Core Measurements of Magnetic Fluctuation-Induced Particle and Momentum Flux in MST

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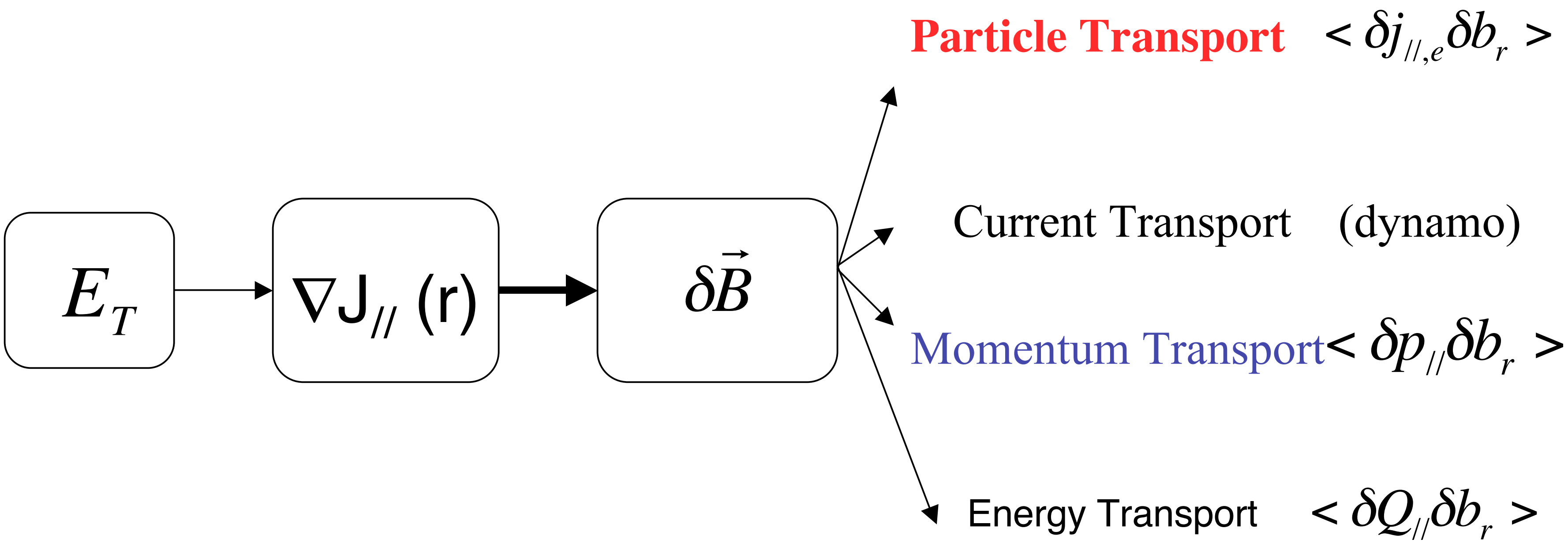
Introduction

Magnetic fluctuations play an important role in particle and momentum transport in the laboratory plasmas



E_T → $\nabla J_{//}$ (r) → $\delta\vec{B}$

Particle Transport $< \delta j_{//,e}\delta b_r >$

Current Transport (dynamo)

Momentum Transport $< \delta p_{//}\delta b_r >$

Energy Transport $< \delta Q_{//}\delta b_r >$

Transport also determines equilibrium dynamics

Introduction

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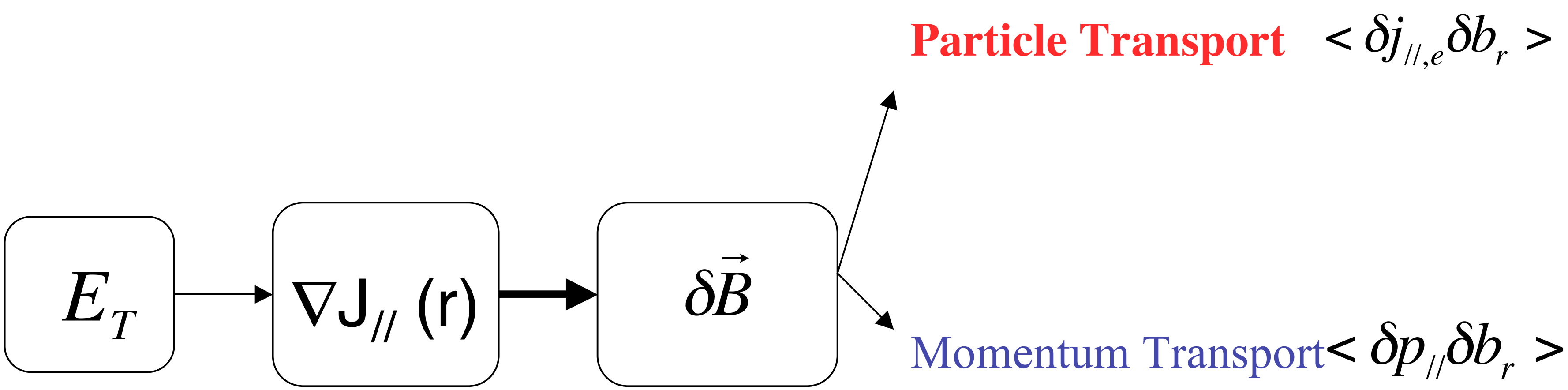


