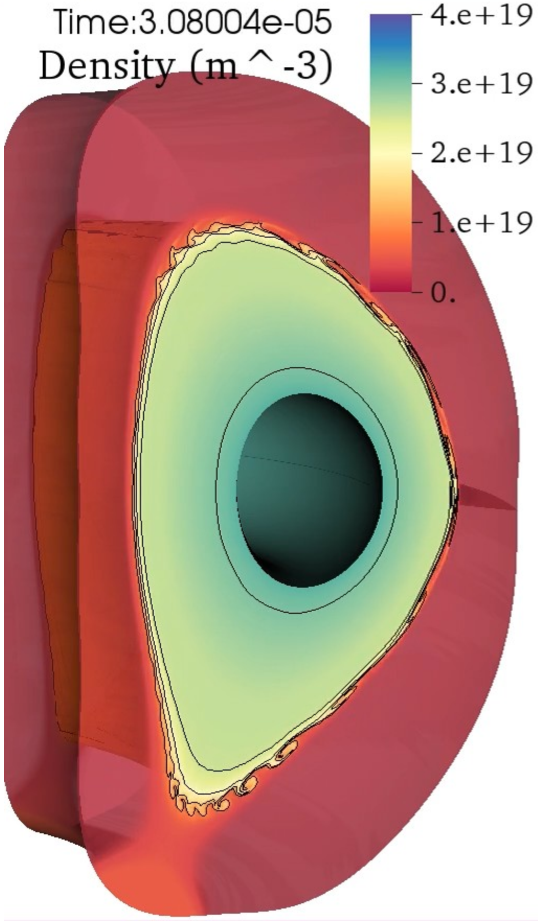
Nonlinear NIMROD modeling of a DIII-D QH-mode discharge

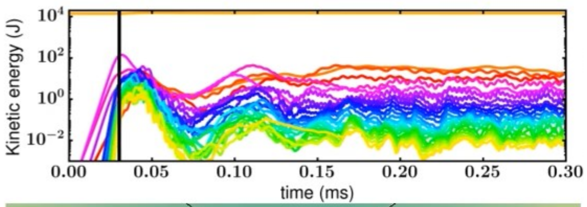
by

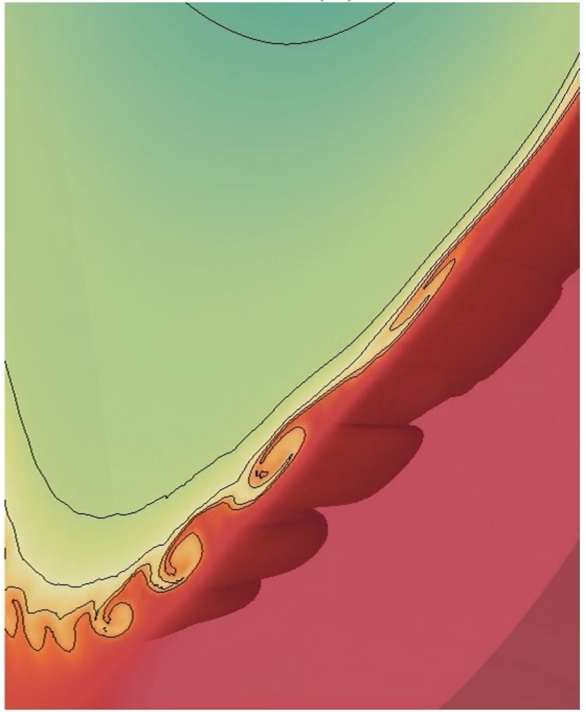
Jacob King (Tech-X)

With contributions from

S. Kruger & A. Pankin (Tech-X);
K. Burrell, X. Chen,
A. Garofalo, R. Groebner &
P. Snyder (General Atomics);
E. Olofsson (ORAU)







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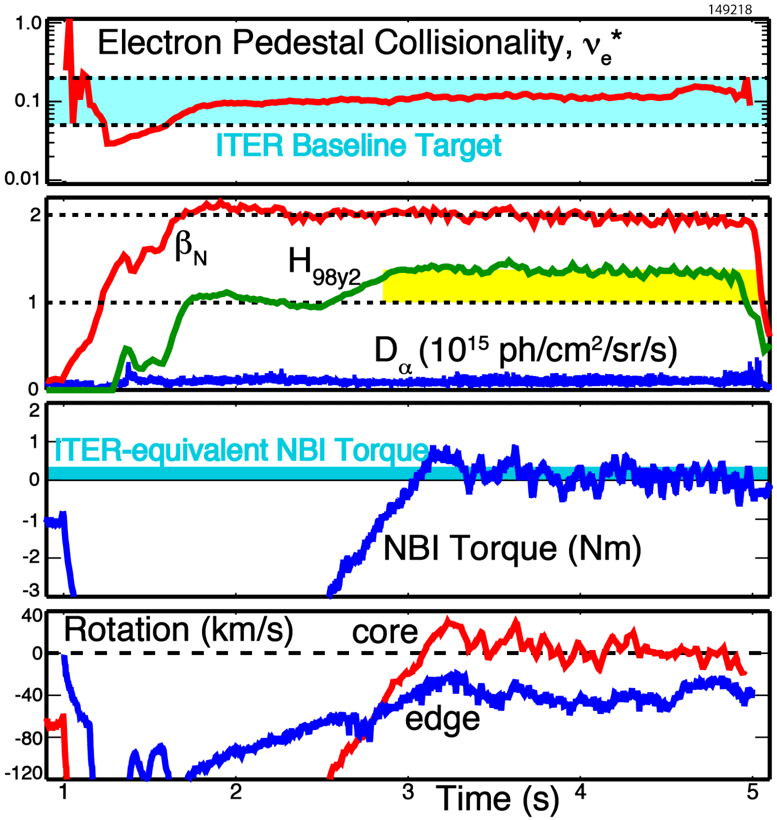
Motivation is to enhance understanding of QH-mode

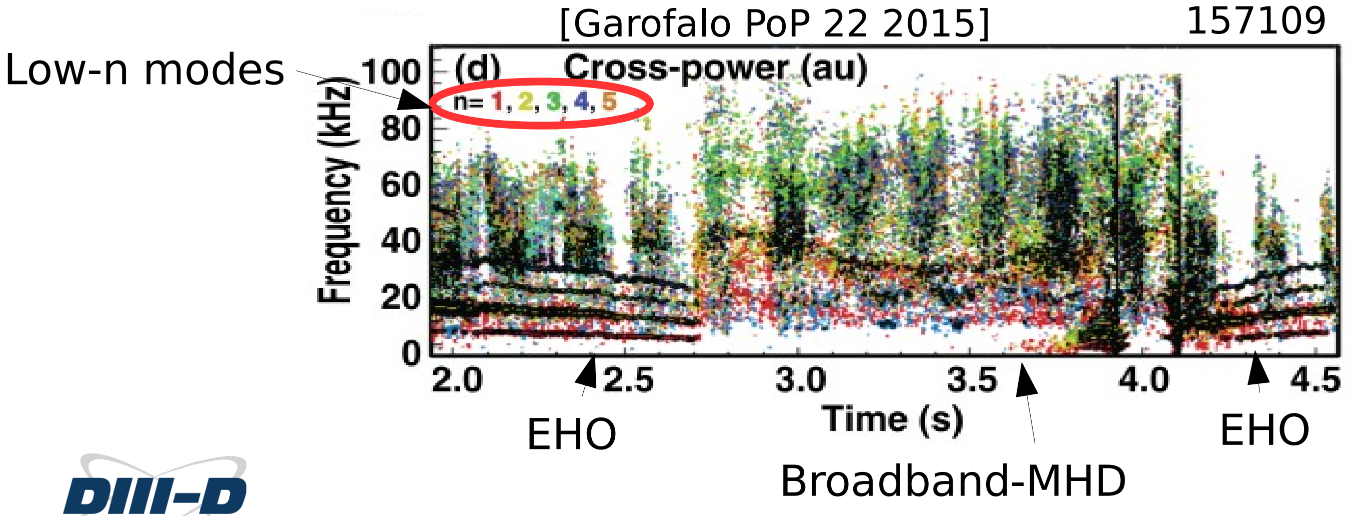
- **Quiescent H-mode is an operational regime without edge-localized modes (ELMs) [Burrell PoP 19 2012 and 2015]**

