An Overview of Momentum Transport in Laboratory Plasmas

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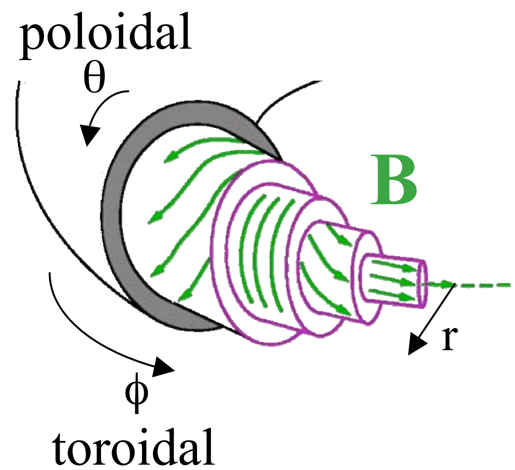
Outline

1. Overview of Flows and Tools in Center Devices
2. Momentum Transport in MST
3. Mechanisms for Momentum Transport
4. Open Questions

MST (Wisc) Experiment and Tools

$R = 1.5$ m
$a = 0.52$ m
$B \sim 0.2$ T

$n \sim 10^{19}$ m^{-3}
$T_{e,i} \sim 300$ eV
$\beta \sim 10$ %

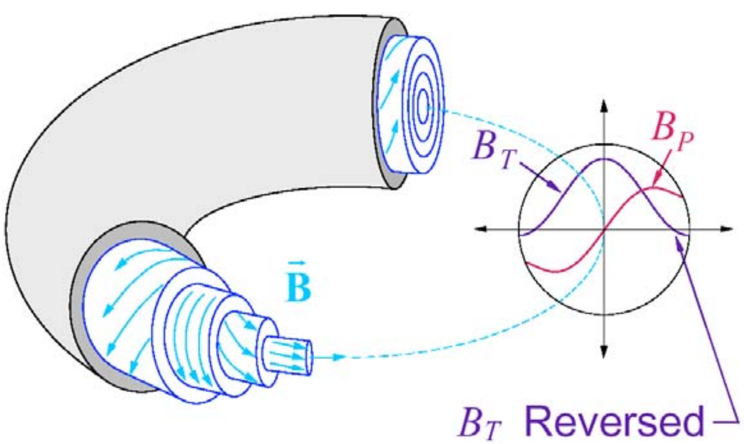


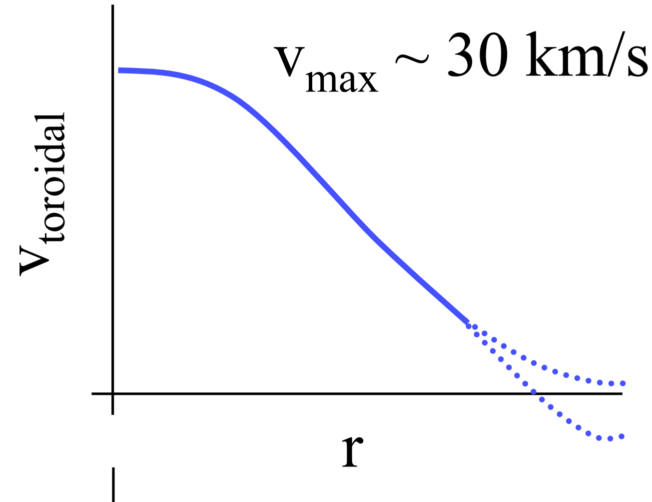
Tools for Momentum Transport Studies:

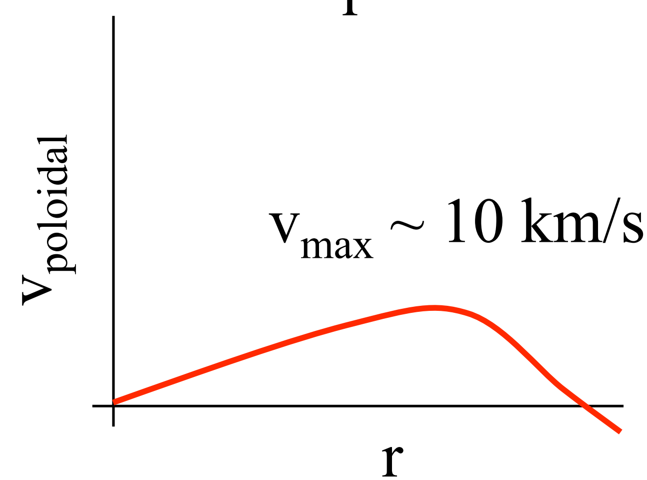
- 11-chord FIR Interferometer / Polarimeter
- Doppler Spectroscopy
  - Passive - chord averaged flow
  - Active Charge Exchange Recombination Spectroscopy (CHERS) with Neutral Beam (soon)
- Coil arrays - magnetic mode rotation
- Insertable probes - Langmuir, Mach, magnetic, spectroscopic (for Doppler)
- Auxiliary flow drivers
  - biased probes in edge - controlled edge flow
  - neutral beam in core (soon) - controlled core flow?

