Rotation, momentum transport, and tearing modes in the MST RFP

Gennady Fiksel
Alexey Kuritsyn (DPP '08, invited talk)
MST group

THE UNIVERSITY of WISCONSIN MADISON

US-Japan MHD workshop, November 23-25 2008, Austin, Texas, USA

Motivation

- Plasma in MST rotates toroidally and poloidally without external momentum input
- Strong correlation between rotation and magnetic tearing fluctuations.

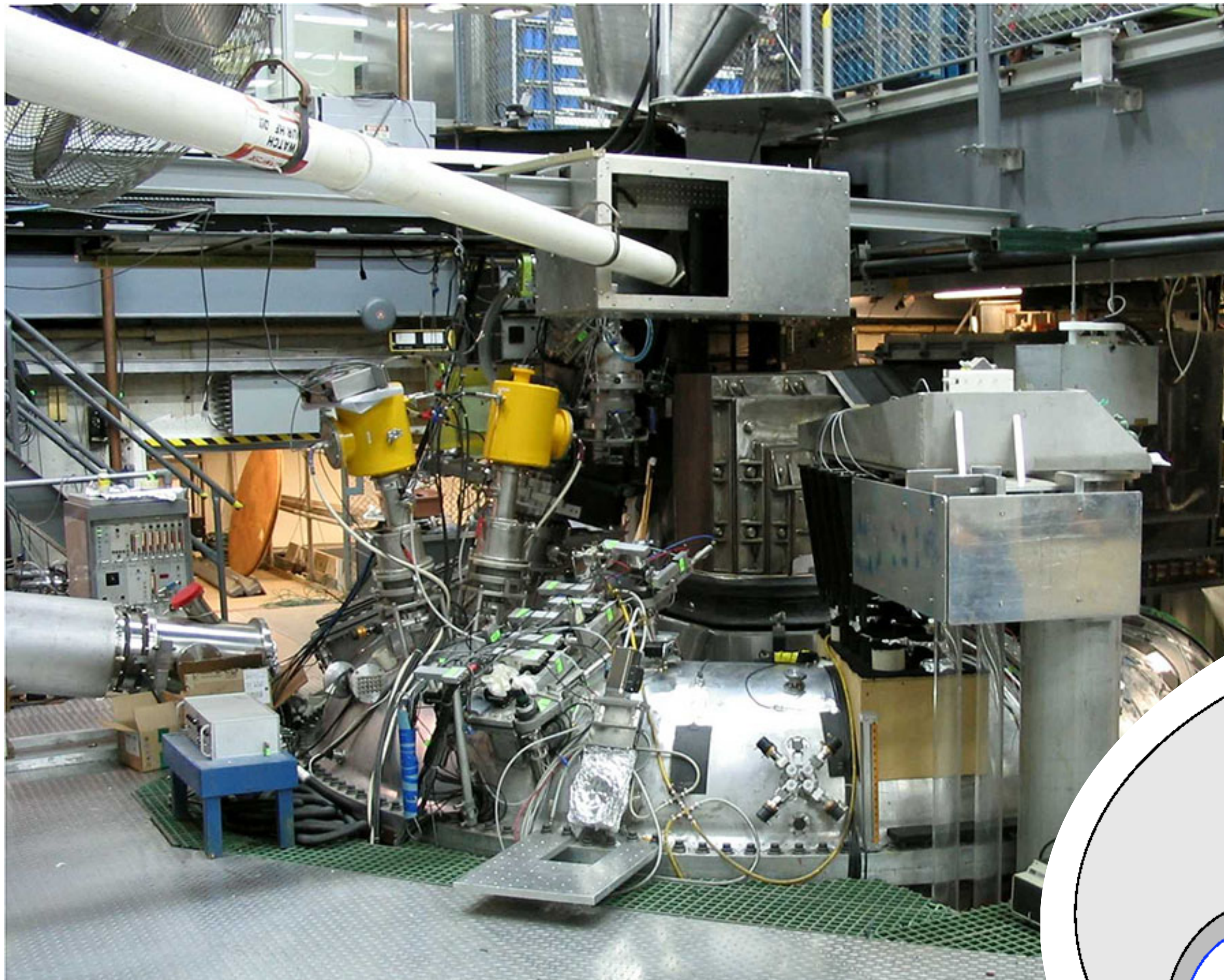
Motivation

- Plasma in MST rotates toroidally and poloidally without external momentum input
- Strong correlation between rotation and magnetic tearing fluctuations.
- Can tearing modes generate internal forces and facilitate momentum transport?

Outline

- MST RFP and magnetic tearing fluctuations
- Momentum transport from edge-applied torque
- Relaxation of momentum profile
- Measurement of Maxwell and Reynolds stresses
- Conclusions

Madison Symmetric Torus Reversed Field Pinch

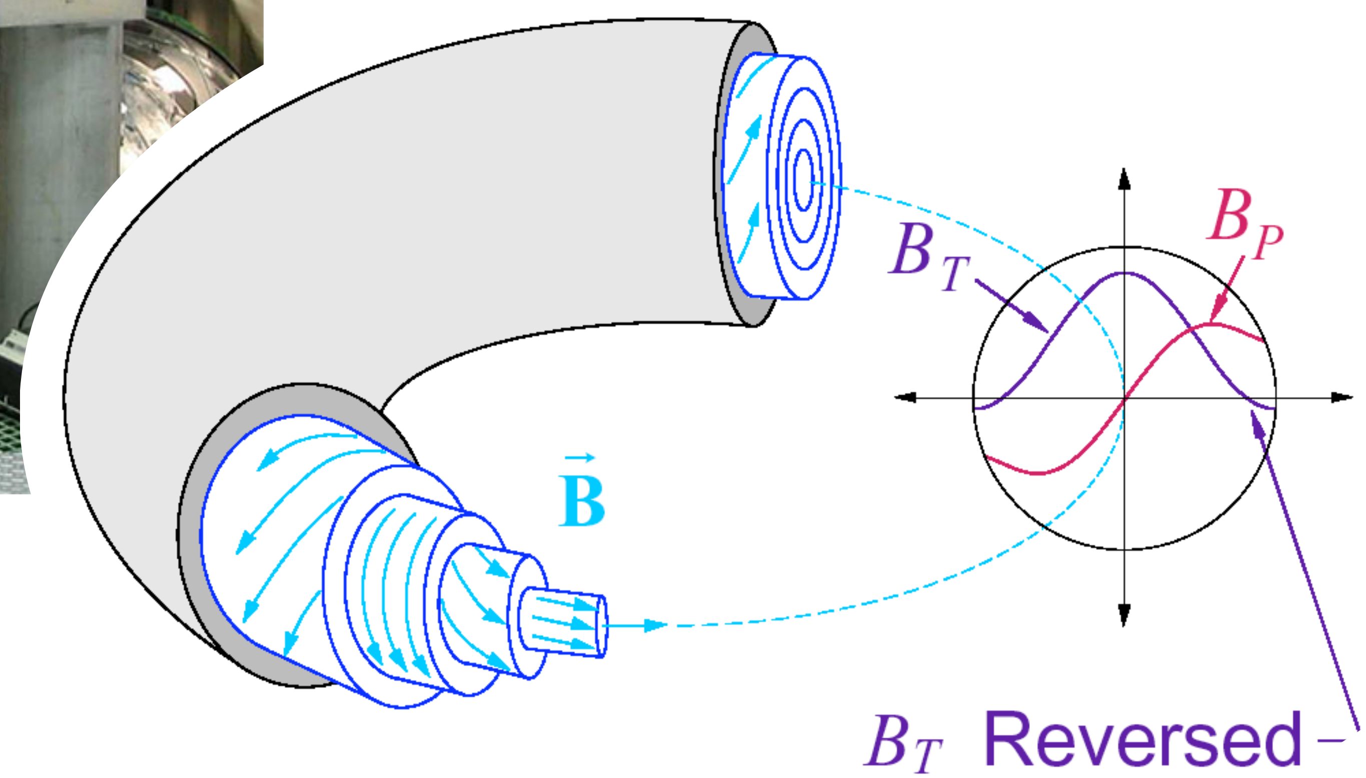


$R = 1.5$ m, $a = 0.5$ m

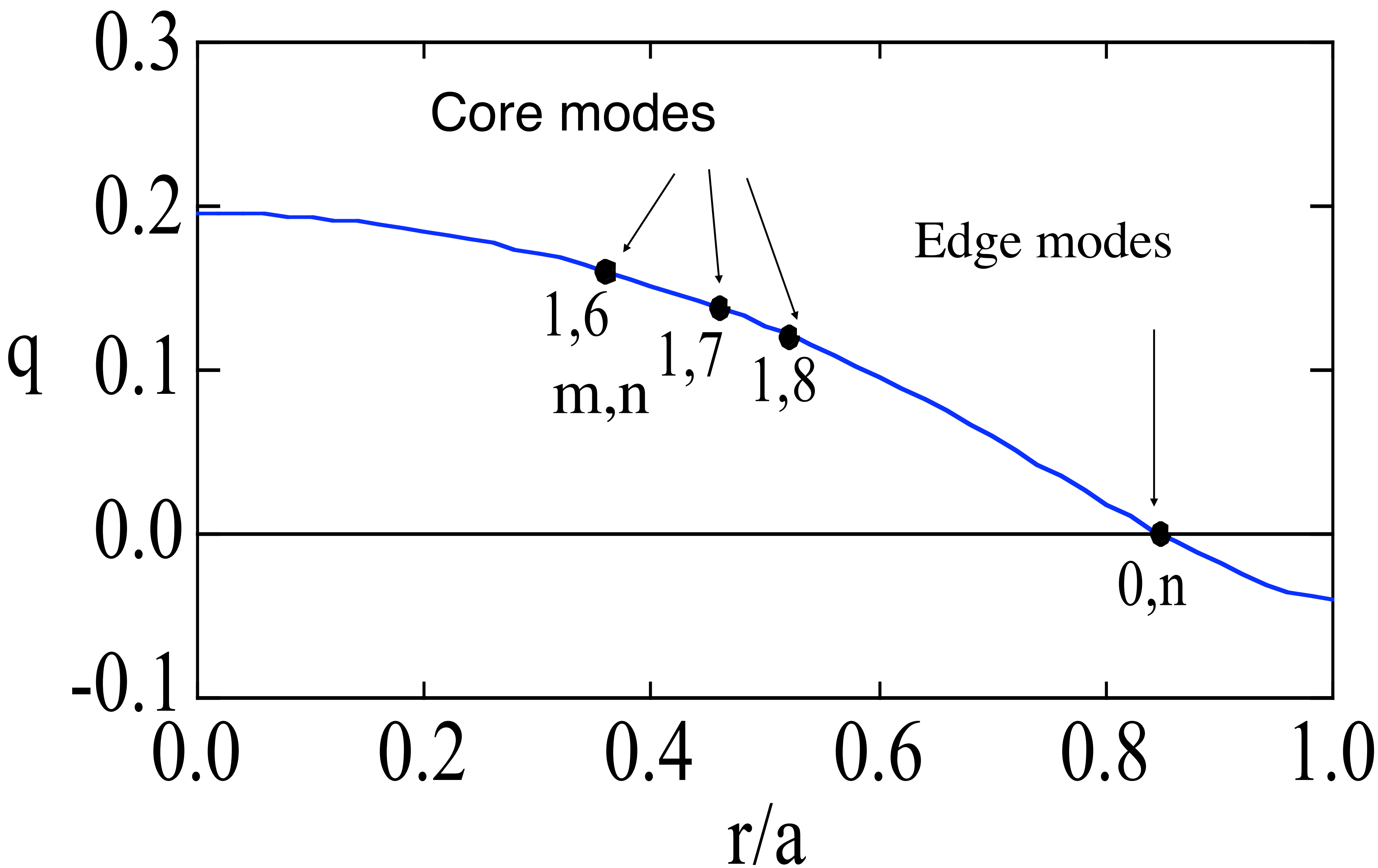
$I_p = 600$ kA, $B = 0.6$ T

(200 kA, 0.2 T for probes)

