Ballistic Contributions to Heat Pulse Propagation on TFTR

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Abstract

Measurements on the TFTR tokamak of the electron temperature profile evolution and soft x-ray emissivity on a fast ($10\mu\text{sec}$) time scale during a sawtooth crash, show that significant heat is deposited beyond the mixing (or reconnection) radius within $200\mu\text{sec}$ following a sawtooth crash. This extended region in which electron heat is redistributed during the sawtooth crash substantially complicates the determination of heat transport properties from the subsequent heat pulse propagation. It is shown that the relaxation of this extended perturbation is consistent with the power balance estimates of the local thermal diffusivity.

The radial propagation of sawtooth induced heat pulses has long been used to study thermal transport in tokamaks [1, 2, 3]. In part, this work was motivated by the 'Kadomtsev' model [4] of the sawtooth crash where the electron heat was redistributed through a reconnection of the helical flux within the reconnection (or mixing) radius, r_m , and no heat was deposited beyond that radius. Thus, the evolution of the electron temperature in the region exterior to the mixing radius would be governed completely by diffusion. This model was consistent with the experimental data that was available at that time, and opened up the possibility of directly measuring the local electron thermal transport coefficient, χ_e . Subsequently, the Kadomtsev model of the sawtooth crash has come into question [5, 6, 7], but the assumption that no heat is deposited beyond the reconnection radius is still fundamental to all perturbative heat pulse propagation analysis methods. (In this paper, 'heat pulse propagation' refers to the relaxation of the temperature perturbation following the sawtooth crash.)

A number of simple methods to determine the local thermal diffusivity based on the evolution of the heat pulse were derived [2, 3, 8, 9], with the assumption that the evolution of the temperature profile outside the mixing radius was governed by a diffusive process with a time-independent χ_e . The thermal diffusivities, χ^{HP} 's, derived by these methods are, in many cases, much larger (3 to 10 times) than the thermal diffusivity derived from power balance, χ^{PB} [3, 9]. Further, different perturbation analysis methods, used on the same data, often give different answers. For the example discussed below, χ^{HP} ranges from 6 m²/sec using the time-to-peak method [2, 3] up to 21 m²/sec using a Fourier analysis method [3, 8]. In the region of interest the power balance χ_e was only 1.5 m²/sec. Many models have been proposed to explain this discrepancy including heat pinches [3], temperature or temperature gradient dependences in χ_e [3], off diagonal terms in the transport matrix [10, 11, 12] or a strong enhancement of χ_e near r_m for a short time following the sawtooth crash (e.g., due to magnetic turbulence) [3, 13].

Fast (10 μ sec) ECE measurements of the electron temperature profile in TFTR have been used to study the sawtooth crash mechanism as well as the propagation of the resulting heat pulse. Two features are observed in this fast data that would not be apparent with slower diagnostics. The first is the 'ballistic' response where, in some cases, heat actually is deposited well beyond the reconnection radius on a very short time-scale, i.e., within $\sim 200 \mu$ sec following the sawtooth crash (Fig. 1). The second is the presence

of a helical distortion of the electron temperature (and presumably the flux surfaces) which has been seen to extend up to 0.15 m beyond the mixing radius of 0.28 m (Fig. 2). This bulging of the flux surfaces has only been seen on moderately high β_T plasmas, $\sim 1\%$ on axis, to date, but the deposition of heat beyond r_m has been observed even in Ohmic plasmas. The example chosen for study in this paper is a 1.7MA, $q(a)=4.4$ plasma with 19MW of neutral beam heating power.

Sawtooth crashes on approximately 20 plasmas have been studied in detail. These shots have covered a wide range of conditions ranging from Ohmically heated to neutral beam heated plasmas with up to 19MW of beam power. While extensive documentation of this effect has been done only on TFTR, that it is observed here calls into question the validity of any sawtooth-induced heat pulse analysis where the initial perturbation cannot be accurately determined. The poloidally symmetric re-distribution of heat out to 0.15 m beyond the reconnection radius in less than 200 μsec has been observed down to β_T of $\sim 0.05\%$ in low density, Ohmic plasmas. The extended perturbation is weaker in similar, but higher density, lower Z_{eff} plasmas, suggesting that the density scaling of χ^{HP} observed on TFTR [14] and the scaling of χ^{HP} with Z_{eff} reported on JET [15] are a scaling of the extent of the extended perturbation.

Numerical simulations of a sawtooth crash with the MH3D code [16] have predicted the presence of the helical bulge in the flux surfaces beyond r_m (Fig 2). This comes about through the inclusion of non-linear finite-pressure (or β) modifications of the $m=1$ sawtooth precursor mode, which extend the eigenfunction beyond r_m . The numerical simulations show a similar amplitude of perturbation to the experiment, including the poloidally asymmetric character of the perturbation, *i.e.*, experimentally and in the simulation the perturbation is much smaller on the high field side. In the present example this feature is measurable up to $\sim 0.15\text{m}$ beyond the mixing radius before the amplitude drops below the noise level. It is only observable during the actual crash phase, but in other cases has been measureable for up to 1 msec before the sawtooth crash. From a careful examination of the phases of the in/out (ECE) and up/down (soft x-ray) signals it is determined to be helical in nature, coincident with the location of the $m=1$ island x-point. This evidence that the magnetic perturbation can extend well beyond the mixing radius supports the conjecture that the magnetic field becomes stochastic in that region immediately following the sawtooth crash.

