Nonlinear modeling of QH-mode with NIMROD

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Motivation / Primary Result

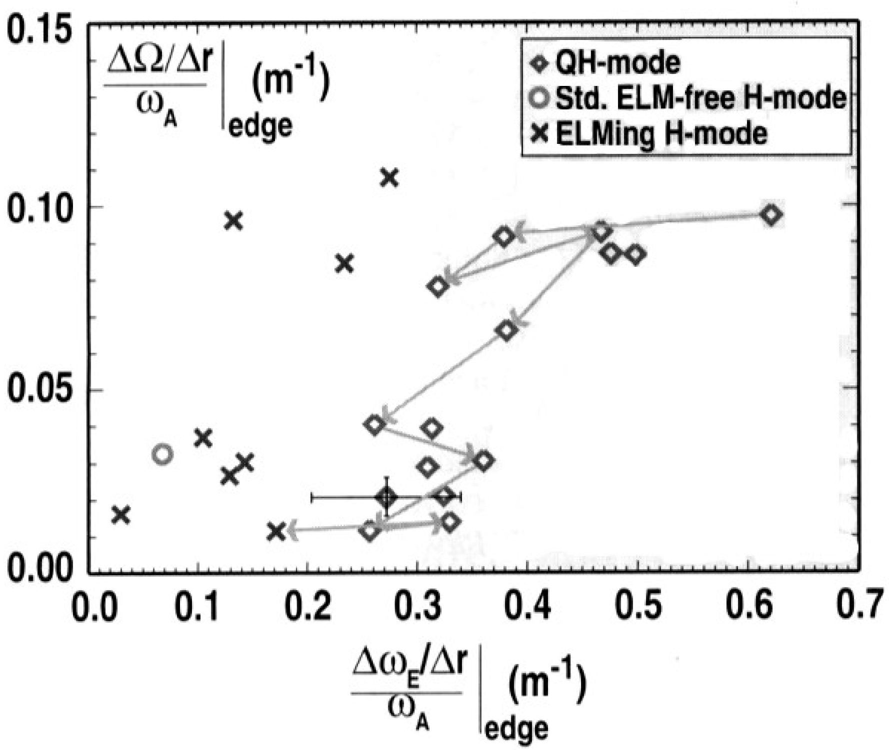
- Low-n dynamics during QH-mode discharges can be modeled with extended-MHD.
- We use the nonlinear, extended-MHD code NIMROD to study QH-mode discharges on DIII-D with broadband MHD.
- Our simulations find a turbulent-MHD state that drives transport in the pedestal.

Overview

- QH-mode background
- General reconstruction considerations
  - How do we determine the initial conditions for NIMROD?
  - Consideration of SOL profiles to avoid a discontinuous current
- Progress on QH-mode (broadband MHD) modeling
  - Nonlinear cases showing saturation
  - Current conclusions and future directions

Tokamak operation with edge harmonic oscillations (EHO) provides access to a quiescent H-mode regime [Burrell 2012]

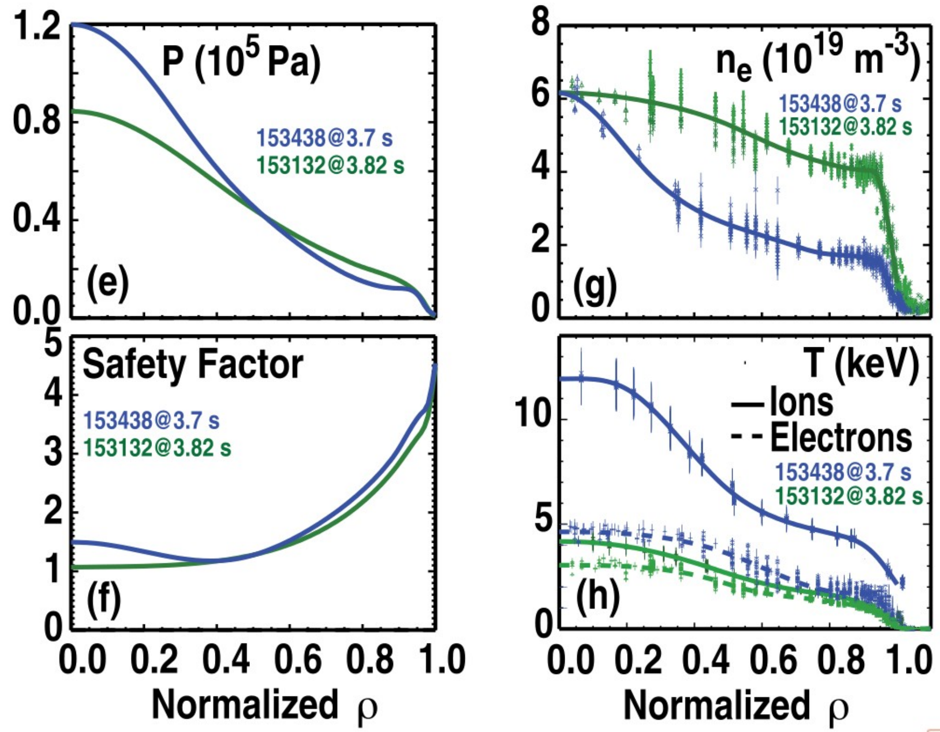
- EHO/broadband MHD: a small toroidal mode number (n~1-5) perturbation localized to the pedestal region [Burrell et al., PoP **19** 056117 (2012) and refs within]
- Access to QH-mode operation regime requires control of the flow profile
- In particular, experimental observations indicate that the ExB flow shear is a key component in the generation of QH-mode [Garofalo et al., NF **51** 083018 (2011)]



