Design, Analyses and R&D for EAST In-vessel Components

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Abstract

In-vessel components are important parts of EAST superconducting tokamak. It is include plasma facing components, passive plates, cryo-pumps, in-vessel coils, etc. The structure design, analyses and related R&D had been compoleted. Divertor is designed as up down symmetric to accommodate both double null and single null plasma operation. Passive plates can supply around 100ms time constant during plasma vertical movements. In-vessel coils are used for plasma vertical movements active control. Each cryo-pumps can supply around $45m^3/s$ pumping speed for particle exhaust. Analyses shows when 1MA plasma current disrupt in 3ms EM loads caused by halo current will not bring unacceptable stress on divertor structure. Bolted divertor thermal structure can sustain $2MW/m^2$ up to 60s operation if plasma facing surface temperature is limited to 1500°C. Thermal testing and structure optimised testing have been made to demonstrate the analyses result.

1. Components introduction

EAST in-vessel components consist of plasma facing components, passive stabilizer, cryo-pump, in-vessel coils, glow discharge(GDC) poles, cleaning RF antennas, limiters etc. The plasma facing components include divertor, limiters, and other first wall. Fig 1 shows some of the in-vessel components.

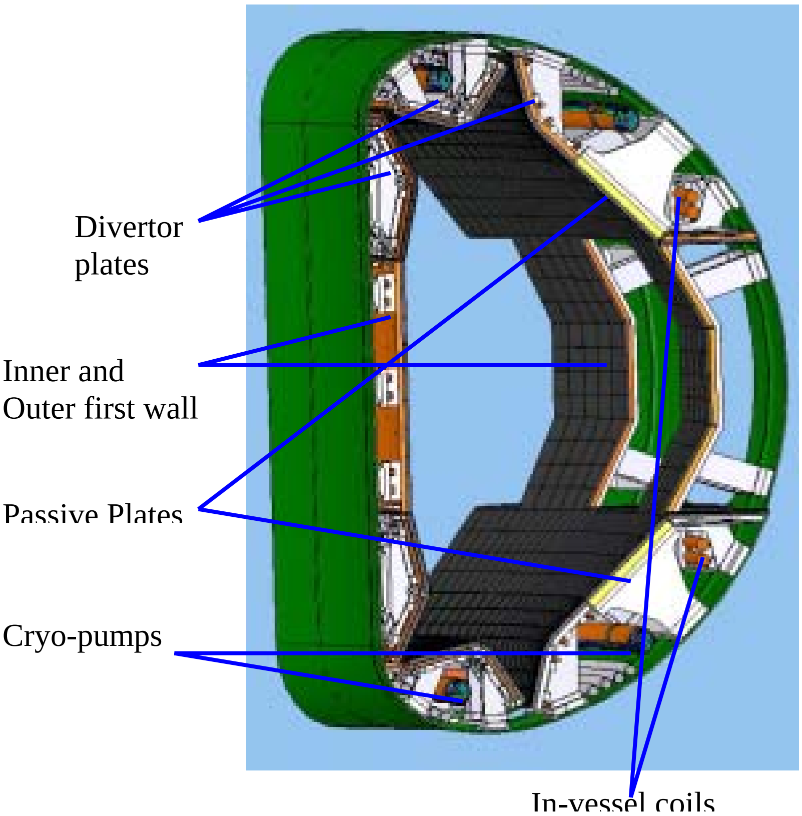


Fig1 In-vessel components configuration

The divertor is designed as up down symmetric to accommodate both double null and single null plasma operation. It is consist of inner divertor plate, outer divertor plate and dome. These three parts formed "V" shape to enhance neutral particles exhaust. The symmetric structure provides large physical experimental flexibility[1]. Passive stabilizer is located outer side of the vacuum vessel. It is copper conductor form a saddle coil consists of upper and lower ring connected by conducted bridge. Graphite tiles attached to passive plate direct and face to plasma. In-vessel water-cooling copper coils are designed for plasma vertical movement active control. At outer side two coils with two turns symmetric to middle plan, and two leads of each turn were through the vacuum vessel port's flange to supply different functions. Total four 4.5K cryo-pumps with same structure and each around 45m^3/s pumping speed were designed for particle exhaust. Each pump is almost full circle in toroidal direction. Four GDC pole will symmetric install on vacuum vessel outer side wall beside horizontal ports. Two RF cleaning antennas also located at vacuum vessel outer side. They are used for RF discharge by ICRF system. GDC and RF cleaning system is typical wall conditioning method for tokamak vacuum vessel.

