Momentum Transport during Spontaneous Reconnection Events and Edge Biasing in the MST Reversed Field Pinch

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In collaboration with

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THE UNIVERSITY of WISCONSIN
MADISON

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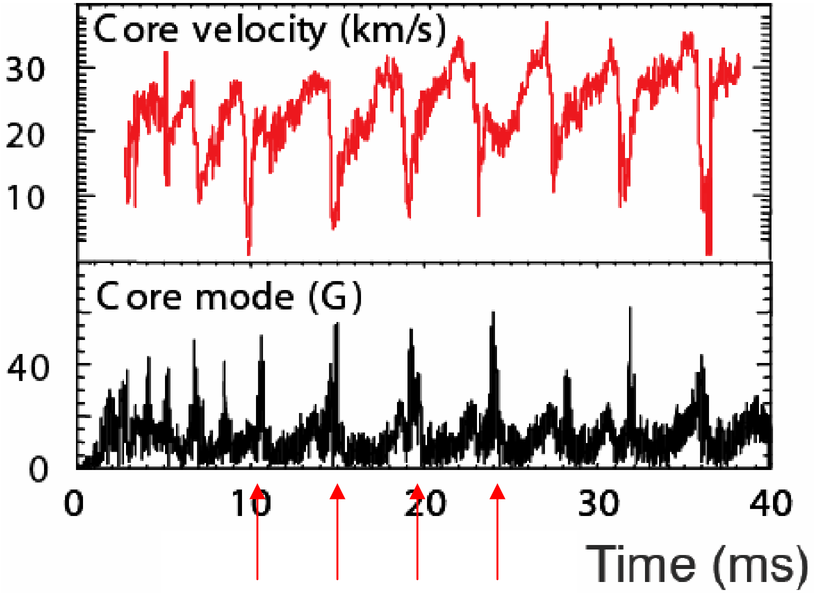
Motivation

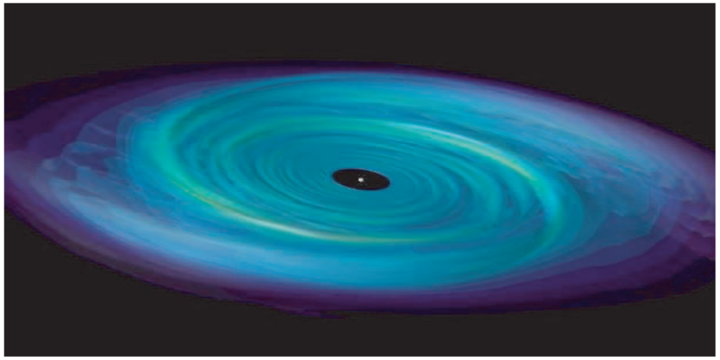
- How is toroidal angular momentum transported?
- What drives spontaneous rotation in RFPs and tokamaks?

MST experiment



Reconnection
(relaxation) events

Accretion Disks

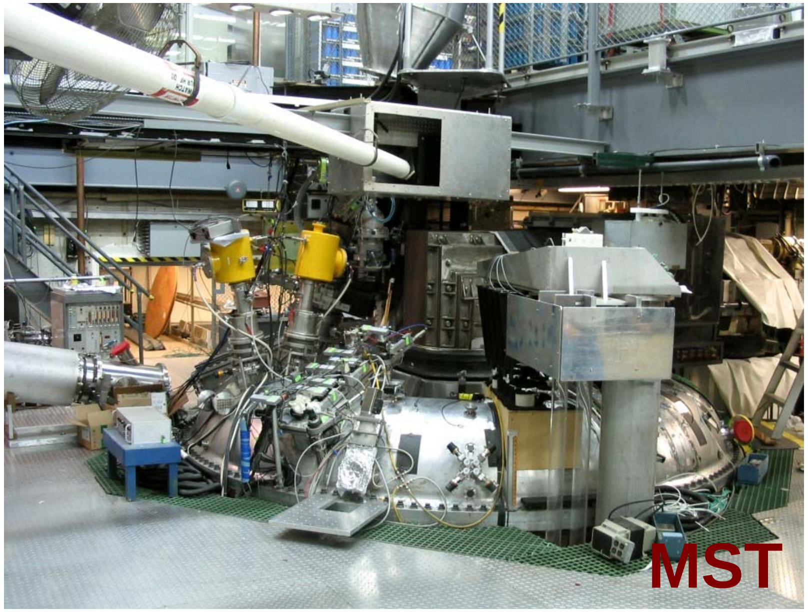


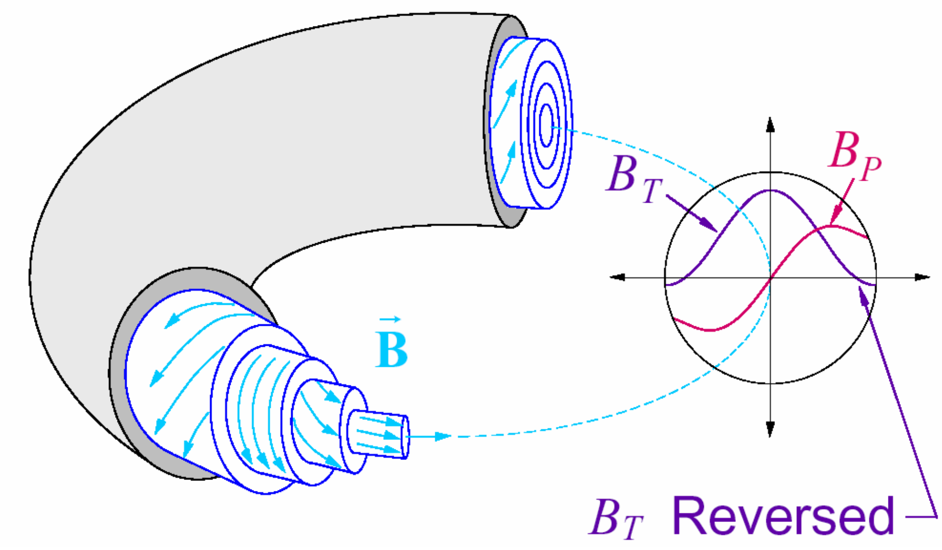
Sudden changes of momentum can not be explained by classical processes

Outline

- Introduction: Madison Symmetric Torus Reversed Field Pinch
- Bulk ion flow measurement techniques
- Relaxation of parallel plasma momentum during reconnection event
- Measurements of non-linear Maxwell and Reynolds stresses
- Momentum transport induced by edge biasing:
  - In standard MST plasma
  - In improved confinement regime (PPCD)
- Comparison of the measured anomalous viscosity with J. Finn’s theory
- Intrinsic plasma rotation between reconnection events
- Summary