- **QH-mode addresses several requirements of ITER/DEMO operation [Garofalo PoP 22 2015 → figure]**



QH-mode is accompanied by low-n perturbations

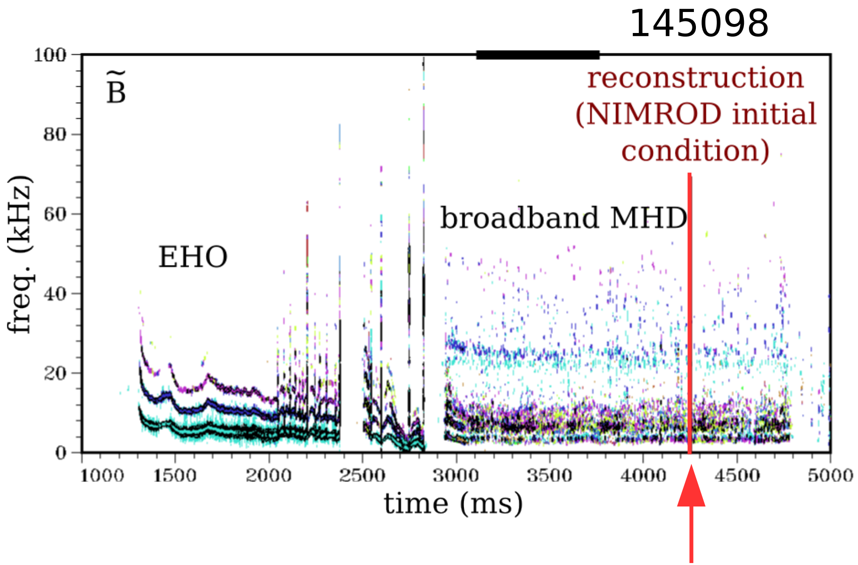
- **Hypothesis: the saturated pert. drives particle and thermal transport to maintain steady state pedestal profiles [Snyder NF 2007]**
- **How well can MHD modeling characterize the low-n perturbations observed during QH-mode?**
- **Published nonlinear results: NIMROD code [King NF 57 2017] & JOREK code [Liu NF 2015]**



Low-n dynamics during QH-mode discharges can be modeled with extended-MHD

- **Critically dependent on inclusion of flow**
  - With flow → low-n saturation
  - Without flow (shear) → high-n dynamics
- **Our simulations find a quasi-turbulent-MHD state that drives transport in the pedestal**
  - Pressure and current gradients are relaxed → saturation
  - Flow profiles are largely unchanged
  - Fluctuation amplitudes and phases lead to larger edge convective particle transport relative to the thermal transport
- **Mode rotates faster than experimental measurements**
  - Indicates limitation of model: need two-fluid and/or resistive wall

Extended-MHD codes start from reconstructed state



Initial state: DIII-D QH-mode shot 145098 at 4250 ms while the discharge is ELM free with broadband MHD (chosen because it is a low-torque discharge relevant to ITER)

- **Initial state: 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 and neoclassical effects
- **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

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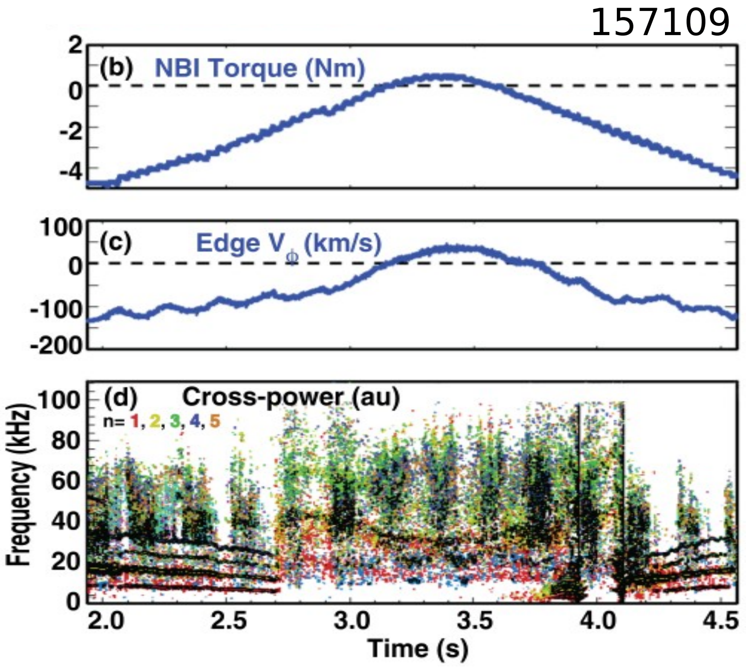
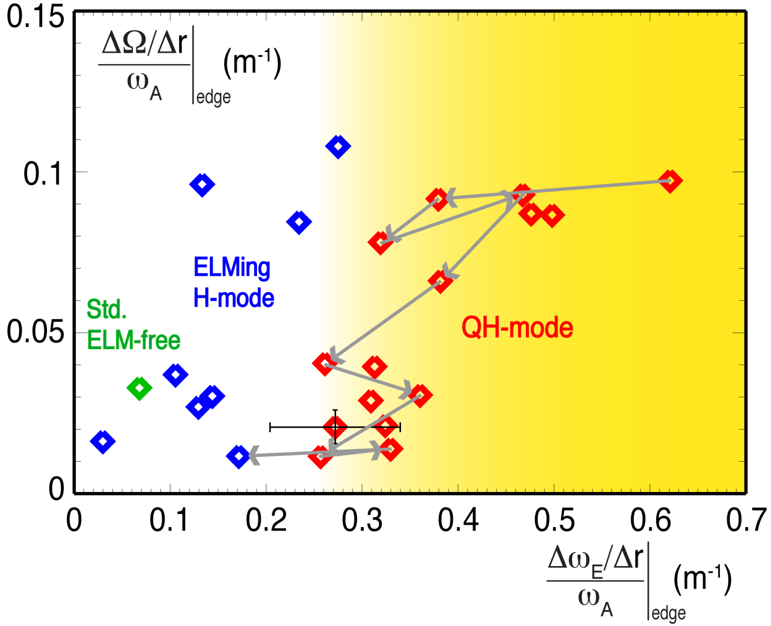
Access to QH-mode requires control of the flow profile

[Garofalo PoP 22 (2015)]



- **In particular, large ExB shear is correlated with QH-mode operation**

[Garofalo NF 2011]



