Magnetic Fluctuations and Transport

X. Garbet

CEA Cadarache

Motivation

Nature of electron transport.
• Dependence of transport on $\beta$.
• Nature of small scale fluctuations.
• Ergodic divertor and stellarator edge.
• RFP's

→ Renewed interest in electromagnetic turbulence and consequences for turbulent transport
Outline

- **Theory**
  - transport associated to magnetic fluctuations
  - stability: effect of $\beta$ (large and small scale fluctuations)
  - non linear effects
- **Experiment**
  - transport
  - measurement of magnetic fluctuations
  - transport of fast electrons
Effect of a Perturbed Magnetic Field

- Main component $\delta B_\perp = \text{rot}(\delta A_\parallel b_{eq})$ (however $\delta B_\parallel$ affects stability at high $\beta$)
- Electric potential $\phi$ never negligible
- 3 main ingredients:
  - Magnetic flutter $\rightarrow \perp$ displacement due to perturbed magnetic field, $B.\nabla = B_{eq}.\nabla + \delta B.\nabla$
  - Ohm's law
    $\eta j_\parallel = -\partial_t A_\parallel - \nabla_\parallel \phi + \nabla_\parallel p_e/n_e + \text{electron inertia}$
  - Ampère equation
    $\nabla_\perp^2 A_\parallel = -\mu_0 j_\parallel$
Alfvén waves

• Ion inertia vs field line bending
  \[ \nabla \cdot \mathbf{j} = 0 \rightarrow n_i m_i d_t \nabla \perp^2 \phi = \nabla_{//} j_{//} + \text{curvature terms} \]
  Alfvén velocity \( v_A = c_s / \beta_e^{1/2} \rightarrow \beta \) comes into play

• Two limits
  \( \beta = 0 \rightarrow \omega \ll k_{//} v_A \rightarrow \text{Boltzmann} \quad \nabla_{//} \phi \approx T_e \nabla_{//} n_e / n_e e \)
  \( \rightarrow \text{Drift waves} \)
  \( \beta = \infty \rightarrow \omega \approx k_{//} v_A \rightarrow \text{MHD} \quad \partial_t A_{//} \approx -\nabla_{//} \phi \)
  \( \rightarrow \text{Ballooning modes} \)

• \( \beta \) drive is quantified in several ways, e.g. \( \alpha = -q^2 R d \beta / dr \) or
  \( \beta_p^* = \beta (qR/L_p)^2 \rightarrow \text{gives weight to the edge.} \)
Transport of test particles

• Magnetic flutter \( \delta v_r \approx (\delta B/B) v// + \) random walk \( \Rightarrow \)

\[
\chi_m = \pi q R \left( \frac{\delta B}{B} \right)^2 v// \quad \text{Rechester-Rosenbluth 78}
\]

\( \Rightarrow \delta B/B \approx 10^{-4} \) produces a \( \chi_m \approx 1 \text{m}^2\text{s}^{-1} \)

Further refinements by Krommes 83, Isichenko 91, Vlad 03,...
\( \Rightarrow \) Test particle approximation is a stringent limitation
\( \Rightarrow \) Appropriate for fast electrons, if orbit average effects are included Mynick 78.
Self-consistent transport

- Fluid approach
  \[ q_\text{r} = \left\langle \frac{\delta Q_{\parallel}}{B} \right\rangle \]

- Can be very different from RR expression due to shielding effect by the electric potential. Example (quasi-linear):
  \[ \delta Q_{\parallel} = \int d^3v \frac{mv^2}{T} v_{\parallel} \delta f \]
  \[ \text{Im}(\delta f) = -\pi n_0 \partial_\psi F_{\text{eq}} \delta (\omega - k_{\parallel} v_{\parallel})(\phi - v_{\parallel} A_{\parallel}) \]
  \[ = 0 \text{ for an MHD mode } \omega A_{\parallel} = k_{\parallel} \phi \]

- Generalized in several ways, e.g. Terry 86

- Very persistent feature of electro-magnetic turbulence.
Comparison with E×B Convective Transport

Electrostatic

Test Particles
\( \chi_{es} \approx (K_\theta \delta\phi/B)^2 \tau_c \)

Fluid
\( q_r = 3/2 <\delta p \delta v_E> \)

Transport channels
all

Magnetic

\( \chi_m \approx (K_\theta \delta A_/B)^2 L_c v_/ \)

\( q_r = <\delta Q_/\delta B/B> \)

\( \chi_{es} \approx \chi_m \) in the MHD limit:
\( \omega \approx k_/v_A \) and
\( \partial_t A_/ \approx -\nabla_/\phi \)
Effect of $\beta$

Linear stability, $k_{\perp} \rho_i < 1$

- $\delta B/B$ increases with $\beta$
  
  Waltz 85

- ITG/TEM modes are stabilised.
  
