Design evolution of the diamond window unit for the ITER EC H&CD upper launcher

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The torus window unit is a very particular component of the ITER EC H&CD upper launcher aiming to provide the primary vacuum and confinement boundary between the vacuum vessel and the transmission lines (TLs). The high power 170 GHz millimeter-wave beams generated by the gyrotrons travel along the TLs and pass through the window units, before being quasi-optically guided into the plasma via the upper launchers. The design of the window unit shall thus meet stringent requirements to guarantee the safety function, the millimeter-wave beam transmission and the structural integrity during normal operation and off-normal events. The unit consists of an ultra-low loss CVD diamond disk brazed to two copper cuffs; this structure is then integrated into a metallic housing by welding. The compliance with the requirements shall be assured by applying the ASME Section III – Subsection NC code and a dedicated experimental qualification program. This paper reports the way in which the design of the unit, already optimized by FEM analyses against the ITER loading conditions, was further improved by the application of the ASME III-NC code, leading to a more feasible and simpler manufacturing and assembling sequence. In addition, the impact of the ITER project decision to change the inner diameter of the waveguide from 63.5 to 50 mm, to improve the beams' mode purity, was assessed and it is also discussed. Different materials for the metallic housing and in particular for the millimeter-wave inserts of the unit were compared using appropriate engineering criteria to mitigate the significant increase of the millimeter-wave thermal loads on the waveguides when the diameter is decreased.

Keywords: ITER, upper launcher, diamond window, waveguide, ASME.

1. Introduction

The torus diamond window unit plays a major role in the ITER electron cyclotron heating and current drive upper launcher (EC H&CD UL) as it allows the transmission of millimeter-wave beams up to 1.5 MW, while being part of the first ITER vacuum and tritium confinement system. The main purpose of the upper launcher is to drive local current in the plasma with the aim of suppressing neoclassical tearing modes. These modes on one side can trigger plasma disruptions generating loads on the plasma facing components and on the other side lead to confinement degradation [1].

The design of the window unit shall meet stringent requirements to guarantee the safety function, the millimeter-wave beam transmission and the structural integrity during normal operation and off-normal events. The design strategy is to have a very rigid outer window frame able to withstand the potential external loads acting on the unit, while thin copper cuffs brazed to the diamond allow indirect cooling of the disk (i.e., no direct contact between disk and coolant). The design driver load combination of the window unit is represented by the severe SL-2 seismic event occurring during the vacuum vessel baking. A dedicated FEM analysis for this load combination already led to a compact and stiff design of the unit with resulting stresses well below the allowable limits [2]. The analysis also showed that the inner sensitive parts of the window, i.e. the disk and the copper cuffs, are not affected by the external loads acting on the unit.

This paper shows how the design of the torus window unit was further improved taking into account the requirements given by the applicable ASME III-NC code and the manufacturing aspects. In addition, it shows the impact on the unit design of the ITER project decision to change the inner diameter of the waveguide (WG) from 63.5 to 50 mm, to improve the beams' mode purity.

2. Design optimized by FEM analysis

The optimized design of the unit by FEM analysis is shown in Fig. 1 with the nomenclature of the parts and the involved materials. Fig. 2 shows an exploded view with the proposed assembling sequence. According to Fig. 1, the window unit consists of a diamond disk brazed to two copper cuffs with embedded cooling channels allowing the indirect cooling of the disk. Two nickel rings, named spacer rings, connected the cuffs to corrugated stainless steel WGs. The WGs were inserted into the cuffs leaving a 100 μm gap only with the diamond disk in order to avoid parasitic excitations in the small cavities of the unit. The WGs had an inner diameter of 63.5 mm and the inner corrugated surface was Cu-coated to mitigate the heat loads acting on the WGs during the beam transmission.

