Convergence of Design and Fabrication Methods for ITER Vacuum Vessel and In-vessel Components

K. Ioki and V. Chuyanov for the ITER International Team and Participant Teams

ITER International Team, Boltzmannstr. 2, 85748 Garching, Germany

e-mail contact of main author: iokik@itereu.de

Abstract. The design of the vacuum vessel (VV) and in-vessel components has progressed since 2001, and several design improvements are summarized in this paper. One of the most critical items is to select the fabrication methods for the VV and to achieve the required tolerances. The fabrication methods have been studied and the VV R&D has been performed to demonstrate the achievable fabrication tolerances. Recently, new R&D has been started in order to fabricate full-scale partial VV models with blanket support housings and keys to establish the fabrication methods and to confirm the achievable tolerances.

1. Introduction

The VV design and additional R&D has progressed in several aspects considering component reliability, maintainability and fabrication costs [1]. The preparation of the procurement specifications for long lead-time items is underway [2], and design documentation has been revised.

2. Design Progress and Selection of Design Solutions

2.1 Vacuum Vessel

Selection of design solutions for the VV and ports has been made, as described in the following.

(a) Nine lower ports

- The current design of the ITER VV has 9 lower ports instead of 18.
- The fabrication cost of all the ports was nearly comparable to that of the main vessel.
- Nine ports located at the sector-sector field joints have been removed, and the remaining 9 ports toroidally centred in each 40° sector can be joined to the main vessel in the factory. This can reduce the work time in the pit.
- Three of these 9 ports are used for divertor cassette maintenance, 4 of them for the pumping as well as pellet injection and the other two for diagnostics (see *FIG. 1-3*).

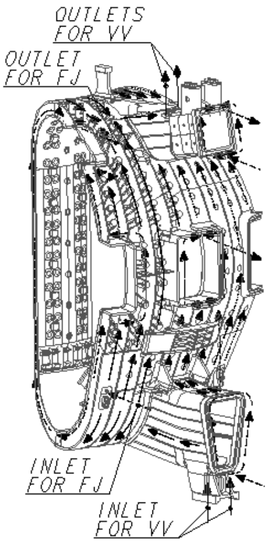

FIG. 1 ITER 2004 Vacuum Vessel

FIG. 2 Lower port and penetrations

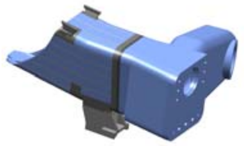

FIG. 3 Cryopump port (Two cryopumps)

(b) Independent cooling configuration in the VV field joint regions (see *FIG. 1*)

- After field joint welding between sectors in the pit, the inter-space in the field joint region can be independently evacuated and leak-tested in this concept.
- Since the surface area of the in-wall shielding is ~7 times larger than that of the VV shells, the total surface area of the whole inter-space volume is very large.
- The total number of the inlet/outlet pipes is increased.

(c) Single-wall port structure at the upper and equatorial levels (see *FIG. 4)*

- A single-wall structure has been introduced for the upper ports and equatorial ports except for the NB ports.
- The single wall structure is not actively cooled and located at the transition between the port structure cooled by the VV cooling system and that by the blanket cooling system.
- These ports have an in-port component ("port plug").
- This concept makes the port plug design simpler and the replacement of a port plug easier because now only one cooling system is used for a port plug.

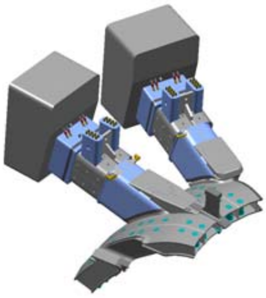

FIG. 4 Upper Port Structure

(d) Vacuum vessel gravity support located below lower ports

- The VV gravity support is now located below the 9 lower ports and supported on the lower ring pedestal of the cryostat.
- The access to the support for assembly and maintenance is improved (see *FIG. 5)*.
- A pot-type sliding bearing supports the downward loads allowing not only horizontal movements but also rotation around a horizontal axis.

