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Design and preliminary thermal validation of the WEST actively cooled upper divertor

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HIGHLIGHTS

- Design of WEST upper divertor target, regarding integration and thermal load specifications.
- The proposed concept enables to sustain in steady state, at least, a maximum heat flux of 8 MWm^{-2}.
- The plasma incident surface is covered with a <30 µm thick W coating.
- HHF tests up to 10.5 MWm^{-2} were successfully performed on the upper divertor prototype.
- Upper divertor targets will be fabricated and installed in the vacuum chamber in 2015.

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ABSTRACT

The WEST (W – for tungsten – Environment in Steady-state Tokamak) project is based on an upgrade of the Tore Supra tokamak, into a double X-point divertor device, while taking advantage of its long discharge capability. Therefore components with tungsten (W) as plasma-facing material will be used. This paper presents the upper divertor of the WEST project (design constraints, thermal performance). This component, with a total surface of 8 m^2 is designed to exhaust 4 MW of conducted power in steady state with a maximum local heat load of 8 MW m^{-2}. The actively cooled heat sink of this upper divertor target is made of CuCrZr. It is covered with a W coating up to 30 µm thickness. The suited thermal behaviour of the component was checked using finite element modelling. Moreover, under high heat flux tests this component had the expected thermal exhaust capability and survived without visible damage up to 10.5 MW m^{-2} in steady-state.

1. Introduction

The WEST (W – for tungsten – Environment in Steady-state Tokamak) project is based on an upgrade of Tore Supra, moving from a carbon based limiter to an X-point tungsten divertor device while keeping advantage of its long discharge capability [1]. This is obtained by the installation of electromagnetic coils in the vacuum vessel in order to create an upper and lower X-point while adapting the plasma environment to this new configuration. After a commissioning phase, the lower divertor will be fully metallic and actively cooled, with ITER-like tungsten (W) monoblocks [2,3]. The upper divertor target (Fig. 1), based on an actively cooled CuCrZr heat sink concept, as well as remaining plasma-facing components (PFCs) will be coated with W.

This paper presents the main features of the WEST upper divertor including the key elements of the design according to the physics specifications (essentially thermal load specifications) and integration constraints. The paper also describes high heat flux (HHF) tests which were performed on a simplified prototype element in the GLADIS facility [4].

2. Thermal load specification

The transformation from the current circular limiter geometry of Tore Supra (TS) to the required X-point configuration (i.e. divertor configuration) allows access to a wide range of plasma equilibria, from lower single null to upper single null passing through double null geometries, including high confinement regime. Based on

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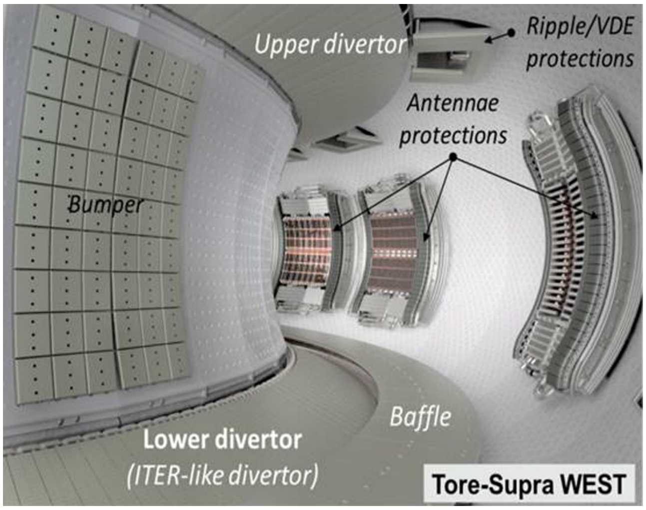

Fig. 1. Tore Supra in the WEST configuration, showing the main plasma facing components.

this plasma operational domain, a rather comprehensive thermal load specification for the WEST PFCs has been developed [5,6] and constitutes now the baseline document for the PFC design. This document also includes specifications for electromagnetic and Halo current forces due to disruption events. However, the conducted plasma heat loads, both transient and steady-state dominate the main design choices for the PFCs (namely, the lower and upper divertor target and the outboard baffle). The heat flux patterns on main PFCs have been computed by a 3D convective model (PFCFlux) [7] of the magnetic configuration (including a non-negligible magnetic field ripple), taking into account the PFC geometries with shadowing effects. Results are driven by the radial decay length (λ_q) and the magnetic configuration.

