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Design, research and development for plasma facing components in JT-60SA

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Abstract

An overview of plasma facing components (PFCs) in JT-60SA is introduced, including the upper divertor, lower divertor, inboard first wall and outboard first wall. These PFCs are upgraded in four stages during a plasma experiment in JT-60SA. At stage one, only a partial inboard first wall and upper divertor are installed with graphite tiles and inertial cooling. At stage two, the remaining PFCs including the outboard first wall and lower divertor are installed, and the inboard surface is fully covered. At stage three, the vertical targets of the lower divertor are replaced with CFC monoblock targets and water cooling. At stage four, the whole carbon wall is replaced with a tungsten wall, and remote handling for the lower divertor is introduced. The research and development on major issues concerning PFCs are presented. Mock-ups of a CFC monoblock target were fabricated and it showed good heat removal of the expected maximum heat load of 15 MW m^{-2} without degradation of the performance. Tungsten-coated samples were fabricated on the CFC and they showed no severe damage at surface temperatures of up to 2000 °C. Laser-welded samples showed good appearance and no defects were found by RT.

Keywords: CFC monoblock target, tungsten coating on CFC, remote handling, laser welding

(Some figures may appear in colour only in the online journal)

1. Introduction

JT-60SA [1] is now under construction, and will be ready for the first plasma as well as the following research phases in 2020. To achieve its missions, such as supporting ITER and develop advanced plasma for DEMO, it has some significant features, including a high plasma current of 5.5 MA, long pulse operation with a flat top of 100 s and a high auxiliary heating power of 41 MW.

There are four kinds of plasma facing components (PFCs) in JT-60SA: the upper divertor, lower divertor, inboard first wall and outboard first wall, shown in figure 1. These PFCs are upgraded during a plasma experiment in JT-60SA. A carbon wall was employed in the early research phases of JT-60SA, and it will be replaced by a tungsten wall later. A tungsten-coated CFC has been developed [2]. The heat load on the vertical targets of the divertor is expected to be 10–15 MW m^{-2} maximum because of the high heating power. Furthermore, a CFC monoblock target has been developed. A long pulse operation of 100 s causes high neutron fluence, and remote handling technology, including laser welding [3], has also been developed.

This paper provides an overview of the PFCs in JT-60SA. PFC installation during the research phases is introduced in chapter two. Highlights of the PFC designs are introduced in chapter three. Research and development on major issues concerning the PFC is introduced in chapter four, including the CFC monoblock target, tungsten coating on the CFC and laser welding.

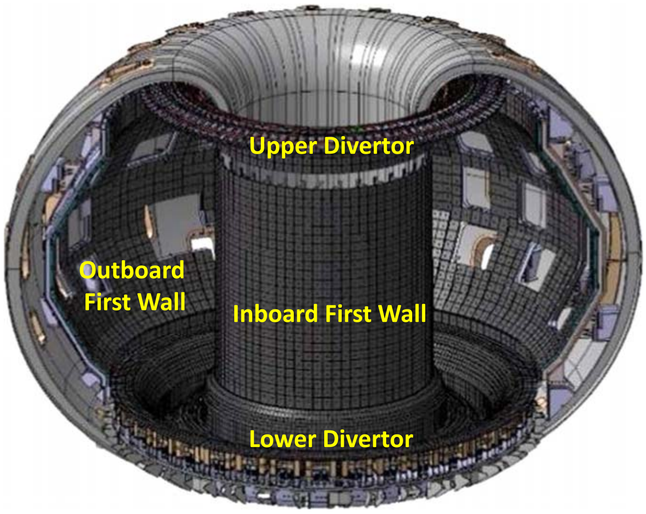


Figure 1. Plasma facing components in JT-60SA.

2. PFC installation during the research phases

The PFCs were installed during the research phases of JT-60SA defined in the JT-60SA research plan [1]. The research phases are consolidated into four PFC stages one to four from the point of view of PFC installation, as summarized in table 1 and below.

2.1. Stage one

At stage one, which corresponds to the former part of initial research phase one, the integrated commissioning of the entire system will be carried out. The plasma current is limited to 2.5 MA. Heating power is low, and its duration is short (1.5 MW $\times$ 5 s). Heat flux due to normal operation is so low that the in-vessel surface does not need to be fully covered. No cooling water for in-vessel components is prepared. Only minimum PFCs are installed, i.e., an upper divertor and inboard first wall with graphite tiles and inertial cooling.

