Finite Pressure Effects on Momentum Transport in a Toroidal Plasma

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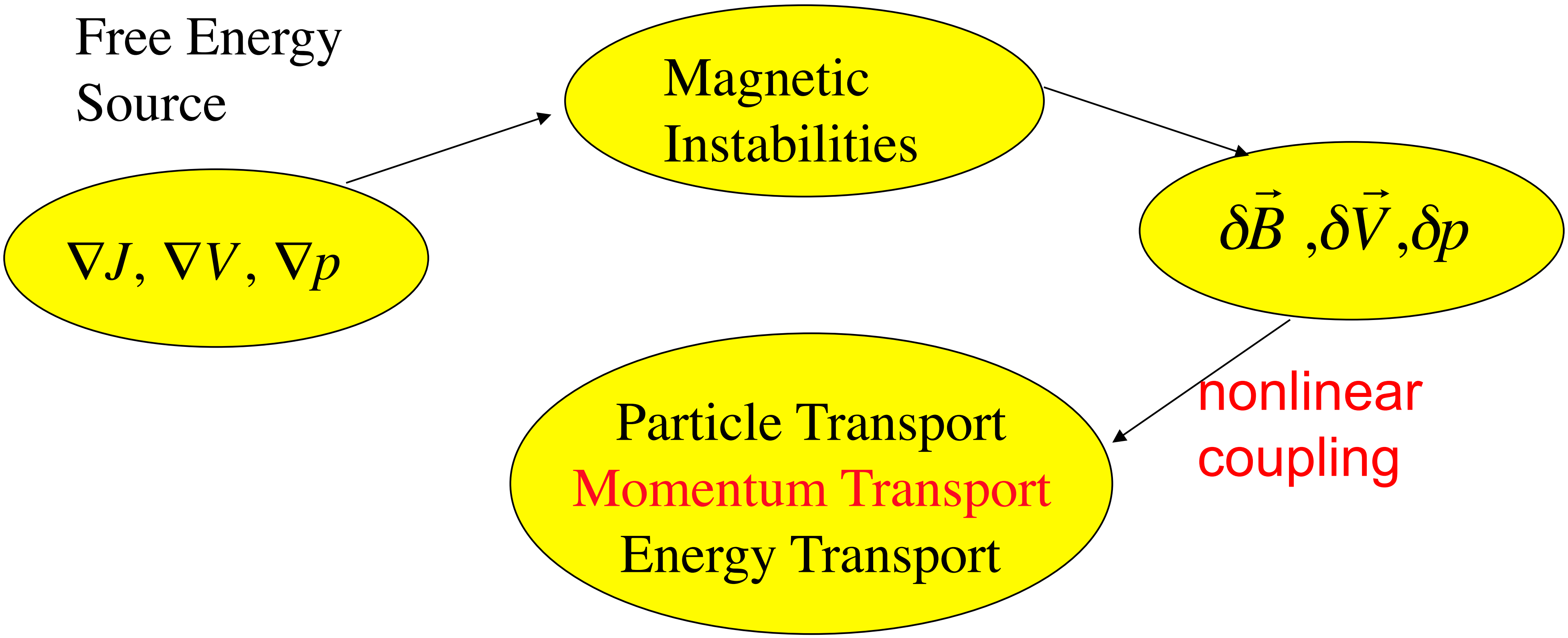
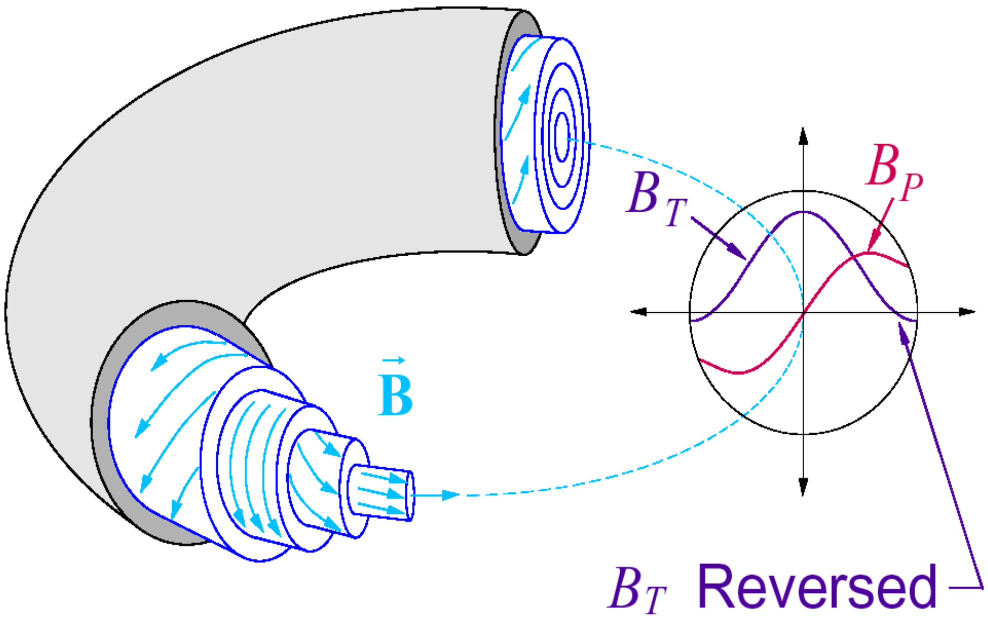
Magnetic Fluctuations Play an Important Role in Momentum Transport

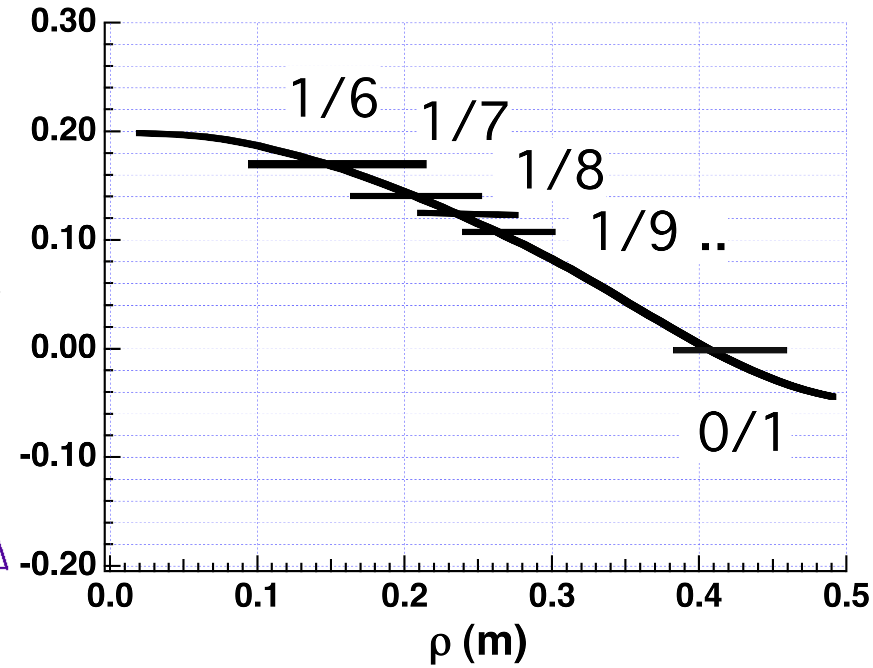


In this talk, we focus on the interaction between tearing instability driven magnetic and pressure fluctuations, resulting in the momentum transport in MST.