from Garofalo 2011

MHD dynamics drive particle transport

- Fluorine impurity transport studies find QH-mode provides as much particle transport as 40 Hz ELMs
- Typically, core temperatures are increased with EHO



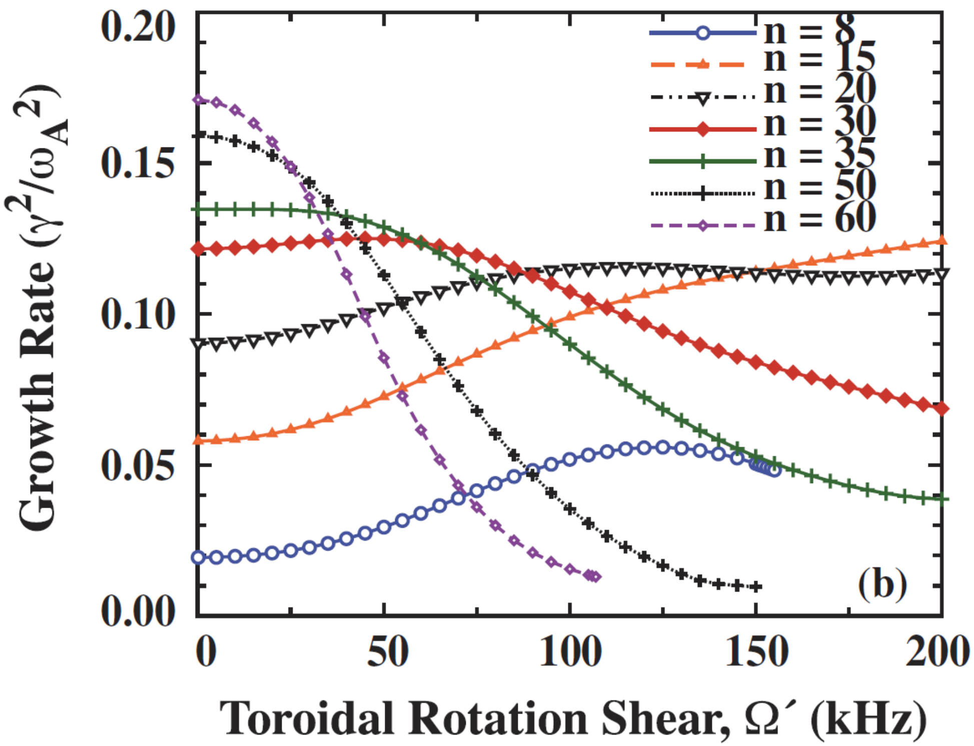
Comparison discharges on DIII-D from Garofalo PoP **22** 056116 2015

Green – ELMing H-mode

Blue – QH-mode with EHO

Physical mechanisms of QH-mode are not fully understood

- Linear MHD calculations suggest EHO may be a saturated kink-peeling mode partially driven by flow-profile shear [Snyder et al., NF **47** 961 (2007)]
  - Flow shear drives low-n modes and stabilizes high-n modes (see figure)
- Hypothesis: the saturated mode drives particle and thermal transport to maintain steady state pedestal profiles
- Why NIMROD?
  - Low-n mode requires global computations
  - Can model realistic x-point geometry
  - Drift stabilization built into model
  - Nonlinear capabilities



