Intrinsic Flow from Magnetic-Fluctuation-Driven Kinetic Stress

David Brower

in collaboration with

W.X. Ding, L. Lin, W.F. Bergerson, A. Almagri, B. Chapman, G. Fiksel, D.J. Den Hartog, J.S. Sarff and the MST Group

Department of Physics & Astronomy, University of California Los Angeles
Department of Physics, University of Wisconsin, Madison
Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas, University of Wisconsin, Madison

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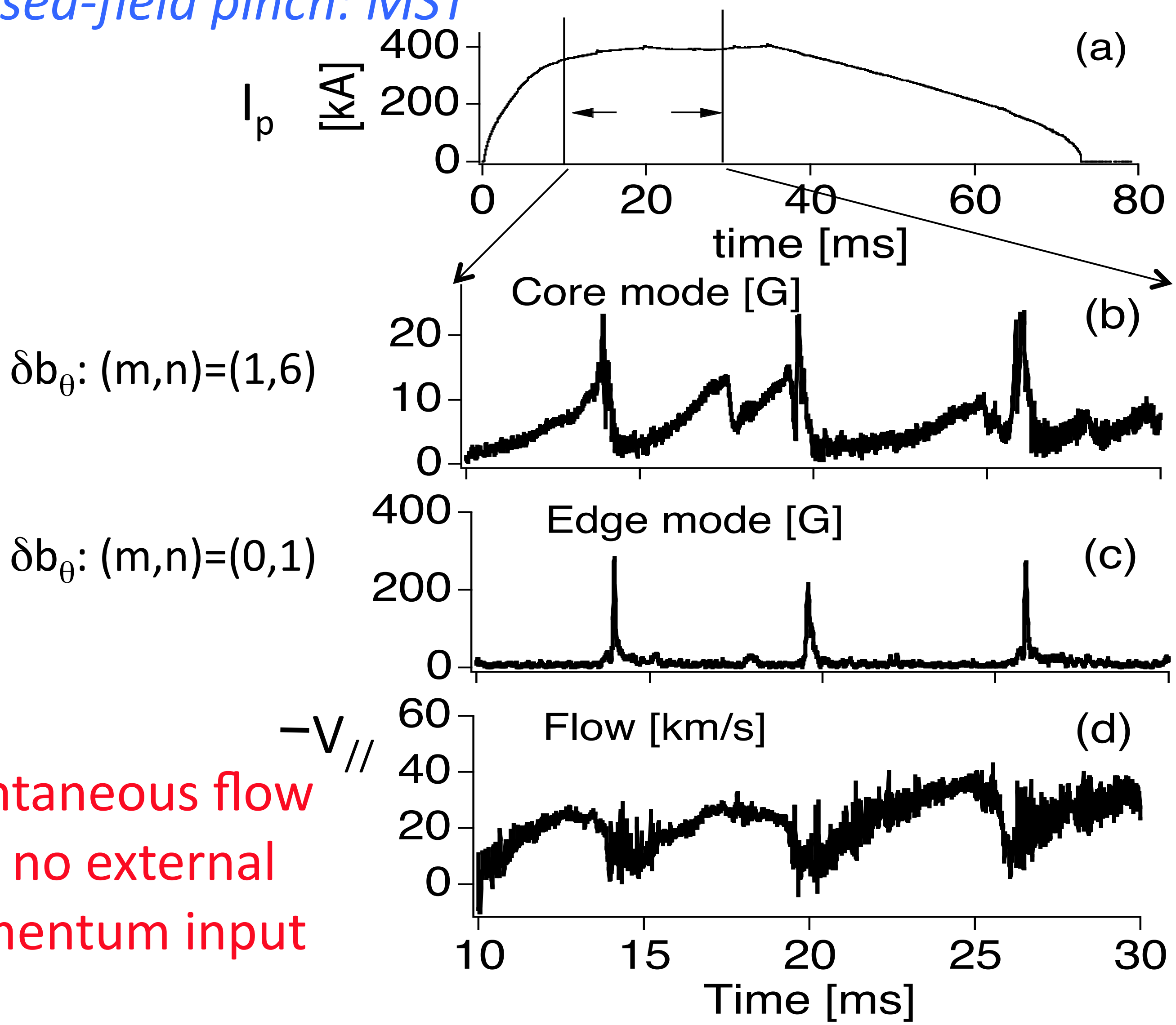
Intrinsic Flow: self-generated during plasma discharge

reversed-field pinch: MST



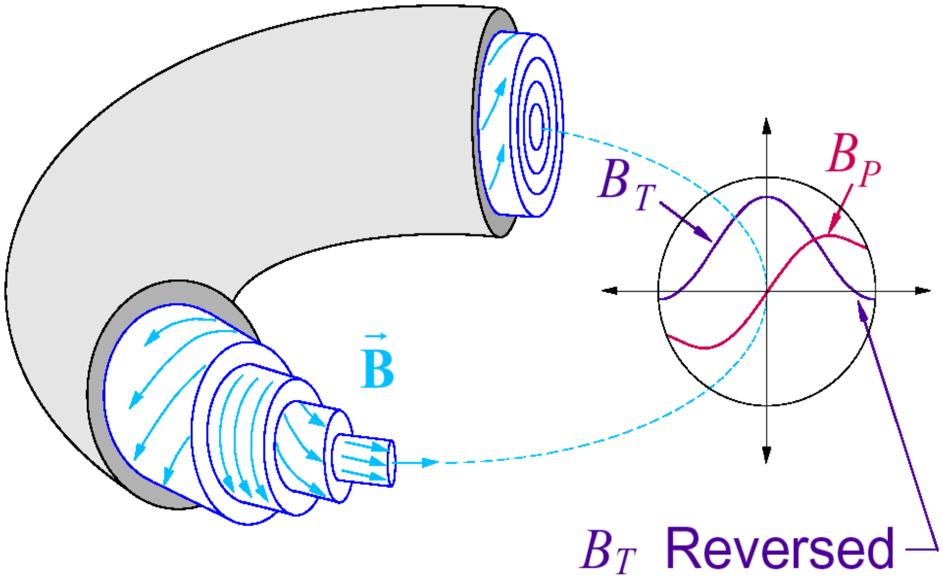
Ohmic discharge

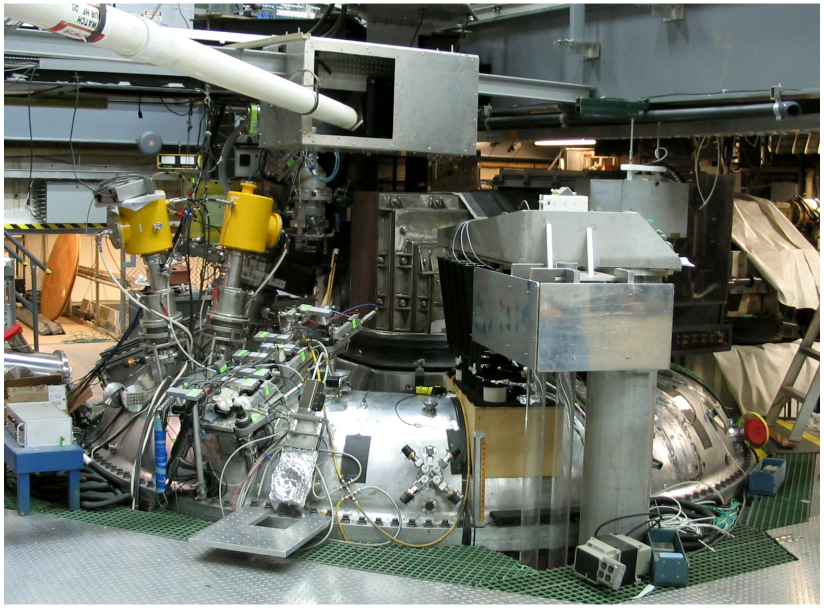
Spontaneous flow with no external momentum input

Flow Generation (co-current)