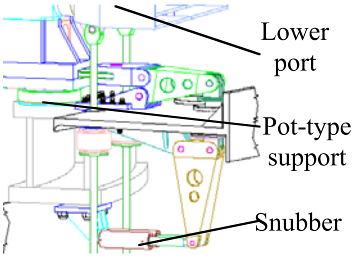

FIG. 5 Radial/vertical support

(e) Double-curvature shells in the upper and lower inboard regions

- A double curvature pressing method is now selected instead of a facetted weled structure for the inner and outer shells in the upper and lower inboard.
- This selection improves the fabrication and NDT process. Very short distances between neighbouring welds can be avoided. The cost impact is to be assessed in the future.

2.2 First Wall and Blanket

(a) Central support leg for first wall panel

- The blanket module consists of first wall (FW) panels and a shield block, as shown in *FIG. 6*. FW panels are supported with a central support leg (CSL) (see *FIG. 7)*.
- Selection of a race-track cross-section for the CSL provides a more robust structure against EM loads due to the halo current.
- The highest halo current per FW panel is 50 kA, and detailed structural analysis shows an 8-10 mm thick weld gives enough margin.
- The cutting and re-welding is remotely done in the hot cell, and YAG laser welding and cutting is selected as the reference method.

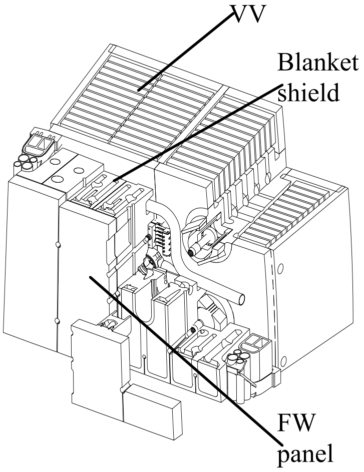

FIG. 6 Outboard blanket module

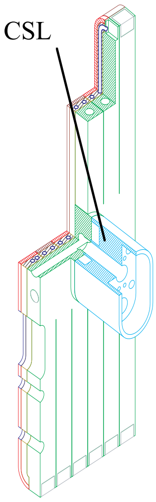

FIG. 7 FW Panel

- The heat input due to YAG laser welding is small, and the welding distortion of the CSL is minimized and the rewelding limit after neutron irradiation is higher.
- The selection leads to a new cooling configuration in the shield block.

(b) Plasma-facing surface to avoid the leading edge problem

- The inboard plasma-facing surface of the FW has been redefined to avoid protruding leading edges, as shown in *FIG. 8*.
- The surface is no longer flat in the overall geometry, but each beryllium tile is flat. The maximum step due to the fabrication and assembly tolerances is assumed to be 2 mm.
- The fabrication method of the newly designed FW is to be assessed.

(c) New coolant flow configuration in the shield block

- In the previous cooling configuration, the pressure drop inside the shield block was relatively high. A new coolant configuration has been selected to reduce significantly the pressure drop down to ~0.05 MPa.
- In this configuration, the pressure drop in poloidal collectors is reduced by using a special shape of flow driver inserted in the co-axial radial cooling channels.

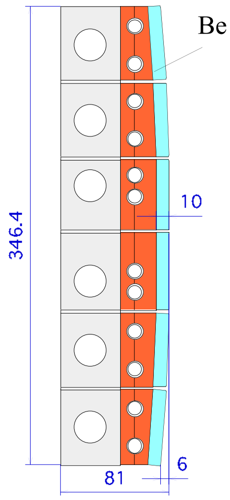

Fig 8 FW panel

- The gap between the drilled radial hole and the flow driver is optimized to be ~ 2mm, which gives a higher heat transfer coefficient to cool the shield block. More uniform flows will be provided in parallel channels even without orifice adjustments.
- Tests on a hydraulic model will be useful to verify analysis results.

