Validation in Modeling Turbulent Laboratory Plasma Phenomena of Relevance to Astrophysics

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Motivation: parameter disparities between laboratory and astrophysical plasmas

- Laboratory experiments will not match all parameters of astrophysical analog
- Scaling arguments will not overcome all discrepancies where multiple processes are involved
- Fix: numerical simulation

  Phenomena is complex: Simple models (do they really apply?)

  Complex codes (can they be believed?)
- Validation: process for showing that model results, predictions are trustworthy

What use can be made of validation in applying lab results to astrophysical systems?

Must have both experimental results *and* a model

Successful validation => understanding

Validation is very tough for turbulent/ nonlinear phenomena

Validation has been adopted in fields like hydrodynamics, aeronautics, atmospheric sciences, etc., to rigorously test numerical models

- Definition: “The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model” - Terry, PoP, 2008
- Linked with verification – demonstration that numerical algorithm produces correct solution of model
- Quantitative exercise
  - Supplants qualitative assessments (‘good agreement’), comparison of similar looking images
  - Quantitative assessment of uncertainties, errors, sensitivities
  - Metrics for goodness of models; linked to tolerances
- Validation in plasmas brings special challenges
  - Limited availability of data
  - Complexity, nonlinearity multiplicity of models
  - Possibility of fortuitous agreement

Why work toward validation?

Besides meeting challenges in interpreting data (from experiment and models) in complex, nonlinear systems like plasmas

For laboratory astrophysics:

- Build culture of performing modeling in conjunction with experiment
- Do experiment and modeling as validation campaigns, designing experiments to create comparisons with most value for validation
- Use validation to test and build understanding of key physical processes
- Use understanding to create predictions for astrophysical plasmas

Validation becomes rigorous to the extent that key activities are performed

Model Qualification

Code verification

Quantitative analysis of uncertainties in experiment, deficiencies in model

Sensitivity analysis

Identification of primacy hierarchy for measured quantities

Creation of validation metrics, including composite metrics

For description see, Terry et al., Phys. Plasmas **15**, 062503 (2008)

Adaptations and recommendations for validation in laboratory astrophysics

- Full validation as recommended by AIAA, BPO, etc. is probably not realistic
  - Must sort out basic mechanisms at work in models and experiment
  - Use validation strategies:
    - Full disclosure of shortcomings (only way to learn)
    - Qualify codes and models
      - How well do model assumptions, validity regimes, conform to reality of experiment?
      - How well can model conform to reality of an astrophysical application?
      - Do key mechanisms still operate?
      - Will likely have to deal with mismatches between model and experiment
    - Consider validation metrics as way of assessing all factors that impact quality and validity of comparison

Three progressive illustrations

1) Saturation of Kelvin-Helmholtz instability
    - Still figuring out basic mechanisms at work in system

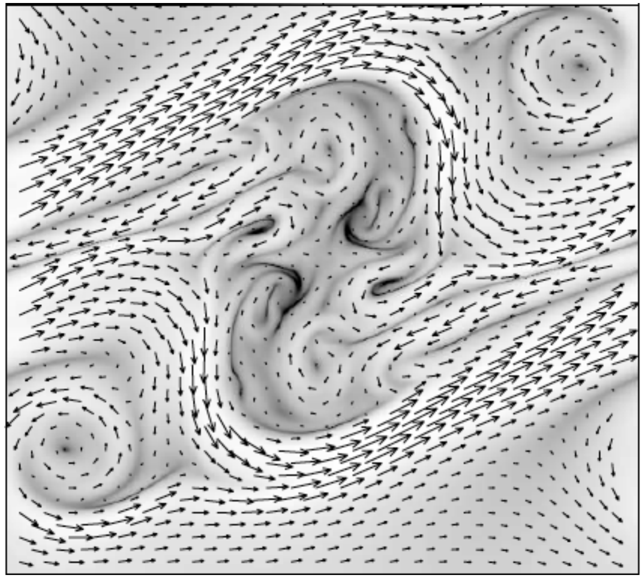
2) Turbulence Cascade in MST
    - Comprehensive gyrokinetic modeling
    - Emerging understanding of basic workings
    - But still have shortfalls in modeling capability

