Pedestal Transport

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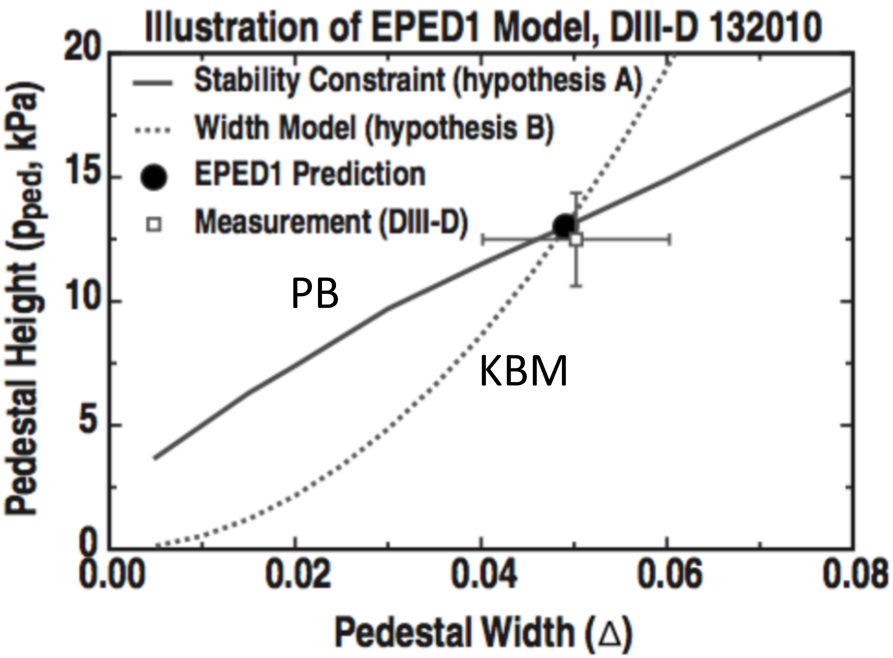
Vienna, July 20, 2017

MHD Pedestal Paradigm (Conventional Wisdom)

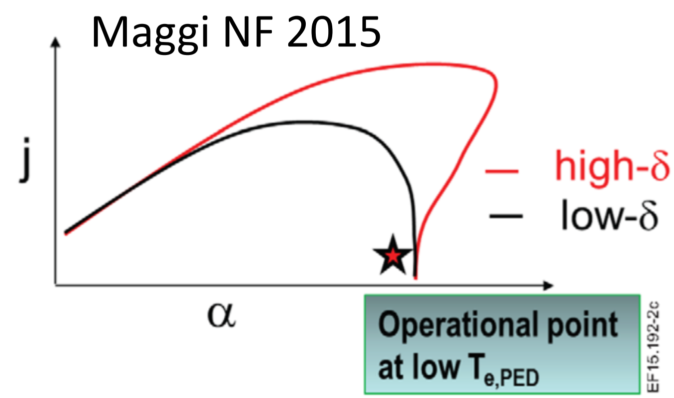
- EPED model
  - Based completely on MHD
  - Predicts width and height of pressure pedestal
  - Consistent with large number of experimental discharges
- Problems:
  - Knows nothing about transport (i.e. what heating power is needed?)
  - Cannot distinguish between T and n (indirectly through bootstrap)
  - Takes pedestal top density as input (i.e. part of the answer is built in)



Snyder '09

Effect of Transport

- Typically limits pedestal temperature
- If temperature is limited, density can sometimes compensate (if not near Greenwald limit)
- Typically limites pedestal pressure via less favorable PB stability at low temperature
- Note also: high temperature (not just pressure) needed for JET DT
  - Even at constant pressure fusion gain goes down drastically as T decreases
- Bottom line: we need to get beyond the MHD-only paradigm. Transport matters!



Preliminaries

- Much can be inferred from basics
  - Fundamental nature of transport mechanisms
  - Sources
  - Inter-ELM profile evolution
  - In different channels
    - Electron heat……………………..χ_e
    - Ion heat…………………………..χ_i
    - Electron particles……………….D_e
    - Impurity / ion particles……….D_z, D_i

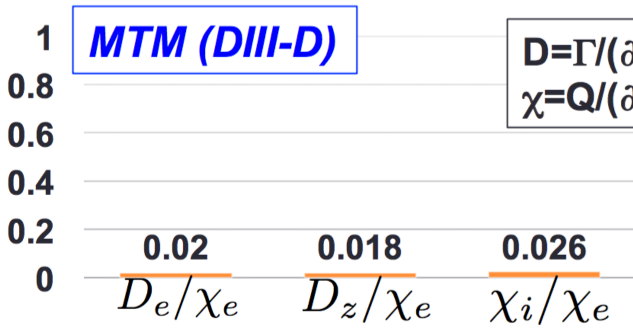
Preliminaries: Candidate Transport Mechanisms

- Microtearing modes (MTM).
  - Electron heat flux, driven by electron temperature gradients, ω_{*e} frequencies
- MHD-like (i.e. KBM)
  - Driven by all gradients, diffusivity in all channels, frequencies ranging from 0 to ω_{*i}
- ETG
  - Small scale, electron heat flux, driven by electron temperature gradients, ω_{*e} frequencies
- ITG (driven by ion temperature gradient, diverse transport, ion frequencies)

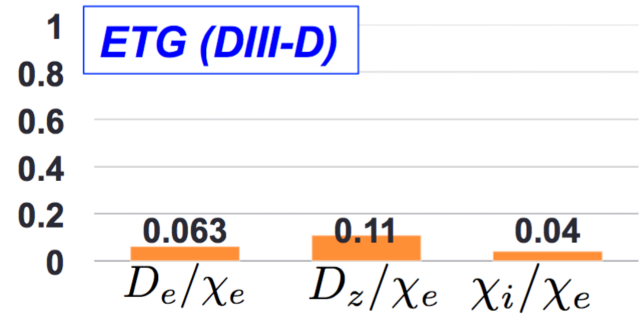
MODE:	T_e	T_i	n_e	n_Z	Inward particle pinch
MHD-like	Yes	Yes	Yes	Yes	No
MTM	Yes	No	No	No	No
ETG	Yes	No	No	No	No
ITG	Some	Yes	Yes	Yes	Yes

