Steady State and Transient Power Handling in JET

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+See annex of J. Pamela et al, "Overview of JET Results", Fusion Energy 2002 (Proc. 19th Int. Conf. Lyon, 2002),IAEA, Vienna.

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Abstract. Steady state and transient power deposition profiles have been measured in the JET MIIGB divertor using improved diagnostics techniques involving the use of fast infra-red, thermocouples and Langmuir probe arrays. In unfuelled type I ELMy H-modes a very narrow power profile is observed at the outer target which we associate with the ion channel. Systematic parameter scans have been carried out and our analysis shows that the average power width scaling is consistent with a classical dependence of perpendicular transport in the SOL. Using the fast IR capability the factors such as rise time, broadening, variability and in/out asymmetry have been studied and lead to the conclusion that type I ELMs in ITER may fall just below the material ablation limits. JET disruptions are very different from type I ELMs in that only a small fraction of the thermal energy reaches the divertor and what does arrive is distributed uniformly over the divertor area. This is very different from the current ITER assumption which puts most of the energy from the thermal quench onto the divertor strike points.

1. Introduction

The actively cooled divertor target for ITER has been tested up to a surface power loading of $25MWm^{-2}$ but the planned operating point is around $10MWm^{-2}$ to allow for excursions. Under fast transient heat loads (assumed to be rectangular in time) due to ELMs or disruptions, the carbon surface will ablate when

$$\Delta W_{div}/(\Delta t^{1/2}A_{div}) = 27\text{-}43MJm^{-2}s^{-1/2} \qquad (1)$$

where ΔW_{div} is the energy deposited in an area A_{div} of the divertor surface and Δt is the duration of the event [10,1]. The low estimate corresponds to an inter-ELM power density of $10MWm^{-2}$ and the upper limit to $5MWm^{-2}$ i.e. lower base temperature.

JET type I ELMy H-modes have been observed with average divertor surface power loads up to $15MWm^{-2}$ and for the largest type I ELMs $\Delta W_{div}/(\Delta t^{1/2}A_{div}) \approx 40MJm^{-2}s^{-1/2}$. Recent JET experiments have characterised the power deposition widths and their scaling and the duration and magnitude of transient heat loads due to ELMs and disruptions.

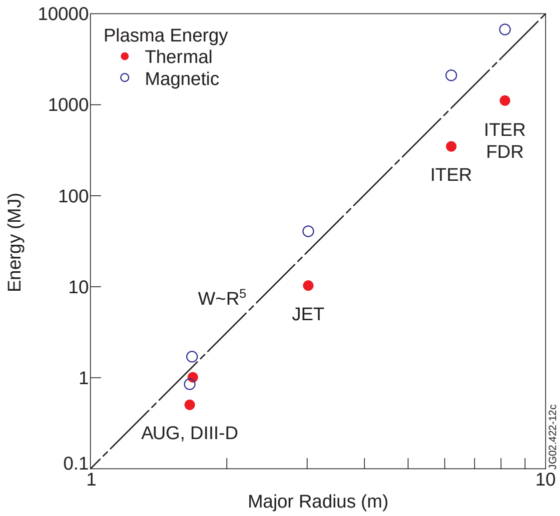

Figure 1 Stored energy increases with tokamak major radius as R^5 and thus the average energy density during disruptions scales as R^3.

Under the assumption of similar Greenwald density fraction and plasma beta, the total thermal and magnetic energy available during a tokamak disruption scales roughly as R^5 where R is major radius (figure 1). The average energy density on the wall scales as R^3. For fixed SOL width the divertor load would scale as R^4. ELMs and disruptions are thus a crucial issue for ITER and studies in large tokamaks like JET are critical for reliable extrapolation to ITER.

2. Steady-state power handling

In high power JET ELMy H-modes, with little or no fuelling, the ELM averaged power profile in the outer divertor shows a narrow feature of order a few mid-plane mm in width. In a 16MW H-mode (figure 2) this narrow layer results in a peak power which ten times higher at the outer than at the inner target. In total, three times more total power flows to the outer target than to the inner target. The power profiles shown in figure 2 were measured by three independent techniques: the first uses a slow sweep of the plasma over an embedded thermocouple (TC) [2], the second an infra-red camera diagnostic (IR) [3,15] and the third Langmuir probes (LP). The peak power from IR agrees with the TC method although the IR does not resolve the steep gradient in the private region. The Langmuir probe profile has a similar shape but the absolute power is 4 times smaller than the IR or TC results. This discrepancy can be related to the fact that Langmuir probes can only measure the electron component of the power reaching the surface since the divertor ion temperature is not measured.

