Testing H-mode Pedestal Transport Models Through Predictive Simulations

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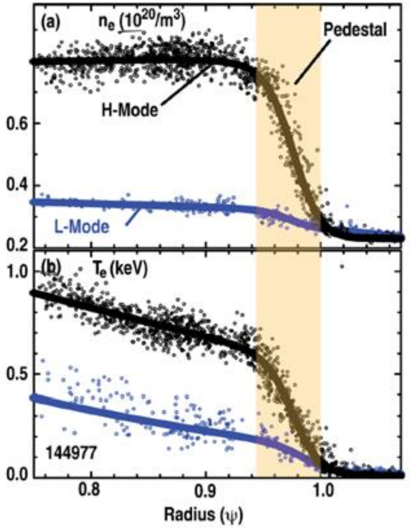
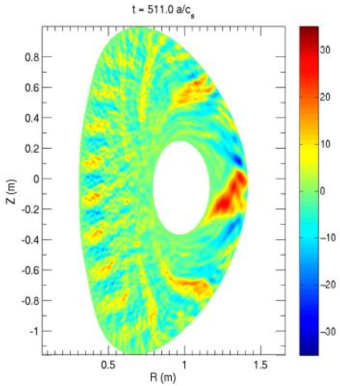
Abstract

A number of theoretical transport mechanisms are predicted to impact the structure of the tokamak pedestal. While collisional diffusion provides a minimum for transport, various turbulent mechanisms and MHD instabilities limit the total temperature, density, and pressure gradients by allowing relatively efficient particle and energy transport. We are particularly interested in these microinstabilities since their role in setting these gradients remains a key research area for predicting fusion performance. This project focused on using transport mechanisms to predict electron temperature and density gradients in the pedestal to test if they can adequately explain experimental data taken from the DIII-D tokamak. This was accomplished by numerically solving coupled transport equations using models based on first-principles simulations in order to predict the steady-state behavior of the gradients. Our results illustrate how the nonlinear mechanisms interact to determine the pedestal structure based on particle and energy source rates.

Background

- H-Mode
  - Sudden jump in core density and drop in number and strength of instabilities
  - Better chance of high fusion gain
- Tokamak Pedestals
  - Large temperature & density gradients
  - Must take several instabilities into account
- Turbulence
  - Responsible for energy and particle transport
  - Limits energy confinement
  - Several different mechanisms responsible
    - ETG, KBM, MTM, ITG, TEM

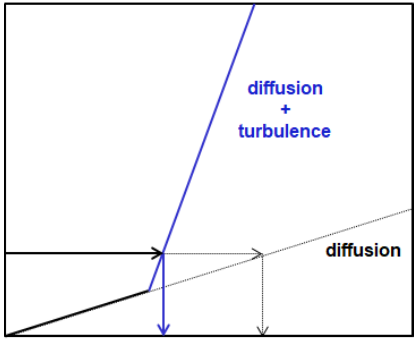




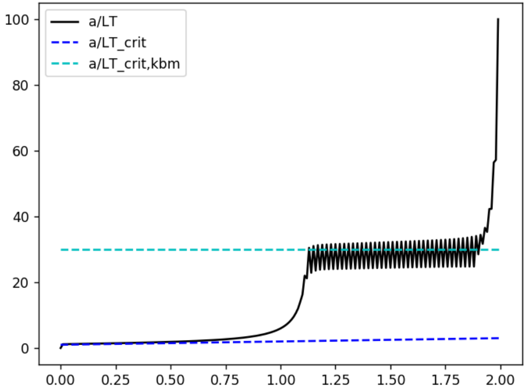
Transport & Instabilities

- Neoclassical Transport (NC)
  - Collisional diffusive process ($D, \chi \sim \langle \Delta x^2 \rangle / \Delta t$)
    - $\Delta x \sim \Delta_{banana}$
- Electron Temperature Gradient (ETG)
  - Non-diffusive, but can be modeled with diffusivity fitted to experimental data from DIII-D[2]
- Kinetic Ballooning Mode (KBM)
  - Plasma reaching pressure gradients too large to be supported by the safety factor, *q*
  - Results in rapid instability, effectively clamping transport

