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Transport and Reconnection in Sawteeth

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I. Introduction

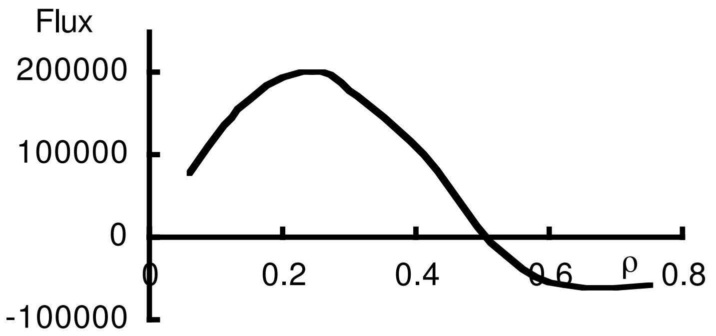
The propagation of the sawtooth [1] heat pulse outward through a plasma has long been studied as a measure of the electron thermal transport [2]. However, the inferences are always based on comparing a few features of the pulse with the predictions of a model. The conclusions are therefore somewhat model-dependent. Since the crash itself results from internal magnetic reconnection [3], the uncertain radial extent of this process has been the largest ambiguity in analysis [4]. The realization of complete electron temperature profiles with high spatial and temporal resolution from ECE makes possible a direct transport analysis that obviates these uncertainties. One can obtain the radial electron heat flux $Q_e(r,t)$ over a sawtooth cycle for comparison with the temperature gradient $\nabla T_e(r,t)$ over the cycle, and, if desired, obtain a $\chi_e(r,t)$. One consequence of this analysis is that the radial heat flux appears negative at the time of the crash at large radii, implying a missing term in the electron energy input. The missing energy is the resistive dissipation that should accompany reconnection; the dissipation can then be estimated from this analysis.

II. Experimental Results

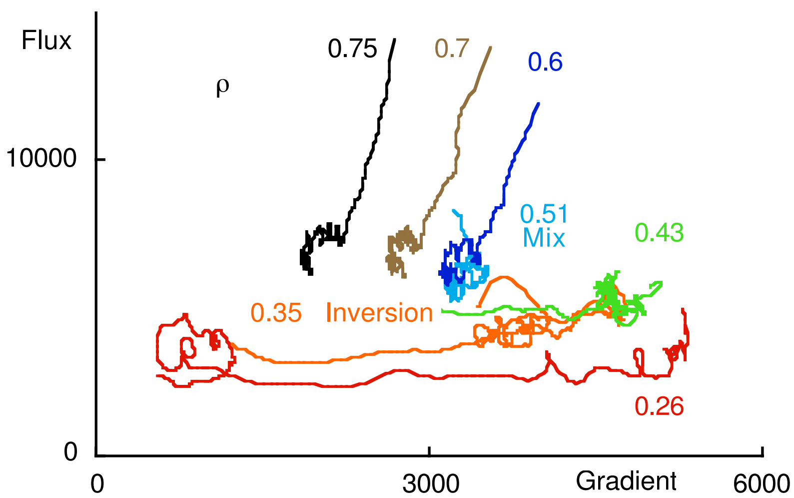
Sawteeth were analyzed in DIII-D using ECE data taken at 50 kHz to 100 kHz under a variety of conditions for which full radial profiles were available with uniform, quasi-periodic sawteeth. The heat flux is obtained from energy conservation with the usual expression

$$Q_e = \frac{1}{r} \int_0^r r\,dr \left[q_e(r,t) - \frac{\partial(\frac{3}{2}nT_e)}{\partial t} \right] \qquad (1)$$

where $q_e(r,t)$ is the net power to the electrons including ohmic and beam inputs, radiation losses, and transfer to the ions, as calculated from transport codes -- ONETWO in these cases. In most applications, the emphasis is on the complexity of calculating q_e, and conditions are chosen (or averaged) to minimize the time derivative. For sawteeth however, the emphasis reverses. The q_e is effectively constant over the sawtooth cycle, and the variations arise from the sawtooth temperature variations. The analysis requires some care, because the effects of noise are greatly magnified by the time derivative, which must be performed on a fast time scale to capture the sawtooth effects. To reduce the noise, an average was taken over ten to thirty nearly periodic consecutive sawteeth to define a composite sawtooth. The averaging is synchronized to the crash to preserve crash dynamics. The average removes both noise and m=1 perturbations. The composite sawtooth is then analyzed through Eq. (1). The radial heat flux as a function of normalized radius at the time of the crash is shown in the figure for a typical large sawtooth ($\Delta T(0)/T(0)$ ~.35%; ρ_{inv} = 0.34). The large positive values near the center represent the expected effect of the reconnection in transferring energy from the core toward the mixing radius. The large negative values at larger radii are unphysical -- one could not have such an energy flow -- but they are not an artifact of poor temperature data. The energy within the plasma is truly increasing by more than the q_e can provide. The explanation is that there is indeed an additional term in q_e at this time, the dissipation from magnetic reconnection. Although the qualitative effect is clear and universal, quantitative evaluation of the dissipation is more difficult. The crash is fast, and the data are noisy at high time resolutions. If one makes the plausible assumption that the radial heat flux during the crash is not less than the average value over the whole cycle, one can obtain a value for the total additional energy that must have been dissipated during the crash (a few time steps in the data.) This energy estimate is much more robust than fluxes and dissipation rates from single time slices, as depicted in the figure. Radially, the additional energy could have been dissipated at any radius less than the radii of negative heat flux. For this case, the dissipated energy is estimated to be 13 kJ, which is roughly 2% of the internal magnetic energy, $1/2L_iI^2$. This is a plausibly small change in l_i associated with the reconnection. It is also the largest dissipated energy for any of the cases analyzed.