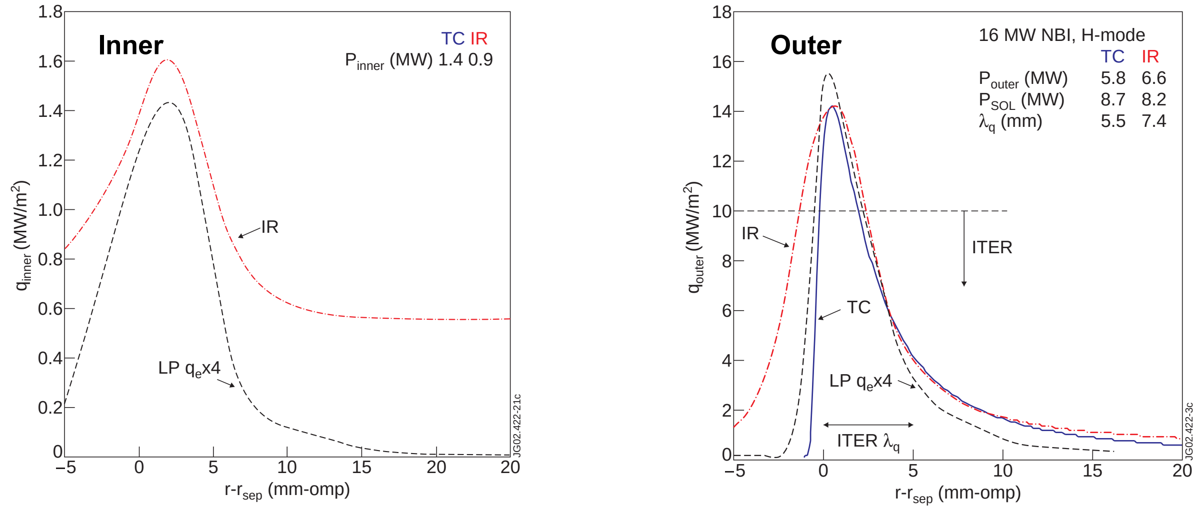

Figure 2. The extracted power profiles measured at the inner and outer divertor targets in an unfuelled type I ELMy H-mode(16MW) by a technique involving a slow sweep of the plasma over an embedded thermocouple (TC), infra-red camera (IR) and target Langmuir probes (LP). A power decay length λ_q of 5mm is assumed in ITER and the steady state surface power density is to be kept below 10MWm^2.

As the neutral beam power is increased at constant electron density, the main SOL becomes less and less collisional ($\nu^*_{iu}\rightarrow 1$), which increases the discrepancy between the electron and ion power channels (figure 3a). Strong gas puffing has the opposite effect; it raises the main SOL collisionality (ν^*_{iu}) and reduces the gap between the electron and total powers (figure 3b). Coupled with the large in/out asymmetry these results have lead to the idea, subsequently validated by numerical simulations, that at low ν^*_{iu}, power flow in the JET SOL is dominated by ion-orbit losses from the edge transport barrier (ETB) region, just inboard of the separatrix [4,5].

