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Plasma facing components of EAST

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ABSTRACT

EAST plasma facing components (PFCs) have the function of protecting the vacuum vessel, heating systems and diagnostic components from the plasma particles and heat loads, and also additional to this particles and heat loads handling. The PFCs are designed up–down symmetry to accommodate with both double null and single null plasma configuration. All PFCs use graphite tile for plasma facing surfaces affixed to copper alloy heat sink considering economical factor. Based on this structural design, detailed structural and thermal analysis had been carried out. A special deep hole drilling technology was developed to drill cooling channels directly on heat sink for high efficient heat removal. A dry lubricate material is used between stainless steel support and heat sink for the purpose of absorption of thermal expansion. And analysis results show that the present PFCs need to be improved for the next stage of steady state operation. The PFCs are installed in the vacuum vessel together with in-vessel coils, cryopump and diagnostic components. The design, analysis, manufacture and assembly have been finished. As indicated, all the in-vessel components were fabricated and assembled successfully and meet the design requirement for the plasma operation.

1. Introduction

The Experimental Advanced Superconducting Tokamak (EAST), that is an advanced steady-state plasma physics experimental device which has been built in ASIPP CAS, has plasma facing components (PFCs) to protect the vacuum vessel, heating systems and diagnostic components from the plasma particles and heat loads. The EAST divertor and other plasma facing components also have functions that are additional to this particles and heat loads handling. The divertor is designed to provide particles exhaust into the divertor cryo-pump, provide recycling control and impurity control. The passive plates stabilize the plasma vertical instability. Active control coils are used for plasma instability control. And magnetic diagnostic systems are installed for measurement of basic plasma parameters such as plasma current and loop voltage, equilibrium plasma configuration determination and MHD phenomena studies. Fig. 1 shows the elevation view of EAST PFCs. EAST is designed for operation with double null or single null divertor plasma, so the divertor geometry is designed as up–down symmetry to provide a large experimental flexibility and is capable of running in a scenario with power conducted along the field lines to the target plates, or in a radioactive divertor mode.

2. Design of EAST plasma facing components

2.1. Design description

The EAST tokamak is designed for long pulse (60–1000 s) capability. However, at the begining of plasma operation of EAST, heating power will reach 4 MW, and peak heat flux will not be more than 3.6 MW/m^2 on divertor plates. Considering the economical factor, brazed tiles are not employed in the initial PFCs engineering. All PFCs use bolted tiles. The EAST PFCs consist of a plasma facing surface affixed to an actively cooled heat sink. All plasma facing surface are one kind of multi-element doped graphite materials. The 15 mm or 20 mm (especially for divertor) thick graphite tiles are bolted to the copper alloy (CuCrZr) heat sink [1] and retrained through the spring washers that allow limited deformation during thermal expansion. This mechanically restrained structure is used for all PFCs system. It is the thermal conductance across the tile to heat sink interface that is very important for the performance of a bolted tile. A thin piece 0.38 mm of graphite sheet is used between the tile and the heat sink to improve the thermal contact. Bolted structure should provide a minimum 0.2 MPa average pressure over the contact area. Water cooling channels are drilled holes directly