Madison Symmetric Torus Reversed Field Pinch – magnetically confined plasma for fusion research





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

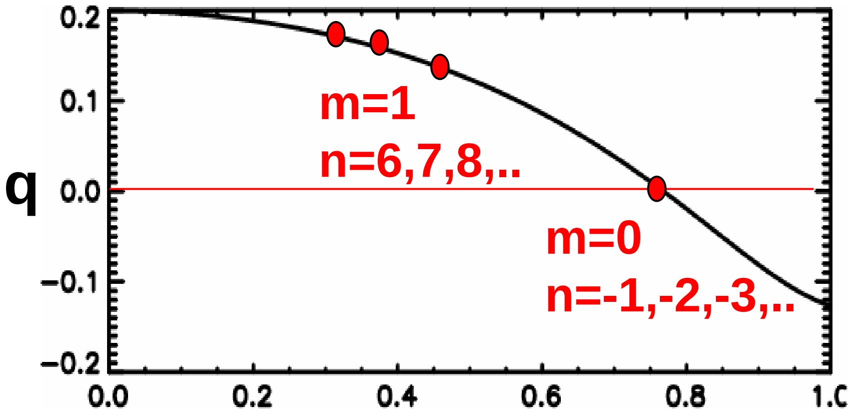
$I_p = 600$ kA, B=0.5 T

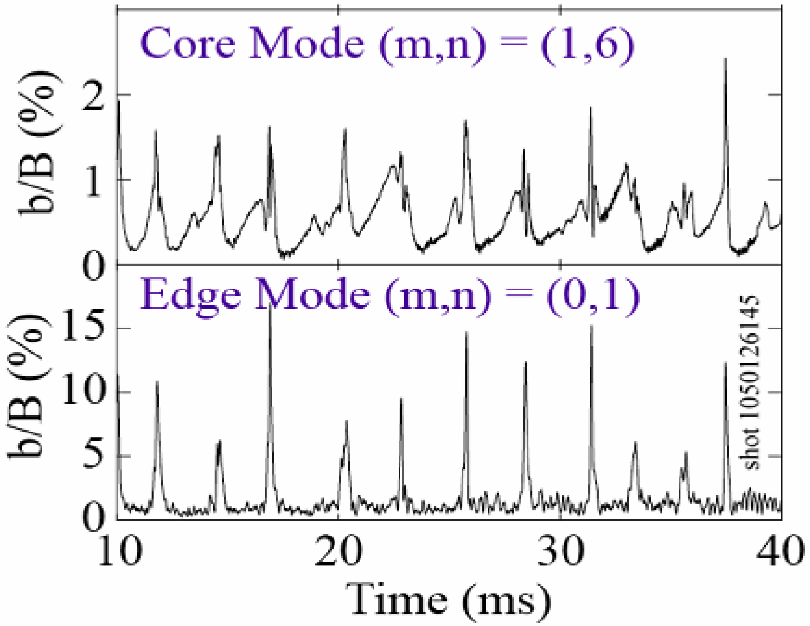
$n_e = 1\text{-}3\times10^{19}$ m^{-3}

T_e, T_i = 1-2 keV

Tearing modes govern RFP performance

- Explore regimes with large magnetic fluctuations.
- Main contribution - from current gradient driven resistive tearing modes that become unstable over the entire plasma volume.

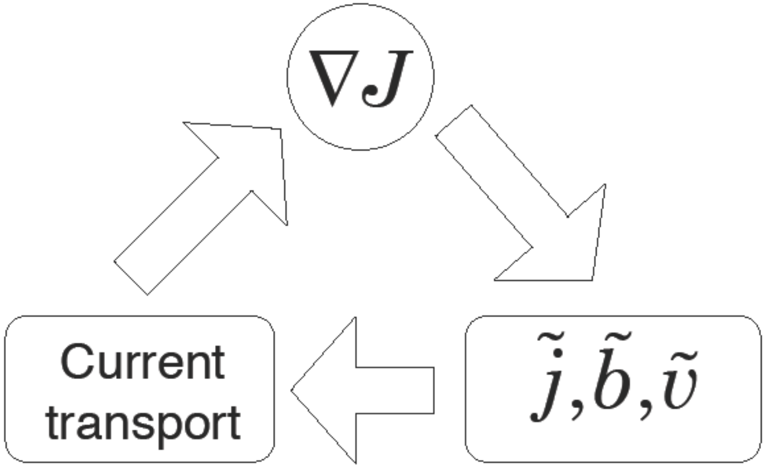


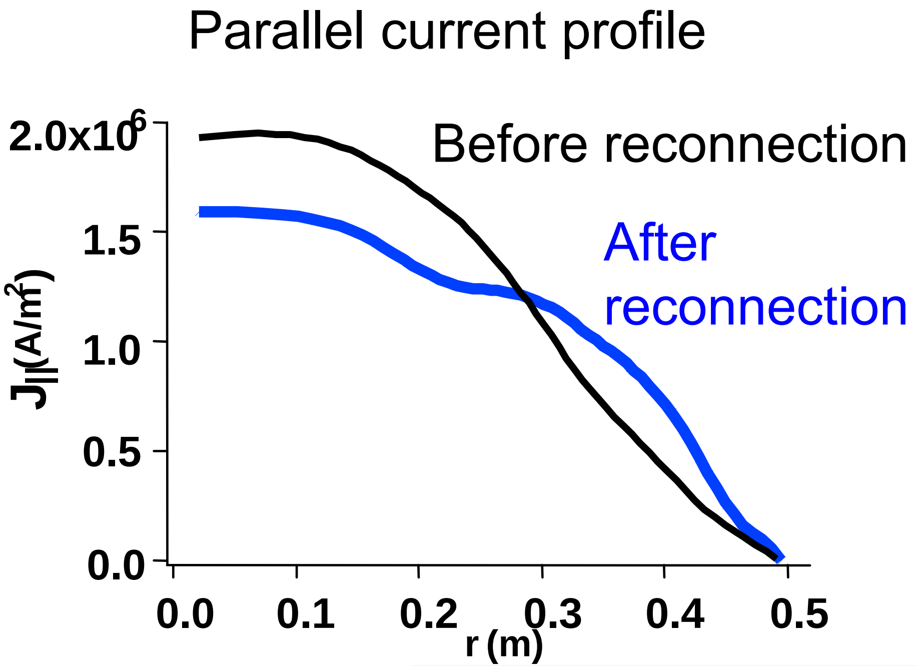


Fluctuations mediate current profile relaxation

- Fast growing multiple tearing relax the current profile via current transport, and reduce the instability drive.
- Taylor relaxation (single fluid). Current profile relaxes to the minimum energy state while conserving the **global** helicity.