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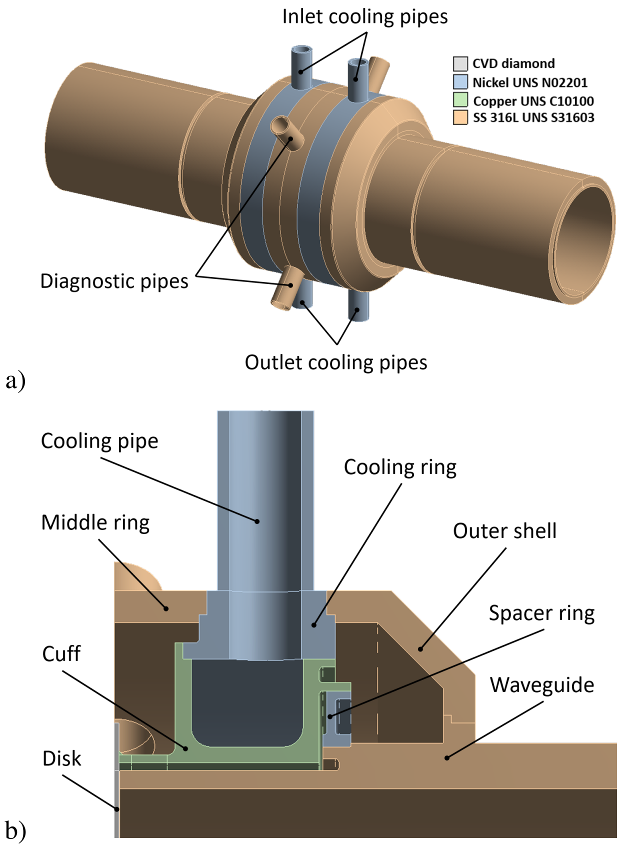

Fig. 1. Design of the window unit optimized by FEM analysis in a global view (a) and detailed view (b). The inner corrugation of the WGs is not shown here.

The cooling channels were closed by external nickel rings, named cooling rings. They were connected to each other by the stainless steel middle rings and to the WGs by the steel outer shells. With reference to Fig. 2a, the window unit optimized by FEM analysis consisted of 13 parts to be assembled by using only two types of joints: brazing between disk and cuffs and electron beam (EB) welding between all other parts. The brazing material is a copper-silver-titanium (CuAgTi) alloy. Titanium creates a good connection with the diamond disk surface as it has a strong affinity with carbon atoms. There were 6×2 symmetric parts plus the diamond disk forming the unit. The two inlet and outlet cooling pipes were integrated parts of the cooling rings, while the four diagnostic pipes were integrated parts of the middle rings.

The total number of joints amounted to 18, in particular to 9×2 because of the symmetry in the unit. Looking at the Fig. 2b, the cuffs were first welded to the cooling rings (box no. 1) and then brazed to the disk (box no. 2), leading to the first subsystem of the unit. In parallel, the WGs were welded to the spacer rings (box no. 3) leading to the second subsystem of the unit. The two subsystems were then joined together by carrying out the weld between the cuffs and the spacer rings shown in the box no. 4. Finally, the outer shells were welded to the assembly (box no. 5) and the middle rings as well (box no. 6). Specific tolerances were defined for the assembling of the parts aiming to guarantee the correct propagation of the beams (e.g. the tolerance for the gap disk-WG). During the prototyping activity of the unit, the way of positioning the parts in the welding process will be investigated in order to be compliant with the given tolerances. The metallic parts of the unit are joined by EB welding as this process allows minimizing the deformations in the unit due to the welded joints. In fact, high welding deformations might lead to the failure of the disk. Therefore, with respect to other welding techniques, the use of the EB welding process preserves the structural integrity of the diamond disk while assembling the unit.

3. Design evolution

The design of the diamond window unit shown in Fig. 1 and Fig. 2, optimized by FEM analysis, was further optimized by the application of the ASME III-NC code, in particular with reference to the requirements stating that the welded joints in the unit shall have complete joint penetration and full fusion (NC-4262a) and also they shall be fully radiographed (NC-5252). The comparison between the design optimized by FEM analysis and the one further improved by ASME is shown in Fig. 3. The steps at the location of the joints, originally inserted to help the joining of the parts, were removed allowing a complete joint penetration.