Madison Symmetric Torus -Reversed Field Pinch



$$q(r) = \frac{r}{R}\frac{B_T}{B_p}$$



$$\beta \sim 6 - 7\%$$

Multiple Overlapping Tearing Modes $\longrightarrow$

Stochastic Magnetic Field on MST

Outline

Measurements of

Fluctuation-Induced Momentum Flux:

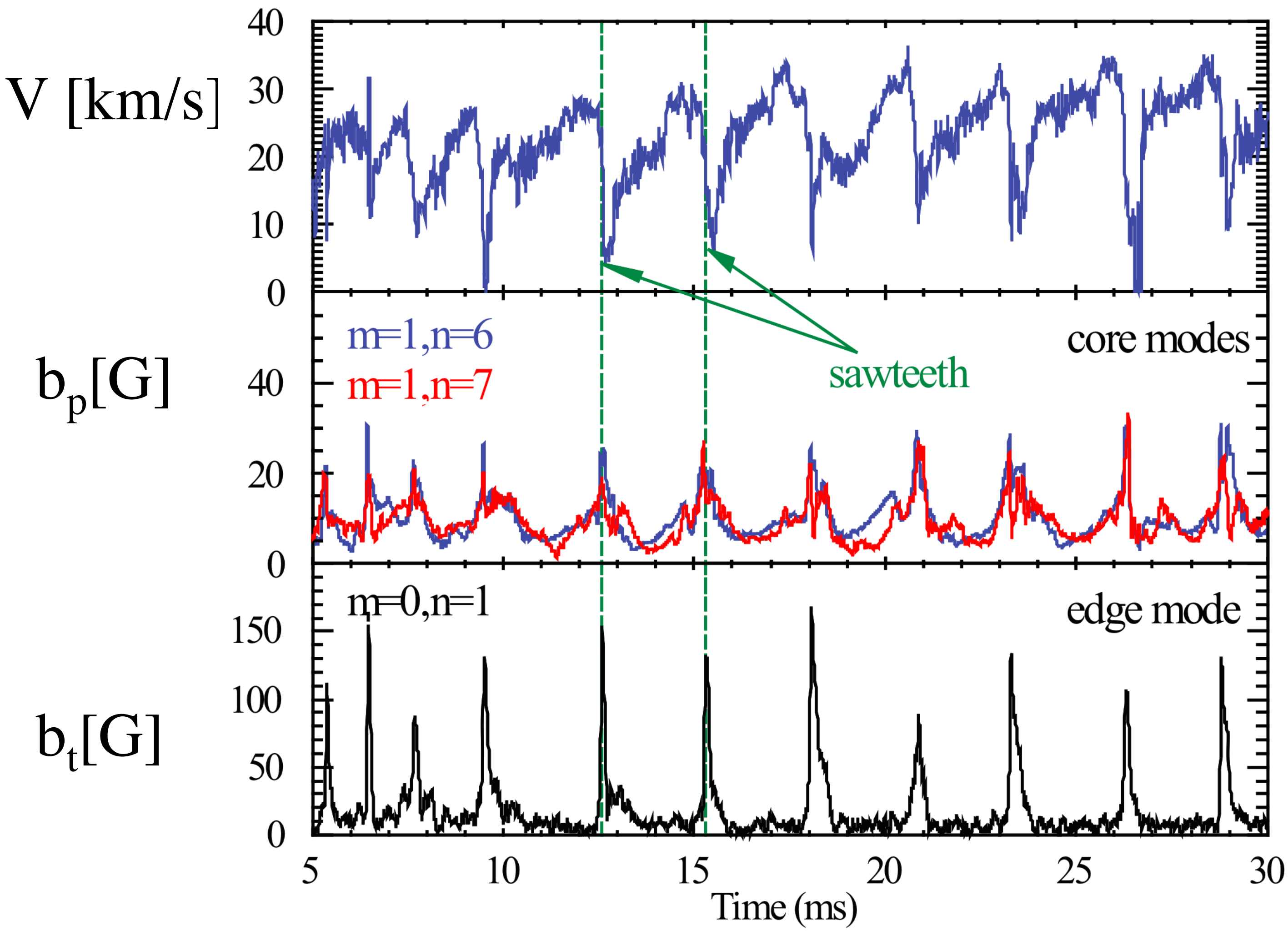
(1) MHD effects on Momentum Transport

-Maxwell stress and Reynolds stress

(2) Kinetic (pressure) effects on Momentum Transport

-Density fluctuations in a stochastic magnetic field

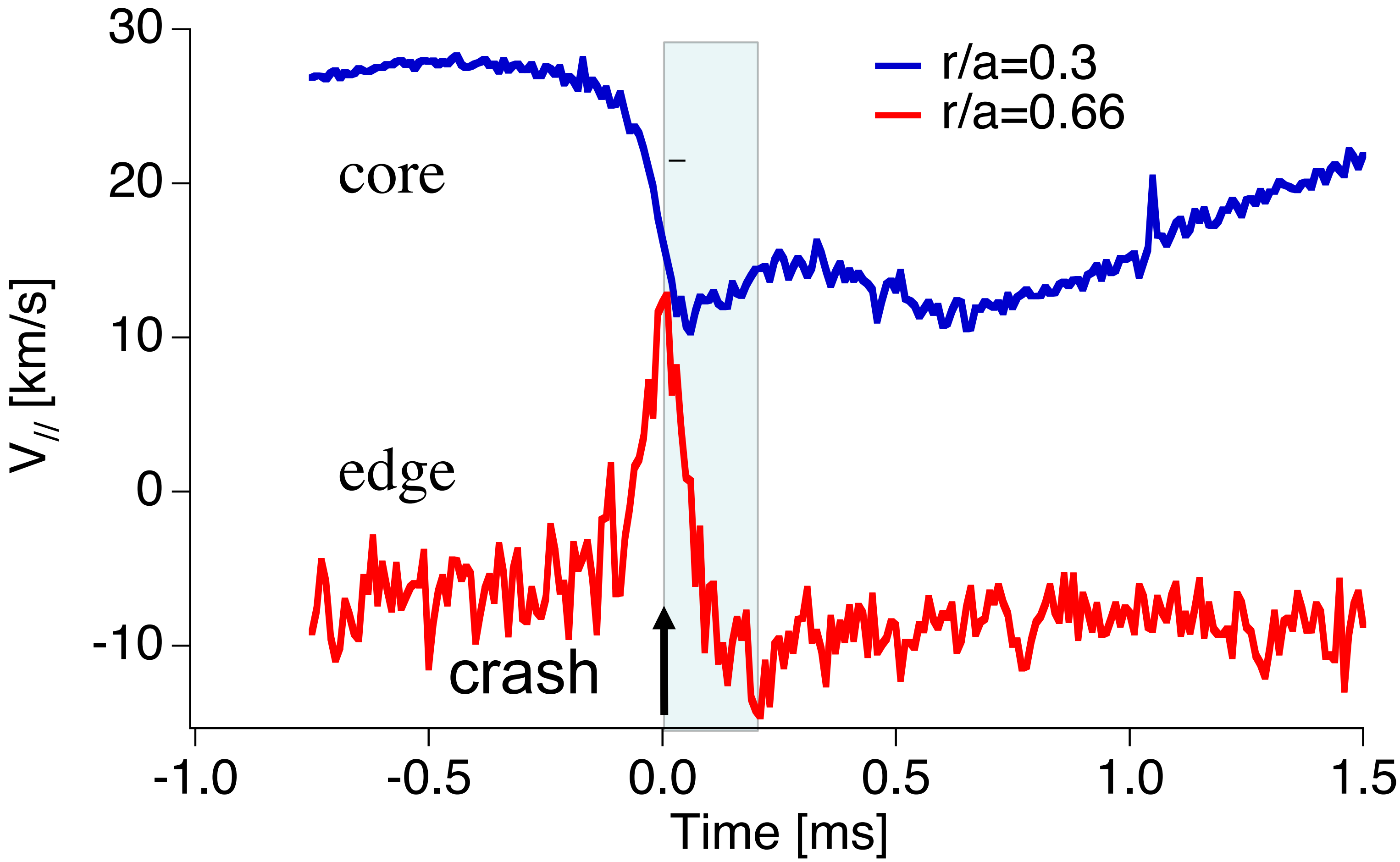
Momentum Transport and Fluctuations in the MST



Toroidal flow in the core

Momentum transport is strongly associated with magnetic fluctuation

Momentum Relaxation during a Sawtooth Event



There is a coupling between the edge and the core flow

Parallel momentum is redistributed within the time scale (~ 100 μs) much faster than classical ion-ion viscous transport time

Momentum transport by Fluctuations in a Torus

$$\rho\left(\frac{\partial}{\partial t}\vec{V} + \vec{V} \bullet \nabla\vec{V}\right) = \vec{J} \times \vec{B} - \nabla \bullet \overleftrightarrow{P}$$

Parallel momentum components

$$\rho\frac{\partial}{\partial t} < V_{//} > = < \delta\vec{J} \times \delta\vec{B} >_{//} - \rho < \delta\vec{V} \bullet \nabla\delta\vec{V} >_{//} - < \nabla \bullet \overleftrightarrow{P} >_{//}$$

