CONFERENCE PRE-PRINT

DEVELOPMENT OF METER-SCALE LARGE W/CU DIVERTOR COMPONENTS FOR FUSION REACTOR AT ASIPP

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Abstract

Actively water-cooled W/Cu components are considered as one of the primary choices of technical solution for the high heat flux removal in fusion reactor divertor. ASIPP initiated the first W/Cu divertor project in 2012, and then the EAST upper divertor was upgraded with W/Cu components in 2014. In 2021, the EAST lower divertor was also upgraded with W/Cu components that significantly improve the capability of high-power operation, contributed to many achievements in plasma research. In recent years, W/Cu divertor technology have being oriented to the development of meter-scale large components for fusion reactor, mainly including, 1) design exploration for continuous high heat flux removal in the closed V corner, 2) qualification of meter-scale divertor components with monoblock structure and conventional materials of pure tungsten and CuCrZr, and 3) development of flat type components with advanced materials. To study engineering feasibility, lot of R&Ds, qualifications and mock-up were executed for the meter-scale long W/Cu PFU with heat removal capacity of 15 MW/m^2. The full-scale prototype of divertor module has been fabricated and tested. Progress has been made on divertor PFC towards CFETR with advanced materials, i.e., potassium-doped tungsten (KW) for armor, oxide dispersion-strengthened copper (ODS-Cu) alloy for heat sink, and reduced activation ferritic/martensitic (RAFM) steel for structure. The small to middle-scale mock-ups as well as prototypes for CFETR have been successfully tested with 1000 cycles of 20 MW/m^2.

1. INTRODUCTION

Divertor, one of the most important in-vessel components in the tokamak, needs to withstand extremely high heat flux from the core plasma. In terms of the ITER-level tokamak, the maximum heat loads on the divertor during normal operation is about 10-15 MW/m2 with the assistance of the detachment. And it will up to GW/m2 during off-normal event in a very short duration (~ms) [1]. Therefore, the capability and reliability are a very critical metrics for the divertor to ensure that it can survive in such terrible conditions.

Up to now, the ITER-like water-cooling divertor is the most mature solution. The prototype plasma facing component (PFC) fabricated with a state-of-the-art technology has been verified by the high heat flux test with at least 5000 load cycles at 10 MW/m2 and 300 cycles at 20 MW/m2 [2]. Hence, the actively water-cooled ITER-like divertor are considered as the baseline technical solution for the divertor with the heat loads expected which is comparable to that of the ITER divertor.

In ASIPP, the first ITER-like W/Cu monoblock has been manufactured successfully by technology of combination of hot isostatic pressing (HIP) and hot radial pressing (HRP). And it withstood 1000 cycles of heat load up to 8.4 MW/m2 [3]. And then, the EAST upper divertor had been decided to upgrade with ITER-like W/Cu monoblock in order to match the increase heat load on the divertor, which had been accomplished in 2014 [4]. Afterwards, the W/Cu monoblock technology was further improved and passed the ITER qualification requirements in 2016 [4]. In 2021, the EAST lower divertor was also upgraded with W/Cu components [5]. Both upper and lower W/Cu divertors significantly improve the capability of high-power operation, contributed to the many achievements in plasma research.

In recent years, lots of R&D work has been done to explore the design and technology of W/Cu components oriented to the DEMO and future fusion reactor in ASIPP, mainly including 1) design exploration for continuous high heat flux removal in the closed V corner, 2) qualification of meter-scale divertor components with monoblock structure and conventional materials of pure tungsten and CuCrZr, and 3) development of flat-type components with advanced materials. Those works aim to support the development of divertor for CFETR.

In this paper, the development and achievement of W/Cu components on EAST have been summarized in section 2. And the design, optimization, manufacture and test for the PFC with a closed V shape is described in section 3.

The development of mock-ups and prototype for meter-scale divertor components and R&D of PFCs towards CFEDR are presented in section 4 and section 5, respectively. Finally, a summary is generated in section 6.

2. DEVELOPMENT AND ACHIEVEMENT OF W/CU COMPONENTS ON EAST MACHINE

The EAST device has been updated several times in order to achieve higher plasma parameters during discharge. And the divertor with high power handling capacity compatible with the plasma configuration has been updated simultaneously. In 2006, the first plasma had been obtained with a non-actively cooled stainless steel plates as the PFC. Afterwards, the full graphite tiles bolted onto water-cooled heat sinks replaced them in 2008, which can withstand the maximum heat load of 2 MW/m2. And the first wall plasma facing material was changed into molybdenum alloy in 2012 in order to be compatible with increasing use of lithium for wall conditioning. With the injection power capability has been updated in EAST, the upper divertor with ITER-like W/Cu monoblock has been installed in the device in the spring of 2014, with the power handling capability of 10 MW/m2 [6]]. Then, the lower divertor with both monoblock and flat type has been equipped in EAST in 2021. Meanwhile, the limiter has also been updated to W/Cu monoblock components. The history of the PFC in EAST is illustrated in FIG. 1.