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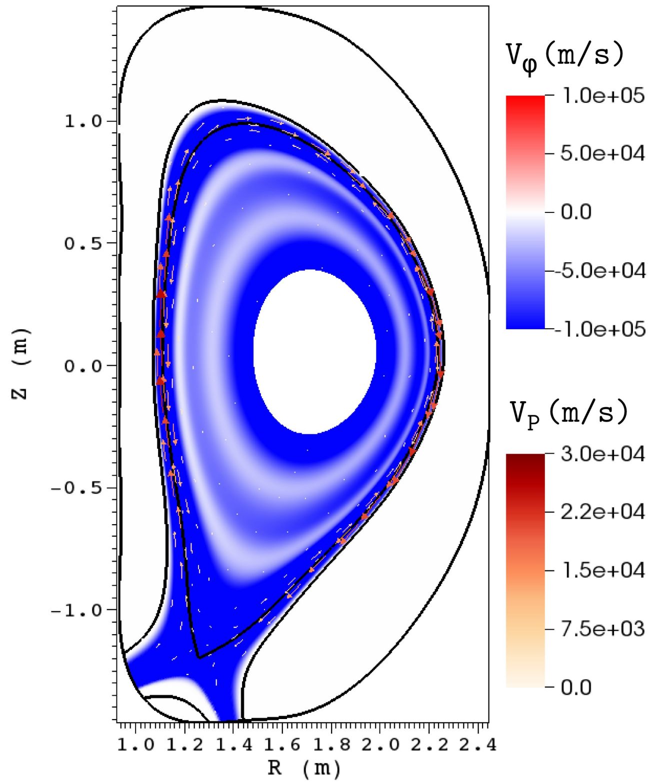
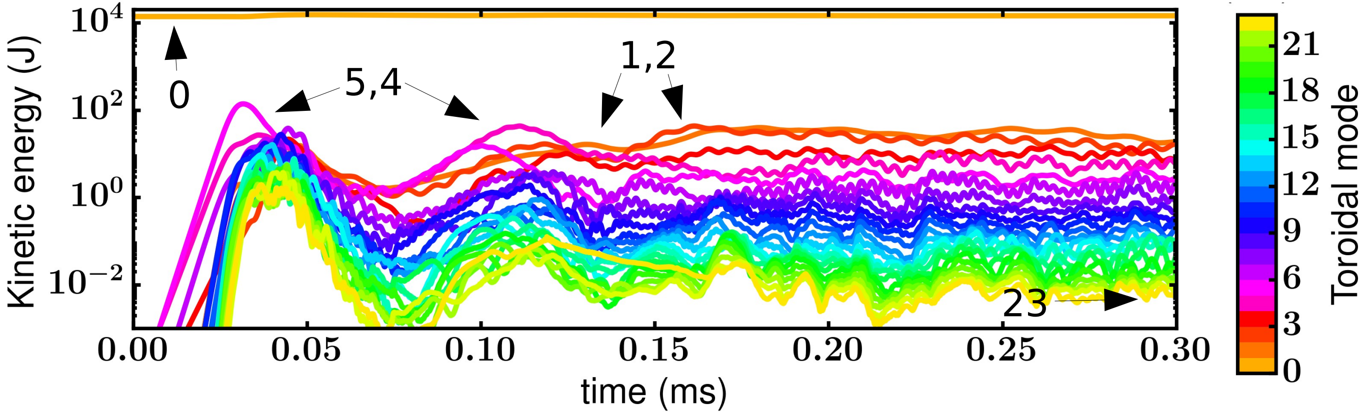
Simulations are performed with and without steady-state flow

- Steady-state toroidal and poloidal flows are inferred from measurements
- Identical initial perturbations for simulations with and without steady-state flow
- Flow (and current) are extrapolated to zero in the SOL region [King PoP submitted]
- NIMROD simulation uses a single-fluid MHD model with Braginskii parallel closures

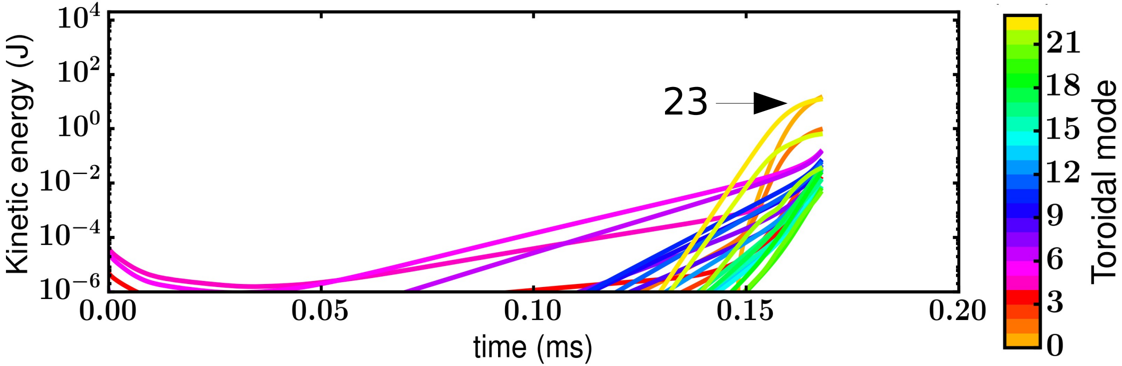


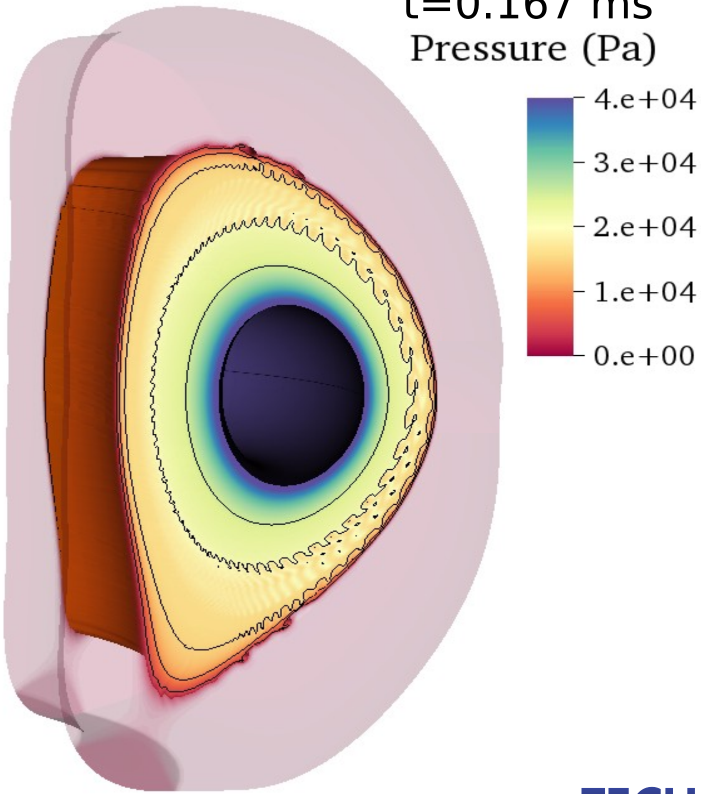
Perturbation amplitudes saturate to a quasi-turbulent state in simulations *with steady-state flow*



- **Simulation initialized with low-n (1-8) small perturbations**
- **n=4,5 dominant during linear [0-0.03 ms] and early saturation [0.05-0.13 ms] stages**
- **Inverse cascade: n=1,2 dominant later [>0.15ms]**
- **As simulation progresses → continued interplay between perturbations with amplitude modulations**

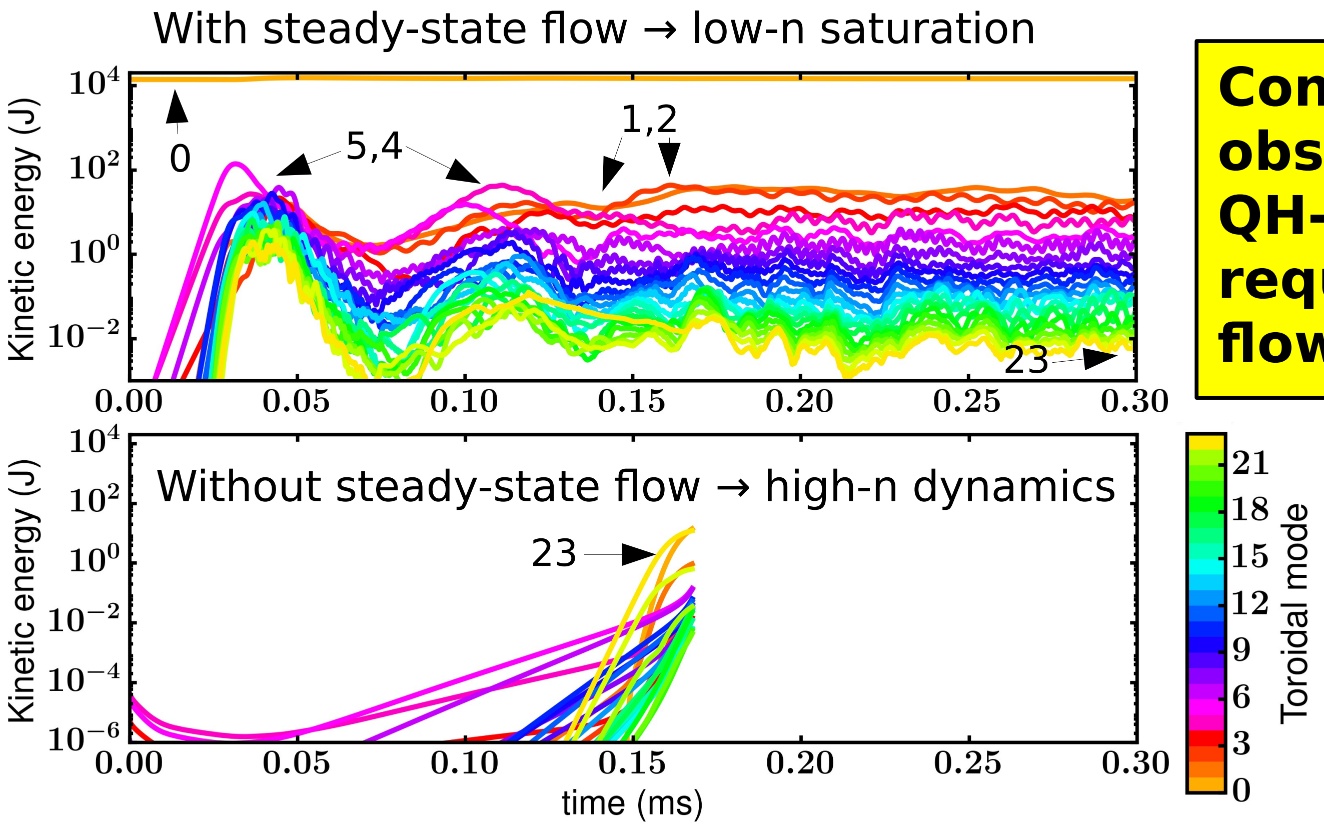
Without steady-state flow, high-n perturbations become dominant without saturation





