Physics of Non-Diffusive Turbulent Transport of Momentum and the Origins of Spontaneous Rotation in Tokamaks

P.H. Diamond 1), C. McDevitt 1), O.D. Gurcan 1), K. Miki 1), T.S. Hahm 2), W. Wang 2), G. Rewoldt 2), I. Holod 3), Z. Lin 3), V. Naulin 4), R. Singh 5)

1) University of California at San Diego, La Jolla, CA 92093-0424 USA
2) Princeton Plasma Physics Laboratory, Princeton, NJ 08543-0451 USA
3) University of California at Irvine, Irvine, CA 92697-4575 USA
4) Association EURATOM-Risø DTU, Roskilde, DK-4000 Denmark
5) Institute for Plasma Research, Bhat, Gandhinagar, 382428 India

e-mail contact of main author: phd@mamacass.ucsd.edu

Abstract. The theory of turbulent transport of toroidal momentum is discussed in the context of the phenomenon of spontaneous/intrinsic rotation. We review the basic phenomenology and survey the fundamental theoretical concepts. We then proceed to an in-depth discussion of the radial flux of toroidal momentum, with special emphasis on the off-diagonal elements, namely the residual stress (the portion independent of *V*) and the pinch. A simple model is developed which unifies these effects in a single framework and which recovers many of the features of the Rice scaling trends for intrinsic rotation. We also discuss extensions to finite beta and the effect of SOL boundary conditions. Several issues for future consideration are identified.

1. Summary of Phenomenology

a) Intrinsic Rotation Basics

- Intrinsic (spontaneous) toroidal rotation observed in nearly all tokamaks
- H-mode phenomenology demonstrates clear empirical trends, L-mode phenomenology remains murky and complex
- In H-mode:
  - i. rotation typically co-current
  - ii. $\Delta v_\phi \sim \Delta W / I_p$, $M_A \sim \beta_N$ [1]
  - iii. no apparent scalings with ,
  - iv. offset in torque scan matches intrinsic rotation[2]
- Observations appear consistent with edge phenomena originating with transition
  - i. Observed co-current velocity builds inward from periphery [3]
  - ii. rotation direction inverts at L-H mode transition

b) Indications of Off-Diagonal Momentum Flux

- Historically, $\chi_\phi \sim \chi_i$ [4], yet many deviations from $\mathrm{Pr} \sim 1$ observed
- ∇P_i –driven momentum pinch suggested by inductive analysis[5]
- Perturbation Experiments From JT-60U [6]
  - i. ripple loss + pulsed beams => pulsed torque
  - ii. inward *V* clearly indicated
- $V_{residual} = V_{measured} - V_{perturbation}$ observed in β-scan on JT-60U [7]
  $V_{residual}$ coincident with region of steep ∇P_i

c) Boundary Condition Effects

- Strong SOL flows observed with
  - i. "strong ballooning" particle flux ↔ outboard mid-plane source
  - ii. SOL symmetry breaking (LSN, USN)
- SOL flow correlated with Δv_ϕ increment in L-mode i.e. C-Mod [8]

LSN $\rightarrow$ $V_{\nabla B}$ toward X-point $\rightarrow$ Δv_{ϕ} co

USN $\rightarrow$ $V_{\nabla B}$ away from X-point $\rightarrow$ Δv_{ϕ} counter

But:

- in H-mode, Δv_{ϕ} is always co

2. Addressing the Phenomenology

i. Focus: Off-Diagonal Momentum Flux in Electrostatic Drift Wave Turbulence – INWARD COMPONENT!?

ii. Beyond "Diffusion and Convection"

- Particle number conserved $\rightarrow$ $\Gamma_n = -D\dfrac{d\langle n\rangle}{dr} + V\langle n\rangle$
  - pinch is only "off-diagonal" for particles
- but: wave-particle momentum exchange possible!