Heat flux ~ heating power



Temperature gradient



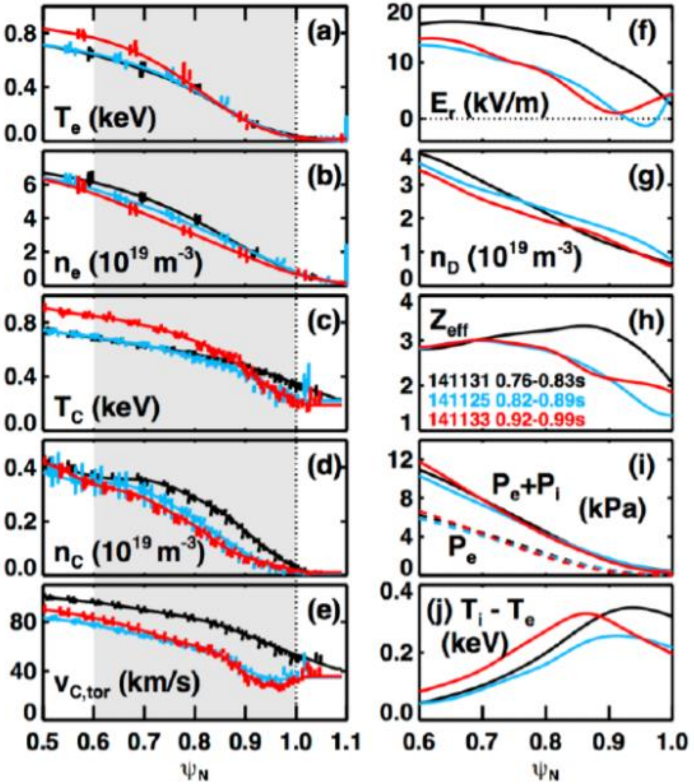
Mathematical Models

- Transport equations written in "closed flux surface" coordinates in terms of particle and heat flux densities
  - $\frac{dn_s}{dt} + \frac{1}{V\prime}\frac{\partial}{\partial r}[V'\langle\nabla r\rangle\Gamma_s] = \sum_k S_{s,k}$ and $\frac{3}{2}n_s\frac{dT_s}{dt} + \frac{1}{V\prime}\frac{\partial}{\partial r}[V'\langle\nabla r\rangle \mathrm{q}_s] = \sum_k P_{s,k}$
- We can write the densities in terms of relevant diffusivities D_s and χ_s
  - $\Gamma_s = -D_s\nabla n_s$ and $q_s = -\chi_s n_s \nabla T_s$
  - Note that both D_s and χ_s are functions of $n, T, \nabla n, \nabla T, \ldots$
- We assume the instability mechanisms can be linearly summed
  - e.g. $\chi_{total} = \chi_{NC} + \chi_{ETG} + \chi_{KBM} + \cdots$
- ETG and KBM transport expressions both of the form:
  - $\chi = \chi_0$ max(0, gradient - threshold)

n_s - specie density
T_s - specie temperature
$\langle\nabla r\rangle$ - avg. rate of change across flux surfaces
V' - flux surface area
q_s - heat flux density
Γ_s - particle flux density
P_s - heat source
S_s - particle source

