Conceptual Design of Plasma Vacuum Vessel for Fusion DEMO Considering Integration of Core Components*)

Arata NISHIMURA[1,2)]

[1)]*National Institute for Fusion Science, Toki 509-5292, Japan*
[2)]*Technical Institute of Physics and Chemistry, China*

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A fusion DEMO will be designed as a long-term D-T reaction machine, and it will provide electricity to the grid. The core components of the fusion DEMO such as superconducting TF coils and vacuum vessel sectors become larger and heavier than those of ITER. The difficulties of manufacturing and handling increase significantly. Therefore, the conceptual design of the plasma vacuum vessel and its leg are carried out based on the consideration of assembly and disassembly processes of the core components. When the global density of the device is assumed to be same as the ITER, the total weight of the fusion DEMO would be about 77,500 tons and one TF coil weigh wound be about 1,200 tons. To carry out the easy works for assembling and disassembling, demountable superconducting TF coils are proposed which will be made of high temperature superconducting tapes so that the enough workspace can be secured. The weld joint of the vacuum vessel with a double wall structure is investigated, and the support leg is designed considering the three-dimensional displacement and the integration processes.

Keywords: fusion DEMO, vacuum vessel, support leg, demountable TF coil, assembly and disassembly processes

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1. Introduction

ITER project [1] is undergoing in France under the collaboration of 7 countries and pole, and it is expected that D-T reaction generates 10 times more energy than the input energy. Beyond the ITER, a commercial scale fusion reactor (DEMO) will be constructed and supply electricity to the grid. Since the fusion energy has high expectations for achieving a carbon-neutral society, the design activity for the fusion DEMO has been promoted in the world. To carry out a practical design of the fusion DEMO, the boundary conditions for the conceptual design must be clarified, and the assembly and disassembly processes must be considered from an engineering viewpoint in parallel with performing the physical design of plasma confinement. The manufacturing drawings of each component would be completed with the consideration of the integration process.

In this paper, the scale of the fusion DEMO will be discussed, and then the conceptual image of the vacuum vessel (VV) will be presented. After that, the assembly and disassembly processes of the core components, which are mainly VV sectors and TF coils, will be illustrated. The application of high temperature superconducting materials will be pointed out, and a new concept of a demountable (divided) TF coil will be discussed.

2. Scale of Fusion DEMO

Japan and EU have a collaborative program named "ITER Broad Approach" and are carrying out the fusion DEMO design [2,3]. Table 1 summarizes the main parameters of JA and EU DEMOs together with the ITER. The major radii of JA and EU DEMOs are about 1.37 and 1.45 times larger than that of the ITER, and the fusion output increases 3 or 4 times. Therefore, when the fusion DEMO size is supposed to be 1.5 times larger than the ITER and the global density is the same as the ITER, the total weight of the fusion DEMO will become around 77,500 tons by considering the 23,000 tons of the ITER [4]. In case that the fusion DEMO has 16 TF coils and 8 VV sectors, the weight of one TF coil and one VV sector will become around 1,200 tons and 1,700 tons, respectively.

From above discussion, it is recognized that the TF coil for the fusion DEMO will be 13.5 m high and 9 m wide, and the outboard will be located about 16 m from the center of the DEMO. The component is very large and

Table 1 Comparison of parameters for ITER, JA and EU DEMOs.

	ITER	JA DEMO	EU DEMO
Major radius (m)	6.2	8.5	9.0
Magnetic field on axis (T)	5.3	5.94	5.9
Fusion output (GW)	0.5	1.46	2.0
Plasma current (MA)	15.0	12.3	18.0

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author's e-mail: nishimura.arata@toki-fs.jp

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very heavy, and it is not easy to turn over the superconducting (SC) TF coil and to carry out the heat treatment for Nb_3Sn generation at 873 K for 200 hours. A high temperature superconducting (HTS) tapes are strong candidates for the TF coils instead of Nb_3Sn [5,6]. It will bring the merits of the high operation temperature, the high current density and the easy SC connection. Moreover, it has a potential to realize the demountable SC coil system.

In this paper, 16 TF coils and 8 diverter ports are assumed virtually to discuss the conceptual design of VV assembly for a fusion DEMO.

3. Plasma Vacuum Vessel

The assembly of the VV sectors is shown in Fig. 1. ECH ports and vertical and horizontal ports for maintenance and instrumentation are ignored in the figure. One vertical NBI port and one tangential NBI port are assumed. Since the large ports break the axis symmetric mechanical balance, the movement and deformation of the VV during the baking or under the earthquake must be evaluated precisely.