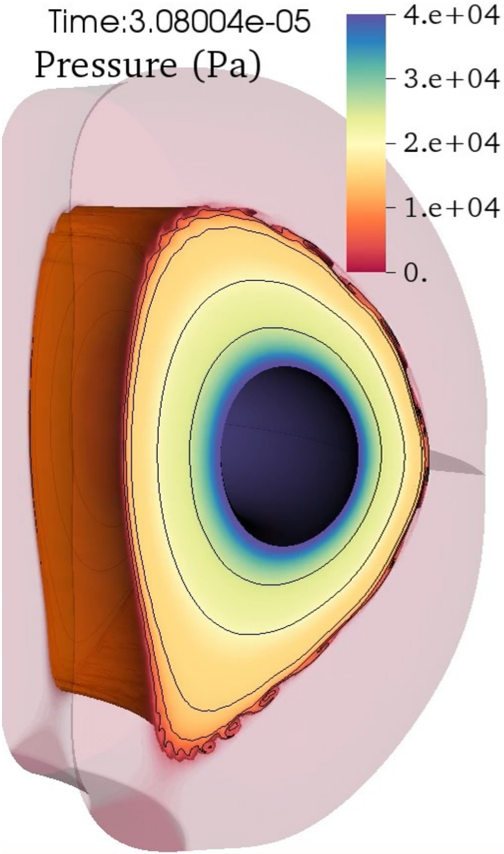
- **Initialization is identical to simulation with steady-state flow**
- **Simulation stops with perturbations at limit of the spatial resolution**
- **Low-n dynamics are sub-dominant**
- **Consistent with extended-MHD ELM simulations**

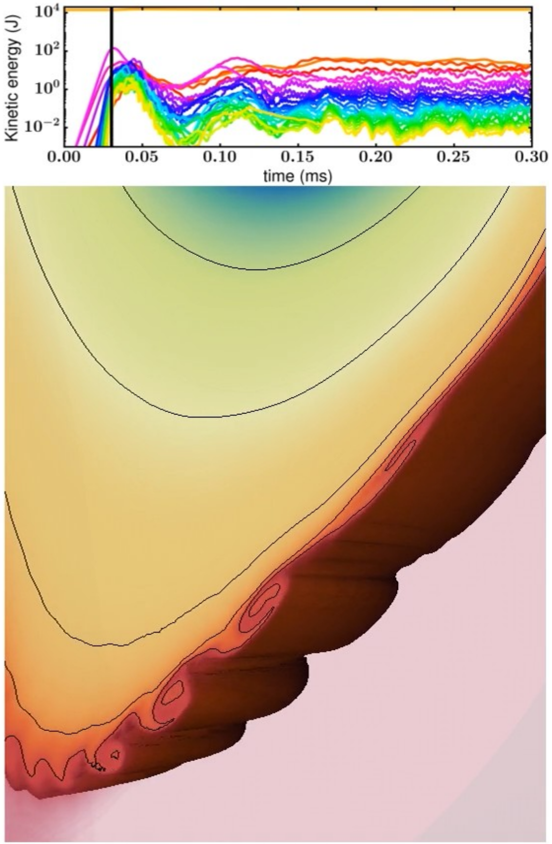
Importance of steady-state flow to low-n saturation is consistent with experimental observations



Consistent with exp. observations that QH-mode access requires large edge flow shear

Returning to simulations *with steady-state flow,* pressure evolution resembles quasi-turbulent state





- **Initial eddies advected by flow**
- **Sheared apart at finite amplitude**
  - [Guo PRL 2015]
- **Leads to quasi-turbulent state**
- **Can we quantify the transport driven by these perturbations?**

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- **Mode rotates faster than experimental measurements**
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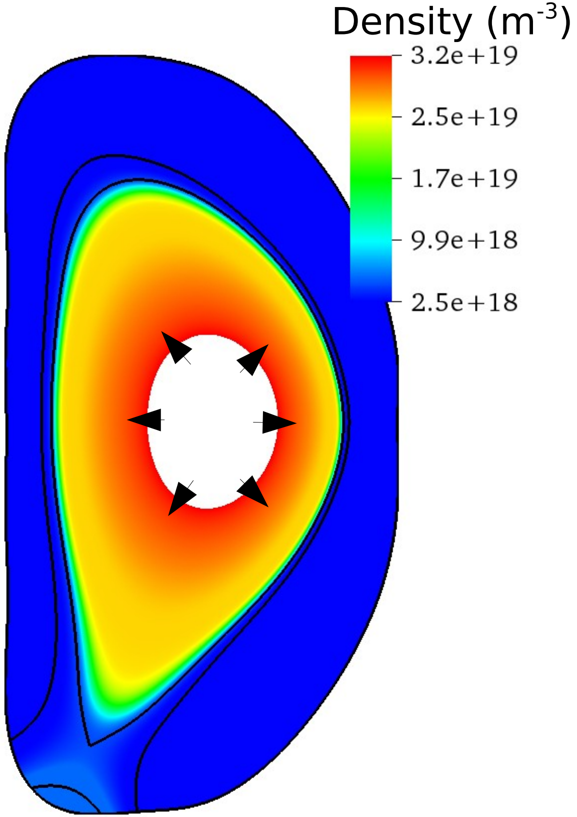
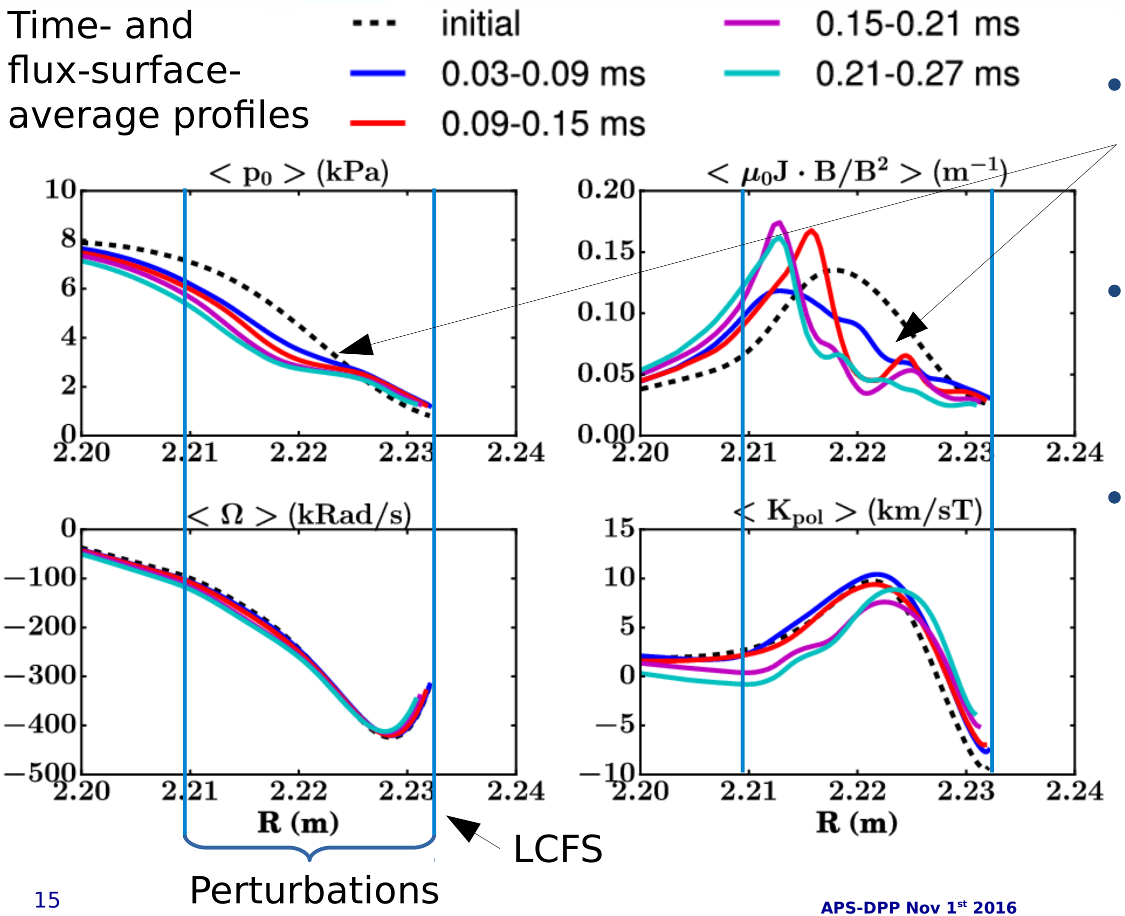
Characterization of transport requires understanding of boundary conditions