E_T

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

$\delta\vec{B}$

Particle Transport $< \delta j_{//,e}\delta b_r >$

Momentum Transport $< \delta p_{//}\delta b_r >$

Transport also determines equilibrium dynamics

Outline

(1) Measurement of density gradient fluctuation $\nabla \tilde{n}_e$

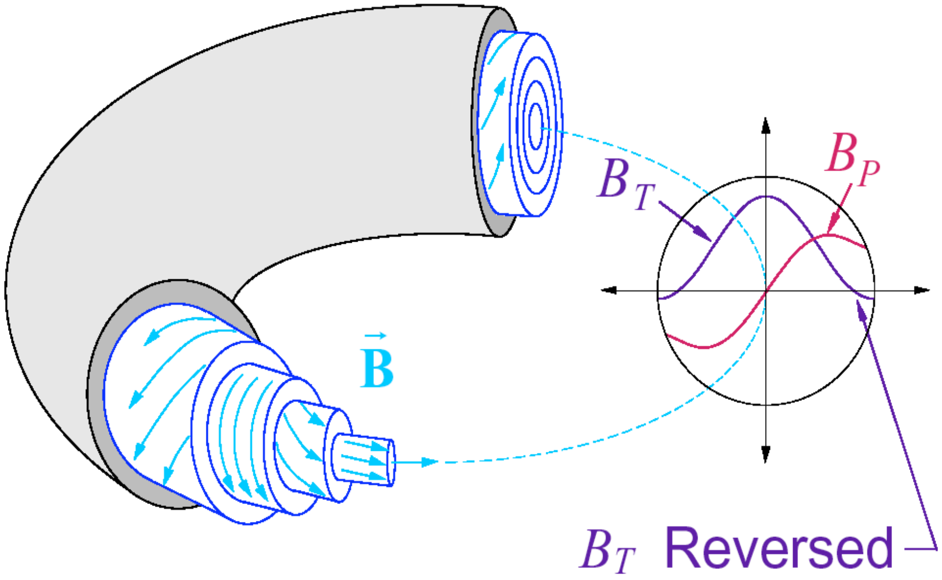
(2) Measurement of particle transport by magnetic fluctuations $\frac{<\delta j_{//,e} \delta b_r>}{eB}$

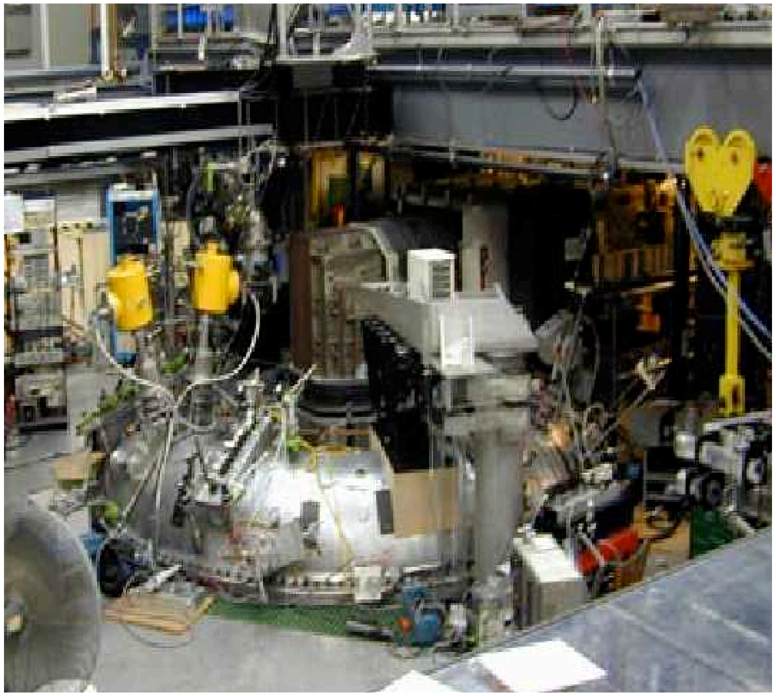
(3) Measurement of momentum transport (convective) $\frac{<\delta p_{//,i} \delta b_r>}{B}$

Identify the role of stochastic magnetic field in particle and momentum transport.

Madison Symmetric Torus

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





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

R_0 = 1.5 m, a = 0.51 m, I_p < 600 kA , B_T ~ 3-4 kG,

$n_e \sim 10^{19}$ $m^{-3,}$,T_{e0} <1.3keV ,β =<p>/B^2(a)=15%

Particle Balance Equation

$$\frac{\partial < n_e >}{\partial t} + \nabla \bullet \Gamma_r = D_\perp \nabla^2 < n_e > + \ < k n_0 n_e(r,t) >$$

$$\Gamma_r = \Gamma_p^M + \Gamma_p^E + \Gamma^{Pinch} + \ldots$$

Electrostatic fluctuations

Magnetic fluctuation induced particle flux

$$\nabla \bullet \Gamma_p^M = \nabla < \frac{\delta j_{//,e} \delta b_r}{eB} >= \boxed{V_{//,e} \nabla \frac{< \delta n \delta b_r >}{B}} + n \nabla \frac{< \delta V_{//,e} \delta b_r >}{B}$$

convective particle flux

Conductive flux

$$j_{//,e} = enV_{//,e}$$
$$B,\ \delta b_r$$

Faraday Rotation plus

Fizeau interferometer

Differential interferometer

Measurement of magnetic fluctuation and mean electron velocity by Faraday rotation

$$\nabla \bullet \Gamma_p^M = V_{//,e} \nabla \frac{< \delta n \delta b_r >}{B} = \boxed{\frac{V_{//,e}}{B} < (\nabla \delta n) \delta b_r >} + \frac{V_{//,e}}{B} < (\delta n) \nabla \delta b_r >$$

$$\nabla b_r(0) \approx 0 \ , \ \delta n(0) = 0$$

Measurement of magnetic fluctuation and mean electron velocity by Faraday rotation

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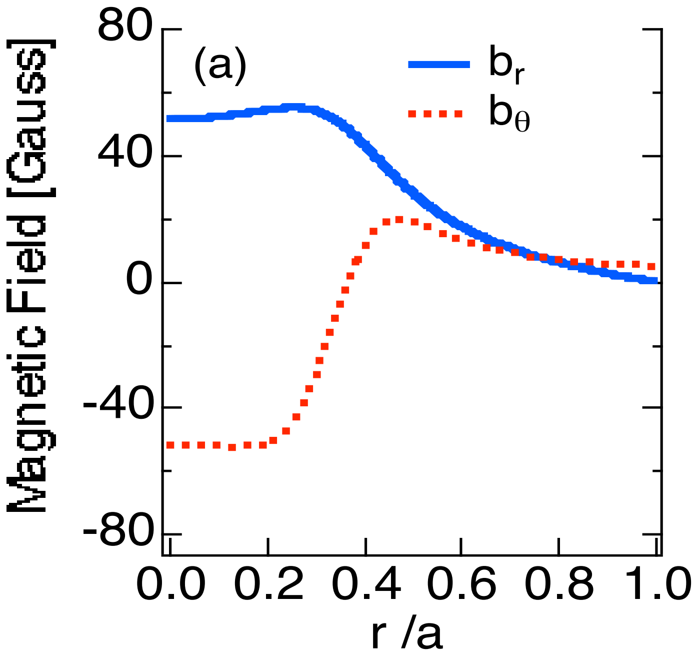