3) Validation campaign for gyrokinetic model of gradient-driven drift coupling instability on LAPD
    - Quantitative comparisons, but limitations in code capability produce mismatches

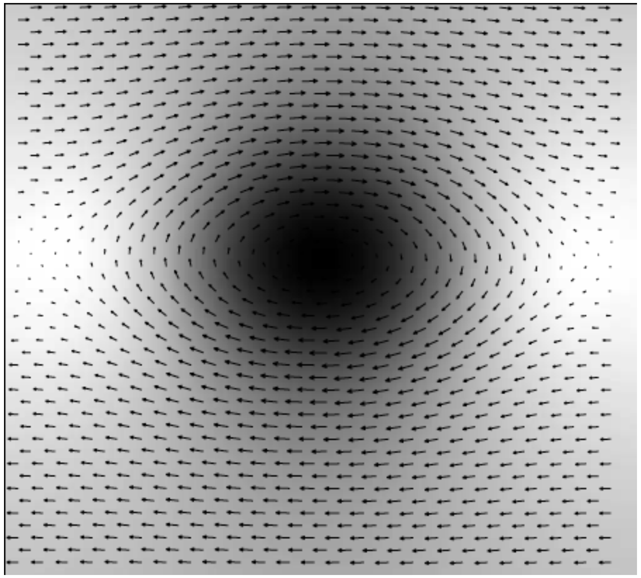
Case 1: How do key instabilities saturate?
KH saturation is governed by more than a cascade to small scales

Kelvin-Helmholtz instability is key process in astrophysics

How does saturation work? - Understand from numerical, analytical models



Palotti, et al.
ApJ 2008



Two cases: B field aligned with flow

- Secondary instability
- Small scale generation, cascade

B field perpendicular to flow

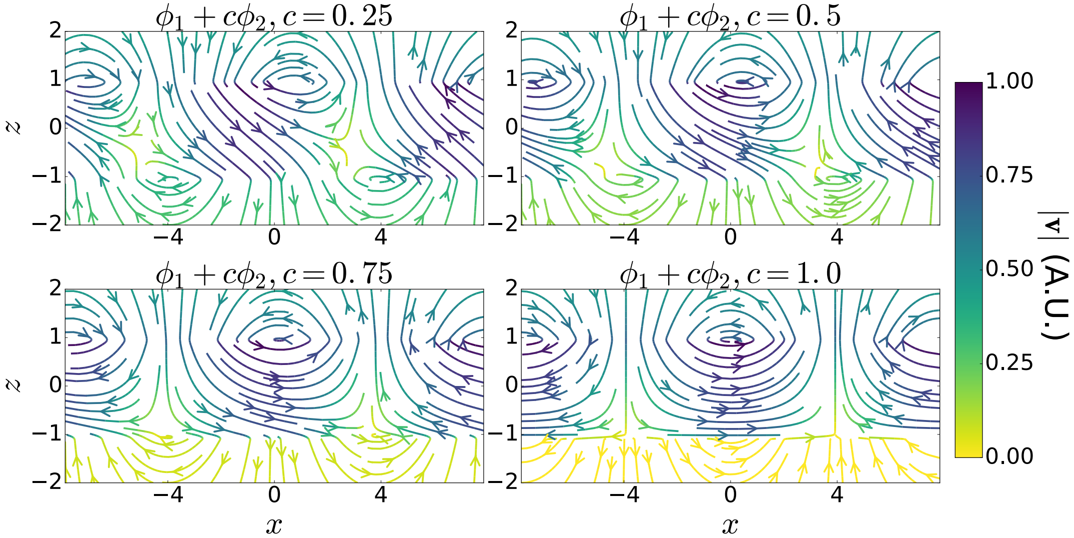
- Single coherent nonlinear eddy
- No smaller scales, no cascade

Why the difference?