Preliminaries: Transport Mechanisms have Very Different Properties

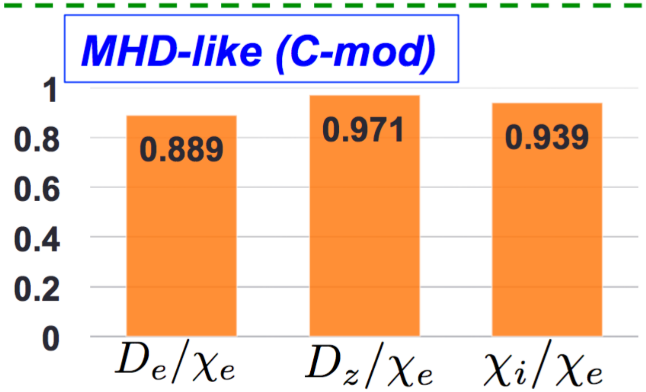
$D=\Gamma/(\partial n/\partial x)$
$\chi=Q/(\partial T/\partial x)$



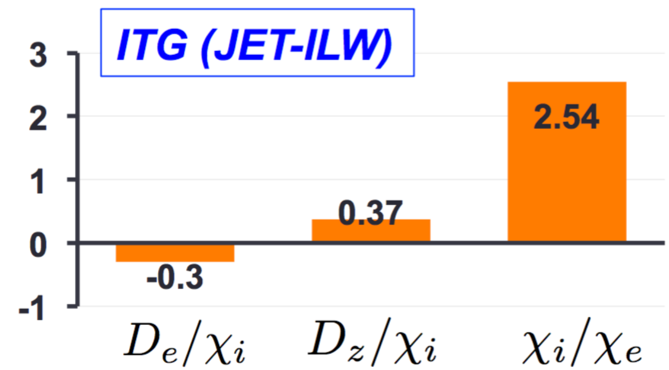
- Magnetic mode driven by ∇T_e
- $\omega \approx \omega_e^*$



- Driven by ∇T_e (η_e)
- Ions don't participate, only T_e transport



- Driven by $\nabla(p_e+p_i)$
- Transport: ALL CHANNELS $\omega \sim 0 - \omega_i^*$
- No inward pinches: only diffusion



- Driven by ∇T_i (η_i)
- Transport: ALL CHANNELS $\omega \sim 0 - \omega_i^*$
- CAN HAVE inward particle pinch

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Preliminaries: Sources based on Very Different Mechanisms

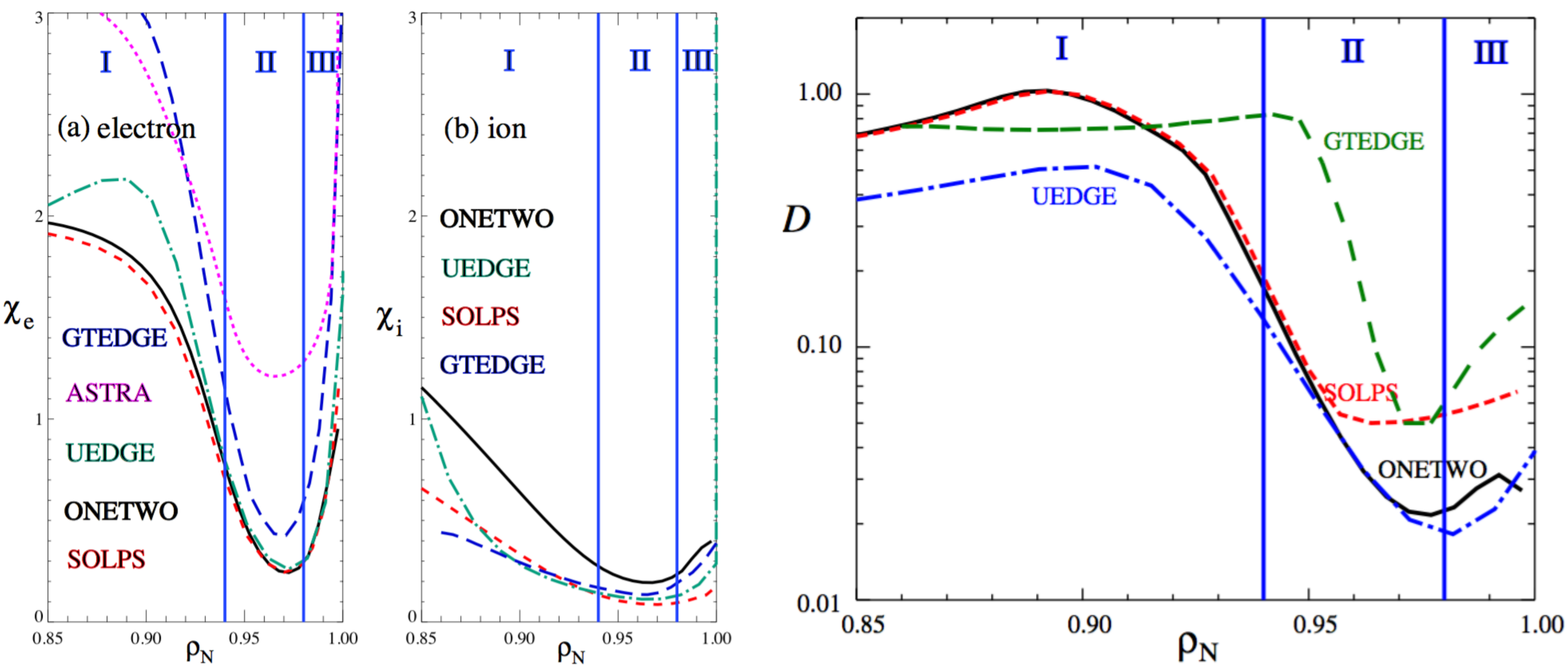
- Electron, ion heat.......................χ_e, χ_i
  - Flux from the core
- Particles…................................D_e
  - Neutral penetration / ionization
  - Pinch? (Possibly from ITG)
- Impurities…...............................D_z
  - Neoclassical impurity pinch
- These are difficult to characterize in the pedestal but the following are reasonable assumptions:
  - Ion heat ~ neoclassical (for large ρ^*)
  - Electron heat larger: needs a turbulent mechanism
  - Particles difficult to characterize, but D_e likely smaller than $\chi_{e,I}$
  - Impurities (neoclassical pinch)

Preliminaries: Sources

Callen NF 2010

Analyzing DIII-D pedestal transport using four edge codes

$D_e << \chi_e \sim 2\, \chi_i$



- Smallness of any transport channel gives bound for χ_{MHD}.

