Fully Active Cooled In-vessel Components of EAST Tokamak

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Abstract: EAST is the first full superconducting tokamak equipped with actively cooled plasma facing components (PFCs). The design and assembly were firstly finished in May 2008. During the two experiment campaigns in 2008 and 2009, the in-vessel components with full graphite tiles as first wall had been operated successfully. However, in some cases, fast particles have been observed, which locally increased power flux density and lead to the damage of the PFCs and other in-vessel components. For safety operation with active water cooling PFCs to handle large input power over long pulse discharge, some design optimization, R&D and maintenance were accomplished to improve the in-vessel components. For the purpose of large plasma current (1MA) operation, the previous separated top and bottom passive stabilizers in low field were electrical connected to stabilize plasma in the case of vertical displace events (VDEs). The design and experiments are described in this paper.

1. Introduction

Since the first plasma discharge on 26th September, 2006, EAST, full superconducting tokamak, has been operated through four experiment campaigns. In the first two campaigns (before 2008), all plasma facing components (PFCs) had stainless steel as first wall. For the long pulse operation with higher power injection, all the PFCs had been upgraded to full graphite tiles bolted to copper alloy heat sink with actively cooled channels in 2008. However, with good performance during plasma operation, the EAST PFCs were damaged in some local areas due to high energy particles and electromagnetic force. To make the PFCs meet the requirement of future 3-5 years campaigns, some maintenance and R&D work of in-vessel components were carried out in 2009. In addition, the separated top and bottom passive stabilizers were connected electrically to stabilize plasma. This paper introduces the main features of EAST fully active cooling in-vessel components, some design improvements and R&D work to promote the reliability of active cooling water system, and the design and activation for passive stabilizers.

2. Updated EAST In-vessel Components Structure Description[1] [2]

EAST has active cooling PFCs equipped with full graphite first wall, which consists of divertor, inner toroidal limiter (high field PFCs), passive stabilizer, low field PFCs. Two moveable poloidal limiters and heating systems (ICRH and LHCD) are installed approximately symmetry in toroidal direction. These PFCs are integrated with magnetic diagnostic components, in-vessel control coils, divertor probes, in-vessel cryopump and vacuum conditioning parts (GDC electrode and ICRF). All the PFCs have the same structure with graphite tiles affixed copper alloy heat sink supported by stainless steel. For assembly and maintenance convenience via the equatorial ports, EAST PFCs are divided into 16 modules along toroidal. FIG.1 shows the elevation view of EAST in-vessel components.

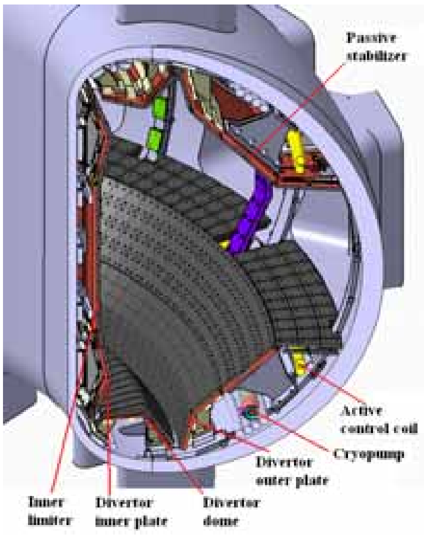

FIG.1. Elevation View of EAST PFCs.

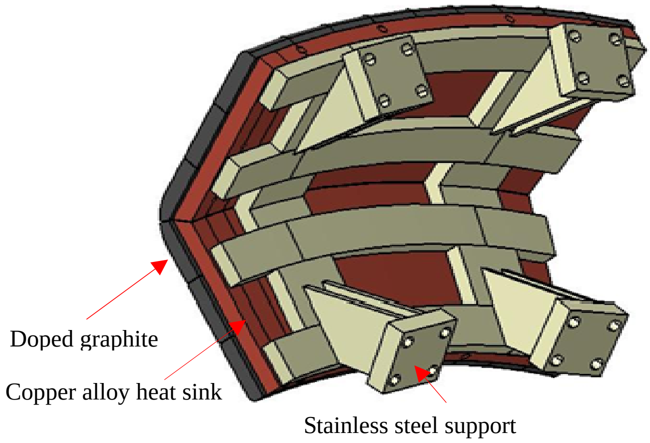

FIG.2. Modular Structure of EAST PFCs.

