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Turbulence spreading and nonlocal transport in magnetized plasmas

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Turbulence Spreading and Nonlocal Transport in Magnetized Plasmas

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Outline

-- Definition of turbulence spreading, TS →

-- Motivation, how can it influence the turbulent transport

-- 1D transport model accounting for turbulence spreading

-- Comparison with a “simple” turbulence simulation: 2D interchange model

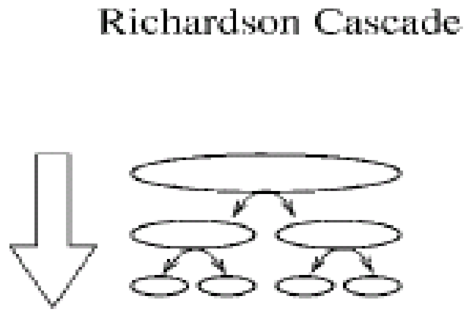
-- Applying the TS transport model to describe perturbative transport experiment in JET

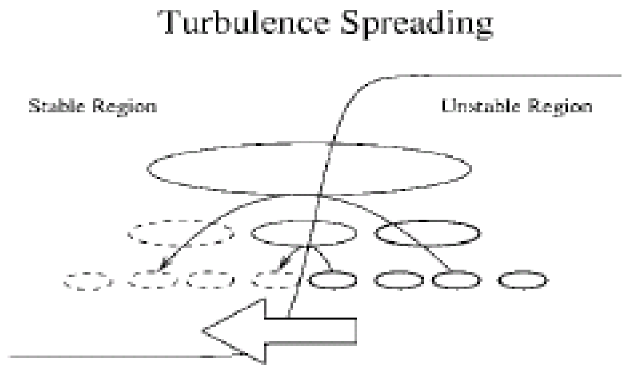
-- Heat modulation and fast heat pulse propagation.

Turbulence Spreading

The turbulence itself is a transported quantity: may spread from unstable regions of generation into stable regions.

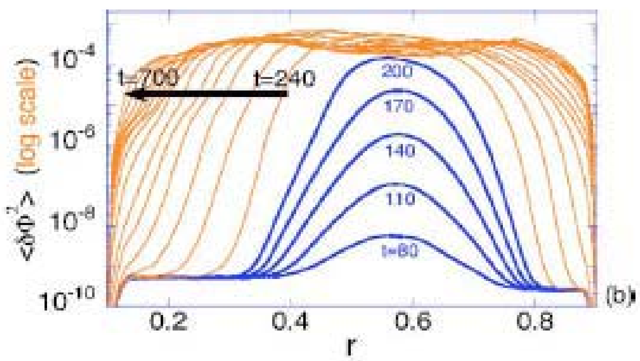
Plasma Turbulence: Garbet *et al,* NF **34**, 963 (1994); Gürcan, Diamond, Hahm, PoP, **13**, 052306 (2006); **14**, 055902 (2007)





Spreading in k-space, from “unstable” k to “stable” k

Spreading in configuration space from unstable region into stable region



Gyrokinetic simulations

Wang *et al. PoP* **14**, 072306 (2007)

Turbulent spreading well-known in fluid turbulence: turbulent overshoot, penetration

Local Transport Models

Quasi-linear approach and mixing length theory [Kadomtsev 1965]: Balance the linear growth of instability, γ, against *D*, the "*turbulent diffusion*"

$$D \propto \frac{\gamma}{k^2}$$

k is a perpendicular wave number of the turbulence.
More refined versions look at turbulent spectra and include off-diagonal terms (f.x. Weiland transport model).

Successful approach, but drawbacks:
Local transport models do not account for:
- high transport at low gradients
- Up-gradient transport
- burstiness
- avalanches
- fast transport events

All observed effects!

Motivation for TS Models

- Turbulent spreading accounts for nonlocal effects
- Include naturally up-gradient transport
- May account for avalanche and bursty transport
- Non-diffusive effects: breaking direct relationship between gradients and fluxes: Ficks law

Note: Turbulent spreading may work in basically two ways:

1. The turbulence spreading takes the stability boundary with it implying enhanced turbulence and transport in the "new" region
2. The turbulence penetrates into a stable region where the modes are damped, implying different transport characteristics as, e.g., up-gradient transport.