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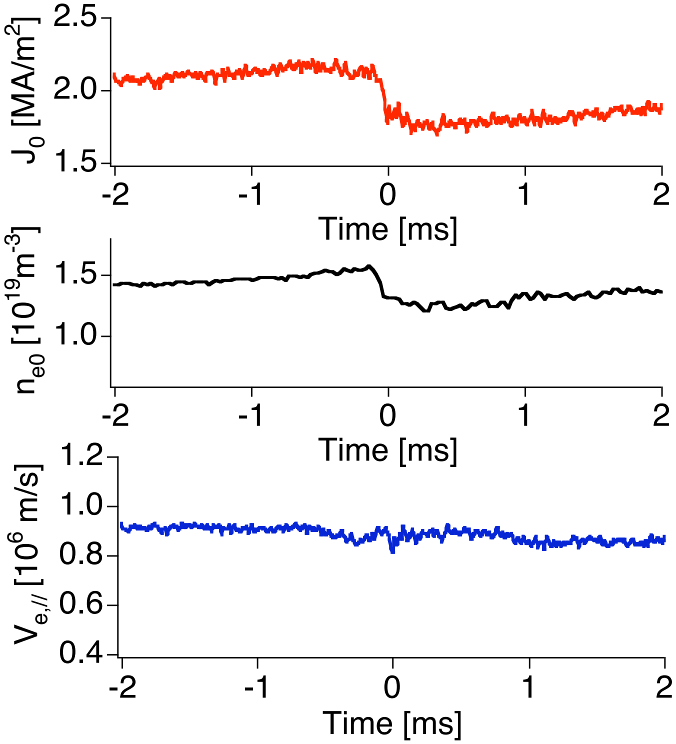
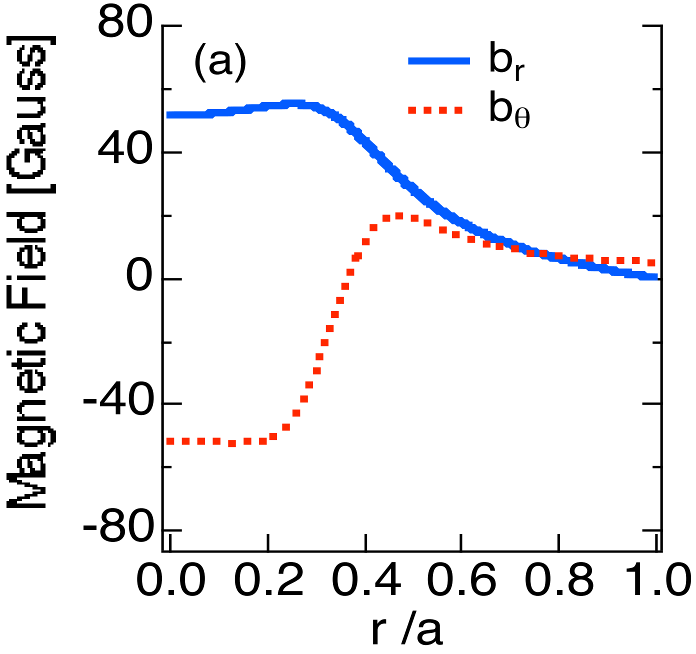
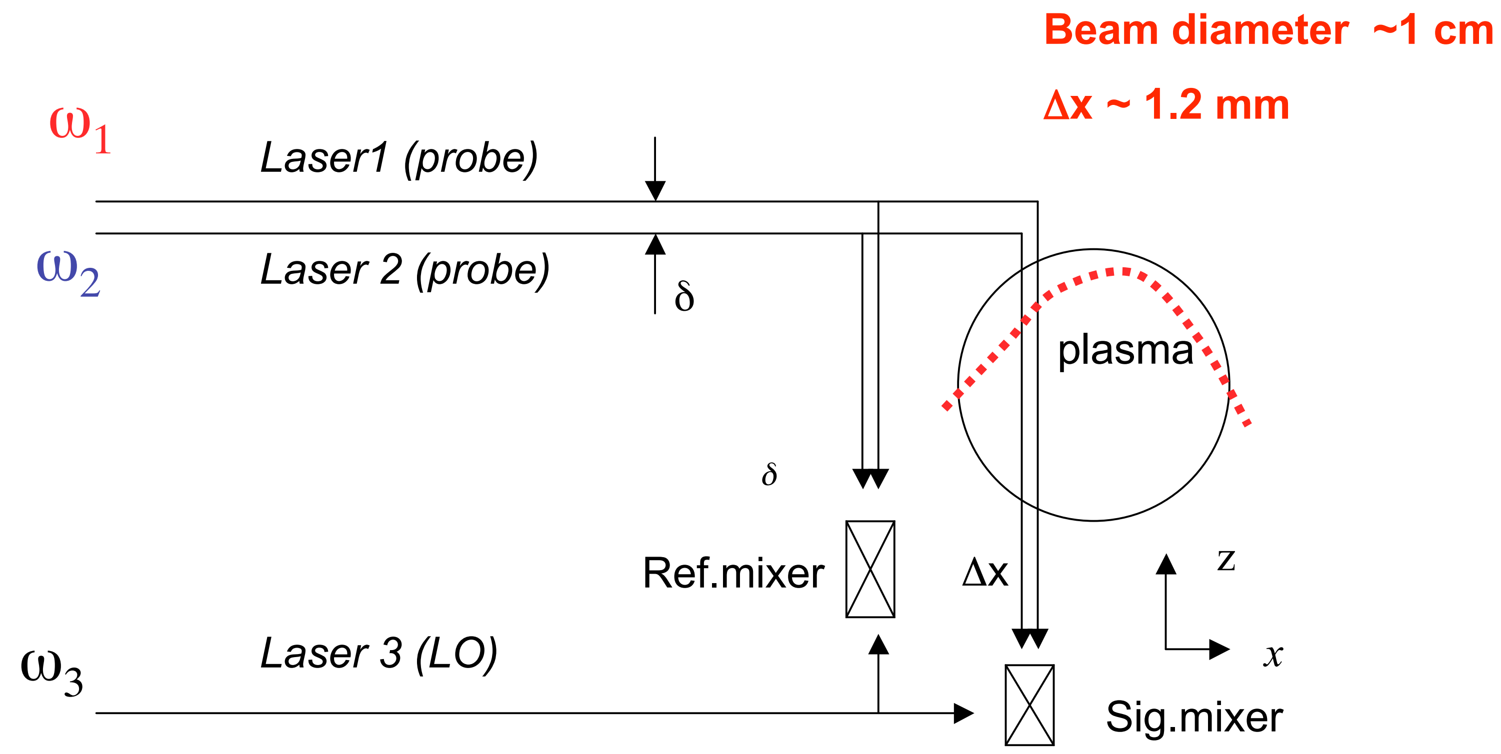
$$V_{//,e} = \frac{J_0}{e n_{e0}}$$





