Transport of Parallel Momentum During Reconnection Events in the Madison Symmetric Torus Reversed Field Pinch

Alexey Kuritsyn

A.F. Almagri, D.L. Brower, D. Craig, B.H. Deng, D.J. Den Hartog, W.X. Ding, F. Ebrahimi, D. Ennis, G. Fiksel, S. Gangadhara, C.C. Hegna, M. Miller, V.V. Mirnov, S.C. Prager, J.S. Sarff

THE UNIVERSITY of WISCONSIN MADISON

12th US-EU TTF Workshop • San Diego, CA • April 17-20, 2007

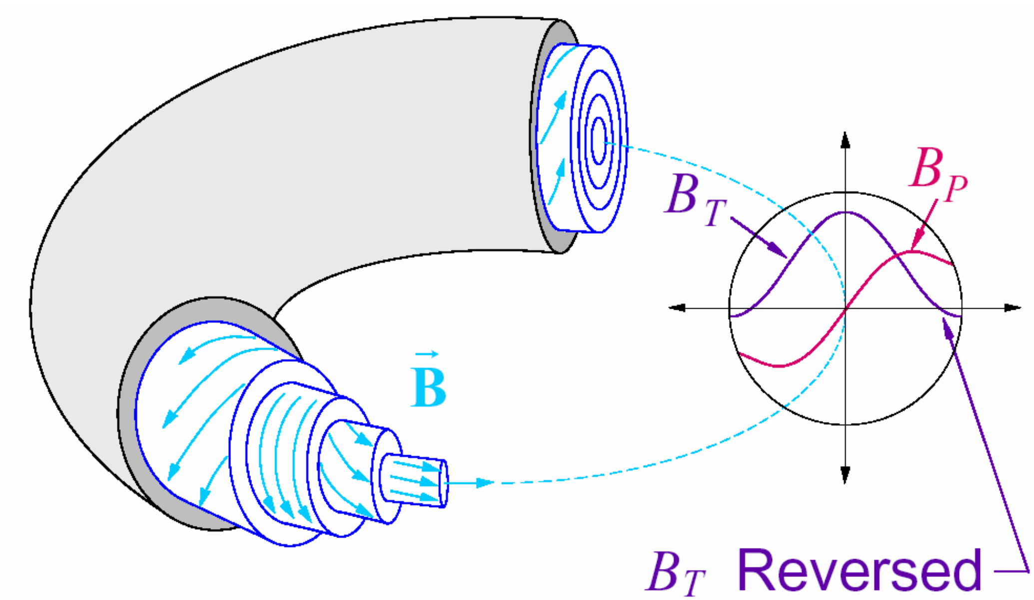
Motivation

- Fluctuation induced non-linear torques play important role in sustainment and transport of both electric current and plasma flow in the reversed field pinch (RFP) .
- The dynamics of flow sustainment and transport in MST is still not well understood:
  - What counter-balances the viscous dissipation?
  - What governs the impulsive changes in the rotation during reconnection?
- Detailed measurements of the non-linear stresses in the RFP scrape-off layer (for example, N. Vianello *et.al*) have been made.
- We present results on measurements of the bulk ion flow dynamics in the core and edge of MST.

Outline

- Bulk ion flow measurement techniques:
  - Core - Rutherford scattering
  - Edge - Mach probe
- Relaxation of parallel plasma momentum during sawtooth crash
- Effect of edge biasing on plasma flow:
  - Standard (F=-0.2) and non-reversed (F=0) regimes
  - Improved confinement regime (PPCD)
- Measurements of non-linear Maxwell stress
- Discussion of possible mechanisms to balance the Maxwell stress based on the local momentum balance:
  - Reynolds stress
  - Radial flow transport
- Summary

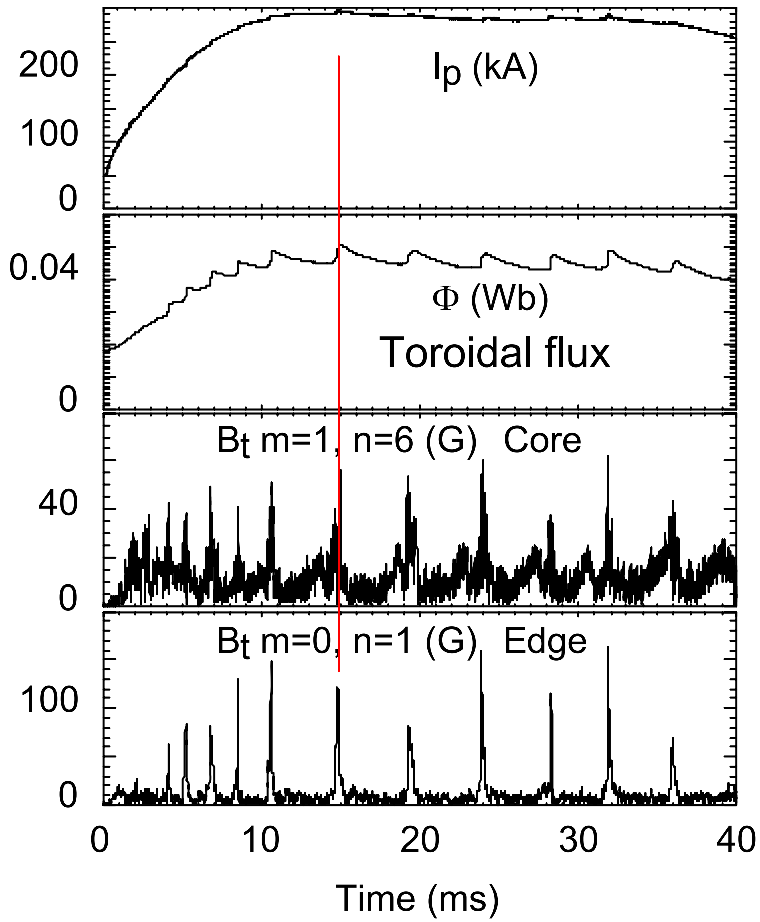
Madison Symmetric Torus Reversed Field Pinch

