Particle Transport due to Stochastic Magnetic Field in a High-Temperature Plasma

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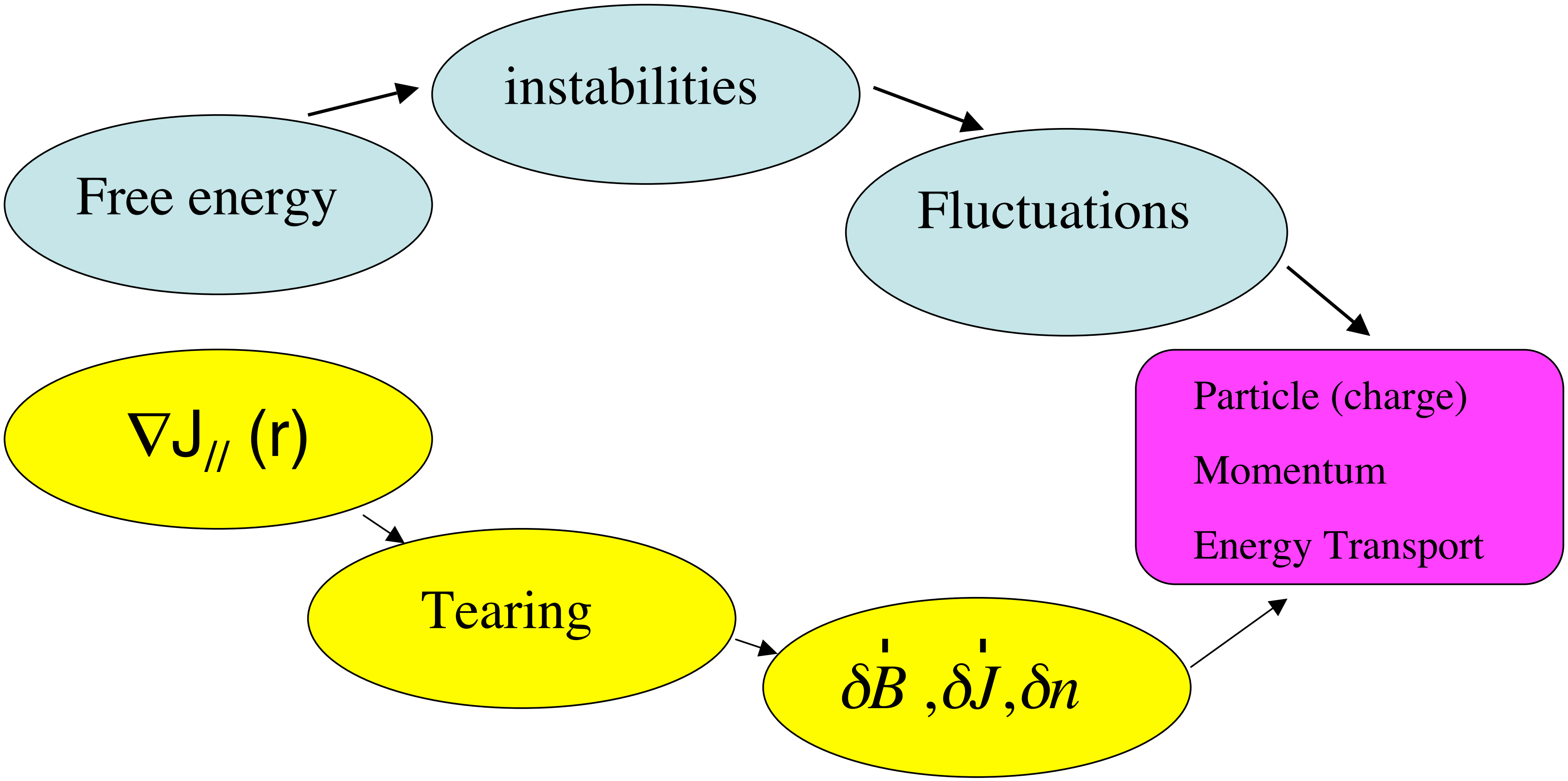
(Oct. 14, 2009 Princeton)