2.2. Stage two

At stage two, which corresponds to the latter part of initial research phase one and all of initial research phase two, the remaining commissioning will be carried out. The plasma current is unlimited and has a maximum of 5.5 MA. Heating power is also significantly increased to 33 MW, however, it is still maintained for a short time of 5 s. The maximum heat load is a high heat flux (10 MW m^{-2}) of short duration (5 s) or a low flux (1 MW m^{-2}) of long duration (100 s). Cooling water can be used from this stage. The remaining PFCs, such as the outboard first wall and lower divertor are installed, resulting in the in-vessel surface being fully covered with a carbon wall. At the vertical targets of the lower divertor, bolted CFC tiles are installed.

2.3. Stage three

At stage three, which corresponds to integrated research phase one, high power and long operation with a full carbon wall will be investigated. The duration of high heating power is extended to 100 s. A high heat flux over a long duration (15 MW m^{-2} $\times$ 100 s) is also expected on the vertical targets of the lower divertor. Thus, the vertical targets are replaced with CFC monoblock targets and water cooling.

2.4. Stage four

At stage four, which corresponds to integrated research phase two and the extended research phase, all carbon walls are replaced by tungsten walls for the plasma experiment. To fabricate the tungsten wall, various plasma facing material candidates have been considered including tungsten-coated CFC/graphite, tungsten-joined CFC/graphite and tungsten solid. At this stage, high neutron fluence is expected and remote handling of the lower divertor cassette is planned.

3. Design of PFCs

3.1. Inboard first wall

The inboard first wall is installed on the inboard vacuum vessel to protect the vacuum vessel and magnetic sensors, as shown in figure 2. It is installed at stage one the first time with graphite tiles and inertial cooling [4]. The heat load due to normal operation is negligibly small. An inboard first wall is also used as a limiter at plasma startup, and its heat load is significant. The shed-roof shape of the graphite tiles enables a heat load with a reasonable limiter configuration value of 2.2 MW m^{-2}. To avoid heat load concentration, the tolerance of the first wall surface height (major radius) should be $\pm$1 mm. To achieve this, a laser tracker system is used for installation, which enables an absolute scale position of several meters with a tolerance of $\pm$0.1 mm. At stage two, it is replaced by water cooling to accommodate the increased heat load due to normal operation. At stage four, graphite tiles are replaced by tungsten tiles.

3.2. Outboard first wall

The outboard first wall is installed on the stabilizing plate at the outboard to protect the plate, magnetic sensors and

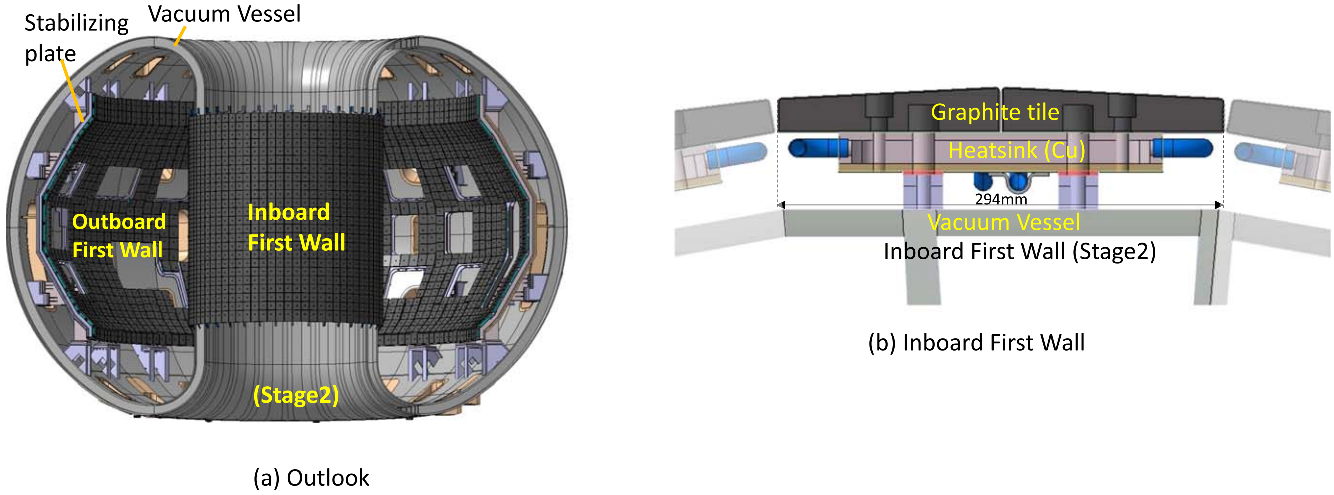


Figure 2. Inboard and outboard first walls.

in-vessel coils, as shown in figure 2. Its specification is almost the same as the inboard first wall except there is no heat load due to the limiter configuration. It is installed at stage two with graphite tiles and water cooling to begin with, and the graphite tiles are replaced by tungsten tiles at stage four.