Ding,et al. PRL (2004)

$\nabla \delta n$ measurement by a new differential interferometer

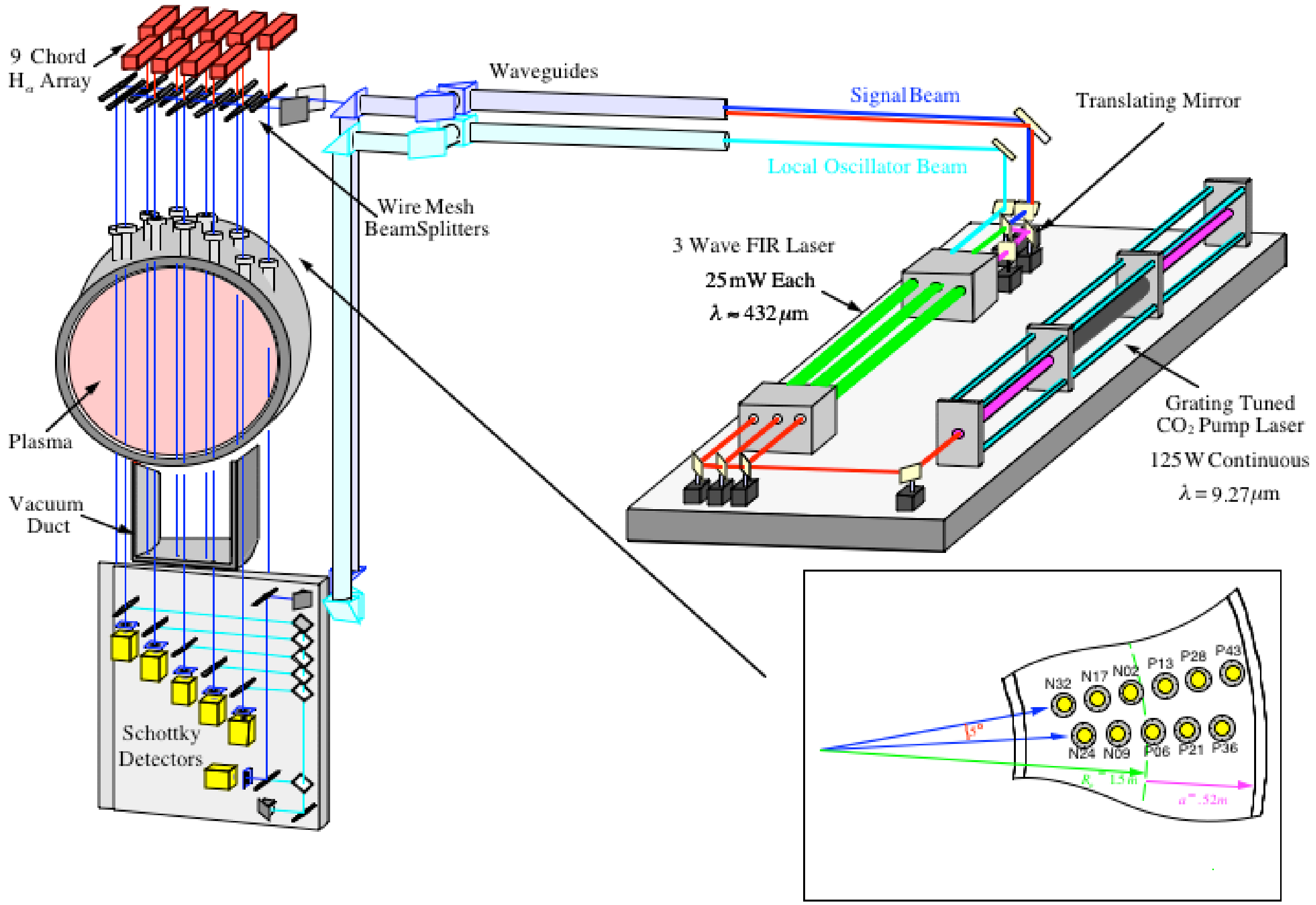


$$\omega_1 - \omega_2 \rightarrow \Delta\phi(x) = \int_{x_1} ndl - \int_{x_2} ndl$$

Differential Interferometer measures phase between closely-spaced laser beams

FIR Differential Interferometer System

MST Far-Infrared Differential Interferometer System



11 chords differential interferometer

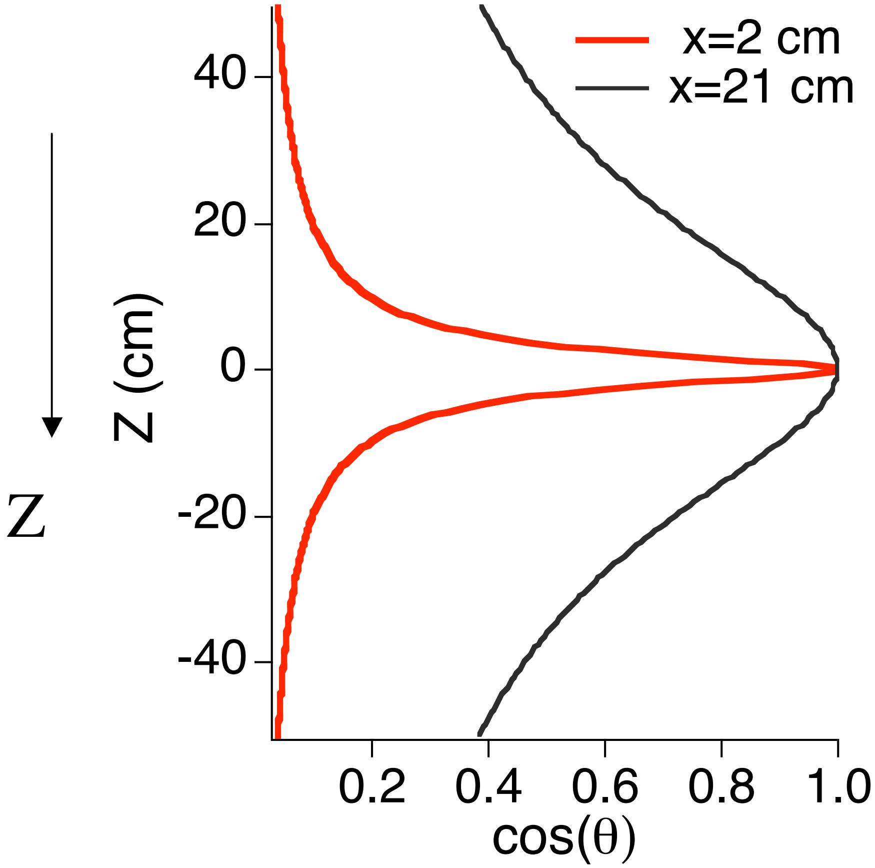
Localization of Density Gradient Fluctuations