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




Parallel current profile

Brower, Ding, PRL (2002)

- Two-fluid (Hegna, 1998). Current and momentum profile relax to the minimum energy state while conserving the helicities for **both species**.

$$\mathbf{J} = \lambda_1 \mathbf{B}$$
$$n\mathbf{V} = \lambda_2 \mathbf{B}$$

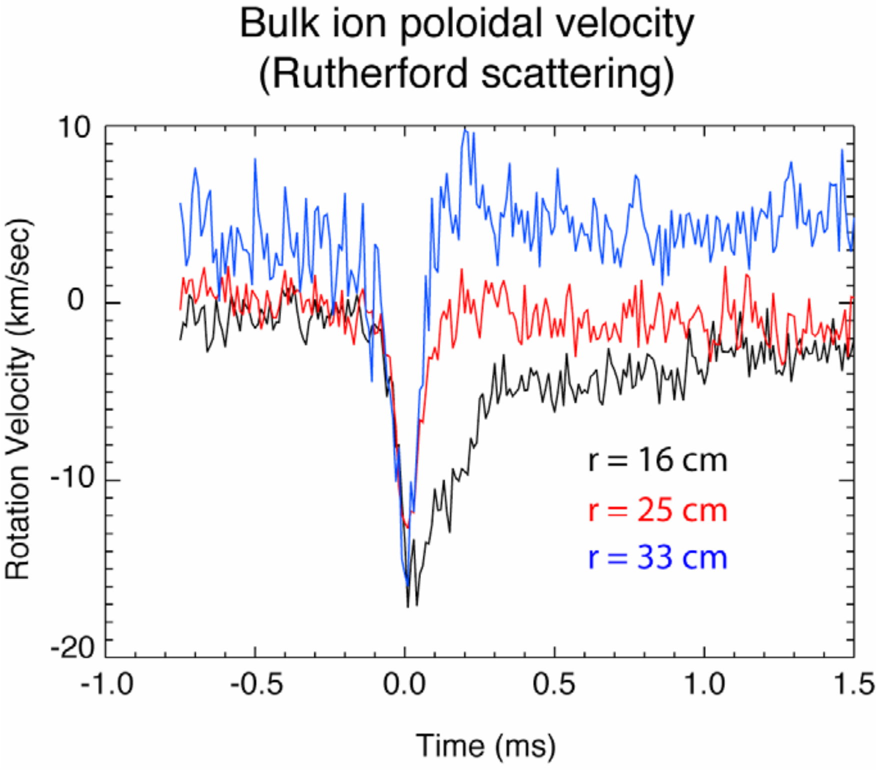
Measurements of bulk flow velocity

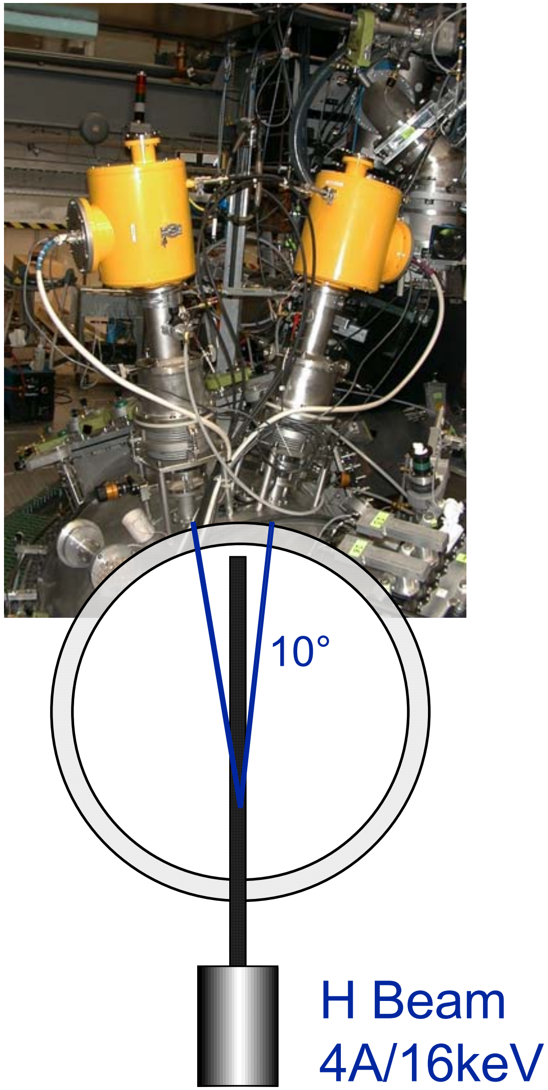
- Rather challenging task:
  - Bulk ion flow. Measurement over entire radial extend.
  - Measure all the vector components of the flow with good spatial (few cm) and temporal (100 kHz) resolution
  - Doppler spectroscopy characterizes minority ions which might or might not represent the parallel bulk flow.

- 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 of core resonant tearing modes - toroidal flow.
    - from the edge toroidal array of 64 magnetic pick-up coils.
  - Passive Doppler spectroscopy (CV line) - toroidal flow.

- Edge flow measurements
  - Mach and optical probes.

Core poloidal rotation changes strongly during reconnection event





- Periodic reconnection events provide basis for conditional averaging over many events

Parallel velocity in the core is reconstructed from mode rotation and Rutherford scattering

$$\boxed{V_{||} = (V_\theta B_\theta + V_\phi B_\phi)/B}$$

- No local measurements of toroidal velocity - work in progress.
- Assume that the core resonant tearing modes are stationary in the rotating plasma frame.
- In the lab frame we measure the Doppler shifted frequency with the toroidal array of magnetic coils.

$$\omega_M = \mathbf{k}\cdot\mathbf{V} = k_\theta V_\theta + k_\phi V_\phi$$

$$\mathbf{k} = \left(\frac{m}{r_s}, \frac{n}{R}\right) \quad \mathbf{k}\cdot\mathbf{B}\Big|_{r_s} = 0$$

