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ABSTRACT

The ITER-like wall project in JET aims at an optimal use of the unique features of JET, such as beryllium and tritium compatibility, to explore operation within the limits of the ITER wall materials. A full replacement of the presently carbon based first wall will result in a mainly beryllium main chamber and a tungsten divertor. At the same time, the JET auxiliary heating power will be upgraded allowing access to ITER-relevant energy loss densities in disruptions and edge localised modes. In this way, the JET wall will go from being almost indestructible, to making the material driven operational constraints predicted for ITER a more immediate reality for JET. This paper describes the methodology being used to define and apply these limits whilst trying to maintain experimental flexibility.

1. INTRODUCTION

The JET ITER-Like Wall (ILW) project [1] and auxiliary power upgrade [2] will be implemented in the same shutdown and will pose new challenges to plasma operation. The presently carbon based first wall will be replaced with a mainly Be main chamber and a W divertor, either as W-coated Carbon Fibre Composite (CFC) or as bulk metal. The Neutral Beam Injection (NBI) power will increase from 24MW for 10s to 34MW for 20s. This paper describes the methodology being used to define and apply the operational limits whilst trying to maintain experimental flexibility. In Section 2 the design objectives and constraints are described, while the resulting engineering limits are discussed in Section 3. The loads due to the NBI are discussed in some detail in Section 4 together with the planned protections. The plasma convective loads on the main chamber Be tiles are discussed in Section 5 and on the divertor in Section 6.

2. ILW DESIGN STRATEGY

One of the key engineering boundary conditions to the design of the ILW is the need to re-use the existing support structures. Therefore disruption loads due to the use of materials far more conductive than CFC had to be reduced. This was achieved by slicing the tile assemblies and introducing new carriers or modifying the design of existing carriers.

Among the engineering objectives were:

- the Be inner and outer poloidal limiters had to be as compatible as the present ones with plasma loads during plasma ramp up and ramp down
- NBI shine through and re-ionisation loads, increased by the NBI upgrade, had to be accommodated
- the design had to offer safe paths to Radio Frequency (RF) driven image currents in limiters and protections surrounding the RF antennas
- the design had to account for Lower Hybrid (LH) sheath loads in the vicinity of the launcher

  Since the scope of the project was defined, it was clear that the strike point loads will have to be adjusted to fit the limits imposed by the new divertor materials.

The strategy applied to achieve the above objectives included [3]:

- Be inner and outer wall limiters: larger format limiter tiles compared to existing ones to minimise wastage of wetted surface needed to shadow edges, slice tiles to reduce eddy current loads, remove plasma facing holes (hiding the fixings of one tile behind the following tile till a top hat covers the last ones) wherever possible to maximise front power handling, introduce castellations (to reduce thermal stresses in hot regions and further reduce eddy loads) and shadow edges.
- Be dump plate: replace full coverage of rounded edge flat tiles with discreet ribs of bi-directional tile assemblies to give better defined area of interception.
- normal NBI shine through on inner wall: use W-coated CFC and exploit the change of geometry needed for the sliced Be tile to ensure the NBI footprints are away from plasma loads and to increase slightly tile thickness and improve energy density capacity.
- bulk W row of divertor tiles: 6 mm thick lamellae perpendicular to the toroidal direction to minimise the eddy loads, plasma facing surface raised by a few millimetres to make space for modified support system.
- add main chamber thermocouples (and re-install divertor ones) to be able to monitor thermal loads and manage operation accordingly.

Consequently, to make space for the carriers holding the Be tile assemblies in the main chamber, the inner wall and the dump plate have moved closer to the plasma. This requires low triangularity configurations to have slightly smaller minor radius and therefore boundary safety factor for the same plasma current and toroidal field and high triangularity configuration to be adjusted not to clash with the upper inner wall protections and the dump plate.

3. ILW design limits

The Be melting temperature is 1278°±5°C, and the tiles are designed to have the surface temperature ~200°C below melting when the castellation root temperature equilibration temperature is <600°C. For thermally thick components (generally the case), this translates in heat pulse of 6MW/m^2 for 10 s for a cold start (200°C) which needs to be adjusted for a hotter start.

For the W-coated CFC the most stringent temperature limit is imposed by W-carbide formation, which increases non linearly with temperature (e.g. diffusion coefficient of C in W increases 100 times between 900°C and 1200°C and another 10 times between 1200°C and 1600°C);initially the surface temperature will be limited to 1200°C. In addition, the results of ELM-like tests [4] indicate that ELM loads should be limited to 330kJ/m^2.