3.3. Upper divertor

The upper divertor is used as the main divertor at stage one, and as a sub-divertor of double null operation as well as the first wall at stages two to four. It was installed at stage one with graphite tiles and inertial cooling. Figure 3 shows a schematic view of the upper divertor, which consists of graphite tiles and stainless steel structures. It is replaced by water cooling at stage three, and the graphite tiles are replaced by tungsten tiles at stage four. Surface tolerance should be ± 1 mm to avoid heat load concentration.

3.4. Lower divertor

The lower divertor [5] is initially installed at stage two and it is used as the main divertor at stages two to four. Considering that remote handling of the divertor is necessary at stage four, it has a divertor cassette design, as shown in figure 4.

The heat load on the divertor is high for a short time ($10\ \mathrm{MW\ m^{-2}} \times 5$ s) or low for a long time ($1\ \mathrm{MW\ m^{-2}} \times 100$ s) at stage two. At stage three, the heat load on the vertical targets is high for a long time ($15\ \mathrm{MW\ m^{-2}} \times 100$ s maximum), and the vertical targets are replaced by CFC monoblock targets. At stage four, all carbon walls are replaced with tungsten.

All of the divertor cassettes have already been procured, as shown in figure 4. To avoid concentration of the heat load due to misalignment, the surface tolerance is required to be ± 1 mm, and the divertor cassettes are designed to satisfy requirements, precisely (± 1 mm) fabricated and also designed to enable precise (± 1 mm) installation with adjustments.

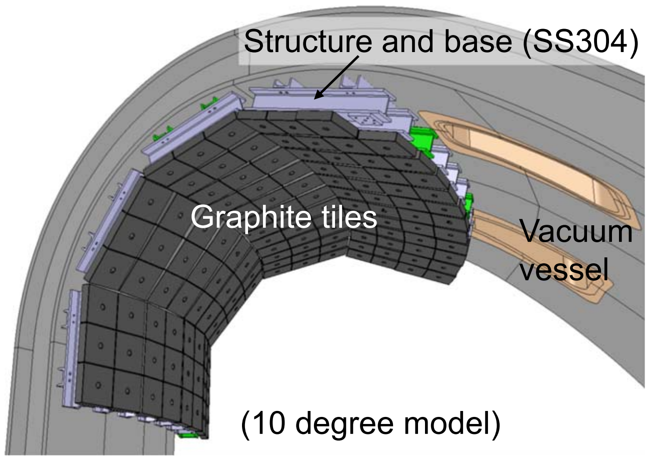


Figure 3. Upper divertor.

3.5. Design evaluation

All PFCs in JT-60SA should be able to withstand various loads in the in-vessel environment such as heat load, electromagnetic forces due to halo and eddy currents, and acceleration due to earthquakes and disruption. An evaluation of the design is summarized in table 2, taking the upper divertor as an example. The design was required to pass for all items. Taking a thermal analysis of the heat load at stage one for example, an analysis model and result are shown in figure 5, which shows the maximum temperature of the tiles and bolts are within acceptable range. Thermal stresses are also confirmed by another analysis to be acceptable. Through these evaluations, the design was validated.

4. Research and development concerning PFCs

4.1. CFC monoblock target

CFC monoblock targets aimed at achieving full spec operation at stage three were developed, and were able to withstand up to

Table 1. Update of PFCs during the research phases.

