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Design, fabrication and assembly of EAST plasma facing components

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EAST, with full superconducting magnetic coils, has been designed and constructed to address the scientific and engineering issues under steady state operation. It has plasma facing components (PFCs) with 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. A special deep hole drilling technology was developed to drill cooling channels directly on heat sink for high efficient heat removal. As the benchmark of assembly for PFCs, the base rails are installed and measured precise based on a new alignment method integrating the optical instruments and a mechanical template. And so is a mechanical check template for checking the surface of first wall. 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.

Keywords: EAST, plasma facing components, design, fabrication, alignment, assembly

1. Introduction

Since the beginning design and construction phase of EAST tokamak, one of its main objectives has been the study of scientific issues such as edge and divertor plasma and plasma surface interaction under steady state operation and engineering mission is to establish the technology basis of entirely superconducting tokamak in support of future reactors. To achieve the steady operation, the EAST comprises 16 D-shaped superconducting toroidal coils, which can create and maintain a toroidal magnetic field B up to 3.5T. The key components of EAST also include 14 poloidal superconducting coils, current leads and superconducting bus-lines, vacuum vessel, thermal shields, cryostate, actively cooled divertor and other plasma facing components [1-3]. The primary function of PFCs is 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 which is a toroidal continuous and space-saving tube under the outer plates and the stabilizer, provide recycling control and impurity control. The passive plates stabilize the plasma vertical instability. Active control coils are used for plasma instability control [4, 5]. Fig.1 shows the elevation view of EAST PFCs.

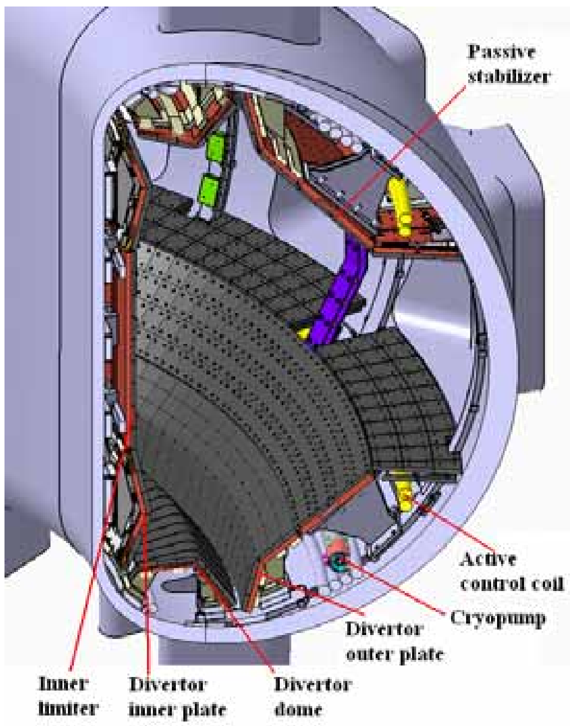

Fig.1 Elevation view of EAST PFCs.

2. Design of EAST plasma facing components

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2.1 Design description

The EAST tokamak is designed for long pulse (60-1000s) capability. However, at the beginning of plasma operation of EAST, heating power will reach 4MW, and peak heat flux will not be more than 3.6 MW/m2 on divertor plates, brazed tiles are not employed in the first 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 for its light weight, high thermal conductance, low-Z, excellent thermal-mechanical properties and good physical/chemical sputtering resistance and good experience gotten on HT-7 tokamak [5-9]. For future high power level plasma operation, the surface material will be replaced by tungsten. The 15mm or 20mm (especially for divertor) thick graphite tiles are bolted to the copper alloy (CuCrZr) heat sink [10] and retrained through the spring washers that allow limited deformation during thermal expansion. PFCs can be divided into two parts, one with a high heat load (divertor plates and limiters) and another with lower heat load. During plasma operation metal atom sputtering is not permitted, therefore different plasma facing material attaching structures are employed which is shown in Fig.2, left one is for lower heat load where the bolt is screwed from the side of graphite tile, right one is for higher heat load where the bolt is screwed from the side of heat sink [11]. It is the thermal conductance across the tile to heat sink interface that are very important for the performance of a bolted tile. A thin piece 0.38mm of graphite sheet is used between the tile and the heat sink to improve the thermal contact. And to make sure the tile and the heat sink contact with each other well and have a good thermal conductance, the test of thermal contact conductance depended on the contact pressure had been done, the results shows that bolted structure should provide a minimum 0.2MPa pressure over the contact area. For efficient heat removal, water cooling channels are drilled holes directly along the 20mm thick heat sink plates. To reduce the thermal stress on the structure when 350℃ baking for the PFCs, a kind of solid lubricate material is chosen for the use between the support and the heat sink to permit relative movement between them. Fig.3 shows the modular structure of EAST PFCs.