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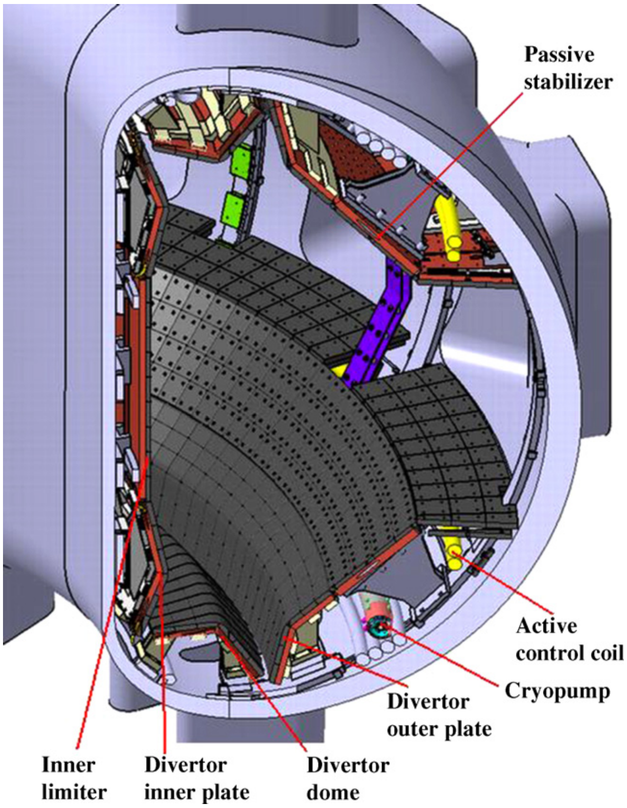

Fig. 1. Elevation view of EAST PFCs.

along the 20 mm thick heat sink plates. Fig. 2 shows the modular structure of EAST PFCs [2–4].

2.2. Divertor

EAST divertor geometry is designed as up–down symmetry to accommodate with both double null and single null plasma configuration. The upper and lower divertor structures each consist of three high heat flux targets: inner, outer and private baffle (dome). The configuration for EAST divertor is vertical targets with an almost open private flux region and dome below/above the X-point. The inner, outer vertical target surface and the magnetic field lines of the divertor separatrix intersect each other at an acute angle of 35° and 40°, respectively. This design reduces the heat fluxes on the target surface while at the same time permit a relative simple target geometry. The vertical targets and dome form a “V” shape and expect particles remain in this region to help distribute heat load uniform on divertor plates. Two gaps between inner, outer target and dome are provided with total 180 m^3/s gas conductance for particle and impurity exhaust by cryopump.

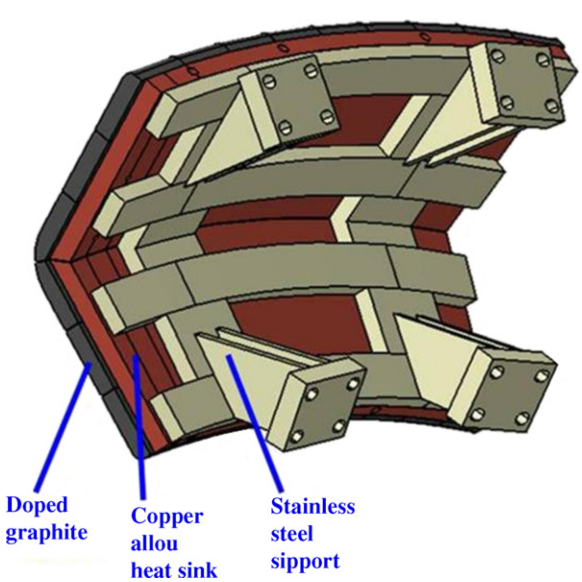

Fig. 2. Modular structure of EAST PFCs.

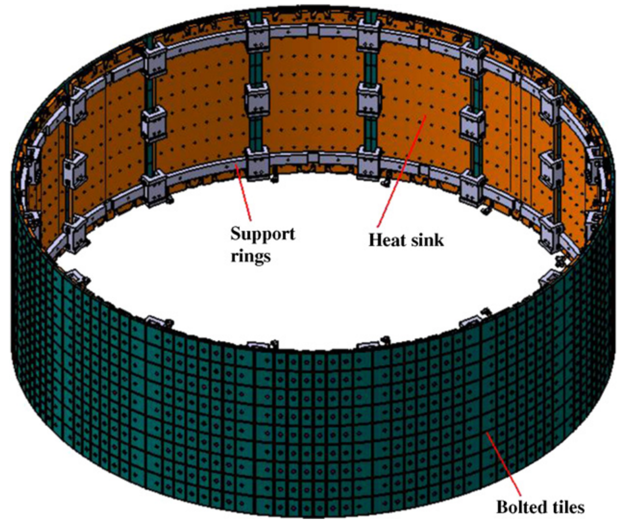

Fig. 3. Inner limiter.

