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Fast Heat Pulse Propagation by Turbulence Spreading

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The propagation of a cold pulse initiated by edge cooling in JET is compared to propagation of the heat wave originating from a modulation of the heating source roughly at mid radius. It is found that the propagation of the cold pulse is by far faster than what could be predicted on the basis of the heat wave propagation, and within local transport models no sufficient explanation for this behaviour can be found. Recently, modelling of the cold pulse propagation using non-local effects and a transport equation that uses fractional derivatives has been successfully applied to model the effect [1]. Here we discuss a model in which the non-locality is introduced by the process of turbulence spreading. Transport models with turbulence spreading have been proposed in [2] and conditions under which the perturbation in the turbulence profile could travel at the required high speed from edge to the core have been established [3]. Here we report on recent results in the modelling of cold pulse propagation using turbulence spreading transport models.

Keywords: nonlocal transport, turbulence, model, cold pulse, turbulence spreading

1. Introduction

Experiments using modulation of the sources of heat and more recently momentum are routinely carried out at the JET tokamak and most of the major magnetic confinement fusion devices. Modulation has proved to be a powerful tool for validating and disseminating various physics-based transport models. For using modulation techniques as a tool in transport investigations, it is usually assumed that the transport properties of the plasma during transient events such as modulation are the same, or at least very close to, the transport properties in steady state. However, it has been found that the transient propagation of a cold pulse initiated by a local cooling near the plasma edge is much faster than the propagation of the heat modulation wave under same plasma conditions [4] . This poses a serious challenge to modelling. Specifically, if the propagation speed of a perturbation is characterised by the local properties of the plasma only and does thus depend solely on the local values of temperature, density and their gradients, it seems impossible to explain both fast and slow propagation of the perturbation at the same local plasma conditions within such local models. This is reflected in the observation that for parameters for which the modulation experiments are well described by a local model such as the critical gradient model (CGM) [4, 5], the model fails to capture the fast propagation of the cold pulse. Alternatively it is possible to model the fast response of the plasma to the cold pulse with the CGM, but at the expense of being unable to reproduce the modulation results. More recently the use of fractional diffusion based transport models [1] has been suggested to introduce the necessary non-locality to be able to describe both heat wave propagation and cold pulse. Indeed within such a non-local model both fast and slow propagations could be reproduced, but it remains unclear which physical process is responsible for the non locality and under which conditions a non-local response of the plasma is triggered.

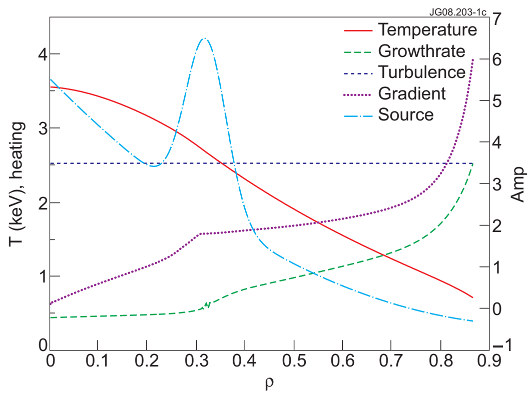

Fig. 1 *Profiles of temperature (red) (in keV) and source profile (blue)(left scale). Right scale: turbulence intensity (cyan), κ_T (magenta) ($\kappa_c = 1.8$) and growthrate (green). ($\rho = r/a$).*

2. Turbulence Spreading Transport Model

We propose an alternative approach that accounts for turbulence spreading [6, 7] as a step towards a physics based model including non locality and describing both the cold pulse transient and the modulation part of experiments. In the Turbulence Spreading Transport Model (TSTM) the local intensity of the turbulent fluctuations in-

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stead of the growthrate is used to determine the fluxes of the transported quantities. The turbulence itself becomes a transported quantity and can spread into linearly stable regions of the plasma raising the transport there to high levels. Consequently the model describes asymmetric radial spreading of the turbulence, up-gradient transport and front propagation [7]. Clearly the turbulence introduces a possibility to trigger non-linear plasma responses, mediated by changes in the turbulence level, which in this model can originate from spatially separated regions.

