*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-1.106 (2004)*

Off-axis electron cyclotron heating and the sandpile paradigm for transport in tokamak plasmas

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1. Introduction

We show that distinctive features of temperature profiles observed in the DIII-D [1] and RTP [2, 3] tokamaks undergoing off-axis electron cyclotron heating (ECH) can be explained by non-diffusive, avalanching transport of thermal energy. A 1D sandpile model [4], amended to accommodate off-axis fuelling [5], is used to represent radial energy transport. There are substantial similarities between the global nonlinear phenomenology of the model and the tokamak plasmas.

2. Results

Figure 1 shows temperature profiles from RTP [3] and the sandpile model with off-axis heating and fuelling. As well as the hollow profiles, the model reproduces peaked profiles for nearly on-axis fuelling. In all cases the outboard profiles coincide. The model profiles also show well-defined peaks around the fuelling location; since there is no diffusion in the model, these are never diffused away.

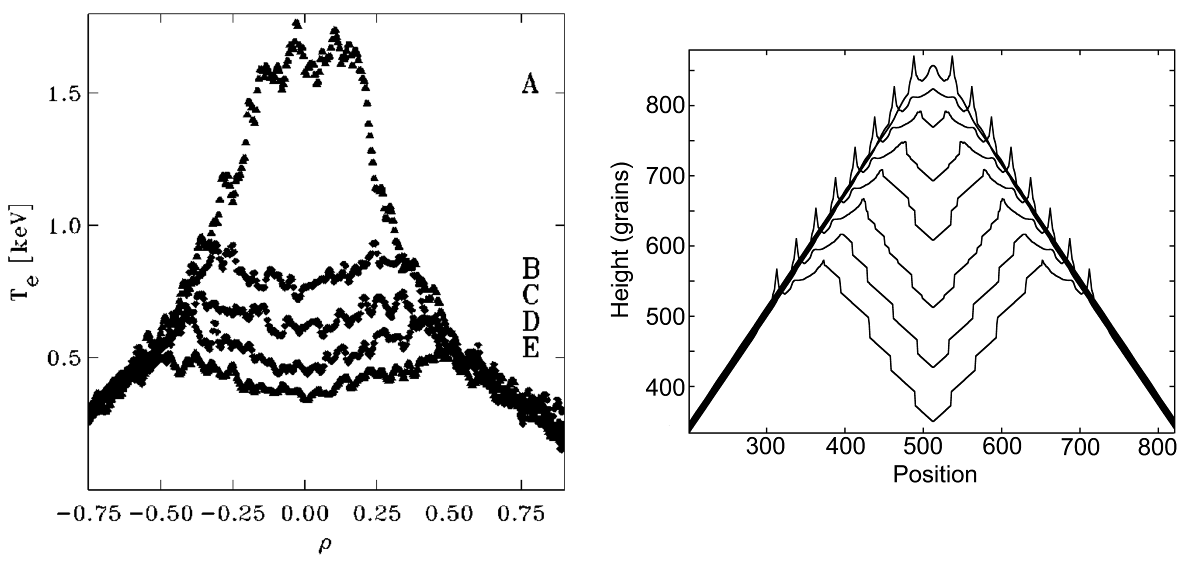

Figure 1: (Left) Electron temperature profiles for different ECH locations in RTP [3]. (Right) Average height profiles for different sandpile model fueling locations [5].