The primary function of EAST divertor shown in Fig. 1 is to improve the entrainment of hydrogen and impurity neutrals. Inner target, outer target and dome consist of carbon tiles, CuCrZr heat sink, stainless steel supports and basis rails. The rails are the alignment basis to toroidal field flux. The divertor structure must have a high enough strength to withstand the loads occurring from both eddy currents and halo current. It must also have some flexibility relative to the vacuum vessel in order to reduce the magnitude of the differential thermal expansion loads that can occur both during operation and 350 °C bake out conditions. Cooling channels are drilled directly on heat sink. Peak heat load is up to 3.6 MW/m^2 and 2 t/h water mass flow rate for inner target, outer target and dome can maintain plasma facing surface temperature limited at 800 °C.

2.3. Other plasma facing components

The inner limiter is placed between the inner target plates of up and down divertors to protect the inside wall of the vacuum vessel. The limiter consists of 16 actively water-cooling panels that are mounted to two toroidal continuous rings (Fig. 3). These rings define the limiter shape and also allow to be aligned to the toroidal field if required. The rings mount to the vacuum vessel with base rings which reduce the stress that results from differential thermal expansion between the limiter and vacuum vessel. Accuracy of limiter is required in ±0.5 mm. Maximum heat load on first wall was estimated to be 0.5 MW/m^2.

The objective of passive stabilizer, at outer place inside vacuum vessel, is to stabilize plasma by inductive current when plasma vertical displacement event (VDE). The principle of stabilizer design is to obtain electric conductance as high as possible and distance to core plasma as short as possible. It is placed on the outer radius of the plasma above and below midplane. The thickness of the stabilizer is 30 mm copper alloy with carbon tiles for protection and coolant channels for cooling.

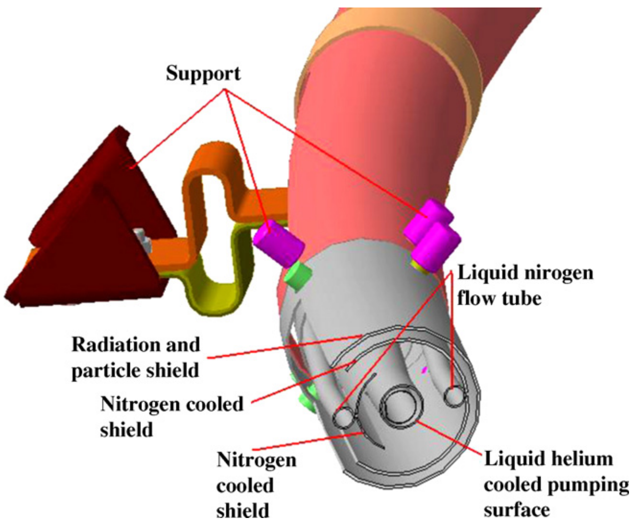

Fig. 4. Elevation view of EAST toroidally continuous cryopump.

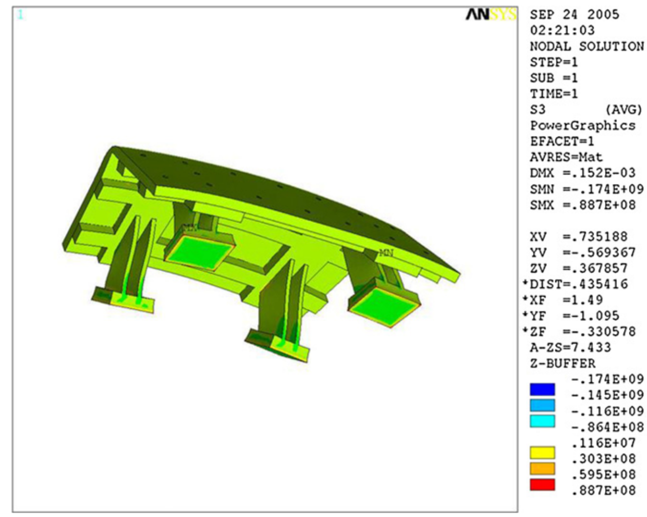

Fig. 5. Stress distribution under case 1 (eddy current + water pressure + self weight).

