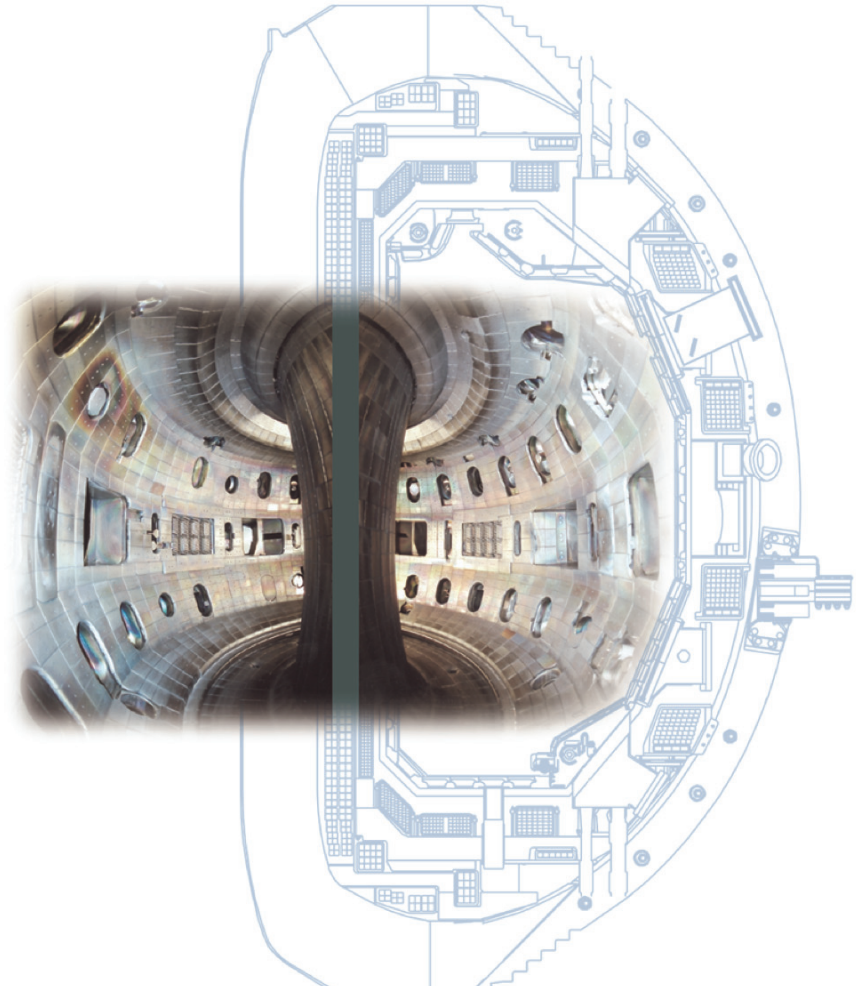
Evidence of an Edge momentum Source in DIII-D H-mode Plasmas and Role of the Reynolds Stress for Intrinsic Rotation

by
S.H. Müller[1]

in collaboration with
J.A. Boedo[1], K.H. Burrell[2], J.S. deGrassie[2]
R.A. Moyer[1], D.L. Rudakov[1], and
W.M. Solomon[3]

With acknowledgments to
P.H. Diamond[1] and G.R. Tynan[1]

[1]University of California-San Diego
[2]General Atomics
[3]Princeton Plasma Physics Laboratory



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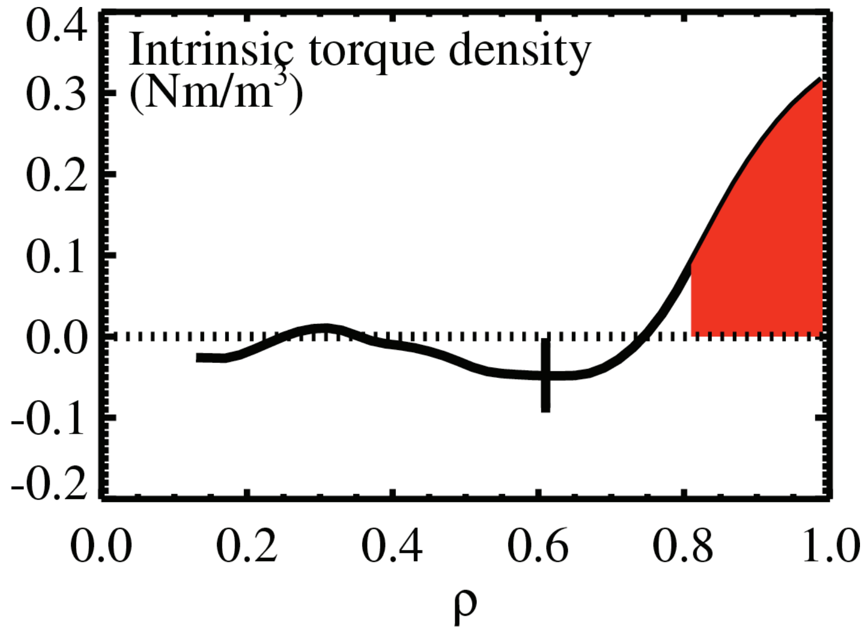
Motivation

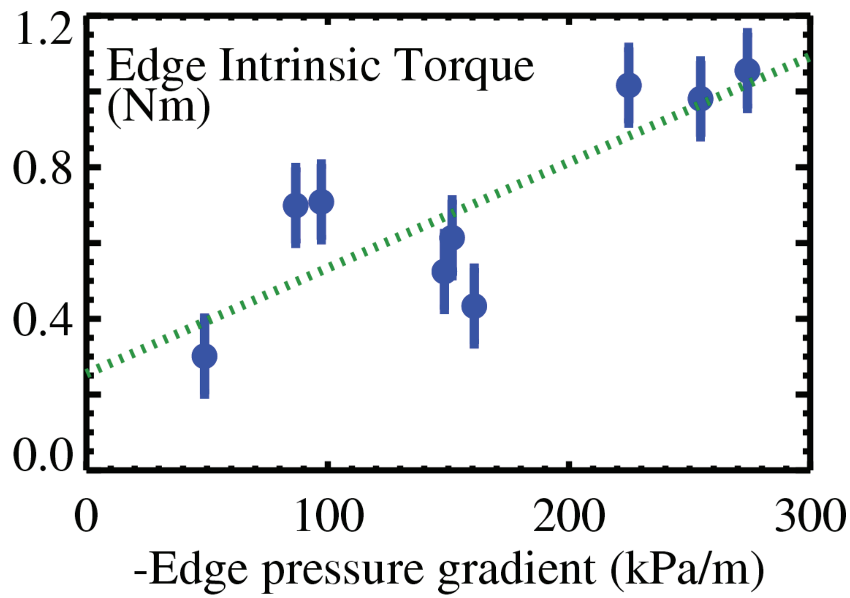
- **Toroidal rotation beneficial for confinement, stability and performance in tokamaks**
  - Self-generated *intrinsic* rotation will gain importance in burning plasmas

- **Experiments find intrinsic torque peaking in edge region**



Motivation

- ***Residual stresses* are candidates to explain edge intrinsic torque**
  - = non-diffusive non-convective turbulent momentum transport
  - ≠ momentum source (cannot *generate* momentum)



- **This talk: *"Is there an inward-directed residual stress at the plasma boundary that drives intrinsic rotation?"***
  - Direct measurements with multi-tip reciprocating Langmuir/Mach probe

Ion Toroidal Angular Momentum Balance and Stress Decomposition

- **Rate of change of toroidal angular momentum density…**

$$\partial_t(mRnv_\varphi) + \nabla\cdot(R\Pi\cdot\hat{\varphi}) - qn(\partial_t + \mathbf{v}\cdot\nabla)\Psi$$
$$-qRn(E_\varphi^{\mathrm{n.a.}} + \hat{\varphi}\cdot\mathbf{v}\times\mathbf{B}^{\mathrm{n.a.}}) - R(C_\varphi + S_\varphi) = 0$$

- **…balanced by divergence of stress tensor** $\Pi_{ij} \equiv m\int d^3u\, u_i u_j f$

- **Change in integral balance** $\partial_t L_\varphi = \tau_\Pi$ **requires finite stress at boundary**

$$L_\varphi(\psi) \equiv \int_{V(\psi)} d^3x\, mRnv_\varphi$$
$$\tau_\Pi(\psi) \equiv -A(\psi)\langle R\Pi_{\varphi\rho}\rangle_\psi$$

