NSTX

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Intrinsic Rotation Generation in NSTX Ohmic H-mode Plasmas

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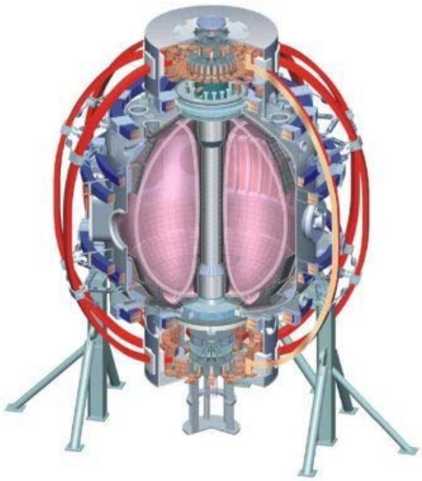

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Introduction

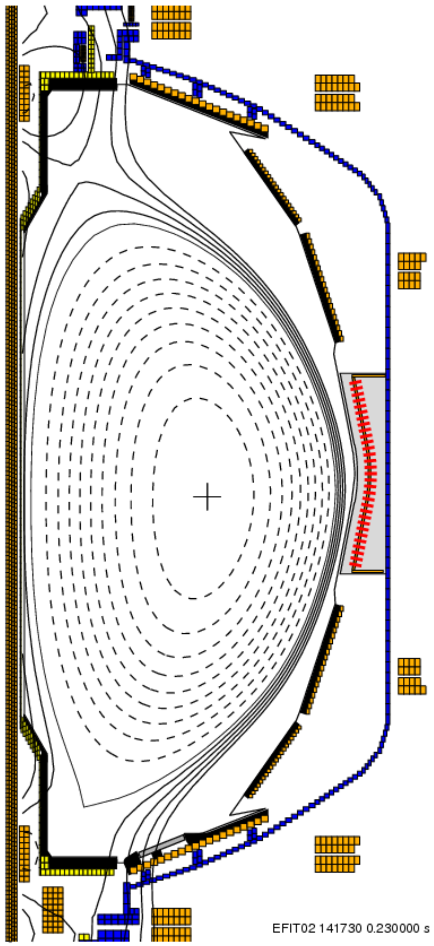
- Intrinsic torque and rotation generation have been observed by passive CHERS, in NSTX Ohmic L-H transition
  - There were Ohmic H-mode plasmas in NSTX (C. Bush, S. Kubota)
  - Passive CHERS provides ion temperature and rotation information

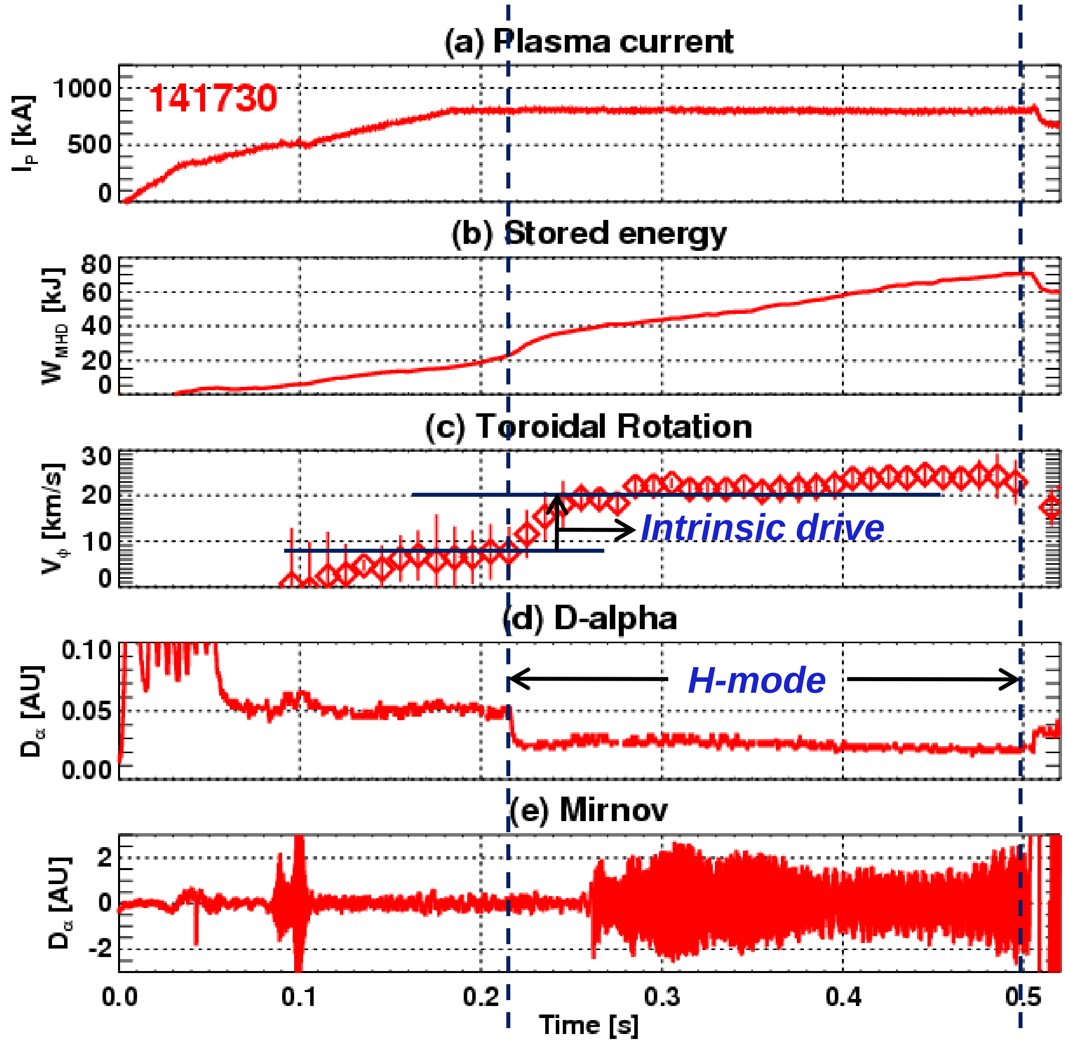
- Rotation jump is clear and perhaps highly free from 'non-intrinsic' torques
  - No NBIs, weak NTVs, short periods for rotation evolution

- Study of intrinsic torque in NSTX can provide unique information and data for STs
  - Intrinsic torque and rotation vs. thermodynamic forces
  - Intrinsic torque and rotation scaling, and Rice scaling

Intrinsic rotation in Ohmic L-H transition (#1)

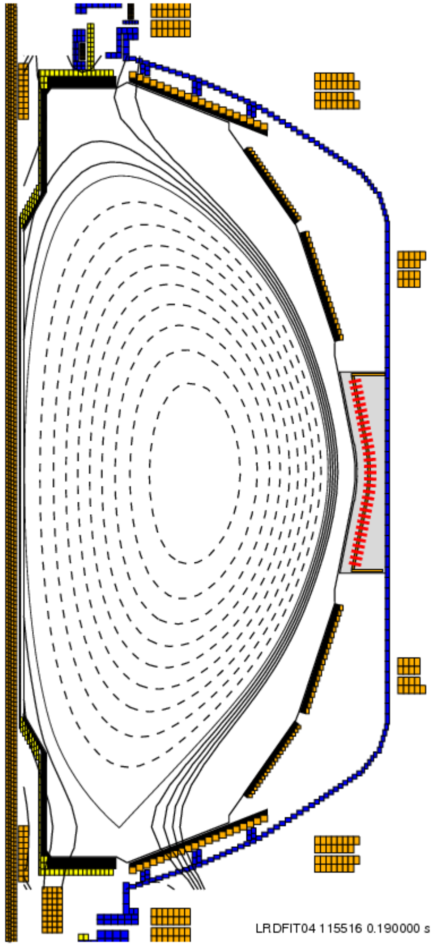
- Rotation is increased by ~10km/s in L-H and stays in H-mode

