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Manufacturing, testing and installation of the full tungsten actively cooled ITER-like divertor in the WEST tokamak

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The WEST (W - for tungsten - Environment in Steady-state Tokamak) platform aims to support the ITER tungsten divertor technology, manufacturing and long pulse operation. For this purpose, the Tore Supra tokamak has been deeply modified (mainly the installation of a lower and upper divertor coil structure), enabling a restart in 2016 and a first phase of operation (Phase I) until the end of 2020. Following this first phase, a limited number of actively cooled PFUs (Plasma Facing Units), based on ITER divertor technology, were industrially produced and implemented into the WEST vacuum vessel. The second phase of operation (Phase II) will be with a full actively cooled divertor. The first WEST experimental campaign with this new configuration (Phase II) started in 2022. This paper reports on the key elements related to the large-scale industrial production, the reception tests, and the installation of the ITER-like divertor components (including embedded instrumentation) into the WEST tokamak. Main manufacturing issues as well as the reception strategy, in particular the handling of non-conformities, are highlighted, mentioning its relevance with ITER divertor specifications. Results related to the assessment of heat removal capability by IR thermography examination and high heat flux test, as well as the He-leak tightness control are also discussed.

Keywords: WEST, Divertor, PFC, W-monoblock

1. Introduction

WEST (W - for tungsten - Environment in Steady-state Tokamak) started successfully to operate from 2016, until the end 2020, with a mix of actively cooled plasma facing units (PFUs), based on ITER divertor technology (namely, massive tungsten (W) monoblocks joined to a CuCrZr heat sink tube with water-cooling), and passive W-coated graphite PFUs on the lower divertor [1, 2]. During this first phase, the pulse length was limited to a few seconds and the experimental program was mainly focused on assessing the power handling capabilities of the ITER-like PFUs ('ITER-like' PFU means: Same material choice, same armour and heat sink geometry (i.e. W-monoblock) but reduced component length). The second phase of WEST operation, aims to address PFU ageing under high particle fluence and integrated long pulse H mode scenario with ELMs [3]. To meet this goal, the lower divertor is now fully equipped with actively cooled, ITER-like PFUs (see Figure 1) which can fulfil stringent requirements in terms of heat exhaust capability (up to 20 MW/m² during slow transients) [4]. The first WEST experimental campaign with this new configuration has started in 2022, with the objective to

get the optimum benefit from WEST to minimize risks for the ITER divertor procurement and operation [5].

After a brief description of the WEST full-W actively cooled divertor, mentioning its relevance with the ITER one, this paper reports, through the major successive steps, on the key aspects relating to the large-scale industrial production as well as the associated controls and tests until its installation (including embedded instrumentation) into the WEST tokamak.



Fig. 1. Overview of the WEST vacuum chamber including the full tungsten actively cooled ITER like divertor

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2. Main features of WEST divertor

The WEST full-W actively cooled divertor constitutes the main plasma-facing component of the tokamak structure and is located in the lower vessel region just below the magnetic X-point. It reproduces the high heat loaded part of the ITER divertor targets (see Figure 2). It is based on the ITER divertor technology: massive tungsten (W) monoblocks (armour thickness 6 mm; axial length 12 mm) joined via a copper interlayer ring to a copper heat sink with water-cooling and assembled in a PFU [2, 6, 7]. In addition, the same tile final machining and surface shaping (i.e. 1° toroidal bevel to avoid leading edges) have been applied everywhere.

The WEST divertor consists of 12 independent toroidal sectors of 30°, each composed of 38 PFUs for a total of 456 to form a toroidal ring structure representing a portion of a cone surface. Each PFU, with a total length of about 500 mm, comprises 35 W-monoblocks with width varying between 26 and 31 mm in the toroidal direction and is attached via four stainless steel legs (so-called, U-shaped fixing) which allow connection to the anchors provided in the ring-shaped stainless steel support structure. Each sector was assembled and tested outside the vacuum vessel, only one hydraulic connection (inlet/outlet) via metallic joint being done inside the vessel.

As for ITER vertical divertor target, WEST PFUs must sustain 10 MW/m² in steady state and close to 20 MW/m² in slow transient [8]. WEST hydraulic cooling loop characteristics allows matching with ITER divertor nominal specifications (inlet pressure 2.5 MPa, coolant temperature 70°C and axial velocity 10 m/s) in order to maintain reasonable margin regarding saturation temperature and critical heat flux.

The WEST divertor design is based on modular sectors allowing to be removable individually. This flexibility

offers hence the possibility to test variants of armour such as: specific shaped upper surfaces (e.g. with/without chamfered edge), various pure tungsten materials such as AT&M (China) grade, ALMT (Japan) grade or advanced tungsten materials (e.g. W-alloyed, nanostructured tungsten), or to run dedicated experiments related to PFUs such as: ageing of pre-damaged PFUs, tests of repaired PFUs, thermal behaviour of out of acceptance criteria PFUs (about gap between monoblocks, defect at interfaces...), providing potentially valuable input to ITER divertor production and operation issues well ahead of the end of the ITER divertor production.

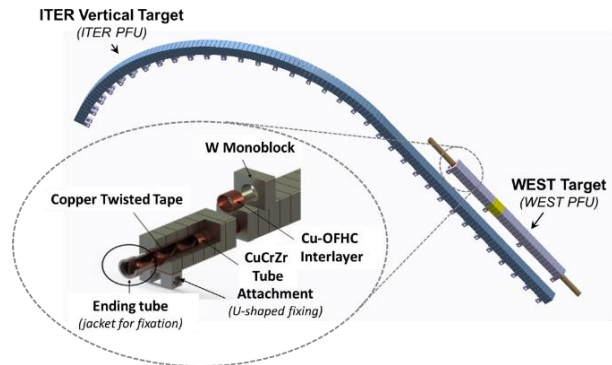


Fig. 2. ITER and WEST Plasma Facing Unit (PFU)

3. PFU manufacturing and reception

3.1. Manufacturing

Whereas ITER divertor target production will be carried out by potential manufacturers qualified by domestic agencies (F4E for IVT [6, 9, 10] and JADA for OVT [6, 11, 12]), WEST PFUs were manufactured by the Chinese company AT&M (Advanced Technology of Materials), with the assistance of an expert team from ASIPP (Institute of Plasma Physics, Chinese Academy of Sciences) [13].