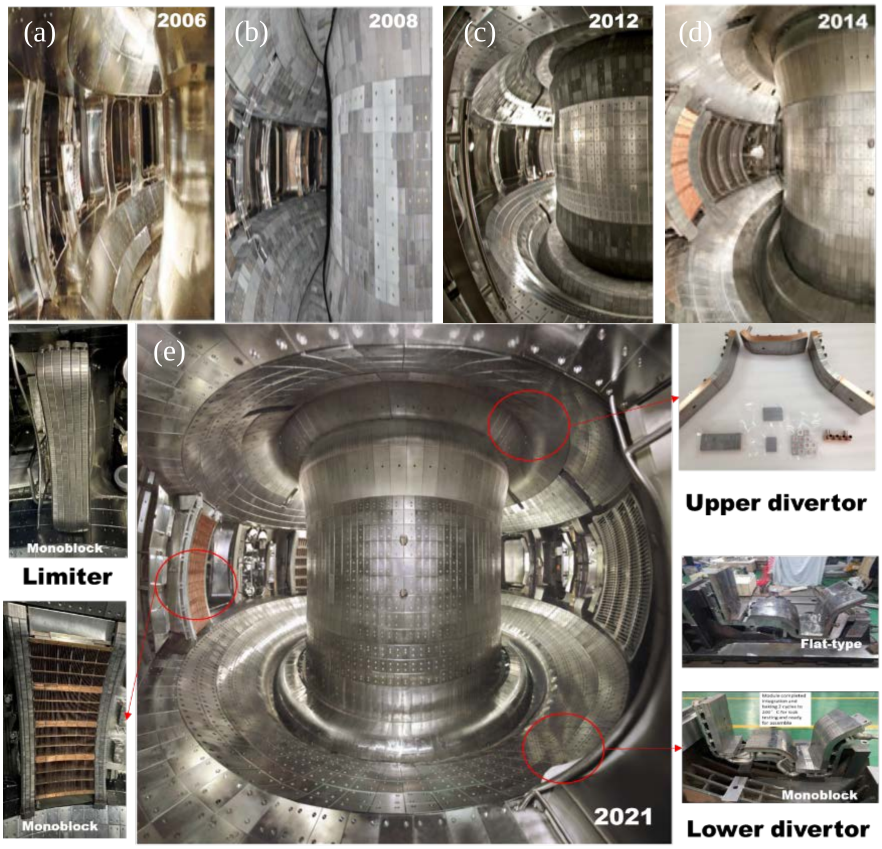

FIG. 1 The history of the PFC in EAST: (a)Non-actively cooled stainless steel plates, (b)water-cooled graphite tiles (1-2 MW/m2), (c)Molybdenum alloy (1-2 MW/m2), (d)Tungsten upper divertor (10 MW/m2), (e)Full tungsten divertor and limiter(10 MW/m2)

Now, the EAST is equipped with full tungsten divertor and limiter. Supported by those components with excellent power handling capacity, EAST has achieved several milestone achievements in the experiments. In 2021, EAST has made an important advance by achieving stable 1056-second steady-state high-temperature plasma operation [7]. Afterwards, EAST achieved a 403-second stationary H-mode plasma in 2023 [8]. Recently, Maintaining plasma operation at these conditions for 1,066 seconds at a temperature of nearly 70 million °C represents a significant milestone for the EAST team in 2025.

3. PFC DESIGN WITH A CLOSED V SHAPE

3.1. V-shape divertor configuration

The Corner Slot (CS) design was proposed at the end of 2016 and implemented on EAST lower divertor in 2021, which is characterized by a right-angled corner at the outer divertor and constituted by horizontal and vertical target plates. A sharp corner slot divertor[1] with better power handling capability has been proposed as a candidate for the next-step divertor upgrade, based on a comparison simulation on different divertor configurations that the divertors with a closed corner on the SOL side exhibit lower temperature near the target plate as shown in FIG 2.