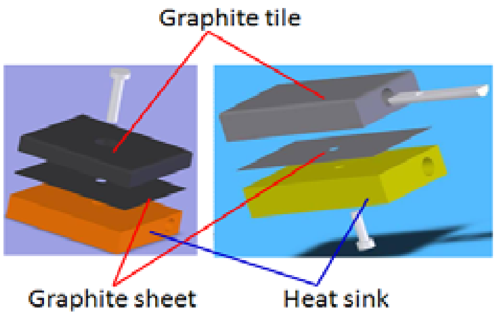

Fig.2 Detailed structural of graphite tiles attached to heat sink.

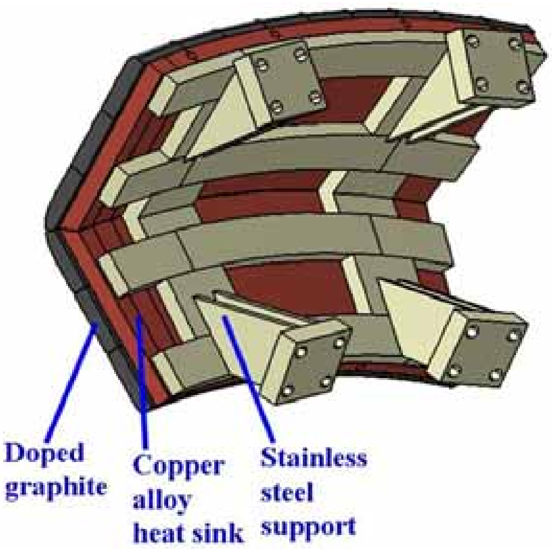

Fig.3 Modular structure of EAST PFCs.

2.2 Divertor

As shown in Fig. 4, EAST is designed for operation with double null or single null divertor plasma, so the divertor geometry is designed as up–down symmetry and to be capable of running in a scenario with power conducted along the field lines to the target plates, or in a radioactive divertor mode. The upper and lower divertor structures each consist of three high heat flux targets: inner, outer and private baffle (dome). The configuration for