Smallness of Any Transport Channel Bounds MHD

- Example: Callen case:

  $\chi_e \sim 10 \times D_e$
  ➔
  $\chi_e > 10 \times \chi_{MHD}$

- Second example: Assume ion heat transport is neoclassical
  - $\chi_i = \chi_{i,NC} \pm \delta$
  - ➔ $\chi_{i,MHD}, \chi_{e,MHD}, D_{MHD} < \delta$

- To the extend that diffusivities are separated in magnitude, we can bound contribution from MHD

- Recall: sources / fluxes have widely varying origins (heating / fueling / seeding) ➔ MHD / KBM from very basic considerations is very unlikely to account for all channels

Data Points for Emerging Pedestal Paradigm

- Ingredients
  - Fundamental properties of transport mechanisms
  - Considerations of sources
  - Observations of inter-ELM profile evolution
  - Fluctuation diagnostics
  - Gyrokinetics

- Roughly Split into two categories
  - Most present-day machines (AUG, DIII-D, C-mod) with strong shear suppression of ITG
  - JET (transition), ITER (extrapolation)
    - Emergence of ITG turbulence?

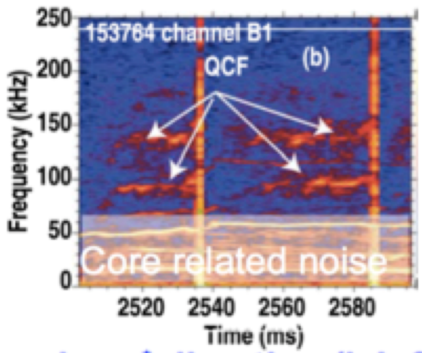
Gyrokinetic Pedestal Simulations

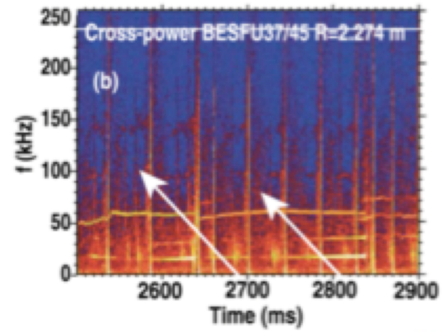
- Is it valid in the pedestal?
  - Mostly—especially at low ρ^* (testing / development / validation / verification very much needed!)
- Is it useful? (Yes) [Even experimentalists are buying our results!]
- Is there anything better at the moment? (No)
- How we run the code (GENE)
  - ETG: same as usual (but needs very high parallel resolution)
  - Ion scales:
    - Some local (not flux tube) with box width comparable to pedestal width (Dirichlet boundary conditions) (LILO)
    - Some global. Challenge is numerical (physical?) instability at high beta. We're getting better with this.
    - Global simulations of quasi-coherent modes (MTM) with limited ky wavenumbers (2-10). Justified by limited number of distinct bands observed in experiment.
- Things we want to do:
  - Improve separatrix boundary condition
  - More robust EM operation
  - Improvements to underlying model (edge-ordered GK?)

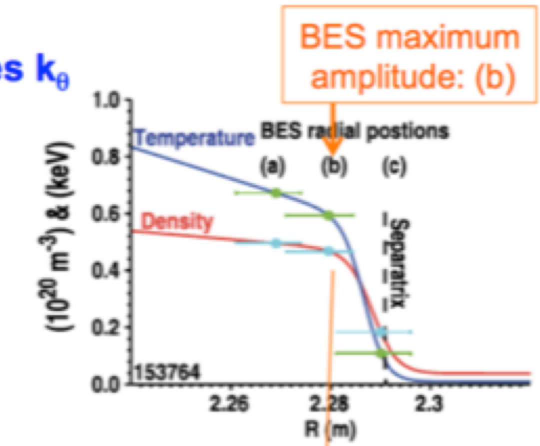
DIII-D Pedestal Fluctuations: Can Rule out KBM from Simple Considerations

DIII-D pedestal (Diallo and Groebner et. al.)*

- **QCM seen on magnetics and BES; BES determines k_θ**



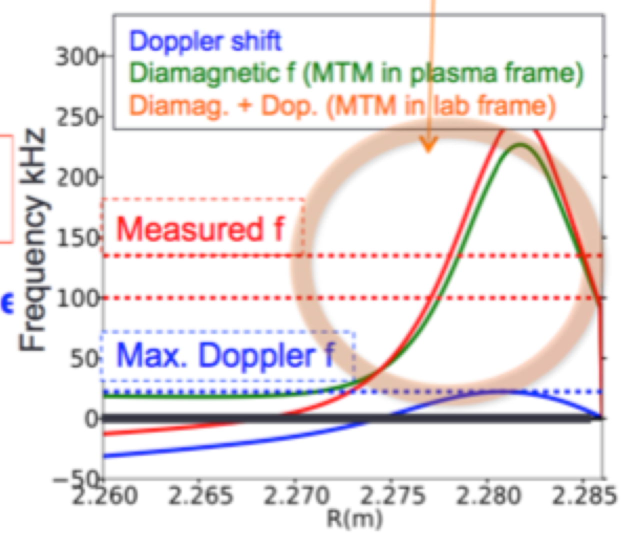




- **ω in ω_e^* direction (lab frame)**
- **E_r Doppler shift ω_D also ω_e^* direction**
- **However, MAXIMUM ω_D only ~ 1/4 ω**