UCLA

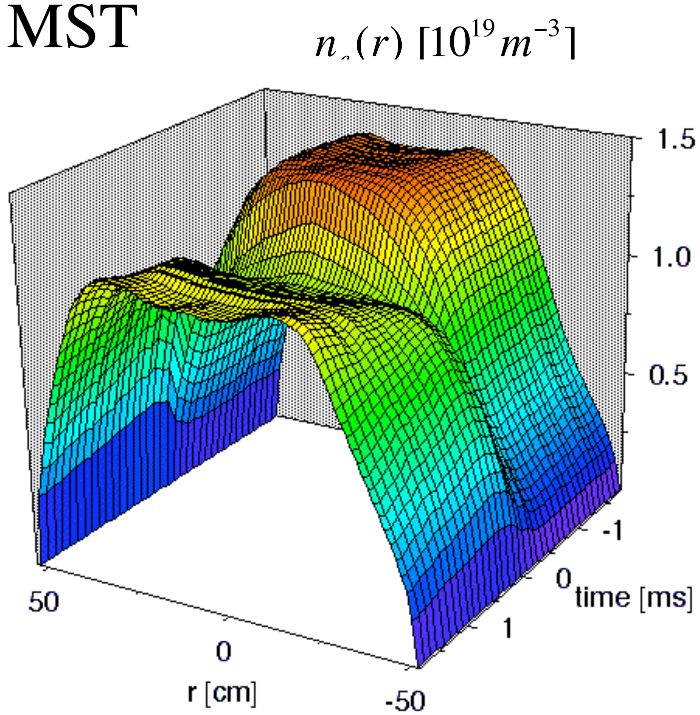
THE UNIVERSITY of WISCONSIN MADISON

Introduction

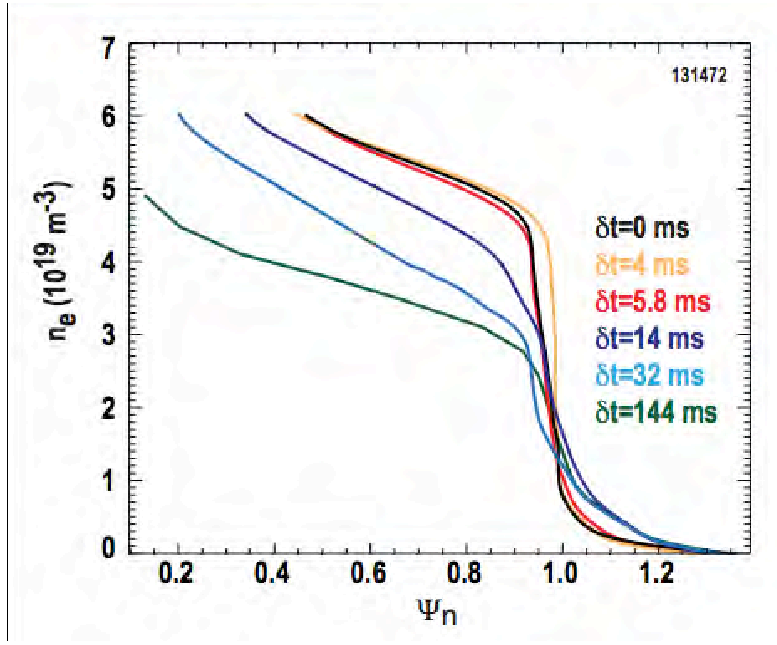


Electron Density Relaxation Due to Magnetic Field Perturbation

MST



DIII-D



L.Zeng (UCLA) et al DIII-D by reflectometry

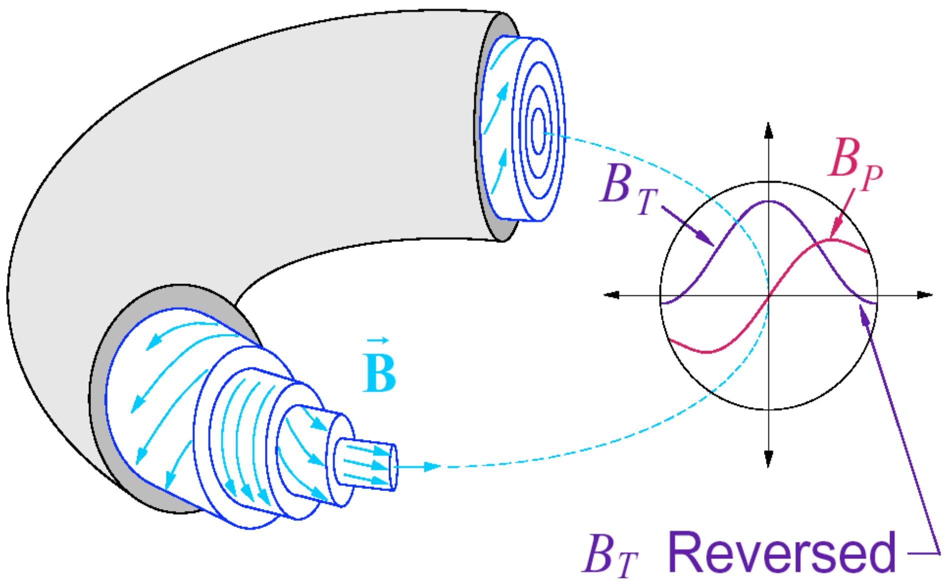
Magnetic Field Fluctuations

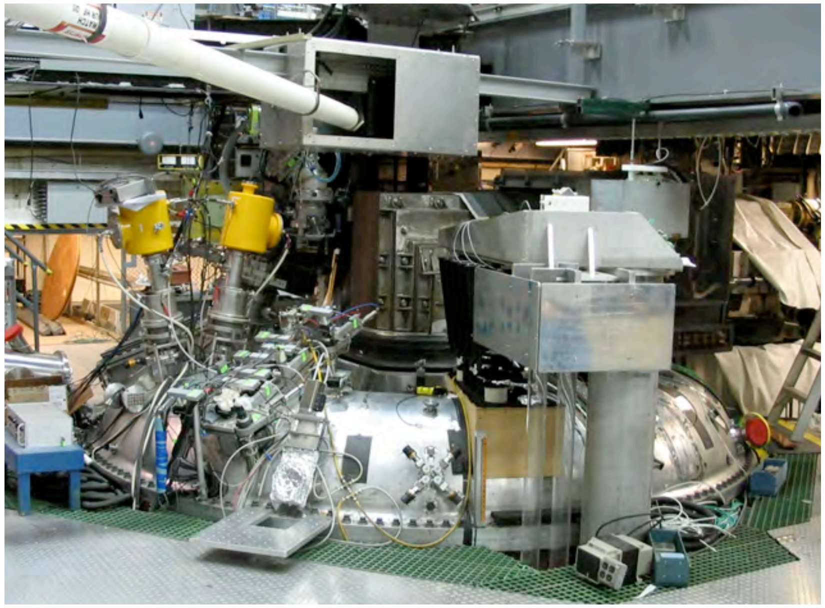
Driven by Tearing Instabilities in MST

Driven by I-coil externally in DIII-D

Madison Symmetric Torus

MST Reversed-Field Pinch (RFP) is toroidal configuration with relatively weak toroidal magnetic field B_T (i.e., $B_T \sim B_p$)





$$q(r) = \frac{r}{R}\frac{B_T}{B_P} < 1$$

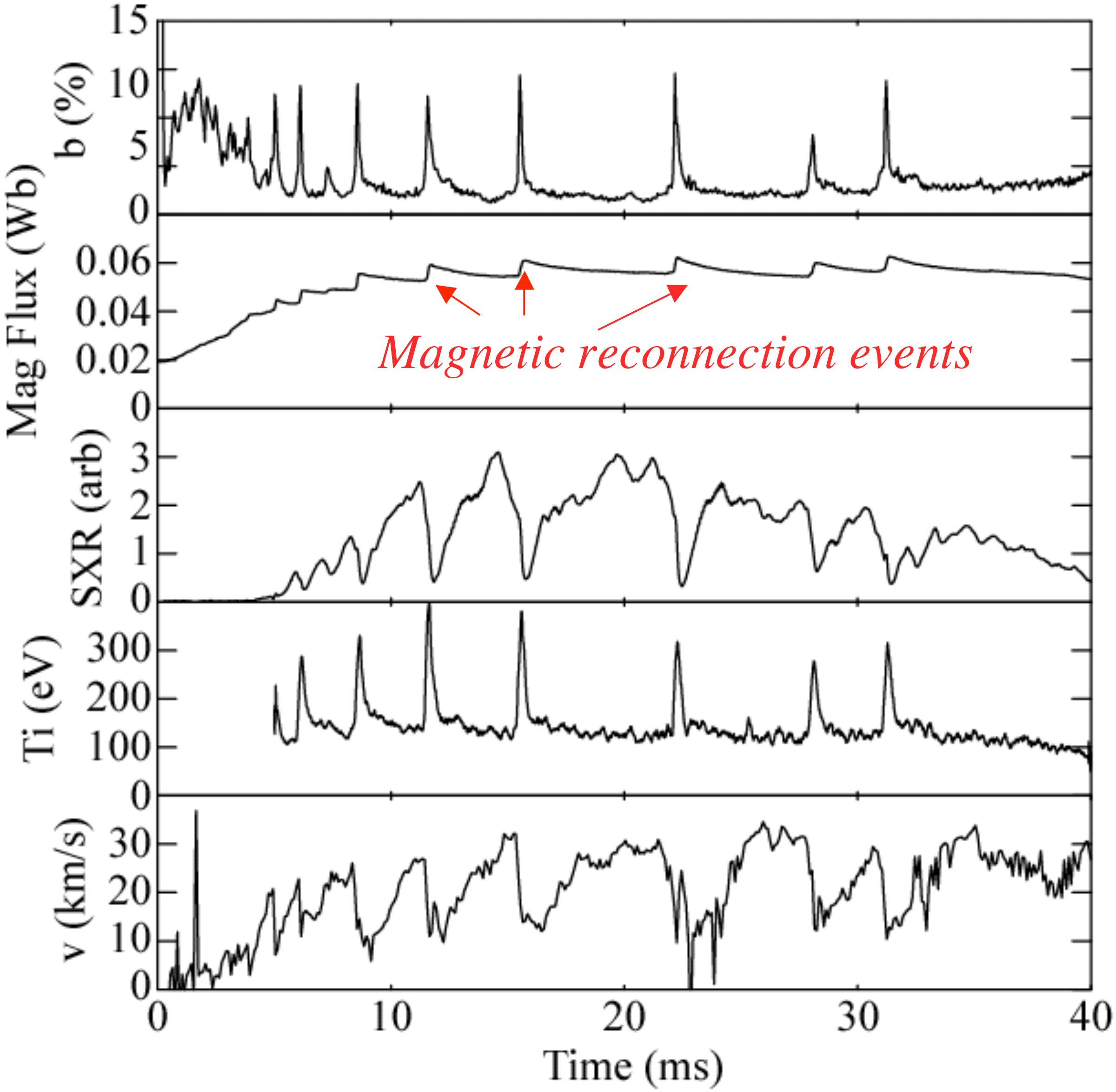
$\beta \sim 7\%$

For plasma w/o current profile control

R_0 = 1.5 m, a = 0.51 m, I_p ~400 kA

B_T ~ 3-4 kG, $n_e \sim 10^{19}$ m^{-3} ,$T_e \sim T_i \sim$300eV

Fluctuations and Transport in the MST



Generation of magnetic flux (dynamo)

Particle and energy transport

Ion heating

Momentum transport

Outline

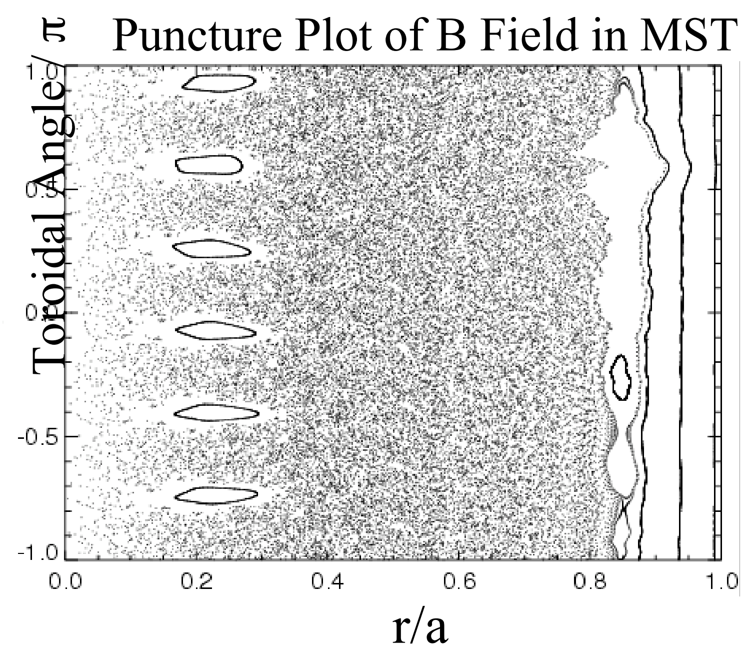
(1) Density Relaxation and particle transport during reconnection;