ELITE results from Snyder 2007

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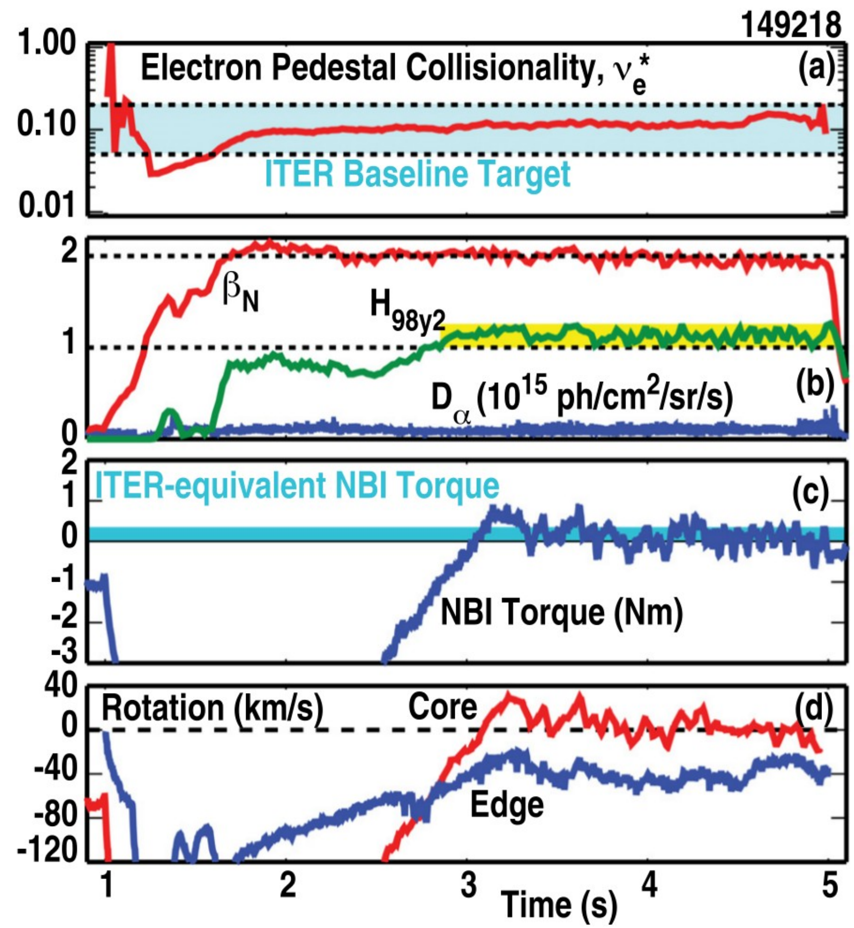
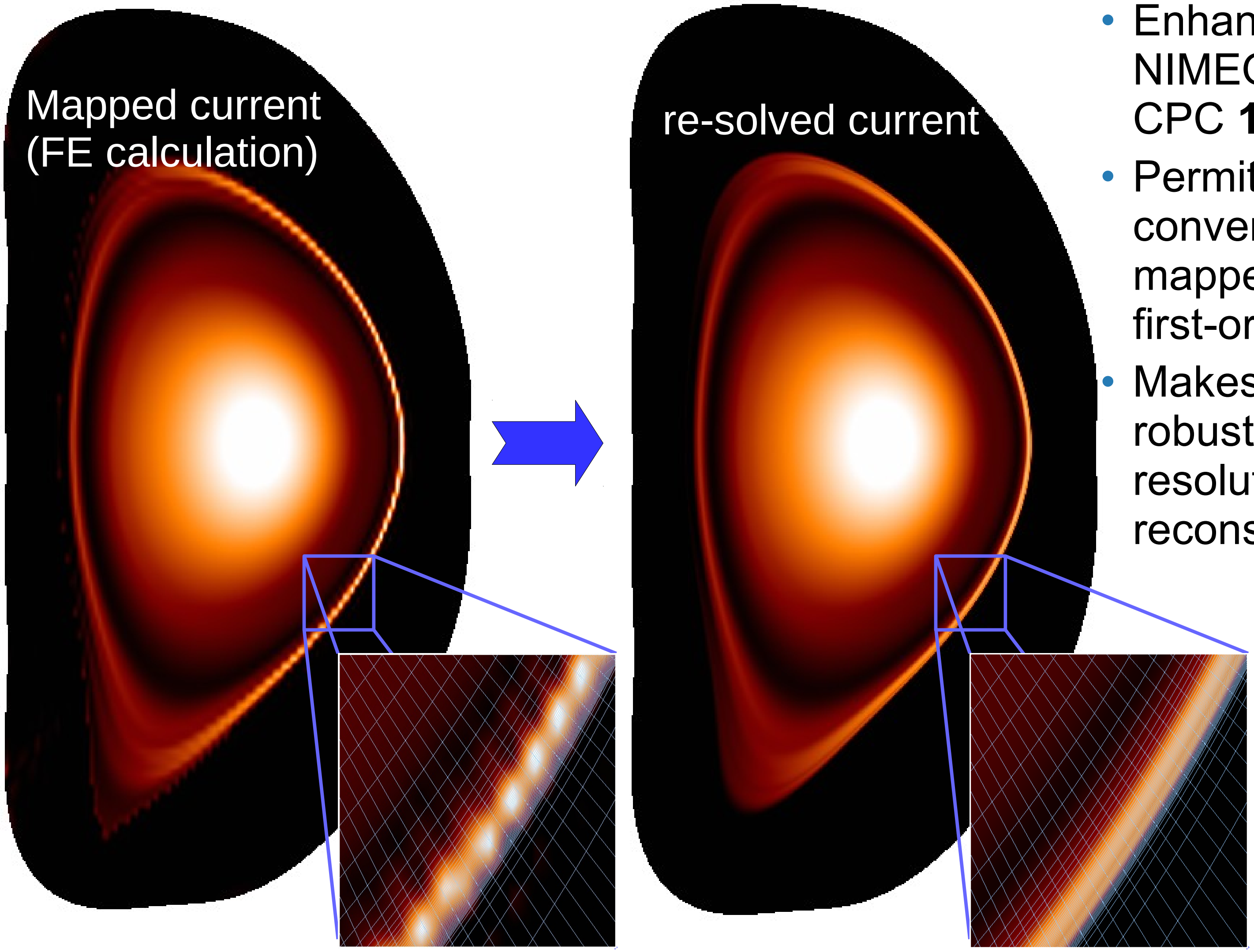
Extended MHD codes start from state late in time within discharge