2. Structure description

The shape of EAST vacuum vessel wall was model press formed, and vacuum vessel was welded from 16 sectors. Based on this technical the vessel wall can't act as benchmark of plasma facing components. A set of rails to be had high precision have been considered installing inside vacuum vessel. These rails were the basis of in-vessel components. All the supports of in-vessel components were connected to the rails. To obtain good alignment of plasma facing surface only need to control size precision of each part and to control the precision of installation dimension chain.

Plasma facing components include high heat load parts and low heat load parts. Divertor plates and limiters sustain high heat load and ion direct bombard. Only radiated heat deposit on other first wall. The plasma facing material was doped graphite and heat sink material was CuCrZr. Graphite foil was used to improve heat conduction between tiles and heat sink Graphite tiles were mechanical connect to heat sink. During plasma operation metal atoms spattering is not permitted different plasma facing material attaching structure have been considered. Fig 2 shows the detail structure of graphite tiles connected to heat sink.

All plasma facing components heat sink were divided into 16 sectors in toroidal direction. Each heat sink sector was model press formed to required shape then drill holes on it and connect the holes in series to form cooling channel. Facets were milled on heat sink for graphite tiles installation. Fig 3 shows the cooling channels structure.

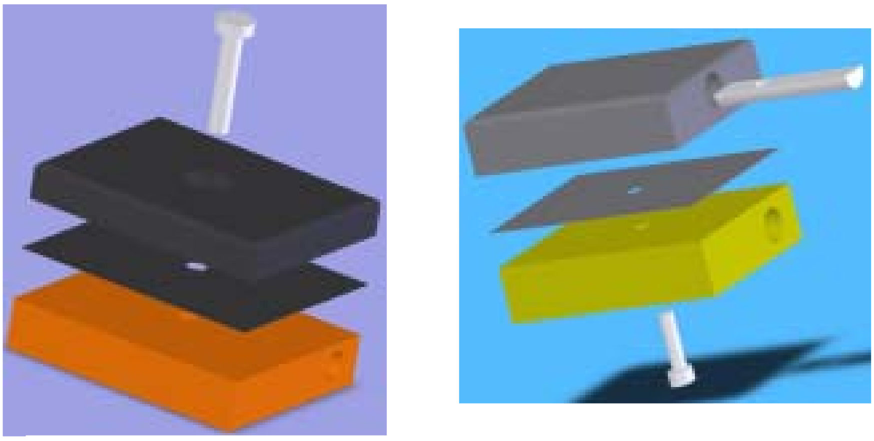

For low heat load parts *For high heat load*

Fig 2 Detail structure of graphite tiles attached to heat sink

Passive stabilizer is acted as part heat sink of first wall. The thickness of passive plate is lager than other heat sink to obtain higher electric conductance. Two copper toroidal rings and connecting bridge form a saddle coil (as Fig4). When plasma has a vertical movement a high current will be induced in the coil and to restrain the movement. Around 100ms duration was supplied for plasma active control. In this duration current was applied to active control coils and achieve fast control plasma movements.

Two moveable limiters are symmetric in toroidal direction. They can be moved ±100mm to control plasma minor radius. Molybdenum tiles are mechanical connect to CuCrZr heat sink with water-cooling. Limiters are only used at the beginning of EAST device testing. When EAST operates in divertor plasma configuration moveable limiters will be leave unused.