Subsonic Parallel and Perpendicular Global Flows Observed in MST

- Characteristic speeds in MST:
  $v_A \sim 10^6$ m/s and $v_{th} \sim 10^5$ m/s
- In core, v mostly parallel to B (and J)
- In edge, have $v_{parallel}$ and v_{perp}
- Origin of flows unclear
  (E_B and ∇P drifts consitent w/ v_{perp})

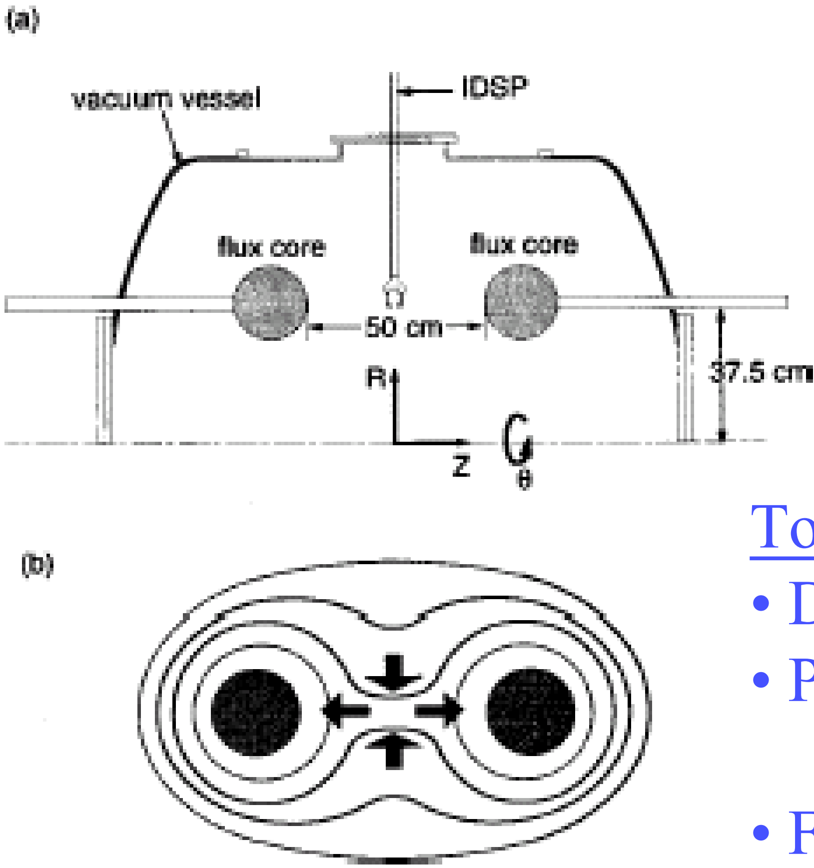






(sketches based on incomplete flow profile measurements)

MRX (Princeton) Experiment and Tools



$n = 1\text{-}20 \times 10^{19}\ m^{-3}$

$T = 4\text{-}30$ eV

$B = 0.05$ T

$\beta = 0.1\text{-}10$

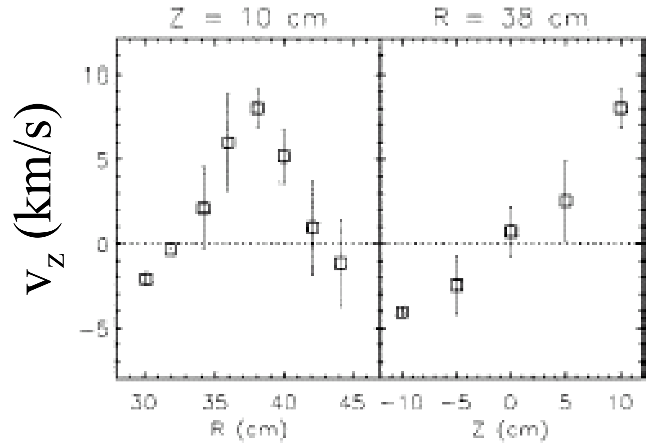
Tools for momentum transport study:

- Doppler spectroscopy
- Probes - Langmuir, Mach, magnetic, spectroscopic (Doppler)
- Flexible magnetic configuration

