Overview on Decade Development of Plasma-Facing Components at ASIPP

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Abstract. The first EAST plasma was ignited in 2006 with non-actively-cooled steel plates as plasma-facing materials and components (PFMC) which were then upgraded into full graphite tiles bolted onto water-cooled copper heat sinks in 2008. And the first wall was changed further into TZM in 2012, while keeping graphite for both of the upper and lower divertors. With rapid increase in H&CD power in EAST, the W/Cu divertor project was launched around the end of 2012, aiming at achieving actively-cooled full W/Cu-PFCs for the upper divertor, with heat removal capability up to 10 MW/m^2. The W/Cu upper divertor was finished in the spring of 2014, consisting of 80 cassette bodies toroidally assembled. Commissioning of the EAST upper W/Cu divertor in 2014 was unsatisfactory and then several practical measures were implemented to improve the design, welding quality and reliability, which helped us achieve successful commissioning in 2015 campaigns. In collaboration with IO and CEA teams, we have demonstrated our technology capability to remove heat loads of 5000 cycles at 10 MW/m^2 and 1000 cycles at 20 MW/m^2 for the small scale monoblock mockups, and surprisingly over 300 cycles at 20 MW/m^2 for the flat-tile ones. The experience and lessons we learned from batch production and commissioning are undoubtedly valuable for ITER engineering validation and tungsten-related plasma physics.

1. Introduction

The first EAST plasma was ignited in 2006 with non-actively-cooled stainless steel plates as the sole plasma-facing materials and components (PFMC) which were then upgraded into full graphite tiles bolted onto water-cooled copper heat sinks in 2008, capable of removing heat loads up to 1-2 MW/m^2 [1, 2], as shown in FIG.1. With increasing use of lithium for wall conditioning, the first wall PFM of EAST was changed into chemically more compatible TZM in 2012, while still keeping graphite as the PFM for both of upper and lower divertors [3]. With rapid increase in H&CD power in EAST recently, the W/Cu divertor project was formally launched around the end of 2012, aiming at actively-cooled full W/Cu-PFCs for the upper divertor around 2013-2014, with heat removal capability up to 10 MW/m^2 [3, 4]. The W/Cu upper divertor was finished in the spring of 2014, consisting of about 15000 W monoblocks for 160 vertical targets and 24000 W flat tiles for 160 baffles and 80 domes, on 80 cassette bodies toroidally assembled [4, 5]. Commissioning of the EAST upper W/Cu divertor in 2014 failed due mainly to leaks of e-beam welding between cooling tube and manifold box. After the campaign, we examined the leaking PFCs and reviewed the whole process, and then implemented several practical measures to improve the connection design, component welding quality and installation welding reliability, which helped us achieve successful commissioning in 2015 campaigns.