The EAST tokamak is designed for long pulse (60-1000s) capability. However, at the earlier plasma operation of EAST, heating power reach 4MW, and peak heat flux is no more than 3.6 MW/m^2 on divertor plates, brazed tiles are not used in the first PFCs engineering. All PFCs use bolted tiles. The EAST PFCs consist of a plasma facing surface affixed to an active cooled heat sink. All plasma facing surface are one kind of multi-element doped graphite materials for its light, high thermal conductance, low-Z, excellent thermal-mechanical properties, good physical/chemical sputtering resistance and good performance on HT-7 tokamak operation [3-7]. The thermal conductance across the tile to heat sink interface is very important for the performance of the bolted tile. A thin 0.38mm graphite sheet is used between the tile and the heat sink to improve the thermal contact. FIG.2 shows the modular structure of EAST PFCs.

EAST is designed for operation with double null or single null divertor plasma, so the divertor 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 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 active water cooling panels that are mounted on two toroidal continuous rings. Maximum heat load on first wall was estimated to be 0.5 MW/m^2.

In-vessel cryo-pump with liquid helium cooling tubes is behind lower divertor outer plates, which are close to the gap between the dome plates and outer plates. The pumping speed of D_2 is about $75m^3/s$, and it could absorb $2500Pa{\cdot}m^3$ 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. FIG.3 shows the cryo-pump cross-section geometry.

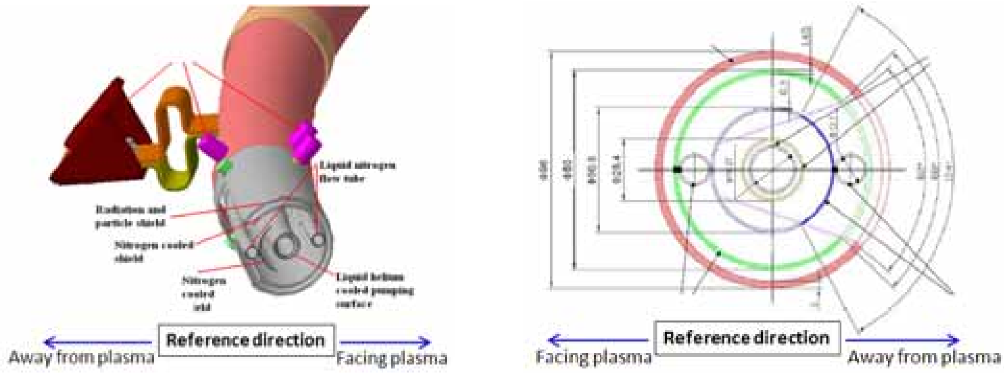

FIG.3. Elevation View of EAST Toroidal Continuous Cryo-pump.

DC glow discharge (GDC, see FIG.4) is employed to clean the first wall of EAST Tokamak. Four DC GDCs distribute equally on the EAST Tokamak vacuum vessel wall. Each GDC is equipped with an anode, a stainless steel cover and four support legs. The size of each anode is 25mm in diameter and 450mm in length. The anode is insulated from stainless steel cover with Al_2O_3 ceramics. The power of DC GDC is transfered to the anode through insulation cable, insulation electrode and its flange. The cover is linked directly to vacuum vessel wall through four support legs. The GDCs can discharge, boronize, siliconize and so on with different operating gases such as H_2, He, $C_2B_{10}H_{12}$, SiH_4 according to physical requirements to clean first walls. After GDC cleaning, the percentage of remaining gases in vacuum vessel is changed greatly and high vacuum in the vacuum vessel can be reached.