2.4. In-vessel coils and cryopump

In-vessel coils and cryopump are not the same structure with the other plasma facing components. In-vessel coils are active feed back coils. They are installed behind first wall and divertor plates to avoid facing plasma directly and fixed to vacuum vessel wall.

The divertor design features in-vessel cryopump located in a plenum under the outer divertor plate and passive stabilizer. In-vessel cryopump with liquid helium cooling tubes is behind down divertor outer plate, which is near the gap between the doom target and outer target. It provides pumping speed of 15 m^3/s. The pump is continuous tubes with slot open to vacuum vessel wall and is supported by flexible supports. Fig. 4 shows the cryopump cross-section geometry. Particles and impurity pass through gaps between target and dome pumped by cryopumps.

2.5. Magnetic diagnostic system

The magnetic diagnostic system includes the magnetic probes, Rogowasky coil, diamagnetic loop and halo current monitor. The magnetic probes consists of little probe and mirnov probe, they measure MHD oscillations, plasma shape and position. The Rogowasky coil can be used for measurement of the total plasma current. Diamagnetic loop, a single conductor around plasma in a circle in poloidal direction, is designed to measure β_θ that is one of the important factors of plasma equilibrium. Halo current monitor diagnose the halo current to study the vertical displacement event (VDE).

3. Structural and thermal analysis

3.1. Structural analysis

The structure of PFCs should have the ability to withstand not only the electromagnetic force due to eddy current when plasma disruption and halo current when vertical displacement events (VDEs) [5,6], but also the pressure of self-weight and cooling water and thermal stress caused by 350 °C baking out. For the calculation of electromagnetic force, the plasma current (1 MA) was assumed to be a thin ring, and the decay time is 3 ms. The maximum eddy current induced by plasma disruption is 42 kA. The halo current caused by VDEs is assumed to be 50% of the plasma current and the toroidal asymmetry factor was chosen as 2 due to toroidal field ripple. Being actively cooled PFCs of EAST, before the plasma operation, the PFCs needs to be baked up to 350 °C for the purpose of obtaining good wall condition for vacuum, and during plasma operation, it will be cooled by high pressure water. According to the load analysis and operation sequence, structural analysis was done under three different important working conditions. And the inner diveror target plate was selected to perform the analysis.

- Case 1: electromagnetic force due to plasma disruption with pressure load (0.5 MPa) of cooling water and self-weight.
- Case 2: electromagnetic force due to vertical displacement events with pressure load (0.5 MPa) of cooling water and self-weight.
- Case 3: 350 °C baking on PFCs for wall condition with pressure load of hot nitrogen and self-weight.

Figs. 5–7 shows the stress distribution of the plate in the case 1, 2, and 3, respectively. The maximum stresses, 88.7 MPa in the case 1 and 90 MPa in the case 2, are lower than the allowable stress of the structural material. In the case 3, the maximum stress is up to 3670 MPa which is unacceptable for structure design, some improvements needs to be done. All above analysis was based on the hypothesis that the heat sink is fixed fully onto the support. So the thermal expansion (about 4 mm) of the divertor plate cannot be absorbed and cause very high thermal stress in the case 3.