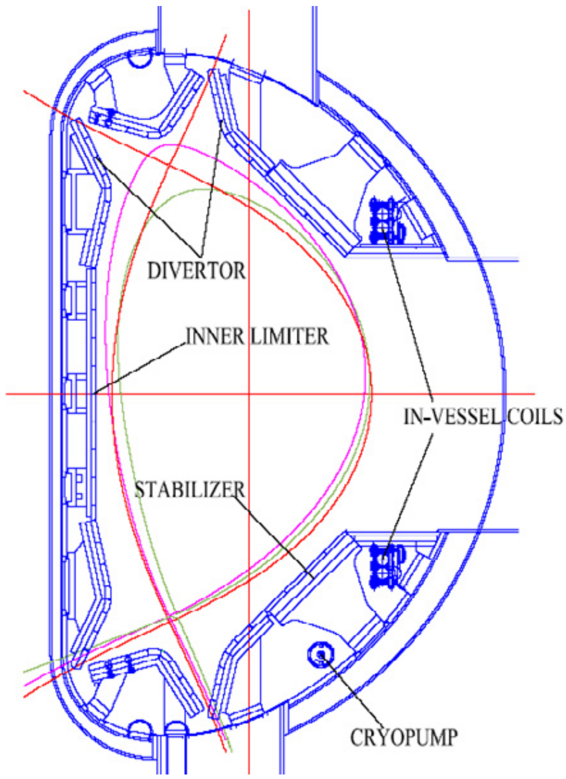

Fig.4 Divertor geometry with typical plasma equilibrium at the targets

EAST divertor is targets with an almost open private flux region and dome below/above the X-point. The inner, outer 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 relative simple target geometry. The 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 180m^3/s gas conductance for particle exhausted by cryopump.

The primary function of EAST divertor shown in Fig.4 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. Targets and dome 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 cooling pipe arrangement, each divertor module is divided into 3 separated loop, inner target, dome plate and outer target. The same with dome plates and outer targets, the 16 inner targets are parallel connection in toroidal direction.

The divertor structure must have a high enough strength to withstand the loads occurring from both eddy currents and halo current. Halo current considered 50% of plasma current and its toroidal asymmetry factor is 2 [11, 12]. Cooling channels are drilled directly on heat sink. Peak heat load is up to 3.6 MW/m2 and 2 t/h water mass flow rate for inner target, outer target and dome can maintain plasma facing surface temperature limited at 800℃.

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.5). 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 tile face is required in ±0.5mm and the minimum and maximum gap between tiles are designed as 0.6mm and 1mm for the thermal expansion absorption and wet area control during operation. Maximum heat load on first wall was estimated to be 0.5 MW/m2.

The objective of passive stabilizer, at outer place inside vacuum vessel, is to stabilize plasma by induced 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 mid-plane. The thickness of the stabilizer is 30mm copper alloy with carbon tiles for protection and coolant channels for cooling.

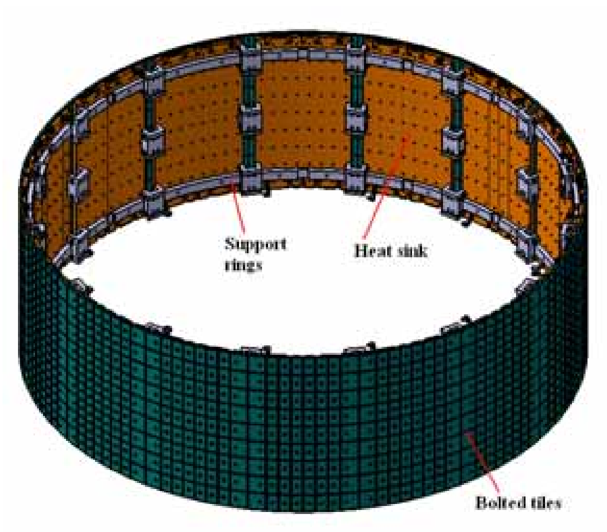

Fig.5 Inner limiter.

