Design of the ITER EDA plasma facing components

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Abstract

The design of the plasma facing components (PFC) in ITER has evolved with the detailed design of the reactor. The structures exposed to the plasma have different requirements according to their functions. The primary wall, surrounding most of the plasma above the null point, is exposed to a moderate heat flux (0.5 MW m⁻²) but has to withstand the highest neutron load. The baffle wall is exposed to a peak heat flux of 3 MW m⁻² and to severe erosion from neutral particles due to their high neutrals pressure in the divertor. The limiter is subjected to the same loads as the primary wall during plasma burn conditions and a higher peak heat flux (depending on its location) during the start-up and shut down phases when the plasma is leaning on its surface. The divertor vertical targets intercept the open magnetic flux surfaces near the separatrix and have to withstand the highest heat flux and erosion in their lower part. The divertor dome is located directly below the null point and works in conditions similar to the baffle. The divertor wings receive similar thermal loads as the dome but can be subjected to high heat shocks and electromagnetic forces during plasma disruption. The paper describes the solutions adopted for the PFC and the results of analyses performed to validate the design. The description is focused on the part of the PFC which is exposed to the plasma. © 1998 Elsevier Science S.A. All rights reserved.

1. Introduction

The surfaces exposed to the plasma are subjected to different conditions according to their position along the last closed magnetic surface and the system to which they belong. The blanket [1] includes (Fig. 1): the primary wall (PW) surrounding most of the plasma above the null point, the limiter, used to limit the plasma during its start-up and shut-down, and the baffle located at the sides of the null point. The divertor includes (Fig. 2): the dome, located just below the null point, the vertical target which intercepts the open magnetic flux surfaces near the separatrix and the wings used to enhance the momentum transfer by charge exchange neutrals from the plasma to the wall and to convert the particle kinetic energy into pressure for pumping.

The thermal-mechanical requirements of each component and main thermal-hydraulic data are summarized in Table 1.* Corresponding author.

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2. Primary wall

The PW is integrated with the shield blanket modules and covers a surface of ~1200 m². Its main functions are:
1. To provide for a low $Z_{eff}$ plasma.
2. To withstand the charged particle flux and the radiation from the plasma in normal and off-normal conditions.

The PW is characterized by a moderate heat flux but has to withstand the highest neutron load. During plasma disruption, it is also subjected to heat shocks (e.g. due to vertical displacement events, VDE) and to high electromagnetic (e.m.) loads. The PW design is shown schematically in Fig. 3. A castellated beryllium armour is attached to a dispersion strengthened copper (DSCu) layer. Stainless steel cooling tubes (1 mm thick) are embedded inside the DSCu layer.

The PW has been designed to minimize the effect of primary loads. The DSCu layer has been therefore firmly attached to the shield structure, to which the e.m. loads are directly transferred. Coolant pressure stresses are minimized by using circular channels.

The DSCu layer works as a heat sink and is needed to maintain low thermal stresses, to provide a margin for off-normal conditions and to allow for a suitable pitch between the SS tubes.

Access (3 cm $\phi$) through the FW is required at specific locations for maintenance. Holes are therefore provided through the DSCu layer. The cooling tubes are routed around the holes. The surface around the holes is chanfered to reduce the peak heat loads during VDE (load increase factors can be found in Pacher [2]).

The Be layer to the DSCu and the DSCu layer to the SS Shield are bonded using HIP technology. Recent experimental results [3,4] have confirmed the robustness of the FW design. Structural performances far beyond the design values have been obtained.

