Torus window development for the ITER ECRH Upper Launcher

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Abstract. For high power transmission in ECRH systems, window materials have to combine ultra low mm-wave loss ($\tan \delta < 10^{-4}$) with an outstanding resistance against crack formation. Specially challenging are the CVD diamond “torus” windows which form the primary tritium confinement to the mm-wave system of the ECRH Upper Launcher for plasma stabilization at ITER and which have to be designed as a compact structure allowing transmission of 2 MW beams at 170 GHz. Special emphasis is given to the window development for the remote steering (RS) launcher, as in contrast to the alternative front steering (FS) launcher, it requires additional capability for off-axis transmission.

1. Introduction
Transmission windows have always been a critical element in ECRH systems as thermal run-away or spontaneous crack formation by thermo-mechanical stresses can set principal limits to the high power performance. With the commercial availability of large area CVD diamond disks, window materials are at hand that combine ultra low mm-wave loss with an outstanding resistance against thermal crack formation, which is essentially due to the unparalleled thermal conductivity of about 2000 W/(m·K)$^{-1}$ at room temperature [1].

Recent permeation tests performed up to 240°C on the CVD diamond window units, which included investigation of the CVD diamond disk, brazing material and metallic cuffs, showed that the only concern is the use of inconel cuffs; effects occurring by permeation through CVD diamond and Cu cuffs can be excluded [2].

Starting from the initial requirements for an input steering angle $\pm 5^\circ$, the extended physics demands, which imply to cover wider plasma areas with adequate current drive efficiency, have led to implement the full input steering range to the square mm-wave waveguide system $\pm 12^\circ$ at the RS torus window.

2. Window design
2.1. Arrangement
Off-axis transmission introduces new design aspects into the window development. The window is placed between the remote steering unit and the in-vessel waveguide (Fig. 1). The isolation valve placed in front of the waveguide allows continuing the launcher operation in case of a window failure by deactivating a single beamline. The window environment must comply with two major geometrical constraints. Firstly, the length of the window socket must allow access to the welding lip at the
interface to the window unit by automated cutting/welding tools. Secondly, the aperture of the window has to reserve a given free diameter for the beam. At the position of diamond disk, the location of the mm-wave beam was analysed for the launching angle $\pm 12^\circ$. It was found that an extended window apertures up to 95 mm is required for the larger steering [3].

![Figure 1](image1.png)

**Figure 1.** Sketch of the window environment: A: Socket and in-vessel square waveguide; B: isolation valve; C: window socket; D: window unit; E: end mirror of the remote steering unit.

2.2. Cooling

For the design of the cooling structure, three alternative concepts were considered: edge cooling, direct and indirect face cooling. These concepts basically differ in the arrangement of the water cooling chambers relative to metal cuffs which are brazed to the disk surface (Fig. 2).

![Figure 2](image2.png)

**Figure 2.** Major variants of cooling structures for window units:

a) edge cooling , b) direct face cooling , c) indirect face cooling ($h_z$ distance of water jacket)

As the constraints for the window aperture require minimizing the cooling structure towards the remote steering unit, face cooling systems were limited to single face only.

3. Analysis of reflection and absorption at the torus window

The optics aspect of the window was used to fix its thickness specifications providing minimum reflection and to assess the heat load at the window caused by mm-wave absorption. To this aim, Fresnel theory was implemented for the two prototypical windows [3]. The first (“standard”) window type (Fig.3a) is characteristic for windows of FS launcher and gyrotron windows where the direction of the beam propagation is normal to the window surface. The second “generalized” window type (Fig.3b) is specific for RS launcher, where during operation the incidence angle of the mm-wave beam at the window surfaces changes significantly which also implies off-axis transmission (beam shift).

The power absorption ratio is related to the reflection and transmission ratios:

$$A = 1 - R - T,$$

where $R$ is the absolute value of the complex reflection coefficient $r$; $T$ is the absolute value of the complex transmission coefficient $t$. 

In general, the transmission and reflection coefficients depend on the polarization of the mm-wave beam, but for the given range of incidence angles \((-12^\circ \leq \theta_i \leq 12^\circ)\), the difference is not significant, meaning that no particular distinction has to be made in the analysis.

