

## Infra Red thermography of ELM-divertor target interactions on TCV

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### Introduction

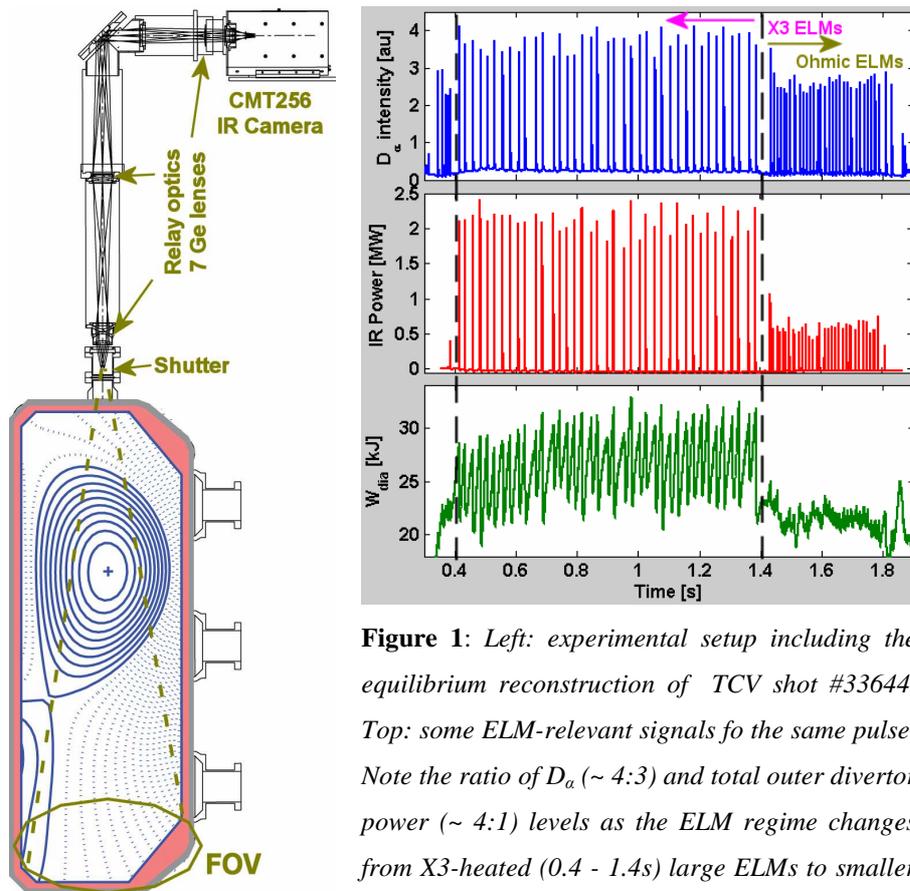
A serious concern for ITER and future fusion reactors is the excessive heat load caused by type-I ELMs, leading to an untimely erosion or melting of the divertor target [1]. Such an event commences with the collapse of the H-mode pedestal, ejecting an important quantity of hot plasma into the scrape-off layer (SOL), where it is convected along the open field lines onto the targets. According to present empirical scalings, type-I ELMs on ITER could deposit as much 10-15 GW/m<sup>2</sup> on the ITER divertor targets [2], values which are unacceptable from the point of view of target lifetime. As a consequence, a great deal of effort is being devoted to understanding the ELM release mechanism from the pedestal, the transport of energy in the SOL, both perpendicular and parallel to field lines, and the nature of power deposition on the targets (timescales, magnitudes, scaling with upstream pedestal parameters [3]). The latter is of particular interest since, if sufficient time and space resolution is available in a measurement of the target power flux, the data can be used not only to provide quantitative assessment of the heat loads from the materials point of view, but also to test physics models of the ELM SOL transport (such as sophisticated particle-in-cell (PIC) kinetic simulations [4], or 2D fluid-monte Carlo treatments [5]). For this purpose, Infra-Red (IR) thermography is an important diagnostic method, measuring absolute target energy deposition and, with the advent of multi-pixel IR sensitive semiconductor detectors and fast read out times, providing time resolution sufficient to resolve the fine details of the ELM-target interaction. If the effects of surface layers on the bulk target substrate can be properly accounted for (see below), IR measurements also have the advantage of measuring the direct surface power flux, without the requirement to account for the target sheath (whose parameters vary significantly during the ELM [4]). Langmuir probes do not have this luxury, nor can they provide the spatial resolution possible with IR. This contribution presents the first IR measurements of ELM heat loads obtained on TCV using a new fast IR camera diagnostic viewing the outer divertor target.