(2) Measured magnetic fluctuation-induced particle flux accounts for particle transport;

$$\Gamma_r^e = \frac{<\delta\Gamma_{//,e}\delta b_r>}{B} \quad (= \frac{<\delta j_{//,e}\delta b_r>}{eB}) \longrightarrow \frac{\partial n_e}{\partial t}$$

GOAL: *Identify the role of stochastic magnetic field in particle transport during reconnection*

Particle Diffusion Rate in a Stochastic Magnetic Field in MST



Magnetic diffusivity coefficient from field line tracing

$$D_m = \frac{<(\Delta r)^2>}{2\Delta l} \sim 1.0\times 10^{-4}\ \mathrm{m}$$

(Hudson and Gennady, 2006)

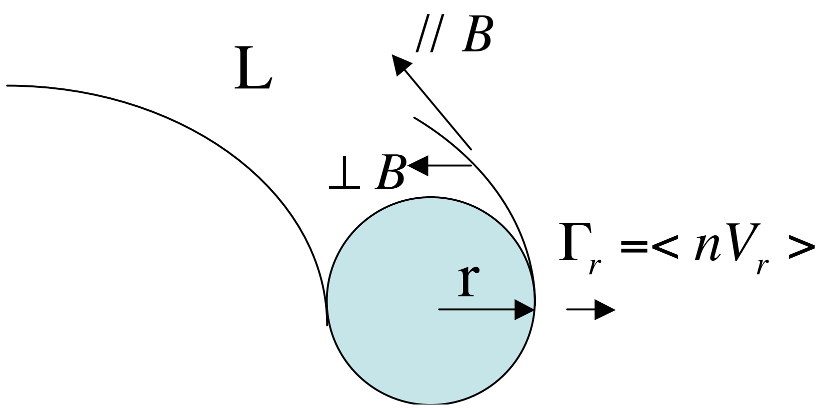
Rechester & Rosenbluth (1978) derived a quasi-linear coefficient

$$D_m = \pi R_0 \sum_{m,n} q(\frac{\delta b_r^{m,n}}{B_0})^2 \sim 2.0\times 10^{-4}\ m$$

Harvey (1981) and Finn (1990) suggest particle diffusion rate $D_i \sim D_m c_s$ (or $V_{i,th}$)

Plugging in MST parameters: $\tau_p \sim$ 1-2 ms (quasi-linear estimate) in ambient case
$\tau_p \sim$ 0.1-0.2 ms (experiment) during relaxation event

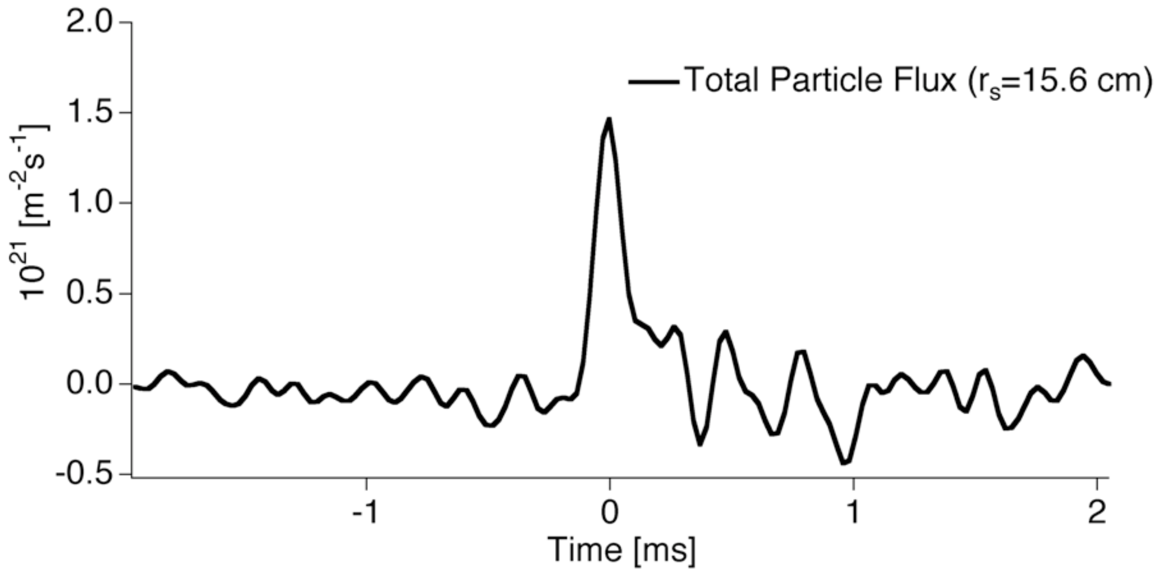
Measured Total Particle Flux during Reconnection



$$\frac{\partial n}{\partial t} + \nabla \bullet < nV_r > = S_e \qquad (S_e << \frac{\partial n}{\partial t})$$

$$\Gamma_r \times 2\pi r L = -\frac{\partial}{\partial t}\int n(r)dV \cong -\frac{\partial \bar{n}}{\partial t}\pi r^2 L$$

$$\Gamma_r = -\frac{\partial \bar{n}}{\partial t}\frac{r}{2}$$



*Total particle flux surges to 1.5*10^{21} $m^{-2}s^{-1}$ during reconnection*

Fluctuation-Induced Particle Flux Contributes to Total Flux

Particle transport is determined by perpendicular momentum balance

$$n\vec{E}_{\perp} + n(\vec{V} \times \vec{B})_{\perp} = 0$$

$$n = n_0 + \delta n$$
$$\vec{E}_{\perp} = \vec{E}_{\perp 0} + \delta\vec{E}_{\perp}$$
$$\vec{V} = \vec{V}_0 + \delta\vec{V}$$
$$\vec{B} = \vec{B}_0 + \delta\vec{B}$$

$$< nV_r > = n_0 \frac{< E_{\perp 0} >}{B_0} + \frac{< \delta n \delta E_{\perp} >}{B_0} + V_{//} \frac{< \delta n \delta b_r >}{B_0} + n_0 \frac{< \delta V_{//} \delta b_r >}{B_0}$$

total flux pinch electrostatic magnetic fluctuation

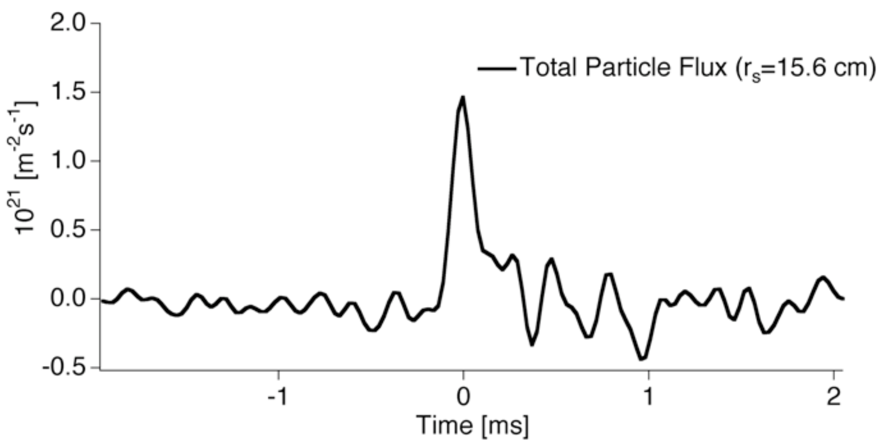
$$\frac{< \delta\Gamma_{//} \delta b_r >}{B_0}$$

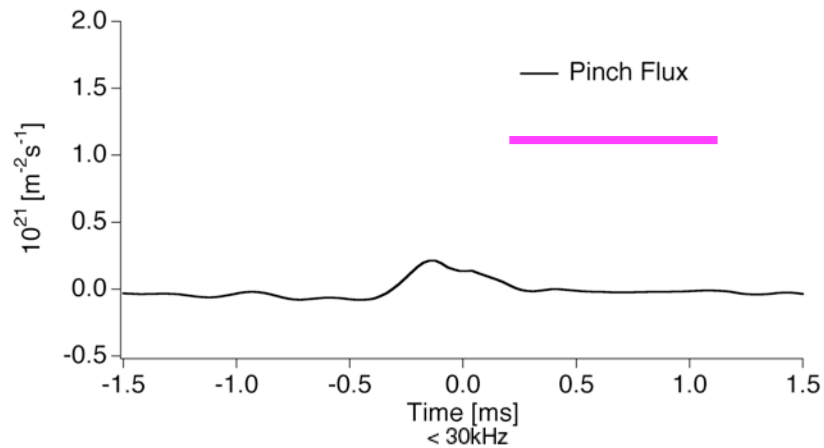
Particle transport arises from particle streaming along stochastic field lines