In detail we consider a 1D model in cylindrical symmetry for the profiles of turbulent energy E and electron temperature T. For simplicity we assume that the density profile is frozen and flat and choose normalisations that bring our model close to the CGM model in the absence of turbulence spreading ($D_0 = 0$):

$$\partial_t E = \frac{1}{r}\partial_r r\left[D_0 E \partial_r E\right] + \gamma E - (\gamma_0 + \beta E)E, \quad (1)$$

$$\partial_t T = -\nabla\cdot q_h + \frac{3}{2}\nabla\cdot\left(\chi_0 T^{5/2} q^{3/2}\frac{\nabla T}{T}\right) + S(r,t). \quad (2)$$

with for positive growth rates

$$\gamma = \lambda\sqrt{\left(\frac{-R\partial_r T_e}{T_e} - \kappa_c\right)},$$

and for subcritical regions

$$\gamma = -0.1\lambda\sqrt{-\left(\frac{-R\partial_r T_e}{T_e} - \kappa_c\right)}.$$

The low damping rate in the subcritical region is introduced to describe the stabilisation of modes in the absence of a better model for growth and damping rates. Here it is mainly responsible for a smallish up-gradient transport as has also been observed in direct numerical simulations [7]. In detail the heatflux from turbulence is calculated as

$$q_h = CET\tanh(\gamma).$$

We motivate the model as follows: The diffusion of the turbulence is taken to be non-linear and proportional to the level of turbulence, with D_0 constant. The energy input rate is proportional to the growth rate of the underlying instability γ. Additionally the turbulent energy has a weak damping (γ_0) and a non-linear saturation (β) described by the last term in Eq. (1). The growth rate is given by the square-root of the deviation of the temperature gradient from a critical value κ_c, i.e., $\gamma = \lambda\sqrt{[\kappa_T - \kappa_c]}$, where λ is a parameter and $\kappa_T \equiv |R\partial_r T|/T$ ($\partial_r T < 0$ for standard profiles) and is used in the present form to mimic trapped electron mode behavior. The temperature T evolves due to a spatially dependent source $S(r)$, the diffusivity, χ_0, and the divergence of the radial turbulent heat flux, $q = \left\langle \tilde{T} v_r \right\rangle$, where $\tilde{T}$ are the temperature fluctuations and v_r is the fluctuating radial velocity component ($E \approx \left\langle v_r^2\right\rangle$). Assuming a finite cross coherence ξ between $\tilde{T}$ and v_r, we express the flux as $q_h = \xi\sqrt{\left\langle\tilde{T}^2\right\rangle\langle v_r^2\rangle}$. We use the growth-rate γ to estimate the cross coherence ξ, with the assumption that once a significant growthrate is achieved the correlation saturates with value one, thus we prescribe $\xi = \tanh(\gamma)$. The relative temperature fluctuation level is assumed proportional to that of the velocity fluctuations, $\tilde{T}/T = C\sqrt{E}$, i.e., $\left\langle\tilde{T}^2\right\rangle = C^2\langle E\rangle\langle T\rangle^2$, where C is a parameter absorbing the spatial scale of the turbulence somewhat analogous to standard mixing length arguments [7]. In general such a system will approach a temperature profile close to the marginally stable one, which thus appears as a stiff profile, with the degree of stiffness measuring by which amount the heatflux has to be increased to obtain a rise in the temperature gradient. For situations in which turbulence spreading is not important the stiffness mainly determined by γ i.e., the capability of the system to generate anomalous transport. In situations where the effects of turbulence spreading become dominant, the stiffness can take values that are determined by the local increase in the turbulence level, a clear consequence of the non locality of the model. It should be noted that within the present model in regions where the turbulence is damped the flux will be negative, thus the transport is up-gradient, with the cross coherence ξ being negative as intrinsic reason for up-gradient transport. As turbulence is able to penetrate into the stable regions of the domain, it contributes to steepening the temperature gradient and increasing the local thermal energy, naturally at the expense of the turbulent energy. It should be stressed that the net transport is always down-gradient, and only a fraction of the turbulence energy will contribute to this up-gradient transport.