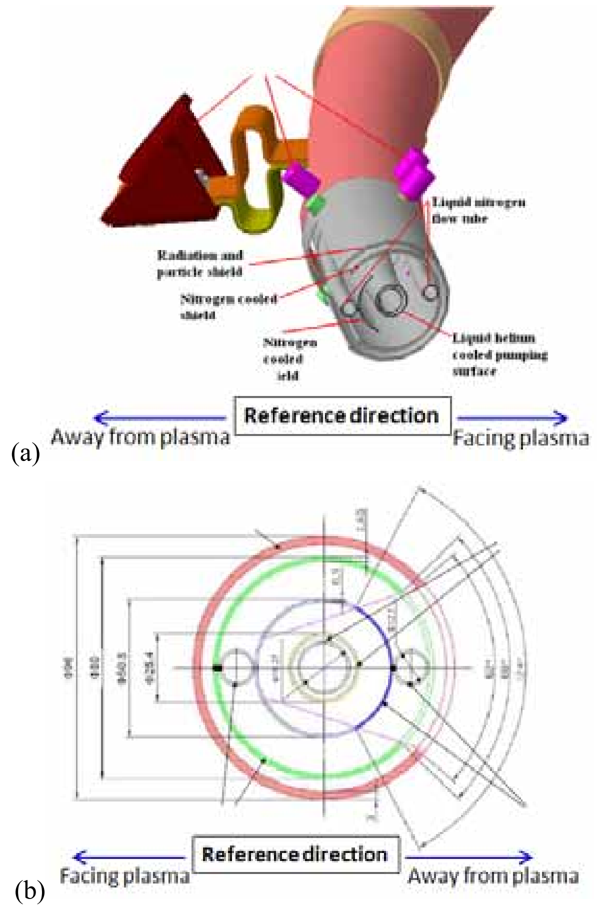

Fig.6 Elevation view of EAST toroidally continuous cryopump.

2.4 In-vessel coils and cryopump

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 dome plates and outer plates. The pumping speed of D_2 is about $75m^3/s$, and it could absorb $2500 Pa \cdot m^3$ of D_2 before saturation [3]. The pump is continuous tubes with slot open to vacuum vessel wall and is attached to the vessel with series of brackets that are stiff vertically and flexible in radial for thermal expansion and contraction. The geometry is similar to DIII-D cryopump. Fig.6 shows the cryopump cross-section geometry. It consists of cryocondensation surface, a nitrogen shield and a particle shield. The condensation surface comprising a 25.4mm stainless tube cooled by supercritical helium. A coaxial 19mm annular tube is inserted in the 25.4mm tube for the purpose of increasing the flow velocity, heat transfer coefficient and flow stability [13, 14]. All the tubes are made by Inconel 625 except the particle shield is SS316L and the insulation parts in the cryopump are made by G10 with ethoxyline coating. Particles and impurity from low divertor region pass through gaps between target and dome pumped by cryopumps.

3. Fabrication and assembly

3.1 Fabrication

To make sure the strength and machining accuracy of the support, the 316L stainless steel parts were welded together to obtain 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 drilling technology was developed for the long cooling hole with small diameter, and some 890mm long with 12mm 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