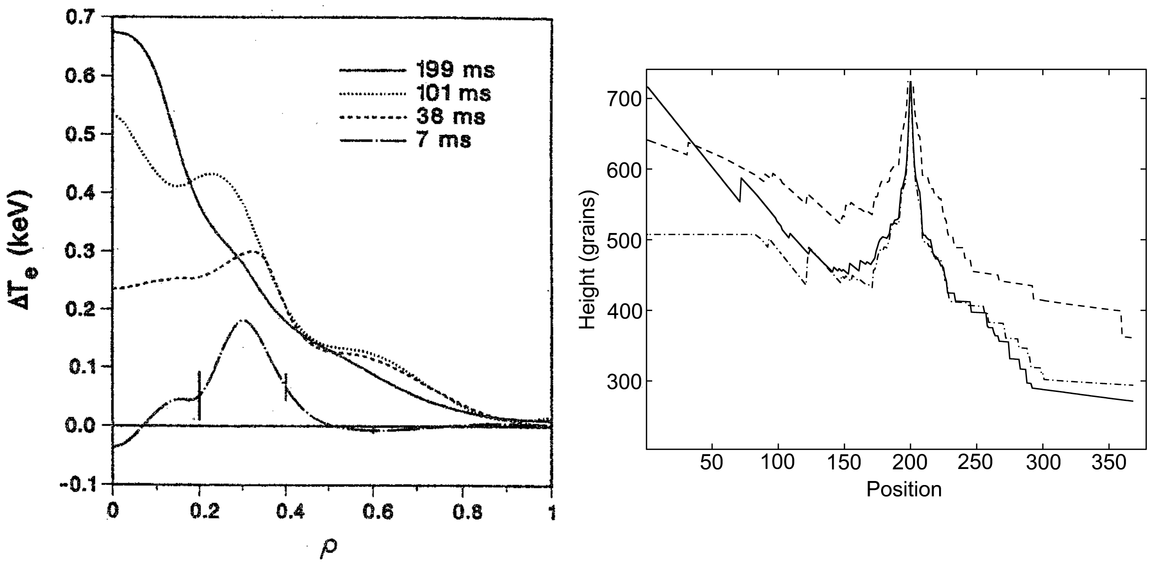

Figure 2: (Left) Increase in electron temperature above the ohmic value, at four times after the start of off-axis ECH for DIII-D [1]. (Right) Increase in the average height profile at sequential times for sandpile model (dash-dot, then dashed, then solid) [5].

The formation of filled inboard profiles in DIII-D [1] and the sandpile model is demonstrated in Fig. 2. On the left are shown radial profiles of the enhancement of T_e in DIII-D during ECH at four different times spanning 200ms after switch-on. On the right is shown the time evolution of the height profile of the sandpile model above its reposed state. This shows first the development of centrally peaked profiles, arising in the sandpile from avalanching transport (the dashed intermediate trace shows that the formation process does not involve uphill transport of material). Second, the slopes outboard of the fuelling location do not change significantly in either case. In the outboard region, the sandpile has already risen to its typical average slope compatible with the fuelling and loss rates.

We now turn to observations of minor and major crash events. Figure 3 shows timeseries of electron temperature in RTP [2] and of height in the sandpile model. Upper traces are taken at the fuelling location, and lower traces at the system centre. At the fuelling points in both cases, there are large fluctuations superimposed on a background of weaker fluctuations. The large fluctuations are known as major crashes, while the weaker fluctuations are referred to as minor crashes. During the major electron temperature crash in RTP, shown in Fig. 3, the

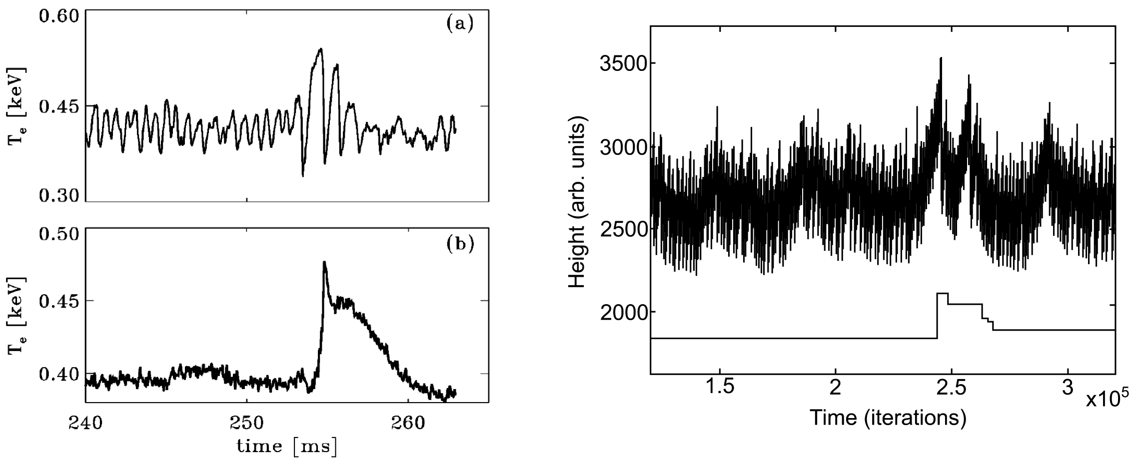

Figure 3: (Left) Time series of RTP electron temperature (a) at the fuelling position and (b) in the center [2] (Right) Time series of sandpile height at the fuelling position (upper) and in the center (lower) [5]. The horizontal (time) axis is measured in number of sand grains added.