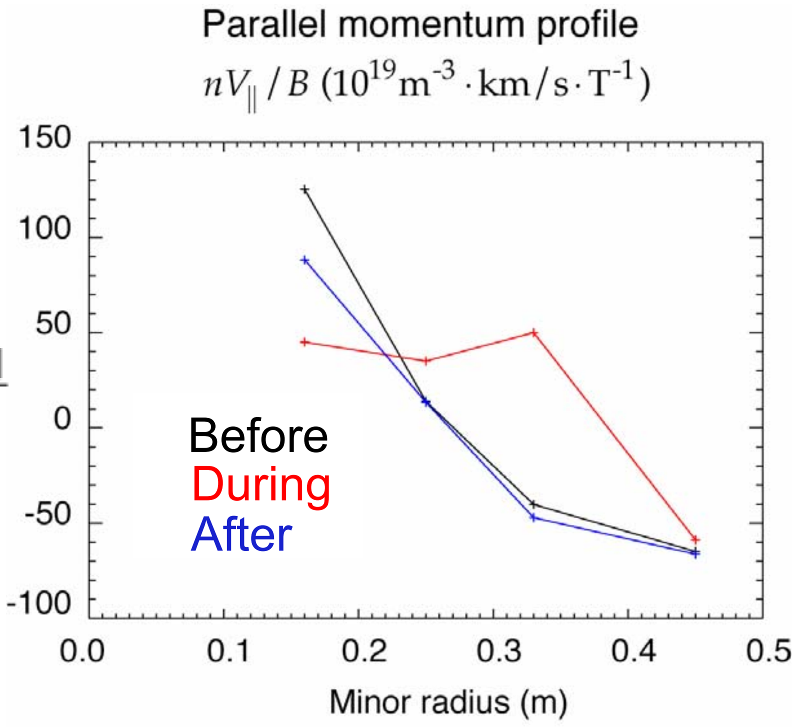
$$\Longrightarrow$$

$$V_{||} = \frac{\omega_M \dfrac{R}{n}\dfrac{B_\phi}{B_\theta} + V_\theta\left(1 + \dfrac{B_\phi^2}{B_\theta^2}\right)}{\left(1 + \dfrac{B_\phi^2}{B_\theta^2}\right)^{1/2}}$$

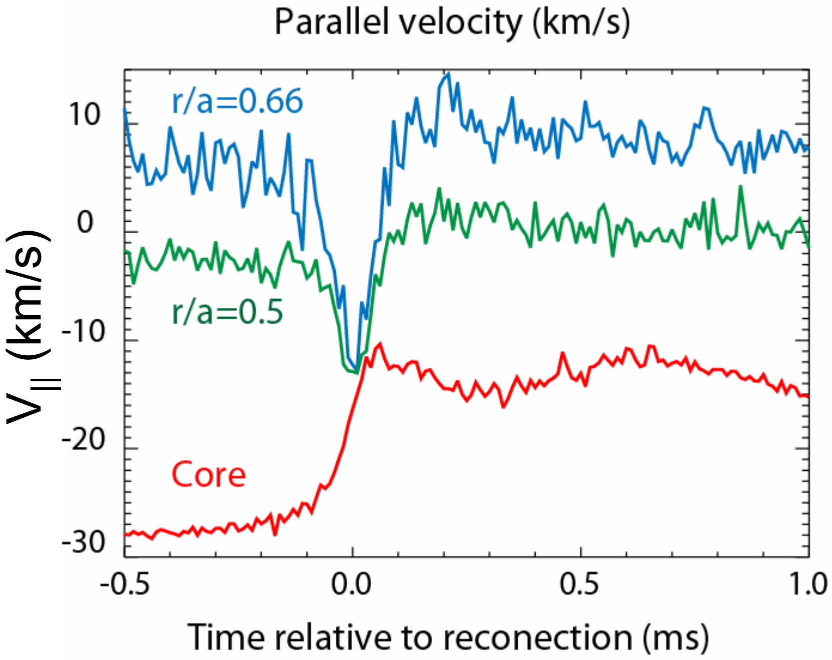
Parallel momentum profile flattens at the reconnection event

Radial Profile

$$\lambda = \frac{nV_{\parallel}}{B}$$



Time Evolution



- While the core parallel flow slows down the edge speeds up
- Can not be explained by classical processes

$$\frac{\partial V_{\parallel}}{\partial t} \approx \frac{-20\ \mathrm{km/s}}{0.2\ \mathrm{ms}} = -10^{8}\ \mathrm{m/s}^{2}$$

$$\tau_{sd}^{class} \simeq 250\ \mathrm{ms}$$

What governs momentum transport?

Parallel momentum balance equation:

$$\underbrace{\frac{\partial V_{\|}}{\partial t}}_{\text{inertia}} = \underbrace{-\left\langle \tilde{\mathbf{v}}\nabla\tilde{\mathbf{v}}\right\rangle_{\|}}_{\text{Reynolds}} + \underbrace{\frac{\left\langle \tilde{\mathbf{j}}\times\tilde{\mathbf{b}}\right\rangle_{\|}}{M_i n_i}}_{\text{Maxwell}} + \underbrace{\nu_{cl}\nabla^2 V_{\|}}_{\text{damp}} - \underbrace{\frac{\Gamma_R}{n_i}\frac{\partial V_{\|}}{\partial r}}_{\text{pinch}}$$

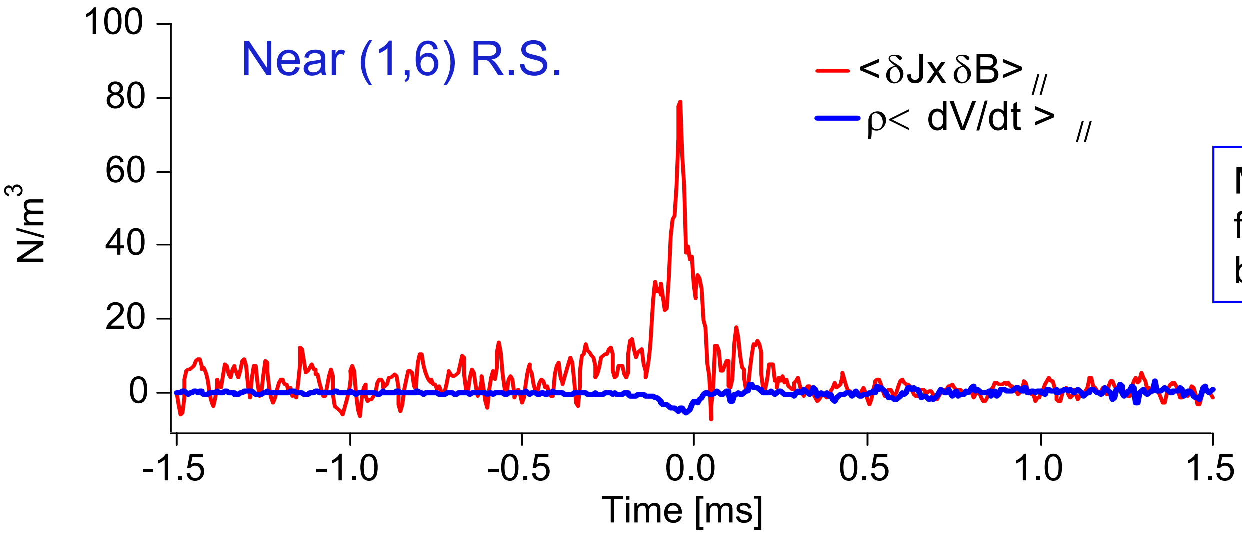
<…> represents flux-surface average

|| - with respect to the unperturbed $\mathbf{B}_0$

Maxwell stress is large and opposite to the flow change in the core

$$\underbrace{\frac{\partial V_\parallel}{\partial t}}_{\text{inertia}} = \underbrace{-\left\langle \tilde{\mathbf{v}}\nabla\tilde{\mathbf{v}}\right\rangle_\parallel}_{\text{Reynolds}} + \underbrace{\frac{\left\langle \tilde{\mathbf{j}}\times\tilde{\mathbf{b}}\right\rangle_\parallel}{M_i n_i}}_{\text{Maxwell}} \underbrace{+\,\nu_{cl}\nabla^2 V_\parallel}_{\text{damp}} \underbrace{-\,\frac{\Gamma_R}{n_i}\frac{\partial V_\parallel}{\partial r}}_{\text{pinch}}$$