$\rightarrow$
$$\Pi_{r,\phi} \cong \langle n\rangle\langle\tilde{v}_r\tilde{v}_\phi\rangle + \langle v_\phi\rangle\langle\tilde{v}_r\tilde{n}\rangle \tag{1}$$

$$\langle\tilde{v}_r\tilde{v}_\phi\rangle = -\chi_\phi\frac{\partial\langle v_\phi\rangle}{\partial r} + V\langle v_\phi\rangle + \Pi_{r,\phi}^{resid}, \tag{2}$$

$\rightarrow$ residual stress/flux possible and distinct from pinch

$\rightarrow$ residual stress acts with boundary condition to generate intrinsic rotation

iii. Key Theoretical Issues

- Flux of wave momentum?
- Origins of symmetry breaking?
- Boundary conditions?

a) Wave Momentum [9]

$\rightarrow$ Momentum Budget:

Resonant+Non-Resonant

Particles + Fields

"Non-Resonant" = "Waves"

$\rightarrow$ Wave momentum flux crucial for fluid-like DWT

b) Calculating $\Pi_{r,\parallel}^{wave}$

- Necessary to compute radial flux of parallel mom. $\leftrightarrow$ $\Pi_{\parallel}^{W} \equiv \sum_k v_{grx}k_{\parallel}N_k$
- In simplest scenario, finite momentum flux requires:
  - Radial wave flux $\leftrightarrow$ $\langle v_{grx}\rangle \neq 0$
  - symmetry breaking $\leftrightarrow$ $\langle k_{\parallel}\rangle \neq 0$

■ Wave Momentum Flux

- Proceed via Chapmen-Enskog expansion (radiation hydrodynamics in large optical depth limit) in Wave Kinetics
  - in short mean free path limit, expansion parameter given by:

$$\tau_{c,\mathbf{k}}(v_{gr}/L_I), \tau_{c,\mathbf{k}}\langle v_E\rangle' \sim \varepsilon\,. \tag{3}$$

- Lowest order: $C_\omega(N_k) = 0$ => saturated spectrum due to wave interactions