Madison Symmetric Torus - MST

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





$$\beta \geq 6\%$$

For plasma w/o current profile control

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

$n_e \sim 10^{19}$ m^{-3} ,$T_e \sim T_i \sim$400eV

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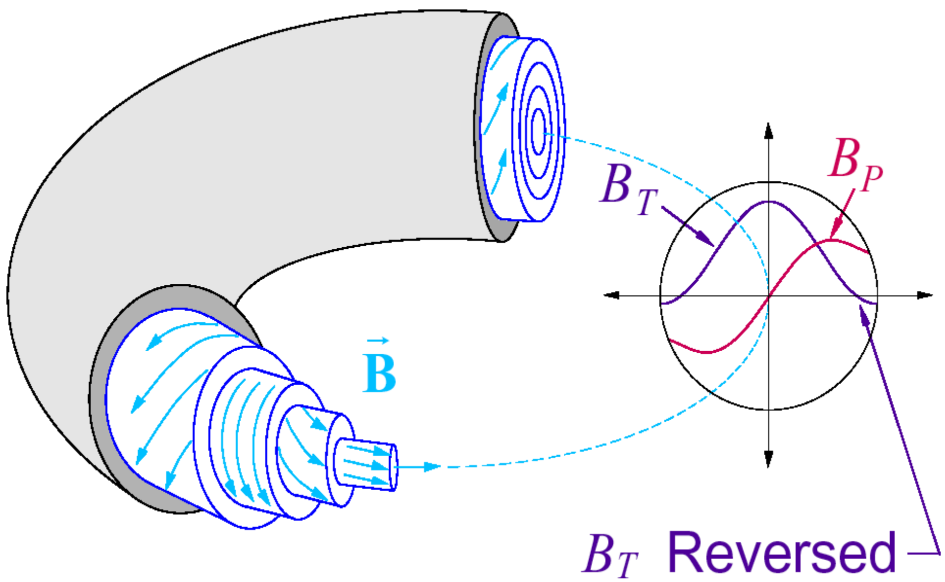
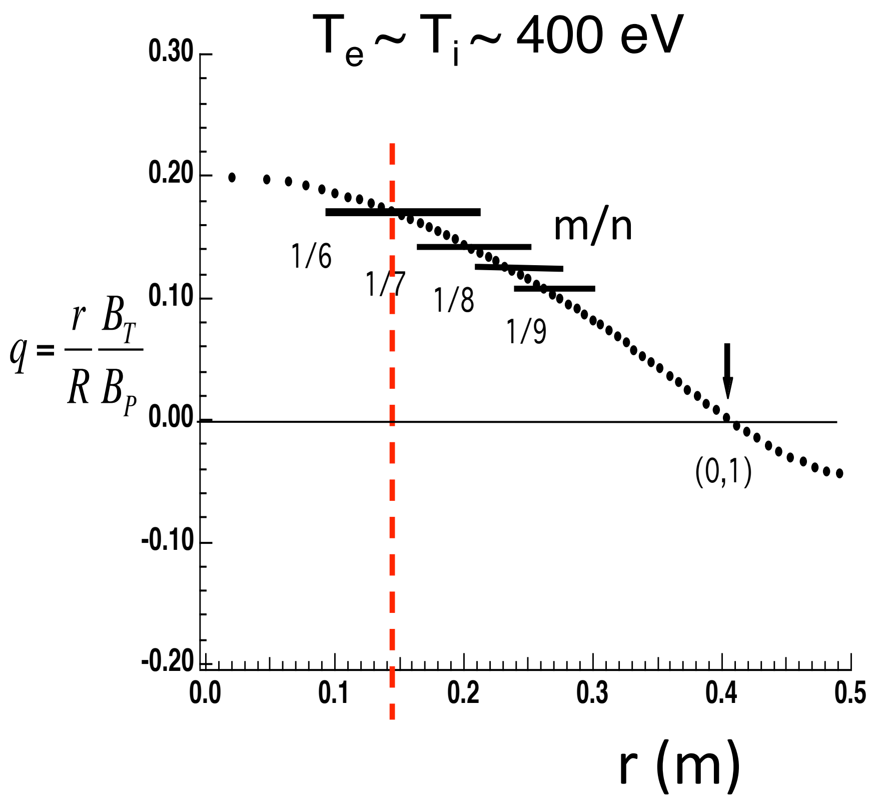


$\beta \geq 6\%$

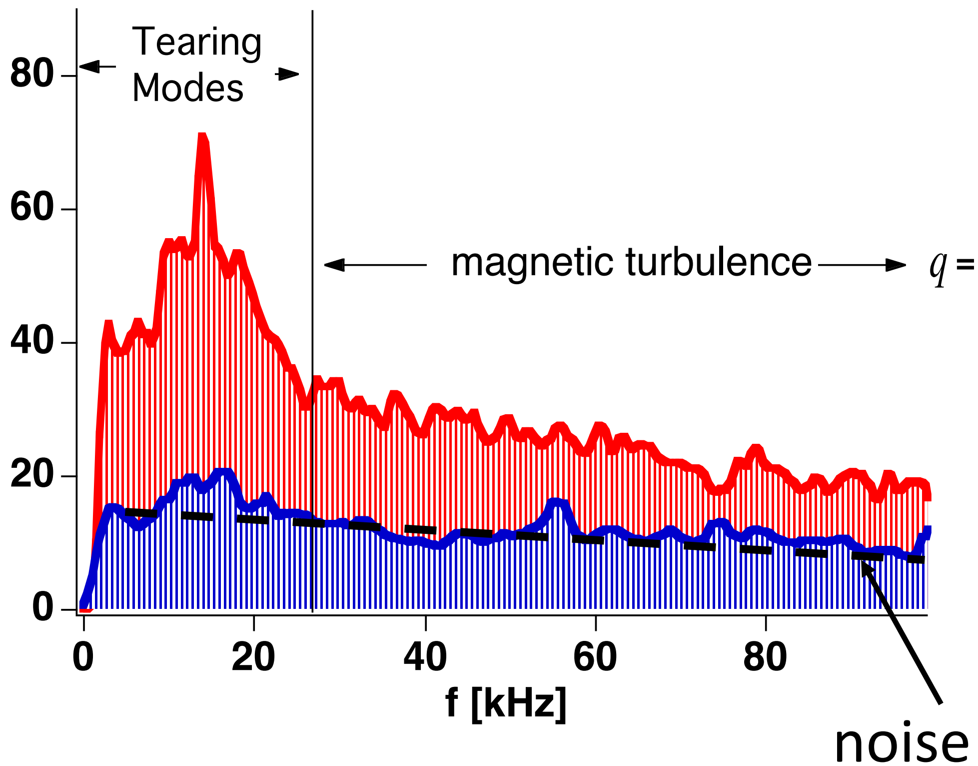


dominant, core resonant modes
m=1, n=6,7,8,9,…

Madison Symmetric Torus - MST

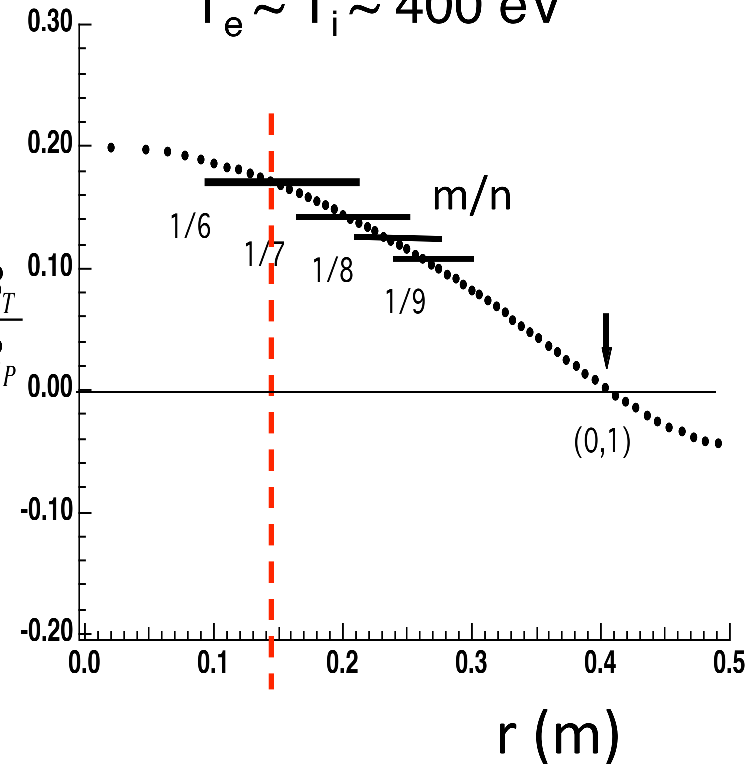
MST Reversed-Field Pinch (RFP) is toroidal configuration with relatively weak toroidal magnetic field B_T (i.e., $B_T \sim B_p$)

