FEM Analyses of the ITER EC H&CD Torus Diamond Window Unit Towards the Prototyping Activity

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The chemical vapour deposition (CVD) diamond torus window unit is a sub-component of the ITER Electron Cyclotron Heating and Current Drive (EC H&CD) system used for a diverse range of applications including plasma heating and control of plasma magneto-hydrodynamic (MHD) instabilities. It consists of an ultra-low loss polycrystalline diamond disk brazed to copper cuffs and then enclosed by a metallic structure. The diamond disk with 1.11 mm thickness already passed successfully the ITER final design review (FDR) in 2018. In view of the complete window assembly FDR, prototyping activities of the window are essential and, therefore, they shall start soon in order to check the feasibility of the proposed manufacturing and assembling sequence of the component. In this perspective, as the design of the systems surrounding the window is currently in development phase, the paper describes the finite element method (FEM) analyses of the window to carry out with the aim to prove the soundness of the design used for the prototyping and also to define requirements for the surrounding systems. Specific methodologies are adopted such as the limit analysis approach for the external loads acting on the window unit. Several combinations of forces and moments are applied to the window unit to find the maximum loads, i.e. the limits loads, which generate stresses in the unit equal to the allowable ones, according to the selected design criteria.

Keywords: ITER, EC system, Diamond window unit, FEM analyses, Limit analysis

1. Introduction and background

A total of 56 torus diamond window units shall be installed in the ITER EC H&CD system consisting of one equatorial launcher (EL) and four upper launchers (ULs) which inject millimeter-wave beams at 170 GHz into the plasma [1]. A global view of the EC system in ITER is shown in Fig. 1. For purely convention reasons, the transmission lines (TLs) are named ex-vessel waveguides (EWs) from the diamond window location down to the port plugs. The EL has 24 EWs at the entry, which are grouped into three sets of eight beams, while each UL has eight EWs entries grouped in two sets of four beams (32 EWs for the four ULs). There is one window unit for each EW.

The torus windows have the fundamental safety role to act as vacuum and confinement barriers during the transmission of the high power millimeter-wave beams. A design beam power of 1.31 MW is considered at the torus window (1.5 MW is the beam power at the gyrotrons). The main part of the window which has to satisfy the safety function is a polycrystalline diamond disk, which is enveloped in a metallic structure, making the window unit a very peculiar fusion component. With respect to other materials, diamond is the only material that complies with the combined microwave, mechanical, thermal, vacuum and safety requirements.

Many efforts have been made in the design development of the UL window to achieve a sufficient maturity level to enable the start of the prototyping and testing activity in view of the ITER FDR, scheduled in 2020 [2,3]. The FDR related to the diamond disk only was already carried out at the end of 2017 (successfully passed in 2018) due to the long procurement time for the 56 disks, each of which requires weeks to manufacture as the growth process is extremely slow. The design developed by KIT shall be also adopted for the EL windows and the procurement of all the 56 torus diamond windows is under European Fusion Domestic Agency's (F4E) responsibility.

As shown in Fig. 2, the UL window units together with the isolation valves are located in a section of the EWs, outside the bio-shield in the ITER port cell. They are enclosed by a support frame, called Ceiling Support Structure (CSS), which is attached to the ceiling. According to the direction of the beam propagation, the units are in between the direct current (DC) breaks and the isolation valves. Each unit has integrated waveguide (WG) stubs on both sides that shall be connected to the EWs via single helicoflex™ seal (SHS) couplings.

In view of the complete window unit FDR in 2020, prototyping activities are essential and they shall start soon in order to check the feasibility of the proposed manufacturing and assembling sequence of the unit. However, before starting the prototyping, a new set of FEM analyses is required to prove the soundness of the window design itself. As the design of the systems surrounding the window is currently still in development phase, specific analysis methodologies like the limit analysis approach are in fact needed for the window.

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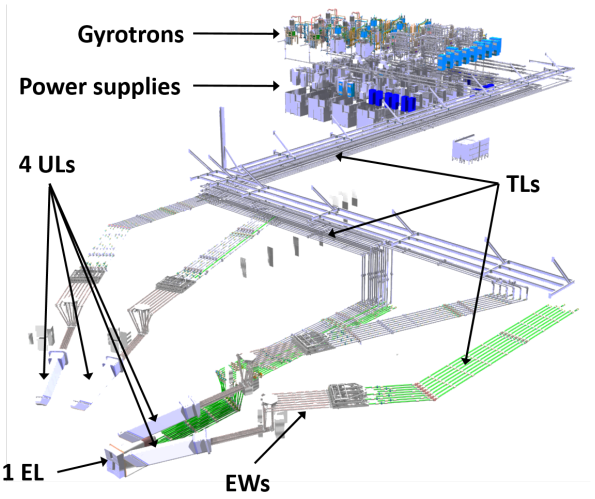

Fig. 1. EC system in ITER.