Transport Model with TS

1D turbulent transport model of heat in the core (density profile fixed), accounting for spreading of turbulence into stable regions: Describe pinch effects and profile stiffness.

$$\frac{\partial E}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r\left[D_0 E \frac{\partial}{\partial r} E\right] + \gamma E - (\gamma_0 + \beta E^2)E, \Rightarrow$$ Turbulent energy, growth and spreading D_0 const.

$$\frac{\partial T}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r} rq + \chi_0 \frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} T + S(r)$$ $\Rightarrow$ Temperature transport

Growth rate: $\gamma = \lambda\left[\kappa_T - \kappa_c\right]$; λ: free parameter; $\kappa_T \equiv |\partial_r T|/T$, κ_c: critical.

The heat flux: $q = \left\langle \tilde{T} v_r \right\rangle$, $E \approx \left\langle v_r^2 \right\rangle$. cross coherence $\xi \propto \gamma$ between $\tilde{T}$ and v_r:

$\Rightarrow q = \xi \sqrt{\left\langle \tilde{T}^2 \right\rangle \left\langle v_r^2 \right\rangle}$, $\tilde{T}/T = C\sqrt{E}$, i.e., and $\left\langle \tilde{T}^2 \right\rangle = C^2 \left\langle E \right\rangle \left\langle T^2 \right\rangle$,

$q = C\gamma ET = C\lambda ET\left[\kappa_T - \kappa_c\right]$. $q < 0$ for $\kappa < \kappa_c$: Up-gradient transport!

Test of TS Transport Model

Similar transport model applies to the transport of density:

$$\frac{\partial n}{\partial t} = -\frac{\partial}{\partial x}\Gamma + S(x,y) \qquad \Gamma = \langle \tilde{n} v_r \rangle$$

Apply a simple 2D interchange model for testing the TS model:

$$\partial_t \Omega + \vec{v} \cdot \nabla \Omega + \mathcal{K}(n) = \mu_\omega \nabla^2 \Omega$$

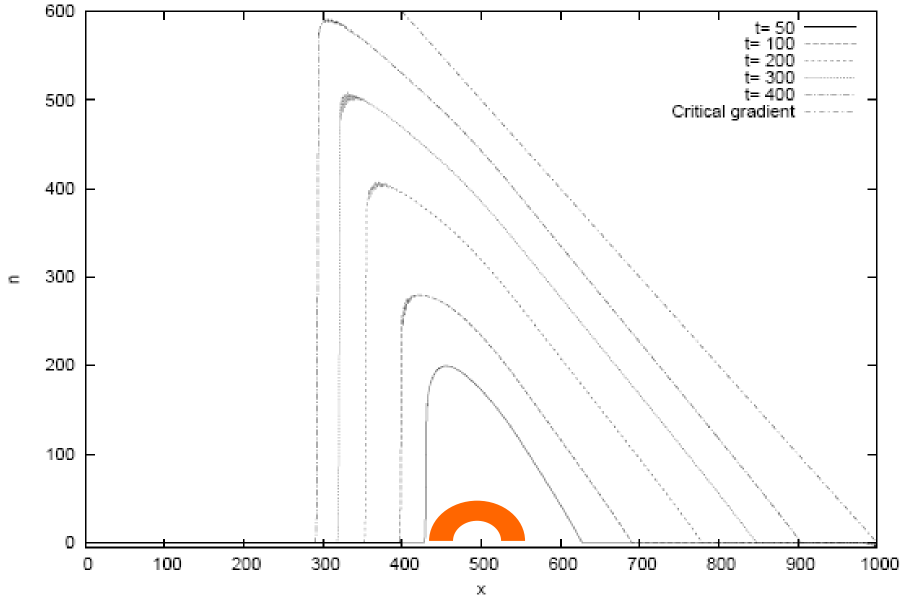
$$\partial_t n + \vec{v} \cdot \nabla n - \underline{n\mathcal{K}(\phi) + \mathcal{K}(n)} = \mu_n \nabla^2 n + S(n)$$