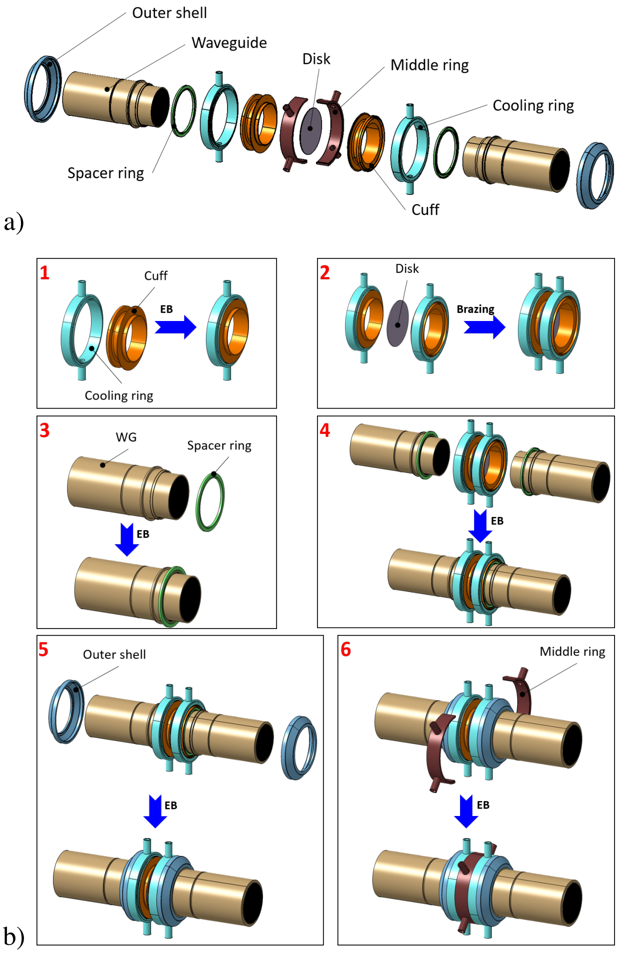

Fig. 2. Exploded view (a) and assembling sequence (b) of the diamond window unit optimized by FEM analysis.

However, if needed for the unit assembling, the joint faces might feature an internal sacrificial step, small enough to be completely absorbed in the melted zone of the welding. Then, the geometry of some joints was improved leaving a certain margin for the extent of the heat affected zone (HAZ) of the welded joints, i.e. the zone of the joining parts affected by the heat released during the welding process. For example, this can be observed at the welds between the cooling ring and the cuff. The optimization of the joints was also affected by the need of having them fully radiographed. As little material as possible was left between the radiation source (e.g. inside the WGs) and the radiographic film (placed around the unit). This can be observed for instance at the weld between the cooling ring and the outer shell.

In the design optimization process, the number of joints to be performed after brazing was minimized, to reduce deformations due to welding processes when the disk is already integrated in the assembly. As shown in Fig. 3, the middle rings were removed from the unit and integrated in one of the two cooling rings, thus giving rise to a new part named cooling-diagnostic ring and reducing by 3 the number of joints to be performed after brazing. In addition, the welding thickness of some joints was reduced to further decrease the energy released in the unit by the welding processes. For instance, the welding thickness of the joints between the outer shells and the assembly was reduced from 4 to 3 mm, but leaving the thickness of the outer shell equal to 4 mm.

4. Design changes for 50 mm diameter reduction

The ITER project decision to reduce the inner diameter of the TLs from 63.5 to 50 mm, in order to be compliant with both the required power and mode purity transmission efficiency, caused a major further revision of the unit design, also taking into account other factors. The design was first simply adapted with all radial dimensions scaled down by the same amount (63.5-50)/2 = 6.75 mm, keeping thus the same joints configurations as in the 63.5 mm version of the unit. At the same time, the length of the unit was significantly reduced by almost half, since the integration of the unit in the WGs lines changed from the General Atomics (GA) couplings to the integrated coupling design concept developed at the SPC institute in Lausanne [3]. The resulting more compact design of the window unit is shown in Fig. 4a. It can be noted that water manifolds were also added for the connection to the feeding water system.

