NSTX

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Intrinsic Rotation and Torque in NSTX Ohmic H-mode Plasmas

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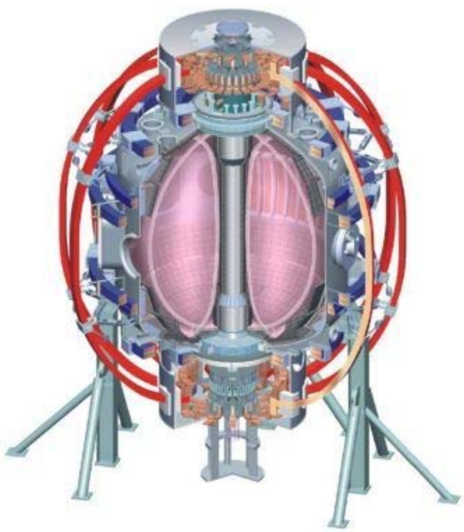
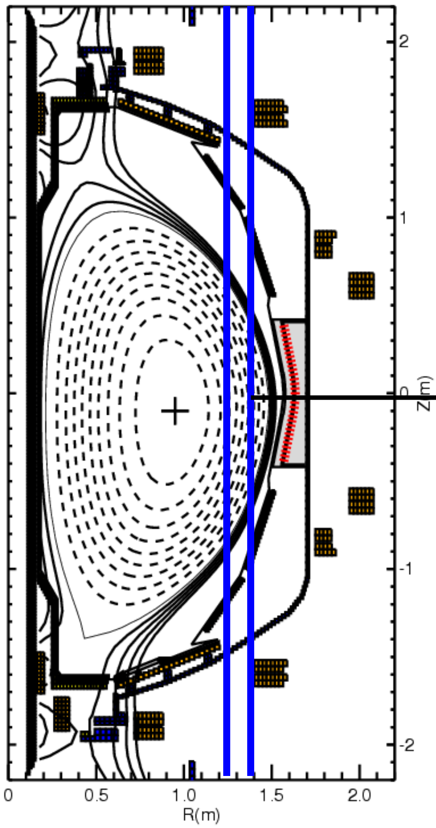


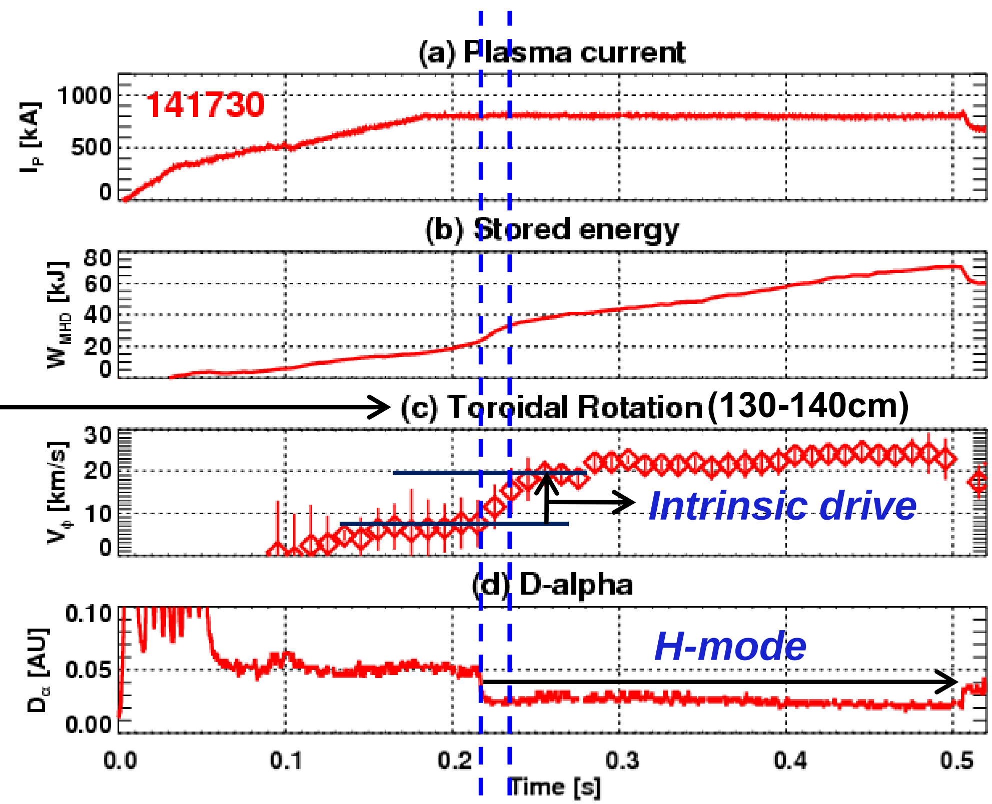
Overview

- Motivation
  - Prediction for toroidal rotation → *ExB* rotation → Stability
- Observation
  - For intrinsic rotation generation in Ohmic H-mode plasmas
- Correlation
  - Between rotation and ion temperature gradient
- Comparison
  - With residual stress theory
- Discussion and Summary

