Integrating tokamak-edge MHD-fluctuation modeling with transport

by

Jacob King
Tech-X Corporation, Boulder, CO USA

With contributions from
S. Kruger, E. Howell
Tech-X Corporation, Boulder, CO USA

A. Pankin, B. Grierson, S. Haskey
Princeton Plasma Physics Laboratory, Princeton, NJ USA

K. Burrell, X. Chen, A. Garofalo, and R. Groebner
General Atomics, San Diego, CA USA

J. Callen, G. McKee, Z. Yan
University of Wisconsin-Madison, Madison, WI USA

S. Taheri
University of Washington, Seattle, WA USA

See Pankin et al., Nucl. Fusion 2020 https://doi.org/10.1088/1741-4326/ab9afe

Work supported by the US Department of Energy, Fusion Energy Sciences
Computational support from NERSC

DIII-D NATIONAL FUSION FACILITY

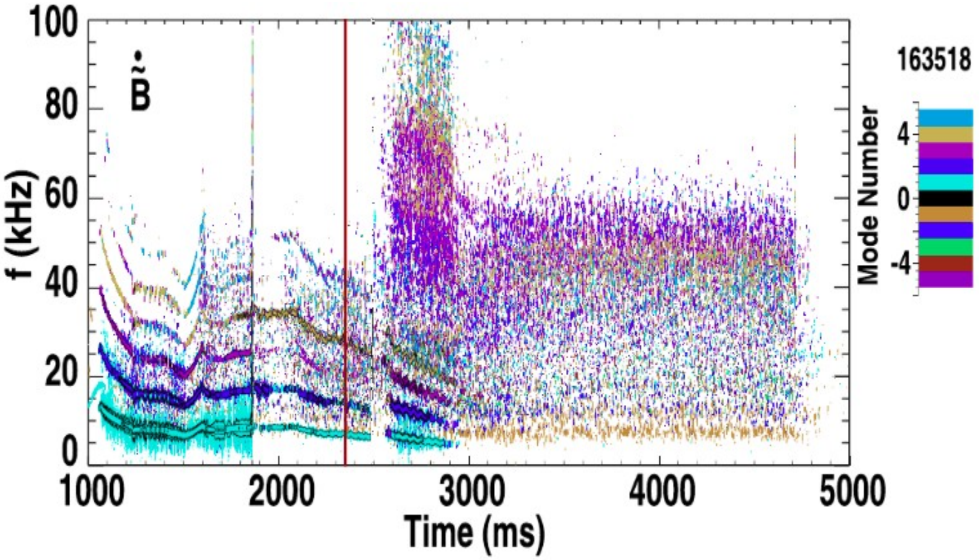
TECH-X

NIMROD
Non-Ideal MHD with Rotation
Open Discussion Project

Goal: Validate NIMROD MHD QH-mode simulations with local perturbation measurements

- **Focus on EHO in QH DIII-D discharge 163518 at 2350 ms**
- **Hypothesis: saturated 3D fluctuations drive particle and thermal transport to maintain steady state pedestal profiles [Snyder NF 2007]**
- **How well can MHD modeling characterize the low-n perturbations observed during QH-mode?**

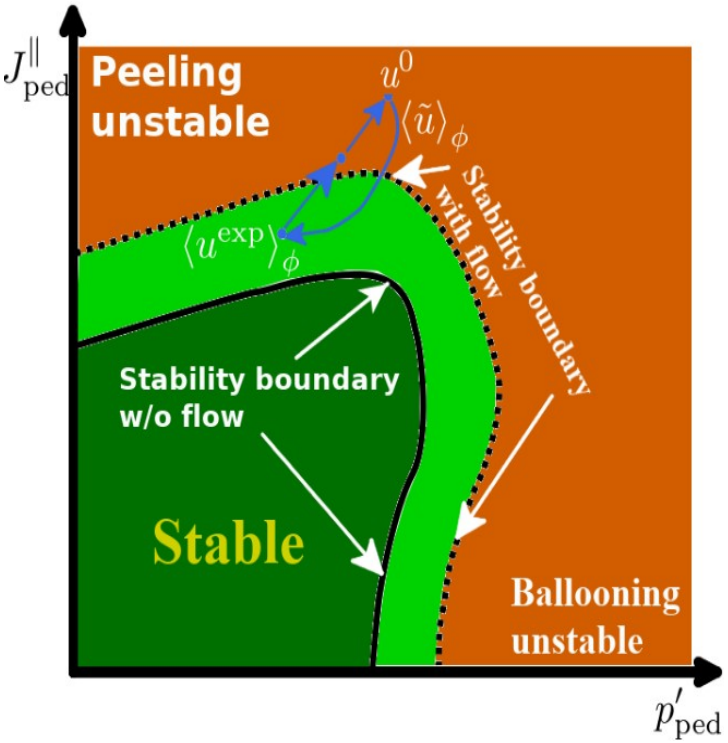
[K. Burrell PoP 2016]

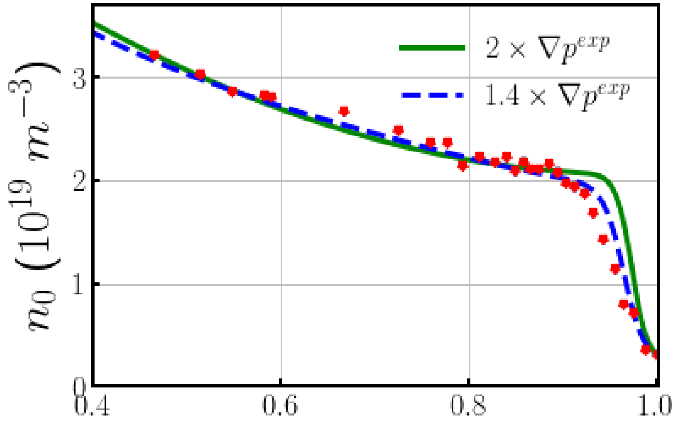


Extended-MHD codes start from reconstructed state

- **Initial plasma and magnetic configuration: reconstructed from measurements constrained by force balance**
- **Assume: 2D evolution of this state is on transport time scale**
  - Transport requires effects outside the scope of MHD: e.g. neutral-beam, high-k turbulence, neoclassical effects, IOL, neutral interaction
- **Model: NIMROD code [Sovinec JCP 04] evolves 3D, nonlinear perturbations around 2D steady state**
  - Perturbations may modify the axisymmetric (n=0) state
  - Consistent with reconstruction when n=0 modification is small

Best-fit reconstruction is stable → increase instability drive by reducing pedestal width



