GYROKINETIC ANALYSIS OF PEDESTALS

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THE IMPORTANCE OF TRANSPORT IN H-MODE PEDESTALS

- ***Pedestal energy losses determine how much heating power is needed to sustain the pedestal, and hence, the core: this determines the denominator of τ_E***

$$\tau_E = \frac{\text{Stored energy}}{\text{heating power (= energy losses)}}$$

- ***Transport of density and impurities are also important, of course***

To project, and optimize, H-mode burning plasmas,

we must understand the transport in pedestals,

and the instabilities that cause it.

- ***We begin by identifying transport agents in todays experiments***

IDENTIFICATION OF INSTABILITIES CAUSING TRANSPORT IN PRESENT EXPERIMENTAL PEDESTALS: WE USE A NEW CONCEPT

Built on exploiting the "fingerprints" of pedestal instabilities

based on <u>what they do</u>

- ***Specifically: their <u>relative</u> transport in different channels: a very important characteristic, whose consequences have not been realized till now***

These differences among instability types are a consequence of <u>fundamental</u> differences in mode physics: <u>what they are</u>

We interpret multiple experimental observations of transport through these characteristic signatures of potential instabilities

We conclude, turbulent energy transport is dominated by
Micro-Tearing Modes (MTM) and Electron Temperature Gradient modes

Whereas, MHD-like modes (e.g. KBM) may dominate density transport

The “transport fingerprints”

- Uniquely different physics of these modes leads to their “fingerprints”, by using:
  - Basic analytic kinetic theory
  - Gyrokinetic simulation

MODE:	χ_i / χ_e	D_e / χ_e	$\frac{D_{Impurity}}{\chi_e}$	Inward particle pinches	Shear Sup-pressed?
MHD-like (e.g. KBM)	~1	~2/3	~2/3	No	NO
MTM	~0	~0	~0	No	NO
ETG	~0	~0	~0	No	NO
ITG/TEM	$\geq$ 1	-0.2 - 1	~ 1	Sometimes	Usually

Note:

$D \equiv \Gamma /(dn/dx)$

$\chi \equiv Q /(dT/dx)$

- Since velocity shear is strong in a pedestal, only a few types of modes can escape shear suppression (the above)

Preview of talk

A. We'll consider experimental observations in several channels, and apply the transport fingerprint concept

A. Derivation of fingerprints

B. Detailed gyrokinetic simulations (GENE) of two DIII-D discharge pedestals
   - Corroborates the general conclusions in A and B

C. The regime of weak velocity shear suppression of ITG/TEM modes in pedestals with low ρ^* (as in burning plasmas)

Experimental observations of pedestal transport in several channels,

and

Conclusions from applying transport fingerprints

1) T_i channel
2) $n_{Impurity}$ channel
3) n_e channel
4) Transport effects from RMPs

Transport channel T_i : Observed ion heat transport is often neoclassical

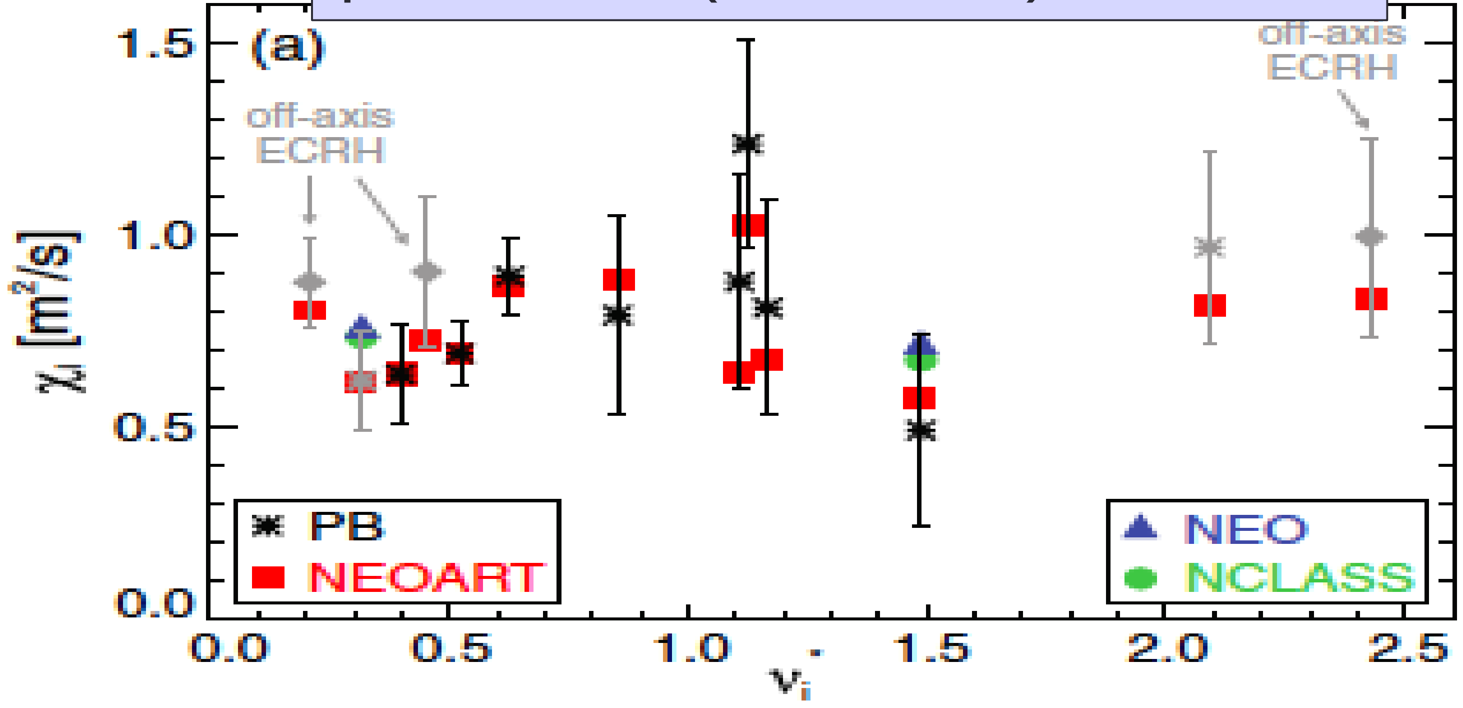
- **ASDEX finds[1] (also DIII-D[2])**
  1) $\chi_i \approx \chi_{neo}$
  2) **But often $\chi_e \sim \chi_i$**
  3) **In this case χ_e >>** $\chi_i - \chi_{neo}$

Ion transport anomaly

- **Recall: MHD-like modes: comparable turbulent χ_i and χ_e**

- **This is inconsistent with MHD-like modes (e.g. KBM) dominating the energy losses**
- **Only modes causing mainly χ_e could dominate turbulent energy losses: MTM and/or ETG**

Experimentally inferred ion χ_i compared to neoclassical code predictions (ASDEX-U)



[1]E. Viezzer et. al. Nucl. Fus. (2017)

[2]J. D. Callen, R. J. Groebner, et. al., Nucl. Fusion 50 (2010) 064004

Transport channel $n_{Impurity}$: Observed impurity transport is often neoclassical

Observed Inter-ELM impurity transport is roughly neoclassical (accumulation)

- Quantitatively agreement on ASDEX[1], C-mod[2]
- Other tokamaks: qualitative agreement

⇒

ELMs are typically needed to expel impurities

- Inter-ELM transport INSUFFICIENT
- BUT, Inter-ELM transport expels MOST energy

IF **inter-ELM MHD-like modes (e.g. KBM) dominated energy losses – *they would* expel the impurities**
So that expulsion would NOT require ELM MHD-like modes

SO: Inter-ELM energy transport must be due instabilities that cause low impurity outward diffusivity compared to energy transport (low D_Z/χ)

SO AGAIN: MTM and ETG are responsible for most energy losses- not KBM- when impurities are roughly neoclassical

[1]T. Pütterich, et. al., J Nucl. Mater 415 (2011) [2]T. Sunn et. al. (2000) Nucl. Fusion 40

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Transport channel n_e : Electron density source is “small”

- **The D_e/χ is estimated to be small on**
  - **JET[1-3]**
  - **DIIID[4,5]**
  - **ASDEX[6,7]**

Uses D_e from ionization source and particle balance, and χ from power balance

- Ionization source is estimated from JINTRAC, EDGE2-D, SOLPS, UEDGE

- **For JET, DIII-D cases: $D_e/(\chi_e+\chi_i)$ ~ 0.07- 0.1**
  - **AGAIN: Too small to be consistent with MHD-like modes dominating power loss**
  - **AGAIN: Only consistent with ETG and/or MTM dominating energy losses; or ITG/TEM if they are not suppressed (their D_e/χ can be small as well)**

[1]F. Koechl et. al. Nucl. Fusion (2017)
[2]L. Horvath, et. al., PPCF (2018)
[3]Kotschenreuther, …., C. Maggi, C. Giroud, V. Parail, A. Chankin, et. al., submitted to NF, in revision
[4]J. D. Callen et. al.Nucl. Fusion (2010)
[5]G.D. Porter et. al. Phys. Plasmas (1998)
[6]L.D. Horton et. al. Nucl. Fusion (2005)
[7]A.. V. Chankin et. al. PPCF (2006)

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A remarkably consistent pattern has emerged from diverse transport channels- MTM and/or ETG dominate energy losses (perhaps ITG/TEM on JET), not MHD-like modes (e.g. KBM) (!!)