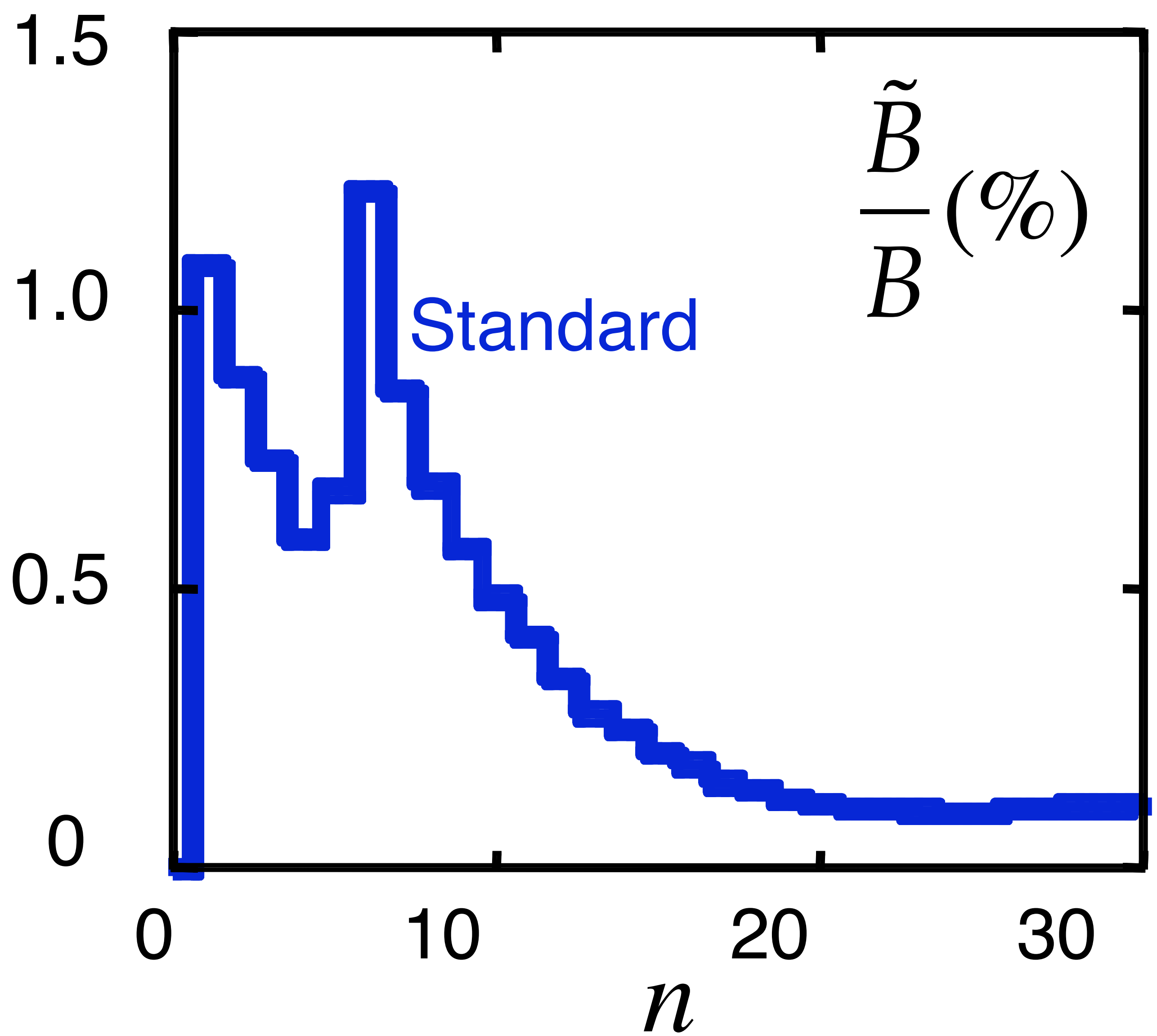
$n_e = 1\text{x}10^{19}$ m^{-3}

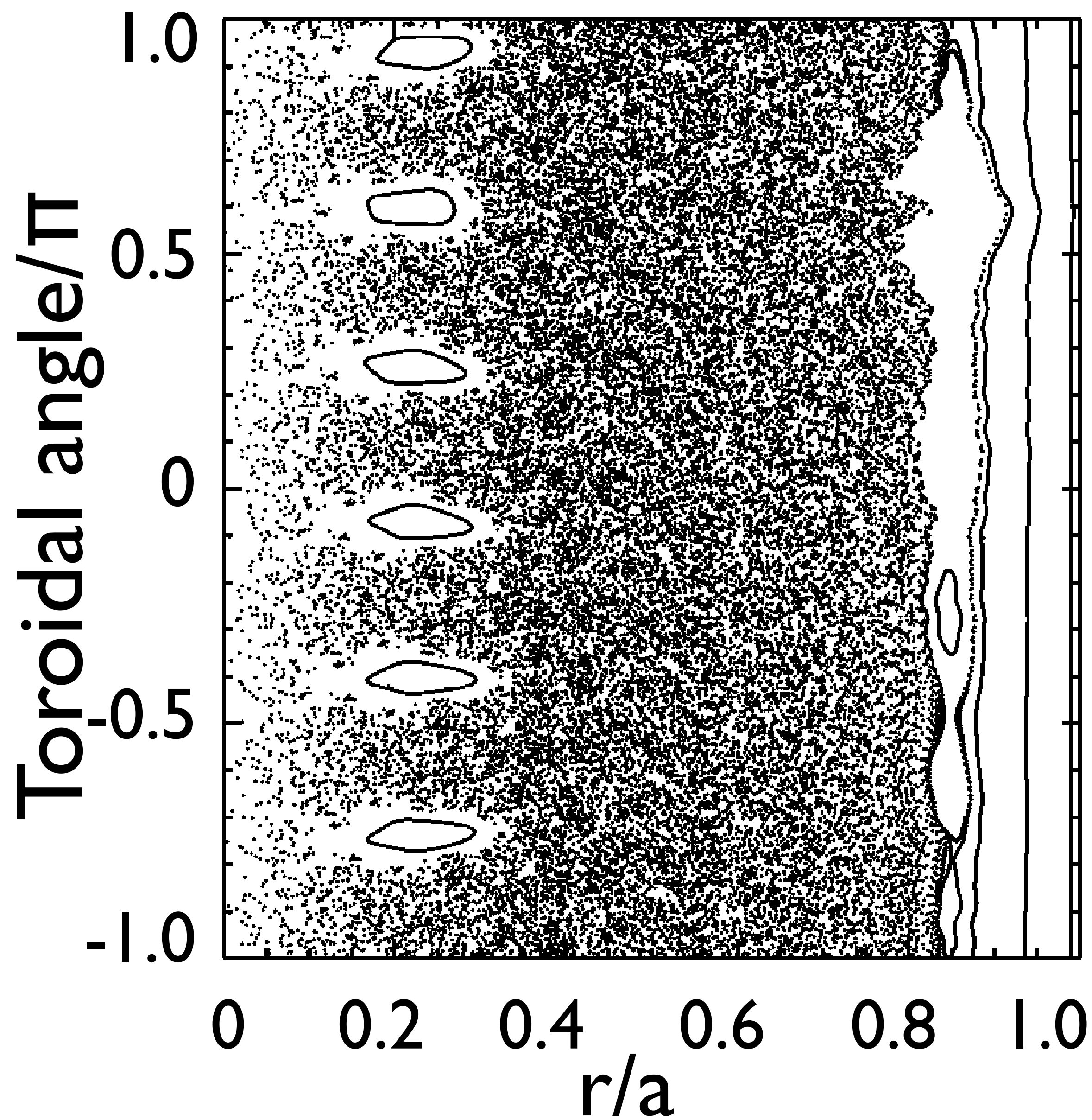


Resistive tearing modes present in RFP. Multiple resonances across the plasma radius



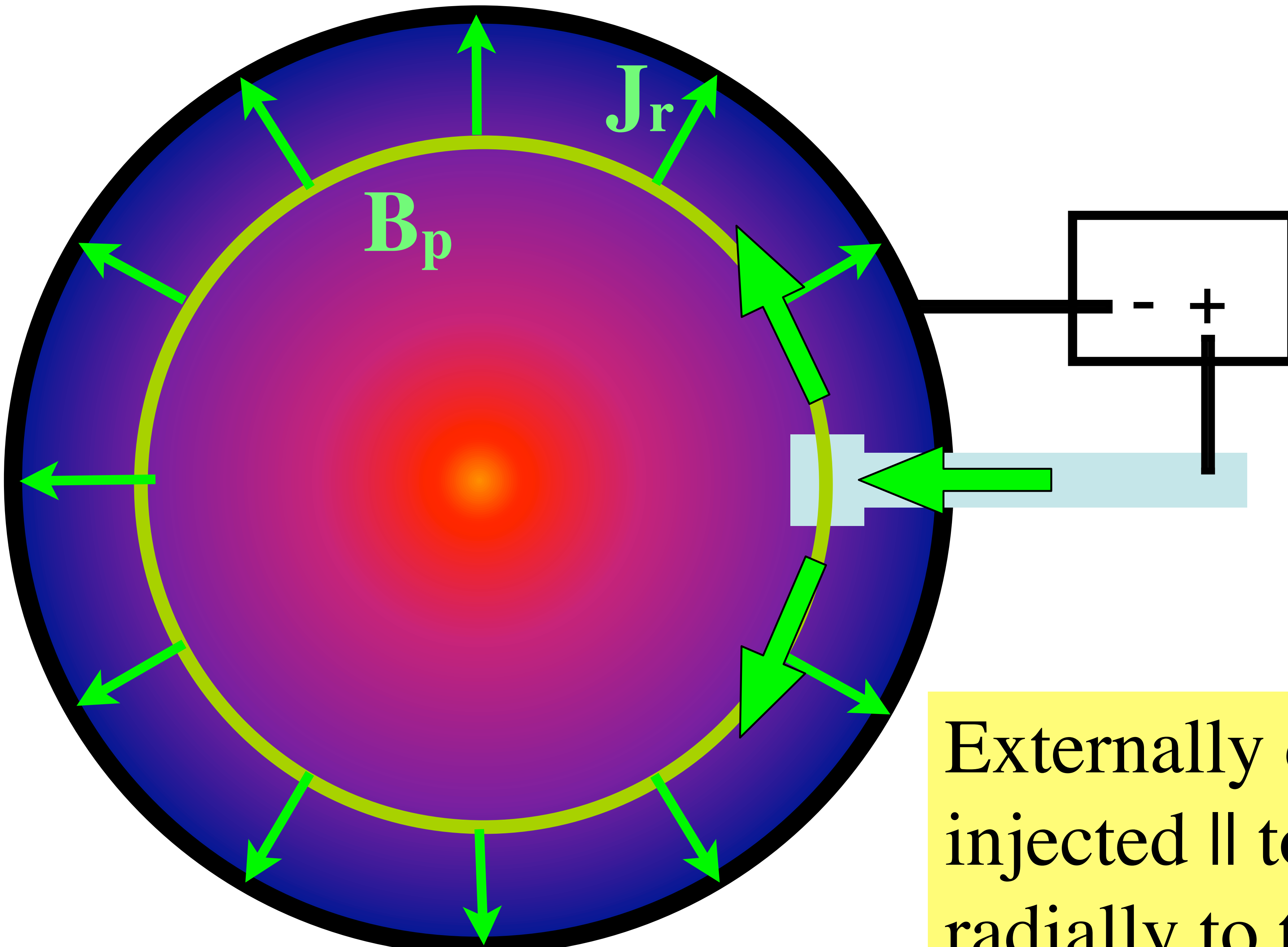
Large fluctuations result in stochastic field and large energy transport





It is known that the energy (and particle) transport is high.
What about momentum transport?

Tool - applying edge torque to plasma via inserted biased electrode



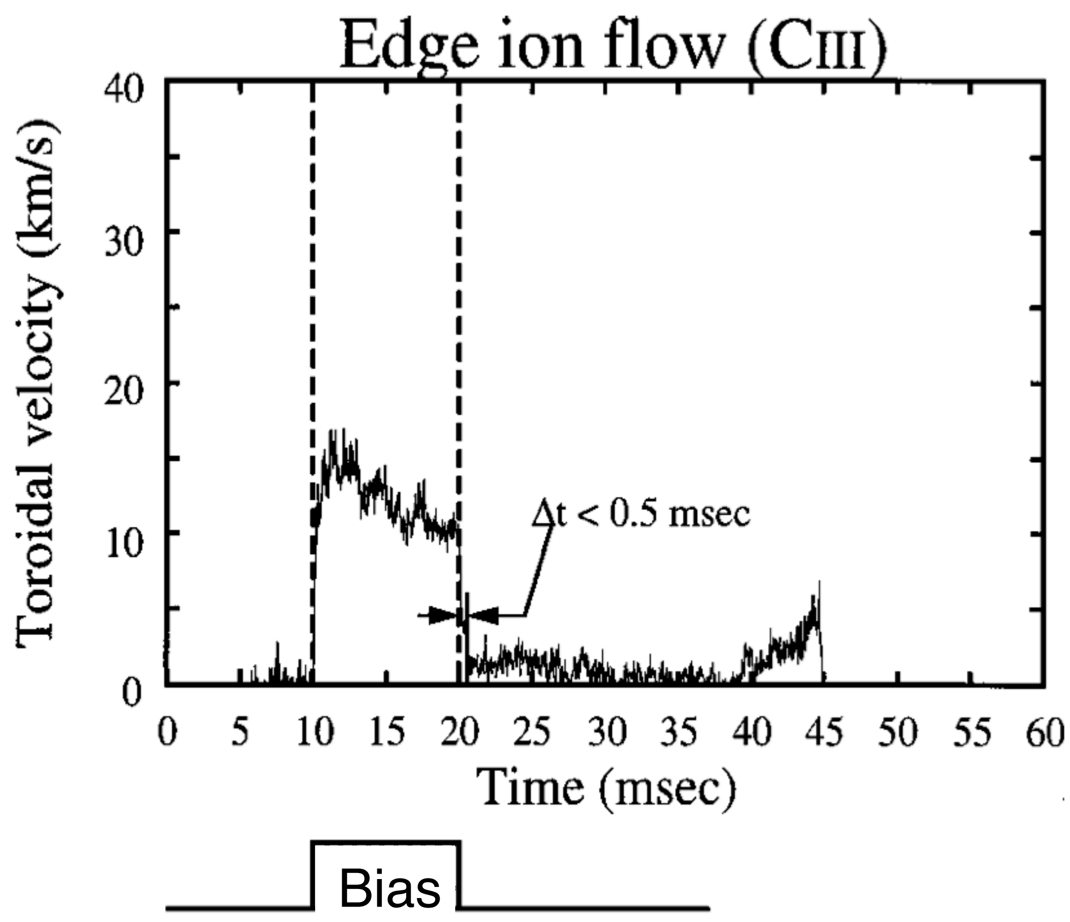
$F_\varphi = J_r x B_p$

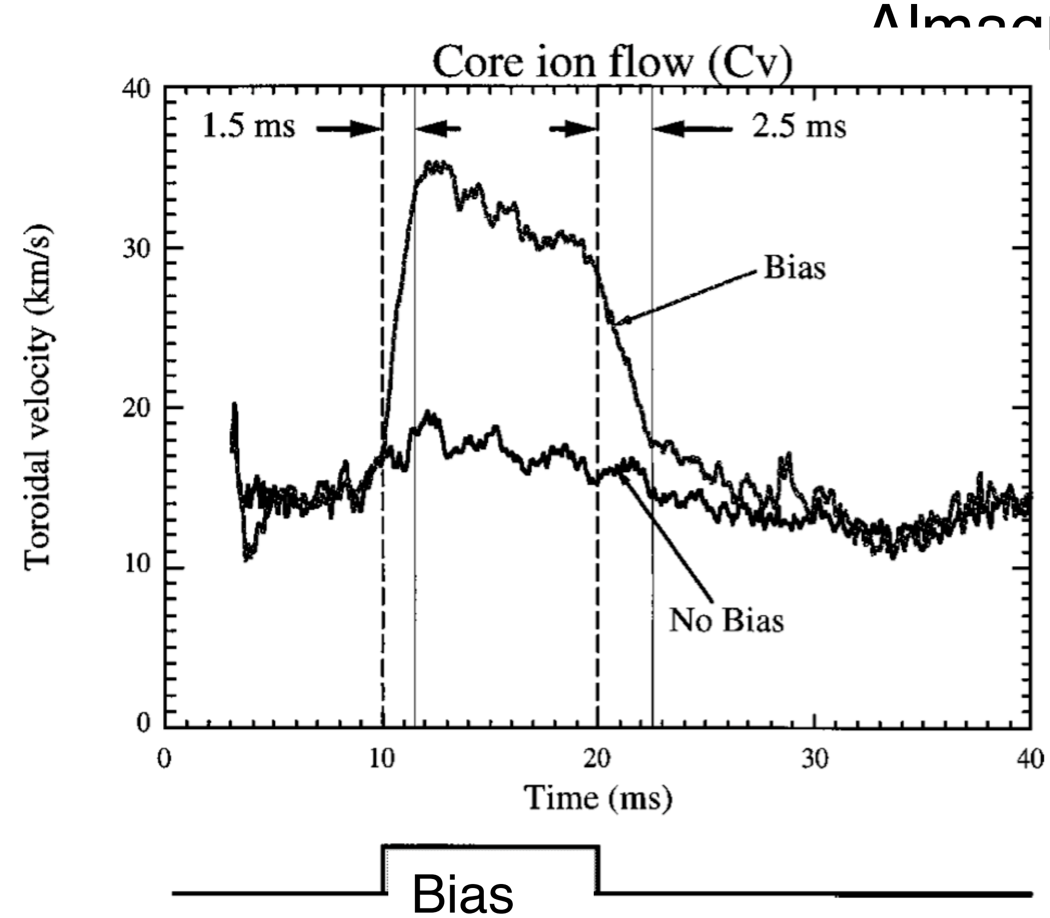
Externally driven current injected || to B and returned radially to the wall.

Radial momentum transport is high

- Edge responds almost instantaneously
- Core responds with a delay but much faster than the collisional rate.