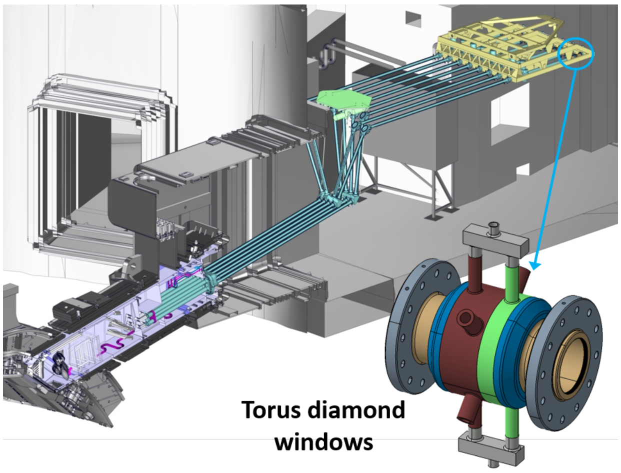

Fig. 2. Windows in the ITER upper launcher.

A limit load is defined by codes like ASME as the load causing overall structural instability. To be clear, limit analysis in this work is instead intended as analysis aiming to find loads / displacements that cause in the window stresses equal to the allowable limits of the materials. The idea is to define requirements for the interface systems of the window in terms of maximum acceptable external loads that might be transmitted to the unit. In the context of the framework contract (F4E-OFC-0842) signed in May 2018 between F4E and the Karlsruhe Institute of Technology (KIT) aiming to the testing of the ITER EC launcher windows, a task order will cover the execution of the new set of FEM analyses.

This paper describes the strategy adopted in the analysis of the window unit prior to the start of the prototyping and testing activities, taking into account the not yet frozen design of the components surrounding the window (e.g., the geometry of the EWs). Further, some expected material degradation occurring in a step of the current assembling sequence needs to be considered.

2. Design of the window unit

The window unit, shown in Fig. 3, consists of two inner parts represented by the diamond disk and the copper cuffs, which are protected by a metallic structure that shall avoid any stress propagation towards the internal side and, at the same time, remove the power absorbed in the disk and the WGs during the beam transmission. The disk has a diameter of 75 mm and a thickness of 1.11 mm, corresponding to 3 times $\lambda/2$ (the half wavelength) of the microwave beam inside the diamond material.

The metallic structure is made by copper-chromium-zirconium (CuCrZr) alloy ITER grade (IG) with a treatment consisting in solution annealing plus ageing. It has a length of 160 mm and a height (the distance inlet-outlet) of 240 mm. Corrugated WGs with 50 mm inner diameter protrude towards the disk leaving a gap of only 100 μm to guarantee a good impedance matching along the transmission line. This gap is one of the most critical aspects to check in the prototype manufacturing as it heavily affects the alignment of the window parts that need to be welded together. The WGs are connected to the EW lines by the coupling flanges on both sides. Manifolds, connected to the feeding water circuit, allow water to enter the channels embedded in the cuffs with the consequence that there is no direct contact of the disk with the coolant.

For the diagnostics of the window, there are currently four pipes in the line of sight of the disk. The preference is to keep at the minimum the diagnostics inside the unit and use the WG portion on the gyrotron side of the unit as a sort of diagnostic pipe to detect, for instance, any leakage across the disk and arcs generation. In this way, the current design of the window would be not affected by the diagnostics. The integration of diagnostic monitoring systems for the window is actually under discussion with F4E/IO and it will be faced in the context of the mentioned framework contract.

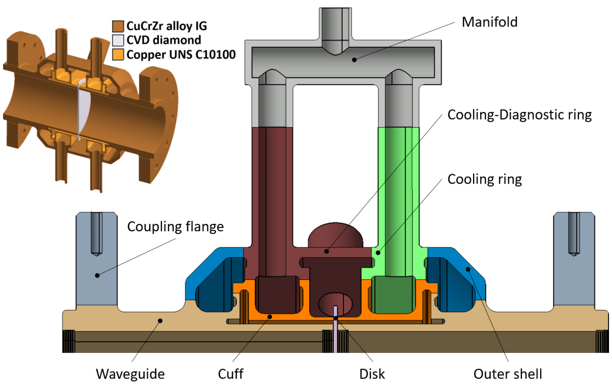

Fig. 3. Current design of the ITER torus EC window with the nomenclature of the parts and the materials.