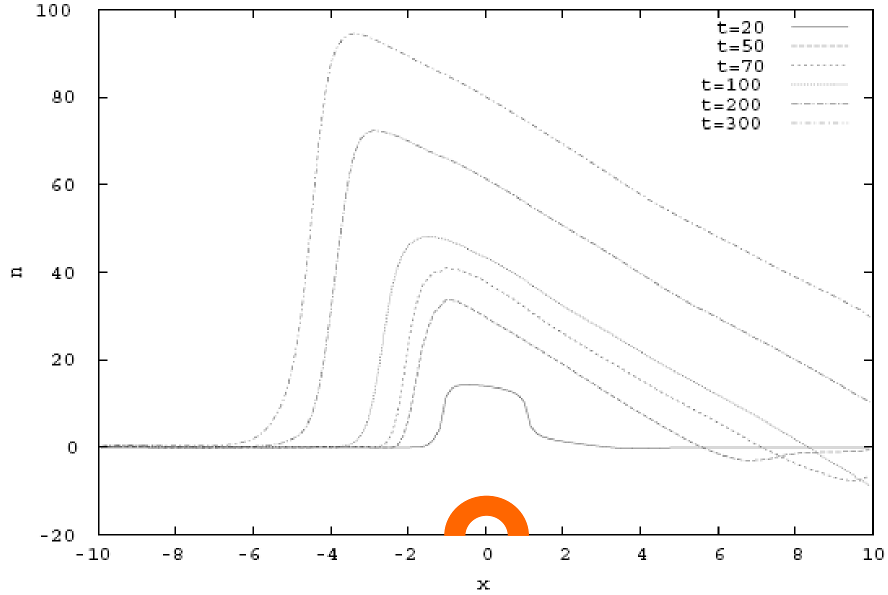
Ω is the vorticity ($\Omega = \nabla^2 \phi$) perpendicular to the (x, y)-plane

Contains curvature as drive, density source and exhibits threshold for instability.

Naulin *et al* Phys Plasma **12**, 122306 (2005)

Evolution of Density Profile





Evolution of profiles in 2d simulation (left), and in TS model (right), location of source indicated

The profile evolves toward a critical profile “marginally stable”