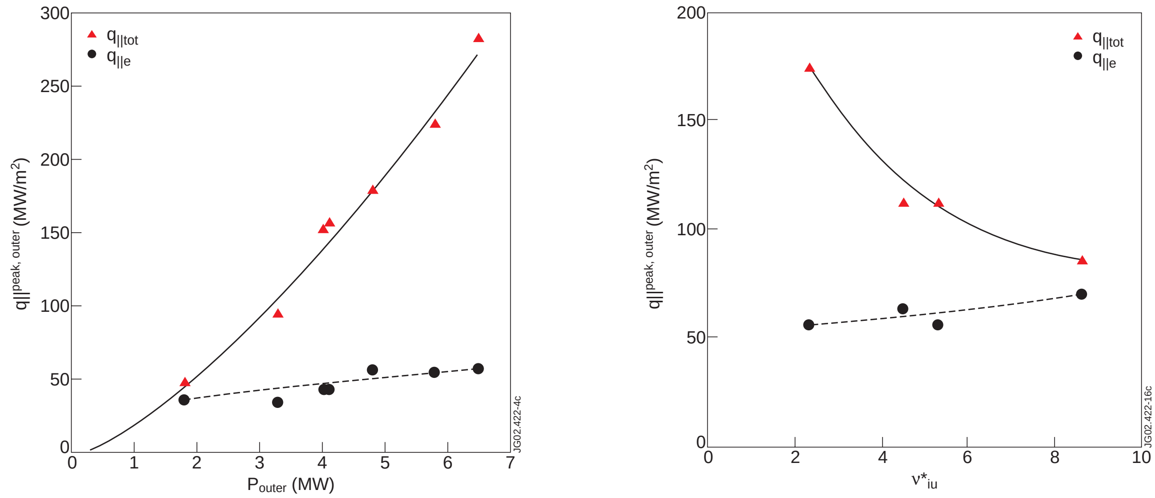

Figure 3(a) Peak parallel power measured at the outer target vs. heating power at constant density and (b) peak parallel power vs. upstream SOL collisionality at constant input power (12MW)

Based on a comparison of deuterium and helium plasmas of different fields, currents, heating power and gas fuelling, the power decay length in the outer divertor was found to scale as [6]:

$$\lambda_q \propto A(Z)\, q_{95}^{0.75}\, B_T^{-1}\, P_t^{-0.4}\, n_{eu}^{0.15} \qquad (2)$$

where A(Z) is the atomic number or charge, q_{95} the safety factor on the 95% flux surface, B_T the toroidal field, P_t the power flow to the outer target and n_{eu} the upstream separatrix density. The A(Z) is written in this way to show that the mass and charge dependence cannot be distinguished until similar shots are obtained in hydrogen plasmas.

The scaling exhibits a negative power dependence i.e. it narrows with increasing power which is opposite to the H-mode prediction found in the ITER Physics Basis [7]. The quality of the fit can be seen in figure 4(a).

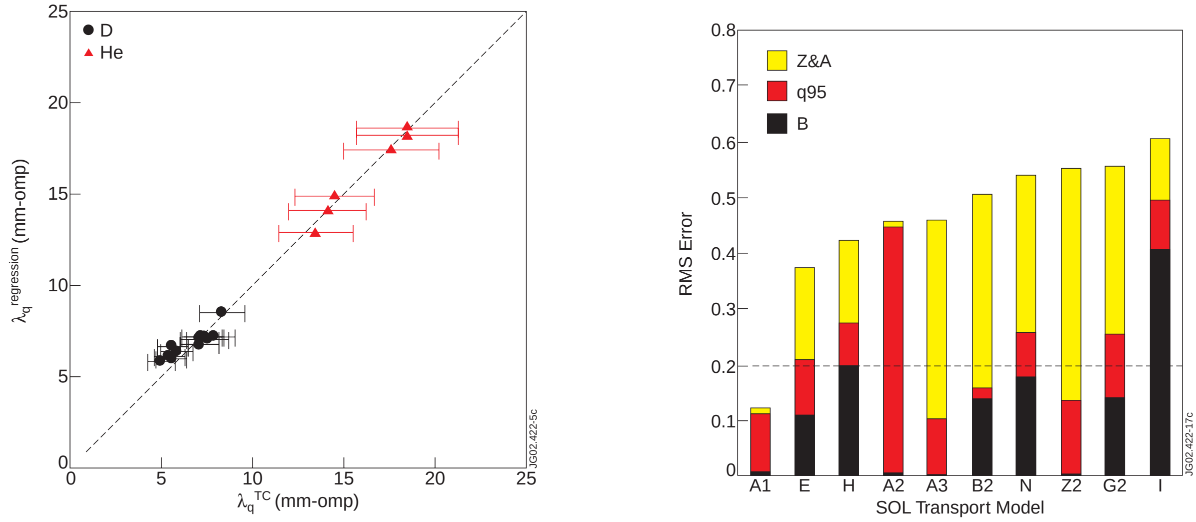

Figure 4(a) Outer power decay length in helium and deuterium discharges plotted against the scaling of equation (2). (b) RMS difference in scaling exponent against top ten models - classical A1, neo-classical A3, MHD interchange E, drift ballooning turbulence H, classical electron conduction A3, Bohm N, poloidal gyro-radius N, endplate MHD B2&G2 and skin depth I. Experimental error is estimated to be ~0.2.