Almagri *et al*, 1998

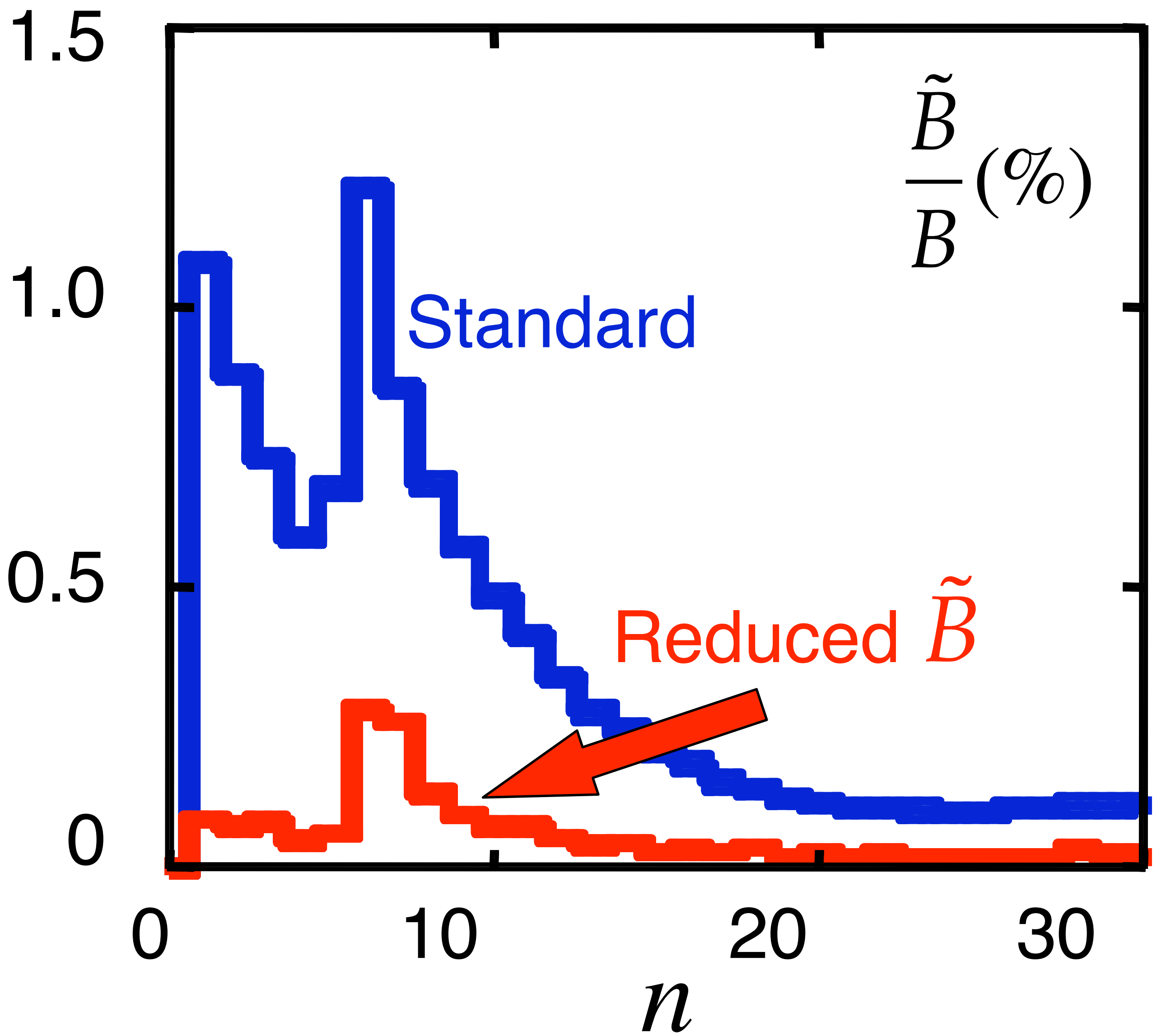


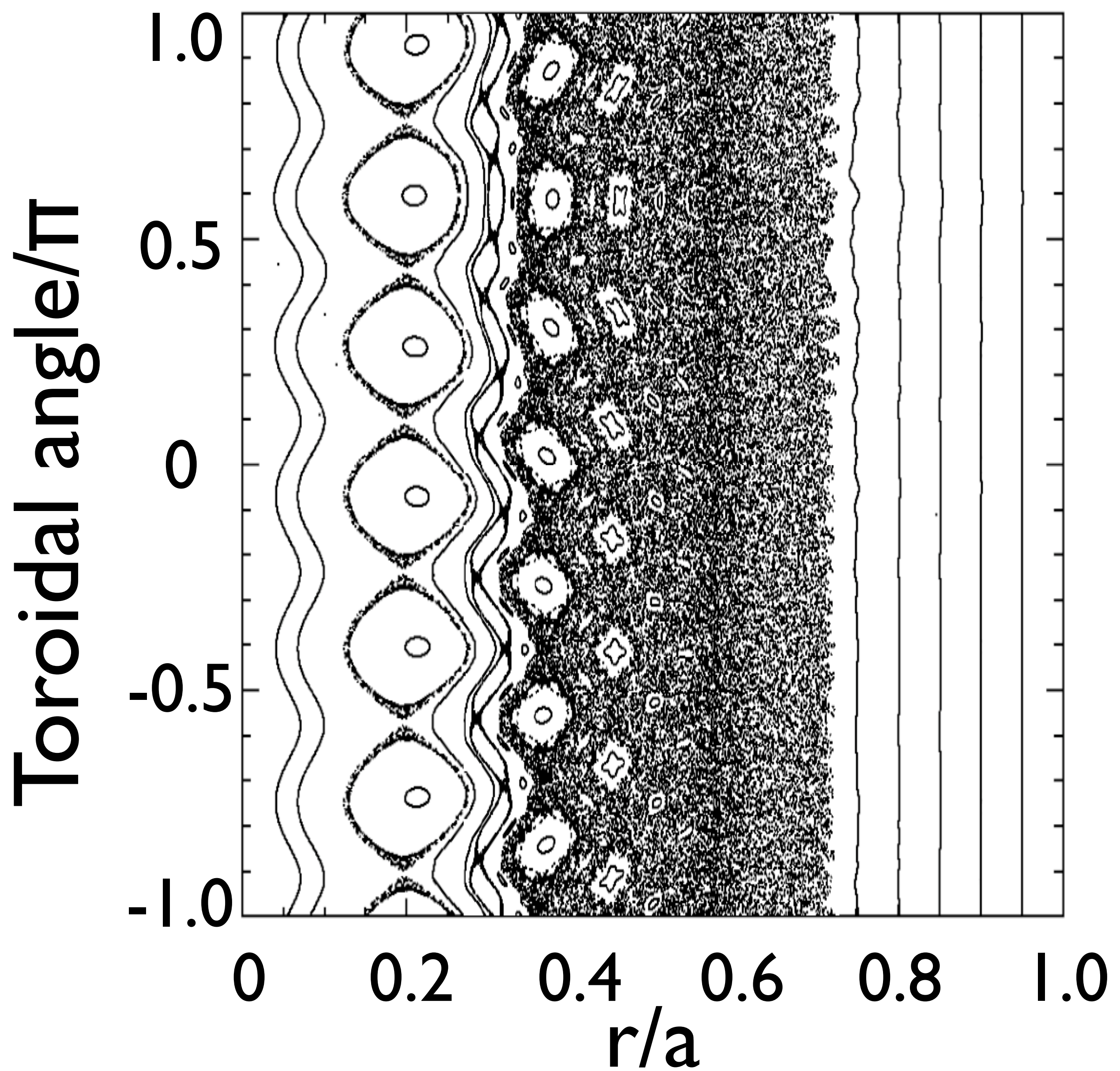


Measured $\nu_{\perp} \sim a^2 / \tau_d \sim 100 \text{ m}^2 / s$

Collisional $\nu_{\perp}^{coll} \sim \rho_i^2 / \tau_i \sim 0.6 \text{ m}^2 / s$

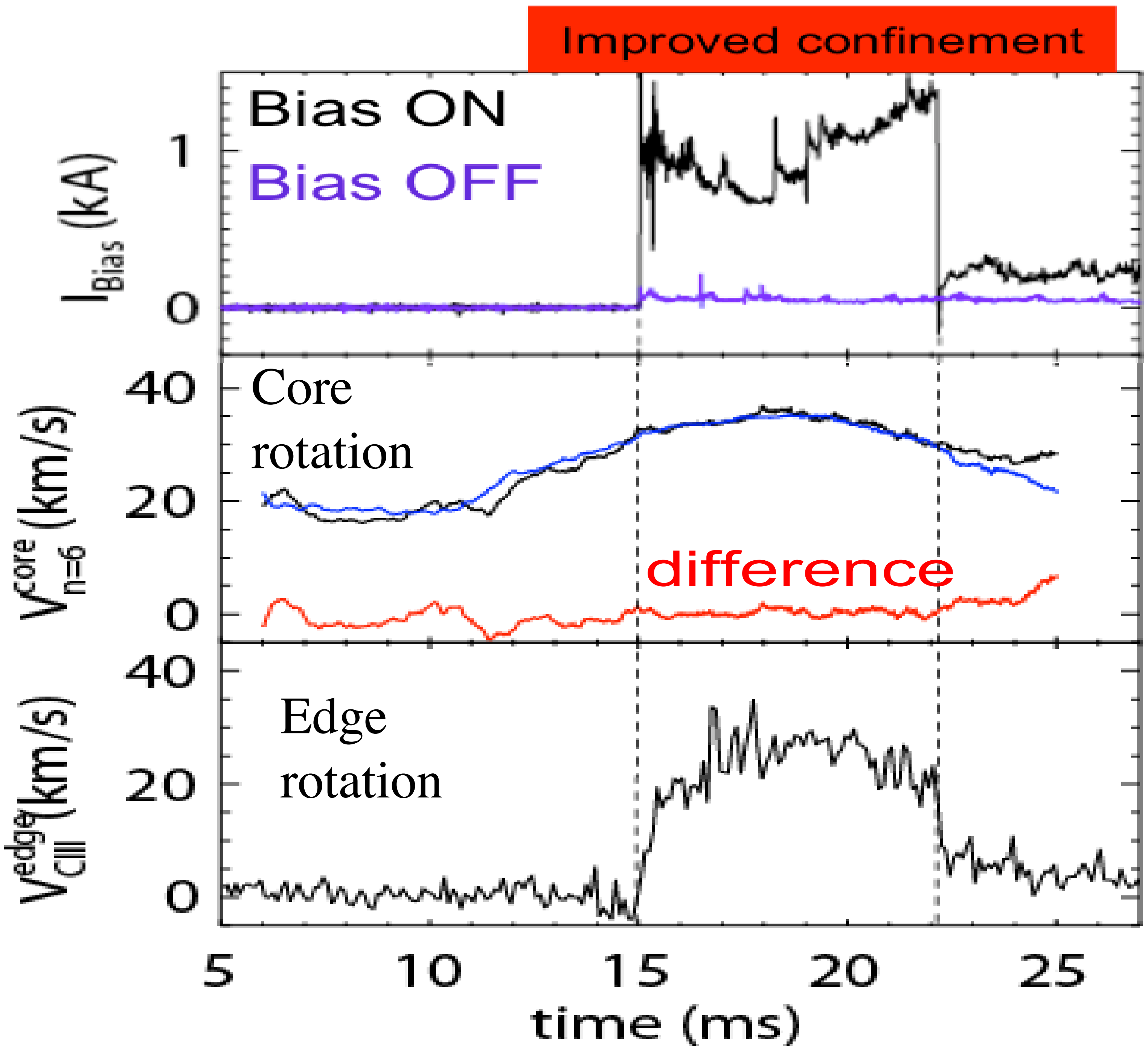
Reduction of magnetic fluctuations with inductive (transient) control of current profile. Field is less stochastic.



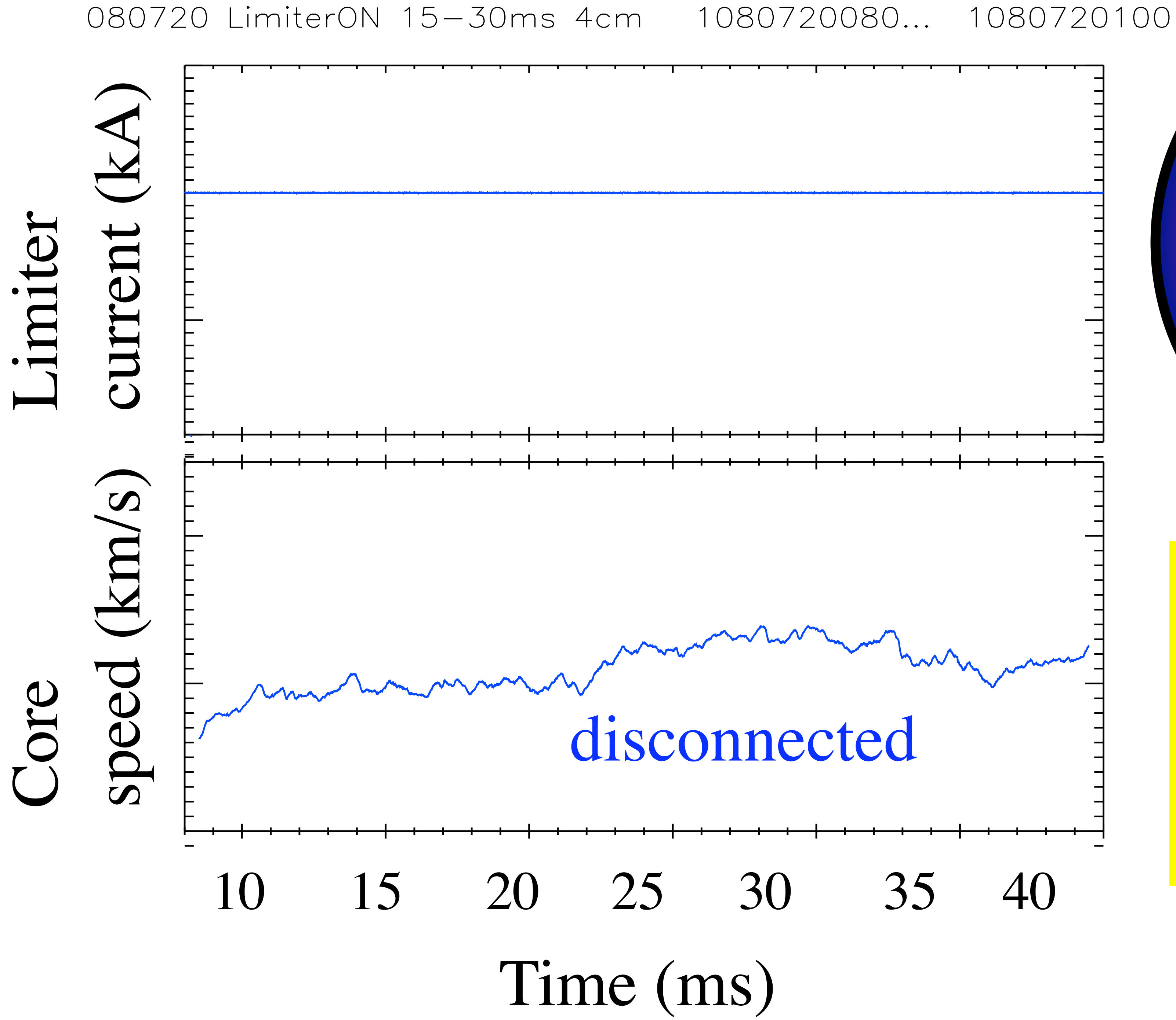


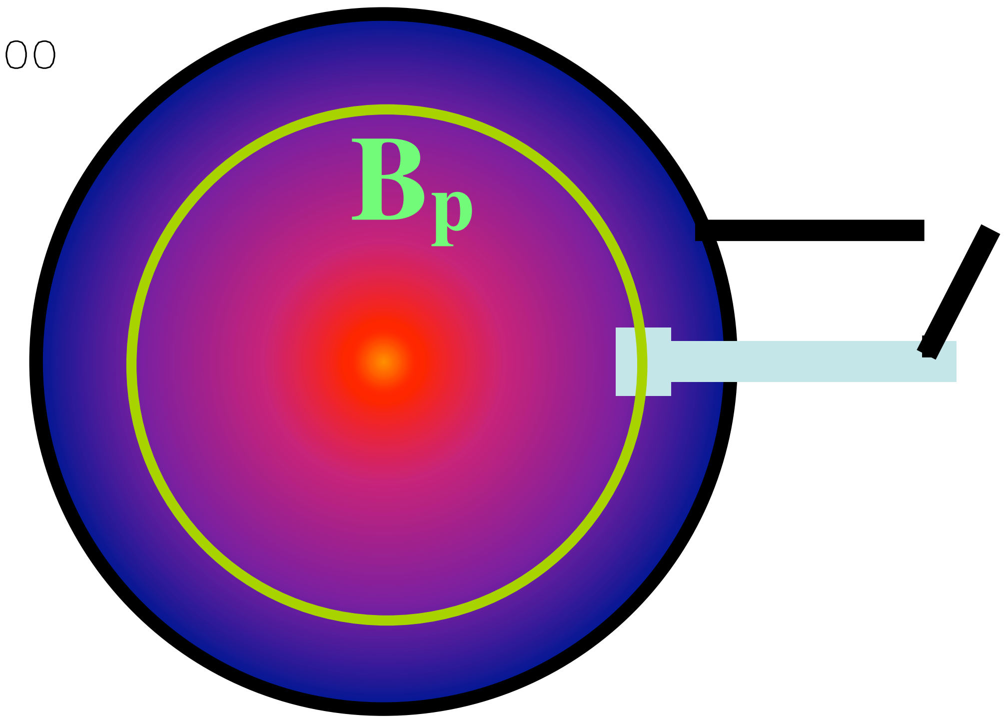
Momentum transport significantly reduced

Fast edge rotation.
No change in the core velocity when torque applied.