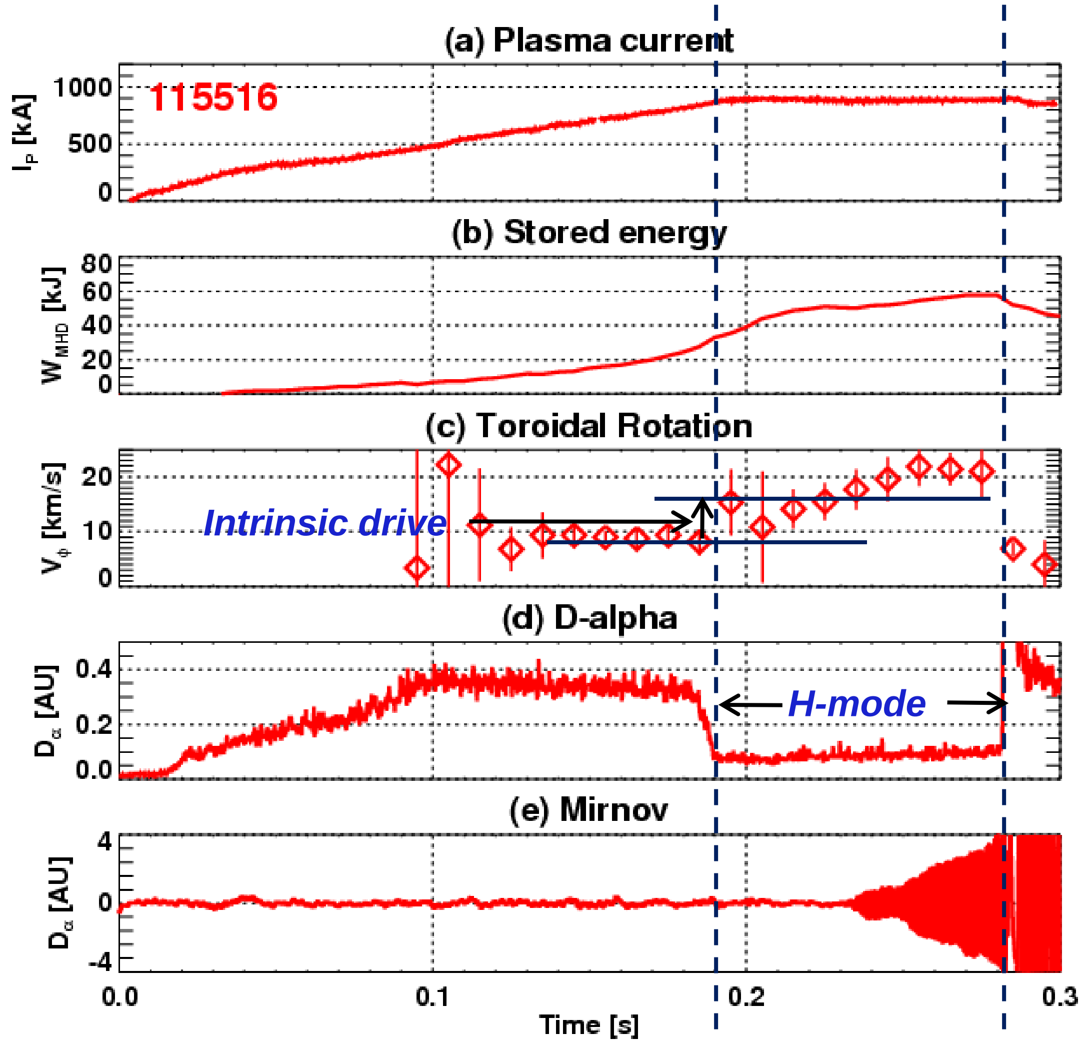




Intrinsic rotation in Ohmic L-H transition (#2)

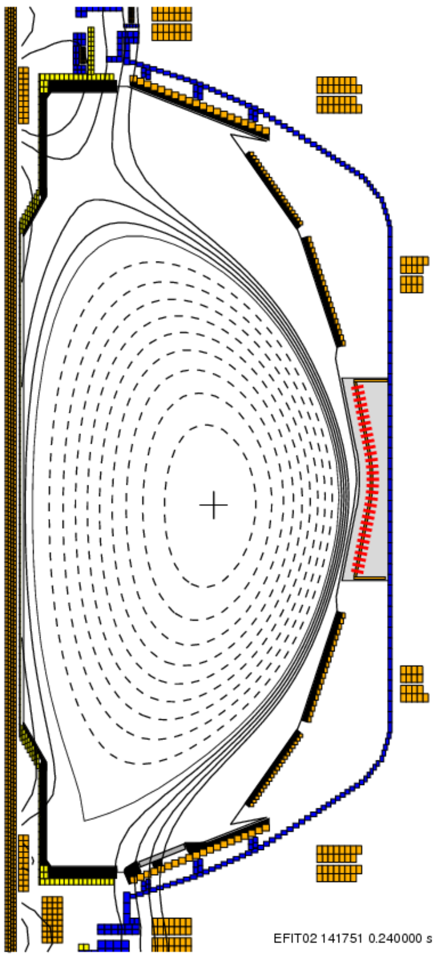
- Rotation is increased by ~10km/s in L-H and slightly evolves in H-mode