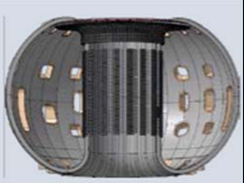
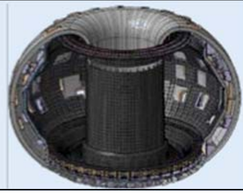
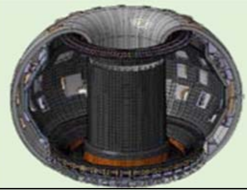
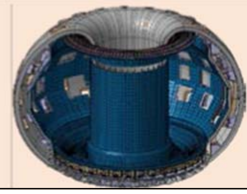
	First Plasma 2020	2023	2026	2030 / 2034
Research phases	Initial Research Phase I	Initial Research Phase II	Integrated Research Phase I	Integrated Res. Phase II / Extended Res. Phase
PFC Stages	Stage 1	Stage 2	Stage 3	Stage 4
Plasma Current	2.5MA	5.5MA	←	←
Heating Power	Total 1.5MW x 5s (2 Gyrotrons) 1.5MW	Total 33 MW x 5s (4 Gyrotrons) 3 MW (8 P-NB) 20MW (2 N-NB) 10MW	Total 37 MW x 100s (9 Gyrotrons) 7 MW (12 P-NB) 20MW (2 N-NB) 10MW	Total 41 MW x 100s (9 Gyrotrons) 7 MW (12 P-NB) 24MW (2 N-NB) 10MW
Cooling Water	No	Cooling Water	←	←
Neutron Fluence	No neutron	Low	Intermediate	High
Max. Heat Flux				
Inboard First Wall	0.02 MW/m^2 x 100s (Limiter configuration) 2.2MW/m^2 x ~5s	0.3MW/m^2 x 100s (Limiter configuration) ←	←	←
Outboard First Wall	0.02 MW/m^2 x 100s	0.3MW/m^2 x 100s	←	←
Upper Divertor	1.5MW/m^2 x 5s + 0.5MW/m^2 x 10s, 1.0MW/m^2 x 30s	In addition, 0.1MW/m^2 x 100s	In addition, 0.45MW/m^2 x 100s	←
Lower Divertor	0.02 MW/m^2 x 100s	(Vertical target) 10MW/m^2 × 5s 3MW/m^2 × 20s (Other) 1MW/m^2 × 100s	(Vertical target) 15MW/m^2 × 100s (Other) ←	←
PFC Installation				
Inboard First Wall	Graphite / inertial (Partially)	Graphite / water (Fully)	←	Tungsten / water
Outboard First Wall	--	Graphite / water	←	Tungsten / water
Upper Divertor	Graphite / inertial	←	Graphite / water	Tungsten / water
Lower Divertor		CFC tiles / water	Monoblock CFC / water (Vertical target)	Tungsten / water (Remote handling)
				

Table 2. Design evaluation; upper divertor at stages one to two as a sample.

Heat load	
(Stage one) 1.5 MW m^{-2} × 5 s + 0.5 MW m^{-2} × 10 s in 600 s cyclic operation	√Passed: 430 °C < limit 2000 °C (graphite)
(Stage two) 0.1 MW m^{-2} × 100 s in 1800 s cyclic operation	√Passed: 320 °C < limit 2000 °C (graphite)
Electromagnetic forces: toroidal field $B_t = 2.25$ T, plasma current $I_p = 2.5$ MA at stage one and 5.5 MA at stage two	
Halo current	√Passed: 81 MPa < limit 130 MPa (SS316L)
Eddy current	√Passed: 2.5 MPa < limit 56.4 MPa (graphite)
Acceleration due to earthquake and disruption	
5G in three directions	√Passed: 1.6 MPa < limit 130 MPa (SS316L)

15 MW m^{-2} for 100 s [6]. As shown in figure 6, the CFC monoblock targets consist of CFC monoblocks, CuCrZr cooling pipes and CFC tiles at the end where the heat load is low, and which are fabricated by vacuum brazing. The surface temperature of the targets should not exceed 2000 °C during operation to avoid the sublimation of carbon. Starting with technology based on ITER research and development [7], several mock-ups were fabricated. The surface temperature was evaluated by the