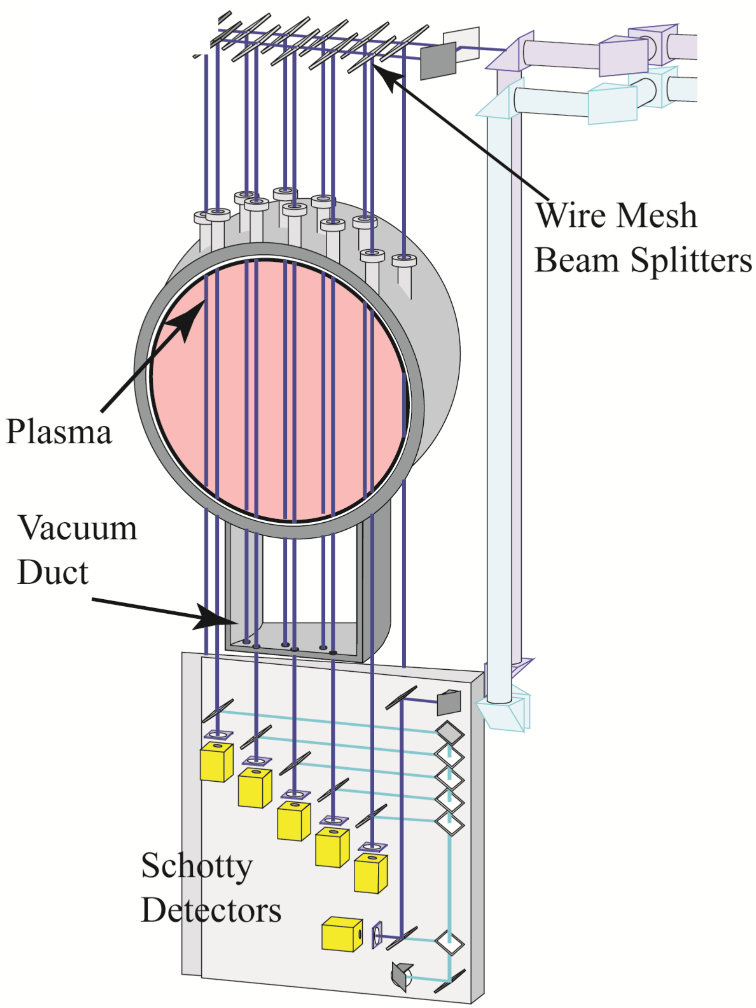
Flow Change

Maxwell Stress

Reynolds stress

Finite pressure effect

Laser-based FIR system is used to measure density and magnetic fluctuations



Interferometer:

$$\phi_{\text{int}}(x) \sim \int n_e dz \quad \Rightarrow n_e, \tilde{n}_e$$

Differential interferometer (Δx 1mm):

$$\partial \phi_{\text{int}} / \partial x \quad \Rightarrow \nabla n_e, \nabla \tilde{n}_e$$

Polarimeter:

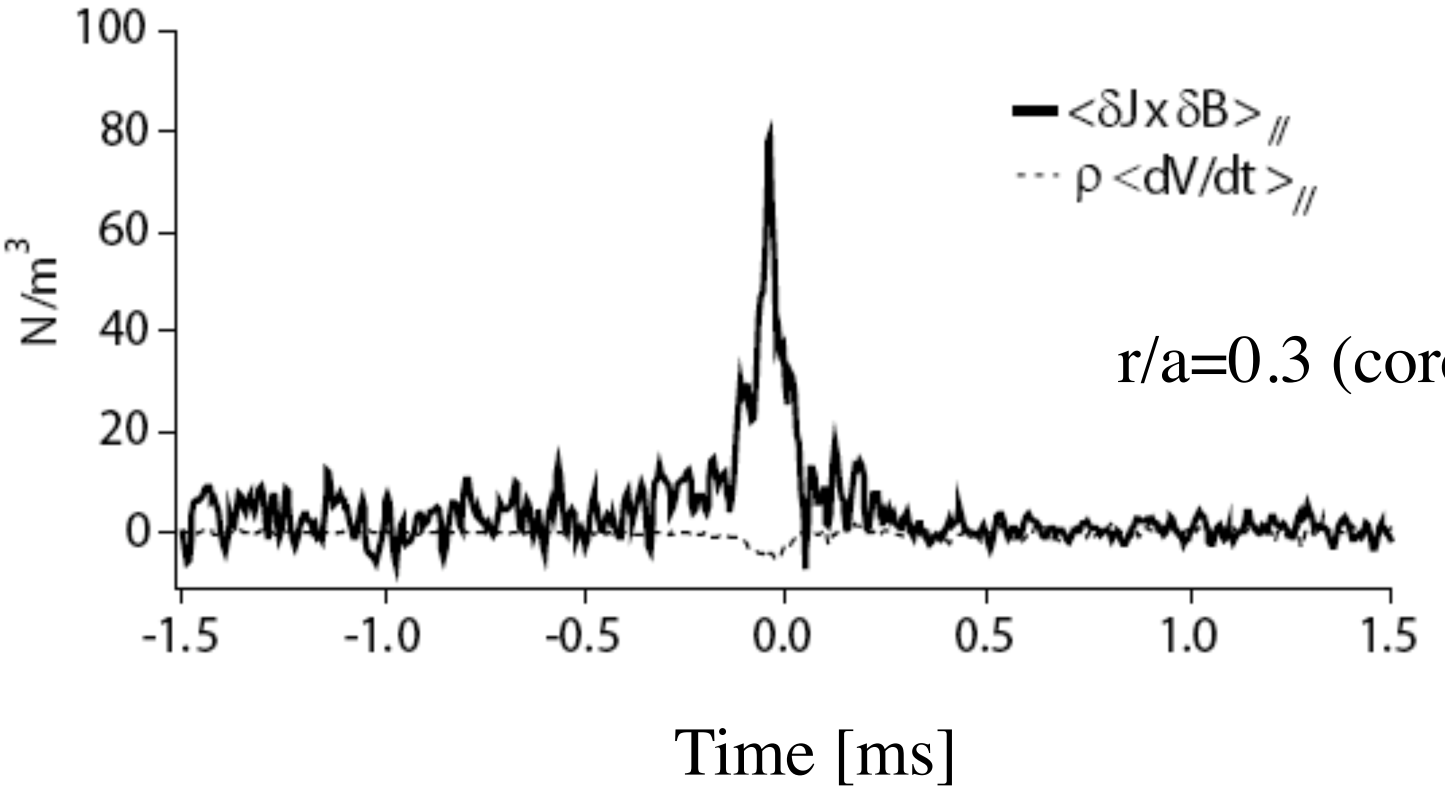
$$\psi_{\text{pol}}(x) \sim \int n_e B_z dz$$

$$\delta \vec{B}, \rightarrow \delta \vec{J} \times \delta \vec{B} \rightarrow (\nabla \times \delta \vec{B}) \times \delta \vec{B}$$

32 magnetic coils: $\Rightarrow (m, n)$

11 chords, Δx ~ 8 cm, phase ~ 0.05°, time response ~ 1μs

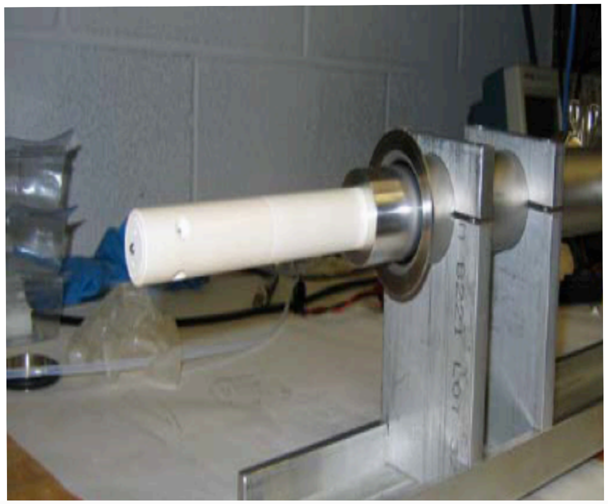
In plasma core, measured Maxwell Stress is much larger than momentum change