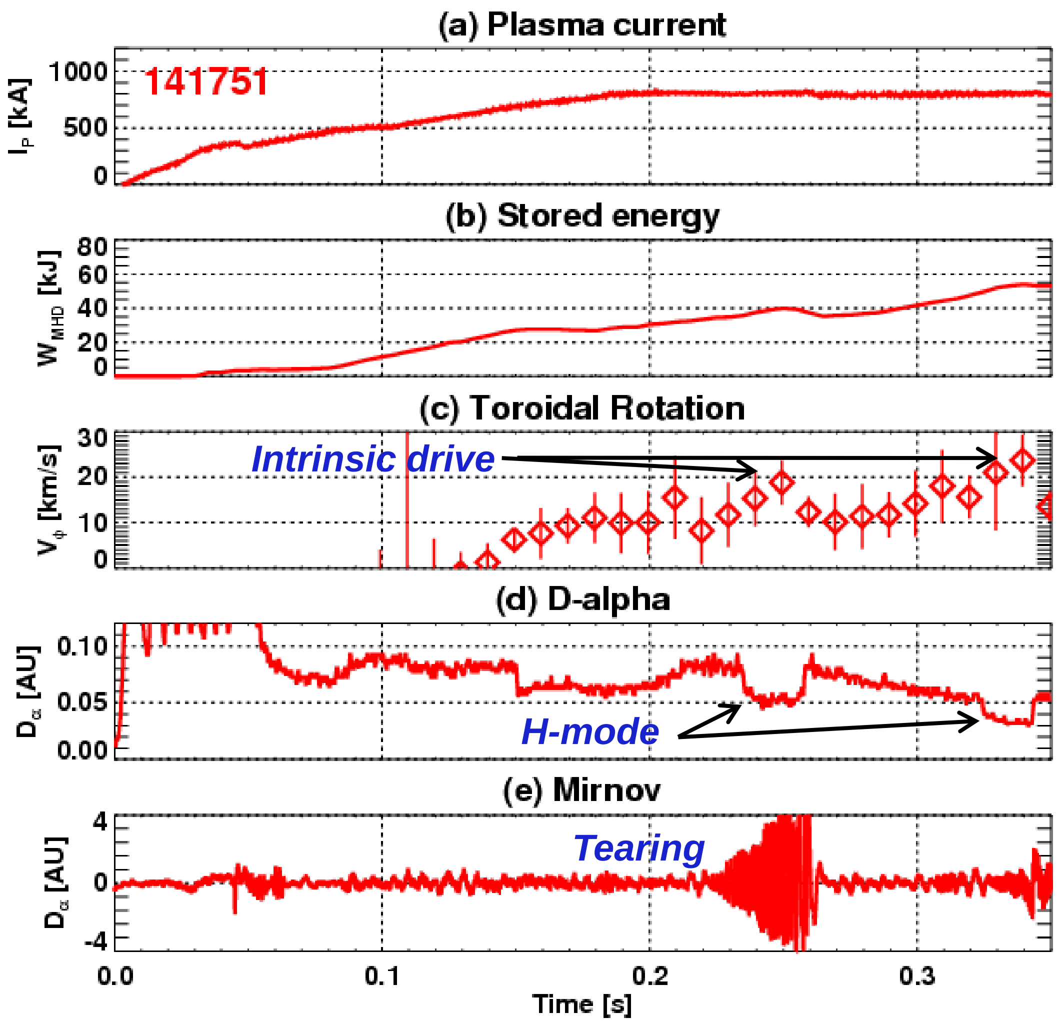




Intrinsic rotation in Ohmic L-H transition (#3)

- Rotation jump is clear in L-H even if tearing mode is present

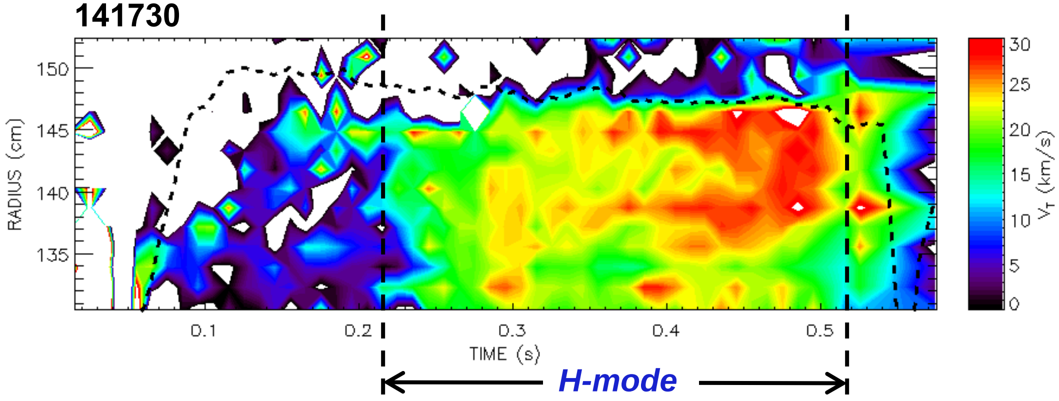


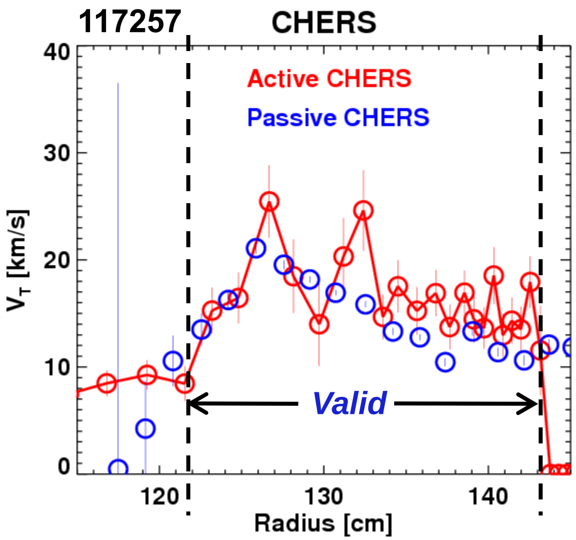


Passive CHERS provides (T_i,V_φ) profile evolution information using background Carbons

Passive CHERS

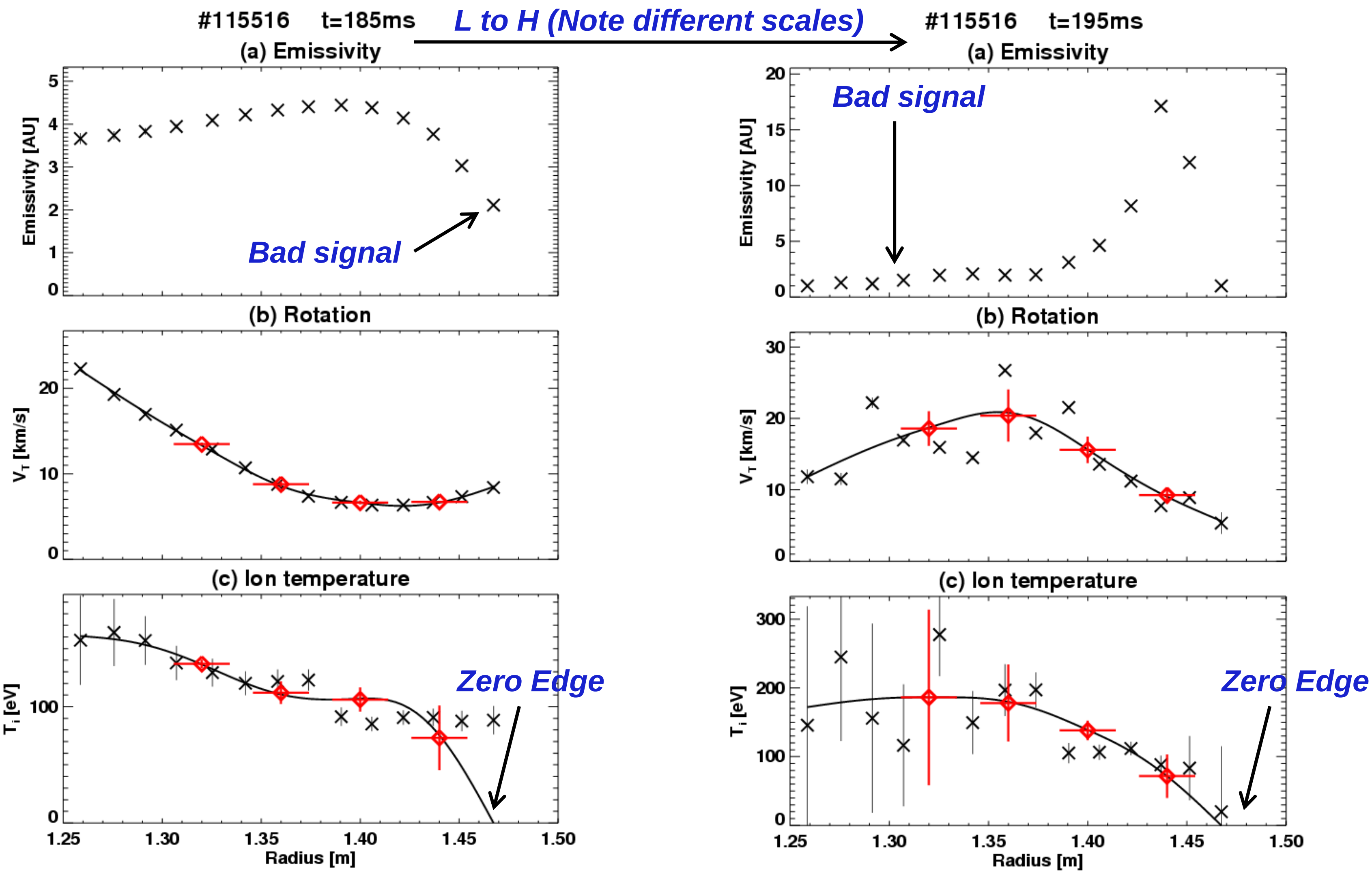
[Bell, POP 17, 082507 (2010)]