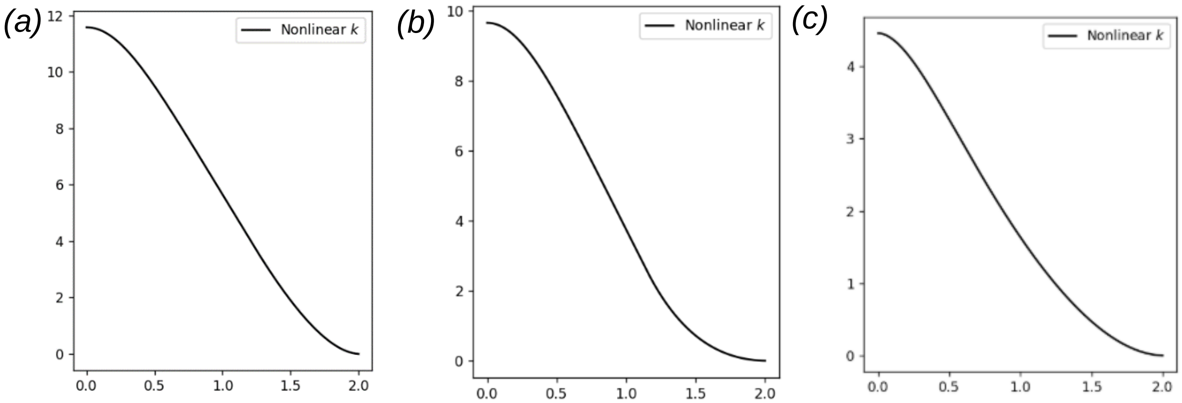
Experimental Data

- Diagnostic data retrieved from DIII-D Tokamak[1]
- Three discharges of interest
  - Different profiles due to transient fluctuations in pressure, ion temperature/density, etc.
  - Can the same transport equations accurately model all 3?
- Relatively large pedestal region
  - Represents ~40% of the normalized coordinate
  - Most pedestals only range from $\psi = 0.8$ to $\psi = 0.95$

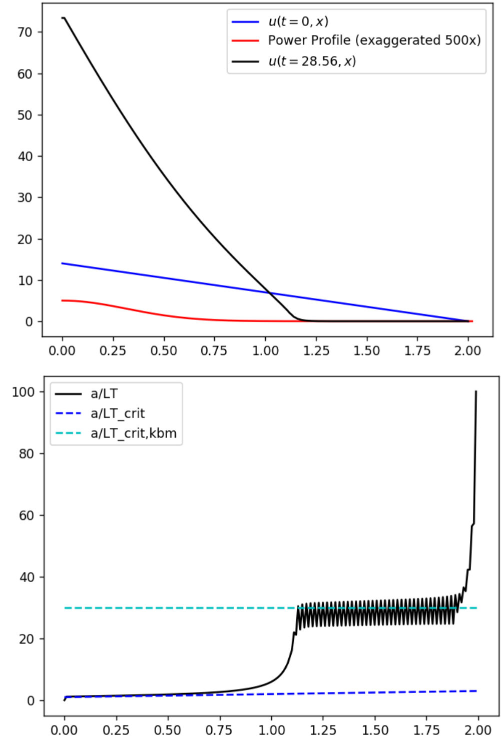


Toy Model

- Treated Transport Equations as modified 1D heat equations with nonlinear diffusivities
  - Solved via forward/central difference scheme with experimental boundary conditions
- Adjusted instability strength and threshold



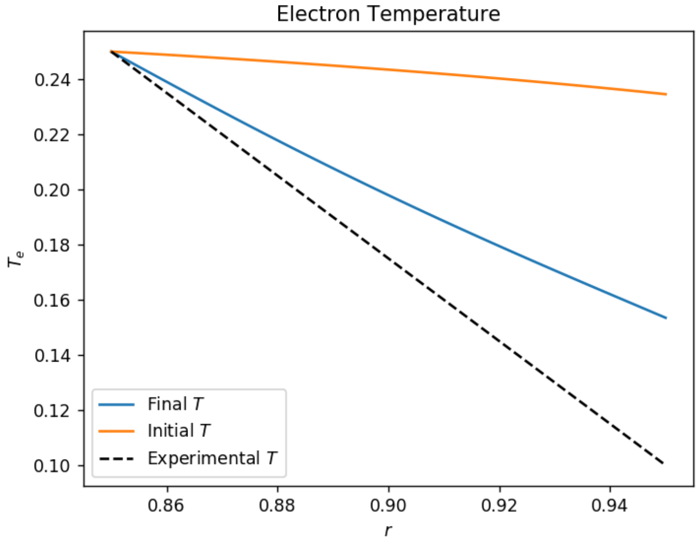
ETG simulations showing the effects of a (a) weak instability (b) strong instability and (c) strong instability with no cutoff on temperature profile