- **Computational domain is toroidal and annular**
  - Annulus avoids potential core instabilities
- **Dirichlet (n,T=constant) boundary conditions applied**
  - Provides unconstrained source of particles and energy on axis
  - Prevents edge perturbations from simply ‘pumping out’ core particles and temperature



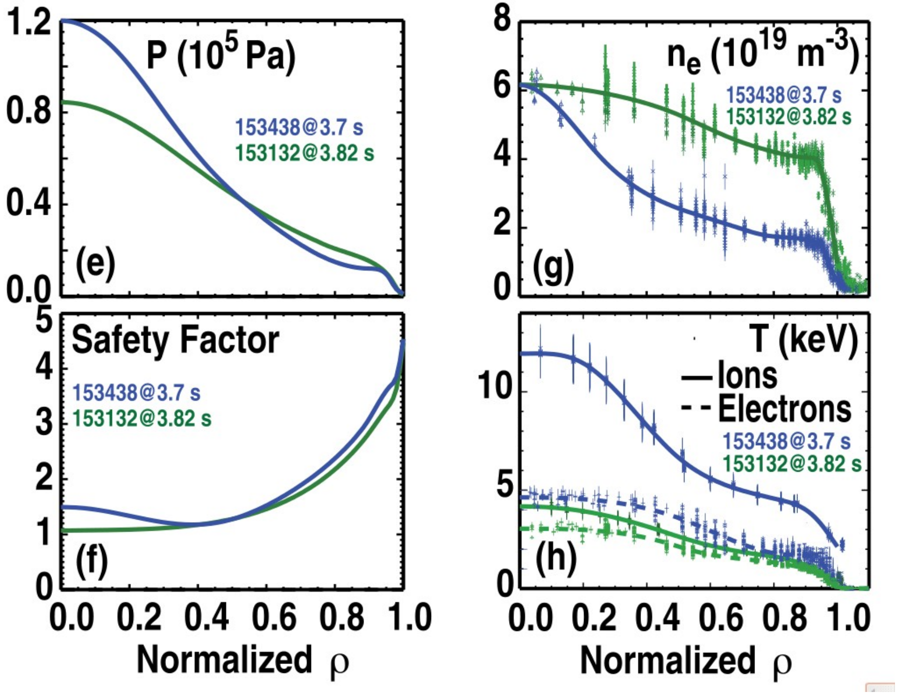
Pressure and current density profiles are flattened leading to saturation



- **Free-energy gradients are reduced**
- **Flow modifications are small**
- **Saturation is related to pressure and current modifications, not flow**

Experimental observations indicate that QH-mode dynamics drive particle transport

- **Fluorine impurity transport studies find QH-mode provides as much particle transport as 40 Hz ELMs**
  - Shown in comparison discharges on DIII-D from [Garofalo PoP 2015]
  - Green – ELMing H-mode
  - Blue – QH-mode with EHO
- **Typically, QH-mode core temperatures are increased similar to the density pump-out effect observed in discharges with RMP fields**



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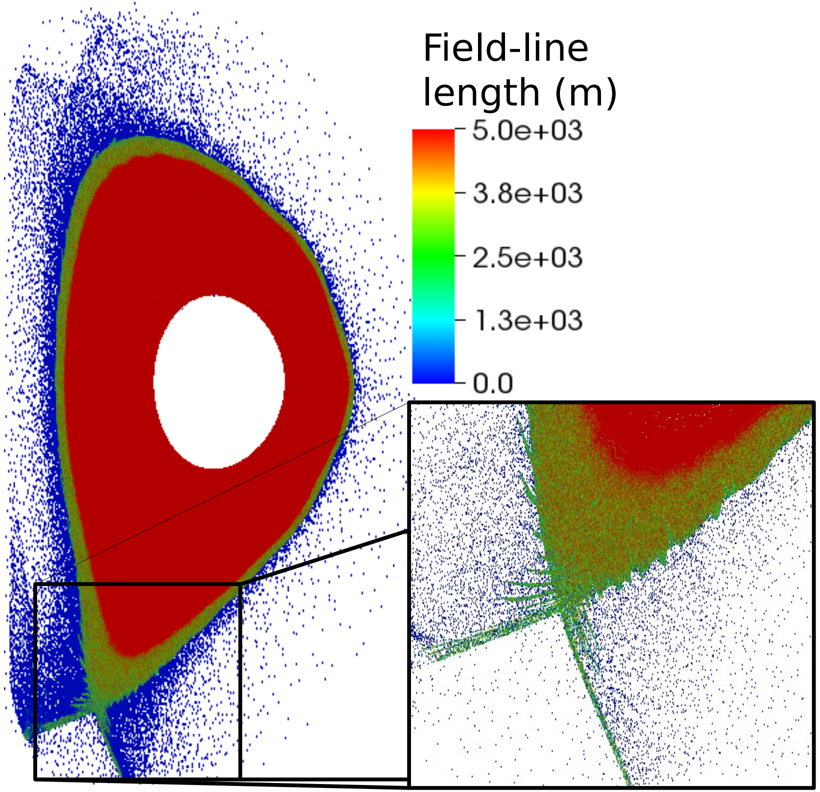
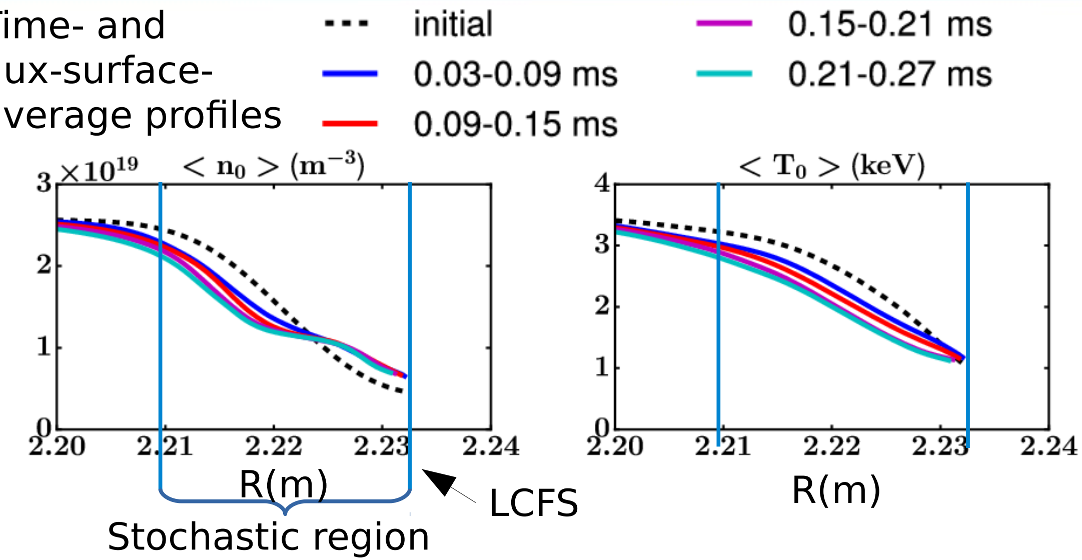
Magnetic field-lines become stochastic within the pedestal region