$\int \delta b_r dl$



$$q = \frac{r}{R}\frac{B_T}{B_P}$$

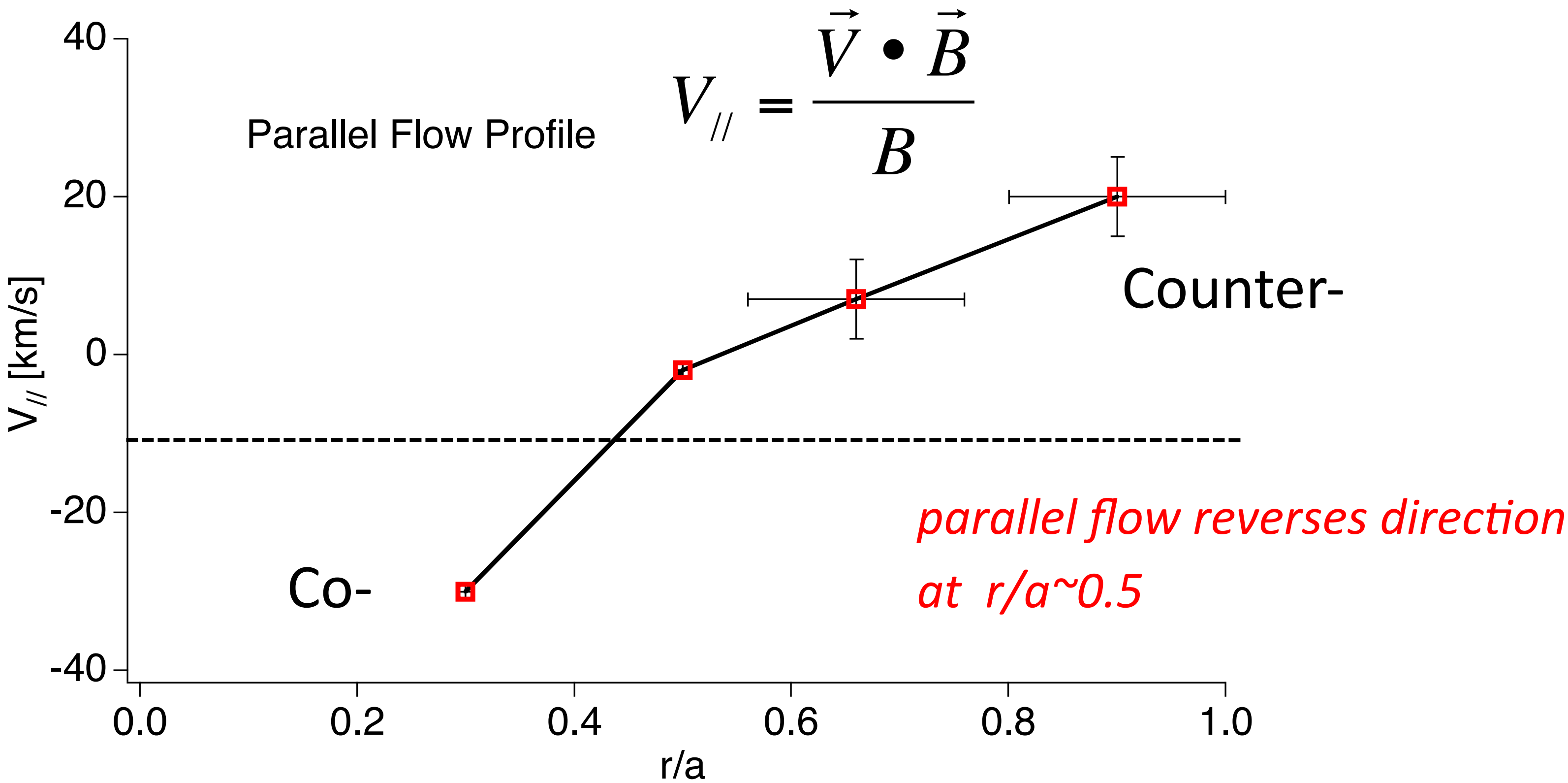
$T_e \sim T_i \sim 400$ eV



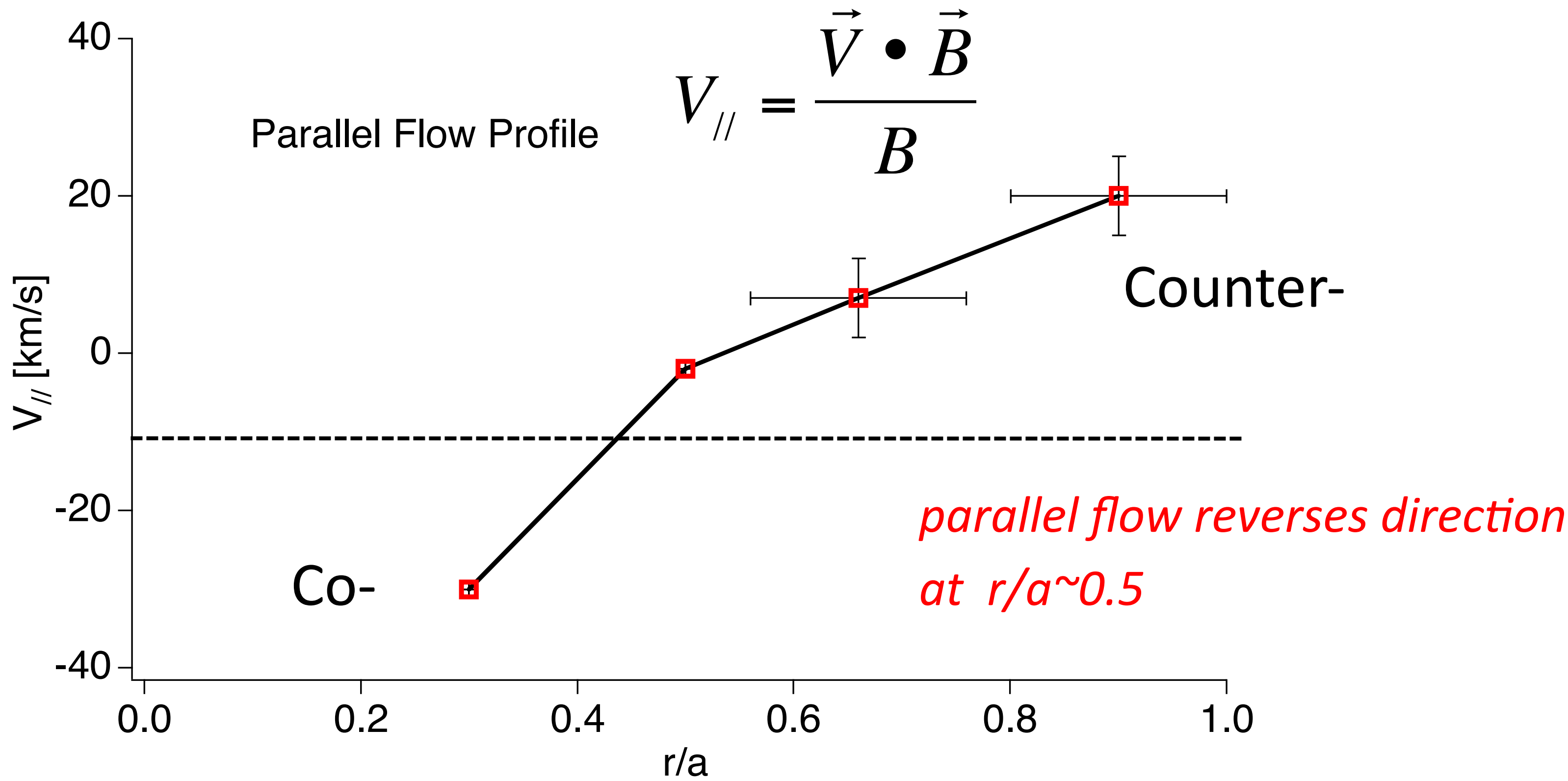
Tearing modes and broadband magnetic turbulence - island overlap leads to stochastic field

dominant, core resonant modes m=1, n=6,7,8,9,…

Parallel flow profile away from sawtooth crash



Parallel flow profile away from sawtooth crash



Issues addressed in this talk:

1) Why is there intrinsic flow?
2) Do magnetic fluctuations influence the flow?
3) What accounts for the flow direction, amplitude and spatial profile?

Kinetic stress

Momentum flux in radial direction due to particles free streaming along fluctuating magnetic field lines:

$$\Pi = < p_{//} \vec{b} \bullet \vec{e}_r > \qquad \text{where} \qquad \vec{b} = \frac{\vec{B}}{B}$$

Kinetic stress

Momentum flux in radial direction due to particles free streaming along fluctuating magnetic field lines:

$$\Pi = < p_{//} \vec{b} \bullet \vec{e}_r > \qquad \text{where} \qquad \vec{b} = \frac{\vec{B}}{B}$$

contribution to the mean (magnetic surface-averaged) momentum flux arising from fluctuations

$$\Pi = \frac{< \delta p_{//} \delta b_r >}{B} \qquad \begin{aligned} p_{//} &= p_{0\,//} + \delta p_{//} \\ \vec{b} &= \frac{\vec{B}}{B} = \vec{b}_0 + \delta \vec{b} \end{aligned}$$

$$\delta p_{//} = T_{//} \delta n + n_o \delta T_{//}$$

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

Kinetic stress

Momentum flux in radial direction due to particles free streaming along fluctuating magnetic field lines:

$$\Pi = < p_{//} \vec{b} \bullet \vec{e}_r > \qquad \text{where} \qquad \vec{b} = \frac{\vec{B}}{B}$$

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$$\Pi = \frac{< \delta p_{//} \delta b_r >}{B}$$

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$$\vec{b} = \frac{\vec{B}}{B} = \vec{b}_0 + \delta \vec{b}$$

$$\delta p_{//} = T_{//} \delta n + n_o \delta T_{//}$$

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

Kinetic stress $\quad -\nabla \bullet \Pi = -\nabla \bullet \left[\Pi^n + \Pi^T \right] \vec{e}_r$

Multiple Fluctuation-Induced Effects on Flow

Parallel momentum components

$$\rho \frac{\partial}{\partial t} < V_{//} > = < \delta J \times \delta B >_{//} - \rho < \delta \vec{V} \bullet \nabla \delta \vec{V} >_{//} - \nabla \bullet \frac{< \delta p_{//} \delta b_r >}{B_0} \vec{e}_r + \mu \nabla^2 \vec{V}$$

Momentum Change

Maxwell Stress

Reynolds stress

Kinetic stress

damping

Measure kinetic stress associated with correlated magnetic and density fluctuations

Investigate balance between kinetic stress and inertial term - simple momentum balance

$$\underline{\rho \frac{\partial}{\partial t} < V_{//} >} \quad \Leftrightarrow \quad -\nabla \bullet \Pi^n \vec{e}_r = \boxed{-\nabla \bullet \left[T_{//} \frac{< \delta n \delta b_r >}{B_0} \right] \vec{e}_r}$$