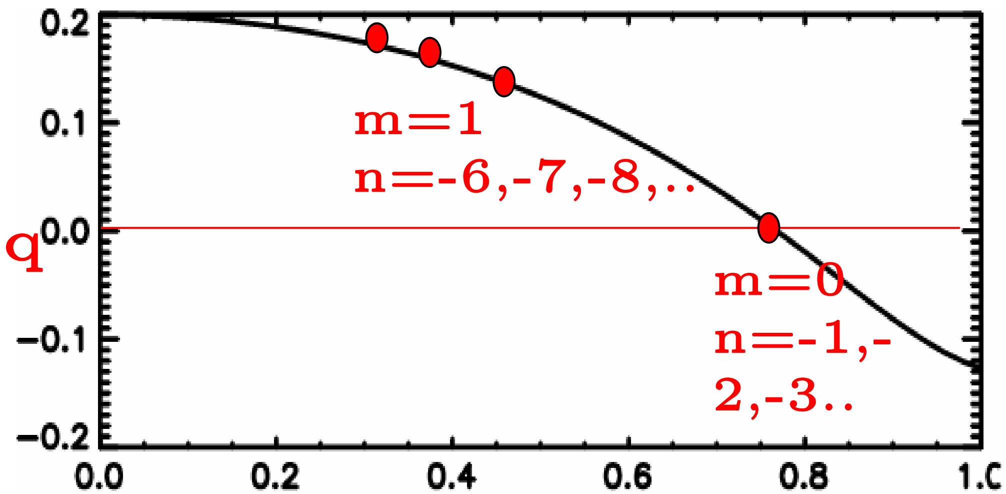


- Toroidal, current-carrying
- Density, $n \sim 10^{13}$ cm^{-3}
- Temperature, $T_{e,i} \sim 1$ keV
- $B / B \sim 2\%$ ($B \leq 0.5$ T)

MST was run at reduced parameters for probes:
$I_p \sim 200$ kA
$n_e \sim 10^{13}$ cm^{-3}
F ~ -0.2

Discrete Dynamo Events in MST

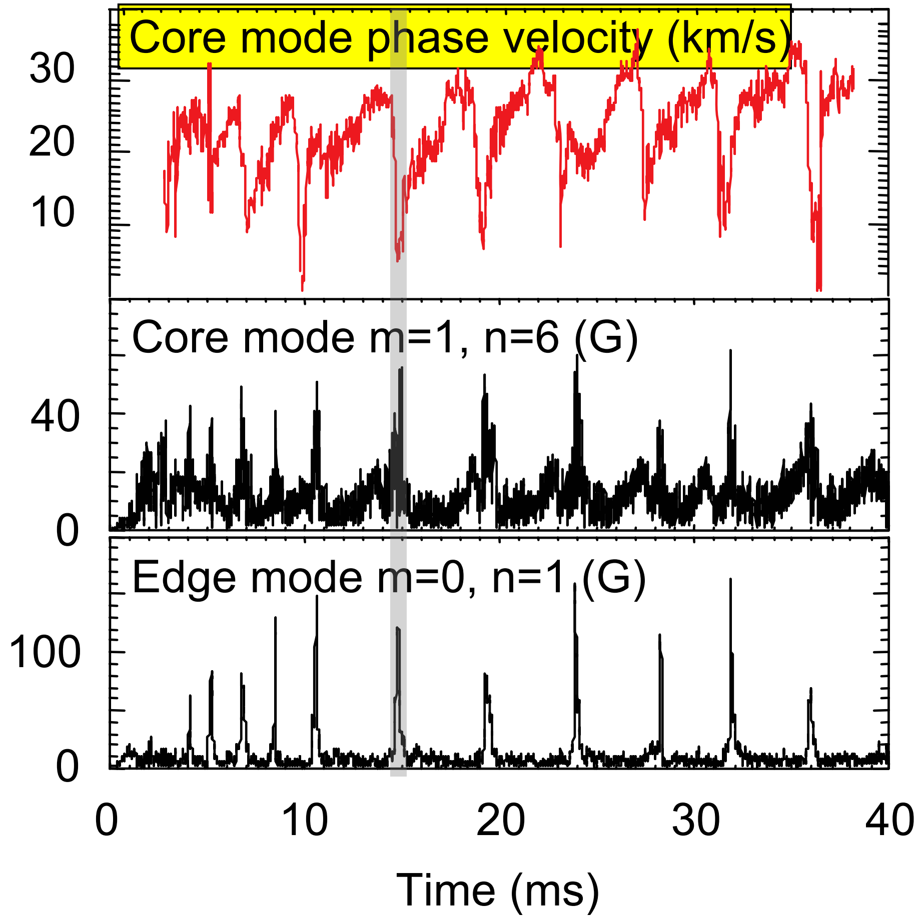




- Magnetic activity is punctuated by regular, sawtooth like bursts
- RFP has many resonant surfaces
- Fluctuation amplitude increases
- Magnetic flux is generated due to dynamo

Periodic braking of plasma rotation at the sawtooth crash

- What drives the continuous flow?
- What drives such abrupt changes in the rotation at the sawtooth crash (reconnection event)?
- How is the momentum re-distributed?