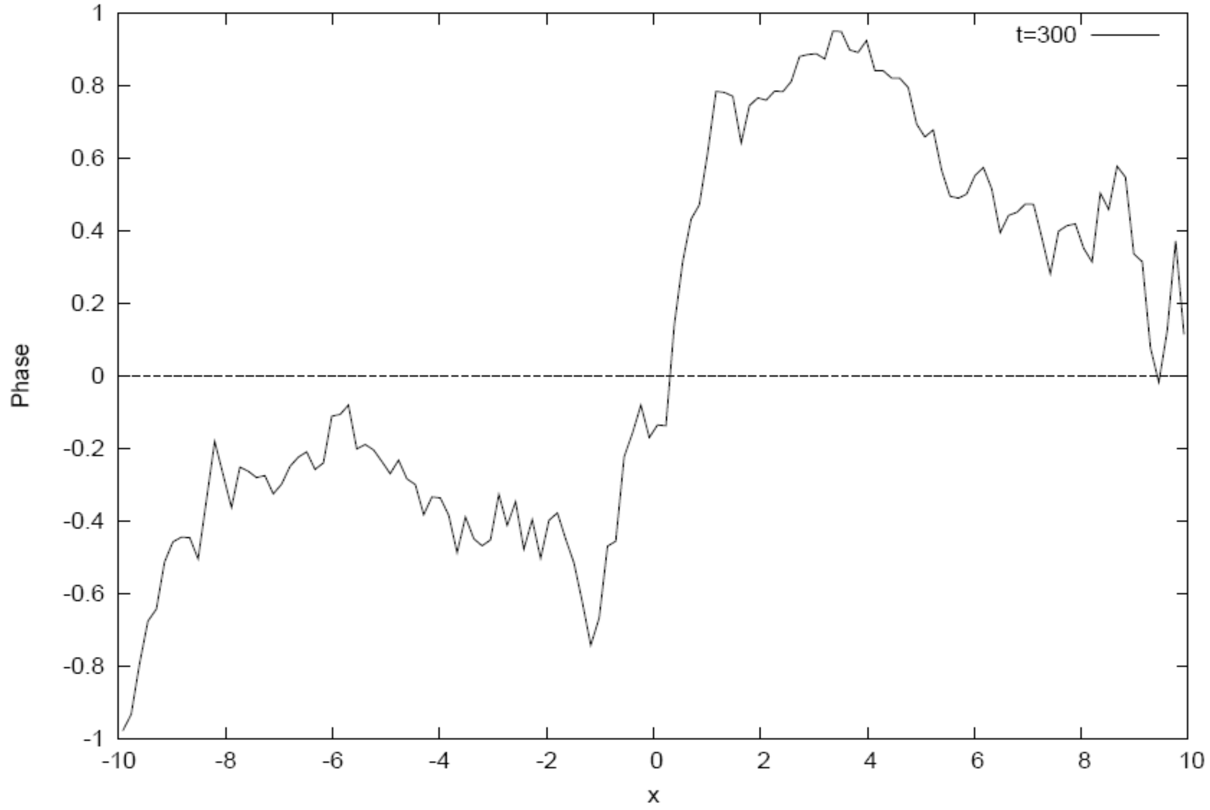
Up-gradient Transport

Where does the energy come from?

- Gradient is a drive for turbulence.
- Energetically the energy input into turbulence is connected with the flux.
- Turbulence is damped in stable regions.
- Turbulent energy is exhausted not in dissipative effects, but in reversal of transport direction.
- Role of stable modes!!!! (which are completely ignored in traditional models)

Stable modes show different phase relationship between turbulence and the transported quantity

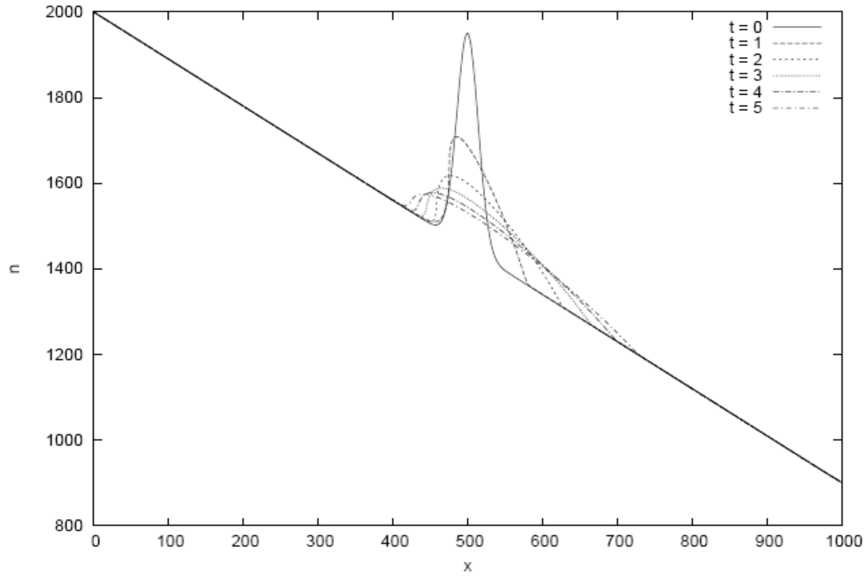
Phase Relation

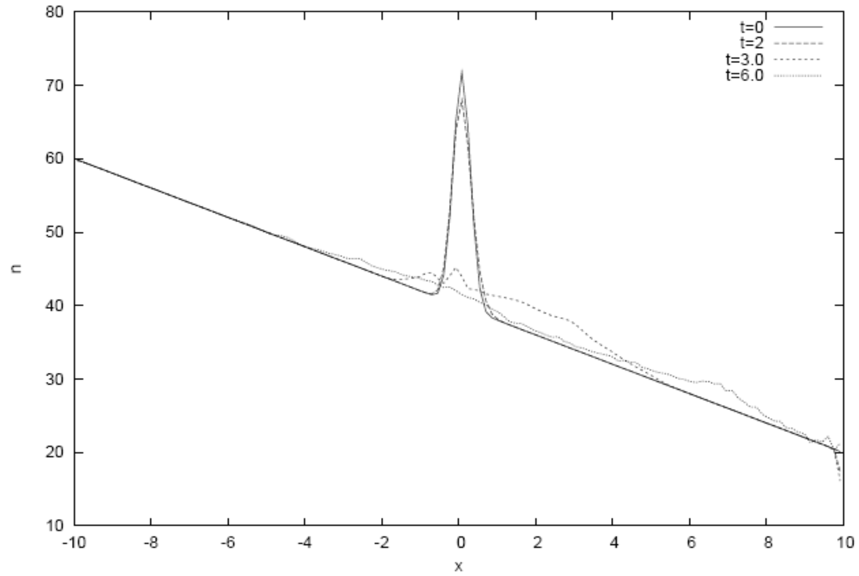


Average phase between density and radial velocity fluctuations

Note: sign of $\Gamma(=\langle\tilde{n}v_r\rangle)$ is determined by sign of phase between n and v_r

