DESIGN AND ANALYSIS OF WINDOWS AND STRUCTURAL COMPONENTS FOR THE ITER ECRH UPPER PORT PLUG

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The structural design of the ECRH Upper Port Plug is developed to integrate mm-wave systems for both limited and full beam focusing. MCNP models were established which allow the neutronics analysis of neutron streaming, nuclear heating and ongoing radioactivation analysis. The first wall panel and the internal shields for which nuclear heating is highest, results from thermo-hydraulic analysis prove the feasibility of the established cooling concept. The design of the CVD diamond window is based on edge-cooling adapted for large apertures. Worst case stress analysis for extreme launching angles indicates the risk of localised plastic deformation in the copper cuffs of the window.

Introduction

The upper port positions for the EC wave launching system on ITER are reserved to stabilise the Neoclassical Tearing Modes (NTM) at the q=3/2 and q=2/1 surfaces by inducing off-axis current drive. The design of the upper port plug systems, which is developed by a working group from various EURATOM associations with the overall coordination at FZK, is specified to convey a total of 20 MW mm-wave power at 170 GHz under continuous wave conditions (>1000s). The mm-wave system design under the lead of FOM Rijnhuizen established reference models based on the remote steering concept [1,2]. Whereas the first reference model did not foresee beam focusing at the fixed front mirror in the steering (poloidal) direction ("limited focusing": LF), a focusing mirror in both the toroidal and poloidal direction is introduced in the latest reference models ("full focusing": FF). This responds to requirements for smaller beam spot size at the absorption layers and for large steering ranges in the plasma in an effort to satisfy adequate NTM stabilisation performance [3]. The waveguide system has to be integrated into the frame of the plug ('main structure') and the blanket shield module (BSM), which closes the gap in the blanket structure and must provide effective neutron and thermal shielding [4]. The basic difference relevant to the structural design (cf. Fig. 1) is an increase in the length of the front mirror combined with short distances between the mirror centres and the end of the square-waveguides. Another important change with respect to the neighbouring components is a limited cut into the lower regular blanket which causes the cut-out at the lower shell of the front shield. The boundary for in-vessel components in the port plug is set by a closure plate at which CVD diamond 'torus' windows form the primary tritium confinement to the mm-wave system. Both structural components and windows form essential parts of the port plug system for which detailed design activities are accompanied by modelling for performance analysis.

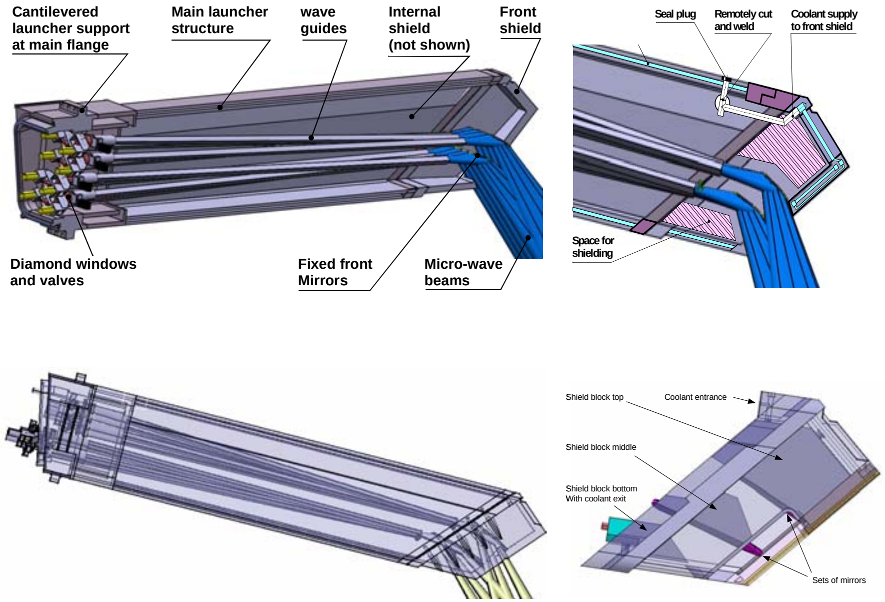


Fig.1 Overview of structural layout of the ECRH upper port plug (left) and sketch of the details of the blanket shield module with the mm-wave system integrated for the limited focusing (LF, top) and full focusing model (FF, bottom).

Design and analysis of the neutron shielding and the cooling circuits

For the LF model, front shield internals have been designed which consisted of an upper and lower shield block, mirror blocks and special filler blocks (cf. Fig.2) to minimise the neutron radiation to the waveguides through a direct line of sight from the plasma chamber. Previous the neutron streaming analyses were performed for a simplified first wall panel configuration with rather large opening [5]. The use of shield blocks results in a reduction of the fast neutron flux at by a factor of about 5 at the waveguide entrance, but a factor less than 2 at the waveguide exits. The resulting fluence at the CVD diamond windows after one full power is yet at or below the limit of 10^{20} n/m^2. An open issue is the dose rate in the surrounding of the window which should be below 100 mSv/h after 10 days reactor shut down. The structural design for the FF reference model includes a full design of the internal shields in the main structure and the BSM. This model has been transformed into a new neutronics model (cf. Fig.2) for Monte Carlo calculations and subsequent activation analysis to determine the shutdown dose rate distribution.