Initially the surface temperature of the bulk W row of divertor tiles might be limited to 1200°C to avoid re-crystallisation completely. Later this limit should be relaxed to 2200°C, which corresponds to 90MJ/m^2 for typical heat pulse durations [5]. At this point, the support structure temperature will drive a lower energy density limit, ~70MJ/m^2 is or less depending on the performance of the clamping system (currently being tested). The high level of segmentation (four independent toroidal stacks and heat path mainly vertical within each stack) makes the energy handling of the bulk W row of tiles more sensitive to the toroidal and poloidal spread of the heat load. The energy capacity scales with the number of stacks among which the energy is divided, making sweeping an attractive option. While the energy capacity of each stack (~1m^2) is proportional to its Toroidal Wetted Fraction (TWF), so if the TWF is 70% the stack energy limit is 50MJ.

4. Neutral beam shine through loads

Two beam boxes, each with 8 lines (called PINIs - Positive Ion Neutral Injectors): 4 called "normal" and hitting the inner wall only, 4 called "tangential" and hitting the inner and the outer wall. The footprints of the normal PINIs are completely contained on W-coated CFC tiles. The tangential PINIs footprints on the inner wall footprints do not affect safety related components, while they do on the outer wall: water manifold, vessel wall, poloidal limiter beam and tile carrier, remote handling bolts, RF antenna supports and knuckles. As the new beams are more focused, the loads on the safety critical components is equal or less than at present, even if the peak power density is higher. For each beam box over 80 locations have been analysed to determine the minimum safe plasma density. The results for 20 s and 5 s NBI pulses are listed in Table 1 and show that none of the limits is driven by integrity related items.

New thermocouples will be installed in some of the tiles under NBI loads. They will be used in the commissioning phase to validate models able to predict cool down times, so that they can be safely applied also to tiles without thermocouples. In addition, the wide angle IR view can, in a special setting, see one set of inner wall normal bank footprints.

The present NBI shine through protection monitors bulk temperature of normal PINI tiles (due to combination of plasma and NBI loads) and switches off the whole bank if the limit is approached. This is sufficient with CFC tiles. The NBI shine through protection is planned to be enhanced to become ILW compatible:

- monitor bulk and surface temperature in both normal and tangential footprints
- switch off offending PINI (and its paired PINI) only (to go live in June 2009 - and as a future development time out till surface temperature becomes compatible with additional load)
- keep the present system (i.e. switch off of full bank) as back up, at higher temperature
- feed NBI loads to plasma load monitoring system which could act too if tiles loaded excessively by plasma SOL loads

5. MAIN CHAMBER PLASMA LOADS

The plasma loads have been computed on the Be main chamber tiles for 5 limiter configurations. For these configurations also the shadowing was checked in detail [6]. In addition, the plasma heat loads have been computed for 3 X-point configurations and 3 Near Double Null (NDN) configurations. All calculations are normalised to 10MW power in SOL and assume a power decay length of 10mm for the outer wall and 20mm for the inner wall. In the limiter configuration the power split is taken as inner:outer = 1:1, while in the X-point configurations as 1:2, for NDN cases 1:2 but with the second

X-point taking a fraction of the SOL power depending on the distance from the separatrix.

The power densities for the limiter configurations are listed in Table 2 and can be scaled to constant (e.g. 10s at 2.9-4.3MW outer or 2.4-4.6MW inner) or linearly increasing (e.g. 10s with peak power 4.8-7.1MW outer or 4.0-7.7MW inner) SOL power limits. The limits for time dependent SOL powers can be estimated using convolution integrals. Ohmic plasma ramp up (and down), assuming the ohmic power [MW] scales as 0.6 times the plasma current [MA] and ~30% radiation, can be accommodated and a limited amount of additional heating could be as well.

The peak power densities for the three X-point configurations studied so far are listed in Table 3. V_4M5_LT is compatible with SOL powers higher than presently achievable even for 20s constant heat pulses. 3MA5_ITER is evenly limited on inner and outer wall, but to <30MW SOL power for 10s, due to the high power density on the outer poloidal limiters, this can be brought in line with the V_4M5_LT loads by increasing the gap between the separatrix and the outer wall by 1cm. 3MA5_HT is strongly limited in the inner top part of the vessel, where the wall to separatrix distance is small, and this configuration needs to be adjusted to fit the new geometry, alternatively the heat pulse power or duration could be reduced. For the NDN configurations the peak power density on the outer strike point varies between 7.5 and 9.5MW/m^2 per 10 MW lost power, indicating that the power pulse for these configurations has to be carefully managed.