B_0 Motional Stark effect

$\delta b_r(r)$ Laser Faraday rotation

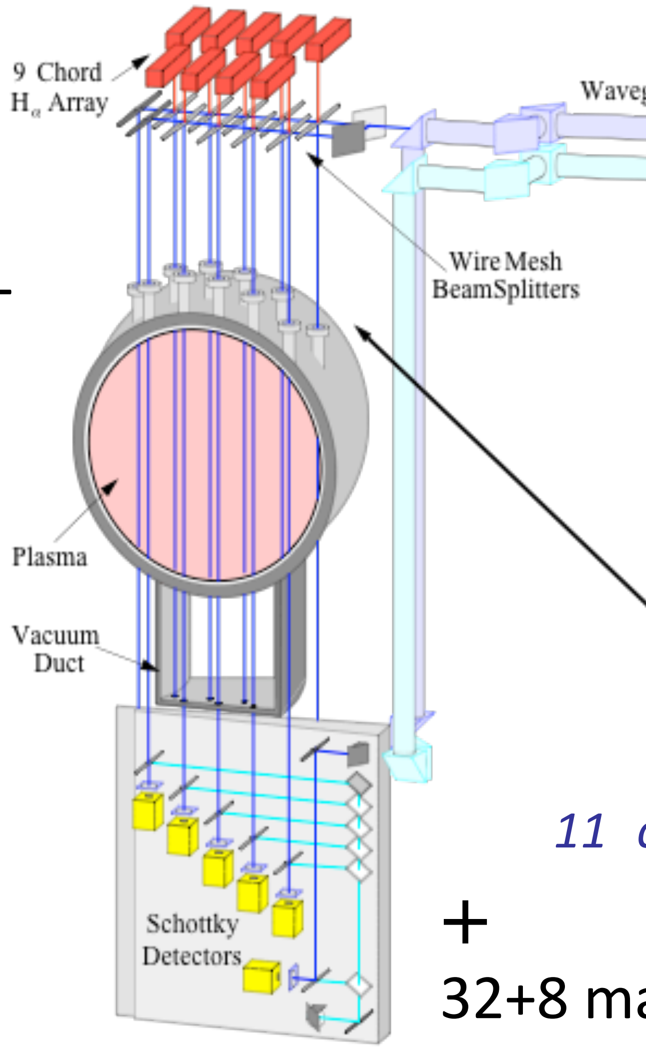
$n \quad \delta n$ Laser (differential) interferometer ($\nabla \delta n_e$)

$T_{//i}$ Rutherford Scattering (bulk deuterium ions), CHERS (impurity)

$T_{//e}$ Thomson scattering

FIR Laser Polarimeter-Interferometer System

MST



$$\phi \sim \int n dl + \int \delta n dl$$

Interferometer ⟶ *density fluctuations*

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

Faraday rotation ⟶ *magnetic field fluctuations*

11 chords, Δx ~ 8 cm, phase ~ 0.05 deg. degree, time response ~ 1 μs

\+

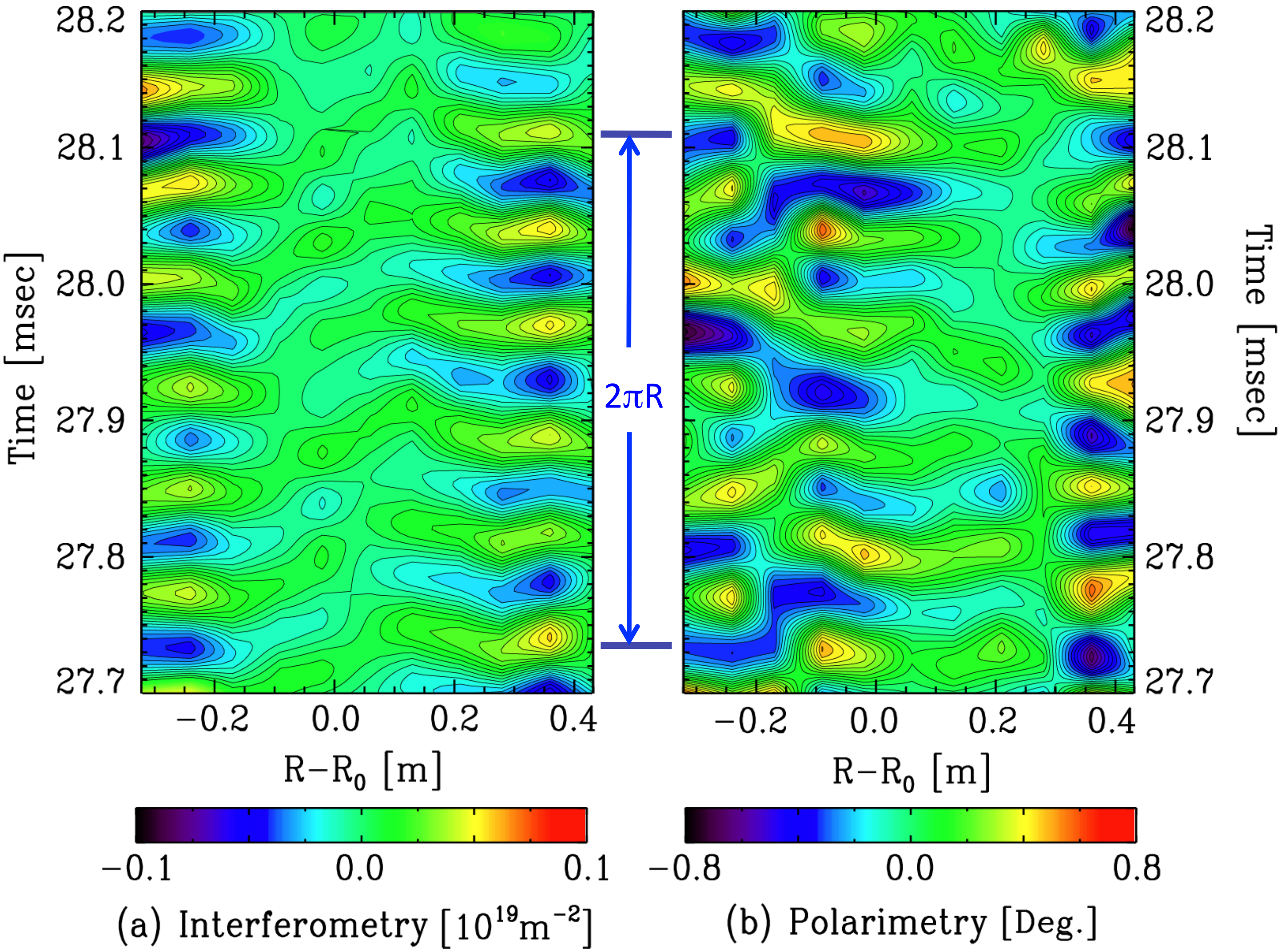
32+8 magnetic coils toroidal-poloidal array (m,n)

Ding, Brower, et al., PRL(2003),(2004),(2009), RSI(2004),(2008)

2-D Space-Time Image of Fluctuations using combined interferometry and Faraday polarimetry

$$\delta\phi \propto \int \delta n\, dl$$

$$\delta\psi \propto \int \delta n\, \vec{B}_o \bullet d\vec{l} + \int n_o\, \delta\vec{b} \bullet d\vec{l}$$



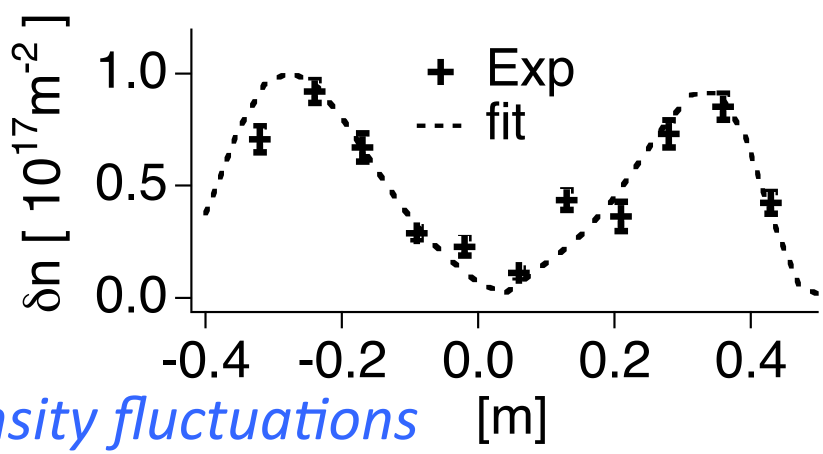
$$-\nabla \bullet \Pi^n =$$

$$-\nabla \bullet \left[T_{//i} \frac{< \delta n \delta b_r >}{B_0} \right]$$

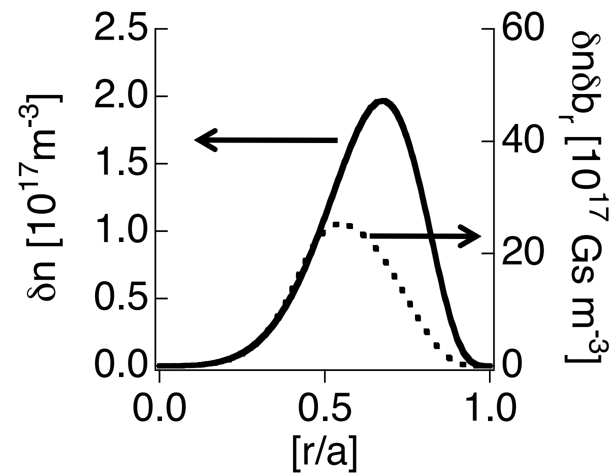
Density and magnetic fluctuation spatial profile