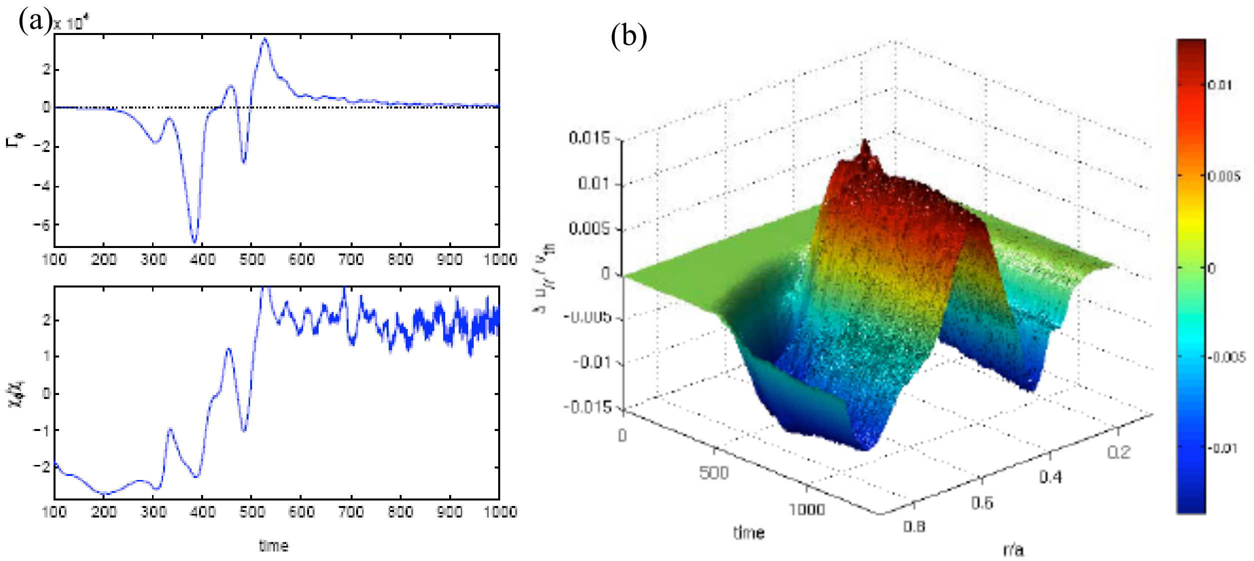

FIG.1 (a) Time evolution of Γ_ϕ *and* χ_ϕ/χ_i*, and (b) that of radial profile of* $\Delta u_\parallel$ *normalized by* v_{th}

- Next order, yields: $\delta N_{\mathbf{k}} = -\tau_{c,\mathbf{k}} v_{gr} \dfrac{\partial \langle N_{\mathbf{k}} \rangle}{\partial r} + \tau_{c,\mathbf{k}} k_\theta \langle v_E \rangle' \dfrac{\partial \langle N_{\mathbf{k}} \rangle}{\partial k_r}$ (4)
- 1st term ~ $\tau_{c,\mathbf{k}} / \tau_{\ln N}$, 2nd term ~ $\tau_{c,\mathbf{k}} \langle v_E \rangle'$
- Wave momentum flux:

$$\Pi^{\omega}_{r,\parallel} = \int d\mathbf{k} k_\parallel \left\{ \langle v_{0r} \rangle \langle N_{\mathbf{k}} \rangle - \tau_{c,\mathbf{k}} v_{gr}^2 \frac{\partial \langle N_{\mathbf{k}} \rangle}{\partial r} + \tau_{c,\mathbf{k}} v_{gr} k_\theta \langle v_E \rangle' \frac{\partial \langle N_{\mathbf{k}} \rangle}{\partial k_r} \right\} \quad (5)$$

- Second term ↔ radiative diffusion of quanta
  - requires gradient in turbulence intensity profile (universally increasing)
  - related to momentum flux from edge?
- Third term ↔ refraction induced wave population imbalance
  - crucial for regimes of strong shear flow
    → most active near edge, or ITB
    → sensitive to L-H mode transition, local steepening in ∇P
- mode dependence via v^*
- Mechanisms of symmetry breaking: → Moments of W.K.E.

1. Influx: radial inflow of wave momentum
   - potentially critical in edge region
   - captures possible influx of momentum from SOL
2. Wind-up: mode sheared by poloidal velocity
   → ala' spiral arm
   - requires magnetic shear, i.e.
   - critical in barrier regions, either pedestal or ITB, but not limited to these
3. Growth asymmetry
   - enters due to parallel velocity shear - unlikely
4. Refraction due to GAMs → refractive force
   - largely unexplored
   - likely to be most important near edge

c) Boundary Condition Effects
- Communication between SOL and Core across LCFS poorly understood
- In some present day discharges, neutral drag strong at edge (DIII-D, TCV)

$\rightarrow$ "no slip" boundary condition reasonable in H-mode
- Important: WON'T be true for ITER, and other plasmas with high neutral opacity

$\rightarrow$ Area for ongoing research

3. Physics of Off-Diagonal Momentum Flux

$$\left\langle \tilde{v}_r \tilde{v}_\phi \right\rangle = -\chi_\phi \frac{\partial \left\langle v_\phi \right\rangle}{\partial r} + V \left\langle v_\phi \right\rangle + \Pi_{r,\phi}^{resid}$$

$\chi_\phi \rightarrow$ turbulent viscosity (largely understood)