3. Methods

The window unit shall withstand the loading conditions specified in the ITER load specifications during normal and off-normal events. In general, the FEM analyses of the window, carried out in ANSYS Workbench, can be grouped in four categories with reference to the external loads, internal loads and the thermo-structural loading during beam transmission and accidental events like the hot spot case (excess heating on one side of the EW wall versus the other side, [4]). The design criteria defined in the applicable ASME III-NC code are applied to the metallic parts of the unit. The theory of failure used in the sub-article NC-3200 (design by analysis) is the maximum shear stress theory, thus the stress results from the analyses are always considered in terms of equivalent Tresca stresses, named stress intensities in ANSYS. For diamond, being a brittle material, stress results are instead taken in terms of first principal stresses.

3.1 Limit analysis approach for external loads

In case of external loads acting on the window (mainly due to vacuum vessel baking, seismic, plasma disruption events, TL thermal expansion), as the units are attached to the EWs, the method of analysis would consist in the sub-modelling strategy [5]:

1. run a global analysis considering the geometry of the EWs assembly and applying the boundary conditions and the loads for the specific load case of interest,
2. run a structural analysis considering the geometry of the window unit and applying at its boundaries the linear / angular displacements or the forces / moments obtained by the global analysis. The resulting stresses would be then linearized in the critical locations and compared with the allowable limits according to the selected design criteria.

In this case, a structural integrity assessment would be performed for each of the external load case given by the ITER load specifications. However, a different approach was required and adopted for the window as the design of the EWs assembly is not yet finalized while the window shall face its FDR in a relatively short time (2020). In fact, a final global analysis to provide the inputs to the window analysis for the external loads cannot be performed at this state. The adopted approach consists therefore in the limit analysis in which linear / angular displacements or forces / moments are applied to the ends of the window with an increasing value in order to find the maximum displacements / loads that generate stresses in the unit equal to the allowable limits, in accordance to the selected design criteria.

These maximum acceptable displacements / loads represent the limit displacements / loads for the window unit. Following this logic, the calculated maximum displacements / loads with a reasonable safety margin are provided as requirements to the designers of the EWs and TLs. For all load cases, the displacements / loads transmitted to the window units shall be lower than the limit values. The compliance with such requirements will guarantee stresses in the window lower than the allowable limits for all external loads.

The methodology consists in carrying out two separate structural analyses, one for the limits referred to the forces acting on the unit and the other one for the limits concerning the moments. In the first analysis, several combinations of forces are applied as parameters by using the ANSYS object named remote force and defining a reasonable number of design points in the ANSYS project. The ranges of the force values are chosen to obtain, for each selected design criterion and for all ASME service levels, maximum stresses in the window lower and also greater than the allowable stresses. In fact, these maximum stresses can be then reported in contour plots to define, for each design criterion and for each ASME service level, the limit combinations of the forces for the window, i.e. the combinations of forces that generate in the unit stresses equal to the limits. In the same fashion, the structural analysis related to the moments is run by applying the ANSYS object named moment and calculating the limit combinations of the moments for the unit.

As shown in Fig. 4 and Fig. 5, a fixed support boundary condition is applied to one end of the unit and the combination of remote forces and moments to the other end. It can be noted that, not considering the manifolds (which do not have any structural function aiming to protect the sensitive inner parts) and the cooling / diagnostic pipes, the cylindrical symmetry of the unit leads to an equivalence between Fy and Fz and between My and Mz in terms of effects in the unit. As a consequence, only the two types of combinations Fx (axial force), Fy (lateral force) and Mx (torsion), My (bending) are applied to the unit and thus the limit combinations are given only for the pairs Fx, Fy and Mx, My. The introduction of the third component would result in a very big number of combinations, very difficult to manage.

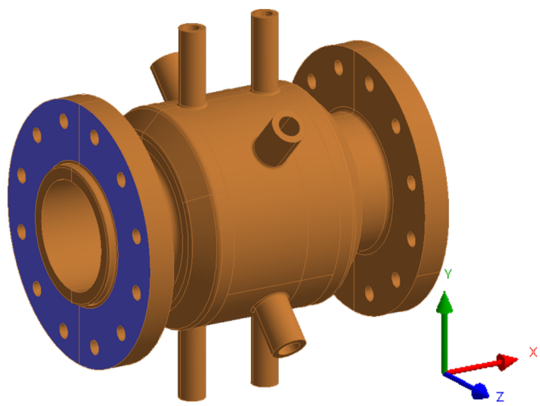

Fig. 4. Fixed support applied to the flange in one end of the window in the limit analysis.