Real time control of limiter loads is not as advanced as that of NBI loads, because of the complexity and the uncertainty in the fundamental parameters (e.g. power decay length) of the plasma load estimates. A clear example of the complexity is shown in Figure 1 for the IWGL in the fourth limiter configuration. The power density calculated on tile 2 accounting only for IWGL-own shadows (blue) is 16MW/m^2, but if the SC (LI) are added (green) the power density decreases to 11MW/m^2, as the portion of the tile with the highest power density is in reality shadowed. The ability to include shadows, even in an approximate way, has not been added to the real time plasma wall protections yet (the system is energy based and relies on separatrix to wall gaps).

6. DIVERTOR PLASMA LOADS

The divertor is the component with the most significant change in performance with respect to the present design. Although the design of all but one tile row is unchanged, the performance deterioration is driven by the change in material. The design of the CFC tiles is identical (apart from a 1 mm radius) to the present one, so maintaining the same energy capability. So far, the divertor energy capability has not been challenged, but with an increase of the power by ~20% and of the duration by a factor of 2, it could be. However, the most limiting constraint will be the surface temperature, unless strike point sweeping is more widely applied.

Each bulk W stack energy limit (<70MJ) could be sufficient to cope with the present energy loading (in no pulse since the LBSRP installation has >70MJ deposited on this row). If the energy load increases 2.4 times sweeping becomes essential. The surface temperature of the W lamellae should not be limiting to operation. However, the local wetted fraction for shallow field line angles is small and could result in hot spots.

For both the W-coated and the bulk W rows another limitation is the reduction of the surface radiation sink (due to the low emissivity of W) and for the bulk W row the low heat flow from the back of the tile assembly. This will result in longer inter-pulse intervals required to reach a starting temperature sufficiently low to be able to accommodate the energy from the following pulse.

Designing a real time W-coated CFC surface temperature protection is complicated by the combination of 1) uncertainty in the power decay length, 2) uncertainty in the inner-outer power split and 3) the need to account for poloidal conduction away from the strike point to maximise heat load at a fixed maximum surface temperature. These three issues are being looked at and from the present status it is difficult to say whether a real time tool is achievable. Less demanding is a protection on the ELM size: the W-coated tiles can take up to 330kJ/m^2 for a few thousands of cycles, the plan is to be able to measure accurately the energy loss of large ELMs and initiate a procedure to take the plasma to a safer operating region, to avoid having more than 1 or 2 ELMs with energy above a certain threshold per pulse.

SUMMARY

The engineering limits offered by the ILW are now well understood. Some of the loads the new plasma facing components will have to withstand have been accurately quantified. However, this is not possible in all cases. For those well characterised, for example NBI, enhanced protection systems have already been designed and are being implemented. For those with large uncertainties and geometrical complications, the design of a new protection system is far less advanced. Finally, for some operational loads, the focus is still in developing models. Where no real time protection tool is available, operation is planned to progress cautiously from known safe conditions towards more challenging ones making full use of the additional diagnostics. As the time to run with the new wall approaches, the material driven operational constraints predicted for ITER become a more immediate reality for JET.

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PINI	**20s n_e [10^{18} m^{-2}]**	**component**	**5s n_e [10^{18} m^{-2}]**	**component**
P1s	61.6	Be IWGL	41	Be IWGL
P1u	47.4	Be IWGL	34	Be WPL
P1u+8	72.4	Be central	52	Be central
P2	93.4	W/CFC tray tile	62.5	Be wing
P3	114.7	IWGL tile	82.9	IWGL tile
P4	107	IWGL tile	74.8	IWGL tile
P5	120.7	IWC tile	92.8	IWC tile
P6s	115.3	IWC tile	87.5	IWC tile
P6u	116.5	IWC tile	88.6	IWC tile
P7s	59.1	Be IWGL	33.2	Be IWGL
P7u	65	Be IWGL	40.5	Be IWGL
P8	53.7	Be tile	32.4	Be IWGL

Table 1: Plasma density needed for 20s and 5s heat pulses for each PINI. Only the most demanding hot spot is listed.

All values in MW/m^2	**Low elongation**	**Medium elongation**	**Full elongation**	**Leaning on inner baffle**	**Just opening X-point**
wPL	Tile 12: 9.75	Tile 15: 14.0	Tile 12: 8.7	Tile 22: 9.45	
nPL	Tile 10: 15.0	Tile 12: 13.0	Tile 23: 13.0	Tile 23: 18.0	
ILA-PL	Tile 7: 13.0	Tile 9: 10.0			
ILA-PP (-9mm wPL)	V Tile 3: 19.0	V Tile 4: 12.0			
A2V	Tile 4-5: 12.0	Tile 6: 12.0			
A2H		4.2	3.0		
LH (-10mm wPL)	Std tile: 7.7	TR bump: 7.2			
SC (UO)			21.0	16.0	18.0
IWGL	Tile 9+14:21.0	Tile 8+13:20		Tile 1: 16.0	Tile 12+15:11
SC (LI)				25.0	
SC (UI)			20.0	14.0	13.0