(d) Shield block design to reduce the EM loads

- In the new cooling configuration, upper and lower slits in the radial direction are made deeper (see *FIG. 9)*.
- The EM loads during disruptions are mitigated by ~10 %.
- Detailed EM analysis has been performed by using a newly defined plasma current quench scenario (40 ms linear decay and 18 ms exponential decay).
- A higher water/structure ratio contributes to reducing the EM loads, and the payload for the blanket remote handling equipment.

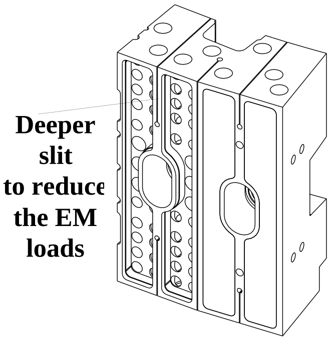

Fig 9 Shield Block

(e) Blanket module segmentation in the NB region

- The blanket module segmentation in the neutral beam (NB) region has been revised.
- Two module segmentation in the poloidal direction has been selected in the equatorial port region, which is the same as the general blanket segmentation (see 10).
- The front liners inside the NB port ducts are eliminated by covering with an extension of the blanket module.
- The diagnostic NB port opening has been made smaller (~ 200 mm diameter).

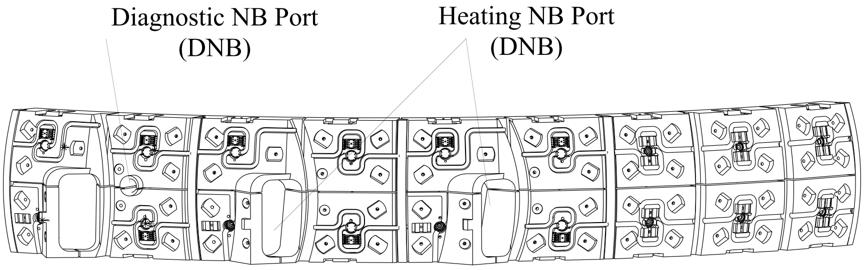

Fig. 10 Blanket Segmentation in the NB Region

3. VV Fabrication Method and Control of Tolerances

(a) Required VV Tolerances

The VV is required to have tight overall profile tolerances to be positioned inside the thermal shield and to provide mechanical structures on the inner shell for in-vessel components. One of the key R&D areas is the development of the vacuum vessel fabrication methods to achieve the required tolerances. Generally, the tolerance is approximately one shell thickness for a welded structure component. However, the tolerances of the ITER vacuum vessel sector are defined on the basis of the physics requirements and the space limitation. The fabrication and assembly/positioning tolerances for the ITER VV at the factory and at the site are summarized in Table 1. These numbers are challenging considering hat the shell thickness is 60 mm and the sector overall dimensions, 8 m wide x 13 m high. To achieve accurate dimensions, the following approaches are essential; (i) accurate rigid fixture, (ii) dimensional control at each step during the fabrication procedure, especially the length of the perimeter, (iii) development of welding methods with less deformation. These required tolerances are consistent with the experience of the full-scale sector model fabrication (L-3 project in the EDA R&D program), and feasibility of the tolerances was demonstrated for the 1998 ITER design. The current vessel design includes keys and support housings for the blanket modules and is more complex. New R&D has been launched (see (f) below) to confirm its feasibility and to select the fabrication methods. The total weld deformation is a combination of overall deformation and local deformations which can be enlarged due to more welds in the current design. However, most of additional welds can be performed by electron beam welding, which results in small distortion.

