Design validation of the CVD diamond window unit for the ITER EC H&CD Upper Launcher

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Introduction and background

The ITER electron cyclotron heating and current drive upper launcher (EC H&CD UL) is a component of the ITER tokamak machine devoted to inject localized high microwave power into the plasma for control of the magneto-hydrodynamic instabilities. The UL consists of an assembly of ex-vessel waveguides (with window units and isolation valves) and an in-vessel port plug [1]. Chemical vapour deposition (CVD) diamond window units act as confinement barriers, while allowing transmission of mm-wave beams between 1 and 2 MW.

The design of the window unit is shown in Fig. 1. It basically consists of a 1.111 mm thick diamond disc brazed to two oxygen-free high conductivity (OFHC) copper cuffs and this structure is then integrated into a metallic housing by EB-welding. The diamond with its very low loss tangent is currently the only material able to allow a proper transmission of power beams up to 2 MW [2]. The window unit is part of the first confinement system and thus it has the most stringent requirements in the ITER safety, quality, vacuum, seismic and tritium classifications [3]. The design of the unit was assessed and optimized by FEM analyses for the required load conditions and combinations [4] to meet such requirements and the main results are reported in this paper.

First, the brazing process is carried out at 800°C and then the temperature of the brazed parts is decreased down to room temperature. Since diamond and copper have very different thermal expansion coefficients, high stresses build up at the interface during the cool down phase. Due to EC power absorption in the disc, the unit requires active cooling. The cooling circuit is placed outside the first confinement boundary of the window unit. This design choice allows separating the coolant from the disc forming the tritium barrier and makes the unit safer, although temperatures and thermal stresses are higher than in the case of a direct cooling of the disc.

The window unit is part of the ex-vessel waveguide system, connected to the ceiling of the port cell (by a support frame) and to the UL port plug (i.e., to the ITER vacuum vessel). Movements of the vessel due to baking, seismic and plasma disruption events, result in forces and moments acting on the unit. During a seismic event, the unit is also subjected to additional loads induced by the oscillation of the support frame. An outer shell surrounding the window unit is required to withstand these loads and ensure its structural integrity.

Finally, the unit is designed to provide a second tritium barrier and allow real-time monitoring of the interspaces to detect potential tritium leakages [5].

Methods

The cool down phase of the brazing process was simulated by a 2D static structural analysis including diamond disc and copper cuffs only. The equilibrium temperature was 800°C and it was decreased down to 20°C. The brazing material was not considered, but non-linear properties were used to account for the plastic behaviour of the copper cuffs. Because of stress singularity issues in the brazing zone, the stresses in the disc were taken at a distance of 51 µm from the singularity points, being this distance the critical crack length of CVD diamond [6-8].

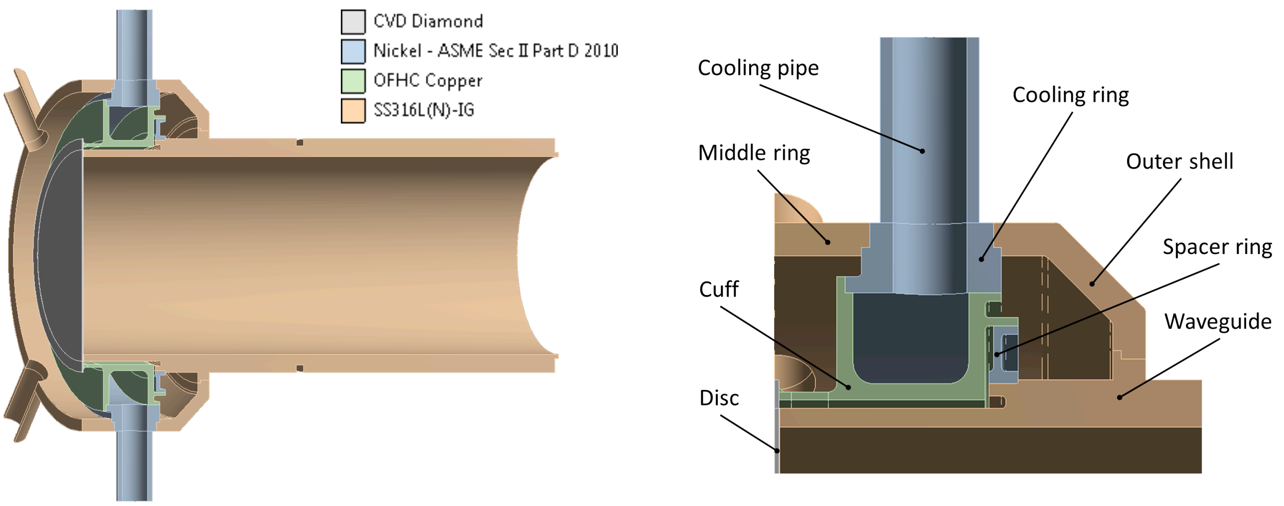

Fig. 1. Design of the diamond window unit for the ITER EC H&CD UL optimized by FEM analyses. Only a quarter of the unit is shown on the left and its different parts are highlighted on the right. Brazing is carried out only between disc and copper cuffs while all other parts are joined by EB welding. The cuffs have embedded channels allowing indirect cooling of the disc (there is a gap of 100 µm between disc and waveguide). Pipes in the middle ring connect the unit to different diagnostic systems to detect for instance any potential tritium leakage (holes in the cooling ring allow connecting the zones to the sides of the ring itself).