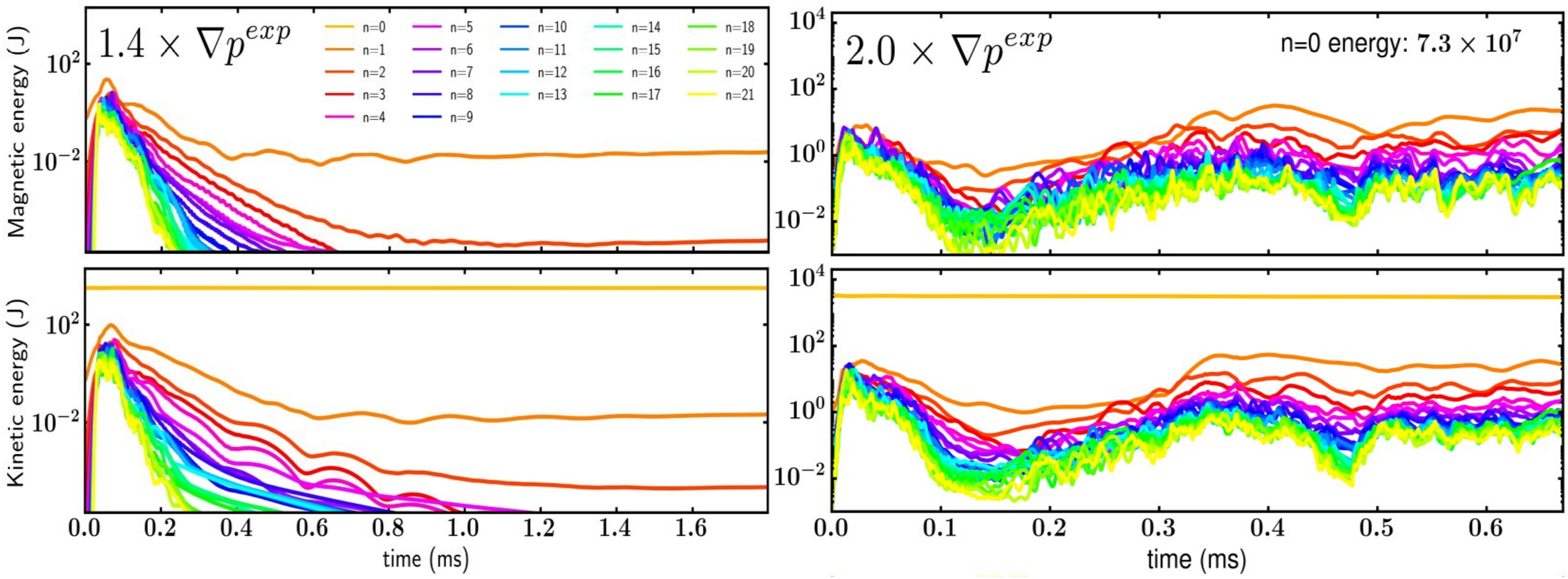


- **EFIT based on “best fit” to experimental data is stable when ExB flow is included**
- **To destabilize: density and temperature gradients increased in the pedestal region**
  - Similar to varyped
- **Nonlinear relaxation expected to relax plasma profiles back towards measured state**

Simulations saturate to states with n=1 dominant, but span from laminar to turbulent

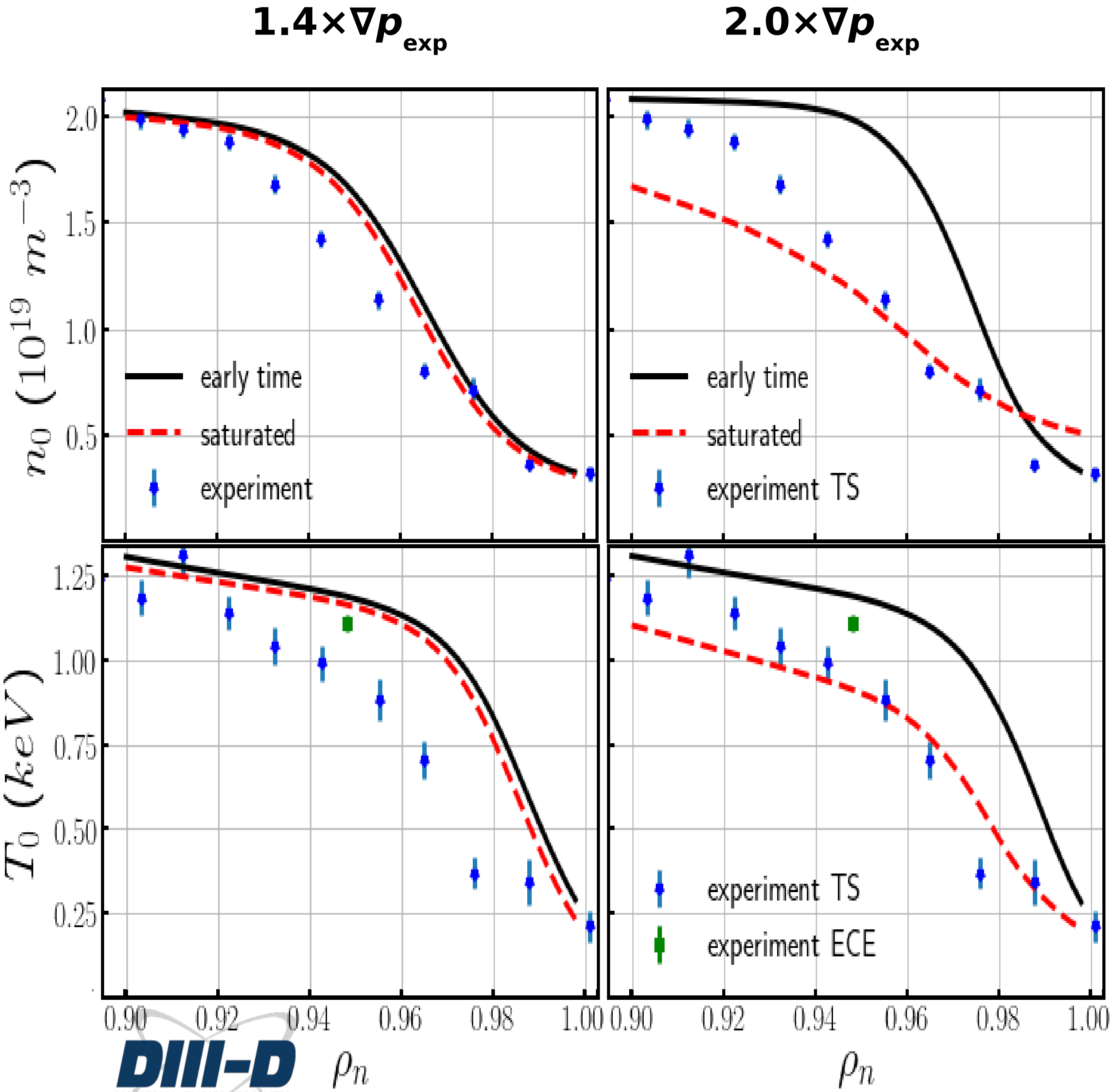
$1.4\times\nabla p_{exp}$
Low-amplitude Laminar