Density Pulse Evolution

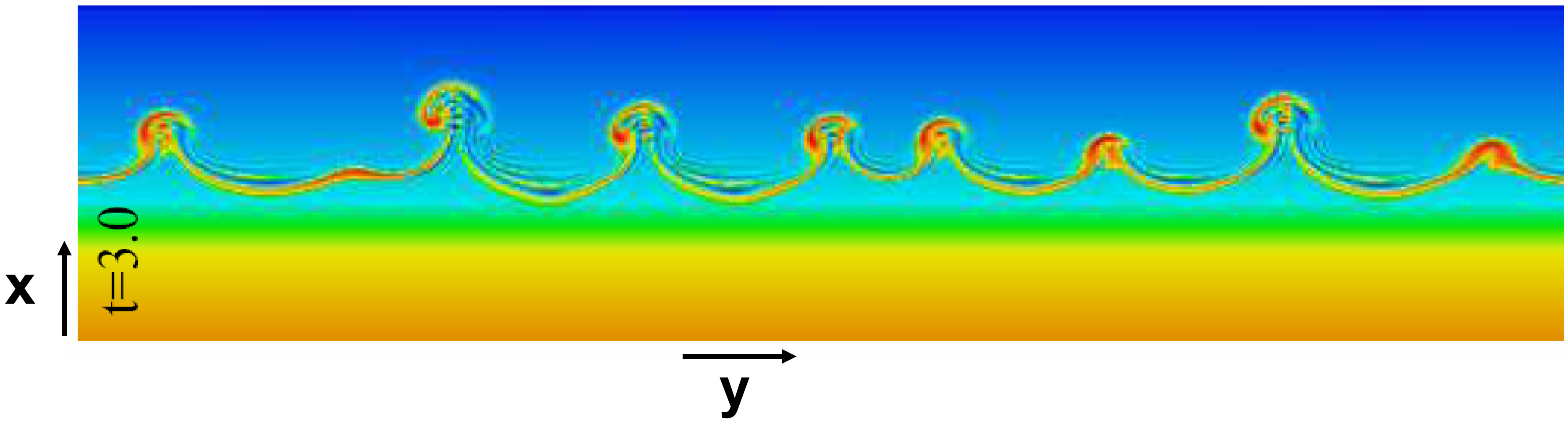




Density pulse initialized on a subcritical background gradient.

Model (left) and 2D simulation (right). Up-gradient transport.

Density Pulse Evolution



Initialize pulse on a subcritical background gradient. Instability develops into mushroom like structures, clearly neither local nor diffusive transport...

However, the mean profile appears to be well described by the 1D transport model!

TS Model and CG Model

$$\frac{\partial E}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r \left[D_0 E \frac{\partial}{\partial r} E\right] + \gamma E - (\gamma_0 + \beta E^2) E,$$

$$\frac{\partial T}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r} r q + \chi_0 \frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} T + S(r)$$

$D_0 = 0$ Critical Gradient Transport model. ⇒ $q_t = C\frac{\lambda^{3/2}}{\beta^{1/2}} T \left[\kappa_T - \kappa_c\right]^{3/2} H\left[\kappa_T - \kappa_c\right] - \chi_0 \partial_r T$

The model then reduce to the standard critical gradient model, CGM, widely used in describing perturbative transport experiments

