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

D.L. Brower

Weixing Ding, B.H. Deng

University of California, Los Angeles, USA

D. Craig, S.C. Prager, J. Sarff, V. Svidzinski

University of Wisconsin-Madison, Madison, Wisconsin, USA

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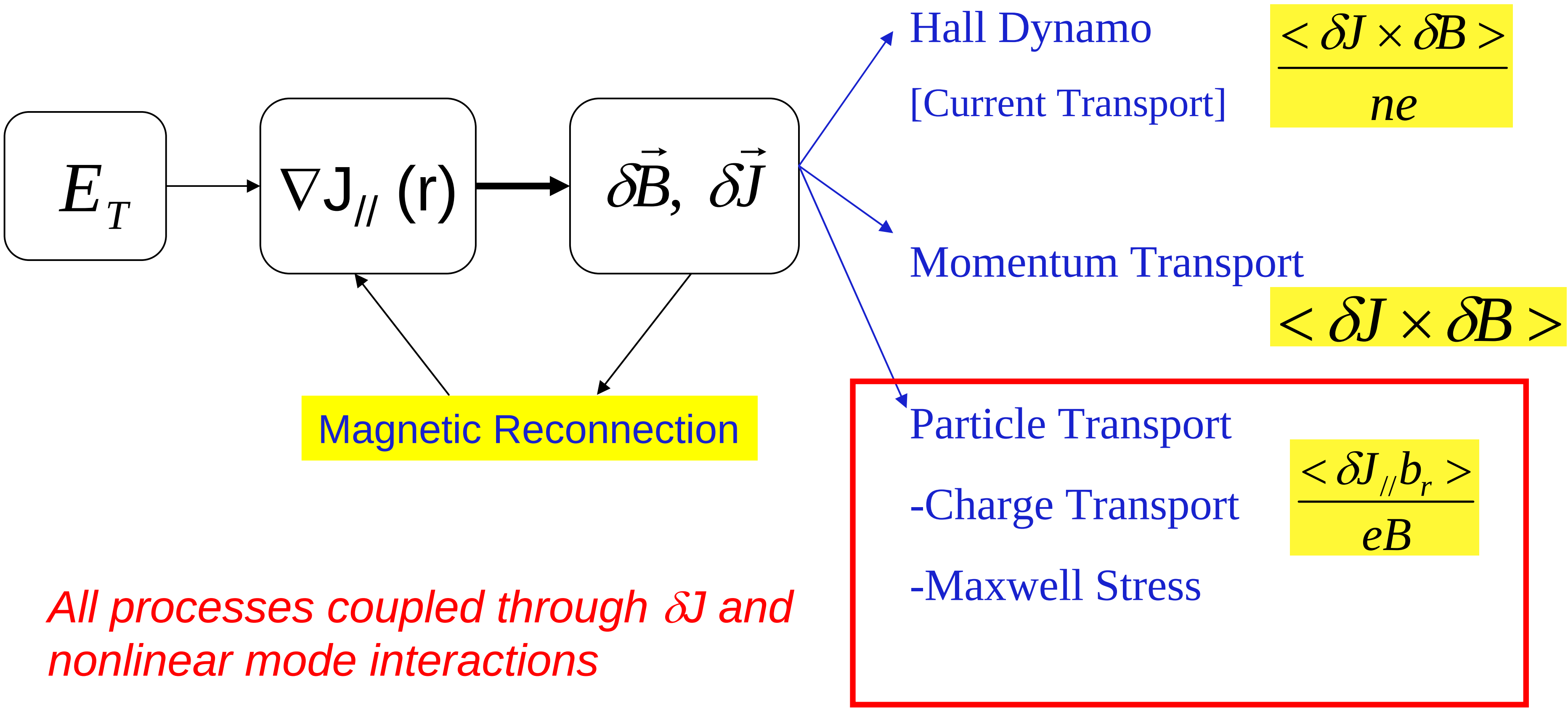
Introduction

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



E_T

$\nabla J_{//}$ (r)

$\delta\vec{B},\ \delta\vec{J}$

Magnetic Reconnection

Hall Dynamo

[Current Transport]