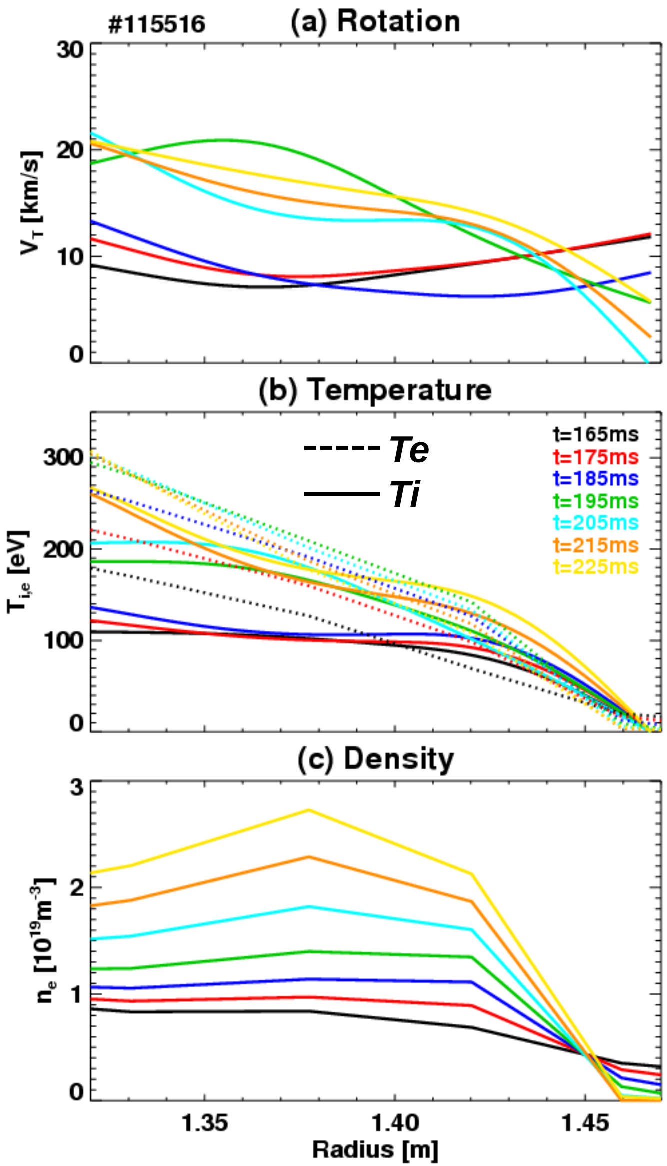
- Passive CHERS measures Carbon impurities (C^{5+}) in the background and gives (T_i,V_φ) profile information
- Passive and active CHERS agree well in the edge, indicating differences can be ignored and ExB can be assumed
  - ExB rotation can be measured by ignoring diamagnetic contribution (since Z is high), but toroidal rotation for main ions may be different – will be discussed later
- (T_i,V_φ) profiles perhaps can be fully used in the edge if adequate fitting procedure is added

Secondary fitting is used for (T_i, V_φ) profiles



**** Errors are propagated to the final analysis and used to rule out bad signals***

Profile evolution clearly shows rotation jump, associated with ion temperature change



- Rotation clearly jumps through L-H transition, and stays in quite a long time afterwards
- T_i (gradient) also clearly changes through L-H transition, and slowly evolves afterwards
- T_e and n_e (gradient) gradually increase through L-H transition

In 10ms around L-H transition,

- **∇T_e, ∇n_e ↑ at the end of pedestal**
- **∇T_i, V_φ ↑ at the top of pedestal**

Rotation change during Ohmic L-H transitions is dominantly driven by intrinsic torque

- Simplified form of rotation evolution is

$$\frac{\partial}{\partial t}\left(mnRV_{\phi}\right)=T_{input}-T_{NTV}-\nabla\cdot\Pi_{\phi}\text{ , where }\Pi_{\phi}=-mnR\left(\chi_{\phi}\frac{\partial V_{\phi}}{\partial r}-V_{pinch}V_{\phi}\right)+\Pi_{r,\phi}^{R}$$

- One can study the residual term alone when removing input torque, NTV, and zeroing rotation, which is however impossible in NSTX
- Nonetheless, through Ohmic L-H transition:

$$T_{input}=0\ \text{ and }\ T_{NTV}\cong T_{1/\nu}\approx 0$$

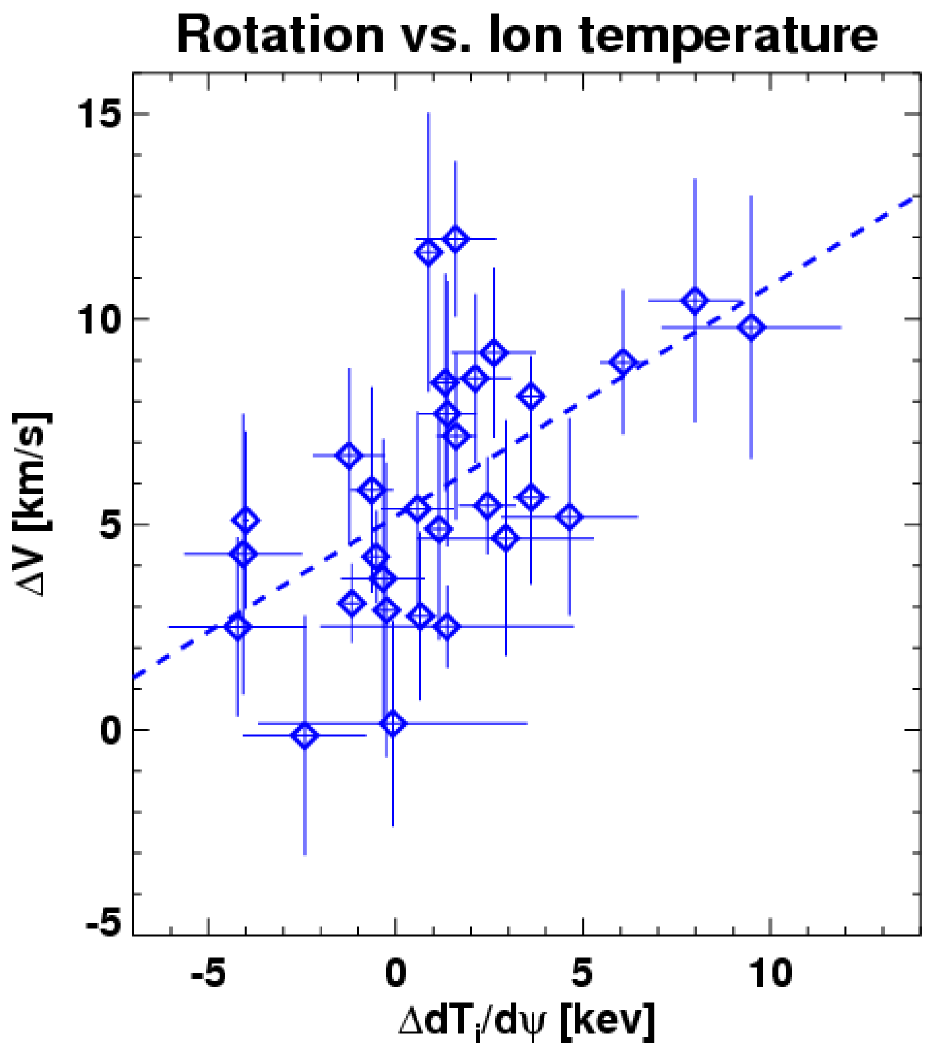
$$\text{ignoring self-dependent evolution on } V_{\phi} \text{ in short time } (10ms)$$