While the beams propagate along the WGs, the millimeter-waves generate currents in the WG walls, dissipating heat directly at the surface (ohmic losses). These losses depend on the frequency, WG diameter, material and corrugation dimensions. Unfortunately, when the diameter of the WGs decreases, the power absorbed in the WG walls increases very significantly. In fact, for the 1.31 MW design beam at the window location, calculations showed a thermal loading of 1577.8 W m^{-2} in the 63.5 mm Cu-coated WGs and 4070.7 W m^{-2}, i.e. 2.6 times greater, in the 50 mm unit. The larger power density at the WG walls required checking the temperature distributions and thermal stresses and deformations. In addition, experimental observations [4] suggested that hot spots in the WGs should be taken into account. These hot spots consist in non-axially symmetric modes in the WGs that lead to an excess heating on one side of the WG wall versus the other side.

FEM steady state thermal and structural analyses were thus carried out considering four different material configurations of the window unit with respect to the transmission of the 1.31 MW design beam and also to the off-normal event of hot spot. In addition, the impact of the material changes on the weldability of the unit design was discussed with TWI in Cambridge [5]. The investigated configurations were:

- Configuration #1: stainless steel WGs with a copper layer onto the inner surface. Same materials as in the 63.5 mm version of the unit.
- Configuration #2a: nickel WGs with a copper layer onto the inner surface. Outer shells and coupling flanges made by nickel too, as nickel already used in the unit.
- Configuration #2b: same as configuration #2a, but without copper coating.
- Configuration #3: copper-chromium-zirconium alloy (CuCrZr) WGs. Outer shells and coupling flanges made by CuCrZr too, since, as stated in discussion with TWI, the EB weld steel – CuCrZr is problematic due to the different thermal expansion coefficients of the materials and the risk of formation of intermetallic compounds in the welding region that might make the region brittle.

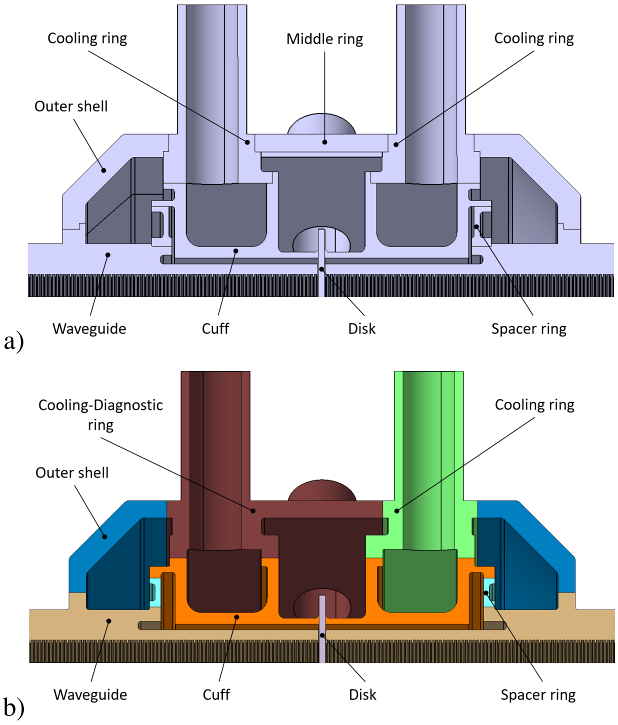

Fig. 3. Comparison between the design optimized by FEM analysis (a) and the design optimized by ASME III-NC (b). The central part of the window unit is shown here.