- **Why is this conclusion found so consistently?**
- **A single ansatz can explain these results**
- **PLUS, it gives conceptual CONSISTENCY with EPED: KBM may enforce marginal stability of pressure profiles in inter-ELM phase**
- **Let us consider a thought experiment……**

Thought experiment: time sequence of inter-ELM pedestal evolution

ANSATZ: source term for n_e is relatively much smaller than for energy

As pedestal steepens in the inter-ELM phase, eventually an MHD-like mode (KBM) becomes unstable, and creates comparable diffusivity in all channels

↓

Since n_e is weakly driven, n_e profile is modified first and most strongly (small D_e suffices)

- **The pressure would be forced to marginal stability by modification of the density profile**
- **T profiles weakly affected: MHD induced $\chi \sim D_e$ would be small compared to power balance requirement**
- **Relatively insignificant energy transport from MHD-like modes**

↓

- **T_e profile would continue to evolve until MTM/ETG saturate it**
- **T_i would be saturated by neoclassical χ plus Coulomb equilibration to e^{-1}**
  - **And the MHD impurity diffusivity $D_{Impurity} \sim D_e$ is small: Impurities still ~neoclassical**
- **If ITG/TEM are not suppressed, they can also saturate T**

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Occam's razor: all previous observations follow, and are consistent with the EPED model, from that single ansatz

Explains experimental observations

- **In diverse channels: T_i, $n_{Impurity}$, $n_{electron}$**
- **And, as we'll indicate: Resonant Magnetic Perturbation transport**

Also gives consistency with EPED: MHD-like modes (like KBM) CAN enforce marginal stability of the inter-ELM pressure profile

- **And yet NOT BE the dominant energy loss mechanism**
- **MHD-like modes could dominate the density profile evolution**
- **MTM/ETG (or also ITG/TEM for JET) would dominate energy losses**

It is very hard to arrive at any other scenario that is qualitatively consistent with all the experimental observations and elements above

Analytical and numerical approaches used to obtain the fingerprints

Using basic kinetic theory: fingerprints of electromagnetic modes are analytically computed

- **Drift kinetic equation is ordered for steep pedestal gradients**
  - *Realistic pedestal conditions included (geometry, full kinetic effects, etc.)*

In the steep gradient region: ω^* is much larger than many other relevant rates, leading to important simplifications

- *Quasi-linear **ratios** of transport in different channels computed*
- ***Results for ratios are independent of details of mode structure***

When $\delta E_{||}$ is small (MHD-like, as in KBM)

- ***All species have similar diffusivities and no pinches***
- *$\delta E_{||}$ small follows when ω in the plasma frame is different from ω_e^**
- *These conditions apply to plasma MHD-like instabilities, i.e. KBM (and RMPs)*

Analytical estimates are corroborated by GENE runs for actual experimental pedestals of JET, DIIID, C-mod (both quasi-linear and non-linear)

Observed transport response to RMPs - further support for conclusions

RMPs, surprisingly, are just like an MHD mode(!!) in the STEEP GRADIENT region. Analysis shows:

⇒Self-consistent plasma response $\delta\phi$ will give $\delta E_{||} \sim 0$ for RMP **(Steep gradient region only)**

⇒**Transport directly induced by RMP has MHD-like fingerprint**

RMP may be considered as an externally driven version of MHD-like mode

- ***Experiments find: RMP causes mainly density transport (pump-out)***
  - Reduces the DENSITY gradient in the steep gradient region
  - DOES NOT reduce or limit the TEMPERATURE gradient

Consistent with our preceding analysis:

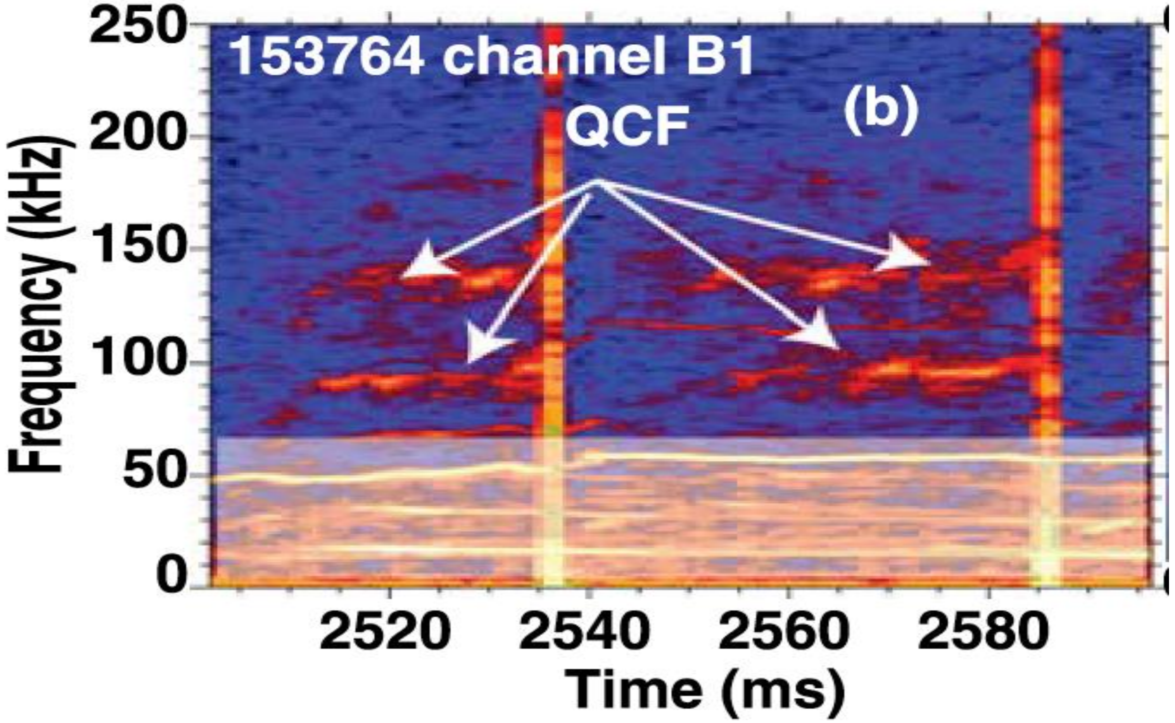
MHD-like modes do not cause primarily energy transport in the steep gradient region

Rather, they cause, mainly, density profile modification

Application of these concepts,
with detailed gyrokinetic simulations using GENE,
to pedestals on two DIII-D shots

Quasi Coherent Fluctuations observed on DIII-D 153764*

- In e^{-1} direction in lab frame
- Doppler shift (from measured E_r) relatively small, so
- In plasma frame, QCF ω is in electron direction, magnitude ~ ω_e*
- Consistent with MTM, not KBM



Local linear gyrokinetic GENE results:

- MTM robustly unstable, also some KBM

Including local Doppler shift, frequencies in lab frame of these:

- KBM ω ~ 4 x too low
- MTM ω ~ 2 x too high
- Nonlinear effects bring MTM ω closer to observations

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

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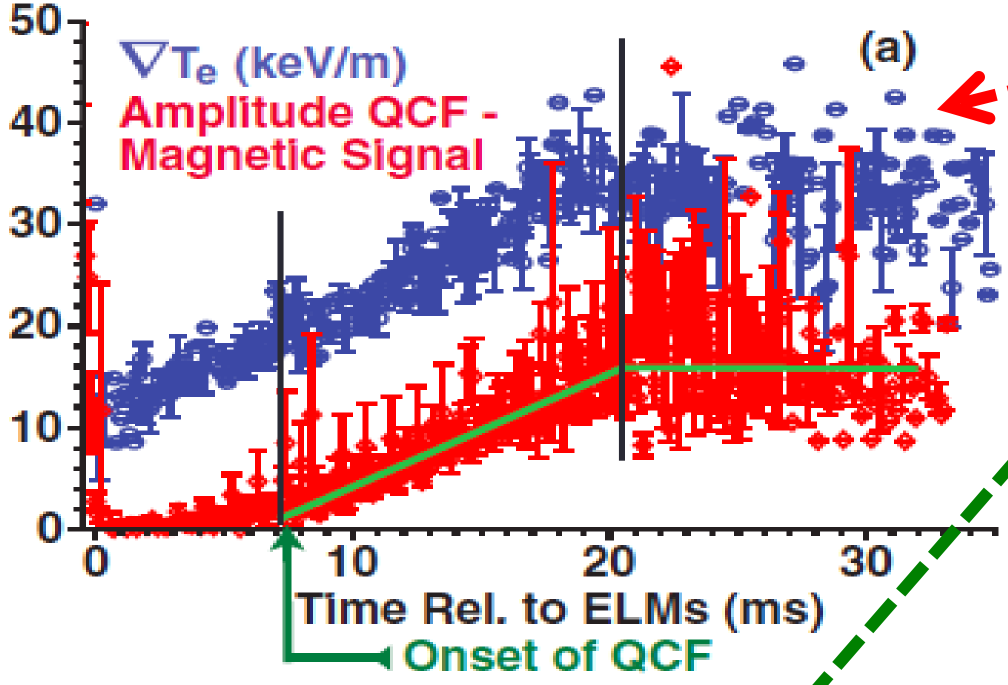
Inter-ELM evolution of profiles on DIII-D153764*

