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Inner and outer power and energy asymmetries during L-mode power staircase pulses with forward and reversed magnetic field

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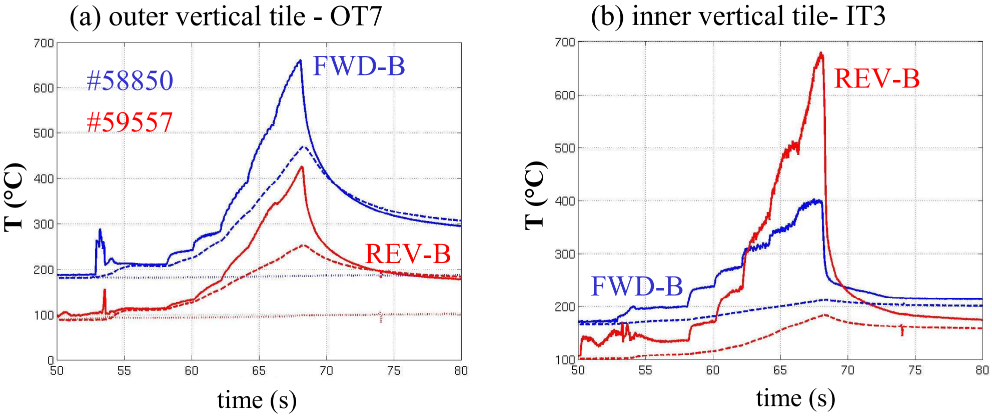
1. Introduction: Measurement of heat flux and energy deposition on the divertor target plates is an essential issue for safety of the plasma facing components and also for the validation of models describing transport of particles and energy in the scrape of layer. In JET, a high time resolution infrared (IR) system and several embedded thermocouples (TC) 10 mm below the tile surface are used to measure the surface and bulk temperatures of the target plates respectively. Time resolved estimates of the heat flux density and energy are computed with the 2D code THEODOR constrained by the IR temperature measurements. This paper reports on analysis of the inner and outer peak heat flux density and energy asymmetries during L-mode power staircase discharges using both IR and TC data with an emphasis on the important question of divertor power asymmetry changes when operating with forward (FWD-B) and reversed toroidal magnetic field (REV-B).

2. Presentation of the IR and TC data.

Power staircase discharges are regularly used in JET to deduce, using IR thermography, the thermal properties of surface layer which accumulate, in particular on the inner divertor targets due to net impurity redeposition there [1]. In a recent reversed toroidal field campaign [2] pulses have been executed for direct comparison with those in normal field. Results of IR analysis for a pair of matched (#59557 in REV and #58850 in FWD-B), deuterium fuelled, L-mode power staircases (neutral beam injection heating with five 2s-steps of 1.4MW each) are compared in detail here. The magnetic configuration is the DOC-L (diagnostic optimized configuration) in the JET MarkIISRP gas box divertor configuration with strike points on the lowest vertical target tiles in the inner and outer divertors (labelled IT3 and OT7, for the inner and outer tiles respectively). Pulse #58850 was performed during FWD-B operation when no surface layer on OT7 is observed but, during which, a rather stable surface layer is always found on IT3. Pulse #59557 was executed early during the REV-B campaign (after a total of 10min of integrated tokamak plasma disharge). At this stage, surface layer are not yet observed on tile OT7, but such layer do appear later in the reversed field campaign [3]. The measured IR and TC temperatures are presented in Fig. 1 for this matched discharge pair showing a remarkable difference of temperature variation between FWD and REV-B. At the inner target (Fig. 1b), the increase of temperature ΔT is almost two times higher during REV-B than during FWD-B operations. This is observed at the surface (full line) and also inside the bulk (dashed line), indicating that the observed temperature difference (between FWD and REV-B) is not due to a possible effect of the surface layer. This difference is analysed in terms of heat flux density and deposited energy by using the THEODOR code.


(a) outer vertical tile - OT7

(b) inner vertical tile- IT3

Figure 1: Peak target surface temperature (IR data - full line) and bulk temperature (TC data - dashed line) on the outer (a) and the inner (b) vertical divertor tiles.

