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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

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ABSTRACT

One of the outstanding problems for a next step fusion device is the handling of the power fluxes into the divertor, in particular regarding fast transient heat deposition by Edge Localised Modes (ELMs). For a next step fusion device, such as ITER, type-I ELMy H-Mode is the reference discharge and therefore of particular interest. At JET a thermography system with high time resolution is able to resolve temperature evolution during and between ELM periods; here, the analysis is focussed so far on type-I ELMy H-Mode discharges with ELM frequencies of 5-35Hz. Influences from surface layers on the target tiles are investigated in special discharges and taken into account. Results about the distribution of ELM and inter-ELM power deposition on the inner and outer divertor target plates are presented. Additionally, the characteristic ELM power deposition time, the temperature rise time and its dependence on pedestal parameters are studied. The thermal impact due to ELMs for ITER is calculated based on predictions for relative ELM mid plane losses and heat flux evolution on the divertor target pointing on a possible exceed the material limits.

1. TEMPERATURE MEASUREMENTS AND HEAT FLUX CALCULATIONS

The 2D IR-system on JET is equipped with a periscope optic for viewing the ITER like MKIIGB Gas Box divertor. The IR-Camera is sensitive to photons in the wavelength range from 3-5ìm, which allows the calculation of the divertor surface temperatures assuming Planck's law for black body radiation (and neglecting further radiation for instance by molecules) with a time resolution of up to 21 µs. A set of ELMy H-Mode discharges with an IR-optimised strike zone position have been performed. The transformation procedure developed to interpret the periscope view was used to deduce poloidal profiles of the temperature distribution on the target tiles [1].

Significant differences between the temperature evolution of the target surface in the inner and outer divertor chamber (split by the septum of MKIIGB) were observed in deuterium discharges. The temperature at the inner leg evolves step like with heating power, whereas an increase with the square root of time was found in the outer leg. Such effects, attributed to a change of the surface properties, have been already reported from ASDEX Upgrade [2] and JET [3]. For discharges in Helium (~40 discharges have been run between the observed changes) the behaviour of the measured surface temperature for the inner divertor changes and becomes equal to the behaviour of the surface temperature on the outer target tiles.

A method to calculate the heat flux deposition from the temperature evolution including these surface layers is the introduction of a heat transmission coefficient in the heat flux calculation as done with the THEODOR code [4]. The deposited energy calculated with this method and that derived by thermocouple measurements are in good agreement[5]. The global balance between input, deposited and radiated energy is matched within error bars of 10- 20% for H-Modes at high P_{heat}. In low powered L-Mode discharges this discrepancy is up 40%, because the background signal from the periscope optics is in the same range as the signal for low temperatures (80^{o} -200^{o}).

2. ENERGY DISTRIBUTION ONTO THE INNER AND OUTER TARGET PLATES IN H-MODE DISCHARGES:

To distinguish between energy deposition during and in between ELMs two method are used. First, a pulse height analysis is performed, in which the power deposition per time interval (which is the frame rate of the 2D array and corresponds to roughly 2ms) is integrated and ordered due to corresponding energy. Another method cuts the higher power deposition during ELMs by defining a start time and end time around the ELM event integrating the power in that time window. Here it should be noted, that the end of the ELM power deposition is difficult to define because it varies in dependence of heat transmission coefficient used for the heat flux calculation. However, due to the reduced heat flux after the ELM for roughly 10-30 ms for type-I ELMs with frequencies in the range of 5-35Hz, the error by choosing various end times for the ELM power deposition interval stays small. Nevertheless, both applied methods come to similar values and are therefore used to derive the energy channels in ELMy H-Mode discharge.

In the table, the distribution of energy in the two type-I ELMy H-Mode discharges is shown (Pulse No: 53764, $P_{NBI} = 9MW$, $n_{av} = 4*10^{19}\ m^{-3}$ & Pulse No: 53765, $P_{NBI} = 16MW$, $n_{av} = 6*10^{19} m^{-3}$). In Pulse No: 53764 both the inner and the outer divertor are attached, whereas in pulse Pulse No: 53765 the inner divertor is partly power detached. The energy deposition due to the type-I ELMs in both discharges is fairly balanced, whereas the inter-ELM energy deposition is dominated by the outer divertor (almost completely if the inner divertor is highly detached). The balanced energy deposition during ELMs found by Thermography and Calorimetry (TC) [6] is close to DIII-D [7] but appears somewhat difference from results reported from ASDEX-Upgrade, where an in/out ratio of 2/1 (or even higher values favouring the inner target) is found during ELMs [8].