For dominate m=1 mode

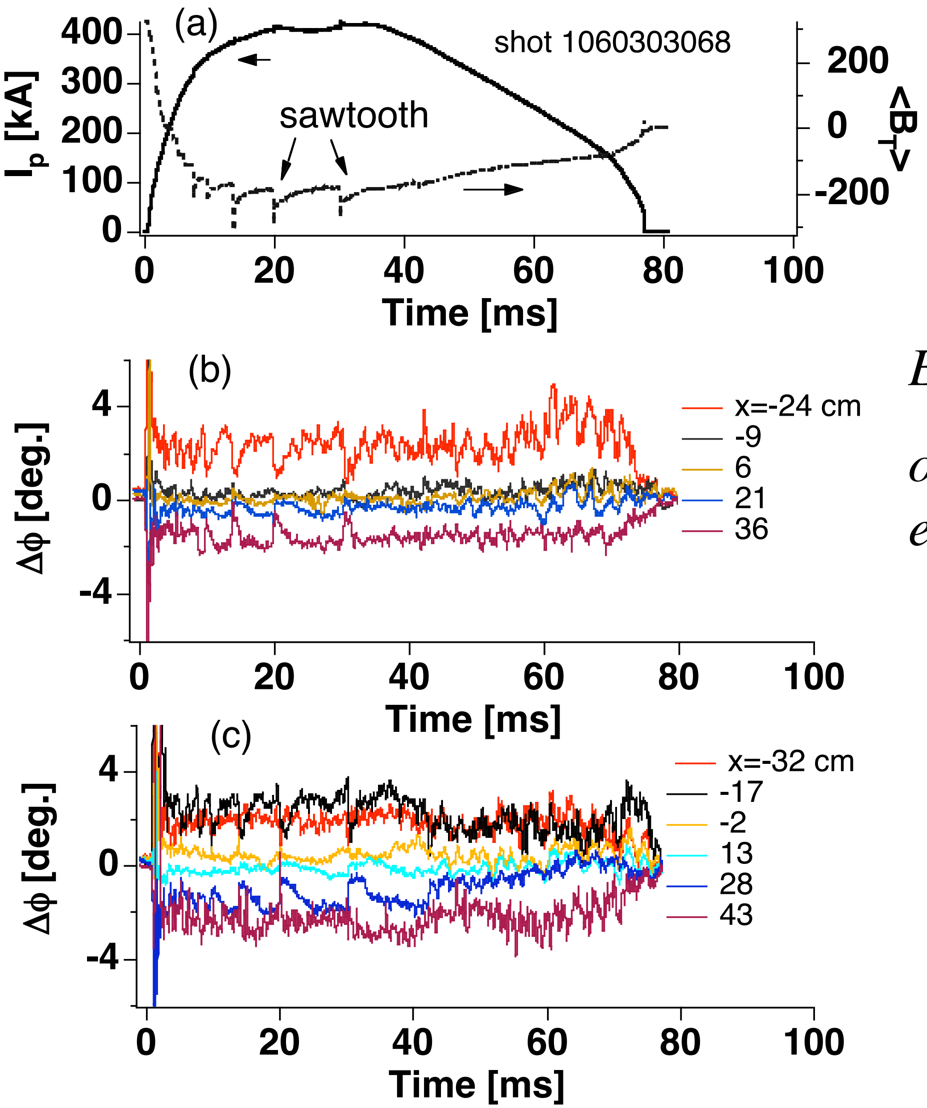
$$\tilde{\phi} = \int \delta n(r) \cos\theta dz$$

$$\left.\frac{\partial \tilde{n}(r)}{\partial r}\right|_{r=0} = \frac{\partial}{\partial x}\tilde{\phi}(x) = \frac{\Delta\tilde{\phi}(x)}{\Delta x}$$

See poster , P48(ding)



