Theory of turbulence and gyrokinetic simulations

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Confinement is a crucial issue for fusion

- Triple product ITER $nDTD\tau E \approx 3 \times 10^2$ m$^3$.keV.s
- Confinement
  \[ \tau_E = \frac{\text{energy content}}{\text{power losses}} \approx \frac{a^2}{\chi} \rightarrow 3.7\text{s in ITER} \]
- Transport is turbulent: understanding, prediction, control.

Outline
1) Basics of turbulent transport.
2) Turbulence self-organisation.
3) Outcomes of theory and simulations.
4) Improved confinement: read the paper!
5) Prospects and conclusion
Several modes can be unstable above a threshold

- Instabilities $\rightarrow$ turbulent transport
- Appear above a threshold $\kappa$.
- Underlie particle, electron and ion heat transport: interplay between all channels.
- Coherence: plasma response + Maxwell equations.
Turbulent transport

- Eddies: ExB velocity

\[ \mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2} \]

→ Assuming a random walk

\[ \chi \approx \langle |\mathbf{v}_E|^2 \rangle \tau_c \]
• Plasma is nearly collisionless $\rightarrow$ kinetic calculation.

• Calculation of 6D distribution function $F(x,v,t)$ is costly.

• Compute instead the distribution of gyrocenters $\bar{F}(x_G,v_{G//},\mu,t)$

• Gyrocenter and particle densities are different.

$\rightarrow$ numerical challenge
Several codes, but not all doing the same thing ...

- **Global**
  - GEM, GT5D, UCAN
  - GTC, ORB5
  - ELMFIRE, GYSELA, ORB5, TEMPEST, XGC

- **Local**
  - GKV, PG3EQ
  - GEM, GT3D
  - GENE, GKW, GS2, GYRO

- **Electrostatic ITG Case**
  - Falchetto 08

- **Trapped Electrons**
  - Falchetto 08
II. Turbulence self-organization

- Why is it difficult? Disparity of spatial and time scales.

- Generation of structures, which back-react on turbulence background:
  - Large scale transport events: feedback via profile relaxation.
  - Zonal flows: feedback via flow shear
Large scale transport events

• Streamers: ExB eddies elongated in the radial direction
  Beyer 00, Champeaux 00.

• Boost radial transport if ExB velocity is large enough.
  Jenko 00, Labit 03, Idomura 05, Lin 05, Candy 08.

• Radially propagating fronts (avalanches). Related to turbulence spreading.
  Garbet 94, Diamond 95, Hahm 04, Gurcan 06.

Idomura 05
ETG turbulence

Poloidal direction
Radial direction
Zonal flows  
Diamond, Itoh, Itoh & Hahm 05

- Low frequency fluctuations of the ExB poloidal velocity.
- Generated via Reynolds and Maxwell stresses.

$$\partial_t V_\theta = -\nabla_r \cdot \langle V_{Er} V_{E\theta} \rangle + \ldots$$

Turbulent amplification $\sim |\phi| V\theta'$

- Damping is weak  Rosenbluth & Hinton 98.

Jolliet 07

![Graph showing ORB5 data, AR from RH theory, and residual flow.](image)

Geodesic Acoustic Modes
Zonal Flows (cont.)

- Strong feedback on turbulence: ExB vortex shearing Biglari 90, Waltz 94, Hahm 95 Clearly seen in all turbulence simulations Hammett 93, Lin 98, Kinsey 05, Villard 02.

- Leads to a self-organized state.

Lin 98 - GTC
III. Outcome of theory and simulations

- **Dimensionless analysis**: scaling with normalised gyroradius at fixed $\beta$ and collisionality.