- **Decomposition, assuming** $\langle v_\rho\rangle = 0$

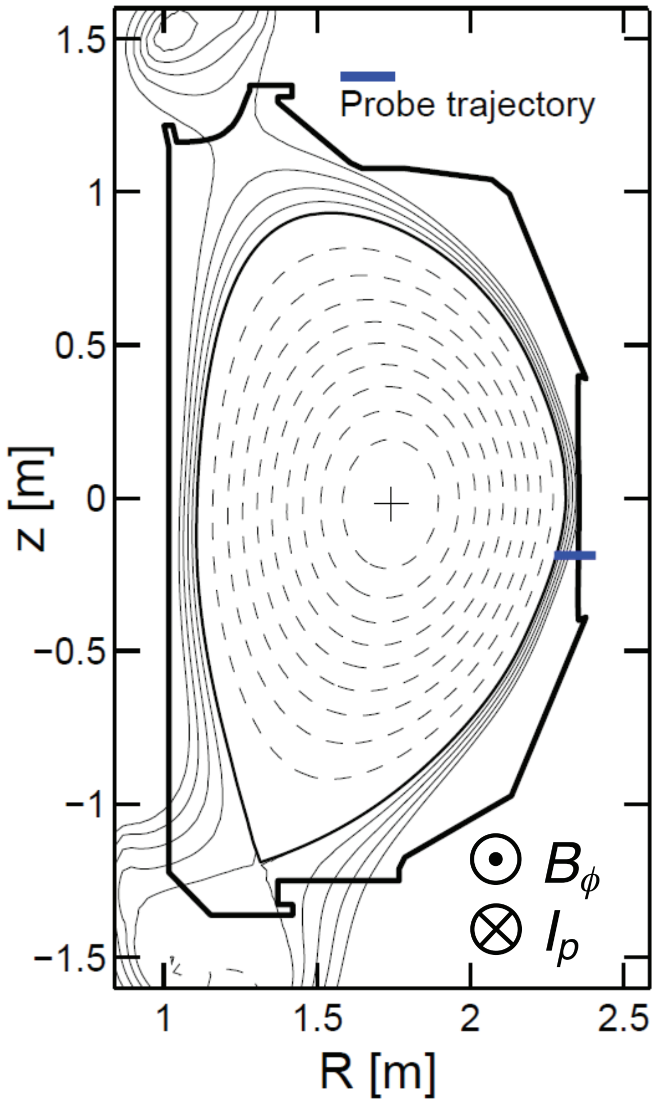
fluid | kinetic

$$\langle\Pi_{\varphi\rho}\rangle = m(\langle n\rangle\langle\tilde{v}_\varphi\tilde{v}_\rho\rangle + \langle v_\varphi\rangle\langle\tilde{n}\tilde{v}_\rho\rangle + \langle\tilde{n}\tilde{v}_\varphi\tilde{v}_\rho\rangle) + \langle\pi_{\varphi\rho}\rangle$$

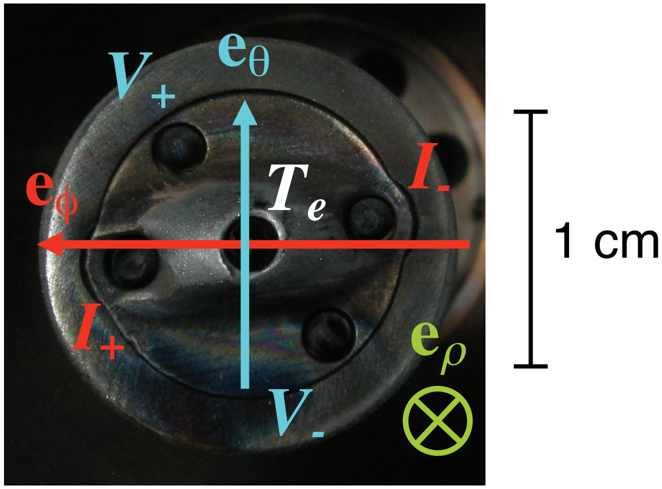
Reynolds stress | Particle transport | Triple correlations | Diffusive and small in Chapman-Enskog closure theory

$\langle\cdot\rangle$ …time average

Multi-tip Reciprocating Langmuir/Mach Probe Can Measure All Terms of Fluid Stress Tensor

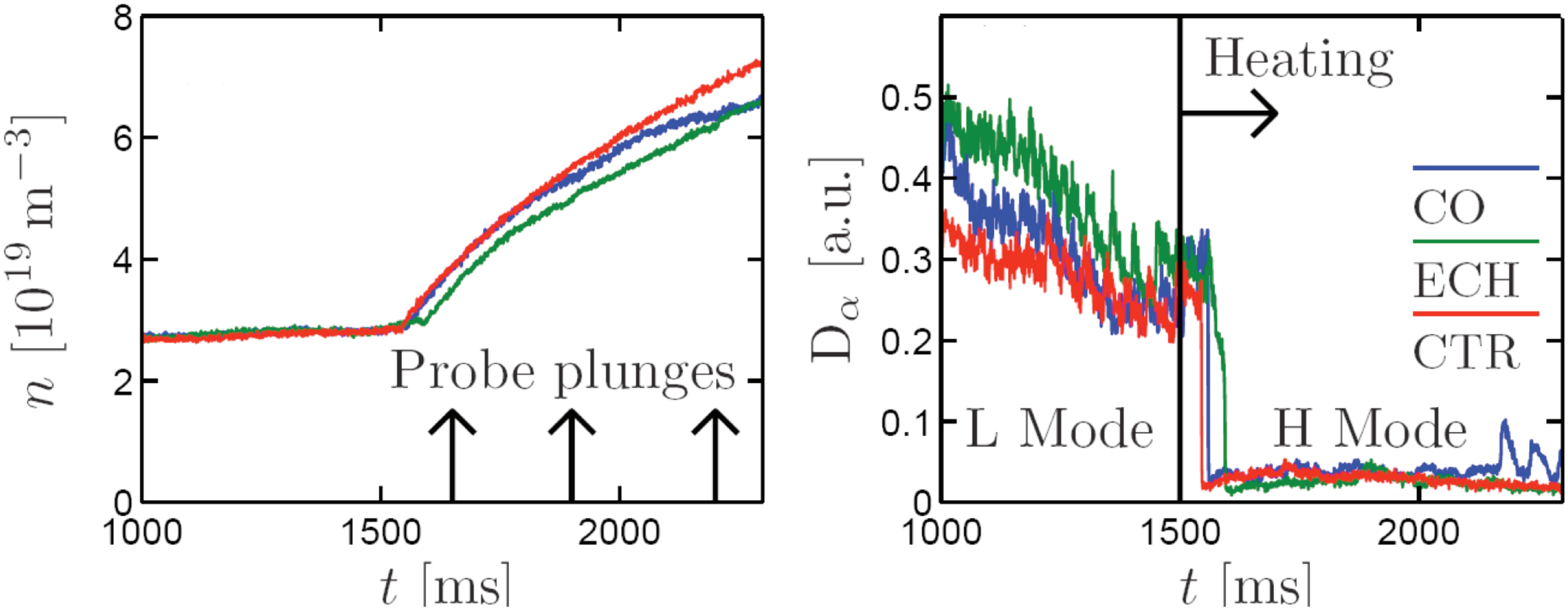


- **5 tips, 4 aligned on flux surface**
  - 1 MHz minimum bandwidth
- **1 proud tip:** $\langle T_e \rangle$, $(\tilde{T}_e)$
- **Mach probe:** $\langle n \rangle$, $\tilde{n}$, $\langle v_\varphi \rangle$, $\tilde{v}_\varphi$
  - Sound speed cancels in combination nv_φ