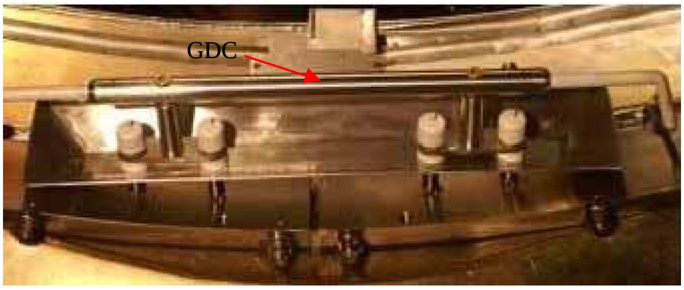

FIG.4. GDC Installed in EAST VV.

3. Design Improvement and R&D Work for The Fully Active Cooling In-vessel Components

The in-vessel components had been worked very well in the last two experiment campaigns and the primary functions were realized. Nevertheless, some damage was found after a campaign like the ablation and desquamation happened on graphite tiles as the power flux deposition was increased locally and the electromagnetic forces were strengthened by the eddy currents and halo currents; the water tubes under divertor around ‘V’ area were penetrated by the fast particles.

To make sure the safety operation of active cooling PFCs, the tile gap between the adjoining PFCs' modules was adjusted to an optimized value for well thermal expansion. The damaged graphite tiles were replaced with proper torque and checked carefully. A protection structure of Mo jacket along toroidal cooling water tubes was designed. Besides, another R&D works on improving the heat exchange efficiency of water cooling channel in the heat sink of PSL. With a called expanded tube technique, the Cu tube is expanded by the high pressure water which results close contact with the internal wall of channel in heat sink plate, so it has no leakage problem and expected efficiency.

3.1. Protecting for Water Cooling Tube around 'V' Region under Divertor

To operate a long pulse experiment, the active cooling PFCs is necessary. So it is very important for cooling water system can work safely during the experiment. Once the cooling pipes and channels were broken or water leakage happened in the vacuum vessel, the plasma will quench and experiment has to be interrupted. During last two experiment campaigns, the EAST PFCs system worked well without cooling water, but one problem is found that the cooling pipes which across the divetor **'V'** region had been damaged (FIG.5).

It is necessary to develop a new structure to protect the cooling pipes. FIG.6 shows that the outer plate graphite become longer than the original to protect the particles from plasma running toward the **'V'** region directly. The increased length of 20mm is selected considering the minimal influence to the cleaning function of divertor. These graphite tiles have been designed to withstand extra heat load from the plasma to protect the components that hide at the bottom of **'V'** region. However, the new graphite tiles cannot be used for all cooling pipes because of space limit under the divertor at some toroidal positions.

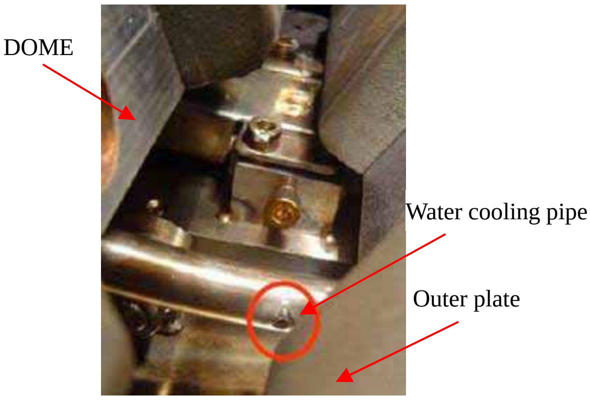

FIG.5. Damage on Cooling Pipes

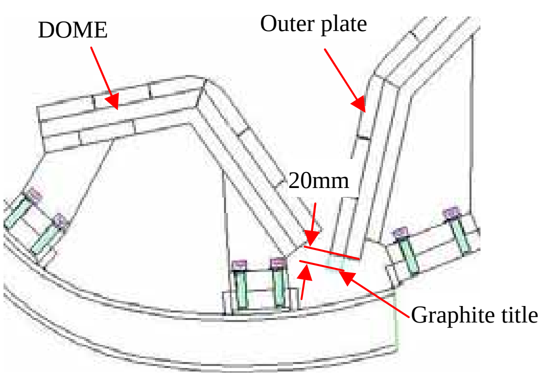

FIG.6. The Extended Graphite Title

A special design of protection of cooling pipe is to use a group of node jacket pipes of 5 mm thick while cooling pipe is only 1mm thick. And the jacket pipes are made of molybdenum (Mo) to face the plasma. Every node has one conic head so that the pipe assembly can easily be suit the central curve of cooling pipe without any gap. Fig.7 and Fig.8 shows the node pipe and its assembly in EAST.