At the global reconnection event (sawtooth crash):

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

Relaxation of parallel flow is predicted by 2-fluid extension of Taylor's approach and by non-linear torques calculations

A theory for self-consistent mean-field forces using two-fluid equations suggest relaxation processes for both parallel current and plasma flow (Hegna, '98)

- Minimizing energy preserving K_s

$$K_e = \int dV_P \mathbf{A}_e \cdot \nabla \times \mathbf{A}_e$$

$$K_i = \int dV_P \mathbf{A}_i \cdot \nabla \times \mathbf{A}_i$$

$$A_s = A + (m_s / q_s) v_s$$

- Predicts current and bulk flow satisfy

$$\mathbf{J}_0 = \lambda_1 \mathbf{B}_0 + O(c / a\Omega_{ci}),$$

$$n_0 \mathbf{V}_0 = \lambda_2 \mathbf{B}_0 + O(c / a\Omega_{ci})$$

- Analytical and numerical analysis of non-linear torques indicates flattening of ion flow – see poster by F. Ebrahimi

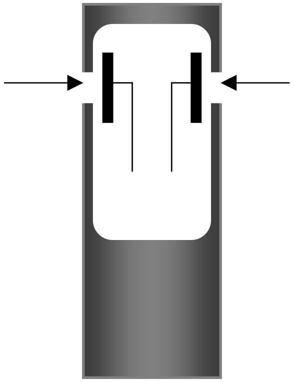
Measurement of parallel bulk velocity

- Rather challenging task:
  - Bulk ion flow. Measurement over entire radial extend.
  - Measure all the vector components of flow.
  - Doppler spectroscopy characterizes minority ions which might or might not represent the parallel bulk flow.

- Core measurements - Rutherford scattering and mode rotation from the toroidal array of 64 magnetic pick-up coils.

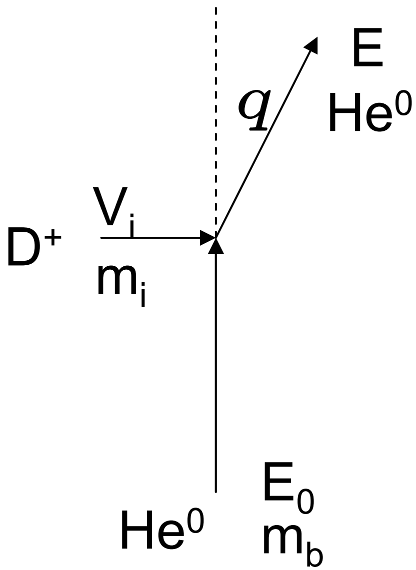
- Edge measurements - Mach probe.

Biased collectors measure ion saturation current



Rutherford scattering is used for local measurement of bulk plasma velocity in the core

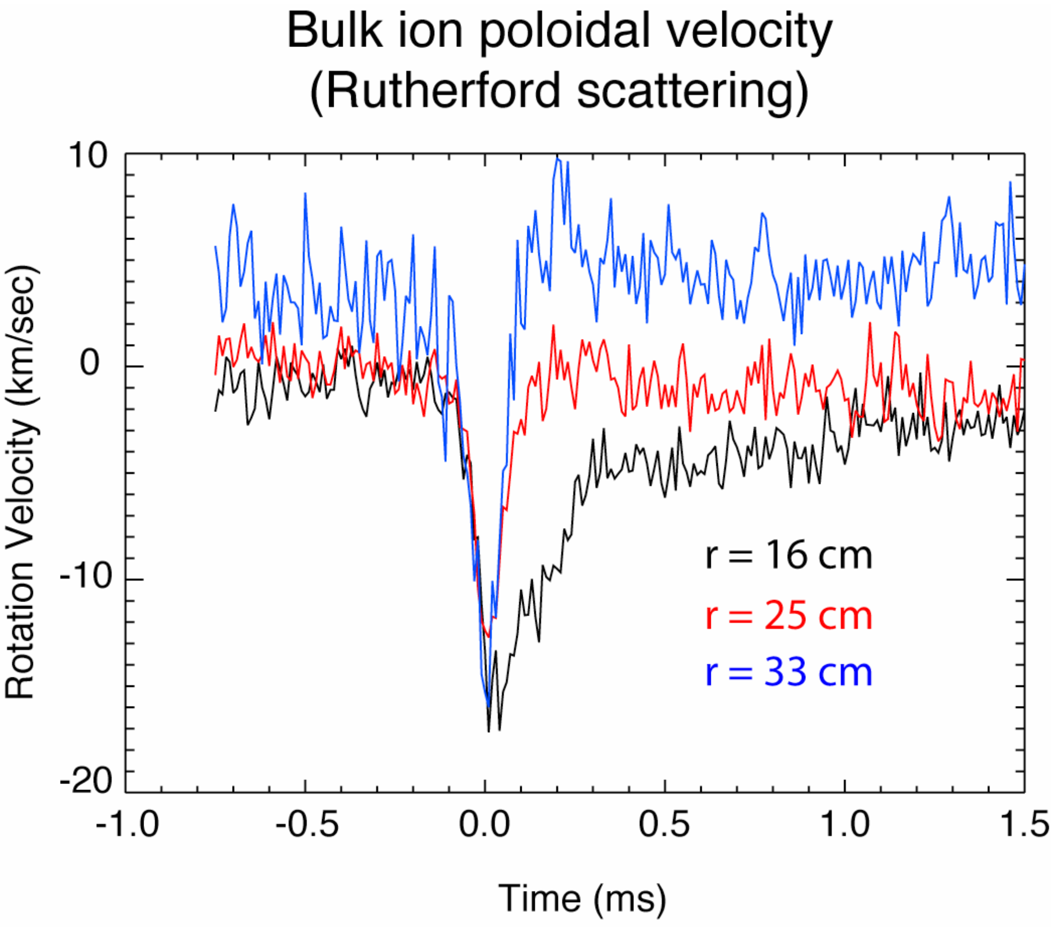
- Unique diagnostic - local properties of **bulk** plasma ions are measured.
- Inject a mono-energetic He beam (17keV) into plasma.
- Measure energy spectra of He atoms scattered from bulk ions (D).
- Plasma flow results in a shift of the energy spectra.
- Localization is determined by crossing of the primary beam and the line of sight.



$$E = E_0\left(1 - \frac{m_b}{m_i}\theta^2\right) + V_i\sqrt{2 m_b E_0}\;\theta$$

- Velocity component in the direction of scattering is measured.
- For the current setup this is the POLOIDAL direction.