The power width scaling of equation (2) has been compared with 30 theoretical models of perpendicular (⊥) heat diffusivity [6,8] under two limiting assumptions of parallel (||) energy transport in the SOL: || convection and || electron conduction. Best fit to the experiment was obtained with ⊥ model A1 (classical ion conduction) and || convection (v), figure 4b. The experimental error was estimated as 0.2, so that A1 is the only consistent model.

The emerging picture of SOL energy transport in ELMy H-modes may be summarised as follows: in a moderately collisional regime (ν^*_{iu}>10), radial transport is dominated by classical ion conduction, which reduces to ion orbit loss in the collisionless regime (ν^*_{iu}<1). Hence, at low collisionality the power deposition width is related to the poloidal gyro-radius, which is the characteristic radial length of ion orbit loss. As collisionality increases, this orbit loss footprint is broadened according to classical ion diffusion [6].

2.1 Implications of JET results for steady state power handling in ITER

The JET scalings suggest a power width at the entrance to the ITER divertor of 3-4mm (outer mid-plane) [6]. This is somewhat narrower than currently assumed but some additional broadening within the high collisionality ITER divertor is expected. Assuming no additional broadening, the more inclined ITER target option, similar radiated power fraction to JET and comparable in/out asymmetry, the peak outer divertor power load predicted for ITER is 20-30MWm^{-2} which is close the proven capability of the ITER target design. However, it is clearly not desirable to operate at this limit and so radiation from seeded impurities may be required to keep the peak power load below 10MWm^{-2} [9].

3. Power loads due to ELMs

The upper limit on the ELM size tolerable in ITER, as dictated by surface ablation, has recently been refined [1,10, 11]. In this section we summarise the factors involved in this re-evaluation and the important contribution made by JET data.

The base assumption used in ITER is a 5mm SOL width (outer mid-plane) which gives a total inner plus outer strike point area of 3m^2. If the heat pulse is rectangular and the duration of the ELM is the ion parallel transit time (220μs in ITER) then the maximum size of ELM tolerable in ITER would be ΔW_{max} = 1.2-1.9MJ (eqn. 1) where the range depends on the assumed inter-ELM power density (5MWm^{-2} to 10MWm^{-2}). However, this estimate of the ablation limit proves to be far too severe for the following reasons:

3.1 ELM rise time and waveform

The ELM rise time as seen at the target by fast IR camera [15], figure 5a, is found to scale as $\tau_{IR} \approx 10^{-4}(\tau_{||}^{Front})^2$, figure 5b, where $\tau_{||}^{front}$ is the ion parallel transit time from the pedestal to the target ($\tau_{||}^{front} = 2\pi Rq_{95}/c_{sped}$). Hence the τ_{IR} predicted for ITER is around 500μs which raises the ablation limit estimated for ITER by a factor 1.5 to ΔW_{max} = 1.9-2.9MJ. In addition to being slower than previously estimated, the power pulse is not rectangular. It rises more or less linearly with time and decays more slowly. Between one quarter and one half of the energy arrives during the rise phase. Thermal calculations based on more realistic waveforms raise ΔW_{max} by another factor of 1.5 to ΔW_{max} =2.7-4.3MJ

3.2 Area of interaction

Fast IR measurements of ELMs in JET indicate that the power profile during an ELM is broader than it is between ELMs by a factor 1-1.5. Also, a more inclined target is being considered which would increase the target area to 5m^2. Taken together these factors increase the ITER ELM energy limit to 4.5-10.7MJ.

The interaction areas quoted assume that the ELM energy is equally split between the inner and outer divertor targets. In smaller devices such as ASDEX Upgrade most of the ELM energy goes to the inner divertor [1] which would be bad for ITER. In JET the energy is split quite evenly with asymmetry factor 1-1.4 (figure 6). This is totally unlike the inter-ELM power which is strongly asymmetric in favour of the outer divertor (figure 2). Taking the in/out asymmetry into account we get ΔW_{max} = 3.2-10.7MJ.