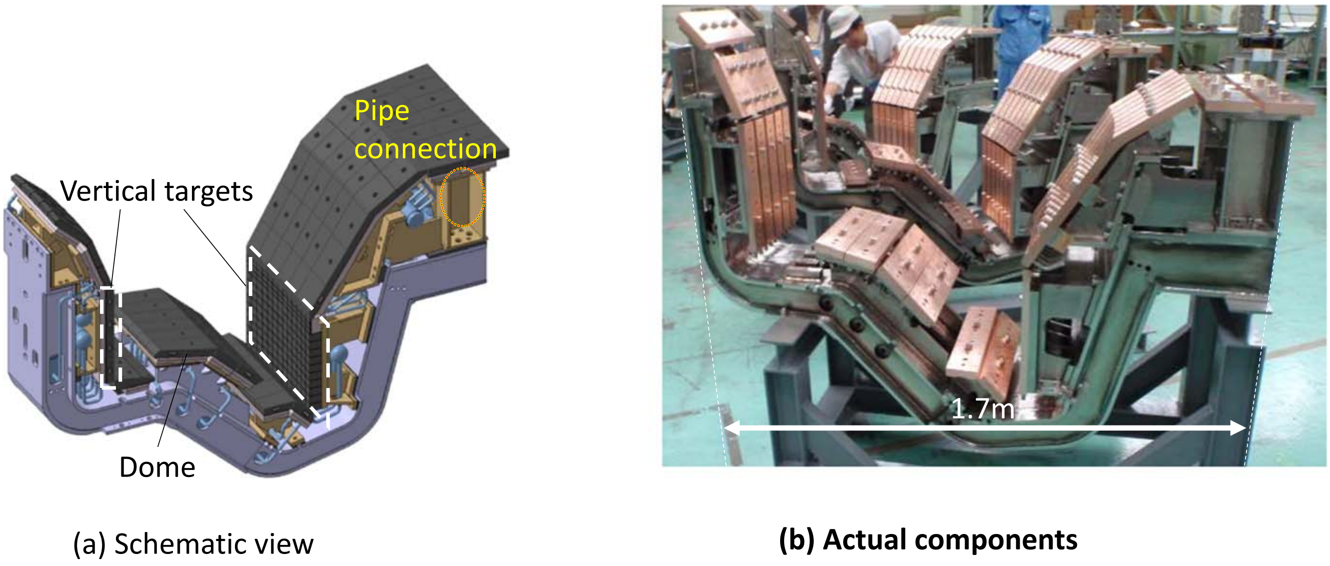


Figure 4. Lower divertor cassette.

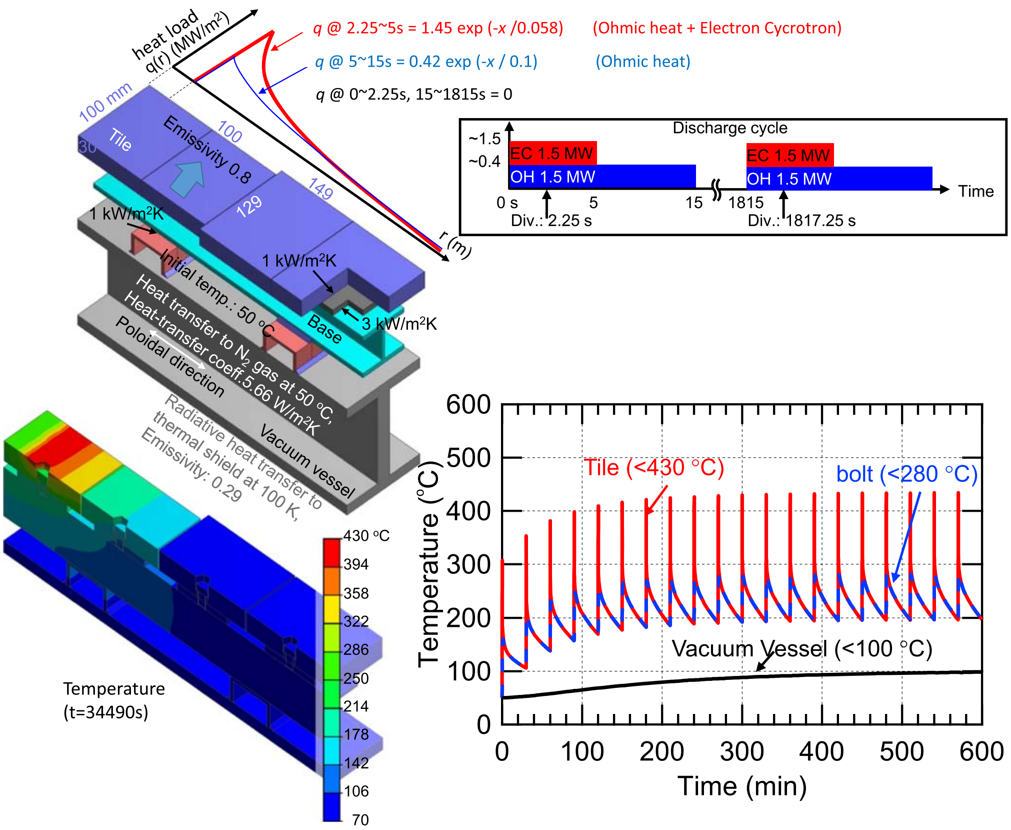


Figure 5. Evaluation of upper divertor on heat load at stage one.

irradiation of a single pulse steady-state heat flux with 15 MW m^{-2} on the JEBIS facility [8] shown in figure 7. Its heat removal was applicable for the JT-60SA divertor targets.