In the plasma frame: NECESSARILY $\omega \sim \omega^*_e$
Consistent with MTM; inconsistent with KBM

- **The position where $\omega \sim \omega_e^* + \omega_D$ is in the range of max mode amplitude (from BES)**

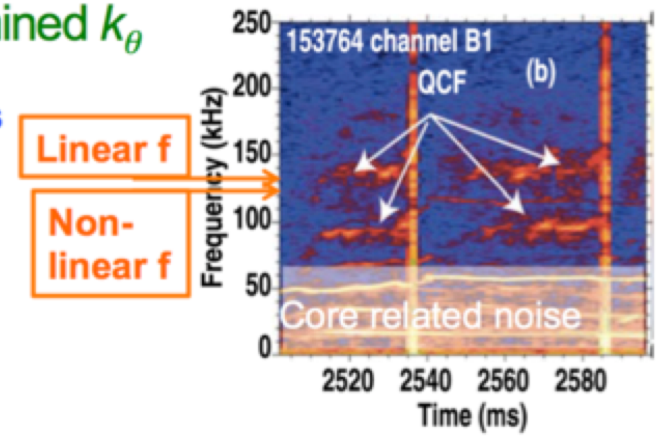


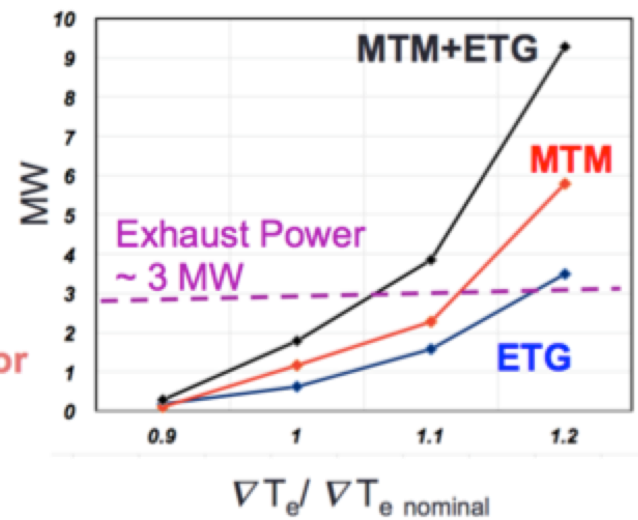
*A. Diallo , R. J. Groebner, et. al.
POP 22, 056111 (2015)

GK Simulations Closely Match Experiment

Gyrokinetic simulations at BES-determined k_θ

- **Linear runs at k_θ (from BES) (n~13): MTMs with f ~ 140 kHz at mid-pedestal**
- **Nonlinear MTM results**
  - *Non-linear downshift of frequency*
  - ***Heat loss is a rapid function of temperature gradient- STIFF TRANPORT***
- **Nonlinear ETG**
  - *Heal loss ~ 1/2 MTM*
  - ***Also stiff transport***
- **Small variations of ∇T_e around nominal easily matches exhaust power (~ 3 MW)**
- **MTM and ETG appear mainly responsible for energy losses**





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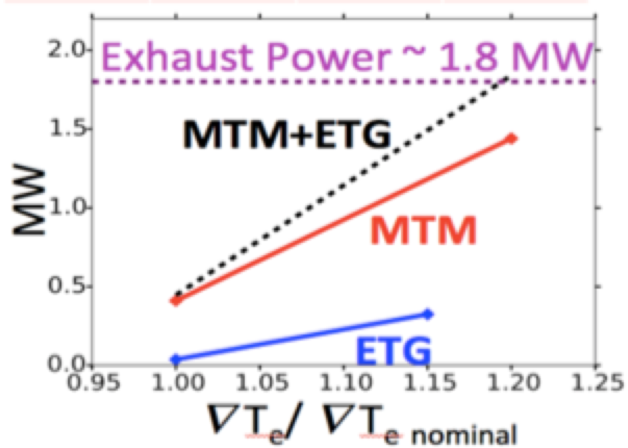
Second DIII-D Discharge (Callen)

Linear and nonlinear GENE runs

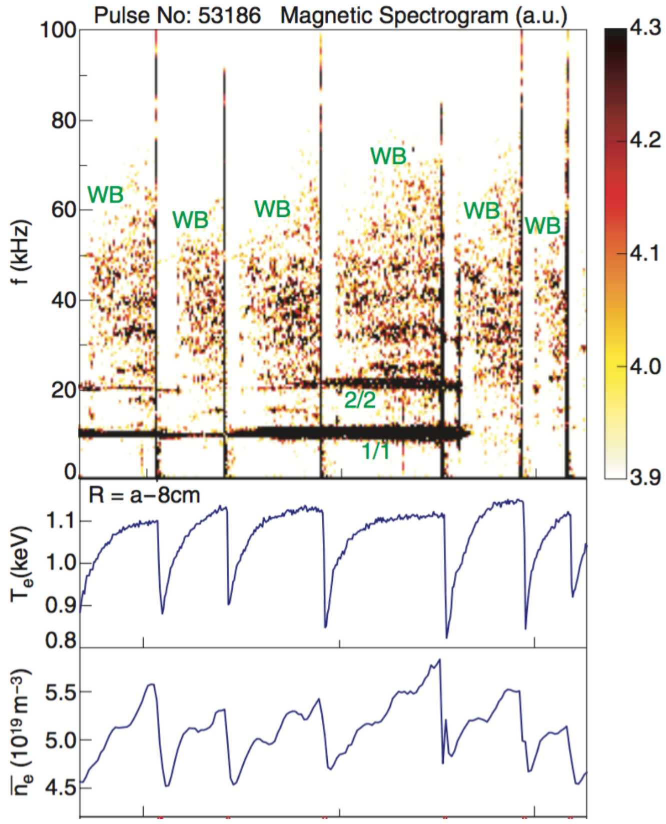
- **Global gyrokinetic**
- **Linear instabilites were found**
  - *MTM for n=16 and 18*
  - *Electrostatic n=20-28*
  - ***Unstable MTM frequency band at ~1.5 times measured values***
- **MTM nonlinear runs**
  - *Strong variation of heat flux with* ∇T_e
  - ***Nonlinear frequency downshift brings frequencies within ~ 20 % of measured values***
  - *Not far from marginal stability*
  - *Reasonable variations around experimental values match electron transport power ~ 1.8 MW*
- ***ES nonlinear runs***
  - ***Nonlinear heat fluxes very small (<1% of MTM)***
- ***ETG nonlinear runs***
  - *Find only 0.1 -0.3 MW (*η_e *smaller than previous shot)*
- ***Electron energy loss (main loss channel) consistent with MTM (+ small ETG)***