Cryo-pumps are used for obtain high pumping speed to exhaust neutral particles and impurity in divertor area. Each cryo-pump almost likes a three layers homocentric pipe toroial ring. The pipe at centre is cooled to 4.5K, middle pipe is 80K and outer side pipe is the same temperature as vacuum vessel. Particle through slots on outer side pipe and middle pipe to centre and is condensed there. Fig 5 is the structure of cryo-pump.

Fig 3 Cooling channel

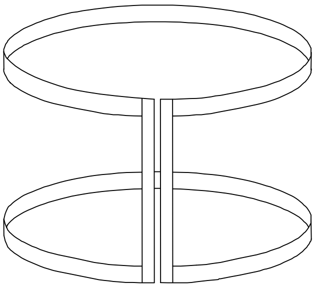


Fig 4 Saddle coil

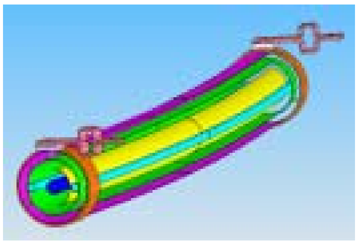


Fig 5 Cryo-pump sector

3. Analyses Description

For all the in-vessel components heat load and mechanical load are important factor to be considered. A series of analyses was made to perform temperature distribution, thermal stress and structure characteristic.

3.1 Structure Analyses[2]

Loads caused by induce current and halo current are serious load for in-vessel components. During in-vessel components bake-out and plasma operation thermal expansion bring high stress on the components. For design halo current was assumed 25% of Ip and toroidal asymmetric factor was assumed 2. To calculate induce current plasma disruption duration was assumed 3ms. In-vessel components bake-out temperature will be 350°C.

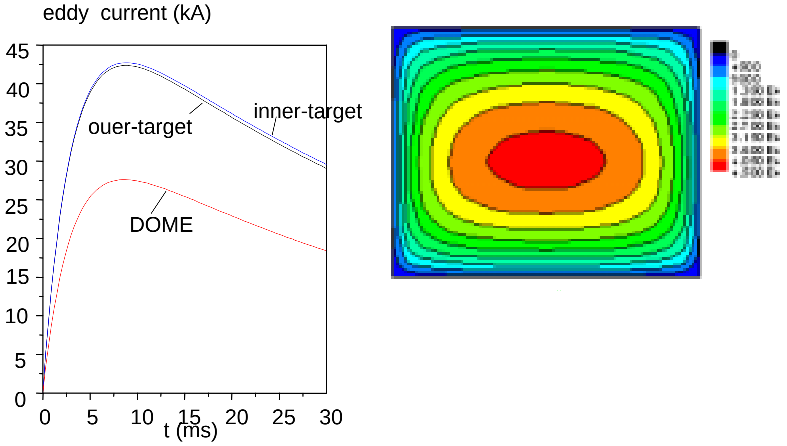


Fig 6 Induce current diversification and distribution

Here only narrate inner divertor plate performance under different load conditions. Fig 6 shows induce current ramp up and decay and current distribute on divertor plate when plasma disrupt in 3ms. The peak induce current is around 42KA and forces on the plate is in normal direction and reversed on opposite edge. These forces produce a twist moment on the plate. This moment cause 88.7MPa stress (as Fig 7 a). Peak halo current in divertor plate heat sink is up to 87.5KA and peak force on divertor plate is 630KN. The highest stress caused by halo current was 90MPa (as Fig 7 b). When in-vessel components bake-out to 350°C thermal expansion divertor plate is around 4mm. If we assume the plate edge was full restricted the analyses result shows stress on the plate is up to 3670MPa. (as Fig7 c). This is unacceptable for structure design. To reduce the stress an optimization has been made. A kind of solid lubricative material was considered use between heat sink and support to obtain movement of the heat sink when expand. Analyses indicated absorb thermal expansion the structure stress reduce ten times (Fig7 d shows the analysis result.). Pick out a graphite tile for analyses showed stress is only 5MPa.