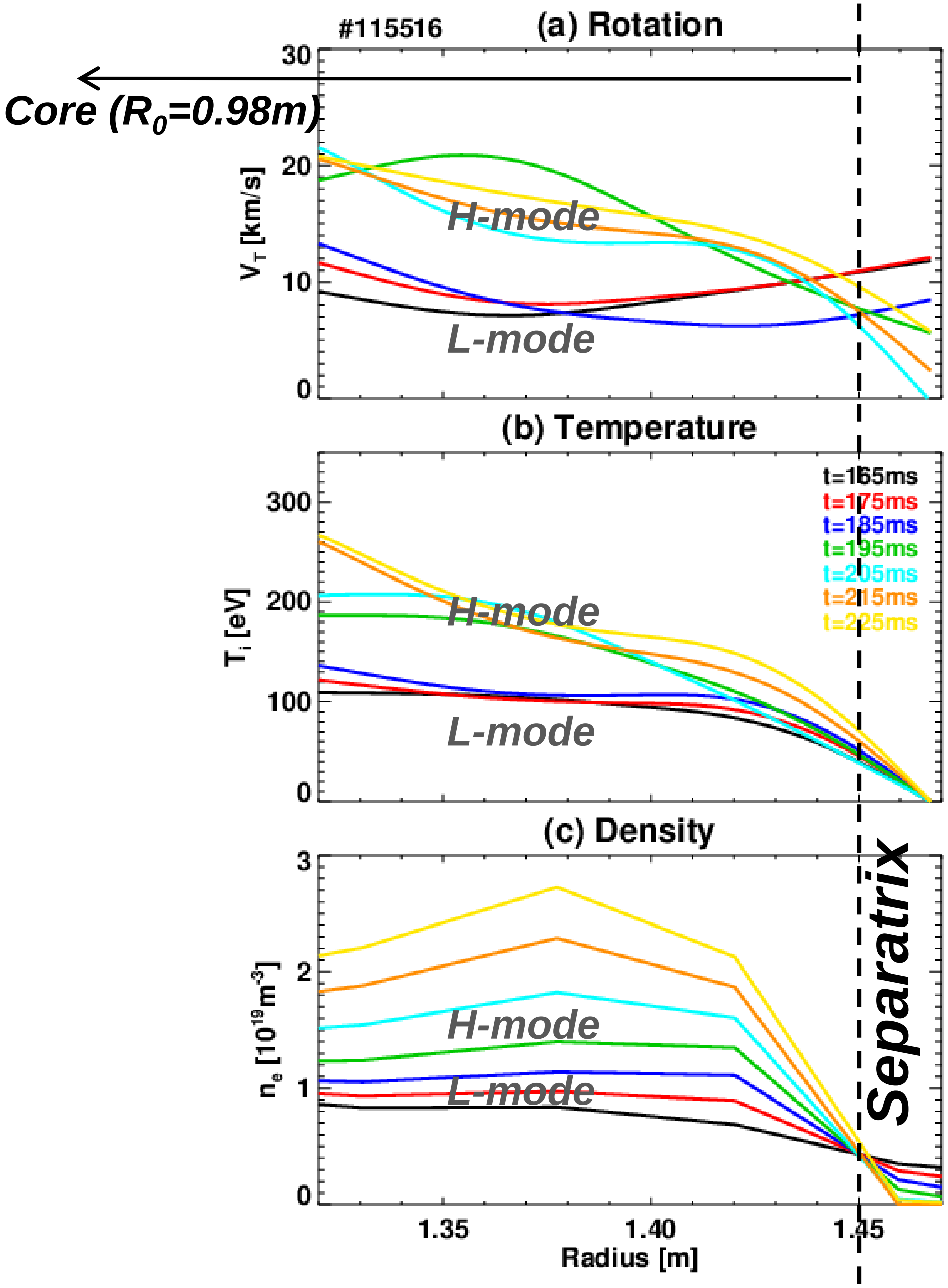
Toroidal rotation increases during Ohmic L-H transition and slowly evolves afterwards

- Toroidal rotation could be well measured without beams by Passive CHERS
  - Passive CHERS measures background carbons **[*Bell, POP 17, 082507 (2010)*]**
- Toroidal rotation increases by up to *10~20km/s* through Ohmic L-H transition
- Toroidal rotation slowly evolves afterwards, towards a balance among various momentum sources – diffusion, convection, counter-torque by MHDs
- So, a short time (~*10ms*) around L-H transition was focused in this study





Profile evolutions show intrinsic rotation may be correlated with ion temperature change



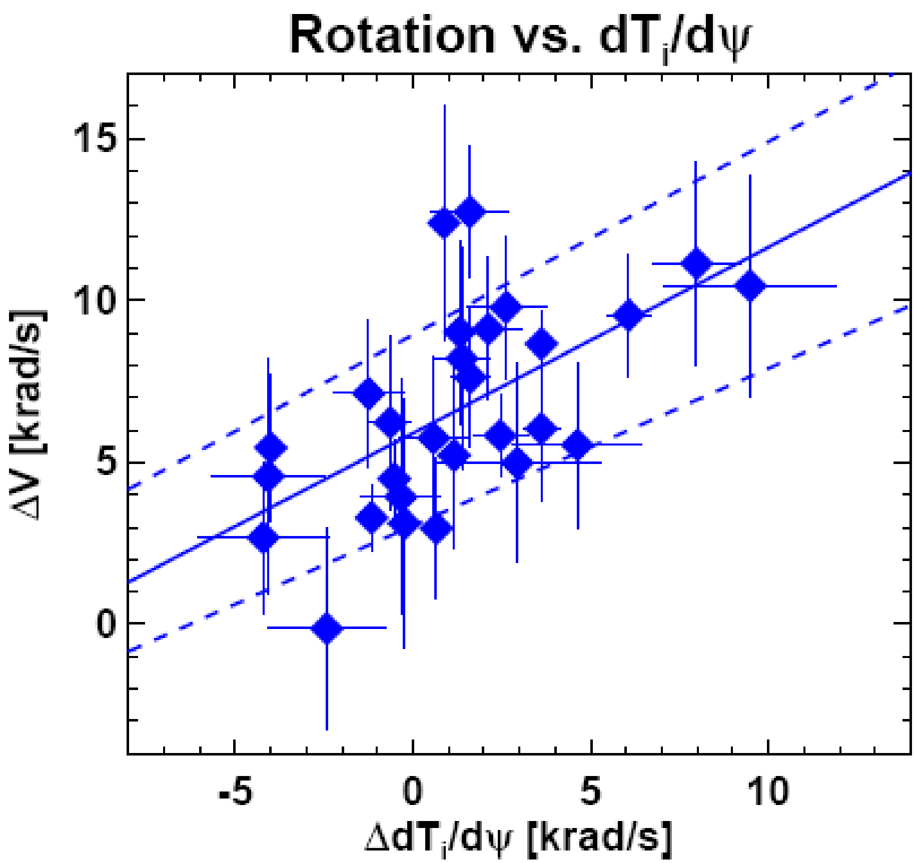
Through L-H Transition,

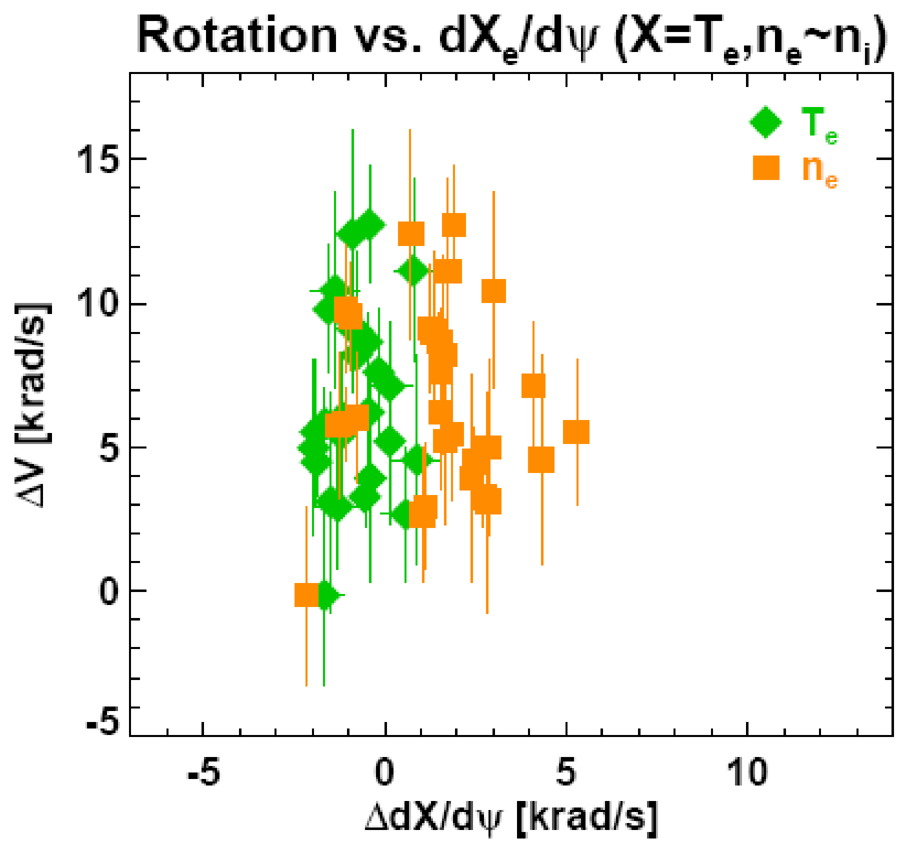
- V_i rapidly increases at ***R<1.40m***, then remains relatively constant
- T_i (and possibly ∇T_i) also rapidly increases at ***R<1.40~1.45m*** and remains relatively constant
- n_e (and T_e) increases gradually driven by the pedestal development, but ∇n_e (and ∇T_e) weakly changes at ***R<1.40m***
- **Observations indicate possibility of correlation between V_i and ∇T_i**