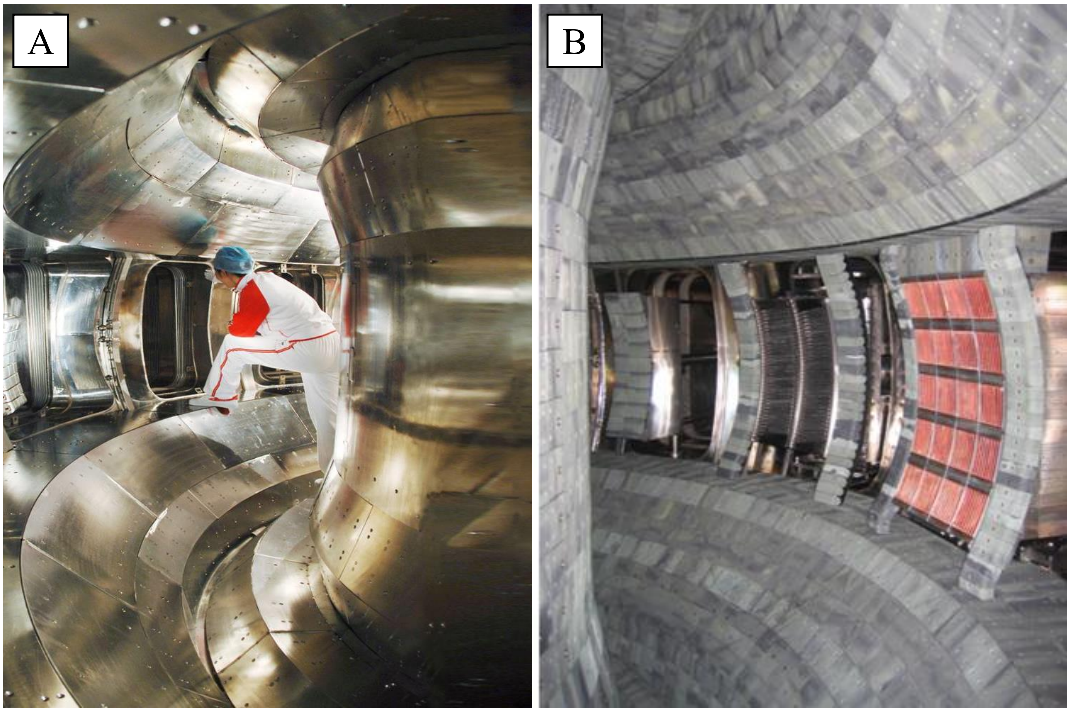

FIG. 1. PFMs for EAST, (A) stainless steel plates in 2006 and (B) full SiC/C tiles in 2008

2. Development of SiC/C and W coating materials for EAST

In order to reduce chemical erosion and hydrogen isotope retention of the carbon based materials (CBM), thick SiC coatings on doped graphite GBST1308 was developed at Shan'xi Institute of Coal Chemistry, Chinese Academy of Sciences (ASICC) by chemical vapour infiltration of Si into the graphite tiles and the following reactions between Si and C [6, 7]. And the SiC/C tiles have been being used as PFM for EAST since 2008. With increase in the heating and driving power in EAST, vacuum plasma sprayed (VPS) W coatings on Cu heat sink were developed at Guangzhou Research Institute of Nonferrous Metals (GZRINM) and Shanghai Institute of Ceramics, Chinese Academy of Sciences (ASSIC). Thick VPS-W coatings were prepared on a W/Cu gradient interlayer of 0.2–0.3 mm to reduce the thermal stresses between coating and substrate. In order to relieve the constraints to reduce thermal stress and prohibit the spreading of cracks in the tungsten coatings, castellation concept has been introduced, and was made at the surface of the heat sink before coating process [8-10].

3. Development of W/Cu divertor for EAST

FIG.2 shows the grand view of the whole PFMC for EAST since 2014. The EAST W/Cu upper divertor was designed as modular structure [5, 11]. There are 80 modules supported by inner rail, outer rail and middle support in vacuum vessel. Each divertor module includes a Cassette Body (CB) and three PFCs, namely inner target, outer targets, and dome, as shown in FIG.3. The CB is a stainless steel welded structure, acting as support and manifold for the PFCs. There are 4 W/Cu monoblock plasma-facing units (PFUs) for the inner targets and 5 PFUs for the outer targets which are connected to flat type baffle and manifold box by Electron Beam Welding (EBW). Manifold boxes act as cooling connections between W/Cu monoblock PFUs and CB to meet the very small space. Dome component consists of upper plate and lower plate which are joined by EBW as well. FIG.4 shows the pictures of W/Cu PFCs for the EAST upper divertor.

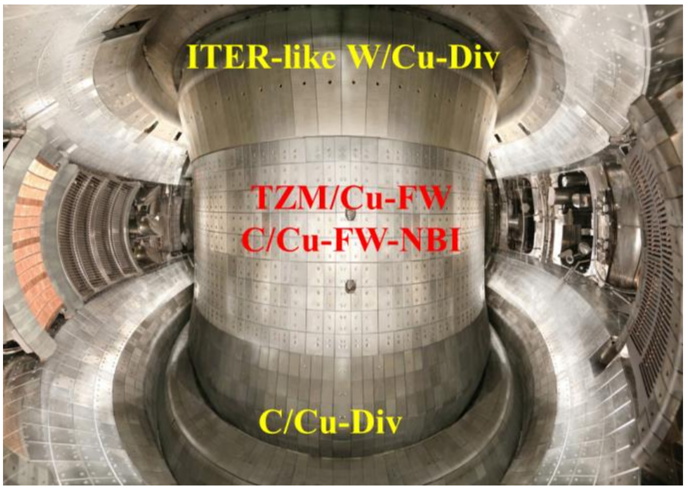

FIG. 2. Grand view of the whole PFMC for EAST since 2014, including ITER-like full W/Cu upper divertor consisting of 80 sets of assembled PFC/ CB, full C tile lower divertor, TZM tile first walls, and C tile shine throughs for neutral beams.

FIG. 3. Assembled set of PFC/CB, consisting of inner and outer targets and dome, with 9 monoblock plasma-facing units and 3 flat-type plates.

