Global simulation of plasma turbulence in laboratory plasmas

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A paradigm of laboratory plasma turbulence, TORPEX

How its dynamics can be approached?

What can we learn from TORPEX simulations?

Some examples: turbulent regimes, transport, non-thermal particle dynamics, simulations/experiments comparison
The TORPEX experiment, paradigm of plasma turbulence

crpp.epfl.ch/basplasmas/

Source (EC and UH resonance)

Parallel losses

Plasma gradients

Magnetic curvature

Fasoli et al., PoP 2006, PPCF 2010
High resolution diagnostics with full coverage

Measurements of all relevant plasma and field parameters
Properties of TORPEX turbulence

\[ n_{\text{fluc}} \sim n_{\text{eq}} \]

\[ L_{\text{eq}} \sim L_{\text{fluc}} \]

\[ L \gg \rho_i \]

\[ T_i \ll T_e \]

\[ \beta \ll 1 \]

\[ \omega \ll \Omega_{ci} \]

\[ L_{||} \gg L_{\perp} \]

Collisional
Fluid model

Collisional Plasma $\rightarrow$ Braginskii model $\rightarrow$ Electrostatic Drift-reduced Bragiskii equations

$\rho_i \ll L, \beta \ll 1, \omega \ll \Omega_{ci}$

**Convection**

$$\frac{\partial n}{\partial t} + [\phi, n] = D_n \nabla^2 n$$

**Diffusion**

$$\frac{2}{R} \left( n \frac{\partial T_e}{\partial y} + T_e \frac{\partial n}{\partial y} - n \frac{\partial \phi}{\partial y} \right)$$

**Magnetic curvature**

$\nabla_{||} (nV_{||e}) + S$

$T_e, \Omega$ (vorticity) $\rightarrow$ similar equations

$V_{||e}, V_{||i} \rightarrow$ parallel momentum balance

$\nabla^2 \phi = \Omega$
Global simulations

Evolve both equilibrium and fluctuations
Anatomy of TORPEX turbulence

• Turbulent regimes?

• Particle transport? Saturation mechanism? Macroscopic structure dynamics?

• Non-thermal particle dynamics?

• How experiments and simulations compare?
The turbulent regimes

Plasma gradients + Magnetic curvature

Ideal interchange $k_\parallel = 0$, $\lambda_v = L_v / N$

Resistive interchange $v \neq 0$, $k_\parallel \neq 0$, $\lambda_v = L_v$

Drift waves $k_\parallel \neq 0$, $\rho_s / \lambda_v = 0.1$

$N$, number of field line turns

$\lambda_v = L_v / N$

P. Ricci et al., PRL (2010)
Transport: saturation mechanism and macroscopic structures (blobs)

- Non-local linear modes grow and saturate when they remove the turbulence drive:

\[ \Gamma = \Gamma(n_0, T_0, L_p, B_z) \]

- Blob dynamics has been analyzed separately in the details:

P. Ricci et al., PRL (2008)

I. Furno et al., PPCF (2011)
Suprathermal particle dynamics displays subdiffusive, diffusive, and superdiffusive dispersion.

Gustafson et al., PRL 2012
Quantitative experiment/simulation comparison

- Comparison performed using a number of observables
- A composite metric that takes into account the “hierarchy level” of each observable is introduced.
- The “quality” of the comparison has to be defined.

Ricci et al., PoP 2009, PoP 2011
Analysis of other configurations

Similar simulation approach used in a number of other devices

- TCV, EPFL
- LAPD, UCLA
- HelCat, UNM
- TCV, EPFL
- Helimak, UTexas
Concluding remarks

What are we learning from TORPEX modeling?

• By using global simulations and evolving both plasma equilibrium and fluctuations, it is possible to interpret the experimental results.
• The turbulence is subject to a number of driving mechanisms, as a competition between ideal interchange, drift waves, and resistive interchange.
• The properties of plasma turbulence reflect the different linear drives and saturates by removing its drive.
• Even in a simple configuration, suprathermal particle dynamics surprisingly shows sub-, super-, and diffusive behavior.
• Similar analysis can be carried out in other basic plasma devices.
• TORPEX is providing an ideal test-bed for a close comparison between experiments and simulations.