$2.0\times\nabla p_{exp}$
Large-Amplitude Turbulent



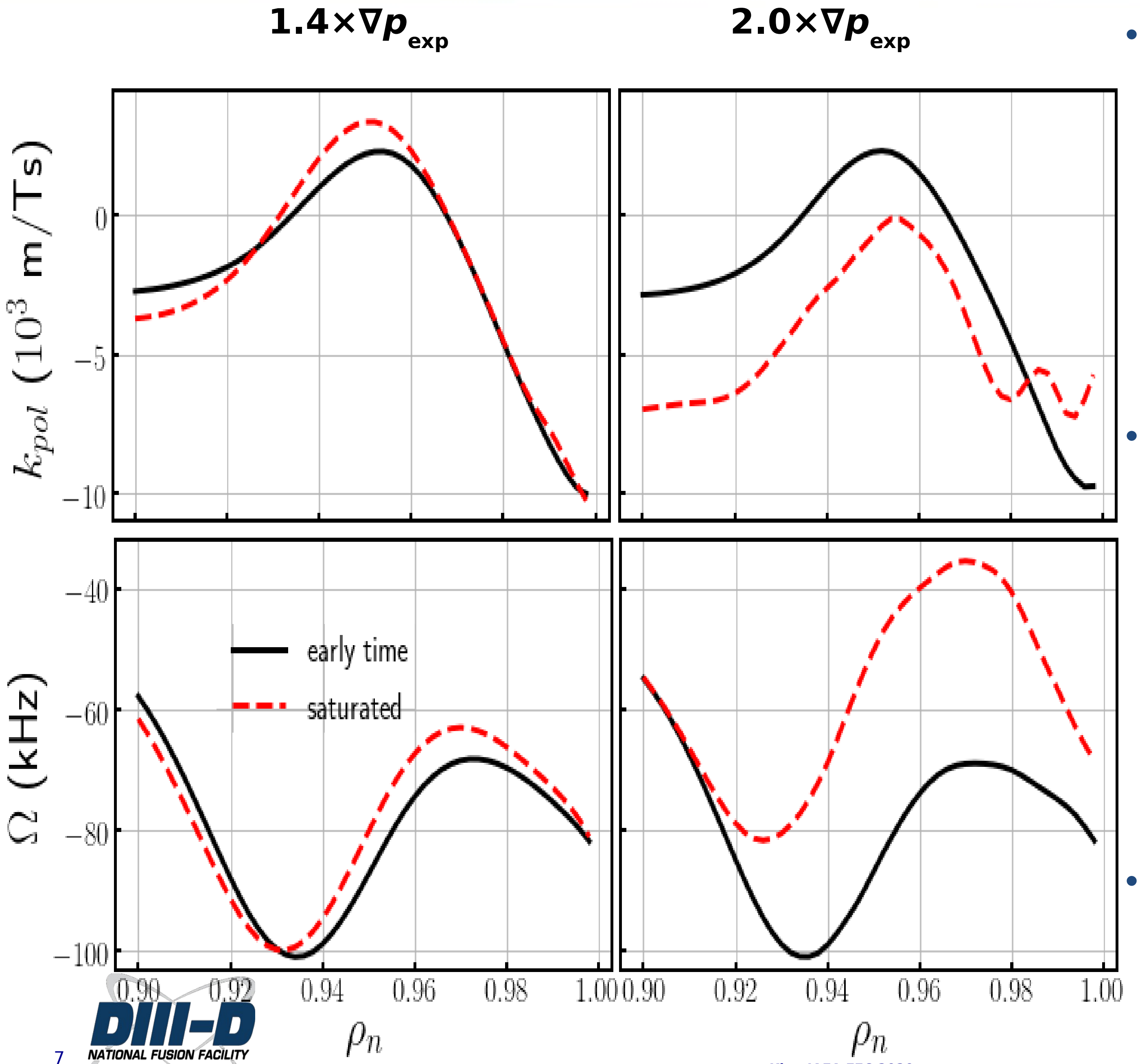
Does one underlying drive better match experiment?

Density and temperature relax towards measured state



- **Weakly driven case exhibits weak relaxation (profiles too steep)**
- **Strongly driven case exhibits strong relaxation**
  - Density transport greater than temperature consistent with [King et al., Phys Plasma 2016]
- **Strongly driven case more consistent with measured profiles**

Rotation profiles evolve from initial profiles → impacts EHO frequencies



- **Initial profile is ExB and neoclassical poloidal flows based on reconstruction**