The V-shape divertor allows the strike point to be located at either horizontal target plate or vertical target plate, which provides additional flexibility in divertor operation and physics study.

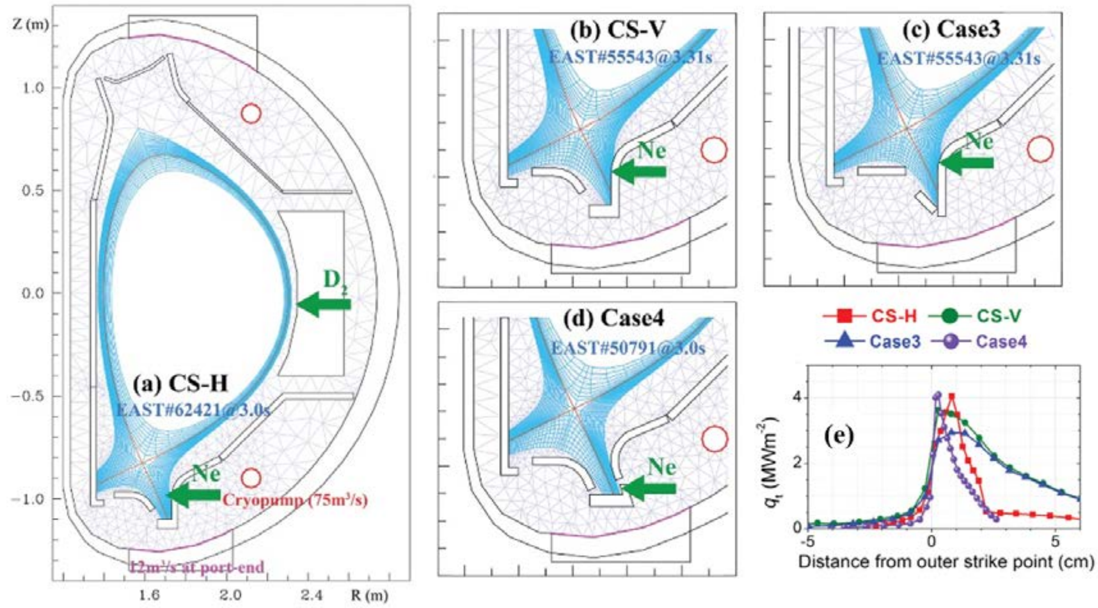

FIG. 2 Computational meshes for SOLPS simulations: (a) CS-H, (b) CS-V, (c) case 3: V-shape corner, (d) case 4: tightly baffled. The cryopump and the pumping port-end are indicated with red and magenta, respectively. The Distributions of qt along the outer target for CS-H (red), CS-V (olive), case 3 (blue), and case 4 (purple) are shown in (e). [9]

3.2. Engineering design of V-shape PFC

The structure boasts a deep slot of V-shape, and the hypervapotron cooling channels within the heat-sink are linked at the root as shown in FIG. 3. The CuCrZr/316L composite plate incorporates a gradual transition zone at the V-joint. This ensures a stainless steel mating surface, thereby mitigating issues inherent to bimetallic welding and enhancing structural stability, details can be found in Ref.[10].

Although simulations confirmed that this structure maintains all materials within their allowable limits under a heat load of 10 $MW \cdot m^{-2}$, structural integrity analysis revealed a risk of failure in the V-region heat sink. This risk was attributed to excessive stress induced by thermal deformation. Consequently, the structure was optimized to achieve stress release in the V-region while preserving its V-configuration and the hypervapotron PFU in the striking area, thereby satisfying all design requirements.