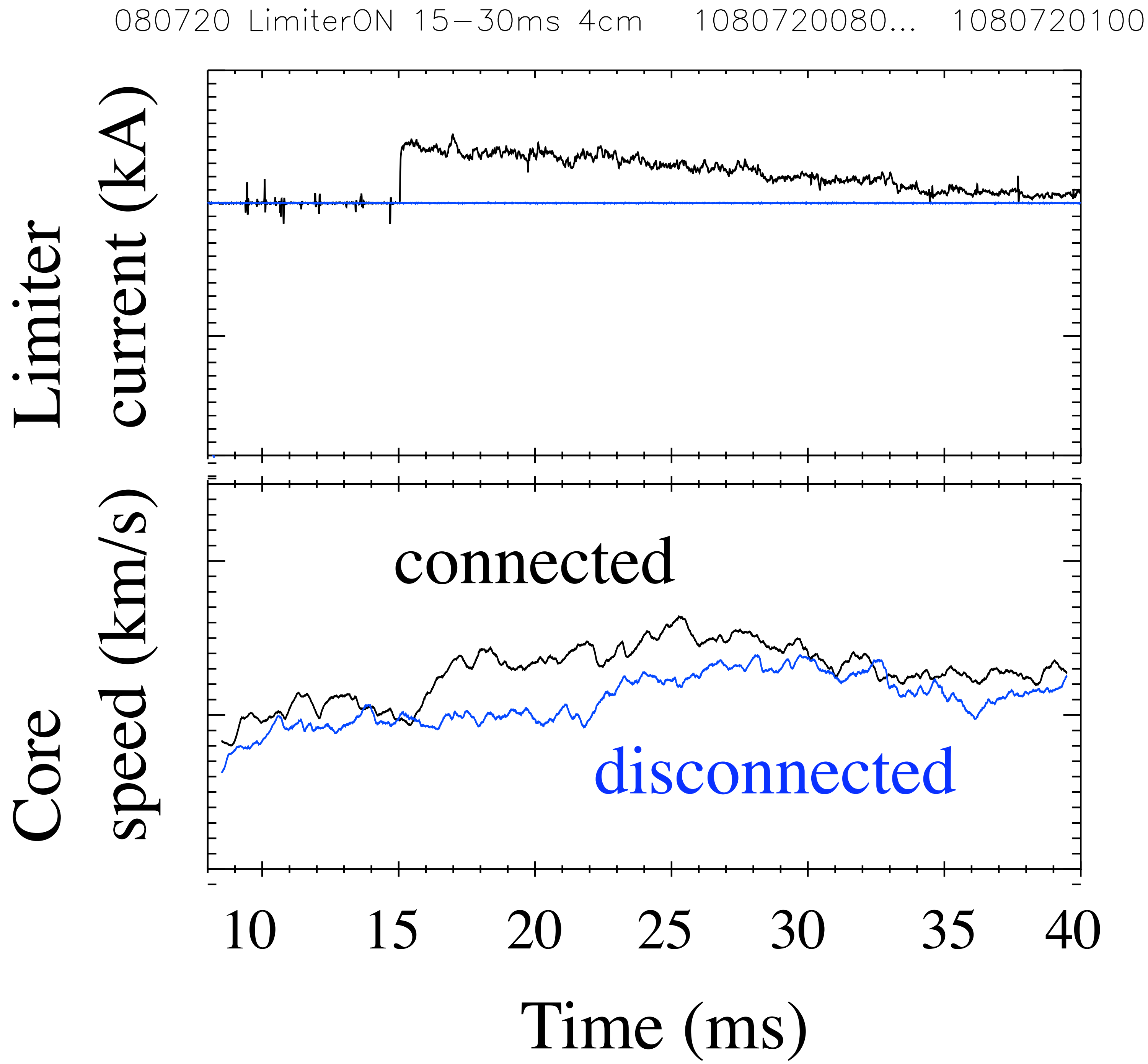
Insertion of an isolated limiter does not change rotation

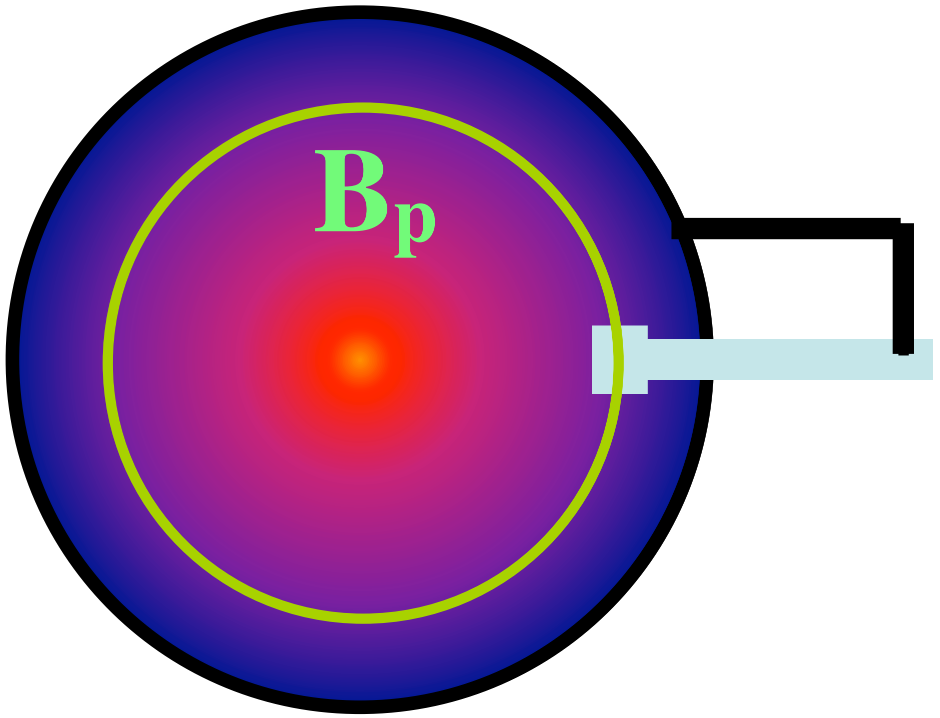




Limiter 10x10 cm inserted into plasma so it intersects B.
No change in rotation.

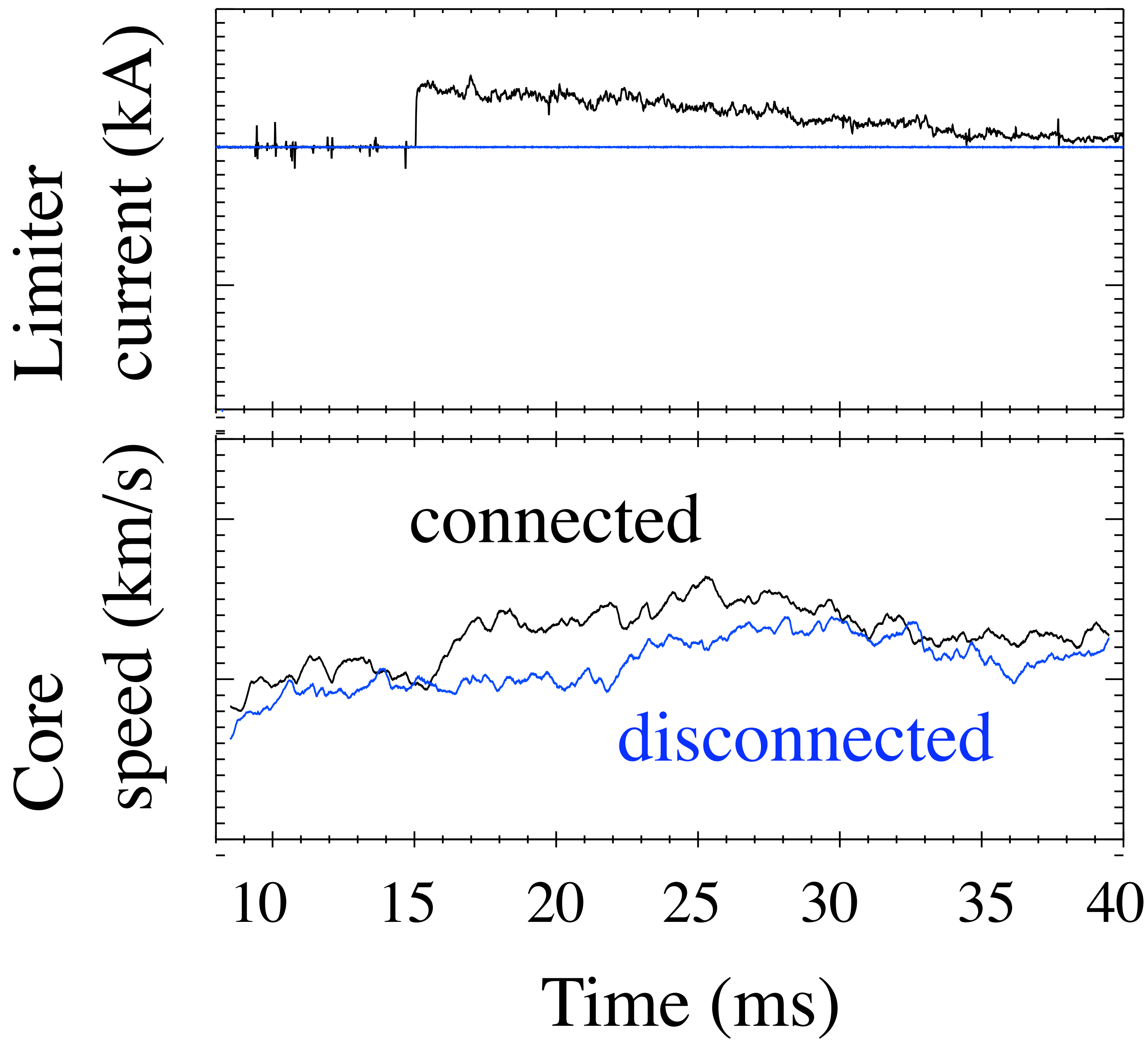
Connecting limiter to the wall speeds plasma up

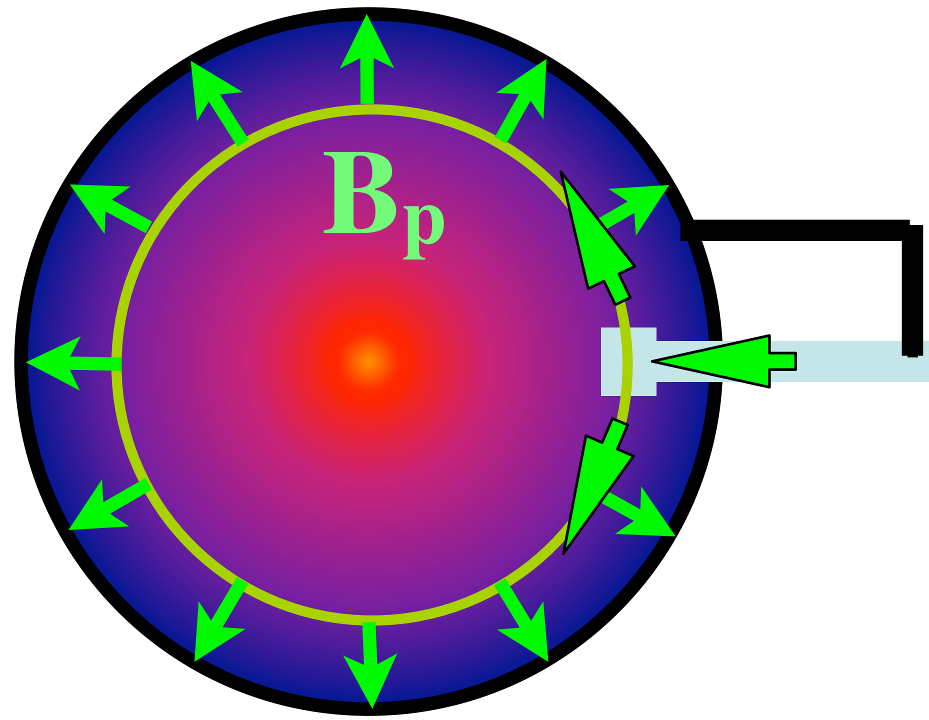




Intrinsic current topology similar to externally driven

Limiter collects primarily electrons,
quasineutrality requires ion current to the wall





Demonstrated so far:

- Anomalously high (x100) momentum transport in regime with magnetic fluctuations and stochastic magnetic field
- Reduction of magnetic fluctuations results in dramatic reduction of momentum transport.
- Rotation can be caused by intrinsic plasma currents.
- What forces govern the magnetic transport?

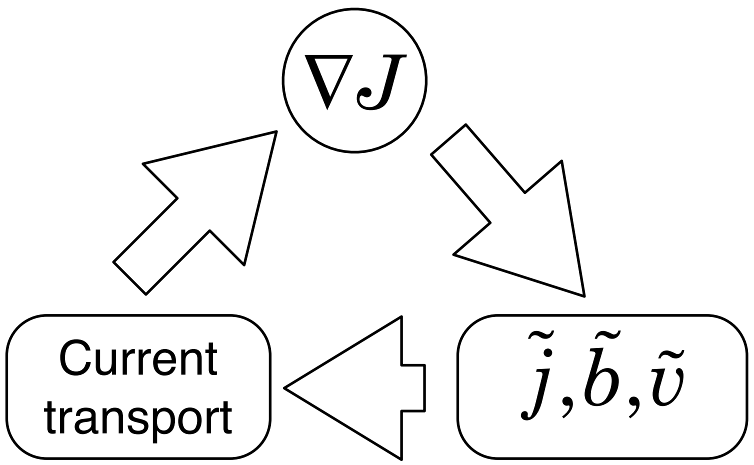
Demonstrated so far:

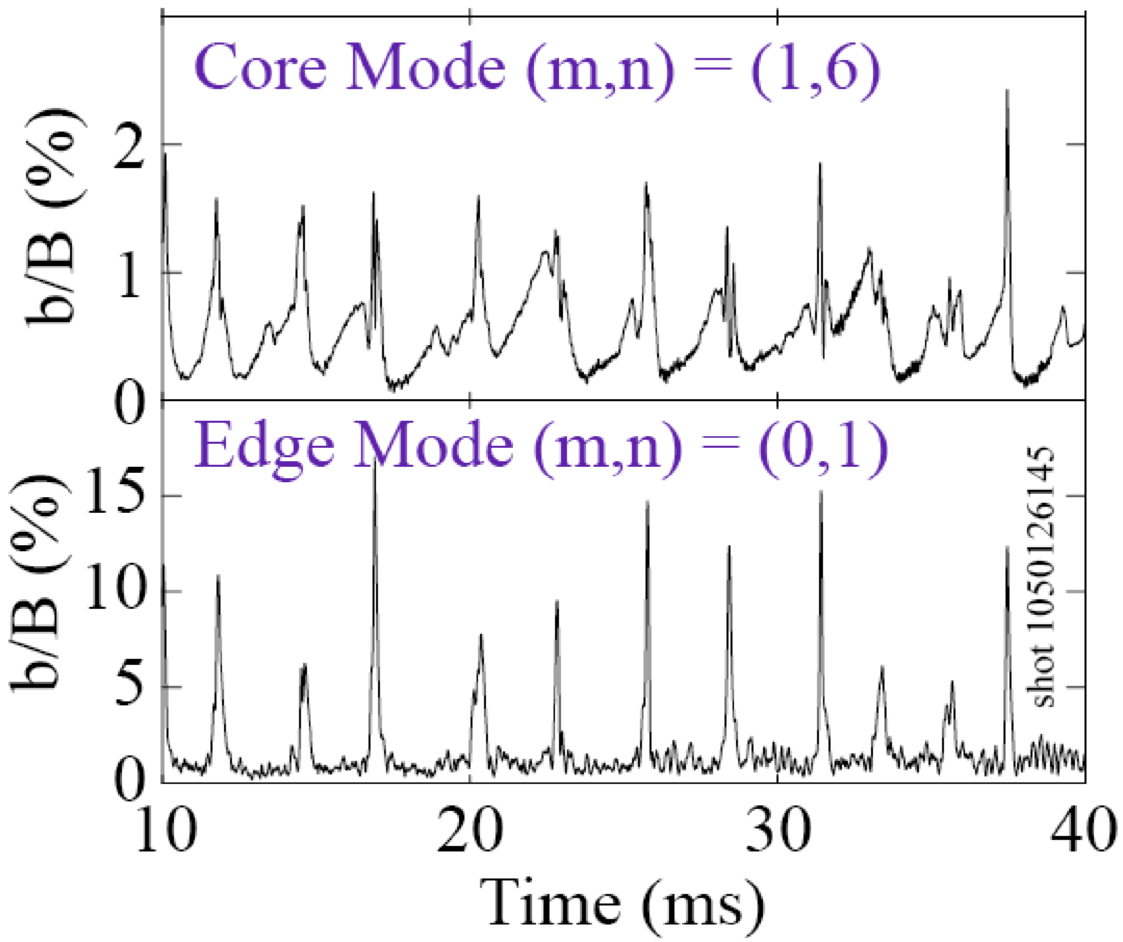
- Anomalously high (x100) momentum transport in regime with magnetic fluctuations and stochastic magnetic field
- Reduction of magnetic fluctuations results in dramatic reduction of momentum transport.
- Rotation can be caused by intrinsic plasma currents.
- What forces govern the magnetic transport?