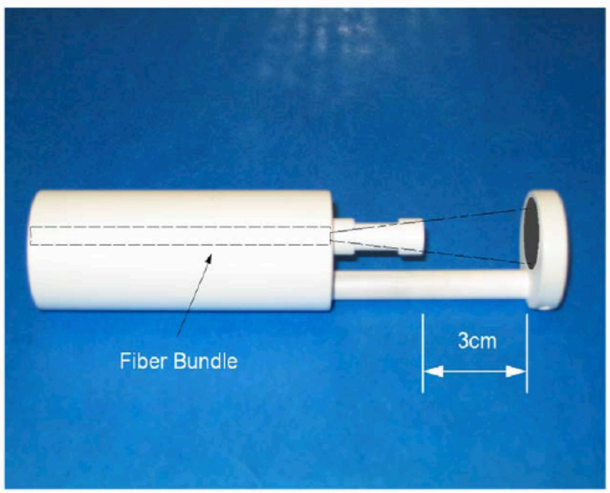


$$\underbrace{\rho \frac{\partial}{\partial t} < V_{//} >}_{- - - -} = \underbrace{< \delta\vec{J} \times \delta\vec{B} >_{//}}_{\text{———}} - \rho < \delta\vec{V} \bullet \nabla \delta\vec{V} >_{//} - < \nabla \bullet \overleftrightarrow{P} >_{//}$$

Reynolds stress is expected to offset huge Maxwell Stress

Various Probes are used to measure Maxwell and Reynolds Stress





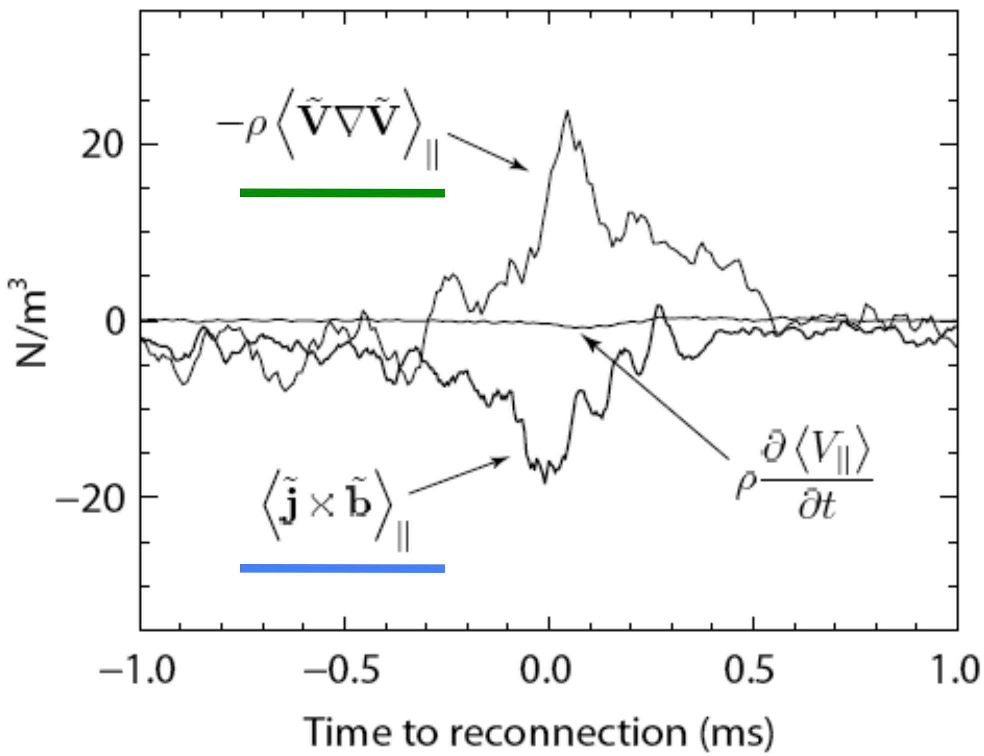
Mach Probe +IDS (optical probe) measure velocity fluctuations

(Reynolds Stress)

Torque probe measures all 3 comp. of j and B

(Maxwell Stress)

In plasma edge, both Maxwell and Reynolds stress are measured



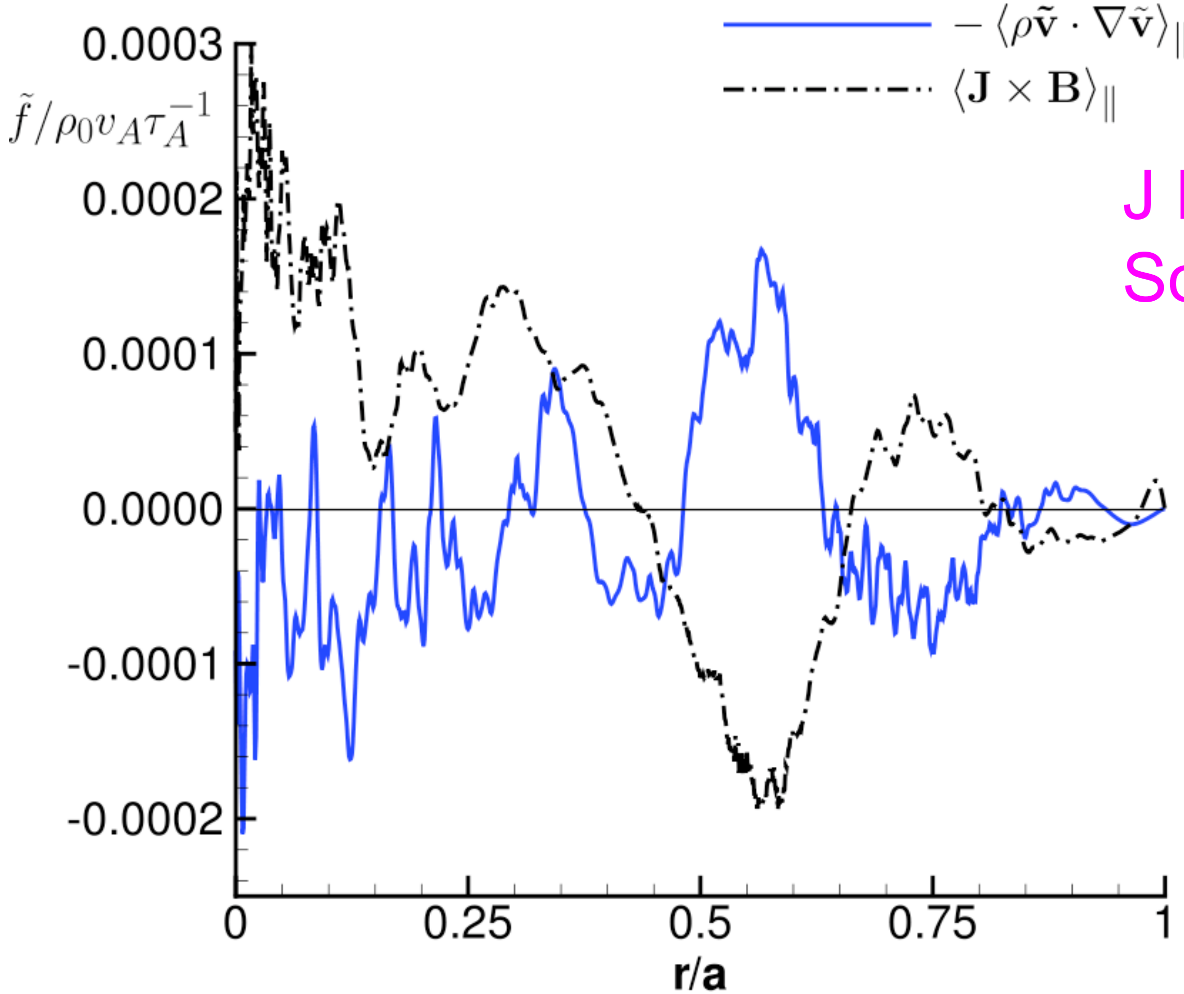
r/a=0.85 (edge)

Kuritsyn, et al PoP 2009

$$\rho\frac{\partial}{\partial t}< V_{//} >= \underbrace{< \delta\vec{J}\times\delta\vec{B} >_{//}}_{\text{Maxwell}} \underbrace{-\rho < \delta\vec{V}\bullet\nabla\delta\vec{V} >_{//}}_{\text{Reynolds}} - < \nabla\bullet\overleftrightarrow{P} >_{//}$$