- **Transport channels**: ion and electron heat channels, particle transport, momentum transport.
Scaling laws
Kadomtsev 75, Connor 77, Waltz 90

- **GyroBohm scaling law**
  \[ \frac{\lambda_c}{a} \equiv \rho^* \quad \frac{\tau_c}{c_s} \equiv \frac{a}{c_s} \rightarrow \chi \equiv \frac{T}{eB} \rho^* \]

- **Gyrokinetic and fluid simulations** find that the scaling is **gyroBohm** when \( \rho^* \rightarrow 0 \)
  Garbet 96, Ottaviani 99, Lin 02, Candy 04.

Scaling with \( \nu^* \) and \( \beta \) still under investigation.
Ion heat transport is rather well understood

- ITG dominated: quite well assessed. Now a test for gyrokinetic codes.
- Profiles are stiff.
- Actual threshold $\geq$ linear value.
Electron heat transport

• Contribution from TEMs when $\nabla n$ or $\nabla T_e$ large enough Ernst 04, Merz 08, Lang 08
• Contribution from ETGs depends on parameters: small for ITG dominated turbulence Candy 06 - significant for TEM/ETG dominant modes Goerler 08 - GENE
Particle transport

- Particle flux:
  \[ \Gamma_e = -D \frac{dn_e}{dr} + Vn_e \]

- Complex physics of turbulent pinch velocity:
  - can reverse direction.
  - effect of collisions is important.

Coppi 78, Tang 86, Garbet 03, Isichenko 96, Hallatschek 05, Dubuit 05, Estrada-Mila 05
Momentum transport and spontaneous spin-up

- A puzzling observation: toroidal rotation without external torque
- Structure of parallel momentum radial flux Dominguez 93, Diamond 94, Garbet 02

$$\frac{\Gamma_U}{n_i m_i} = -\chi_u \frac{dU_{\parallel}}{dr} + V_u U_{\parallel} + S$$

Momentum pinch

residual stress (ExB shear)

- Still an open issue Hahm 06, Gurcan 06, Peeters 07, Waltz 07, Peeters 08.
IV. Where are we going to?

• Reduced transport models.

• Statistical models of turbulence

• Ab-initio simulations
Reduced transport models

- Flux \( \Phi_T = \frac{3}{2} \langle p v_E \rangle \)
- Quasi-linear theory: cross phase given by linear theory
Vedenov 61, Drummond 63, Horton 83 — some support from simulations
Dannert 04, Lin 07, Casati 08.

- Fluctuation spectra: mixing-length rule Prandtl 25
\[
\frac{e \delta \phi_k}{T} \approx \frac{\delta p_k}{p} \approx \frac{1}{kL_p}
\]

- Basis of most transport models: GLF23, Weiland, CDBM, Qualikiz…Still in progress.
A new generation of codes

• Aim:
  - full distribution function, full torus.
  - steady-state, driven by sources
  - coupling to the SOL
  - neoclassical transport
• Challenging - first results in the literature. Ku 06, Heikkinen 08, Dif-Pradalier 08, Scott 08, McMillan 08, Xu 08.
Progress is tied to high performance computers

<table>
<thead>
<tr>
<th>Simulation (numbers are indicative)</th>
<th>Time needed for 1 simulation with a 100TFlops HPC</th>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulence steady state electrostatic ITG/TEM, global $1/\rho^* = 512$ ($\sim$ITER)</td>
<td>1 day</td>
<td>100 GB</td>
</tr>
<tr>
<td>Confinement time $1/\rho^* = 512$ electrostatic ITG/TEM.</td>
<td>1 year</td>
<td>50 TB</td>
</tr>
<tr>
<td>Turbulence steady state, electromagnetic, ITG/TEM/ETG</td>
<td>10 years</td>
<td>1 PB</td>
</tr>
</tbody>
</table>

→ Need for multi-petaflops computers
Conclusions

• Dimensionless scaling law: gyroBohm at small $\rho^*$. Scaling with $\nu$ and $\beta$ still to be clarified.

• Some consensus on ion heat transport, not far from agreement for electron heat and particle transport, momentum transport still debated.

• Understanding of transport barriers: far from satisfactory –