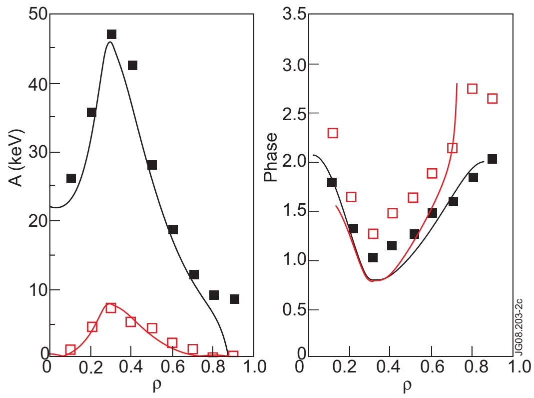

Fig. 2 *Fourier-analysis of the heat modulation in comparison with JET pulse 55809 (points), numerical results from TSTM as lines. Amplitude a) and phase b) evolution of fundamental (black) and third harmonic (blue).*

It should be noted that for zero turbulence spreading $D_0 = 0$ the model approaches the CGM model(e.g., Ref. [5] given by:

$$\partial_t T = \frac{3}{2}\nabla\cdot q^{3/2}T^{5/2}\left[\chi_s\left(\frac{-R\nabla T}{T} - \kappa_c\right)_H + \chi_0\right]\frac{\nabla T}{T} \quad (3)$$

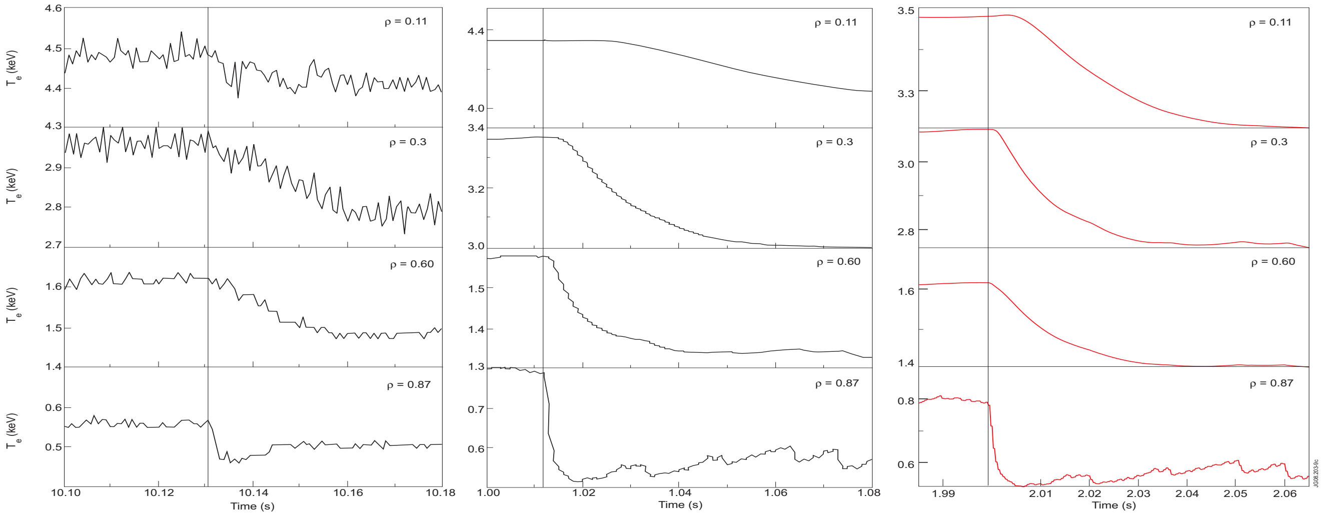

Fig. 3 *Cold pulse in experiment JET pulse 55809 (left) and simulations with CGM (middle) and TSTM (right), vertical lines indicate start of cold pulse.*

where the index H indicates the Heaviside function of the bracket multiplied to the bracket. We will now apply the TSTM to describe transient heat transport phenomena with particular attention to the heat modulation and cold pulse experiments in JET [4] and compare as well to CGM results.