Line-integrated: (1,6) mode

Local profiles



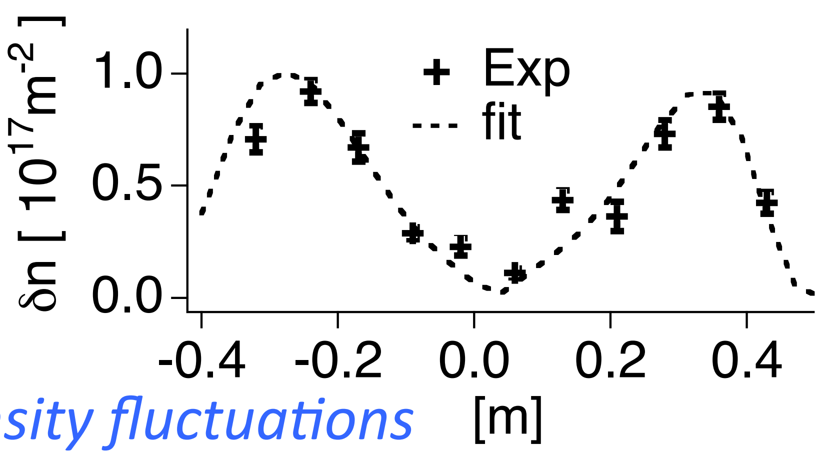
Density fluctuations



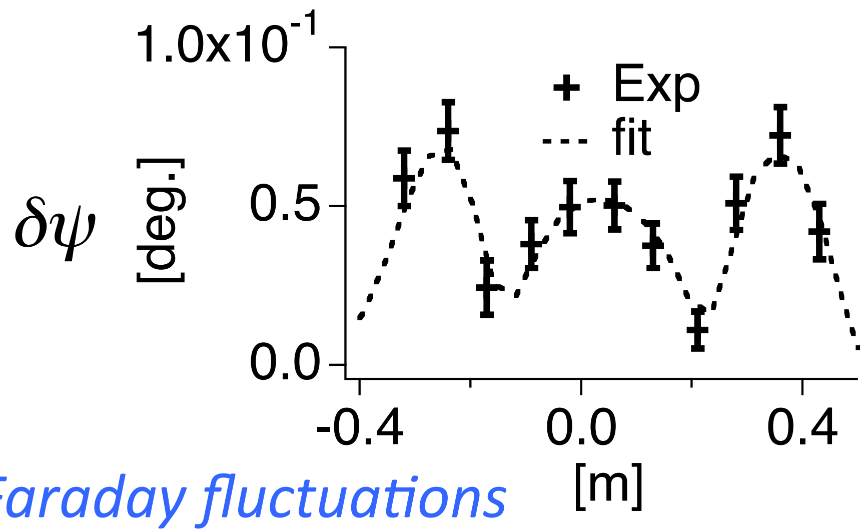
Inversion: parameterized fitting

Density and magnetic fluctuation spatial profile

Line-integrated: (1,6) mode

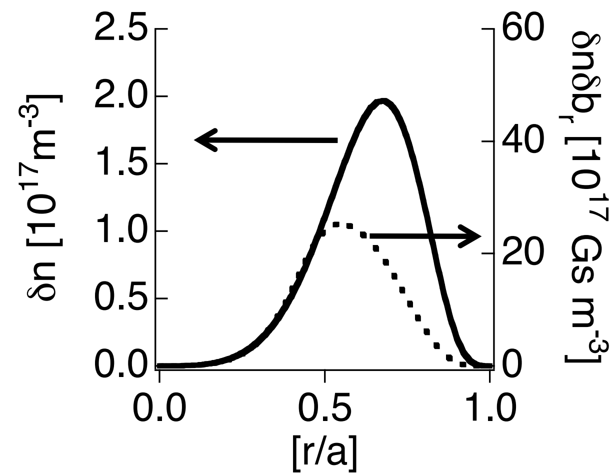


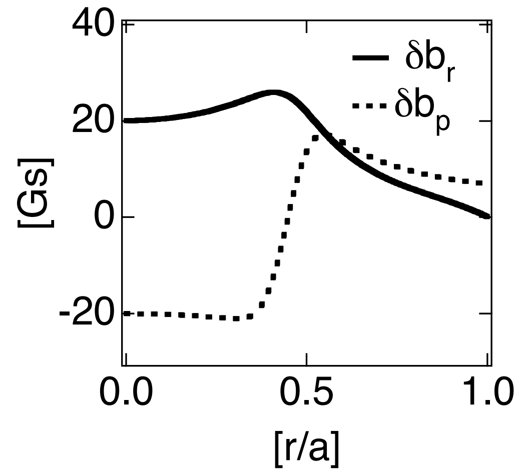
Density fluctuations



Faraday fluctuations

Local profiles

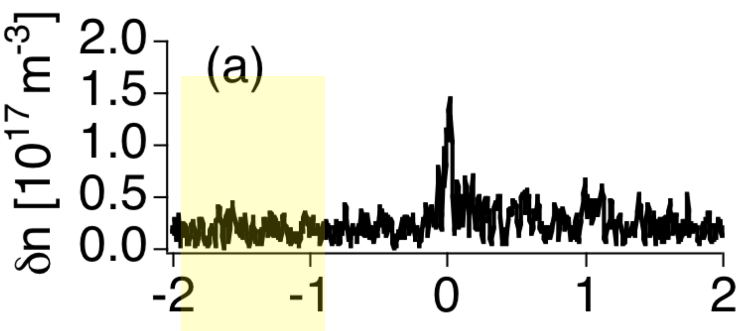




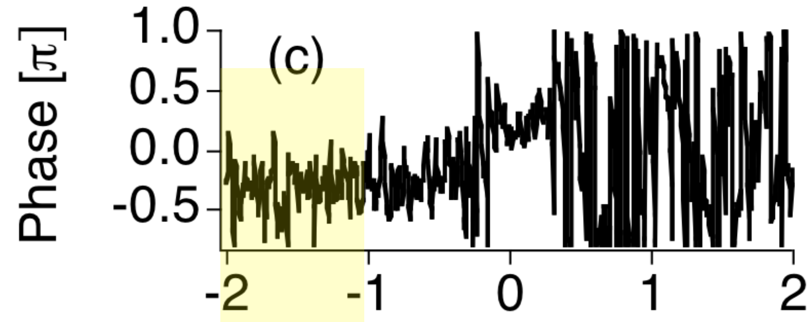
Inversion: parameterized fitting

Measurement of Density Fluctuation-induced Momentum Flux

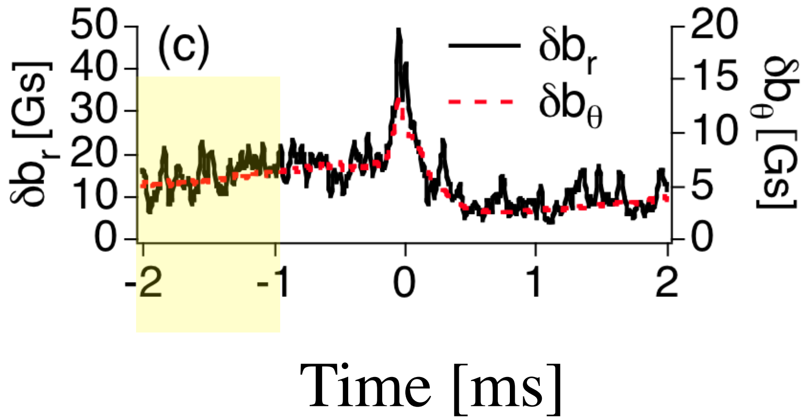
Density Fluctuation



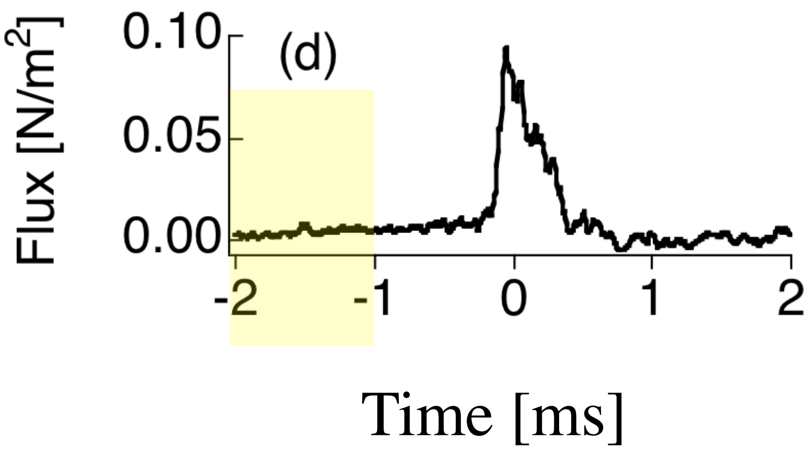
δn - δb phase