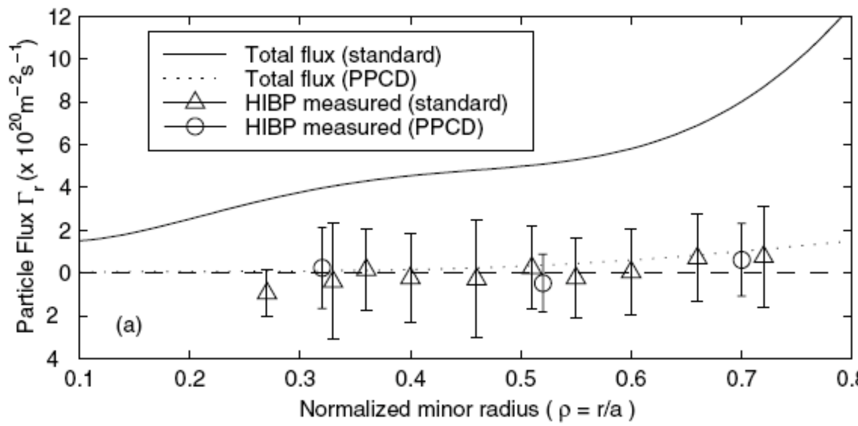
Pinch and electrostatic fluctuation-induced particle flux are *negligible*

$$\Gamma_r = \langle nV_r \rangle = n_0 \frac{\langle E_{\perp 0} \rangle}{B_0} + \frac{\langle \delta n \delta E_\perp \rangle}{B_0} + V_{//} \frac{\langle \delta n \delta b_r \rangle}{B_0} + n_0 \frac{\langle \delta V_{//} \delta b_r \rangle}{B_0}$$

total flux pinch electrostatic magnetic fluctuation



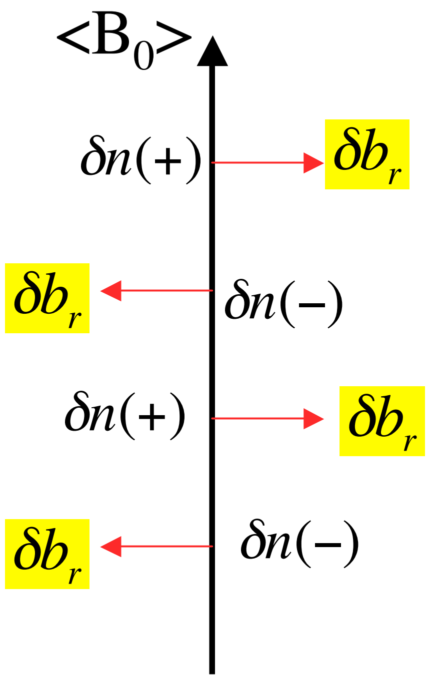




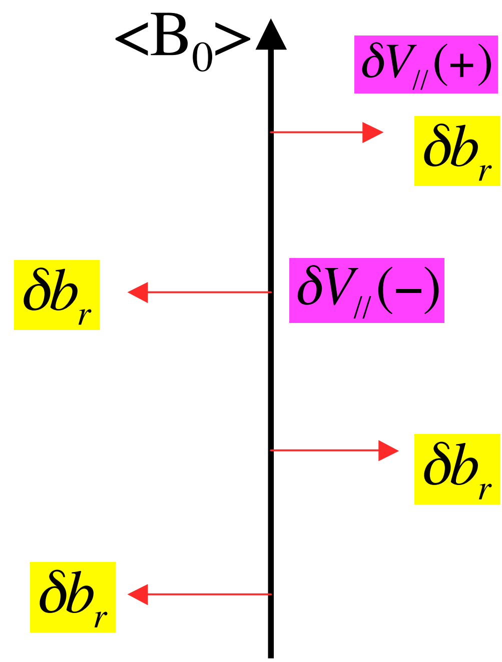
Lei, et al. PRL 2002

Magnetic Fluctuation-Induced Particle Flux

$$\Gamma_r^M = V_{//}\frac{<\delta n \delta b_r>}{B_0} + n\frac{<\delta V_{//}\delta b_r>}{B_0}$$



Density-fluctuation dependent flux



Velocity-fluctuation dependent flux

Measurement of Magnetic Fluctuation-Induced Particle Flux

$$\Gamma_r = V_{//} \frac{< \delta n \delta b_r >}{B_0} + n \frac{< \delta u_{//} \delta b_r >}{B_0}$$

$V_{//,e} = \frac{J}{ne}$ Laser Faraday rotation $B_\theta \longrightarrow J = \nabla \times B$

B_0 Motion Stark effect

$\delta b_r(r)$ Laser Faraday rotation

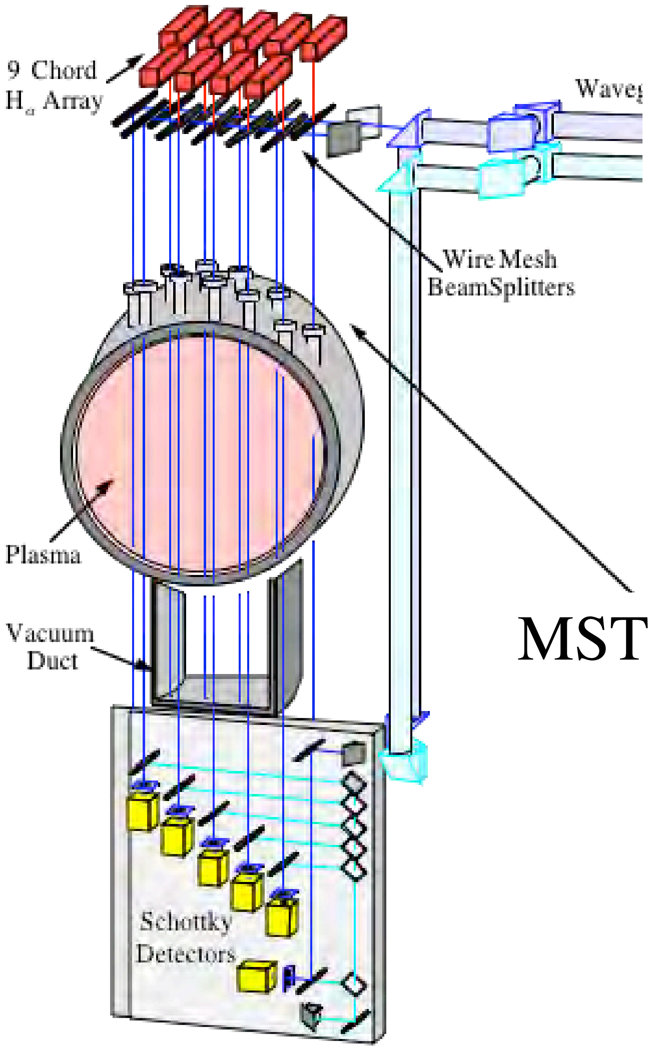
δn_e Laser interferometer ($\nabla \delta n_e$)

$V_{//,i}$, $\delta V_{//,i}$ CHERS, Mode Rotation, Ion Doppler Spectroscopy

$\delta V_{//,e}$ Not measured, inferred from quasi-neutrality

7 independent quantities are needed to determine electron and ion flux

FIR Polarimeter-Interferometer System



$$\phi \sim \int n dl + \int \tilde{n} dl$$

Interferometer → *density fluctuation*

$$\Psi \sim \int n\vec{B} \bullet d\vec{l} + \int n\tilde{\vec{b}} \bullet d\vec{l} + \int \tilde{n}\vec{B} \bullet d\vec{l}$$

Faraday rotation → *magnetic field*

See poster: P03-23(Bergerson)

Ding, Brower, et al

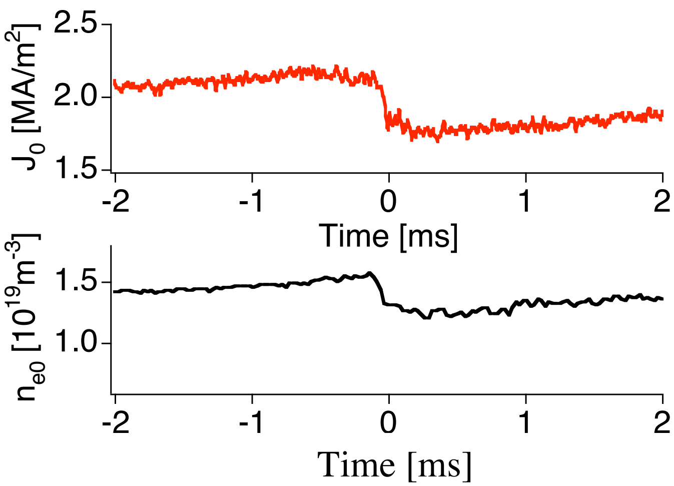
PRL(2003),(2004)