$$\frac{\partial}{\partial t}\left(mnRV_{\phi}\right)\approx-\nabla\cdot\Pi_{r,\phi}^{R}$$

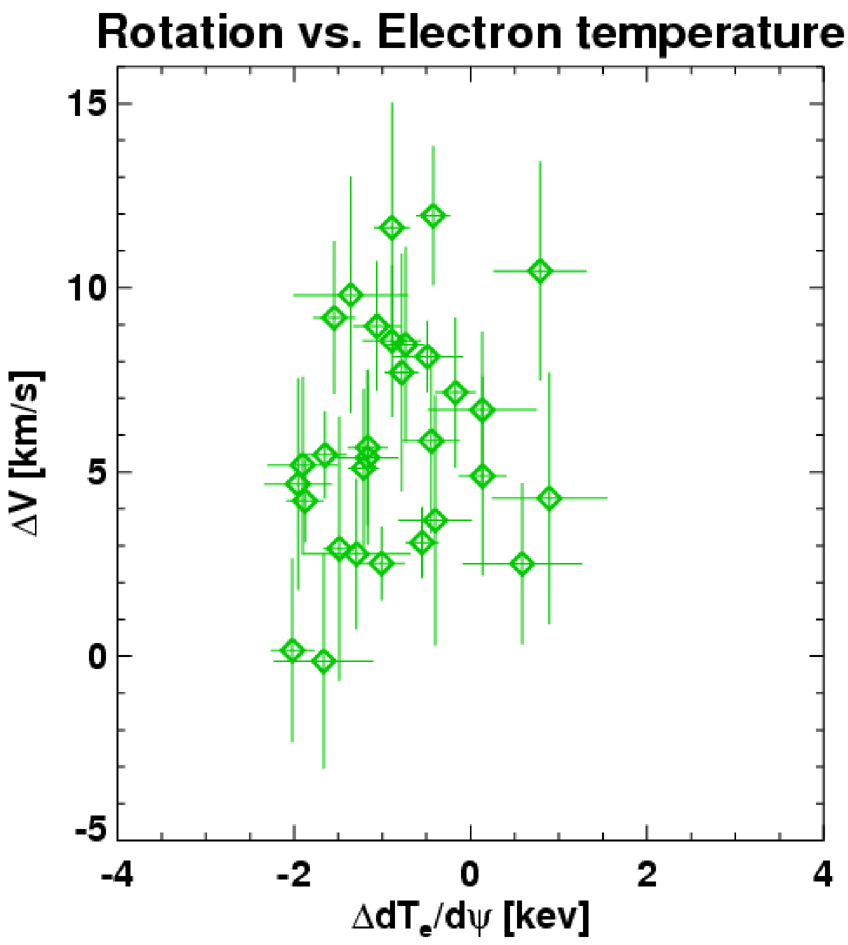
$$\text{e.g. } \frac{\partial V}{\partial t}=V+C\rightarrow V=C\delta t+\mathrm{O}(\delta t^{2})$$

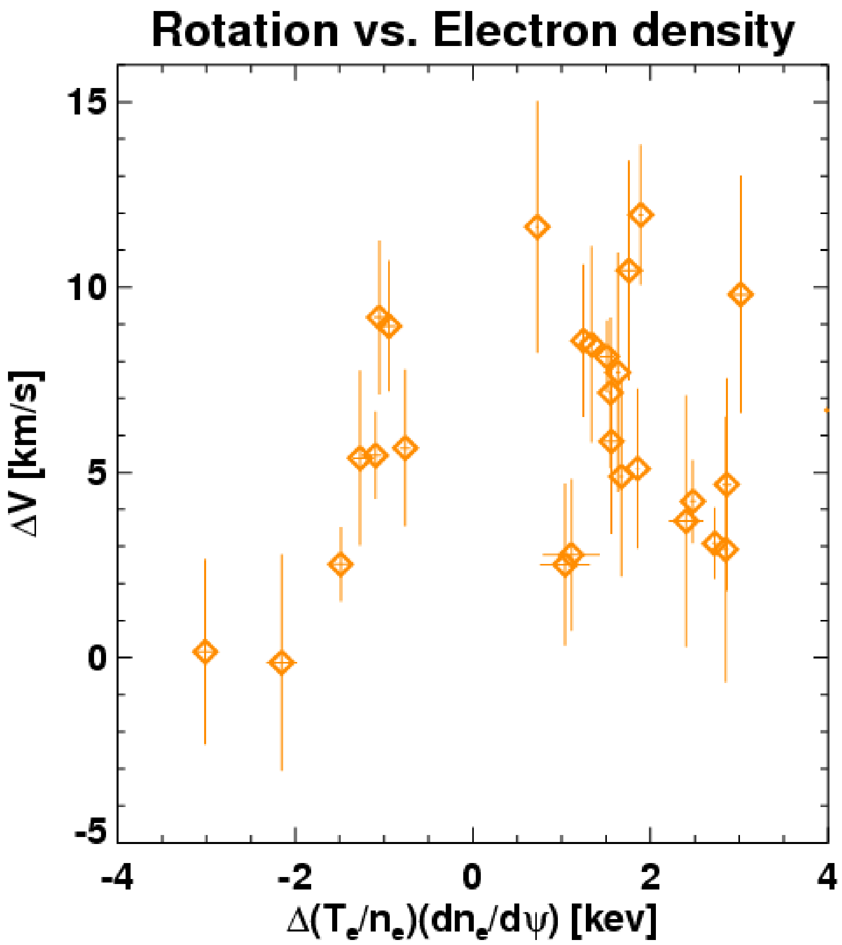
- Here the goal is to investigate $\Delta\left[V_{\phi}\right]\left(\text{or } \tau_{\phi}\right)\propto\Delta\left[\nabla\cdot\Pi_{r,\phi}^{R}\right]\propto\Delta\left[\frac{\partial n_{e,i}}{\partial r}\text{ or }\frac{\partial T_{e,i}}{\partial r}\right]$