### Experiment

Figure 1 illustrates the implementation of the new IR diagnostic on TCV together with the time evolution of the D<sub>α</sub> emission, the divertor peak power fluxes and the plasma stored energy during an ELMing H-mode discharge with forward toroidal field (I<sub>p</sub> = 340 kA, B<sub>T</sub> = 1.44 T,  $\bar{n} = 5 \cdot 10^{19} m^{-3}$ ) comprising a long X3 ECRH heated phase (~ 600 kW absorbed power) and a shorter ohmic phase at the end of the pulse. During the X3 phase, the ELMs are largest (f<sub>ELM,X3</sub> = 40 Hz, ΔW<sub>ELM</sub>/W ~ 15-35%), returning to smaller ELMs (f<sub>ELM,OH</sub> = 80 Hz, ΔW<sub>ELM</sub>/W ~ 5-10%) in the ohmic H-mode phase. At such large values of ΔW<sub>ELM</sub>/W, these smaller ELMs would be classified at type-I, in contrast to the usual ohmic H-mode on TCV, when f<sub>ELM,OH</sub> ~ 150 -200 Hz, ΔW<sub>ELM</sub>/W ~ 2-4% and the ELMs are thought to be of type-III [6]. In the case of the larger, X3 heated ELMs, no classification has yet been possible but they

are likely to be type-I [7]). In what follows, the two different ELM phases will simply be referred to as “ohmic” and “X3” ELMs.

The new fast, snap-shot type IR camera (CMT 256, Thermosensorik GmbH) and associated germanium relay optics image the vacuum vessel floor (outer target) from the top of the machine, providing straightforward viewing with the tile surfaces perpendicular to the focal plane. The camera is equipped with a 256x256 CMT focal plane array sensitive in the 1.5 - 5.1  $\mu\text{m}$  wavelength range operating at a full frame acquisition rate of 880 Hz, and up to 25 kHz in sub-array mode (freely configurable in 8x8 pixel units) with minimum integration times of  $\tau_{\text{int}} = 1 \mu\text{s}$ . At these high framing speeds, the  $\sim 40 \mu\text{s}$  time resolution is easily



**Figure 1:** Left: experimental setup including the equilibrium reconstruction of TCV shot #33644. Top: some ELM-relevant signals for the same pulse. Note the ratio of  $D_\alpha$  ( $\sim 4:3$ ) and total outer divertor power ( $\sim 4:1$ ) levels as the ELM regime changes from X3-heated (0.4 - 1.4s) large ELMs to smaller ELMs in the ohmic phase.