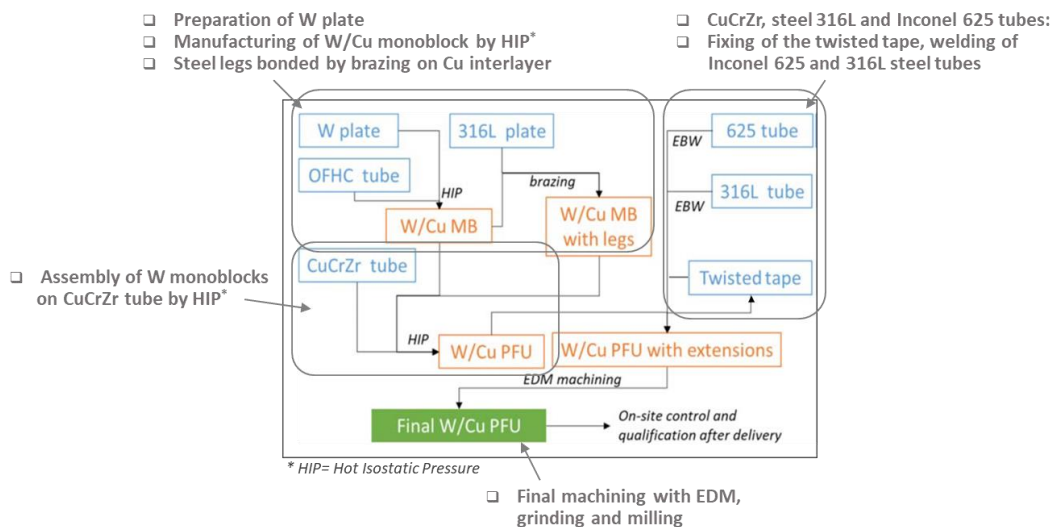


Fig. 3. Flowchart of the manufacturing process – Initial product (blue); intermediae products (orange) and final product (green)

The main manufacturing steps[7] (see Figure 3) can be summarized as followed: Each PFU is made of 35 W-monoblocks (MB) assembled on a CuCrZr heat sink tube via a OFHC copper interlayer ring, using hot isostatic pressing (HIP) as assembly process. A first HIP to join W and OFHC copper is performed at high temperature (close to 900°C), whereas the second HIP to join W/Cu MB to CuCrZr tube (inner diameter of 12 mm and wall thickness of 1.5 mm) is performed at low temperature (close to 600°C), see Figures 2 and 3. The pressure applied during the HIP process is in the range 100-200 MPa. The fixation of the PFU on the divertor plate sector is ensured by legs, fixed on four MB. According to the design, the support leg made of 316LN was prior joined by vacuum brazing onto the rear surface of the W/Cu monoblock via a ~1 mm thick pure copper interlayer that was bonded to W/Cu monoblock by HIP in advance. The brazing temperature is about 1000 °C, using CuGe as brazing filler. Thereafter, a twisted tape is inserted inside the tube, a stainless steel tube is welded by electron beam on both ends (the heterogeneous stainless steel/CuCrZr tube-to-tube transition is ensured via an Inconel 625 ring), and a precise external machining (including surface shaping) of the complete PFU is performed by EDM (Electrical Discharge Machining), milling and grinding. The most important features are the alignment of the attachment holes in the legs, the width of the PFU and the 1° bevel shaping (i.e. around 0.5 height). The last manufacturing step, before tightness control, is thus focused on the precise dimensional control (in the range of 0.05 mm) of the PFU (dimensional check around 70 points is executed by the manufacturer). Gap tolerances between monoblocks into PFUs (0.5 +/- 0.1mm) are detailed in [7, 14].

After a prior additional R&D phase to make more reliable the manufacturing, the quality of the industrial production was very satisfying regarding the specifications, both for standards and diagnostic PFUs [14]. Hence, the delivery, as required, of 456 qualified PFUs to CEA/IRFM (corresponding to 15960 W-monoblocks in total), needed the manufacturing of a greater quantity by the manufacturer, namely ~600 PFUs (i.e. ~30% more mainly during the additional R&D phase) due to failures occurring during the W/Cu to CuCrZr tubes by HIP process or other non-conformities (out of tolerances, surface breakage, tightness, etc). Some non-conformities due to defects in the heterogeneous stainless steel/CuCrZr tube-to-tube transition joined by electron beam welding (EBW) was observed during the manufacturing process by X-ray inspection and repaired by a 2nd EBW (all conform). This non-conformity concerned smaller than 3% of the total production. We can hence regroup into four categories the main grounds for rejection during manufacturing phase (i.e.

additional R&D, optimization (series) process and series production – see Figure 4):

- (i) HIP issue (e.g. canning leak, wrong temperature/pressure cycle regulation, decanning issues).
- (ii) Defect at an interface (W/Copper or Copper/Copper) larger than the requirement (defects must be smaller than 4 mm (monoblock thickness direction along the tube axis) by 6 mm (extension around the tube)).
- (iii) Dimensional (e.g. gap between monoblocks out of tolerances mainly caused by the pressure applied during the HIP joining process or the alignment of the attachment holes in the legs).
- (iv) Other (including failure (cracks or surface breakage) after machining or during hot helium leak test resulting in a strong oxidization¹ of the component).

The maximum charge into the used HIP furnace for the WEST PFU industrial (series) production was 20 PFU (or close to 700 individual monoblocks for W/Cu joining), however the charge in HIP furnace for each joining process evolved all along the industrial manufacturing. The charge into the furnace was typically close to 10% of the maximum charge during the first five months (i.e. during the additional R&D period) to reach about 50% after seven months (i.e. at the end of the optimization process period), then close to 100% until the last delivery once the process is reliable.

Therefore, we can see an evolution of rejection rate between the first deliveries (mid-2019) and the last ones (mid-2020) at CEA-Cadarache (see Figure 4). This rejection rate is mainly dominated by HIP issue, namely:

- direct (i.e. during the HIP joining process): leak (e.g. tightness issue related to the canning) (i)
- or indirect (i.e. as consequence of HIP joining process): defect at the material interfaces (ii) or gap between monoblocks out of tolerance caused in particular by the pressure on the extremities of the HIP canning (iii)

The rejection rate was very large in the first 5 months of the series production (higher than 50%). To make the upscaling of the manufacturing production more reliable, a better precise monitoring of both simultaneous applied temperatures and pressure as well as the gap between W-monoblocks, but also by improving the canning and its welding, was implemented.