Maxwell and Reynolds stresses are in opposite directions and largely offset

Two-fluid NIMROD simulation for RFP has been carried out



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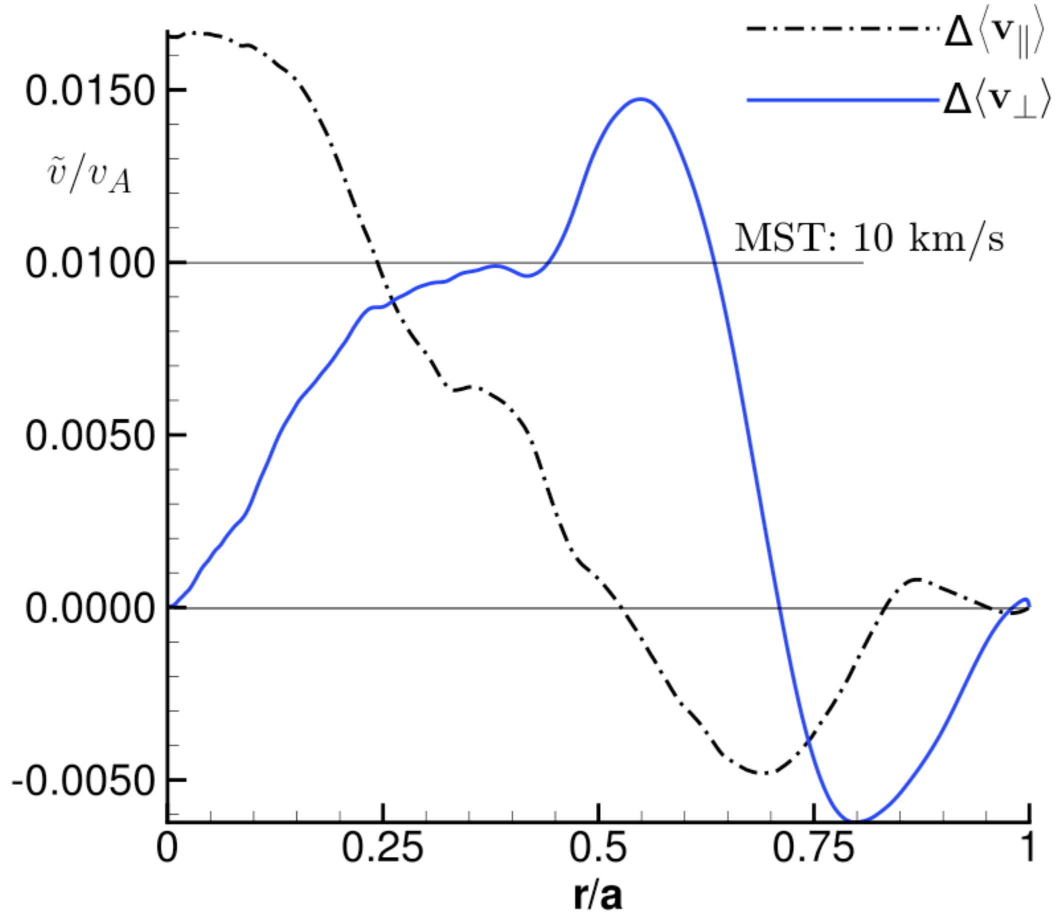
Reynolds and Maxwell stresses from fluctuations are large and tend to balance each other, similar to observations in MST

Parallel and Perpendicular Flows Appear as a Natural Consequence of Two-fluid Relaxation



Two-fluid NIMROD simulation

Simulations produce a flow modification quantitatively similar to measurements on MST

Kinetic effects on Momentum beyond MHD

$$\rho \frac{\partial}{\partial t} < V_{//} > = < \delta \vec{J} \times \delta \vec{B} >_{//} - \rho < \delta \vec{V} \bullet \nabla \delta \vec{V} >_{//} - < \nabla \bullet \overleftrightarrow{P} >_{//}$$

$$< \nabla \bullet \overleftrightarrow{P} >_{//} = \nabla \bullet < p_{//} \vec{b} > - \cancel{< p_{\perp} \nabla \bullet \vec{b} >}$$

$$\overleftrightarrow{P} = p_{\perp} \overleftrightarrow{I} + (p_{//} - p_{\perp}) \vec{b} \vec{b}$$

$$\vec{b} = \frac{\vec{B}}{B}$$

$$Flux = < p_{//} \vec{b} > \bullet \vec{e}_r = \frac{< \delta p_{//} \delta b_r >}{B}$$

$$\rho \frac{\partial}{\partial t} < V_{//} > = < \delta \vec{J} \times \delta \vec{B} >_{//} - \rho < \delta \vec{V} \bullet \nabla \delta \vec{V} >_{//} - \nabla \bullet \frac{< \delta p_{//} \delta b_r >}{B} \vec{e}_r + \ldots$$

Kinetic Stress

Parallel Pressure Fluctuation-Induced Momentum Transport

$$\rho \frac{\partial}{\partial t} < V_{//} > = < \delta \vec{J} \times \delta \vec{B} >_{//} - \rho < \delta \vec{V} \bullet \nabla \delta \vec{V} >_{//} - \nabla \bullet \boxed{\frac{< \delta p_{//} \delta b_r >}{B} \vec{e}_r} + \ldots$$

$$Flux = \frac{< \delta p_{//} \delta b_r >}{B} = T_{//} \frac{< \delta n \delta b_r >}{B} + n \frac{< \delta T_{//} \delta b_r >}{B}$$

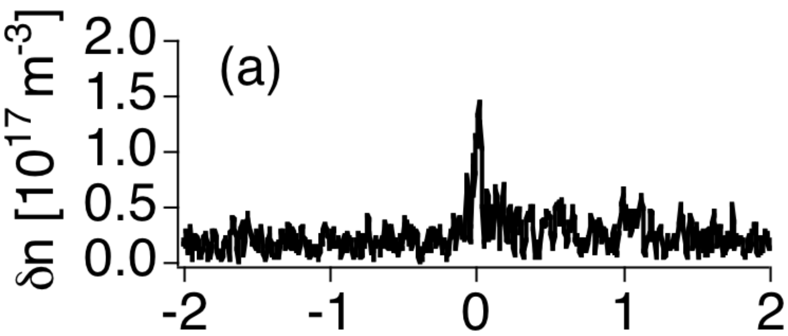
Density correlated with magnetic fluctuation

Temperature correlated with magnetic fluctuation

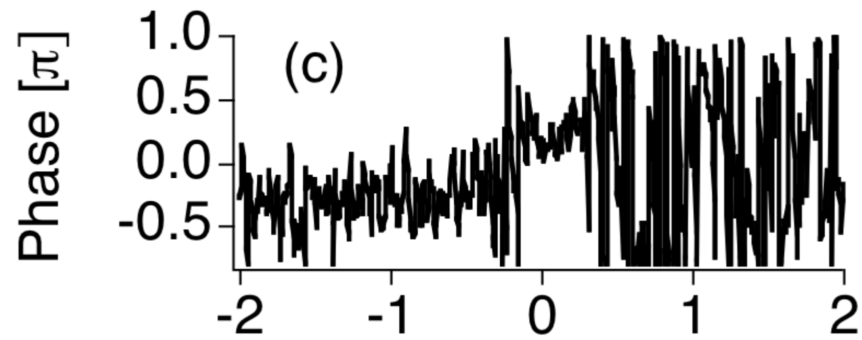
Here, we focus on the role of density fluctuation on momentum transport