Best correlation can be found between $\Delta(\nabla T_i, V_\varphi)$



Correlations are not good for $\Delta(\nabla T_e, \nabla n_e, V_\varphi)$





Experiment and recent theory agree well with small Prandtl number

- ExB shear is directly related to thermodynamic force

  [*McDevitt, POP 16, 052302 (2009)*]

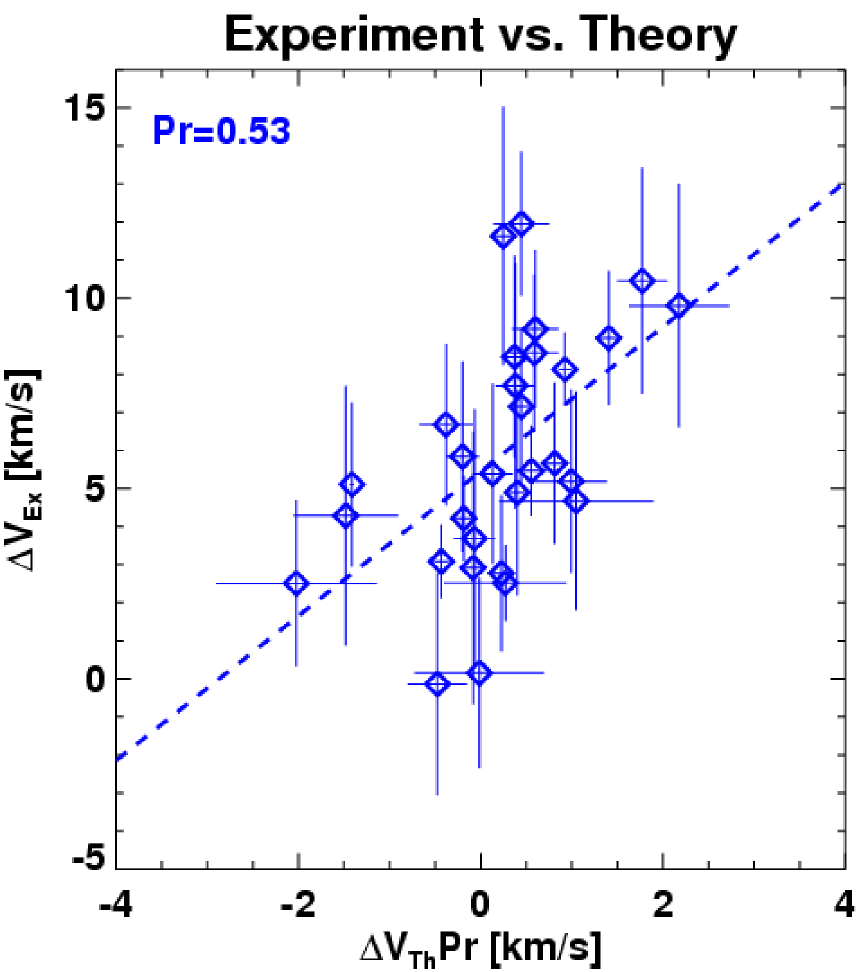
- A theoretical form for intrinsic rotation generation is given by

$$\langle V_{\parallel} \rangle \cong \frac{1}{2}\rho_* v_{thi} \frac{\chi_i}{\chi_\phi}\frac{L_s}{L_T}\sqrt{\frac{T_i}{T_e}} \qquad \mathrm{Pr} \equiv \frac{\chi_\phi}{\chi_i}$$

  [*Kosuga, POP 17, 102313 (2010)*]

  [*Rice, PRL 106, 215001 (2011)*]

- Experiment and theory correlates well with Pr~0.53
  - This small Prandtl number is consistent with previous NSTX momentum transport studies



Uncertainty exists due to difference between impurity and main ion rotations

- Difference between main ion rotation and impurity rotation may not be ignorable when rotation is low
- The 1st order gyro-expansions of moment equations give

$$V_s \cdot \nabla \varphi = -\left(\frac{d\Phi}{d\psi} + \frac{1}{Z_s e n_s} \frac{dP_s}{d\psi} - qV_s \cdot \nabla \theta \right) = -\left(\frac{d\Phi}{d\psi} + \frac{1}{Z_s e n_s} \frac{dP_s}{d\psi} - \frac{c_p}{Z_s e} \frac{dT_s}{d\psi} \right)$$

- For Carbon species (Z=5-6) or Argon species (Z=13-14), diamagnetic rotations and poloidal flows can be ignored
- For main ions,
  - If poloidal flows follow neoclassical predictions, two rotations are similar

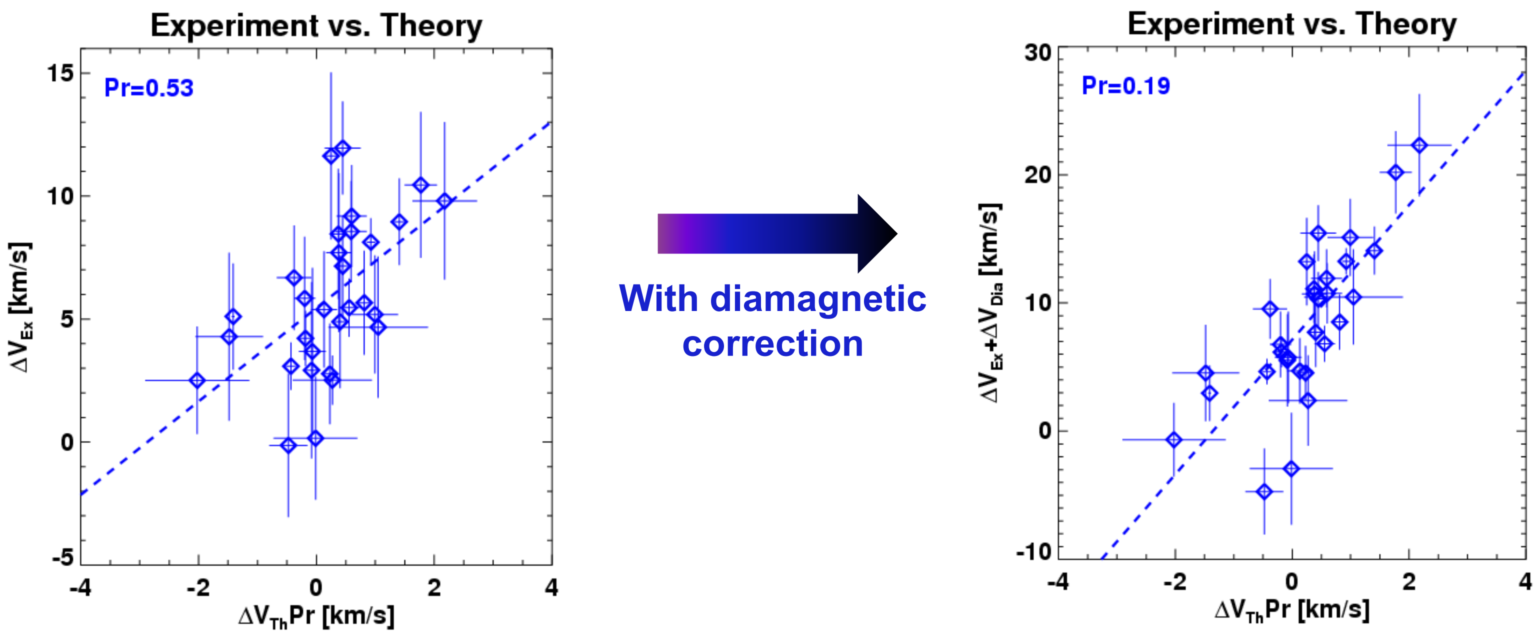
$$V_i \cdot \nabla \varphi \cong V_s \cdot \nabla \varphi - \frac{1}{e n_i} \frac{dP_i}{d\psi} + \frac{1}{e} \frac{dT_i}{d\psi} = V_s \cdot \nabla \varphi - \frac{T_i}{e n_i} \frac{dn_i}{d\psi}$$