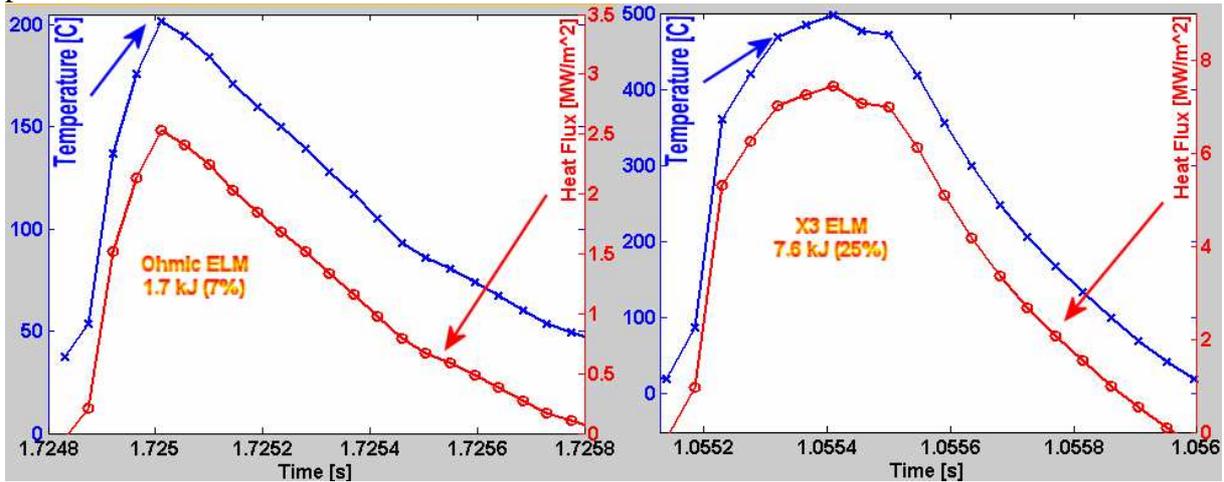
sufficient to provide several measurement points during the critical rise time period of the target power flux during the ELM cycle (as shown in Fig. 2). The recorded tile surface temperature data is used to calculate target incident heat fluxes with the 2D finite difference code THEODOR [8], using temperature dependent thermal parameters of the polycrystalline graphite TCV target

tiles, together with a simple model for the thin layers present on tile surfaces (due to boronisation and redeposition processes). Whilst these thin deposited layers complicate the derivation of heat fluxes from surface temperatures, they are also critically important to the usefulness of the IR diagnostic on TCV for ELM physics: their presence significantly increases the system sensitivity - even small ELMs with  $\Delta W_{\text{ELM}} \sim$  few 100 J can be easily resolved (see below and Fig. 2).

### Data analysis

Typically, the thermal response of the tile surface to the ELM heat load is enormous in comparison to what would be expected on the basis of a simple semi-infinite solid

approximation for bulk graphite. Assuming that 50% of  $\Delta W_{\text{ELM}}$  arrives on the vessel floor and imposing a single exponential radial profile with  $\lambda_p = 3$  cm (based on measurements of the ELM power flux profile) yields a rise of 30 °C for the ohmic phase (small) ELM shown in Fig. 2. In reality, the rise exceeds 150 °C. Applying the same semi-infinite solid approximation on bulk graphite, but by taking the actual peak heat flux value computed using THEODOR ( $2.5 \text{ MWm}^{-2}$ , using a simple layer model in the code) yields only a 6 K rise, insufficient to be resolved by the system at the low integration times required if the maximum time resolution is to be achieved. It is thus precisely the surface layers that make this analysis possible for these small TCV ELMs.



**Figure 2:** Temperatures and power fluxes for an ELM in the ohmic phase of the discharge in Fig. 1 (left) and a large ELM during the X3 phase (right). The acquisition rate permits the study of individual ELM events, with several points recorded already in the rise phase. The temperatures are quite large – a consequence of thin layers poorly coupled to the tile surface.

It is interesting to note from Fig. 2 that the ELM rise time,  $\tau_{\text{ir}}$  (defined as the time for the IR power flux to reach its peak value beginning from 10% of the peak) is longer for the X3 ELMs than for the ohmic phase ELMs even though parallel transit times are shorter given the higher pedestal temperatures during the X3 phase (see also Fig. 3). This may be a feature of these ECRH plasmas which are primarily electron heated, in contrast to the more usual type-I ELMs produced in neutral beam heated discharges.