Differences can arise from extent of stable mode excitation in nonlinear saturation

Kelvin-Helmholtz instability with B ⊥ v excites conjugate stable mode

Stable mode modifies flow, removes hyperbolic points, transient instability


Fraser et al, arXiv 2017

Magnetic field alignment affects stable mode

$$\Gamma_{\mathrm{MHD}} = \Gamma_{\mathrm{HD}} \left[1 - \left(\frac{2}{M_a} \frac{\hat{e}_k \cdot \hat{e}_{B_0}}{\hat{e}_k \cdot \hat{e}_{U_0}} \right)^2 \right]^{1/2}$$

When B || v:

- Conjugate symmetry broken, stable-mode damping (γ_2) >> growth (γ_1)

⇒ Weaker stable mode

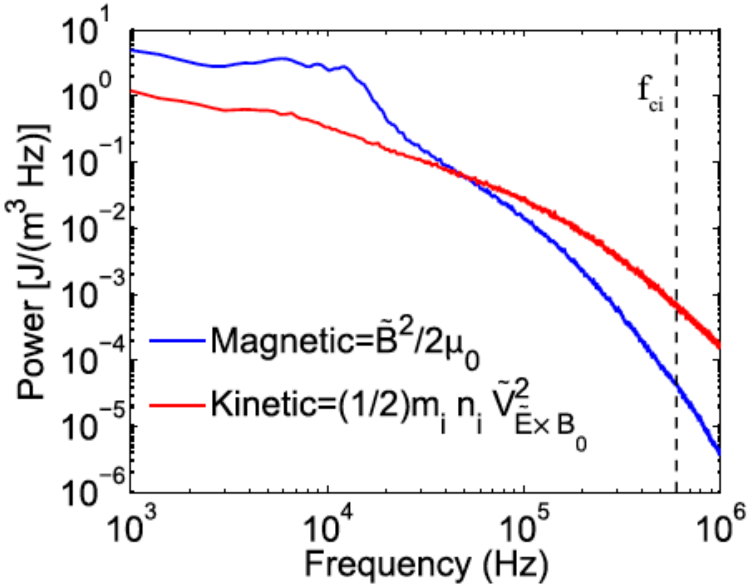
$$P_t \equiv \frac{D_1 C_2}{C_1^2 (2 + \gamma_2/\gamma_1)} \approx 1$$

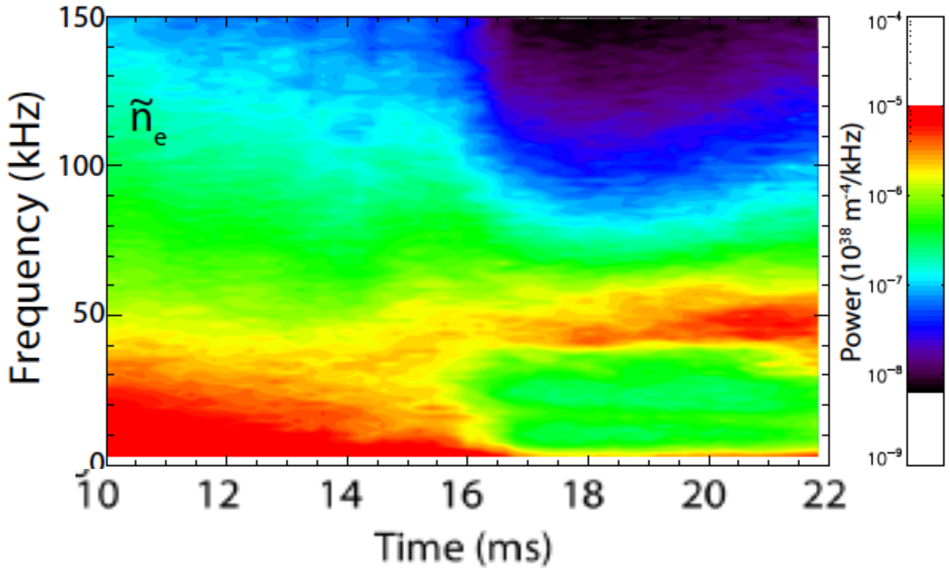
for stable mode to affect saturation

Saturation physics must be understood for interpretation of model, experiment

Case 2: Turbulent cascade in MST encounters complex plasma physics not generally found in conceptual models