RSI(2004),(2008)

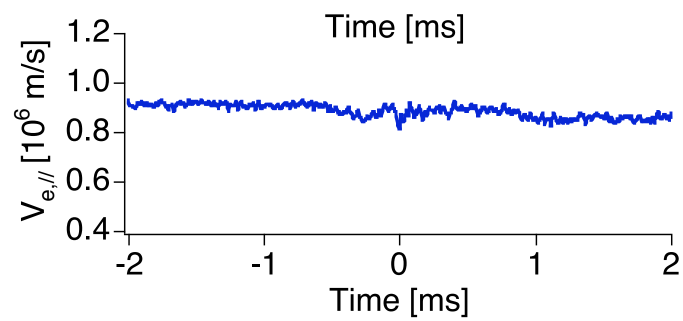
11 chords, separation 8 cm,phase resolution 0.05 degree, time response up to 1μs

Measurement of Equilibrium Magnetic Field and Current Denisty

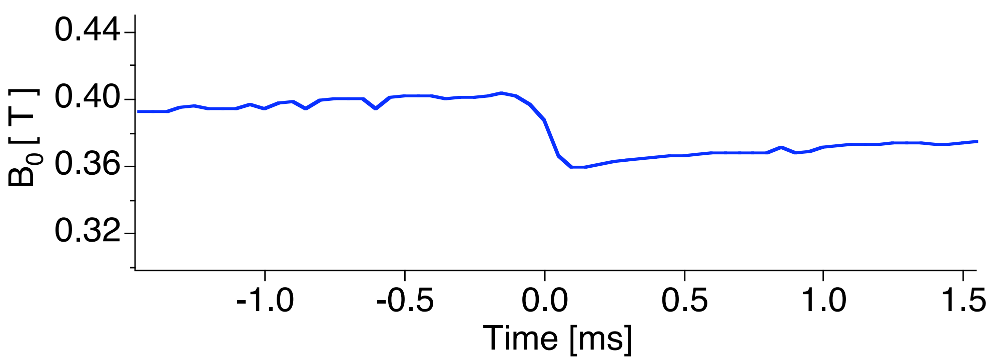
$$V_{//,e}\frac{<\delta n\delta b_r>}{B_0}$$



$$V_{//,e}=\frac{J_0}{en_{e0}}$$



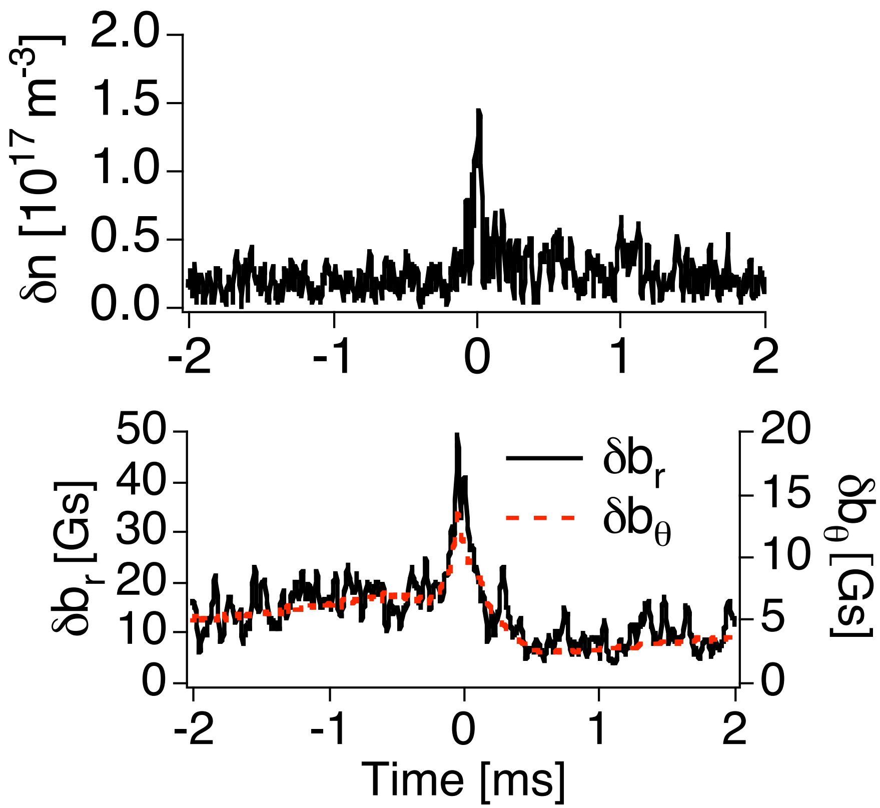
By Faraday rotation

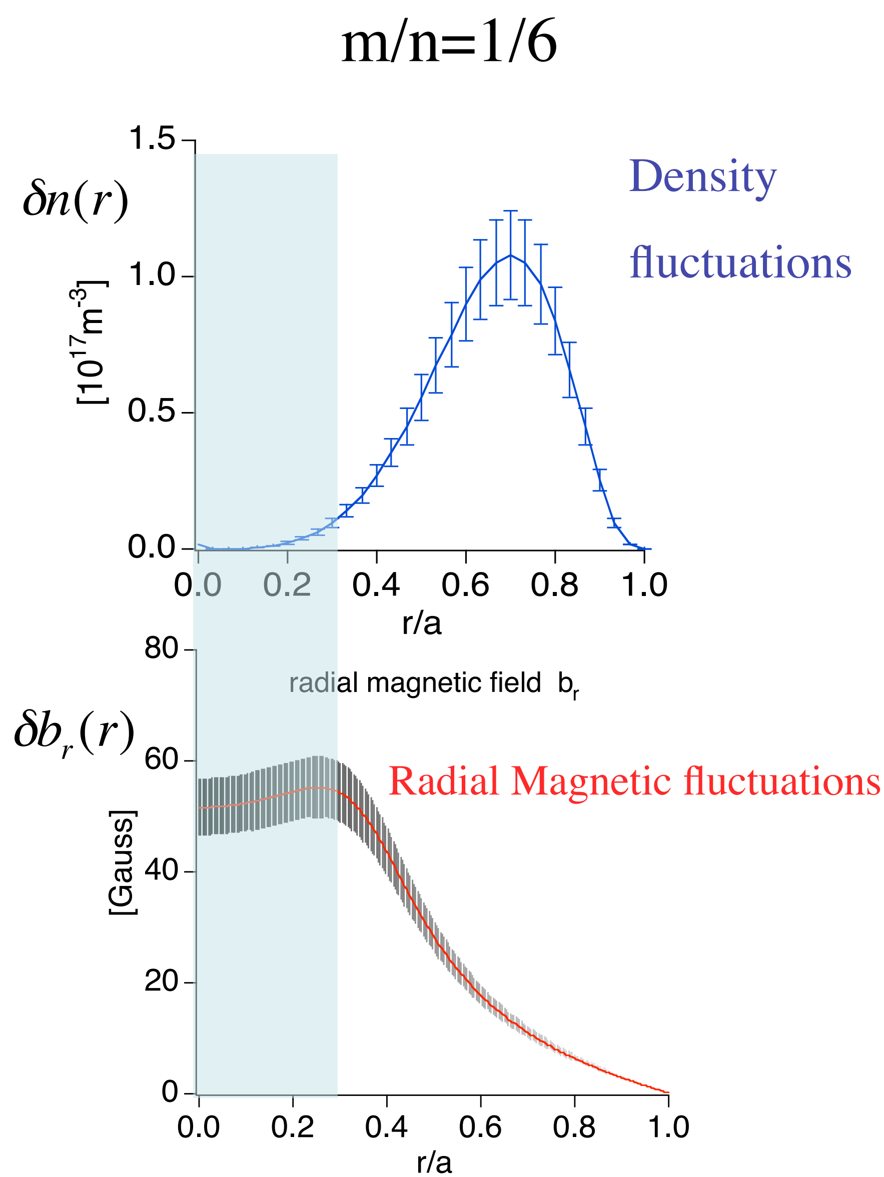


By Motion Stark Effect

Measurement of *density and magnetic fluctuation*

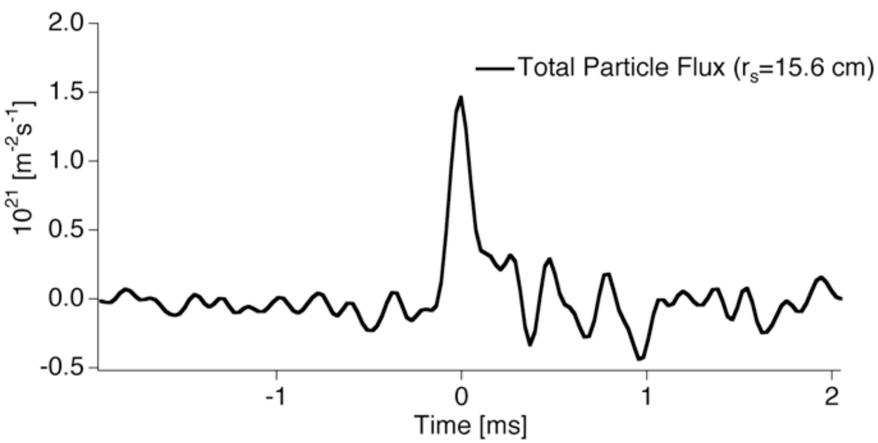
$$V_{//,e} \frac{<\delta n \delta b_r>}{B_0}$$