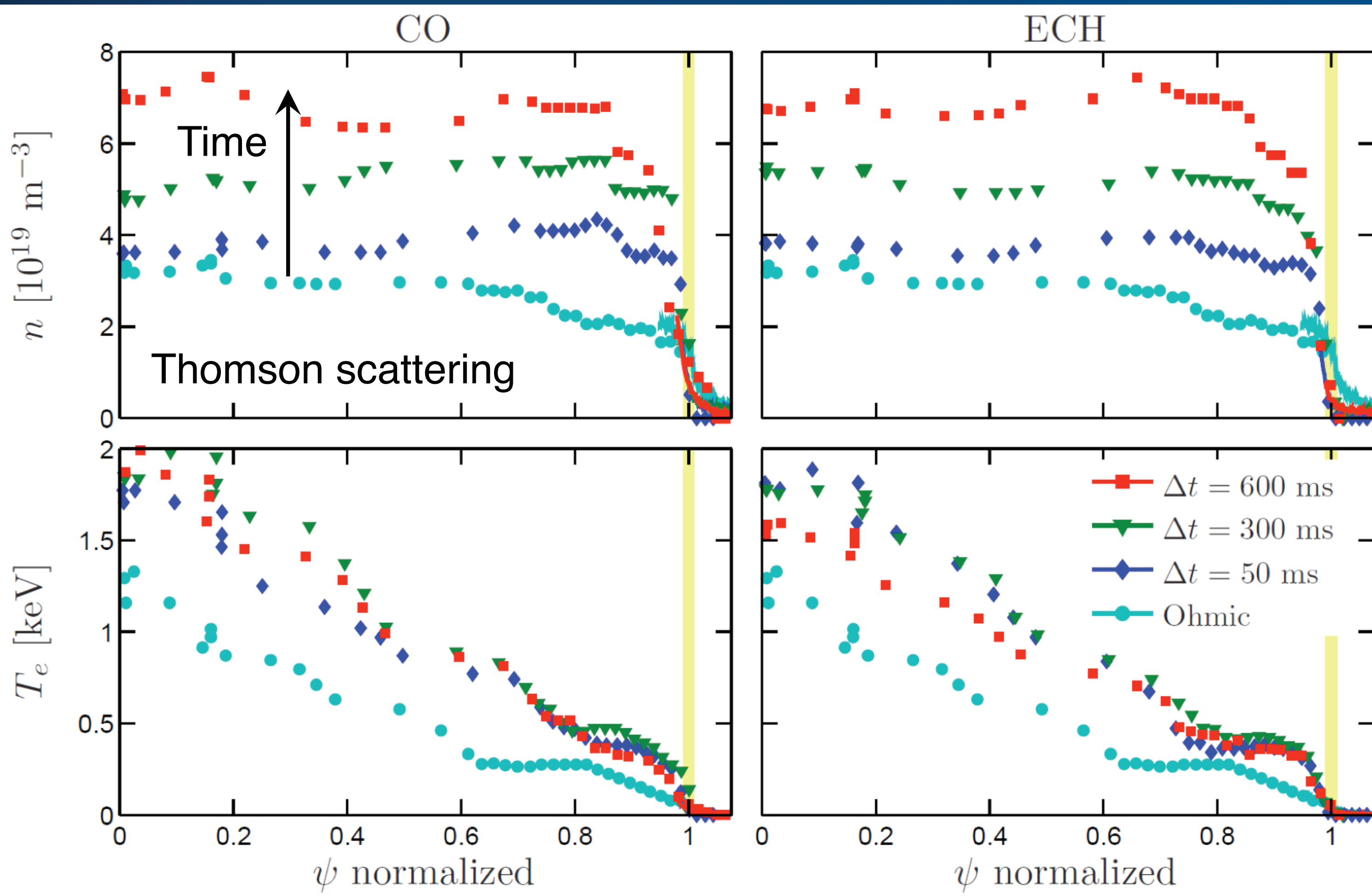
- **Floating potential:** $\tilde{v}_\rho \simeq -\tilde{E}_\theta / B_\varphi$

Probe Plunges at Different Time Delays After L-H Transition



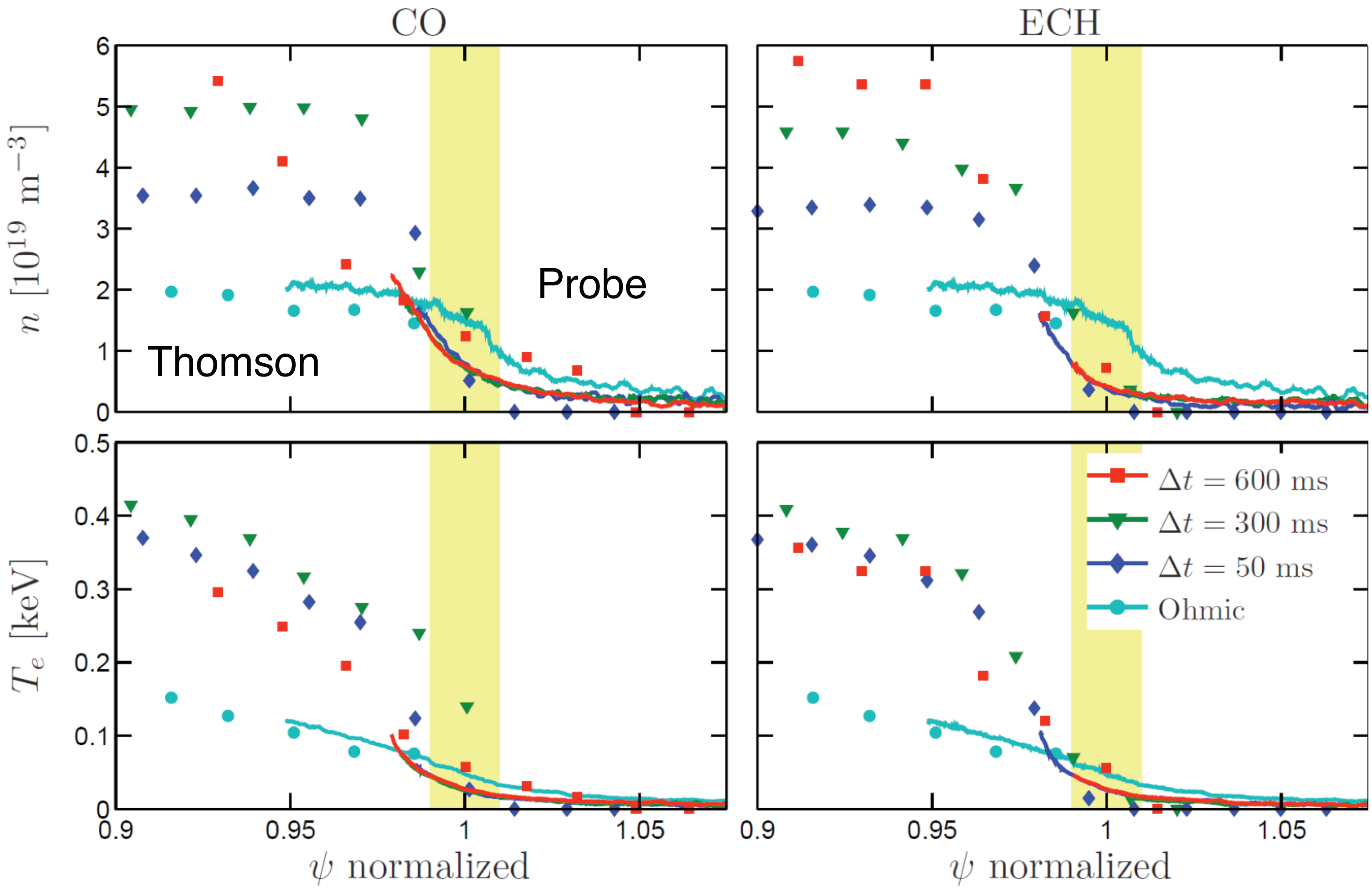
- **Shot-to-shot basis to exclude history of perturbations**
  - C^{6+} rotation snapshot from beam blip immediately *after* probe plunge
- **Vary torque by changing heating scheme (co/ctr NBI, ECH)**
  - Power constant at 1 MW for probe operation