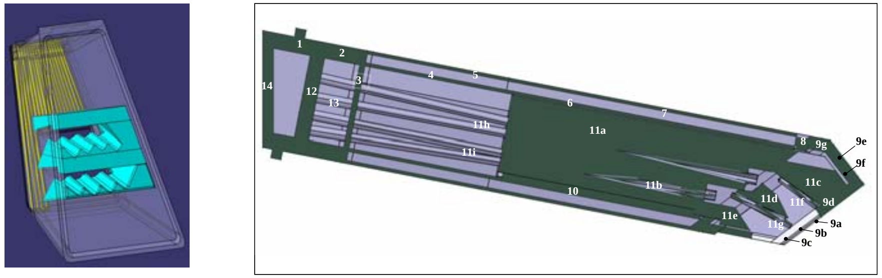


Fig. 2 Left: Shape of the mirror and filler blocks in the blanket shield module (LF model). Right: Design basis for neutronics analysis of the FF model (11a, c, d, e: shield blocks).

For the LF model the nuclear heating rate was determined for the actual configuration of the front shield internals. They compare well with earlier estimates based on regular blanket modules (cf. Fig. 3): they are lower by 20% at the front part (50 – 150 mm behind the first wall, full markers), but show local increases in the neighbourhood of the cut-outs for the mm-wave beams (open markers).

This result consolidates the thermo-hydraulic estimates for the cooling design of the BSM. The heat generation at the front panel amounts to about 220 kW. The cooling structure of the first wall panel was described earlier for the FF model [4]. Adaptations to the different mm-wave beam arrangements can be made by minor changes in configurations of the cooling tubes. The cooling circuit is fed by blanket water and is designed to enter at the first the front panel. With a mass flow rate of 3.1 kg/s, estimated peak temperatures of the structure at front channels are 250°C, and the overall coolant rise is 17 K which proves the feasibility of the concept. The volume of the shield modules in the BSM is 0.15 m^3. With an average of 1 MW/m^3 of nuclear heating, the heat generation is comparable and can be handled with the projected cooling parameters.

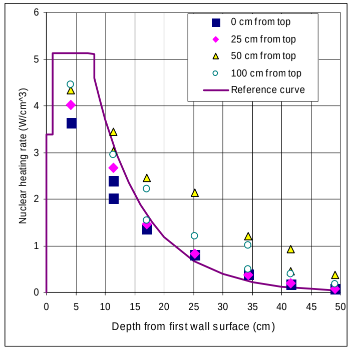


Fig. 3 Nuclear heating rate over the depth of the blanket shield module.

CVD Diamond window

The ECH windows separate the primary vacuum of the in-vessel components from the secondary vacuum in which the remote steering units are operated. They will be equipped with CVD diamond disks of 106 mm dia., being the maximum size for which the growth processes and the brazing technologies are established. In front of the waveguide sockets, insulation valves are placed to which the window structures are attached by a window sockets (cf. Fig.4). This introduces two major geometrical constraints:

- The length of the window socket should allow access to the welding lip at the interface to the window unit by remote cutting/welding tools.

- The aperture of the window has to reserve a given free diameter for the beam (characterised by the beam radius w_1). Typical cut-off values are $3 \cdot w_1$.

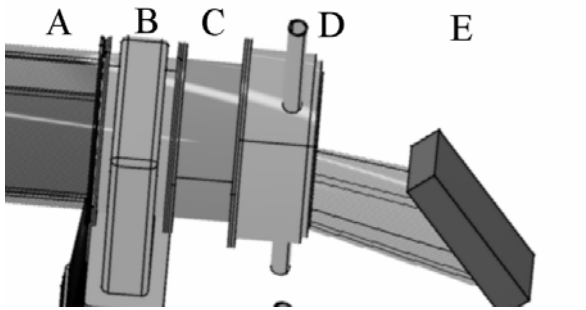
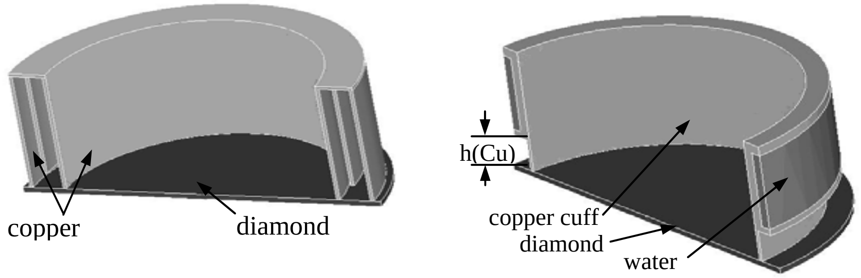
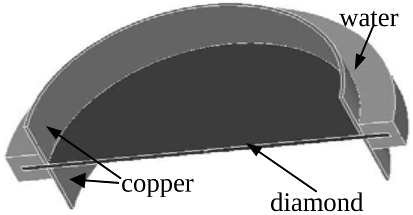


Fig.4 Sketch of the window environment: A – waveguide (socket); B – isolation valve; C – window socket; D – window unit; E – end mirror of the remote steering unit.