One sector has one diverter port and one VV leg is attached to the bottom of the diverter port. The VV leg will support the weight of the VV and internal components such as diverter cassettes and blanket modules. The weight of the coolant for the diverters and blankets must be added to the design load together with neutron absorber plates installed between walls. Also, the attention will be paid for the gap between the TF coil and the VV, because the TF coil will shrink about 60 mm during cool down and the VV will expand about 50 mm when the 200 C baking is carried out, in case that the outer radius of the VV and the outboard position of the TF coil are located about 15 m from the center. If there is not enough gap, the thermal shield (TS) on the VV touches the TF coil. This is a serious risk.

The VV has a double wall structure, and the cooling water flows in the space between walls from the bottom to the top of the VV to capture the fusion neutrons. The image of the weld joints between VV sectors is shown in Fig. 2 which is a modification of the figure in [4]. Since the VV is a nuclear boundary, a volumetric non-destructive test (NDT) must be carried out for all weld joints. As the workspace is limited, a phased array ultrasonic testing is a candidate method for the NDT. Most of the welding can be performed only from the plasma side, the wider splice plate is designed for the inside wall joint. Inconsistencies between the plates to be welded can be corrected with these splice plates. In addition, the butt joint between the splice plates is necessary, and the NDT of the T-shape joint is considerably difficult. So, the preliminary investigation is required. Also, the super insulation on the TS must be protected from the welding arc using the backing plate. It should be noticed that all welding positions are required to perform the construction of the VV.

A design of the VV leg is show in Fig. 3. The original concept was established in Large Helical Device project in 1990 s [7]. Since the leg was designed for the support of SC helical coils made of NbTi, the long thermal conductive path from room temperature to 4.5 K was considered.

The VV leg for the fusion DEMO must support the heavy dead weight of the VV and have ability to deform in the major radius direction, because the VV expands when the baking at 200 C is carried out. Moreover, the

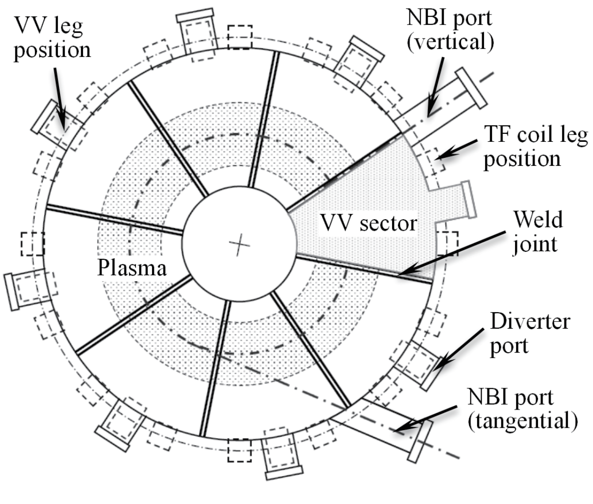


Fig. 1 Top view of VV assembly.

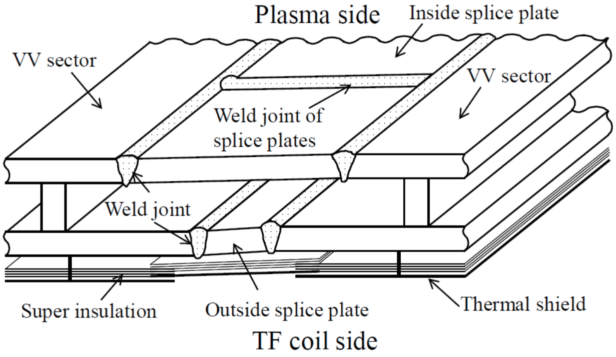


Fig. 2 Image of weld joints between VV sectors [4].

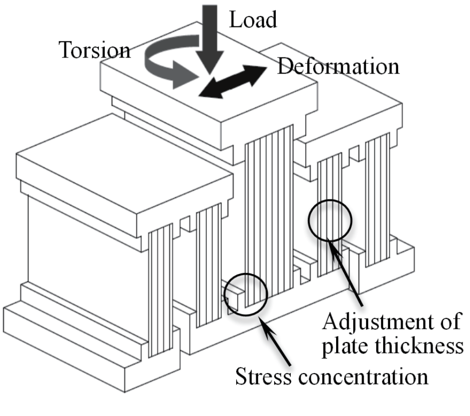


Fig. 3 Design of VV leg.