Measurement of Density Fluctuation-induced Momentum Flux

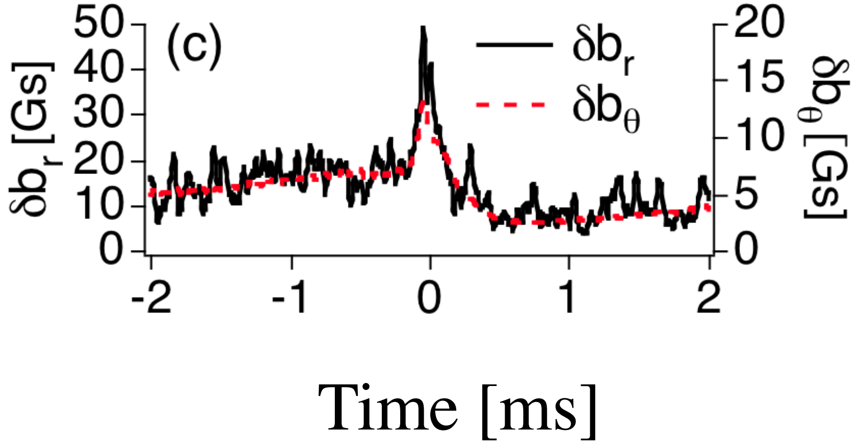
Density Fluctuation



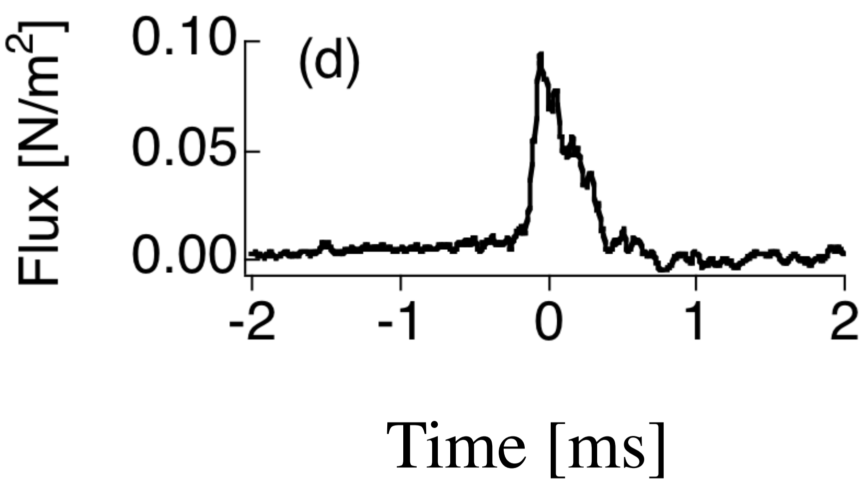
Phase between δn and δb



Magnetic Fluctuation

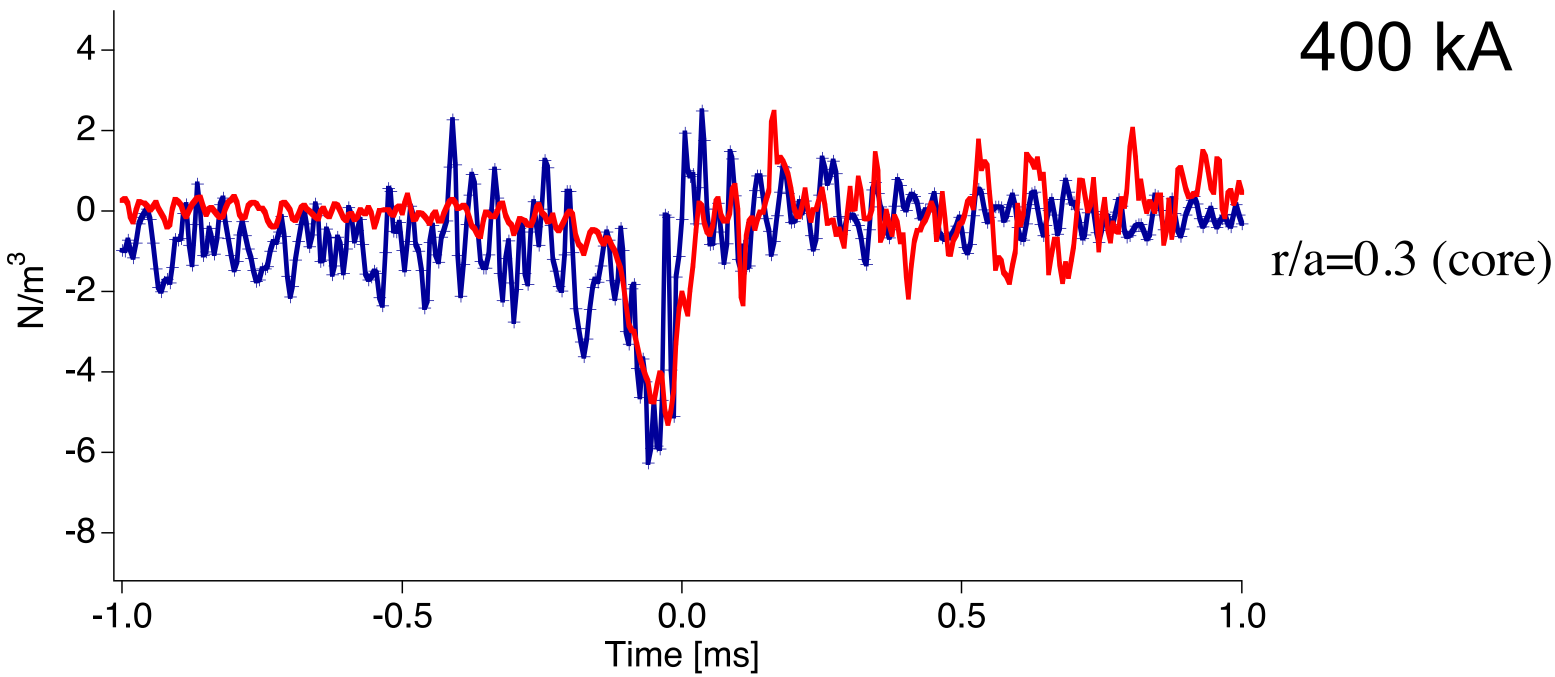


Momentum Flux



Momentum flux surges at sawtooth crash

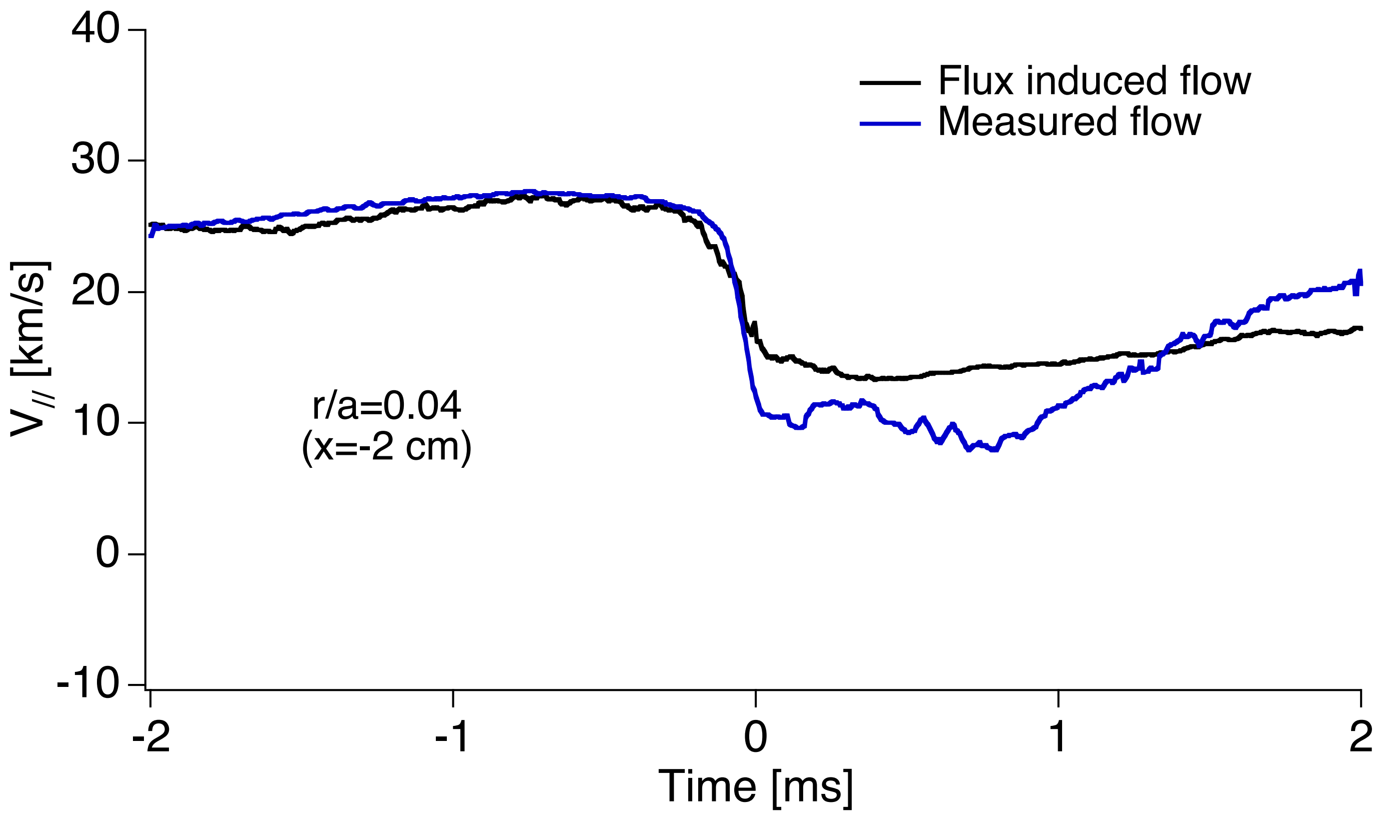
Density fluctuation-induced force is comparable to momentum change



$$\rho \frac{\partial}{\partial t} < V_{//} > = < \delta \vec{J} \times \delta \vec{B} >_{//} - \rho < \delta \vec{V} \bullet \nabla \delta \vec{V} >_{//} - \nabla \bullet \frac{< \delta p_{//} \delta b_r >}{B} \vec{e}_r$$

