Thesis Outline: Numerical Studies of Turbulence in LAPD

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1 Introduction

- The problem of anomalous transport in tokamaks
- Understanding the nature of turbulence in LAPD
- The use of simulation to acquire spatial data and theoretical understanding
- The nonlinear instability in LAPD

2 Turbulence and Instability

2.1 The Kolmogorov Paradigm of Turbulence

- High Reynolds number neutral fluid turbulence
- Energy injection, cascading, and dissipation
- *Figure*: Standard cascading figure

2.2 The Standard Plasma Paradigm of Linear Instability

- The plethora of linear instabilities in plasma physics
- The dual cascade
- The problem of low Reynolds number, lack of inertial range, etc. in plasmas
- The reliance on linear theory for understanding and quasi-linear calculations

2.3 Nonlinear Instability: Subcritical and Supercritical Instability

- Subcritical turbulence in pipe (Poiselle) flow
- *Figure*: Pitchfork diagrams and explanation of sub and supercritical instability
- Note that other kinds of nonlinear instabilities exist

2.4 Nonlinear Instability in Plasmas

- ITG (Dimits shift) in GK Simulations
- TEM (Ernst) GK Simulations
- Various subcritical plasma instabilities
- Bruce Scott self-organization findings
- Drake, Biskamp, Zeiler papers

3 The Braginskii Fluid Model and LAPD

3.1 LAPD Suitability to Fluid Model

- High collisionality (collision mfp over the machine length) and neglect of Landau damping
- FLR effects

3.2 Braginskii Equations

- Origin of the equations
- Assumptions and orderings
- Write the full equations (Tokamaks book?)
- Describe the meaning of the terms

3.3 The Vorticity Equation

- Justify the quasi-neutrality condition
- Derive the Vorticity Equation

3.4 Minimizing the Equation Set for LAPD parameters

- Neglect of ion temperature and parallel velocity fluctuations
- The electrostatic justification
- Make a comparison of the collision to mass to inductive effects on the adiabatic response (see B.D. Scott paper)
- *Figure*: Beta scans comparing ES vs EM growth rates

4 LAPD Simulation Details

4.1 The Equations

- Partially linearized equations (with ϕ_0?)

4.2 Finite Difference Schemes

- Quasi-staggered method
- Advection schemes and positivity
- Artificial diffusion and grid convergence reference to appendix

4.3 Sources

- *Figure*: Relaxation without the sources caused by transport
- Simple density and temperature sources (removal of azimuthal average)
- Positivity-preserving sources

4.4 Boundary Conditions

- The annular geometry and justification of zero-value radial boundaries
- Periodic, zero-value, and zero-derivative axial boundaries
- Sheath boundary condition and specific implementation

4.5 Profiles and Parameters

- *Figure*: Density and temperature profiles
- Zero mean potential profile justified by biasing experiment

5 Linear Instabilities

5.1 Drift waves

- Linearized equations
- *Figure*: Physical mechanism
- *Figure*: Growth rates with periodic, zero-value and zero-derivative boundary conditions

5.2 Conducting Wall Mode

- Physical mechanism
- The reduced fluid equations used in BOUT++
- Specific implementation of the boundary condition
- *Figure*: Growth rates with comparison to drift waves

6 The Nature of the Turbulence

6.1 A Visual Examination

- *Figure*: 2D and 3D movies of the turbulence
- *Figure*: Movie comparison to camera data

- Note the formation of long parallel wavelength structures

6.2 A Statistical Examination

- *Figure*: Spectra, PDFs, Fluctuation Levels
- Note that the experimental and simulation frequency spectra are not exponential
- *Figure*: Correlation Plots: simulation and exp.

7 Energy Dynamics Formalism

7.1 Total Energy and Dynamics

- State the physical energy
- Derive the full energy evolution
- Discuss the meaning of the pieces (sources, transfers, etc.)
- Discuss the conservation (and lack of it) for the advective nonlinearities with reference to first paper

7.2 Spectral Energy Dynamics

- Derive the spectral density energy evolution
- State the results for the other energy expressions

8 Nonlinear Instability for the Periodic Simulation

8.1 The Energy Spectra

- *Figure*: The energy spectra - The energetic dominance of $k_{\parallel} = 0$ fluctuations
- Our original misunderstanding of the $k_{\parallel} = 0$ structure origins due to the

standard linear instability picture

8.2 Energy Dynamics Result

- *Figure*: The full detailed dynamics from first paper
- *Figure*: The full diagram from the second paper
- *Figure*: The reduced diagram from the first paper
- *Figure*: The growth rate, linear vs nonlinear

8.3 n=0 Suppression

- *Figure*: The coherent turbulence (movie or snapshot) - *Figure*: The statistical difference
- *Figure*: The energy dynamics and growth rates
- *Figure*: The role of zonal flows

9 Energy Dynamics for the Non-periodic Simulations

9.1 The Importance of Axial Boundary Conditions

- Discuss the need to explore different boundary conditions with reference to linear growth rate curves
- *Figure*: The statistics of the different cases

9.2 Fourier Decomposing Non-periodic Functions

- *Figure*: The power law vs exponential convergence
- The appendix of the second paper

9.3 Energy Dynamics Results

- *Figure*: Energy flow diagrams (at least for the sheath case, maybe one more)
- Growth rate plots: linear vs nonlinear

9.4 Linear vs Nonlinear Structure Correlation

- Section from the second paper
- *Figure*: Ratio of fastest growing mode energy to total energy

10 The Finite Mean Flow Simulations

10.1 The Biasing Experiment

- Shear suppression paradigm
- Simulations not focusing on dynamical profile evolution yet

10.2 New Linear Instabilities

- KH
- Rotational Interchange
- *Figure*: Isolation of KH and IC instabilities

10.3 Statistical Comparisons to Experiment

- *Figure*: Unbiased, medium and high biases
- Note the skewed pdfs due to the radial force and blob production

10.4 Energy Dynamics Results

- The new terms in the energy dynamics and their meaning
- Instability drive comparisons
- *Figure*: Energy flow diagram

- The coherent mode?

11 Conclusion

- Future work

12 Appendix 1: The BOUT++ Code

12.1 The Object-Oriented Fluid Framework

- The original BOUT
- The advantage of BOUT++
- Parallel framework

12.2 Explicit Finite Differences

- The time solver options and the one I use
- The spatial finite difference schemes

12.3 The Physics Inputs

- Explanation of the grid file
- lapd-drift.cxx
- The input file

13 Appendix 2: Grid Convergence

- Grid convergence paper
- *Figure*: U1 advection figures in the paper
- *Figure*: Arakawa advection figures in the paper