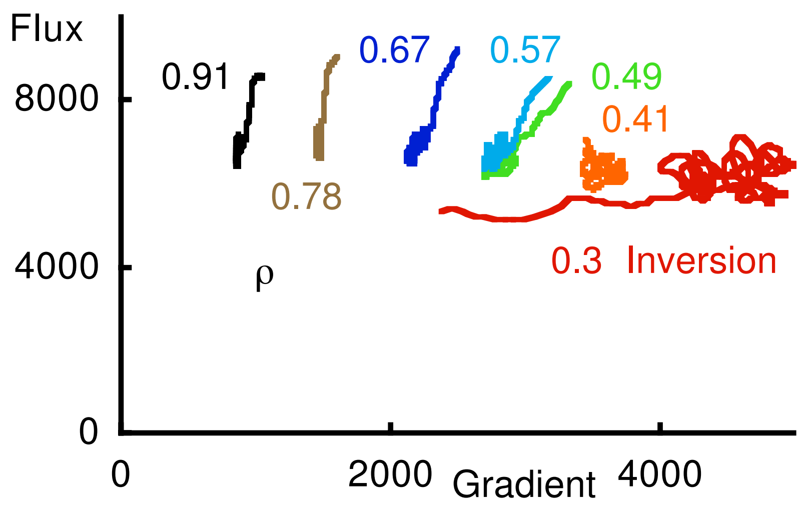


Excluding the brief interval of the crash (~1% of the cycle), the fluxes at all radii are normal. One can exclude the effects of reconnection and still interpret the result of Eq.(1) as representing the effect of transport processes over almost all of the cycle. Motivated by the principle



that the fluxes are driven by gradients, one can plot the trajectories of Q_e versus ∇T_e over the sawtooth cycle at various radii as shown in the figure. Note that the fluxes are more than an order of magnitude less than the values during reconnection. The patterns are diverse, with no consistent form for $Q_e(\nabla T_e)$. In the outer portion of the plasma, the trajectories are generally steep, as would be expected from a very stiff critical gradient model. However, the stiff portion of the trajectory corresponds only to the strong heat pulse immediately following the crash. Later in the cycle the gradient changes further with comparatively little change in flux. The behavior changes completely inside the half radius, which also corresponds to the mixing radius in this case. Here the gradients change substantially over the course of the sawtooth cycle as the profiles steepen, but the fluxes change little. There is no indication of a gradient drive. The inversion radius is especially significant, for this is a point at which the temperature change over the sawtooth cycle is least.

The trajectories of $Q_e(\nabla T_e)$ over the sawtooth cycle for more typical, smaller L-mode sawteeth ($\Delta T(0)/T(0)$ ~.30%; ρ_{inv} = 0.26) show the same features, an example of which is shown in the figure. The crash interval is excluded from the plot. The trajectories in the outer region are again quite steep, which would require very stiff transport. The trajectories at middle radii are much less steep and representative of what one might expect for a typical critical-gradient or nonlinear transport process. However, the trajectories at smaller radii again lose any indication of a gradient-driven flux. The fluxes are also negative during the crash in this case. The reconnective dissipation is estimated to be 4 kJ for a Δl_i of 1% at the crash.



These results are quite general. Trajectories of the same shape are found for all sawtooth amplitudes, down to ohmic cases, although the range of Q_e and ∇T_e explored over the cycle is smaller and the data quality is lower. Even for ohmic sawteeth, there are indications of reconnective dissipation. The extent of the reconnection can be quite small, with Δl_i ~ 0.2%.

III. Conclusions

With $T_e(r,t)$ data of sufficient quality, the temperature variations over the sawtooth cycle may be analyzed directly for transport. The first surprise, although in retrospect it is natural, is the appearance of additional energy in the system as the crash occurs. This energy is plausibly identified with the resistive dissipation that must accompany magnetic reconnection. It is consistent with a small decrease in internal inductance ($\Delta l_i \leq 2\%$) during the crash. Excluding times near the crash, when this additional dissipation occurs and high levels of magnetic transport develop, the remainder of the sawtooth cycle explores a small range of T_e, ∇T_e, etc. that may be analyzed for transport and should represent the normal transport processes of the system. Since the results do not suggest a flux driven primarily by a gradient with proportionality χ, the measurements are presented at the more fundamental level of $Q_e(\nabla T_e)$. A challenging diversity of behaviors is observed. In the outer region of the plasma, the trajectories are very steep, with large changes in flux while the gradient remains almost fixed. One the other hand, the inner regions have large variations in gradient over the sawtooth cycle with little change in the heat flux. Intermediate radii can exhibit either more "normal" behavior or incoherent variations in flux and gradient.

Modern diagnostics make sawteeth a much more informative process for examining transport, but the results only add to the enigma of electron thermal transport.

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