Pulse No: 53764				Pulse No: 53765			
Inner (tile #3)		Outer (tile #7)		Inner (tile #3)		Outer (tile #7)	
21 MJ (TC: 16MJ)		31 MJ (TC: 33MJ)		27 MJ (TC: 24MJ)		80 MJ (TC: 80MJ)	
inter ELM	ELM	inter ELM	ELM	inter ELM	ELM	inter ELM	ELM
12 MJ	9 MJ	21 MJ	10 MJ	7 MJ	20 MJ	55 MJ	25 MJ

Table 1: Energy distribution for two H-Mode discharges derived by IR-measurements. The derived values by Thermocouples measurements (TC) are shown for comparison.

3. ELM POWER DEPOSITION TIMES ON THE DIVERTOR TARGET

An important aspect of the mechanism that governs the power deposition onto to the target plates and its consequences for a next step fusion device like ITER is the characteristic time of SOL energy transport by ELMs. The time of the largest temperature rise on the outer target during reproducable type-I ELMs compare with the pedestal plasma parameters just before the ELM event occurs. For the analysis presented here, investigations have been mainly focussed on the outer divertor, because the view in the inner divertor is much more restricted. Nevertheless, for some discharges a comparison of inner and outer target was performed and lead to the same conclusions concerning the characteristic time for ELM target load.

In figure 2 examples for the heat flux evolution on the outer target is given for type-I ELMs in discharges with various plasma densities. The time, in which the heat flux rises from the inter-ELM value to the maximum heat flux during the ELM event is taken as the reference time. The time of the maximum heat flux corresponds to the maximum target temperarture. Here, to reduce the data scatter, about 10-35 similar ELMs (corresponding to 1 second) during the flat top phase are averaged to one coherent ELM. In figure 3, the correlation of these ELM rise times with the parallel ion transport time defined by the ion sound speed and the connection length ($\tau_{||} = L_c / c_s$) is shown. Typically, the parallel ion transport time in JET ranges values 100 ms to 550 µs. Measurements in the JET MKIIa divertor [10] which reported ELM power deposition times of 100 ms were from discharges at high Ip and high pedestal temperatures of > 2.5 keV and, hence, short $\tau_{||}$.

4. EXTRAPOLATION OF THE TYPE-I ELM POWER FLUXES TO ITER

Multi-machine parametrisation for the relative ELM losses predict values around 10-15MJ for ITER in the expected edge collisionality range and a corresponding parallel ion transport time of 240µs in the SOL[9]. The maximum target heat load for ITER can be derived assuming the above mentioned deposition time and the same temporal evolution of the ELM heat flux as found in JET MKIIGB (as well as on ASDEX Upgrade). Here, it should be noted that only a fraction of the target load energy arrives during the defined ELM power deposition time, whereas some more power arrives in the tail after the maximum heat flux. Again, due to the influence of surface layers the fraction of the energy deposited during the rise of the peak heat flux and its decline can only be given within certain limits. Nevertheless, it is reasonable to assume that a similar energy flow occurs before and after the peak heat flux (although the heat flux measurements in figure 2 indicate even less critical values). Further information about the heat flux profile and the relative size of the ELM power deposition compared to mid plane losses has been gained in JET MKIIGB divertor campaign and are compatible to results reported from ASDEX Upgrade, DIII-D and JT60-U [11][12]:

- The profile broadening during ELMs does not exceed values 1.5 times the inter-ELM profile. Applying this finding to ITER the wetted area becomes ~5m^2 for each leg.
- The power deposition time is believed to follow the ion transport time in the SOL (as shown in figure 3) and is therefore assumed to be around 550µs.
- The ratio of the energy released during the ELM crash and arriving on the target plate is around values of 0.6 and is deposited balanced on the inner and outer divertor.