  Rewoldt 87, Zonca 01, Falchetto 02

- Onset of kinetic ballooning modes above a critical $\beta$.
  
  Rewoldt 87

- Shafranov shift is stabilising at large $\beta$. 
Dependence on $\beta - k_\perp \rho_i < 1$

- Non linear simulations: $\chi_e, \chi_i$ ultimately increase with $\beta$
- Due to the onset of kinetic ballooning modes. Snyder 01
- Transport dominated by ExB turbulent convection. Waltz 02

![Graph showing dependence of $\chi_i/(c_s \rho_s^2/L_n)$ on $\beta$ with different flutter regimes.](image)
Transport associated to magnetic flutter is significant close to the MHD limit

- Not clear why shielding is less effective.
Collisonality plays an important role in the edge

• $\beta$ stabilizing at low collisionality $\nu^*$
  $\rightarrow$ L-H transition ?
• destabilizing at high $\nu^*$
  $\rightarrow$ density limit ?

Rogers 98

$1/\nu^*$
Small scale (1): ETG modes

- $k_\perp \rho_i > 1$ modes with electrostatic parity.
  Horton 88, Drake 88
- Kinetic simulations consistent with Okhawa scaling Jenko 01,
  $$\chi_e = \frac{\rho_e^2 v_T e}{\beta_e q R}$$
  but not fluid simulations Labit 03

![Graph showing $\chi_e/\chi_B$ vs. $x$.]
• Modes with tearing parity and negative $\Delta'$, unstable in the linear collisional regime Hazeltine 75

• Weakly unstable in the linear collisionless regime. Farengo 83, Lau 90

• Self-sustained in non-linear regime $k_\perp \rho_i > 1$ Garbet 88, Chatenet 96

• Unstable in low R/a device Dorland 98, e.g. in NSTX Bourdelle 03

Small scales (2): microtearing modes
More non-linear effects ...

• **Alfvén waves:** cancellation between Reynolds and Maxwell stress tensors Diamond 91 → Reduces Zonal Flow generation

\[
\partial_t V_\theta = -\nabla \cdot \langle v_{Er} v_{E\theta} \rangle + \frac{1}{\mu_0 n_i m_i} \nabla \cdot \langle B_r B_\theta \rangle
\]

• **Generation of Zonal Fields** Diamond 00
  - similar to the generation of Zonal Flows Smolyakov 02, Kaw 02, ...
  - connected to dynamo effect Gruzinov 03, Thyagaraja 00

• **Turbulent reconnection:** may control saturation Zeiler 00

• **Magnetic fluctuations are prone to inverse cascade** Biskamp 89, Horton 88
Conclusion (theory part)

• The transport related to self-consistent magnetic fluctuations calculated with a test particle approximation is too large: "shielding" effects. Transport is often dominated by \( E \times B \) turbulent convection.

• However linear and NL effects are important for \( \beta > m_e/m_i \). The observable consequence is a variation of transport with \( \beta \).

• Close to the \( \beta \) limit, the transport due to magnetic flutter could be as large as \( E \times B \) convection.
Measurements of magnetic fluctuations - Effect on Transport

Magnetic fluctuations in core fusion plasmas are not well documented.

Some experimental results however:

- Externally imposed magnetic fluctuations.
- Global scaling laws - Density limit.
- Tokamaks.
- RFP's.
- Fast Electrons.
Externally imposed magnetic fluctuations.

- **Ergodic Divertor**: the transport follows the Rechester-Rosenbluth prediction. Mc Cool 89, Ghendrih 96
- **Same in stochastic edge of stellarators.**

![Graph showing temperature profile](image-url)
Electromagnetic effects seem to be important in the plasma edge

• Most of global scaling laws depend on $\beta$ once recast in a dimensionless form, for instance

$$\tau_{E,\text{elmyH}} \approx \rho_*^{-2.7} \beta^{-1}$$

• Most of this $\beta$ dependence comes from the edge in H mode (type I ELM's) Cordey 02, confirmed in DIII-D?

• A degradation with $\beta$ is also observed in the L mode: also comes from the edge?