TABLE 1: VV FABRICATION AND ASSEMBLY/POSITIONING TOLERANCES

Parameter	Unit	Value
Fabrication tolerance of VV sector at factory		
- Sector overall height	mm	± 20
- Sector overall width	mm	± 20
- Surface deviations of a 40-degree sector from the reference geometry (both for the plasma- and cryostat-facing surfaces)	mm	± 10 (= *(1))
- Sector wall thickness (distance from inner to outer surface)	mm	± 5
Details		
*(1)Surface tolerances of a 40-degree sector from the reference geometry after fabrication at factory	mm	± 10
*(2)Vessel weld distortion due to field/shop welds at the site	mm	± 5
*(3)Torus positioning versus ideal location with all support fixtures removed	mm	± 3
*(4)Sector wall thickness (distance inner-outer - shell)	mm	± 5
*(5)Mismatch of the sector surfaces at field joints	mm	± 5
Assembly/positioning tolerances at site		
- Surface deviations of the torus from the reference geometry after assembly at the pit	mm	± 15 (= *(1)+*(2))
- Surface deviations of the torus from the reference tokamak geometry after positioning at the pit (Final deviations)	mm	± 18 (= *(1)+*(2)+*(3))

(b) Fabrication Procedure

One of important criteria for the vessel sector fabrication is that the inner shell should be welded in good quality (butt joint) and inspected from both sides. According to this criterion, the sector fabrication procedure has been proposed, and industry partners in the Participant Teams have also developed detailed procedures in the same line. Requirements of proper access for inspection to welds have strongly influenced the detailed vessel design and the fabrication procedure.

Conventional pressure vessel manufacturing techniques and procedures are applied to the VV. A basic fabrication sequence is: marking => cutting => forming => assembly => welding => inspection/testing => cleaning => packing => shipping => on-site inspection. To minimize the final assembly time on site, and to deliver a vessel structure with a high quality, the VV is to be fabricated in the factory as 9 sectors each spanning 40°. The port stub extensions on the lateral sides of the sector are not installed in the factory. This allows the TF coils to be installed in the assembly area. In the factory, three sets of three sectors manufactured in parallel are considered with several months of overlap between the sets. Therefore, some of the fixtures and jigs will be reused for the sector fabrication.

Two options have mainly been considered for the sector fabrication scheme. One is to complete the inner shell first because it forms the first confinement boundary. Butt weld joints can be fully applied to the inner shell and inspection can be easily performed. Next, all ribs and module support housings would be welded to the inner shell. After shields have been installed, the outer shell would be welded (with a one-sided weld and access from the rib side). Another concept is to utilize poloidal segments of a double wall structure, which are fabricated first and then welded together to form a sector). Butt weld joints are also fully applied to the plates that make up the inner shell. This scheme was employed for the full-scale vessel sector fabrication in the L-3 R&D project. In addition to the two schemes, an alternative scheme based on the mixture of the two schemes can be considered (Option 3 - see *FIG. 11*). Poloidal segments of the vessel without the outer shells are to be completed first. After the segments are welded together to form a poloidally closed shape, the outer shells will be welded.

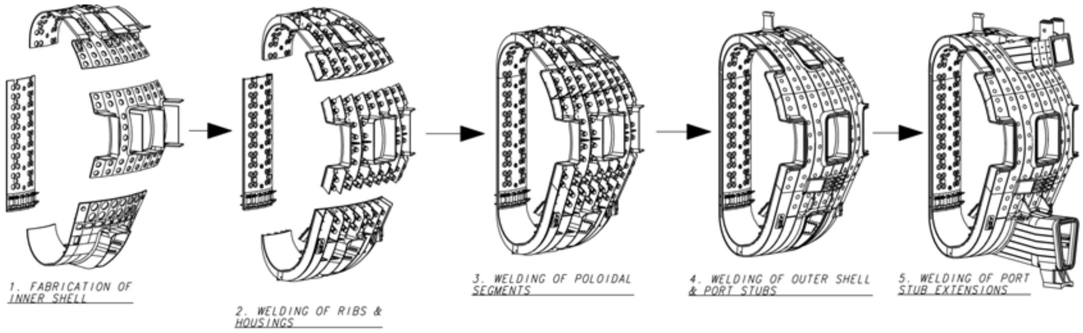

FIG. 11 Fabrication Procedure of a VV Sector (Option 3)

In the detailed VV fabrication procedure, the module support panel including four flanges for the flexible support housings and an inter-modular key would be manufactured first, and the panels welded to the inner shell. Recently, a direct welding of the housings/keys to the inner shell has been studied and seems feasible when EB-welding is utilized. The latter approach is preferable since less welding/machining is required (see *FIG. 12*).