- Largest balance is JxB=∇p for magnetized plasmas
- Axisymmetric tokamak evolution is slow evolution of this force balance
- Experimentally: *Reconstructions* used to describe evolution
  - Use Grad-Shafranov solution constrained by experimental measurements to describe magnetic geometry and shape: EFIT dominant code
  - Routinely perform transport analysis to understand sources and fluxes from state to state
- How should extended MHD codes best model experiment given this paradigm?
  - Requires understanding of reconstruction details
  - Ultimate goal: understanding of sources/fluxes eliminates free parameters and provides greatest value



Discharge with EHO from Garofalo 2015

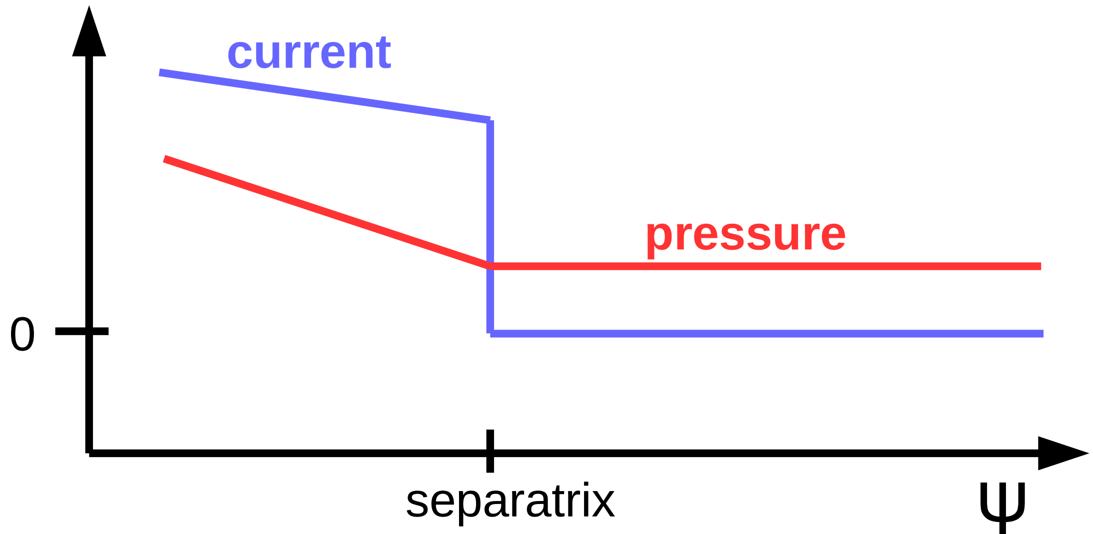
Recent development: re-solve for fields from EFIT for numerical accuracy



- Enhancement to NIMEQ [Howell et al., CPC **185** 1415 (2014)]
- Permits spatial convergence where mapped EFIT fields are first-order accurate
- Makes NIMROD more robust with (low resolution) experimental reconstructions