Magnetic Fluctuation

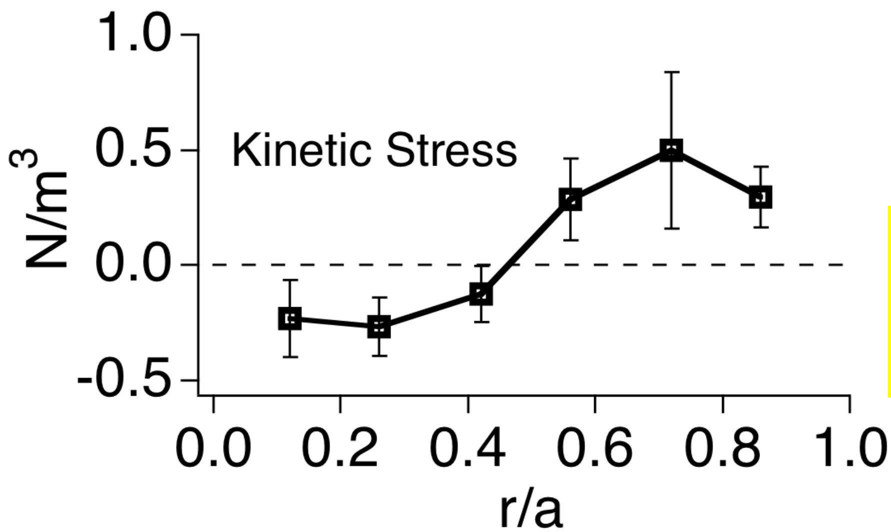


Momentum Flux



This talk will focus on momentum flux – kinetic stress away from sawtooth crash

Kinetic Stress Profile
(away from sawtooth crash)

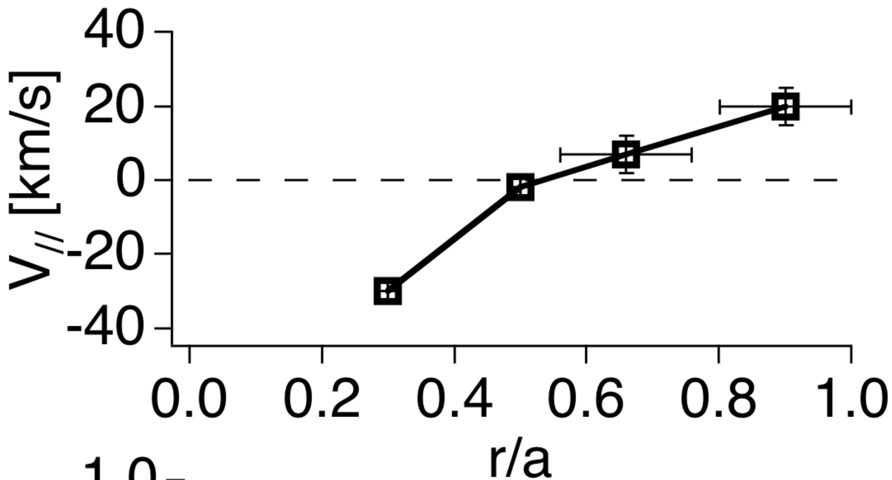


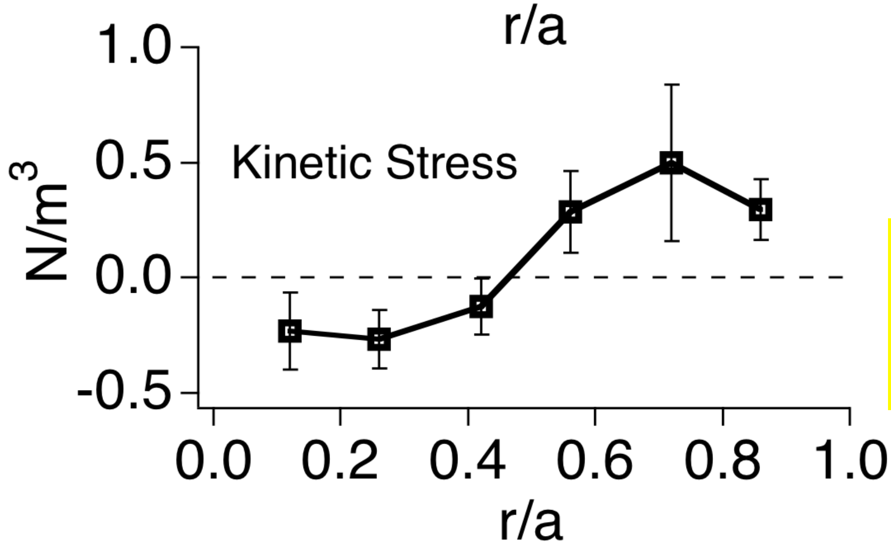
$$-\nabla \bullet \Pi^n =$$
$$-\nabla \bullet \left[T_{//i} \frac{< \delta n \delta b_r >}{B_0} \right]$$

(m,n)=1,6-15

CORE r/a<0.5: force in co-current direction
EDGE r/a>0.5: force in counter-current direction

Kinetic Stress Profile (away from sawtooth crash)



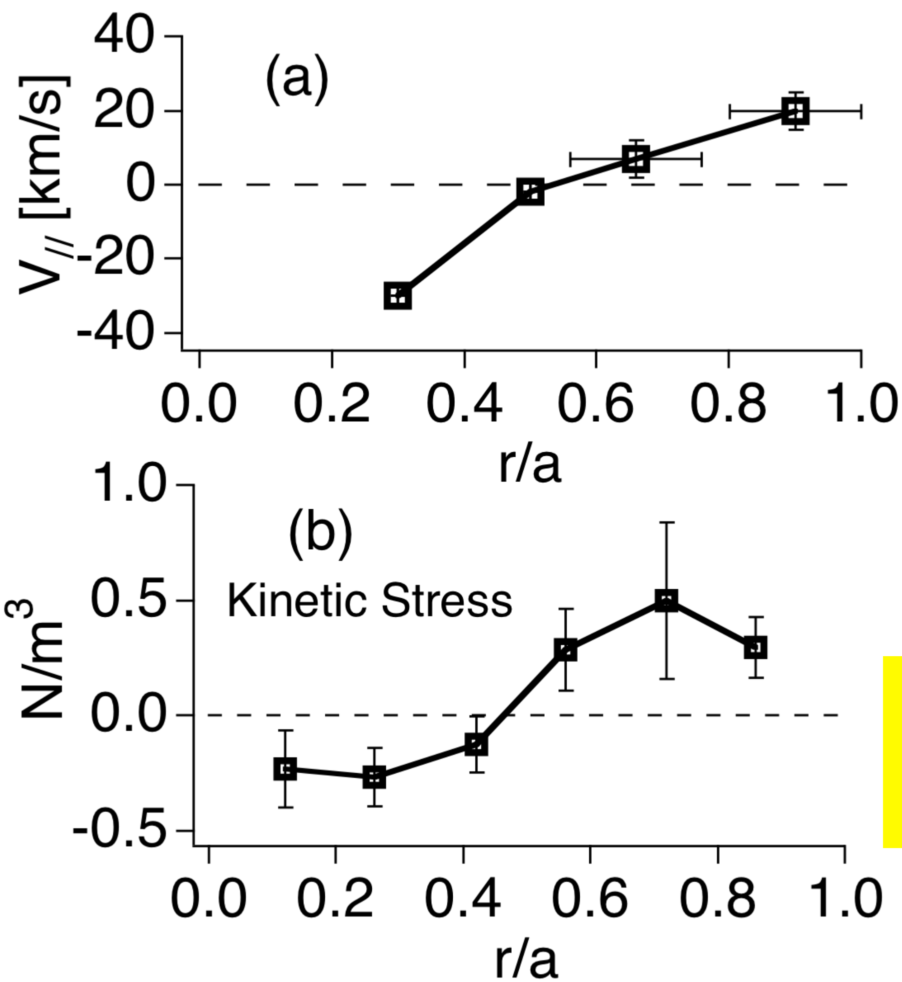


$$-\nabla \bullet \Pi^n = -\nabla \bullet \left[T_{//i} \frac{<\delta n \delta b_r>}{B_0} \right]$$