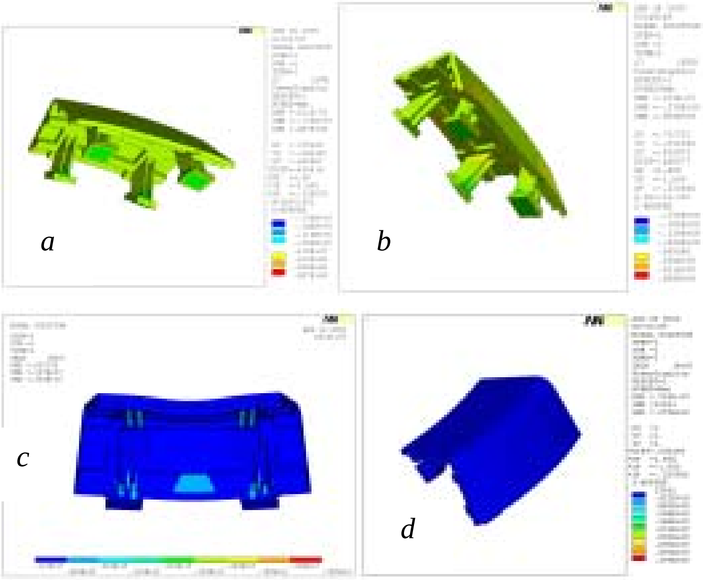
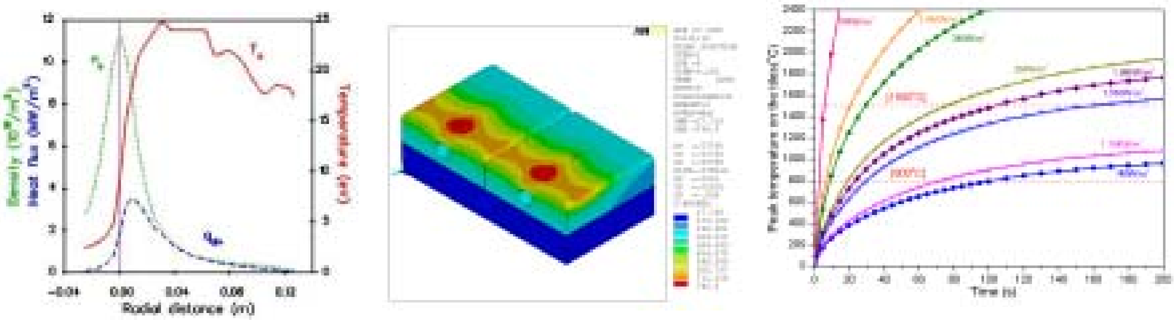


Fig7 Analyses result under different load conditions

3.2 Thermal analyses

For EAST superconducting tokamak divertor plasma configuration will be the main operation mode. Highest heat load is on divertor plates. To make detail thermal analyses for divertor plates is necessary. Considered the device plasma heating power will be go up step by step. The divertor plate's thermal structure at present stage is only need to accommodate 2-3MW/m^2. Graphite tiles attached to heat sink by mechanical connection as described upper.

The graphite material used for EAST divertor PFCs is doped graphite with SiC coating. Although the plasma facing material thermal conductivity is 150W/mK and cooling channels are direct cutting on heat sink, the graphite foil thermal conductivity in thickness direction is only 5W/mK and contacting thermal conductance is only 18KW/m^{2}K. These conditions determined the bolted thermal structure has limited thermal transfer capability. Heat load from plasma is not uniform distribute on the plate. Around strike point 80% heat load accumulate within ±2cm width. The heat load distribution shows as Fig8 (a)[3]. Under different heat load condition peak temperature on plasma facing surface is showed as Fig8 (b) and (c). For stable operation the tiles temperature is not permit more than 1500°C. From Fig9 (b) we can see under the temperature limit if discharge pulse length more then 100s the highest heat flux should be below 1.5MW/m^2. For steady state plasma operation the divertor should improve in next phase.