Best correlation was found between rotation and ion temperature gradient change

- Best correlation was found between jumps in V_φ and ∇T_i, compared to ∇T_e, ∇n_e, (~∇n_i, expectation for n_c=2~3%n_e , based on NBI blip check)

$$\Delta V \sim C_t \Delta\left(\frac{dT_i}{d\psi}\right) \sim 0.57\Delta\left(\frac{dT_i}{d\psi}\right) \sim 0.57\Delta V_{diamag}$$





Intrinsic rotation is established by intrinsic torque, and also momentum diffusion and convection

- Simplified (and cylindrical) form of torque balance is

$$\frac{\partial}{\partial t}\left(Mn_i RV_{i\varphi}\right)=T_{input}-T_{NTV}-\nabla\cdot\Pi_{i\varphi}\text{ , where }\Pi_{i\varphi}=-Mn_i R\left(\chi_{i\varphi}\frac{\partial V_{i\varphi}}{\partial r}-V_{pinch}V_{i\varphi}\right)+\Pi^{rs}_{r,i\varphi}$$

- There is no input torque, and also torque by intrinsic error field is very small in Ohmic plasmas due to high collisionality

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

- During the short time in LH transition, $\Delta\text{t}=10ms<<\tau_{\varphi}$

$$\frac{\Delta\left(Mn_i RV_{i\varphi}\right)}{\Delta t}=-\frac{\left(Mn_i RV_{i\varphi}\right)}{\tau_{\varphi}}-\nabla\cdot\Pi^{rs}_{r,i\varphi}\approx-\nabla\cdot\Pi^{rs}_{r,i\varphi}=T^{rs}_{\varphi}$$

Intrinsic torque is best correlated with ion temperature gradient, as predicted by residual stress theory

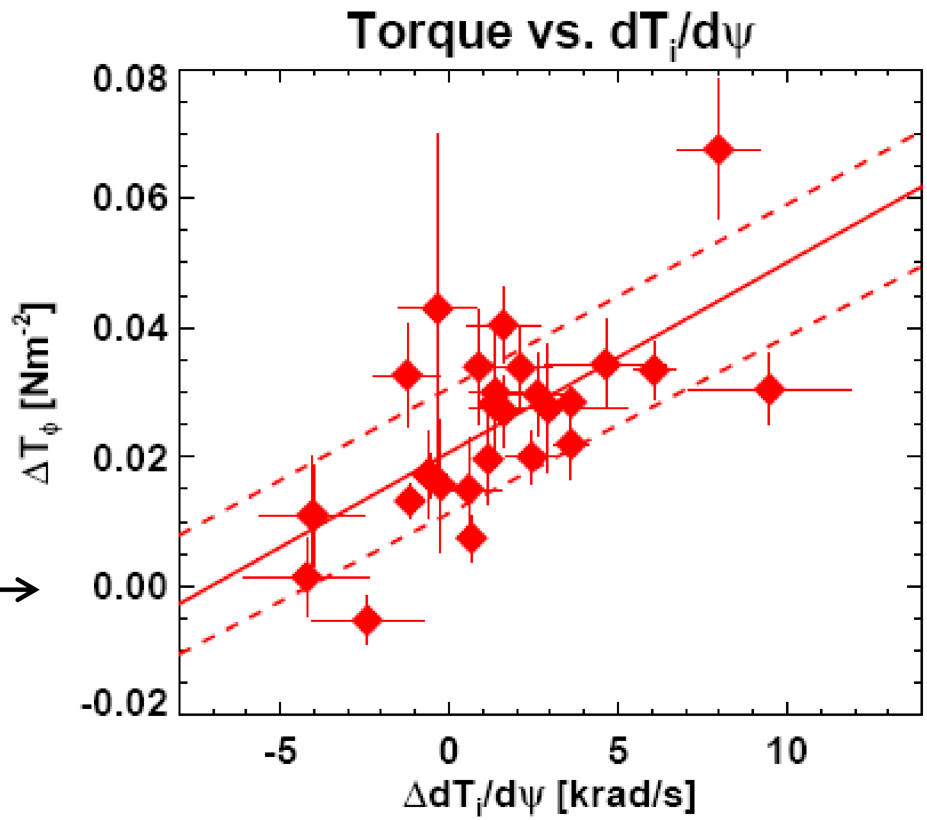
- ITG-driven residual stress theory predicts: **[*Diamond, POP 15, 012303 (2008)*]**

$$\Pi_{r\|}^{rs} \approx -\rho_* \chi_i \frac{L_s}{2c_s}\left(\frac{\nabla T}{T}\right)^2 v_{thi}^2$$

- With constant L_T, torque is given by:

$$T_\varphi^{rs} \approx -\nabla \cdot \Pi_{r\|}^{rs} \approx \frac{MnR}{2\hat{s}L_T^2}\chi_i\left(R\frac{dT}{d\psi}\right)$$

- Measured torque give the best correlation with ∇T_i →



- However the exact fits result in the wide range of χ_i
  - Intrinsic torque may be correlated with higher derivatives of T_i

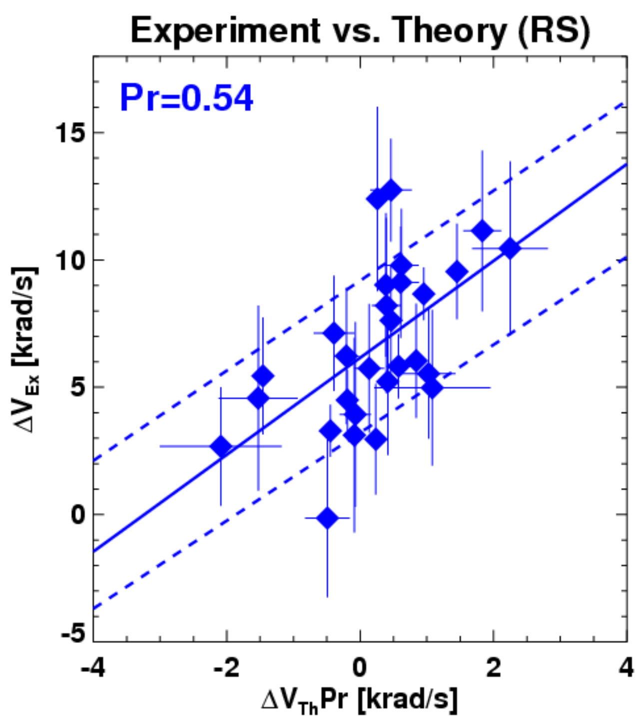
Residual stress theory predicts the established rotation to be smaller than diamagnetic rotation