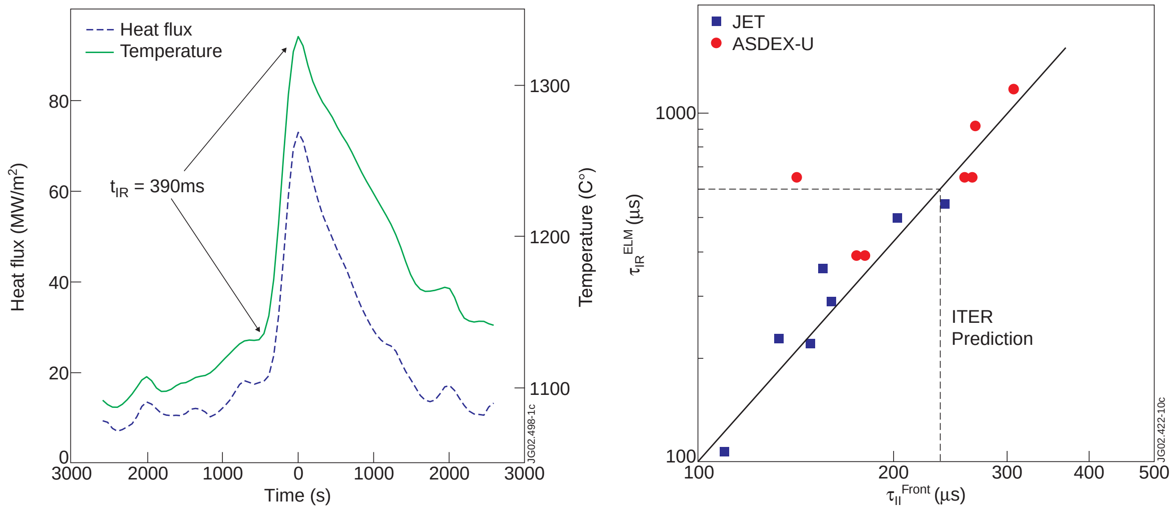

Figure 5(a) Time evolution of peak power and temperature at the JET divertor during a type I ELM [15]. (b) Scaling of ELM rise time τ_{IR} with ion parallel transit time $\tau_{||} = 2\pi Rq_{95}/c_{sped}$ in JET and ASDEX-Upgrade [13]

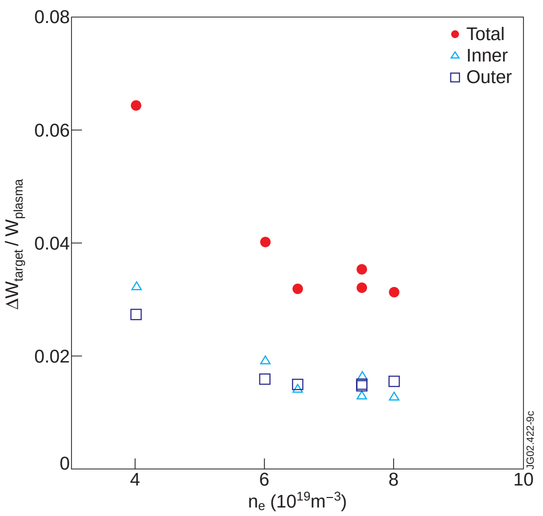

Figure 6 In/out asymmetry in JET ELMs

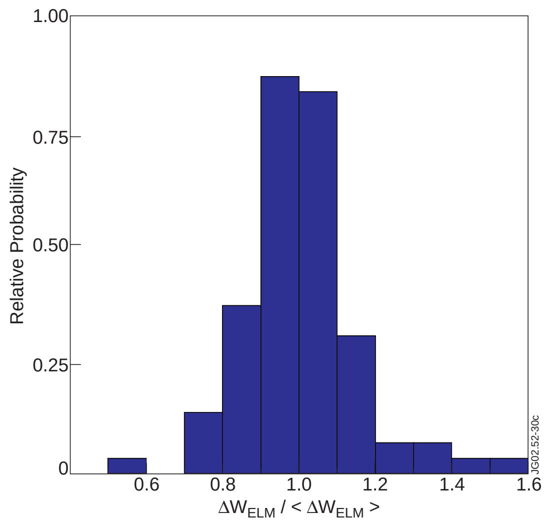

Figure 7 Distribution of type I ELM energy loss in JET.

3.3 Fraction of ELM energy reaching the divertor

Not all the energy which is observed to leave the main plasma in JET arrives at the target plate. We can typically account for 0.5-0.8 of ELM energy at the divertor target. The cause of this ELM energy loss is not known but if it applied in ITER then the maximum tolerable ELM would be in the range ΔW_{max} = 4-21MJ (1-6% of total stored energy). Whilst the use of extrinsic impurities has been shown to be effective at reducing the inter-ELM power load the additional radiation increase the dissipation of ELM energy except in the case of extremely small ELMs [9].