$$\mathrm{v} = \Omega_{E\times B} R\hat{\Phi} + k_{pol}(\psi)\mathrm{B}$$

$$\Omega_{E\times B} = \frac{\mathbf{E}\cdot\nabla\psi}{|\nabla\psi|^2}$$

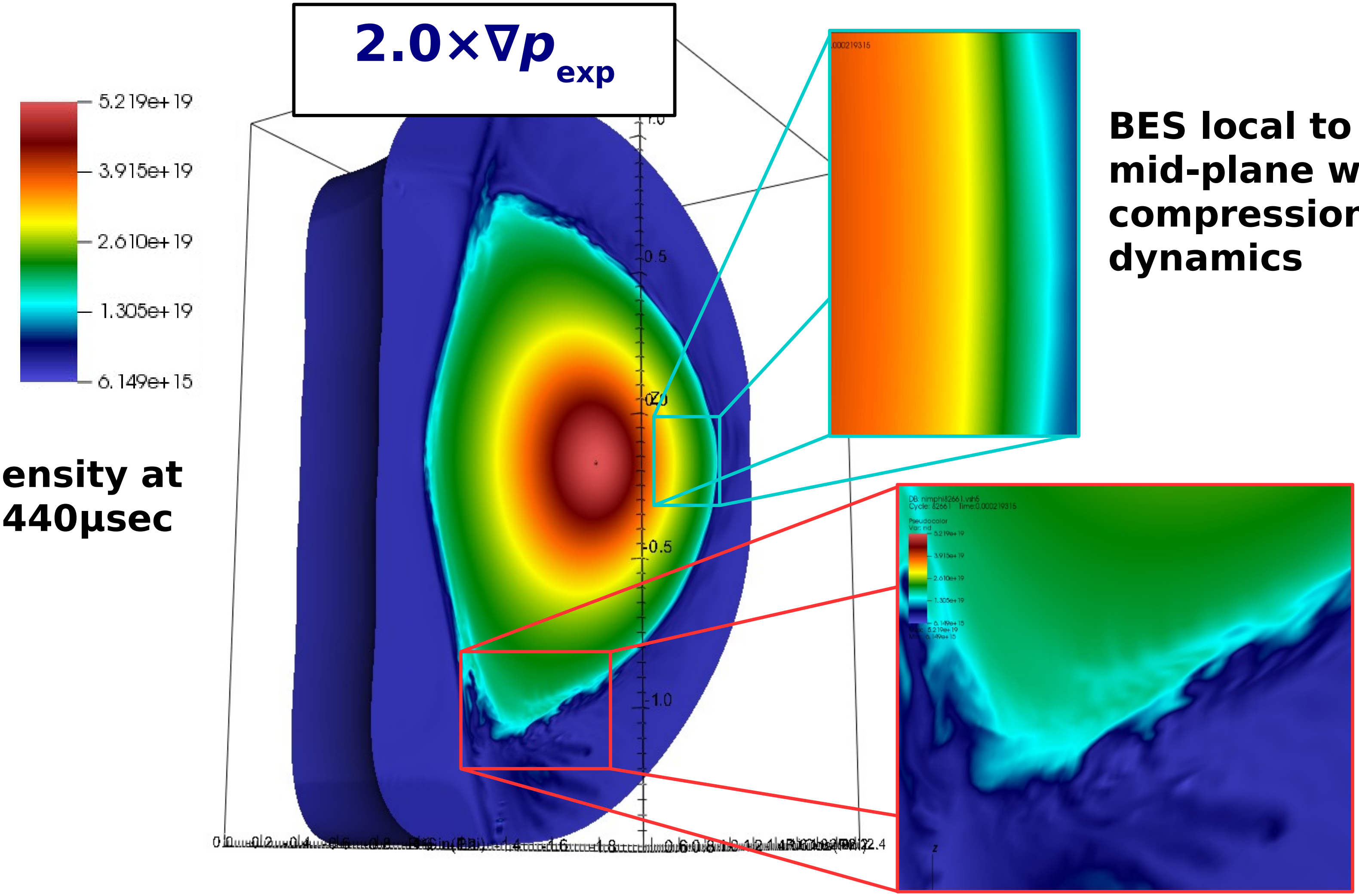
- **With time dynamics, MHD-fluctuation-induced flows are generated and basic FSA quantities are compared**

$$k_{pol}(\psi) = \left\langle \frac{v_{pol}}{B_{pol}} \right\rangle$$

$$\Omega = \left\langle \frac{\mathbf{v}_\Phi}{R} \right\rangle$$

- **Large deviation in strongly driven case impacts mode frequency**

Strongly-driven turbulent simulation shows large density perturbations

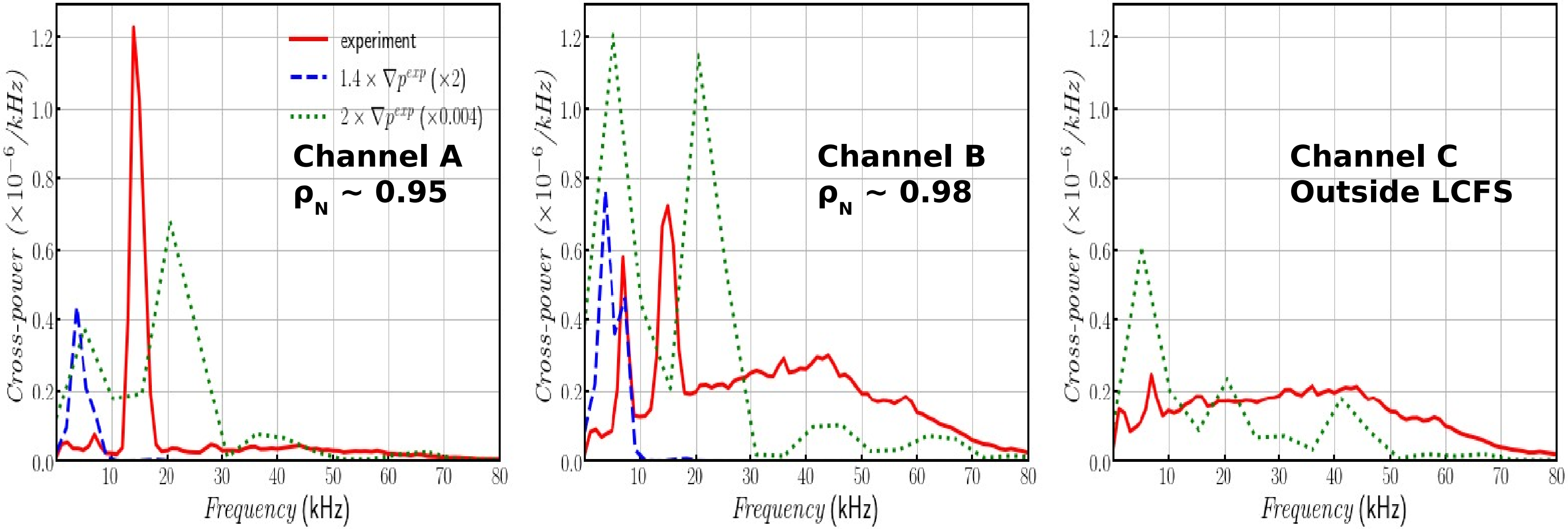


$2.0\times\nabla p_{exp}$

Density at ~440µsec

BES local to outboard mid-plane where flux compression smooths dynamics

Amplitude of BES measurements is bracketed by synthetic diagnostic analysis of simulations