- If residual stress theory is used to predict the finally established rotation:

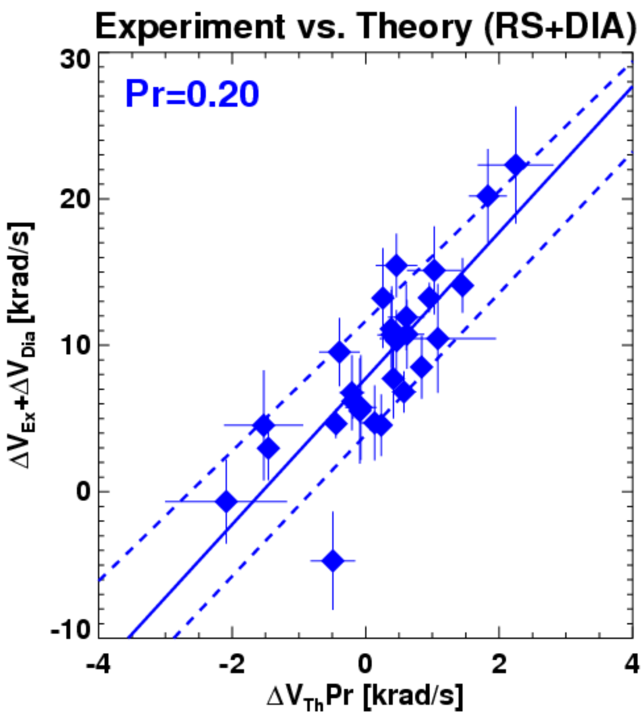
$$V_{i\varphi}^{rs} \cong \frac{1}{2}\rho_* v_{thi} \frac{\chi_i}{\chi_{\varphi,eff}} \frac{L_s}{L_T} \sqrt{\frac{T_i}{T_e}} \rightarrow \cong \frac{1}{2\hat{s}\,\mathrm{Pr}} \frac{1}{eB_\theta} \frac{dT_i}{dr} \cong \frac{1}{2\hat{s}\,\mathrm{Pr}} V_{diamag}$$

[Kosuga, POP 17, 102313 (2010)] **[Rice, PRL 106, 215001 (2011)]**

$$\text{If } \mathrm{Pr} \sim 1 \text{ and } 2\hat{s} > 1 \text{ as usual, } V_{i\varphi}^{rs} < V_{diamag}$$



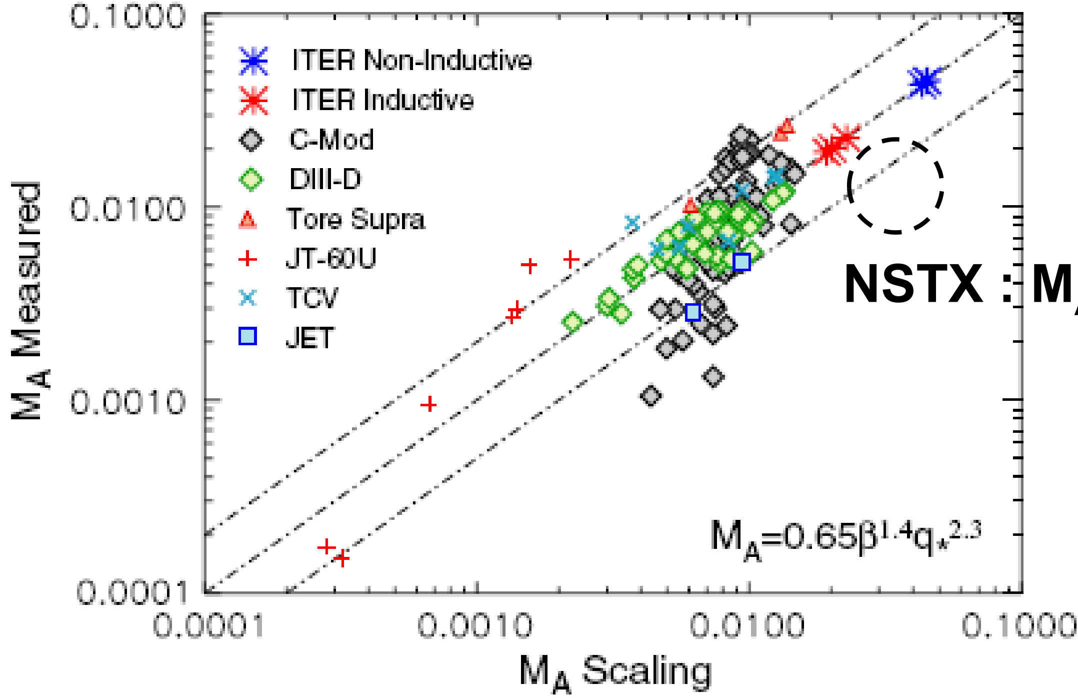
With (Neoclassical) diamagnetic correction



NSTX results can be combined with other tokamak scaling on intrinsic rotation

- NSTX intrinsic rotation through L-H transitions can be combined with empirical scaling of conventional tokamaks
- However, NSTX results yield small proportional factor, probably due to large toroidal β and q_* in ST

[*Rice, NF 47, 1618 (2007)*]



NSTX : M_A<0.30$\beta^{1.4}q_*^{2.3}$

Summary

- Intrinsic rotation generation was observed during Ohmic L-H transitions, using passive CHERS measurements
- Best correlation for toroidal rotation and torque can be found with ∇T_i as residual stress theory predicted
  - However, the fits are not so robust quantitatively, and the intrinsic torque may be correlated with higher derivatives of T_i as theory also predicted
- NSTX intrinsic rotation can be combined with tokamak rotation scaling
- However, uncertainty in determining intrinsic toroidal rotation or ExB rotation is as large as poloidal rotation or diamagnetic rotation