Based on these findings, an optimistic calculation would assume that 60% of the mid plane energy loss (15MJ) is deposited balanced on both targets and that half of the target load is deposited during a constant rise of the heat flux within a time of 550 µs; In this case the thermal load results in ~20MJm^{-2} s$^{-1/2}$ (15MJ*0.6*0.5*0.5/5m^2/$\sqrt{550}$µs). It should be noted, that these value would be valid only for the average ELM, whereas single particular larger ELM events still could exceed the material limits (40MJm^{-2}s$^{-1/2}$ for tungsten melting and 20MJm^{-2}s$^{-1/2}$ for carbon ablation).

Complementary, an upper limit for the expected ITER heat load due to type-I ELMs is calculated next; here it is assumed, that all the energy of 15MJ is deposited with a constant heat flux of 240 ms duration on the wetted area (for one leg), leading to a thermal impact of ~200 MJm^{-2}s$^{-1/2}$(15MJ/ 5m^2/$\sqrt{240\mu s}$).

Both values indicate, that type-I ELMs in ITER may be in the range or well above the ablation limit for carbon or melting for tungsten. Extrapolation of present results for ITER range from being unacceptable from the divertor life time point of view to being marginally acceptable. Experiments are necessary to understand which is the physics mechanism (pedestal collisionality or parallel SOL energy transport). Such a physics based scaling will provide a more realistic (within smaller error bars) extrapolation of type-I ELM energy load to ITER.

5. CONCLUSIONS

Using a fast 2D IR system in the ITER like JET MKIIGB divertor, ELMy H-Mode discharges have been investigated with particular focus on SOL transport by type-I ELMs. The influence of surface layers has been taken into account using the THEODOR code for heat flux calculations. It is found, that the energy deposition on the inner and outer divertor is fairly balanced whereas the inter-ELM deposition is governed by the outer divertor. The rise time of the temperature on the outer target was analysed for type-I ELMy H-Mode discharges and shows a clear correlation to the parallel ion transport time in the SOL. Based on these findings, as well as on further assumptions about the expected ITER pedestal plasma properties, lower and upper limits for the ablation limit during ELMs in the ITER type-I reference scenario have been calculated. These results show, that ITER will operate with type-I ELMs close to or above the material limits.

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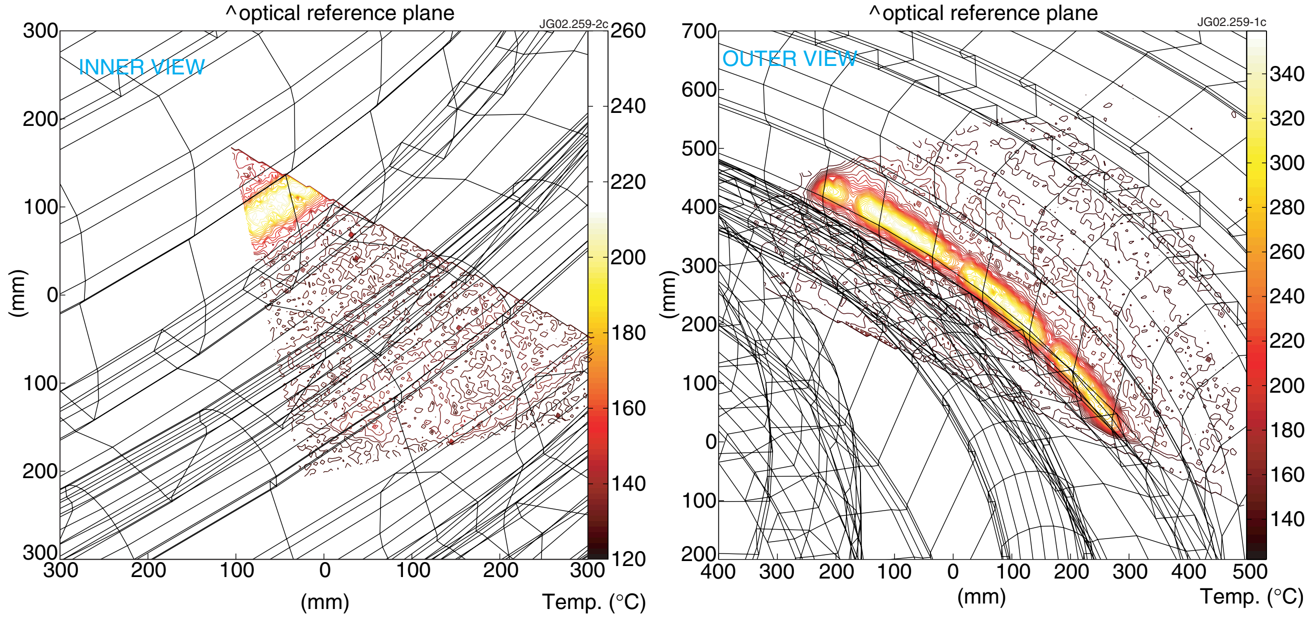