3.1. Reflection

For minimising power reflection from the CVD diamond windows (less than \(R < -20\) dB) the disk thickness \((d)\) must be close to resonant thickness condition, which is given when \(d\) is equal to an integer number of the half wavelength in the material:

\[
d = n \cdot \frac{\lambda_{m,1}}{2}.
\]

where \(\lambda_{m,1}\) is wavelength in material of the window disk, \(n = 1, 2, 3\ldots\)

The best specification for \(d\) and its tolerances was determined by modelling of the reflection ratio allowing a frequency drift for the mm-wave beam of up to \(\pm 0.5\) GHz around 170.0 GHz as a conservative case. A summary of the analysis is given in Table 1.

| Table 1. Maximum power reflection for the various window configurations |
|---------------------------------------------------------------|
| FS torus windows, gyrotron windows | RS torus windows for upper launcher |
| Steering range, \(\theta [^\circ] = \pm 12\) | |
| Reflection, \(R\) [dB] | |
| \(f = 170\) GHz | \(< -25\) | \(< -20\) |
| \(f = 170 \pm 0.1\) GHz | \(< -24\) | \(< -19\) |
| \(f = 170 \pm 0.5\) GHz | \(< -20\) | \(< -17\) |
| Thickness of the disk, \(d\) which provides \(R \leq -20\) dB | |
| \(f = 170\) GHz | \(1.852 \text{ mm} \pm 6 \mu\text{m}\) | \(1.855 \text{ mm} \pm 9 \mu\text{m}\) |

For the steering range \(\pm 12^\circ\), the optimum thickness of the window is slightly higher (1.855 mm) than for no-steering mode of operation (1.852 mm). For the most conservative case of the frequency drift, the reflection condition has to be relaxed to allow \(R < -17\) dB when characteristic practical tolerances in the disk thickness are accepted to be \(\pm 10 \mu\text{m}\).
3.2. Absorption

For the discussion of the power absorption ($P_{\text{abs}}$) in the window units, only dielectric losses in CVD-diamond disks were considered. It was found that there is only a minor dependence on the incidence angles in the range of interest ($\theta \leq 12^\circ$): $\Delta P_{\text{abs}} / P_{\text{abs}} < 2\%$ [2]. Therefore the absorbed power was kept constant in numerical calculations over the whole steering range:

$$P_{\text{abs}} = \frac{P_0}{c_0} f \cdot \pi (1 + \varepsilon_r) \tan \delta \cdot d$$

where $P_0$ is the mm-wave beam power; $c_0$ is the light velocity, $f$ is the frequency.

For example, for a 2MW beam at $f = 170.0$ GHz propagating through a CVD diamond window ($d = 1.855$ mm) having “guaranteed” losses $\tan \delta = 4 \times 10^{-5}$ [1], the absorbed power is 1800 W.

4. Thermo-hydraulic and thermal analysis

4.1. Comparison of the different cooling concepts

The three different cooling concepts (see chapter 2) were analysed for CVD diamond disks brazed to OFHC copper cuffs with a wall thickness of 1 mm. In order to assess the efficiency of the alternative cooling concepts, thermo-hydraulic analysis was performed. The coolant supply was considered for two extreme scenarios; the high temperature/ high pressure scenario given for connection to the FW/BLK primary heat transfer system (“blanket cooling water” at $T = 100^\circ$C; $p = 3$ MPa) and the standard temperature/ pressure scenario given for dedicated cooling loop ($T = 20^\circ$C; $p \approx 0.2$ MPa). The calculations were initiated by studying the influence of the water flow rate on the characteristic window temperatures in the disk ($T_{\text{cent}}$, $T_{\text{edge}}$) for a window aperture of 80 mm except for indirect cooling, for which the aperture was increased to 90 mm. Results of the analysis are summarized in Table 2. The thermo-hydraulic as well as the thermal analysis of the different cooling concepts showed that edge cooling concept provides the most effective cooling for extended apertures. The direct face cooling is limited to window apertures of 90 mm and thus cannot provide the full steering range. For indirect face cooling, the temperature at the disk center is about 100°C higher than in the case of edge cooling.

|                   | Edge cooling | Direct face cooling | Indirect face cooling |
|-------------------|--------------|--------------------|----------------------|
| Flow rate, min    |              |                    |                      |
|                   | 4            | 20                 | 4                    | 20                    |
| $T_{\text{cent}}$ $^\circ$C | 106          | 95                 | 141                  | 103                   | 211                  | 197                  |
| $T_{\text{edge}}$ $^\circ$C | 22-38        | 20-23              | 67-71                | 28-30                 | 132-136              | 119-120              |
| $\Delta T$ $^\circ$C | 68-84        | 72-75              | 70-74                | 73-75                 | 75-79                | 77-78                |