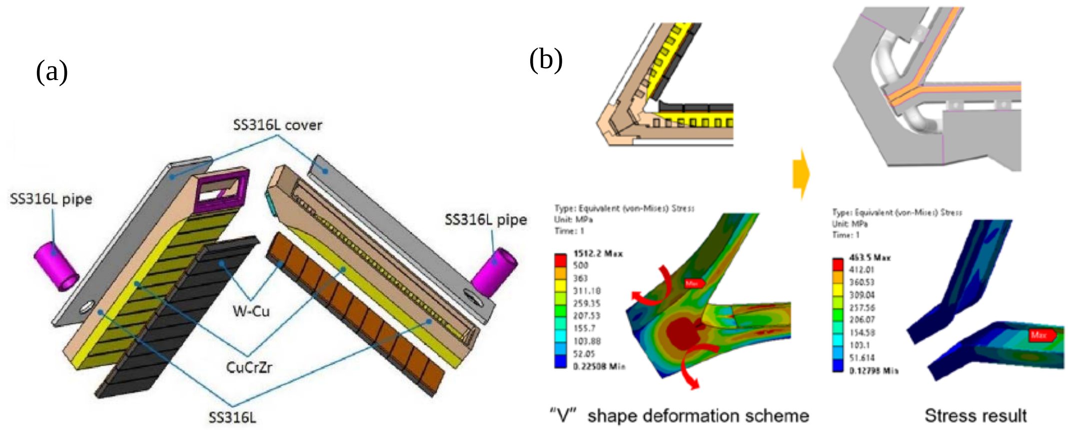

FIG. 3 (a)Engineering design for the V-shape PFC in divertor with flat-type structure[10]; (b)Optimization of the V-shape PFC by

3.3. Manufacture and test for mock-up

Two distinct technical approaches, namely a combination of explosive welding and brazing, and hot isostatic pressing (HIP), were employed to develop mock-ups. Both methods have demonstrated their technical maturity and reliability through years of operational experience in the EAST lower divertor. Furthermore, an optimal heat treatment process for the CuCrZr/316L composite plate was identified through the combination and optimization of multiple schemes. This process ensures that the bonding interface between the dissimilar metals maintains excellent strength at the heterogeneous transition section within the V-region. For details, please refer to Ref.[11]. Non-destructive testing such as hydraulic, baking, leakage, defect detection on interface have been implemented.

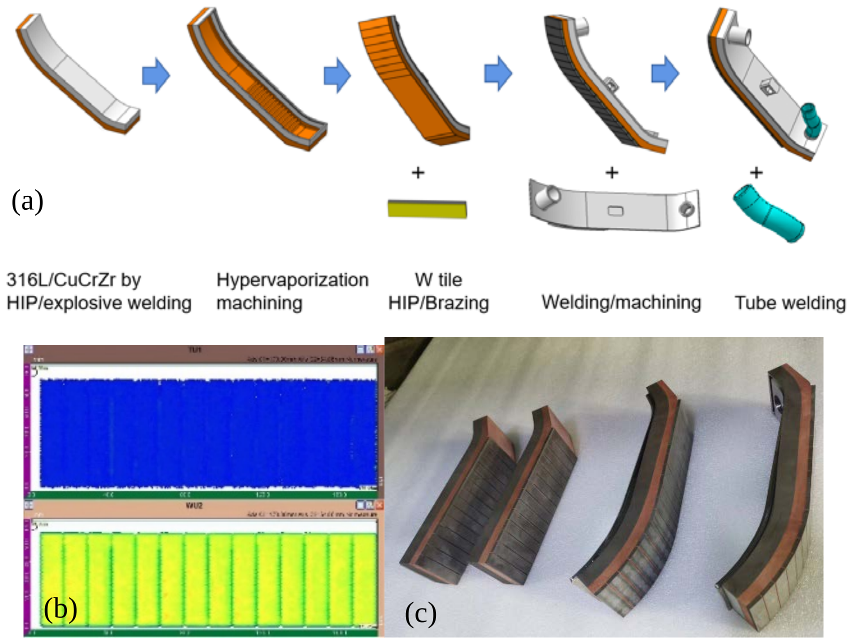

FIG. 4 (a)Manufacturing processes for the mock-up; (b)non-destructive inspection on interfaces of W/Cu and Cu/CuCrZr; (c)two sets of mock-ups

One PFU by brazing was selected for High heat flux(HHF) test under stationary heat flux of 15MW/m2 with coolant condition of Inlet temperature: 20℃, pressure: 1 MPa, mass flow: 1.5 kg/s. The strike zone is set on the first tungsten tile, see FIG. 5, to verify the heat remove capacity at the V-shape conner. The maximum temperature measured on the tile surface is around 750°C, and after 1000 cycles of 10s on and 10s off, no visual damage on the tested mock-up.