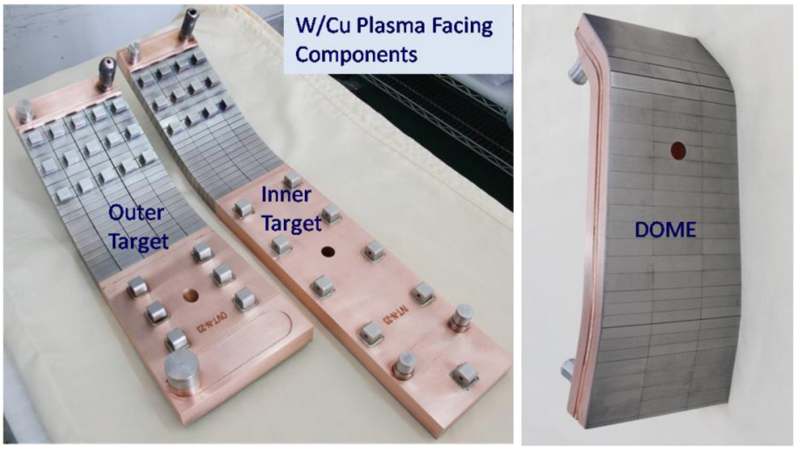

FIG. 4. W/Cu PFCs for EAST upper divertor.

The EAST team has devoted for years great time and energy into the development of two different types of W/Cu actively-cooled PFCs for the project [12-18]. The monoblock PFCs for vertical targets are manufactured by hot isostatic pressing (HIP) for cladding oxygen free Cu (OFC) to the inner surface of the W monoblocks, and then HIPing for the bonding between the clad monoblocks and CuCrZr cooling tube. FIG.5 shows pictures of W/Cu monoblock and PFU for EAST upper divertor. Three W/Cu monoblocks of one PFU are joined with the supporting legs by brazing which mounted onto CB via pins. The flat-tile PFCs for baffles and domes are manufactured by casting OFC onto the rear side of W tiles firstly, followed by HIPing of the W/OFC tiles onto CuCrZr heat sink plate. In order to control the bonding quality and ensure the lifetime of the PFCs and the safety of EAST device, the non-destructive testing (NDT) quality control system has been established. The acceptance criterion for the W/Cu and Cu/CuCrZr joints of the W/Cu monoblock PFUs is that no defects shall be greater than 2×3 mm, and that for the flat-tile PFCs requires defects less than Φ2 mm.

4. High heat flux test of W/Cu PFCs

An assessment of the behaviour of PFCs under cycling heat loads is essential to qualify PFCs due to high number of operating cycles and the expected surface heat load. The full scale W/Cu monoblock PFUs for EAST upper divertor have been tested via an electron beam facility with the power of 6 kW in Beijing Zhongke Electric Co. Ltd. Only one monoblock was tested due to the limitation of the electron beam power. Heat loads were 15 s on and 15 s off. The parameter of the cooling water is 4 m/s, 20 ^{o}C. The W/Cu monoblock PFUs survived 1000 cycles of heat loads of 10 MW/m^2 and no damage was observed. Flat type W/Cu mock-ups were also tested by this electron been facility with cooling water of 4 m/s, 20 ^{o}C. Flat type W/Cu mock-ups withstood 1000 cycles of 5 MW/m^2 successfully. Recently, in collaboration with IO, we have further demonstrated our technology capability to remove heat loads of 5000 cycles at 10 MW/m^2 and 1000 cycles at 20 MW/m^2 for the 6 small scale monoblock mockups in accordance with the qualification program [19], and macro-cracks [20, 21] that did not impair the thermal performance, appeared in two out of 24 monoblocks after 300 thermal cycles at 20 MW/m^2. The HHF test in collaboration with CEA-WEST team, demonstrated the durability of flat-tile W/Cu mockups over 300 cycles at 20 MW/m^2. FIG.6 shows W/Cu monoblock mockups tested by IO team on IDIF [22]. FIG.7 shows the flat type mockup tested by WEST team on JUDITH-1 [23].