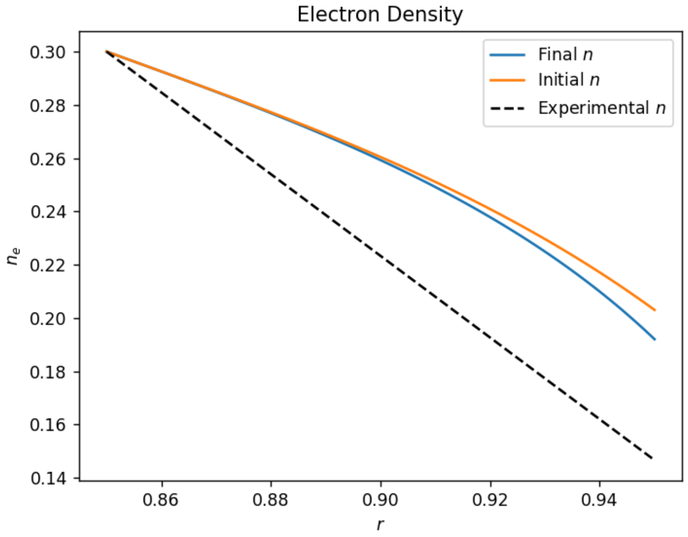


KBM threshold clamping further temperature diffusion

Predictive Simulation

- More realistic steady-state solver developed
  - Repeatedly looped profiles through transport equations until they converged to steady state

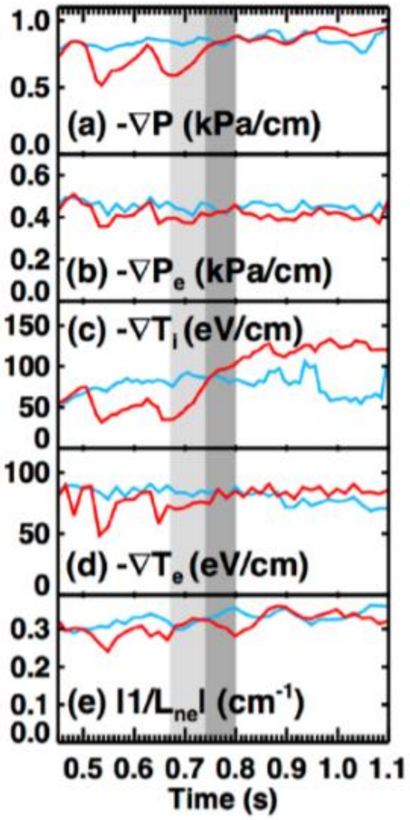




First and final iterations of predicted electron temperature and density profiles assuming only neoclassical transport

Future Work & Questions

- Does adding additional microinstabilites create more accurate pedestal transport?
  - KBM, MTM, ITG, etc.
- Can introducing transient fluctuations model the different discharges?
  - Introduces non-trivial time dependence into transport equations
- Can we assume discharges are necessarily steady state?



Acknowledgements / References

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[3] Kotschenreuther, M. (2019). Gyrokinetic analysis and simulation of pedestals, to identify the culprits for energy losses using fingerprints. *Nuclear Fusion, 59*(9). doi:10.1088/1741-4326

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Images:

[5] A.W. Leonard (2014)

[6] GYRO simulation (Candy, Waltz)

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