Comparison between Density Fluctuation-induced Flow and Plasma Flow

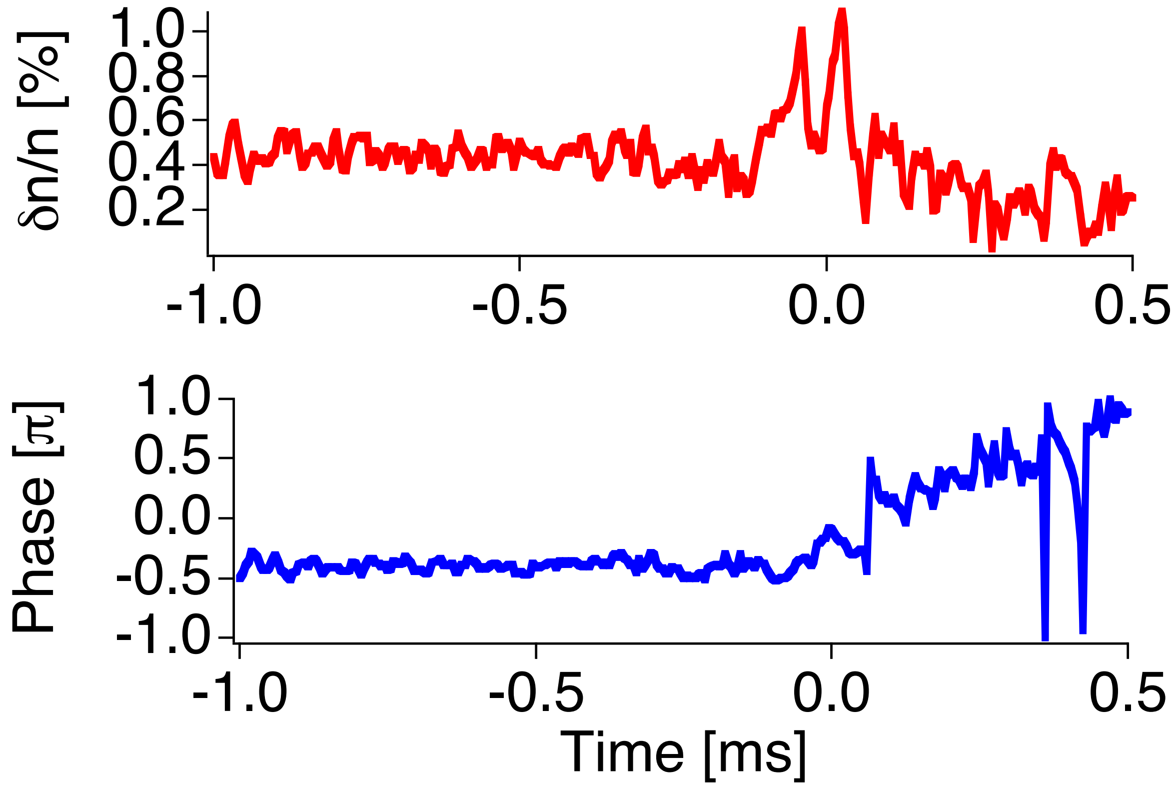
$$V_{//}(t) = V_{//,-2} - \frac{1}{nM}\int_{-2}^{t}\left[\nabla \bullet \frac{<\delta p_{//}\delta b_r>}{B}\vec{e}_r\right]dt$$



Direction of density fluctuation-induced force is consistent with flow change

The Effect of Phase between Fluctuations on Momentum Flux

$$Flux = T\frac{<\delta n \delta b_r>}{B} \sim |\delta n||\delta b_r|\cos\delta_{n,b}$$



Why does phase change during a sawtooth cycle?

Coupling between Density Fluctuations and Magnetic Fluctuations in Plasmas

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \left(n_e \vec{V}_e \right) = 0$$

[Fluctuation. Equation]

$$\frac{\partial \delta n}{\partial t} = -\delta v_r \nabla n_0 - \delta v_r \nabla \delta n - \dots. \qquad [1]$$

[Magnetic field line equation]

$$\frac{dr}{b_r} = \frac{dl}{B} \longrightarrow \delta v_r = \delta b_r \frac{V_{//,e}}{B} \qquad [2]$$

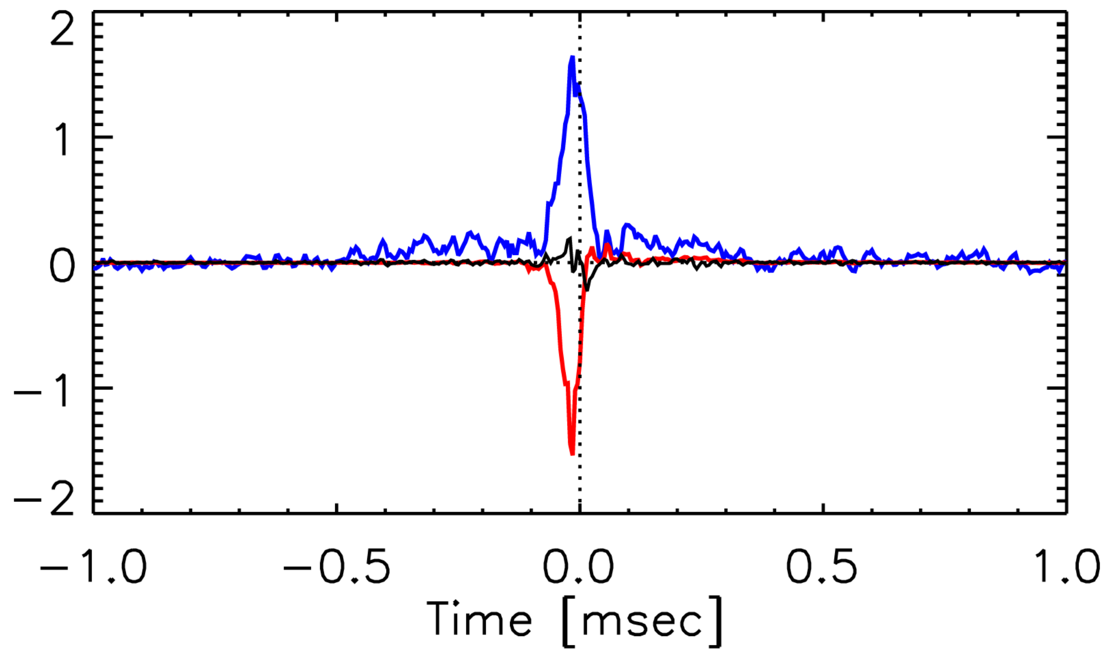
$\times\ \delta n \longrightarrow$

$$\underbrace{\left(\frac{B}{2V_{//,e}}\right)\frac{\partial}{\partial t} < \delta n^2 >}_{\text{Fluct. Energy}} = \underbrace{- < \delta n \delta b_r > \nabla n_0}_{\text{Quasi-linear}} \underbrace{- \sum < \delta n \delta b_r \nabla \delta n >}_{\text{Nonlinear terms}} - \dots \qquad [3]$$

Fluct. Energy Quasi-linear Nonlinear terms

< ... > Flux Surface Average

Nonlinear Coupling between Density and Magnetic Fluctuations is Significant over Sawtooth



$$\left(\frac{B}{2V_{//}}\right)\frac{\partial}{\partial t} < \delta n^2 > = - < \delta n \delta b_r > \nabla n_0 - \sum < \delta n \delta b_r \nabla \delta n > - \ldots$$

$$< \delta n \delta b_r > = -\frac{1}{\nabla n_0} \sum < \delta n \delta b_r \nabla \delta n > - \ldots$$