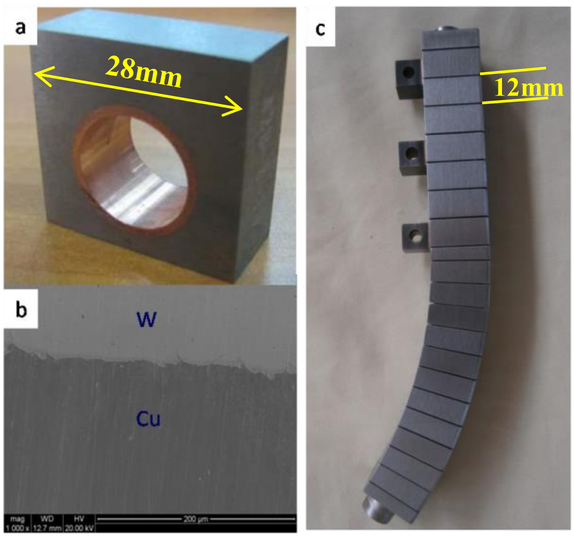

FIG. 5. (a) W/Cu monoblock; (b) SEM picture of W/Cu joint and (c) PFU for EAST upper divertor.

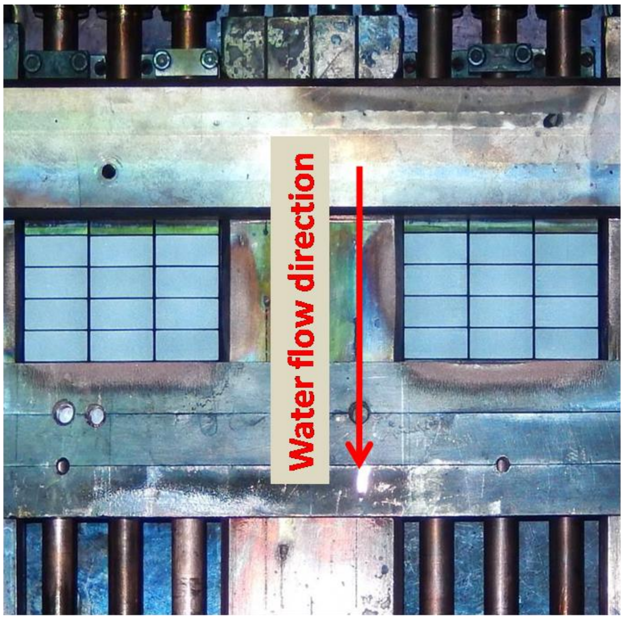

FIG. 6. HHF testing for 6 W/Cu monoblockmockups (28 mm×26 mm×86 mm consisting of 7 monoblocks) by IO team on IDTF, showing here good bonding and surface images after IO required heat loads of 5000 cycles at 10 MW/m^2 + 300 cycles at 20 MW/m^2.

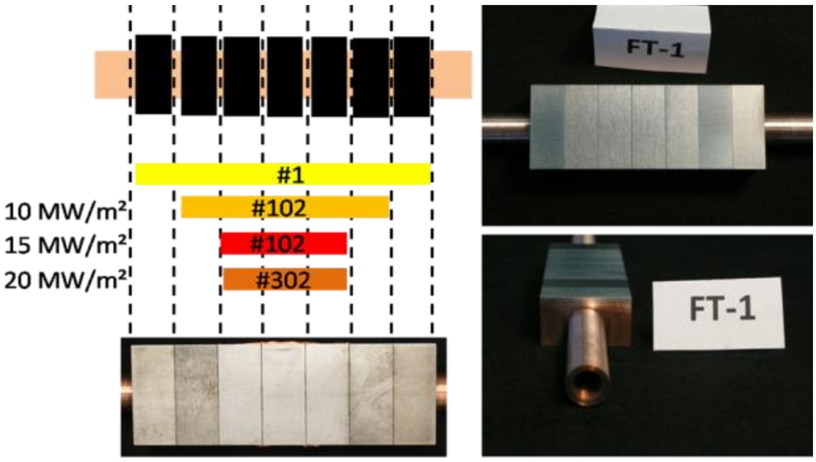

FIG. 7. HHF testing for a flat-tile mockup (28 mm× 26 mm×86 mm with 7 tiles of 2 mm thick) by WEST team on JUDITH-1, showing excellent performance.

