

An Overview of Momentum Transport in Laboratory Plasmas

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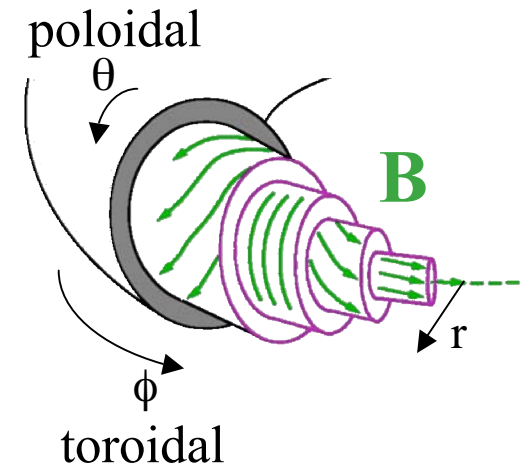
Planning Meeting of *Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas*

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

$$\begin{array}{ll} R = 1.5 \text{ m} & n \sim 10^{19} \text{ m}^{-3} \\ a = 0.52 \text{ m} & T_{e,i} \sim 300 \text{ eV} \\ B \sim 0.2 \text{ T} & \beta \sim 10 \% \end{array}$$

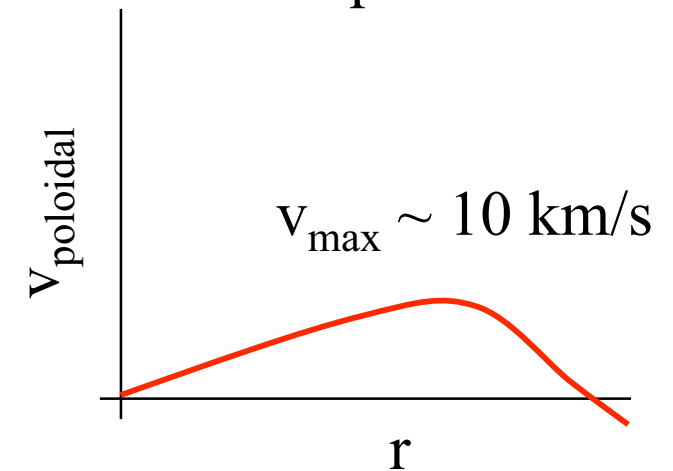
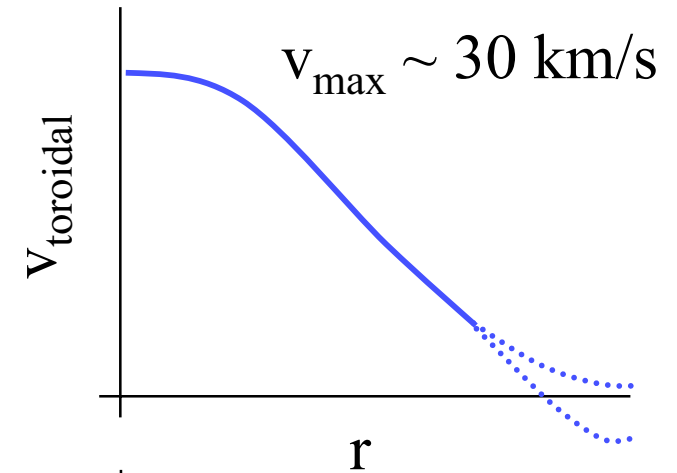
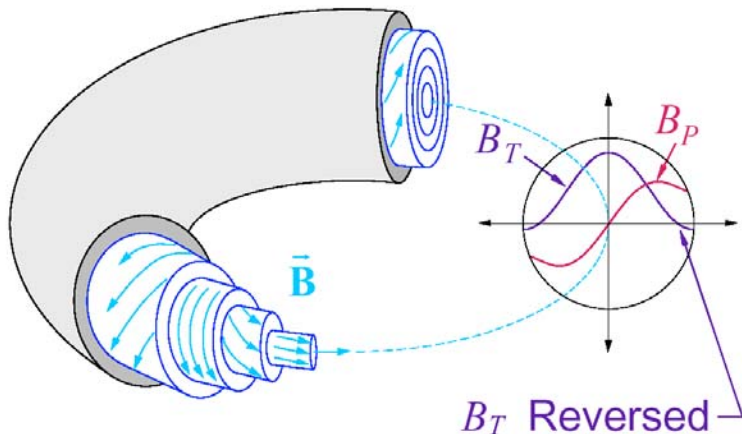


Tools for Momentum Transport Studies:

- 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?