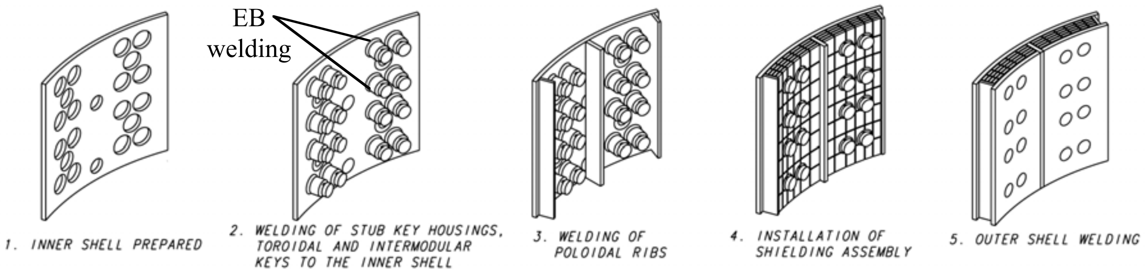

FIG. 12 Direct Welding of the Module Supports and Keys

The assembly sequence of VV sectors has been studied and it was proposed that the final welding be performed in parallel at 2 locations. The estimated residual stress due to the non-symmetric layout of the last welds is ~80MPa, which is acceptable. However, as shown in *FIG. 13*, a new sequence has been proposed to achieve a symmetric layout of the last welds. In this sequence, the final welding is performed in parallel at 3 locations between 120 degree sectors. This sequence has the advantage of reducing residual stresses and the global deformation will be smaller. After the sector fabrication is completed, the sectors are dimensionally checked. The machining of the splice plates and the removable part of the triangular support structure will be made based on measurement of the fabricated sectors. However, the final machining of the splice plates and the removable parts will be made after the installation of the sectors in the pit. To ensure a satisfactory manufacturing of the VV components, the fabrication (especially the assembly of the parts) will be conducted in a temperature-controlled environment. Reference temperature is 20°C ±5°C. In the assembly, the temperature of all parts shall be uniform within ±5°C.

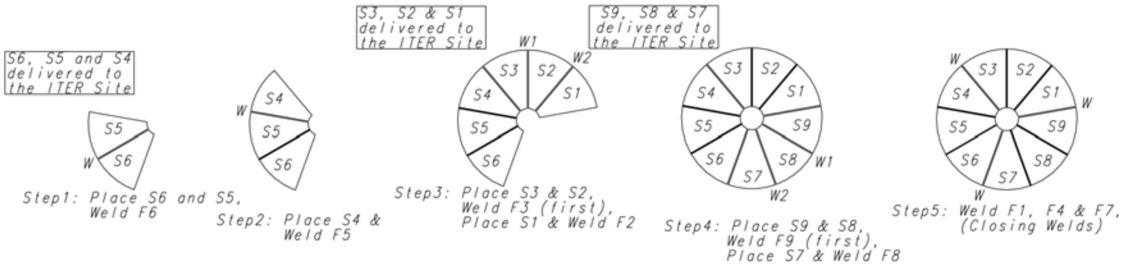

FIG. 13 Assembly Sequence of the VV Sectors in the Pit

(c) Welding Methods and Distortions

All conventional manual, automatic, and most advanced welding processes can be used for the VV. Tungsten inert gas welding (TIG) is the preferred conventional method to be used for the VV, and it is also recommended to use automatic narrow gap TIG (NG-TIG) welding at some locations including the splice plate field joints (see *FIG. 14*). Metal inert gas (MIG) welding, metal active gas (MAG) welding, and electron beam (EB) welding are also considered as ways to increase the welding productivity, as long as the requirements of the accepted code or standard are satisfied. Initiation and stopping points of all welded passes and weld layers can be staggered to balance the welding distortion. To decrease the deformation, EB-welding is used as much as possible (see *FIG. 12 and 15*).