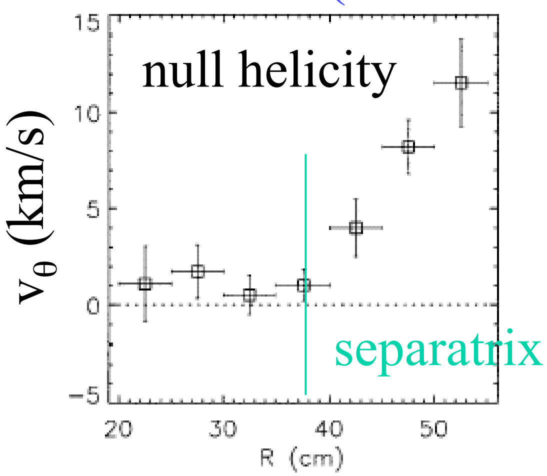
Flow Observations in MRX

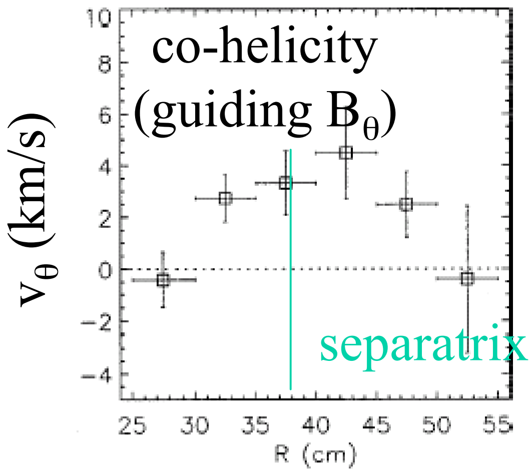
- Characteristic speeds in MRX:
  - $v_A \sim 4 \times 10^4$ m/s (He plasma)
  - $v_{th} \sim 3 \times 10^4$ m/s
- Two kinds of flows:
  1. v associated with reconnection
  2. toroidal (azimuthal) flows
     → origin not fully understood

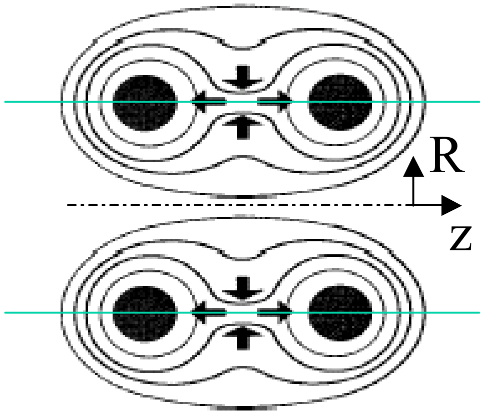
Reconnection flows



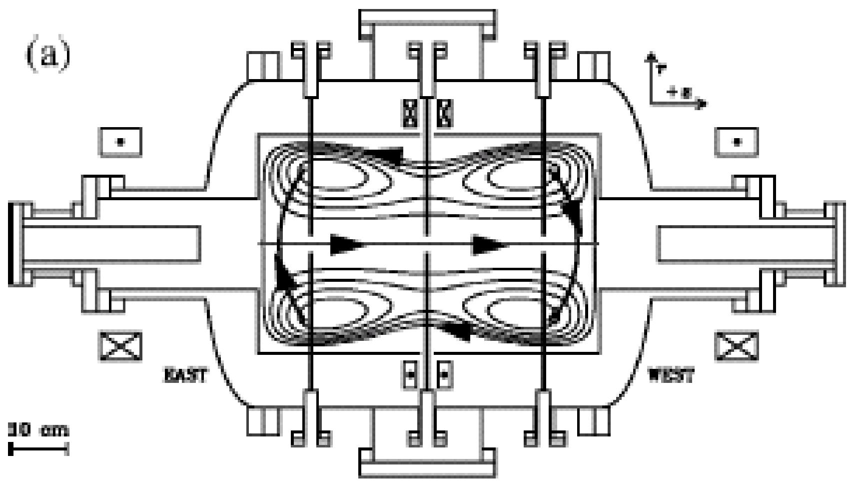
Toroidal (out of reconnection plane) flows







