Analysis and prediction of momentum pinch in spherical tokamaks

W. Guttenfelder[1], A.R. Field[2], I. Lupelli[2], J.-K. Park[1], T. Tala[3], S.M. Kaye[1], M. Peters[4], Y. Ren[1], W.M. Solomon[1]
[1]PPPL, [2]CCFE, [3]VTT-Finland, [4]Indiana University

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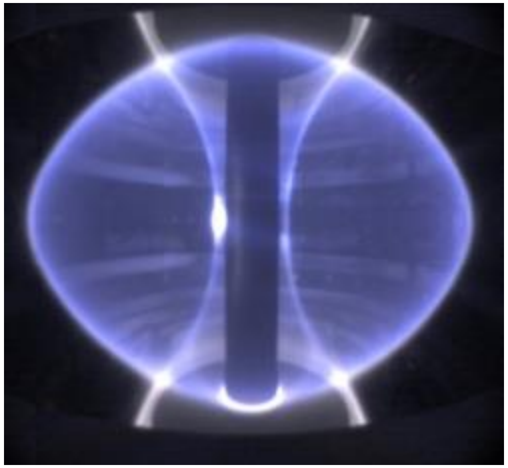
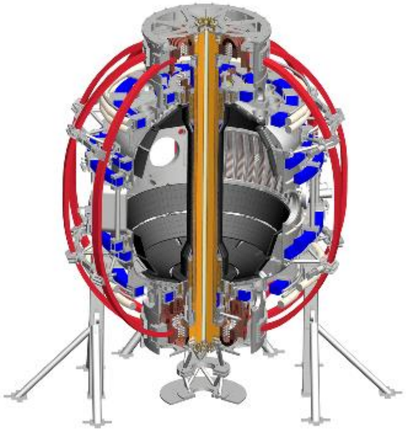




Overview

- Previous perturbative measurements performed for NSTX H-modes identified an inward momentum pinch, RV_φ/χ_φ=(-1)-(-7) [Solomon, PRL 2008; Kaye, NF 2009]

- However, quasi-linear gyrokinetic simulations predict very weak or outward momentum convection, RV_φ/χ_φ=0-2, due to kinetic ballooning modes (KBM) at high beta [Guttenfelder, TTF 2013, APS 2013]

- **Performed perturbative momentum transport experiments in MAST L-mode plasma (2013) to validate with theory at low beta (avoids complication of electromagnetic effects)**

- **Experimental results (this poster) find similar momentum pinch RV_φ/χ_φ=(-2)-(-11); gyrokinetic analysis now beginning**

Background & Motivation

Interpretation of toroidal angular momentum transport often assumes diffusive and convective components

- Transport equation: $$\frac{\partial}{\partial t}\left(n_i m_i \left\langle R^2 \right\rangle \Omega\right) + \nabla \cdot \Pi_\varphi = S_\Omega \rightarrow \sum_s (\cdots)$$
- *Assumed* transport form: $$\Pi_\varphi = -nmR\chi_\varphi (R\nabla\Omega) + nmV_\varphi (R\Omega)$$

Prandtl number $\boxed{\mathrm{Pr} = \frac{\chi_\varphi}{\chi_i}}$

Pinch parameter $\boxed{\frac{RV_\varphi}{\chi_\varphi}}$

$$\hat{\Pi}_\varphi = \hat{\chi}_\varphi \left(\hat{u}' + \frac{RV_\varphi}{\chi_\varphi} \hat{u} \right)$$

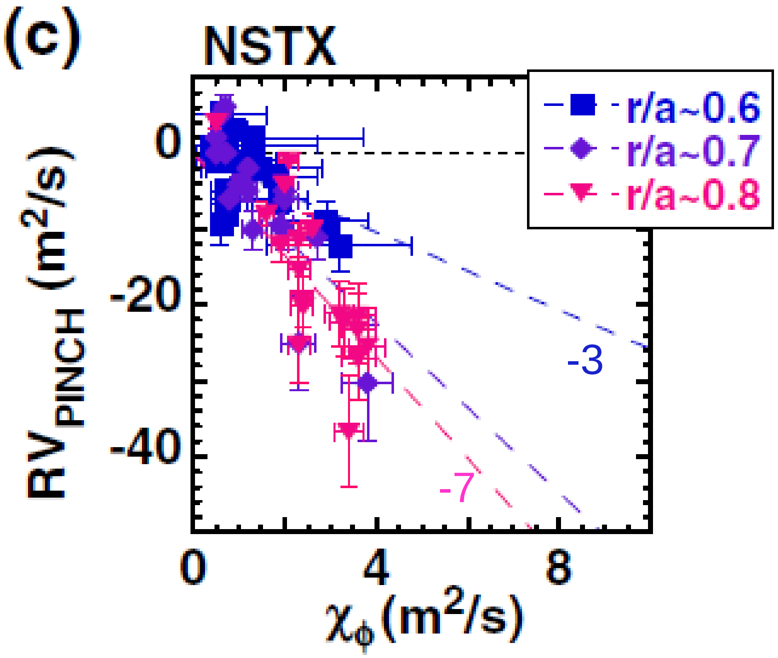
$$\hat{u}' = \frac{-R^2 \nabla\Omega}{c_s} \qquad \hat{u} = \frac{R\Omega}{c_s}$$

- Pinch expected due to Coriolis drift [Peeters, 2007], turbulent equipartition + thermoelectric force [Hahm, 2007]

Perturbative NSTX H-mode experiments (using n=3 magnetic braking) indicate existence of an inward momentum pinch

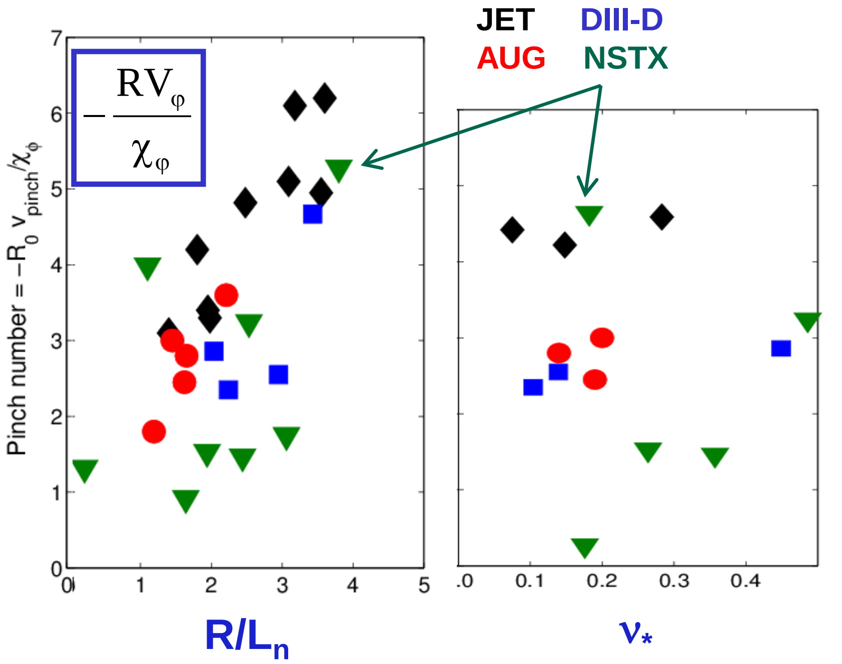
- $RV_\varphi/\chi_\varphi \approx -(1\text{-}7)$ for many NSTX discharges & radii

(Solomon et al., PRL 2008, PoP 2010; Yoshida et al., NF 2012)



- Possible dependence on density gradient (R/L_n), less clear with collisionality (ν^*)

(Tala et al., IAEA 2012)