2.1. PW analyses

Because of its robust design, primary stresses in the FW are small and will not be considered here. The thermal behaviour of the PW has been analyzed in transient conditions during the first two pulses after preheating of the structures at 140°C. The stress distribution has been computed at the times where the most severe thermal gradients were found. The entire cross section of an inboard equatorial module has been modeled in detail and thermal loads have been applied as in Table 1.
Table 1
Main data for the plasma facing components

<table>
<thead>
<tr>
<th>Specifications (Units)</th>
<th>Blanket</th>
<th>Divertor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PW max</td>
<td>Limiter</td>
</tr>
<tr>
<td></td>
<td>Belt</td>
<td>Port</td>
</tr>
<tr>
<td>Peak heat flux (MW m$^{-2}$)</td>
<td>0.5</td>
<td>5(10)</td>
</tr>
<tr>
<td>Average heat flux (MW m$^{-2}$)</td>
<td>0.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Water temp. inlet (°C)</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>Water press. inlet (MPa)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Neutron wall load (MW m$^{-2}$)</td>
<td>1.19</td>
<td>1.16</td>
</tr>
<tr>
<td>VDE peak h. load/dur. (MJ m$^{-2}$ s$^{-1}$)</td>
<td>60/0.3</td>
<td>NA</td>
</tr>
<tr>
<td>Disr. ther. quench (TQ) (MJ m$^{-2}$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* A large VDE’s are thought not to occur on limiter and divertor. TQ load is included in VDE for PW and baffle; for limiters in limiter regime it has not been determined yet but is expected to be low because plasma energy is low.

and Cardella [5]. A bulk water temperature of 165°C (averaged between inlet and outlet) has been assumed. For the mechanical analysis, generalized plain strain boundary conditions have been applied out of plane.

The analysis results have shown that a significant thermal gradient exists in transient conditions within the PW module because the time constant of its plasma facing side is considerably smaller than that of the rear part. This causes a maximum temperature difference of +50°C (Be tiles excluded) to occur between the PW and the module backside 220 s after the cycle begins, whereas the backside is 40°C warmer 1320 s during the cooling down phase.

The thermal behaviour across the thickness of the PW module is shown in Fig. 4. No sharp difference exists between the PW and the underlying SS zone. The analysis is conservative because in reality the outlet water is routed from the FW to the rear shield; this should somewhat reduce the thermal gradient within the module.

Maximum Von Mises stresses in the DSCu and in the PW SS tubes are 159 and 228 MPa respectively at $t = 220$ s. During cooling down ($t = 1320$

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Fig. 3. PW cross section.

Fig. 4. Averaged temperature history in FW and shield layers (detail of the FEM model).
The belt limiter FW has been designed similarly to the PW, Fig. 5. Slits have been derived between the coolant tubes in the DSCu in order to increase the thermal performances by allowing free thermal expansion in the toroidal direction. The SS tubes have been substituted by a thin liner (0.2 mm thick), which permits to connect the limiter cooling system to that of the PW without incurring severe corrosion problems.

An accurate alignment (± 3 mm absolute with respect to the magnetic flux surface with no leading edges) is required to limit the peak heat flux to acceptable values. Be is used as armour. The Be thickness has been limited to 7 mm in order to avoid high temperature during normal operation. The peak heat flux can be increased locally (factor 2) near penetrations and gaps [2]. In these regions the liner can be substituted by a thin Ni plating to avoid excessive thermal stresses, the Be thickness is reduced to 4 mm, the DSCu thickness below the Be armour is reduced to 3 mm and the pitch between the tube is also reduced to 16–17 mm. This optimization is possible since recent studies show that plasma VDE events, for which a thicker armour would be needed, do not occur in the limiter region.

In the case of armour damage, techniques are being developed for its repair by plasma spray. The manufacturing technology of the PW module is also used for the belt limiter. For the Be/DSCu joints other technologies such as silver free brazing are in development as for the divertor [6].

3.2. Port limiter

Local port limiters are being designed as an alternative to the belt limiters mainly:

1. Because penetrations and gaps in the belt limiter result in high localized peak loads requiring high flow rate cooling on a large surface.
2. In order to ease the surface alignment and maintenance, mitigating armour erosion and plasma damage problems.

The limiter is located in two horizontal ports and is attached to a shield plug adjustable from the port. The maintenance and the coolant supply will be provided from the port avoiding penetrations or gaps in the FW surface.
The limiter is made of modular poloidal plates joined together only at their outboard side (Figs. 6 and 7). A deep radial gap (1 mm) is left between the plates. This solution result in a considerable decrease of the e.m. loads (~10% of those in a continuous shield, total shear load ~150 kN) and of the thermal stresses because the plates are free to expand in the toroidal direction in their hotter part.