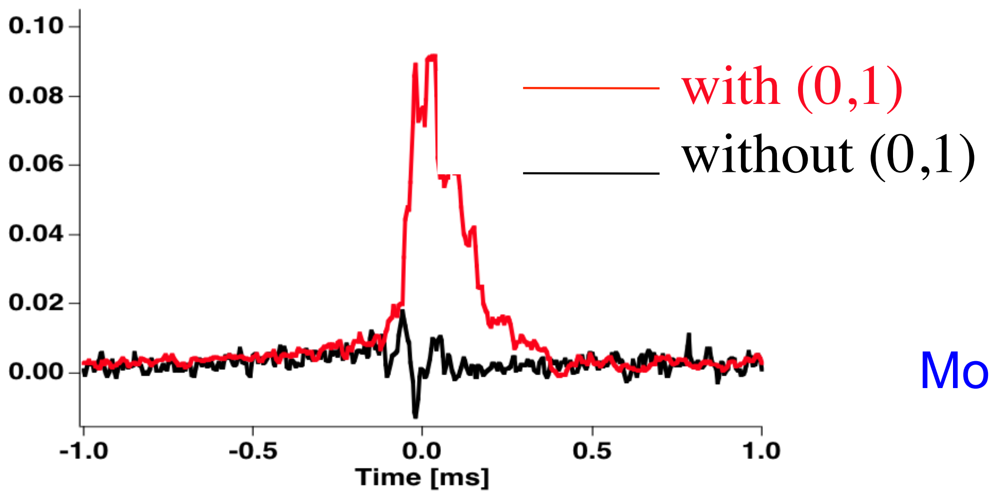
Removal of (0,1) Edge Mode Reduces Nonlinear Coupling

$$< \delta n_k \delta b_{r,k} >= -\frac{1}{\nabla n_0} \sum_{k=k_1 \pm k_2} < \delta n_k \delta b_{r,k_1} \nabla \delta n_{k_2} > - \ldots$$

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

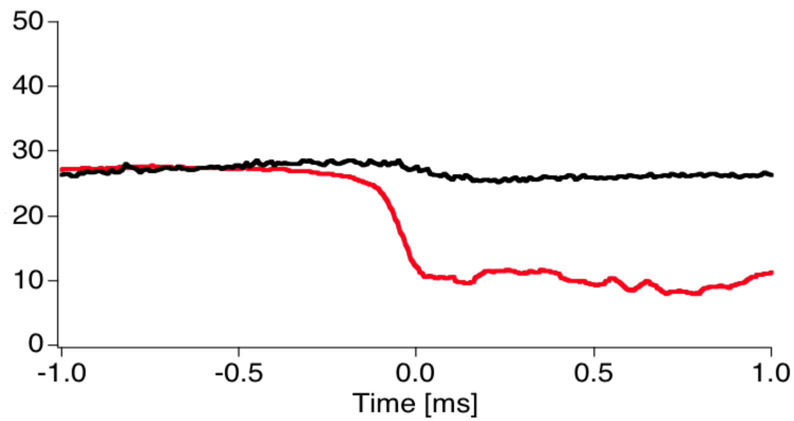
$$\vec{k} = \vec{k}_1 \pm \vec{k}_2$$

Flux[N/m^2]



Momentum Flux

$V_{//}$ [km/s]



Plasma Flow

This confirms the importance of nonlinear coupling on momentum transport on MST

Summary

(1) Kinetic stress, Maxwell stress and Reynolds Stress are measured to be important on momentum transport for MST plasmas.

(2) Nonlinear coupling can alter the phase between fluctuations, leading to finite momentum transport.

Pressure fluctuation is important for momentum transport at fusion-relevant beta

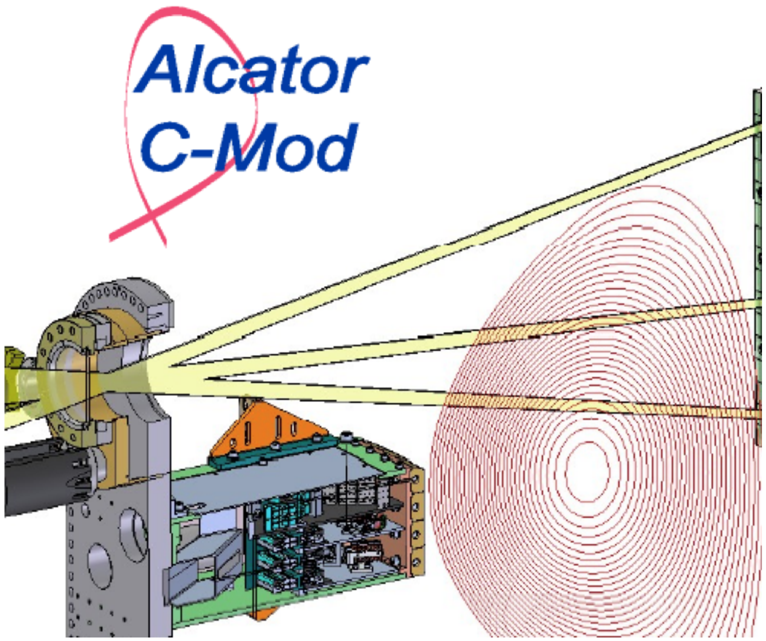
Open Issues

- What is the role of temperature fluctuation on Momentum Transport? (*Code Prediction*)

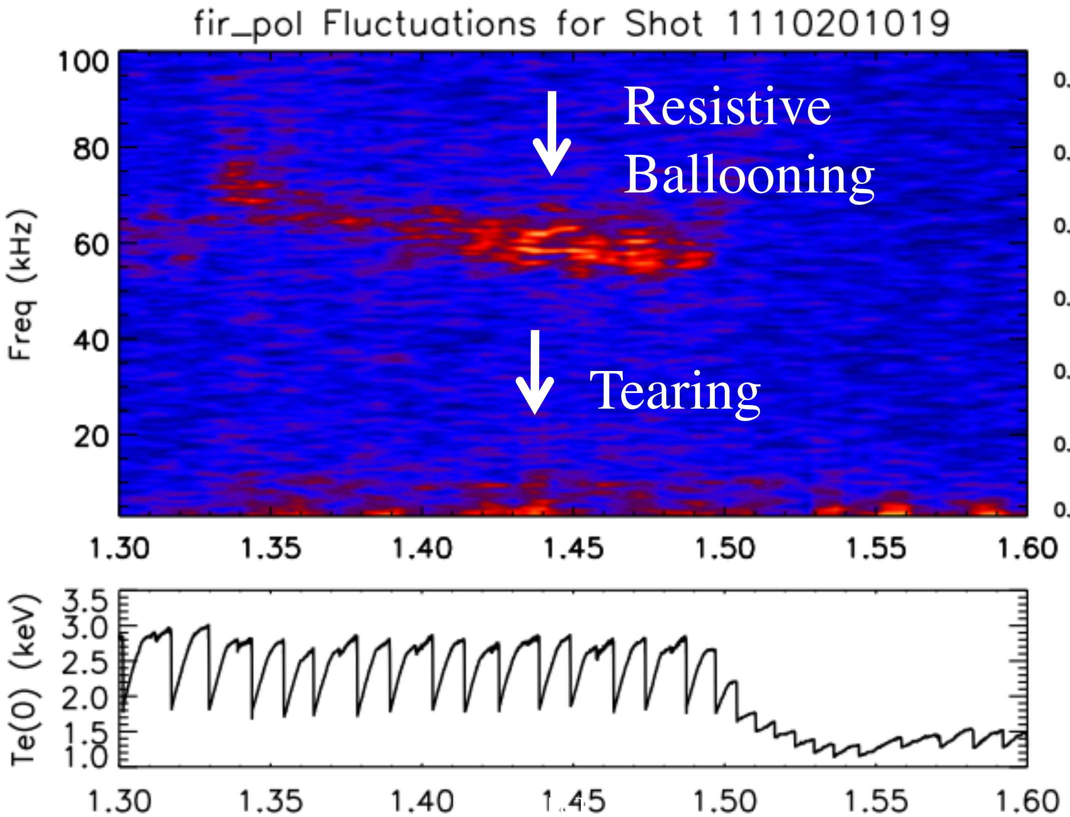
$$\frac{<\delta p_{//}\delta b_r>}{B} = T\frac{<\delta n\delta b_r>}{B} + n\frac{<\delta T_{//}\delta b_r>}{B}$$

- (2) Fluid Stress Measurements in the core. (*Code Validation*)

Advanced Faraday Rotation System on C-Mod



Multiple chords with 4MHz bandwidth



by Irby, Xu, Bergerson, Brower, Ding, etc

Faraday Rotation Fluctuations are Measured on C-Mod , providing new opportunity to study transport on Tokamak.