$V \rightarrow$ (inward) convective velocity $\rightarrow$ pinch

$\Pi_{r,\phi}^{resid} \rightarrow$ residual stress (nonlinear wave $\rightarrow$ particle momentum deposition)

a) Is there an Inward Flux?
- Gyrokinetic turbulence drives off-diagonal and diffusive momentum transport – from GTS simulations (FIG. 1)
  - A robust, large inward Γ_ϕ is found in post-saturation phase of ITG turbulence
  - Core plasma spins up with $\Delta u_\parallel$ few % of v_{th} (no momentum source at edge)
  - Smaller Γ_ϕ in long-time steady state is likely diffusive with effective χ_ϕ / χ_i on order of unity, consistent with experiments and early ITG theory
- GTC simulations of Toroidal Momentum Transport
  - Constant angular velocity (rigid rotation case) (FIG. 2(a)) :
    - Inward momentum flux (pinch);
    - Redistribution of momentum (spinning up towards the center)
  - Sheared rotation case (FIG. 2(b))
    - Flux separation: subtracting pinch contribution from the total flux gives diffusive flux

      $\mathrm{Pr} \equiv \chi_\phi^{diff} / \chi_i \approx 0.2 - 0.7$
  - Quasilinear estimates:

$$D(\mathbf{v}) = \frac{1}{2} \frac{\left\langle \Delta x^2 \right\rangle}{\tau} = \frac{\pi c^2}{2B^2 V} \sum_{\mathbf{k}} \int \frac{d\omega}{2\pi} \left\langle \delta\phi^2 \right\rangle_{k,\omega} k_y^2 J_0^2 (k_\perp \rho_i) \delta(k_\parallel v_\parallel - \omega)$$

$$\chi_\phi^{\mathrm{QL}} = \frac{1}{n \nabla (R v_\parallel)} \int d\mathbf{v} R v_\parallel D(\mathbf{v}) \nabla f(\mathbf{v})$$

$$\chi_i^{\mathrm{QL}} = \frac{1}{n \nabla T} \int d\mathbf{v} \frac{m v^2}{2} D(\mathbf{v}) \nabla f(\mathbf{v})$$

- Due to smaller velocity weight $\chi_\phi / \chi_i < 1$ if ratio of particle's resonant energy to thermal energy is larger than unity

Based on measured fluctuation spectra: $\mathrm{Pr}^{\mathrm{QL}} \equiv \chi_\phi^{\mathrm{QL}} / \chi_i^{\mathrm{QL}} \approx 0.7$ [10]

b) Physics of Residual Stress
- Key Point: $\rightarrow$ $\left\langle v_E \right\rangle' \neq 0$ converts poloidal shear into toroidal shear via: asymmetry in wave $\rightarrow$ particle momentum deposition

■ Residual Stress
- Finite $\left\langle v_E \right\rangle'$ +generic acoustic coupling

→ shifted spectral envelope (FIG. 3)
→special case of "wind-up" asymmetry

- $\langle k_{\|}\rangle \neq 0$ [11]
- imbalance in

→ acoustic populations
→ momentum deposition by ion Landau damping

- Underlying physics for ITG driven off-diagonal momentum transport is related to zonal flow shear
  - Self-generated zonal flow is quasi stationary in global ITG
  - → showing existence of toroidal zonal flow
- Mechanism: generation of residual stress due to $k_{\|}$ symmetry breaking induced by quasi-stationary ZF shear [extending the mechanism due to mean ExB shear[12]]

$$\langle k_{\|}\rangle(r) = \frac{1}{qR_0}\frac{\sum (nq-m)\delta\Phi_{mn}^2}{\sum \delta\Phi_{mn}^2}$$

- Residual stress causes rotation buildup in pedestal (FIG.4)
  - Sharp gradients cause a "torque density"

    $\nabla\langle p\rangle \rightarrow \langle v_E\rangle'$ →asymmetry → residual stress
  - Leading to a net rotation due to the off-diagonal term → effective local source

    $$\frac{\partial}{\partial t}\overline{V}_\phi + \Pi_{r,\phi}(a_-) = 0$$
  - H-mode spin-up …

c) Physics of Momentum Pinch

- Key point: $\nabla\cdot\mathbf{v}_{E\times B} \neq 0$ in torus!