FIG.7. Structure of Node Jacket Pipe

FIG.8. Jacket Pipe Assembly

In order to find out which material and how much thickness is optimal, the temperature rise of three different types of materials with different thickness under the same heat flux is calculated numerically. As shown in FIG.9, for the same type of material, the peak temperature decreases with the thickness of the pipe. For the same thickness, the peak temperature of wolframium(W) material is the highest, and its melting temperature is also the highest, while the peak temperature of Mo material is the lowest, and its melting temperature is in middle, in contrast, the peak temperature of steel material is high while its melting temperature is the lowest, which is not suitable.

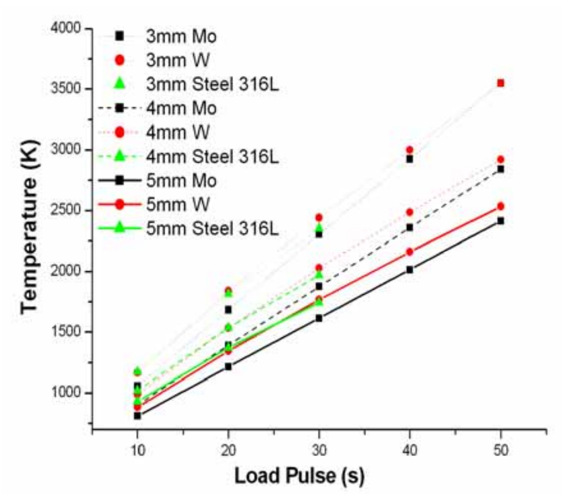

FIG.9. Peak Temperature vs. Loaded Pulse and Jacket Pipe Thickness

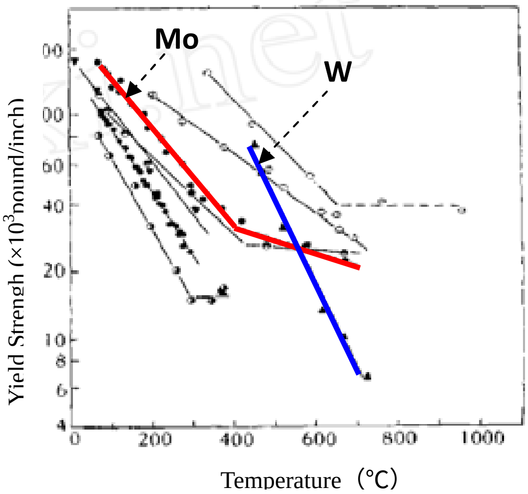

FIG.10. Yield Strength vs. Temperature

The relationship between the yield strength and the temperature of the material Mo and W is shown in FIG.10. As shown in the figure, the yield strength of Mo is higher than W when the temperature is higher than 570℃. In conclusion, we decide to select the Mo as the pipe material and take the thickness of 5mm.

3.2. Optimization of Heat Sink Cooled Structure

For safety operation of cooling water system, the cooling structure in heat sink is as important as the cooling tube in the vacuum vessel. The original design is that water cooling channels are drilled directly on the heat sink plates, and each module of water channels are connected in series. However, due to unstable quality of chromium-bronze, even if it has a minor crack, it will be extremely high sensitive to brittle transition temperature [4, 5]. It caused seven leakages during last two experiment campaigns. To solve this problem, the heat-sink structure needs to be optimized; one structure design was proposed that putting a 10mm diameter copper tube in 12mm diameter original cooling channel of heat sink. So it is necessary to know the heat exchange performance of cooling tube inside the heat-sink compared with the original unchanged one as well to implement a test to compare different style of connection between tube and heat-sink.