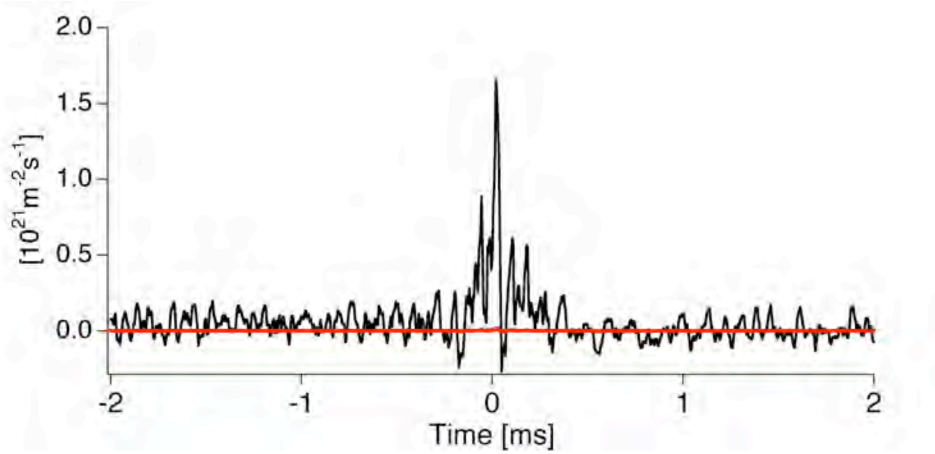


Magnetic fluctuation-induced electron particle flux

(Total Flux) $\Gamma_r = \langle nV_r \rangle = V_{//,e} \frac{\langle \delta n \delta b_r \rangle}{B_0} + n_0 \frac{\langle \delta V_{//,e} \delta b_r \rangle}{B_0}$



$\langle nV_r \rangle = \langle nV_{r,e} \rangle = \langle nV_{r,i} \rangle$



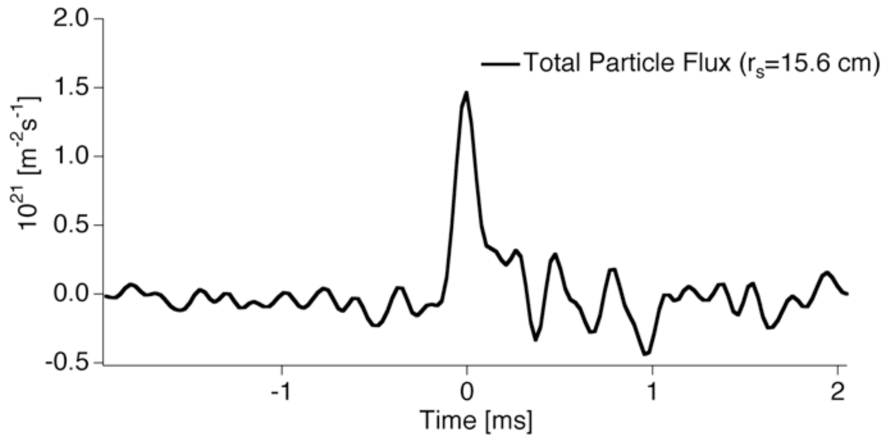
$V_{//,e} \frac{\langle \delta n \delta b_r \rangle}{B_0}$

$V_{//,i} \frac{\langle \delta n \delta b_r \rangle}{B_0}$

Density fluctuation contributes to electron particle flux

Magnetic fluctuation-induced ion particle flux

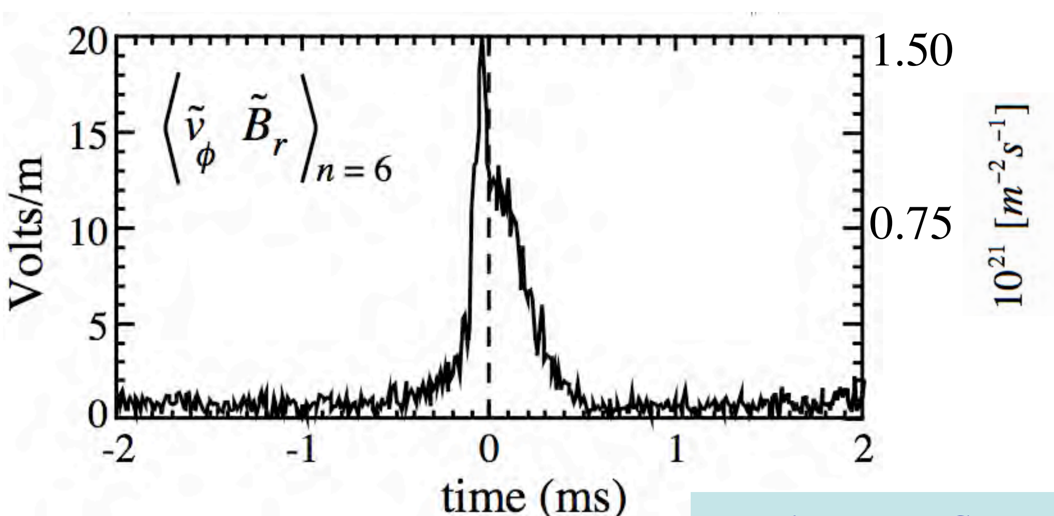
(Ion Flux) $\Gamma_r = \langle nV_r \rangle = V_{//,i} \frac{\langle \delta n \delta b_r \rangle}{B_0} + n_0 \frac{\langle \delta V_{//,i} \delta b_r \rangle}{B_0}$



$\langle nV_r \rangle$

$E_\perp = \langle \delta v_\phi \times \delta b_r \rangle$

$V_{r,i} = E_\perp \times B_0 / B_0^2$

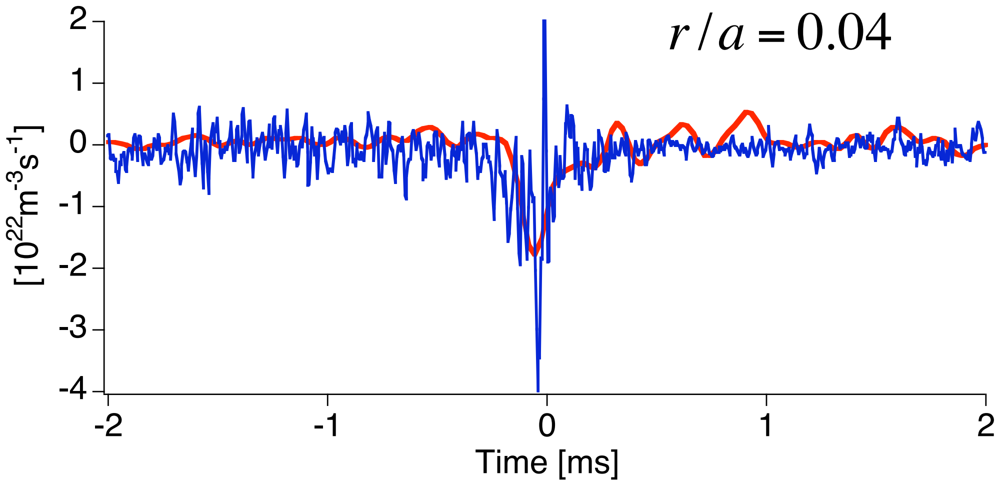


$\Gamma_{r,i} = n_0 V_{r,i} = n_0 \frac{\langle \delta V_{//,i} \delta b_r \rangle}{B_0}$