MST has turbulent cascade of magnetic turbulence from global to micro scales





Thuecks et al. (standard, probes)

No equipartition

Duff (FIR diag., J-profile flattening)

Instability at high frequency

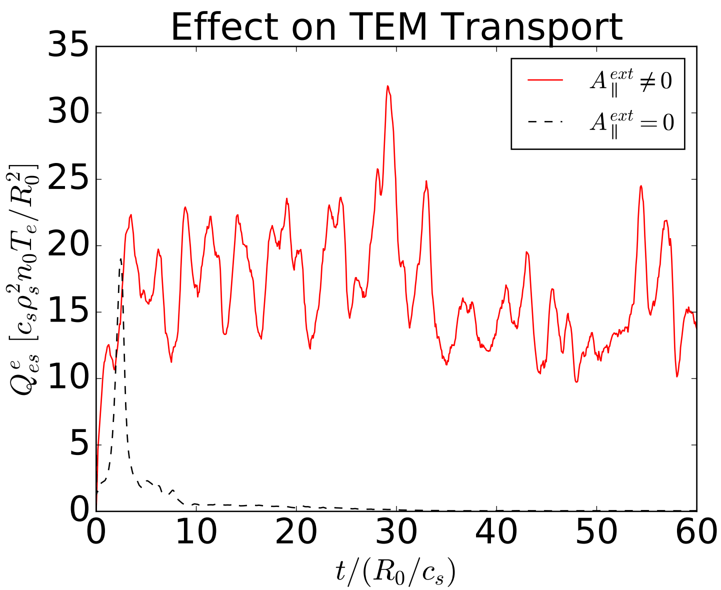
Ripe for modeling with gyrokinetics – great for microinstability, turbulence

Compare: wavenumber, frequency, gradient sensitivity, radial location, transport fluxes

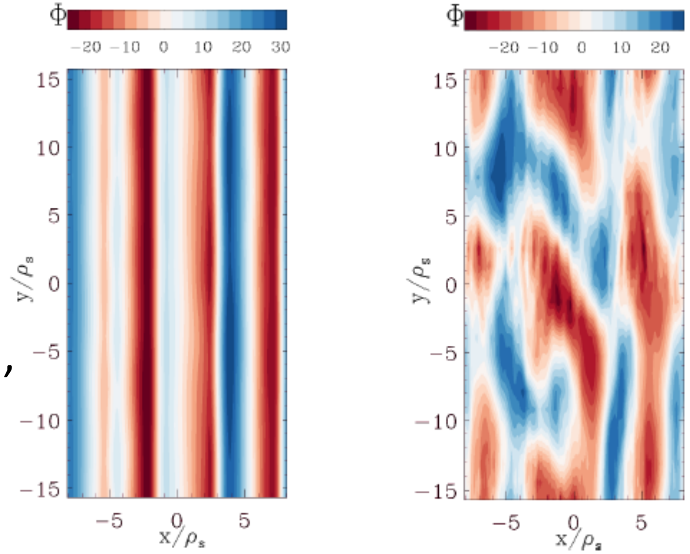
To get nonzero fluxes, tearing modes have to be included in microscale turbulence modeling