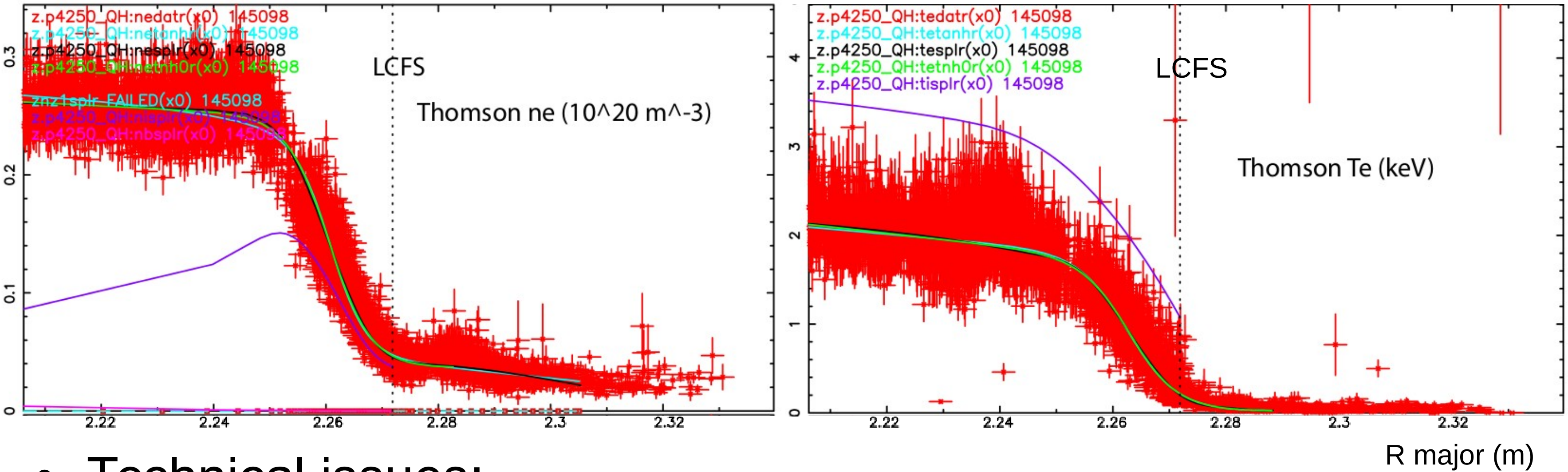
Reconstructions typically contain discontinuous current profiles across the separatrix

- Beyond separatrix: Current free
  - → No gradients in pressure
- QH-mode: large current drive (lives on the peeling boundary) and thus large discontinuity
  - Discontinuity is problematic for re-solves
  - Discontinuity is problematic for nonlinear NIMROD computations
  - Discontinuity is not physical



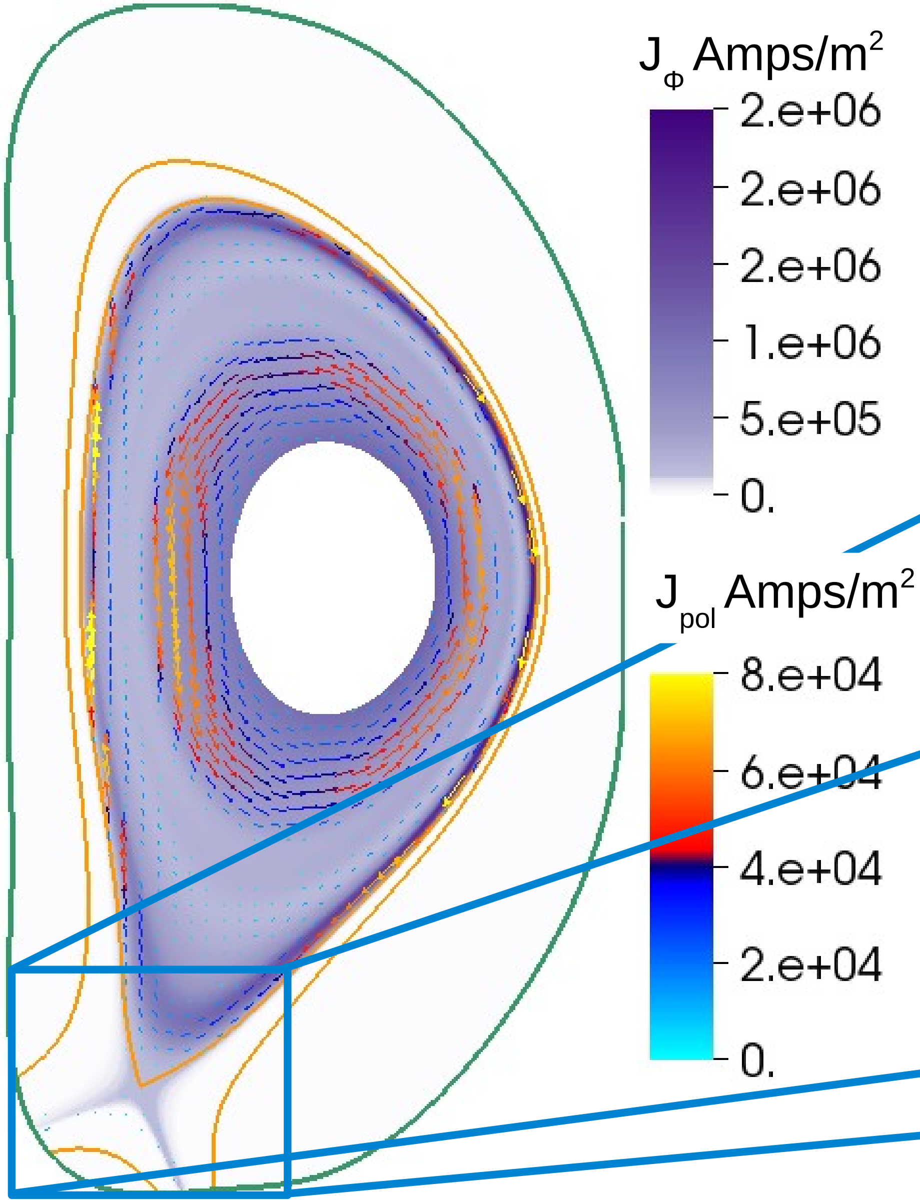
Towards more realistic modeling: Inclusion of SOL currents