The load combination given by seismic event during baking of the vacuum vessel is the driver for the design of the outer shell. The units are located in the section of the ex-vessel waveguide system that is connected to the ceiling via a support frame. The most stringent ITER seismic event (i.e. SL-2) was considered for the analysis. Acceleration spectra, seismic and baking displacements were first applied to the waveguide system and they resulted in forces and moments acting on the units via the frame. Then, these loads were applied to the unit to investigate different geometrical configurations of the outer shell, taking into account also the need of a second tritium barrier.

The thermo-fluid dynamic behaviour of the unit was investigated by a CFD conjugate heat transfer analysis with reference to a 1 MW HE_{11} mode beam at 170 GHz. A loss tangent of 2×10^{-5} was used for the diamond disc and a water mass flow rate of 20 l/min at 20°C was considered for the complete window unit (there are two inlet pipes). The resulting temperature distribution in the disc and the copper cuffs (the other parts do not give any contribution to the cooling) was then transferred to a structural analysis of the unit together with dead weight, fluid pressure and external atmospheric pressure to calculate the stresses in the unit during operating condition. The stresses in the disc were subsequently summed up to the residual stresses generated in the disc by the cool down phase of the brazing process.

Finally, a sensitivity analysis was carried out by varying the inlet mass flow rate to characterize the thermal-hydraulic performance of the unit.

Results

The design of the window unit was enhanced to ensure the required reserve margins against the most critical ITER load combinations. A second tritium barrier, with monitored interspaces, was incorporated in the design. An optimum solution, reported in Fig. 1, was found by increasing the thickness of both the middle ring and the cooling ring, and therefore making the outer shell as the second tritium barrier. This configuration made the design more compact, stiffer and simpler to manufacture with respect to other investigated design variants. The very rigid outer frame is so able to withstand the external loads acting on the unit while the thin copper cuffs brazed to the diamond allow indirect cooling of the disc. For instance, the outer frame reduces the stresses in the nickel spacer rings to about 30 MPa, for the case of an SL-2 seismic event occurring during the baking of the ITER vessel.

The maximum principal stress in the disc due to the cool down phase of the brazing process is 142 MPa in the brazing zone. The very different thermal expansion coefficient between copper and diamond (ratio of 16 to 1 at 20°C) induces high thermal stresses at the interface between the two materials. However, the resulting stress is below the safe limit for diamond, that is assumed to be in the order of 150 MPa (with an ultimate stress around 450-500 MPa [8]). The cuffs experience plastic behaviour with stresses between 80 and 100 MPa in the most part of the contact surface with diamond. Only in very small portions, the stress increases up to 140 MPa.

The thermal-hydraulic performance of the unit is adequate. The beam power absorption in the disc results in temperatures of the disc lower than 60°C while the pressure drop in the cooling channel is limited to 5.7 kPa. The stresses in the disc associated with the mm-wave operations of the UL are below 30 MPa. However, the residual stresses due to the brazing should also be considered. A conservative approach is to sum the principal stresses in the brazing zone of the disc, which would result in a maximum stress of 151 MPa as shown in Fig. 2. This value is equal to the safe stress limit assumed for diamond, as introduced before. Finally, it shall be noted that the thermal performance of the unit is very stable with regards to variations of the inlet mass flow rate. In fact, the heat removal strategy is based on thermal conduction through the diamond and thin copper inserts, rather than direct cooling. For example, if the mass flow rate is reduced by 4 times, the maximum temperature located at the centre of the disc increases only by 4°C.

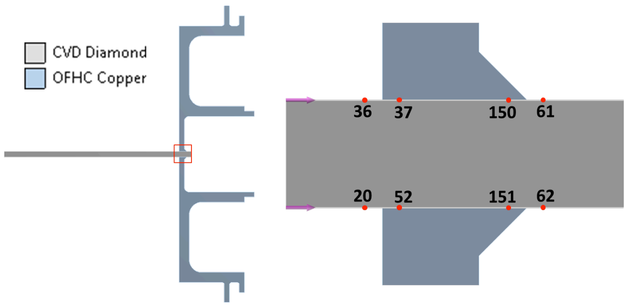

Fig. 2. Maximum principal stresses in the disc at 51 μm (red dots) distance from the singularity points in the brazing zone for brazing plus operating condition of the unit. Values are in MPa.

Acknowledgements

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