Toroidal n number	Stable / Unstable	Freq. (kHz)	Mode Type
4	Stable	11.4	
8	Stable	24.2	
10	Stable	29.9	
12	Stable	39.4	
14	Stable	43.9	
16	Unstable	287.9	MTM
18	Unstable	328.9	MTM
20	Unstable	59.9	ES
24	Unstable	69.9	ES
28	Unstable	79.5	ES



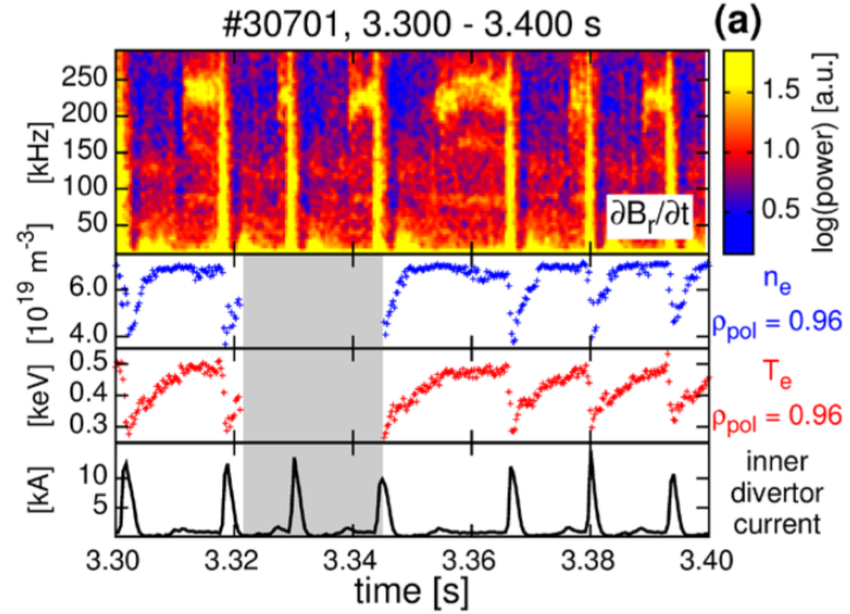
Similar Observations on JET / AUG

JET: 'Washboard' modes



Perez et al PPCF 2004

AUG



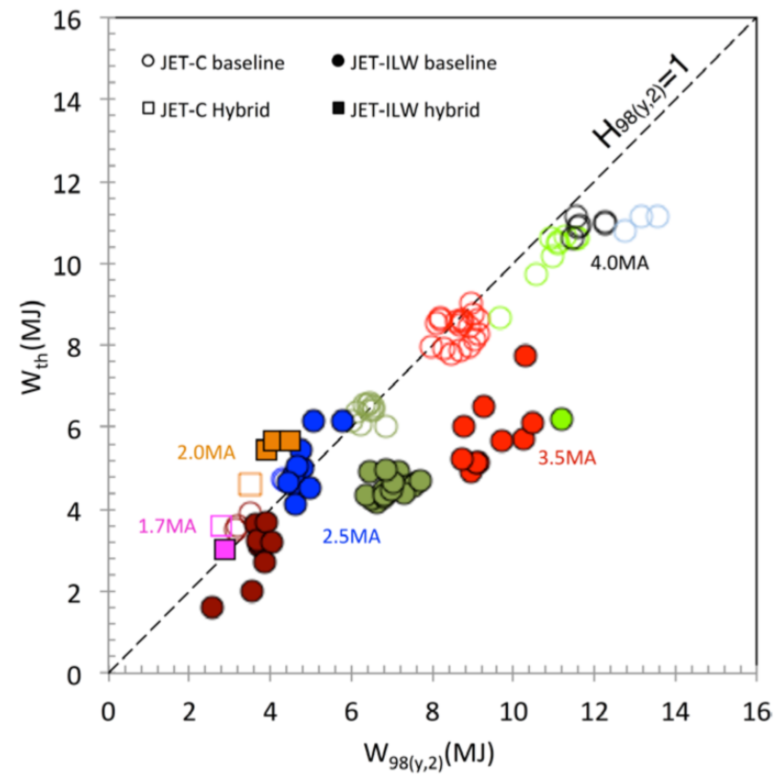
Laggner et al PPCF 2016

High ρ^* Pedestal Picture

- Magnetic fluctuations observed experimentally appear to usually (always?) be MTM and not KBM
- Is KBM active?
  - Often (probably), but its role is limited to density transport (i.e. modifying density profile to keep pressure profile at marginal stability
- ETG and MTM responsible for heat flux
- EPED:
  - A useful 0^{th} order framework for limits / structure of pressure profile
  - Very questionable for predicting / extrapolating to foreign parameter regimes
- Do things change as ρ^* decreases?