Den Hartog et. Al ,PoP,1999

Velocity fluctuation contributes to ion flux

Magnetic Fluctuation Induced Flux Balances the Change of Density

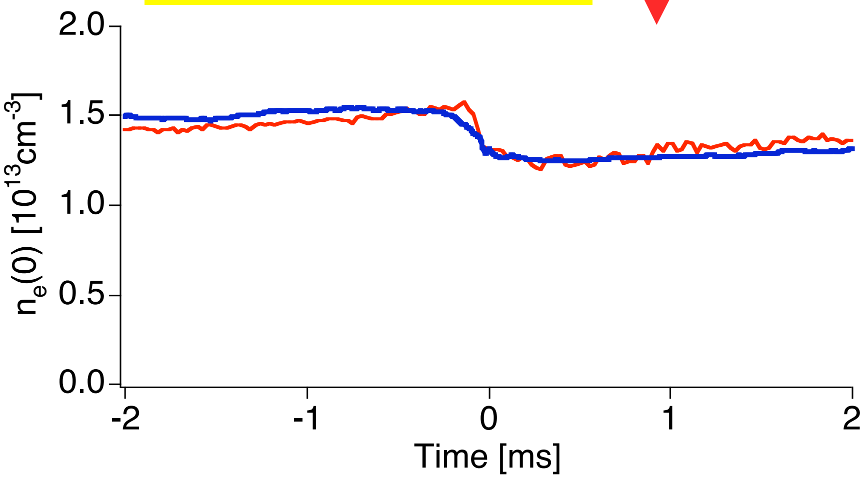


Red: $\frac{\partial \langle n_e \rangle}{\partial t}$

Blue: $-\nabla \bullet \Gamma_r^e$

$$\frac{\partial \langle n_e \rangle}{\partial t} + \nabla \bullet \Gamma_r^e \approx 0$$

Integrating over time

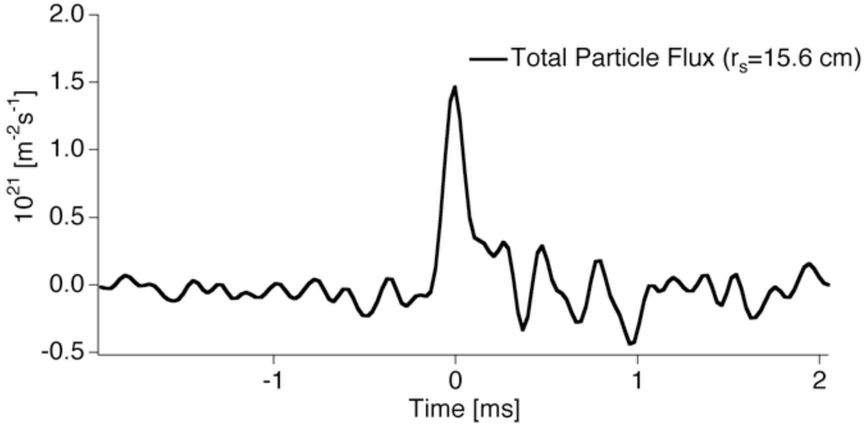


Red: $\langle n_e \rangle$

Blue: $-\int \nabla \bullet \Gamma_r^e \, dt$

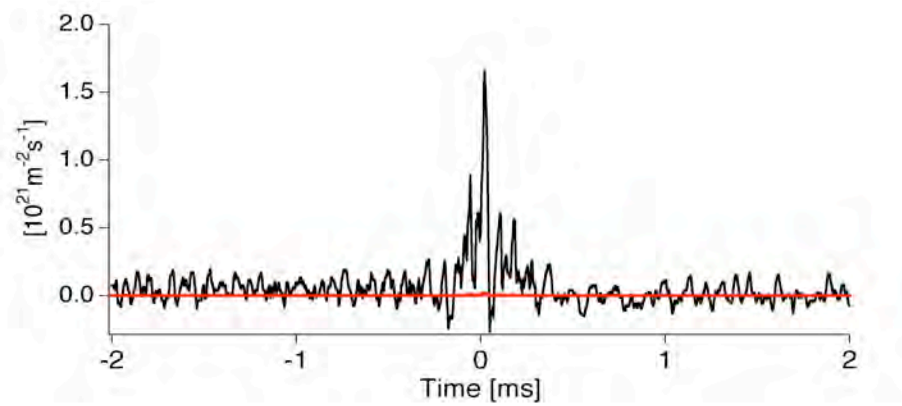
Magnetic fluctuation induced particle transport drives density change

Electron and ion flux arise from different mechanism



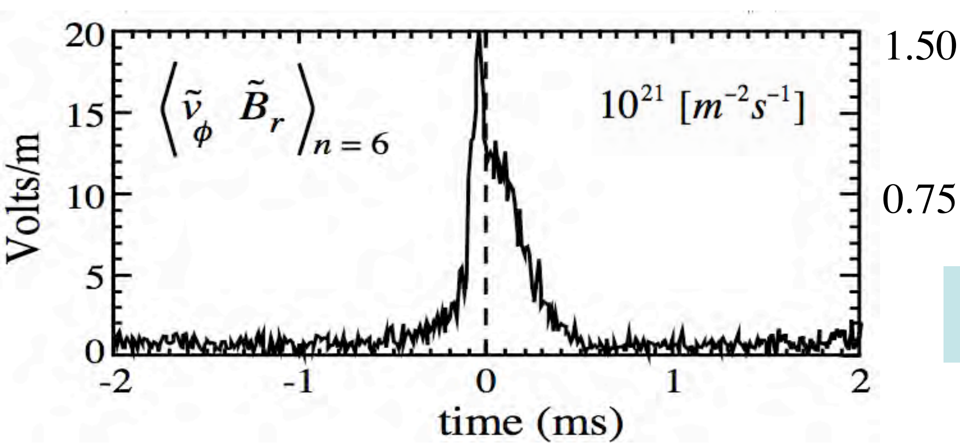
Total flux $<nV_r>$

$$< nV_r > = V_{//} \frac{< \delta n \delta b_r >}{B_0} + n_0 \frac{< \delta V_{//} \delta b_r >}{B_0}$$



Electron flux

$$< nV_{r,e} > = V_{//,e} \frac{< \delta n \delta b_r >}{B_0} + n_0 \frac{< \delta V_{//,e} \delta b_r >}{B_0}$$



$$< nV_{r,i} > = V_{//} \frac{< \delta n \delta b_r >}{B_0} + n_0 \frac{< \delta V_{//,i} \delta b_r >}{B_0}$$

Ion flux

Ambipolarity of Particle Transport
(difference between electron and ion particle flux)

$$\Gamma_q = \Gamma_{r,i} - \Gamma_{r,e} =$$

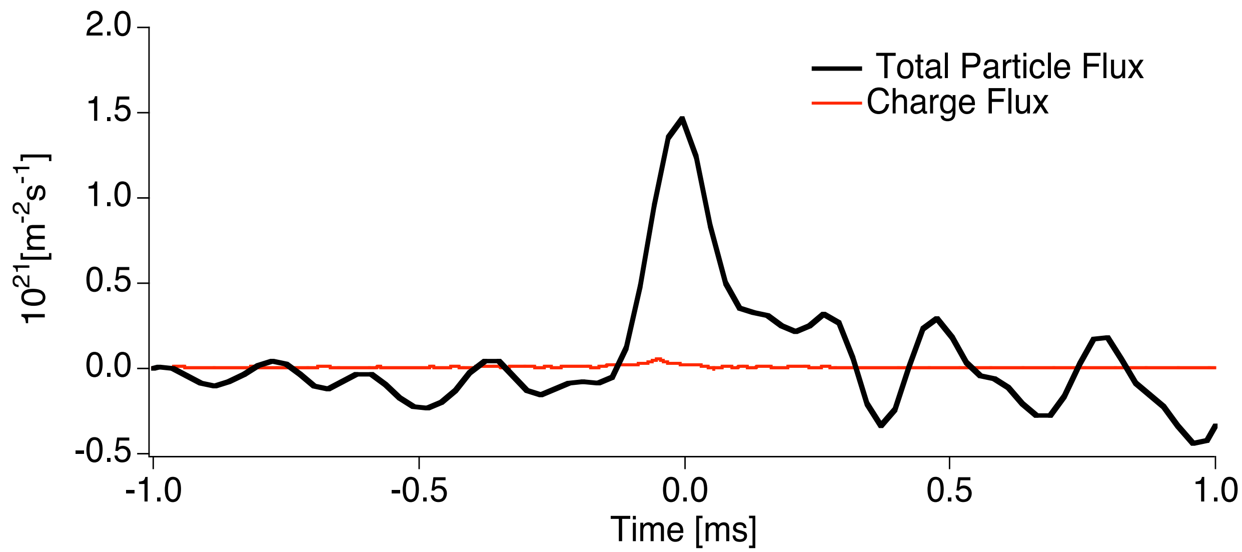
$$= \frac{< \tilde{j}_{//}\tilde{b}_r >}{eB} \approx \frac{R}{nB^2}\left(\frac{m}{r}B_p + \frac{n}{R}B_T\right)\frac{1}{e\mu_0} < \frac{1}{r}\tilde{b}_r \frac{\partial}{\partial r} r\tilde{b}_\theta >$$

$$\approx \frac{R}{neB^2}(\vec{k} \bullet \vec{B}) \,|\tilde{b}_r||\tilde{j}_\phi|\cos(\Delta)$$

