface is covered by a 80 K shield plate and pipes for helium gas.

dumb-bell, and under-coil sections (bottom plates for HC space), corresponding to the grip of the dumb-bell.

4.2. Construction and common differences

The 20 half-sector units, each covered with 80 K thermal shielding plates as shown in Fig. 6 (also shown in the hatched part of Fig. 1), were assembled and installed between the helical coils. They were supported by a winding case that also fixed the position of the helical coils. This assembly of helical coils, half-sector units, and winding core (see Fig. 7) was then placed on the supporting structure and welded to it.

Common differences of the setting on the winding core and after-welded horizontal torus parts were 5 and 7 mm, respectively. After the winding core was removed, the under-coil sections of the vacuum vessel were installed. The common differences will be larger after welding of the under-coil sections. The final common difference of the plasma vacuum vessel is taken to be < 15 mm at the port centre. Flanges with small ports are set up to the cryostat with a common difference of < 2 mm.

5. Conclusion

The LHD plasma vacuum vessel is designed, which maintains good vacuum conditions, removes heat from the plasma, and protects superconducting coils from the plasma heat. The construction of the vacuum vessel has been started, and many small segments are patched together by welding to form the complete vessel shape. The space between the coil and the plasma is very narrow. Many components such as cooling

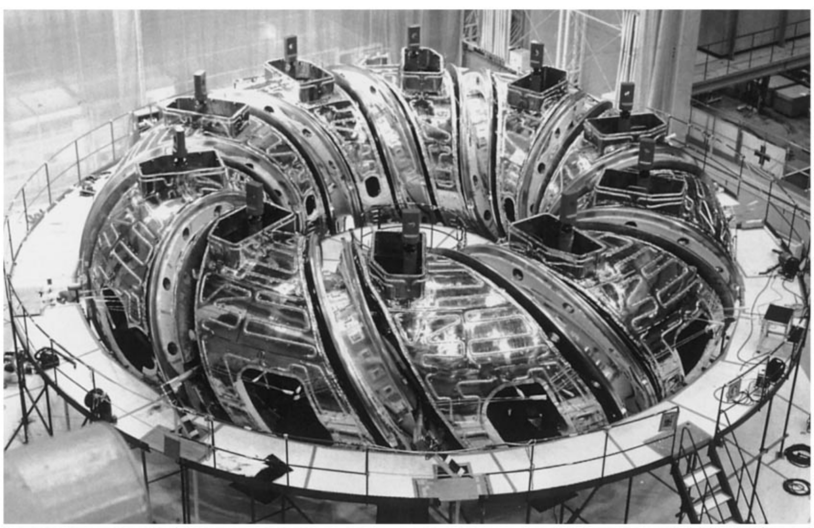


Fig. 7. Construction of the plasma vacuum vessel. Twenty half sector units of the vacuum vessel are installed between the helical coils on the winding core.

pipes, first wall, and thermal shield will be installed. These technologies are also quite important to reactor design.

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