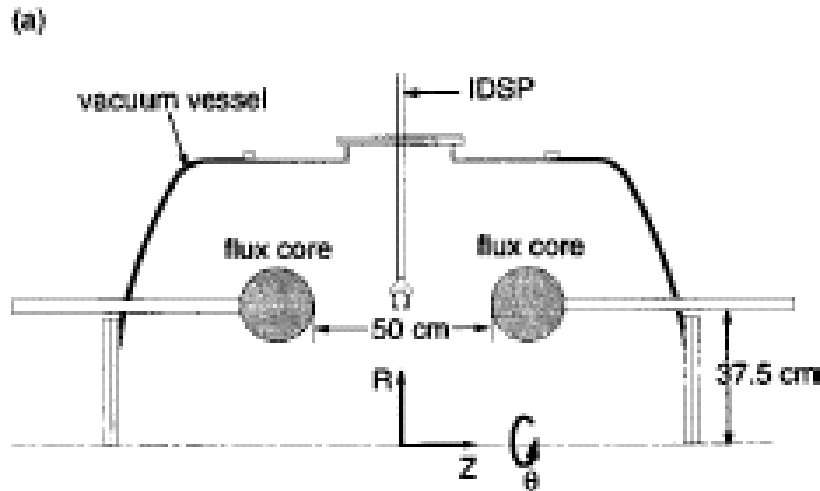
Subsonic Parallel and Perpendicular Global Flows Observed in MST

- Characteristic speeds in MST:
 $v_A \sim 10^6 \text{ m/s}$ and $v_{th} \sim 10^5 \text{ m/s}$
- 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 consistent w/ v_{perp})



(sketches based on incomplete flow profile measurements)

MRX (Princeton) Experiment and Tools

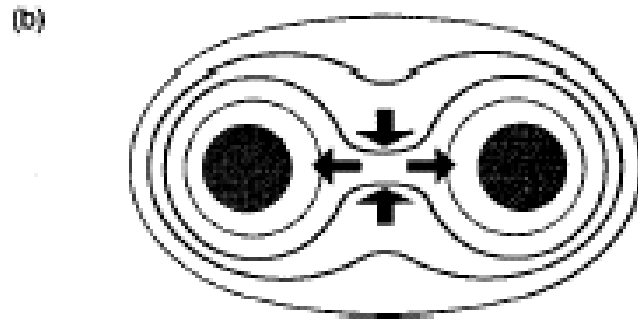


$$n = 1-20 \times 10^{19} \text{ m}^{-3}$$

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

$$B = 0.05 \text{ T}$$

$$\beta = 0.1-10$$



Tools for momentum transport study:

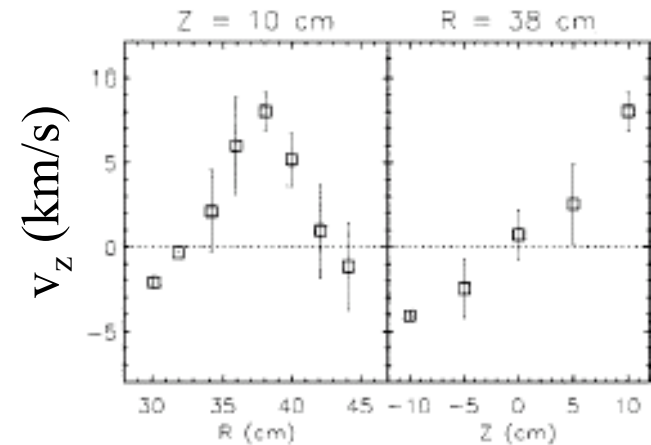
- Doppler spectroscopy
- Probes - Langmuir, Mach, magnetic, spectroscopic (Doppler)
- Flexible magnetic configuration