4.2. Assignment of effective film coefficients for the edge cooling design.

Because of its superior cooling efficiency at large window apertures, the edge-cooling concept was chosen for the lay-out of a single disk window for the RS launcher. In order to assign the optimum cooling conditions, additional 3D thermo-hydraulic analysis of the structure was performed (Table 3). Higher mm-wave absorption (1800 W) was included to describe the case of “guaranteed” loss.
Table 3. Temperature of the diamond disk: finalisation of the thermo-hydraulic parameters.

| Water flow rate, [l/min] | 5  | 10  | 20  |
|--------------------------|----|-----|-----|
| Inlet velocity, [m/s]    | 1.0| 2.05| 4.1 |
| $T_{\text{cent}}$, [°C]  | 208| 200 | 194 |
| $T_{\text{edge}}$, [°C]  | 21-51| 20-43| 20-33|
| $\Delta T$, [°C]        | 157-187| 157-180| 161-174|
| $T_{\text{water}}$, [°C] | 20-54| 20-47| 20-38|
| $\alpha_T$, [Wm$^{-2}$K$^{-1}$] | 14000| 23000| 45000|

The results of the modeling indicate a stable and tolerable temperature profile which can be achieved by a film coefficient of 23 kW/(m$^2$·K) for the dedicated cooling water.

5. Stress analysis
The stresses in the RS torus window unit are in general composed of internal stress and external stress contributions. The internal stress term can be formed in the cool-down phase of the brazing process caused by the mismatch in thermal expansion between the CVD diamond and the copper cuff. External stress terms arise during window operation and/or during off-normal events like overpressure on one side of the diamond disk. For the given design, the internal stress was not taken into account because the structure can respond to the axially symmetric strain by plastic deformation in the soft copper (OFHC) cuffs [5]. The external terms which arise during window operation are caused by the mm-wave absorption (heating) and water pressure in the cooling circuits.

The evaluation of stress profiles was based on the maximum level of principle stress ($S_1$) for CVD diamond because its typical ‘ceramic-like’ mechanical behaviour and on the maximum level of equivalent (“Von Mises”, VM) stress for the metallic structures. As limits for tolerable stress the following values were taken: 120-150 MPa (1/3 of ultimate bending strength) for CVD diamond [5], 50 MPa (Yield Strength “YS”) for the copper cuffs and 300 MPa for the steel springs.

5.1. Stress terms caused by mm-wave heating
Heating of the disk due to absorption of the mm-wave power is the dominant factor that causes stresses in the window if the cooling is supplied with a system with relatively low water pressure up to 0.2-0.3 MPa. The steel connections (springs) to housing were reshaped to improve the mechanical performance of the edge cooling window: U-shaped, 0.8 mm thick steel spring proved to provide acceptable stress profiles. To quantify the ‘overshot’ of the stress levels in the copper structure, the peak stresses in the different materials were determined for an ‘ad-hoc’ use of strengthened copper with YS = 150 MPa.

Table 4. Peak stress values of window insert with an U-spring: effect of mm-wave absorption

| Steering, [°] | 0  | 10  | 12  | 12* | Limits |
|--------------|----|-----|-----|-----|-------|
| Shift, [mm]  | 0  | 22.5| 27.0|     |       |
| $S_1$, / Diamond, [MPa] | 51 | 90 | 93 | 96 | 120-150 |
| $P_{\text{abs}}$, 1800W [MPa] | Near disk | 15-30 | 40-60 | 50 | 60-70 | 50 |
| VM / Copper, | Cuff center | ~ 7 | 20 | 20 | 29 | *) 150 |
| VM / Steel, [MPa] | | 6 | 15 | 19 | 18 | 200-300 |

For the “guaranteed case” of mm-wave absorption of 1800 W and at extreme 12° steering angles all materials, including OFHC copper in particular, can be expected to stay in the elastic regime. Maximum stress in steel springs (VM ≈ 20 MPa) is well below critical level. Peak principal stress in the diamond disk of about 95 MPa is approaching the critical limit of 120-150 MPa. The key aspect to improve the performance of the RS torus window with respect to the stress profile is indeed the
selection of CVD diamond disks which are superior as compared to the “guaranteed” level of the dielectric loss.

5.2. Stress terms caused by the water pressure

The cooling circuits, which are readily available, provide cooling water with the following specifications: 1) Blanket FW/BLK PHTS (normal operation): $T = 100^\circ C$, $P = 3$ MPa. 2) Component cooling water system (CCWS): $T = 40^\circ C$, $P = 1$ MPa. For both alternatives, the high water pressure becomes a major factor that defines the peak stresses in the torus window. Therefore stress analysis was performed to assess the upper limit of the water pressure compatible with the window design in order to decide on the applicability of the alternative cooling systems.