  →TEP-like pinch
  - N.B.: Symmetry Breaking ↔ Ballooning Structure
- Turbulent Equipartition of Magnetically Weighted Quantities
  - Turbulence Equipartition Pinch (TEP) of density has been demonstrated via simple model with nonuniform B [13]

$$\partial_t n + \nabla\cdot(nv_E) = 0\,, \qquad \nabla\cdot v_E \neq 0\,, \qquad (\partial_t + \mathbf{v}_E\cdot\nabla)\left(\frac{n}{B}\right) = 0$$

  - Extended to trapped electrons in tokamaks[14]
  - Turbulence Mixing → Relaxation towards canonical profiles [15]
  - Inward Pinch in the observed field n as a consequence of a tendency towards homogenization of the locally conserved field n/B
  - For angular momentum density[16]

$$\partial_t(nU_{\|}R) + \nabla\cdot(nU_{\|}Rv_E) = 0\,, \quad \nabla\cdot v_E \neq 0\,, \quad (\partial_t + \mathbf{v}_E\cdot\nabla)\left(\frac{nU_{\|}R}{B^2}\right) \approx 0$$

    Inward Pinch in observed quantity $nU_{\|}R$ is a consequence of a tendency towards Homogenization of the locally conserved quantity $nU_{\|}R/B^2$
- Curvature driven toroidal momentum pinch
  - Curvature driven toroidal momentum pinch[16] have two parts:
  1) TEP pinch: mode-independent, inward
  2) Thermo-electric pinch: mode-dependent
  - For the model we consider TEP part only.
  - TEP pinch of Angular Momentum:

- diffusion of the "magnetically weighted" field leading to an effective convective flow in the "observed field"
- is part of the general derivation from conservative gyrokinetic equations [16].
- can be shown to correspond to local conservation of "magnetically weighted" angular momentum[16,17]

$$L_\phi / B^2$$

- Pinch of momentum from diffusion of magnetically weighted momentum
- Homogenization (mixing) of the locally conserved quantity "$nU_{||}R/B^2$" occurs via diffusion of the magnetically weighted angular momentum.

$$\Pi_{\text{MWA}} = \left\langle \delta v_r \delta(nU_{||}R/B^2) \right\rangle = \text{...quasilinear calc.} = -\chi_{\text{MWA}} \frac{d}{dr}\left(\frac{nU_{||}R}{B^2}\right)$$

Separating the $d/dr(1/B^2)$ drive from $d/dr(nU_{||}R)$ the drive , we get

$$= [-\chi_{\text{Ang}} d/dr(1/B^2) + V_{\text{pinch}}(nU_{||}R)]/B^2$$

with $V_{\text{pinch}}/\chi_{\text{Ang}} = -B^2 d/dr(1/B^2) \approx -2/R$!

- Inward Pinch in observed quantity $nU_{||}R$ is a consequence of tendency towards a canonical profile with

$$\nabla(nU_{||}R/B^2) \approx 0$$

- Values from theories are in the range of experimental relevance for NSTX [18]
- The two candidates: [16,19]
- Perturbative Momentum Studies using Magnetic Braking
  - Pinch at various radii
- Can L_n dependence be discriminated?

4. Toward a Simple, Tractable Model

- Key Points: → $\langle v_\phi \rangle$ profile → 1) $\Pi^R_{r,\phi}$ due $\langle v_E \rangle'$ → rotation at L-H transition

$$\Delta(\nabla P) \leftrightarrow \Delta W_p$$

2) V_{TEP} due $\nabla \cdot v_E \neq 0$ → peaking on axis

→ couple to simple L-H transition model (a la Hinton)

N.B. $\Pi^R_{r,\phi}$ decays with $\langle v_E \rangle'$ slower than $\chi_\phi, \chi_i, D \ldots$