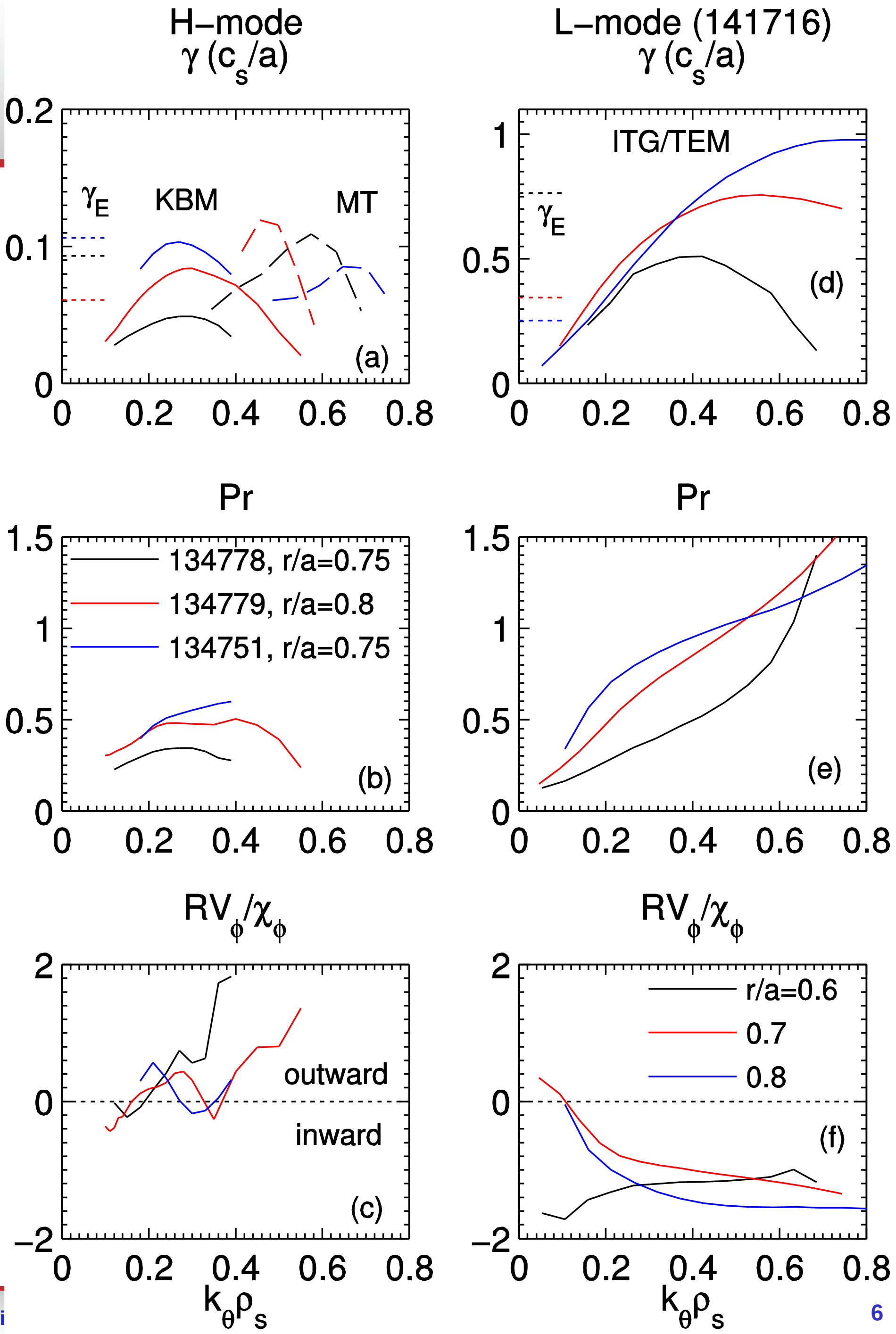
- Local, linear gyrokinetic simulations of ITG turbulence describe pinch and scaling in conventional tokamaks ⇒ **does this hold for STs?**

Local, linear sims unable to explain measured pinch

- Guttenfelder (TTF, 2013) showed gyrokinetic simulations (GYRO) predicting linear stability, Pr and pinch (following Peeters, 2007)

- In H-modes, mix of microtearing (MT) and KBM predicted unstable
- No momentum transport for MT but KBM predicts:
  - Small Pr~0.3-0.5
  - **Small or outward convection, RV_φ/χ_φ~0-2**
  - **Pinch insensitive to parameter variations (R/L_n, ν_*, …)**

- In L-mode, ITG/TEM unstable:
  - Larger Pr≤1
  - **Small inward pinch, RV_φ/χ_φ ~ -2-0**
  - **Pinch insensitive to parameter variations (R/L_n, ν_*, …)**



MAST experiments

MAST experiment M9-TC11 ran in August 2013

- Acquired shots in both L-mode and H-mode, at two plasma currents (400, 600 kA)
- Used short n=4 (H-mode) and n=3 (L-mode) RMP fields to perturb rotation
  - Also obtained some BES & DBS turbulence measurements

- Analysis of H-mode rotation complicated by saturated n=1 internal-kink mode, occurs as q approaches unity, $q \rightarrow 1^+$ [I. Chapman, NF (2010)]
  - May be able to interpret momentum transport if accounting for NTV torque due to saturated n=1 kink [M.D. Hua, PPCF (2010)]
- 600 kA L-mode flat-top too short before transition to H-mode

- **400 kA L-mode shots worked best (longer duration) – Analysis of NTV torque and momentum transport to follow**

- Also obtained one repeat shot in 400 kA L-mode with NBI modulation (Sept 11, 2013) – influence of power/torque modulation on rotation unclear, more analysis in the future

Obtained repeatable 400 kA L-modes

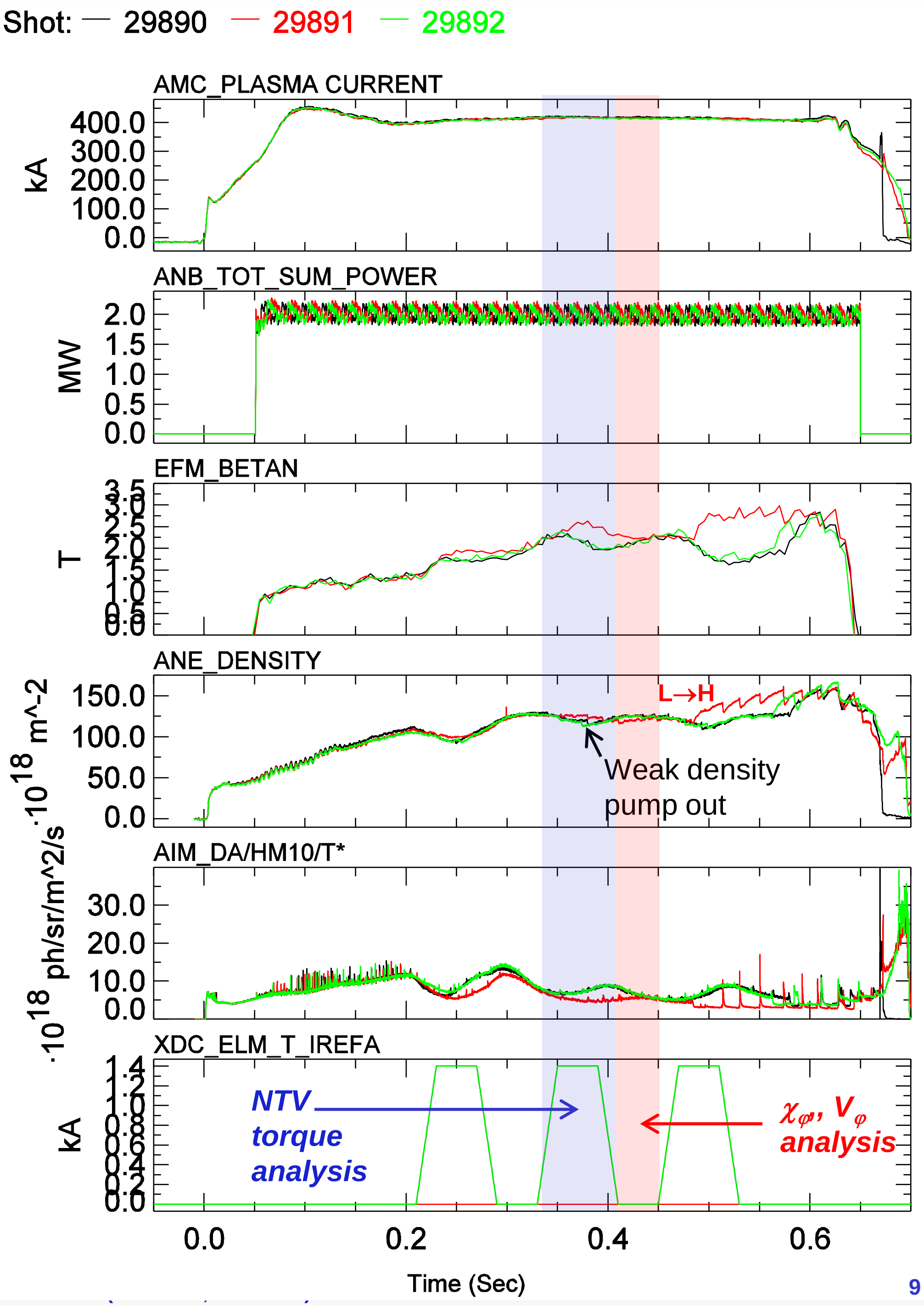
- LSN L-mode, 2 MW
  - $\langle n_e \rangle = 2.3\times10^{19}$ m^{-3}
  - $B_T = 0.5$ T
  - $q_{95} \approx 5$
- Three n=3 field pulses applied