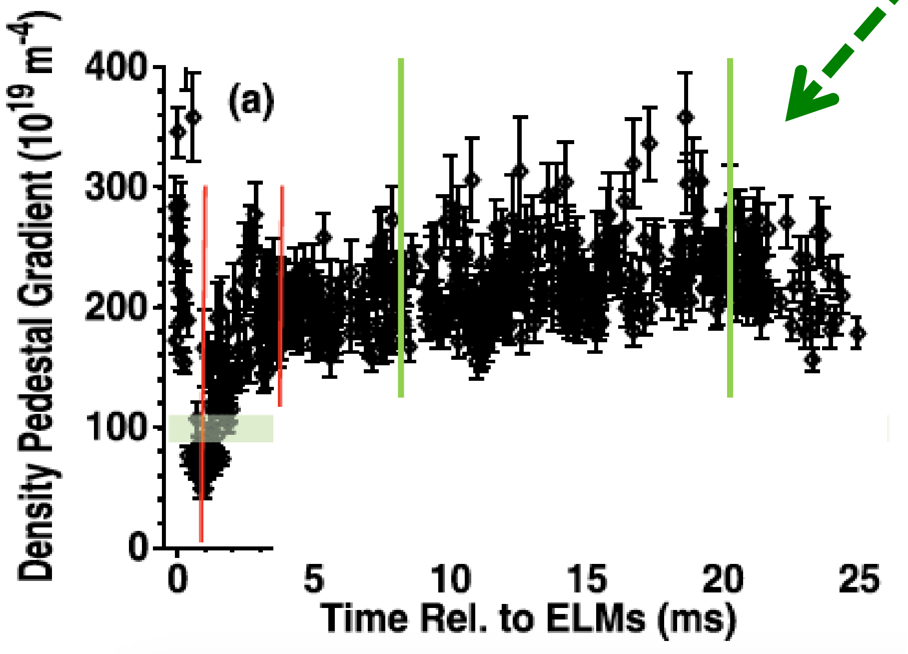


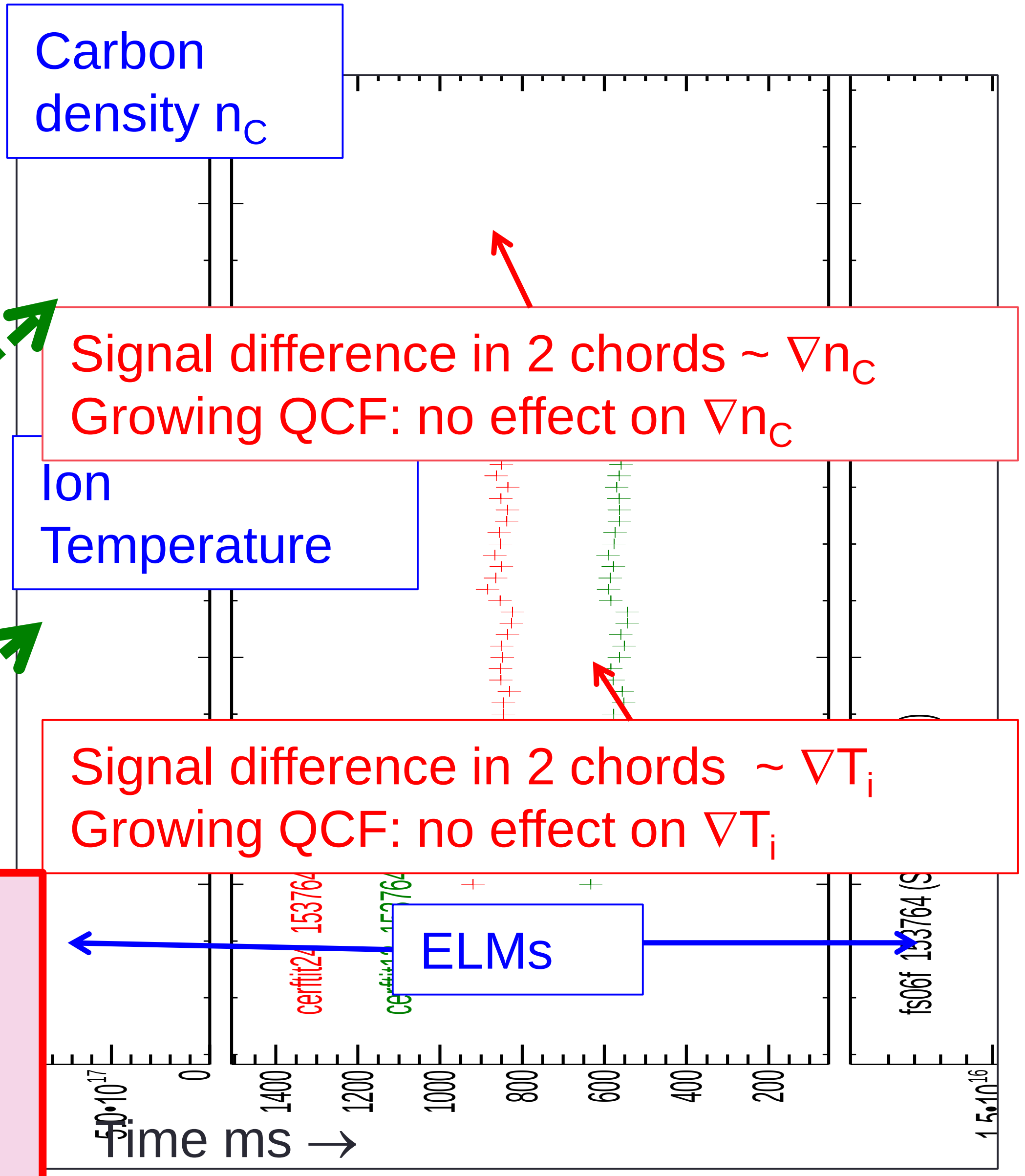
Growing QCF highly correlated* with ∇T_e

Growing QCF: NO effect on ∇n_e

Growing QCF: NO effect on ∇n_{Carbon}

Growing QCF: NO effect on ∇T_i





Inter ELM Evolution:

- **Consistent with MTM**
- **Inconsistent with KBM**

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

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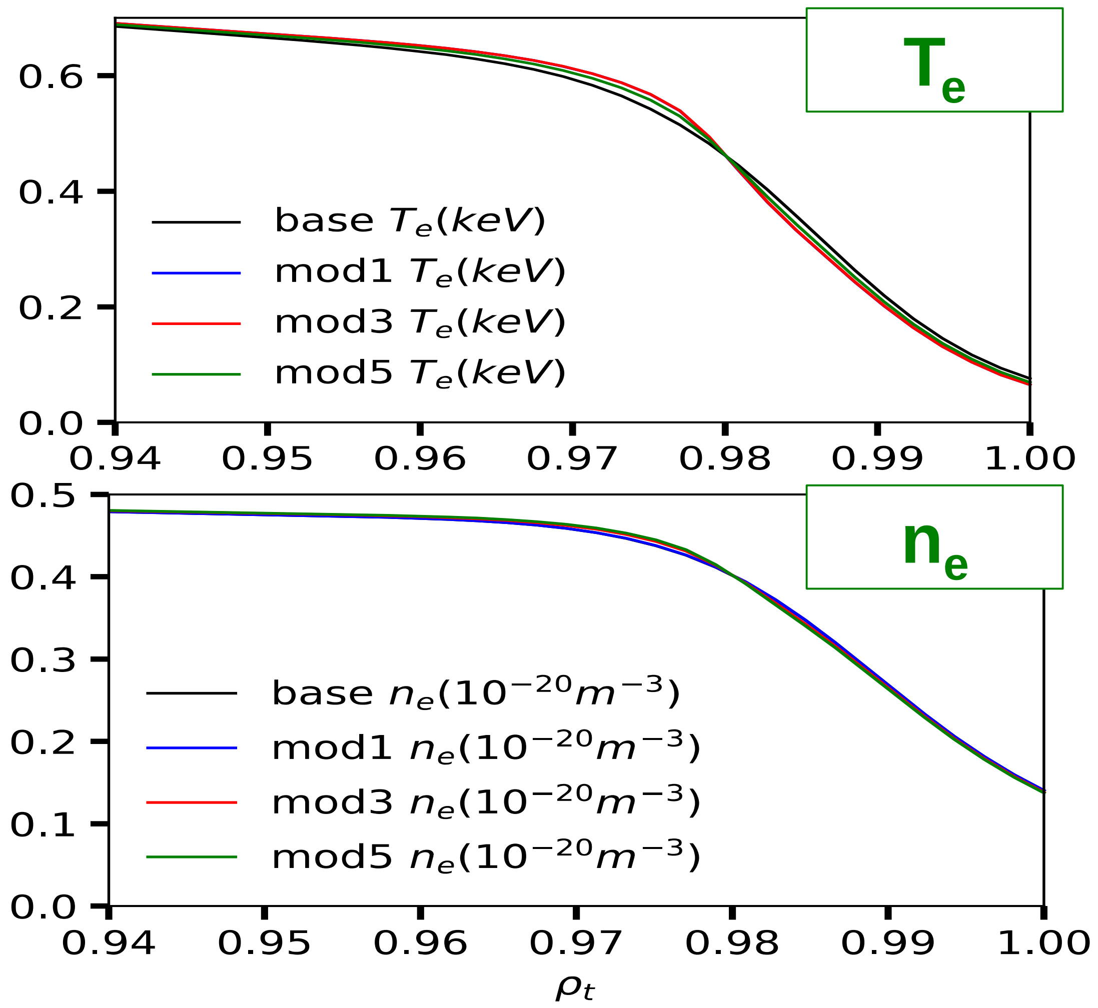
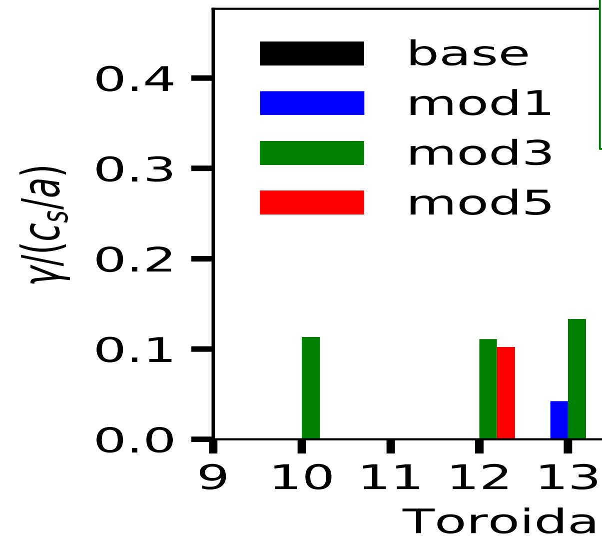
DIII-D 153764: Global MTM instability spectra match QCF