→ fix $\langle v_\phi \rangle$ on boundary

- Simple Self Consistent Model
  - Conservation Laws:

$$\frac{\partial n}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_n) = S_n$$
$$\frac{\partial P}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(rQ) = H$$
$$\frac{\partial L_\phi}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\Pi_\phi) = \tau_\phi$$

, where

$$\Gamma_n = -D_0 \frac{\partial n}{\partial r} - D_1 \varepsilon\left(\frac{\partial n}{\partial r} + V_r n\right)$$
$$\Pi_\phi = -\nu_0 \frac{\partial L_\phi}{\partial r} - \nu_1 \varepsilon\left(\frac{\partial L_\phi}{\partial r} + V_r L_\phi\right) + S$$
$$S = -\varepsilon\alpha(r)\left(1 - \frac{\sigma}{P_0}\frac{\partial P}{\partial r}\right)\frac{\partial v_{E_y}}{\partial r}$$
$$Q = -\chi_0 \frac{\partial P}{\partial r} - \chi_1 \varepsilon \frac{\partial P}{\partial r}$$

Algebraic Relations:

$$\frac{\partial v_{E_y}}{\partial r} = \left(\frac{\mu}{n_0 P_0}\right)\frac{\partial n}{\partial r}\frac{\partial P}{\partial r} + \ldots$$

$$\varepsilon = \frac{\varepsilon_0}{[1+\beta(\partial v_{E_y}/\partial r)^2]}$$

$$v_\phi(r,t) = \left[\frac{L_\phi(r,t)}{n(r,t)}\right]\lambda_2(r)$$

TEP (weak ballooning case):

$$V_r = -\lambda_1 \frac{\partial}{\partial r}(\lambda_1^{-1}) \quad \leftrightarrow \quad \nabla \cdot (\mathrm{v_E}\lambda_1) = 0$$

$$\lambda_2(r) \approx (1 - r^2/R_0^2)$$

$$\alpha(r) \propto (1 + r^2/R_0^2)\alpha_0$$

B.C.'s: $L_\phi(a) = v_\phi(a) = P(a) = 0$, $n(a) = n_a$

- Implications of the Model and Scaling Trends
  - Dimensional analysis estimate for pedestal flow velocity suggests a width scaling: $v_\phi / v_{th} \propto (\rho_s / L_s)(w_{ped}/a)$
  - This is "width" scaling for pressure profile, but the simple model links width to height $w \sim P$.

$$v_\phi \sim C\frac{\rho_s\sqrt{T_i}\,n_{ped}}{L_s n} \sim \frac{C}{R}\frac{\rho_s}{L_s}\sqrt{\frac{T_e}{T_i}}\frac{[n_{ped}T_iV_p]}{[nv_{te}V_p/R]}$$

  - Where $n_{ped}T_iV_p \rightarrow W_p$: Stored Energy
  - I_p scaling not obvious $\rightarrow$ other pedestal physics?
  - Model is not quantitatively accurate.
    - but yields self-consistent H-mode.
    - predicts a scaling of the pedestal toroidal velocity with the pedestal width.
- Comments re: Model
  - $\langle v_\theta \rangle$ evolution not addressed. Evidence for anomaly and for significant role in exists (JET, C-Mod...)
  - results insensitive to $\langle v_\phi(a) \rangle$ b.c., but core-SOL coupling must be addressed
  - pedestal physics controls spontaneous rotation
    - $\langle v_\phi \rangle \sim w_{ped}$, $w_{ped} \sim P_{ped}$
    - easy to recover ΔW_p scaling
    - I_p scaling elusive

5. Forefront Topics

a) Electromagnetics and Saturation

- Resonant component of turbulent momentum flux is proportional to $|\delta E_\parallel|^2$
  - inclusion of inductive component allows for reduction/enhancement of $\delta E_\parallel$
- For large aspect ratio, a quasilinear calculation yields resonant component [20]:

$$\Pi_\parallel^{\mathrm{tot}} = \sum_k \frac{\Pi_{\parallel k}^{ES}}{(1+\mathrm{Re}\,\chi_k^{AA})^2}$$