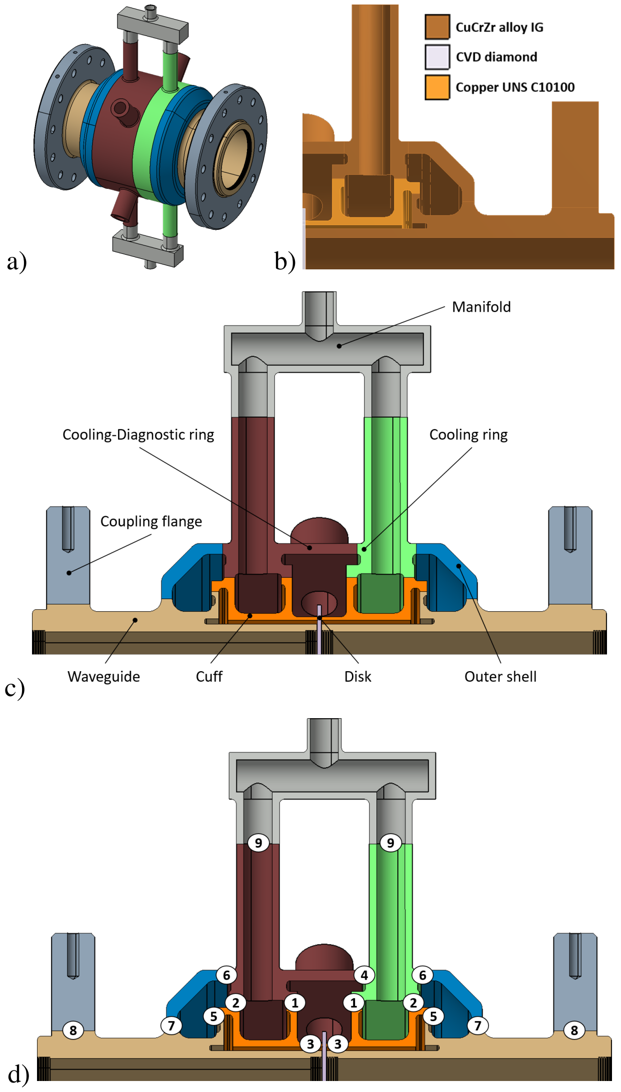

Fig. 4. Current design of the window unit in a global view (a), detailed view with the indication of the materials (b), section view with the parts forming it (c) and section view with the proposed sequence of joints (d).

The assessment indicated the configuration #3 as the best compromise for the material configuration of the unit. In fact, the CuCrZr version of the unit meets the structural criteria even in the hot spot case, providing high safety margins against the allowable limits. It does not require any inner coating onto the WGs, thus leading to a simpler unit manufacturing and removing the issues connected to the uncertainties on the temperature limit for the copper coating. Last, it results in some joints that, with respect to the nickel option, have a lower weld shrinkage with consequent lower deformations induced in the unit. In fact, as stated in discussion with TWI [5], the weld shrinkage is about 10-12% for nickel and only 2-3% for CuCrZr.

The nickel in the unit design was introduced in the past in order to have an intermediate material between copper and steel parts, with good weldability with both materials. As shown in Fig. 4b and Fig. 4c, being the WGs made by CuCrZr, the material of the spacer rings was thus changed to this alloy and they were consequently integrated in the WGs, decreasing the total number of joints after brazing. At this point, the cooling ring, the cooling-diagnostic ring and the manifolds were also made by CuCrZr alloy to reduce the number of the involved materials and to simply therefore the manufacturing of the unit.

5. Conclusions and outlook

In this paper, the evolution of the design of the torus window unit, already optimized by FEM analysis, was discussed with respect to the application of the ASME III-NC code, the ITER project decision to change the inner diameter of the WGs from 63.5 to 50 mm and the manufacturing aspects. It was shown that a sufficiently mature design was achieved to start the prototyping and testing activity in view of the ITER final design review (FDR), scheduled at the end of 2019.

The manufacturing of window prototypes is essential to check the feasibility of the proposed manufacturing and assembling sequence of the unit. The current location and sequence of joints is shown in Fig. 4d. There are three types of joints in the window unit: brazing between disk and cuffs (joints #3), orbital TIG welding between the pipes of the cooling-diagnostic/cooling rings and the pipes of the manifolds (joints #9) and EB welding among all other parts of the unit. The total number of joints is 19, in particular 7x2 symmetric joints with respect to the middle plane of the disk, plus joint #4 and the 4 orbital welds for the cooling connection.

ASME III-NC code shall be applied for the manufacturing, assembling and qualification of the window unit prototypes, as for the series production of the 56 torus windows required for the ITER EC upper and equatorial launchers.

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