For the next step, a cyclic test on the fabricated mock-ups is planned. Also, full-scale mock-ups with the same dimension as the actual components are planned to be fabricated.

Figure 6. CFC monoblock target.

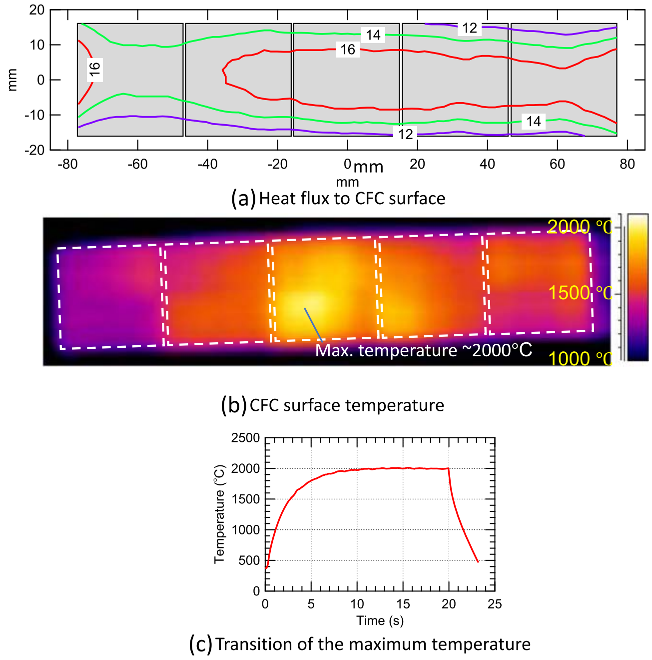


Figure 7. Heat load test on CFC monoblock target.