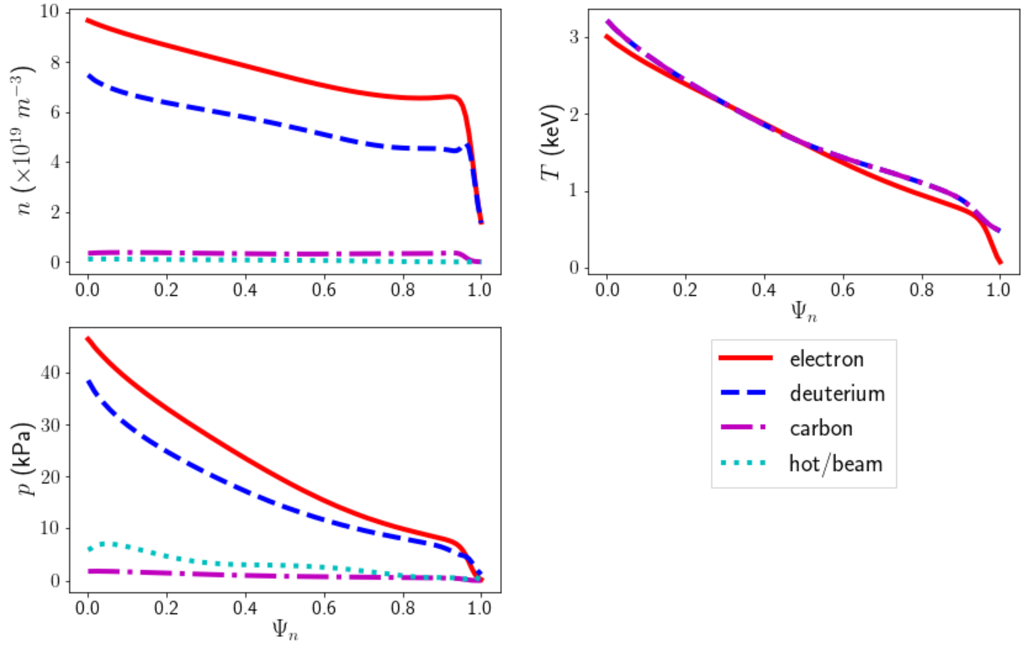


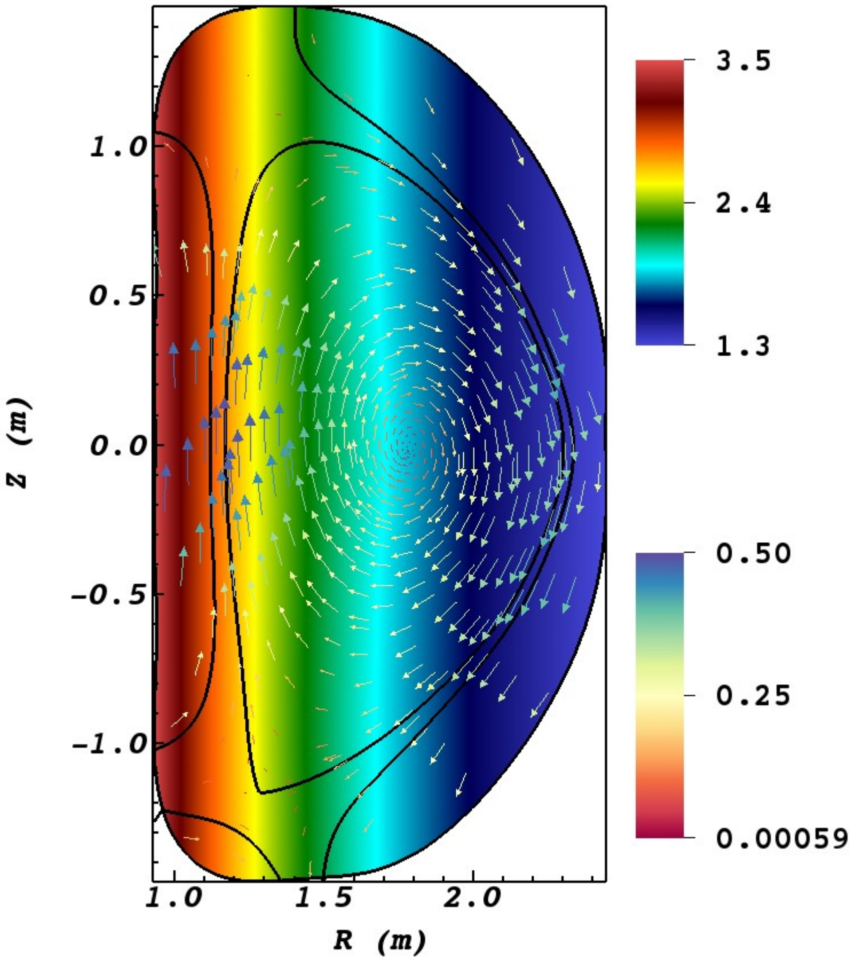
- **Both simulation and experiment transition from single to double peak structure when moving radially outward**
- **Frequencies are not consistent given flow profile modification from MHD fluctuations**

Validation promising but imperfect; complicated by

- **Changes to magnetic surface location when increasing instability drive**
  - Need to keep {p,n,T}(R,Z) fixed for comparison to local measurements at fixed R,Z
  - Not straight-forward with current profile redistribution which modifies ψ(R,Z) as profiles often specified as {p,n,T}(ψ)
- **Rotation profile modification confounds local diagnostic comparisons which rely on frequency analysis**
- **Next: consider other sources of momentum transport from effects outside the MHD model**

Focus on 2D ion-orbit-loss and neutral momentum transport in DIII-D shot 164988





This shot has minimal 3D magnetic Perturbation → tests 2D model equations

Ion-orbit-loss model from analytic work by Shaing

FSA particle loss rate

Without collisions no pitch-angle scattering into loss cone

Losses are limited by collisions and distance from LCFS

$$\left\langle \frac{\partial n}{\partial t} \right\rangle_{orb} = -\frac{2.25}{\sqrt{\pi}} \frac{n\,\nu_i}{\sqrt{2\,|S|\,\epsilon}} \exp\left[-\left(\nu_*^{1/4} + \frac{\Omega\sqrt{|S|}}{RB_t v_{Ti}} \frac{|\psi-\psi_s|}{\sqrt{2\epsilon}}\right)^2\right]$$

$$S = 1 + \frac{{RB_t}^2}{\Omega_{c0}} \frac{e\Phi''}{m}$$

S is ‘orbit-squeezing’ factor that decreases IOL outside minimum of E_r well

$$\mathbf{\Gamma}_{orb} = -\hat{r}\,(\Delta r)\,(\partial n/\partial t)_{orb}$$

IOL particle flux acts like a current

$$\langle \mathbf{B}_p \cdot \nabla \cdot \mathbf{\Pi}_{orb} \rangle = e\mathbf{\Gamma}_{orb} \times \mathbf{B} \cdot \mathbf{B}_p$$