inertia	Reynolds	Maxwell	damp	pinch
$-10^8\,\mathrm{m/s^2}$ Reconnection	?	$\geq 10^9\,\mathrm{m/s^2}$	$-10^5\,\mathrm{m/s^2}$	?



Measured using FIR laser faraday rotation diagnostic by W.X. Ding et al. (UCLA)

What balances the Maxwell stress?

$$\underbrace{\frac{\partial V_\parallel}{\partial t}}_{\substack{\text{inertia}\\ -10^8\mathrm{m/s^2}\\ \text{Reconnection}}} = -\underbrace{\langle \tilde{\mathbf{v}}\nabla\tilde{\mathbf{v}}\rangle_\parallel}_{\substack{\text{Reynolds}\\ ?}} + \underbrace{\frac{\left\langle \tilde{\mathbf{j}}\times\tilde{\mathbf{b}}\right\rangle_\parallel}{M_i n_i}}_{\substack{\text{Maxwell}\\ \geq 10^9\mathrm{m/s^2}}} + \underbrace{\nu_{cl}\nabla^2 V_\parallel}_{\substack{\text{damp}\\ -10^5\mathrm{m/s^2}}} - \underbrace{\frac{\Gamma_R}{n_i}\frac{\partial V_\parallel}{\partial r}}_{\substack{\text{pinch}\\ ?}}$$

Two possible mechanisms to balance the Maxwell stress:

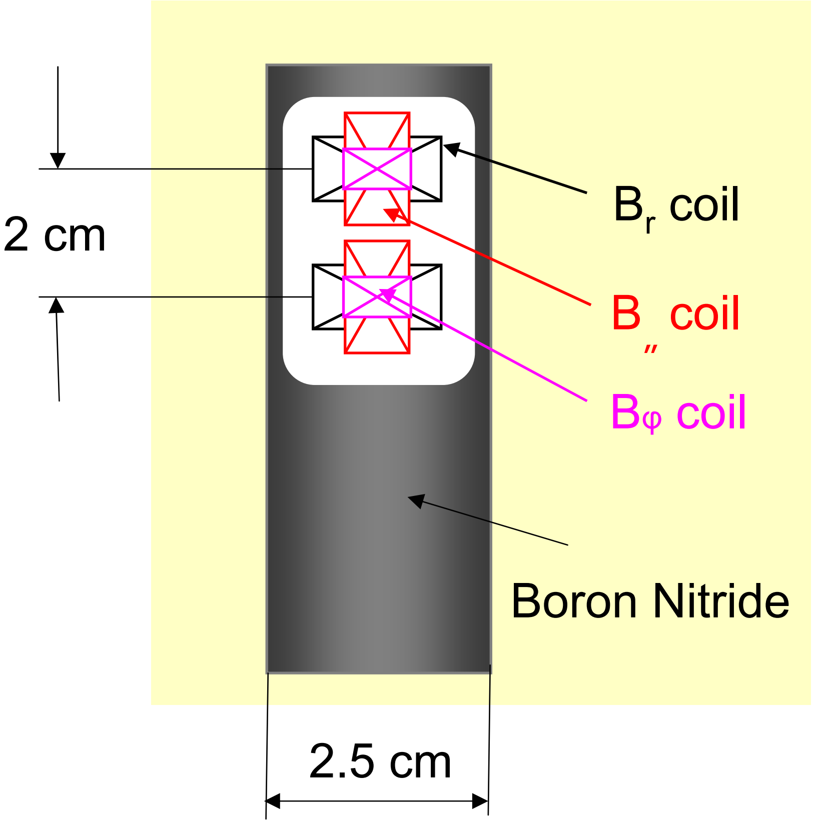
1. Reynolds stress: $\langle \tilde{\mathbf{v}}\nabla\tilde{\mathbf{v}}\rangle_\parallel$

2. Radial flow transport: $\frac{\Gamma_R}{n_i}\frac{\partial V_\parallel}{\partial r}$

   Requires $V_R = \frac{\Gamma_R}{n_i} \geq 1\mathrm{km/s}$ - too large?

Maxwell and Reynolds stresses measured by the probes in the edge

Maxwell stress



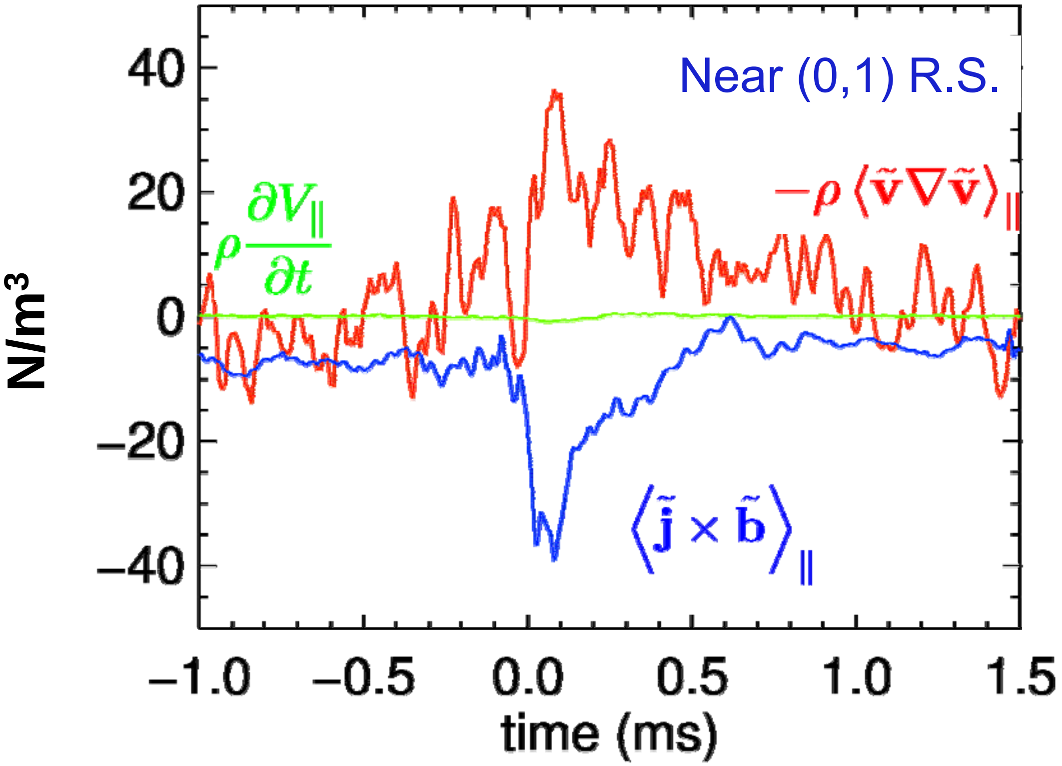
$$\left\langle \tilde{j} \times \tilde{B} \right\rangle_\theta = \frac{1}{\mu_0}\left(\frac{d}{dr} + \frac{2}{r}\right)\left\langle \tilde{B}_r \tilde{B}_\theta \right\rangle$$