- Answer this question by exploring a regime with spontaneous bursts of magnetic fluctuations. Varying fluctuation amplitude allows us to track the dynamics of the associated forces.

Magnetic activity has both continuous and discrete character. Relaxation of current profile

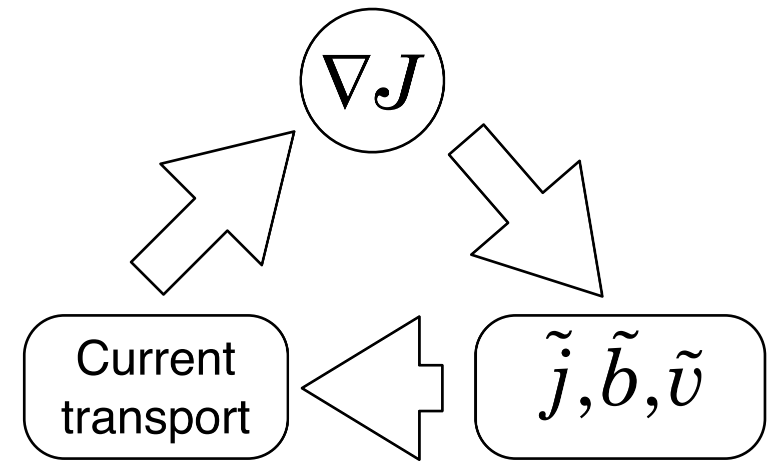
- Current driven tearing modes relax the current profile via current transport.
- Instability drive decreases.
- Current profile peaks, the cycle repeats.

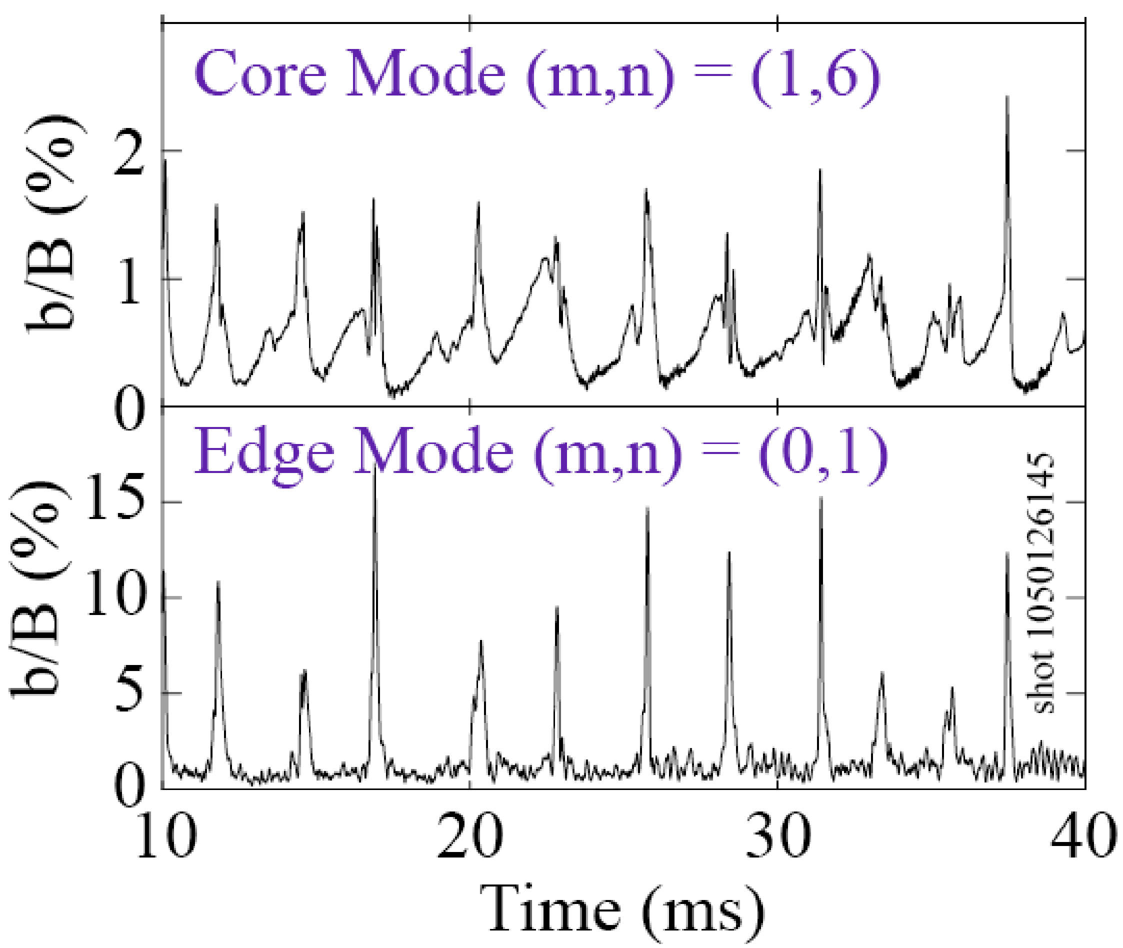




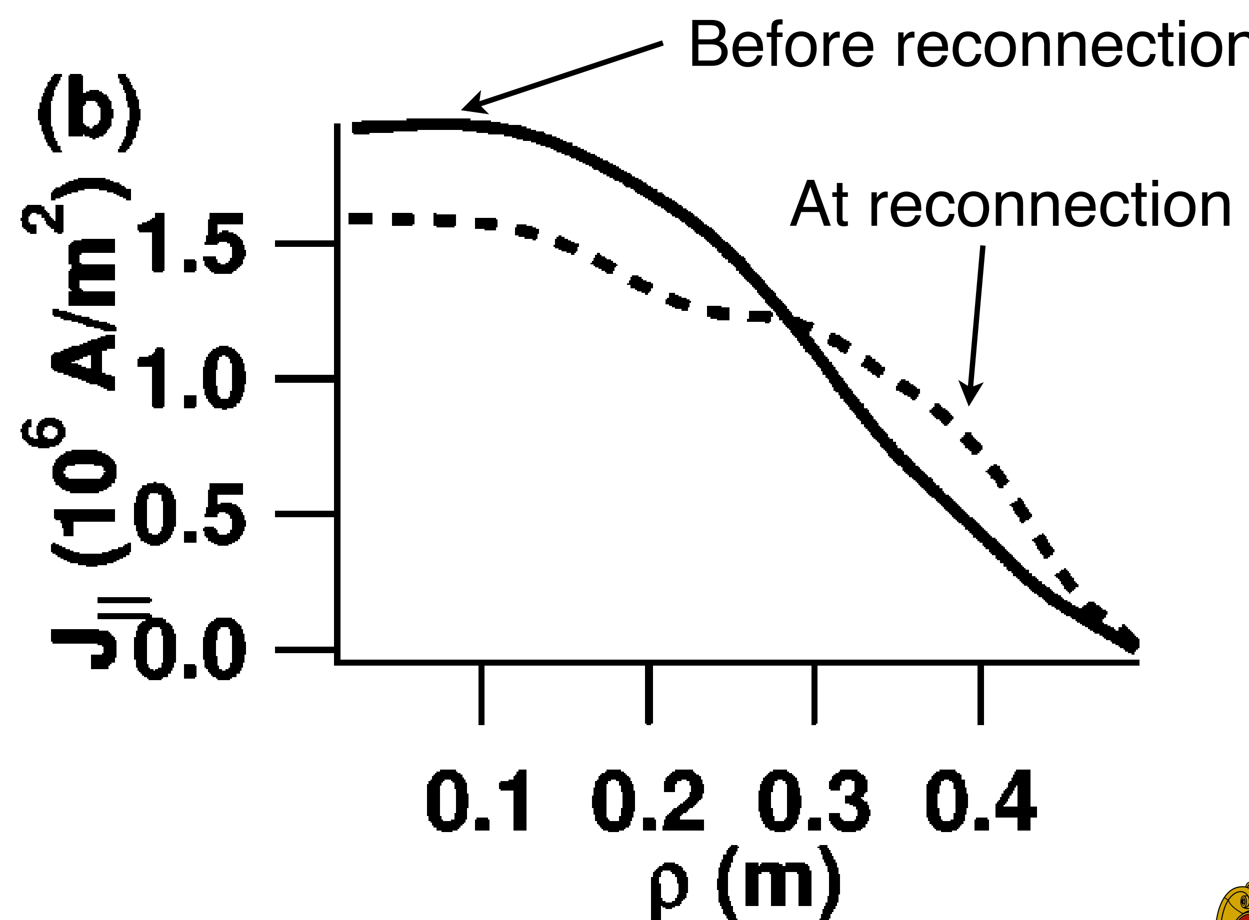
Magnetic activity has both continuous and discrete character. Relaxation of current profile

- Current driven tearing modes relax the current profile via current transport.
- Instability drive decreases.
- Current profile peaks, the cycle repeats.





Brower, Ding, 2002



Momentum is predicted to relax similarly to current by 2-fluid extension of Taylor's paradigm

- Single fluid (Taylor, 1974). Current profile relaxes to the minimum energy state while conserving the **global** helicity

$$K = \int \mathbf{A} \cdot \mathbf{B} \, dV = \int \mathbf{A} \cdot \nabla \times \mathbf{A} \, dV \quad \Rightarrow \quad \mathbf{J} = \lambda \mathbf{B}$$

current relaxation

Momentum is predicted to relax similarly to current by 2-fluid extension of Taylor's paradigm

- Single fluid (Taylor, 1974). Current profile relaxes to the minimum energy state while conserving the **global** helicity

$$K = \int \mathbf{A} \cdot \mathbf{B} \, \mathrm{d}V = \int \mathbf{A} \cdot \nabla \times \mathbf{A} \, \mathrm{d}V \quad \Rightarrow \quad \mathbf{J} = \lambda \mathbf{B}$$

current relaxation

- Two-fluid (Steinhauer, Hegna). Current and momentum profiles relax to the minimum energy state while conserving the helicities for **each species**

$$K_e = \int \mathbf{A}_e \cdot \nabla \times \mathbf{A}_e \, \mathrm{d}V$$

$$K_i = \int \mathbf{A}_i \cdot \nabla \times \mathbf{A}_i \, \mathrm{d}V$$

$$\mathbf{A}_s = \mathbf{A} + (m_s / q_s) \mathbf{v}_s$$

$\Rightarrow$

$$\mathbf{J} = \lambda_1 \mathbf{B}$$

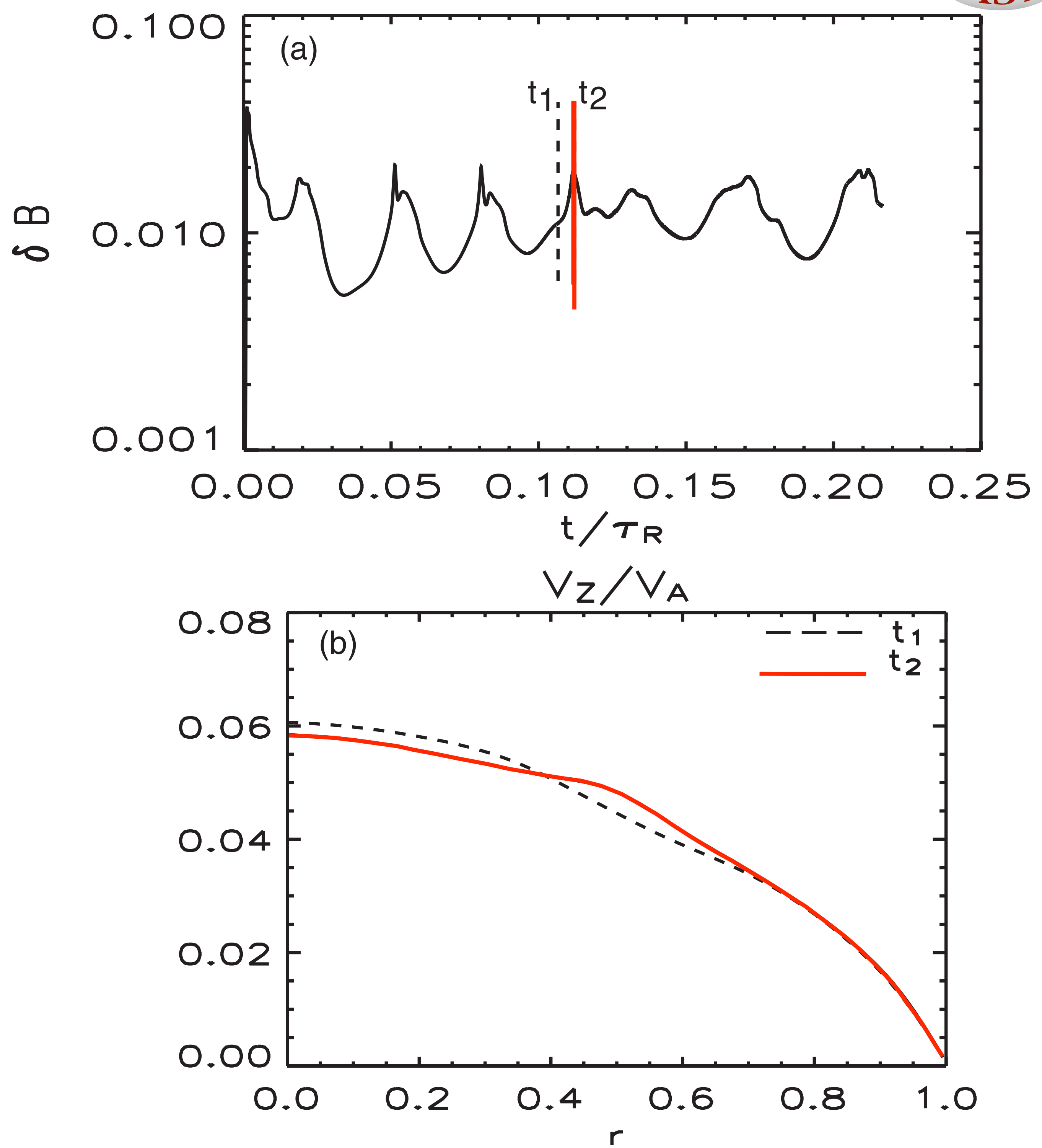
current relaxation

$$n\mathbf{V} = \lambda_2 \mathbf{B}$$

momentum relaxation

Numerical demonstration of flow profile flattening

- Non-linear resistive MHD (DEBS)
- Ad hoc flow profile
- Periodic relaxation events - similar to experiment