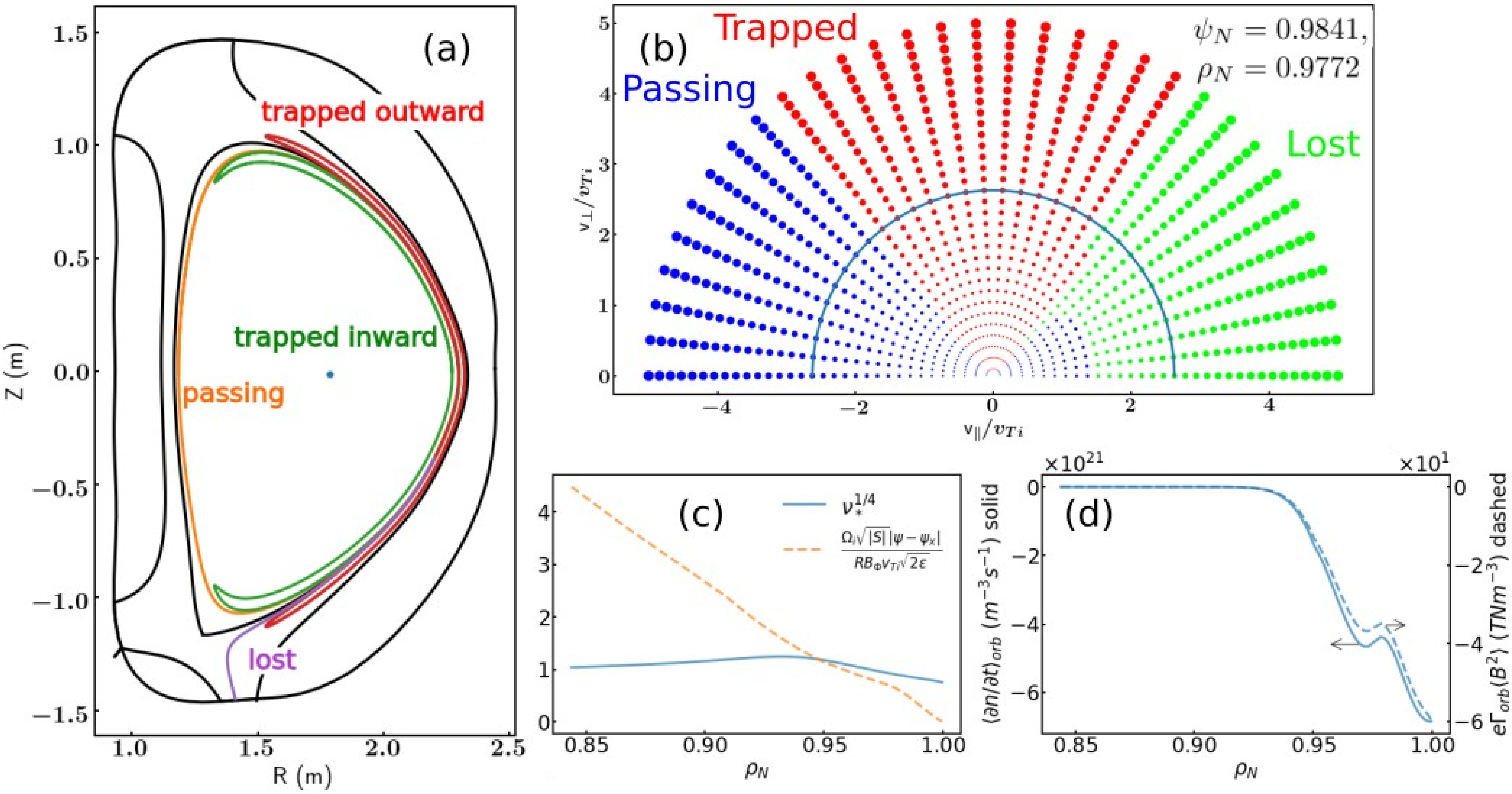
$$\langle \mathbf{B}_t \cdot \nabla \cdot \mathbf{\Pi}_{orb} \rangle = e\mathbf{\Gamma}_{orb} \times \mathbf{B} \cdot \mathbf{B}_t$$

IOL leads to viscous forces &

co-current torque

Shaing et al., PFB 2 June (1990); Shaing PFB 2 Jan (1992); Shaing PFB 2 Oct (1992)

Model equations predict large IOL torques at edge



Next: investigate torque from full plasma-neutral model

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{v}) = \Gamma^{ion} - \Gamma^{rec}$$

$$\rho = \sum_{\alpha \neq n} \rho_\alpha \quad \rho \mathbf{v} = \sum_{\alpha \neq n} \rho_\alpha \mathbf{v}_\alpha \quad n_I = \sum_{\alpha \neq n,e} n_\alpha$$

$$\frac{\partial n_n}{\partial t} + \nabla \cdot (n_n \mathbf{v}_n) = \Gamma^{rec} - \Gamma^{ion}$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} + \nabla p + \nabla \cdot \mathbf{\Pi} = \mathbf{J} \times \mathbf{B} + \left(\Gamma^{ion} + \Gamma^{cx}\right) m_i \left(\mathbf{v}_n - \mathbf{v}\right) + \mathbf{R}^{cx}_{in} - \mathbf{R}^{cx}_{ni}$$

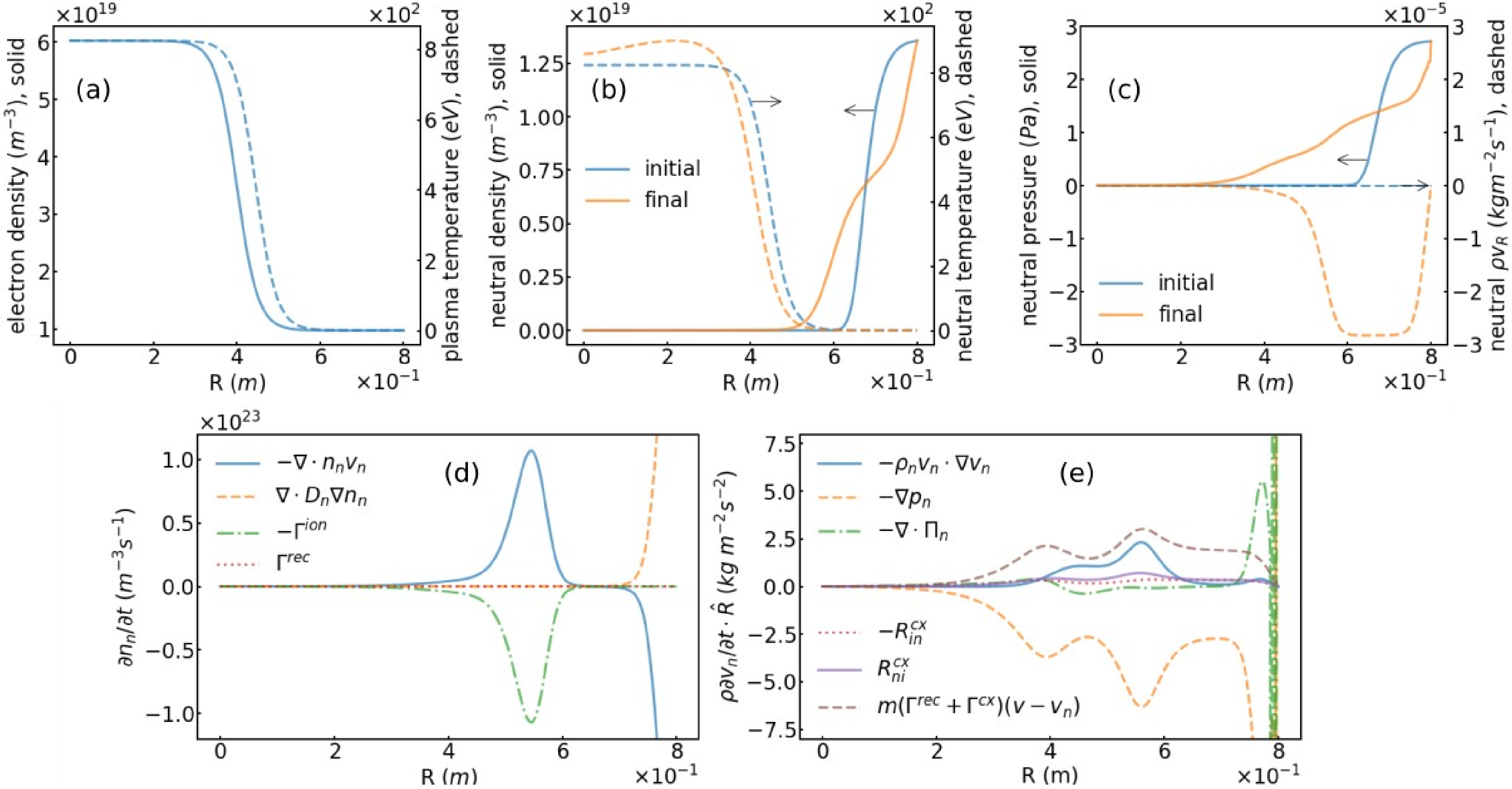
$$\rho_n \frac{\partial \mathbf{v}_n}{\partial t} + \rho_n \mathbf{v}_n \cdot \nabla \mathbf{v}_n + \nabla p_n + \nabla \cdot \mathbf{\Pi}_n = -\left(\Gamma^{rec} + \Gamma^{cx}\right) m_i \left(\mathbf{v}_n - \mathbf{v}\right) - \mathbf{R}^{cx}_{in} + \mathbf{R}^{cx}_{ni}$$