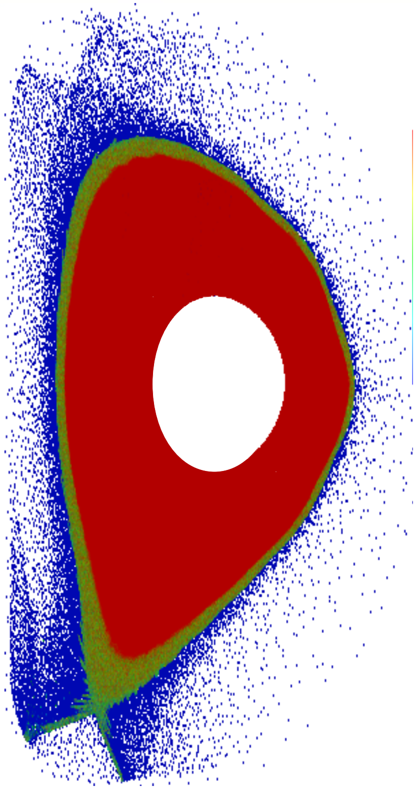


- **Anisotropic thermal conduction in model:**
  - $\chi_{||}=10^8$ m²/s
    - approximate ion value with T_i=1 keV
  - Expectation of dominant conductive transport
  - Would lead to thermal, not particle, transport unlike experiment

Flattening of density profile is large compared to temperature profile

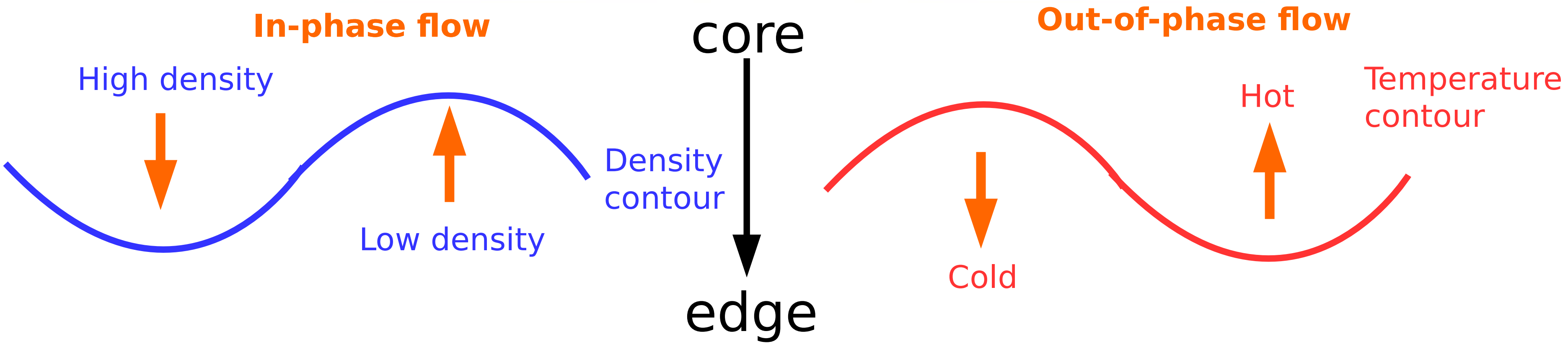
Time- and flux-surface-average profiles





- **Result is surprising with stochastic fieldlines and large anisotropic thermal conduction**
- **Qualitatively consistent with observations of density pump-out during QH-mode**

Fluctuation-induced transport is dependent on the relative perturbation phases



- **Density and temperature equations differ substantially with anisotropic thermal conduction**

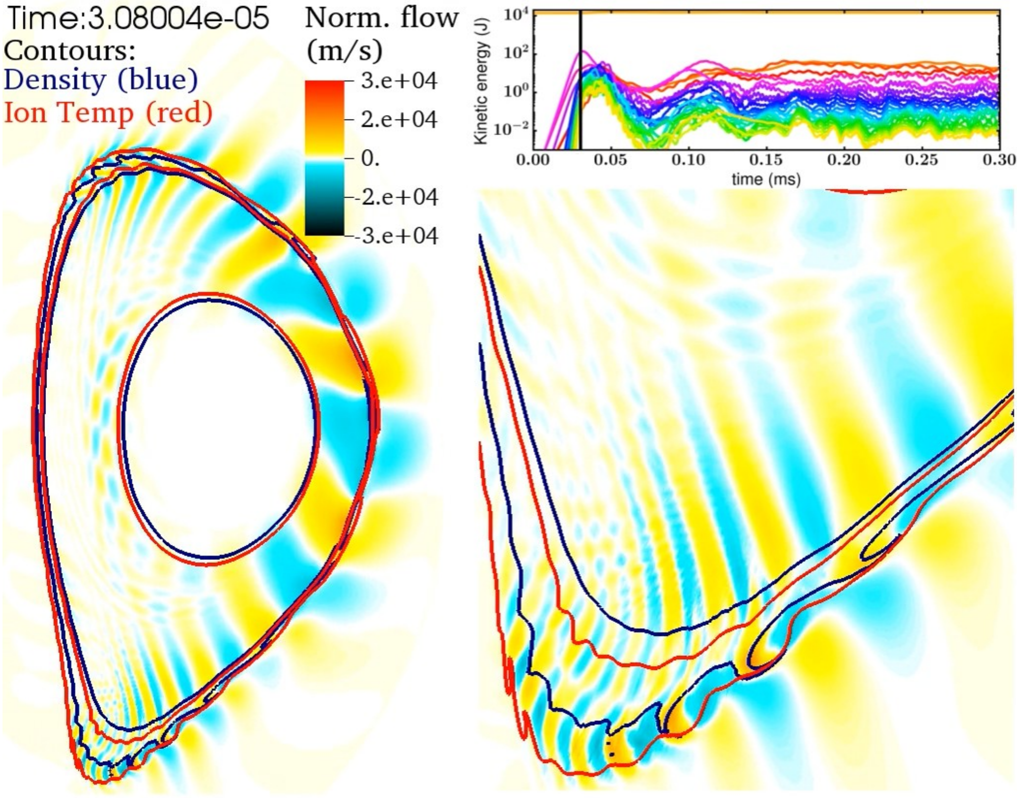
$$\frac{dn}{dt} = -n\nabla \cdot \mathbf{v} + D_n \nabla^2 n$$

$$\frac{n}{\Gamma - 1}\frac{dT}{dt} = -nT\nabla \cdot \mathbf{v} + \nabla \cdot \left[n\left(\chi_\perp + \chi_\parallel \hat{\mathbf{b}}\hat{\mathbf{b}}\cdot\right)\nabla T\right]$$

$\chi_{||}=10^8$ m^2/s

$D_n = \chi_\perp=1$ m^2/s

Phase differences enhance particle transport relative to thermal transport



- **Convective transport impacted by the phase relative to the perturbed normal flow**
  - Density → In phase with normal flow
  - Temperature → mixed phase relative to flow

Timescale estimates show convective transport dominates conductive losses

$$\tau_{conv,n} \simeq \frac{L_\perp n_0}{< \tilde{n}\tilde{v}_n >} \simeq 3 \times 10^{-4}\ s$$

$$\tau_{conv,T} \simeq \frac{L_\perp T_0}{< \tilde{T}\tilde{v}_n >} \simeq 6 \times 10^{-4}\ s$$

