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INTRODUCTION

Transient transport and heat modulation experiments are routinely carried out at most of the major devices and have proved powerful tools for testing various physics-based transport models. Experiments in JET [1] have shown that the transient propagation of a cold pulse initiated by a local cooling near the plasma edge is found to be much faster than the propagation of the heat modulation. This poses a serious challenge to modelling and up till now it has apparently not been possible to explain both effects within the same model. The modulation experiments are well described by the critical gradient model, CGM [1, 2], which, however, cannot describe fast propagation of the cold pulse for the same parameters.

We propose an alternative approach that accounts for turbulence spreading [3, 4] as a step towards a model describing both the cold pulse transient and the modulation experiments. In this model the local intensity of the turbulent fluctuations is used to determine the fluxes of the transported quantities. The turbulence itself is 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 [4]. Here we apply it to describe transient heat transport phenomena with particular attention to the heat modulation and cold pulse experiments in JET [1]. The results show the fast response in the core to a cold pulse edge perturbation, while the modulated heat wave is propagating according to the description by a standard CGM.

We consider a 1D model in cylinder symmetry for the pro profiles of turbulent energy E and electron temperature T. Assuming that the density pro le is frozen and at:

$$\frac{\delta E}{\delta t} = \frac{1}{r}\frac{\delta}{\delta r} r\left[D_0 E\frac{\delta}{\delta r}\right] E + \gamma_E - (\gamma_0 + \beta_E{}^2)E, \tag{1}$$

$$\frac{\delta T}{\delta t} = -\frac{1}{r}\frac{\delta}{\delta r} rq + \chi_0 \frac{1}{r}\frac{\delta}{\delta r} r\frac{\delta}{\delta r} T + S - (r). \tag{2}$$

The diffusion of the turbulence is taken to be non-linear, 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 nonlinear saturation (β) described by the last term in Eq. (1). The growth rate is given by the deviation of the temperature gradient from a critical value κ_c, i.e., $\gamma = \lambda[\kappa_T - \kappa_c]$, where l is a free parameter and $\kappa_T \equiv |\partial_r T|/T$. 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, $q = \langle\tilde{T}v_r\rangle$, where $\tilde{T}$ is the temperature fluctuations and v_r is the fluctuating radial velocity component ($E \approx \langle v_r^2\rangle$). Assuming a finite cross coherence ξ between T and v_r, we express the flux as $q = \xi\sqrt{\langle\tilde{T}^2\rangle\langle v_r^2\rangle}$. We use the growth-rate γ to estimate the cross coherence ξ and assume that the relative temperature fluctuation level is proportional to that of the velocity fluctuations, $T/T = C\sqrt{E}$, i.e., $\langle\tilde{T}^2\rangle = C^2\langle E\rangle\langle T\rangle^2$, where C is a parameter absorbing the spatial scale of the turbulence somewhat analogous to standard mixing length arguments [4]. Then the heat flux reads:

$$q = C\gamma ET = C\gamma ET\,[\kappa_T - \kappa_c] \qquad (3)$$

The anomalous transport is proportional to the energy in the turbulence and scales with the cross coherence, $\xi \propto \gamma$, between temperature fluctuations and turbulent velocity. Turbulence is exited as the threshold gradient κ_c is exceeded. The free energy in the gradient above the critical one is converted into turbulent energy by a necessary down-gradient net-flux. The system approaches a temperature profile close to the marginally stable one, which thus appears as a stiff profile, with the stiffness mainly determined by $\xi \propto \gamma$, i.e., the capability of the system to generate anomalous transport. In regions where the turbulence is damped the flux will be negative, thus the transport is up-gradient, i.e., the cross coherence ξ is the intrinsic reason for up-gradient transport. Turbulence is able to penetrate into the stable regions of the domain, steepening the temperature gradient and increasing the thermal energy, naturally at the expense of the turbulent energy. It should be stressed that the net transport is always down-gradient, and only part of the transport contribute to the pinch effect.