$$\frac{<\delta J \times \delta B>}{ne}$$

Momentum Transport

$$<\delta J \times \delta B>$$

Particle Transport

-Charge Transport

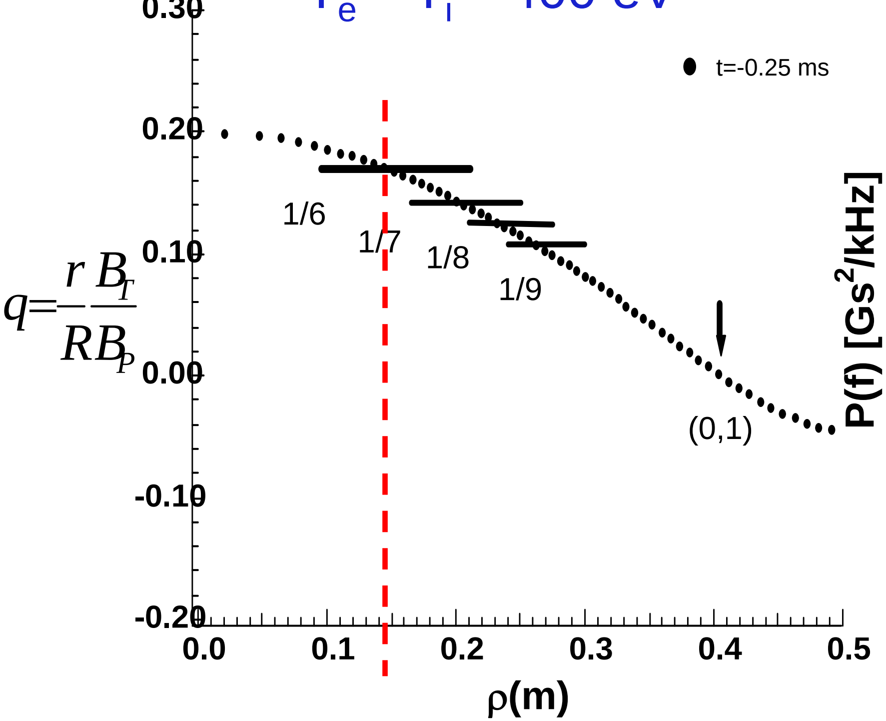
-Maxwell Stress

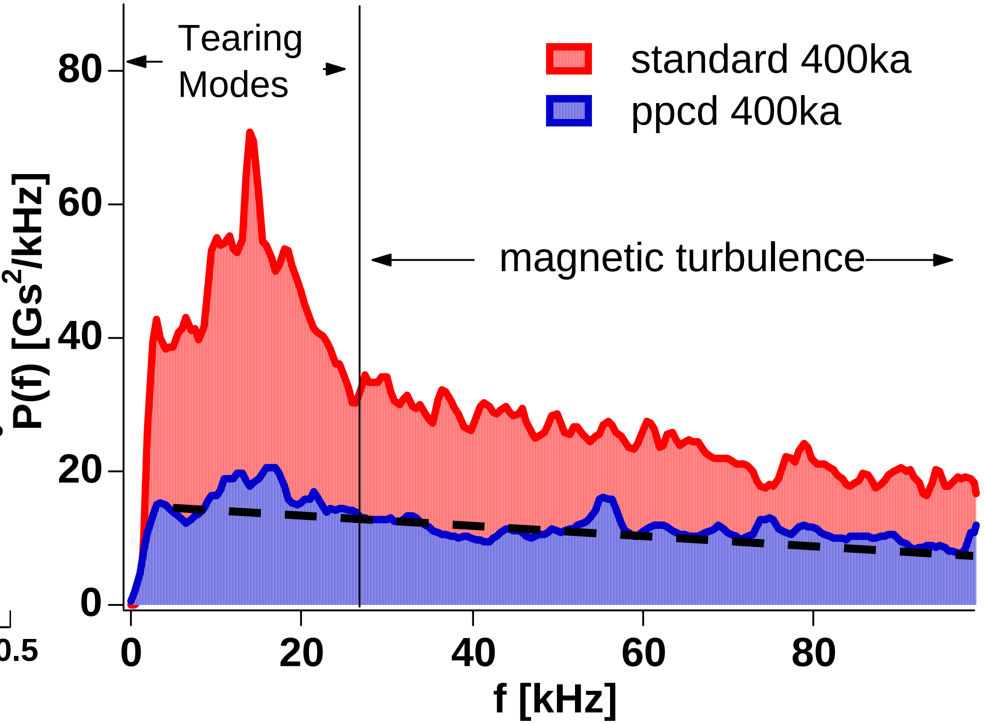
$$\frac{<\delta J_{//} b_r>}{eB}$$

All processes coupled through δJ and nonlinear mode interactions

q Profile and Core Magnetic Fluctuation Spectrum

$T_e \sim T_i \sim 400$ eV





Tearing modes and broadband magnetic turbulence

Magnetic Fluctuation-Driven Charge Flux

Fluctuation-Induced Particle flux

$$\Gamma_\alpha = \frac{\left\langle \delta n \, \delta E_\perp \right\rangle}{B} + \frac{\left\langle \delta j_{//,\alpha} \delta b_r \right\rangle}{q_\alpha B}$$

$$\uparrow \qquad\qquad\qquad \uparrow$$

Electrostatic **Magnetic**

$$non-ambipolarflux: \quad \Gamma_q = \Gamma_i - \Gamma_e = \frac{\left\langle \tilde{j}_\parallel \tilde{b}_r \right\rangle}{eB_0}$$

Radial Charge Transport $j_r = e\Gamma_q$

Magnetic Fluctuation-Driven Charge Flux and Maxwell Stress

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

$$\Gamma_q \approx \frac{1}{eB}\frac{B_\phi}{B}(1 - \frac{m}{nq(r)}) \underline{< \tilde{j}_\phi \tilde{b}_r >}$$

where $\vec{k} \bullet \vec{B} = \frac{n}{R} B_\phi + \frac{m}{r} B_\theta$ *and* $\frac{B_\phi}{B}(1 - \frac{B_\theta R m}{B_\phi n r})\frac{< \delta b_r \delta b_\theta >}{r} \approx 0$