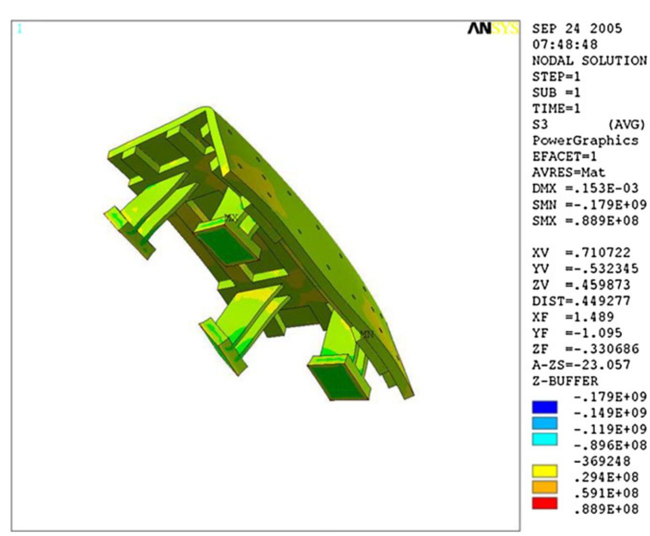

Fig. 6. Stress distribution under case 2 (halo current + water pressure + self weight).

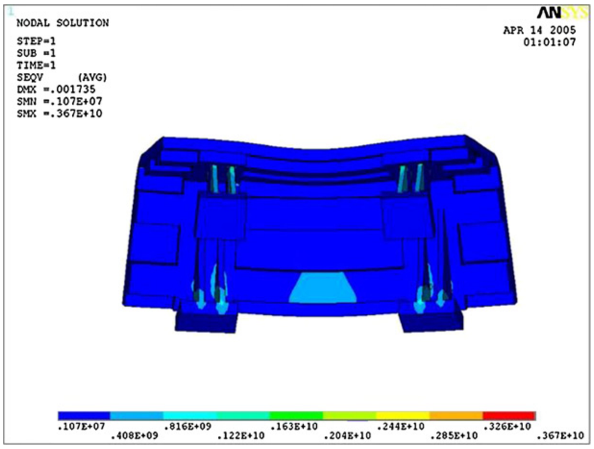

Fig. 7. Stress distribution under case 3 (baking + hot nitrogen pressure + self weight).

To reduce the thermal stress, a kind of solid lubricate material is chosen for the use between the support and the heat sink to permit relative movement between them. The friction factor of this material to both stainless steel and copper alloy are lower than 0.35 even under vacuum environment. Since the thermal expansion is absorbed by the movement, the analysis indicates that the structural stress intensity is reduced to 379 MPa.

3.2. Thermal analysis

The divertor and other PFCs have the function of handling the particles and heat load from plasma and the plasma heating power will be increased gradually. So it is necessary to do a detailed thermal analysis for the PFCs, especially the divertor because the divertor configuration is the main operation mode on EAST. During the conceptual design phase, thermal analysis results drove a selection of cooling hole drilled directly on the heat sink among three candidates [2]. During the first stage operation of EAST, the peak heat flux on divertor plate will not be more than 3.6 MW/m^2, so, bolted structure is used for the attachment of graphite tiles to heat sink considering economical factor. But then, the thermal contact conductance between them is a key issue for the heat handling. Some tests for thermal contact conductance had been carried out and results shows the thermal contact conductance depends on the contact pressure and surface roughness. A 0.38 thickness graphite sheet is used between tile and heat sink to improve the heat contact. The heat load from plasma is not uniformly distributed on the plate, and around the strike point about 80% of the heat load accumulated in an area ±2 mm (shown in Fig. 8) [3]. For different heat load on the plate, thermal analysis results (Fig. 9) show that if the surface temperature of the tile is required to be lower than 800 °C and