Figure 1a,b:View of the IR imaging system into JET MKIIGB divertor. The view is split into an outer (a) and inner (b) part. Due to the restriction of the divertor survey by the septum, special discharges with infra red optimised strike zone positions have been performed; here, as an example, a L-Mode in a helium plasma is presented.

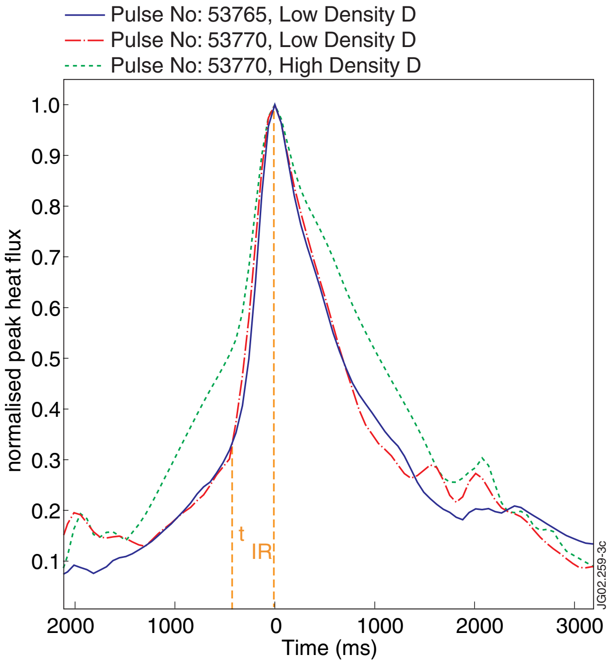

Figure 2: Normalied ELM peak heat flux density for 2 discharges (with/without gas puff). For the low density phase in Pulse No: 53765 and Pulse No: 53770 the ELM power deposition time is nearly equal, whereas in the high density phase (with reduced pedestal temperature) the power is distributed over a longer time.

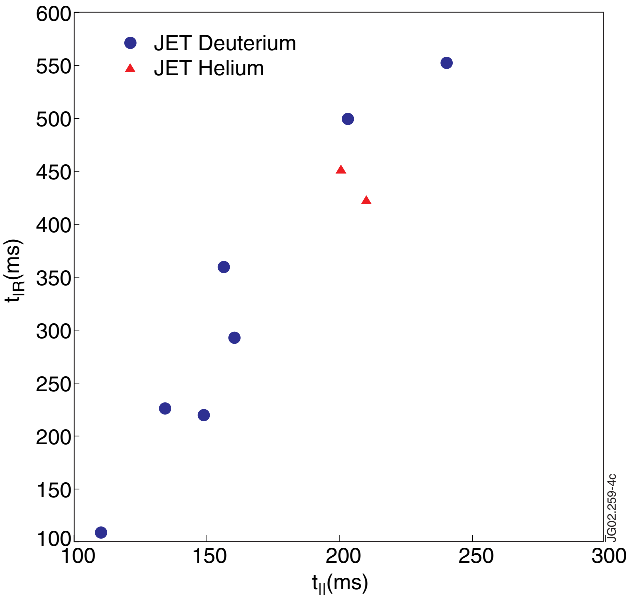

Figure 3: Correlation of the ELM power deposition time and the parallel ion flight time in the SOL. The ELM power deposition time varies in the range of 100 ms up to 550 ms .Values for the ELM power deposition time in JET MKIIGB helium discharges as well as ASDEX Upgrade discharges are included.