Profile Evolution Identical for Different Heating Schemes



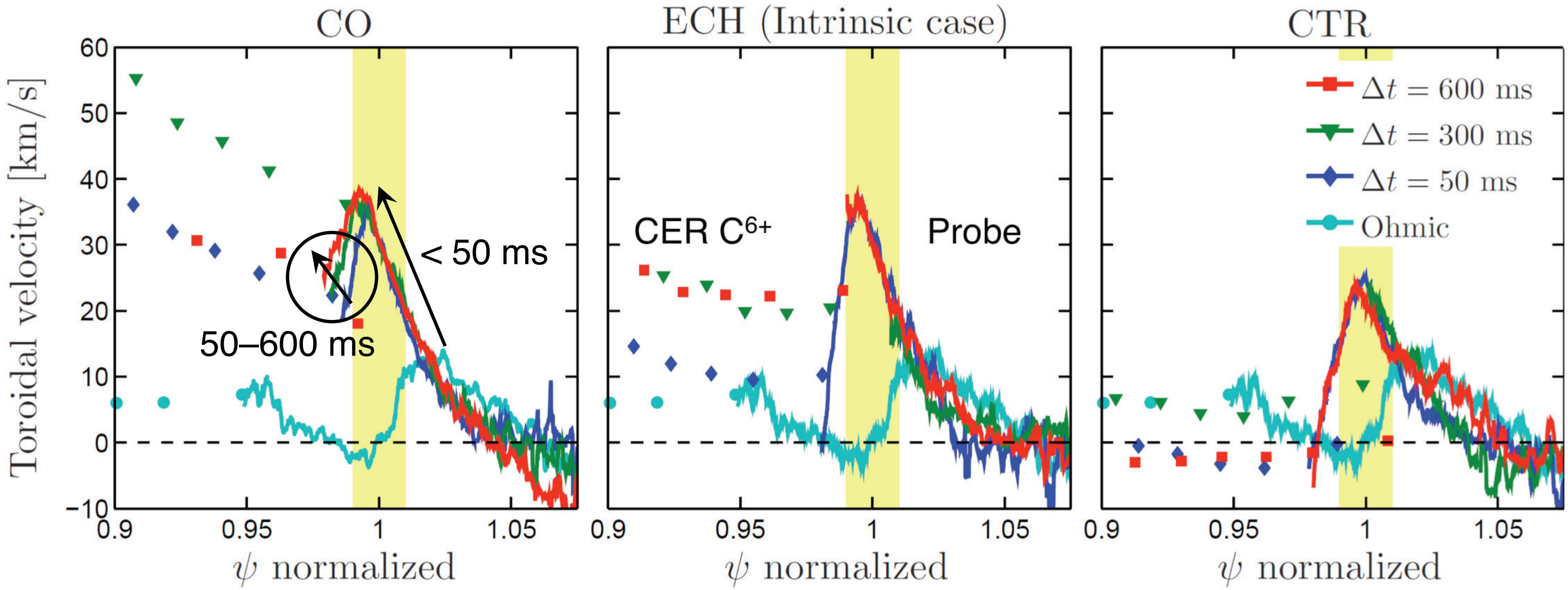
- **Density flat, rises linearly, beam fueling negligible**
- **T_e peaked**

No Change in Gradients in Lower Pedestal



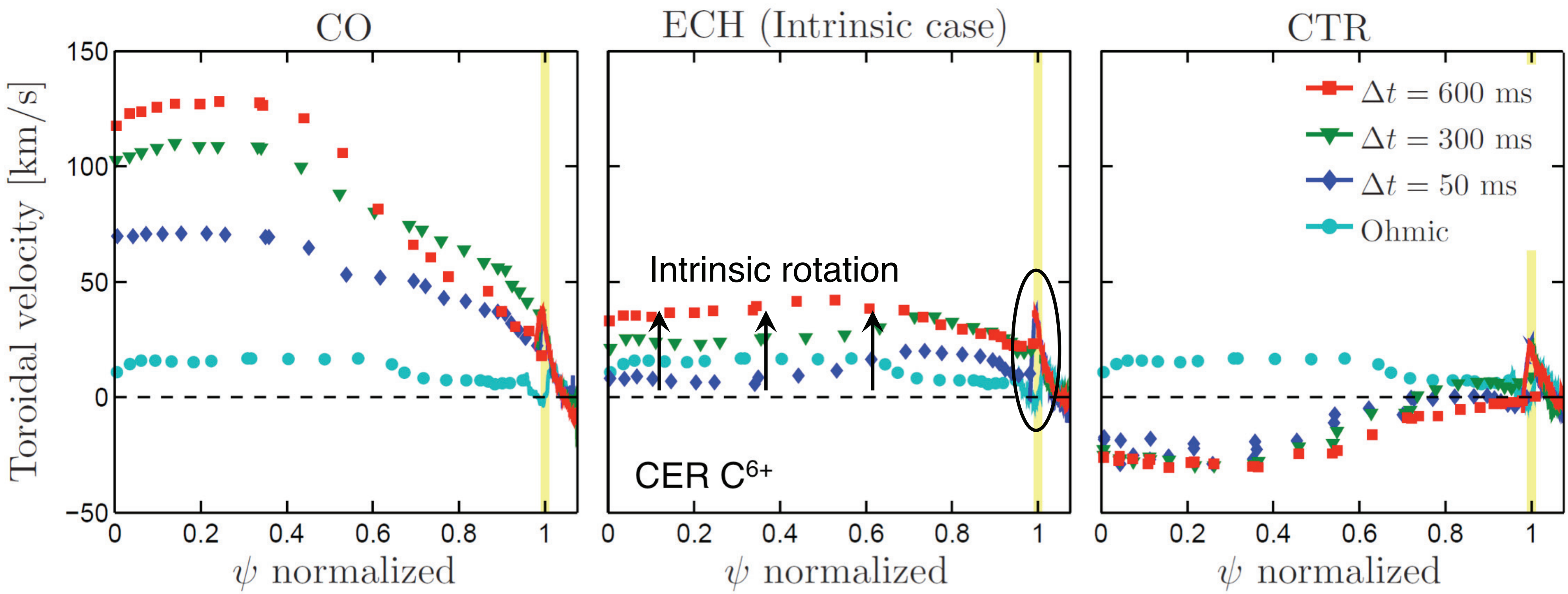
- **Density rise fully absorbed by pedestal height and width**
- **Probe *n*, T_e profiles agree with Thomson scattering**

Mach Probe Observes Narrow Co-current Rotation Layer at Separatrix



- Layer rotates co-current, even when counter torque is applied
- Undetected by CER system tuned to C^{6+} impurity rotation
- Develops within 50 ms after L-H transition
- Very little evolution from 50-600 ms

Observation of Co-rotation Layer Correlated with Development of Intrinsic Core Rotation



- **Flat intrinsic rotation profile appears to approach boundary velocity**

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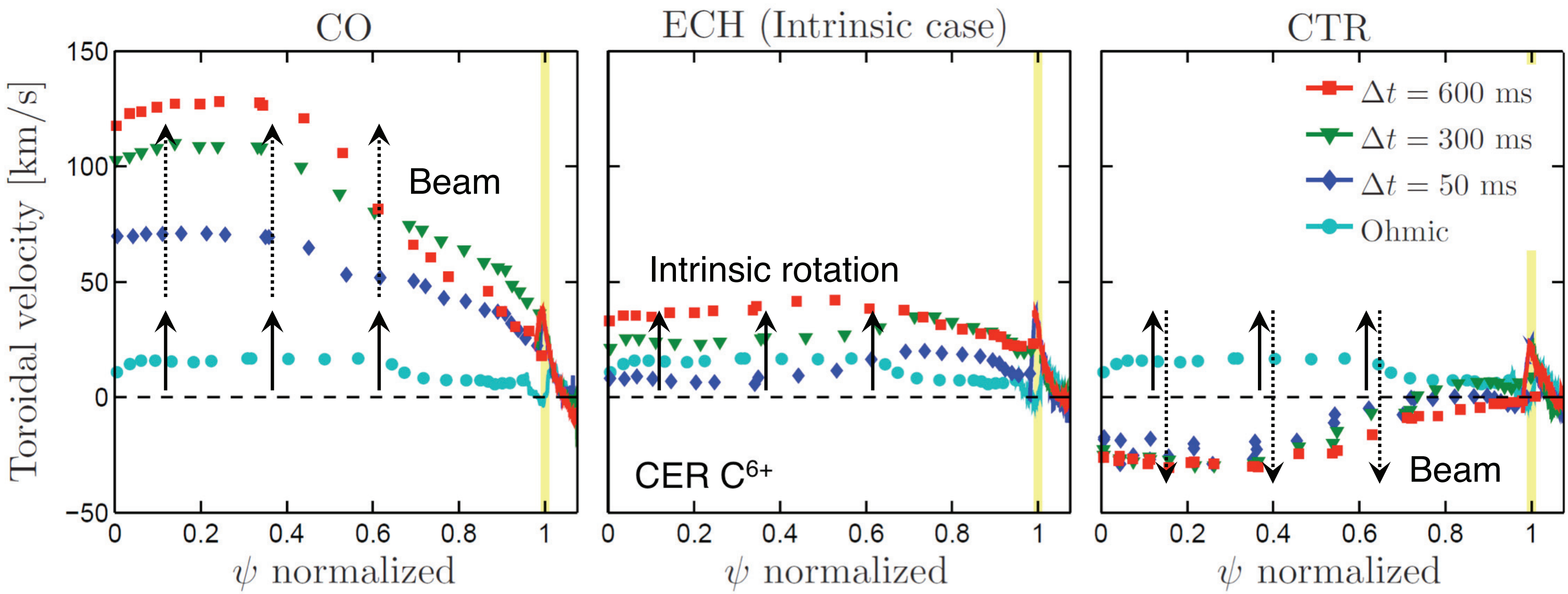