SSX (Swarthmore) Experiment and Tools



$n = 1\text{-}100 \times 10^{19}\ m^{-3}$

$T = 20$ eV

$B = 0.2$ T

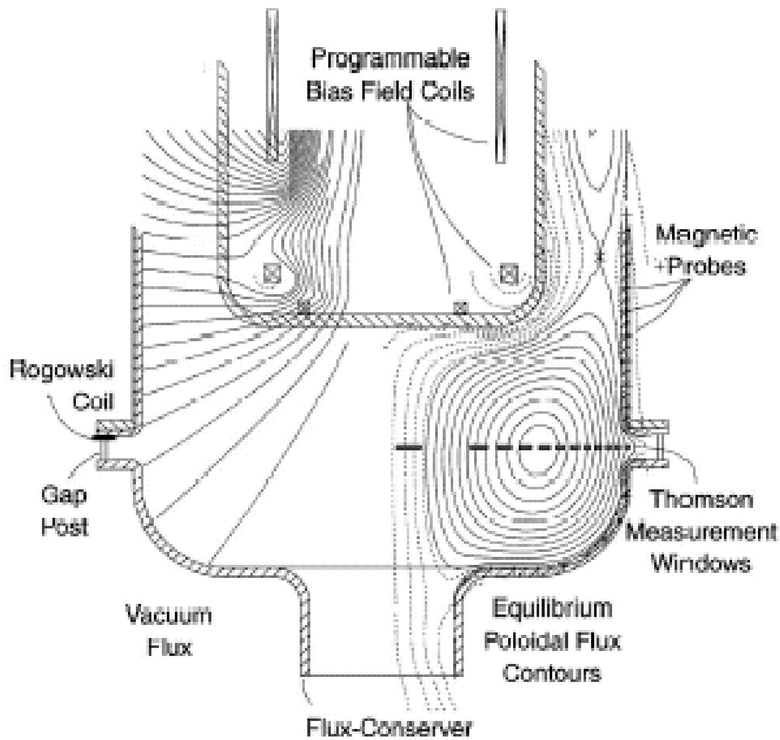
$\beta = 0.1\text{-}1$

$v_A \sim 4 \times 10^5$ m/s

$v_{th} \sim 4 \times 10^4$ m/s

- Observe bulk flows with $v \sim 0.2\text{-}0.4\ v_A \sim v_{th}$
- Flow mostly toroidal, perpendicular to B
- Very dynamic plasma - merging, tilting, etc.
- Tools for momentum transport study:
  - Probes - Mach, magnetic
  - Doppler spectroscopy (soon)
  - Flexible magnetic configuration