Reynolds stress

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

Assume $\nabla \cdot \mathbf{V} = 0$

Maxwell and Reynolds stresses balance in the edge

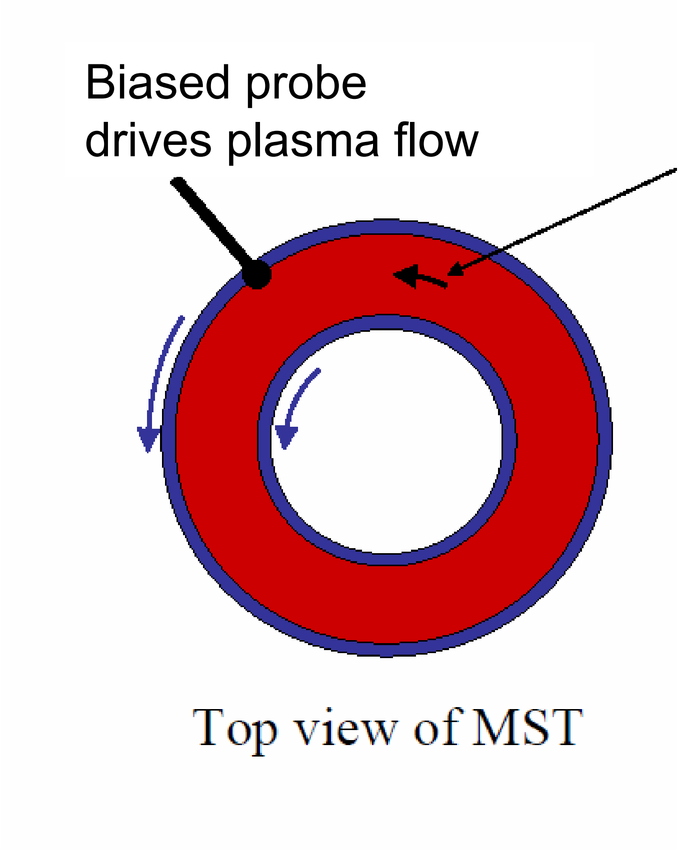


$$\rho\frac{\partial V_{\|}}{\partial t}=-\rho\left\langle\tilde{\mathbf{v}}\nabla\tilde{\mathbf{v}}\right\rangle_{\|}+\left\langle\tilde{\mathbf{j}}\times\tilde{\mathbf{b}}\right\rangle_{\|}+\ldots$$

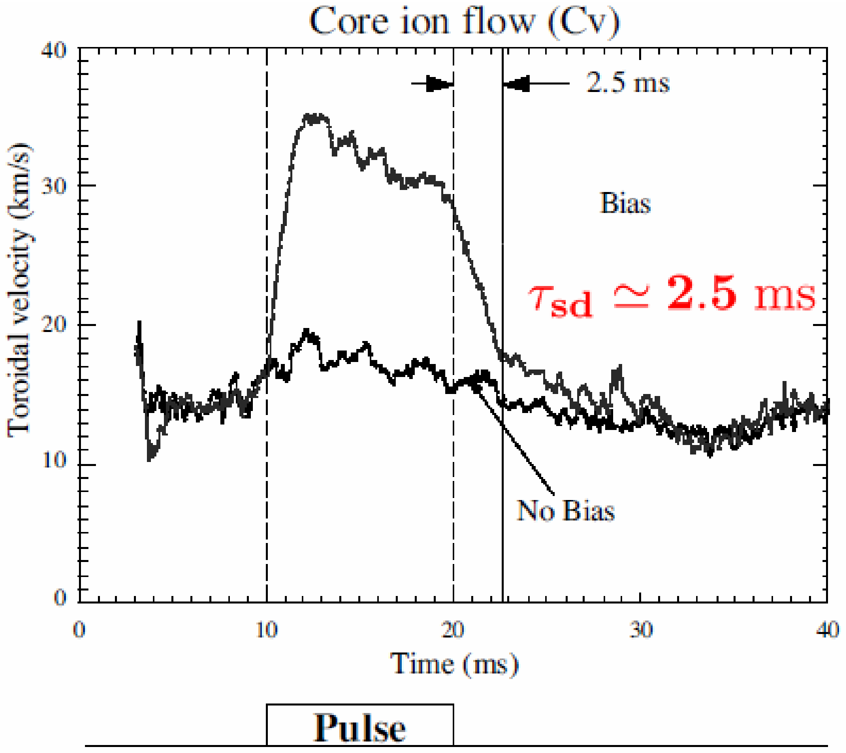
Momentum Transport Induced by Edge Biasing

Biased electrodes are used to drive core plasma rotation

- Electrodes inserted into the edge and positively biased with respect to the wall
- Produces external torque $j_r \times B_p$ in the toroidal direction and drives edge flow
- Core responds in few ms



Top view of MST



Standard RFP discharge

Plasma flow decays anomalously fast in standard plasma

- Electrodes inserted into the edge and positively biased with respect to the wall
- Produces external torque $j_r \times B_p$ in the toroidal direction and drives edge flow
- Core responds in few ms

Flow dumping after bias is turned off is phenomenologically governed by:

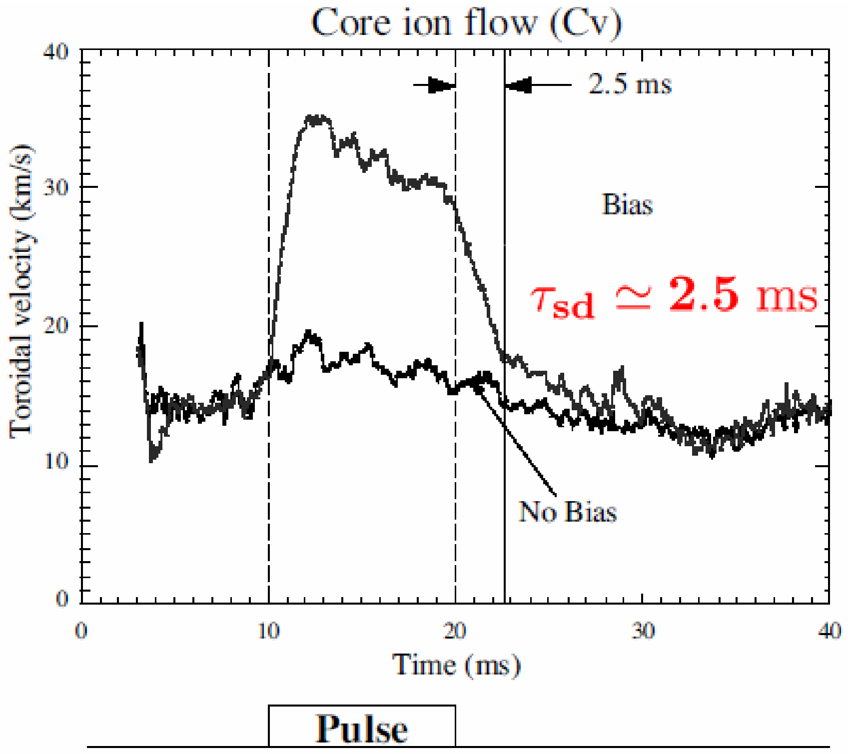
$$\boxed{\frac{\partial V_\parallel}{\partial t} \approx \nu \nabla^2 V_\parallel}$$

Kinematic viscosity (momentum diffusivity) is anomalous :

$$\nu \approx \frac{(\Delta r)^2}{\tau_{sd}} = 55\ \mathrm{m}^2/\mathrm{s}$$

$$\nu_\perp^{Brag} \approx \rho_i^2/\tau_i \approx 0.6\ \mathrm{m}^2/\mathrm{s}$$

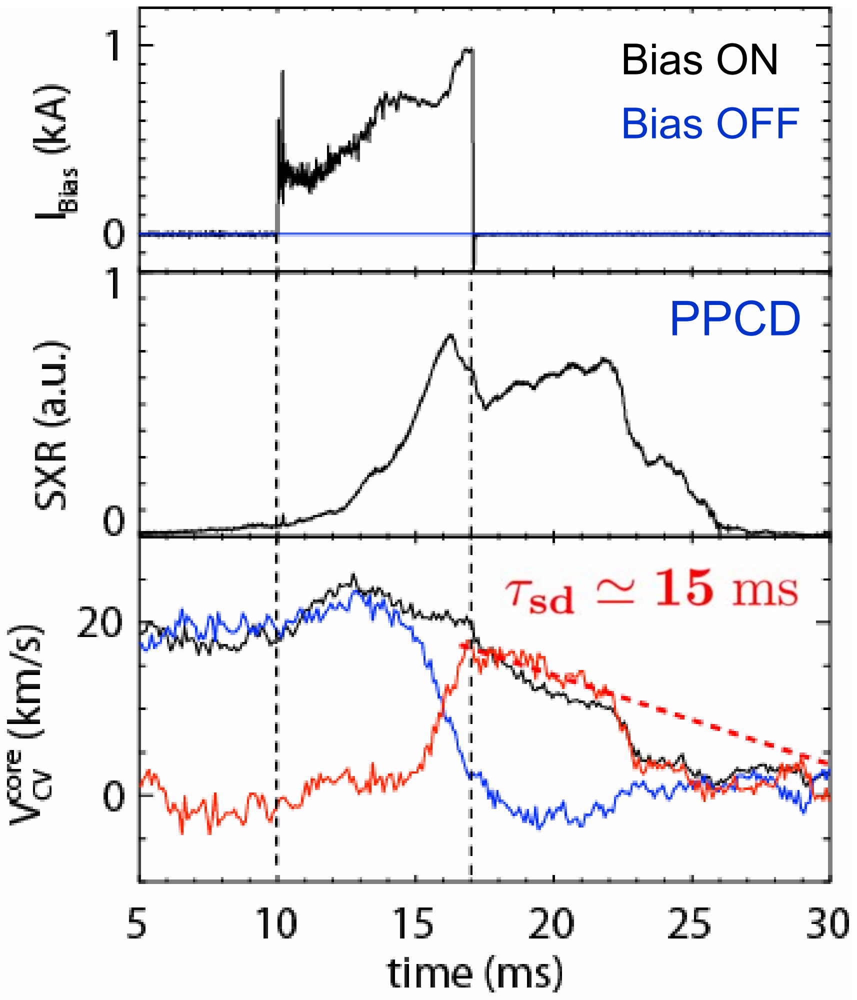
$$\frac{\tau_{sd}^{class}}{\tau_{sd}} \simeq 100$$



Standard RFP discharge

A.F. Almagri et al, PoP(1998)

PPCD results in 6-fold increase of momentum confinement



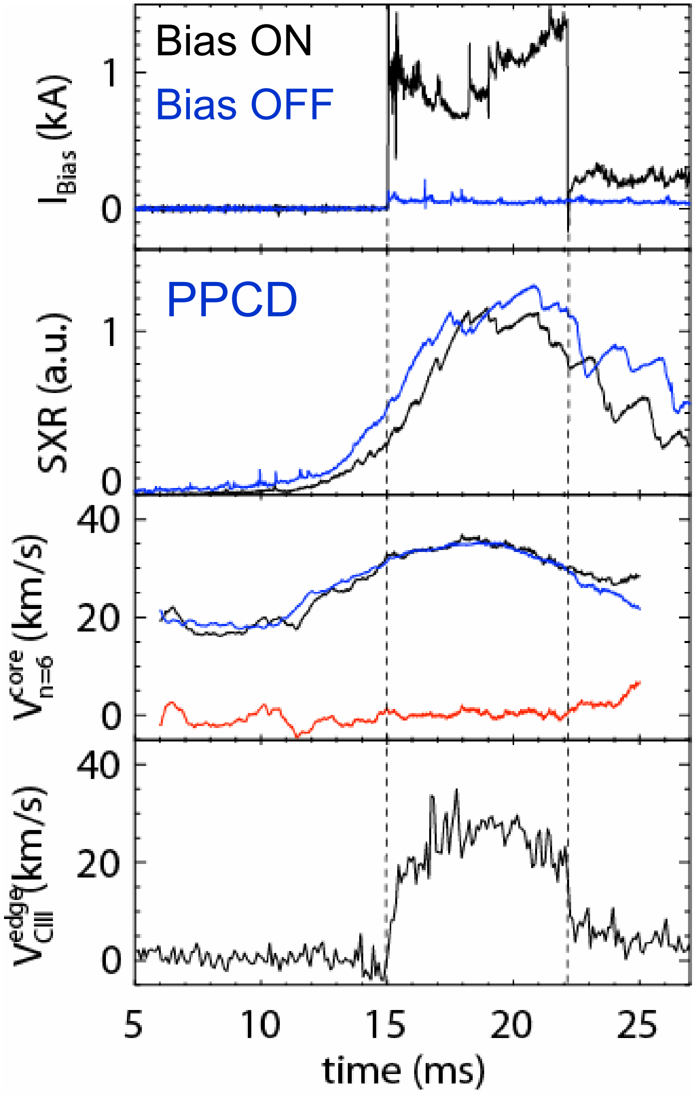
Current profile control through pulsed poloidal current drive (PPCD) results in improved energy and particle confinement