$$\begin{aligned} n_I k_B \frac{\partial T_I}{\partial t} + n_I k_B \mathbf{v} \cdot \nabla T_I + (\Gamma - 1)\, n_I k_B T_I \nabla \cdot \mathbf{v} = -k_B T_I \left(\Gamma^{ion} - \Gamma^{rec}\right) \\ + (\Gamma - 1)\left[\nabla \cdot \mathbf{q} + \mathbf{\Pi} : \nabla \mathbf{v} + Q^{ion} - Q^{rec} + Q^{cx}_{in} - Q^{cx}_{ni}\right. \\ \left. + \left(\Gamma^{ion} + \Gamma^{cx}\right) \frac{m_i}{2} \left(\mathbf{v} - \mathbf{v}_n\right)^2 - \mathbf{R}^{cx}_{in} \cdot \left(\mathbf{v} - \mathbf{v}_n\right)\right] \end{aligned}$$

$$\begin{aligned} n_n k_B \frac{\partial T_n}{\partial t} + n_n k_B \mathbf{v}_n \cdot \nabla T_n + (\Gamma - 1)\, n_n k_B T_n \nabla \cdot \mathbf{v}_n = -k_B T_n \left(\Gamma^{ion} - \Gamma^{rec}\right) \\ + (\Gamma - 1)\left[\nabla \cdot \mathbf{q}_n + \mathbf{\Pi}_n : \nabla \mathbf{v}_n - Q^{ion} + Q^{rec} - Q^{cx}_{in} + Q^{cx}_{ni}\right. \\ \left. + \left(\Gamma^{rec} + \Gamma^{cx}\right) \frac{m_i}{2} \left(\mathbf{v} - \mathbf{v}_n\right)^2 + \mathbf{R}^{cx}_{ni} \cdot \left(\mathbf{v} - \mathbf{v}_n\right)\right] \end{aligned}$$

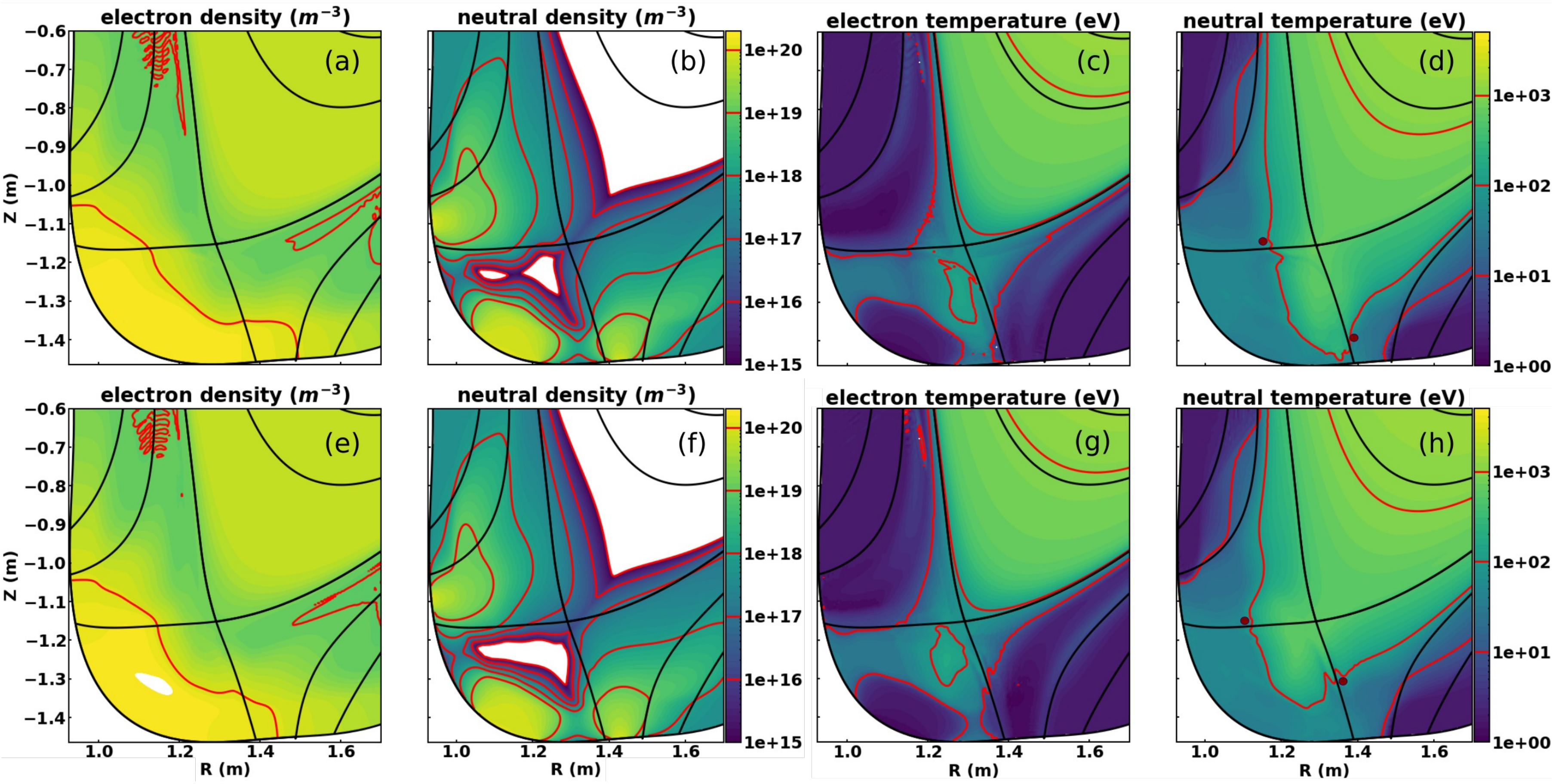
[Meier & Shumlak POP 19 072508 (2012)]