Time History of Differential Interferometer

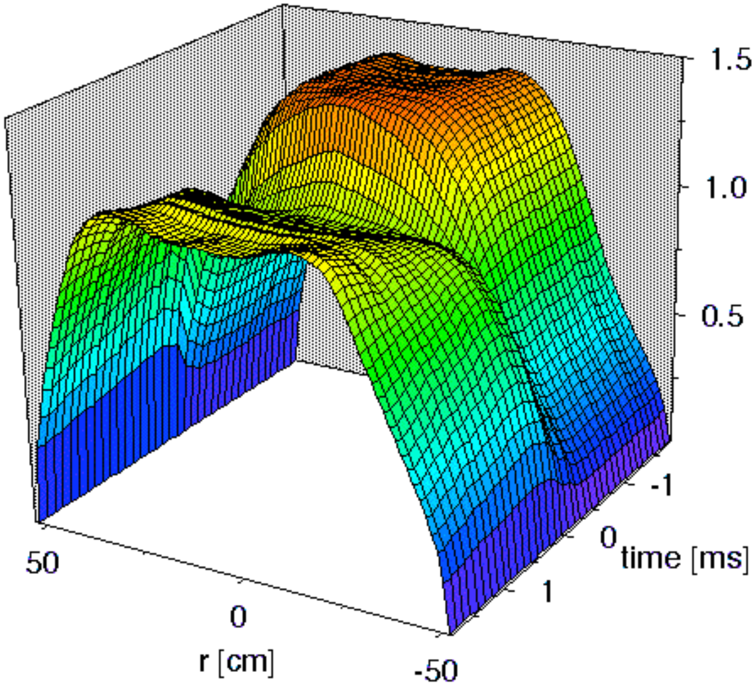


Ensemble average $< \frac{\Delta\tilde{\phi}}{\Delta x}\delta b_r >$

over multiple sawtooth events

Density Change and Convective Particle Flux

$n_e(r)\ [10^{13} cm^{-3}]$



Density redistributes within 300 μs

Density Change and Convective Particle Flux

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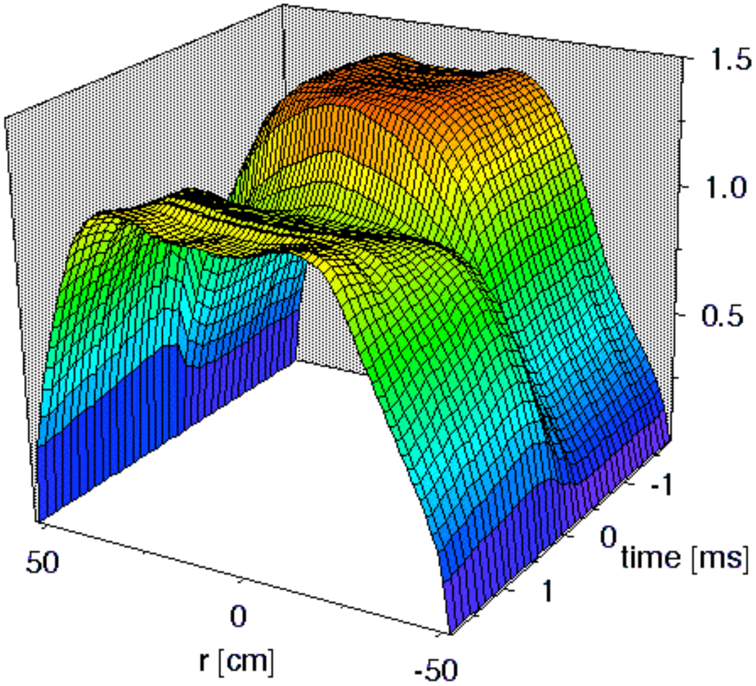

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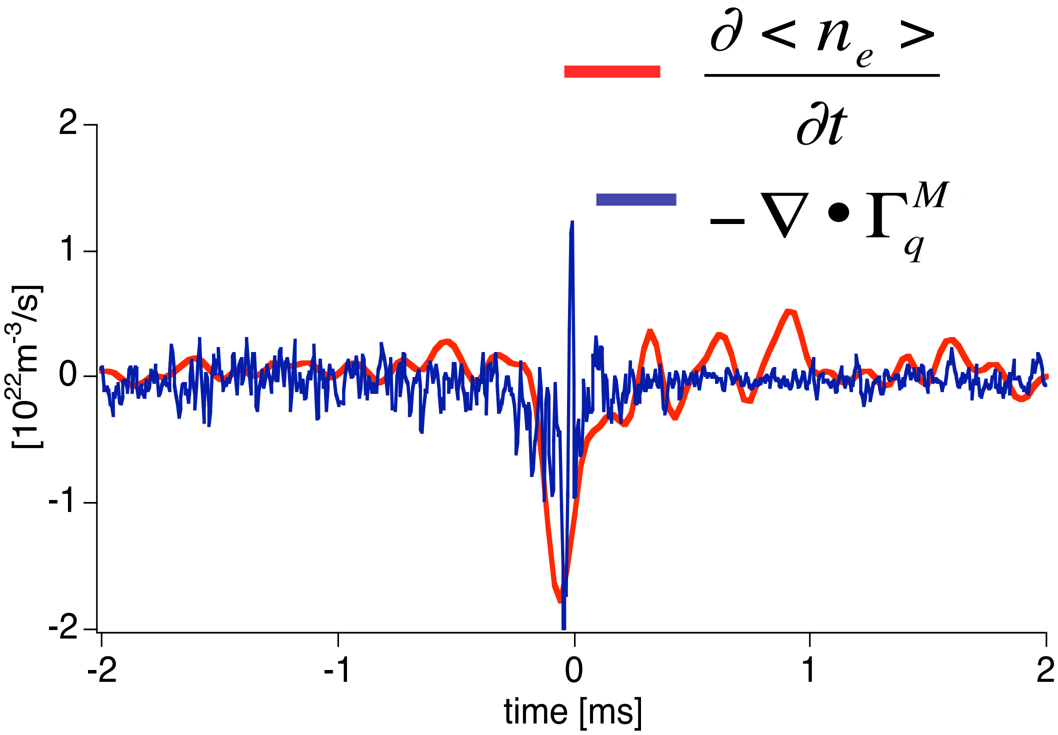


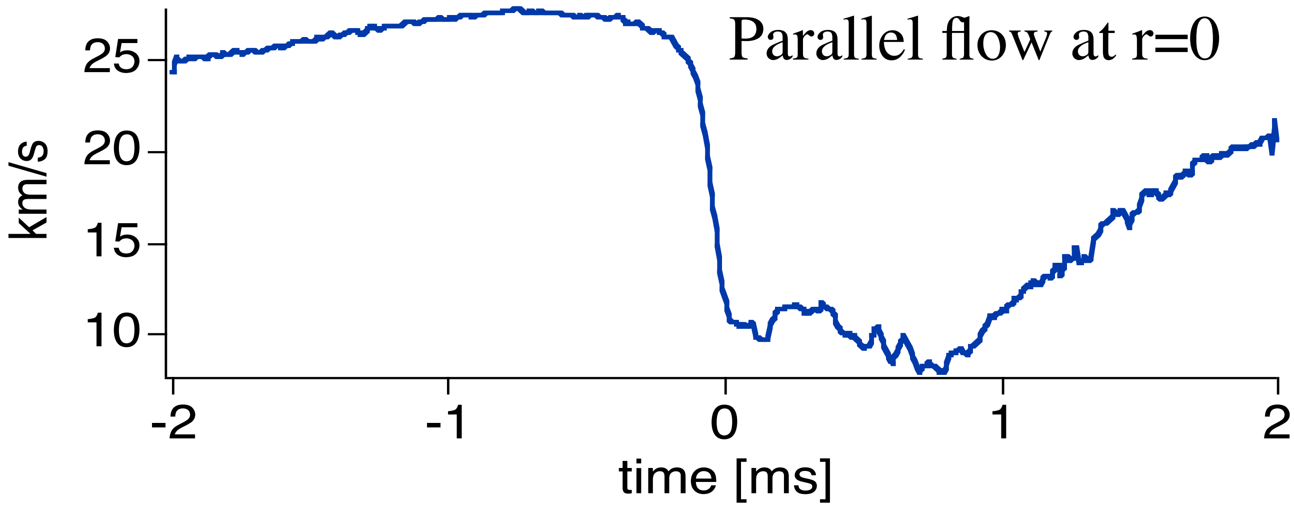
🟥 $\frac{\partial < n_e >}{\partial t}$

🟦 $-\nabla \bullet \Gamma_q^M$

$$\frac{\partial < n_e >}{\partial t} + \nabla \bullet \Gamma_q^M \approx 0$$

Density change is balanced by the convective particle transport

Momentum dynamics



Parallel momentum changes much faster than classical dissipation

Parallel Momentum Balance

$$\frac{\partial}{\partial t} < \rho V_{//} > + \nabla \bullet \Gamma_p = \nu_{//} \nabla^2 < \rho V_{//} > + M(r,t) \text{ (other momentum sources)}$$