Flow Observations in MRX

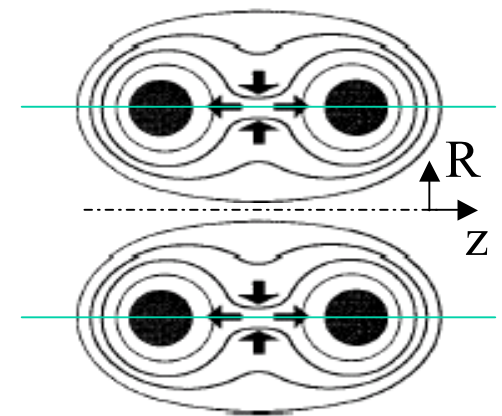
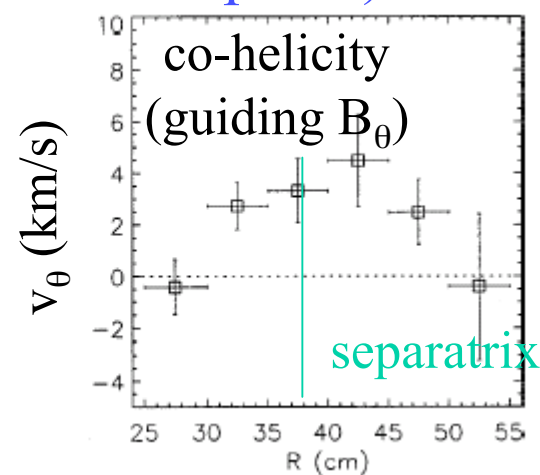
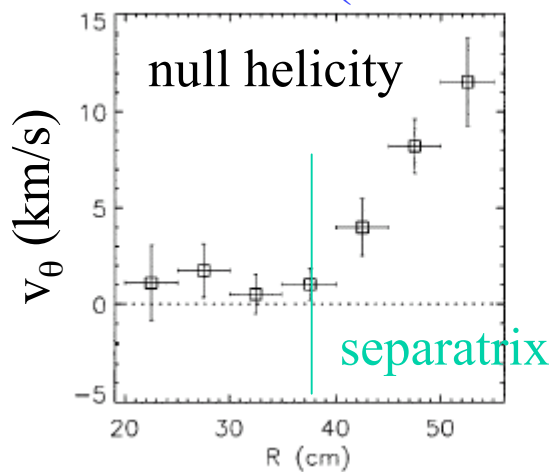
- Characteristic speeds in MRX:
 - $v_A \sim 4 \times 10^4 \text{ m/s}$ (He plasma)
 - $v_{th} \sim 3 \times 10^4 \text{ m/s}$
- Two kinds of flows:
 1. v associated with reconnection
 2. toroidal (azimuthal) flows

