32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-2.006 (2005)

ELM calorimetry in JET

Emilia R. Solano[1], Phillip H. Edmonds[2], Yann Corre[3], Philip Andrew[4], Stefan Jachmich[5] and JET EFDA contributors *

[1]*Asociación EURATOM/CIEMAT para Fusión, Avda. Complutense, 22, 28040 Madrid, Spain*
[2] *Ribera de Manzanares, 79, Madrid, 28008, Spain*
[3] *Association EURATOM-CEA, DSM/DRFC, CEA Cadarache, 13108 St Paul lez Durance,France*
[4]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, UK*
[5]*ERM/KMS-LPP, Association EURATOM-Belgian State, Brussels, Belgium*

In JET, hot edge plasmas are produced suppressing gas fuelling during the neutral beam heating phase of the discharge. With sufficient heating power an H-mode is obtained and, with sufficient triangularity, large (0.5 to 2 MJ) and infrequent (1 Hz) compound ELMs are observed, without return to L-mode. ELM-associated strike point upward movements have been documented in these pulses [1,2]. A question remains: where is the energy deposited?

Thermocouples (TCs) embedded 1cm deep in the divertor tiles can provide information on heat deposition, as the ELMs studied are sufficiently large and infrequent that heat flows due to individual ELMs can be identified. During the H-mode phase of the plasma pulse, the strike points are located at the height of the lower TC in the inner and outer vertical divertor target tiles, -1.64 m. Upper TCs are located 10 cm above the lower ones, in the same tiles. Typically, the inter-ELM SOL width is ~1-3 target cm. During the ELMing phase of the discharge, the bulk of the temperature (T) rise is near the lower TCs, as shown in Fig. 1 (red traces in top row). Heat pulses associated with ELMs are observed on the T and dT/dt traces, particularly in the lower TC of the inner tile and the upper TC of the outer tile. These measurements show that ELMs deposit considerable heat at and above the pre ELM strike position. At each of the 9 ELMs in this pulse ~2 MJ

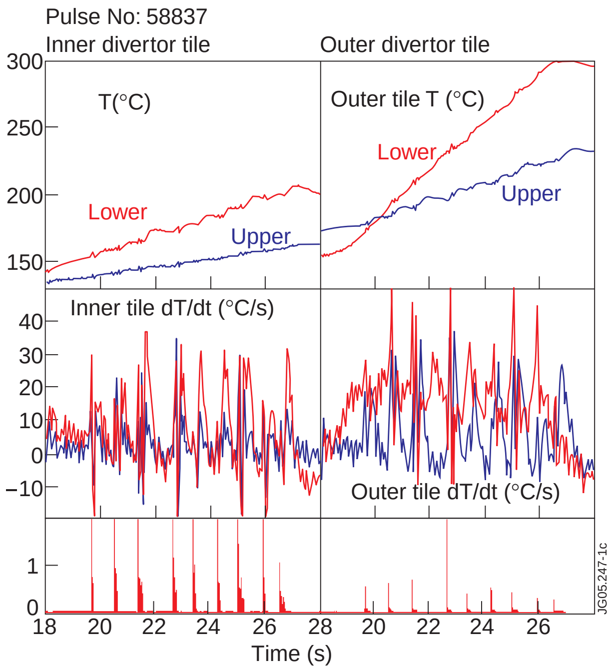

Fig. 1: measurements at inner (left) and outer (right) divertor tiles. Top row: temperature in lower and upper TCs. Middle rows: dT/dt (negative spikes at ELM times due to noise pick-up). Bottom rows: D_α signals, showing ELM times.

* See Appendix of J.Pamela et al., Fusion Energy 2004, Proc. 20th Int. Conf. Vilamoura, 2004, IAEA, Vienna

of diamagnetic energy is lost from the plasma. The 8th ELM appears not to reach the upper outer TC, all others do. During this pulse 46.5 MJ (60% of total energy input) are deposited in the outer lower tile, and 15 MJ (20%) in the inner tile. ELM heat pulses are deposited near both lower and upper TCs. In the outer divertor tile ELM heat pulses arrive in phase with ELMs at the upper TC, out of phase at the lower TC. This implies that arrival of ELM heat pulses at the outer lower TC must be indirect: heat is deposited elsewhere and conducted to the lower outer TC, and/or arrives later, when the strike point has returned to the pre-ELM position.

Langmuir probe (LP) and infrared data (IR) [1, 2] both show a transient increase in signal at the ELM, (< 100 μs), at least 10 cm away from the pre-ELM strike position. We refer to this phase as the front of the ELM. It is followed by a longer compound ELM phase (~250 ms) with the strike point displaced 2-3 cm above the pre-ELM strike position. This is illustrated in Fig. 3, where Theodor IR-derived [4] heat power deposition profiles are shown (averaged for 100 ms in each phase): before the ELM (black), during the compound ELM phase (blue) and soon after the ELM (green). The IR diagnostic can not resolve power density at the front of the ELM pulse.