SSPX (LLNL) Experiment



$n = 2\text{-}10 \times 10^{19}\ m^{-3}$

$T = 20\text{-}200$ eV

$B = 0.6$ T

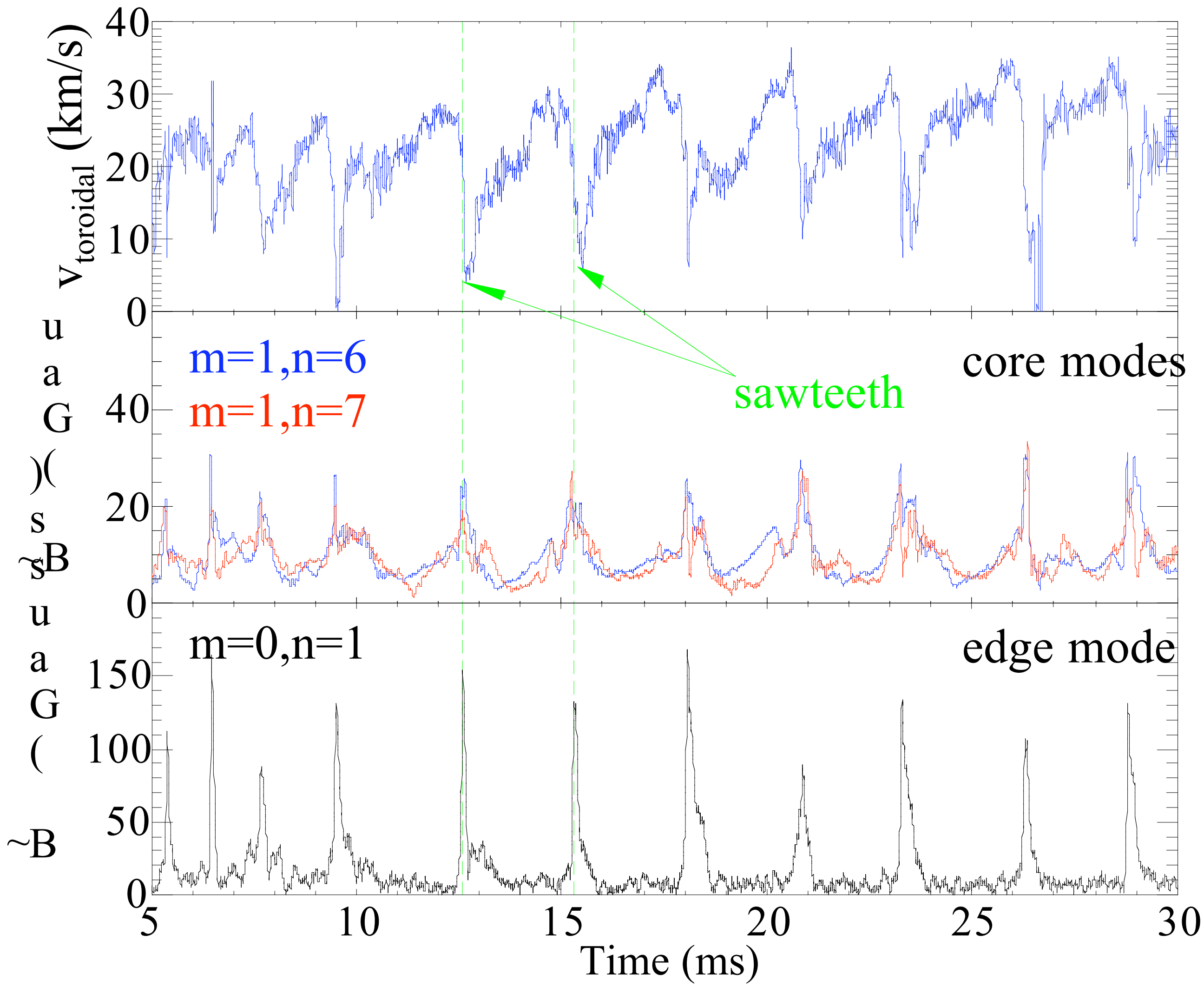
$\beta \sim 10\%$

$v_A \sim 2 \times 10^6$ m/s

$v_{th} \sim 2 \times 10^5$ m/s

- Observe toroidal flows ~ 6×10^4 m/s during startup
  - possibly driven by strong $E_{applied} \times B$ at boundary
- Tools for momentum transport study:
  - Doppler spectroscopy (only in first 100 μs)
  - Coil arrays - magnetic mode rotation

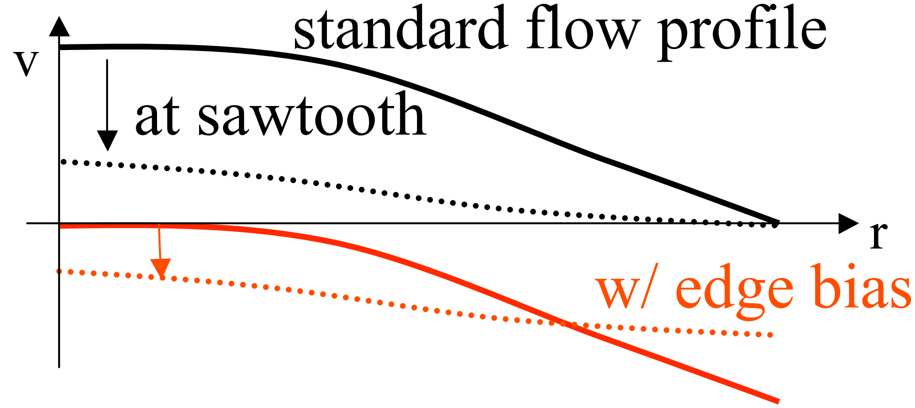
Core Momentum Changes Rapidly During Sawtooth Events in MST