This additional R&D phase enabled thus to reduce drastically the leakage during the HIP process and the defect issues at the interfaces, and to reach a rejection rate close to 15% for the last 10 months of the series production with a first full batch (~80 PFUs) delivered from January 2020 and a last delivery in October 2020.

¹ During the manufacturing phase, tightness issues of the vacuum vessel used for the hot He-leak test have been

encountered for one batch resulting in a strong oxidization (air contact) and rejection of all components included in the concerned batch.

All delivered components included in the first batch of 80 PFUs (namely, ~20% of the complete production) undergone systematic several controls (*acceptance* tests and *reception* tests – see Section 3.2) before acceptance. Regarding the following batches (according to the results

obtained on the first batch), *acceptance* tests were kept as mandatory (i.e. visual, dimensional and tightness) whereas other (*reception* tests) were performed by sampling.

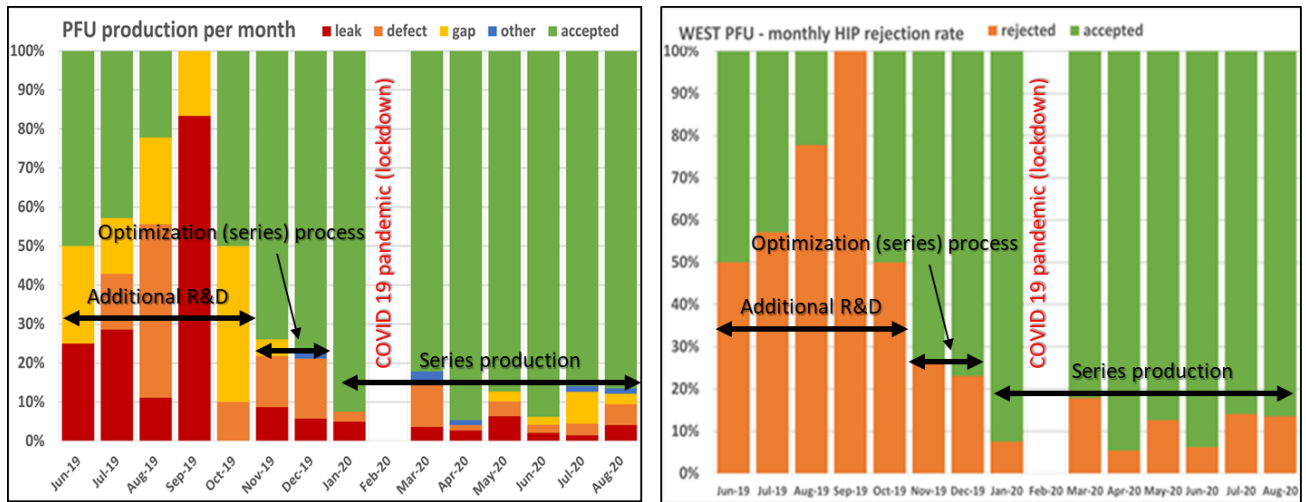


Fig. 4. Evolution of the rejection rate during manufacturing phase - Main grounds for rejection (left), Rejection rate after HIP (right) -

3.2. Reception

After the delivery at CEA-Cadarache, dedicated tests were realised on delivered PFUs before their installation into the WEST tokamak. Some of these tests (called *acceptance* tests) such as visual inspection, dimensional control and cold He-leak testing were performed systematically on all PFUs in order to check the strict compliance with the technical specifications [15, 16]. The main visual characteristics checked and which must be fulfilled are: bevel orientation of surface shaping and location along the PFU, chamfer presence on the block edges, blocks free of broken parts and twisted tape presence. Other observations such as strips, strains or discoloration are reported (where necessary) and can induce some recommendations in terms of positioning onto the sector. The visual inspection is followed by a fast systematic checking of each elementary component on a dedicated template to prevent any issue during the sector preparation phase. The aim of cold He-leak test was to check the tightness of the heterogeneous stainless steel/CuCrZr tube-to-tube transition (via Inconel ring) of PFUs at room temperature (detector sensitivity $< 1.10^{-11}$ Pa.m³.s⁻¹, leak rate $< 5.10^{-11}$ Pa.m³.s⁻¹) – see [17, 18]. Other tests (called *reception* tests), performed by randomly sampling and according to the HIP batch, are intended to provide specific information about each PFU such as material characterization (W and CuCrZr hardness test) or heat exhaust capability of PFUs (IR thermography [19, 20] and HHF test [21, 22]). All of these tests lead to the conclusion that PFU components meet globally the main requirements driven by technical specifications and the quality remained relatively stable during the series production phase.

However, cross-checking between ultrasonic testing, systematically performed by the manufacturer on all delivered PFUs to control and measure the compliance of potential defect at interfaces, and the tests by IR thermography as well as under high heat flux (both performed by sampling during *reception* tests) to assess the heat transfer capability, deserve some comments (see Figure 5).

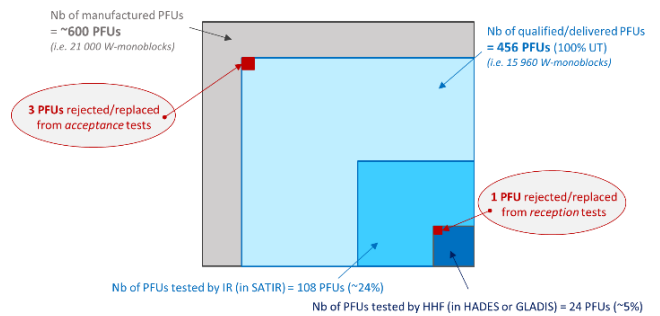


Fig. 5. Summary of acceptance and reception tests regarding the qualified PFUs

The manufacturer produced about 600 PFUs in total (i.e. ~21 000 W-monoblocks) in order to reach the required number of 456 PFUs qualified by UT (i.e. 15 960 W-monoblocks) to be delivered at CEA-Cadarache. 100% of 456 delivered PFUs underwent *acceptance* tests, which enabled to identify some non-conformities exclusively related to the visual inspection (e.g. broken monoblocks, strips, stains, etc...), induced by final machining or to the dimensional control. Only 3 PFUs (< 1%) were rejected from *acceptance* tests due to non-conformities, one identified from the dimensional control (poloidal length out of the tolerances, emphasized by the manufacturer but anyway tested on a dedicated template

by CEA) and two other ones identified from the visual inspection (cracks close to the U-shaped fixing). These three PFUs were replaced by other compliant PFUs. The other non-conformities were the subject of a derogation sheet (i.e. deviation request) and finally accepted having no impact in terms of integration into the WEST machine and operation.