Linear comparisons work great – show that TEM is the instability

Big problem: fluxes are close to zero in model, while sizable in experiment



Williams et al., under prep



Simulations show very strong zonal flows, which kill the fluxes

The fix: impose external B fluctuation to represent residual tearing spectrum

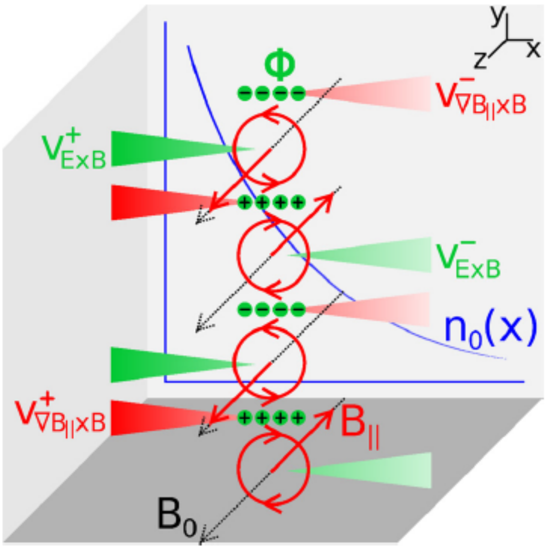
Zonal flows are greatly reduced, fluxes come up to experimental level

Lab: complex integrated nonlinear physics over large scale range

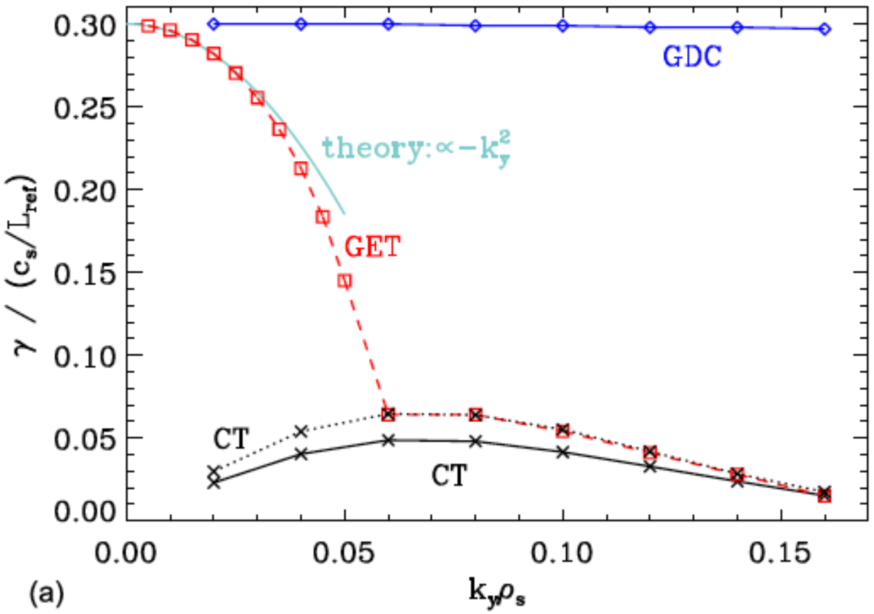
Challenge for modeling: Realistic integrated modeling (MHD and micro)

Case 3: Validation efforts for GDC instability in LAPD illustrate challenges and opportunities for validation

Gradient-driven drift coupling (GDC) instability potentially enhances reconnection in astrophysical plasmas



Pueschel et al., PoP, 2015



GDC is new kinetic instability of coupled fluctuations in ϕ and $B_{||}$

Favored by finite beta and low magnetic shear

Compare with finite-beta, $B_{||}$ fluctuations observed in LAPD – validation?