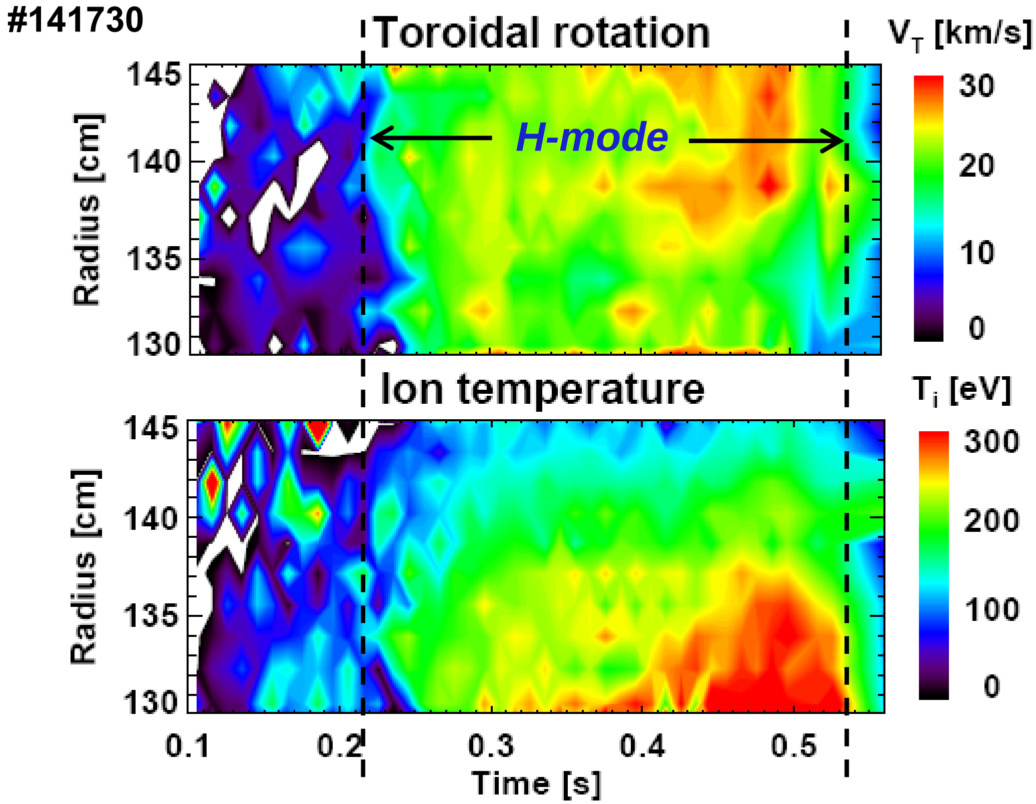
$$E \times B \ \text{rotation}: \frac{d\Phi}{d\psi} = \left(C_t + C_p\right)\frac{dT_i}{d\psi}$$

Back up

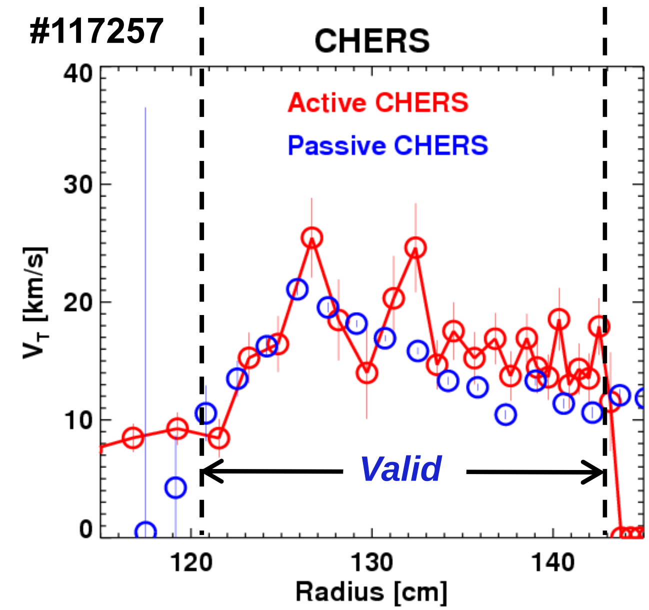
Toroidal rotation and ion temperature profiles in Ohmic plasmas were measured by passive CHERS

- Passive CHERS measures Carbon impurities (C^{5+}) in the background and gives (T_i, V_φ) profile information **[Bell, POP 17, 082507 (2010)]**
- Passive CHERS agrees well with active CHERS in the edge – checked with NBI blips in similar target plasmas
- (T_i, V_φ) profiles in the edge were fully used after adequate smoothing

Passive CHERS



Comparison with Active CHERS



Experiment and recent theory agree well using Prandtl number as a free parameter

- One mechanism for intrinsic rotation:
  - *ExB* shear, which is directly related to thermodynamic force, can cause symmetry breaking and residual stress

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

- A theoretical quantification for intrinsic rotation:

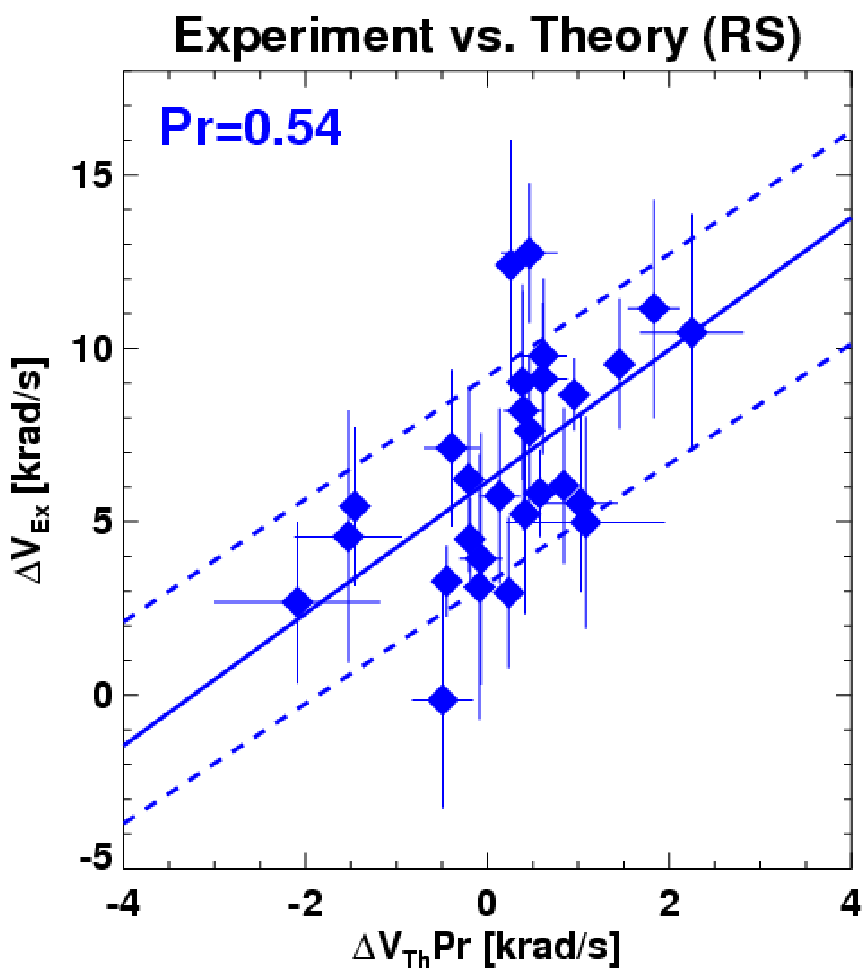
$$\langle V_{\parallel} \rangle \cong \frac{1}{2}\rho_* v_{thi} \frac{\chi_i}{\chi_{\phi,eff}} \frac{L_s}{L_T} \sqrt{\frac{T_i}{T_e}} \qquad \mathrm{Pr} \equiv \frac{\chi_{\phi,eff}}{\chi_i}$$