VV leg is twisted slightly because of the unbalance of the VV weight, the non-uniform temperature change during the baking and the earthquake and so on. The assembly scenario described below is created based on self-standing of the VV sector by the VV leg. So, the leg must support parts of the VV sector during the assembly of core components.

By adopting three-step plate spring structure, the height becomes lower and more compact than a simple plate spring structure. As shown in Fig. 3, some stress concentration might occur at the corner of the bundling fixture of the spring plates. Also, the spring plate thickness is confirmed by analyzing the stiffness of the VV leg.

There are eight VV legs and the torus must be on a plane. In order to achieve and keep the flat plane, the precise measurement system for positioning is required, and it must work periodically. Special and great care must be taken for the measurement, such as keeping the room temperature constant throughout the year. The building where the fusion DEMO is installed is very large and the air conditioning equipment should be on and working all the time.

4. Consideration of Assembly Process

The assembly and disassembly processes of the core components are investigated. Figures 4 and 5 illustrate the top view and the cross-sectional image of the assembly process. These figures are modifications of those in [4]. As mentioned above, it was supposed that one TF coil and one VV sector weigh about 1,200 and 1,700 tons, respectively. The size in length is 1.5 times larger than the components of the ITER. They are very heavy and large.

At first, consider the case that one VV sector with the thermal shield (TS) is installed in the planned position in the TF coils. This is one process that the VV sector would be cut into a lot of parts, and they would be brought in the torus space and welded. In this case, it is easy to suppose that it takes a long time to manufacture it including the volumetric NDT. So, it is better to bring in larger size parts and reduce the welding at the field. Also, the blanket modules are expected to be replaced periodically in a scheduled time and all replacement works of the activated items must be performed securely and perfectly with remote handling. So, the wide workspace is preferred for the work. In addition, when the fusion DEMO is disassembled after the D-T operation, all components including the VV and the TF coils are activated heavily. All disassemble works will also be implemented by remote handing, it needs wide space. If the enough space is provided, the work will be completed in the shortest possible time and the radiation exposure can be reduced.

If the TF coil should be divided and connected with the SC joints, the wider workspace can be provided. A demountable (divided) SC TF coil will be a good idea in order to realize those works. ARC project which is running at Plasma and Fusion Science Center in MIT and Commonwealth Fusion Systems already opened the concept of the demountable SC magnet, and a SC joint with a large cross-section has been discussed [8, 9]. A TF model coil for SPARC which is pre-ARC project was fabricated with YBCO tapes and achieved over 20 T successfully in September 2021 [10]. Since it is expected that the SC joint technology of HTS conductor would be advanced more in several years, the demountable SC TF coil is applied here in order to produce a wider space for the installation, the maintenance of the blanket modules and the removal of the VV and the TF coils. In addition, the TF coil is a DC coil and AC losses are expected to be lower.

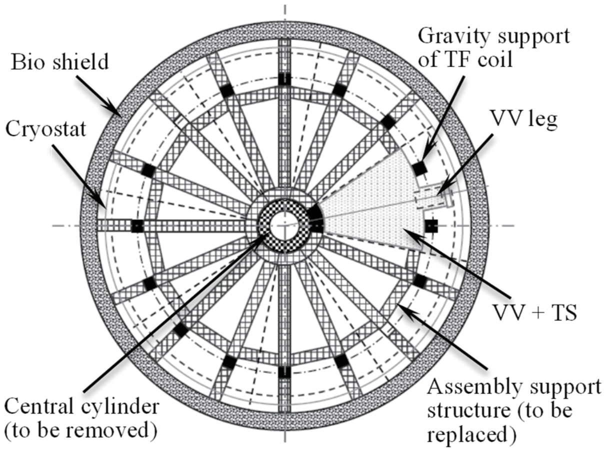


Fig. 4 Top view of core structure assembly [4].