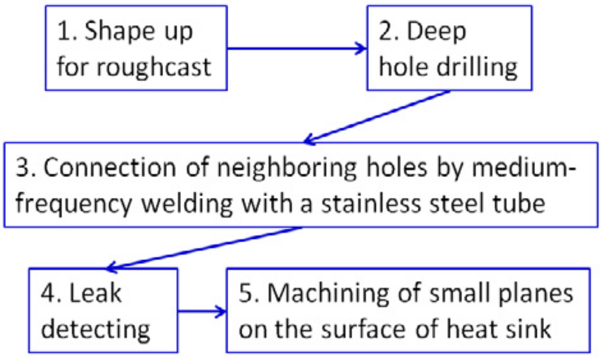

Fig.7 The flow chart of main machining process for heat sink

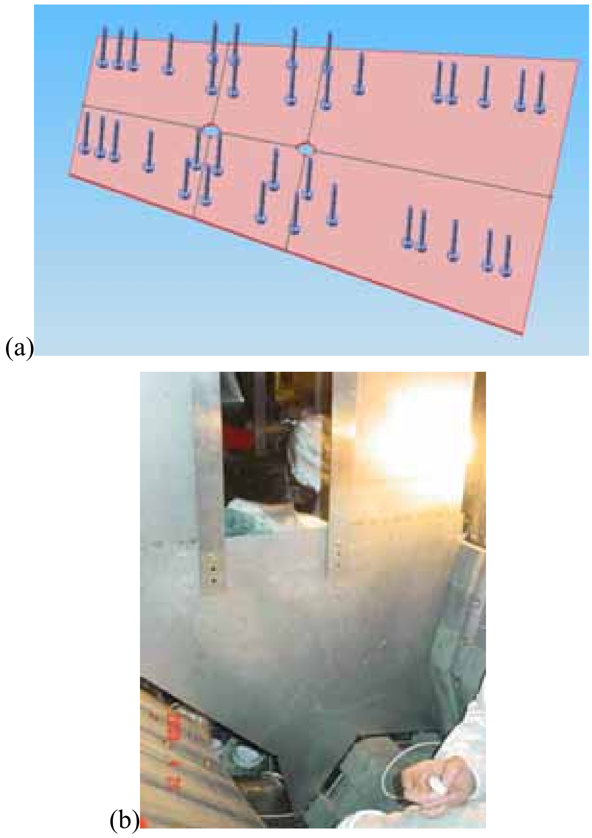

Fig.8 The mechanical benchmark template (a) and checking template (b).

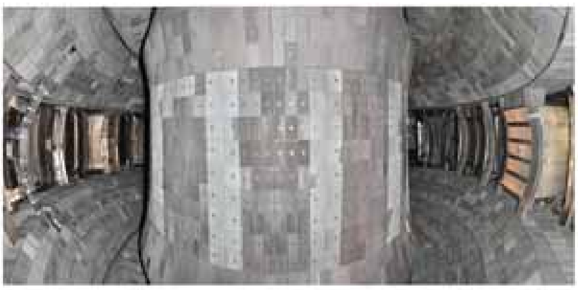

Fig.9 Final aspect of EAST plasma facing components

small planes were processed for the purpose of adaption to graphite tile installation and accuracy requirement of plasma facing surface. Fig.7 presents the flow chart of main machining procedure for heat sink. The accuracy of the surface for heat sink must be controlled in ±0.5mm, and the leakage of cooling channels of one heat sink caused by tube welding or material itself should be lower than $1\times10^{-10}\,Pa\cdot m^3\cdot s^{-1}$ under 1 MPa pressure at room temperature.

3. 2 Alignment and assembly [15]

As one of the key components of EAST Tokamak, the PFCs should have the ability for exhausting energy and reduction of impurity generation and meet some requirements related to magnetic surface shape. The magnetic field lines and the first wall intersect with a certain angle and the plasma energy deposits on PFCs along magnetic field lines. To avoid the local heat load congregation and ablation for the material of the first wall, all the PFCs should have the high assembly accuracy about 0.5mm. A set of base rails are designed to compensate the error of fabrication and assembly of vacuum vessel as the benchmark of the assembly for PFCs. A new alignment method integrating the optical instruments and mechanical benchmark template which is just a flat plate covering the divertor module area in toroidal direction is applied. At the same time, some measure points on the basis rails have been made according to the projection of the measure holes on template. And a check template which is designed according to the theoretical dimension of the cross section of first wall shrinking 5mm is used to calibrate the first wall after assembly.

When assembly, first the basis rails are adjusted to ensure the vertical align the measure points on basis rails and the corresponding measure holes on template, which makes the radial and toroidal direction position of divertor is correct. After the assembly of the electromagnetic diagnostic components and water pipes of main cooling loop for PFCs and also in-vessel coils and cryopump. The PFCs assembly began with 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. Then, for the alignment, last the height of divertor should be adjusted to the accurate position.

Fig.8 shows the mechanical benchmark template and checking template and Fig.9 is the final view of EAST PFCs in the vacuum vessel.

4. Conclusion

EAST plasma facing components are designed up-down symmetry having the flexibility for limiter, single null, double null configurations with wide range shaping and flexibility for different fueling method. EAST PFCs is a modular design with the benefit of easily assembly and disassembly. The modules have enough flexibility to align the components with respect to the magnetic fields. All PFCs are the same structure with graphite plasma facing surface affixed to copper alloy heat sink by bolts. Cooling channel is drilled directly on the heat sink for high efficiency of heat removal. A 0.38mm 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. A new alignment method integrating the optical instruments and mechanical benchmark template has been developed for the accurate assembly.

Finally, all the first wall components were fabricated and assembled successfully and meet the design requirement for the plasma operation.

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