A be castellated armour could be joined to the Cu heat sink by HIP using an intermediate layer or the carbon fibre composites (CFC) monoblock design (Fig. 8) can be used for high proven performance (see also Section 5) [6–8].

The FW can be manufactured and inspected separately before being joined to the SS shield. In each plate the coolant first cools the FW and then enters a serpentine inside the plates. A swirl tape is inserted inside the FW DSCu tubes to enhance the critical heat flux (CHF). The cooling system of the port limiter is joined to that of the divertor (no SS liner required).

For the estimated incident heat flux [9], the local coolant conditions and CHF were evaluated [10]. The results are summarized in Fig. 9 for a velocity of 12 m s⁻¹ and with a 20% increase in the incident heat flux. The minimum CHF margin in this case is > 1.5 and the pressure drop is ~1.4 Mpa.

Thermo-mechanical analyses for the port limiter are in progress. In general lower stresses than for the belt limiter are present in the shield part. For the monoblock FW the same results as in the case of the divertor are expected.
3.3. Belt limiter analyses

In order to follow the mutual interactions between the FW and the shield block during the complex limiter heating cycles a 2D transient thermal analysis of an entire mid-plane limiter cross-section during a full operating cycle (2000 s) has been performed. Stresses and strains have been then evaluated at selected times. Elastoplastic analyses with an elastic/full plastic stress strain curve have been performed. Two main working regimes are identified for the limiter:

1. The start-up and shut-down, with 5 MW m\(^{-2}\) high heat flux and no volumetric heating.
2. The burn, with 0.5 MW m\(^{-2}\) heat flux and a volumetric heating decreasing radially outwards.

The mechanical boundary conditions were as in Section 2.1. A maximum Be temperature of 737°C has been calculated at the armour surface during start-up and shut-down (Fig. 10). The temperature range of the DSCu and SS liner are 201–393 and 183–324°C respectively. The temperature evolution with the time at selected locations in the limiter is shown in Fig. 10. The FW has a short time constant and follows the heat flux histogram so that steady state conditions are reached at the end of the start-up. The shield module reaches steady state throughout after ~700 s.

Stresses in the bulk of the limiter are below the \(3S_m\) value and can be considered acceptable. The zone where high plastic strains occur is mainly limited to the Be/Cu interface; for the evaluation of the joints the same considerations as in Section 2.1 apply; experiments are performed in conjunction with the baffle development [12].

4. Baffle

The baffles (inboard and outboard) are located opposite the null point on each side. Their FW surface is aligned to the magnetic flux surface passing 6 cm outside the separatrix at the outboard mid plane and is shaped to achieve a reduction of neutral density between the divertor and the main plasma chamber by \(10^4\). The lower baffle FW are subjected to high erosion due to the bombardment of charge exchange neutrals. In order to guarantee a suitable erosion lifetime the armour of the lower baffle is in tungsten. Be (alternatively C) is used for the upper baffles.

The baffle FW is similar to that of the belt limiter (Fig. 5). The armour thickness is 1 cm for Be and W and 3 cm for CFC. Two options are considered for the attachment of the FW to the shield. In the first option the FW is fully integrated (HIPed) with the shield as in Fig. 5. In the second option the FW is welded using discontinuous pads (Fig. 11). The main advantage of the latter solution is that the difficult Be/DSCu joint is made in separate small units, which after inspection can be attached to the main blocks minimizing the risk of large material waste. The main disadvantage is the high number of welds and
complications in the collector design. For the lower baffle with tungsten armour, active metal casting [12] will be used and the tungsten armour will be highly castellated (Fig. 12b) to increase its resistance to high heat fluxes.

4.1. Baffle analysis

Similar thermo-mechanical analyses as for the belt limiter have been performed for the baffle. Max. temperatures are ~650°C in the Be and the W armour. For the stresses similar conclusion as for the limiter apply. Detailed results can be found in Salavy et al. [11].