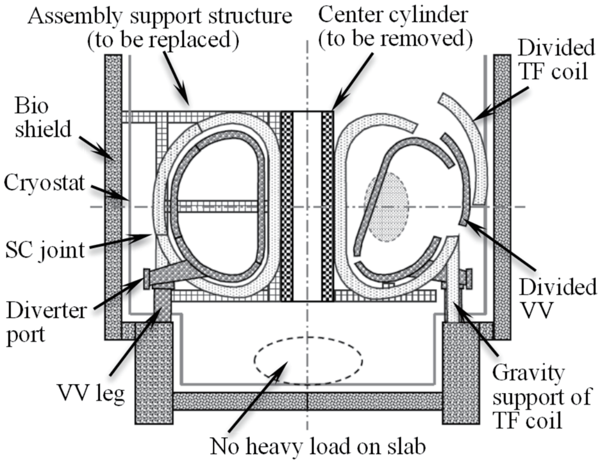
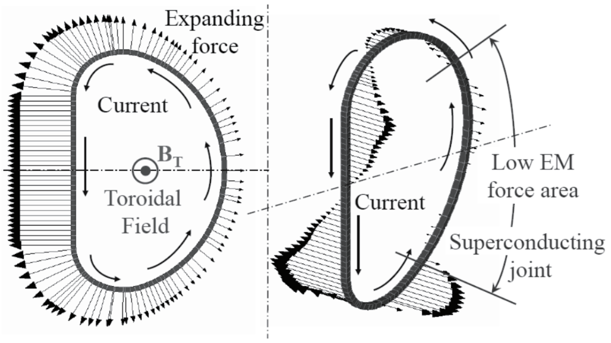


Fig. 5 Cross-sectional view of core structure assembly.

The electro-magnetic (EM) force on the ITER TF coil is shown in Fig. 6 [11]. (a) shows distribution of in-plane force. Expanding force in the outboard becomes smaller. (b) shows out-of-plane force distribution. The force in torus direction becomes opposite above and below the equator, and the EM force becomes smaller in the outboard. Since it is more advantageous for the SC joint to get a lower EM force, it is decided to place the SC joints in the outboard region. The location of the SC joint is shown in Fig. 5.



(a) In-plane force. (b) Out-of-plane force.

Fig. 6 Example of EM force on ITER TF coil.

The VV sector is divided into three parts, namely, the bottom part with the VV leg, the inboard part and the outboard part. The weight of each part is not clear here, but the total weight is supposed about 1,700 tons. Two lower TF coils are installed first and connected to the assembly support structure. Then the bottom part of the VV sector is lifted up and lowered and moved sideways and set at the planned location. It is supported by the assembly support structure and the VV leg. The inboard and outboard VV sector parts are installed and welded after temporary assembling. The welding process is already discussed in Fig. 2.

The same process is performed in sequence to complete the whole VV structure by replacing the assembly support structure with the TF coils and the VV parts. As explained before, the lower TF coil and the bottom part of the VV sector must stand by themselves. As the last stage, another divided TF coil is installed and connected with the lower TF coil using the SC joint technology.

When the blanket modules are replaced, TF coils will be separated, and the outboard VV sector part will be removed so that the wide space will be prepared for the replacement. The detailed structure of the VV sector parts will be conceptually designed in the future.

When the D-T operation is finished and the core structure is disassembled, the divided TF coil is separated first at the SC joints, and then the VV sector is cut into several parts which are taken out of the construction pit. By dividing into large size parts, the work time in the radiation environment can be shortened. These works are carried out using the remote handling.

It should be noted that the detailed design of each component is conducted based on the assembly and disassembly scenario described above, and it is supposed that each component design can be progressed gradually through the deep communications and discussions among all design teams.

5. Summary

The conceptual design of the VV and the VV leg for the fusion DEMO is carried out considering the assembly and disassembly processes of the core components mainly consist of the TF coils and the VV sectors. The main results are summarized as follows:

(1) The scale of the fusion DEMO was supposed to be about 1.5 times larger than the ITER, and the rough evaluation of the core component weight was presented. One TF coil weighs about 1,200 tons and one VV sector is about 1,700 tons. The outboard of the TF coil is located about 15 or 16 m from the center of the device.

(2) The conceptual VV design was illustrated with two NBI ports, and the welding joint of double wall structure including the splice plates joints was proposed taking account of the volumetric NDT. The VV leg with three-stage plate spring was presented based on the success of the Large Helical Device project. The height is low, and it is compact.

(3) The assembly and disassembly processes of the core components was discussed, and the demountable SC TF coil was considered to keep the wider workspace and reduce the time to implement the work. It is necessary to consider the disassemble process, because all components are activated with D-T neutrons.

(4) High temperature SC materials are strong candidates for the TF coils of the fusion DEMO. The further development of the practical technologies is anticipated to promote the fusion application.

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