fluctuations are greater at the fuelling location than in the centre. In the centre, the crash has a sharply defined leading edge, after which it relaxes slowly; at the fuelling location, large oscillations are observed. The sandpile model successfully reproduces these aspects of the behaviour, and further similarities are shown in Fig, 4. This displays the system profiles before (dotted) and after (solid) the major crash events shown in Fig. 3. Before the major crashes, both profiles are peak at the fuelling location, declining inboard to form a hollow

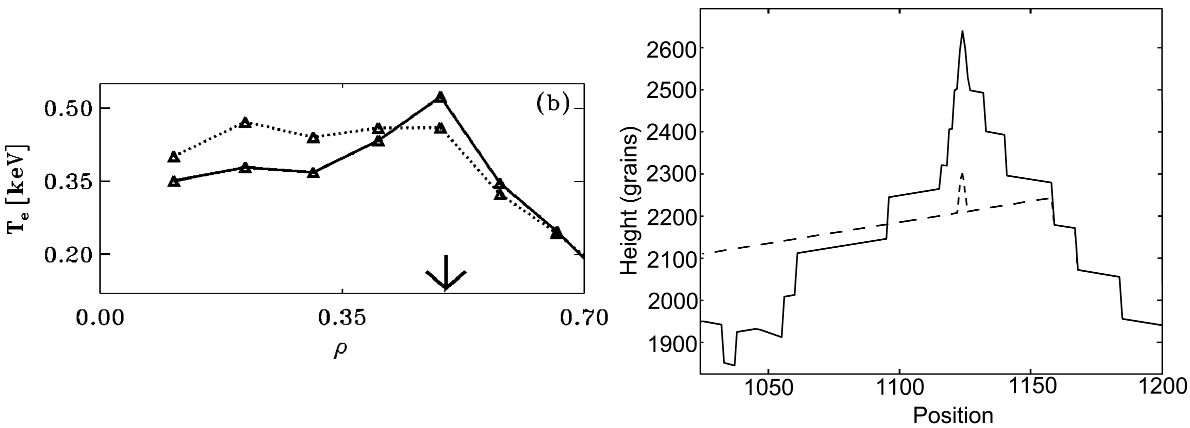

Figure 4: (Left) RTP [2], and (Right) sandpile [5], profiles immediately before (solid line) and after (dotted line) the major crashes shown in Fig. 3. The system centre is on the left in both figures. The minor crash affects only the region near the fuelling location, whereas the major crash affects the whole central region.

profile. After the major crashes, the peaks at the fuelling locations are removed and the inboard profiles are flattened. Outboard, the gradients remain largely unaffected. We infer that major crashes in the tokamak, as in the sandpile model, result from of inward transport, while minor crashes are due to outward transport.

3. Conclusions

A specific sandpile model [4, 5] generates profiles and time-varying nonlinear transport phenomenology that have significant points of contact with the observed consequences of off-axis ECH in the DIII-D [1] and RTP [2, 3] tokamaks. As noted by the original observers, many of the tokamak effects are paradoxical when viewed from the perspective of a diffusive transport paradigm. It is clear that they constitute important evidence bearing on the balance between diffusive and nondiffusive (notably avalanching, see for example [6]) transport in tokamak plasmas. The present work supports the hypothesis that avalanching transport may play a role in many plasmas, and that in some circumstances it can provide a mechanism for the dominant observed effects.

Acknowledgement

The authors thank T. C. Luce, C. C. Petty, and M. R. de Baar for their kind permission to reproduce images, and for helpful discussions. This work was supported in part by Euratom and the United Kingdom Engineering and Physical Sciences Research Councils.

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