The increase in the electron temperature extending to about 0.15 m beyond r_m and occurring over a 200 μ sec period following the sawtooth crash is poloidally symmetric and can be simulated with a local enhancement of the thermal diffusivity by a factor of about 40 immediately outside the mixing radius. A likely explanation for this enhancement in transport would be stochasticization of the flux surfaces for a short time following the sawtooth crash [3, 17, 18]. Indeed, the MH3D code simulation shows a stochastic region extending from the mixing radius to the $q=2$ surface (from $r = 0.28$ to 0.58 m). However, the code was run with a value of S (the ratio of the resistive to Alfvén times) than in the experiment ($\sim 10^5$ vs. $\sim 10^9$ for the experiment) for speed of computation: thus the actual stochastic region in the experiment may be somewhat smaller.

Simulations of the heat pulse propagation that do not take account of the extended perturbation at the sawtooth crash, using the χ_e derived from power balance (calculated with the time dependent transport analysis code, TRANSP [19], and averaged in time over the sawtooth period) predict a much slower rate of rise of the heat pulse near the mixing radius (Fig. 3). Similarly, simulations with an enhanced χ_e chosen to be five times the power balance value, so that the simulated and experimental heat pulses had a similar time-to-peak at $r = 0.65$ m also did not have a fast enough rate of rise just outside the mixing radius (Fig. 4). Simulations with the local χ_e transiently enhanced following the crash can qualitatively reproduce the heat pulse evolution in the region outside the mixing radius (Figs. 5 and 6). The time and spatial dependence of χ_e used in the simulation was

$$\chi_e(r, t) = (0.3 + 9(r/a)^2)e^{(2.8(r/a)^2)}(1 + 150e^{(-t/\tau - 23(r/a)^2)}), \quad (1)$$

where $\tau = 1$ msec. This relatively simple model accurately reproduces the experimental data in the heat pulse propagation region.

It is of particular importance that with this model, after 1-2 msec following the sawtooth crash the thermal diffusivity in the heat pulse propagation region is hardly perturbed, and the perturbation as set up with the transiently enhanced χ_e relaxes with the power balance χ_e . As described above, though, the propagation of the heat pulse, as analyzed with the time-to-peak or extended time-to-peak methods is faster than expected from the power balance calculation of χ_e .

Summary

Significant progress has been made in resolving the long standing mystery of the anomalously rapid propagation of sawtooth induced heat pulses. Contrary to previous assumptions made in the studies of sawtooth-induced heat pulse propagation, heat is seen to be deposited well beyond the mixing radius on a short time-scale [$\leq 50\mu\text{sec}$ with $(m,n)=(1,1)$ structure, $\leq 200\mu\text{sec}$ axisymmetrical] following the sawtooth crash. As the evolution of the electron temperature profile in this region is no longer completely governed by a time independent χ_e , the present methods of analyzing heat pulse propagation are not applicable. Simulations suggest that the extended perturbation relaxes on a time scale consistent with the equilibrium power balance value of χ_e , at least for the high auxiliary heating power cases studied. Other effects which have recently been invoked in the study of heat pulse propagation [10, 11, 12] may still be important in understanding transient transport phenomena, but great care must be exercised in their application to the analysis of sawtooth-induced heat pulse propagation. The discovery that heat is transported beyond the mixing radius during the sawtooth crash shows that the physics of sawtooth crashes is richer than previously assumed.

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Fig. 1 Profiles of the electron temperature before (solid) and 200 μ sec after (broken) a sawtooth crash (the same as in Fig. 1). (The parameters for this shot were $I_p = 1.7$ MA, $q(a) = 4.4$, NBI power ≈ 19 MW, $a = 0.8$ m, $R = 2.45$ m and $B_T = 4.7$ Tesla.)

Fig. 2 Contours of constant temperature reconstructed from the ECE temperature data for shot 30904 and from the MH3D simulation for parameters similar to those of shot 30904.

Fig. 3 Comparison of heat pulse data from ECE emission (solid line) to simulated heat pulses (dotted line) where the power balance profile has been used, $\chi(r) = (0.3 + 9(r/a)^2)e^{2.6(r/a)^2}$.

Fig. 4 Comparison of heat pulse data (from ECE emission) and simulated data using $5\chi(r)$ as used in Fig. 3.

Fig. 5 Simulation of the heat pulse propagation where the thermal diffusivity is enhanced as $\chi(r, t) = (0.3 + 9(r/a)^2)e^{2.6(r/a)^2}(1 + 100e^{-23r^2 - 1000t})$, where $n_e(r) = e^{-2.6(r/a)^2}$.

Fig. 6 The thermal diffusivity as used in Fig 5.

FIG. 1

Reconstruction of ECE Data

MH3D Code Simulation

Shot 30904

FIG. 3

Shot 30904

FIG. 4

shot 30904

FIG. 5

FIG. 6