Among 456 PFUs qualified by UT and accepted from the acceptance tests, 108 PFUs (i.e. ~24%) were tested by IR thermography on the SATIR facility at Cadarache [19, 20] in the frame of the reception tests. These tests pointed out thermal imperfections on 46 monoblocks related to 8 PFUs (i.e. ~7% of tested PFUs) of which one PFU concentrated thermal imperfections on all its 35 monoblocks (see Figure 6). Thermal imperfections exceeding the acceptance limit set for SATIR control (i.e. $DT_{ref} Max > 6^{\circ}C$ regarding WEST PFU components) enable to point out a quality of the component as questionable in terms of heat transfer (detailed information about SATIR acceptance criteria are provided in [15, 16]). By using high heat flux (HHF) test facilities, such as HADES at CEA-Cadarache [21] and GLADIS at IPP-Garching [22], 24 PFUs among 108 tested on SATIR (including the three PFUs with thermal imperfections located away from end blocks: PFU #266, PFU #300 and PFU #551) were HHF controlled (≤ 100 cycles up to nominal heat flux, namely $10 MW/m^2$). No notable overheating was observed except for the three PFUs for which thermal imperfections had been revealed by SATIR. A surface temperature higher than the one

expected for a PFU without defect were noticed on PFU #300 (~50% higher) (see Figure 7) as well as PFU #266 and PFU #551 (~10% higher for both – see Figure 8). It was finally decided to reject and replace the PFU #300 by another compliant one. All other PFUs characterized by a thermal imperfection were kept as spares and will be mounted (if needed) into specific locations where heat load remains moderate. A few additional PFUs (~10%), not included in this analysis, were supplied and installed for some of them, to have a full actively cooled divertor for the WEST phase II.

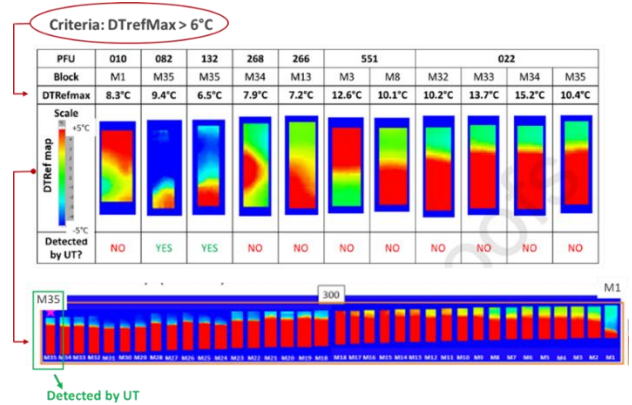


Fig. 6. $DT_{ref}Max$ cartography obtained by IR thermography (SATIR facility) for plasma facing surface (top): W-monoblocks of 7 PFUs (#010, #082, #132, #268, #266, #551 and #022) with thermal imperfection (bottom): All 35 W-monoblocks of the PFU#300

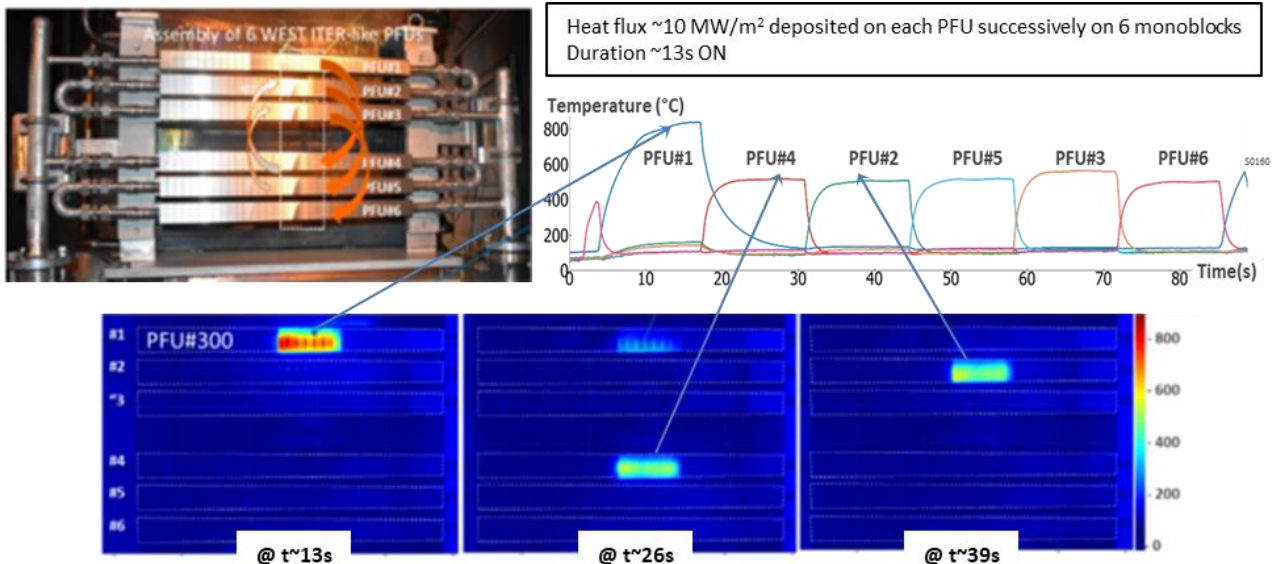


Fig. 7. Results of HHF test (HADES facility) for “questionable” PFU #300

Subsequently, all thermal imperfections revealed by thermographic examination on monoblocks located close to high heat loads areas in operation (i.e. far from end blocks) were tested under HHF and have systematically shown an abnormal overheating under heat flux at $10 MW/m^2$ without any sign of propagation after 100

cycles. However, an attempt to cycle at a higher heat flux PFU #266 and PFU #551 (up to $15 MW/m^2$ – see Figure 8) showed a progressive increase in the surface temperature (from ~10% to ~20% in just 10 cycles) suggesting a progressive degradation of the heat removal capacity of these PFUs due to the heat load cycles.