We relate the present model to standard CGMs (e.g., Ref. [2]), which have been widely applied to describe perturbative transport experiments, by considering $D_0 = 0$, i.e., the turbulence is not allowed to spread. Then the stationary solution of Eq. (1) in the unstable regime reads: $E^2 = (\gamma - \gamma_0) = b$. Using Eq. (3) we obtain (neglecting $\gamma_0 (<< \gamma)$):

$$q_t = C\,\frac{\lambda^{3/2}}{\beta^{1/2}}\,T\,[\kappa_T - \kappa_c]^{3/2}\,H\,[\kappa_T - \kappa_c] - \chi_0 \delta_r T \qquad (4)$$

where H is the Heaviside function. From that we may formally obtain an effective diffusivity $\chi^{eff} = -q_t/\partial_r T$, which indeed resembles the diffusivity applied in the CGM, with a stiffness parameter related to $C\,\lambda^{3/2} / \beta^{1/2}$. However, the present model differs from the CGM, because the turbulence level develops self-consistently in response to the changes in the gradient and will not be uniform, the flux is proportional to the instantaneous turbulent energy and will evolve accordingly.

The system Eq. (1) and a) b) Eq. (2) with Eq. (3) is solved numerically, using a third order stiffly stable time stepping scheme, with a spatial resolution of 1000 grid points. With the source profile modelling an off-axis heating profile le we have performed simulations over a wide range of parameters, and observed stiff transport behavior, upgradient transport and temperature peaking. We have revealed anomalous fast cold pulse propagation in response to a localized cooling at the edge. For selected parameters, we have also observed the polarity reversal, i.e., the edge cooling results in a transient temperature increase at the center as first observed in TEXT [5].

Here we concentrate on the modelling of the perturbative transport experiments in JET by Mantica *et al.* [1]. Specifically we have considered Pulse No: 55809. We use the source pro le (off-axis ICH + NBI heating) from this experiment in absolute units and measure the temperature in keV. In Fig. 1 we have plotted the source profile and temperature profile in the saturated state, which indeed match the experimental ones for parameters $\kappa_c = 1.8$; $\lambda = 2$, $D_0 = 0.001$ and $C = 2$. Furthermore, we show the profile of the turbulent energy and from the accompanying profile of κ_T we observe that turbulence has spread slightly into the stable regime ($\kappa_T < \kappa_c$), where the flux is observed to be negative, i.e.,up-gradient.

In Fig.2 we consider the propagation of a heat wave, excited by modulating the off-axis ICH heating. The evolution of the amplitude and phase of the temperature modulation versus radius is compared with the experimental results. The agreement is satisfactory, given the assumptions of this simplified model, where only the electron transport channel is included. We have examined the propagation of a cold pulse in the simulations for the same set of parameters. The pulse is initiated at $t = 2.4$s by applying a rapid temperature decrease (of 100eV, lasting 30ms) at $\rho = 1$. In Fig.3 we show the evolution of the temperature at different radii. The pulse propagates rapidly and the response time until the temperature has decreased by 30eV at r=0:1 is found to be 18 ms. This time is still significantly longer than the experimental measured value, 4 ms [1], but it is shorter than the response time obtained by the CGM (≤23ms) as shown in Fig.4.

CONCLUSION

In conclusion, the presented model is able to describe essential features of transient transport events including the fast propagation of a cold pulses compared to the slower propagation of heat modulation waves. Relaxing the present strong simpli cations, as e.g., the frozen density pro le and only accounting for the electron channel for heat transport, would lead to more detailed agreement with experiment. The introduction of turbulence spreading in more elaborated transport models holds promise for accurate description of anomalous transient transport events. In future work we plan to integrate this concept into the JET suite of transport codes.