$\nabla \times \delta \vec{B} = \mu_0 \delta \vec{J}$ and $\frac{| r - r_s |}{r_s} << 1$ *and* $\langle .... \rangle$ *denotes flux surface average*

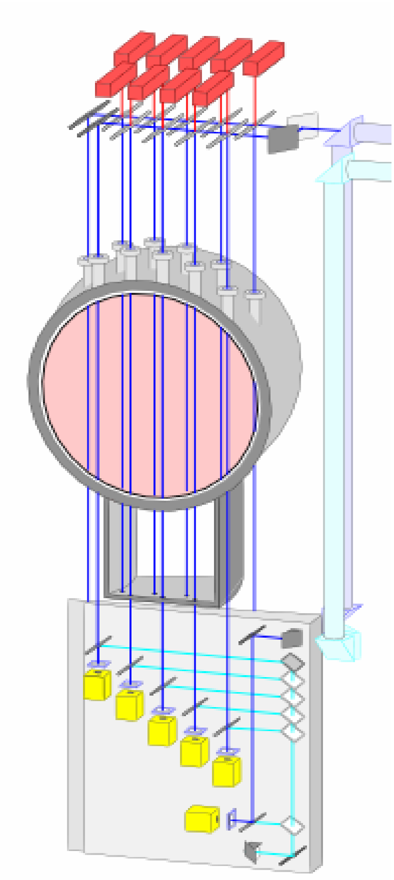
$< \tilde{j}_\phi \tilde{b}_r >$ Lorentz force equivalent to Maxwell Stress $\frac{\partial}{\partial r} < \delta b_r \delta b_\theta >$

Fast polarimeter measures core mean and fluctuating *B* & *J*

Faraday rotation angle $\Psi \sim \int n\mathbf{B}\cdot\mathbf{dl}$

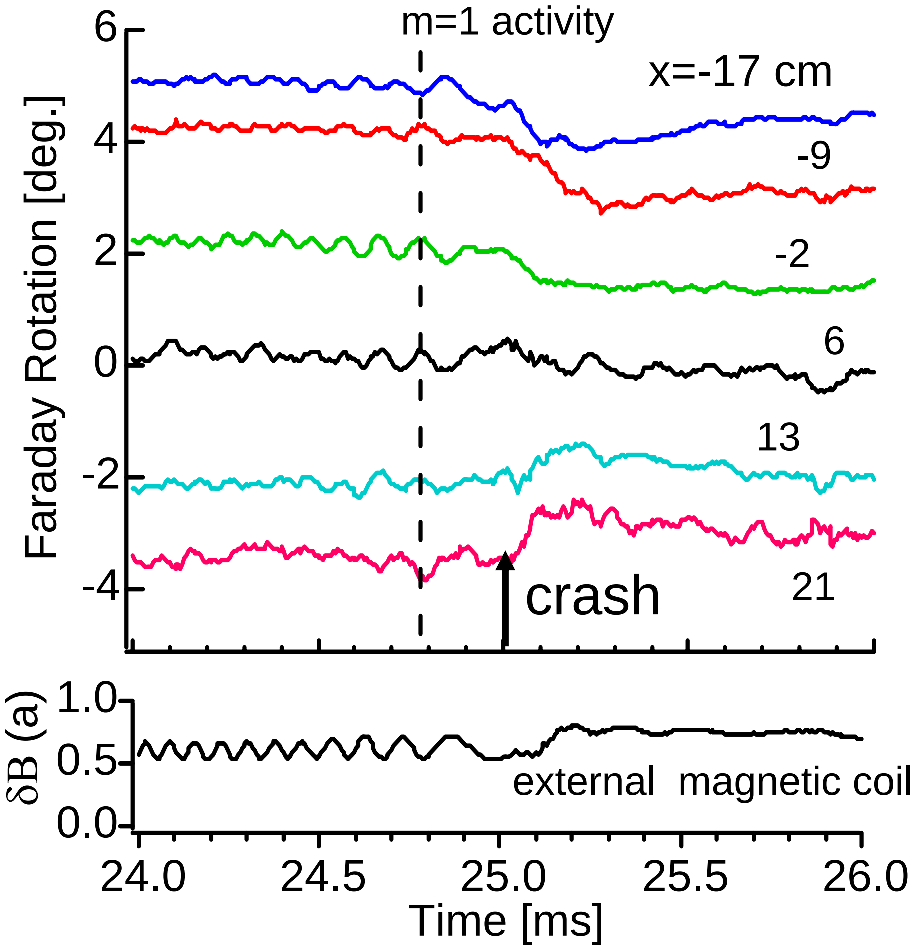
$$\delta\Psi = c_F \int n_0 \delta\vec{B} \bullet d\vec{l} + c_F \int \cancelto{\sim 0}{\delta n \vec{B}_0} \bullet d\vec{l}$$