Core poloidal rotation changes strongly during sawtooth crash



Calculation of parallel velocity in the core

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

No local measurements of toroidal velocity - work in progress.

Assume the tearing modes are stationary in the rotating plasma frame.

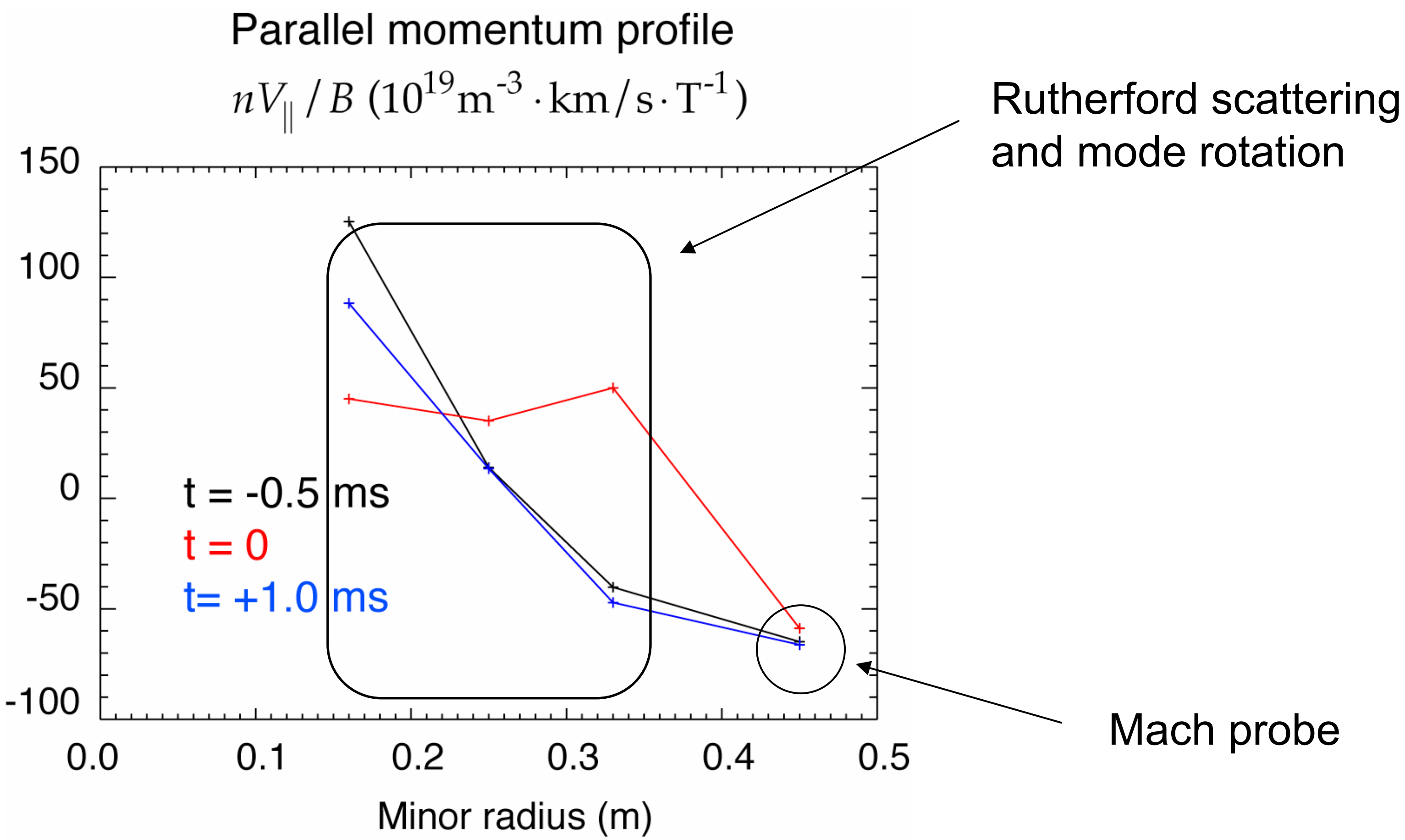
In the lab frame we measure the Doppler shifted frequency with the toroidal array of magnetic coils.

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

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

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

Parallel momentum flattens at the sawtooth crash



Parallel momentum balance equation

$$\frac{\partial V_\parallel}{\partial t} = -\langle \tilde{\mathbf{v}} \nabla \tilde{\mathbf{v}} \rangle_\parallel + \frac{\left\langle \tilde{\mathbf{j}} \times \tilde{\mathbf{b}} \right\rangle_\parallel}{M_i n_i} + \nu \nabla^2 V_\parallel - \frac{\Gamma_R}{n_i}\frac{\partial V_\parallel}{\partial r} - \gamma_n V_\parallel$$

inertia	RS	drive	MS	damp
$-10^8 \mathrm{m/s^2}$ Reconnection	?		$\geq 10^9 \mathrm{m/s^2}$	?