29890 – N×I_{RMP} = 4×1.4 kA

29891 – no RMP

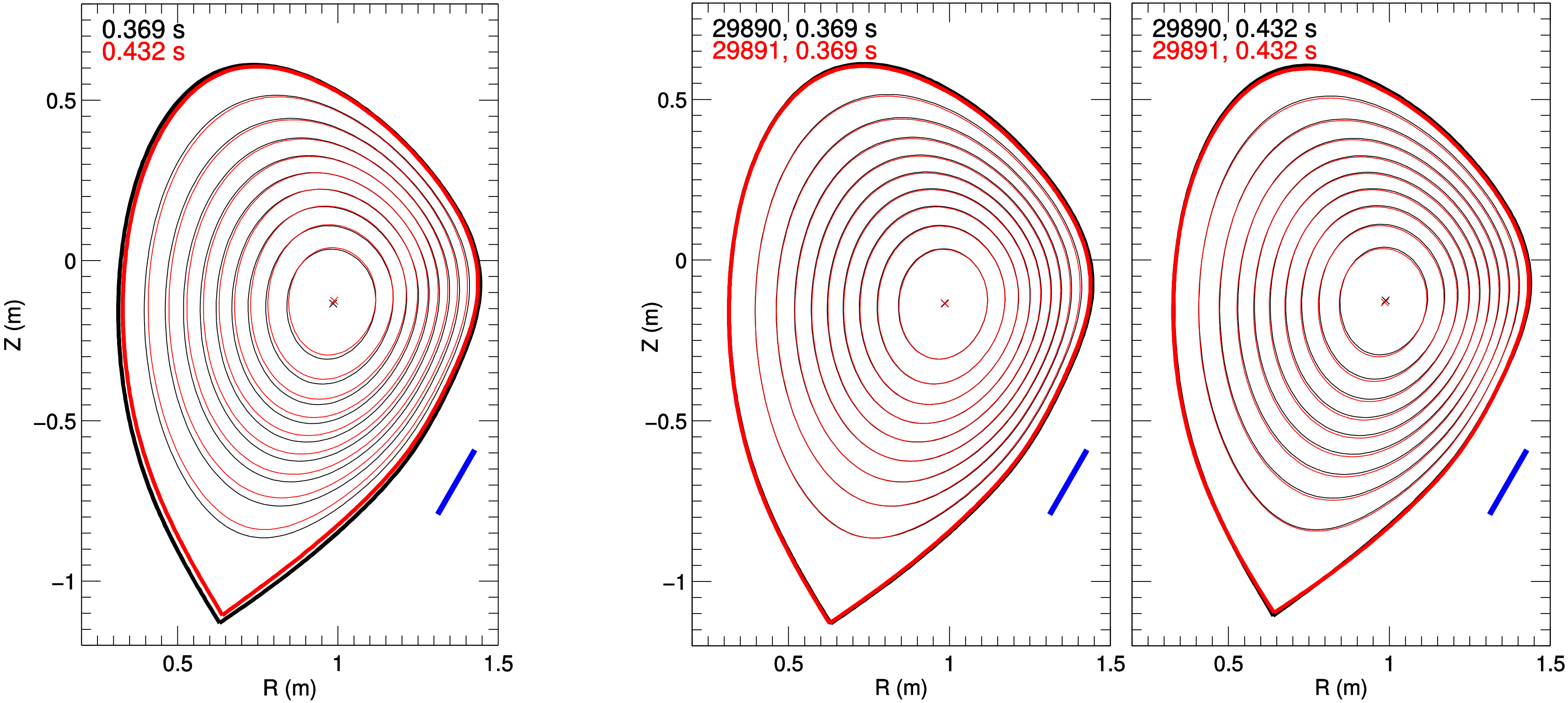
29892 – N×I_{RMP} = 4×1.4 kA (repeat, second BES location)

- Weak density pump out in L-mode w/ RMP, drop in β_N
- Without RMP, eventual transition into H-mode (t~0.47 s)



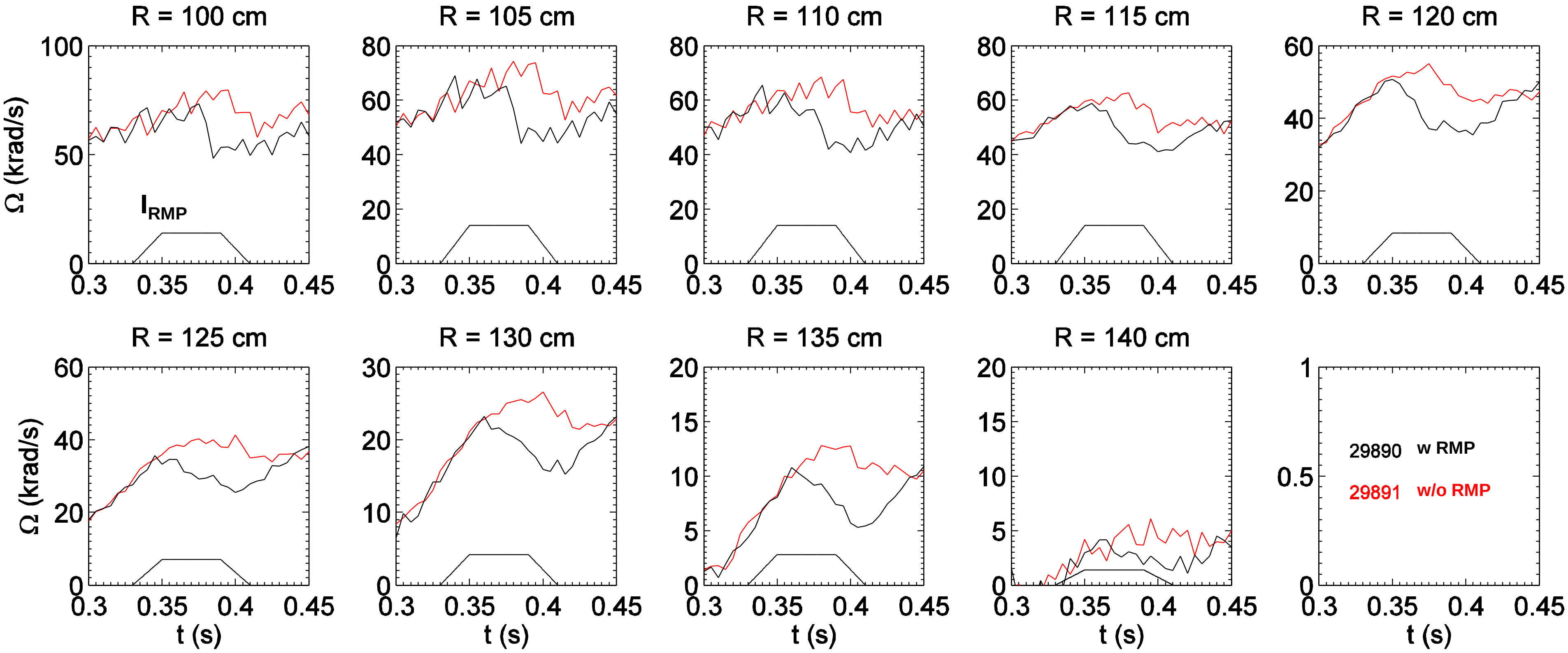
To obtain sufficient rotation braking required strong bias to lower single null