11-chord FIR laser



+

32 magnetic coils toroidal array



Current Fluctuation Measurement Method

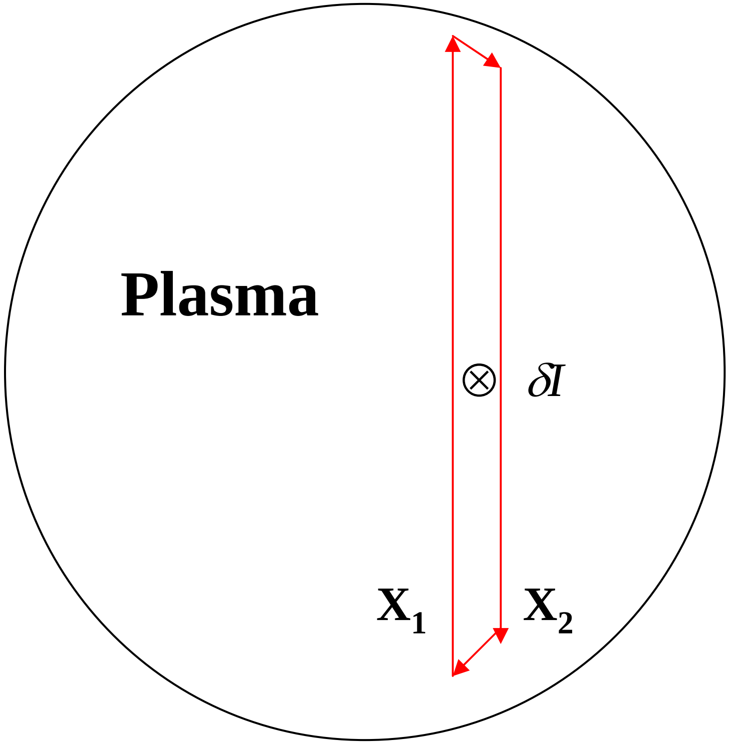
Ampere's Law : $\oint_L \delta\vec{B} \bullet d\vec{l} = \mu_0 \delta I$

Faraday Rotation Fluctuation:

$$\delta\Psi = c_F \int n_0 \delta\vec{B} \bullet d\vec{l} \approx c_F \overline{n}_0 \int \delta\vec{B} \bullet d\vec{l}$$

$$\oint_L \delta\vec{B} \bullet d\vec{l} \approx \left[\int \delta B_z dz\right]_{x1} - \left[\int \delta B_z dz\right]_{x2}$$

$$\approx \mu_0 \delta I_\phi = \frac{\delta\Psi_1 - \delta\Psi_2}{c_F \overline{n}_0}$$



Loop between polarimeter chords is equivalent to a Rogowski coil measurement

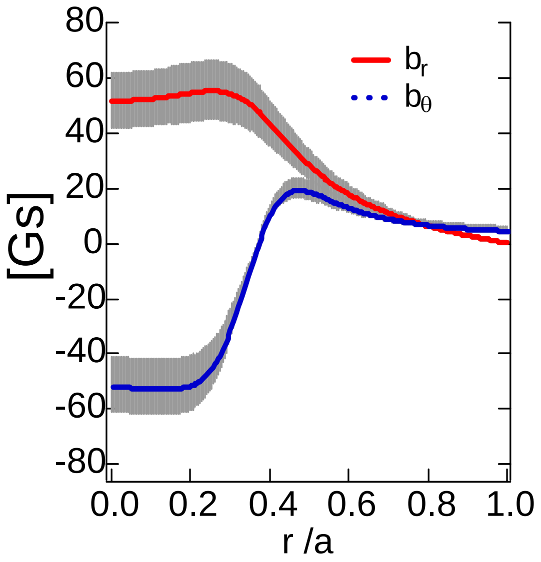
Ding, Brower et al. PRL (2003)