Figure 3 compiles several quantities of interest with regard to ELM studies plotted against ELM expelled energy fraction for all of the ELMs in the discharge of Fig. 1. The integral energy to peak,  $W_{\text{IR}}$ , is an important quantity. In combination with  $\tau_{\text{ir}}$ , it determines the maximum surface temperature that will be reached by a surface in response to the ELM transient [9]. For the large X3 ELMs,  $W_{\text{IR}}$  (normalized to the total energy deposited during the ELM,  $E_{\text{IR}}$ ) takes values in the range 0.3-0.4 in common with measurements of type-I ELMs on JET [10] and recent PIC simulations [4]. The ratio of  $E_{\text{IR}}/\Delta W$  shows that for these TCV X3 ELMs, only at most 25% of the ELM energy drop is recovered at the outer target and that in some cases as little as 15% is found. Radiation losses due to the ELM cannot be accounted for here, nor is a measurement available at the inner target. Recent observations on ASDEX Upgrade and JET [11] have revealed a trend for the ELM to deposit more energy on the inner than outer targets in forward field. In addition, a number of machines find significant ELM-main wall interactions (including TCV during these X3 ELMs, see [12]). It

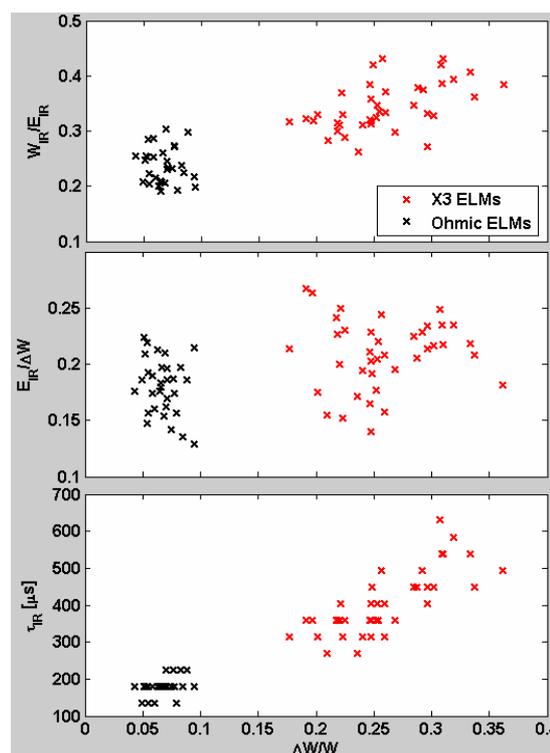
is thus entirely plausible that only relatively small fractions of the ELM energy drop are found at the outer target. Regarding the scaling of  $\tau_{ir}$  in this discharge, the lack of good edge pedestal data prevent a reliable comparison with the parallel transit times ( $\tau_{\parallel} = L_{\parallel}/c_{s,ped}$ ). Approximate values of  $T_{e,ped} \sim 300 - 500$  eV estimated from core Thomson scattering profiles place  $\tau_{\parallel}$  in the range 80 - 100  $\mu$ s for the X3, and 90 - 110  $\mu$ s for the ohmic ELMs. This is considerably shorter than the  $\tau_{ir}$  data in Fig. 3, which is of the order 300 - 600  $\mu$ s for the X3, and 100 - 200  $\mu$ s for the ohmic ELMs. These values, especially those in the X3 phase, considerably exceed the apparent trend observed from a plot showing the same two quantities for JET, JT-60U, MAST and AUG data [13], this possibly being a consequence of predominant X3 heating.

### Acknowledgement

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**Figure 3:** Scaling-related quantities from TCV #33644. Ratio of IR integral energy to peak ( $W_{ir}$ ) and total IR energy ( $E_{ir}$ ),  $E_{ir}$  and total diamagnetic energy loss and IR time to peak ( $\tau_{ir}$ ) as a function of ELM expelled energy fraction.