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- **Total rotation = Diffusive inward transport from edge layer + Beam driven rotation?**

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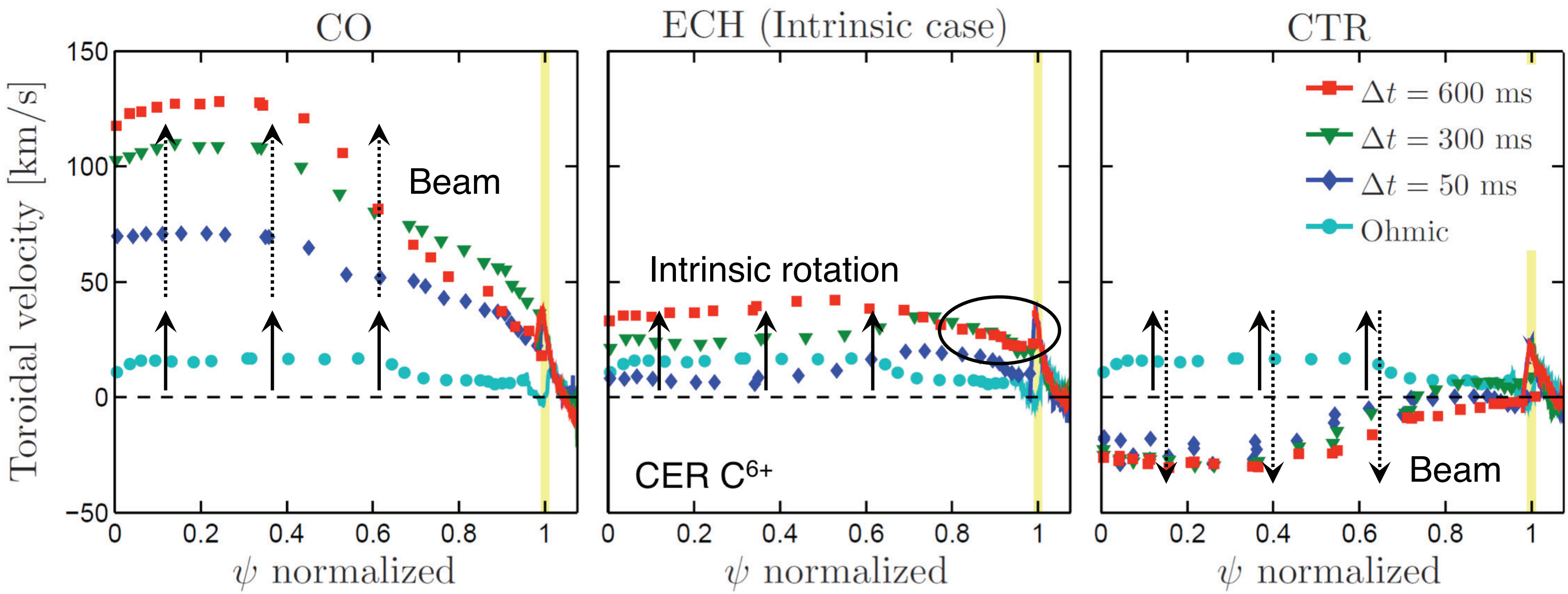
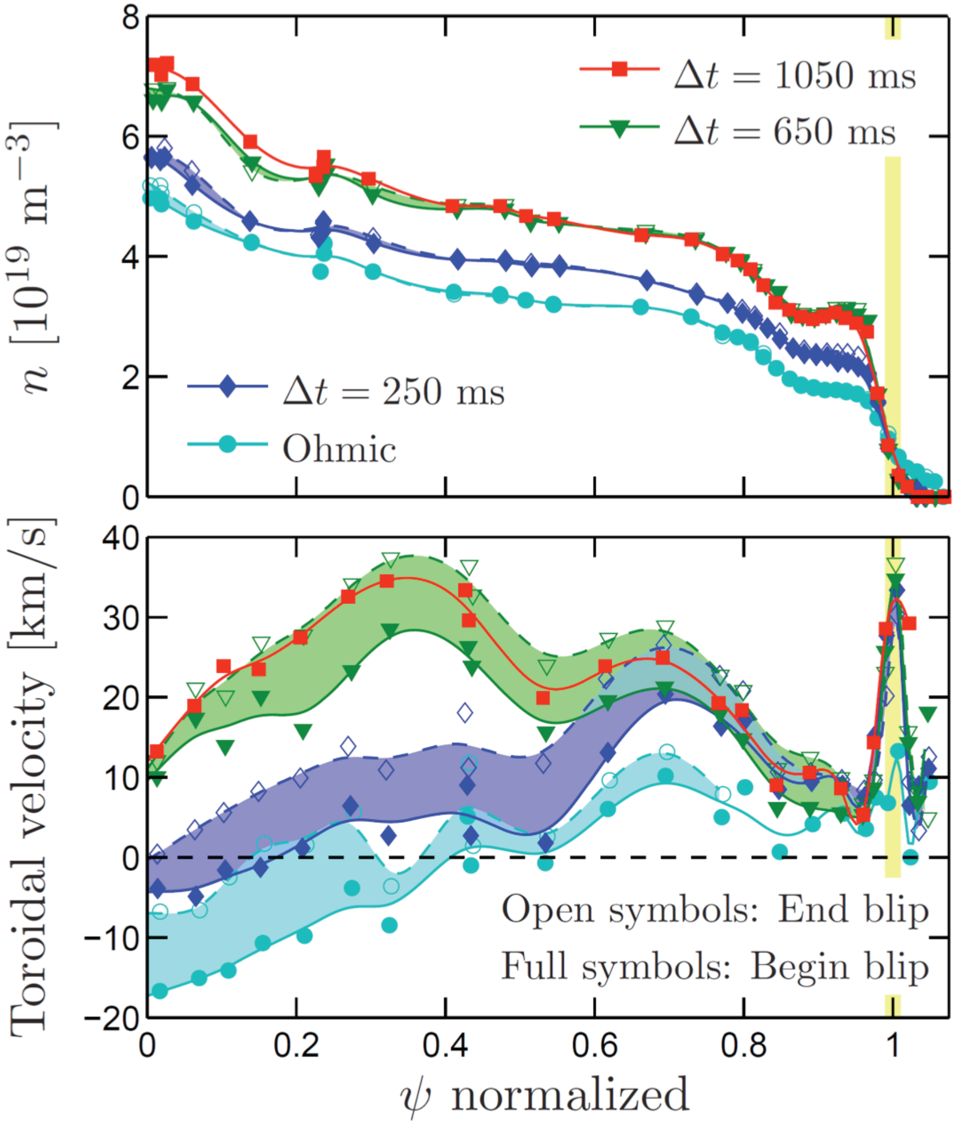


- **Flat intrinsic rotation profile appears to approach boundary velocity**
- **Total rotation = diffusive inward transport from edge layer + Beam driven rotation?**
- **But… dip in profile inconsistent**
  - Artifact from C^{6+} impurity measurement or real?