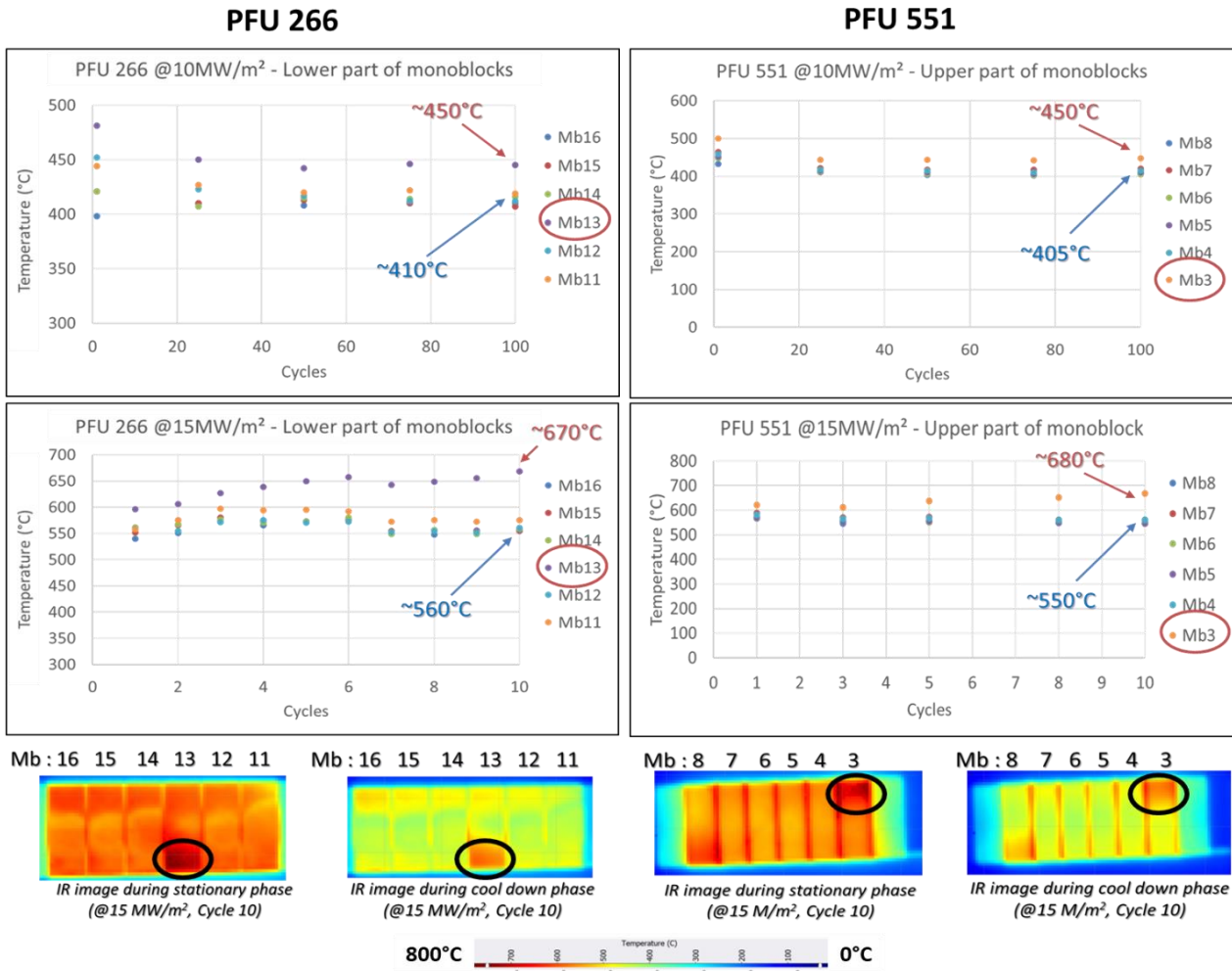


Fig. 8. Results of HHF test (HADES facility) for “questionable” PFU #266 and PFU#351: (top) Apparent temperature evolution vs. number of cycle at 10 MW/m² (100 cycles) and 15 MW/m² (10 cycles) with associated IR thermography images at the last cycle

To summarize, less than 8% of PFUs (namely 8 PFUs) and less than 2% of monoblocks (namely 46 monoblocks) tested with the infrared thermography (SATIR), among 108 PFUs (i.e. ~24% of the total series production, namely 456 PFUs), pointed out thermal imperfections, while the UT had not revealed any non-conformity at the level of the W/Cu, Cu/CuCrZr interfaces. Thereafter, the three PFUs characterized by a thermal imperfection located away from end blocks which have been detected by IR thermography (SATIR), namely PFU #266, PFU #300 and PFU #551, have been tested under high heat flux in the HADES facility and showed a systematic degraded thermal exhaust capability on the concerned monoblocks.

So, beside the UT performed systematically by the manufacturer during the manufacturing process, which is based on the impulse-echo immersion technic and which enables to inspect each interface (W/Cu and Cu/CuCrZr), IR thermography performed randomly on nearly 25% of the total series production after delivery in the frame of the reception test at CEA-Cadarache, appeared a very useful non-destructive examination to assess the heat transfer capability of actively cooled PFC and thus to

adjust by sampling an appropriate and relevant number of HHF tests.

4. Sectors preparation and installation into WEST tokamak

4.1. Surface of PFUs sector

Based on WEST vacuum chamber size and the geometry of ITER-like PFU (in particular the width of components), 456 PFUs in total, constituted of 35 W-monoblocks each, were integrated all around the toroidal ring structure. A 30° sector angular subdivision has been defined with respect to the aperture of the WEST tokamak port from which each sector has been inserted. Each sector is made of 38 consecutive PFU components mounted in the toroidal direction on the stainless steel support structure (see Figure 9). Bearing surface of support structure was machined with a tolerance of 0.05 mm and each PFU is mounted from the four stainless steel U-shaped fixings brazed on the tungsten monoblocks with a pin on an anchor pawn (bolted to the support structure) including an oblong hole enabling a clearance of +/- 1 mm. The PFU is then adjusted from a comparator (digital comparator with rotating display) to center the PFU in order to respect as much as possible the

clearance of ± 1 mm. The vertical alignment was controlled by 3D metrology (and corrected if necessary) using a laser robotic arm [23] before welding the water manifolds to the cooling pipes in which pressurised water will flow to cool it. Gaps between PFU components follow therefore the following requirements: 0.3-1.0 mm between PFUs of a given sector; 0.5-1.2 mm between PFUs from adjacent sectors for gaps in the toroidal direction; 0.5 mm between monoblocks in a given PFU for gaps in the poloidal direction, whereas the relative maximum vertical misalignment does not exceed 0.3 mm.