Measured Magnetic and Current Density Fluctuation Profiles

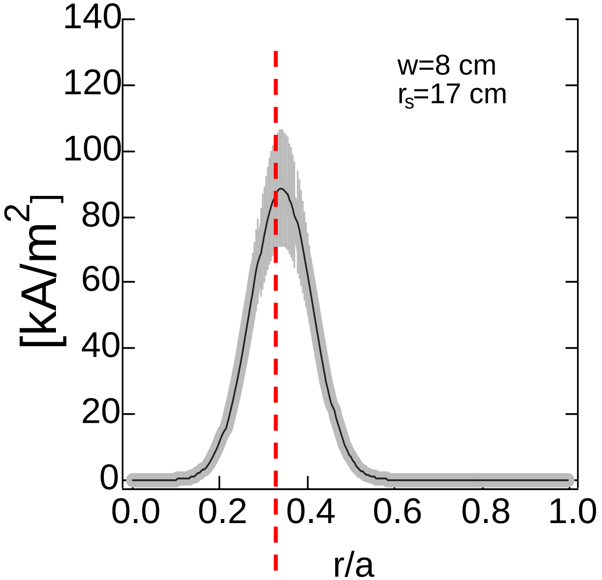
(m,n)=(1,6) resistive tearing mode

spatially localized in core,

peaks at resonant surface

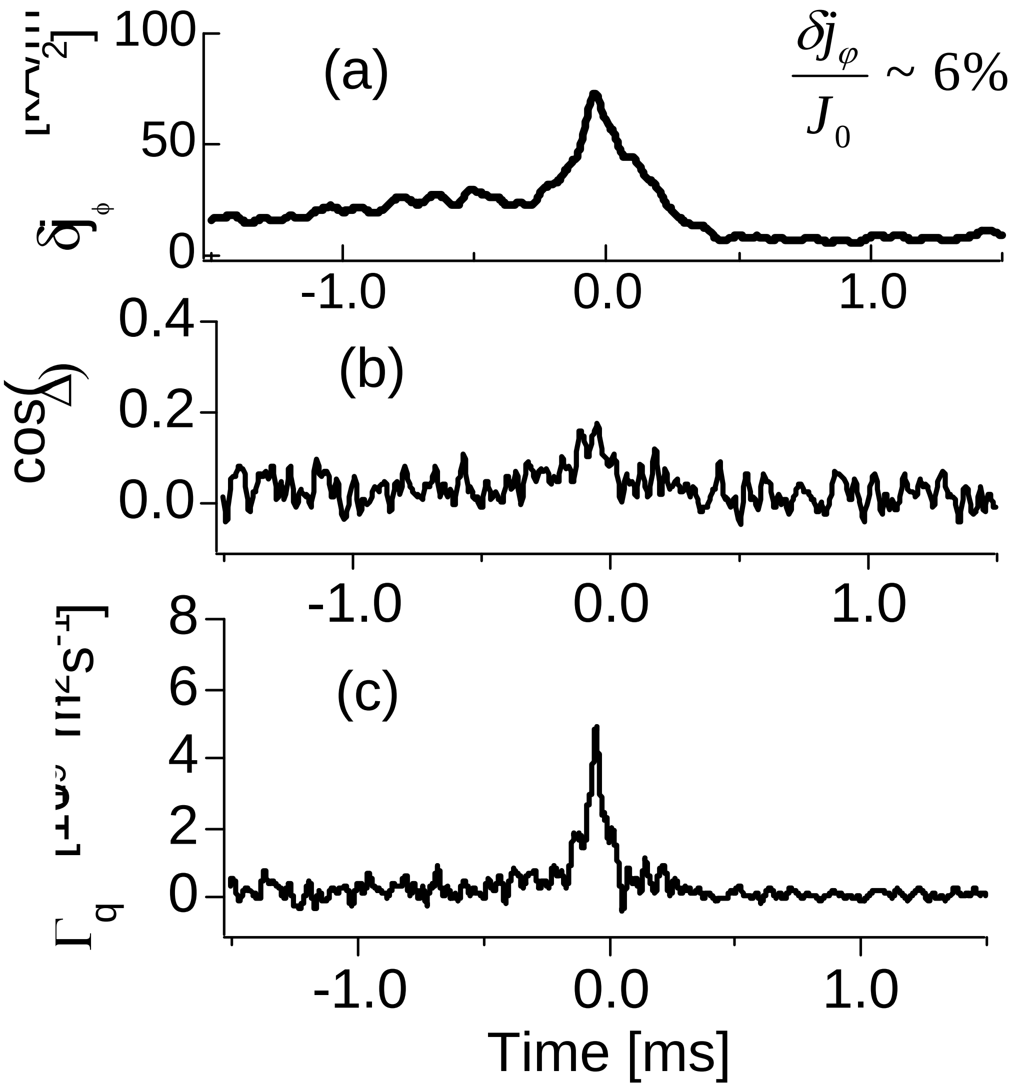


$$\frac{\delta B}{B} \sim 1\%$$



$r=r_{q(1,6)}$

Magnetic Fluctuation-Induced Charge Flux



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

δj_ϕ & δb_r peak at crash

Phase deviates from $\pi/2$ at crash

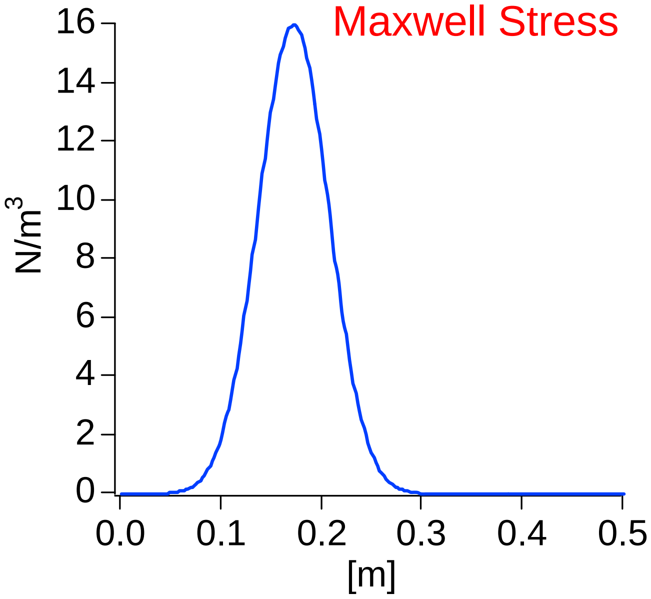
$\Gamma_q \neq 0$ *at crash*

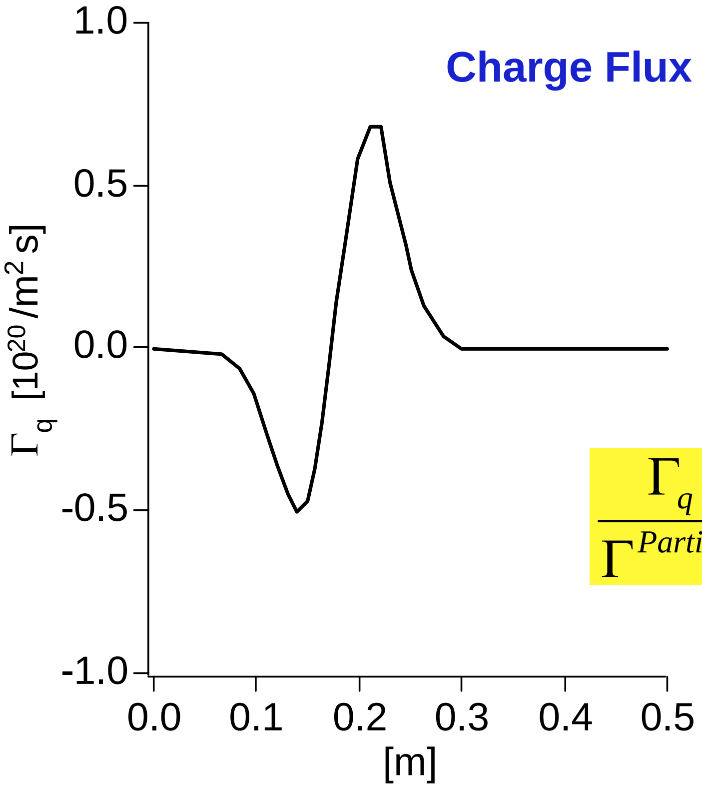
non-ambipolar flux

Measured Charge Flux at sawtooth crash in MST

$$\Gamma_q = \frac{<\tilde{j}_{//}\tilde{b}_r>}{eB} = \frac{1}{eB}\frac{R}{nB}(\vec{k}\bullet\vec{B}) < \frac{1}{r}\tilde{b}_r\frac{\partial}{\partial r}r\tilde{b}_\theta >= \frac{1}{eB}\frac{B_T}{B}(1 - \frac{m}{nq(r)}) < \tilde{j}_\phi\tilde{b}_r >$$

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





$$\frac{\Gamma_q}{\Gamma^{Particle}} \leq 1\%$$