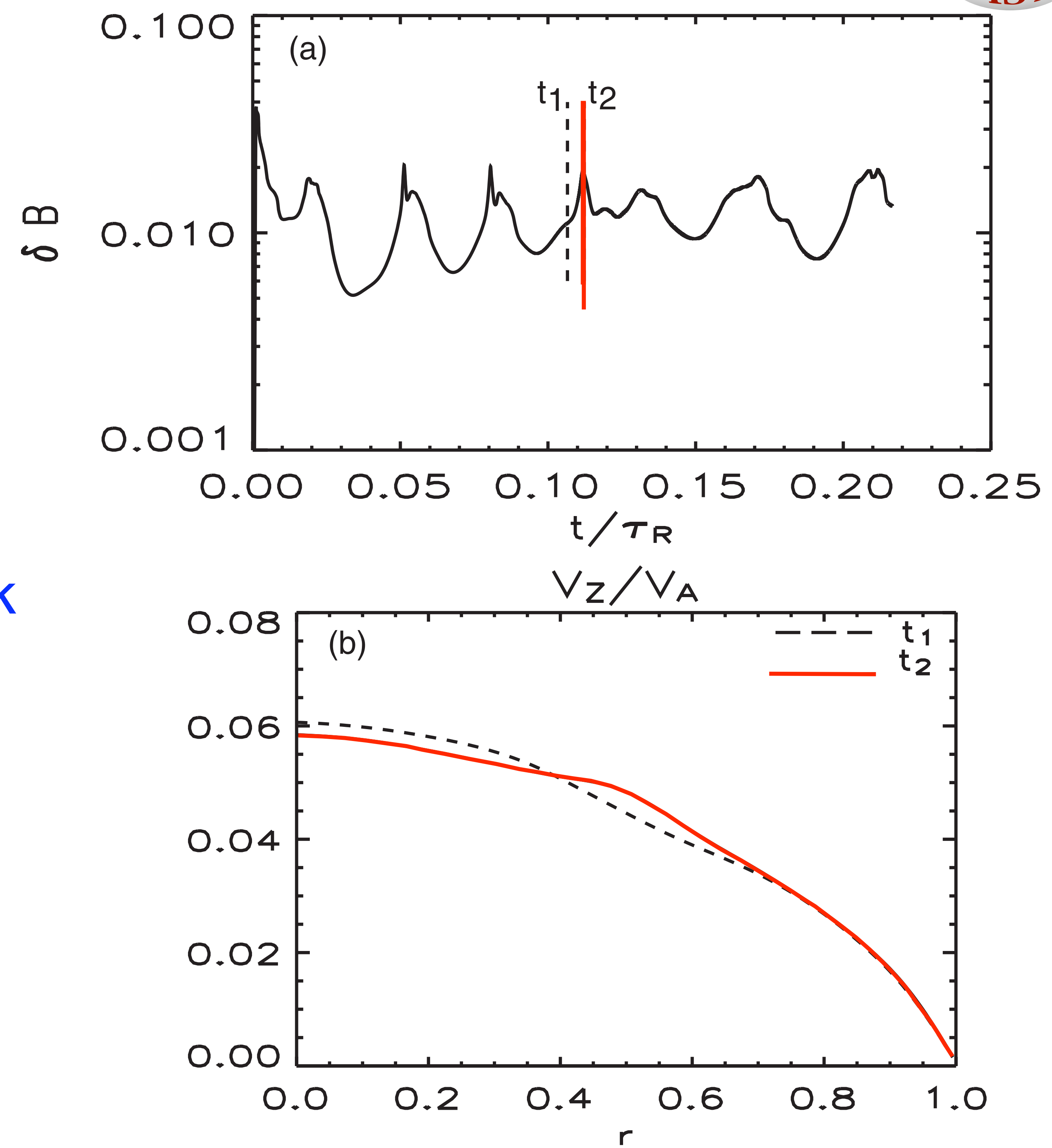


Ebrahimi, Mirnov *et. al. 2007*

Numerical demonstration of flow profile flattening

- Non-linear resistive MHD (DEBS)
- Ad hoc flow profile
- Periodic relaxation events - similar to experiment

- (1) Flow profile flattens at the peak of the fluctuations

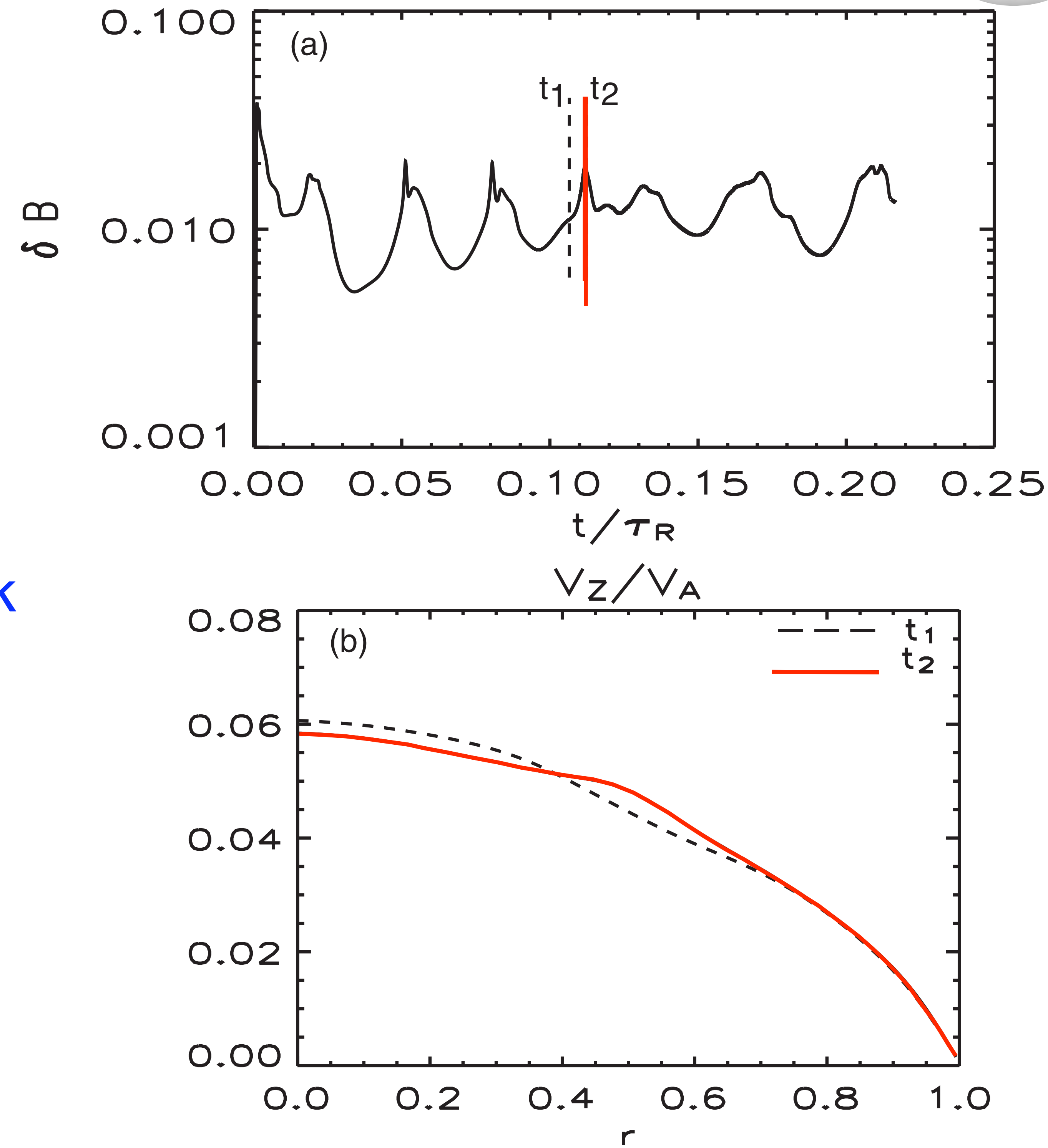


Ebrahimi, Mirnov *et. al. 2007*

Numerical demonstration of flow profile flattening

- Non-linear resistive MHD (DEBS)
- Ad hoc flow profile
- Periodic relaxation events - similar to experiment

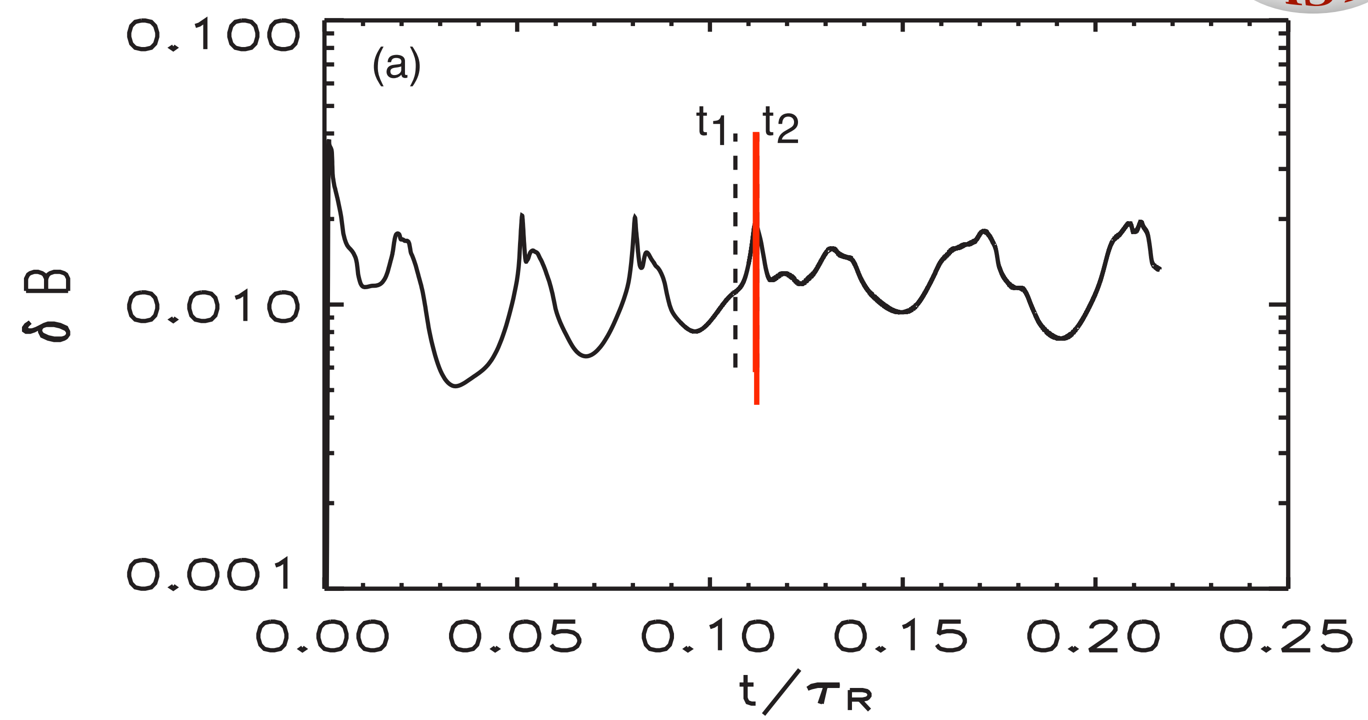
- (1) Flow profile flattens at the peak of the fluctuations
- (2) Multiple, nonlinearly coupled modes greatly enhance momentum transport in comparison with a single mode



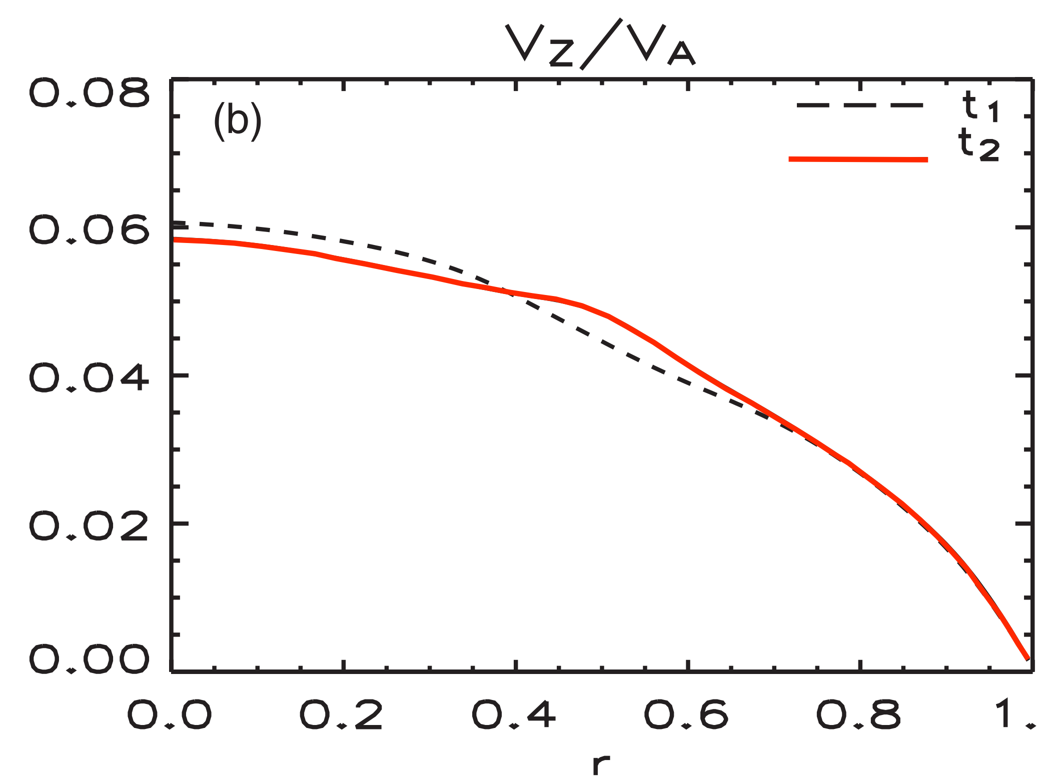
Ebrahimi, Mirnov *et. al. 2007*

Numerical demonstration of flow profile flattening

- Non-linear resistive MHD (DEBS)
- Ad hoc flow profile
- Periodic relaxation events - similar to experiment



- (1) Flow profile flattens at the peak of the fluctuations
- (2) Multiple, nonlinearly coupled modes greatly enhance momentum transport in comparison with a single mode
- (3) Both Maxwell and Reynolds stresses are responsible