Welded subassemblies of the VV components can be subjected to a dimensional stability heat treatment if necessary. In this case, the heat treatment will be performed in a non-oxidizing, non-carbonizing neutral atmosphere. The subassemblies will be heat treated prior to the final machining. Post-forming or post-weld heat treatment is normally not required for the fabrication of SS 316 L(N) stainless steel vessels.

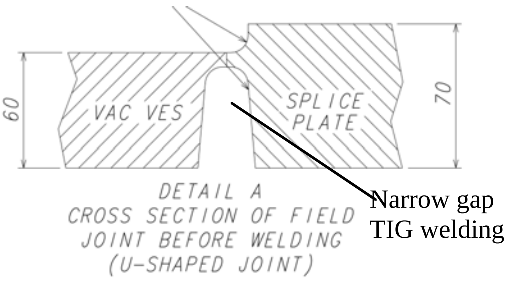

FIG. 14 NG-TIG welding at VV field joint

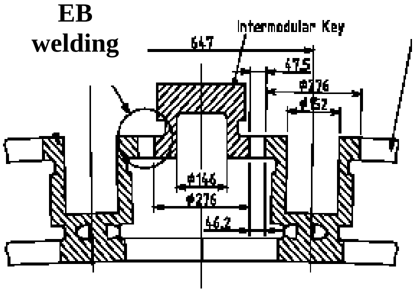

FIG. 15 EB welding on the VV inner shell

(d) Development of Non Destructive Examination Methods for Welds

Most weld joints have conventional configurations and are to be radiographically inspected to assure 100% weld efficiency. They are easily code/standard qualified. However, the one-sided weld joints between the outer shell and the ribs/housings and the field joints cannot be radiographically inspected and will be inspected by UT (ultrasonic testing). In this case, a reduced joint efficiency may need to be considered. R&D is being carried out on UT inspection on one-sided 60 mm thick plate in the inner and outer shell configuration. Considering the limited access, the use of waves launched at an angle of 20 or 30 degree as well as 45 and 60 degree has been tested, as shown in *FIG. 16*. Regarding the surface inspection of welds, the applicability of LPT (liquid penetrant dye test) during the initial assembly phase has been assessed, and it is proposed to select suitable liquid penetrant with very low impurities (sulfur and halogen) and a limited amount of high temperature vaporization components. As a possible alternative to LPT, a photothermal camera method has been developed and tested. In inspections carried out on weldment surfaces from narrow gap TIG in 60 mm stainless steel, the photothermal camera is generally more sensitive and reliable than LPT and better discriminates linear (>1.6 mm) and rounded (>4 mm) flaws [1,3].