- $\mathrm{Re}\,\chi_k^{AA} \sim \beta(qR/L_n)^2 \rightarrow$ either high β or steep density gradients lead to significant EM impact
- For drift waves: $\mathrm{Re}\,\chi_k^{AA} > 0$
  - novel means of quenching $\Pi_{\|}^{\mathrm{ES}}$ for high β or steep density grad.
- For ITG: $\mathrm{Re}\,\chi_k^{AA} < 0$
  - slight enhancement of $\Pi_{\|}^{\mathrm{ES}}$ above level predicted by ES prediction
- Non-resonant component qualitatively similar, with important exception that only off-diagonal terms are modified to lowest order
- Alfven waves provide alternate channel for momentum transport aside from well studied limit of ES microturbulence – B.P. relevant
- Off-diagonal component of momentum flux requires finite $\delta E_{\|}$
- KSAWs provide natural candidate for transport of parallel momentum
  - dispersive corrections introduce a radial group velocity/finite $\delta E_{\|}$
  - mode conversion of TAEs at resonant surfaces provide robust generation mechanism
- Residual stress for each branch computed via a quasilinear calculation
  - imbalance in Elsasser populations required for finite levels of off-diagonal transport
  - symmetry breaking likely induced by asymmetry in energetic particle drive

b) Boundary Effects

- L-mode edge + asymmetry => SOL circulation => $\Delta v_\phi > 0$, or < 0
  - impact on L-H power threshold
- Key Question: How can SOL flow influence core plasma?
  "Tail wags the dog?"
- Key Quantity: $S_{\|}(r) \rightarrow$ flow speed profile

$$\frac{dS_{\|}(r)}{dr} > 0\text{, away from } r_{\mathrm{sep}}$$

  - suggested by particle balance
  - confirmed by C-Mod, DIII-D
- Possible Mechanisms:
  - inward turbulent diffusive momentum flux (any SOL mechanism)
  - parallel shear flow instability: $\nabla\langle v_{\|}\rangle$ vs. $\nabla\langle n\rangle$ is key competition

6. Looking Ahead – Open issues

a) MFE Experiment

- dual perturbation $(\delta v_\phi, \delta P)$ experiments
  - disentangle V, $\Pi_{r,\phi}^{R}$
- explore synergy of intrinsic rotation with transition, pedestal physics. Slow transitions helpful here!?
  - Δv_ϕ (ped) analogue of Rice plot
  - Δv_ϕ vs. P_{ped}? I_{p} scaling?
  - neutral opacity scans

- intrinsic rotation on electron dominated regimes (ITER relevant!)
  - CTEM as transport agent
  - explore mode dependency (IOC?)
- intrinsic rotation synergy with ITB (c.f. JT-60U)

b) MFE Theory
- Numerous technical details:
- "Blob ejection" [21] $\rightarrow$ recoil?
  $\rightarrow$ H-mode?
- Major Unknown: Poloidal Momentum
  - many cases of deviation from standard neoclassical

  need:
    - improved neoclassical
    - turbulent flux => V, Π
    - $\langle E_r \rangle$ structure across separatrix

  $\rightarrow$ $\langle v_\theta \rangle$, $\langle v_\phi \rangle$ strongly coupled
- AE critical in Burning Plasmas
  - role of field momentum?
  - role of cross-scale coupling?

c) Thoughts on the 'Big Picture'

"General Circulation in the Tokamak" as a fascinating and critical problem?!
- Ocean/Atmosphere
  - Rotation, continents, solar heating, eddys, jets, Hadley cells, annular modes, and western boundary layer
- Tokamak
  - B-geometry, boundary, heat flux, drift-ITG, zonal flows, poloidal flows, KH of zonal flows, and pedestal
- Hierarchical structure of "global" flow pattern?

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