Phase and amplitude impact

$$\tau_{cond,\|} \simeq \frac{L_\|^2}{\chi_\|} \simeq 10^{-2}\ s$$

$$\tau_{cond,\perp} \simeq \frac{L_\perp^2}{\chi_\perp} \simeq 10^{-3}\ s$$

$$\tau_{cond,\|} \simeq \frac{L_\|}{v_{Te}} \simeq 10^{-3}\ s$$

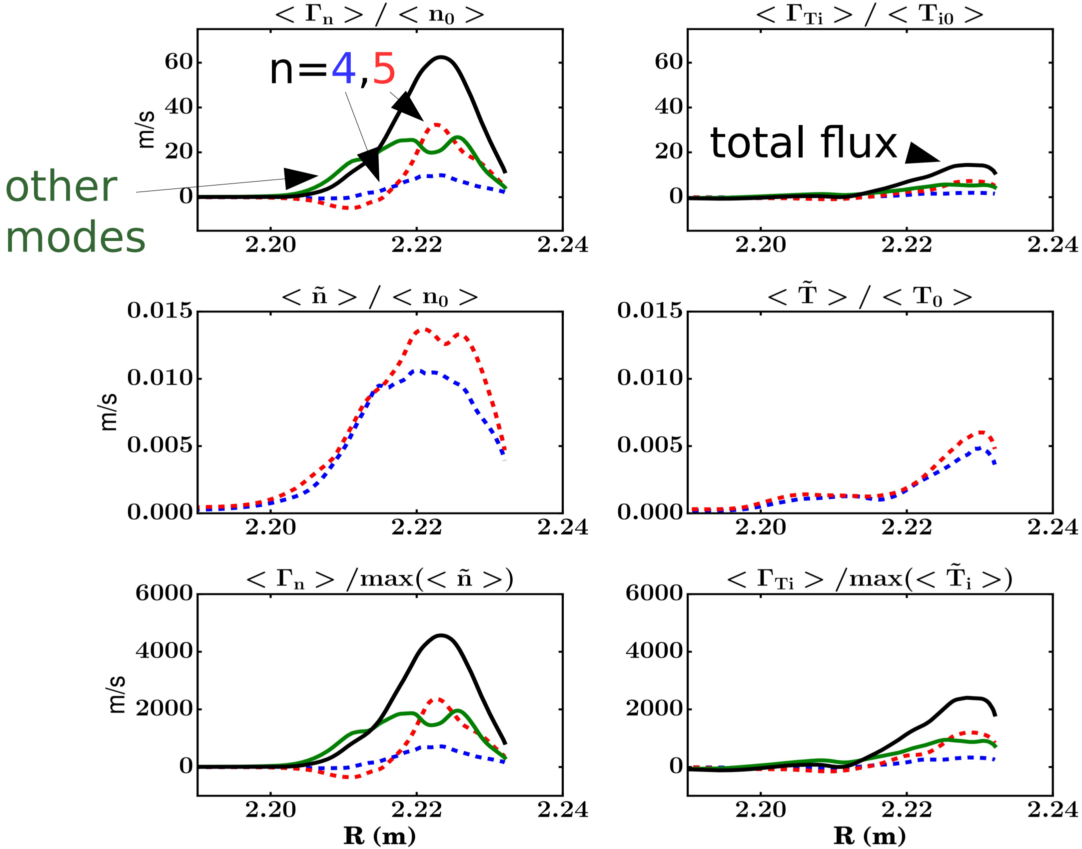
- **The conductive losses are small even with an estimate in the collisionless limit**

$$L_\| \simeq 10^3\ m, \quad L_\perp \simeq 0.03\ m,$$

$$\chi_\| \simeq 10^8\ m^2/s, \quad \chi_\perp \simeq 1\ m^2/s,$$

$$v_{Te} \simeq 10^6\ m/s$$

Phase and amplitude differences explain convective transport



Time- and flux-surface averages from 0.03-0.09 ms

- **Fluctuation-induced density transport is much larger than thermal transport**
- **Density perturbations are larger than temperature**
- **Flux difference must be due to the relative phases**

$$\langle \Gamma_f \rangle = \left\langle \tilde{f} \tilde{v}_n \right\rangle$$

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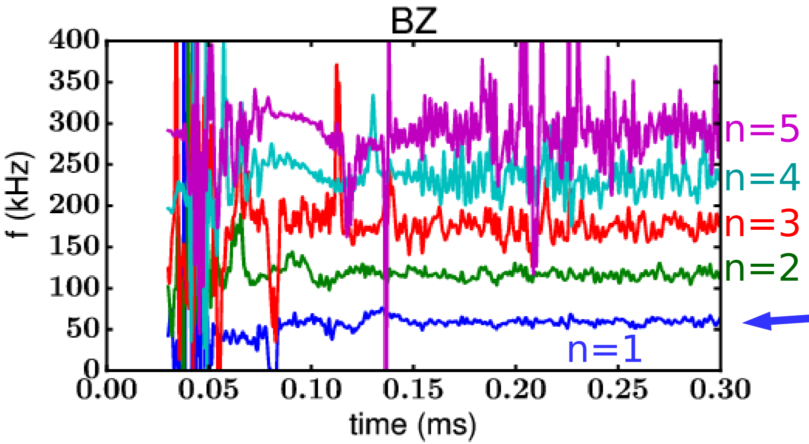
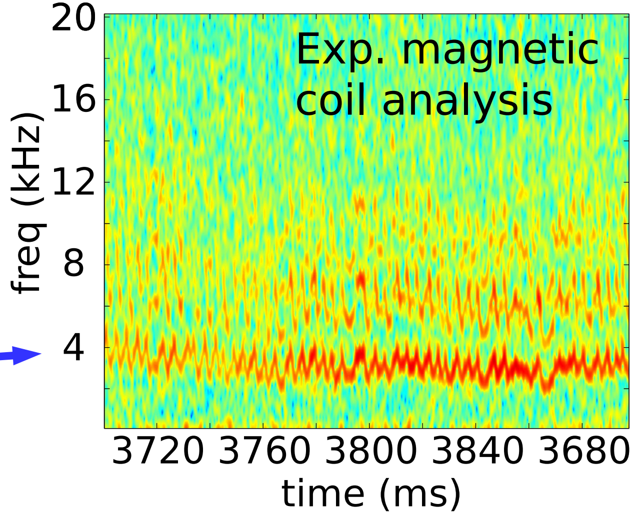
Frequency analysis shows simulated rotation to be much faster than observations

Simulation: probe at R=2.22m

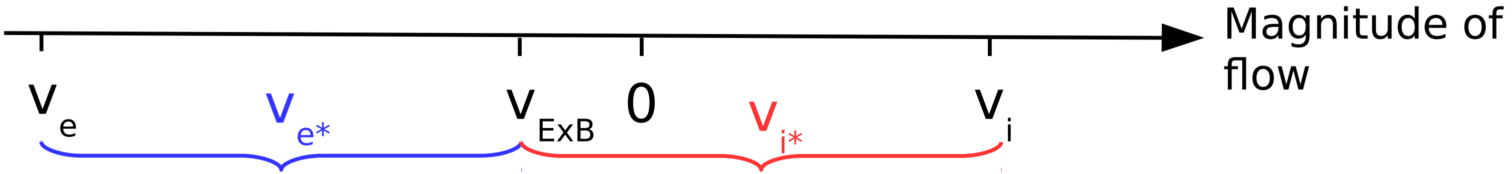




- **Need to include two-fluid and/or resistive wall in model?**
- **Two-fluid effects modify frequencies [e.g. Coppi PF 64; King PoP 14]**

Open questions remain

- **Two-fluid effects change frequencies through differential electron motion**
  - clear need to incorporate → **Does this produce frequencies consistent with experiment?**



- **Can we distinguish broadband and edge harmonic oscillation (EHO) perturbations with modeling?**
  - Likely requires at least two-fluid modeling as perturbations rotate in different directions
- **Can we predict power flow from perturbations?**
  - Constrained by experiment
  - Currently model uses enhanced dissipation for computational practicality without heating → power prediction requires realistic dissipation and heating