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

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

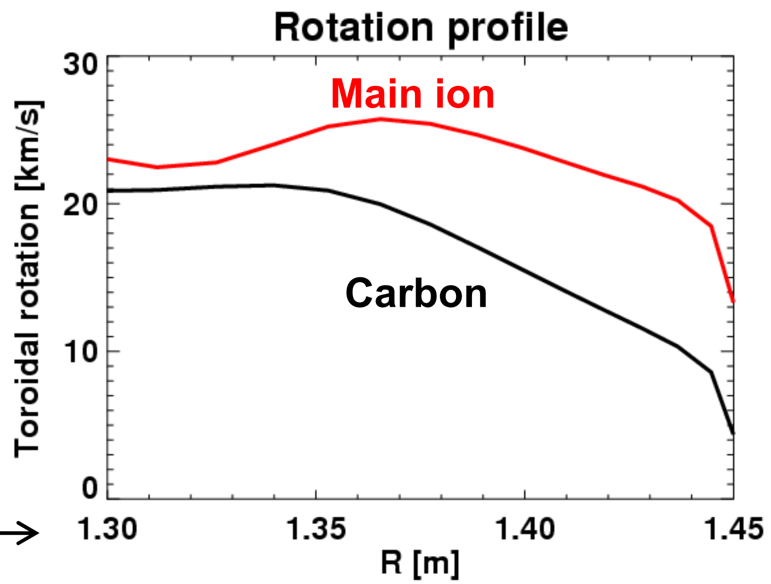
  - Possible toroidal effects are ignored in this comparison

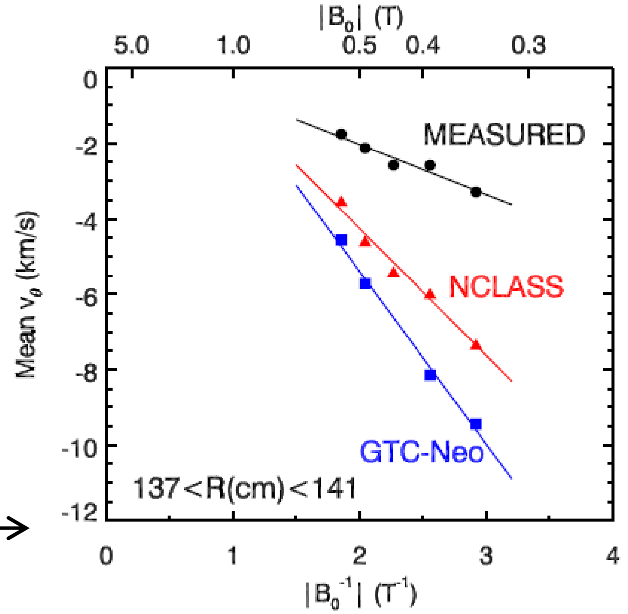
- Experiment in NSTX and theory can be best correlated with *Pr~0.54*



Main ion rotation is required for comparison with theory, but may largely differ from impurity rotation

- Main ion V_φ is required instead of impurity ion $V_{s\varphi}$
  - Difference can be large when V_φ is low without auxiliary heating
- One way is to use neoclassical theory
  - NCLASS is used in a few shots with Z_{eff}~1.5 (by NBI blip check)
  - Neoclassical theory calculates poloidal rotation V_θ (main ion), $V_{s\theta}$ (impurity ion) through parallel force balance equations
- However, present neoclassical predictions were particularly failed in NSTX – Ignorable poloidal rotation may be a better assumption in NSTX





[Bell, POP 17, 082507 (2010)]

Difference in toroidal rotation can be estimated by difference in poloidal rotation

- Equilibrium flow for each species obeys

$$V_s \cdot \nabla\varphi = -\left(\frac{d\Phi}{d\psi} + \frac{1}{Z_s e n_s}\frac{dP_s}{d\psi} - qV_s \cdot \nabla\theta\right) \text{ where } \psi = \frac{\psi_p}{2\pi} \text{ and } qV_s \cdot \nabla\theta = \frac{I}{R^2}\frac{V_{s\theta}}{B_\theta}$$

- So difference in toroidal rotation is given by

$$V_i \cdot \nabla\varphi - V_s \cdot \nabla\varphi = -\left(\frac{1}{en_i}\frac{dP_i}{d\psi} - \frac{1}{Z_s e n_s}\frac{dP_s}{d\psi}\right) + \frac{I}{R^2}\left(\frac{V_{i\theta}}{B_\theta} - \frac{V_{s\theta}}{B_\theta}\right)$$

- If poloidal and impurity pressure are ignored (considering R^{-2} too)

$$V_i \cdot \nabla\varphi - V_s \cdot \nabla\varphi \approx -\frac{1}{en_i}\frac{dP_i}{d\psi}$$

- If parallel flows are strictly equilibrated,

$$V_i \cdot \nabla\varphi - V_s \cdot \nabla\varphi = \left(1 - \frac{I^2}{B^2 R^2}\right)\left(-\frac{1}{en_i}\frac{dP_i}{d\psi}\right) \approx 0$$

- Even more rigorous parallel force and heat flux balance likely yields

$$0 \le \left(V_i \cdot \nabla\varphi - V_s \cdot \nabla\varphi\right) \le -\frac{1}{en_i}\frac{dP_i}{d\psi}$$

Every flow component involved in rotation balance is an order of diamagnetic rotation

- Every flow component associated with intrinsic rotation determination is an order of diamagnetic rotation

$$\text{Neglecting } \frac{T}{n}\frac{dn}{d\psi}, \quad \begin{array}{l} \text{Impurity rotation}: V_s\cdot\nabla\varphi = C_{ts}\dfrac{dT_i}{d\psi},\ qV_s\cdot\nabla\theta = C_{ps}\dfrac{dT_i}{d\psi} \\ \text{Main ion rotation}: V\cdot\nabla\varphi = C_t\dfrac{dT_i}{d\psi},\ qV\cdot\nabla\theta = C_p\dfrac{dT_i}{d\psi} \end{array}$$

- Force balance equation:

$$C_t\frac{dT_i}{d\psi} = \left(C_{ts} + 1 - C_p + C_{ps}\right)\frac{dT_i}{d\psi} \text{ where } \left(C_{ts}, C_p, C_{ps}\right) \le 1$$

  – Note these terms are not small in the pedestal

$$\frac{dT_i}{d\psi}\left[krad\cdot s^{-1}\right] \approx 5\varepsilon\sqrt{\kappa}\,\frac{dT/dr\left[keV\cdot m^{-1}\right]}{I_p\left[MA\right]}$$