• No $\beta$ effect in the core: at fixed $\rho_*$ and $\nu^*$, $\chi \approx \beta^0$ Petty 98
Is the density limit a $\beta$ limit?

Greenwald 01

- $\alpha = -q^2 R d\beta / dr = \alpha_c + \text{neutral penetration} \to \text{Greenwald limit.}$

- The L-H transition part of the model was tested in DIII-D Carlstrom 99, AUG Suttrop 99, JET, ...

\[ \approx 1/\nu^* \]
# Measurement of magnetic fluctuations

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Magnetic fluctuations are small in the far edge, but increase rapidly in the core

• Usually very small in the SOL $\delta B/B \approx 10^{-5}$ but grows rapidly in the plasma core.

• Not correlated with energy confinement time in Asdex. Giannone 89
Stochastic magnetic field lines may play an important role during relaxation events

- Field line stochasticization by ELM's is an option … M.Becoulet 03

- Same for sawteeth… Lichtenberg 80, Baty 91,..
The level of magnetic fluctuations radially increases

Measured with Cross-Polarizing Scattering diagnostics

- Signal radially localized at the cut-off layer.
- Measurement at $k=1250\text{m}^{-1}$, extrapolated with a box-type spectrum.

$$\Rightarrow \frac{\delta B}{B} \approx 3.10^{-5} \div 10^{-4}$$
Rechester Rosenbluth diffusivity agrees with the value calculated from power balance analysis

- \((\delta B/B)^2\) is large: could justify in itself \(\chi_e\) with RR formula Colas 97
- Well correlated with confinement.
- However Rechester Rosenbluth is known to overestimate the diffusivity...
Heat flux is driven by magnetic fluctuations in the core of RFP's

- Heat flux driven by magnetic fluctuations agrees with the source integral in the core of MST Fiksel 94, Prager 96
- Lower than Rechester Rosenbluth prediction Terry 96
Current drive improves the confinement in RFP's

- New diagnostic: fast polarimetry
- Well correlated with a decrease of $\delta B$ when confinement is improved.

Ding 03
Transport of Runaways

- Sensitive to $(\delta B/B)^2$: easily verified with an Ergodic Divertor. Orbit average corrections are needed.
- $\delta B/B \approx 2 \times 10^{-4}$ in Asdex $\Rightarrow$ may affect $\chi_{Te}$
- Too small in TEXT to justify $\chi_{Te}$

Kwon 88
Transport of Suprathermal Electrons (LHCD)

- Energy in the range of 100keV: less sensitive to orbit corrections, but small slowing-down time scale.
- Fast electrons are usually well confined in Tokamaks Peysson 93
- Questioned recently in TCV (but ECCD) Coda 03
Conclusions

• Transport often dominated by $E \times B$ turbulent convection, but magnetic fluctuations play an important role via non linear effects. Some effects (stress tensor, Zonal Fields, turbulent reconnection,...) are still under theoretical investigation.

• Unfortunately, magnetic fluctuations in core fusion plasmas are not well documented. The issue deserves a larger effort:
  - the level of $\delta B/B$ was found to be significant in several devices ($10^{-5} \div 10^{-4}$) but the parametric dependence is unclear.
  - the wavenumber spectrum is not known, nor the time dynamics.
  - even less information on Zonal Fields.
Conclusions (cont.)

• Electromagnetic effects should affect the dependence of confinement on $\beta$ : results are contradictory, both in theory and experiment.

• Nature of $\beta$ limit. Transport associated to magnetic flutter could be dominant at high $\beta$ : issue to be clarified in turbulence simulations. Is there a contradiction with coil measurements in the edge? Probably important in tokamak edge : density limit, edge confinement.

• Magnetic flutter could also be important during relaxation events: ELM's and sawteeth.
Non linear flutter is crucial.
Magnetic effects important when $\beta > m_e/m_i$.

Camargo 96, Scott 01

No flutter

Reference

Linear flutter

ITG, edge
Turbulent Reconnection

- Controls the saturation of electromagnetic ITG modes.
- Occurs above a critical (low) value of $\beta$. 

Contour of constant $A_{//}$
Cross-Polarization Scattering

- Polarising mirror effect.
- Amplification of the incident beam
- Spatial localisation of the measurements
Consistent with Magnetic and Density Fluctuation Measurements

- The behavior of \((\delta n/n)^2\) and \((\delta B/B)^2\) with \(dT_e/T_e\,dr\) is consistent with the existence of a threshold.
- Agrees with the value determined from transport analysis.