5. Divertor

The ITER divertor comprises plasma facing parts which differ geometrically and in armour materials according to the different requirements and loading conditions (Fig. 2). Divertor physics performance, loads and the implication of geometry and materials selection are discussed in Janeschitz et al. and Vieder et al. [7,12]. The vertical targets (VT) intercept the open magnetic flux surfaces outside the separatrix and have to withstand the largest particle fluxes and thermal loads. In each of the 60 cassettes, into which the divertor system is subdivided, there are two inner and two outer target assemblies. Each assembly comprises identical units riveted together (18 units for the outer target and 14 units for the inner target).

The design of the high heat flux part of the lower part of the VT (a straight section ~0.6 m long poloidally) is based on CFC monoblocks (Fig. 8), which are cooled by an internal, 1 mm thick, 10 mm inner diameter DSCu tube. This is joined to the CFC blocks using active metal casting [12].

To enhance the thermohydraulic performance, a swirl tape inside the tube act as turbulence promoter. The water axial velocity is about 12 m s⁻¹ and a safety margin of 1.3 against CHF is assured during the worst transient [10].

Under normal condition (5 MW m⁻²), the CFC-heat sink interface reaches a maximum temperature of 223°C, while the peak temperature is 408°C during power excursion up to 20 MW m⁻².

The low cycle fatigue lifetime for this concept was evaluated through linear elastic analysis, using a reference temperature of 150°C. The peak Von Mises stress in the heat sink is 114 MPa at 5 MW m⁻² (corresponding to more than 3x10⁸ cycles) and 350 MPa at 20 MW m⁻² (more than 10⁸ cycles). This design has also experimentally shown the best thermal performance so far, resisting up to 30 MW m⁻² for up to 10⁸ cycles [12].

Alternative design options based on CFC flat armour tiles joined to a hollow Cu-alloy bar have also been analyzed (this concept would simplify the manufacturing process). However, the temperature at the sink armour interface (277°C) and the Von Mises stress (about 250 MPa) are higher than that of the monoblock design.

In the upper part of the VT a tungsten armour is selected for its lower sputtering erosion rate and
T-retention. In order to reduce the thermal stress in the W armour and at tile/heat-sink interface, a macro-brush design has been developed: square W pins (4.5 \times 4.5 \text{ mm}; 10 \text{ mm thick}) are joined to the flat surface of a DSCu or CuCrZr hollow bar through a soft cast copper inter-layer. The maximum temperature at the armour heat sink interface at 5 MW m\(^{-2}\) is about 310°C; the Von Mises stress in the heat sink peaks at 180 MPa, and the expected lifetime is above \(3 \times 10^4\) cycles. Tests of mock-ups in e-beam facility have shown that this concept survives \(10^4\) cycles at \(~16\) MW m\(^{-2}\) \([7,12]\).

A similar armour design (W macro-brush) is also used for the high heat flux part of the divertor dome, located directly below the null point. In this case the heat sink is a rectangular hyperboloton channel (made in DS copper), which provides effective cooling also at the channel ends. This concept provides a CHF margin of more than two.

The design of the leading edge of the wing, where a large part of the energy released during a plasma disruption can be deposited, is based again on a similar macro-brush W armour. An alterative design foresees the use of 1 mm thick W lamellae joined to a DS copper circular heat sink through a soft copper interlayer \([6]\). The peak temperature in the copper would be about 270°C at 5 MW m\(^{-2}\) (Von Mises stress is 200 MPa). The expected lifetime for this concept is above \(3 \times 10^4\) cycles.

Fig. 12 shows schematically the two armour concepts considered for W armour.

6. Conclusions

Different design solutions have been developed for each ITER plasma facing component depending on its specifications and functions.

The thermal-mechanical analyses and the performed R&D (development of joining techniques, manufacturing and testing mock-ups of each component) show the basic adequacy of the designs to meet their requirement. The final design feasibility assessment and validation will be performed by further testing of large scale mock-ups and by manufacturing prototypes of each component.

References