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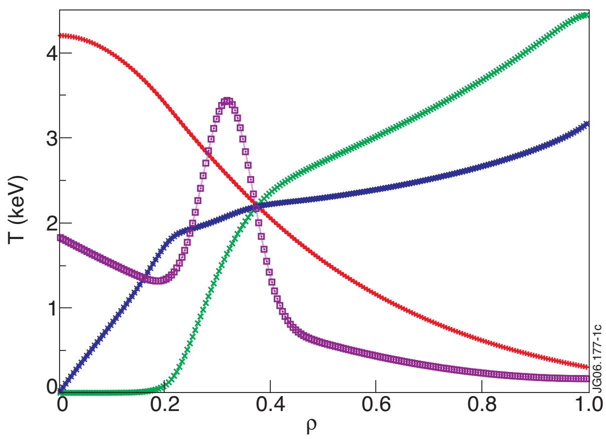

Figure 1: Profiles of temperature (red) (measured in keV), turbulence intensity (green), κ_T (blue)(κ_c = 1.8) and source profile (magenta) ($\rho = r/a$).

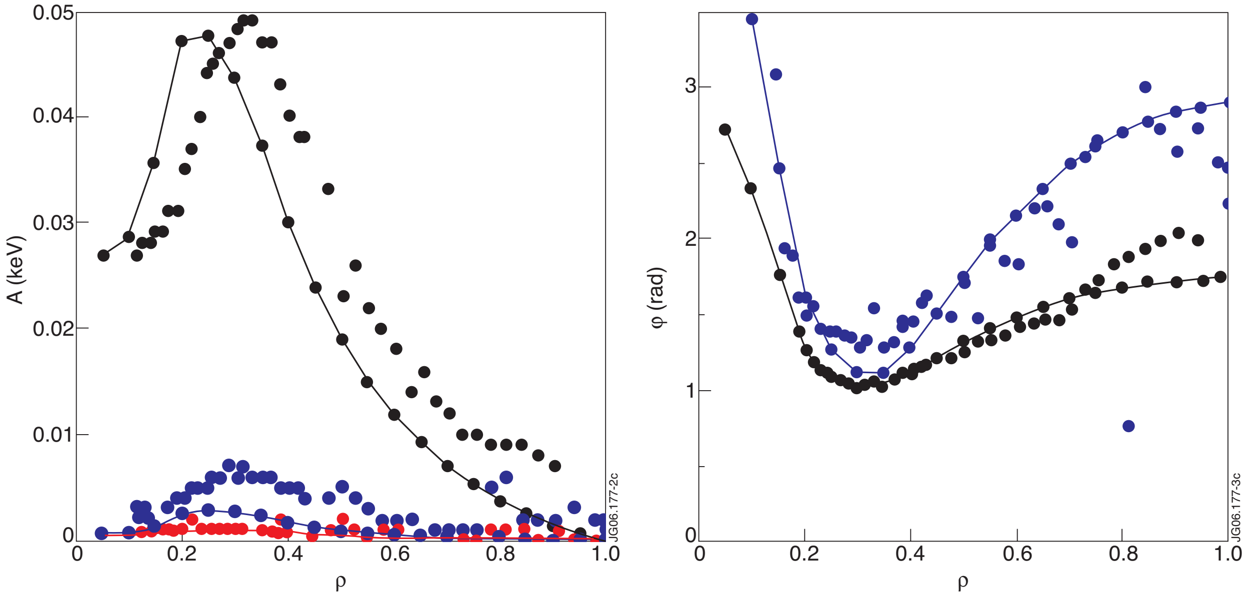

Figure 2: Fourier-analysis of the heat modulation incomparison with JET Pulse No: 55809, numerical results as lines points. Amplitude a) and phase b) evolution of fundamental (black), second harmonic (red) and third harmonic (blue).

