On fluid Models of turbulence, structures and transport in ExB partially magnetized plasmas

A. Smolyakov[1]

O. Chapurin[1], O. Koshkarov[1], I. Romadanov[1],

Y. Raitses,[2,] I. Kaganovich[2,]

G. Hagelaar[3], S. Sadouni[3]

M. Cappelli[4]

1University of Saskatchewan, Canada

[2]Princeton University and PPPL

[3]Stanford University

[4]LAPLACE & Université Paul Sabatier

ExB Plasmas Workshop, PPPL Nov 1-2, 2018

Comments on:

- **Do we need fluid models?**
- **Why do we need fluid models?**
- **Is there any relevant physics that can be adequately described by fluid models?**

What can we get/expect from fluid theory/simulations?

- Common wisdom: Fluid theory describes well large scale phenomena
  - Length scales $k_\perp^2 \rho_e^2 \leq 1$ but also $k_\perp^2 \rho_e^2 \geq 1$ with extended (Pade type) closures
  - Time scales $\omega < \omega_{ce}$
- Common wisdom: Fluid theory does not describe kinetic/resonant and complex phase space phenomena, e.g. Landau damping and wave-particle interactions/drive, phase mixing in velocity space…
  - Eg cold unmagnetized ions may be OK within fluid models but for finite temperature $\omega < v_{Ti} / L$ kinetic description is required
    - **Do we need the kinetic model for ions and neutrals?**
    - What happens with electrons along the magnetic field lines? Parallel resonances?Sheath boundary conditions?

but (on a positive side)

- Closures (eg Hammett-Perkins) are being developed for some linear wave-particle resonance phenomena to be used in fluid equations

What can we get/expect from fluid theory/simulations in context of ExB plasma (eg Hall thruster)?

- Common knowledge: gradients of plasma density, magnetic field in combination with ExB dridt and resistivity result in wide range of "fluid" mode and instabilities: gradient-drift modes, lower hybrid, Simon-Hoh, ion sound, … All of them can be put into the framework of fluid equations/models.
  - Simon, Hoh, Tilinin, Esipchuk, Timofeev, Fridman, Sakawa, … Litvak, Fisch, Chablier, Ahedo, Fernandez,…Frias, Smolyakov, Lakhin,
- Suppression of some most violent modes with magnetic field profiling was successfully guided by the fluid models (Morozov stabilization criteria $E \cdot \nabla(n/B) > 0$)

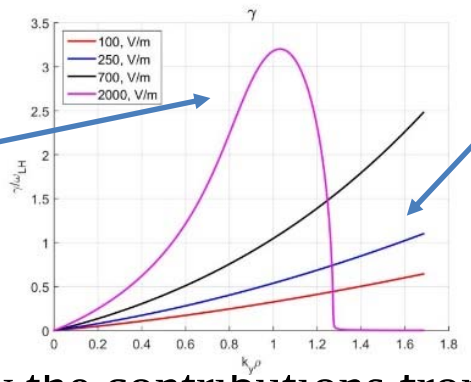
Common knowledge of two important facts about ExB devices (including Hall thrusters)

- Electron transport is anomalous (often)
- Large structures (spokes, breathing modes,..) are observed (often)

Large (long-wavelength) length scales VS small length scales

- Typically (often) coexist

  The most unstable linearly are small scale modes (e.g. lower-hybrid type)



Improper physics model: Cut-off at short scales:

$\rho_e^2, \lambda_{De}^2, \ldots$

- Anomalous transport is often dominated by the contributions from large scale modes, as seen from simple maxing length arguments and simulations

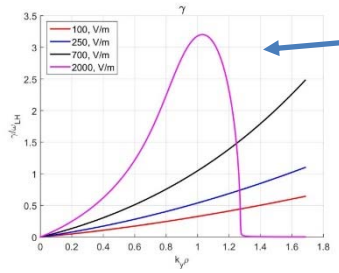
$$D \sim \frac{(\Delta x)^2}{\tau} \sim \frac{\gamma}{k^2}$$