3. Simulation results

The system Eq. (1) and Eq. (2) is solved numerically, using a third order stiffly stable time stepping scheme, with a spatial resolution of 1000 grid points. With the source profile modeling an off-axis heating profile we have performed simulations over a wide range of parameters. For selected parameters, we observe polarity reversal, i.e., the edge cooling results in a transient temperature increase at the center as first observed in TEXT [8]. We concentrate on modeling the perturbative transport experiments in JET by Mantica *et al*. [4]. Specifically we have considered shot No. 55809. We use the source profile (off-axis ICH + NBI heating) from this experiment. The results shown for the TSTM are for parameters $C = 0.5$, $\lambda = 1.7$ and $D_0 = 35$. The growth rate was chosen as large as possible and is at present limited by numerical instabilities, D_0 determines the speed of the turbulence response, resulting in a rather flat turbulence profile at the value given. C is the principal value to fit the modulation behavior. Saturation of the turbulence is chosen at $\beta = 1$ and $\chi_0 = 0.6$ taken close to the values used in CGM modeling. Simulations start from noise and are run to steady state, reached after typically 0.5 to 1 second, with cold pulse triggered at 2.5 seconds and modulation started at 4 seconds, after decay of the cold pulse perturbation. In Fig. 1 the source profile and temperature profile in the saturated state are depicted (left y-scale). The temperature profile is a fair match to the experimental one. Furthermore, in the same figure the profile of the turbulent energy is show, which is mainly flat due to the high value of turbulence spreading. The profile of

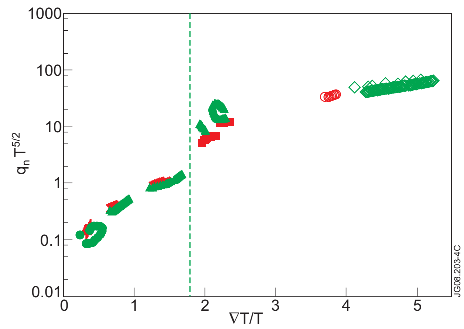

Fig. 4 *Flux gradient relationship for TSTM during modulation (red) and during cold pulse (green). The vertical line indicates the critical gradient. Note the logarithmic scale. Note strong non-linearity in response to the cold pulse.*

the temperature gradient κ_T shows that the plasma is stable until a radius $\rho = 0.3$, where the heatflux is observed to be negative, i.e., up-gradient. Outside of $\rho = 0.3$ the gradient exceeds the critical one ($\kappa_T < \kappa_c$). Figure Fig. 2 shows the results from the modulation part of the simulations. While the amplitude of the first and third harmonic are well reproduced, only the phase for the first harmonic fits well. The phase of the third harmonic could agree better. Figure Fig. 3 shows electron temperature traces from experiment and modeling by CGM and TSTM respectively. Parameter values taken from the best achieved fit to the modulation data. Temperature values are clearly reproduced better in the CGM model, but it should be mentioned that the main effort of the fitting was aimed at providing a good fit for the modulation and cold pulse data. In the TSTM modeling the drop in electron temperature occurs rather quickly and we measure a 30eV drop at after 11ms, compared with 4ms for the experiment and 22ms for the CGM. It is worthwhile to note that the innermost trace for the TSTM model shows a slight increase in temperature just after the cold pulse is triggered, that is a reversal in the polarity of the pulse. This is due to the turbulence profile adjusting on a very short timescale (see Figure 5), leading transiently to up-gradient transport.

