Magnetic Fluctuation-Induced Particle Transport and Zonal Flow Generation in MST

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Magnetic and Current Density fluctuations play an important role in transport and plasma relaxation for the Reversed Field Pinch (RFP) and tokamak configurations.

\[
\nabla J_{\parallel} (r) \rightarrow \delta B, \delta J
\]

\[
E_T \rightarrow \nabla J_{\parallel} (r) \rightarrow \delta B, \delta J
\]

Hall Dynamo
\[
\frac{\langle \delta J \times \delta B \rangle}{ne}
\]

Momentum Transport
\[
\langle \delta J \times \delta B \rangle
\]

Magnetic Reconnection

Particle Transport
- Charge Transport
- Maxwell Stress
\[
\frac{\langle \delta J_{\parallel} b_r \rangle}{eB}
\]

All processes coupled through \( \delta J \) and nonlinear mode interactions.
**q Profile and Core Magnetic Fluctuation Spectrum**

\[ q = \frac{r B_r}{R B_p} \]

\[ T_e \sim T_i \sim 400 \text{ eV} \]

Tearing modes and broadband magnetic turbulence

\[ P(f) \text{ [Gs}^2/\text{kHz]} \]

\[ f \text{ [kHz]} \]

standard 400ka

ppcd 400ka

magnetic turbulence

**Tearing modes and broadband magnetic turbulence**
Magnetic Fluctuation-Driven Charge Flux

**Fluctuation-Induced Particle flux**

\[
\Gamma_\alpha = \left< \delta n \delta E_\perp \right> + \left< \delta j_{\parallel,\alpha} \delta b_r \right> \\
\frac{B}{q_\alpha B} \\
\text{Electrostatic} \quad \text{Magnetic}
\]

**non-ambipolar flux:**

\[
\Gamma_q = \Gamma_i - \Gamma_e = \left< \tilde{j}_\parallel \tilde{b}_r \right> \frac{eB_0}{eB_0} = e\Gamma_q
\]

**Radial Charge Transport**

\[ j_r = e\Gamma_q \]
Magnetic Fluctuation-Driven Charge Flux and Maxwell Stress

\[ \Gamma_q = \frac{\langle \tilde{j}_\phi \tilde{b}_r \rangle}{eB} = \frac{1}{eB} \left[ \langle \delta j_\phi \delta b_r \rangle \frac{B_\phi}{B} + \langle \delta j_\theta \delta b_r \rangle \frac{B_\theta}{B} \right] \approx \frac{1}{eB} \frac{R}{nB} \left( k \cdot \tilde{B} \right) \frac{1}{r} \tilde{b}_r \frac{\partial}{\partial r} \tilde{r} \tilde{b}_\theta > \]

\[ \Gamma_q \approx \frac{1}{eB} \frac{B_\phi}{B} \left( 1 - \frac{m}{nq(r)} \right) \langle \tilde{j}_\phi \tilde{b}_r \rangle \]

where \( \tilde{k} \cdot \tilde{B} = \frac{n}{R} B_\phi + \frac{m}{r} B_\theta \) and \( \frac{B_\phi}{B} \left( 1 - \frac{B_\theta Rm}{B_\phi nr} \right) \frac{\langle \delta b_r \delta b_\theta \rangle}{r} \approx 0 \)

\[ \nabla \times \delta \tilde{B} = \mu_0 \delta \tilde{J} \] and \( \frac{|r - r_s|}{r_s} \ll 1 \) and \( \langle ... \rangle \) denotes flux surface average

\[ \langle \tilde{j}_\phi \tilde{b}_r \rangle \] Lorentz force equivalent to Maxwell Stress \( \frac{\partial}{\partial r} \langle \delta b_r \delta b_\theta \rangle \)
Fast polarimeter measures core mean and fluctuating $B$ & $J$

Faraday rotation angle

$$\Psi \sim \int nB \cdot dl$$

$$\partial \Psi = c_F \int n_0 \delta B \cdot d\ell + c_F \int \delta nB_0 \cdot d\ell$$

11-chord FIR laser

32 magnetic coils toroidal array

$\sim 0$

$m=1$ activity

$x=-17 \text{ cm}$

Faraday Rotation [deg.]