The method of connection between heat-sink and copper tube influences the thermal conductivity. It must ensure copper tube and heat sink contact tightly regardless the temperature changing. There are some ways for connecting heat-sink and copper tube we think about: cooling the heat-sink while heating the tube to assemble for interference fit; using high pressure to ensure residual stress between cooper tube and heat-sink; high temperature vacuum brazing. Each tyoe of mockup (FIG. 11) was fabricated and the test was implemented to compare the thermal conductivity of each connection in the University of Science and Technology of China.

Test results are shown in FIG.12, in which the temperature of 473K or 573K in the legend represent the temperature of heat-sink side wall. The thermal conductance is evaluated by the water temperature grade, which can be computed by the equation $\Delta Q = C_p m \Delta T$. It gives conclusions as follows: The original one of no tube in heat-sink is always best. The thermal conductive performance of the brazing mockup is closest (10% less) to the original one, while the expanded tube mockup is 20% less. The mechanical conjoint ratio deside the thermal contact quality. The brazing is more complicated and expensive than high-pressure expanded tube technique.

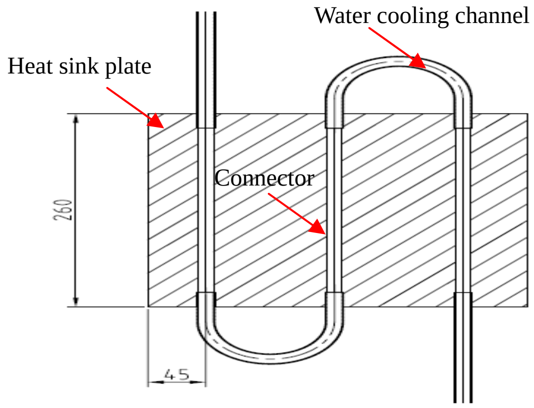

FIG.11. Original Structure of Test Mock-up

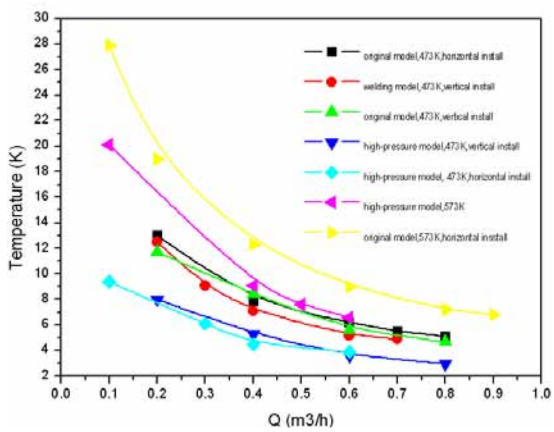

FIG.12. The Thermal Performance of Test Mock-up

3.3. Activation of The Passive Stabilizer

The primary function of the passive stabilizers, as one of the main components installed in the vacuum vessel, is used as low field limiter to protect the vacuum vessel and in-vessel control coils from particles and direct plasma heating. For large plasma current (1MA) operation, the previous separated up and down passive stabilizers in low field were proposed to be electrical connected to stabilize plasma in the case of vertical displace events (VDEs). A technique of plasma spray ceramic is employed as insulation between the passive stabilizer and vacuum vessel wall.

Two copper toroidal rings which share one couple of coaxial bridges form a saddle coil. (FIG.13). There are three kinds of Cu electric connectors between each pair of adjacent passive stabilizer heat sink board which are used to make up the stabilizer loop in different assembly condition, such as the copper flexible connector, copper plate connector used in the position which has probes and copper U-shaped plates connection used where RF antenna exists. The current bridges are coaxial and insulated from each other in order to counterpoise the electromagnetic forces (FIG.14). To prevent arcing between the current bridges, the selected resistors are connected across two terminals of each bridge. For the water cooling tubes which go through the passive stabilizer heat sink board are connected with the vacuum vessel and they have much bigger resistance (about $10^{-2}\Omega$ per tube) than stabilizer itself, the tubes are used as the electric break from the vacuum vessel. The passive plate with a saddle connection can produce a radial magnetic field produced by the eddy currents in the plates, which is induced by vertical plasma motion (FIG.15). The purpose of the passive stabilizers loop is to reduce the growth rates of vertical instability and make the active control of the plasma possible. The passive plate with a time constant of 100 ms will be provided for the plasma vertical position control on fast time scales, then the currents in the active control coil will immediately compensate for the decay of the currents in the passive plate and restrain the plasma vertical displacement. The passive stabilizers loop is assembled successfully(FIG.16).