Two possible mechanisms to balance the Maxwell stress:

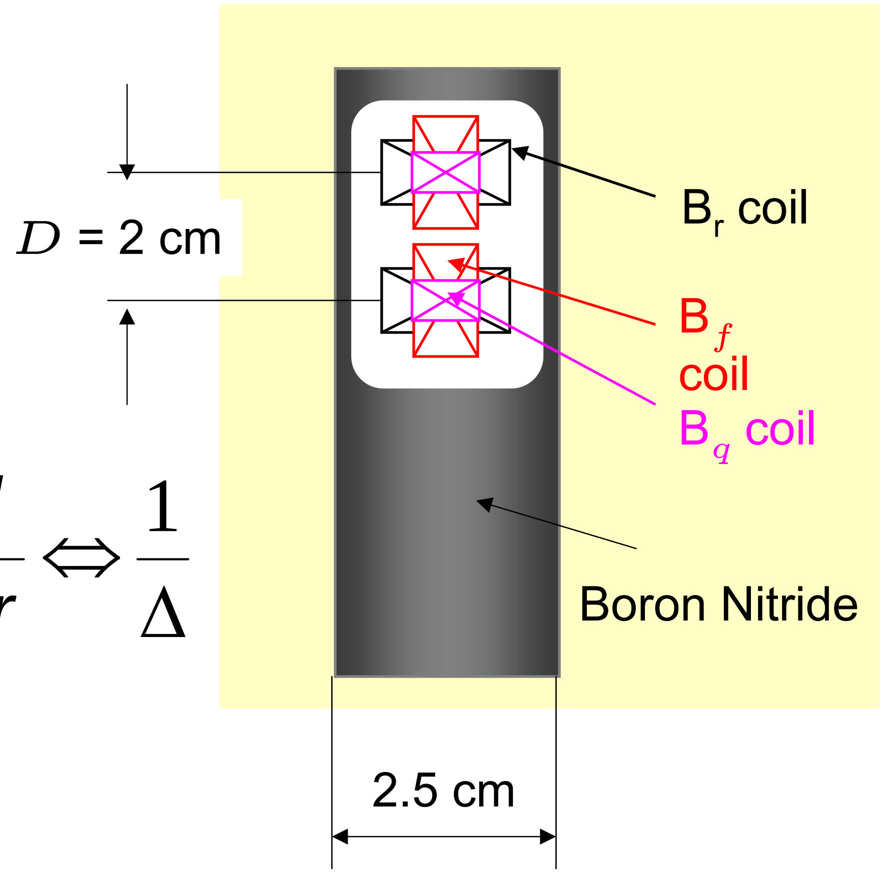
1. Reynolds stress: $\langle \tilde{\mathbf{v}} \nabla \tilde{\mathbf{v}} \rangle_\parallel$
2. Radial flow transport: $\frac{\Gamma_R}{n_i}\frac{\partial V_\parallel}{\partial r}$

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

See talk and poster by W.X. Ding for measurements of magnetically driven transport

Maxwell stress is measured by magnetic probe

Insertable magnetic probe measures all three magnetic field components simultaneously at two radial positions in the plasma edge



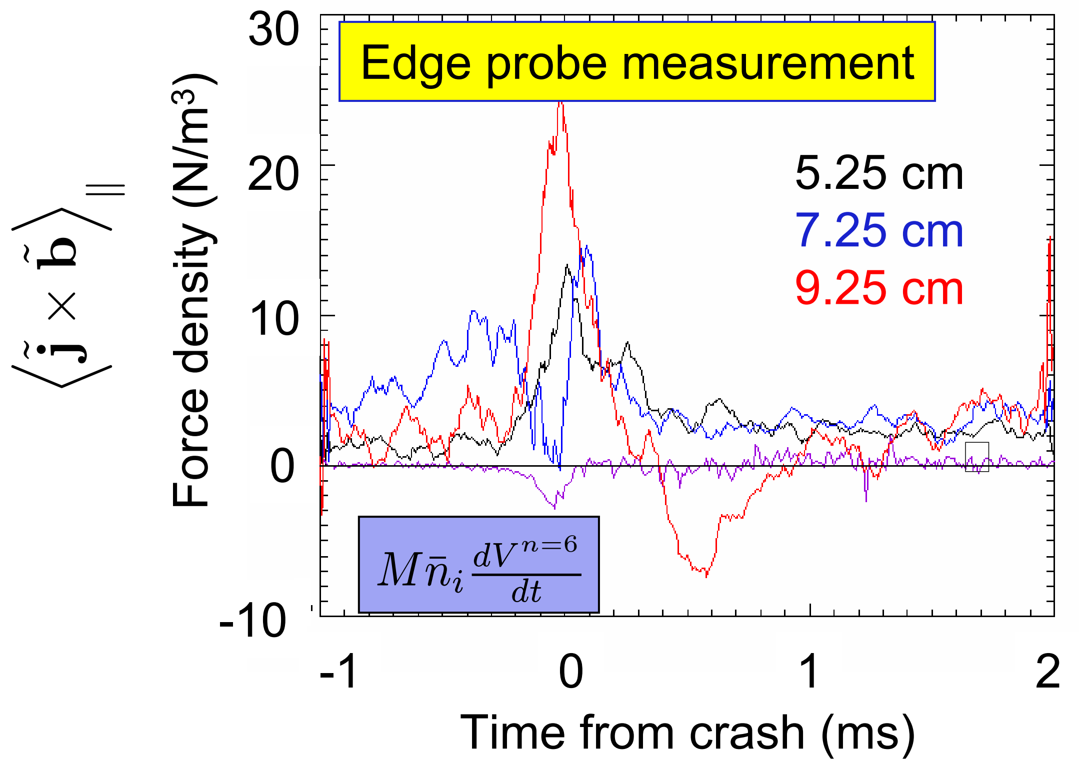
$$\frac{d}{dr} \Leftrightarrow \frac{1}{\Delta}$$

Maxwell stress:

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

< > denotes averaging over magnetic flux surface

Maxwell stress is large in the edge and in the core and opposes the flow change during sawtooth crash



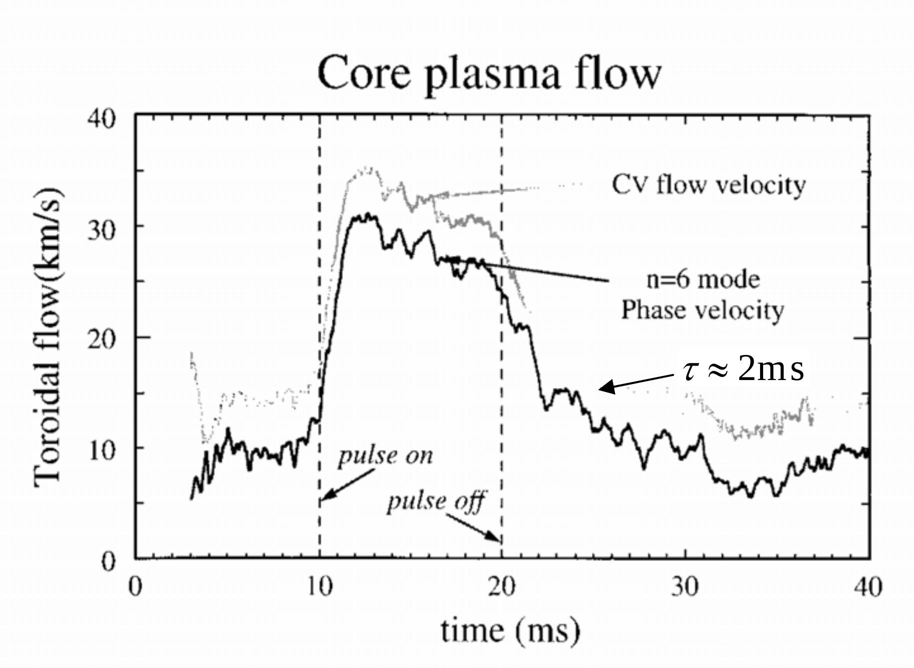
$$\frac{\left\langle \tilde{\mathbf{j}} \times \tilde{\mathbf{b}} \right\rangle_{\parallel}}{M_i n_i} \geq 10^9 \ \mathrm{m/s^2}$$

Core measurements (W. Ding *et. al.*) give similar results

In the quiescent plasma, Maxwell stress is in the direction of plasma rotation, but is still very large (W.X. Ding et. al.)

Edge plasma biasing experiment

A.F. Almagri et al, PoP'1998



Flow dumping after bias is turned off is governed by:

$$\frac{\partial V_\parallel}{\partial t} \approx \nu_\perp \nabla^2 V_\parallel$$

Anomalous viscosity:

$$\nu_\perp \approx \frac{(\Delta r)^2}{\tau_{sd}} = \frac{(0.37\ \mathrm{m})^2}{2\ \mathrm{ms}} = 55\ \mathrm{m}^2/\mathrm{s}$$

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

$$\frac{\partial V_\parallel}{\partial t} \approx \frac{-20\ \mathrm{km/s}}{2\ \mathrm{ms}} = -10^7\ \mathrm{m/s}^2$$

Expectation: possible x10 increase during reconnection

Local balance of Maxwell and Reynolds stresses during sawtooth crash results in very fine spatial scale of velocity fluctuations

Compare the momentum balance terms during reconnection:

$$\frac{\partial V_\parallel}{\partial t} = -\langle \tilde{\mathbf{v}} \nabla \tilde{\mathbf{v}} \rangle_\parallel + \frac{\left\langle \tilde{\mathbf{j}} \times \tilde{\mathbf{b}} \right\rangle_\parallel}{M_i n_i} + \nu \nabla^2 V_\parallel - \frac{\Gamma_R}{n_i}\frac{\partial V_\parallel}{\partial r} - \gamma_n V_\parallel$$

$\frac{\partial V_\parallel}{\partial t}$	$-\langle \tilde{\mathbf{v}} \nabla \tilde{\mathbf{v}} \rangle_\parallel$	$\frac{\langle \tilde{\mathbf{j}} \times \tilde{\mathbf{b}} \rangle_\parallel}{M_i n_i}$	$\nu \nabla^2 V_\parallel - \frac{\Gamma_R}{n_i}\frac{\partial V_\parallel}{\partial r} - \gamma_n V_\parallel$
$-10^8 \mathrm{m/s^2}$	$10^9 \mathrm{m/s^2}$	$10^9 \mathrm{m/s^2}$	$10^7 \mathrm{m/s^2}$ steady-state $10^8 \mathrm{m/s^2}$ reconnection