Evidence Breakdown of Shear Suppression on JET-ILW

- JET is largest tokamak in operation: has access to smallest values of ρ^* (although still not ITER values)
- Neoclassical theory (well supported by experiment [e.g., Viezzer NF 2016]) predicts shear rates to scale like ρ^*: $\gamma_{ExB} \propto \rho^*$
- With installation of ITER-like wall (ILW), degradation of confinement as I, B increase (i.e. as ρ^* decreases)
- Consistent with emergence of ITG turbulence (although other effects are surely also at play)
- Hatch et al NF '17: demonstrates ways in which transport trends consistent with ILW trends (gas puffing, impurity seeding, temperature limitation, etc)

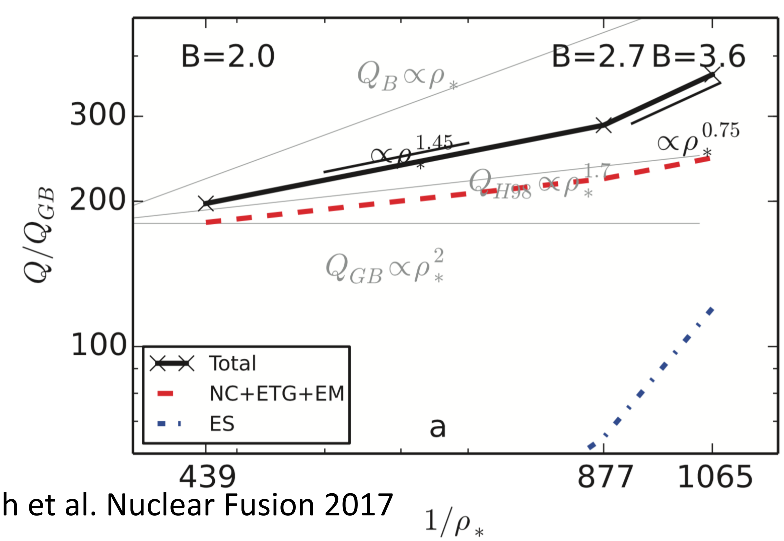


Nunes PPCF '16

Emergence of ITG Turbulence at Low ρ*

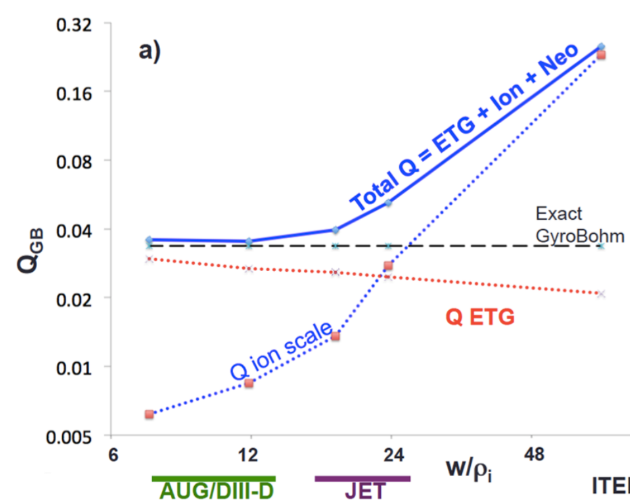
- Expectation: ITG turbulence in pedestal will become important at low ρ*
  - Perhaps already for JET (under unfavorable conditions)
  - Likely for ITER
  - Consistent with present-day ρ* scalings, which show little dependence of pedestal properties on ρ*

JET with ITER-like Wall



Hatch et al. Nuclear Fusion 2017

ITER-like Parameters



Kotschenreuther et al. Nuclear Fusion 2017

Clump / Decorrelation Theories of Shear Suppression

- Pedestal ITG is slab-like➔ early decorrelation theories are highly relevant
  - T. H. Dupree, Physics of Fluids **15** 334 (1972)
  - K.-C. Shaing and E. C. Crume Jr, *Phys. Rev. Lett.*, **63**, 2369 (1989).
  - H. Biglari, P. H. Diamond, and P. W. Terry, *Phys. Fluids B* **2**, 1 (1990)
  - **Y.Z. Zhang and S.M. Mahajan, *Phys. Fluids B* 4 1385 (1992).**
- Start with generic fluid equation

$$\partial_t \xi + \boxed{\bar{v}(x)\partial_y \xi} + \boxed{\tilde{v}(x,y,t)\partial_x \xi} = q(x,y,t)$$

- How do fluctuations decay under combined **advection from shear flow** and **turbulent flow**?
- Balanced with generic **gradient drive**:

$$\boxed{\frac{\langle \tilde{T}^2/T_0^2 \rangle}{\tau_c} = \frac{D}{L^2}}$$

Result: Prediction of Suppression Given Shear Rate

Solve polynomial equation: $P(P - \frac{1}{3})(P - 1) = \frac{2}{3} W^2 P^{2\alpha}$

For suppression level: $P^{-1} \equiv \frac{\Delta_{x0}^2}{\Delta_x^2} \frac{\langle \tilde{T}^2 \rangle}{\langle \tilde{T}_0^2 \rangle}$

For a given shear rate: $W = \gamma_{E \times B} \tau_{c0} \Theta$

Anisotropy Factor:
$\Theta = \Delta_x / \Delta_y$

Need relation between nonlinear diffusivity and fluctuation amplitude:

$$D = D_* \langle \tilde{T}^2 \rangle^\alpha$$

Experimental Observations: Favorable Comparisons with Zhang-Mahajan 92

TEXTOR: Boedo et al Nucl. Fusion **42** (2002)

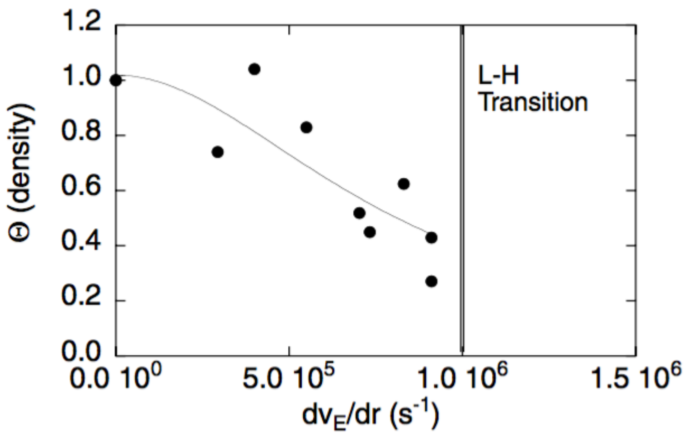
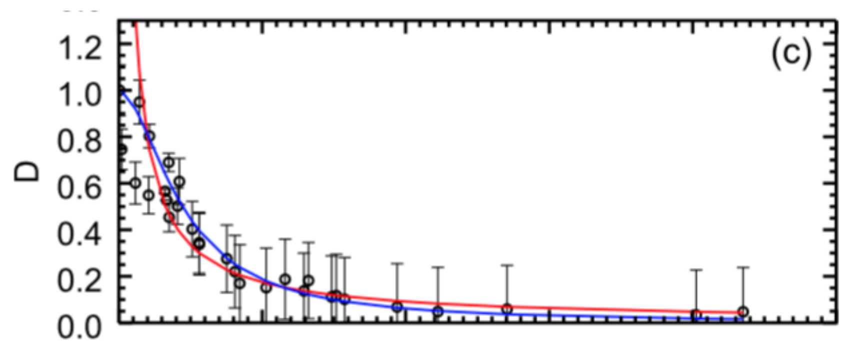