- Varied profiles within error bars, computed new self-consistent MHD equilibria





GENE Growth rates vs toroidal mode number

Toroidal n instability spectrum:

- **Always isolated, sparse instabilities in n**
- ***This should lead to coherent fluctuations just as observed*** **(rather than broadband)**
- Actual n numbers of instability are very sensitive to small profile changes
- Mod 5 within ~ 10% of measured QCF k_θ
- Linear frequencies still ~ 2 x higher

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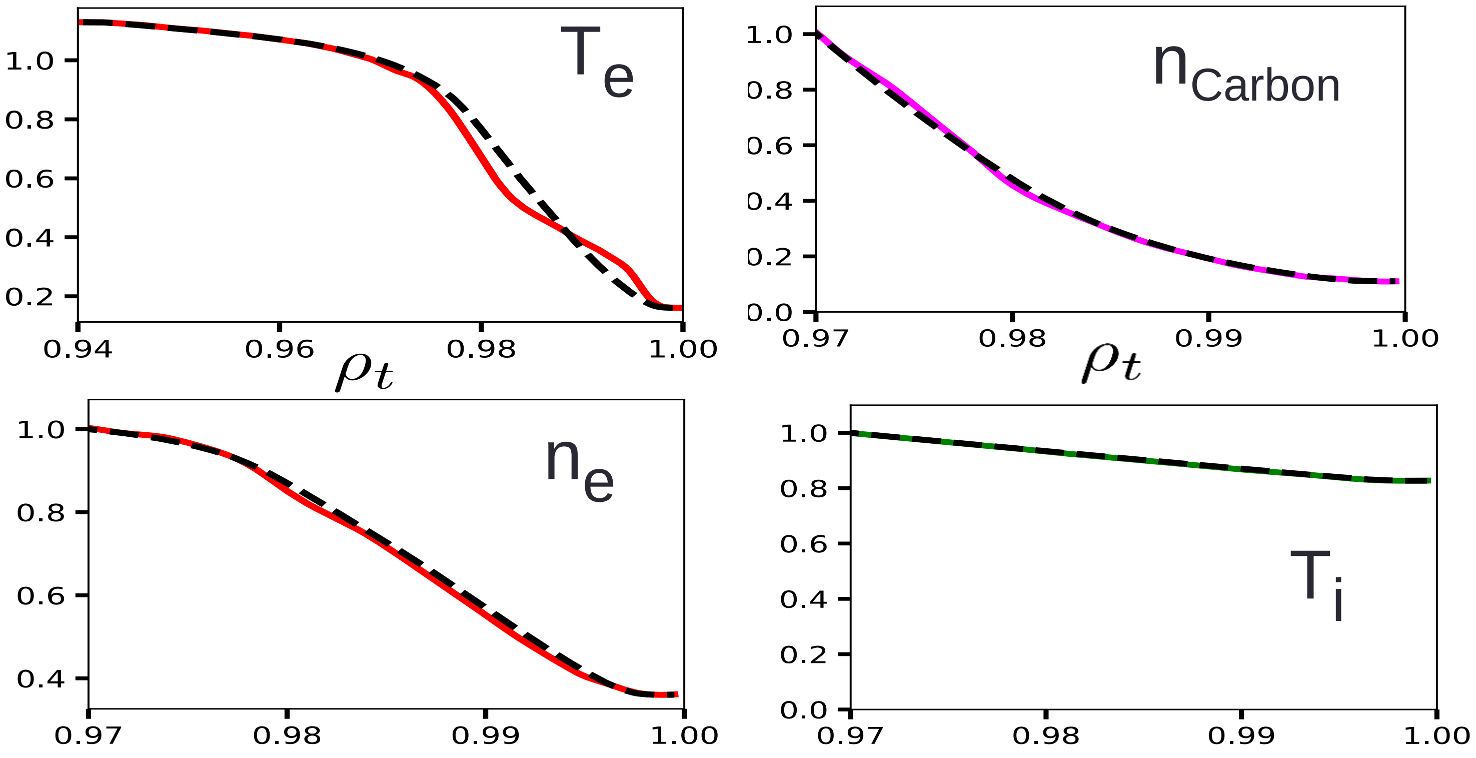
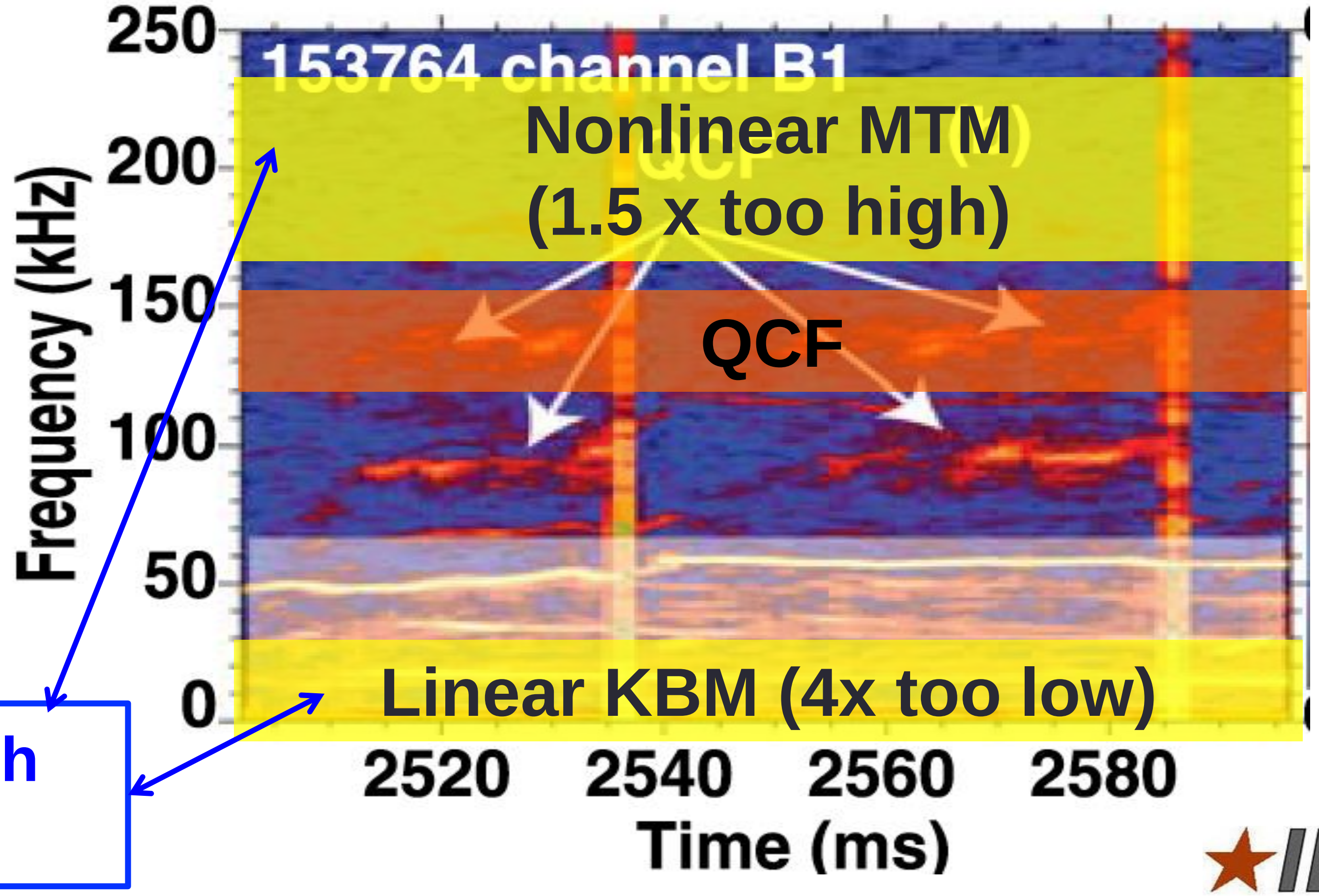
DIII-D 153764 Nonlinear Global MTM Simulations

MTM QCF **ONLY** affect T_e profile
Not other channels
Consistent with observations



Mode Type	Frequency (kHz)
MTM (global linear)	-350
MTM (non-linear downshift and broadening of linear frequency)	~ - 200 (strong nonlinear downshift by 40%)
KBM (local linear)	~ -35



Mod 5 case: MTM roughly match QCF frequency, not KBM

DIII-D 153764 nonlinear simulations (cont.)