He Plasmas: CER Main-ion Rotation Measurement Confirms Existence of Layer and Persistence of "Dip"



- **ECH H-mode in He plasma**
  - ELMing
- **10-ms beam blips at 400 ms interval, 1 ms CER integration**
  - Not on shot-to-shot basis
  - Blips account for most of rotation development (bands)

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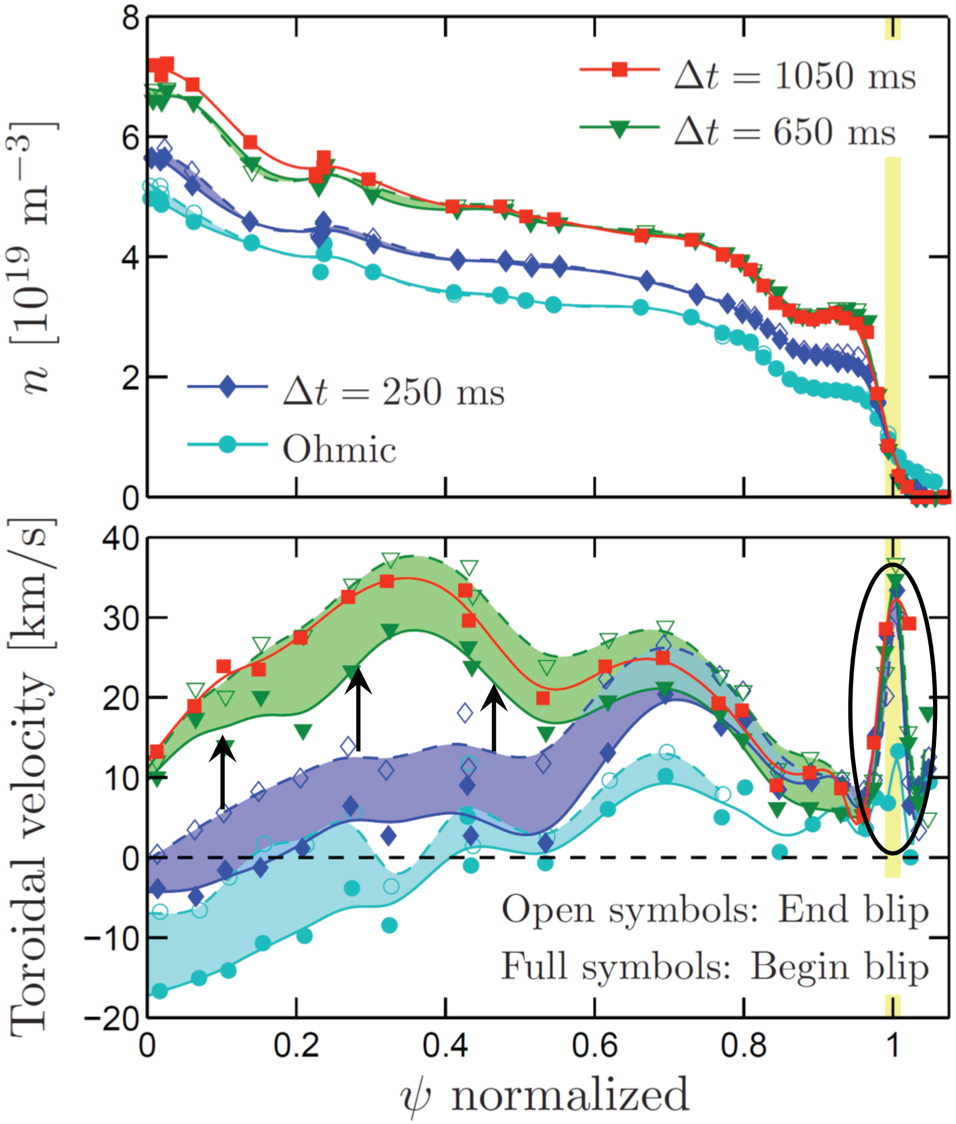

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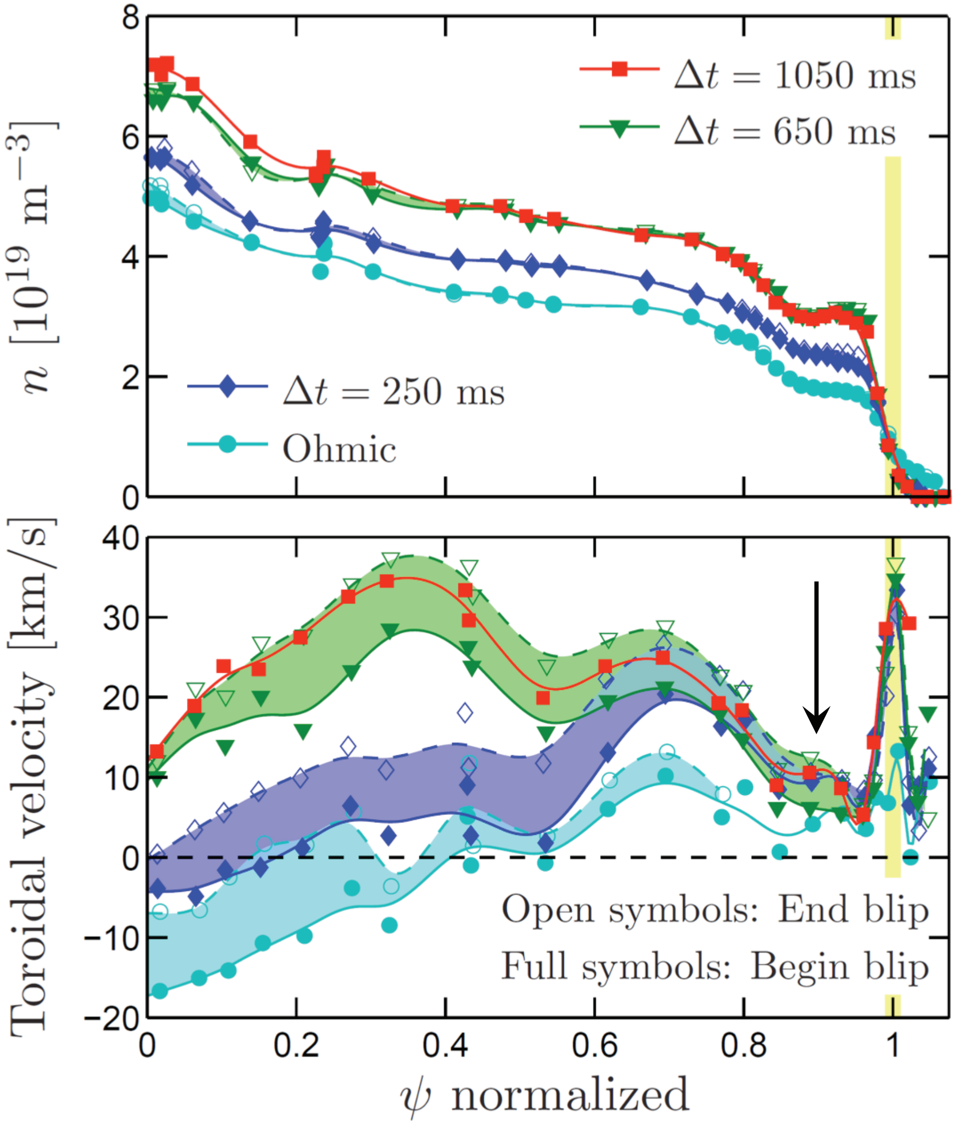