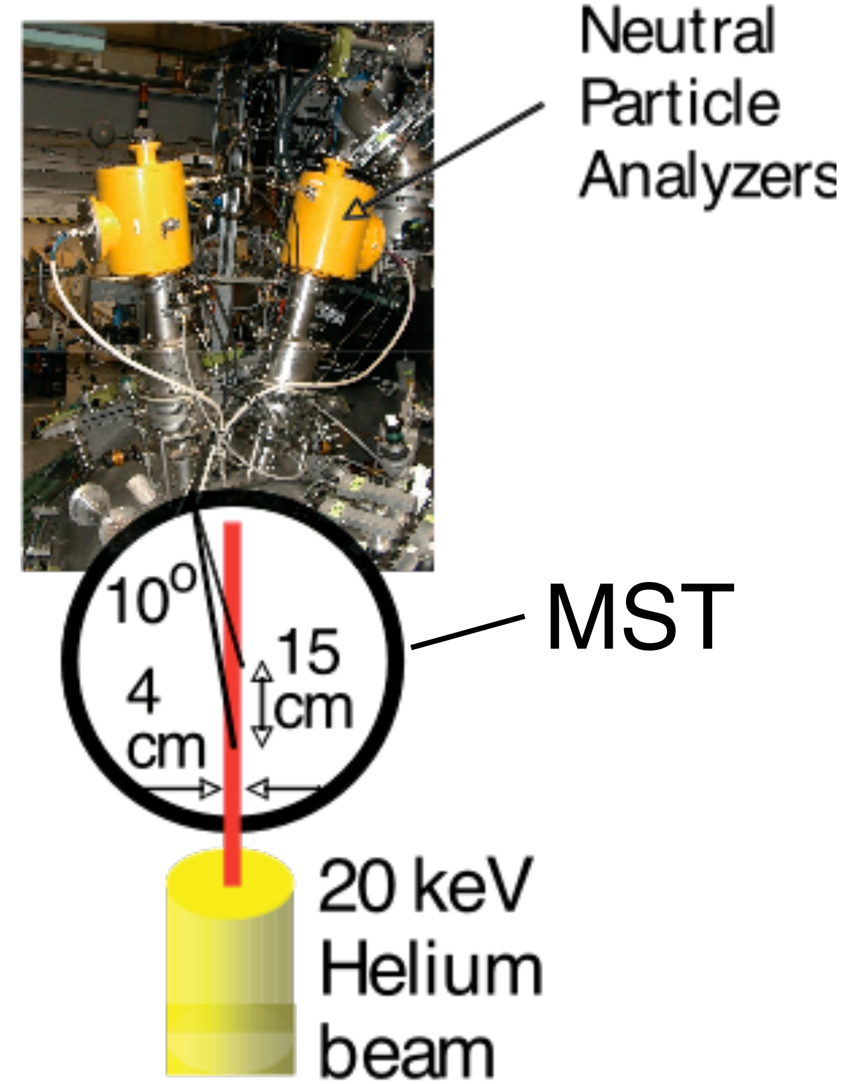


Ebrahimi, Mirnov *et. al. 2007*

How everything is measured

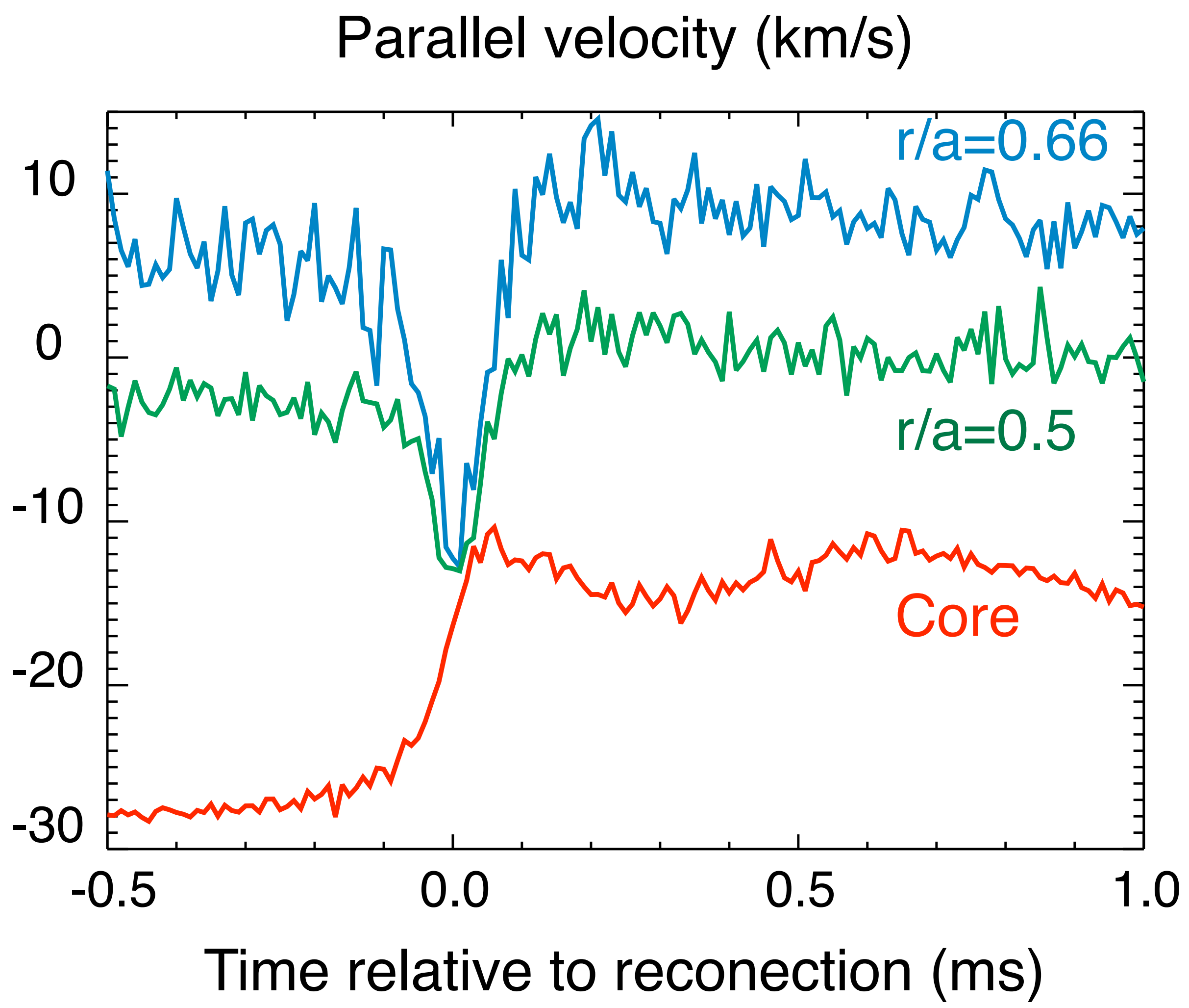
- Core flow measurements
  - Rutherford scattering – poloidal flow
    - local measurement; utilizes scattering of mono-energetic He beam (16 keV) from bulk plasma ions (D)
  - Mode rotation - toroidal flow
    - core resonant tearing modes from the edge toroidal array of 64 pick-up coils

Rutherford scattering



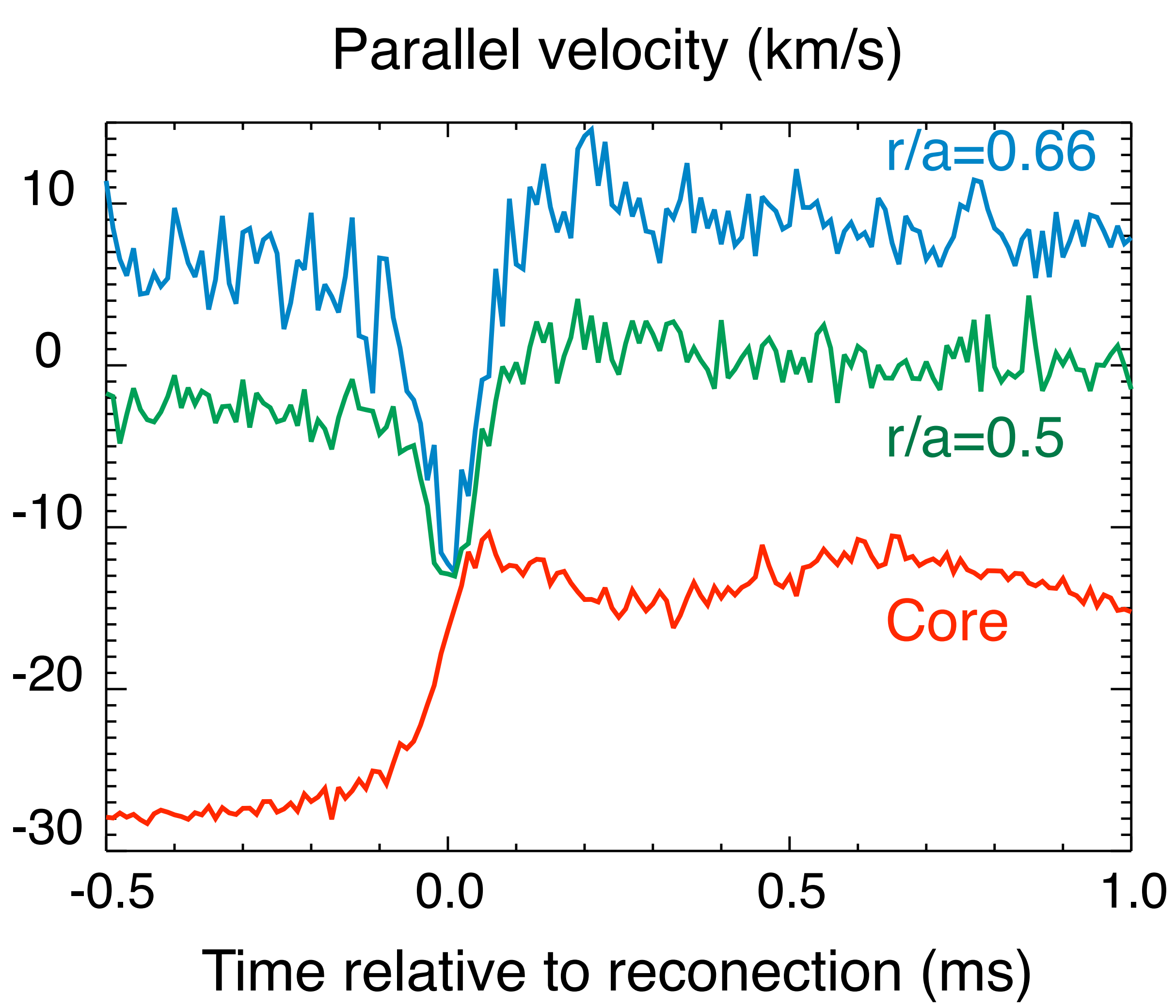
(1) Experiment - parallel flow profile flattens during reconnections

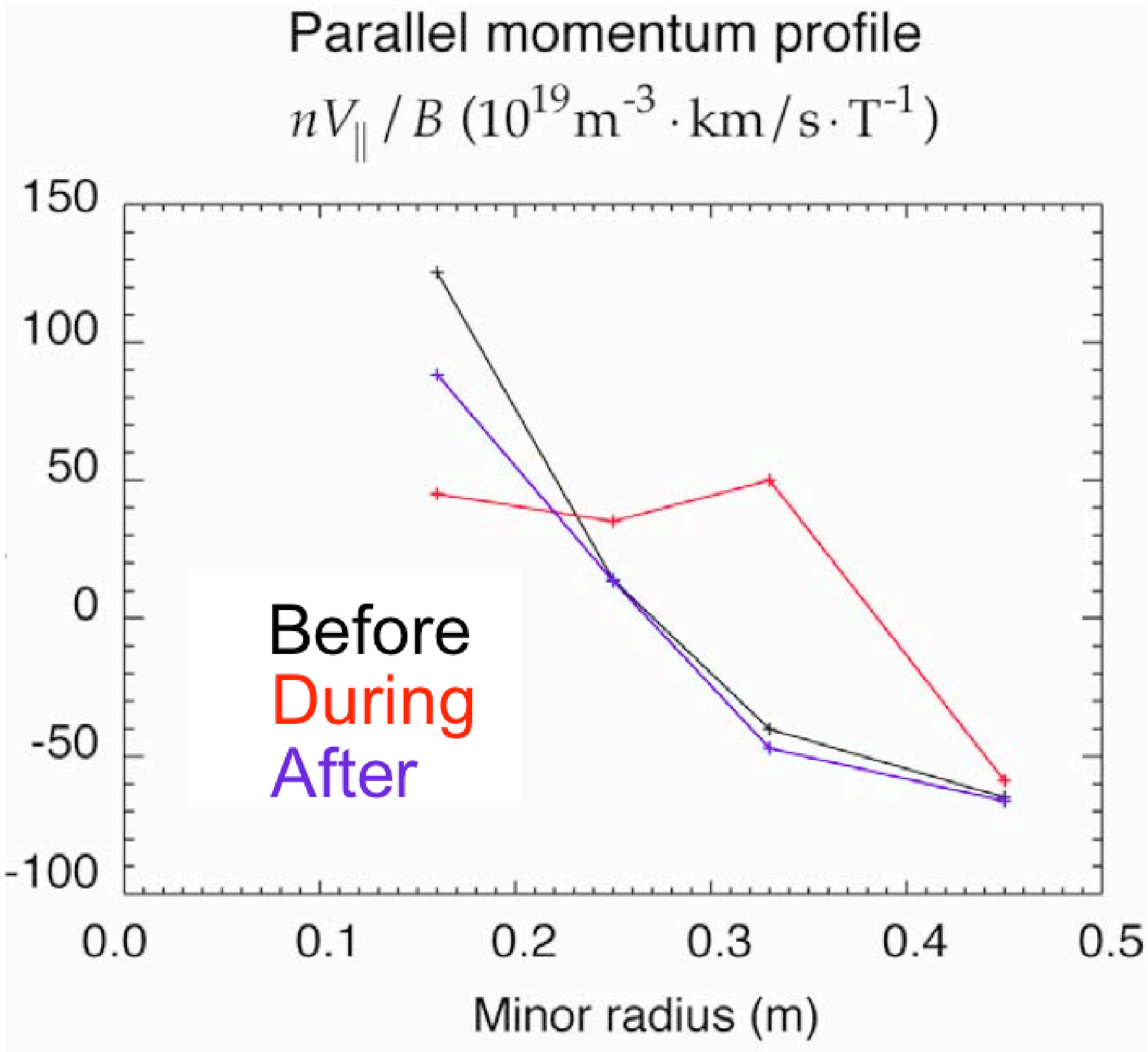
- The core parallel flow slows down, the edge speeds up
- Transport of parallel momentum across the plasma.
- Much faster than classical diffusion



(1) Experiment - parallel flow profile flattens during reconnections

- The core parallel flow slows down, the edge speeds up
- Transport of parallel momentum across the plasma.
- Much faster than classical diffusion