- Heat loss from ETG and MTM varies by factor of several for the different profile modifications
- Mod 5 case close to matching power balance
- ETG + MTM give ~ 2 MW losses
- Close to experimental loss ~ 3 MW

DIIID 98889 results[1]

Published transport analysis & spectrogram:

- χ_i ~ neoclassical
- $\chi_e \sim 2\chi_i$
- D_e ~ is order of mag. smaller than χ_e
- Spectrogram: two QCF f ~ 200-300 kHz (e^{-1} direction)

Only consistent with MTM/ETG, not KBM

GENE results (global)

- Qualitatively similar to 153764:
- MTM are only significant instabilities, and roughly consistent with observations
- Nonlinear MTM:
  - Give ~ 2.6 MW electron heat transport, roughly similar to 1.9 MW from transport analysis
  - Low instability induced transport in all other channels
  - Two QCF with freq ~ 1.5 x observed (e^{-1} direction)

[1]J. D. Callen, R. J. Groebner, et. al., Nucl. Fusion 50 (2010) 064004

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WE TURN NOW TO ITG/TEM MODES

In past publications, our GENE simulations find that these can lead to excessive energy transport in the pedestal of ITER and JET-ILW

[1]M. Kotschenreuther, D.R. Hatch, S. Mahajan, Nucl. Fusion 57 (2017) 064001
[2]D.R. Hatch, M. Kotschenreuther, S. Mahajan, et. al., Nucl. Fusion 57 (2017) 036020
[3]Chang et al Nucl. Fusion **57** (2017) 116023

Pedestal ITG simulation results agree with the analytic theory of velocity shear suppression of Zhang & Mahajan*

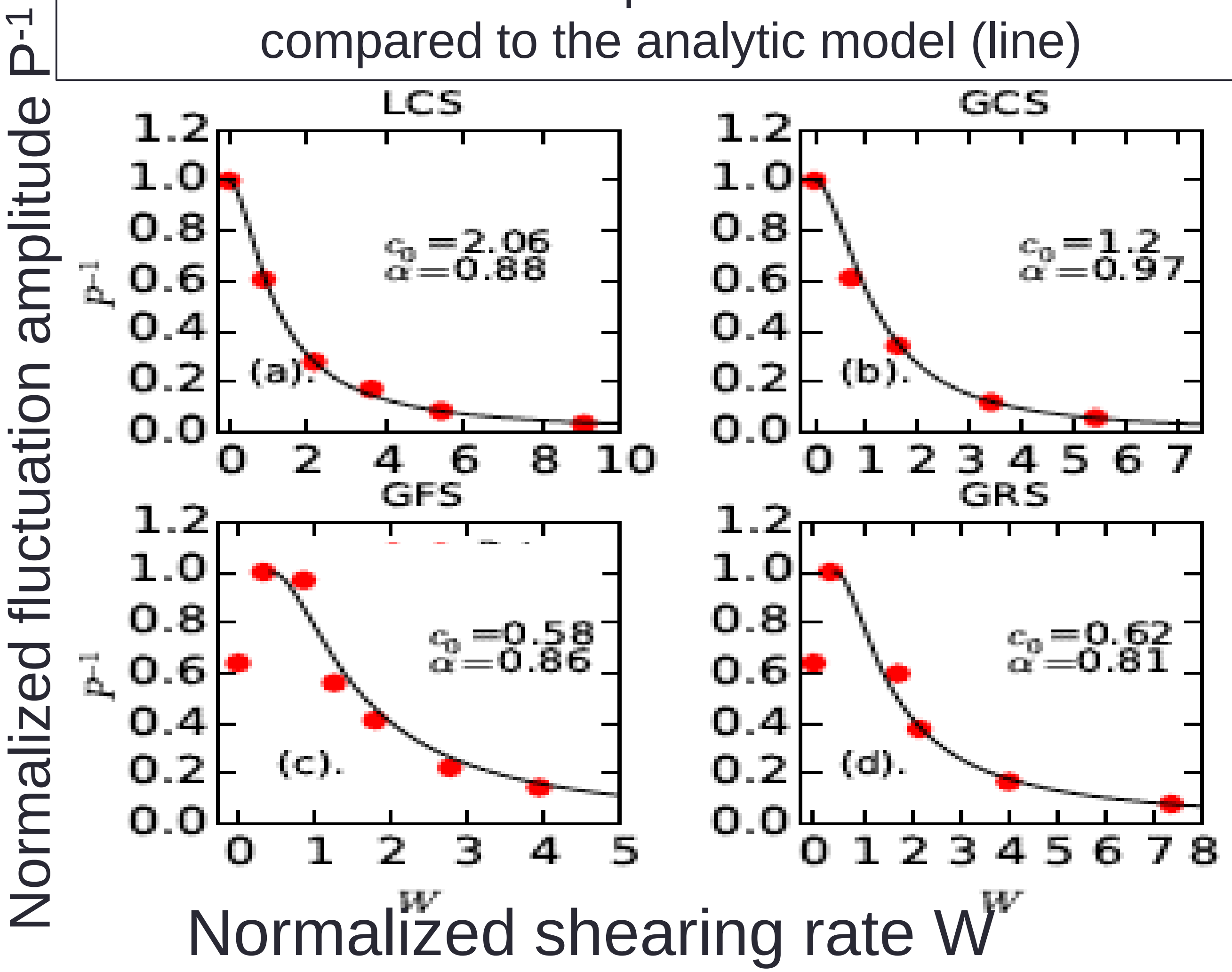
- ***The transition from strong to weak shear suppression is described by this analytic theory***
- ***Agreement between theory and simulations is excellent***
- ***This corroborates simulation results[1-3]:***

> ***1) ITER is in the regime of weak shear suppression***
> ***2) Most present experiments are in the regime of strong suppression***
> ***3) JET-ILW on borderline***

- ***Hence, ITER may need to operate in regimes of weak ITG/TEM instability***

*Y. Z. Zhang and S. M. Mahajan, Physics of Fluids B, **5**, (1993) 2000

GENE simulations (dots) of shear suppression of ITG in a pedestal compared to the analytic model (line)

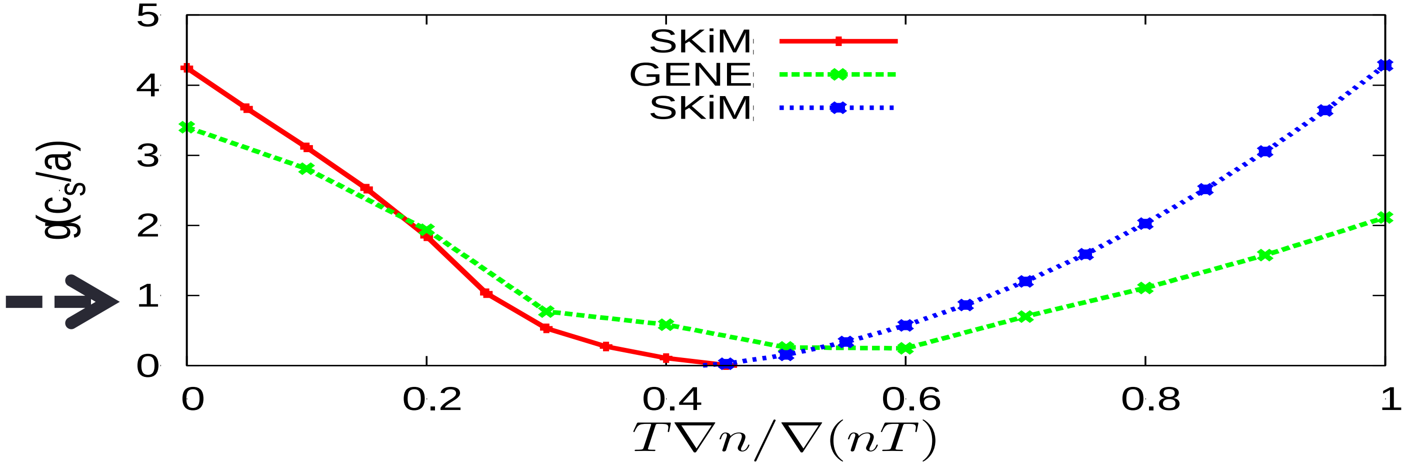


[1]M. Kotschenreuther, D.R. Hatch, S. Mahajan, Nucl. Fusion 57 (2017) 064001
[2]D.R. Hatch, M. Kotschenreuther, S. Mahajan, et. al., Nucl. Fusion 57 (2017) 036020
[3]Chang et al Nucl. Fusion **57** (2017) 116023