$\delta B$ (a)

Time [ms]
Current Fluctuation Measurement Method

Ampere's Law: \[ \oint_L \vec{dB} \cdot d\vec{l} = \mu_0 \delta I \]

Faraday Rotation Fluctuation:
\[ \delta \Psi = c_F \int n_0 \delta B \cdot d\vec{l} \approx c_F n_0 \int \delta B \cdot d\vec{l} \]

\[ \oint L \delta B \cdot d\vec{l} \approx \left[ \int \delta B_z \, dz \right]_{x_1} - \left[ \int \delta B_z \, dz \right]_{x_2} \]

\[ \approx \mu_0 \delta I \phi = \frac{\delta \Psi_1 - \delta \Psi_2}{c_F n_0} \]

Loop between polarimeter chords is equivalent to a Rogowski coil measurement

Ding, Brower et al. PRL (2003)
Measured Magnetic and Current Density Fluctuation Profiles

\((m,n)=(1,6)\) resistive tearing mode

Spatially localized in core, peaks at resonant surface.

\(\frac{\delta B}{B} \sim 1\%\)

\(r=r_{q(1,6)}\)
Magnetic Fluctuation-Induced Charge Flux

\( \frac{\delta j_{\phi}}{J_0} \sim 6\% \)

\( (m,n)=(1,6) \) tearing mode

\( \delta j_{\phi} \& \delta b_r \) peak at crash

Phase deviates from \( \pi/2 \) at crash

\( \Gamma_q \neq 0 \) at crash

non-ambipolar flux
Measured Charge Flux at sawtooth crash in MST

\[ \Gamma_q = \frac{\langle \tilde{j}_{\parallel} \tilde{b}_r \rangle}{eB} = \frac{1}{eB nB} \frac{R}{(k \cdot \tilde{B})} < \frac{1}{r} \tilde{b}_r \frac{\partial}{\partial r} r \tilde{b}_\theta > \geq \frac{1}{eB B} \left( 1 - \frac{m}{nq(r)} \right) < \tilde{j}_\phi \tilde{b}_r > \]

\[ \frac{\partial}{\partial r} < \delta b_r \delta b_\theta > \Rightarrow \frac{1}{\mu_0} < \tilde{j}_\phi \tilde{b}_r > \]

Maxwell Stress

Charge Flux

\[ \frac{\Gamma_q}{\Gamma_{Particle}} \leq 1\% \]

Charge flux is radially localized and changes sign across resonant surface
Charge Transport and Radial Electric Field

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot \vec{J} = 0, \quad \nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \quad \Rightarrow \quad \varepsilon_0 \frac{\partial \vec{E}_r}{\partial t} = \sum_j q_j \Gamma_r^j \]

\[ \frac{\langle \vec{j}_r \parallel \vec{b}_r \rangle}{B} \rightarrow 1 \sim 4 \text{ [A/m}^2\text{]} \text{ at the core (FIR Faraday)} \]

\[ \Delta \tilde{E}_r = \int \frac{\langle \vec{j}_r \parallel \tilde{\vec{b}}_r \rangle}{\varepsilon_0 B} dt \]

Leads to a huge electric field, \( \sim 50 \text{ MV/m in core} \)

However, shielding occurs due to ion polarization current

\[ \sum_j q_j \Gamma_r^j \approx -\varepsilon_0 \left( \frac{c}{V_A} \right)^2 \frac{\partial \vec{E}_r}{\partial t} - \frac{\langle \vec{j}_r \parallel \tilde{\vec{b}}_r \rangle}{B} - \frac{\mu}{B} \nabla^2 V_{E \times B} \]

- Ion polarization drift
- Magnetic charge flux
- Classical charge flux (damping from collisions)

Classical charge flux arises from radial flow due to \( \mathbf{F} \times \mathbf{B} \) drift
- \( \mathbf{F} \) viscous force perpendicular to \( \mathbf{B} \)
- \( \mu \) perpendicular viscosity coefficient
- \( V_{E \times B} \) fluctuation-induced mean flow

Radial electric field is established due to non-ambipolar transport,

but electric field is reduced by \( 10^4 \) due to shielding by the ion polarization drift.
Localized Radial Electric Field and ExB Flow

(1) ExB generates flow and flow shear

(2) Flow is toroidally and poloidally symmetric (m=0,n=0) zero-frequency zonal flow

(3) No net momentum change
Charge transport and mode-Mode Coupling

\[ r_k^1 \pm r_k^2 = r_k^3 \]

\[ \begin{pmatrix} 1 \\ 7 \end{pmatrix} - \begin{pmatrix} 1 \\ 6 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \]

1. Phase angle between \( \delta j \) & \( \delta b \) \( \sim \pi/2 \)
2. \( \Gamma_q \) reduced x5

Charge transport maximum during nonlinear mode-mode coupling
Measurements indicate the following:

- Tearing mode
  \[ \nabla J_{\parallel}(r) \rightarrow \delta \vec{B}, \delta \vec{J} \]

- Nonlinear Mode coupling
- Non-ambipolar Charge Transport \(<\delta j_{\parallel}/b_r>\)
  - Electric Field and Flow shear
  - Zonal flow

implications