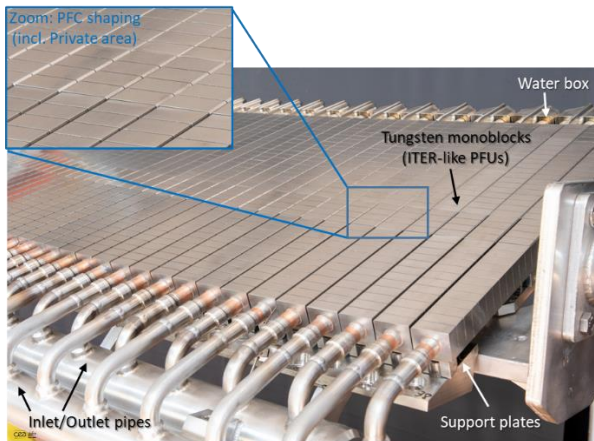


Fig. 9. View of one assembled sector

4.2. PFUs diagnostic

The WEST divertor is largely instrumented thanks to the inclusion of various probes within dedicated PFUs (so-called PFU-DIAG) including in particular specific machining (groove, space, etc...). Monitoring of the deposited energy is thus possible using instrumentation such as thermo-couples, calorimetry and fibre Bragg gratings. Measurement of local plasma parameters, such as the electron temperature, density, and floating potential, from which the heat load can also be derived, is provided by the installation of Langmuir probes.

4.2.1. Langmuir probe systems (see Figures 10 and 11)

Langmuir probes (LPs) have been thus designed, manufactured and installed inside 10 WEST PFUs in the vicinity of the separatrix strike points on the divertor target to characterize the plasma parameters [24]. Three different kinds of Langmuir probes (namely, pop-up, mousetrap and wafer) onto 3 sectors in total (Q2B, Q5A and Q6A) were installed:

- 27 pop-up probes (see Figure 10-a) onto Q2B sector to ensure fast ELM measurements covering the entire divertor region from high field side (HFS) to low field side (LFS) at two different toroidal location ripple maxima to study the effect of WEST's large toroidal magnetic field ripple. The pop-up probes consists of Tantalum (Ta) and are positioned at the center of each monoblock (12.5 mm apart) and have a diameter of 3.5 mm. Electrical insulation from the

PFU is made using boron nitride rings [24]. Both types of probes protrude 1 mm above the divertor surface when their drive coils are activated. The pop-up probes can be inserted briefly into the plasma upon request by passing a current through a drive coil that moves under the influence of the Lentz law.

- 3 mousetrap probes (see Figure 10-b) onto Q2B and Q5A sectors at HFS and LFS ripple minima (1 μ s). The mousetrap consists of 4 Ta pins of 1 mm diameter oriented along the magnetic field and distributed poloidally between two monoblocks. Using the same principle as the pop-up probes, namely a drive coil to make them move briefly into the plasma to make measurements, these probes are designed to measure the electron energy distribution function and were manufactured by the Bulgarian Association.
- 56 wafer probes (see Figure 11) with slow data acquisition (4 ms) onto Q6A sector. These probes are permanently mounted into the PFUs (they are bolted directly into the sides of individual monoblocks) and will measure all the time with a 4 ms time resolution.

The pop-up probes and mousetrap probes are briefly exposed to plasma and so should not suffer. The wafer probes, on the other hand, are permanently subjected to the same harsh conditions as the divertor itself, but can only be cooled by indirect contact with the targets via heat conduction through an electrical insulator (0.1 mm thick sheets of phlogopite mica) and to a lesser degree via thermal radiation. The probes themselves are made of pure W by powder injection moulding produced by Karlsruhe Institute of Technology [25]. Therefore, the long discharge duration and the expected high heat flux in WEST imposed that the wafer LPs had to be flush with the PFU surface within which they were embedded in order to maximize their chance of survival. An alignment of ± 20 μ m with respect to the PFU surface was thus sought. The control and adjustment is performed by a confocal microscopy measurement during the sector preparation. An altitude map of the probes alignment at the PFU surface was made by a first round of confocal microscopy measurement. Then, if required, an adjustment has been performed by placing a rectified ruler on the top surface of each monoblock and manually pressing the wafer probe onto it while carefully tightening the two screws. The alignment of the pins was then measured again by a second round of confocal microscopy. A strip of sheet metal was spot-welded between the two screws to prevent them from turning during operation. The majority of the probes protrude slightly above the surface target. The largest measured misalignments is close to 26 μ m [26].

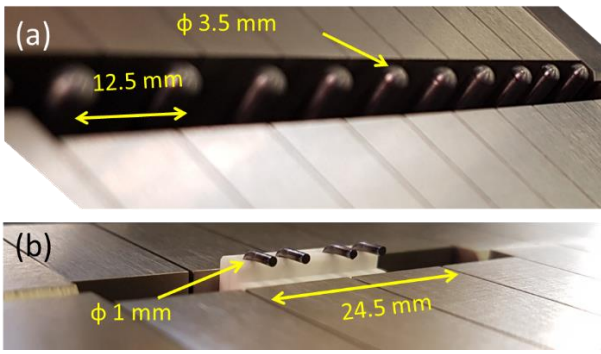


Fig. 10. Photos of PFUs diagnostic with (a) an array of pop-up probes and (b) a mousetrap probe



Fig. 11. View of PFUs diagnostic with embedded Langmuir probes (wafer probes)