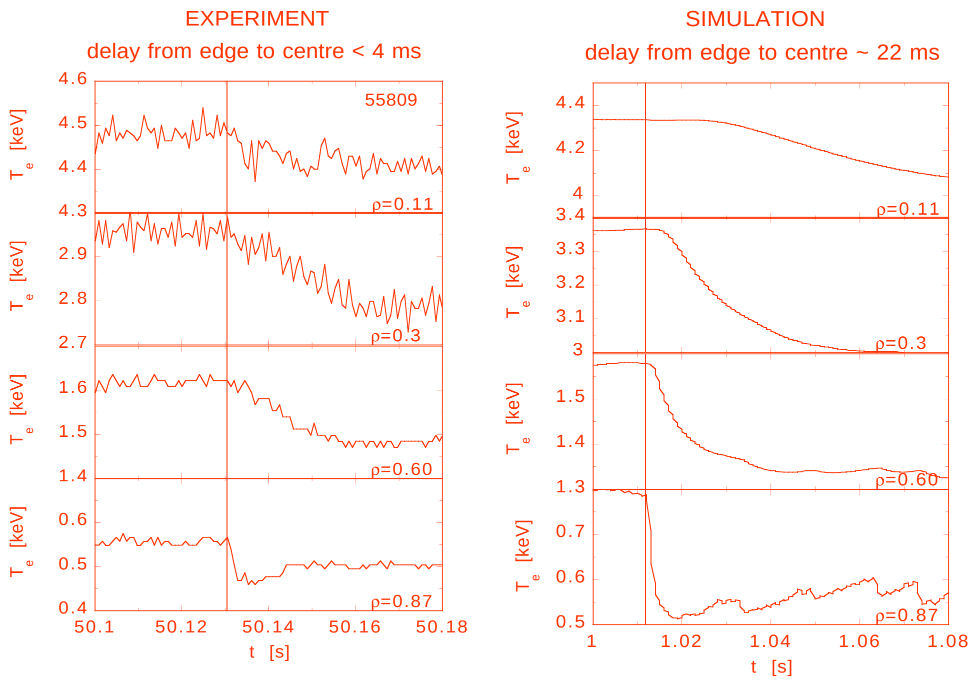
Imbeaux *et al.* PPCF **43**, 1503 (2001)

Mantica & Ryter, C.R. Physique **7**, 634 (2006)

Transient Transport Events

Application to transient transport events in JET: Fast propagation of cold pulse

P. Mantica et al., (Proc. 19thIAEA Conf. Lyon, 2002) EX/P1-04, IAEA 2002



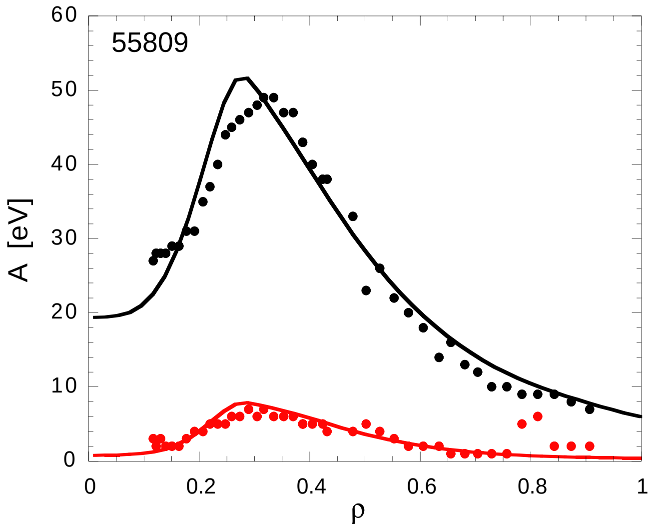
Cold pulse experiment, JET # 55809; CGM simulation with coefficients fitting heat modulation experiment, too slow for cold pulse.

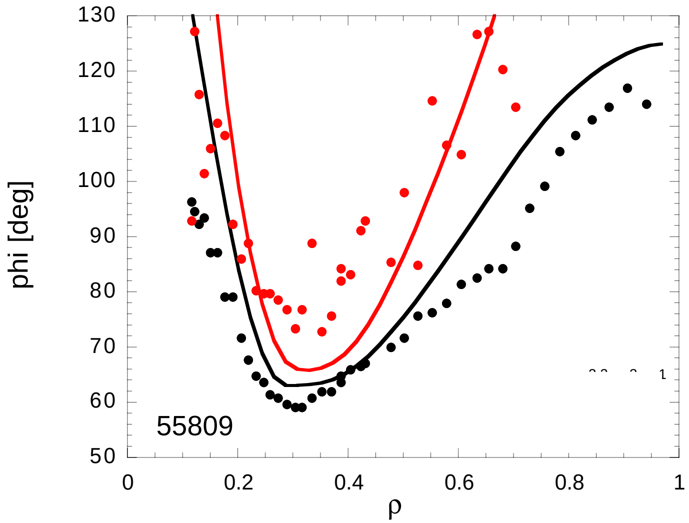
Transient cold pulse, initiated by local cooling at the edge

The pulse propagates much faster than heat modulation, which is well described by a "standard" critical gradient model, CGM.