Opportunities also exist for experiments with pair plasmas (ASTRA-GEMINI)

Experiment: fluctuations in B_z, n, T peak in pedestal region, increase with beta; $B_\perp$ peaks on axis

Gyrokinetic GDC calculation for LAPD parameters: qualification shows that

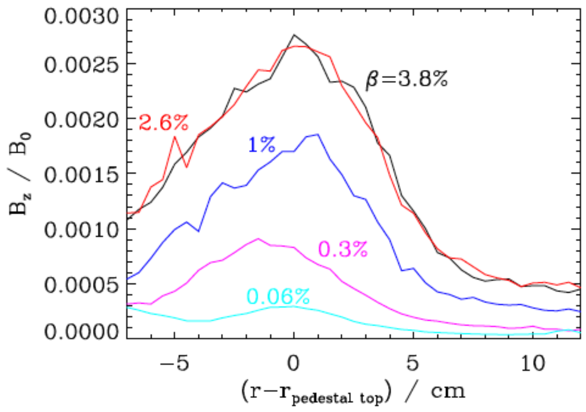
- Code cannot match expt collisionality, but

  γ -> constant as ν -> LAPD value
- LAPD pedestal is few x ρ_i

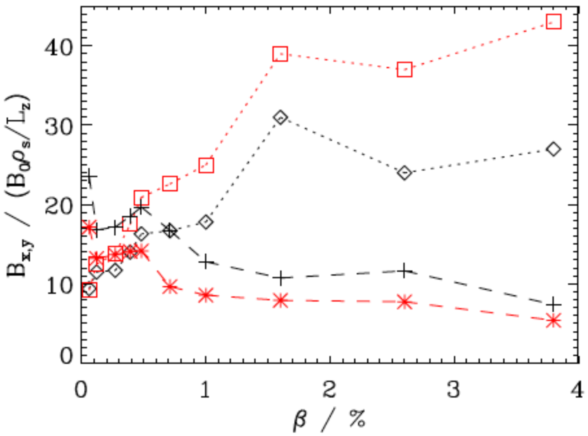
  Radial domain must be increased in simulation

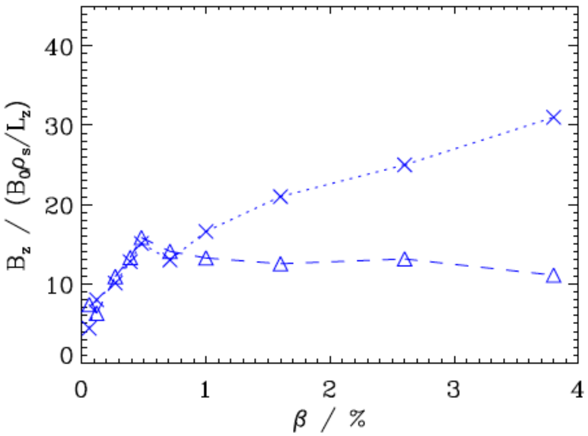
  Requires rescaling of fluctuation levels
- B_z, n, T fluctuations levels as function of beta

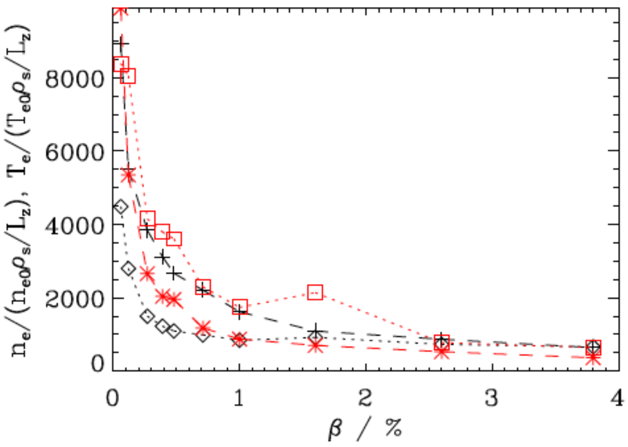
  agree with experiment to within factor of 2; $B_\perp$ does not agree



Pueschel et al., PPCF 2017







Needed: global gyrokinetic solver that can handle fluctuations in $B_{||}$

Conclusions

Without pursuing full-blown validation, validation practices and culture could help laboratory experiments bridge the gap between terrestrial plasmas and astrophysical plasmas

Modeling in conjunction with experiment is critical

Design experimental campaigns for most valuable comparisons

Disclose difficulties and shortcomings

Adjustments will be needed