4.2.2. Temperature measurement system (see Figure 12)

Measuring the temperature in plasma-facing components (PFCs) provides information both on plasma parameters in the divertor region and on the thermal stress experienced by PFCs [27, 28 and 29]. If the thermocouples are possible candidate and have been installed (20 in total) into 2 PFUs onto two sectors (Q1A and Q6A), Fiber Bragg gratings (FBGs) are also interesting candidates for this application because they are immune to electromagnetic interferences and their ability to be multiplexed allows an extended spatial coverage. Five fibers, each of them including fourteen Bragg gratings, have been embedded into WEST PFUs (i.e. 5 PFUs in total), through a 2.5 mm deep lateral groove localized at 5 mm beneath the top of bulk tungsten monoblocks, able to operate up to their signal-collapsing limit at 1200°C. The use of an inscribed fibers by using femtosecond laser allowed improving and make more reliable the previous system (namely regenerated Bragg gratings) used during the first phase of WEST (2016-2020). In addition to their outstanding thermal stability, femtosecond FBGs benefit from higher signal-to-noise ratios than regenerated FBGs. The period and length of the gratings are designed to increase the number of measurement spots to fourteen gratings per fiber, regularly distributed over 17 cm, while ensuring robust detection even with strong thermal gradients (no

overlapping or deformation of Bragg peaks). The system can operate up to 1200 °C with gradients reaching 200 °C/mm perpendicularly and 40 °C/mm in parallel to the fiber.

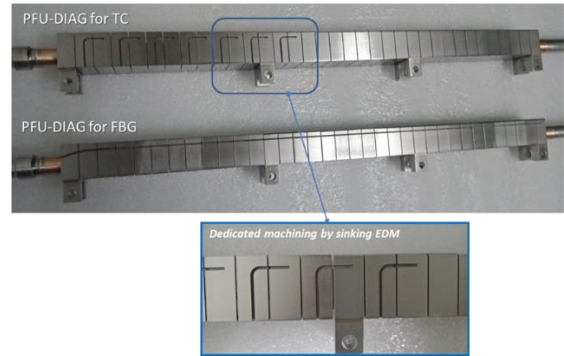


Fig. 12. View of PFUs diagnostic with embedded temperature measurement sensors (thermocouples and FBG)

4.3. Cooling system

Each 30° sector is composed of 19 sets of two PFU connected in series by means of water box and fed in parallel by a manifold. The design has to take into account not only the available space but also the deformation of the support structure in operation and the final assembly sequence of the connection to the water feeding pipes and the plug-ins via CF-flanges in the vacuum vessel. The design of the pipes was checked to ensure it has enough flexibility to allow thermal deformation/movements.

Due to the restricted available space and maximum pressure drop required for one 30° sector, specific technology using a combination of conventional stainless steel machining and Inconel 3D printing based on the Sintering Laser Melting (SLM) technology for the central part has been developed and qualified to produce the water manifolds (see Figure 13). The conformity of the powder used (Inconel material) has been verified beforehand, in particular in terms of particle size and heat treatment, and then mechanical tests on dedicated specimens manufactured by 3D printing have been performed. These tests showed that the material met the requirements specified in the applicable standards. Subsequently, each part produced in 3D printing underwent a first X-ray inspection to check the absence of porosity. The same control was also carried out at the end of the final step to check all the welds made by TIG welding. Thereafter, the connection between PFUs by means of water box, pipes and manifolds were made by TIG (Tungsten Inert Gas) orbital welding with full penetration and without filler material. A total of 1368 orbital welds was needed to complete the cooling system. No welding inside vacuum chamber is realised to connect hydraulically the inlet/outlet parts of the assembled sector. The connection to the WEST hydraulic loop into the vacuum chamber is performed via CF-flanges by dedicated joints (see Section 4.5).

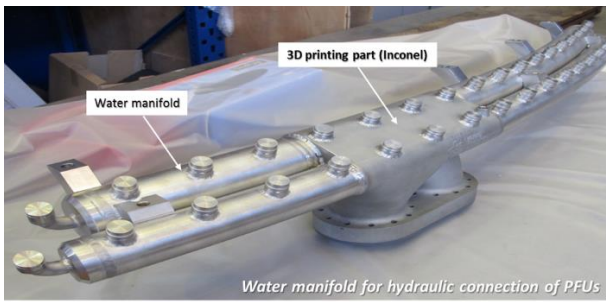


Fig. 13. View of water manifold using a combination of conventional steel machining and Inconel 3D printing based on the Sintering Laser Melting (SLM) technology

4.4. Control testing

Even if critical sub-components, such as PFUs are tightness tested in particular at the end of the manufacturing phase by the manufacturer (hot leak test) or during the acceptance test at CEA/IRFM (cold leak test), it is of paramount importance to qualify the tightness of any actively cooled components before their installation in the machine, to fulfil the machine availability constraints. So, sector preparation step (i.e. precise PFUs mounting and connection welding to water boxes and the hydraulic header) concludes by a leak (helium) tightness test to check that each sector fulfils the vacuum requirements to create a plasma. A relevant test procedure has been developed at CEA/IRFM from the large experience of the Tore Supra teams in the implementation of actively cooled plasma-facing components and is used since 1990s [17]. This procedure, which includes a cold and hot helium leak tests has been thus performed for each sector before their installation into the WEST machine.

A dedicated hydraulic assembly, including two sectors, has been prepared to perform this ultimate test outside (see Figure 14). It has been set up in a large cylindrical vacuum test tank (< 5 m³) and the cooling circuits have been pressurized with helium. Each hydraulic assembly has been thus submitted to two temperature cycles from operation temperature (70°C) up to the baking temperature level in Tore Supra/WEST (200°C) for two pressurization tests (4 MPa at operation temperature and 3 MPa at 200°C at each stage) with the following criterions:

- 4 MPa at 70 °C, detector sensitivity <2.10⁻¹⁰ Pa.m³.s⁻¹, leak rate <5.10⁻¹⁰ Pa.m³.s⁻¹
- 3 MPa at 200 °C, detector sensitivity <2.10⁻⁸ Pa.m³.s⁻¹, leak rate <5.10⁻⁸ Pa.m³.s⁻¹

Before its installation in the test stand, hydraulic assembly is tested by helium spraying method at room temperature, the cooling circuits being evacuated and connected to a helium detector. This tightness test must be successful, namely the measured leak rate must be lower than 5.10⁻¹¹ Pa m³ s⁻¹ (detector sensitivity <1.10⁻¹¹ Pa.m³.s⁻¹). All prepared PFU sectors successfully passed the full leak test procedure (no leakage were observed).