5. Performance of EAST W/Cu divertor during campaigns

Commissioning of the EAST upper W/Cu divertor in 2014 failed due mainly to leaks of e-beam welding between cooling tube and manifold box during the EAST baking around 200 ˚C. After the campaign, we examined the leaking PFCs carefully and reviewed the whole process from design, manufacturing to installation, and then put forward several practical measures to improve connection design, component welding quality and installation welding reliability, which helped us pass smoothly the baking and even the discharge phases in 2015 campaigns. Firstly, ultrasonic NDT technique for the welding seams between cooling tube and manifold box was developed to control the quality of the seams, which is similar to that for the W/Cu monoblock PFUs as shown in FIG.8. The second measure is to optimize the cooling tube connection. Cooling tubes welded directly to CB suffered high thermal stress during baking, which led to the leaking of e-beam welding seams. In order to reduce the thermal stress, the hard welding was updated into flexible connection with soft bellows, as shown in FIG.9. Analyses showed that thermal stress of the EBW seams with new connections while baking up to 250 ˚C is in safe range. The third measure is to perform helium leak detection on the pre-assembled divertor module at 250 ˚C to simulate the actual condition of PFCs baking in EAST. In the 2015 spring EAST campaign, the W/Cu upper divertor survived after 3 weeks baking of 200 ˚C. At the end of campaign, tens of shots of upper single null (USN) plasma with the input power of ~4 MW were discharged. During these tens of shots, one shot of upper USN plasma with duration of 30 s and 10 s H mode was achieved. The results of this campaign demonstrated that the measures to control the seam quality of the W/Cu PFCs took effect. In the 2015 winter and 2016 spring campaigns, the W/Cu upper divertor withstood more severe irradiation by EAST plasma and no leaks occurred.

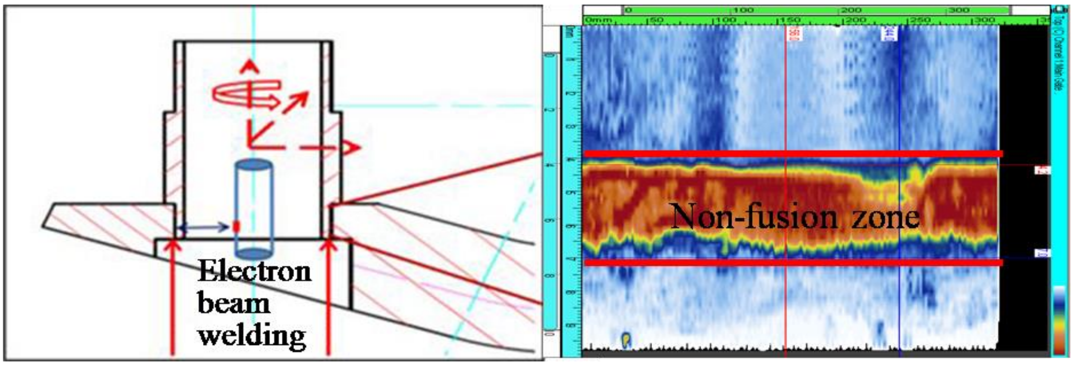

FIG. 8. NDT method directly measuring the depth distribution of e-beam welding between cooling tube & manifold box.

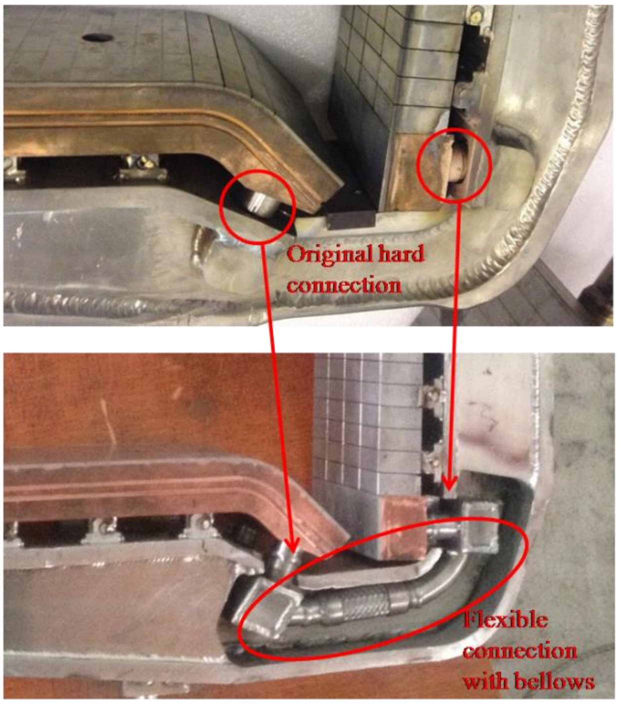

FIG. 9. Changes in connection design between cooling tube and CB to reduce the thermal stress.

6. Summary and outlook

Tungsten has been selected as PFM for the whole ITER divertor from Day 1 and the technologies for batch-scale manufacturing of the W/Cu-PFCs are still away from maturity, not to mention testing under practical long pulse tokamak plasmas. So far, key technologies being developed at ASIPP have already shown great HHF performance in laboratory testing. The experience and lessons obtained from batch production, further commissioning and plasma operation on EAST are undoubtedly valuable for ITER engineering validation and key physics related to tungsten.

Acknowledgments

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