- The experimental reconstruction doesn't set the gradient of thermodynamic quantities to zero on the LCFS because <u>they aren't measured to be zero</u>

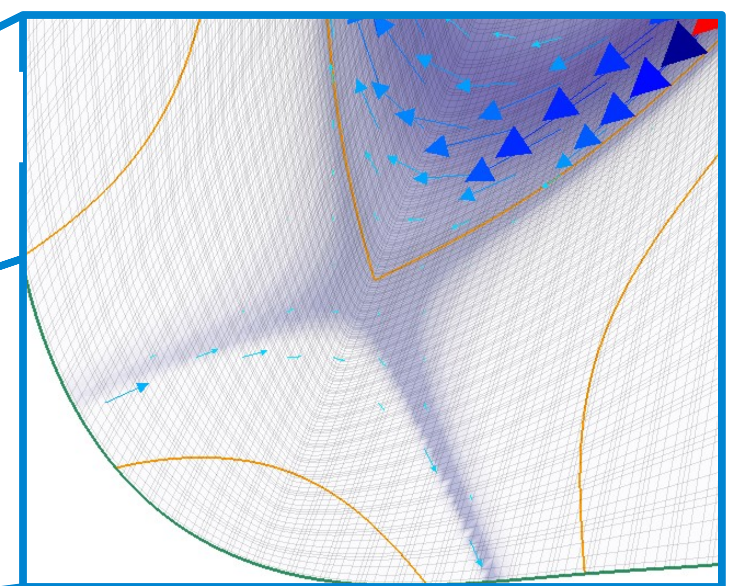


- Technical issues:
  - EFIT profiles only extend to LCFS
  - How do we extrapolate while minimizing free parameters?
  - Result should be as close as possible to known measurements

Currents (and flows) extend into the divertor



- Force balance is enforced through-out the domain
- Divertor current limited to less than the ion saturation current [~10^5 A/m^2 for this case]
- Inclusion of divertor strike points is of interest, but QH-mode edge dynamics are localized elsewhere