- n=3 field applied using only lower 12 coils (blue)
- Some variation in assumed 2D (axisymmetric) shape during/after applied n=3 field (from MSE-constrained EFIT++)
- However, variation largely due to plasma evolution regardless of n=3 field
  - Axisymmetric equilibrium similar to control shot (29891) *without* n=3 fields



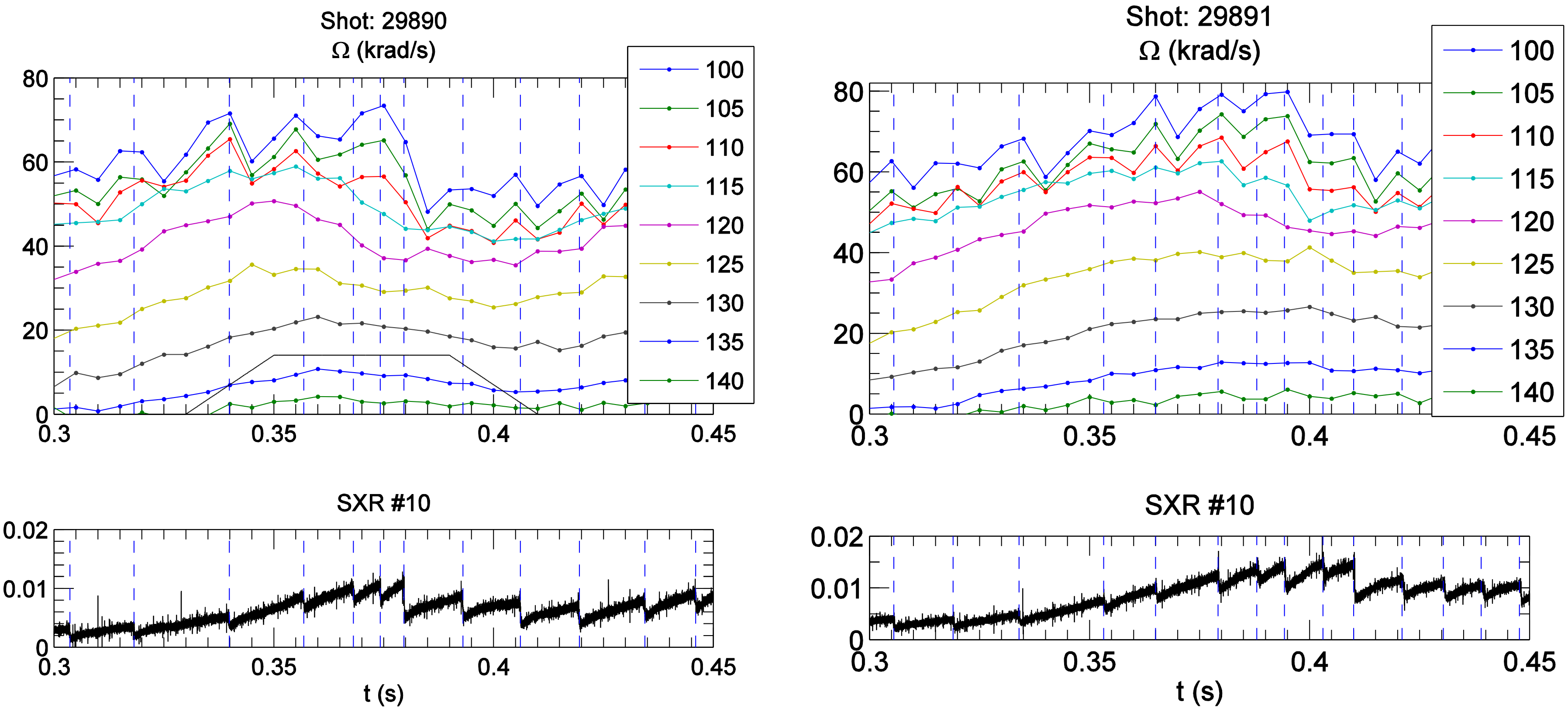
Changes in toroidal flow due to n=3 RMP observed

- Unfortunately have not reached steady conditions before & after perturbation
- **Control shot w/o n=3 RMP (29891) provides a baseline for analysis**
- Response of rotation to applied n=3 field appears delayed (depending on location)



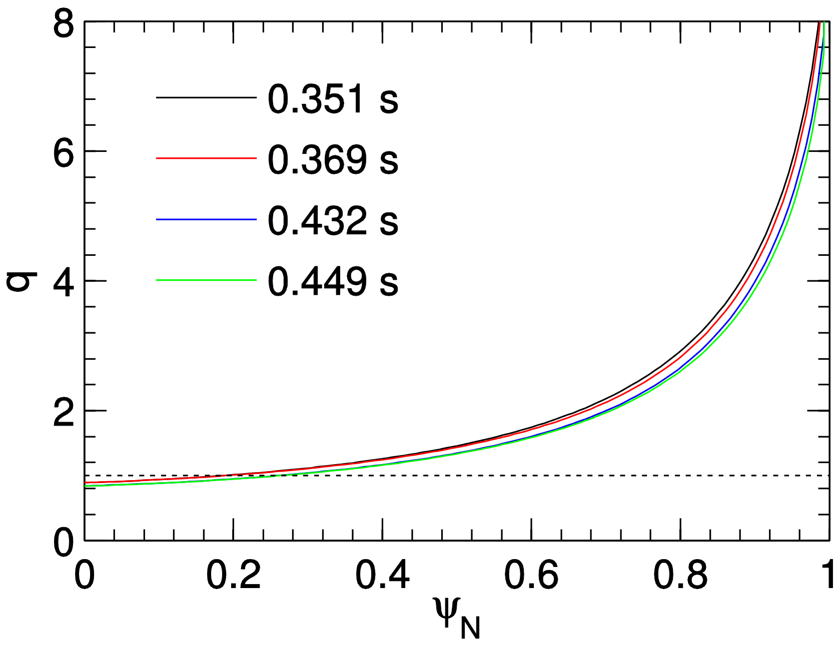
Effect of sawteeth visible in central rotation