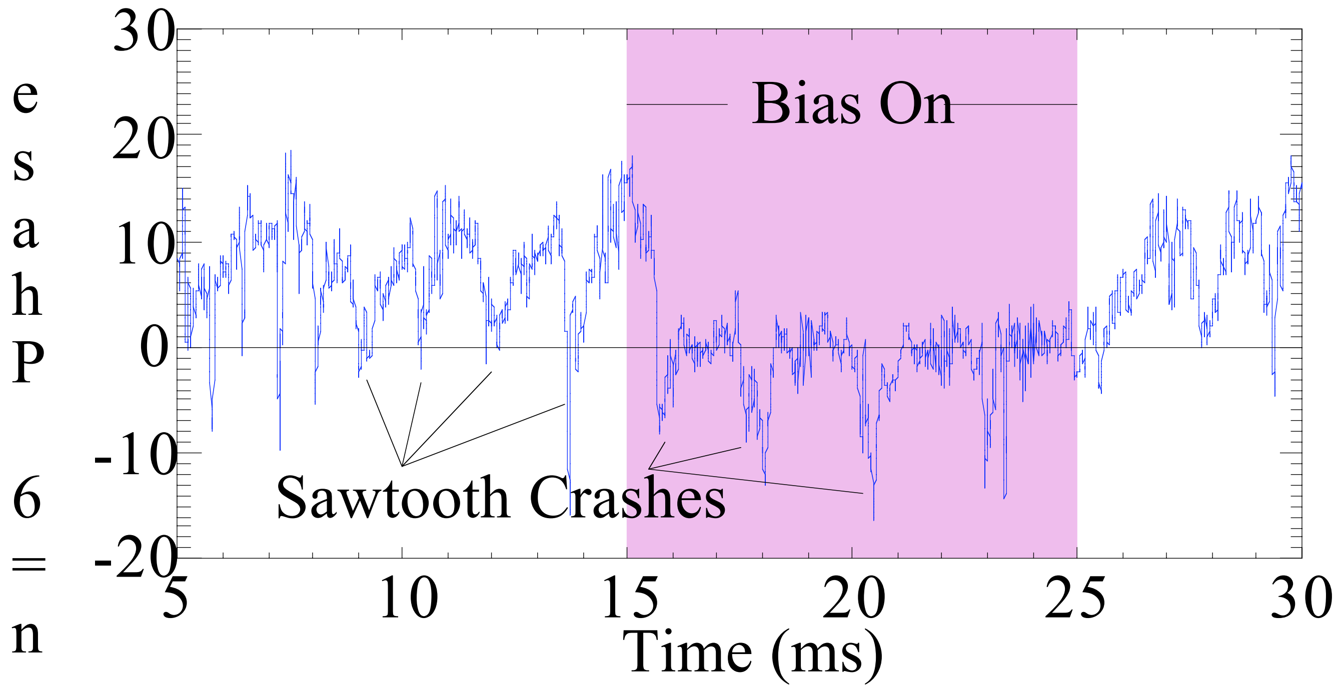


- Core rotation slows in ~ 100 μs
- Not classical
  - 100 times too fast
  - n, T, ... do not change enough on this timescale
- Core and edge magnetic fluctuations peak strongly

Momentum is *Transported* from Core to Edge

- How do we know it's not just momentum loss?
- Use biased probe in edge to shift flow profile down

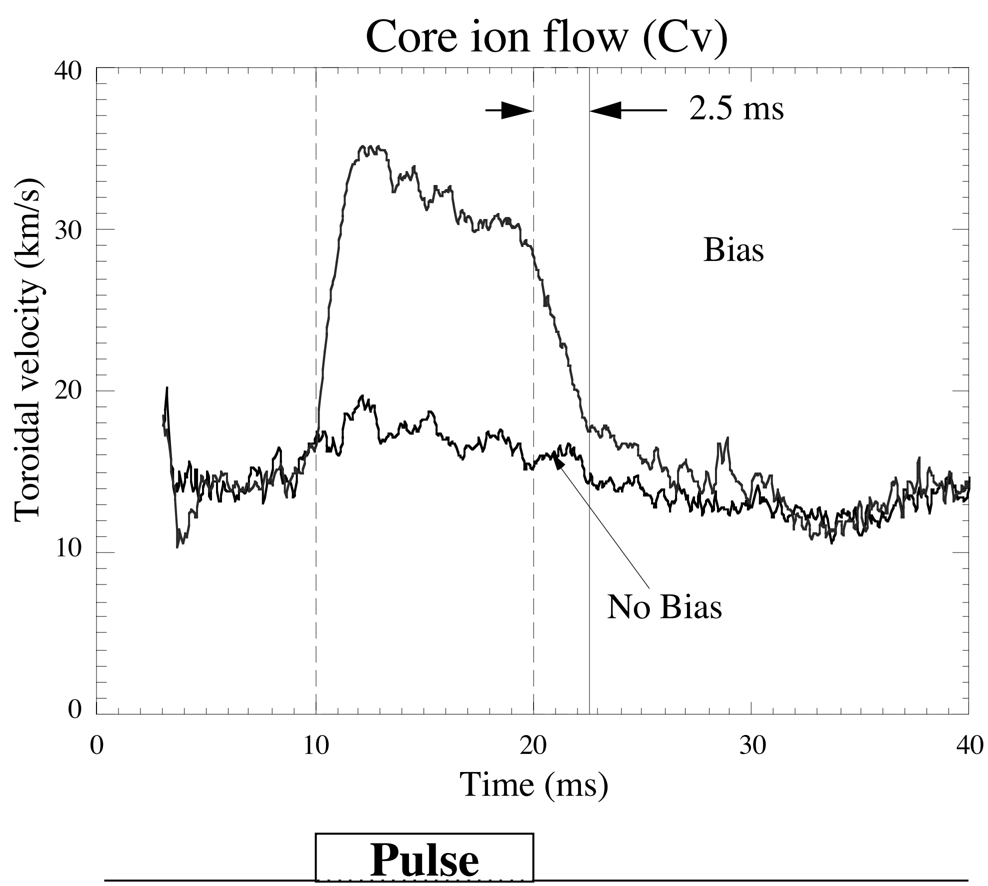




- Core then *speeds up* to rotate with edge at crashes

Flow Damping Experiments

- Using biased probes, create square pulse of high speed *edge* flow and watch *core* response.
- Core responds with ~1-3 ms delay.