Regimes of weak ITG/TEM instability in pedestals

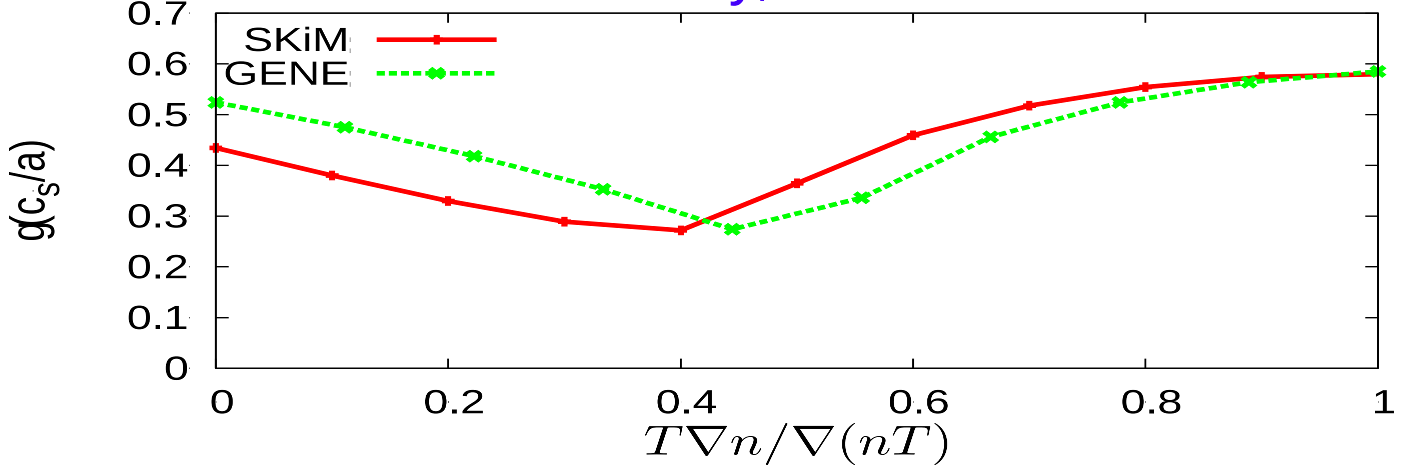
- ***Pedestal ITG/TEM are dramatically stabilized by density gradients (& impurities, high β_{pol})***
- ***This is quite different from core-like modes***
- ***Have developed analytic Simplified Kinetic Model (SKIM) for this regime, which agrees with GENE***
- ***It shows how the pedestal ITG/TEM is in a different regime from the core, even linearly, leading to the possibility of stabilization***
- ***Encouraging nonlinear simulations show the linear stabilization effects are robust***

Pedestal Geometry, Pedestal Gradients



Fraction of pressure gradient from density gradients

Core-like Geometry, Core-like Gradients



Fraction of pressure gradient from density gradients

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Conclusions

- **Transport fingerprint concept has been developed**
- **Diverse observations of pedestal transport imply that:**
  - **Inter-ELM Energy losses dominated by MTM and/or ETG or drift modes**
- ***Detailed* gyrokinetic analysis on two pedestals on DIII-D has, for the first time, identified QCF seen in magnetic probes as MTM instabilities**
- **QCF from MTM, like those observed, can lead to large energy transport**
- **Analytic models of velocity shear suppression agree well with simulations**
- **Regimes of weak ITG/TEM instability have been found and understood analytically; these may be needed for H-mode burning plasmas**

Back-up slides

ACKNOWLEDGEMENTS

- ***This work has been a collaboration between several institutions***

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Gyrokinetic simulations with GENE confirm the analytic theory

Discharge	Simulation Type	Mode Type	$\lvert \mathbf{b} \cdot \delta E_{\parallel} \rvert$	D_e/χ_e	D_Z/χ_e	χ_i/χ_e	$\frac{\langle \omega_{pl} \rangle}{\langle \omega^* \rangle}$	$\frac{Q_{ES}}{Q_{EM}}$	n
JET-C 78697	Gl. Lin.	MHD	0.03	0.89	0.43	0.44	5.21	1.3	4
	Gl. Lin.	MTM	0.41	0.01	0.01	0.01	-0.65	0.06	8
JET-ILW 82585	Gl. Lin.	MTM	0.43	0.01	NA	0.01	-0.92	0.2	14
C-mod 1120815027	Gl. Lin.	MHD	0.18	0.80	0.74	1.05	0.57	8.4	11
	Gl. NL	MHD		0.67	0.50	0.86		22.	11
	Gl. Lin.	MTM	0.43	0.04	0.05	0.07	-1.65	0.13	10
DIII-D 153764	CG Lin.	MTM	0.51	0.01	0.01	0.01	-0.94	0.01	14
	CG NL	MTM		0.01	0.01	0.01		0.01	14
	Gl. Lin.	MHD	0.11	0.78	0.77	1.29	0.35	5.78	26
	Loc. Lin.	MHD	0.18	0.70	0.71	1.00	0.01	340.	26
DIII-D 98889	Gl. Lin.	MTM	0.56	0.04	0.06	0.08	-0.71	0.41	18
	Gl. NL	MTM		0.02	0.03	0.03		0.18	18
	Gl. Lin.	MHD	0.06	0.54	0.65	0.71	0.51	14.8	12

Table 1: A summary of simulation results for several experimental pedestals. MHD modes are shaded. Simulation type is either 1) Global (Gl.:full profile variation) 2) taking the gradients to be constant over the pedestal using values at the mid-pedestal (CG) or 3) local linear (Loc. Lin). Simulations are either linear or nonlinear. Mode type is either MHD-like or MTM. The MTM have an electron heat flux which is strongly dominated by the magnetic contribution relative to the electrostatic one ($Q_{ES}/Q_{EM} << 1$) distinguishing them from modes where the ExB convection dominates ($Q_{ES}/Q_{EM} > 1$). The average $dE_{||}$, is indicated by the spatial average (denoted by <…>, weighted by the absolute value of heat flux) of the difference over the sum of electrostatic and inductive fields, $|\mathbf{b}\cdot dE_{||}| = \langle|\mathbf{b}\cdot \mathbf{dE}_{ES} - \mathbf{b}\cdot \mathbf{dE}_{EM}|\rangle/(\langle|\mathbf{b}\cdot \mathbf{dE}_{ES}|\rangle+\langle|\mathbf{b}\cdot \mathbf{dE}_{EM}|\rangle)$. The ratio of frequency in the plasma frame w_{pl} to w^* is found using the same weighed spatial average, normalized to the same weighted average of w^*. For normalization of modes in the ion direction, we use w_i^*, for electron directed modes, w_e^*. Toroidal mode number n is also given.

Applications to JET: washboard modes

- **Magnetic signals on DIII-D, ASDEX are very similar to JET washboard modes***
- **Washboard modes: all the characteristics of MTMs:**
  - Frequency in plasma frame thought to be ~ ω^*_e
  - Amplitude correlates with electron energy transport
  - Don't affect density
  - Apparently don't limit impurity build-up: ELMs still needed for that
  - Our previous analysis of a JET-ILW discharge found that MTM plus ETG could match power balance (Hatch, Kotschenreuther, et. al. Nucl. Fusion 56 (2016) 104003)
- **Recent estimates of the density source term in several JET pedestals[1,2] also finds that, typically, $D_{eff} << \chi_{eff}$**
- **Likely that energy losses are dominated by MTM, ETG – and possibly ITG**
- **ITG to be considered in future paper**

[1]C. P. Perez et. al. Plasma Phys. Control. Fusion 46 (2004)
Also similar behavior for other JET shots we are analysing

[2]F. Koechl et. al. Nucl. Fusion (2017)
[3]F. Koechl, V. Parail, and C. Maggi, private communication

Applications of gyrokinetic picture to JET, DIII-D, C-mod, ASDEX etc.