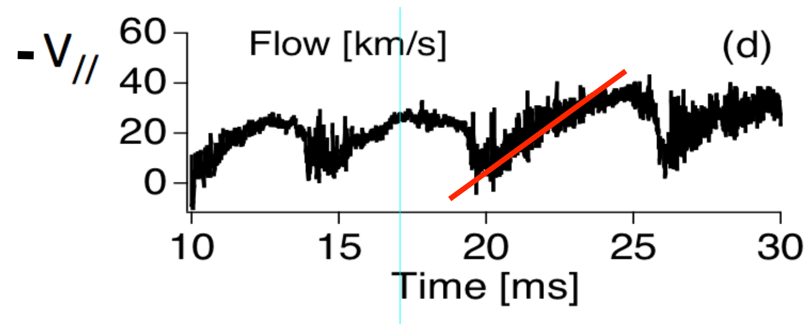
(m,n)=1,6-15

kinetic stress has same sign and spatial distribution as parallel flow

Kinetic Stress Profile
(away from sawtooth crash)



r/a=0.2



$$\boxed{\rho \Delta V_{//} / \Delta t \approx -0.20 \ \mathrm{N/m^3}}$$

$$-\nabla \bullet \Pi^n =$$

$$-\nabla \bullet \left[T_{//i} \frac{< \delta n \delta b_r >}{B_0} \right]$$

(m,n)=1,6-15

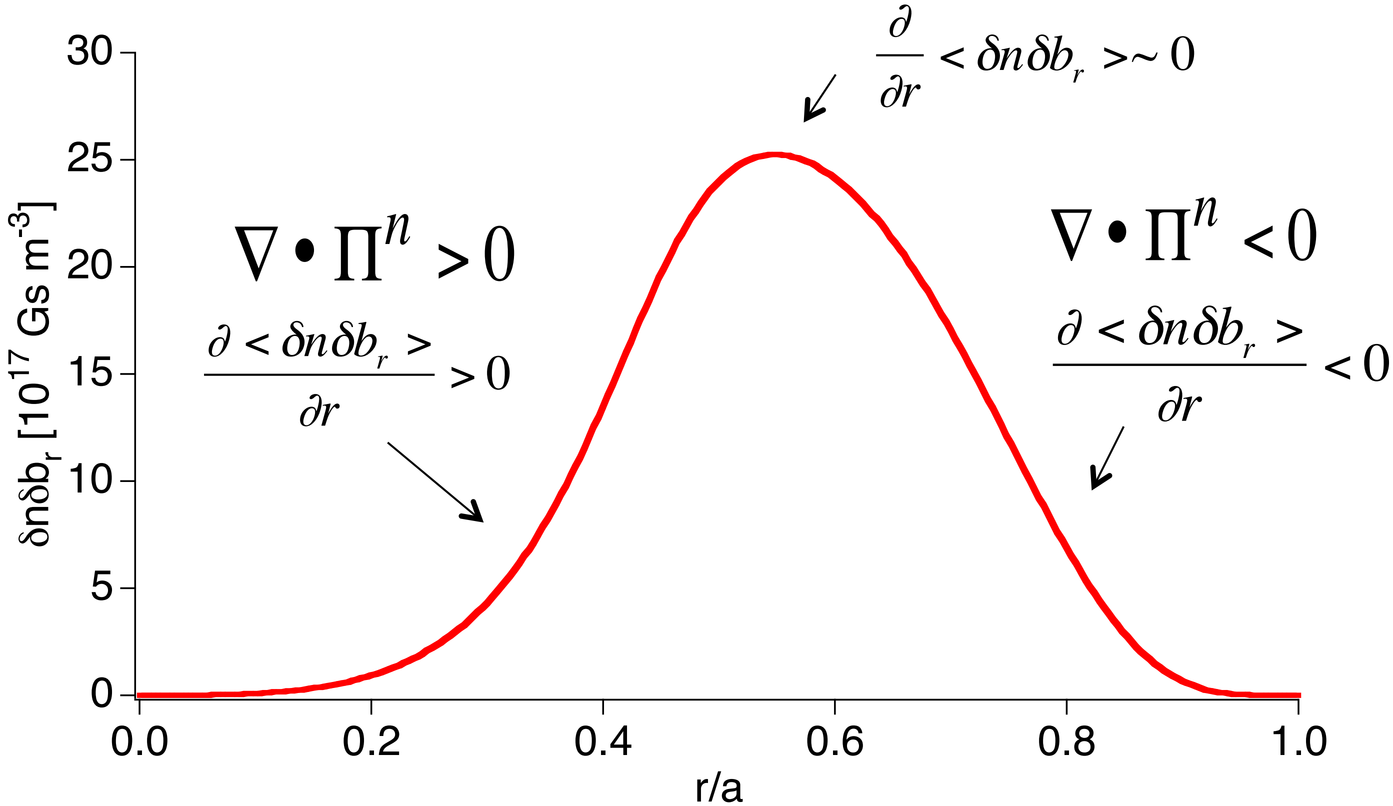
kinetic stress has same sign, spatial distribution and amplitude as parallel flow

Product $\delta n \delta b_r$ reaches maximum near half radius

(m,n)=1,6 only

$$-\nabla \bullet \Pi^n = -\nabla \bullet \left[T_{//i} \frac{< \delta n \delta b_r >}{B_0} \right]$$

$\delta n \delta b_r$



Kinetic stress becomes zero when fluctuation-induced flux reaches maximum

Flow Damping

$$\rho \frac{\partial < V_{//} >}{\partial t} = -\nabla \bullet < \Pi^n \vec{e}_r > + \mu^T \nabla^2 < V_{//} > + \sum R$$

Kinetic stress

Anomalous damping

Residual stress

$$\nabla^2 < V_{//} > \cong \frac{\rho}{} < V_{//} >$$

Flow Damping

$$\rho \frac{\partial < V_{//} >}{\partial t} = -\nabla \bullet < \Pi^n \vec{e}_r > + \mu^T \nabla^2 < V_{//} > + \sum R$$

Kinetic stress | Anomalous damping | Residual stress

Steady-state case: $\rho \frac{\partial < V_{//} >}{\partial t} \approx 0$

$$\nabla \bullet (\Pi^n \vec{e}_r) = \mu^T \nabla^2 < V_{//} > \cong \frac{\rho}{\tau_m} < V_{//} >$$

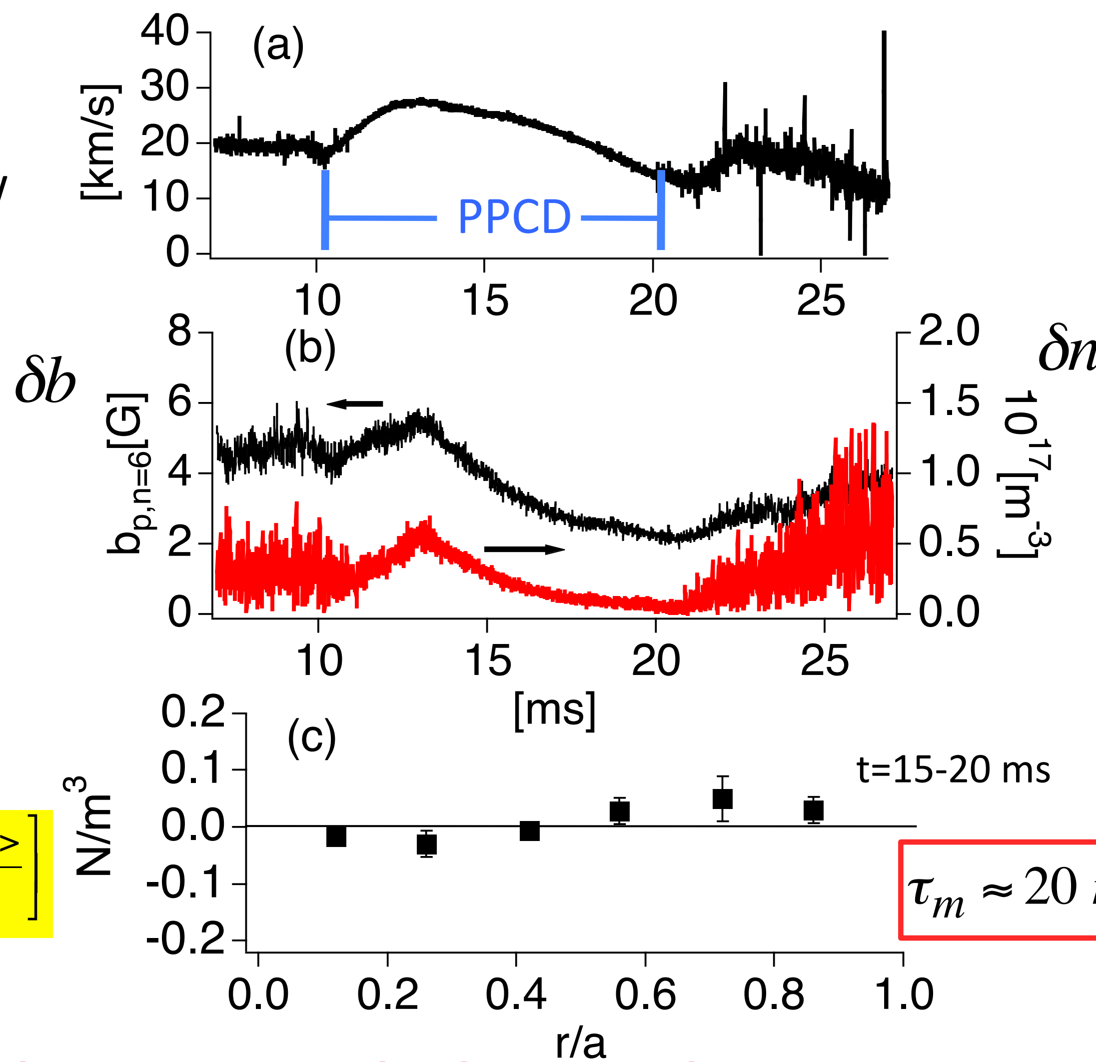
$$\boxed{\tau_m \approx 1\ ms} << \quad classical\ viscous\ time \approx 250\ ms$$

Flow damping strongly anomalous away from sawtooth crash

Measurements of Intrinsic Flow and Kinetic Stress during Enhanced Confinement (PPCD)