A 2D model of the outer divertor tile was constructed, assuming a rectangular cross-section of the tile. The grid size is 4x4 mm, the time step is 25 ms. The material characteristics are taken from [3]. The thermal conductivity is 240W/m°K in the toroidal and inward directions, and 56 W/m°K in the vertical direction, parallel to tile plasma facing surface. First, simple input power profiles are used to characterise temperature response. For instance, shown in Fig. 2 is the T change (blue) produced by periodic 50 ms heat pulses of amplitude 4 MW/m^2 (pink), applied over 1.2 cm of tile height. In the first 4 heat pulses, 44 kJ arrive 1.2 cm away from the TC location (Z_{TC}), producing small T changes. In the last 3 the energy arrives at the TC height and above, raising T about 3° per pulse.

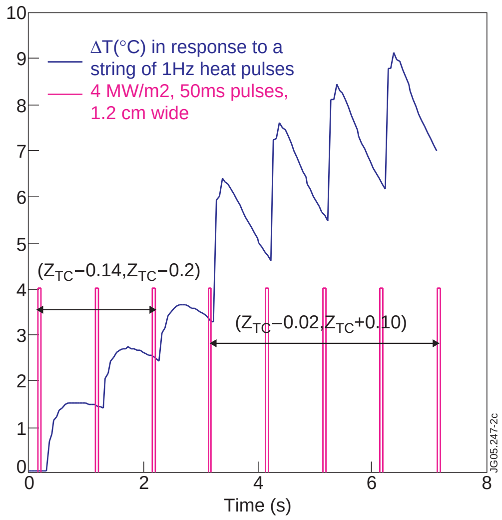

Fig. 2: T 1 cm deep into divertor tile, in response to heat pulse oscillations, placed away or near the TC location

Taking into account the sensitivity of TC response to heat deposition location, we attempted to model the traces of the upper and lower TCs in the outer tile. Power density profiles were

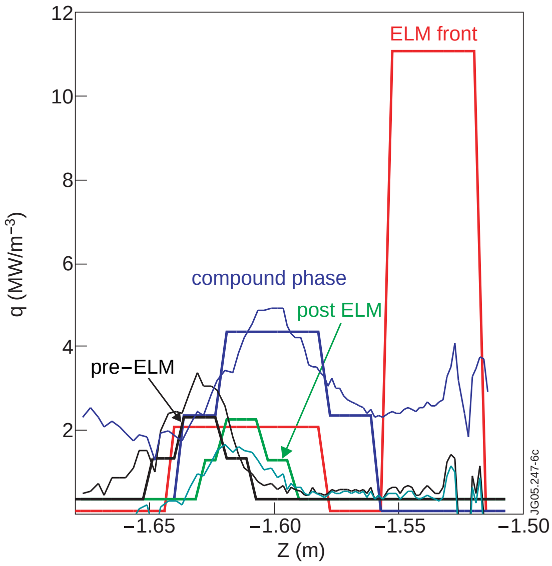

Fig. 3: Profiles of power density on outer divertor during various ELM phases from model (block profiles) and IR data, refer to text.

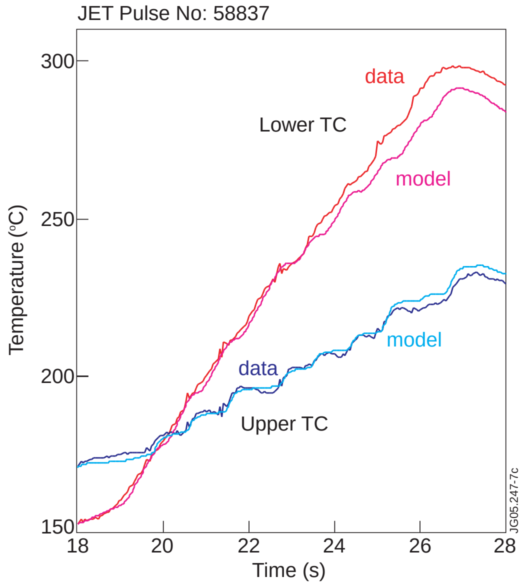

Fig. 4: Measured and modelled T at TC locations (-1.64 and –1.54 m) from profiles of Fig. 3

constructed for each relevant phase, based on IR data. Two sets of profiles were chosen, shown in Figs. 3 and 5. In between ELMs, power is assumed to arrive at the pre-ELM strike position (black). At the front of each ELM, a heat pulse is deposited in 25 ms (red), followed by a phase of ELM heat deposition (blue) and an H-mode phase (green), both 3 cm above the pre-ELM position (strike positions confirmed by Langmuir probe data). The aim of these simulations was to reproduce TC signals with minimum energy, in an attempt to arrive at a lower bound on the ELM energy deposited away from the pre-ELM strike position. The results of the simulations are shown in Figs 4 and 6, where the lower (red) and upper (blue) TC measurements can be compared with the model results (pink and green, respectively). Both match the upper TC data reasonably well. The match is not so good for the lower TC, which is likely to be affected by slowly conducted heat deposited away from the pre-ELM strike position (recall that dT/dt is out of phase with the ELM, as was shown in Fig. 1). Overall, 20 MJ are deposited on the tile in these simulations, presumably the missing 25 MJ are deposited away from the TC locations.