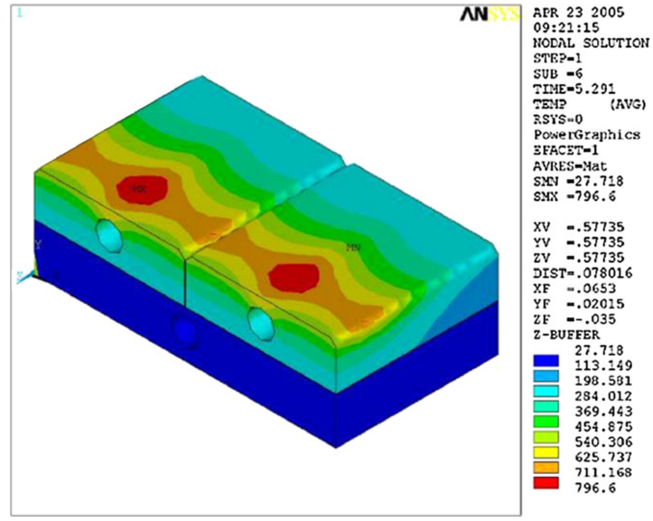

Fig. 8. Thermal analysis module.

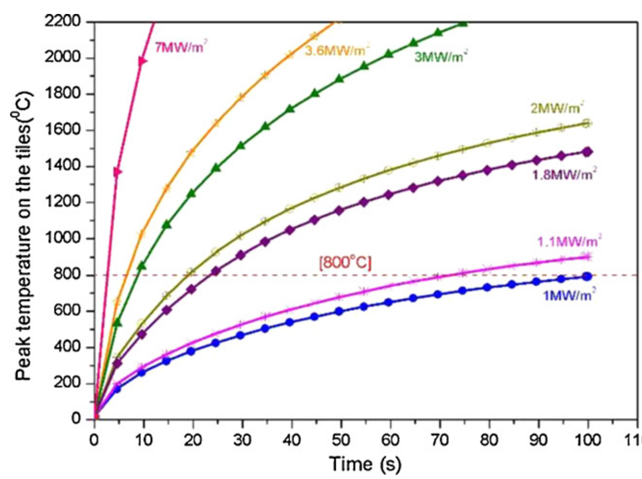

Fig. 9. Surface temperature change with time under different heat flux.

the time of plasma discharge pulse is beyond 100 s, the peak heat flux must be below 1 MW/m^2. So the present PFCs cannot satisfy a steady state operation. To calculate how much time need for cooling down the PFCs to the initial temperature, the analysis has been done. As shown in Fig. 10, if the heat flux on the plate is 1 MW/m^2, it will needs a 200 s break down between two plasma pulse, and 300 s when the heat flux is 7 MW/m^2. It is because if the heat flux is lower, the heat deposited onto the plate could be partially removed when the temperature of first wall material increasing, and if the heat

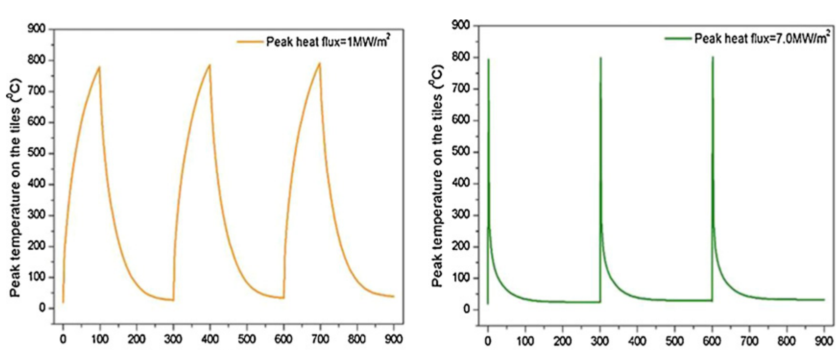

Fig. 10. The time of cooling down in two different heat fluxes.