(m,n) are poloidal and toroidal mode number

$$\nabla \times \delta\vec{B} = \mu_0 \delta\vec{J}$$

$$\frac{|r - r_s|}{r_s} << 1$$



Γ_r

Γ_q

$$\Gamma_q \approx 2\%\Gamma_r$$

Ding, et al. PRL 2007

Particle diffusivity is (30X) larger than QL prediction

Harvey (1981)

(with ambipolariy)

$$D_i \sim D_m V_{i,th}$$

Rechester&Rosenbluth(1978)

(without ambipolarity)

$$\chi_e^{RR}(D_e) \sim D_m V_{e,th}$$

$$30 \times D_m V_{i,th} \quad \sim \quad D^{Exp} = 730 \text{ m}^2/s \quad \sim \quad 0.5 \times D_m V_{e,th}$$

(30 times) Predicted Particle Transport

~Predicted Heat Transport

Experimentally, particle diffusion rate is approximately electron diffusion rate in a stochastic magnetic field.

Summary

(1) Rapid particle transport is observed in MST associated with the stochastic field;

(2) Electron particle flux $V_{//,e}\frac{<\delta n \delta b_r>}{B}$ is comparable to ion flux ($n\frac{<\delta V_{//,i}\delta b_r>}{B}$), accounting for global density change during a reconnection event;

(3) Particle transport is much larger than the expected from quasi-linear theory.

Magnetic Fluctuation Measurement Method

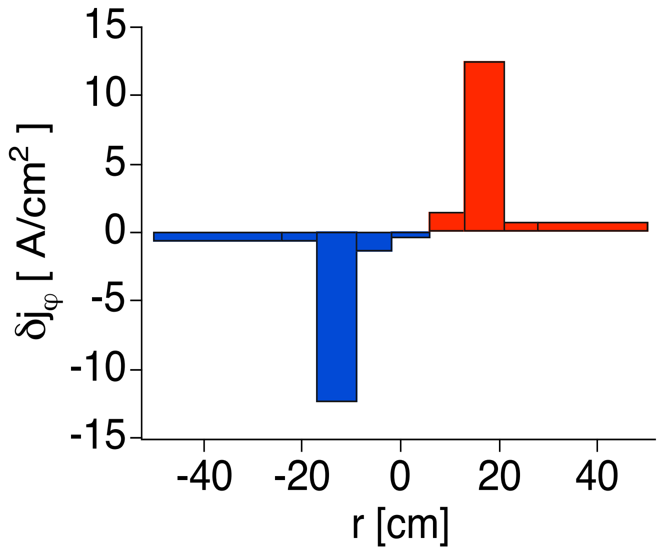
Ampere's Law : $\oint_L \delta\vec{B} \bullet d\vec{l} = \mu_0 \delta I$

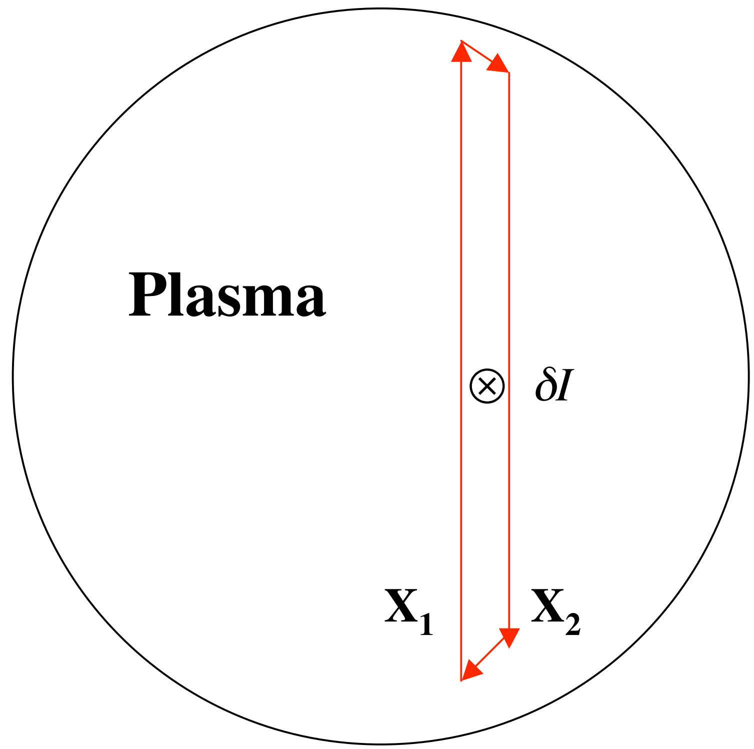
Faraday Rotation Fluctuation :

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

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

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

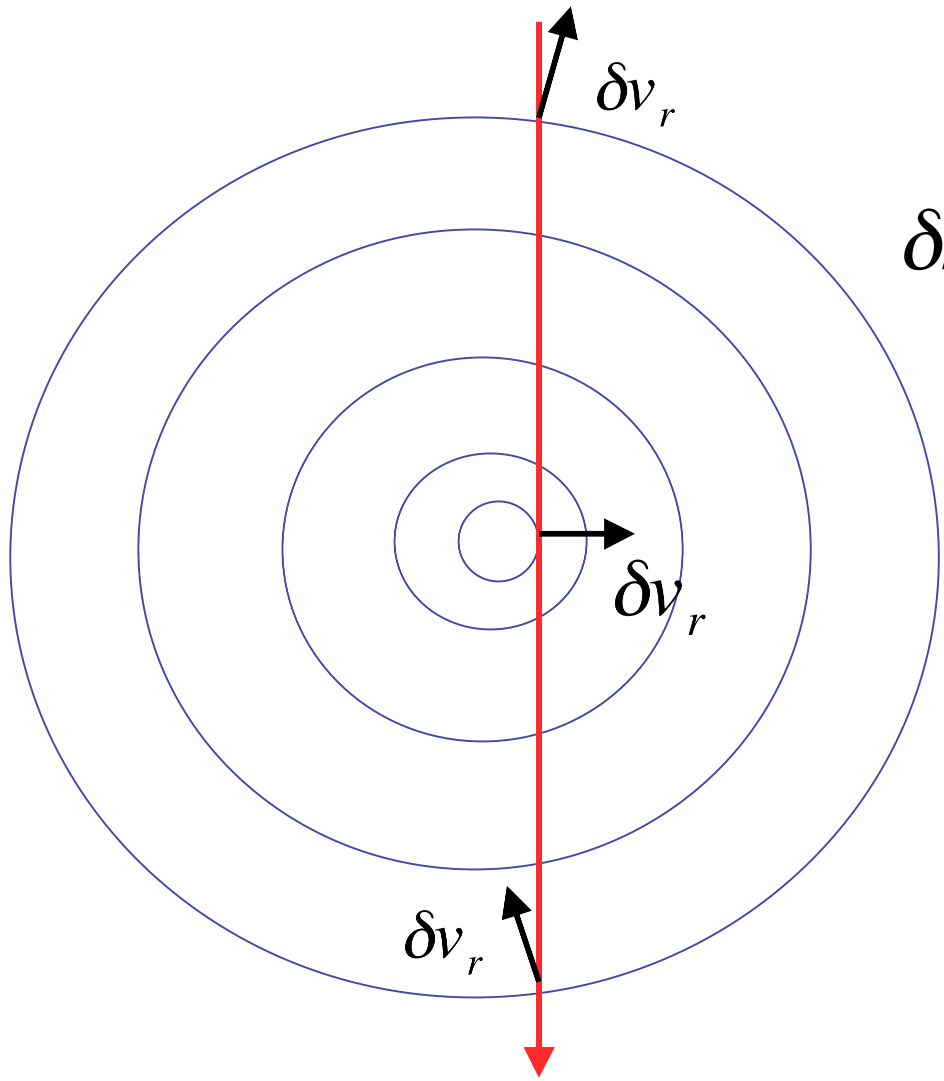




Ding, et al. PRL (2003)

Localization of Density Fluctuations

Physically



$$\delta n \sim -\delta \vec{v}_r \bullet \nabla n_0$$

$$m = 1$$