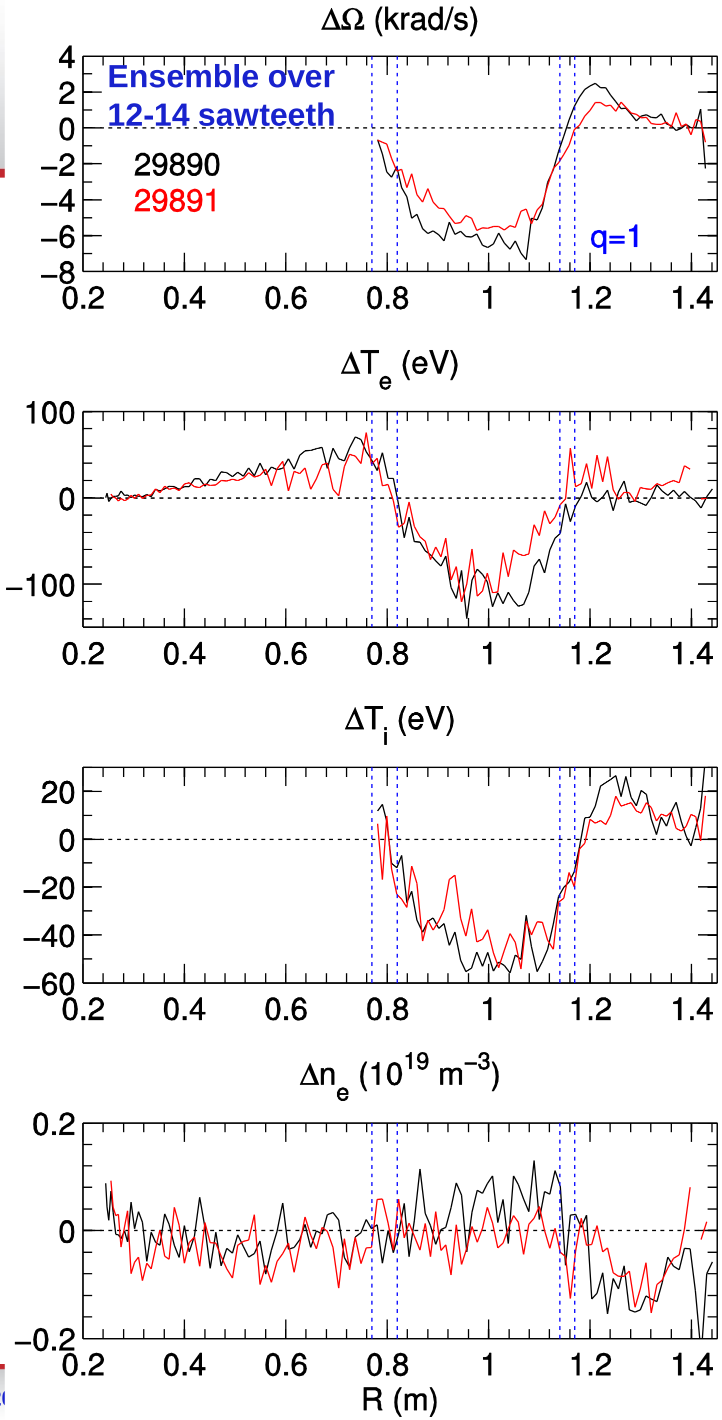
- Sawteeth occur with period $(\Delta t)_{ST} \approx 6\text{-}22$ ms (average ~12 ms)
- CXRS measurement sampling of $\Delta t = 5$ ms
- Can ensemble difference just before/after to estimate average $\Delta\Omega_{ST}$, $\Delta T_{e,ST}$, …



Sawteeth cause ~6 krad/s (~8%) deceleration inside inversion radius

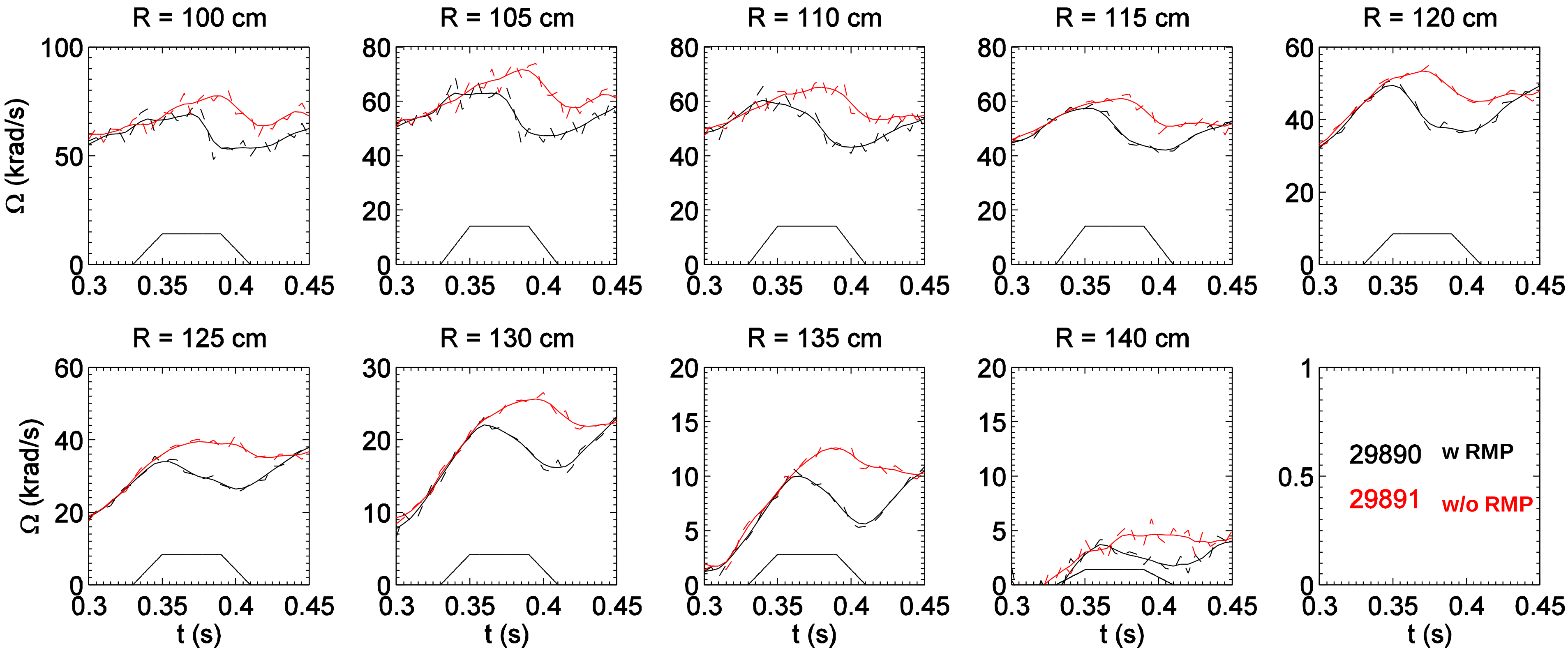
- q=1 surface ψ_N~0.19-0.26 (R_{out}~114-118 cm) consistent with ΔT_e inversion
- ΔT_e ~ 120 eV (~16% of $T_{e,0}$~750)
- ΔT_i ~ 50 eV (~6% of $T_{i,0}$~800)





Using filtered data (and TRANSP analysis) to infer NTV torque and perturbative momentum transport

- Smoothed with zero-phase FIR filter (Δt_{filt}=15 ms) to remove sawtooth oscillations
- Local ST perturbations $\Delta\Omega_{ST}$~2-6 krad/s smaller than $\Delta\Omega_{NTV}$~10-20 krad/s



Confinement and NTV torque analysis

First determine 0D confinement time and NTV torque

- Integrating over volume leads to 0D angular momentum

$$\frac{\partial}{\partial t}\left(\sum_i n_i m_i \left\langle R^2 \right\rangle \Omega\right) + \frac{1}{V'}\frac{\partial}{\partial \rho}\left[V' \cdot \Pi\right] = \sum T_{source} - \sum T_{sink}$$

$$\Downarrow$$

volume integrate

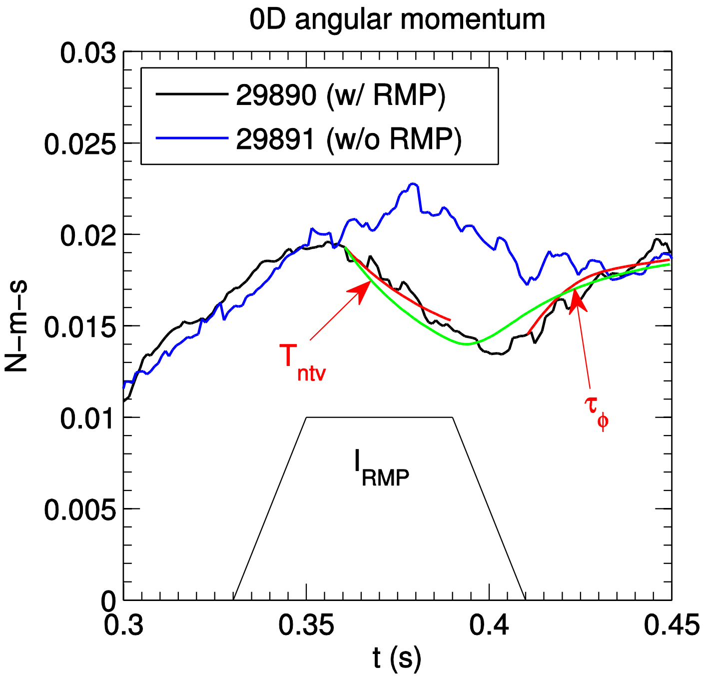
$$\frac{\partial L}{\partial t} + \frac{L}{\tau_\varphi} = T_{NBI} - T_{NTV}$$