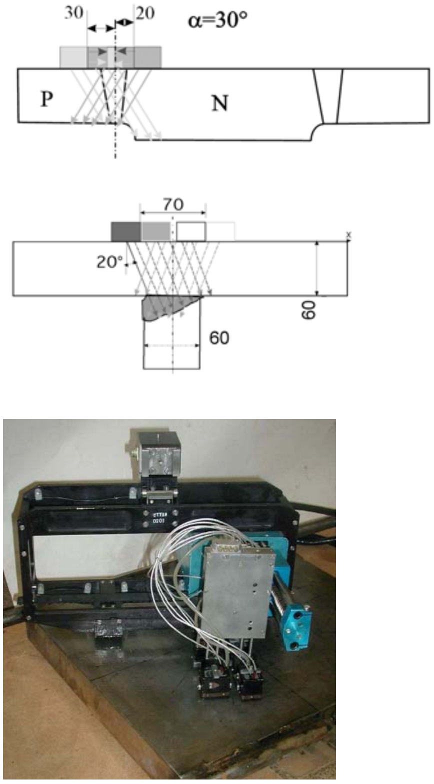

FIG. 16 Ultrasonic testing of small angle waves

(e) Fixtures and Jigs to Control Tolerances

During fabrication at the factory and shipment of the VV, special fixtures and jigs will be required to support sector and port/stub extensions and to connect sector/port-stub-extensions. The sector and port/stub extension support fixtures are used to prevent deformations during transport and welding of the field joint at site. The sector/port-stub-extension connecting fixture is used to connect a sector and port stub extensions and maintains their relative positions during the joint welding. Welding and inspecting machines used for the field joints will be mounted on the rails that are positioned along the joint.

(f) R&D of Fabrication of Full-scale Partial VV Mock-ups

Since the basic design of the ITER VV is similar to the sector fabricated during the EDA, the fabrication of the full-scale sector model has also confirmed the fundamental feasibility of the present ITER double wall design [4]. The achieved tolerances in this R&D are summarized in Table 2. The assembly and field joint welding required for the sectors remains the same. Recently the fabrication of full-scale partial VV sector models including the attachments of the blanket modules are now going on in the EUPT [5] and JAPT to confirm the fabrication methods and achievable tolerances.

TABLE 2: ACHIEVED VV SECTOR TOLERANCES IN L3 PROJECT R&D

Individual Poloidal Segments	± 3 mm
Overall Sector Height	± 5 mm
Overall Sector Width	± 5 mm
Machined Edge of Field Joint	± 3 mm

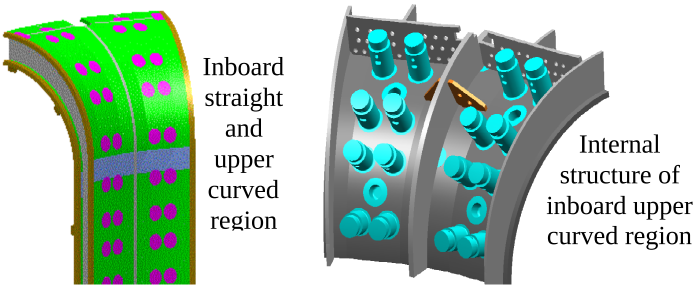

FIG. 16 Full-scale partial model to be fabricated and tested

4. Conclusions

Based on interactive work between design activities and R&D programs, most of the ITER VV and in-vessel component designs are converging by joint efforts of the International Team and Participant Teams. Additional R&D on full-scale VV partial models are now on-going and to be completed before the start of ITER construction.

5. Acknowledgments

Contributions by the all Participant Teams are greatly appreciated. Especially, the authors are grateful to Dr. L. Jones, EUPT, Dr. M. Nakahira, JAPT, and Dr. V. Krylov, RFPT for their intensive efforts on the VV design and R&D activities.

References

[1] IOKI, K., et al., Design Improvements and R&D Achievements for Vacuum Vessel and In-vessel Components Towards ITER Construction, Nuclear fusion Vol. 43 (2003) 268-273.

[2] IOKI, K., et al., ITER nuclear components, preparing for the construction and R&D results, Journal of Nuclear Materials, 329-333 (2004) 31-38.

[3] JONES, L., et al., Towards advanced welding methods for the ITER vacuum vessel sectors, The 22nd Symposium on Fusion Technology, Helsinki (2002).

[4] NAKAHIRA, M., et al., Integration Test of ITER Full-scale Vacuum Vessel Sector, Proc. of IAEA Fusion Energy Conference 1998, Page 1045, ITER RP1/24.

[5] JONES, L., et al., ITER Vacuum Vessel Sector Manufacturing Development in Europe, The 23nd Symposium on Fusion Technology, Venice (2004).