Classical ion-ion damping time is ≥ 100 ms

Classical Mechanisms for Momentum Transport

- Classical collisions (ion-ion, ion-neutral, …)
  - not dominant in Center devices ($\tau > 100$ ms in MST)
- Modification of classical viscosity by non-uniform B (trapping)
  - important in other fusion devices; may be in Center devices too ($\tau \sim 1$-10 ms in MST)
- Neutral Particles - charge exchange momentum transfer
  - probably important in Center devices ($\tau \sim 1$-10 ms in MST)

Fluctuation Mechanisms for Momentum Transport

- Convective momentum transport
  - may be important in Center Devices ($\tau \sim$ 1-10 ms in MST)
- Reynolds Stress → $\nabla \cdot (\mathbf{v_k v_k})$ (contained in $\mathbf{v_k} \cdot \nabla \mathbf{v_k}$)
  - important in tokamak edge; unclear in Center devices ($\tau \sim$ 10 ms)
- Magnetic fluctuations (topic of most interest for Center)

  → J_k x B_k = magnetic analog of Reynolds Stress $\nabla \cdot (\mathbf{B_k B_k})$
  - important in MST ($\tau \sim$ 0.1 ms), unknown in other devices
  - MRI effects come through this term

  → Particle motions in stochastic field lines
  - may be important ($\tau \sim$ 30 ms in MST)

Magnetic Maxwell Stress From Nonlinearly Coupled Tearing Modes

- Nonlinear mode coupling can give $\tilde{J}_{\mathbf{k}} \sim \tilde{B}_{\mathbf{k'}} \tilde{B}_{\mathbf{k-k'}}$
- Toroidal forces at resonant positions where $\mathbf{k}\cdot\mathbf{B} = 0$
- Forces are differential (3 forces at 3 locations all add to 0)
- Force for mode **k** has the form:

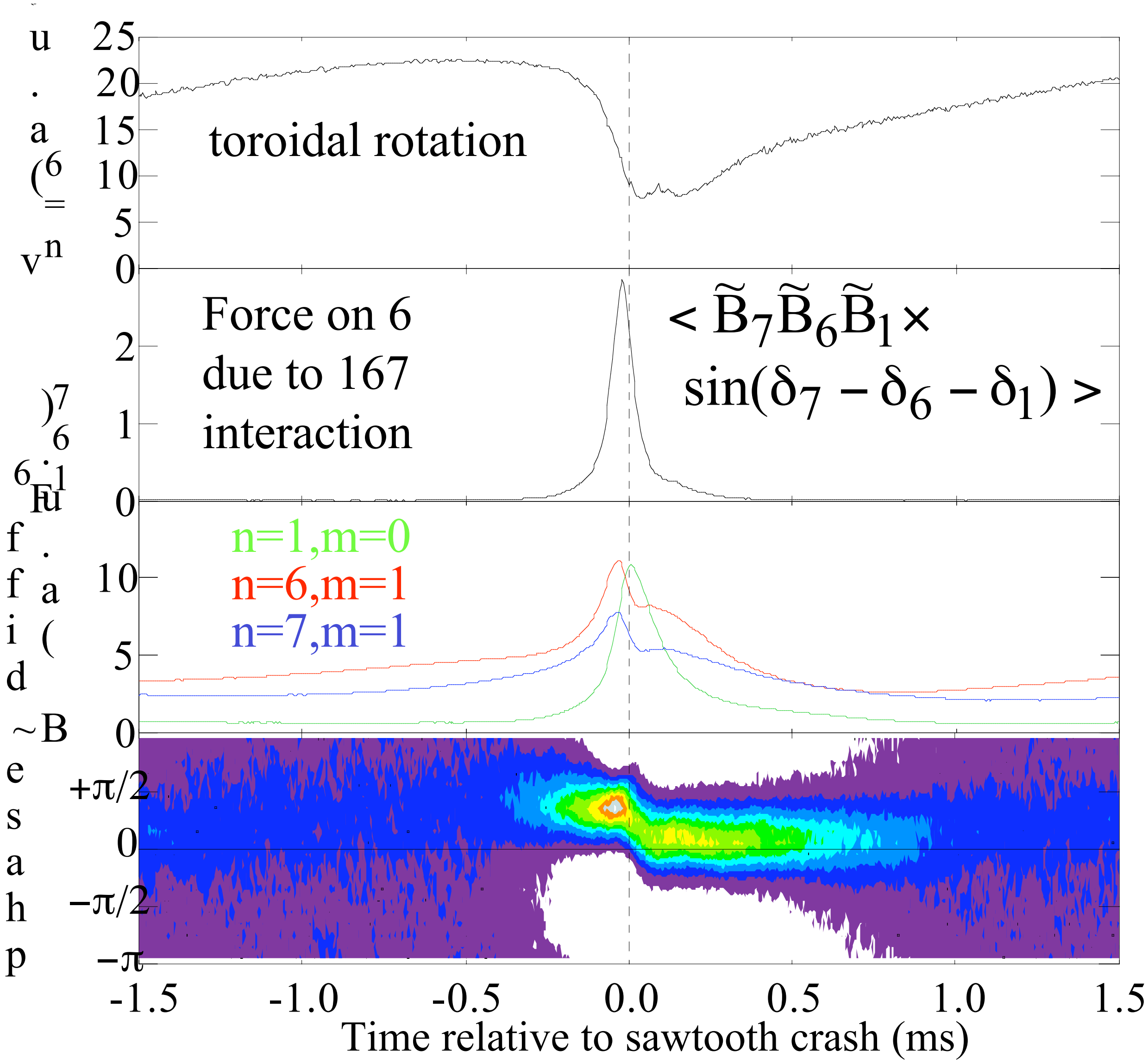
$$F_{\mathbf{k}} \sim \sum_{\mathbf{k'}} C_{\mathbf{k,k',k-k'}} B_{\mathbf{k}} B_{\mathbf{k'}} B_{\mathbf{k-k'}} \sin(-\delta_{\mathbf{k}} + \delta_{\mathbf{k'}} + \delta_{\mathbf{k-k'}})$$