Three cases with different loads were considered: 1) Water pressure of 3 MPa corresponding to operation of the torus window with blanket water cooling circuits in absence of mm-wave transmission (Fig. 4a). 2) Combined load: water pressure 3 MPa and 1800 W mm-wave heat load corresponding operation of the torus window under mm-wave transmission (Fig. 4b). 3) Variable water pressure loads in range 0.7 - 1.2 MPa to find the upper limit which can be tolerated for window based on U-shaped springs (Fig. 4c).

From the colour diagram of the equivalent stress the major influence of the high water pressure is clearly seen. At 3 MPa, the longer copper cuff is fully plastically deformed. The maximum water pressure is reached at 0.8 MPa, as the peak VM stress in copper cuffs is just at the critical limit of 50 MPa in central structure of the cuff.

The final modeling of the window structure was therefore made applying the combined load of water pressure (0.8 MPa) and mm-wave absorption (1800 W). Results of the stress analysis which are summarized in Table 5 indicate that the mm-wave heating at extreme steering angles and the related off-axis deposition induces additional stress in diamond disk. But these peak stresses are only slightly higher (by 5 MPa) than for the earlier case of the pure mm-wave heating effect. Further more, no significant change is induced in the membrane stresses at the centre of the cuffs.

Table 5: Stress analysis of the torus window: water pressure 0.8 MPa and $P_{\text{abs}} = 1800$ W

| Steering, [$^\circ$] | 0  | 12 | 12* | Limits         |
|---------------------|----|----|-----|----------------|
| S1 / Diamond, [MPa]| 44 | 96 | 100 | 100-150        |
| VM / Copper, [MPa]  |    |    |     |                |
| Near disk           | 72 | 50 | 90  | 50             |
| Cuff center         | 47 | 46 | 46  | *) 150         |
| VM / Steel, [MPa]   | 48 | 52 | 52  | 200-300        |
The stress analyses showed that the actual torus window cannot be operated with blanket water as it will not withstand the membrane stresses caused by water pressure of 3 MPa. However, integration of the RS torus cooling loop into the component cooling water circuit is capable to solve the problem, if water pressure reduced to or below 0.8 MPa.

6. Window unit
The lateral homogeneity of the CVD diamond disk had been measured by a recognised and internationally outstanding measurement technique based on a hemispherical open resonator set-up [7]. The final thickness was kept within the specified tolerances (± 10 µm) and the dielectric loss was intermediate between the ‘low loss’ and ‘guaranteed loss specifications’. For manufacturing of the window unit set of the brazing and welding operation was performed. The assembled window unit is shown in Fig.5. The window flange was modified to be bolted to the isolation for a frequent assembly and disassembly possibility during experiments.

![Figure 5. Window unit.](Image)

Helium leak rate was determined between the two faces of the CVD diamond disc by covering the window component with a bag to represent the secondary vacuum environment. The flange at the window socket was connected to a He leak detector to assign the He rate at the in-vessel part of the window being at the primary vacuum of the ITER plasma chamber. The characteristic leak rate was determined to be < 1·10^{-9} mbar·l/s, which is fully consistent with the conditions of ITER operation as well as for the single beamline tests.

7. Conclusions
For the separation between the primary (plasma) and secondary vacuum in the remote steering (RS) upper launcher, a single disk torus window unit was designed as a compact structure which allows off-axis transmission of 2 MW beams at 170 GHz. Three alternative cooling concepts have been analyzed for implementation at the torus window: edge-cooling, direct and indirect stripe cooling of the disk surfaces (face cooling). The thermo-hydraulic as well as thermal assessment provided that edge cooling is the most efficient for cooling of large area disks which are characteristic for the RS windows.

The window geometry was based on a CVD diamond disk of 106 mm diameter integrated into a window housing providing an aperture of 95 mm which is just at the limit to provide the maximum available input steering range to the square mm-wave waveguide system (± 12°). This means that for even for the “guaranteed case” of mm-wave absorption of 1800 W and at extreme 12° steering angles, all materials, including OFHC copper in particular, can be expected to stay in the elastic regime. Peak principal stress in the diamond disk of about 95 MPa is approaching the critical limit of 120-150 MPa. The key aspect to improve the performance of the RS torus window with respect to the stress profile to select CVD diamond disks with respect to dielectric loss.
The finite element modeling clearly indicates that the actual torus window which is based on the Ag-(Cu-) brazing technology cannot be operated with blanket water as it will not withstand the membrane stresses caused by water pressure of 3 MPa. However, integration of the RS torus cooling loop into the component cooling water circuit is capable to solve the problem.

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