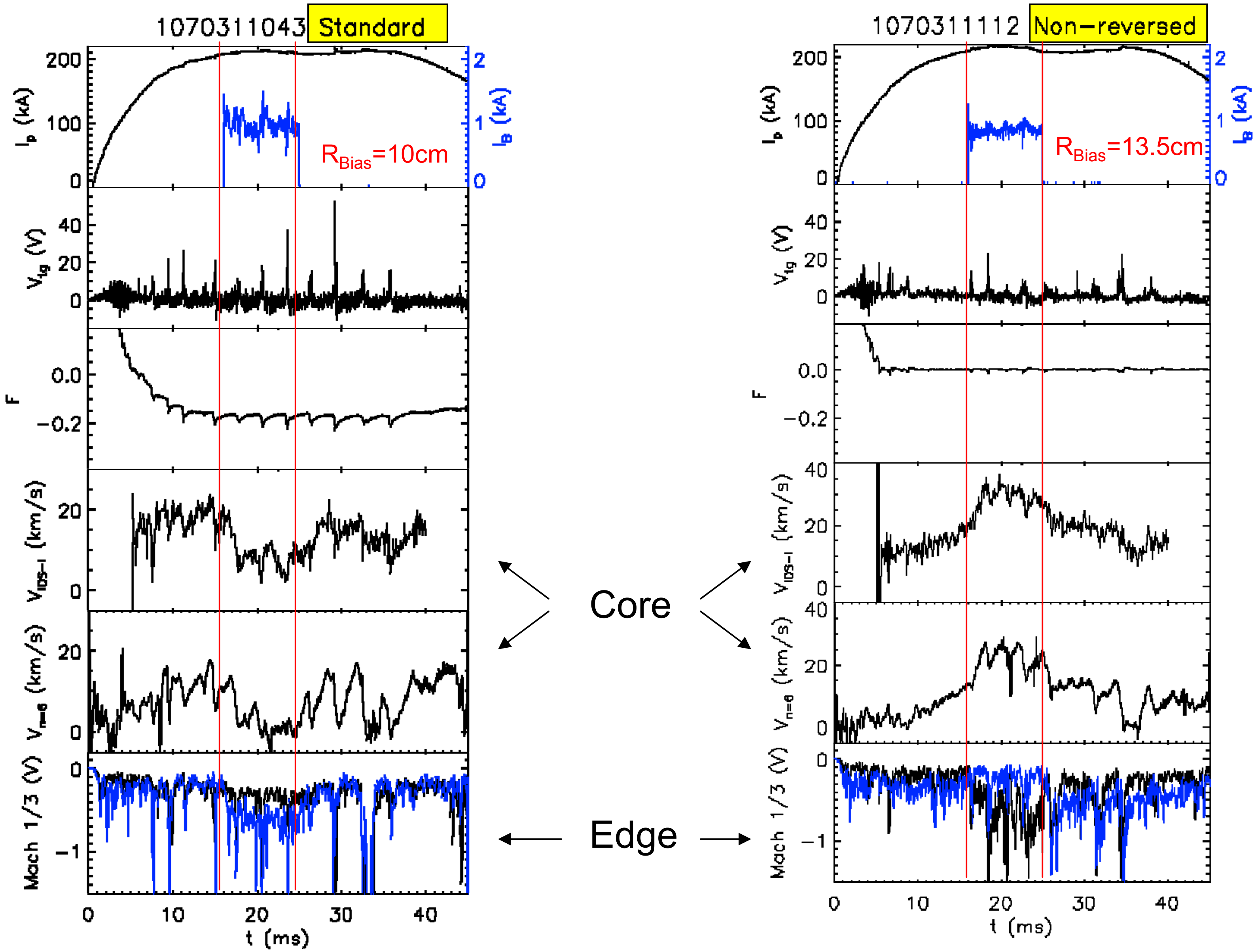
Local balance requires $\tilde{v}^2/\delta = 10^9 \mathrm{m/s^2}$

Measured (CHERS, Mach) $\tilde{v} \approx 5 \mathrm{km/s}$

Spatial scale of velocity fluctuations $\delta \approx 2 \mathrm{cm}$

This is also in agreement with EXTRAP direct measurements of the Reynolds stress in the edge

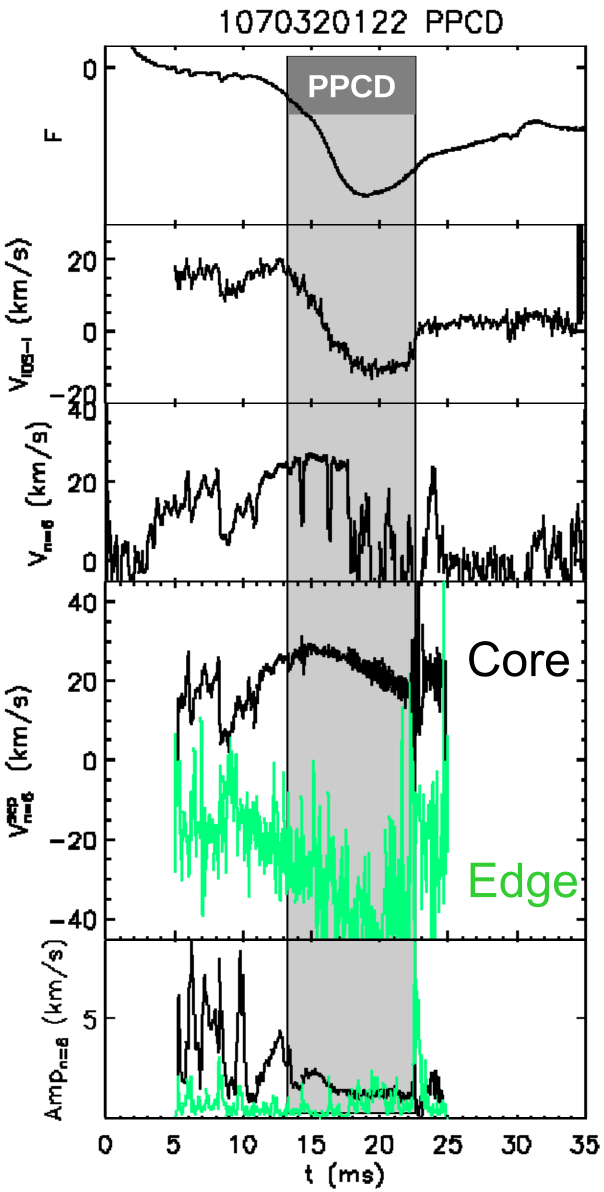
Edge biasing changes flow in the standard and F=0 plasmas



Edge biasing has weaker effect on plasma rotation in the improved confinement regime (PPCD) than in the standard regime

- Pulsed parallel (poloidal) current drive (PPCD) technique is applied to drive edge plasma current (replaces dynamo drive).
- Level of magnetic fluctuations is reduced.
- Magnetic flux surfaces in the core and restored, which leads to the reduction of transport and improved plasma confinement.
- Velocity measurements are challenging in PPCD.
- Preliminary data suggest that in the improved confinement regime it is harder to change toroidal plasma rotation with the edge biasing than in standard or non-reversed plasmas (velocity measurements are reliable only during first few ms).
- Toroidal CHERS system is under construction to perform local measurements of the plasma velocity in the core.