Figure 4. Scaling of normalized density fluctuations with shear (solid circles) and the fit by the ZM prediction (solid curve). The shear at which the L–H transition occurs is indicated.

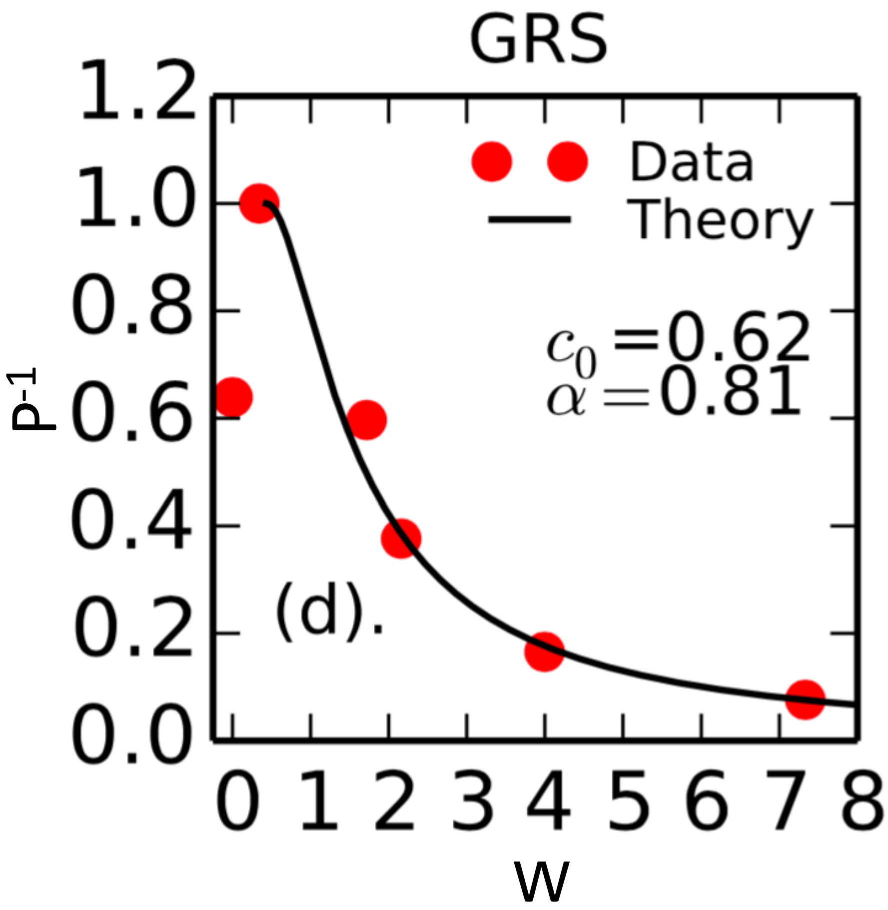
LAPD: Schaffner et al Phys. Plasmas **20** (2013)



Shear Rate

Comparison: Global ρ* Scan

- Global simulation (includes profile variation)
- ρ* scan (fixing other dimensionless parameters)
- Generalization of Zhang-Mahajan to include intrinsic ρ* effects
- E_r set self-consistently by neoclassical

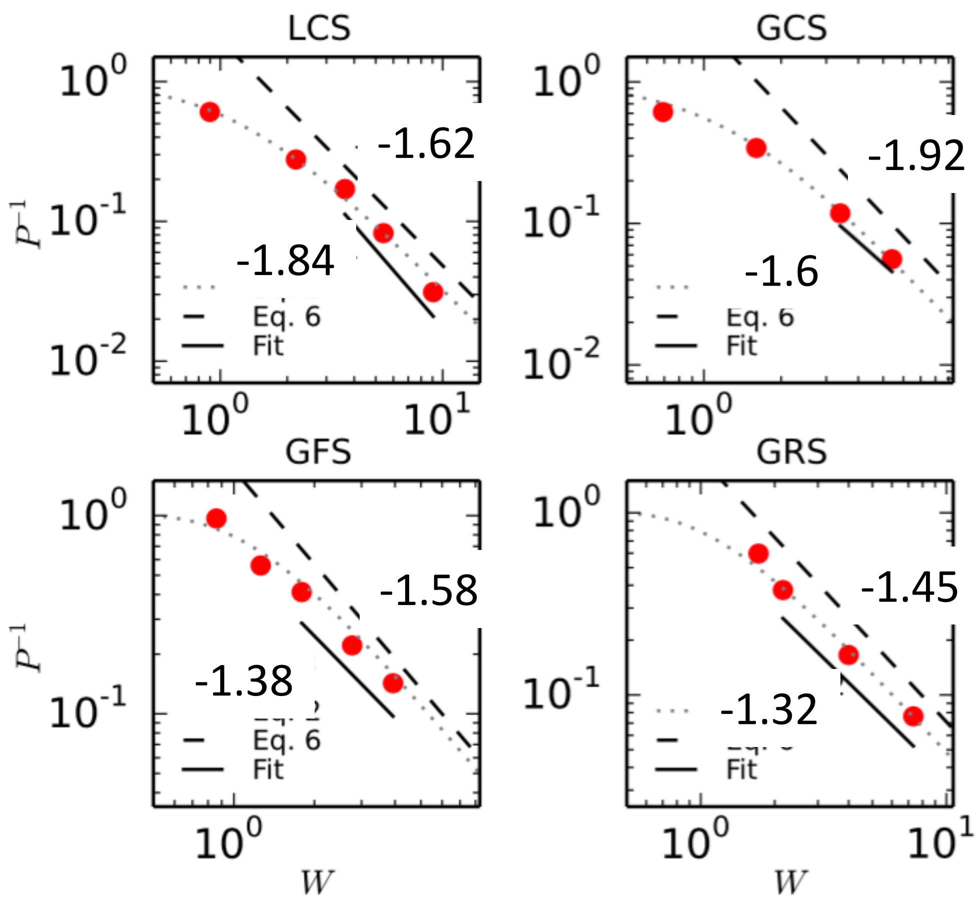


Agreement Also in Asymptotic Limit

- Strong shear limit:

$$P^{-1} = (2/3)^{1/(2\alpha-3)} W^{2/(2\alpha-3)}$$

- Scaling strongly dependent on α
  - Strong check on internal consistency: empirical values of α consistent with asymptotic scaling



Implications for Pedestal Transport

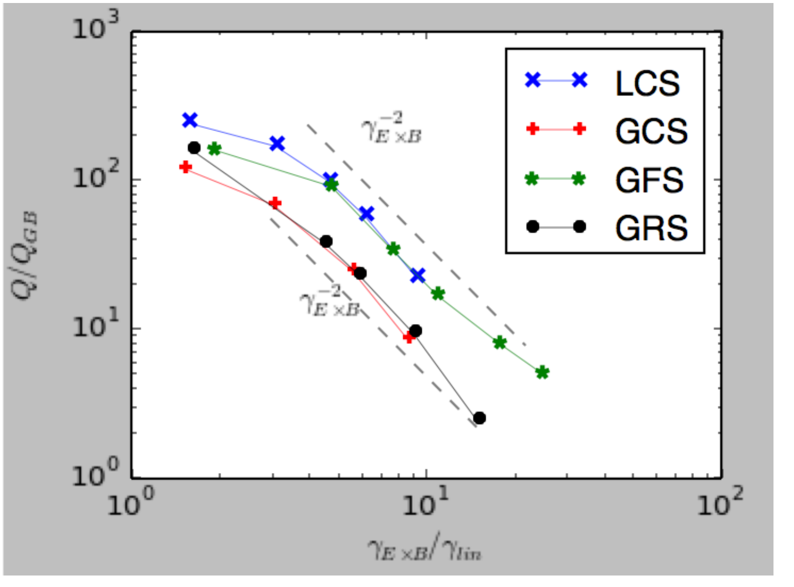
- Rough translation:

$$Q/Q_{GB} \propto \rho_*^{-2}$$

- ITG pedestal transport is 2 factors of ρ* less favorable than gyroBohm, 1 factor worse than Bohm (i.e. no scaling with gyroradius)

- Possible result: severe limitation on pedestal top T (like JET-ILW)

- Note: This is not only an ITER problem. Any low ρ* device (i.e., ARC) is potentially susceptible. Future machine design needs to take this into consideration (good divertor would help, etc)



Optimizing Pedestal Transport

- ExB shear rates likely difficult to modify
- Lots of potential avenues for decreasing growth rates:
  - Pedestal ITG growth rates very sensitive to $\eta = L_n/L_T$ (which varies greatly in experimental pedestals)➔how to manipulate it? Most obvious: improved divertors to decrease separatrix density
  - Transport strongly decreased by impurity seeding (ion dilution)
  - Geometry: high beta_pol (e.g. hybrid operation) appears to be beneficial

Table 3. Transport losses for ITER pedestal for different parameters.

Transport (MW)	$Z_{eff} = 1$	$Z_{eff} = 2$ (nitrogen)	$Z_{eff} = 2$ high n_{SEP}/n_{PED}	$Z_{eff} = 2$ low n_{SEP}/n_{PED}	$Z_{eff} = 2$ width $\times$ 1.5	$Z_{eff} = 2$ width $\times$ 0.67
Total	500	180	500	60	210	130
ETG only	25	17	34	12	13	20

Kotsch. et al NF 2017

Interesting Open Questions

- Multi scale in pedestal
  - Pedestal ETG is slab-like (isotropic instead of streamers). Are multiscale interactions different? Interaction with background-shear-dominated (not ZF mediated) ITG? Interaction with microtearing?
  - Triple scale interaction?
    - Very low n MTM
    - Intermediate ITG
    - High k ETG
- Is there (when?) an ITG particle pinch?
- Can we model KBM? Other MHD modes?
- Dynamic interaction between NC and turbulence?
- Edge-motivated GK orderings—what changes?
- Sepratrix boundary condition, cross-separatrix coupling?

Rederivation of Zhang-Mahajan

- Using BDT orbit equations and ZM derivation (result is very similar to ZM 92)

Construct two point correlation function

$$C_{12} \equiv \langle \xi(x_1, y_1, t)\xi(x_2, y_2, t)\rangle \equiv \langle \xi_1 \xi_2 \rangle$$

Evolves (in center of mass coordinates):

$$(\partial_t + \omega_s x_- \partial_{y_-} - \partial_{x_-}(k_{0i}^2 x_{i-}^2) D \partial_{x_-}) C_{12} = Q$$

Diffusivity:

$$D \equiv D_{11} = \tau \langle \tilde{v}_1 \tilde{v}_1 \rangle$$

Take "moments" of Green's function:

$$M^{ij}(t) \equiv \int \mathrm{d}\boldsymbol{x}\, G(\boldsymbol{x}, t; \boldsymbol{x}_0, 0) x^i x^j$$

Resulting system of equations (algebraic when d/dt → ω):

$$\begin{aligned}
\partial_t M^{11} &= 2Dk_\perp^2 \left(3M^{11} + \sin^2\theta M^{22}\right) \\
\partial_t M^{12} &= \omega_s M^{11} + 2Dk_\perp^2 M^{12} \\
\partial_t M^{22} &= 2\omega_s M^{12}
\end{aligned}$$