Turbulent transport of fast ions in the simple magnetized torus

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Simple magnetized torus (SMT)

• Our inspiration is the TORPEX SMT at CRPP
TORPEX turbulence in drift-wave, ideal-interchange and resistive-interchange modes
Ideal interchange mode in SMT: \( k_\parallel \equiv 0 \)

Mode (coherent) and blob (intermittent) regions
Injection of fast ions in center of the box
Using full Lorentz force: no drift approximation
Amplitude of fluctuations \( \xi : \Phi = \Phi_0 + \xi \tilde{\Phi} \)
Fast ions in SMT turbulence

TORPEX is equipped with a Li$^{+6}$ source at $\mathcal{E} = 100 – 1000$ eV

Our goal is to establish a comprehensive theoretical framework for understanding dispersion of the fast ions in SMT ideal-interchange mode turbulence, including TORPEX.
SMT (a) versus slab (b) fast ions

Drift approximation

- Curvature and $\nabla B$ drift

$$\mathbf{v}_{SMT} = \frac{1}{r} \left( \frac{v_\bot^2}{2} + v_\parallel^2 \right) \frac{\hat{z}}{\Omega_L}$$

- Larmor motion defining a gyrocenter

$$\mathbf{v}_{E \times B} = \frac{\mathbf{E} \times \mathbf{B}}{B^2} = \frac{E_r}{B} \hat{z} - \frac{E_z}{B} \hat{r}$$

$$\langle \mathbf{v}_{E \times B} \rangle_R = \frac{1}{2\pi} \int \mathbf{v}_{E \times B} (R - \rho) d\theta$$

$E_2 > E_1$
Phases of dispersion for SMT

\[ \sigma^2 \equiv \left\langle (\delta x - \langle \delta x \rangle)^2 \right\rangle \propto t^\gamma \quad \delta x \equiv x - x_0 \]

I. Short ballistic phase
\[ \gamma \sim 2 \]

II. Intermediate phase:
\[ \gamma > 1 \text{ if } \mathcal{E} < 50 \]
\[ \gamma < 1 \text{ if } \mathcal{E} > 50 \]

III. Slow transition to asymptotic phase:
\[ \gamma \sim 1 \]
Ballistic phase for gyrocenters

\[ \frac{|v_{0,\perp}|}{|\Delta v_{\perp}|} \sim 1 \]

\[ \Delta v_{\perp} \equiv v_{\perp}(\tau_{ba}) - v_{0,\perp} \]

\[ \tau_{ba} \sim \frac{\lambda_c}{2\pi v_{SMT}} \]

\[ \tau_{ba} \sim \frac{\lambda_c}{2\pi \langle v_E \times B \rangle_R} \]
As the turbulence amplitude, $\xi$, is increased post hoc, the estimate for $\tau_{ba}$ is bounded from above at small $\xi$ by the Eulerian correlation time: $\tau_{ba} \sim \tau_c$
γ scan in $\xi$ and $\mathcal{E}$ for SMT

Superdiffusion at low $\mathcal{E}$ due to large step sizes in the coherent mode region

Subdiffusion at large injection energy in SMT due to curvature drift, which causes radial trapping at the $t_r > 4t_z$ boundary

Larmor averaging causes diffusion for large $\xi$

Small $\xi$ results in slow radial transport due to disconnected topology

Colors: value of $\gamma$ for scan in injection energy $\mathcal{E}$ and turbulent amplitude $\xi$. 
\( \gamma \) scan in \( \xi \) and \( \mathcal{E} \) for slab

Superdiffusion for low \( \mathcal{E} \)

Increased Larmor averaging causes diffusion, but never subdiffusion

Small \( \xi \) results show slow radial transport due to disconnected topology

Colors: value of \( \gamma \) for scan in injection energy \( \mathcal{E} \) and turbulent amplitude \( \xi \).
Prediction for TORPEX

- Measurement limited by:
  - toroidal resolution of detector
  - boundaries of TORPEX

- Requires an injection energy large enough for a significant curvature drift, but not so large that the population is lost to the boundaries.

\[ \gamma \sim 2 \]
\[ \gamma \sim 0.6 \]
Radial spreading due to plasma is consistent with simulations.

Measurement of $\gamma$ in ballistic and subdiffusive phases will be accessible with new toroidal sliding rail.

First measurements: single time point

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<tr>
<th>Theory</th>
<th>Experiment</th>
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<td><img src="image2" alt="Experiment Image" /></td>
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B field, no plasma

B field + plasma
Conclusions

• We have established a framework for interpreting fast ion data in simple magnetized torii and related experiments.

• We showed the interplay of some fundamental influences on transport:
  – Turbulent ExB drifts with gyroaveraging
  – Curvature and $\nabla B$ drifts perpendicular to pressure gradient

• Experimental comparisons are encouraging and will advance soon.