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- **Progress required:**
  - Accurate equilibrium from experimental data
  - Verification to understand accuracy requirements [King PoP 2016]
  - Extrapolation of profiles into SOL region [King PoP submitted]
  - Close collaboration with DIII-D team

- QH-mode is accompanied by low-n perturbations
- Low-n dynamics during QH-mode discharges can be modeled with extended-MHD
- Extended-MHD codes start from reconstructed state
- Low-n dynamics during QH-mode discharges can be modeled with extended-MHD
- Access to QH-mode operation regime requires control of the flow profile
- Simulations are performed with and without steady-state flow
- Perturbation amplitudes saturate to a quasi-turbulent state in simulations with steady-state flow
- Without steady-state flow, high-n perturbations become dominant without saturation
- Importance of steady-state flow to low-n saturation is consistent with experimental observations
- Returning to simulations with steady-state flow, pressure evolution resembles quasi-turbulent state
- Low-n dynamics during QH-mode discharges can be modeled with extended-MHD
- Characterization of transport requires understanding of boundary conditions
- Pressure and current density profiles are flattened leading to saturation
- Experimental observations indicate that QH-mode dynamics drive particle transport
- Magnetic field-lines become stochastic within the pedestal region
- Flattening of density profile is large compared to temperature profile
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- Timescale estimates show convective transport dominates conductive losses
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- Open questions remain
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We use NIMROD to model the MHD evolution of low-n perturbations

$$\frac{dn}{dt} = -n\nabla\cdot\mathbf{v} + D_n\nabla^2 n$$

Sovinec et al., JCP 2004

$$m_i n\frac{d\mathbf{v}}{dt} = \mathbf{J}\times\mathbf{B} - \nabla p - \nabla\cdot\mathbf{\Pi}_{||} - \nabla\cdot\nu_\perp m_i n\mathbf{W}$$

$$\mathbf{\Pi}_{||} = \nu_{||}m_i n\left(\hat{\mathbf{b}}\hat{\mathbf{b}} - \frac{1}{3}\mathbf{I}\right)\left(3\hat{\mathbf{b}}\cdot\nabla\mathbf{v}_\alpha\cdot\hat{\mathbf{b}} - \nabla\cdot\mathbf{v}_\alpha\right)$$

$$\frac{n}{\Gamma-1}\frac{dT}{dt} = -nT\nabla\cdot\mathbf{v} + \nabla\cdot\left[n\left(\chi_\perp + \chi_{||}\hat{\mathbf{b}}\hat{\mathbf{b}}\cdot\right)\nabla T\right]$$

$$\frac{\partial\mathbf{B}}{\partial t} = -\nabla\times\mathbf{E} \qquad \mathbf{E} = -\mathbf{v}\times\mathbf{B} + \eta\mathbf{J}$$

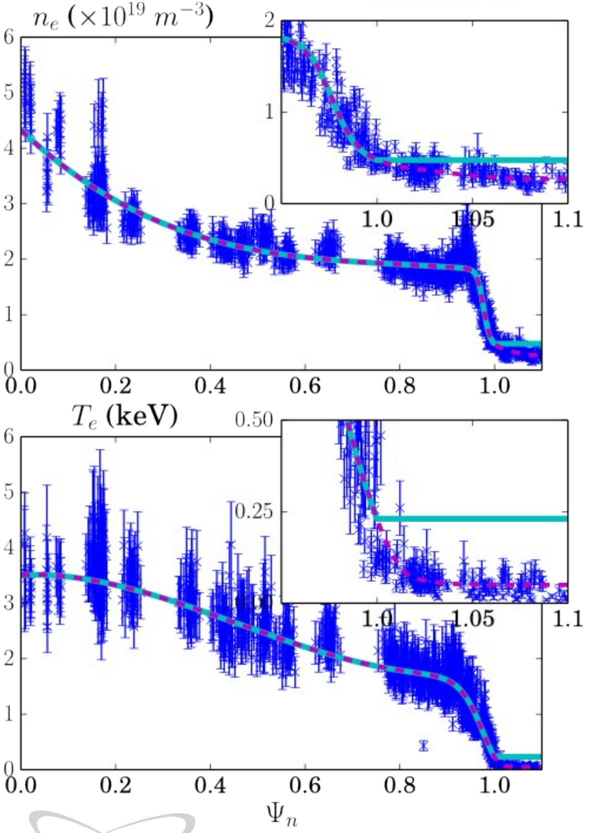
$$\eta,\nu_\perp \propto T^{-3/2} \quad S_{core} = 1.1\times10^6$$

$$\nu_\perp = \chi_\perp = D_n = 1m^2/s$$

$$\mathbf{J} = \nabla\times\mathbf{B} \qquad p_\alpha = nT_\alpha$$

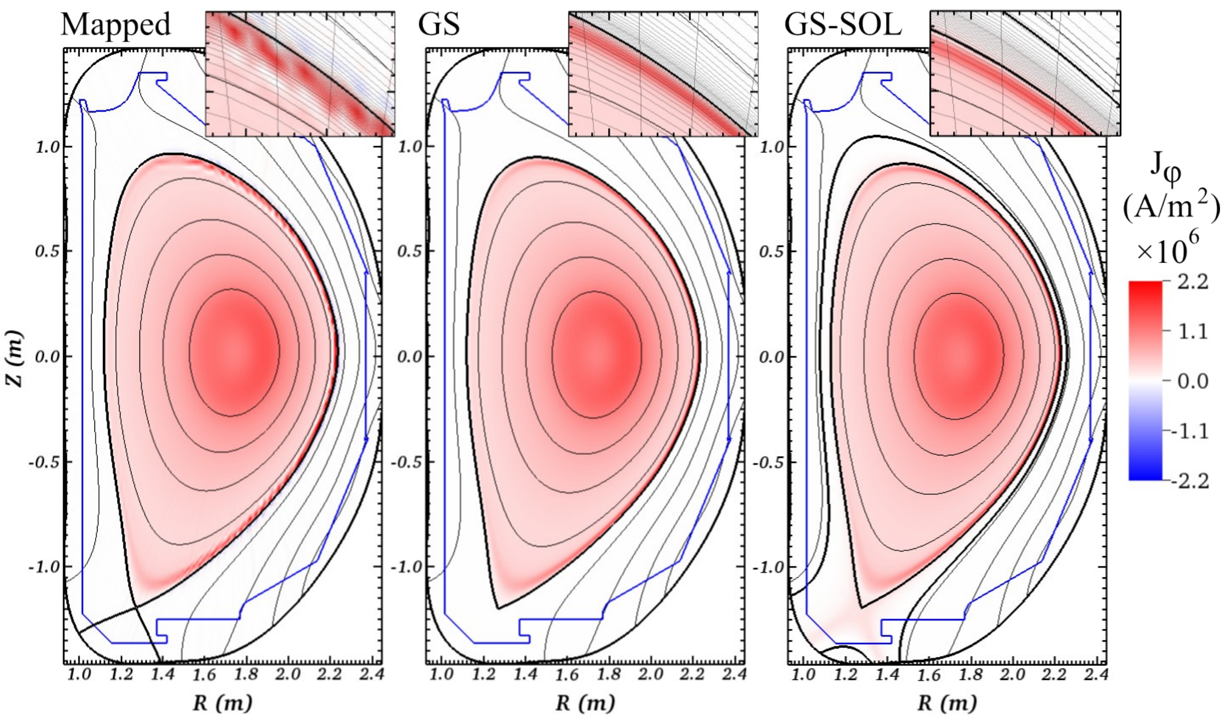
$$\nu_{||} = 1\times10^5 m^2/s \quad \chi_{||} = 1\times10^8 m^2/s$$

For these edge cases, reconstruction is modified to include SOL profiles



- **Non-zero pressure gradient produces non-zero current at LCFS**
  - Reconstruction: discontinuous p
  - Experiment: continuous p
- **Use Thomson measurements to guide extrapolation of p outside LCFS**
- **Resolve Grad-Shafranov Eqn → enforce force balance**

Including SOL profiles eliminates problematic discontinuous current at LCFS



- **Divertor current limited by ion sat. current [~10^5 A/m^2]**
- **Linear stability not affected by inclusion of SOL profiles**
- **Perturbation dynamics are not impacted by SOL footpoints**
- **See King PoP submitted**