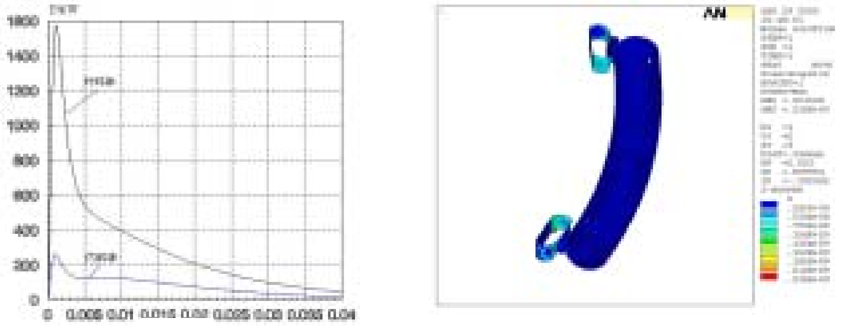


a b c

Fig 8 Divertor plate heat load and thermal analyses result

3.3 Cryo-pump Analyses

Particle load for EAST include fuelling, wall recycling and NBI. Particle from fuelling is ~11Pam^3, from wall recycling is ~132 Pam^3. Power of NBI was assumed 8MW, accelerate voltage was assumed 80KV then from equation $P_{NBI} = D_N \times E \times (n_f + n_h / 2 + n_t / 3) \times e$ can calculate D_N~4Pam^3/s. For 1000s pulse operation the total particle load is ~4100 Pam^3. If the divertor area neutral particle pressure was assumed 0.1Pa the cryo-pump pumping speed should not less than 41 m^3/s. The cryo-pump pumping speed was calculated 53m^3/s for one ring. They are adequacy for EAST present and future steady state operation.



a *b*

Fig 9 Cryo-pump induce current heating power and structure stress

EAST in-vessel cryo-pump was designed as full ring in toroidal direction. To decrease induce current produce high heat load on cryogenic parts is benefits for keeping pumping speed. The material use for cryo-pump is inconel 625. This material has good strength character, lower thermal conductivity and high resistance. Inconel 625 pipes used for cryo-pump is thin wall pipes. Power bring by induce current in case plasma disrupt in 3ms shows as Fig 9 (a). This power cause cryogenic parts temperature goes up only 0.26K. It will not affect cryo-pump pumping speed seriously. From Fig 10(b) can see force caused by induce current on cryo-pump only bring 238MPa stress. It is much lower than inconel 625 yield stress (~600MPa).

3. R&D

For mechanical connection thermal structure the contacting thermal conductance is a key parameter. A sample consists of graphite pole contacted to copper pole was made to measure the factor. Put this sample in a vacuum chamber and change the pressure between them. Heat the sample by a definite power. Measure the temperature jump at the interface ΔT. The contacting thermal conductance can calculate by equation $R = \dfrac{Au \bullet \Delta T}{Q}$ (where R is contacting thermal conductance Au is contacting area, Q is power to the sample). Fig 10 shows the result of the measurement.

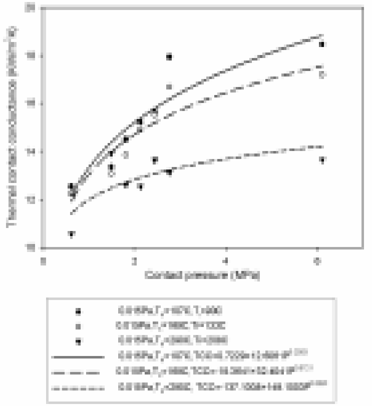


Fig10 contacting thermal conductance measure result

What about peak temperature on PFS (Plasma Facing Surface) when the heat load applies on it? A testing block with graphite tile bolted to CuCrZr and a cooling channel go through the heat sink was made (as Fig 11 a) to perform the thermal character of high heat load components. A thermal couple was put in a hole and distance to graphite tile top surface 1mm. In electron gun facility the testing block was heated by different heat load. The cooling water mass flow rate and connecting pressure between graphite tile and heat sink was changed to compare the temperature change on PFS. Fig 11 (b) (c) shows the relationship of water mass flow rate and PFS temperature, connecting bolt screw down moment and PFS temperature respectively. The steps of curves on the figure means different heating power.