  - If poloidal flows are negligible, diamagnetic corrections are needed

$$V_i \cdot \nabla \varphi \cong V_s \cdot \nabla \varphi - \frac{1}{e n_i} \frac{dP_i}{d\psi} = V_s \cdot \nabla \varphi - \frac{T_i}{e n_i} \frac{dn_i}{d\psi} - \frac{1}{e} \frac{dT_i}{d\psi}$$

Uncertainty with diamagnetic or poloidal rotation is as large as intrinsic rotation

- Diamagnetic correction for measurements:



- Diamagnetic contribution in theory:

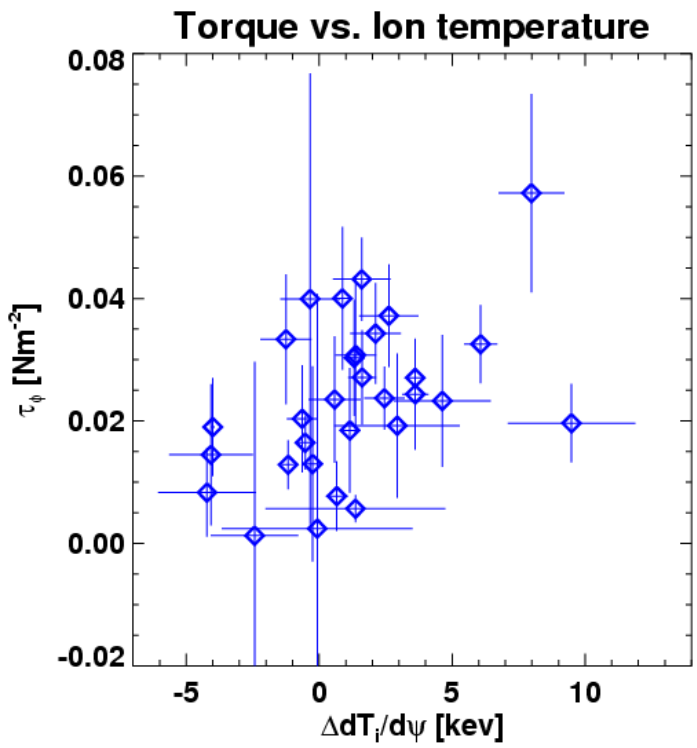
$$V_{RS} \cong \frac{1}{2}\rho_* v_{thi} \frac{\chi_i}{\chi_\phi} \frac{L_s}{L_T} \sqrt{\frac{T_i}{T_e}} \cong \frac{1}{2\hat{s}\,\mathrm{Pr}} \frac{1}{eB_\theta} \frac{dT_i}{dr} \cong \frac{1}{2\hat{s}\,\mathrm{Pr}} V_{Diamagnetic}$$

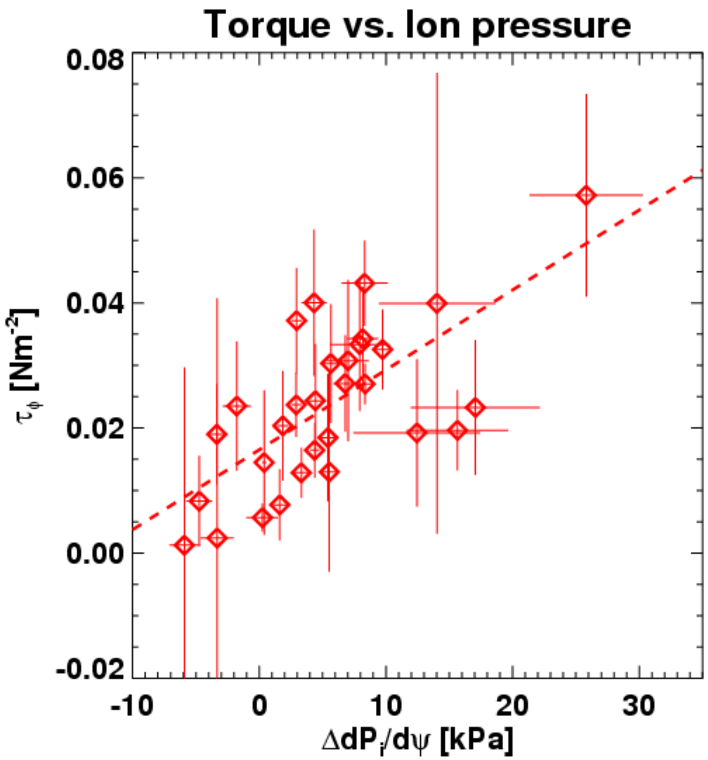
$$\text{If } \mathrm{Pr} \sim 1 \text{ and } 2\hat{s} >> 1 \text{ as usual, } V_{RS} << V_{Diamagnetic}$$

Intrinsic torque scaling is essentially needed rather than intrinsic rotation scaling

- Torque is more fundamental than rotation in theory
- Intrinsic torque is better correlated with ∇P_i than ∇T_i

$$V_\phi \propto \nabla T_i, \text{so } \tau_\phi \propto \frac{\partial (n_i R V_\phi)}{\partial t} \propto n_i \nabla T_i \propto \nabla P_i\ ?$$