- Can fit to recovery *after* RMP (T_{NTV}=0) to infer τ_φ
- Can then use τ_φ *during* RMP to infer T_{NTV}

- Alternatively, can fit entire response (during and after RMP) to simultaneously solve for τ_φ and T_{NTV} (assuming T_{NTV}~I_{RMP}^2)

Momentum confinement time comparable to energy confinement time

- Inferred $\tau_\varphi \approx 28$ ms comparable to energy confinement time $\tau_E \approx 30$ ms
  - For reference, $\tau_{E,th} \approx 19$, $\tau_{E,e} \approx 13$ ms
- $T_{NTV} \approx 0.21$-0.28 N-m ($T_{NBI} \approx 0.7$ N-m), depending on fit approach
- Unfortunately we do not have long steady periods before and after
  - Clearly missing some additional background evolution
  - Also not accounting for apparent delayed onset of rotation braking

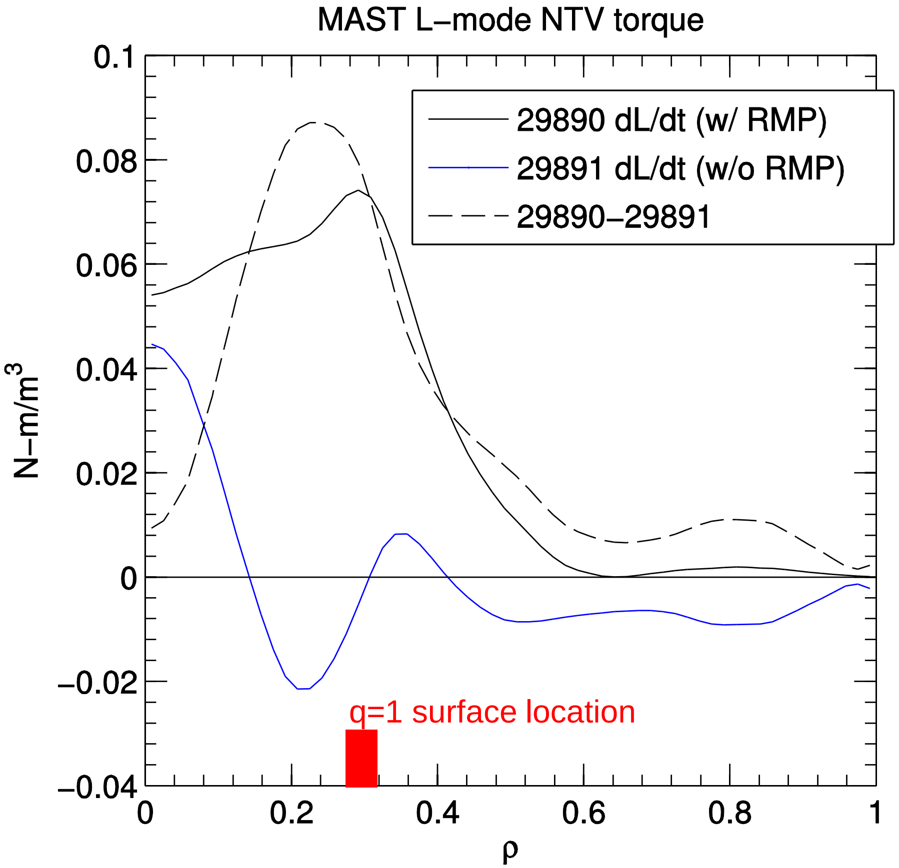


	τ_φ (ms)	T_{NTV} (N-m)
separate fit	28	0.21
integrated fit	27	0.28

NTV torque peaked near axis, in contrast to typical H-mode results

- T_{NTV} determined from TRANSP dL(ρ)/dt, averaged over 0.36-0.39 s

- Total NTV torque ~ 0.15 N-m
  - 0.19 N-m if subtract dL/dt during same period from control shot w/o RMP
  - Compared to 0.20-0.28 N-m from 0D analysis



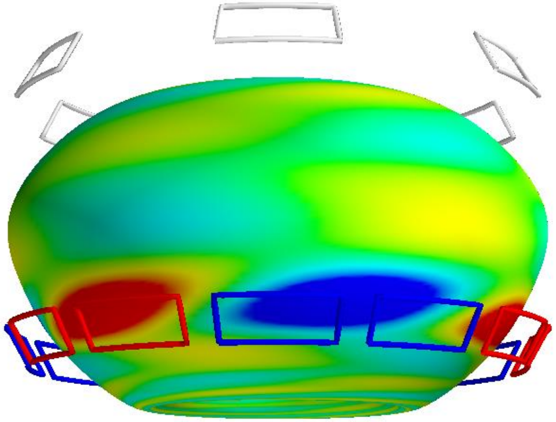
IPEC-PENT modeling predicts similar range of core-dominant NTV torque, but profiles are different due to q=1 subtlety

- Lower coil n=3 configuration generates both resonant and non-resonant components of the field

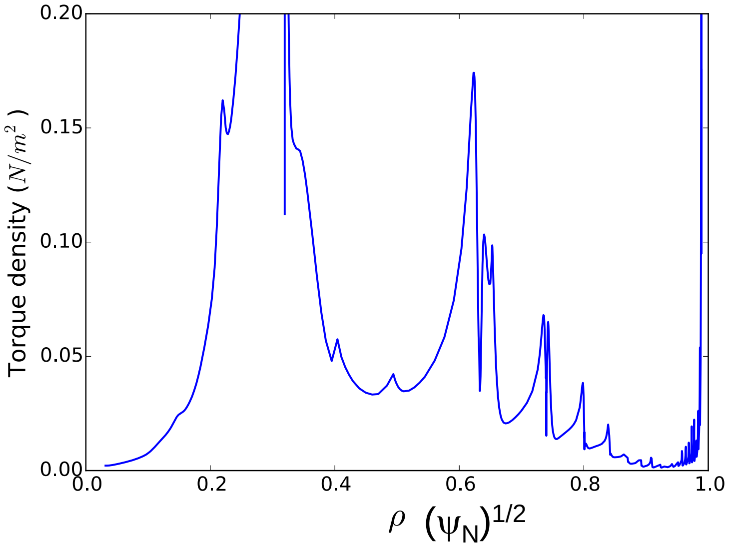
- Total NTV by trapped and passing ions = 0.13~0.36N-m for q_{min}=0.95~1.05
    - NTV torque is strong at the core by l=1,2 bounce resonances, and also by low enough collisionality due to peaked temperature profile

- But wrong in details: Non-linear saturation of the field inside q<1, potato orbits at the center, and finite-orbit averaging near the peaks can be all important

MAST lower n=3 (IPEC)



NTV torque density profiles by IPEC-PENT: Total NTV = 0.36N-m (q_{min}=0.95)



Momentum pinch analysis

Method to infer χ_φ and V_φ from transient rotation response *after* RMP turn-off

- TRANSP solves for momentum flux, Π, using the flux-surface-averaged toroidal angular momentum transport equation (Goldston, Varenna 1985), plus NUBEAM calculations for torque sources & sinks:

$$\frac{\partial}{\partial t}\left(\sum_i n_i m_i \langle R^2 \rangle \Omega\right) + \frac{1}{V'}\frac{\partial}{\partial \rho}\left[V' \cdot \Pi\right] = \sum T_{source} - \sum T_{sink}$$

- *Assuming* momentum flux composed of only diffusive and convective contributions:

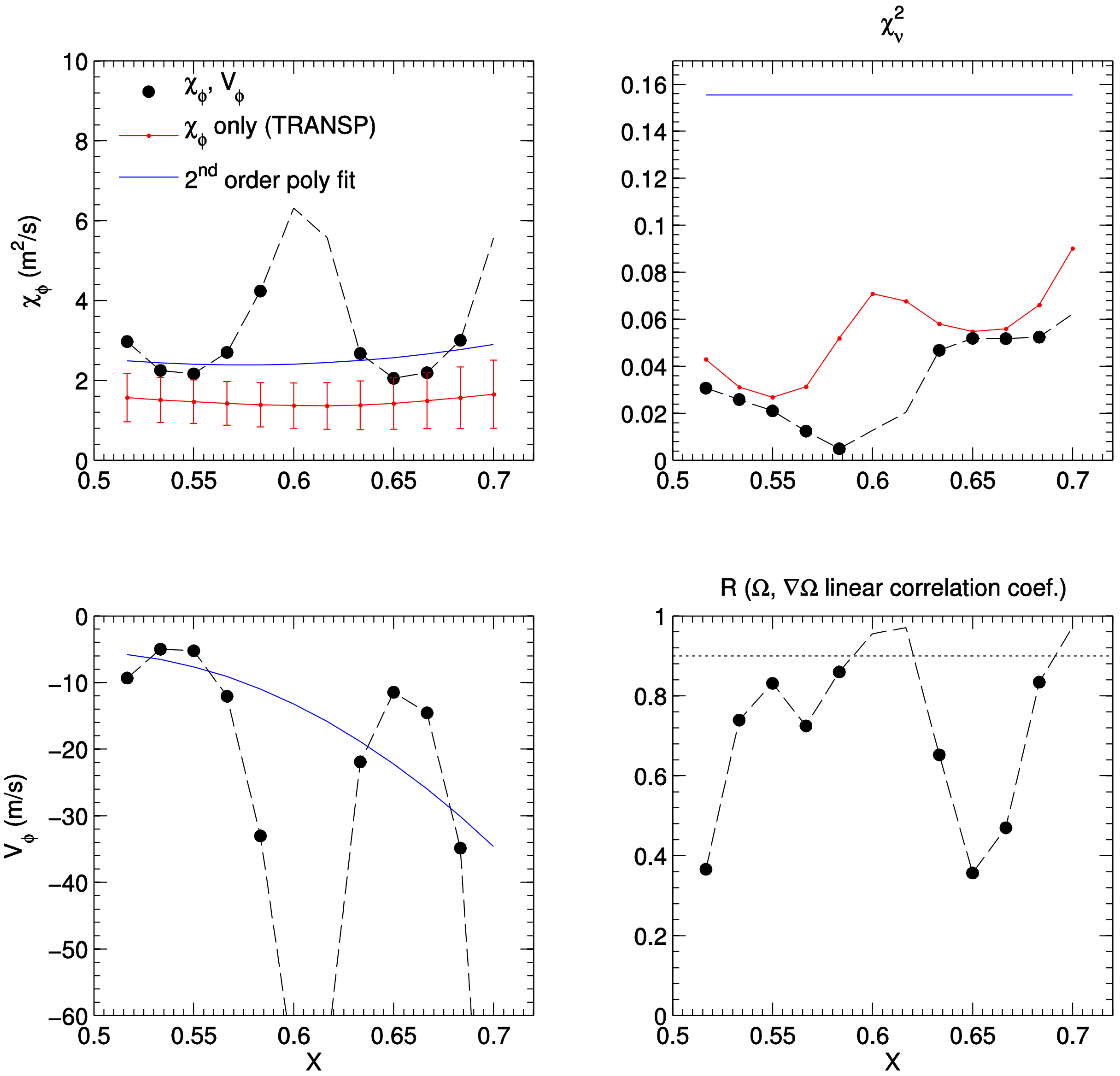
$$\Pi = \sum_i n_i m_i \left[-\left\langle R^2 (\nabla\rho)^2 \right\rangle \chi_\varphi \frac{\partial \Omega}{\partial \rho} + \left\langle R^2 \right\rangle \left\langle \nabla\rho \right\rangle V_\varphi \Omega \right]$$

we can use $\Pi(\rho,t)$, $d\Omega/d\rho(\rho,t)$, and $\Omega(\rho,t)$ in a nonlinear least squares fit algorithm to determine best fit $\chi_\varphi(\rho)$, $V_\varphi(\rho)$ (assumed constant in time)

- Note: method only valid if $d\Omega/d\rho(t)$ and $\Omega(t)$ are sufficiently decorrelated

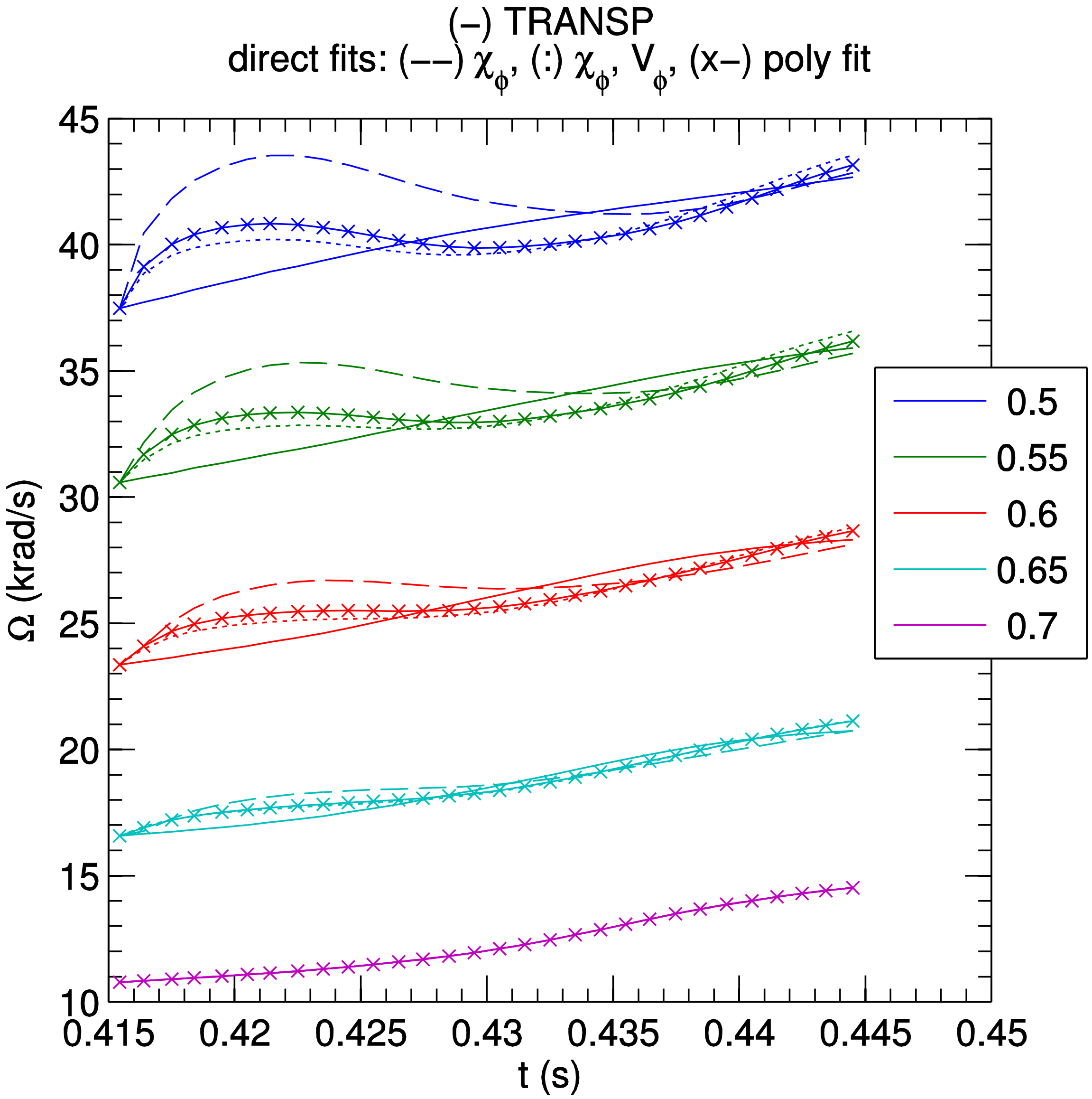
Transient recovery implies an inward momentum pinch