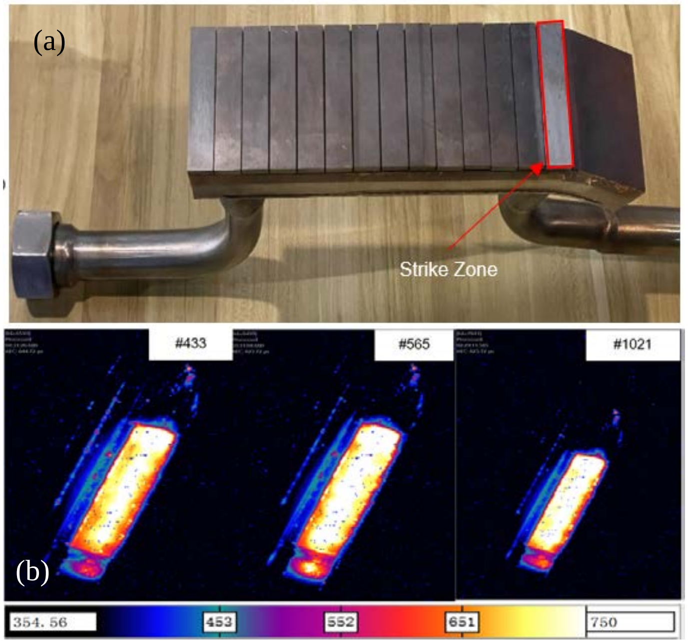

FIG. 5 (a)Mock-up after HHF test; (b)temperature measurement on the tungsten tile at the 433rd , 565th and 1021st cycle and the maximum temperature is 750 ℃.

4. MOCK-UPS AND PROTOTYPE FOR METER-SCALE DIVERTOR COMPONENTS

Building upon the aforementioned V-shape divertor PFC design, the engineering design and development of a meter-scale V-divertor PFC have been initiated to assess its feasibility for future application in larger-scale fusion devices and reactors.

4.1. Meter-scale divertor PFC design

In future large-scale fusion reactors, the size of the divertor will increase significantly. For instance, the length of the ITER divertor PFC will exceed 1 meter, posing greater challenges to the fabrication of tungsten-copper PFCs. At the same time, the heat load they withstand will rise with increasing operational power. To address this, engineering design efforts have been undertaken for large-scale divertor PFCs.

As shown in FIG. 6, in a divertor configuration with a closed V-shaped angle between the horizontal and vertical target plates, the length of the outer target plate—comprising the vertical target plate and the baffle—will reach approximately 1.2 meters. In this design, the vertical target plate is designed to withstand a steady-state heat load of 15 MW/m2 and adopts monoblock structure. In contrast, the baffle region, being a low heat-load area, uses a flat-type structure to reduce manufacturing difficulty and cost.

To accommodate the width constraints of the tungsten blocks, this design pairs two monoblock structures with a single flat-type structure. This design employs the heterogeneous transition structure (Section 3.3), using an alloy Inconel-625 interlayer to facilitate the connection of the CuCrZr tubes to the stainless steel. The cooling circuit is formed by incorporating a stainless steel water box at the opposite end of the two monoblock structures.

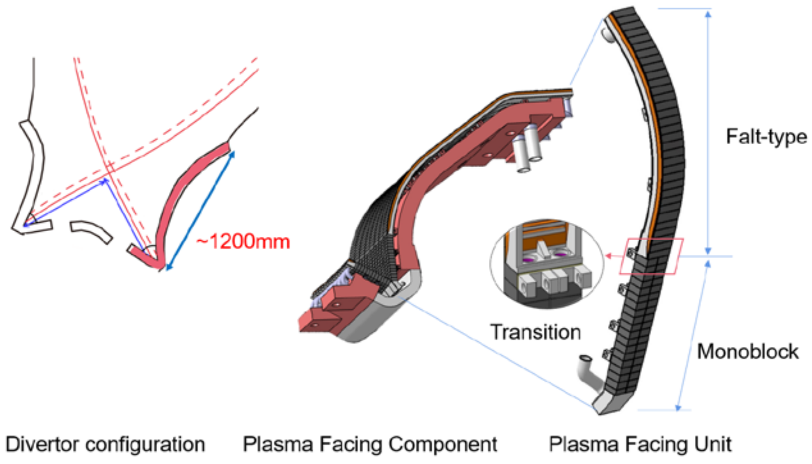

FIG. 6 Larger scale PFC design for fusion reactor

4.2. HHF test on PFU mock-up

Following the process qualification of key production steps, including CuCrZr mechanical properties after heat treatment, CuCrZr/316L interface, monoblock support leg joint and CuCrZr-316L tube to tube junction, the thermal fatigue performance of the monoblock structure was validated via high heat flux testing on a small-scale mock-up by HIP. This test aimed to verify its heat exhaust capability of 15 MW/m² in the striking zone. The mock-up successfully endured 5,000 cycles under an electron beam load of 15 MW/m² with a 15-second pulse duration, with no signs of structural failure such as melting (FIG. 7(a)). The temperature difference between the inlet and outlet coolant remained stable, with the maximum temperature stabilizing at approximately 1600°C. The only observed change was an increase in surface roughness on the tungsten. This change in surface reflectivity subsequently led to an apparent temperature rise in measurements taken by the infrared thermometer, as shown in FIG. 7(b).