Charge flux is radially localized and changes sign across resonant surface

Charge Transport and Radial Electric Field

$$\frac{\partial\rho}{\partial t}+\nabla\bullet\vec{J}=0,\qquad \nabla\bullet\vec{E}=\frac{\rho}{\varepsilon_0}\qquad\Rightarrow\qquad \varepsilon_0\frac{\partial E_r}{\partial t}=\sum_j q_j\Gamma_r^j$$

$$\frac{<\tilde{j}_{//}\tilde{b}_r>}{B}\longrightarrow$$

1~4 [A/m^2] at the core (FIR Faraday)

$$\Delta\tilde{E}_r=\int\frac{<\tilde{j}_{//}\tilde{b}_r>}{\varepsilon_0 B}dt$$

Leads to a huge electric field, ~50 MV/m in core

However, shielding occurs due to ion polarization current

$$\sum_j q_j\Gamma_j^r\approx\underline{-\varepsilon_0\left(\frac{c}{V_A}\right)^2\frac{\partial E_r}{\partial t}}-\underline{\frac{<\tilde{j}_{//}\tilde{b}_r>}{B}}-\underline{\frac{\mu}{B}\nabla^2 V_{E\times B}}$$

Ion polarization drift

magnetic charge flux

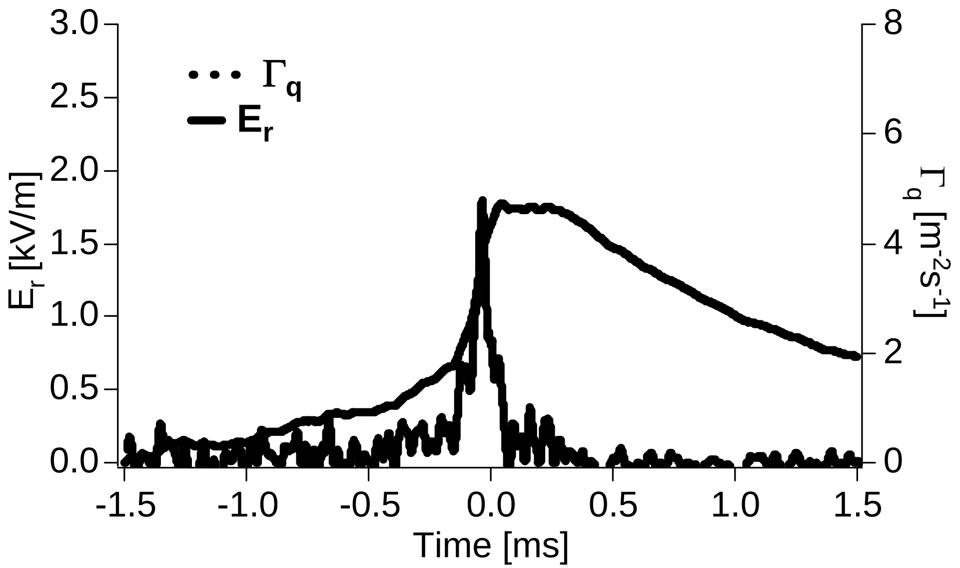
classical charge flux (damping from collisions)