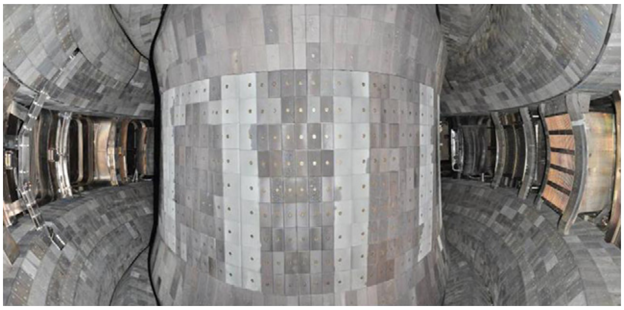

Fig. 11. Final aspect of EAST plasma facing components.

flux is higher, nearly all the heat deposited onto the plate should be removed during the break down time.

4. Manufacture and assembly

4.1. Manufacture

Because of the restricted room in the vacuum vessel and shape requirement of the surface of PFCs, the supports are designed with complicated and compact structure. The supports must be strength high enough to withstand the electromagnetic forces and adapt to the accuracy requirements of the surface of PFCs. So the 316 L stainless steel parts were welded form the complicated structure, and then the supports were machined by numerical control machine to make sure the strength and accuracy of it.

The heat sink is made of copper alloy and required to have high thermal conductance for heat removal and strength enough for electromagnetic forces and thermal stress. The alloy roughcast was shaped up before machining. For more efficient heat removal in PFCs, cooling channel was drilled directly on the heat sink which brings difficulty in machining process. A special drilling technology was developed for the long cooling hole with small diameter, and some 890 mm long with 12 mm diameter deep hole were drilled successful on inner limiter heat sink and also other size deep holes on other PFCs heat sink. Two neighboring holes are connected by a stainless steel tube based on a special medium-frequency induction welding technology. When the deep cooling channels had been drilled, the heat sink surface was machined and many small planes were processed for the purpose of adaption to graphite tile installation and accuracy requirement of plasma facing surface. The accuracy of heat sink must be controlled in ± 0.5 mm, and the leakage of cooling channels of one heat sink caused by tube welding or material itself should be lower than 1×10^{-10} Pa m^3 s^{-1} under 1 MPa pressure at room temperature.

4.2. Assembly

All PFCs consist of carbon tiles, CuCrZr heat sink, stainless steel supports and basis rails. The rails are the alignment basis to toroidal field flux. When all of these rails are welded to vacuum vessel wall the precision of them cannot be changed again, then accuracy of plasma facing surface to field surface is depended on precision of each module fabrication. All PFCs were divided into 16 modules in toroidal direction, respectively. They can be taken in and out from vacuum vessel horizontal ports, and easy for maintaining and modifying. For the whole assembly of in-vessel components, the base rails were welded to vacuum vessel wall as installing benchmark of the PFCs, then the electromagnetic diagnostic components and water pipes of main cooling loop for PFCs were installed, and also in-vessel coils and cryopump were assembled in this period. The PFCs assembly began when all the other components which are not facing the plasma directly had been installed. The supports were installed onto base rails, and on which the heat sink were fixed. The plasma facing surface which is doped graphite affixed to the actively cooled heat sink by bolts. Fig. 11 is the final view of EAST PFCs in the vacuum vessel.

5. Conclusion

EAST plasma facing components are designed up–down symmetry to accommodate with both single null and double null plasma operation. All PFCs are the same structure with graphite plasma facing surface affixed to copper alloy heat sink by bolts. Thermal analysis drove a selection of structure design that the cooling channel is drilled directly on the heat sink for high efficiency of heat removal, so a special deep hole drilling technology was developed to conquer the long hole drilling. A 0.38 mm graphite sheet is used between tiles and heat sink to improve the heat contact conductance. The heat sink is supported by stainless steel support which is installed onto the base rails and a dry lubricate material is used between heat sink and support for the purpose of thermal expansion absorption and thermal stress reduction. Finally, all the first wall components were fabricated and assembled successfully and meet the design requirement for the plasma operation.

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