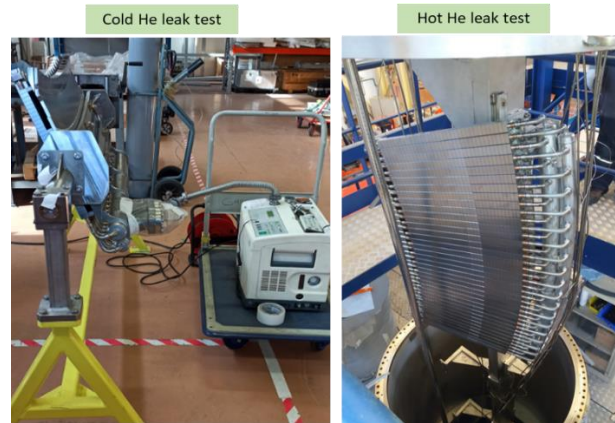


Fig. 14. (left) View of mobile set up for cold He-leak test by helium spraying method (before hot He-leak test) - (right) View of assembled sector during introduction into vacuum test tank for hot He-leak test

4.5. Installation into WEST tokamak

Besides the technical challenge of PFUs assembly onto dedicated sectors requiring regular controls (misalignment tolerances, tightness, etc...) during all along assembly phase, the operation difficulty was then to install this WEST divertor transformation within the short timescale imposed by the scheduled shutdown between two WEST experimental campaigns.

Prior real time simulations by virtual reality equipment available at CEA/IRM allowed optimizing the integration of assembled 30° sectors through WEST median ports as well as the installation procedure into vacuum chamber. Each assembled sector being particularly fragile and weighting about 400 kg, compact handling tools were designed and certified by CEA to manage displacement and connection inside the restricted volumes of access ports and vacuum vessel. Thereafter, each assembled sector, introduced into the vacuum vessel, is hydraulically connected by dedicated joint (*Helicoflex*® metallic joints) to the WEST hydraulic loop. The overall executive work lasted 16 weeks for preparation phases (i.e. assembling phase, 3D-metrology and He-leak tightness control of sectors) and 5 weeks for the in-vessel mounting.

A dedicated metrology campaign (carried out by SETIS [30], a Degaud group company (France) expert for industrial measurement (EPR reactor, Jules Horowitz, LMJ chamber, CERN)), as an integral part of the installation of any major components into WEST machine, was performed by the laser tracker technique associated to a scanning system to measure with an accuracy of 0.1 mm the real position of WEST lower divertor relative to a fixed reference (namely, the machine axis) and that of each sector in relation to its neighbours (gap, vertical misalignment, etc...) – see Figure 15. A set of measurement system is actually

established. The system uses the base points established in the WEST vacuum chamber to get the coordinate of each point on the divertor, then calculates the position relative to machine axis.

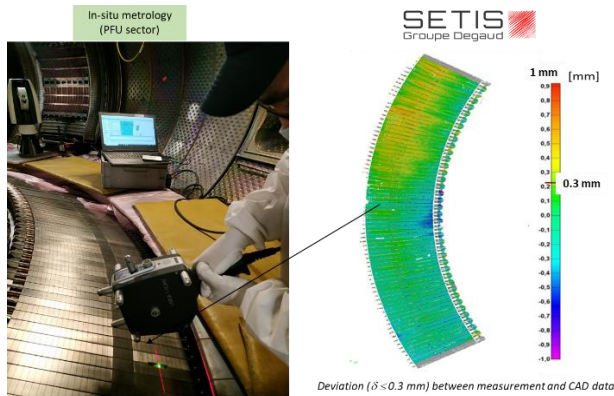


Fig. 15. Final in-situ metrology of WEST divertor: (left) Laser tracker technic associated to a scanning system for one PFU sector - (right) Example of obtained cartography regarding PFU alignment (comparison of the CAD data with the vacuum chamber environment as-rebuilt)

5. Conclusion and Summary

Despite a delay of few months originating due to technical and environmental issues, the production of the 456 actively cooled ITER-like PFUs for WEST lower divertor was successfully achieved. The quality assessment, through an extensive program of reception tests, showed stable quality of the series production regarding the specifications, both for standard and diagnostics PFUs. The reduced number of NCRs (Non Conformance Reports) validate the additional R&D carried out prior to prepare this industrial production.

The assembly phase on dedicated sectors, including precise mounting and tricky connection welding to the hydraulic header followed by a hot helium leak test as well as by its installation into the WEST vacuum chamber, is now finished since end 2021, finalizing henceforth the WEST tokamak evolution and initiating the operation of phase II. The first experimental campaigns in this new configuration (i.e. with a full actively cooled lower divertor) has thus started in summer 2022.

Therefore, with the manufacturing and the reception of nearly 500 PFUs, WEST provided for the first time the complete qualification of an industrial production of actively cooled W monoblocks components representative of the ITER divertor ones ahead of ITER series fabrication. In addition, with a first experimental campaign (C6 campaign) in summer 2022, WEST offers also for the first time an integrated test in a tokamak environment, taking advantage of the unique long pulse capabilities and the high power offered by the new upgraded Tore Supra platform.

Finally, the technical and managerial lessons learned from the manufacturing and reception of the series production of WEST PFUs are summarized hereinafter:

- Prior to the start of manufacturing, each purchased batch of material has to be fully qualified through pre-material analysis or relevant samples to guarantee as much as possible a stable quality during series production.
- Close collaboration between supplier (manufacturer) and customer is essential through the validation of manufacturing and control processes, early consolidation of acceptance criteria and extensive evaluation of first batch (as pre-series parts).
- Thorough quality of inspections during manufacturing process is important to guarantee a high level of confidence.
- Reception tests (in addition of acceptance tests) are highly recommended, but must be considered carefully (as supplementary controls and through a relevant sampling). For example, regarding the WEST PFU production, beside UT performed by the manufacturer before delivery, IR thermography non-destructive examination carried out on-site during the reception tests appeared very useful to assess the heat transfer capability of actively cooled PFC and thus to adjust by sampling an appropriate and relevant number of HHF tests.
- Despite a strict compliance with technical specification, the challenging assembly tolerances needs a fast systematic final checking of each elementary component on a dedicated template during the reception tests to prevent any scheduling risk (slipping) and over-cost.

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