- Using both χ_φ and V_φ improves the quality of fit (χ_ν^2 smaller than χ_φ-only fit)
- At locations where there is a strong Ω-∇Ω linear correlation (Pearson product R→1), method is ill-posed ⇒ χ_φ & V_φ tend to large values
  - Symbols are analyzed points for arbitrary R<0.9 cutoff
- *Assuming* smoothly varying transport coefficients forces smoother χ_φ, V_φ profiles
  - Best fit (lowest χ_ν^2) using quadratic polynomial

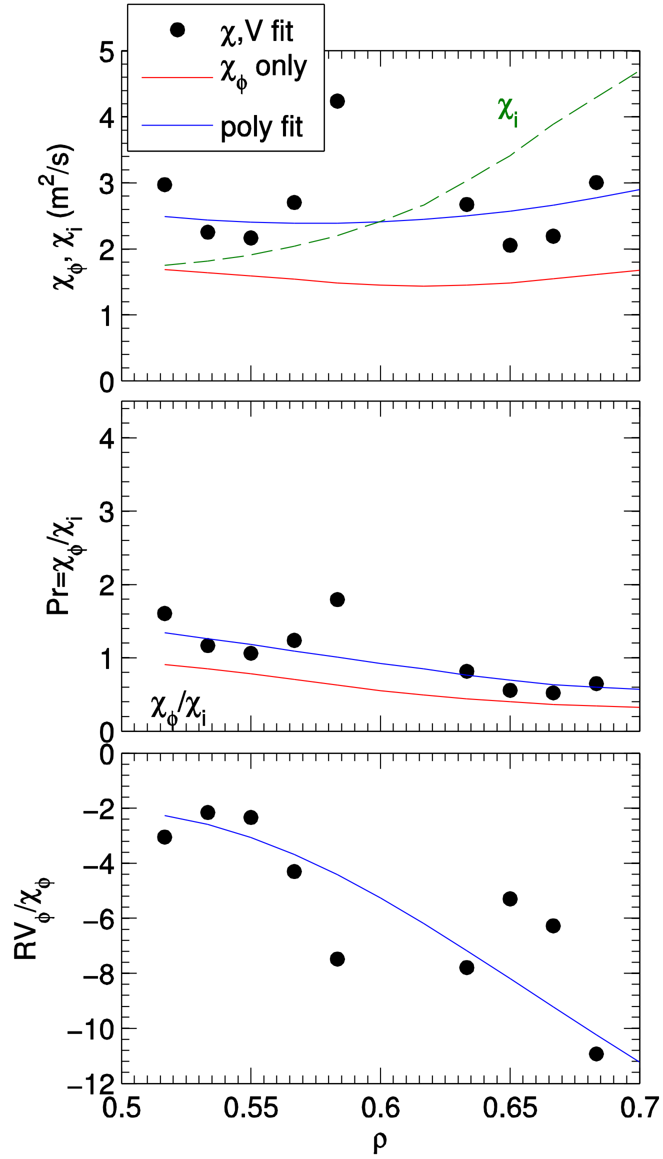


Predicted $\Omega(t)$ response improved when including convection (χ_φ & V_φ) as opposed to diffusion only (χ_φ)

- Details of time response not accurately reproduced



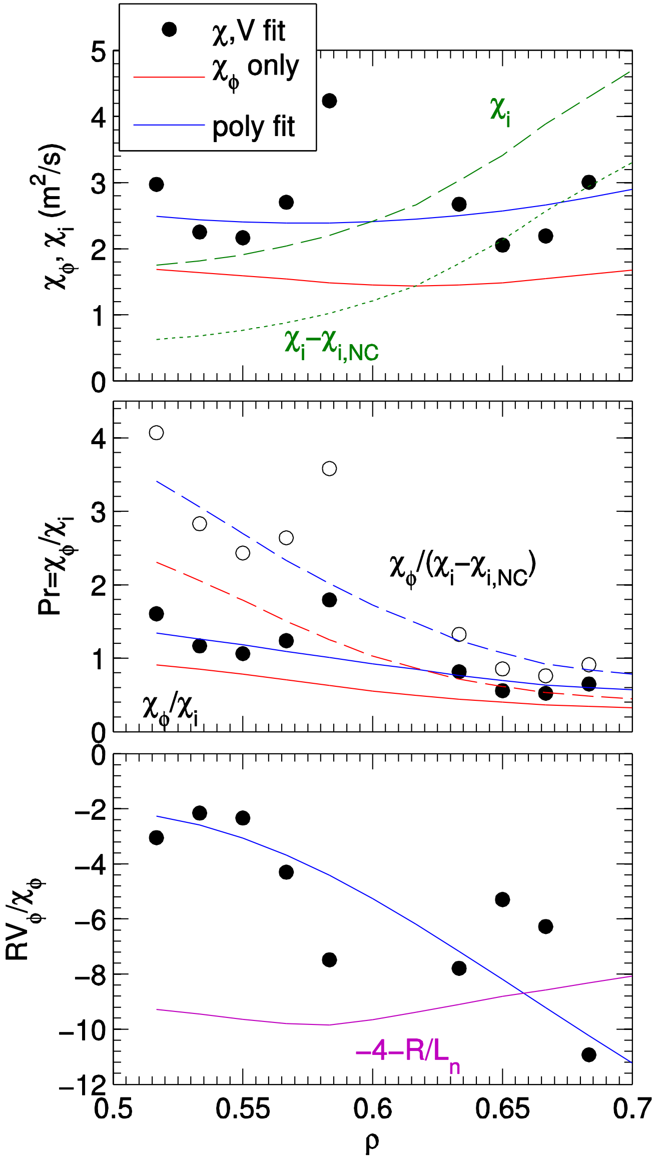
Resulting Prandtl number Pr~0.5-2.0, Pinch parameter RV_φ/χ_φ ~ (-2) to (-11)



Subtracting neoclassical ion thermal transport leads to larger Pr~0.8-4.0

- In L-mode, $\chi_{i,NC}$ smaller than χ_i but still substantial contribution
- $\chi_e \sim 3\cdot\chi_i$, additional uncertainty from $T_e \sim T_i$ collisional energy exchange

- Local, quasi-linear Coriolis pinch theory [Peeters, PRL 2007] gives: $RV_\varphi/\chi_\varphi = -4 - R/L_n \sim (-9)$, in range of measurement but flat in radius



Gyrokinetic analysis proceeding on this shot

- Will start with local linear & nonlinear GYRO runs for momentum pinch

- Additional effects beyond momentum pinch may be present in ST plasmas and will be investigated, e.g.:
  - Residual stress (Π_{RS}) from profile shearing at large ρ_s/L [e.g., Camenen, NF (2011)]
  - Centrifugal effects ~$\nabla(u^2/2)=u\cdot u'$ [R. Buchholz et al., Phys. Plasmas (2015)]

$$\hat{\Pi} = \hat{\chi}_\varphi \left[u' + \left(\frac{RV_\varphi}{\chi_\varphi} \right) u + \left(\frac{C_{cf}}{\chi_\varphi} \frac{c_s}{R} \right) u \cdot u' \right] + \hat{\Pi}_{RS}$$

Summary

- n=3 fields applied to perturbatively brake plasma rotation in low-beta MAST L-mode
  - Analysis implies NTV torque profile peaked in core
  - *Assuming* diffusion & convection is all that matters (χ_φ, V_φ), response after removal of NTV torque indicates inward momentum pinch, RV_φ/χ_φ~(-2) – (-11)

- Limitations in interpretation due to unsteady conditions, correlation between Ω-$\nabla\Omega$
  - Will try to improve analysis by fitting to modeled $\Omega(t)$ from integrating momentum transport equation

- Gyrokinetic predictions proceeding to predict RV_φ/χ_φ and other possible effects that may be important (centrifugal, finite ρ_*)

- Similar NSTX-U L-mode experiment planned for upcoming run campaign