- Most important information is *ExB* rotation:

$$\frac{d\Phi}{d\psi} = \underline{\left(C_{ts} + C_{ps}\right)}\frac{dT_i}{d\psi}$$

ExB rotation is important for stability, and is competing with other diamagnetic rotations

- Imaginary part of δW_k in RWM stability: **[*Park, POP 18, 110702 (2011)*]**

$$\delta W_k = \int dV \int_0^\infty dx \int_0^1 d\kappa^2 \sum_{nmm'} \frac{f_{nmm'}(\kappa)}{2n} \frac{n^2 \left[\left(C_{ts} + C_{ps} + 1 - C_N(x,\kappa) \right) \frac{dT_i}{d\psi} \right]}{n^2 \left[\left(C_{ts} + C_{ps} - C_B(x,\kappa) \right) \frac{dT_i}{d\psi} \right]^2 + \nu(x,\kappa)^2}$$

$$\text{where magnetic pression } C_B \approx \left\langle \mu \frac{dB}{d\psi} \right\rangle_b \Big/ \frac{dT}{d\psi} \leq 1,$$

$$\text{and Neoclassical offset } C_N \leq 2.5 \ \text{(For ITER, } C_N \approx 0)$$

- RWM kinetic stabilization will be maximized by resonance :

$$C_{ts} + C_{ps} - C_B \cong 0$$

- Stability is often a complex function of *ExB* rotation, unless *ExB* rotation can be strengthened by auxiliary heating
- So it is important to precisely predict *ExB* rotation, by both toroidal and poloidal flows of impurity ions if possible

Non-axisymmetry can be possibly imposed in ITER, and so new torque balance should be solved

- RMP, NRMF (for QH), intrinsic error field and its correction field are under active consideration in ITER, so various T_{NTV} is expected

- With rotation scaling (or use intrinsic torque scaling),

$$\frac{nmR^2}{\tau_\varphi}\left(C_{ts}+C_{ps}+1-C_p\right)\frac{dT_i}{d\psi}=T_{INT} \quad \text{and} \quad \frac{nmR^2}{\tau_\varphi}\left(C_{tsf}+C_{psf}+1-C_p\right)\frac{dT_i}{d\psi}=T_{INT}-T_{NTV}-T_{NBI}$$

- Rotation will be newly established at:

$$T_{NBI}+\frac{nmR^2}{\tau_\varphi}\left(C_{tsf}+C_{psf}-C_{ts}-C_{ps}\right)\frac{dT_i}{d\psi}=-\int_0^\infty dx\int_0^1 d\kappa^2\sum_{nmm'}f_{nmm'}(x,\kappa)\frac{n^2\left[\left(C_{tsf}+C_{psf}+1-C_N(x,\kappa)\right)\frac{dT_i}{d\psi}\right]}{n^2\left[\left(C_{tsf}+C_{psf}-C_B(x,\kappa)\right)\frac{dT_i}{d\psi}\right]^2+\nu(x,\kappa)^2}$$

$$\left(T_{NTV}=2in\delta W_k\right)$$ **[Park, POP 18, 110702 (2011)]**

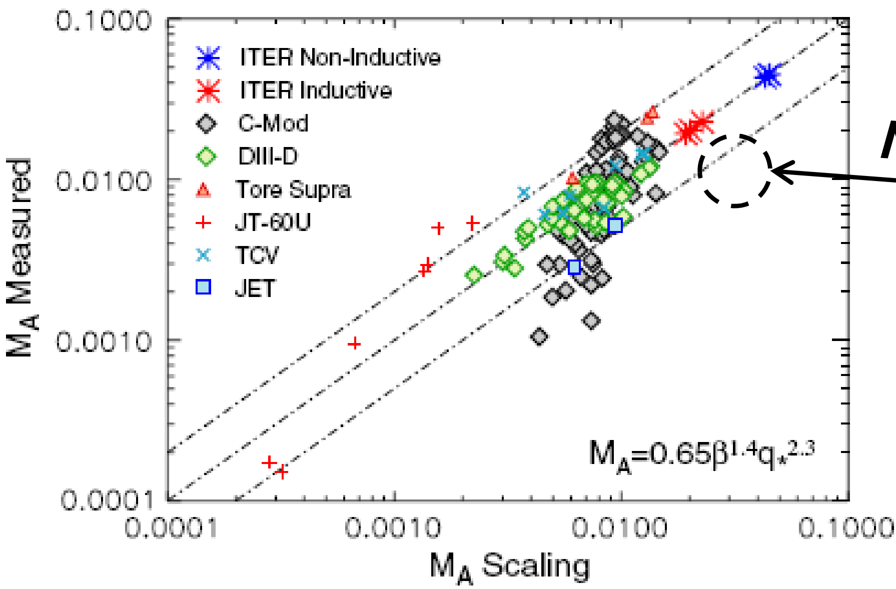
- Final *ExB* rotation will determine stability:

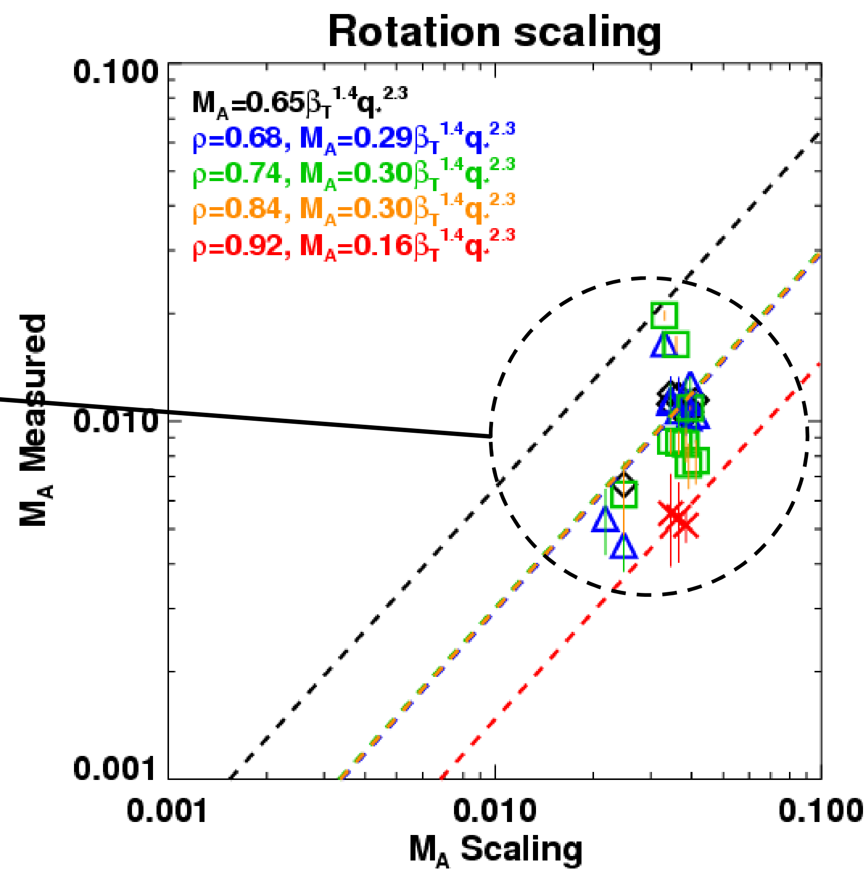
$$\frac{d\Phi}{d\psi}=\left(C_{tsf}+C_{psf}\right)\frac{dT_i}{d\psi}$$