3.4 Predicting the ELM magnitude in ITER

Recent JET data has been central to the development of scalings for ELM energy loss (ΔW_{ped}) which have dramatically improved the fit to the experimental data and thus the degree of confidence in ITER predictions [12]. Two scalings have been the main focus of attention: the first is based simply on pedestal collisionality, the second is based on the idea that the loss of energy from the pedestal is limited by a parallel transport bottleneck and so the ion parallel transit time from the pedestal to the target is a critical parameter ($\tau_{\|}^{front} = 2\pi Rq_{95}/c_{sped}$). If ELM size is limited by ion parallel transport then the scaling predicts ΔW_{ped} = 7MJ for type I ELMs in ITER. If pedestal collisionality is the scaling factor then this rises to 13.5MJ. This is not the end of the story however, because ELMs are not perfectly uniform in size. In JET discharges with regular ELMs, the largest ELMs are about 1.5 times larger than the average (figure 7). The estimated energy of these critical ELMs in ITER is thus ~10-20MJ. This must be compared with our estimate for the maximum tolerable ELM size in ITER which is ΔW_{max} = 4-21MJ. The ablation limit and predicted ELM size are thus quite comparable.

4. Disruptions

The current ITER assumption for disruptions is that the thermal quench behaves like an extremely large ELM event. In particular, it is assumed that the magnetic equilibrium does not change during the thermal quench and that there is no significant additional broadening of the scrape-off layer so that most of the stored energy arrives at the divertor strike points. If this were to happen then the target surface would be ablated and complex vapour shielding calculations have been carried out to evaluate the material loss. The uncertainty of melt layer physics during disruptions is the principal reason why a tungsten divertor is currently not the first option for ITER despite its clear advantages with respect to tritium retention.

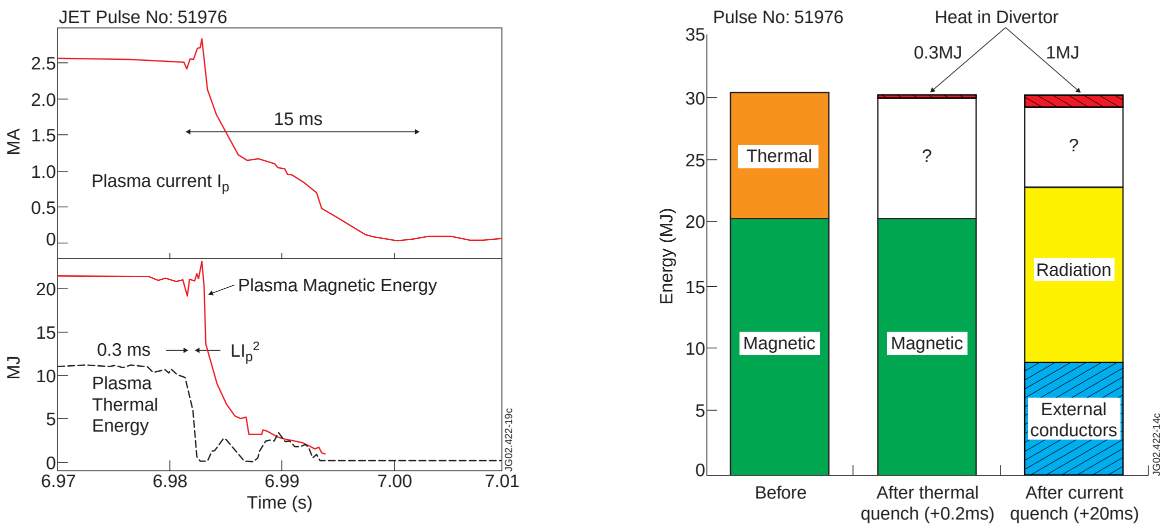

Figure 8. A JET disruption in which the thermal energy is lost in 0.3ms and magnetic energy over 20ms, (b) energy balance after thermal quench (ΔW_{th}= 10MJ) and after the loss of magnetic energy (ΔW_{mag}= 20MJ) disruption - question marks show unaccounted or unresolved contributions.