Challenge: explain both effects within the same model!

Heat Modulation





T_e modulation by off-axis ICH

Compared with CGM

For ρ > 0.3 unstable profile, for ρ < 0.3 stable profile

Compared with cold pulse propagation:

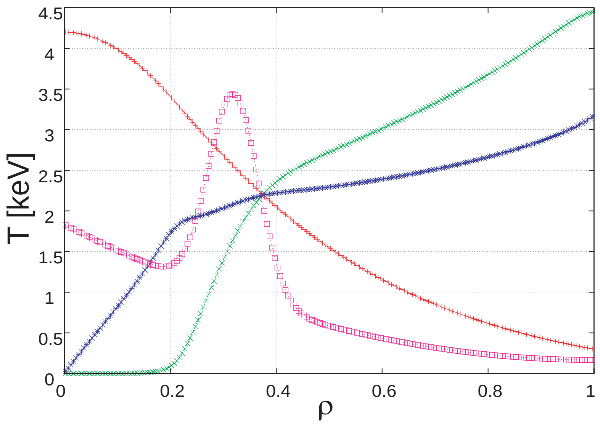
Surprising result:

ρ>0.3: the plasma is stiff and both perturbations propagate fast

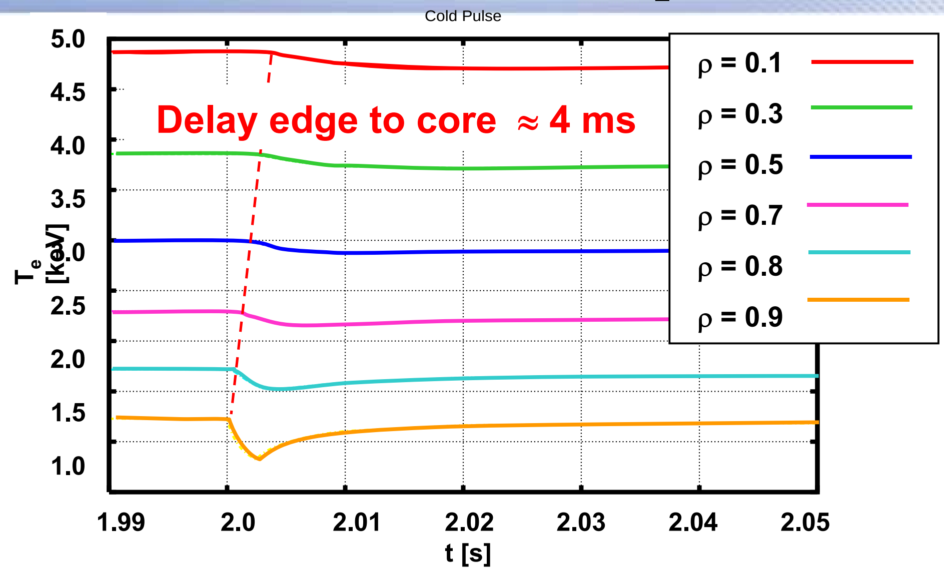
ρ<0.3: the plasma is below threshold and heat wave slows down and is damped **BUT cold pulse still travels fast**!

Incompatible with local transport models!