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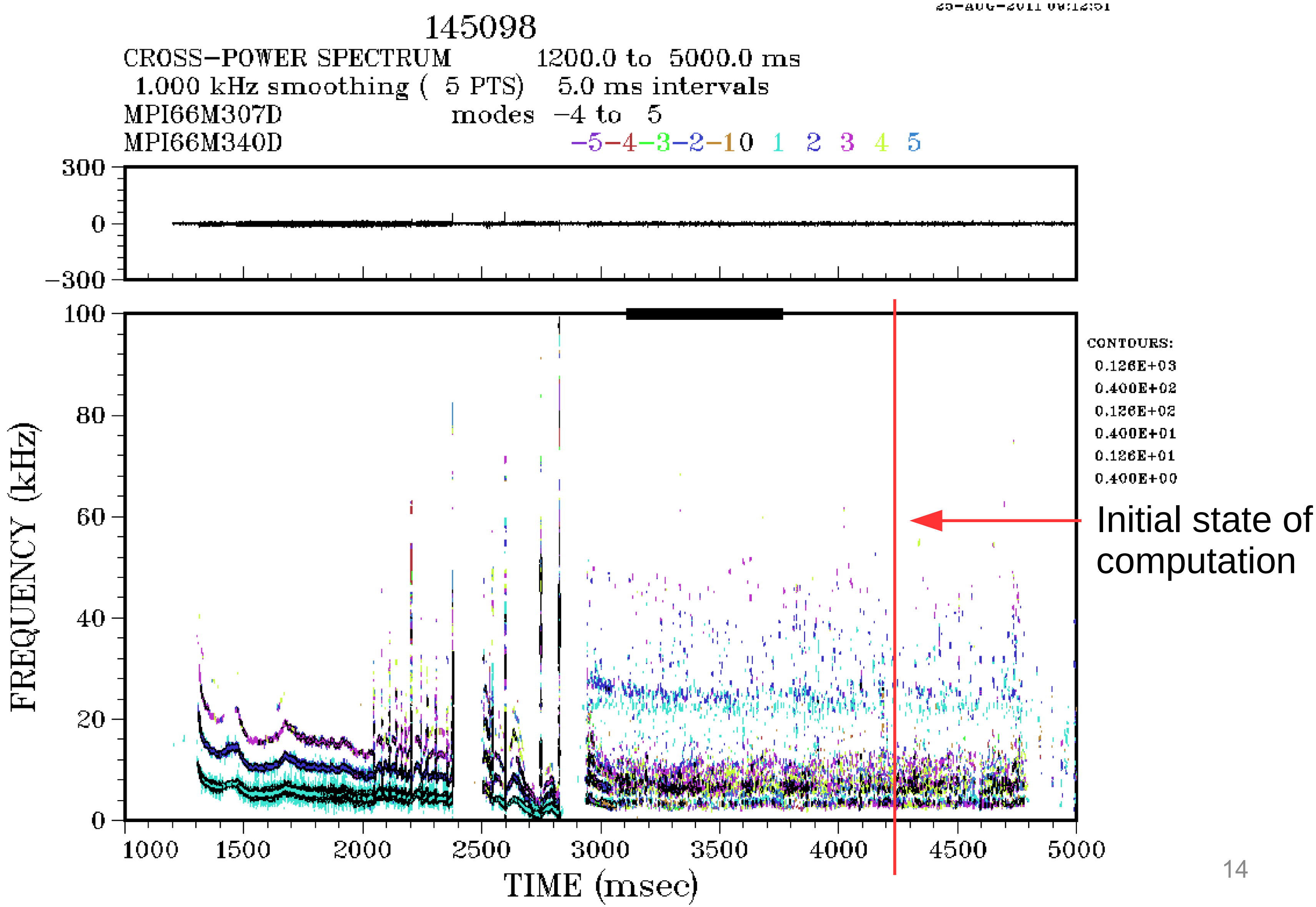
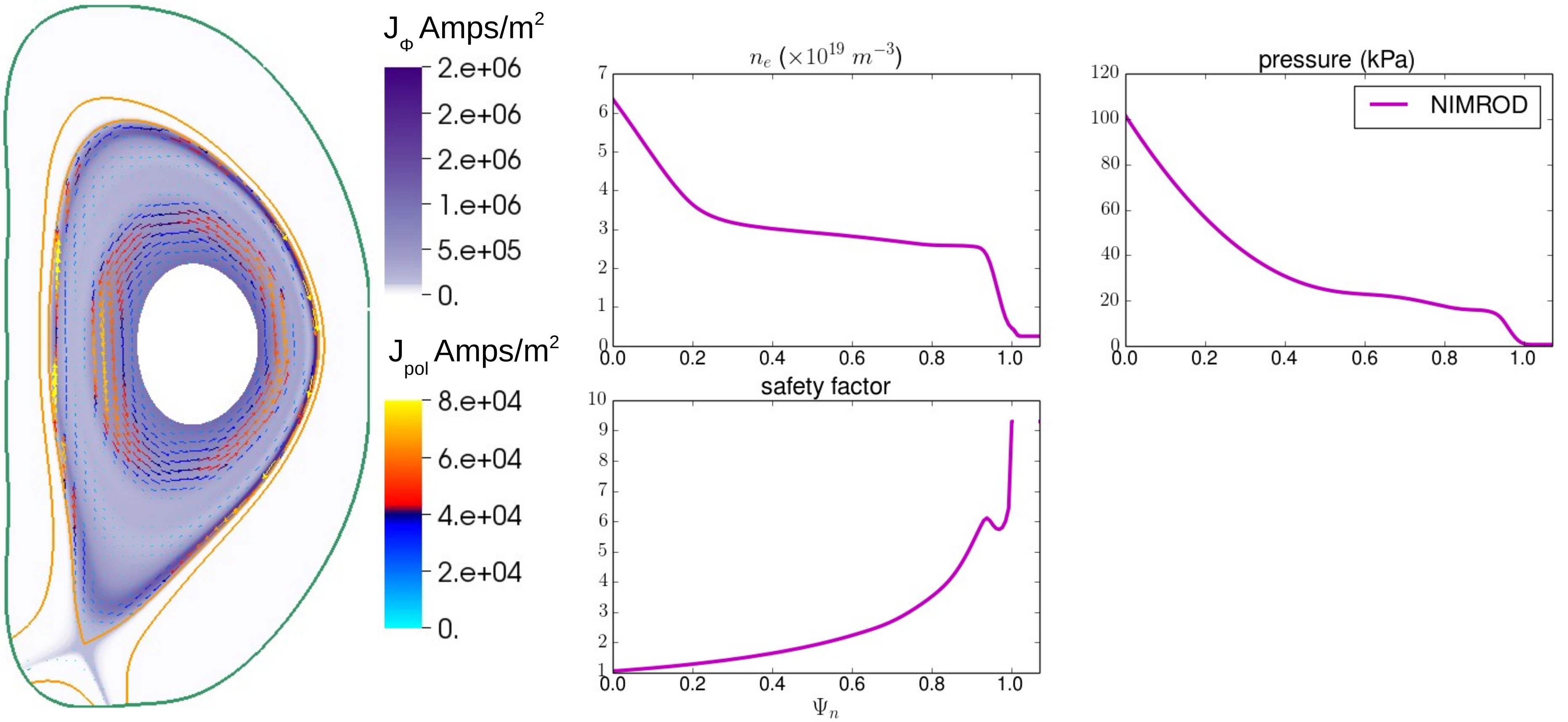
We analyze DIII-D shot 145098 at 4250 ms while the discharge is ELM free with broadband MHD