In present design the length of the window socket was fixed to 33 mm. At the position of the diamond disk, the location of the mm-wave beam (w_1= 13.4 mm) was analysed for the launching angles of ± 5° and of ± 12°. Whereas for the smaller range, window apertures of 80 mm are fully adequate, an extension of the window apertures to 95 mm is required for ± 12°. Because of the extreme requests for large window apertures, special variants of cooling structures were considered with a minimum length of metallic parts towards the remote steering unit: edge cooling, direct and indirect single face cooling (cf. Fig. 5). Comparative thermo-hydraulic as well as thermo-mechanical analyses were performed for axial transmission of a 2 MW beam which gives rise to a total absorbed power of 880 W in the diamond disk (reference dielectric loss: $\tan\delta = 2 \cdot 10^{-5}$). The edge cooling concept provides the most effective cooling, whereas the direct face cooling cannot fulfil the design requirement for window apertures above 90 mm. For indirect face cooling, the temperature at the disk center is about 90 K higher than in the case of edge cooling.



Direct face cooling (1 side) Indirect face cooling (1 side)



Edge cooling

Fig.5 Sketch of the cooling structures for the three studied concepts.

Table 1. Thermal analysis of the alternative cooling concepts.
Absorbed power P_{abs} = 880W, water consumption 4 *l* / min.

T_{water}	Parameters	Edge cooling		Direct face cooling		Indirect face cooling, h = 10mm	
	aperture	80	95	80	90	80	95
293K (20°C)	T_{cent} [K]	379	392	414	417	493	481
	T_{edge} [K]	295-311	310	340-344	337	420	401
	ΔT [K]	68-84	82	70-74	80	73	80
	α_T, [$Wm^{-2}K^{-1}$]	9000		2400	3000	4000	
373K (100°C)	T_{cent} [K]	459	471	505	497	574	562
	T_{edge} [K]	375-391	389	423-444	417	501	482
	ΔT [K]	68-84	82	61-82	80	73	80
	α_T, [$Wm^{-2}K^{-1}$]	10000		1700	3000	3700	

Heating of the disk due to mm-wave absorption is the dominant factor that causes stresses in the window structure if internal stress after the brazing can be excluded by plastic deformation in the cooper cuffs. Again the smallest stress was found for the edge cooling concept. Therefore this concept was selected for the actual window design including flexible steel connections to the outer steel housing to minimise the stresses in the structure. The following stress limits are considered: 150 MPa (1/3 of ultimate bending strength) for the diamond, 50 MPa (Yield Strength) for the copper cuffs and 300 MPa for steel connections. As a worst case scenario, increased losses (2000 W, i.e. “guaranteed” tanδ levels of $4 \cdot 10^{-5}$ and 2 MW beam) and moderate coolant throughput (4 *l* /min) was studied for different angles of off-axis beam propagation by 3D analysis as the beam off-axis shift (amounting to 27 mm for steering angles of ± 12°) destroys the axi-symmetry of the temperature distribution and increases stresses in the structure. Mises stress in the copper cuffs is beyond safe limits, therefore a dedicated study is required to which extent rather localised plastic deformation can be tolerated in the copper cuffs.

Table 2. Stress occurring in the edge cooled window under different steering angles (worst case: 2000 W absorbed power, 4 *l*/min water consumption).
* - strengthened copper (Yield strength = 150 MPa).

Parameters	Steering [°]						
	0	6	6*	10	10*	12	12*
Shift [mm]	0	13.4		22.5		27	
T_{max} [K]	473	466		459		452	
T_{edge} [K]	310	304-320		301-331		299-338	
ΔT [K]	163	146-162		128-158		114-153	
S_1 /Diamond [MPa]	53	75	78	89	91	96	100
S_1 / Copper [MPa]	29	40	46	43	55	44	60
S_1 / Steel [MPa]	47	67	67	86	85	97	95
Mises/Copper [MPa]	35	50	54-57	50	70-73	50	80-86

Acknowledgment

This work is being carried out under the EFDA technology research programme activities, EFDA technology task TW3-TPHE-ECHULA and B2

References

[1] A.G.A. Verhoeven et al., Proc. of IAEA TM on ECRH physics and technology, Kloster Seeon, Germany, 2003, available at http://www.ipp.mpg.de/tmseeon
[2] A.G.A. Verhoeven et al., Proceedings of this conference
[3] H. Zohm et al., Proceedings of this conference
[4] R. Heidinger et al., Proc. of IAEA TM on ECRH physics and technology, as [1]
[5] U. Fischer et al., Proc. of IAEA TM on ECRH physics and technology, as [1]