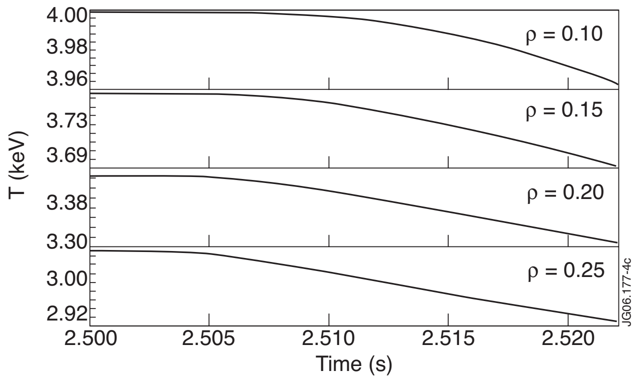

Figure 3: Evolution of the cold pulse.

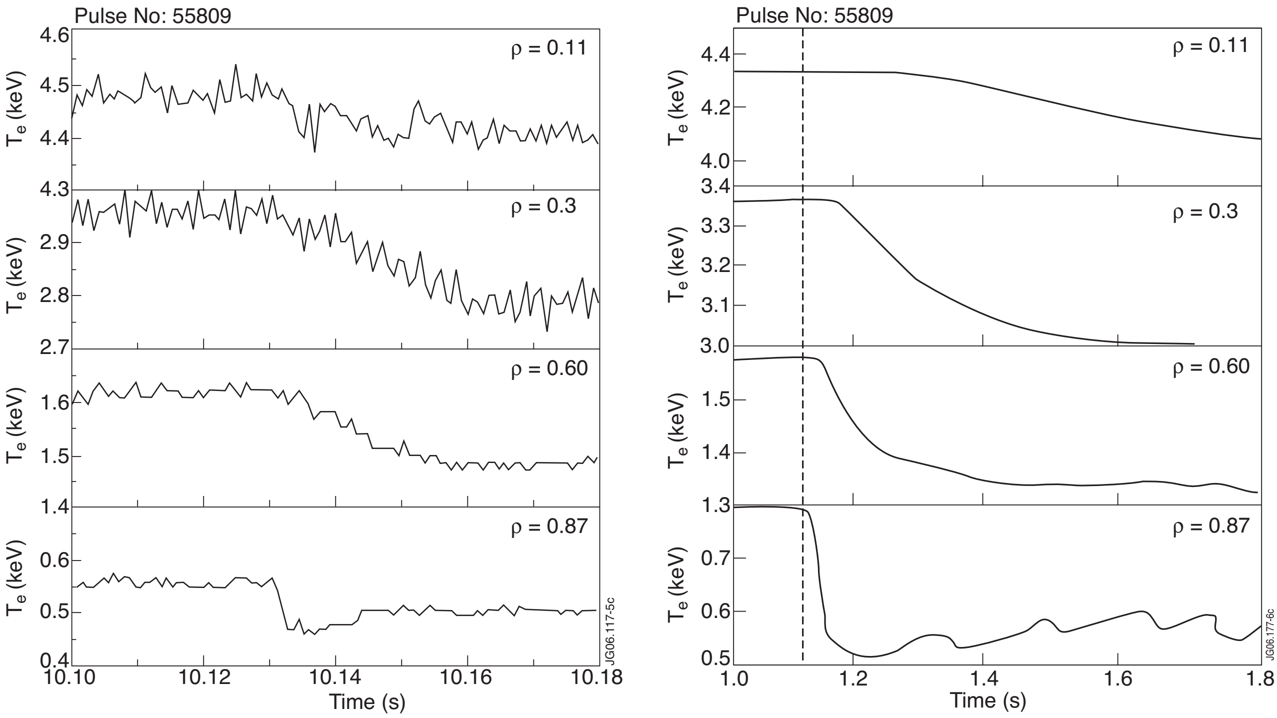

Figure 4: Cold pulse experiment, JET Pulse No: 55809. a) Experiment. b) Simulation with CGM.