3. Heat flux density and energy calculation.

A simple model based on heat transmission between the surface layer and the bulk material is used to extract the incoming heat flux density and the surface layer properties. With this model, the excess temperature due to the surface layer is assumed proportional to the variation of the heat flux density, Q, during each step: $\Delta T_s = \Delta Q_s / H_{layer}$, where H_{layer} represents the heat exchange coefficient between the surface layer and the bulk material. Previous analysis of the surface layer properties using power staircase discharges [1] have shown that H_{in} (heat exchange coefficient on the inner tile IT3) lies in the range [5 – 10] $kW \cdot m^{-2} \cdot K^{-1}$. A power variation of H_{in} was also proposed in [1] as a way to better match the cool down phase after power switch off. Computation of the heat flux density and energy content deposited on the tile, including the surface layer is performed using the THEODOR code [4]. The surface layer properties found in [1] are employed again here: $H_{out}=200\ kW \cdot m^{-2} \cdot K^{-1}$ on the outer tile; $H_{in}=5$ and $10\ kW \cdot m^{-2} \cdot K^{-1}$ are used on the inner tile to take into account uncertainties about the surface layer properties. Using the fact that several 100s after the end of each discharge the entire bulk temperature is uniform, the TC cool down curve can be extrapolated backwards in time to determine in a robust way the total energy content deposited on each tile by each discharge [5]. Thermocouple and simulated (IR + THEODOR) data for the two pulses discussed here are compared in Fig. 2. Both are in qualitative good agreement. On the outer vertical tile, the energy is reduced when the magnetic field is reversed whilst on the inner energy increases. The out/in energy ratio, taken from TC data between tile IT3 and OT7 only ($A_{7/3}=E_{T7}/E_{T3}$), is $A_{7/3} \sim 3.1 \pm 0.5$ in FWD-B (where ±0.5 is the gap between TC and IR-THEODOR calculations using $H_{in}=5$ and $10\ kW \cdot m^{-2} \cdot K^{-1}$) and less pronounced with REV-B, $A_{7/3} \sim 1.7 \pm 0.3$.

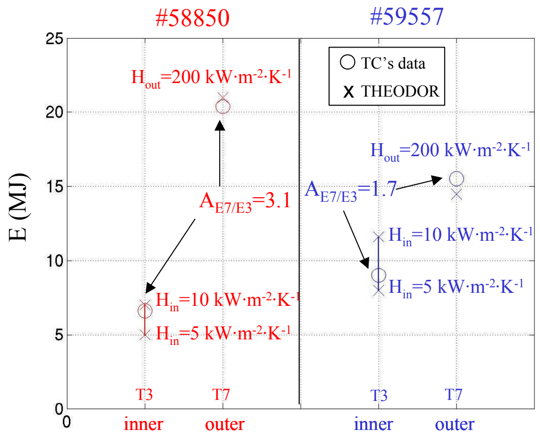


Figure 2: Measured TC (circles) and derived IR-THEODOR (crosses) tile energies for #58850 (FWD) and #59557 (REV).

4. Energy and heat flux asymmetries.

The ratios $A_Q=Q_{out}/Q_{in}$ computed with THEODOR are plotted in Fig. 3a as a function of the input power. The global trend is discussed by looking at the average of the two simulations (H_{in}=5 and 10 kW·m^{-2}·K^{-1}). In FWD-B the out/in heat flux density asymmetry increases as the input power increases until A_Q~5, the heat flux density is strongly unbalanced in favour of the outer target. In REV-B, the out/in heat flux density asymmetry is more balanced between the inner and outer tiles ($1 \le A_Q \le 2$) showing a weak dependence with the input power. For comparison with thermocouples data (see next section), the energy asymmetry computed with THEODOR is plotted in Fig.3b as a function of energy weighted power (pertinent to compare different operated scenario). Because of the inner and outer difference of wetted area, the peak heat flux density out/in asymmetry is more pronounced than the energy asymmetry (true if the heat flux is higher on the outer tile). The crucial issue concerns the heat flux density and energy asymmetries that agree to show a remarkable difference between FWD and REV-B operations while the injected neutral beam power is increasing.