→ origin not fully understood

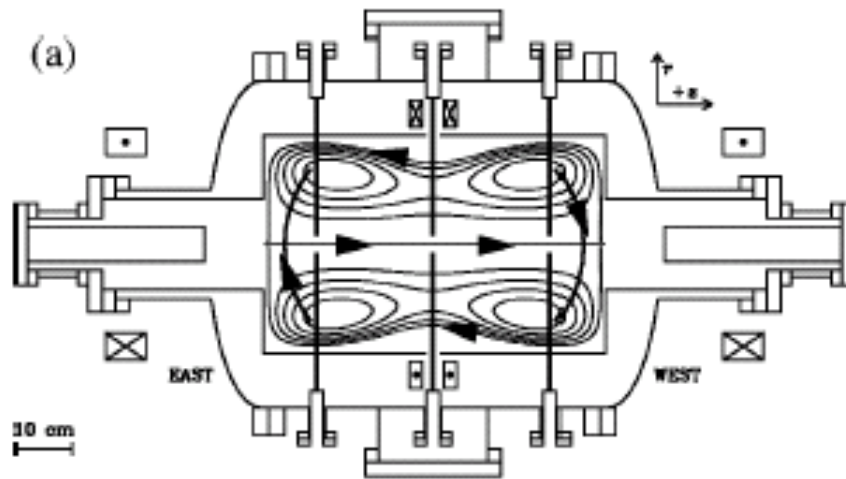
Reconnection flows



Toroidal (out of reconnection plane) flows



SSX (Swarthmore) Experiment and Tools



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

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

$$B = 0.2 \text{ T}$$

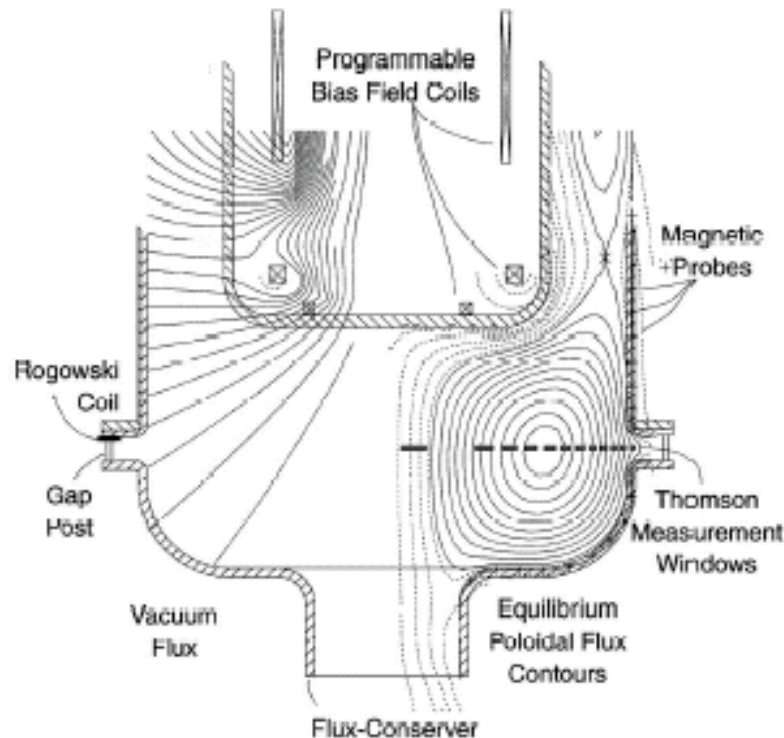
$$\beta = 0.1-1$$

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

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

- Observe bulk flows with $v \sim 0.2-0.4 v_A \sim v_{th}$
- 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