Determination of plasma rotation in PPCD is challenging

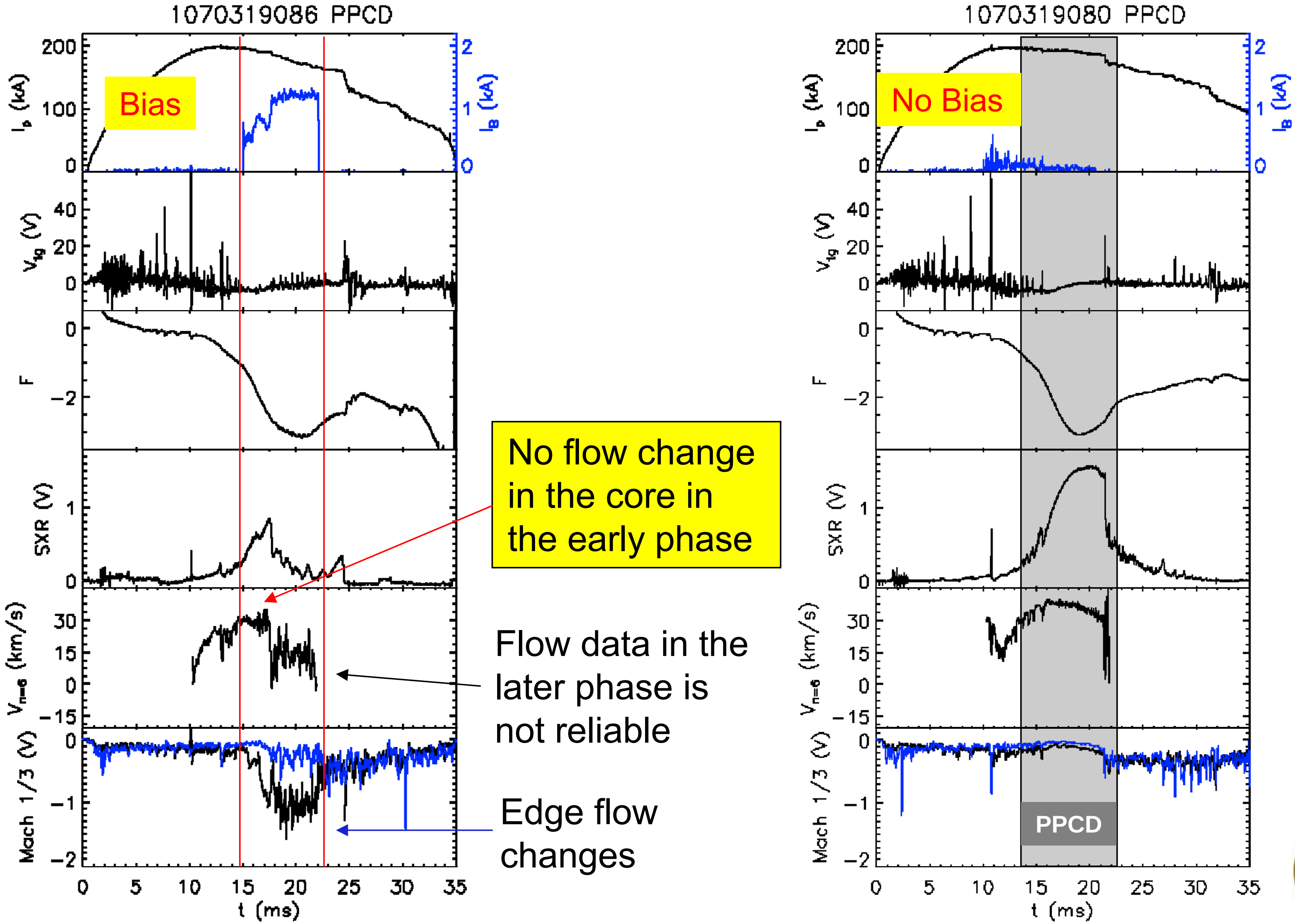


- Passive spectroscopy does not work well, because emission profile of CV line hollows in the core and shifts to the edge, when the core electron temperature increases as a result of improved confinement.

- Using mode rotation of the core m=1,n=6 mode as a proxy for the toroidal plasma rotation is also not straightforward, because the edge m=1,n=-6 mode becomes resonant in the edge during PPCD (when q profile becomes very negative) and mixes up with the core mode.

- However, since these edge and core modes are rotating in the opposite directions, their separation is possible under certain conditions.

In PPCD effect of biasing on the core plasma rotation is reduced



Summary

- Relaxation of the parallel momentum carried by the bulk ions is measured in the core and in the edge of the MST plasma during sawtooth crash. The parallel flow profile flattens in the core - similar to the electrical current.
- Maxwell stress measured in the edge and in the core is large - about 10 times larger than the inertial term and is in the opposite direction.
- This leads to a conclusion that other terms in the momentum balance must be important in the edge as well as in the core during reconnection events.
- Equating the Reynolds and Maxwell stresses results in a very fine spatial scale of the velocity fluctuations - about 2cm.
- Preliminary measurements show that the effect of edge biasing on plasma rotation is more pronounced in standard plasma than in PPCD, which implies that magnetic field line stochasticity affects the momentum transport in a quiescent plasma.