Classical charge flux arises from radial flow due to **F**x**B** drift
F viscous force perpendicular to **B**
μ perpendicular viscosity coefficient
V_{ExB} fluctuation-induced mean flow

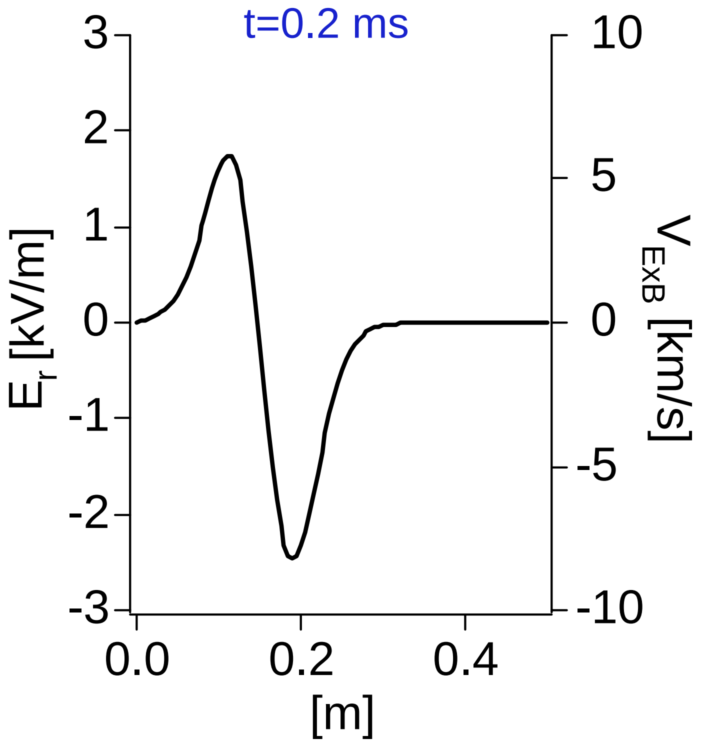
Radial electric field is established due to non-ambipolar transport,

but electric field is reduced by 10^4 due to shielding by the ion polarization drift.

Localized Radial Electric Field and ExB Flow



Peak occurs at sawtooth crash



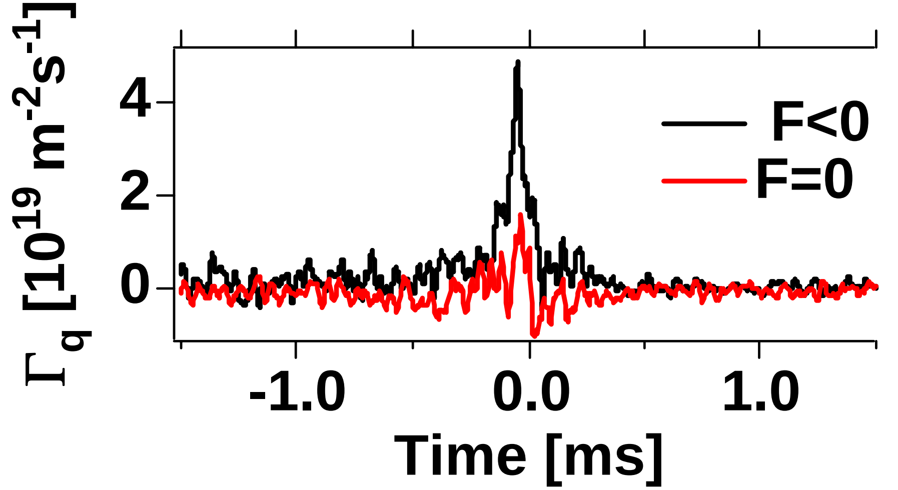
Charge flux generates a local E_r with spatial scale ~5 cm that changes sign across resonant surface