Table 2: Peak front power density for limiter configurations on the inner and outer limiters (normalised to 10MW power in the SOL, assuming 1/3 inner and 2/3 outer, power decay length: 20mm inner and 10mm outer)

All values in MW/m^2	V_4M5_LT	3MA5_HT3	3MA5_ITER
wPL	Tile 19: 0.38	Tile 11: 0.07	Tile 13: 1.1
nPL	Tile 16: 0.58	Tile 10: 0.11	Tile 13: 1.7
ILA-PL	Tile 15R: 0.45	Tile 8L: 0.13	
A2V	Tile 8: 0.54	Tile 4: 0.12	
LH	Tile 62R: 0.69	Tile 36L: 0.10	Tile 45L: 2.0
IWGL	Tile 14: 0.26	W/CFC top hat: 0.27	W/CFC top hat: 0.15
SC (UI)	0.49	3.97	2.10
Dump plate		Outer: 3.1	

Table 3: Peak front power density for X-point configurations on the inner and outer limiters (normalised to 10MW power in the SOL, assuming 1/3 inner and 2/3 outer, power decay length: 20mm inner and 10mm outer)

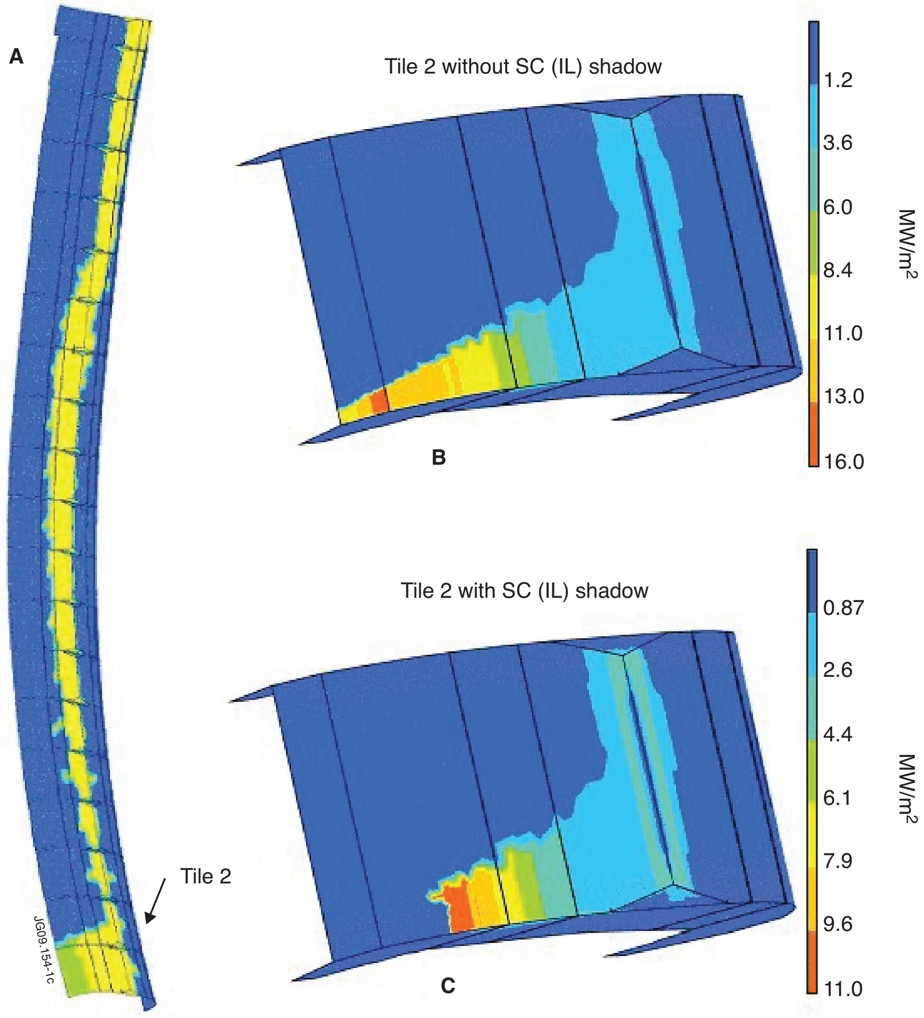

Figure 1: Power density on IWGL tile 2 with (yellow and green) and without (only yellow) SC (LI) shadowing.