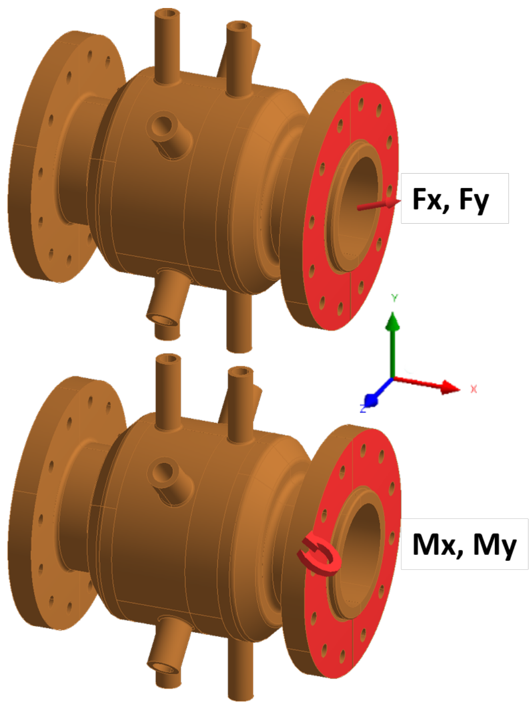

Fig. 5. Combination of remote forces and moments applied to the flange in one end of the window.

For each combination of forces and moments, the resulting stress intensities are linearized along proper stress classification lines (SCLs), drawn in the most critical regions of the unit, in order to obtain the stress components (e.g., the bending component) that shall be used in the selected design criteria. The maximum value of the stress components of interest along the various SCLs is then used for the generation of the plots. The stresses due to the external loads acting on the window unit are considered as primary stresses and, therefore, the following design criteria taken from [6] apply:

$$Pm \leq kSm$$

$$Pm + Pb \leq 1.5kSm$$

being Pm the general membrane stress intensity, Pb the bending stress intensities, Sm the stress intensity limit and k the stress intensity factor specified by the code with reference to the ASME service level (A, C or D).

Stress contour plots are finally generated for each selected design criterion as a function of the applied forces / moments combinations. An example is shown in Fig. 6 with reference to the Pm+Pb component. These plots were generated in the context of a test run in view of the analysis to perform in the F4E framework contract. They show the maximum value of Pm+Pb obtained in the window when a specific combination of forces or moments is applied. The lines at constant stress equal to the allowable limits for the ASME service levels A, C and D represent the limit lines, i.e. the lines that provide the limit combinations of forces and moments for that design criterion and service level.

These plots shall be given as requirements from the window perspective to the designers of the systems surrounding the window unit, i.e. the EWs system and the TLs system. The stresses intensities generated in the unit by the external loads due to both the EWs and TLs systems shall lay in the area of the plots underneath the limit lines of interest.

However, in general, forces and moments are applied at the same time and thus, for the specific design criterion of interest, the total stress intensity due to both forces and moments have to be considered in the comparison with the allowable limits. Even if dealing with equivalent stresses, the simplest and most conservative way is to sum up the stresses in the plots due to the forces and moments. For this purpose, grids of stress values generated directly from the plots are very useful.