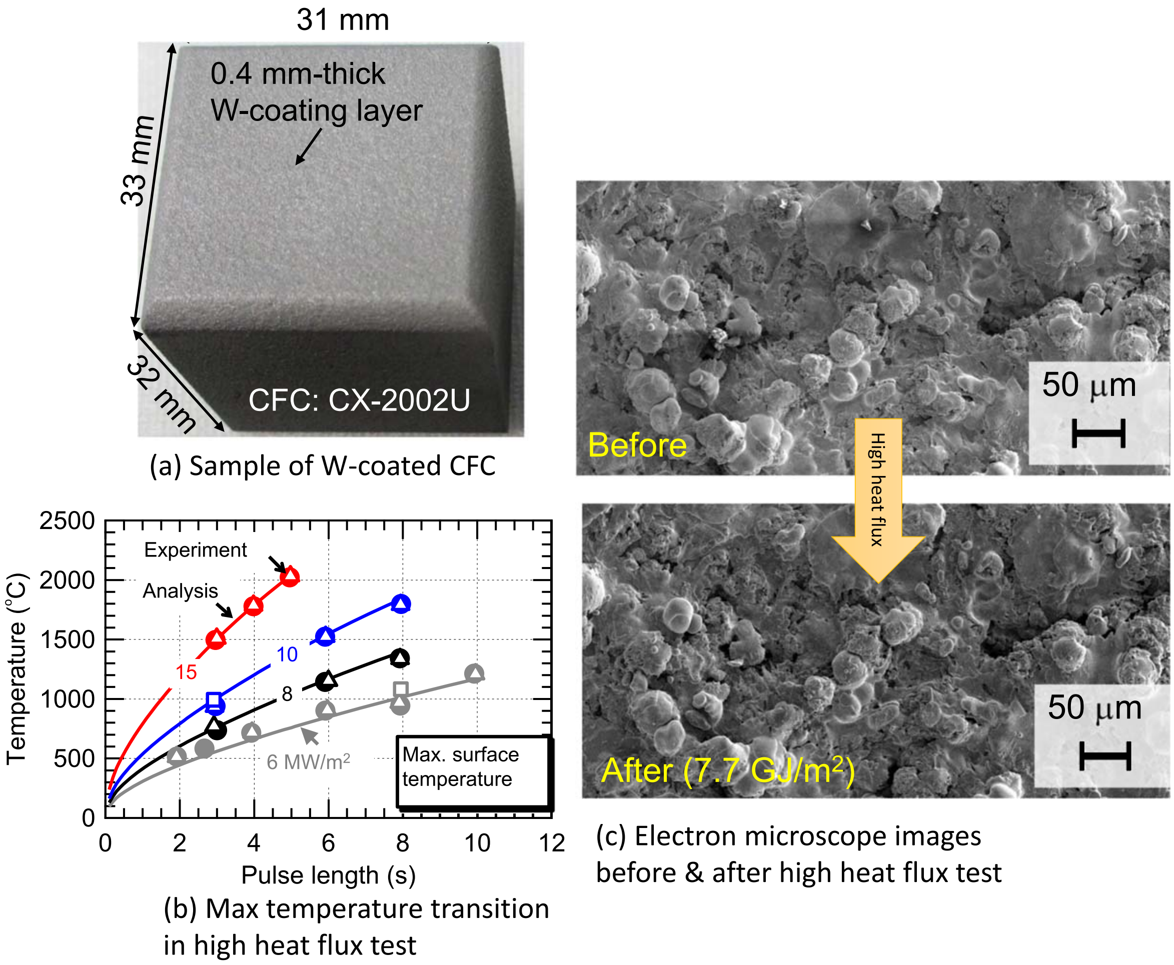


Figure 8. Tungsten-coated CFC. Reproduced from [2].