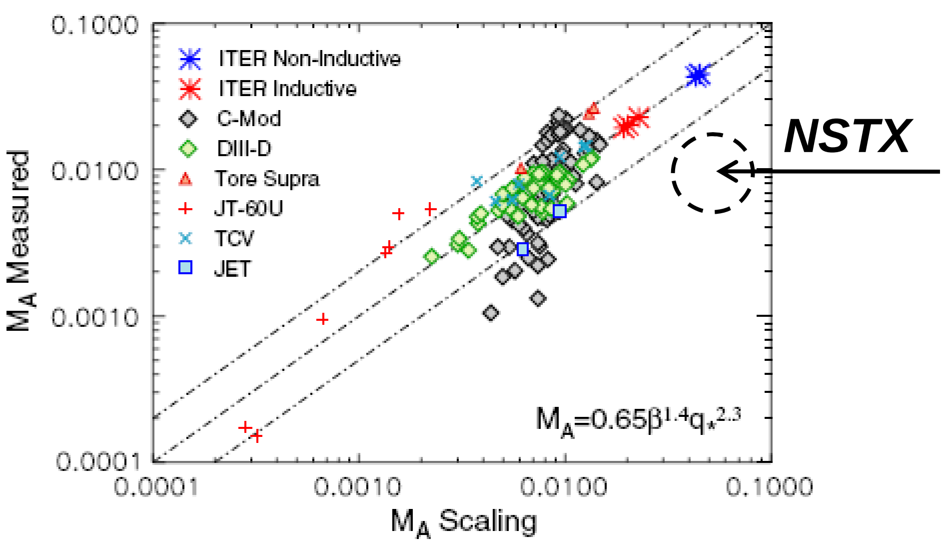


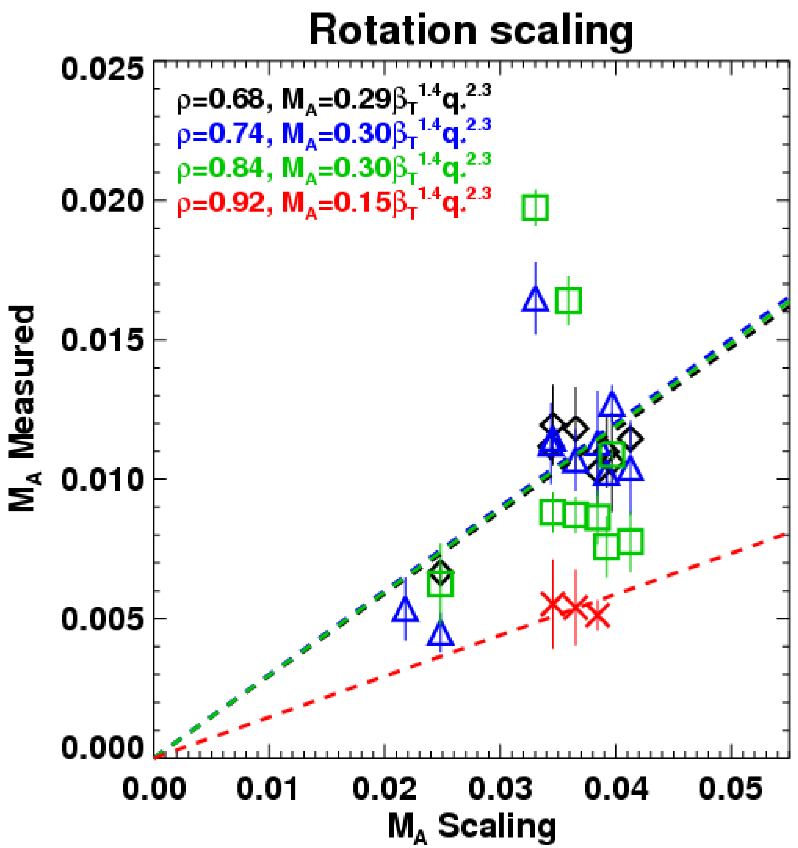


Comparison with other tokamak scaling (by Rice)

- NSTX intrinsic rotation through L-H transitions may follow empirical scaling of conventional tokamaks (by Rice)
- However, NSTX results yield small proportional factor due to large toroidal β and q_* in ST

[Rice, NF 47, 1618 (2007)]

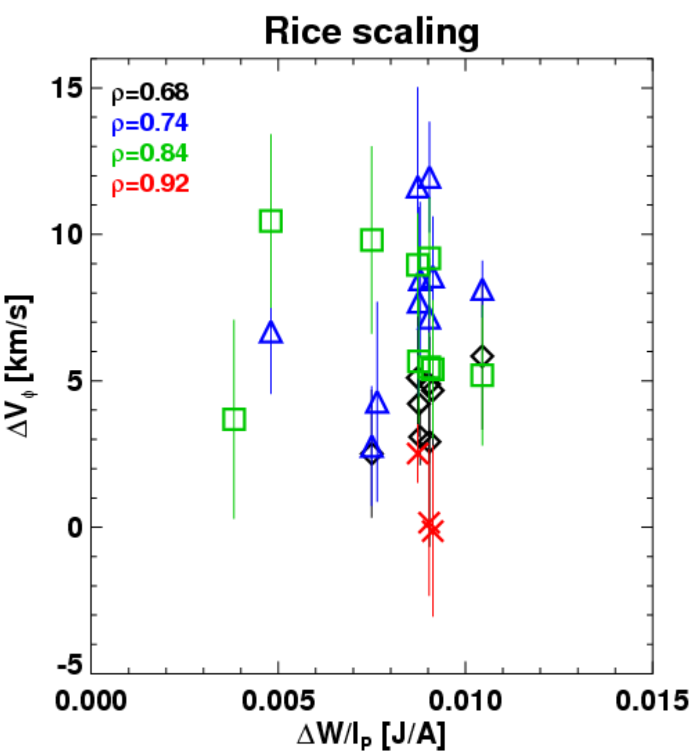




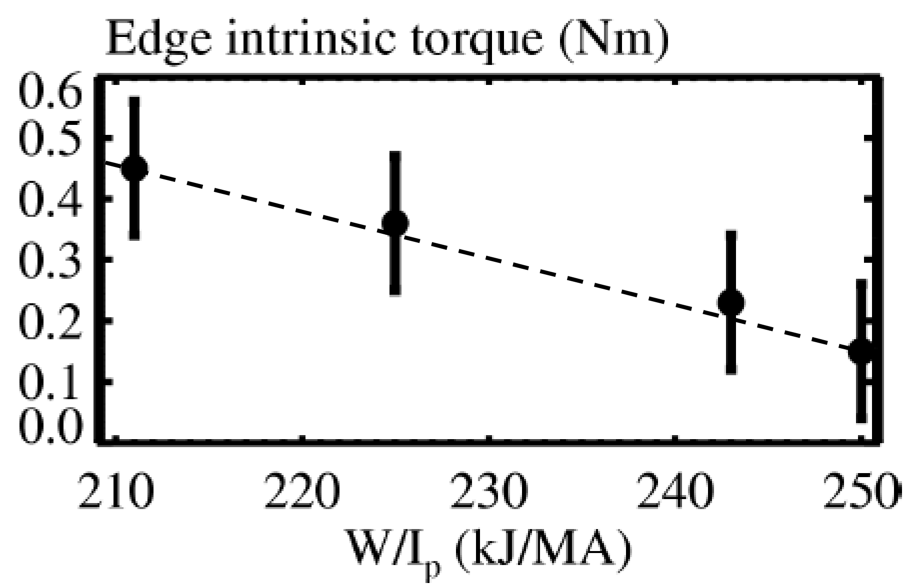
Comparison with Rice scaling

- NSTX data do not follow Rice scaling?

Scaling for Ohmic plasmas
(J.-K. Park)



Scaling from NBI plasmas
(W. M. Solomon)



Summary and Future work

- NSTX intrinsic rotation studies are successfully done through Ohmic L-H transitions, using Passive CHERS
- Best correlation can be found between (∇T_i, V_φ) and (∇P_i, τ_φ)
- Theory and experiment agree well with small Pr
- However, uncertainty with diamagnetic or poloidal rotation is as large as intrinsic rotation itself
- This smallness of intrinsic rotation can be seen by $V_{RS} \cong \frac{1}{2\hat{s}\,\mathrm{Pr}} V_{Diamagnetic}$

- NSTX intrinsic rotation may follow empirical scaling with small proportional factor, but does not follow Rice scaling
- Future work may include
  - TRANSP and NCLASS calculations
  - Intrinsic NTV calculations
  - Pinch and diffusivity calculations?

It is hard to estimate other terms of momentum transport in this analysis

- Simplified momentum transport:

$$\frac{\partial}{\partial t}\left(mnRV_{\phi}\right)=\nabla\cdot\left[mnR\left(\chi_{\phi}\frac{\partial V_{\phi}}{\partial r}-V_{pinch}V_{\phi}\right)+\Pi_{r,\phi}^{R}\right]\longrightarrow\frac{\partial L}{\partial t}=T_{RS}-\frac{L}{\tau_{\phi}}$$

- It requires at least three time slices to estimate both quantities
- However, changes except L-H transition are not apparent and would not be reliable in terms of errors