coupling coefficient

phases of modes

For more see: C.C. Hegna, Phys. Plasmas **3**, 4646 (1996)
R. Fitzpatrick, Phys. Plasmas **6**, 1168 (1999)

Mode Amplitudes and Phases Combine to Give Mean J_B Forces in MST



- Average many similar sawteeth together (1700)
- Mean J×B force has right time dependence
- Force peaks due to amplitude rise <u>and</u> appearance of preferred phase between modes

Summary of Experimental Evidence for Magnetic Maxwell Stress in MST

- Non-classical core momentum change during sawteeth
- Momentum is redistributed between core and edge
- Core and edge magnetic fluctuations burst strongly
- Phases of coupled modes align to produce $\langle \tilde{\mathbf{J}} \times \tilde{\mathbf{B}} \rangle$ which matches $\rho \frac{\partial v_\phi}{\partial t}$ in time dependence and magnitude (*inferred from edge measurements of B*)
- *Core* momentum change disappears when *edge* modes are removed from plasma
- Direct measurement of $\langle \tilde{\mathbf{J}} \times \tilde{\mathbf{B}} \rangle$ still needed

Parallel Momentum Relaxation

- Taylor relaxation - single fluid MHD
  - → Global helicity ($\int \mathbf{A}\cdot\mathbf{B}\, dV$) "conserved"
  - → Relax to minimum magnetic energy (via v×B)
  - → Constant $\mathbf{J}\cdot\mathbf{B}/B^2$ profile
- 2-fluid relaxation (e.g. see C.C. Hegna, *Phys Plasmas* **5**, 2257 (1998) and refs)
  - → Generalized helicity for each species ($\int \mathbf{A}_s\cdot\mathbf{B}_s\, dV$) is "conserved"
    where $\mathbf{A}_s = \mathbf{A} + (m_s/q_s)\, \mathbf{v}_s$ and $\mathbf{B}_s = \nabla\times\mathbf{A}_s$
  - → Relax to minimum magnetic + flow energy (via v×B and J×B)
  - → Constant $\mathbf{J}\cdot\mathbf{B}/B^2$ and $n\mathbf{v}\cdot\mathbf{B}/B^2$ profiles
  - → Parallel current and parallel momentum profiles get coupled
- Open question whether this actually happens in lab or space

Open Questions

- Origin of flows
  - unknown in all 4 Center devices
  - can think of this as momentum transport problem
  - couples to turbulent particle and energy transport
    - → e.g. non-ambipolar transport gives $E \Rightarrow v$
- Momentum evolution during relaxation
  - Is $\langle J \times B \rangle$ from fluctuations important in our experiments?
    - → Can this be measured directly?
  - Are flow and current profiles coupled in lab?
- Are there astrophysical situations where lab transport mechanisms may apply or vice-versa?
  - Do coupled magnetic fluctuations produce momentum transport as a general feature?
  - Is 2-fluid relaxation a useful paradigm?