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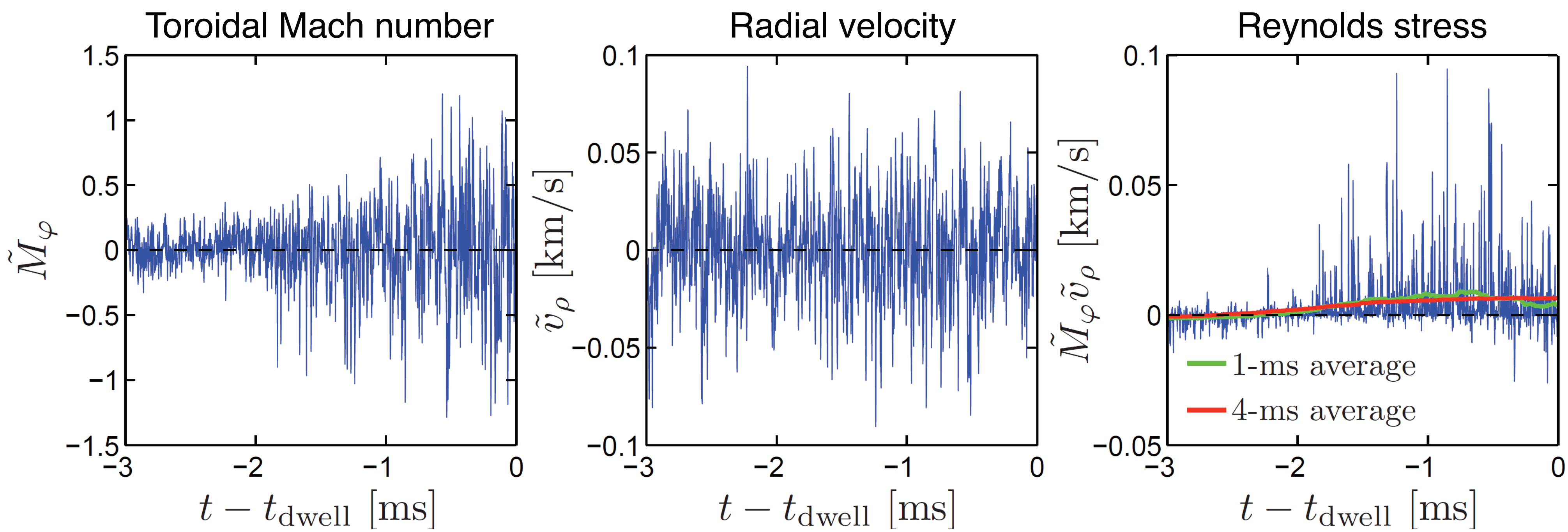
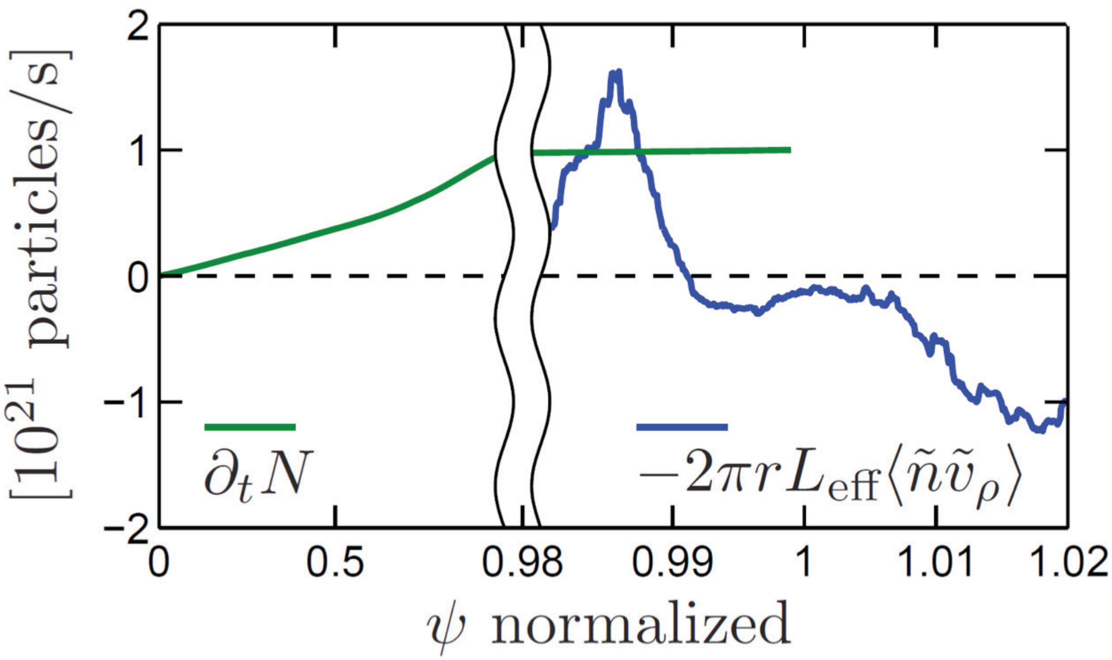
- **But… Dip clearly not filling in**
  - Transport from layer into core must be non-diffusive

Turbulent Momentum Transport Measurements: Raw Fluctuation Data and Analysis



- **1-ms sliding median filter for background subtraction**
  - 2 mm of probe motion
- **4-ms sliding average**
- **Results insensitive to halving/doubling of choices**

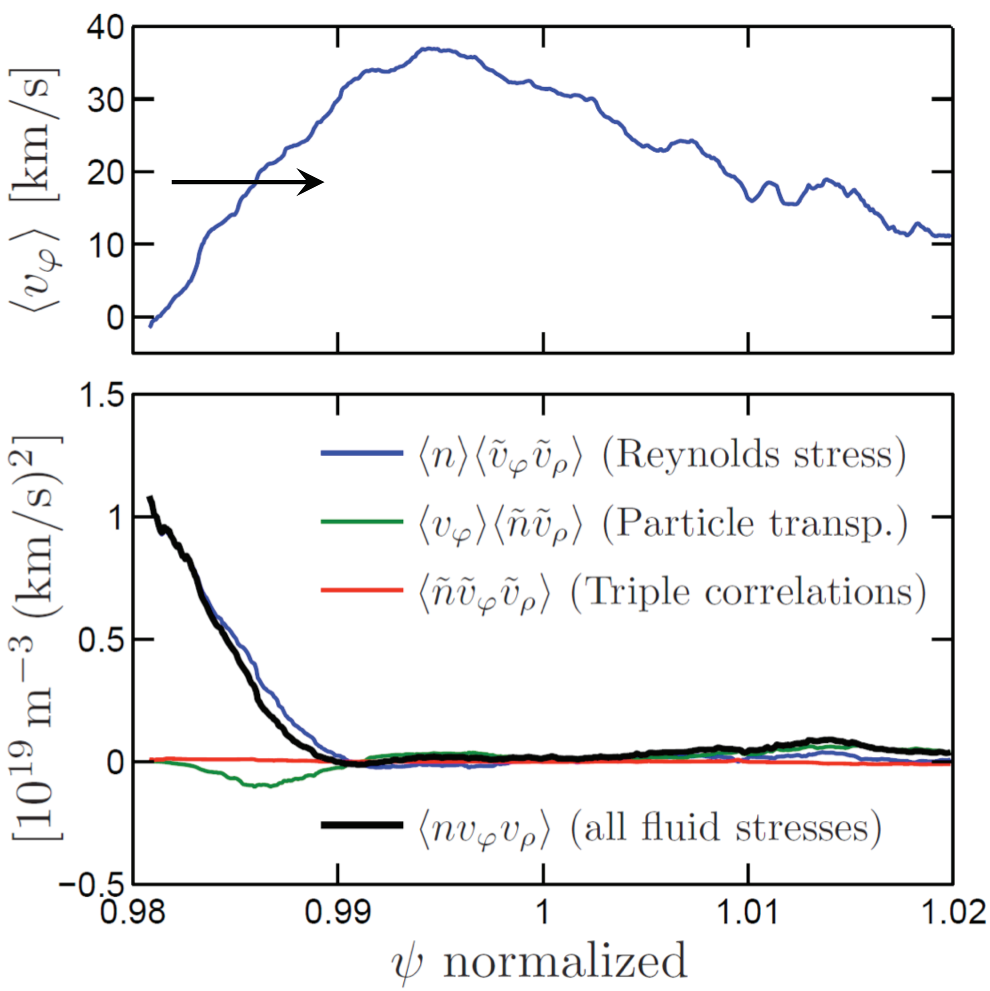
Measured Turbulent Particle Transport Consistent with Increase of Core Particle Inventory



+Sn

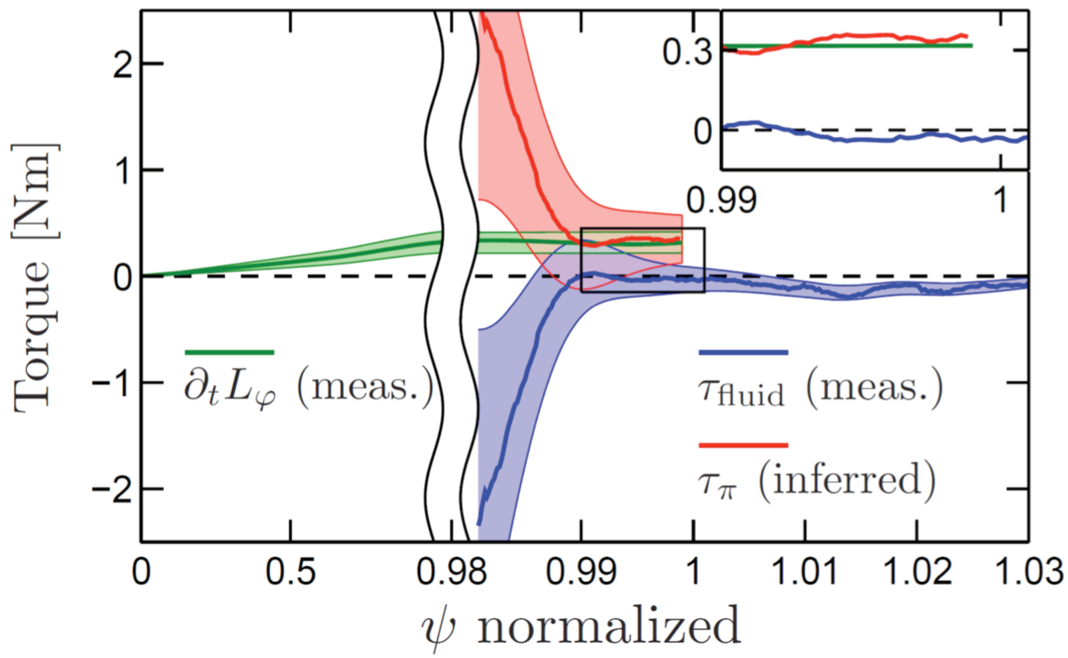
- **Assume measurements are representative for effective poloidal length of L_{eff} ~ 2 m on low-field side**
- **Consistent with main ionization source in vicinity of separatrix**