4. Nonlocality and stiffness

To investigate non locality in the TSTM, we first consider the relationship between normalised heat flux and local gradient. For the CGM, which features local transport only, we find for

$$q_h = \frac{3}{2}q^{3/2}T^{5/2}\left[\chi_s\left(\frac{-R\nabla T}{T}-\kappa_c\right)_H+\chi_0\right]\frac{\nabla T}{T} \quad (4)$$

so that if we plot the heatflux normalised with $q^{3/2}T^{5/2}$ we find straight line segments with the slope ξ being the stiffness of the model. Clearly there is a transition from low stiffness χ_0 to high anomalous stiffness once the critical gradient is exceeded. The whole dynamics of the model is determined by these two parameters. As both modulation and cold pulse experience the same local stiffness and the propagation speed of a perturbation is roughly proportional to the stiffness, the model cannot accommodate for two different perturbation propagation velocities, reflected in the 20 ms delay for the cold pulse arrival. For the TSTM the situation is fundamentally different, as can be seen from Figure 4. As long as the change in the plasma is slow and the turbulence is everywhere close to its saturated value, we find a behaviour that is very similar to the CGM model behavior, namely for every radial position a near linear dependence between flux and gradient, so that the concept of a well defined local stiffness is fulfilled. The actual values for the stiffness should not be to far away from the ones described in the CGM model, as the modulation part of the experiment was well described within the CGM. Actually the observation that for slow or weak perturbations the non locality is small explains why in most practical situations local models are indeed very successful in modeling transport. In case of the large and rapid perturbation of the cold pulse, however, the situation changes and the trajectories in the flux gradient diagram become more complex. Specifically, we see that during the cold pulse the transport rises sharply even before the gradient changes. This is due to the fast propagation of turbulence intensity from the edge to the core of the plasma. An increased level of turbulence then increases transport and this changes the local gradient, see Figure 5. Initially the turbulence increase toward the edge, when the cold pulse is triggered the turbulence increases fastly at the edge and then propagates inwards on a fast time scale. There is no well defined slope of the trajectories in this case, showing that the concept of a local stiffness parameter is invalid in this situation. Fig. 6 shows the nonlocal response after the cold pulse in more detail. The trajectory evolves clockwise and shows an increase in transport as gradient decreases, a behavior not compatible with local transport models.

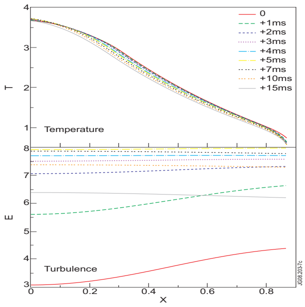

Fig. 5 *Temperature (top) and turbulence intensity field (bottom) after cold pulse initiation.*

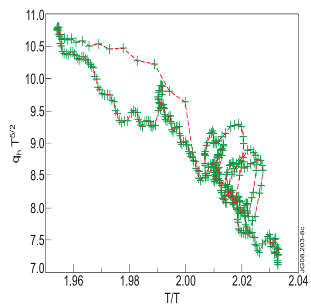

Fig. 6 *Flux gradient relation after cold pulse at r = 0.4. The trajectory evolves clockwise.*

Interesting in this context is the behavior in the very center, where the gradient is below critical initially. The increase in turbulence here leads for a short time to an increase in temperature, with the flux going down, e.g. an inversion of the cold pulse, before the increased gradient reverses the heat flux and the temperature decays.

5. Conclusion

We have shown that the TSTM can reproduce both fast cold pulse propagation and slow modulation heat wave expansion at the same parameters. Even though the fitting of the temperature profile could be better, here we convey the two points that for different responses of the plasma to different perturbations (modulation and cold pulse) non locality is a necessity, which appears naturally in the TSTM. The strong non locality is introduced to the system through the propagation of turbulence intensity, which can give rise to increased transport without a change in the local temperature gradients. For these situations the concept of stiffness does not hold as the dependency between flux and gradient is non-local and complex. There are clear ways to improve the model further, but in addition non locality produces clear signatures which could be tested experimentally, so it would be interesting to check in experiment if non-local effects in the flux/gradient relationship can be found.

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