- Contrary to 3D neutral fluid turbulence (Kolmogorov cascade to small scales), in magnetized plasma energy flow direction can be from small to large scale –

  INVERSE CASCADE: Large scale modes/structures can be formed by nonlinear drive/self-organization (modulational instability) from small scale modes (modulational instability of lower hybrid/gradient drift modes- 70s-80s, … Lakhin, Smolyakov PoP 2016 for ExB plasmas)

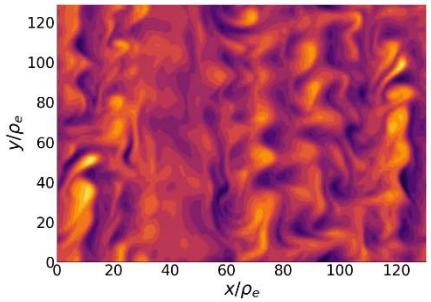
2D fluid model and simulations (azimuthal – axial) of

gradient-drift/Simon-Hoh/resistive/lower-hybrid modes with ExB, density gradient and ion beam; but double-periodic, no gradients evolution
Smolyakov et al., PPCF 2017



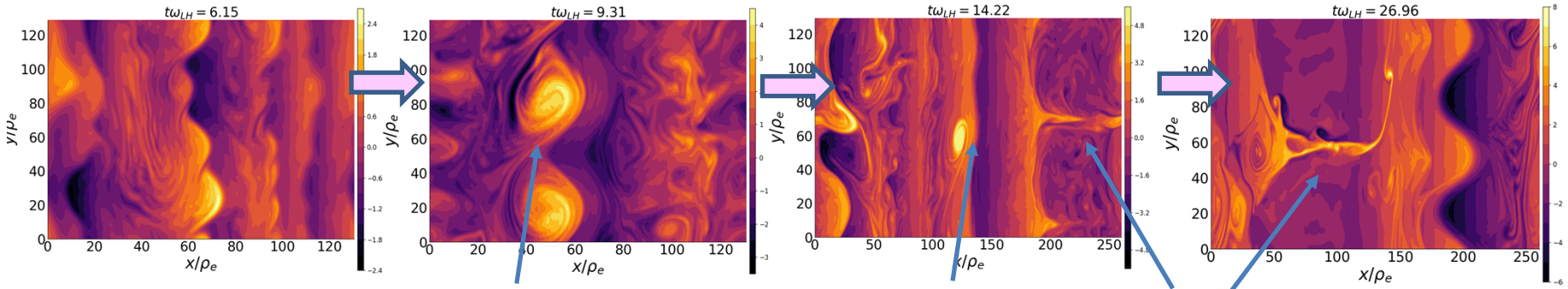
Small scales are most unstable

Late stage linear instability



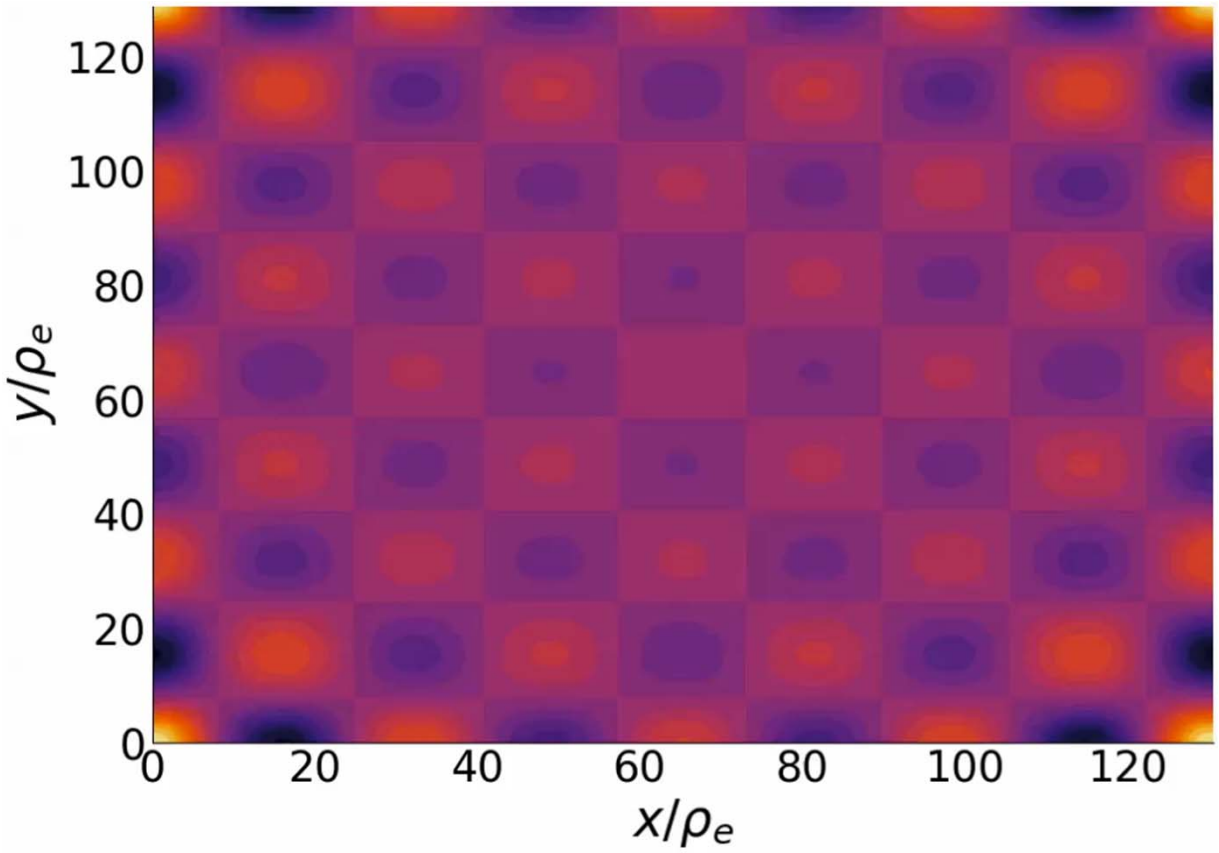