Momentum Transport By Reynolds Stress Directed Outward, Up The Gradient



- **Total fluid stresses contribute to *outward* momentum transport**
  - Transport by Reynolds stress always <u>*outward*</u>
  - Contribution from particle transport <u>*inward*</u>, but much smaller
  - Triple correlations negligible
- **Stress measurements similar for co/ctr driven cases**
- **Reynolds stress non-diffusive non-convective (*residual stress*)**
  - Tries to sustains edge co-rotation layer

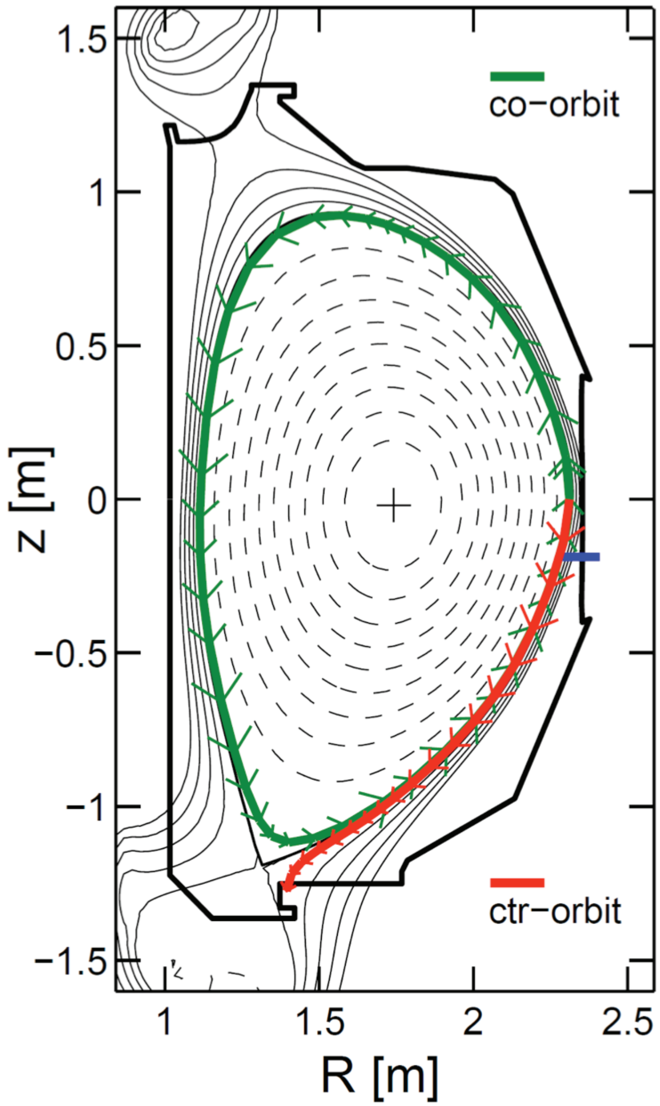
Global Torque Balance: Fluid Stresses *Inconsistent* With Change of Core Angular Momentum



- **Assume measurements representative for L_{eff} ~ 2 m**
- **Torque from total fluid stresses *in wrong direction***
  - Magnitude too small at separatrix to provide +0.3 Nm
- **Postulate existence of large kinetic stresses**

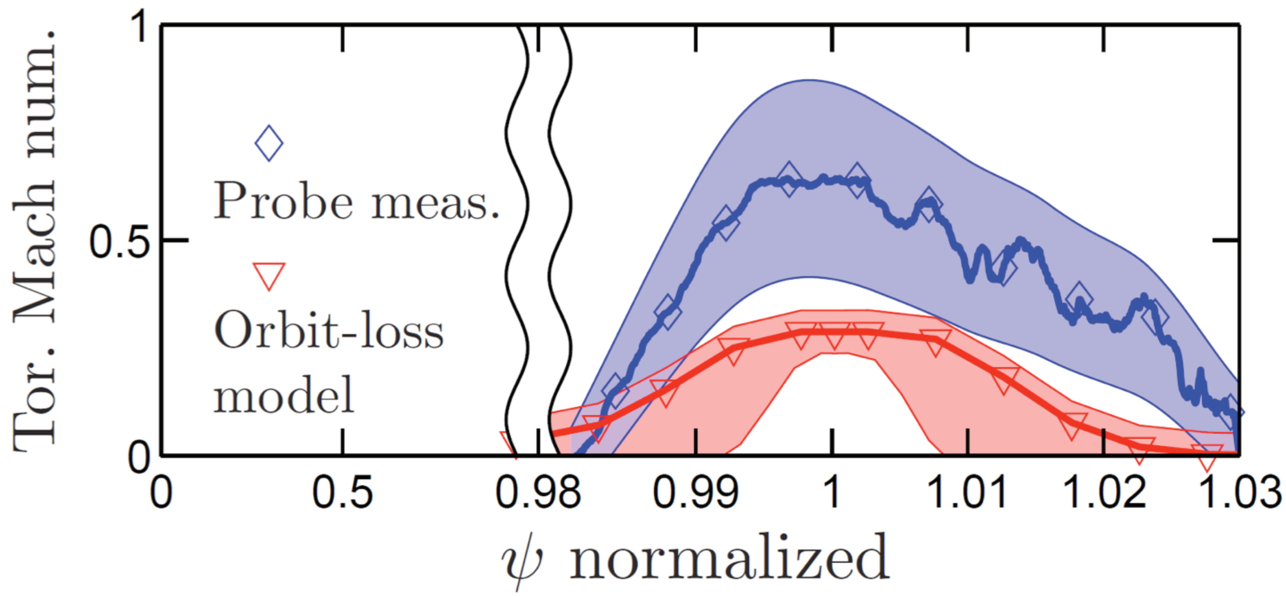
$$\langle \Pi_{\varphi\rho} \rangle = m\langle n v_\varphi v_\rho \rangle + \langle \pi_{\varphi\rho} \rangle$$

Ion Orbit Loss is Possible Mechanism Leading to Large Kinetic Stresses Close to Separatrix



- **Conservation of canonical angular momentum**
  - Co-going ions drift inward
  - Counter-going ions drifts outward
- **Preferential loss of counter-going ions in vicinity of separatrix**
  - Timescale ~100 μs
- **Mechanism leads to loss cone in velocity space**
  - Alters moments of distribution function, including toroidal velocity and stress tensor
  - Generated stresses also non-diffusive and non-convective

Simple Orbit Loss Model Correctly Predicts Features of Edge Co-rotation Layer



- **Velocity moment of distribution function with empty loss cone**
  - Model correctly predicts existence, direction, position and width of co-rotation layer
  - Underestimates magnitude by factor of 2
- **Highlights necessity to include purely kinetic effects in search for residual stresses in H-mode pedestal**

Conclusions

- **Narrow co-current rotation layer observed at separatrix in correlation with build-up of intrinsic core rotation**
  - Persistent dip in profile requires complicated non-diffusive momentum transport patterns
- **Measured fluid turbulent stresses not consistent with core spin-up: Postulate existence of large kinetic stresses**
  - Not really surprising: Chapman-Enskog closure theory breaks down, since gradient scale lengths of order ρ_i in H-mode pedestal
- **Co-rotation layer and need for kinetic stresses point to important role of ion orbit losses**
  - Need development of appropriate theory and dynamical models