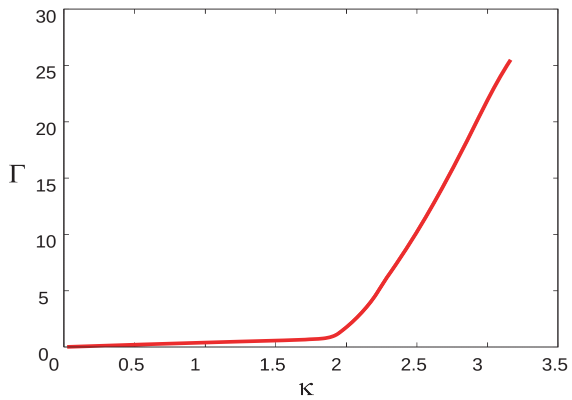
Perturbative Transport I



Profiles: T, E, κ_T, $S(r)$
off-axis ICH + NBI



Cold pulse propagation



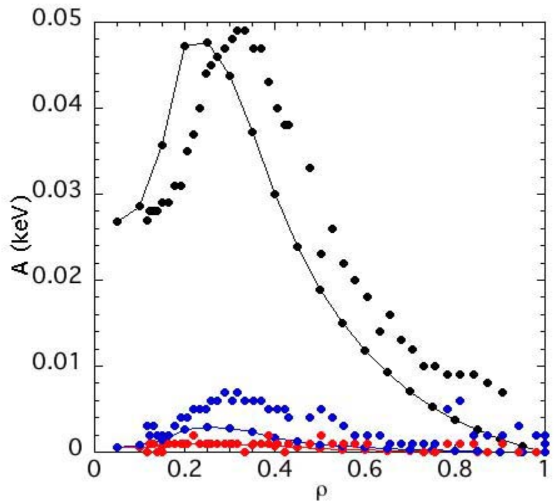
Stiffness: $\Gamma = q_t/T$
$(q_t = q - \chi_0 \nabla T)$ vs κ_T

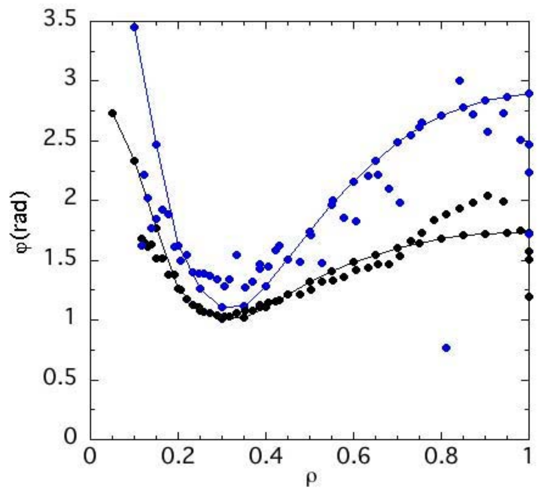
Fast cold pulse propagation easily modelled for a wide parameter range; even pulse reversal (increasing centre temperature response) have been modelled.

Challenge: model both heat modulation experiment and cold pulse propagation!

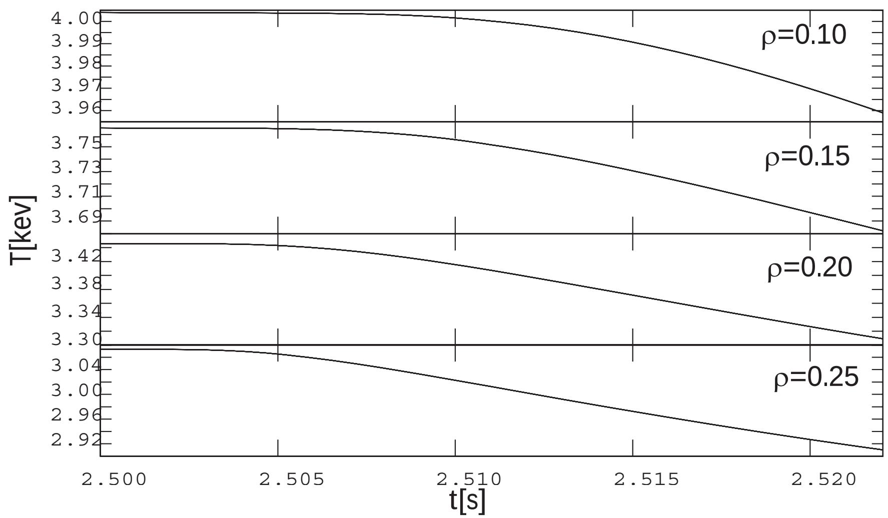
Rasmussen *et al.*, EPS 2006 Rome

Perturbative Transport II





The heat modulation comparing JETpulse 55809; numerical results: linespoints. Amplitude and phase: Fundamental (black), second (red) and third harmonic (blue)



Cold pulse evolution: < 18 ms

A step in the right direction!

But room for improvements:

Account for more than one transport channel

Investigate influence of ITB

Integrate TS model with real dispersion relation solver

Conclusion

- Turbulent spreading is important in many systems – in plasmas often observed, also in turbulence simulations, incl. gyro-kinetic simulations
- Turbulence spreading models allows for introduction of “non-locality” into transport models
- It accounts directly for pinch effects – up-gradient transport
- Results of the TS model compare well with turbulence simulations – at least for interchange model
- A first step to include more complicated transport processes into “simple” models