Nonlinear development leads to the long wavelength modes (inverse energy cascade) and structures: **vorticies**, **zonal flows**, **streamers**
Koshkarov et al, 2018

time



Large scale modes

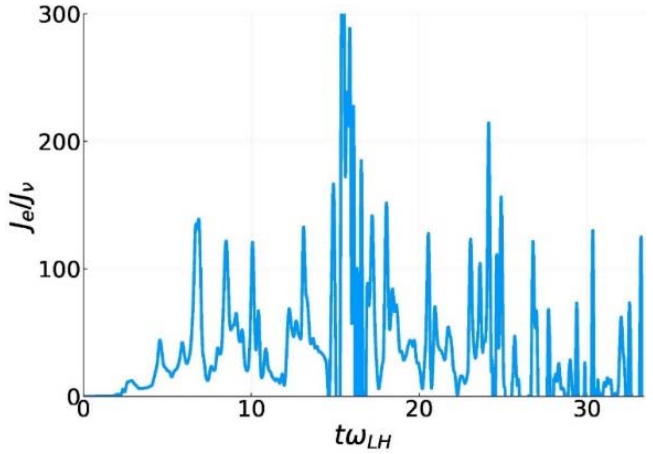
Vorticies, zonal flows and streamers



Inverse cascade, self organization
and coherent structures
Where does Jupiter get his stripes?

What about the electron transport?

- **Anomalous current is highly intermittent (both in fluid and kinetic simulations)**



Transport does not look like a diffusion process . If so, it cannot be characterized by the diffusion/mobility parametrization. In general requires SOC (self-organized-criticality) methods for avalanche like transport. K-E closure models used in gas dynamics are not appropriate due to large fluctuations ~50-100% . **Watch for presence of relatively rare but large events? Experimental confirmation? Emerging challenge?**

Thank you.