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

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

$$B = 0.6 \text{ T}$$

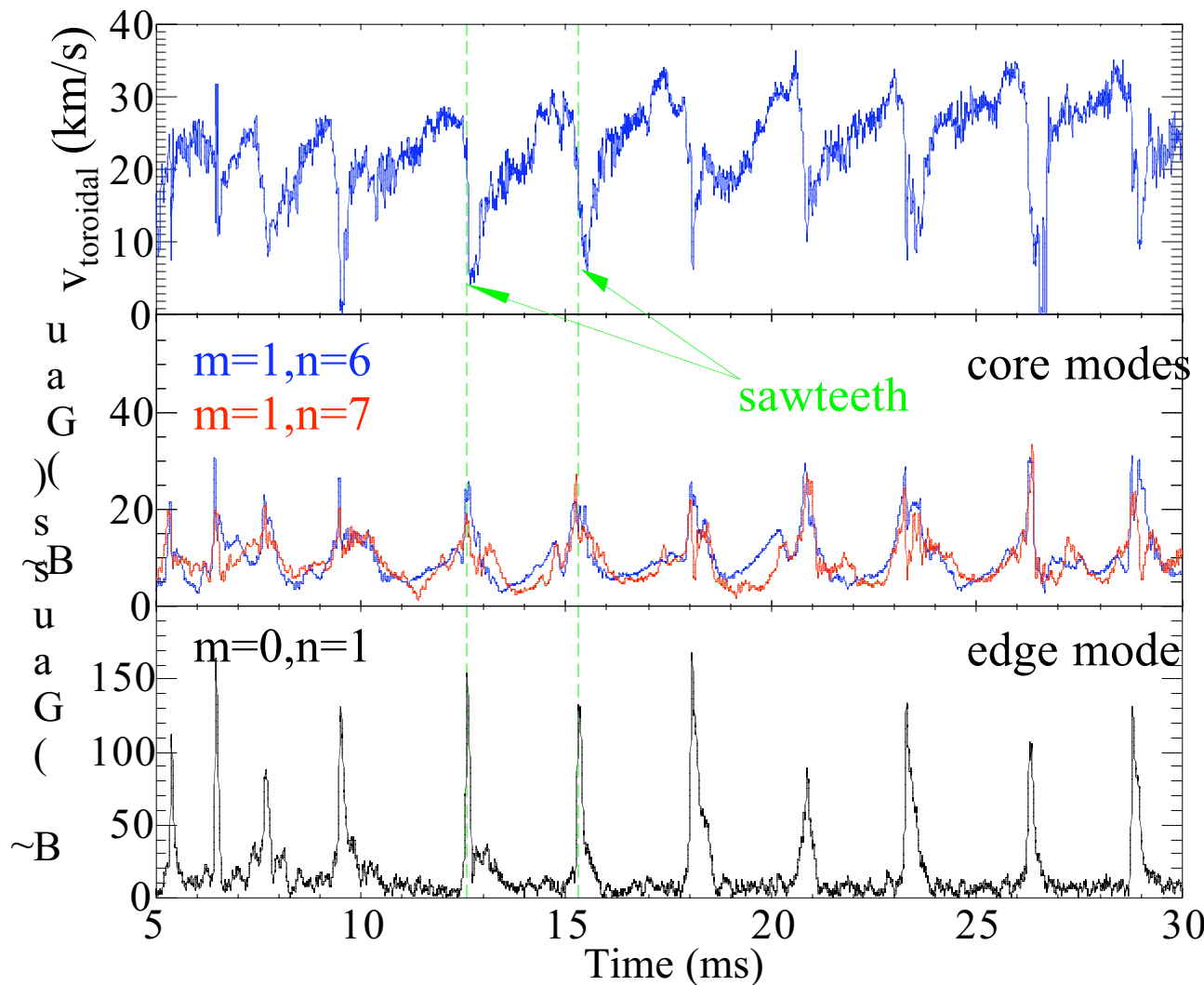
$$\beta \sim 10\%$$

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

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

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