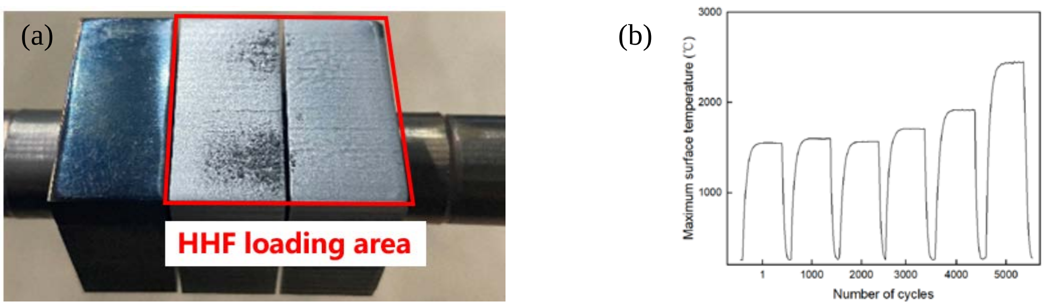

FIG. 7 (a)Monoblock mock-up after HHF test, (b)surface temperature measured during HHF test

A medium-sized PFU mock-up of 500mm length was employed to test the thermal fatigue performance of the transition region, which combined monoblock and flat-type structure. After 1000 cycles of 2 MW/m2 plus 1000 cycles of 5 MW/m2, no visual damage on the transition surface was observed, shown in FIG. 8 .

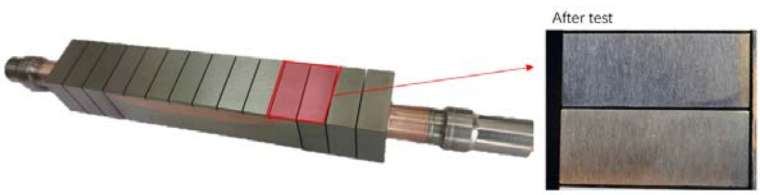

FIG. 8 Medium-sized PFU mock-up after HHF test

4.3. Fabrication of Large-scale PFC prototype

Two technical schemes—Hot Isostatic Pressing (HIP) and brazing—were retained for the large-scale PFC prototype. PFU prototypes exceeding 1.2 meters in length were developed using each method and successfully passed all acceptance tests, including pressure, leak rate, and dimensional inspections. Through the qualification of key processes, coupled with high heat flux testing on small and medium-sized mock-ups, the necessary technology and capability for implementing this V-shaped PFC in future fusion reactors have been mastered and validated. This effort culminated in the successful fabrication of full-scale prototypes for both the PFU and the PFC, as illustrated in FIG. 8.

(a)

FIG. 9 (a)PFU and (b)PFC prototype

5. R&D OF PFCS TOWARDS CFETR

As a part of Comprehensive Research Facility for Fusion Technology (CRAFT) project, a divertor prototype will be built to evaluate candidate plasma-facing materials and component mock-ups for China Fusion Engineering Test Reactor (CFETR).

Advanced materials, i.e.potassium-doped tungsten (KW) for armor, oxide dispersion-strengthened copper (ODS-Cu) alloy for heat sink.and reduced activation ferritic/martensitic (RAFM) steel for structure [12]. A gap in ODS-Cu material properties in the process of testing and developing large-size (>1700 mm x 180 mm x 28 mm) commercially purchased products. The small to middle-scale mock-ups as well as prototypes for CFETR have been successfully tested with 1000 cycles of 20 MW/m2.

6. SUMMARY

Capitalizing on years of dedicated technological development, the EAST device was outfitted with full-tungsten upper and lower divertors, thereby enabling a range of key operational accomplishments. In direct response to the demands for increased size and enhanced technical capabilities in future fusion reactors, ASIPP initiated and conducted the engineering design of a closed V-shaped divertor PFC. A comprehensive development strategy, encompassing vital process certification and high heat flux tests on prototypes, validated the design and culminated in the realization of a full-size, meter-scale prototype. Meanwhile, research targeting CFETR remains actively in progress, with substantial headway already realized in the industrial-scale production of advanced materials and the subsequent fabrication of prototypes. The experience and lessons obtained from manufacturing, testing and plasma operation on EAST and CRAFT are undoubtedly valuable for CFETR engineering validation.

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