See Poster P54 (Kuritsyn)

Fluctuation induced momentum flux

$$\Gamma_q = \Gamma_q^M + \Gamma_q^E \leftarrow$$

Electrostatics fluctuations

Magnetic fluctuations

$$\nabla \bullet \Gamma_q^M = \nabla < \frac{\delta p_{//} \delta b_r}{B} > = \boxed{T_{//} \nabla \frac{< \delta n \delta b_r >}{B}} + n \nabla \frac{< \delta T_{//} \delta b_r >}{B}$$

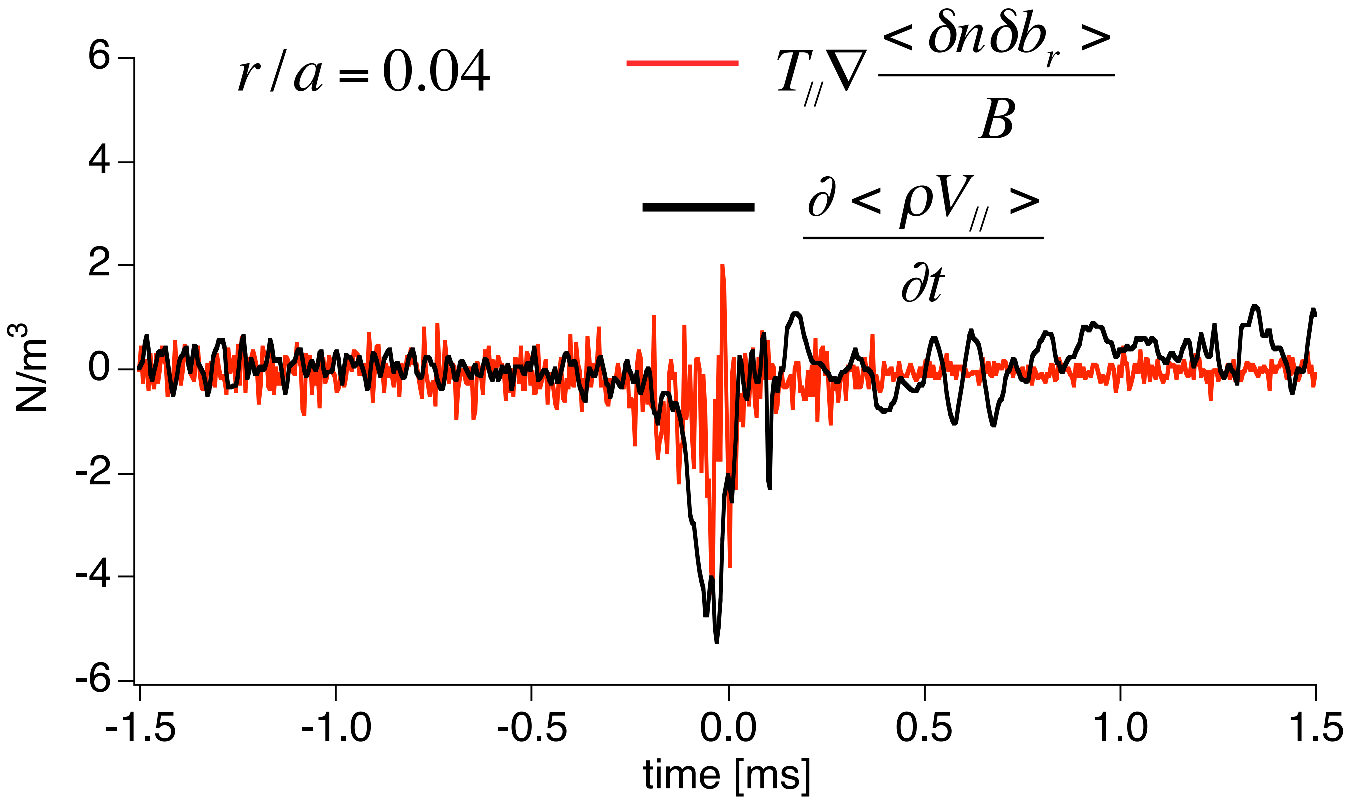
convective momentum flux

Conductive momentum flux

$$\frac{T_{//}}{V_{//,e}} \nabla \bullet \Gamma_p^M$$

← Particle flux

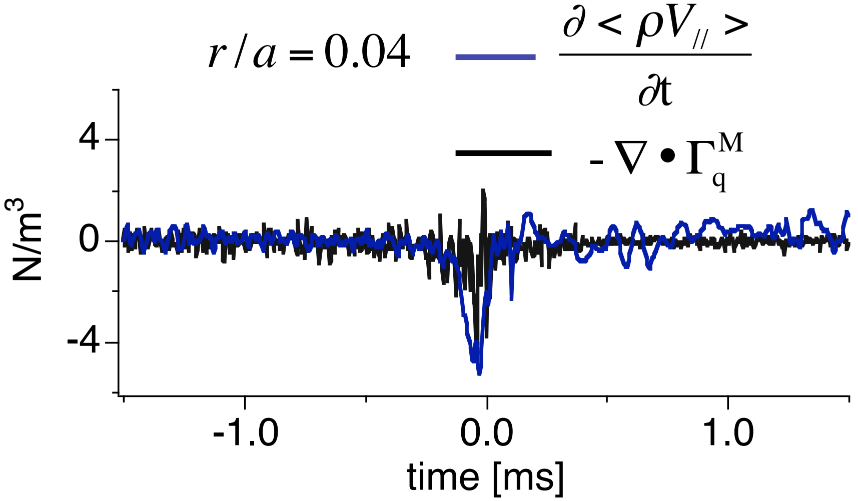
Magnetic momentum flux and parallel momentum change