1D plasma neutral case demonstrates basic physics



- **Ballistic expansion force is balanced by charge exchange and advection**
- **Particle source from wall is ionized inside pedestal**

2D neutral model with ion, electons and neutral fluids produces in/out board asymmetry in heat flux



electron density (m^{-3})

neutral density (m^{-3})

electron temperature (eV)

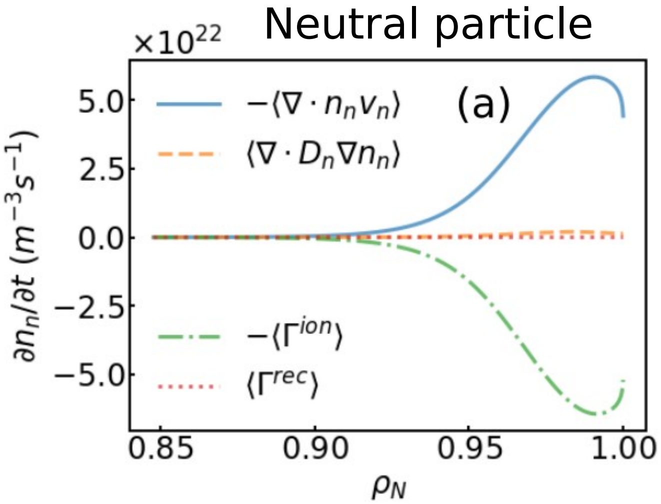
neutral temperature (eV)

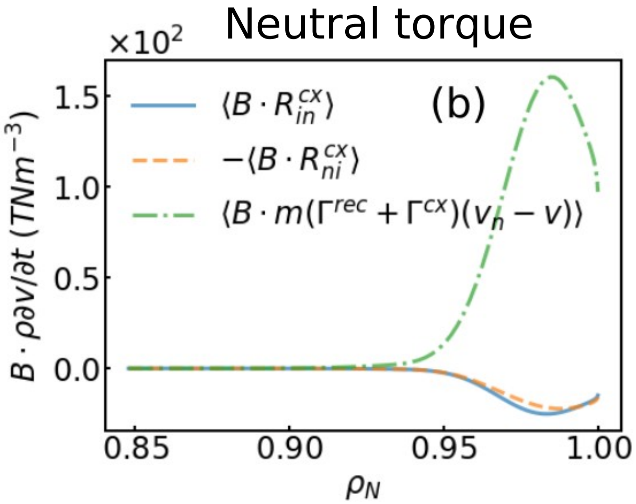
Normal B_T (a-d)

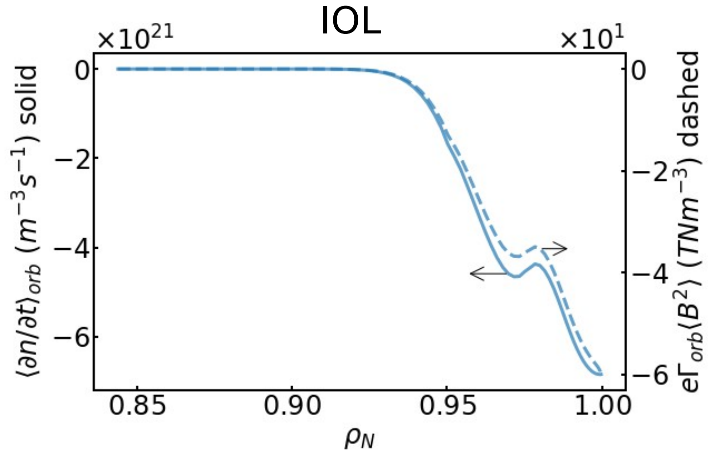
Rev B_T (e-h)

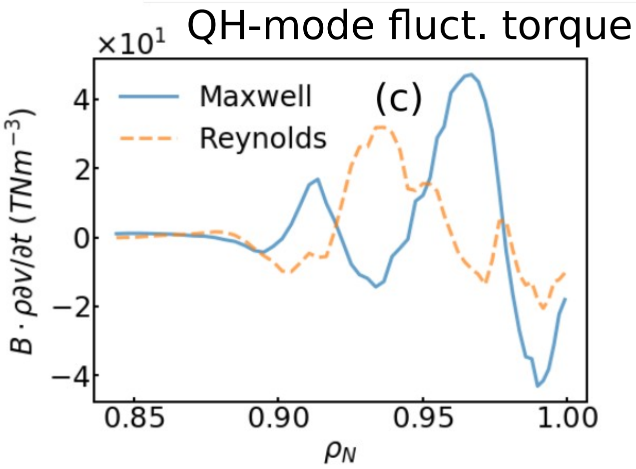
- **Asymmetry is not present without dynamic electron fluid**

Neutral torque is balances opposes IOL torque


Neutral particle


Neutral torque


IOL


QH-mode fluct. torque

QH-mode fluctuation torque is from *over-driven* case is comparable

Torques outside MHD are comparable and should be accounted for in MHD simulations

Conclusions

- **Validation QH-mode simulations scan the underlying drive**
  - Simulations bracket the fluctuation amplitude of BES observations
  - Fluctuation-induced momentum transport modifies rotation
  - Frequency comparison to BES measurements do not agree
- **Sources of momentum transport outside the MHD model are large**
  - Ion-orbit loss produces a co-current parallel torque in the edge
  - Calculation of the neutral CX force shows it balances the IOL torque
  - The torque from the Maxwell and Reynolds stresses of the over-driven QH-mode fluctuations is at most comparable to the IOL/neutral torques
- **Incorporation of IOL/neutral torques is needed during nonlinear QH-mode simulation**