In this paper, the study is focused on the upper divertor target, for the upper single null configuration. For this configuration, two reference scenarios are studied, corresponding to the two extreme positions of the X-point relatively to the divertor. Expected heat flux patterns on main PFCs have been computed using 10 MW power conducted through the separatrix (Psol) (no radiative power taken into account) and different λ_q. A maximum local incident heat flux density of 8 MW m^{-2} is expected on upper divertor targets.

3. Description of upper divertor

3.1. Main features

For the WEST operation, the upper divertor target has to be interchangeable with the lower divertor target (W ITER-like divertor). For this reason, the WEST upper divertor consists of 12 independent toroidal sectors of 30° [3], each composed of 38 copper alloy plasma-facing units (Cu-PFUs). As for the lower divertor, 456 components form a toroidal ring structure representing a portion of a cone surface [3]. For each 30° sector, components are connected in series (two to four components) and feed in parallel by a collector. Based on Tore Supra hydraulic loop, the inlet pressure and coolant temperature are set to 33 bar and 70 °C, respectively. In the worst case, the coolant velocity is 5 m s^{-1}. With regard to the hydraulic loop characteristics and its cooling capacity, the maximum allowable extracted power for each Cu-PFU is 12.5 kW. Then, the total possible extracted power for the whole upper divertor is 5.7 MW.

Each Cu-PFU is composed of a CuCrZr heat sink. The dimensions are ~449 mm × 32 mm × 42 mm (Fig. 2). The incident surface of the Cu-PFU is covered with W coating (<30 μm thickness) [8]. The cooling channel diameter is 8 mm and the minimum distance between

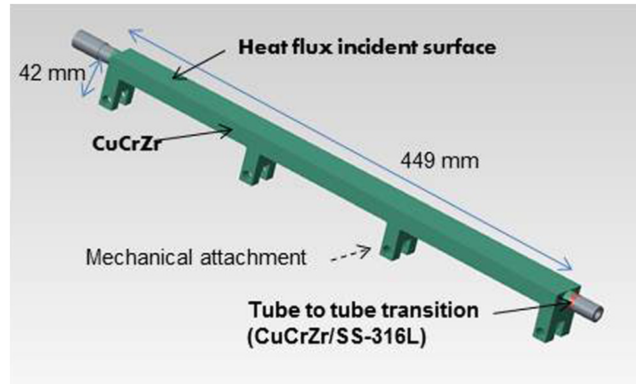

Fig. 2. CuCrZr heat sink geometry of Cu-PFU.

Fig. 3. Cu-PFU prototype with W coating (~30 μm).

the loaded surface and the cooling channel is ~3 mm. The cooling channel will be performed by deep drilling. CuCrZr is chosen for its advantages with regard to its thermal and mechanical properties. A CuCrZr/SS-316L transition is needed in order to connect the Cu-PFUs to the hydraulic header.

In order to evaluate the thermomechanical behaviour under thermal cycling of the Cu-PFU, HHF tests were performed. A picture of a simplified prototype is presented in Fig. 3.

3.2. Integration

Each Cu-PFU exhibits four mechanical attachment points arranged on the backside of Cu-PFU opposite to the heat flux incident surface, to allow mounting onto a dedicated steel supporting structure so called divertor support. Geometry of the mechanical attachments is chosen in order that divertor support is the same for the upper and the lower divertor targets [3]. The divertor support is presented in Fig. 4. Each attachment point is a U-shaped-fixing made of CuCrZr incorporating a bore of 8 mm for the insertion of a pin in SS-316L which allows connection to the anchors provided in the ring-shaped support structure (Fig. 4). The anchors are equipped with a horizontal oblong bore for the insertion of the attachment axes allowing horizontal component movement during thermal expansion.

A major issue for PFCs is the leading edge (i.e. exposed surfaces) due to gaps between components (toroidal gap in the 0.6 ± 0.4 mm range), and vertical misalignments due to manufacturing and assembly tolerances. Values of possible vertical misalignment are presented in [3]. To mitigate the effect of leading edges caused by the interception of particles following magnetic field lines at glancing incident angles (α = 2°–3°) in the high heat flux areas (i.e. close to the strike-point regions), round edges or fish-scale geometries (Fig. 5) are studied to shape the Cu-PFU surface. The detrimental thermal effect on the component could be the local melting of CuCrZr (1080 °C) occurring before the W melting (3410 °C).

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