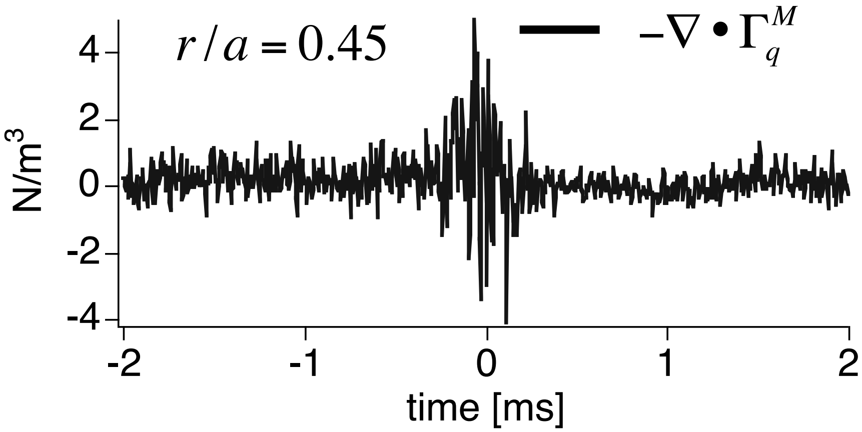


$$\frac{\partial <\rho V_{//}>}{\partial t} + T_{//}\nabla \frac{<\delta n \delta b_r>}{B} \approx 0$$

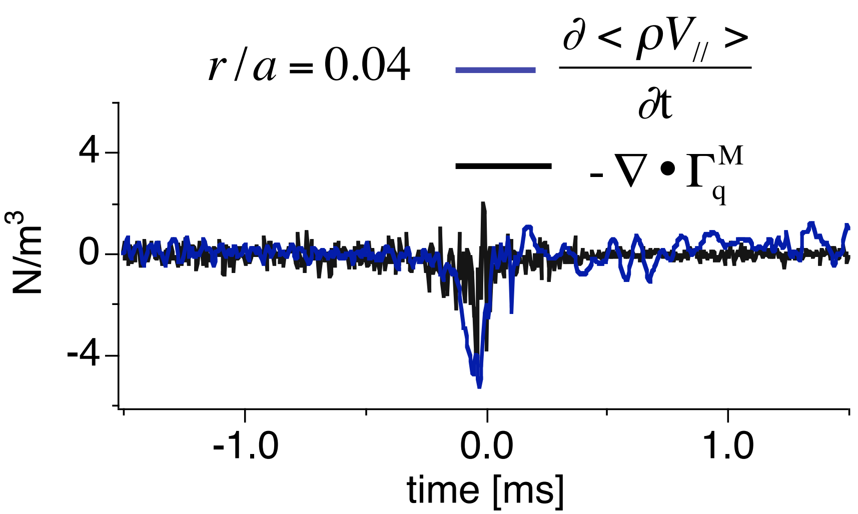
Momentum flux significantly contributes to parallel momentum change

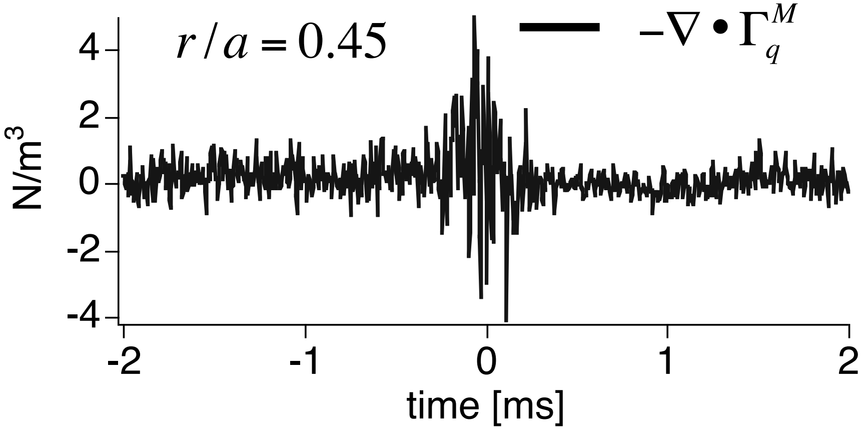
Momentum flux changes direction away from magnetic axis



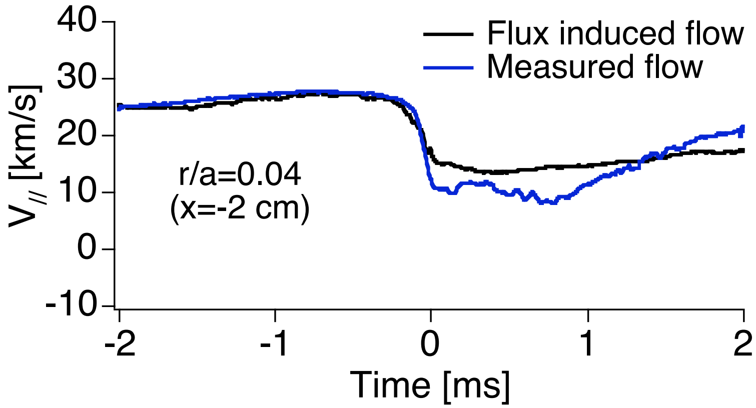


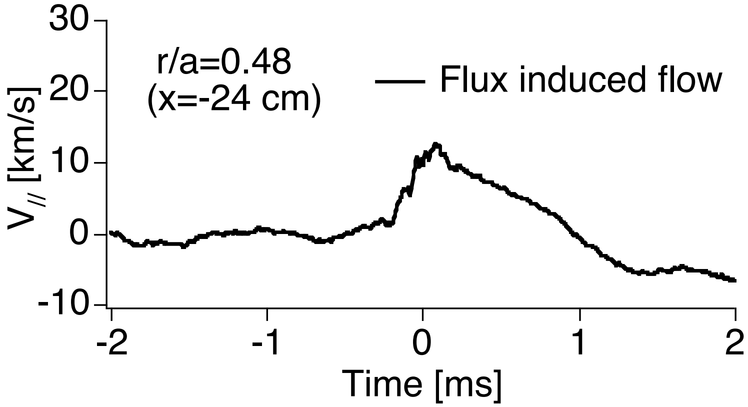
Momentum flux changes direction away from magnetic axis





$$V_{//} = \int (\nabla \bullet \Gamma_q^M) dt + V_0(t = -2ms)$$





The change of direction is consistent with momentum transport instead of total momentum loss

Summary

(1) Convective particle transport due to stochastic magnetic field has been measured by differential interferometer and Faraday rotation

(2) Magnetic particle flux can account for the change of density on magnetic axis

(3) Magnetic momentum flux significantly contributes to the change of parallel momentum in the core

Relevant poster: P48(ding), P100 (Brower), P54(Kuritsyn), P52(Ebrahimi)