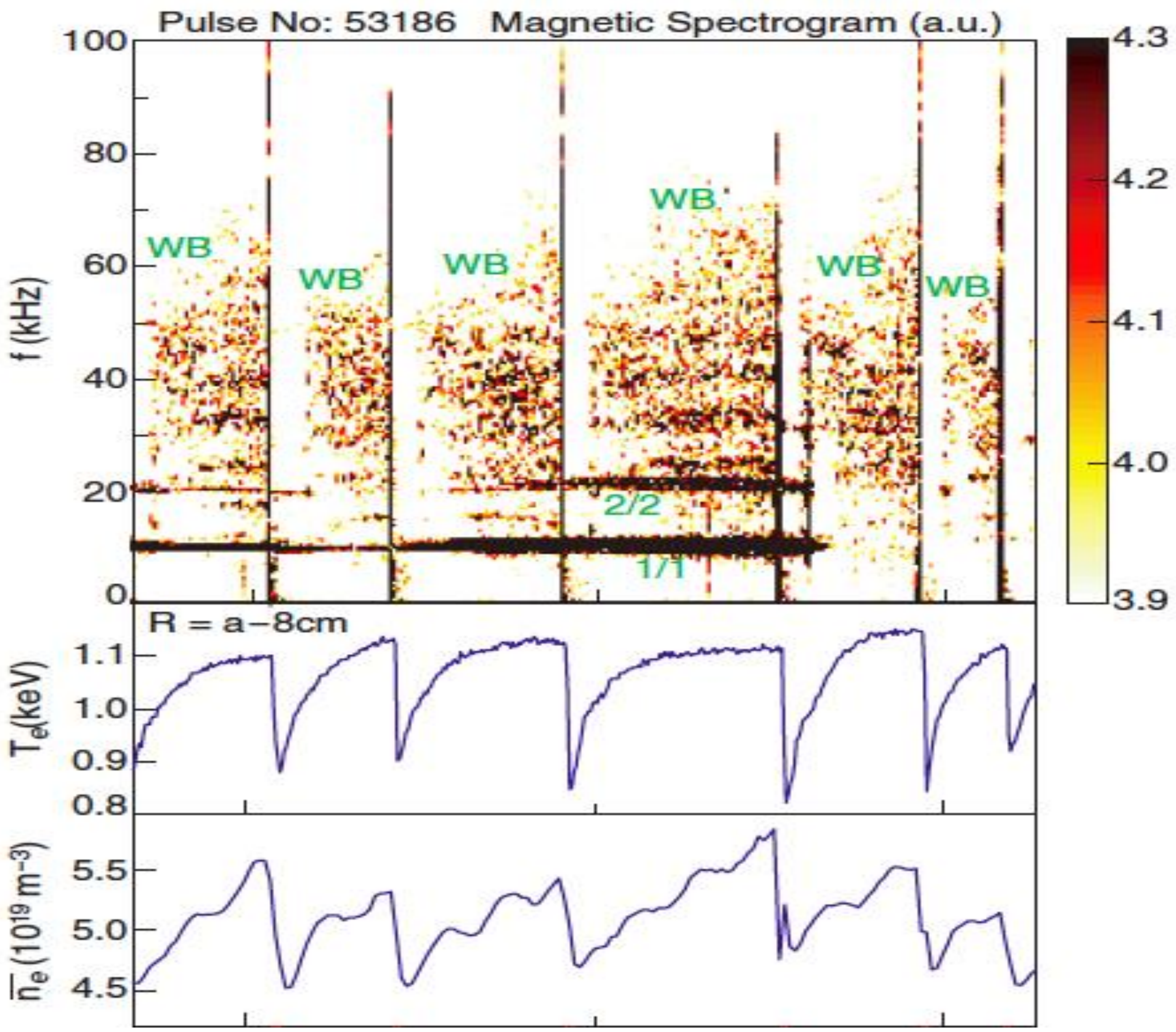
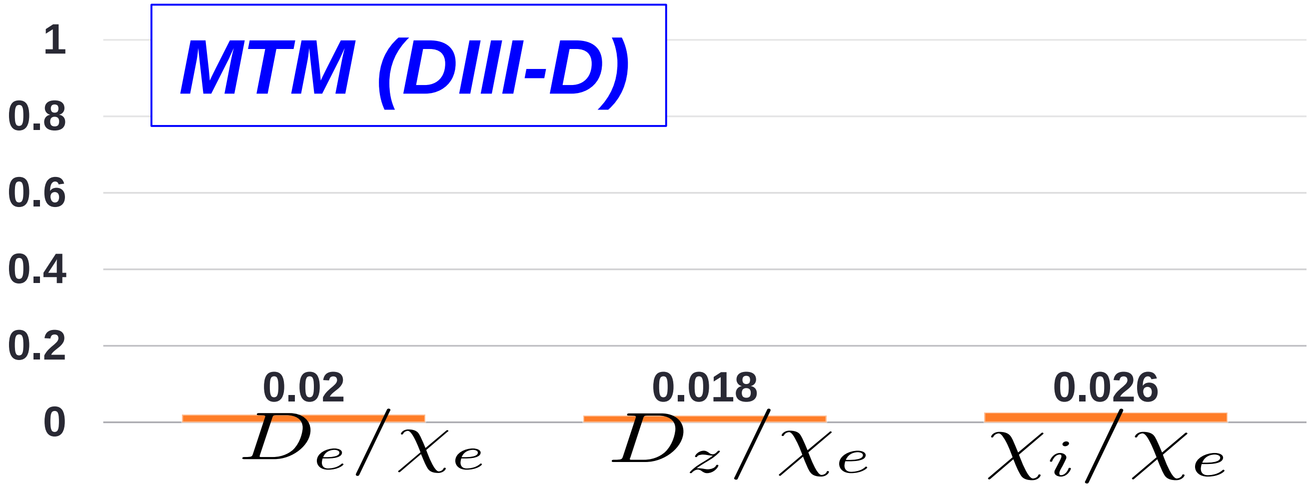
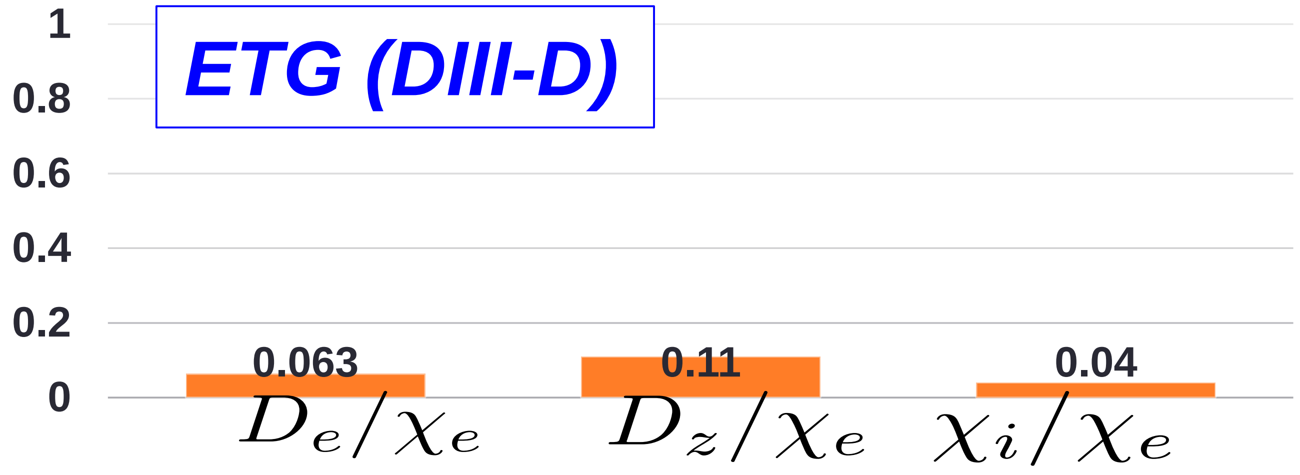


Fig. from C. P. Perez et. al. Plasma Phys. Control. Fusion 46 (2004)
Also similar behavior for shot #78697, under analysis

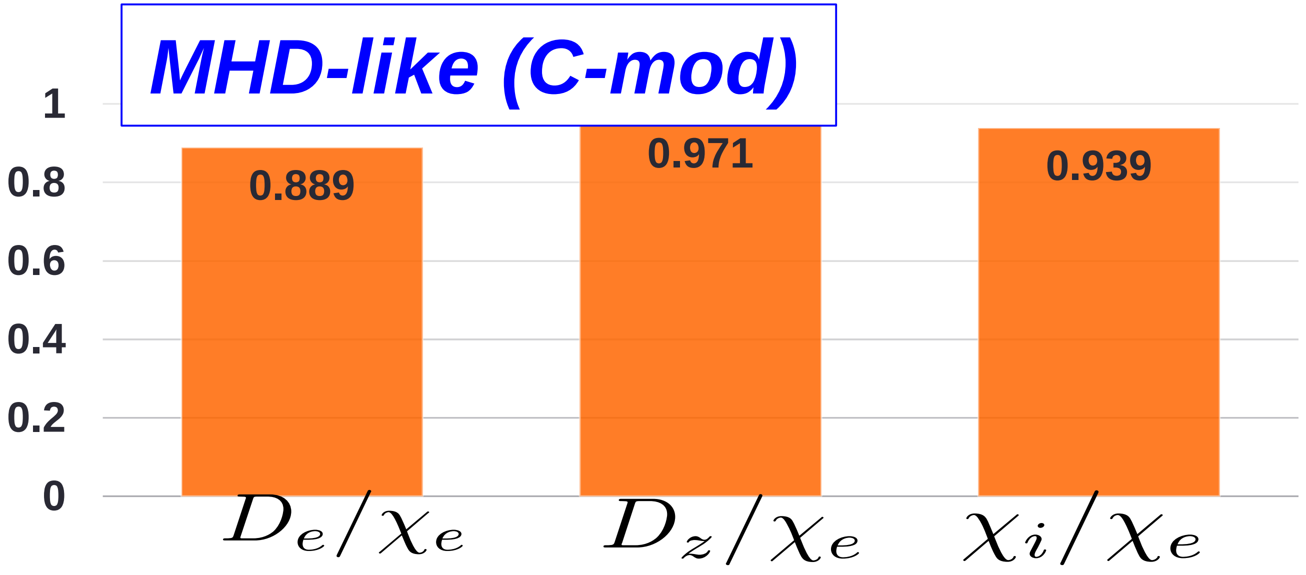
Instabilities: very different effects on transport channels: “transport fingerprint”