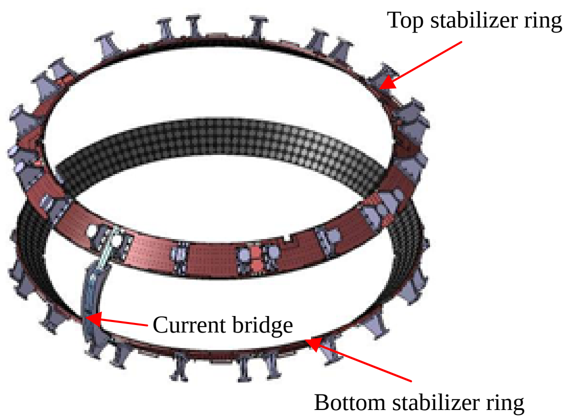

FIG.13. Structure of Passive Stabilizers Loop

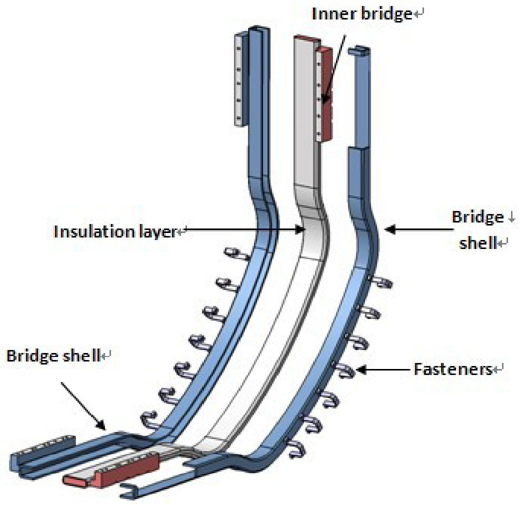

Fig.14. Coaxial and Symmetrical Structure of Current Bridge

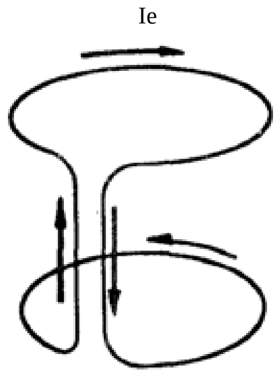

Fig15. The eddy current in PSL saddle coil

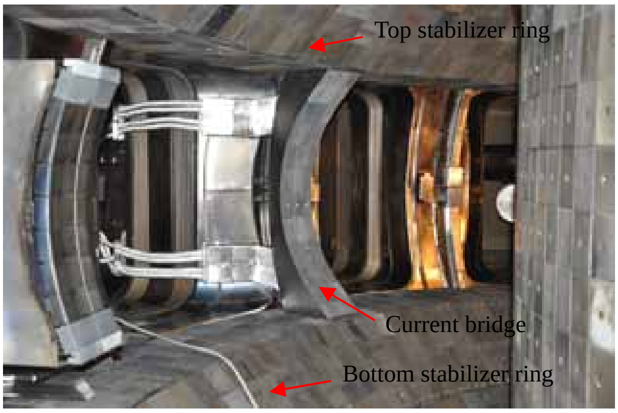

Fig16. Global view of the passive stabilizers.

4. Conclusion

After the maintenance for the failure parts and activation of the passive stabilizer the EAST in-vessel components have been improved in 2009. Now the in-vessel components should have the ability of safety operation with active cooled PFCs when handling high power injection over long pulse plasma discharge and effective plasma stabilization when VDEs happened. It is anticipated that this refurbished in-vessel components would give important contribution to the EAST experiments in the future 3-5 years.

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