NSTX results can be combined with other tokamak scaling on intrinsic rotation

- NSTX intrinsic rotation through L-H transitions can be combined with empirical scaling of conventional tokamaks (by Rice)
- However, NSTX results yield small proportional factor, probably due to large toroidal β and q* in ST

[Rice, NF 47, 1618 (2007)]





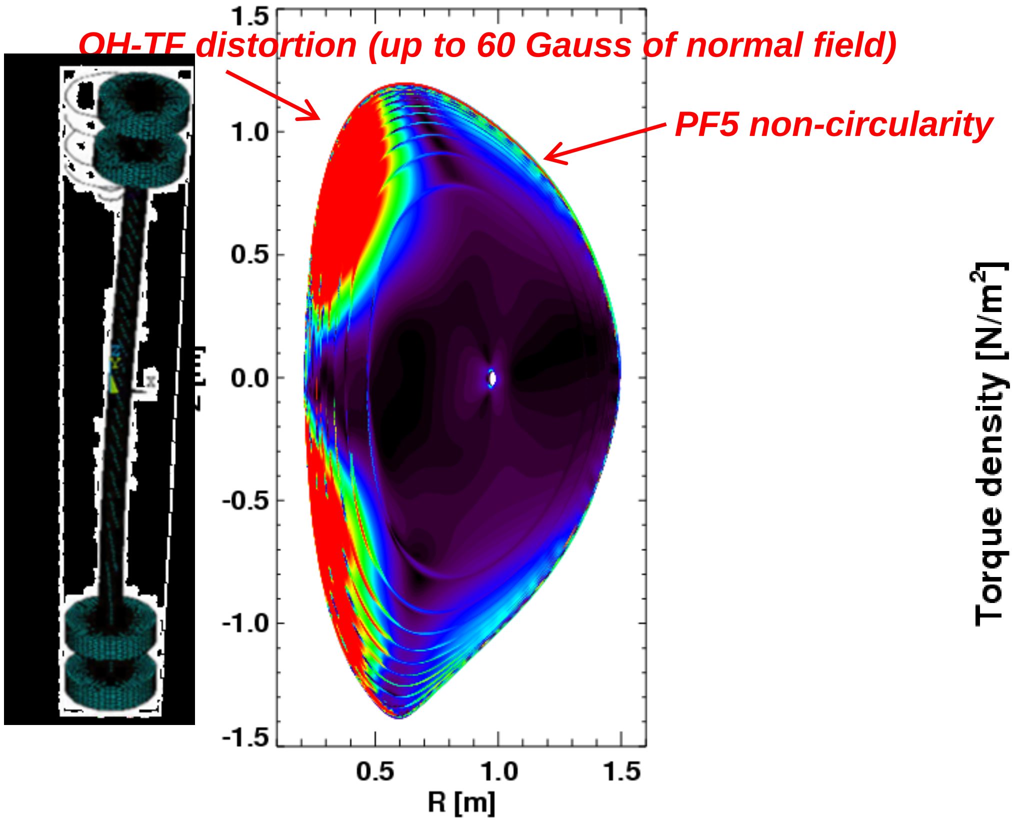
"Intrinsic error torque" is ignorable in Ohmic plasmas compared to measured "intrinsic torque"

- Intrinsic error torque exists (even can be small) due to imperfect coils
- Actual calculation in Ohmic H-mode shows this "intrinsic error torque" is much less than measured "intrinsic torque", so is ignored in our analysis
- This does not mean "intrinsic error torque" is generally small, since NTV is small for low β but can increase rapidly with β (e.g.) Even without collisionality dependency:

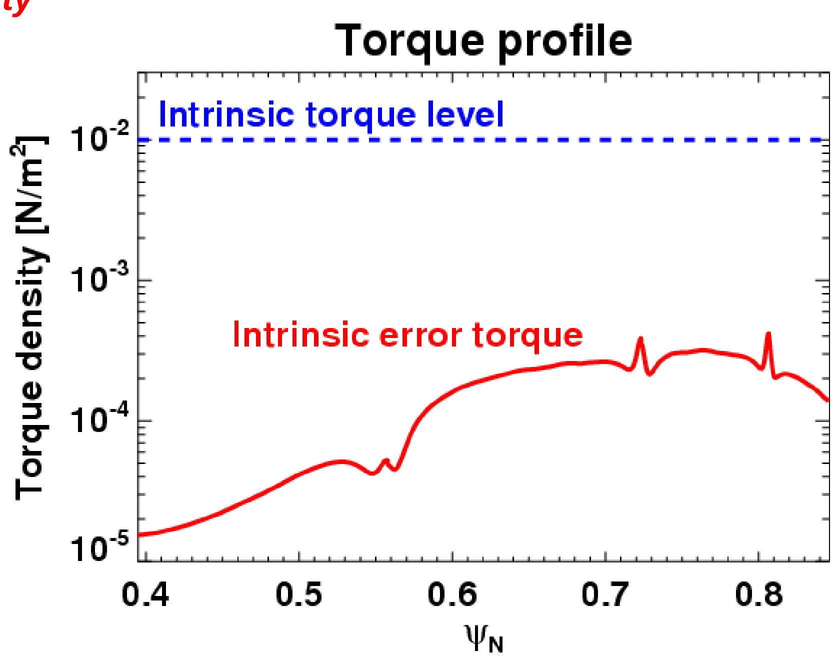
$$T_{NTV} \propto p_i(\delta B)^2 \propto p_i\left(\vec{\xi}\cdot\nabla p_i+\cdots\right)^2 \propto p_i^{\,3}$$

[Park, PRL 102, 065002 (2009)]

IPEC |dB| for NSTX intrinsic errors



Combined NTV based on IPEC |dB|



Summary (TTF)

- 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) as theory
- NSTX intrinsic rotation can be combined with empirical Rice scaling, but with small proportional factor
- However, uncertainty in determining intrinsic ion rotation is as large as measurement since every flow component is in a similar order
- Many stability involves each flow in a similar order too
- Most important component is *ExB*, and its measurement and scaling should be highly precise to predict stability in ITER – Both toroidal and poloidal flow measurements of impurity ions are perhaps essential

$$E \times B \ \text{rotation}: \frac{d\Phi}{d\psi} = \underline{\left(C_{ts} + C_{ps}\right)} \frac{dT_i}{d\psi}$$

- In intrinsic environment, torque can be inferred if rotation scaling exists as well as momentum confinement scaling (or vice versa), and so torque balance, rotation evolution, stability can be determined