Analyses shows thermal expansion brings high stress. What is the actual situation? Testing had been made to obtain the first-hand data. A piece of 550x200x20 CuCrZr plate with elliptical holes was bolted to rigid supports (as Fig12 a). One case bolted CuCrZr plate directly to support and heated the plate to 300°C. Another case between CuCrZr plat and support a kind of solid lubricative washers were put in and also heated the plate to300°C. In vacuum environment between stainless steel and CuCrZr friction factor is 2.97, but between the lubricative material and stain steel/CuCrZr friction factor is only 0.35. In these two cases micrometers were used measure thermal expansion. Compare the results can find in the length direction the distance of plate move is different. If the plate is in free state when heated to 300°C the expansion is 2.5mm in length direction. When the screw down moment is 40Nm the first case expansion is 2.28mm and the second case expansion is 2.325mm. Fig 12 b shows the different of expansion in two cases.

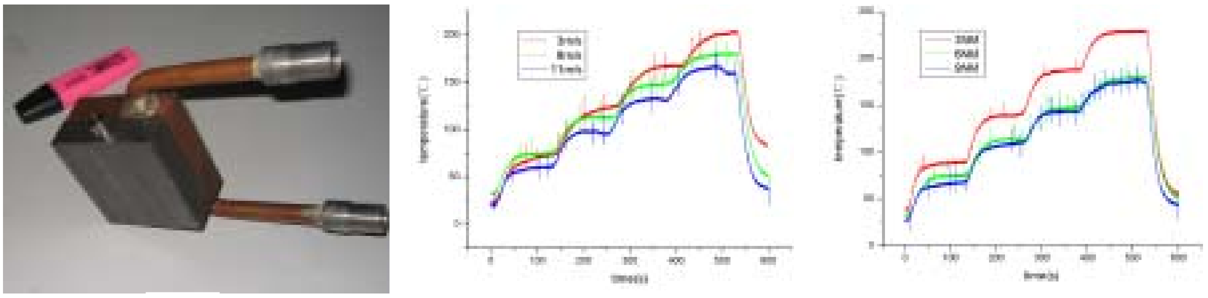

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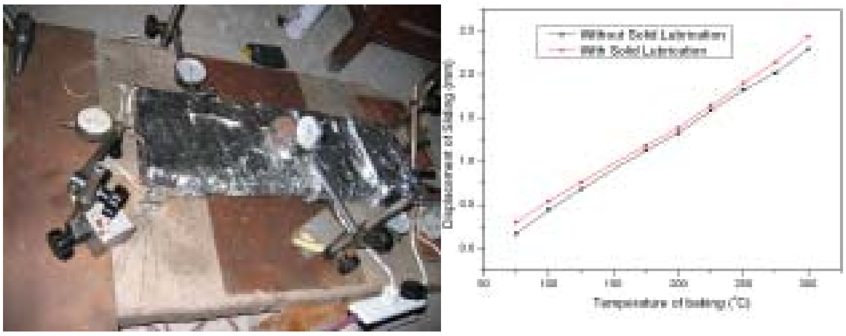
Fig 11 Thermal chraracter testing result



a b

Fig 12 Thermal expansion testing

For EAST first plasma facing component is different with the design have been described. Stainless steel plats are instead of CuCrZr heat sink and graphite tiles. This structure is just to get experience for plasma facing components design optimization, fabrication, installation and for divertor plasma operation.

Conclusion

The first plasma in-vessel components have been installed in the vacuum vessel. The first plasma with Ip=150KA and pulse length 800ms obtained on 26th September 2006. Some physics experiment will be done in next campaign operation. The graphite first wall plasma facing components will reference the experience of first plasma in-vessel components to optimize the design. Fabrication and installation is expected in the second half of 2007.

Reference

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