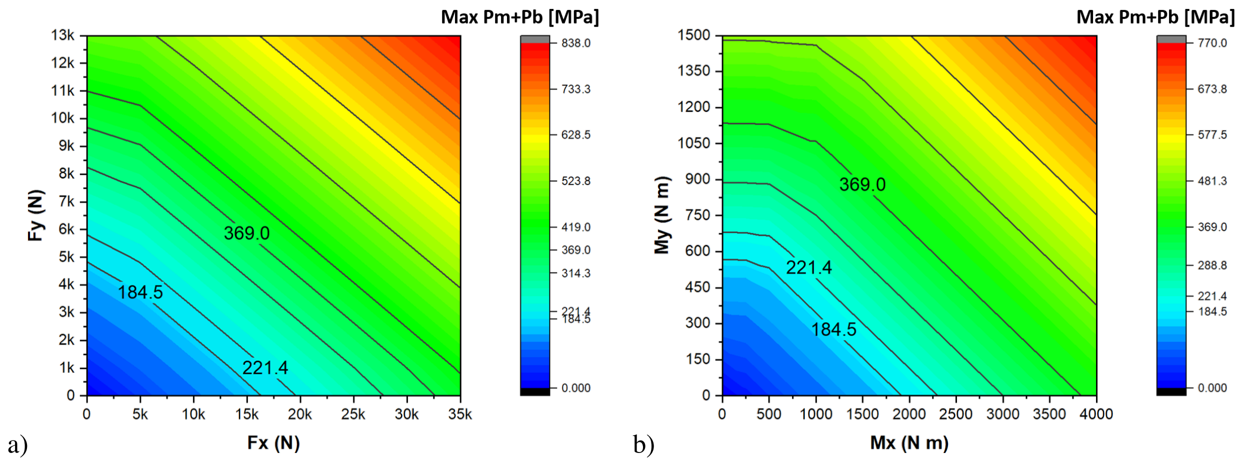

Fig. 6. Example of stress contour plots for the maximum membrane plus bending stress component generated in the window unit when combinations of Fx, Fy (a) or Mx, My (b) are applied. The lines at constant stress of 184.5 MPa, 221.4 MPa and 369 MPa correspond to the allowable limit of this stress component respectively for the ASME service levels A, C and D. The stress plots refer to the CuCrZr alloy IG for the treatment consisting in solution annealing plus ageing.

3.2 Analysis strategy in view of the prototyping

A dedicated set of FEM analyses is required to prove the soundness of the window design before starting the prototyping activity. In fact, looking at the current assembling sequence of the unit [3], the CuCrZr cooling and cooling-diagnostic rings in Fig. 3 are first welded to the copper cuffs and then the cuffs are brazed to the diamond disk. The brazing process is carried out at about 900 °C in a vacuum oven and then the temperature of the involved parts is decreased down to room temperature.

The rings, which form the outer frame aiming to protect the sensitive inner parts of the window, are therefore subject to this strong temperature cycle that might cause a degradation of the CuCrZr properties with a consequent negative impact on the structural behavior of the unit. Since in the previous FEM analyses of the unit, the properties of the virgin CuCrZr alloy IG were used for the rings, F4E has carried out tensile tests aiming to check the expected properties degradation and measure the modified properties of the CuCrZr.

The following next steps are planned within the window development. First, new structural analyses shall be performed by using the results of the tensile tests to check the impact of the material degradation on the capability of the window outer frame to withstand the external loads (avoiding thus any stress propagation towards disk and cuffs). Depending on the analysis results, the design of the window unit might require some changes aiming to counteract the material degradation of the CuCrZr cooling and cooling-diagnostic rings. In addition, in this phase, some other changes like increasing the thickness of the coupling flanges by few millimeters (to have a common approach in the integration of the components in the EWs) might be included in agreement with F4E and ITER Organization (IO).

The following limit analysis approach, which substitutes all analyses of the unit involving the external loads specified by ITER, rules the choice and the type of load combinations to run for the thermal and structural analyses in order to show that the agreed design of the window unit is sound enough for the prototyping and testing. Some worst case scenarios (i.e., scenarios where the sum of the stresses due to forces and moments equals the allowable limits) of the limit analysis, performed with the agreed window design, will be combined with normal operation, normal operation plus internal fire (combination of external and thermal loads) and also with normal operation plus overpressure (combination of external, thermal and internal loads).

It will be checked for instance if overlap of the stresses due to different load sources occurs or how much the allowable limits are overpassed with the loads added to the worst case scenarios from limit analysis. These analyses will be completed by the ones concerning the hot spot case, the misalignment of the beam from the disk center and the failure of the feeding water system (to know the maximum time the window can operate safely with heating loads).

4. Conclusions

The UL torus diamond window unit shall face soon prototyping and testing activities in view of its FDR, scheduled in 2020, to prove the feasibility of the manufacturing and assembling sequence of the unit. Although several FEM analyses of the window were performed in the past, before entering the prototyping phase, a new set of analyses is however required to account for the not yet frozen design of the components surrounding the window and the expected material degradation of the CuCrZr cooling and cooling-diagnostic rings, subject to the temperature cycle of the brazing process.

This paper showed the strategy for this new set of analyses aiming on one side to define requirements from the window perspective to the designers of the EWs system and the TLs system and, on the other side, to prove the soundness of the window design. The limit analysis approach was introduced to cover all cases involving the external loads defined in the ITER load specifications and, clearly, due to its nature, this approach determines the choice and the type of load combinations to investigate prior to the start of prototyping and testing.

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