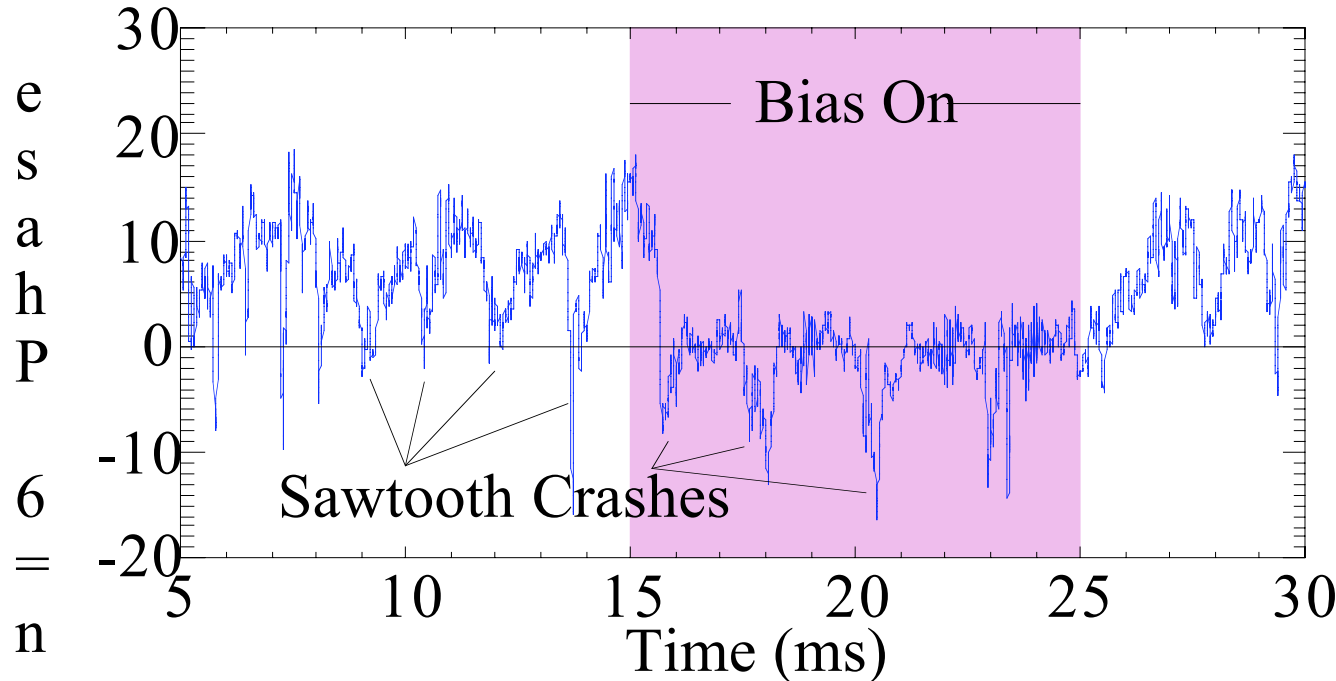
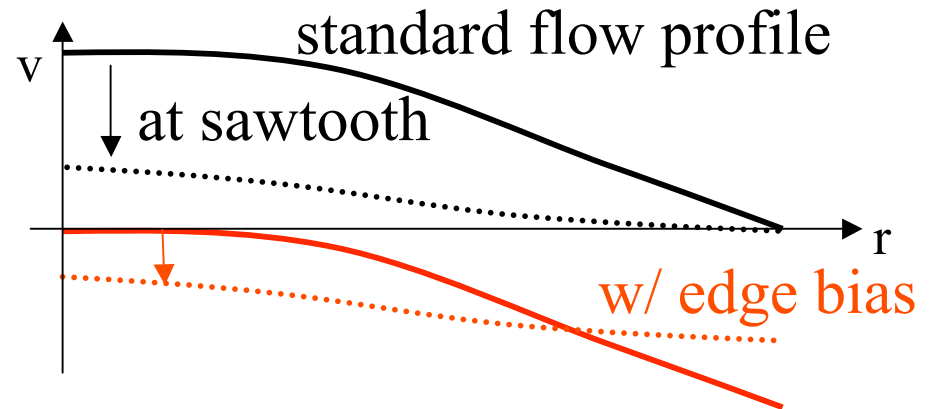
Core Momentum Changes Rapidly During Sawtooth Events in MST



- Core rotation slows in $\sim 100 \mu\text{s}$
- Not classical
 - 100 times too fast
 - n, T, \dots do not change enough on this timescale
- Core and edge magnetic fluctuations peak strongly