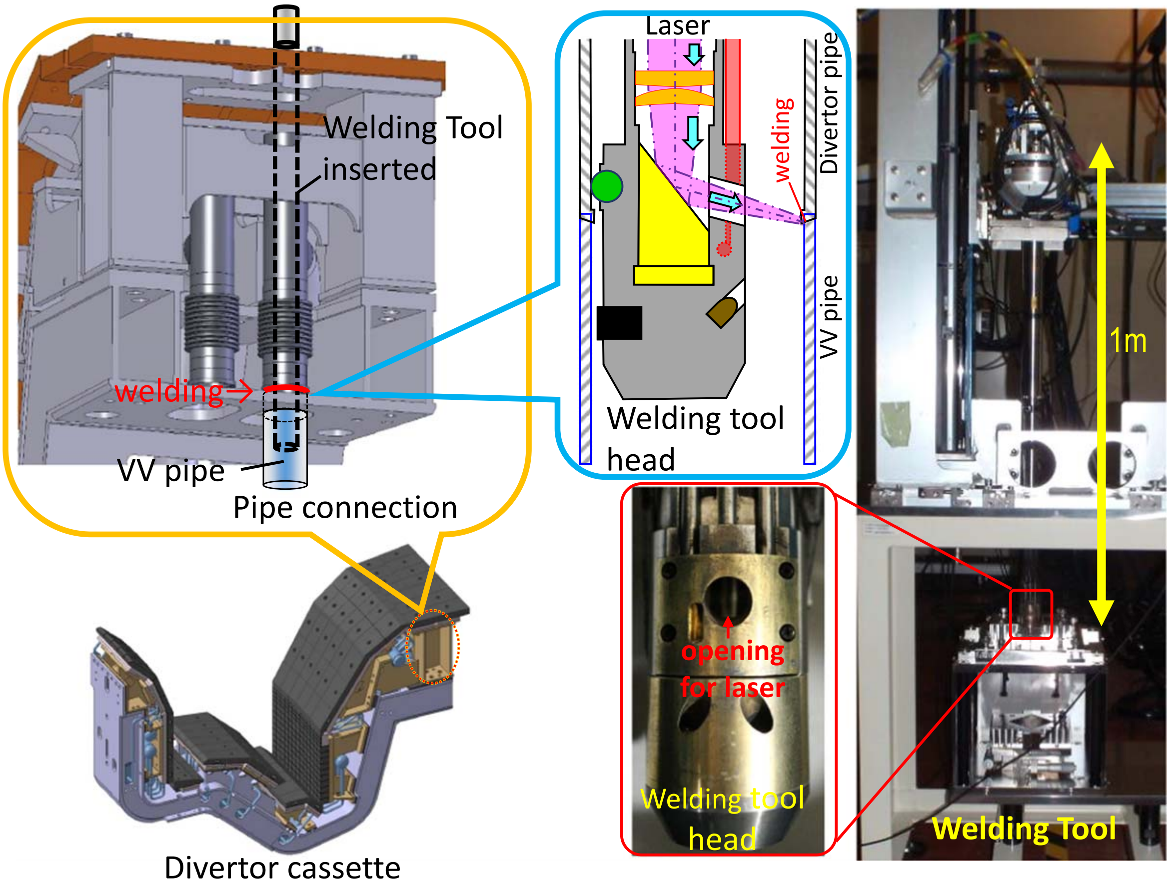


Figure 9. Laser welding tool.

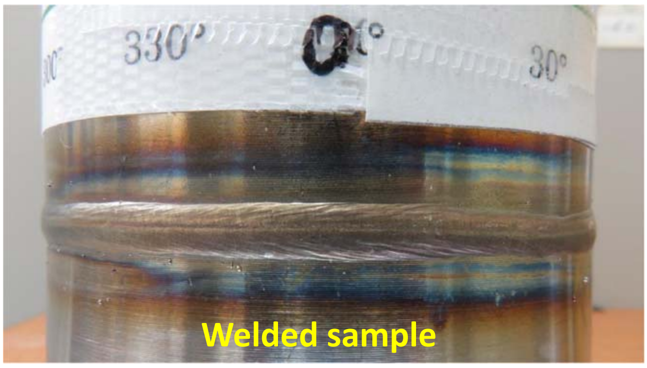


Figure 10. Laser-welded sample.

4.2. Tungsten coating on CFC

Tungsten coating on the CFC was developed with the aim of replacing the carbon wall with a tungsten wall at stage four [2]. The samples shown in figure 8(a) were fabricated by coating tungsten on CFC blocks using a vacuum plasma spray (VPS) method for application to the divertor target. High heat flux tests were carried out on the samples by the GLADIS facility [2]. The measured surface temperatures agreed well with the analysis, as shown in figure 8(b). The result showed that the thermal resistivity between the tungsten coating layer and CFC was negligibly small, because it was assumed to be zero in the analysis. Figure 8(c) shows electron microscope images of the same position before and after the high heat flux test with a surface temperature of up to 2000 °C and a fluence of 7.7 GJ m^{-2}. Melting, cracking and delamination were not found, but some recrystallization was [2]. These results indicate that the tungsten coating can withstand surface temperatures of up to 2000 °C, as expected for the water-cooled monoblock target.

For application to the divertor target, tungsten-coated CFC monoblock target mock-ups were fabricated and a steady-state cyclic heat flux test planned for them.

4.3. Laser welding technology for divertor pipe

Laser welding technology for cooling water pipes between the divertor cassettes and the vacuum vessel was developed with the aim of achieving remote handling at stage four [3].

To weld the pipes, the welding tool shown in figure 9 is inserted from the top of the pipes; then the welding tool head rotates emitting a laser at the opening. The samples were well welded; they had a good appearance as shown in figure 10 and no defects were found after radiographic testing (RT). The welded joint also passed a water pressure test and a helium leak test. It was shown that the laser welding technology was applicable for JT-60SA.

For the next step, a welding test on the divertor cassette mock-up is planned.

5. Summary

An overview of the PFCs in JT-60SA has been presented.

- The PFCs will be upgraded during the plasma experiment.
- To avoid concentration of heat load, the inboard first wall, upper divertor and lower divertor need to be installed precisely (with a surface tolerance of ±1 mm).
  The components, including the divertor cassettes, were manufactured precisely.
  The inboard first wall and upper divertor will be precisely installed using a laser tracker system.
- Research and development concerning the PFCs has been presented.
  Mock-ups of the CFC monoblock target showed good heat removal of 15 MW m^{-2} without degradation of performance. A cyclic test and fabrication of larger mock-ups were planned with the aim of achieving mass production for full power operation at stage three (integrated research phase one).
  Tungsten-coated samples on the CFC showed no severe damage at temperatures of up to 2000 °C. Fabrication of the tungsten- coated monoblock mock-up and its cyclic test are planned with the aim of having a tungsten wall at stage four (integrated research phase two and later).
  The laser-welded samples had a good appearance and no defects. Mock-up welding tests and the development of remote handling technology (other than laser welding) are planned with the aim of achieving remote handling at stage four (integrated research phase two and later).

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