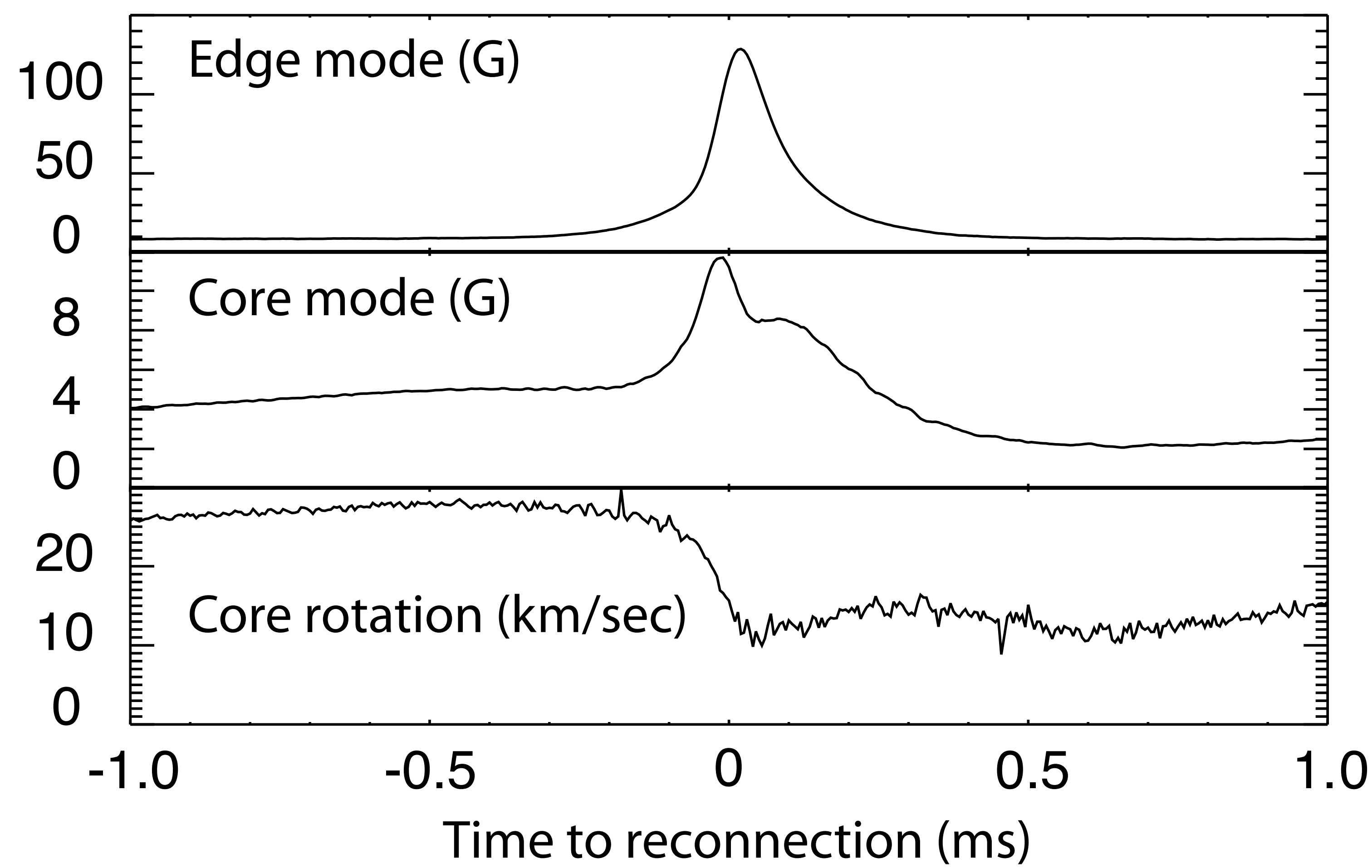




(2) No momentum transport from a single mode

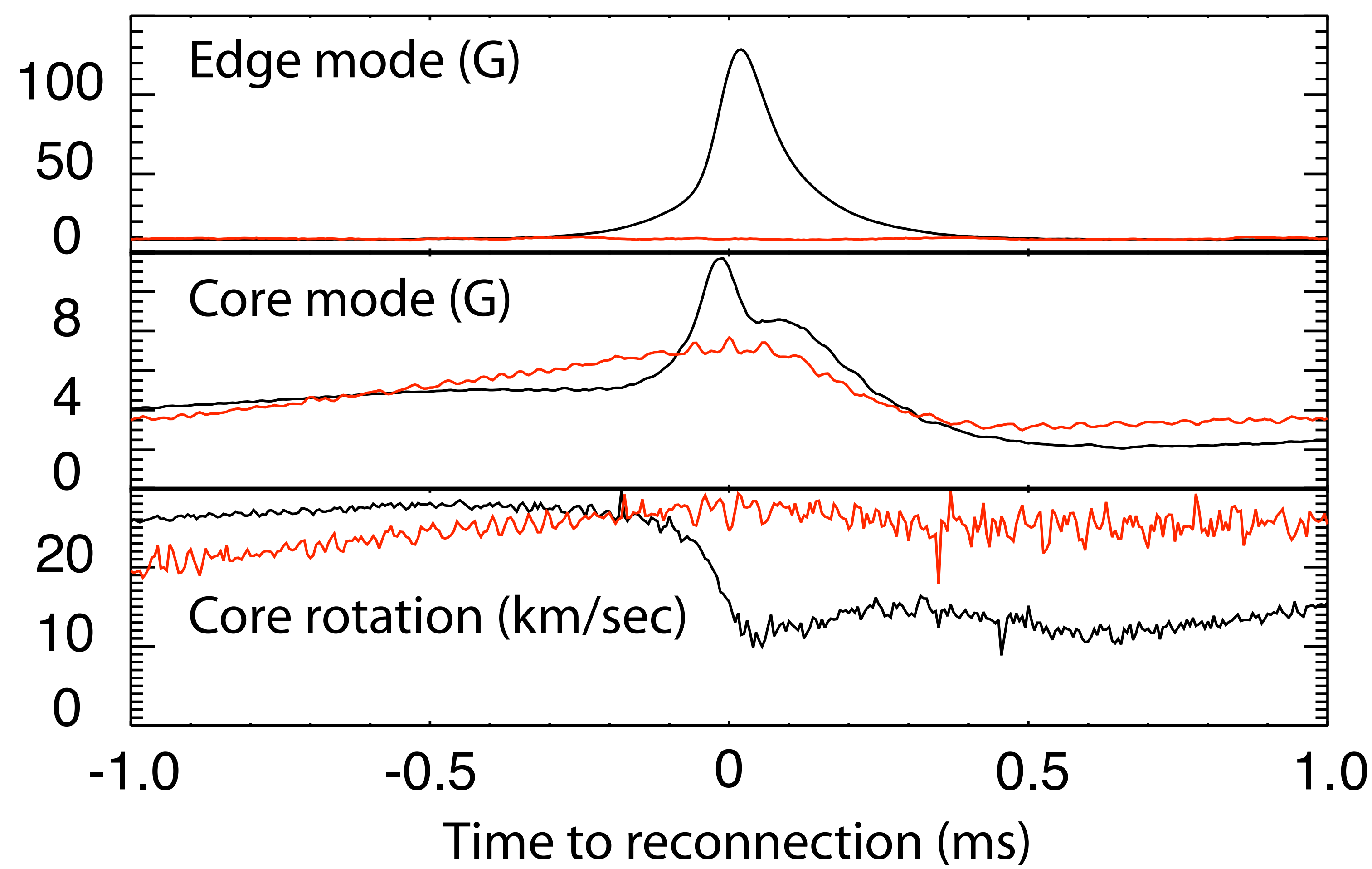
- Numerical modeling - momentum transport from a single mode is much lower than when multiple, non-linearly coupled modes are present.

- Edge mode is large
- Core mode is large
- Large momentum transport



(2) No momentum transport from a single mode

- Numerical modeling - momentum transport from a single mode is much lower than when multiple, non-linearly coupled modes are present.



- Edge mode is large
- Core mode is large
- Large momentum transport

- Edge modes are small
- Core modes are large
- No momentum transport

What forces govern the ion momentum balance?

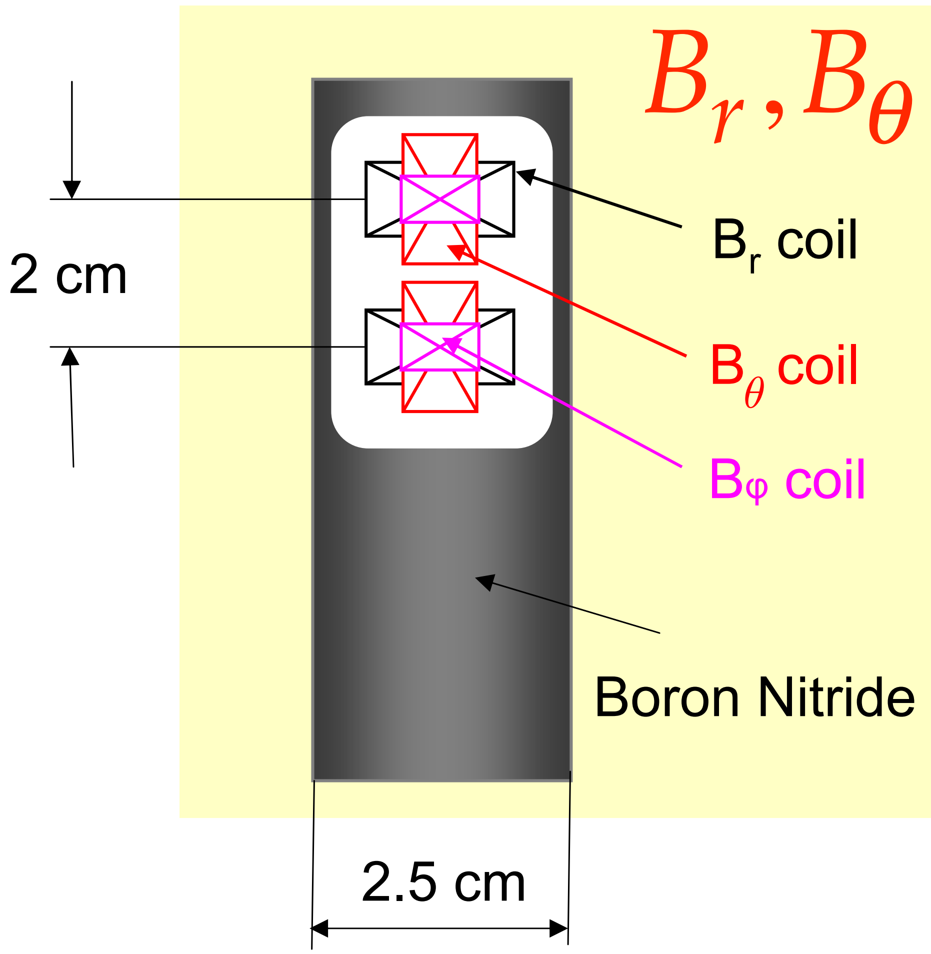
Consider a simplified balance equation:

Reynolds Maxwell

$$\rho \frac{\partial \mathbf{V}}{\partial t} = -\rho \langle \tilde{\mathbf{v}} \nabla \tilde{\mathbf{v}} \rangle + \langle \tilde{\mathbf{j}} \times \tilde{\mathbf{b}} \rangle$$

Parallel Maxwell and Reynolds stresses measured by probes in the edge

Maxwell stress



Reynolds stress

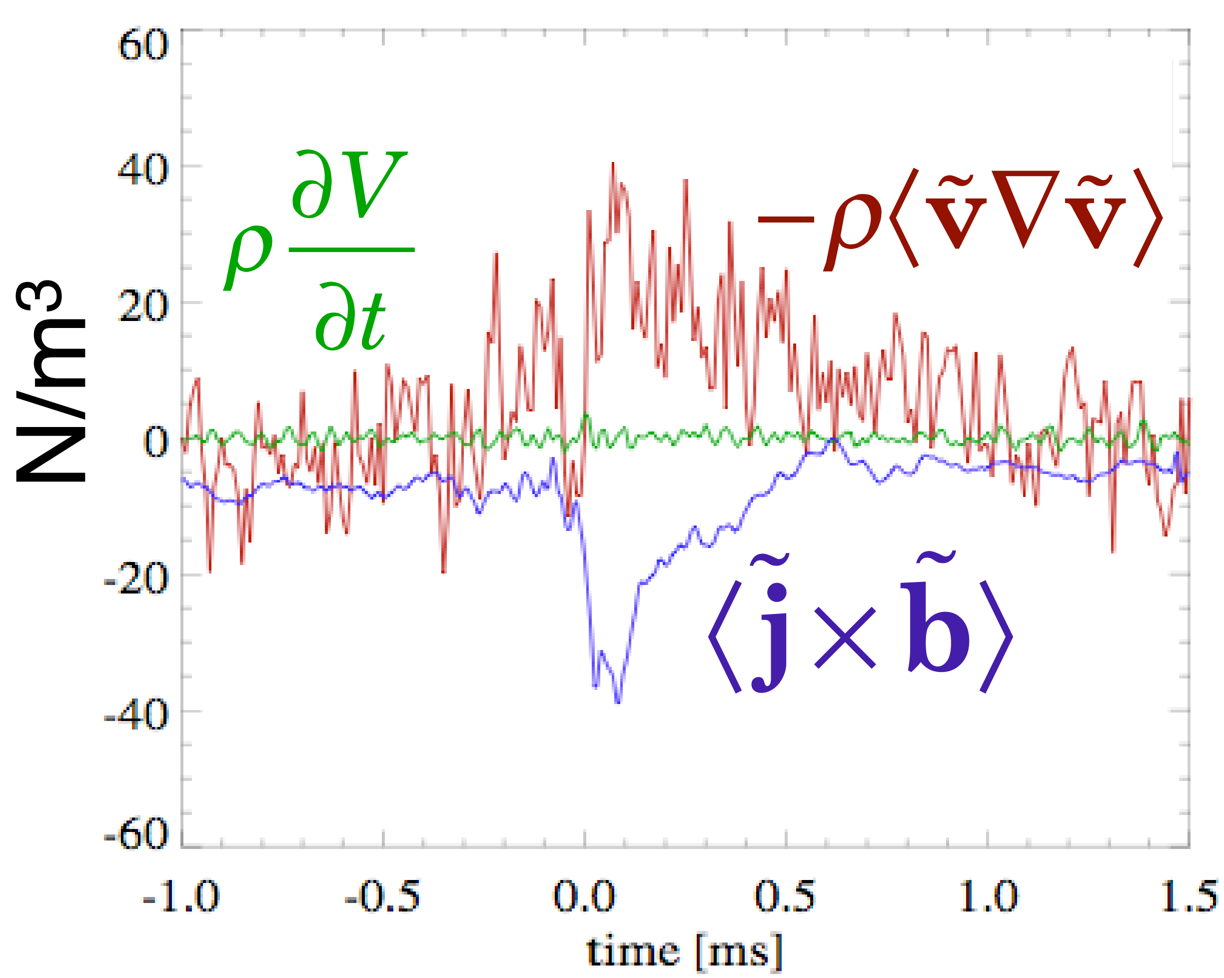
$$\left\langle \tilde{j}\times\tilde{B}\right\rangle_\theta = \frac{1}{\mu_0}\left(\frac{d}{dr}+\frac{2}{r}\right)\left\langle \tilde{B}_r\tilde{B}_\theta\right\rangle$$

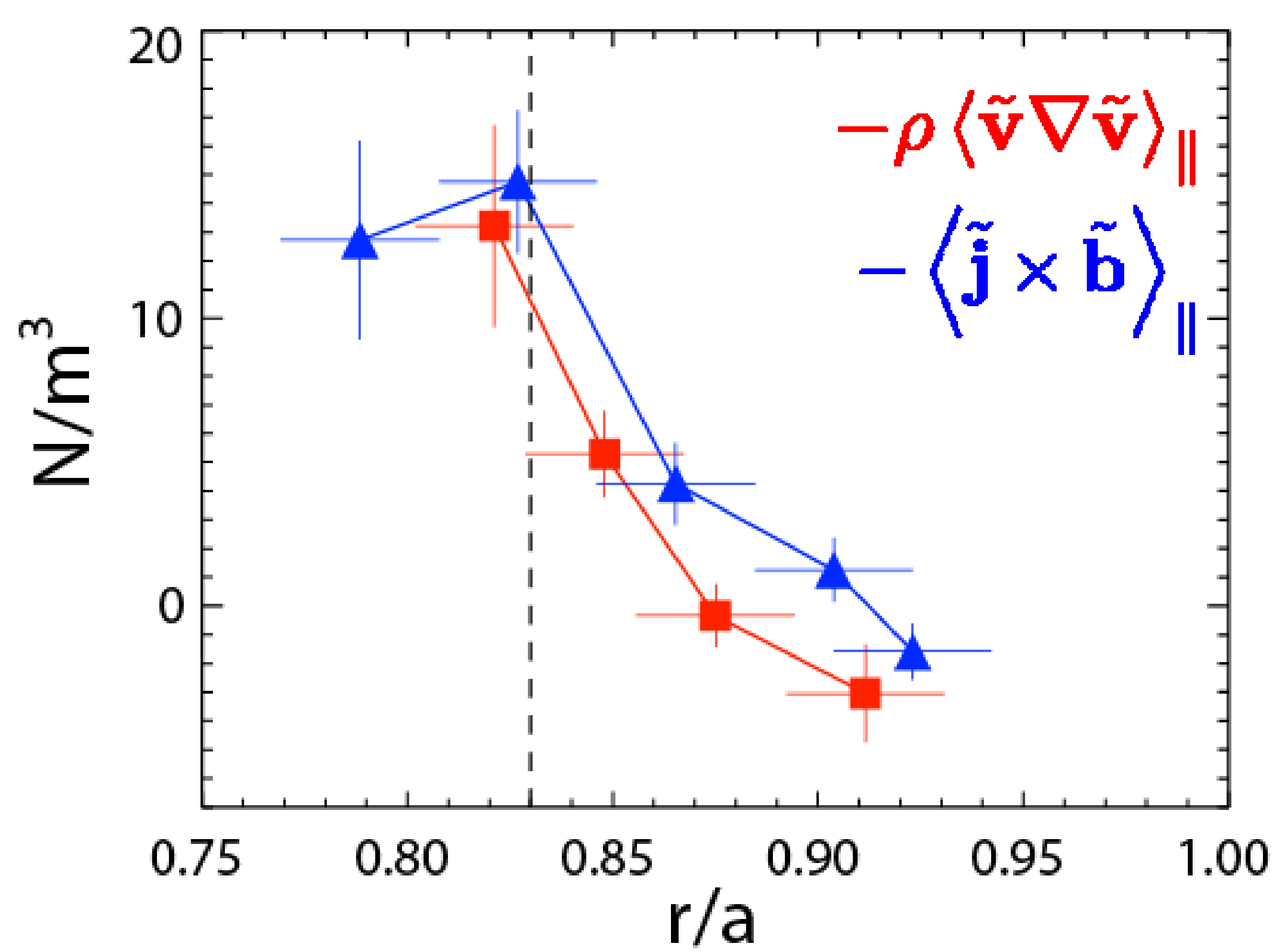
$$\left\langle \tilde{V}\nabla\tilde{V}\right\rangle_\theta = \left(\frac{d}{dr}+\frac{2}{r}\right)\left\langle \tilde{V}_r\tilde{V}_\theta\right\rangle$$

Components parallel to B

(3) Maxwell and Reynolds stresses are large

- Both Maxwell and Reynolds stresses are much larger than the inertial term.
- Maximum at the reversal surface.
- They are in the opposite directions and balance each other.





Conclusions

- Internally resonant tearing modes affect the momentum transport. Shown by analytical and numerical simulations, and measurements.
- Relaxation of momentum profile is measured
- Non-linear coupling of multiple modes is important
- Driving forces - fluctuation induced Maxwell and Reynolds stresses. Both are large and balance each other.

Future addition - toroidal CHERS view and toroidal NBI