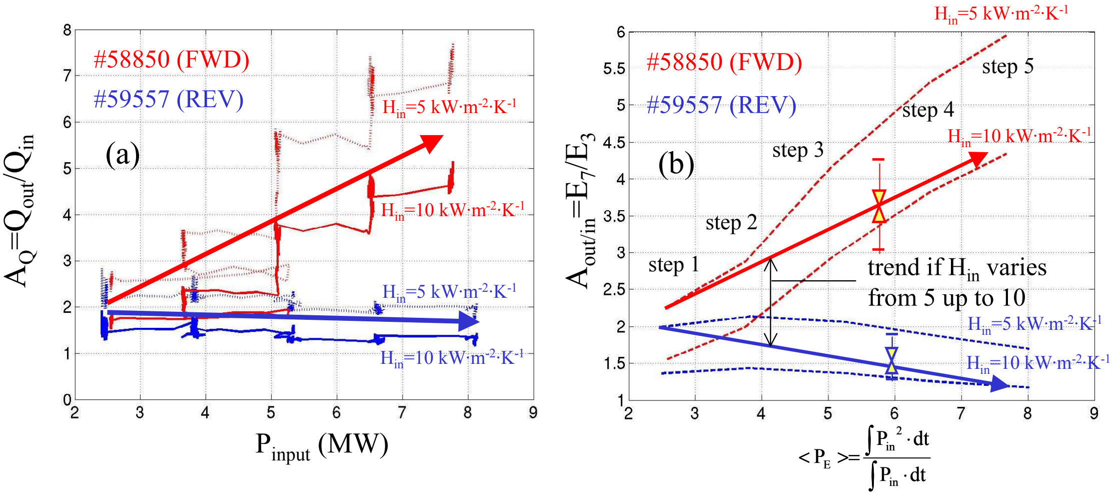


Figure 3: a) Out/in heat flux density ratios and (b) energy asymmetry computed with THEODOR during the matched discharge pair.

5 Extension of the asymmetry analysis.

To check if this situation is marginal or representative of the energy and heat flux distribution during FWD and REV-B operations, an extension of this analysis is presented in Fig. 4. The energy asymmetry from a selected list of L-mode discharges (using the same DOC-L magnetic configuration) is plotted as a function of the energy weighted power integrated during the divertor phase. To illustrate the results, the abscissa is positive for REV-B discharges (blue) and negative for FWD-B discharges (red). In FWD-B operation, the energy asymmetry increases whilst the power weighted to the energy increases (from 1.5 up to about 8 MW), the inner and outer energy are strongly unbalanced at the highest power. In REV-B operations, the energy asymmetry conversely decreases whilst the power weighted to the energy increases (from 1.5 up to 8 MW), the inner and outer energy are almost balanced at the highest power. The variation of E7/E3 are slightly different between the IR data (Fig.3b) and the TC data (Fig. 4). The reason for this is not clear, although it would be consistent with a variation of the heat exchange coefficient depicted in fig.3b, but over a wider range. Nevertheless, the trends observed in FWD and REV-B during power staircase discharges are globally coherent (variation and magnitude of the asymmetry) on a larger set of data points. The trend (including FWD and REV-B) observed with TC data gives also credit to the suggested variation of the heat exchange coefficient [1] as presented in Fig. 3b, where asymmetry in FWD gets less steep while it gets steeper in REV-B.

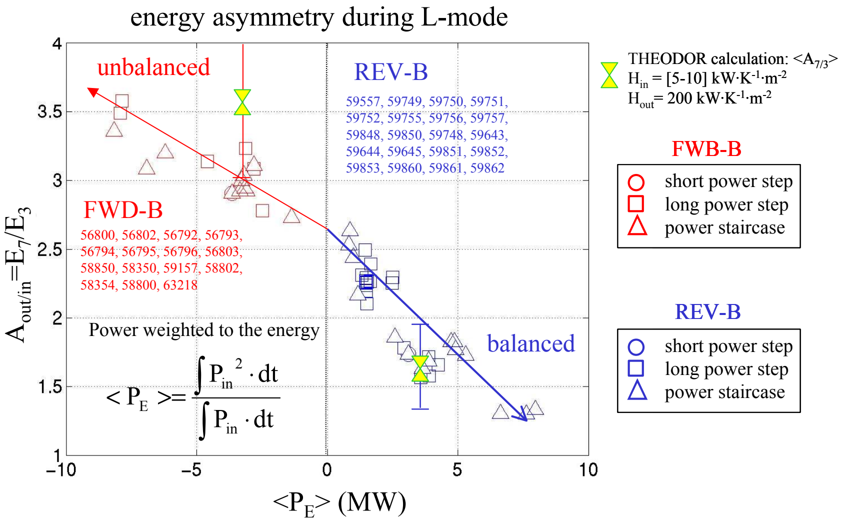


Figure 4: Energy asymmetry versus energy weighted power in FWD (red) and REV-B (blue) operations. Theodor calculations are plotted for #58850 and #59557.

6 Conclusions.

IR and TC temperature data, energy and heat flux density asymmetry measurements are consistent in a wide range of plasma parameters. For the FWD-B power staircase discharge THEODOR calculations show that the peak heat flux density asymmetry increases from A_Q~2 up to A_Q~5 whilst the neutral beam injected power increases (from 1.5 up to 8 MW). The situation is different during REV-B where the heat flux density asymmetry is more balanced ($1 \le A_Q \le 2$), but still favouring the outer targets. Those results are confirmed by a large number of L-mode pulses. Since the observed variation of asymmetry depends of the direction of the magnetic field, that one can be attributed to variation of drifts effect with the injected power ([2], [6], [7], [8]). Finally, this experimental analysis demonstrates that the heat exchange coefficient between the surface layer and the bulk material could depend on the power imposing the temperature as it was suggested in [1].

Reference:

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