(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

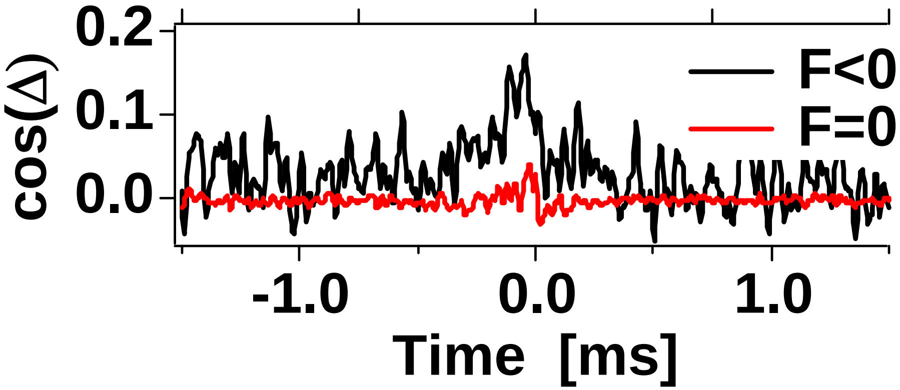


with k_3(m=0,n=1)

without k_3(m=0,n=1)

$$\vec{k}_1 \pm \vec{k}_2 = \vec{k}_3$$

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

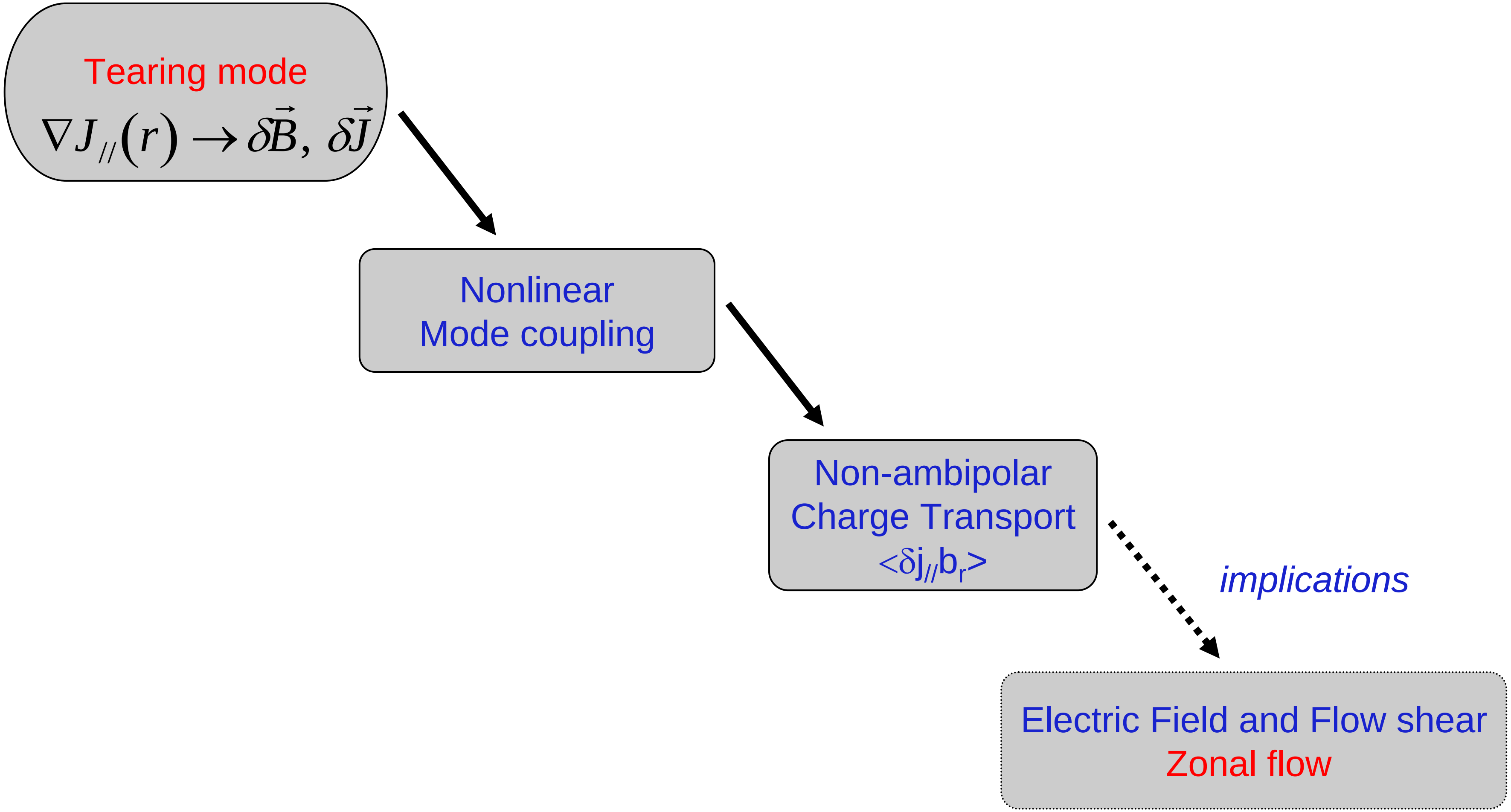


1. Phase angle between δj & δb ~ $\pi/2$
2. Γ_q reduced x5

Charge transport maximum during nonlinear mode-mode coupling

Summary

Measurements indicate the following:



Tearing mode

$\nabla J_{//}(r) \rightarrow \delta\vec{B},\ \delta\vec{J}$

Nonlinear
Mode coupling

Non-ambipolar
Charge Transport
$<\delta j_{//} b_r>$

implications

Electric Field and Flow shear
Zonal flow