Although we describe here a particular disruption, many different disruptions have been studied and the result appears quite general [14]. In our example (figure 8) the total thermal energy was 10MJ before the disruption. After the rapid loss of thermal energy, 0.2ms later, we can only account for 0.3MJ in the divertor (figure 8b) and magnetics reconstructions show very little change in the equilibrium. The bolometer system is too slow to show whether the remaining 9.7MJ are radiated or whether they are directly convected to the main chamber wall. After another 20ms the magnetic energy has decayed and both IR and thermocouple measurements show that 1MJ has arrived in the divertor which corresponds to 3% of the total thermal plus magnetic energy. Almost half the total energy is radiated but we cannot yet distinguish between thermal quench and decay of magnetic energy. Over 40% of the plasma's magnetic energy is returned to the external circuits during the current decay.Fast infra-red and thermocouple analysis are consistent with respect to the energy balance and both show that the power is deposited quite uniformly across the divertor (figure 9).

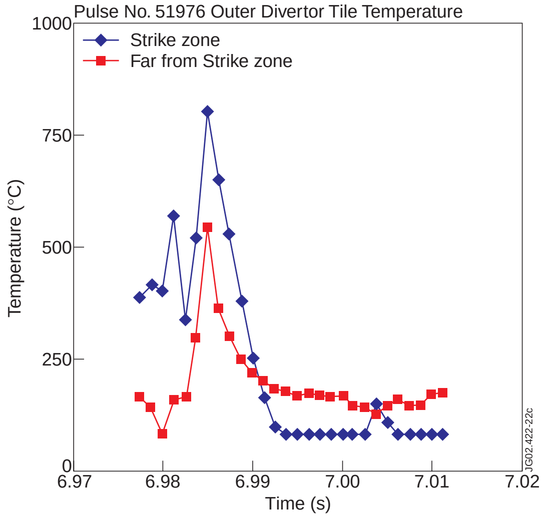

Figure 9 Evolution of surface temperature near to and far from the strike point in a ΔW_{th}= 5.6MJ disruption.

If the JET results extrapolate to ITER then disruptions would not damage a tungsten target. However, we do not at present know where and by what processes the missing thermal and magnetic energy are deposited in the main chamber. If this energy deposition is not sufficiently uniform then additional damage to main chamber components might be expected.

5. Discussion and Conclusions

Recent JET experiments and analysis have demonstrated the importance of edge collisionality for the physics of divertor power loading both during and between ELMs. Since collisionality decreases strongly with machine size, JET routinely operates in an ITER relevant regime which is difficult or impossible to access in smaller devices. These new ideas have enabled us to develop more physically justifiable predictions for ITER. The results suggest a power width at the entrance to the ITER divertor of 3-4mm (outer mid-plane) which is somewhat narrower than currently assumed. Some additional broadening within the high collisionality ITER divertor is expected. Even without significant broadening, predicted steady state surface power loads are close to the proven limits for the actively cooled divertor elements. However, additional radiation from extrinsic impurities may still be required to give a margin for power excursions [9].

Extrapolations of the surface energy density associated with type I ELMs found in JET to ITER show that small type I ELMs expelling 2-5% of total stored energy may be acceptable for the carbon target. So far, tungsten has been second choice due to the belief that serious melt layer loss would occur during disruptions. However, the response to ELMs is similar to carbon and it has significant advantages with respect to tritium retention.

Disruptions involve 100% loss of thermal energy in a timescale comparable to that of an ELM and are thus a major concern for ITER. The current ITER assumption is that much of the 350MJ of thermal energy arrives in the divertor rather like a giant ELM. In JET however, the energy deposited in the divertor is rather small and uniformly spread. If ITER were similar then the divertor surfaces would stay below the ablation limit. This is an important observation since disruptions are one of significant reason why the use of tungsten at the ITER strike points is still being debated. However, where the thermal energy is deposited in the main chamber and the physics behind the JET observations are unresolved. These issues can only be fully addressed when the new diagnostics currently planned for JET become operational after the 2004 shutdown.

Predictions for the power handling capability in ITER are now more realistic than in the past and look much more optimistic but the development of radiating plasmas with extrinsic impurity seeding and small ELMs is still a priority both from the point of view of steady state and transient power loads. Discharges compatible with both steady state and transient thermal limits have been demonstrated in JET [9]. Radiation from extrinsic radiation has been used to push the discharge into a ELM regime whilst maintaining sufficient density and confinement. There is however no evidence from experiment or modelling that ELMs of any significant magnitude can be buffered by impurity radiation due to the high power densities associated with ELM events.

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Acknowledgements

Particular thanks to P.Andrew, T.Eich, W.Fundamenski, A.Loarte, A.Herrmann and V.Riccardo for their direct contributions to this paper. The work was partly funded by EURATOM and the UK Department of Trade and Industry.