Momentum is *Transported* from Core to Edge

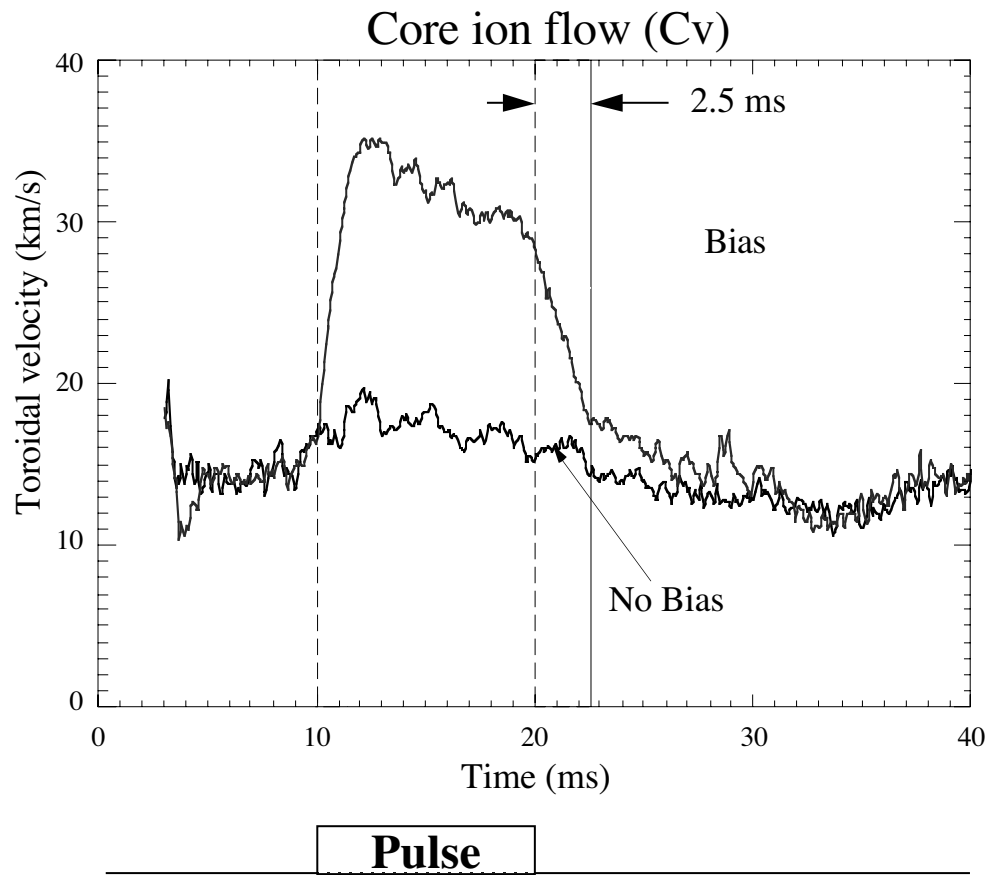
- How do we know it's not just momentum loss?
- Use biased probe in edge to shift flow profile down



- 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 $\sim 1-3$ 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 $\rightarrow \nabla \cdot (\mathbf{v}_k \mathbf{v}_k)$ (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**)
 - $\rightarrow \mathbf{J}_k \times \mathbf{B}_k =$ magnetic analog of Reynolds Stress $\nabla \cdot (\mathbf{B}_k \mathbf{B}_k)$
 - important in MST ($\tau \sim 0.1$ ms), unknown in other devices
 - MRI effects come through this term
 - \rightarrow 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 $\tilde{\mathbf{J}}_{\mathbf{k}} \sim \tilde{\mathbf{B}}_{\mathbf{k}'} \tilde{\mathbf{B}}_{\mathbf{k}-\mathbf{k}'}$
- 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 \mathbf{k} has the form:

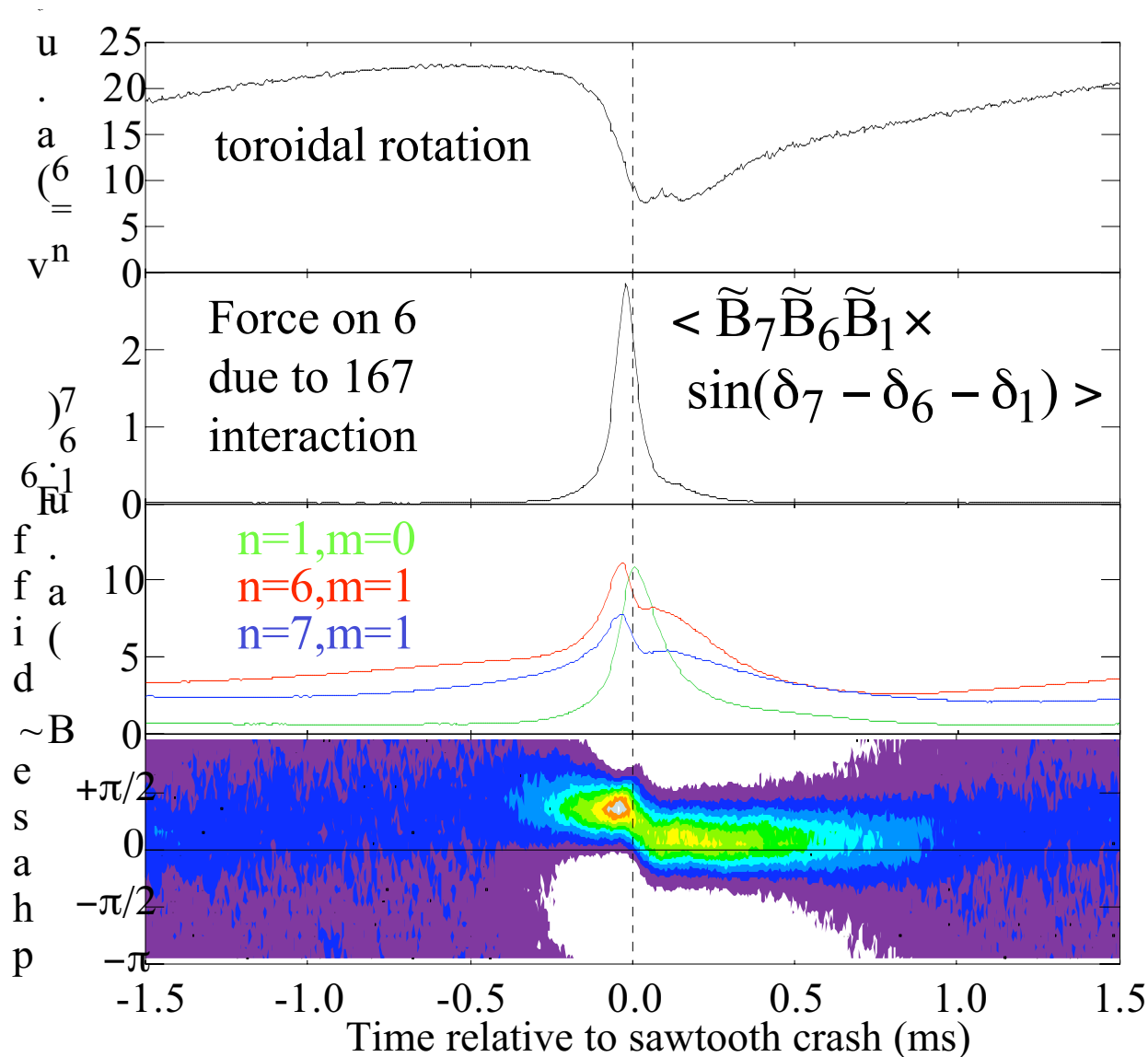
$$F_{\mathbf{k}} \sim \sum_{\mathbf{k}'} C_{\mathbf{k},\mathbf{k}',\mathbf{k}-\mathbf{k}'} B_{\mathbf{k}} B_{\mathbf{k}'} B_{\mathbf{k}-\mathbf{k}'} \sin(-\delta_{\mathbf{k}} + \delta_{\mathbf{k}'} + \delta_{\mathbf{k}-\mathbf{k}'})$$

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 $J \times B$ force has right time dependence
- Force peaks due to amplitude rise and 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 $\mathbf{v} \times \mathbf{B}$)
 - 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 $\mathbf{v} \times \mathbf{B}$ and $\mathbf{J} \times \mathbf{B}$)
 - 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?