In the simulation plotted in Figs. 3 and 4, the "front of the ELM" deposits 250 kJ near the upper TC, and ~500 kJ are deposited at the displaced strike position during the compound ELM phase. For Figs. 5 and 6 there is no distinguishable "front of the ELM" phase: 800 kJ are deposited over much of the tile for the whole ELM duration, with a broad peak at the displaced strike position. The match with TC data is equally good, so we can not distinguish

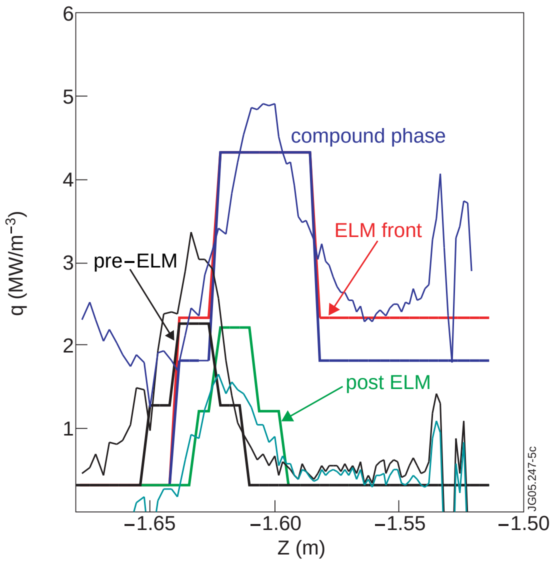

Fig. 5: a different choice of heat deposition profiles

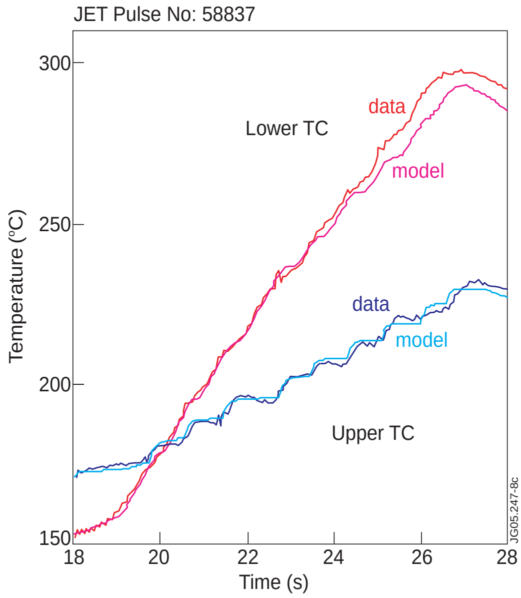

Fig. 6: corresponding measured and simulated T at TCs.

between these two possibilities. All we can say is that at each ELM considerable energy must be deposited near the upper thermocouples. As in both cases we only account for about half of the ELM energy arriving at the outer lower tile (estimated to be 1.5 MJ), up to 500 kJ could be deposited significantly far away from the pre-ELM strike position.

In conclusion: using thermocouple measurements as a benchmark, input powers from IR measurements and strike positions from IR and Langmuir probes, a 2D finite element model of heat conduction in the outer divertor tile indicates that 250-500 kJ must be deposited up to 10 cm away from the pre-ELM strike position in 2 MJ infrequent compound ELMs in JET.

In ITER, it is necessary to arrive at the H-mode early in the pulse. Operation with no gas puff and marginal input power above the H-mode power threshold are the conditions that lead to these infrequent and large compound ELMs at JET, which deposit power away from the pre-programmed strike point position. It would be prudent to adapt target design in next generation tokamaks to include appropriate materials and incidence angles in a broad area around the strike position.

Acknowledgements: this work has been conducted under the European Fusion Development Agreement, and funded in part by a Ramón y Cajal grant of the Spanish Ministry of Education and Science.

[1] E. R. Solano, Y. Corre, F. Villone, et al., Jour. of Nucl. Mater., **337-339** (2005) 747-750

[2] E. R. Solano, S. Jachmich, F. Villone et al., Proc. of the 20th IAEA Fusion Energy Conference 2004, 1st-6th November 2004, Villamoura, Portugal

[3] V. Riccardo, W. Fundamenski and G. F. Matthews, Plasma Phys. Control. Fusion 43 (2001) 881-906.

[4] A. Herrmann and ASDEX Upgrade Team, Europhysics Conference, Abstracts (CD-ROM, Proc. of the 28th EPS Conference on Controlled Fusion and Plasma Physics, Madeira 2001), p. 2109 (2001)