Applying PPCD after core toroidal rotation is induced by edge biasing leads to the 6-fold increase in the momentum confinement

CV emission rapidly shifts towards the edge, when core T_e increases → need to compare with bias off case

$\tau_{sd} \simeq 3 \times \tau_E$

Inward momentum transport is reduced in PPCD



Core and edge are decoupled

No change in the core rotation, when bias is applied during PPCD

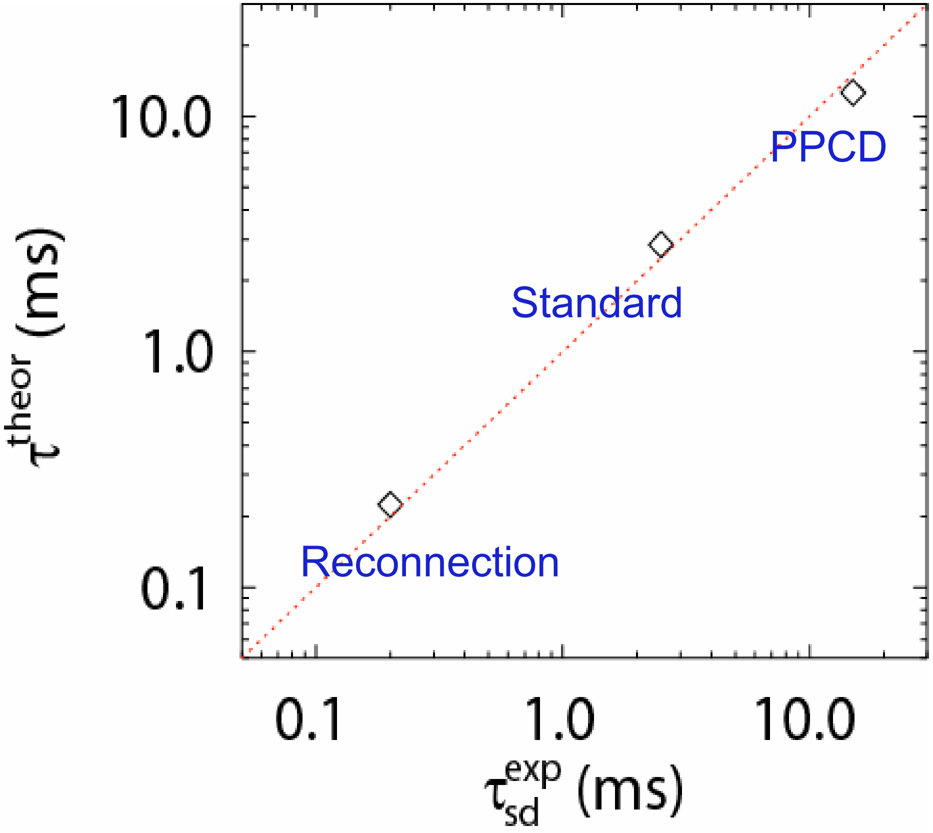
Large edge rotation (3 times larger than in standard plasma, while the torque is the same)

Observations agree well with the theory of stochastic diffusion due to magnetic fluctuations

- The magnetic field in MST is typically stochastic and should contribute to the momentum transport
- J. Finn (Phys. Fluids B, 1992) suggests momentum diffusion with

$$\boxed{\nu = D_m c_s = \left(\frac{\delta B}{B}\right)^2 l_c c_s}$$

l_c – parallel correlation length
c_s – ion sound speed



What drives intrinsic plasma rotation in MST?

- Toroidal plasma rotation is observed with speed of 20-30 km/s (~0.25c_s) when there is no external momentum input (no beams, or RF), but there still has to be an intrinsic torque caused by the presence of the boundary (wall) or magnetic coils.
- Rotation is required to satisfy radial momentum balance, but its origin is not fully understood.
- Plasma rotation reverses, when I_p (or B_p) is reversed

$$\underbrace{E_r}_{1500\,\frac{\mathrm{V}}{\mathrm{m}}>0} + \underbrace{\mathbf{V}\times\mathbf{B}\Big|_r}_{-2000\,\frac{\mathrm{V}}{\mathrm{m}}<0} \underbrace{-\frac{1}{n_i Z_i e}\frac{dP_i}{dr}}_{500\,\frac{\mathrm{V}}{\mathrm{m}}>0} = 0$$

- Possible mechanisms:
  - Fast ion losses (charge exchange with neutrals, collisions with the wall) resulting in edge rotation due to recoil, which then drags the core?
  - Internal turbulent torques could cause core plasma to rotate in one direction, edge plasma in the other direction (total momentum is conserved). Then, edge rotation is damped by viscous effects, so left only with rotating core?
  - Something else …?

Summary

- Relaxation of the parallel momentum carried by the bulk ions is measured in the core and in the edge of the MST RFP plasma through the reconnection (relaxation) event. The parallel flow profile flattens in the core similar to the electrical current.
- Maxwell stress is about 10 times larger than the inertial term in the edge and in the core.
- Edge probe measurements indicate that Maxwell and Reynolds stresses are approximately equal and opposite to each other, thus providing the momentum balance.
- Improved confinement leads to six-fold increase of the momentum confinement.
- The anomalous kinematic viscosity measured in 3 regimes: during the reconnection event, standard plasma, and improved confinement agrees with magnetically driven momentum transport theory by J. Finn et al (1992).
- Plasma rotation in the quiescent plasma between reconnection events is required to satisfy the radial momentum balance, but it’s origin is not fully understood…

The End