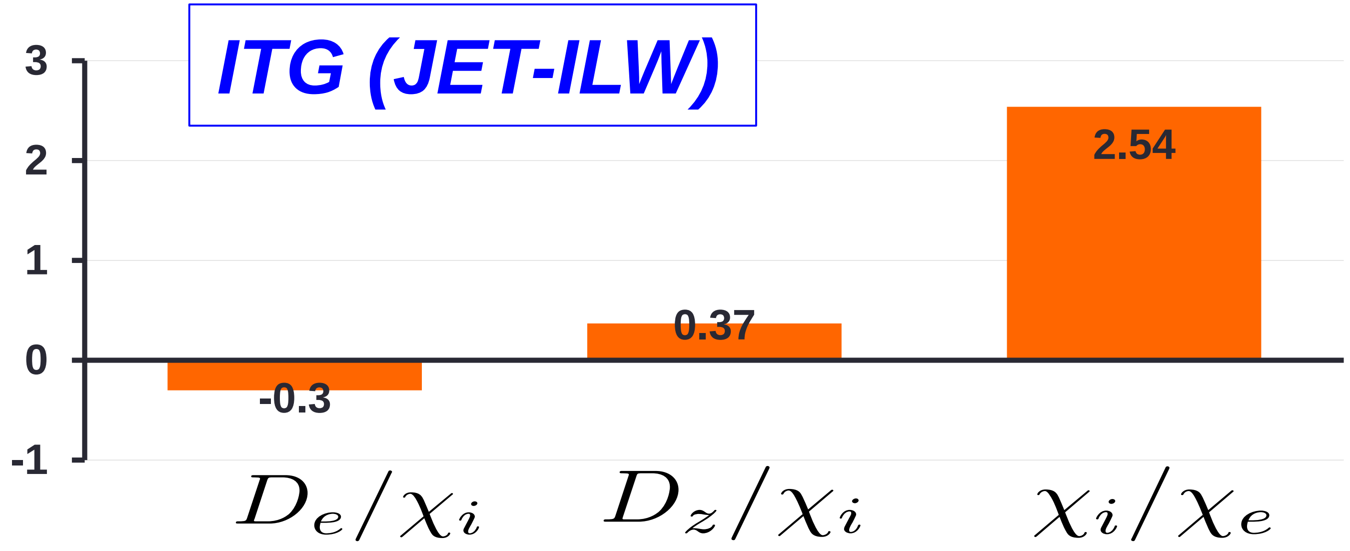
- Magnetic mode driven by ∇T_e
- $\omega \approx \omega_e{}^*$



- 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

Gyrokinetic Quasi-Linear (Q-L) theory: summary of analysis

- Standard manipulations of DKE for linear fluctuations
- Very revealing to subtract out the purely convective response δf_{conv} due only to ExB drift: $d\,\delta f_{conv}/dt + \delta v_{ExB} \cdot \nabla f_0 = 0$
- Obtain an exact kinetic equation for the deviation from this response

$$-i\omega_{pl}\,\delta f_{dev} + (\mathbf{v}_d + v_{||}\,\mathbf{b}) \cdot \nabla\,\delta f_{dev} + C(\delta f_{dev}) = (1-\omega_s^*/\omega_{pl})\,(q_s\,\delta E_{||}/T_s)\,v_{||} + (\mathbf{v}_d \cdot \nabla q_s \phi/T_s)\,(\omega^*/\omega_{pl})\,f_M \quad Eq(1)$$

$$\delta f_{s\,conv} = (\omega_s^*/\omega_{pl})\,(q_s\,\delta\phi/T_s) \quad Eq(2)$$

$\delta E_{||}$ term

drift term

$\omega_{pl} = \omega^* - \omega(r)_{ExB}$ is the locally Doppler shifted mode freq.

$\delta E_{||} = -\nabla_{||}\delta\phi$ □ $i(\omega - \omega(r)_{ExB})$ is in the PLASMA frame

- Eq(1) implies that deviations from purely convective response are driven only by $\delta E_{||}$ and a magnetic drift term
- For steep pedestal gradients, and frequencies ~ ω^*, the drift term is relatively small by ~ L_{ped}/R (very small)
- Hence, MHD-like modes with small $\delta E_{||}$ have a purely convective response in a pedestal
  - Insertion of δf_{conv} into the expression for QL fluxes shows purely diffusive flux with comparable diffusivity for all species

What about primarily electrostatic (ES) modes?

- **A primarily electrostatic mode, necessarily, has a small inductive *inductive $\delta E_{||}$* , *so $\delta E_{||}$ is not small***

- **Transport channels can be very different for ES modes (e.g. ITG/TEM)**

- ***The arguments leading to the criterion for small $\delta E_{||}$ can be obviated for such modes in a pedestal when the passing electrons are highly adiabatic (so*** $\delta j_{||}$ is small even when ***$\delta E_{||}$ is not) that they do not produce much current***
  - ***In other words, the resonant layer is a very small, and relatively little transport happens from that region, unlike electromagnetic modes***

- ***Such ES modes typically have much lower growth rate than KBM, so that velocity shear in a pedestal can often suppress them (JET-ILW is one of the exceptions, as is the low velocity shear I-mode regime in C-mod, and ITER woiuld be an exception too)***

Basic consequence of the DKE and quasi-neutrality:

- **For pedestal parameters, there are two possibilities for modes with strong magnetic perturbations:**

1) ***$E_{||} \approx 0$: an MHD-like mode***
   - ***All transport channels have similar diffusivity***
   - ***This pertains if ω is NOT close to ω_e****

2) ***$\omega \approx \omega_e$* ; a specific ω is needed***
   - ***Transport channels can be very different: mainly electron heat***
   - ***This is the situation for an MTM***

- ***These analytic conclusions are corroborated by many GENE simulations for pedestals on multiple machines***

- ***When magnetic fluctuations are observed in a pedestal, it is of great importance whether $\omega \approx \omega_e$**** **in the plasma frame or not: bears strongly on which transport channels should be affected**

These are algebraic consequences of the DKE

- **Theses results do not depend very strongly on the spatial dependencies of the field fluctuations**

- ***They do not depend on whether the magnetic perturbation has a contribution from currents external to the plasma (RMP)***

- ***They are, primarily, sensitive to the frequency in the plasma frame ω_{pl} , and, whether $\delta E_{||}$ is small in the plasma frame***

The transport fingerprint follows from Drift Kinetic Quasi-Linear (Q-L) theory

- **We apply a steep gradient ordering to the**

- **Gyrokinetic Q-L theory: reasonable estimate for pedestal modes**
  - *Q-L quite successful for relative transport channels in core turbulence*

- **We use the drift kinetic equation (DKE)**
  - Allows for strong equilibrium variations over the fluctuation scales within a formally rigorous ordering
  - Requires small Larmor radius (in total **B**) compared to the pedestal gradient scales L_{ped} and fluctuation scales — satisfied in mid pedestal to top pedestal (marginal near separatrix)

INSTABILITIES AND TRANSPORT IN H-MODE PEDESTALS

- **Candidates for residual transport found in gyrokinetic simulations (by many authors):**

- ***Huge differences in underlying physics***
- ***Commensurate differences in nature of transport, and its projection to burning plasmas***

- *MHD-like -Kinetic Ballooning Mode (KBM)*
- *Electron Temperature Gradient (ETG) mode*
- *Micro Tearing Modes (MTM)*
- *Ion Temperature Gradient/Trapped e Mode (ITG/TEM)*

- **We have found that the instability fingerprint concept is strongly anchored in the fundamental analytical properties of the drift kinetic equation**
- **It has also been verified by our gyrokinetic simulations**

WE TURN NOW TO ITG/TEM MODES

- ***Gyrokinetic simulations (and analytic models, next slide) find that shear suppression of these modes can fail when:***
  - ***ρ* is reduced velocity shear decreases (velocity shear ~ ρ*)***
  - ***low Z impurities are reduced***
- ***At the low ρ* of ITER, simulations find that they cause large pedestal transport[1,2], due to the low velocity shear ~ ρ****
- ***Also predicted to be significant in high field JET***
- ***We consider these modes next…..***

[1]M. Kotschenreuther, D.R. Hatch, S. Mahajan, Nucl. Fusion 57 (2017) 064001
[2]D.R. Hatch, M. Kotschenreuther, S. Mahajan, et. al., Nucl. Fusion 57 (2017) 036020
[3]Chang et al Nucl. Fusion **57** (2017) 116023