During PPCD, RFP has tokamak-like confinement

Intrinsic Flow



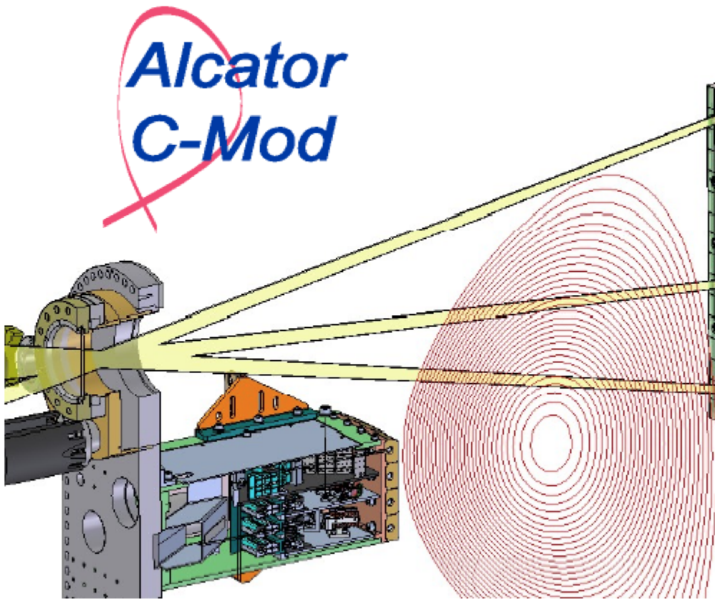
Kinetic stress

$$-\nabla \bullet \Pi^n = -\nabla \bullet \left[T_{//i} \frac{<\delta n \delta b_r>}{B_0} \right]$$

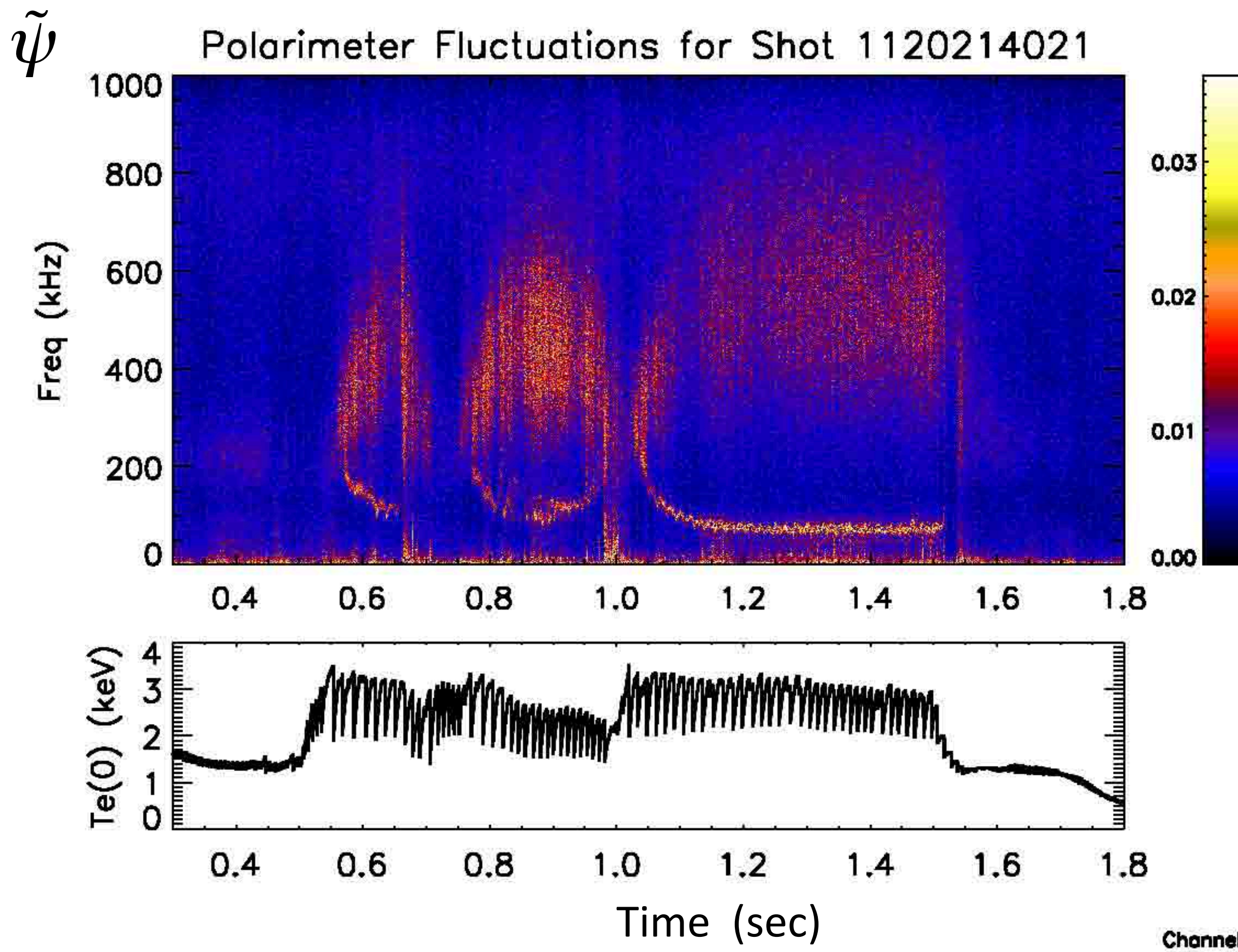
$$\tau_m \approx 20\ ms$$

Intrinsic flow and Kinetic stress track changes in fluctuation amplitudes

Advanced Faraday Rotation System on C-Mod



Multiple chords with 4 MHz bandwidth



Faraday Rotation Fluctuations are measured on C-Mod, providing new opportunity to study transport in Tokamaks (we hope.....)

Summary

- Kinetic stress, the correlated product between density fluctuations and magnetic fluctuations, acts to *drive* plasma flow

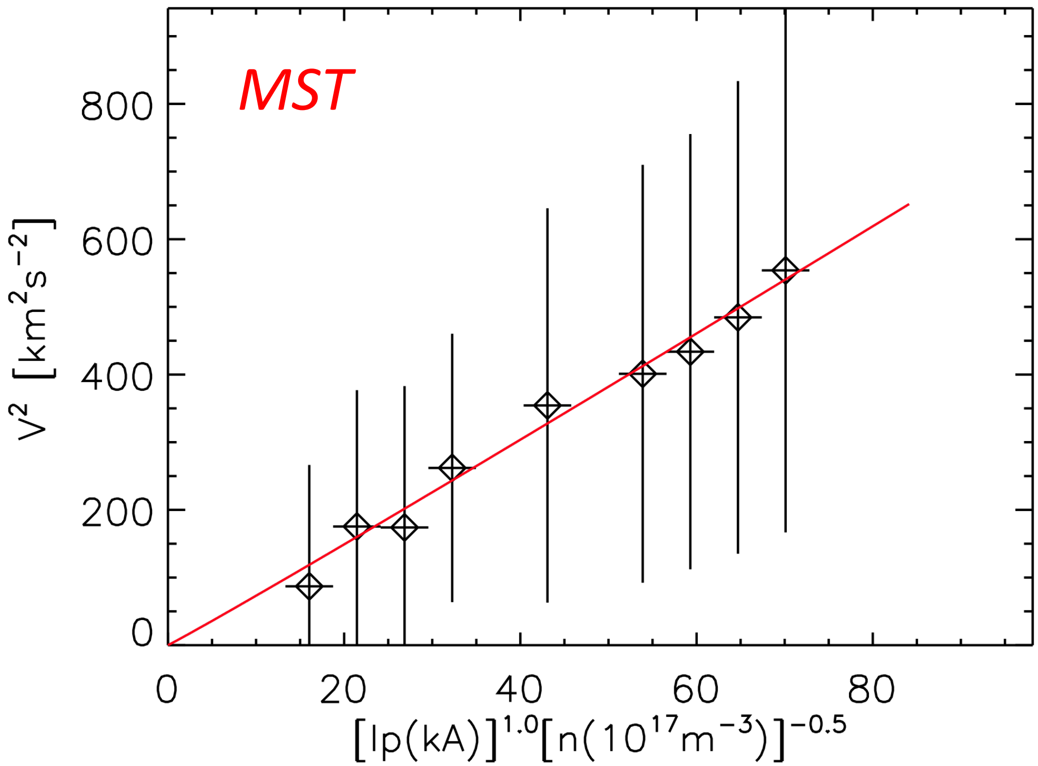
- Kinetic stress is consistent with observed flow generation
  - spatial distribution, direction and amplitude of force

- In PPCD plasmas with good (tokamak-like) confinement,

  (1) core flow is reduced and momentum confinement increases when density and magnetic fluctuations are suppressed

  (2) flow dynamics likely governed by other effects (es turbulence) in addition to magnetic fluctuation driven kinetic stress .

Plasma Flow Scaling in MST



Tokamaks:
Rice scaling (NF-2007)
Parra (PRL-2012)

$$V_{//} \sim \frac{\Delta W}{I_p} \quad \Rightarrow \quad \nabla p$$

error bars reflect
stnd deviation of total
events (not mean)

Core toroidal plasma flow scaling in RFP:

$$V_{//} \sim \frac{I_p^{0.5}}{n_e^{0.25}} \quad \Rightarrow \quad \left\langle \delta p_{//} \delta b_r \right\rangle$$