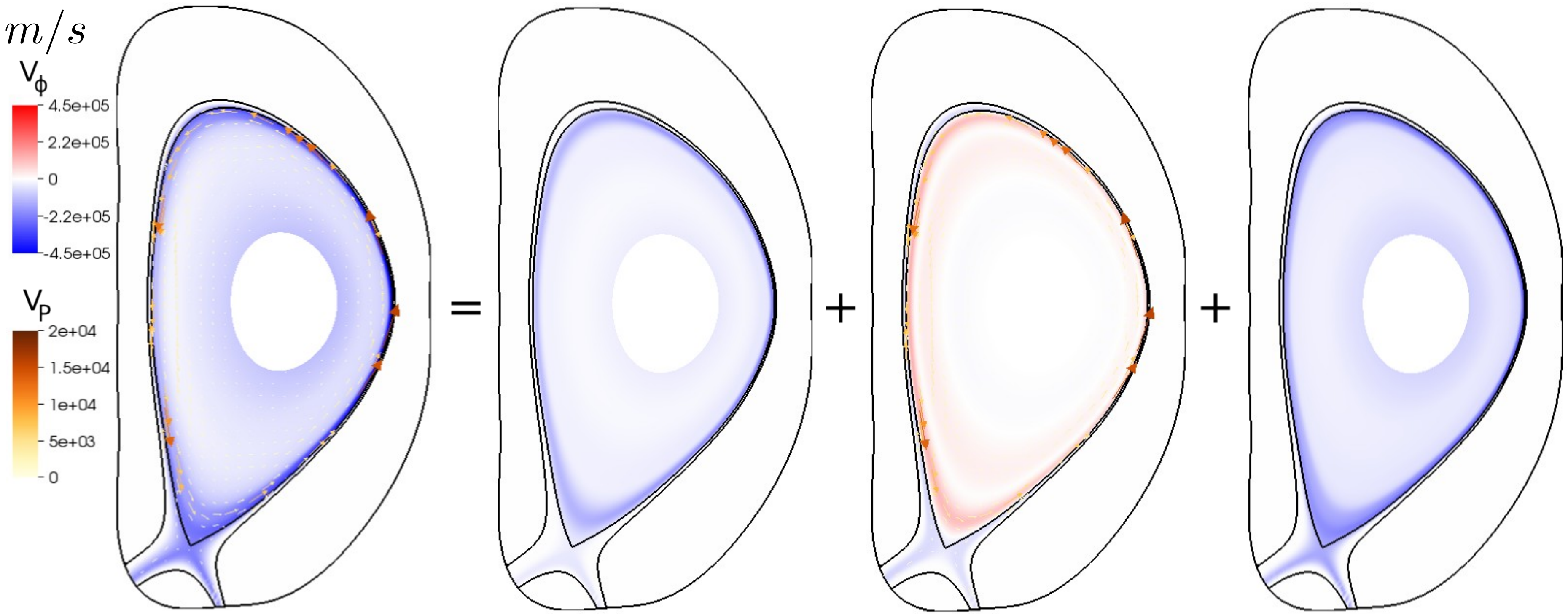
Current density and pressure and q profiles



- Our nonlinear computations use a single-fluid MHD model with anisotropic thermal conduction ($\chi_{\|}/\chi_{\perp}=10^8$) with 24 toroidal Fourier modes
- This computation is initialized from a linear two-fluid computations with full ion FLR effects (ion gyroviscosity and cross heat fluxes) of modes n=1-8 that is run until the largest linear perturbations reaches a magnetic energy amplitude of $2\text{x}10^{-6}$ J

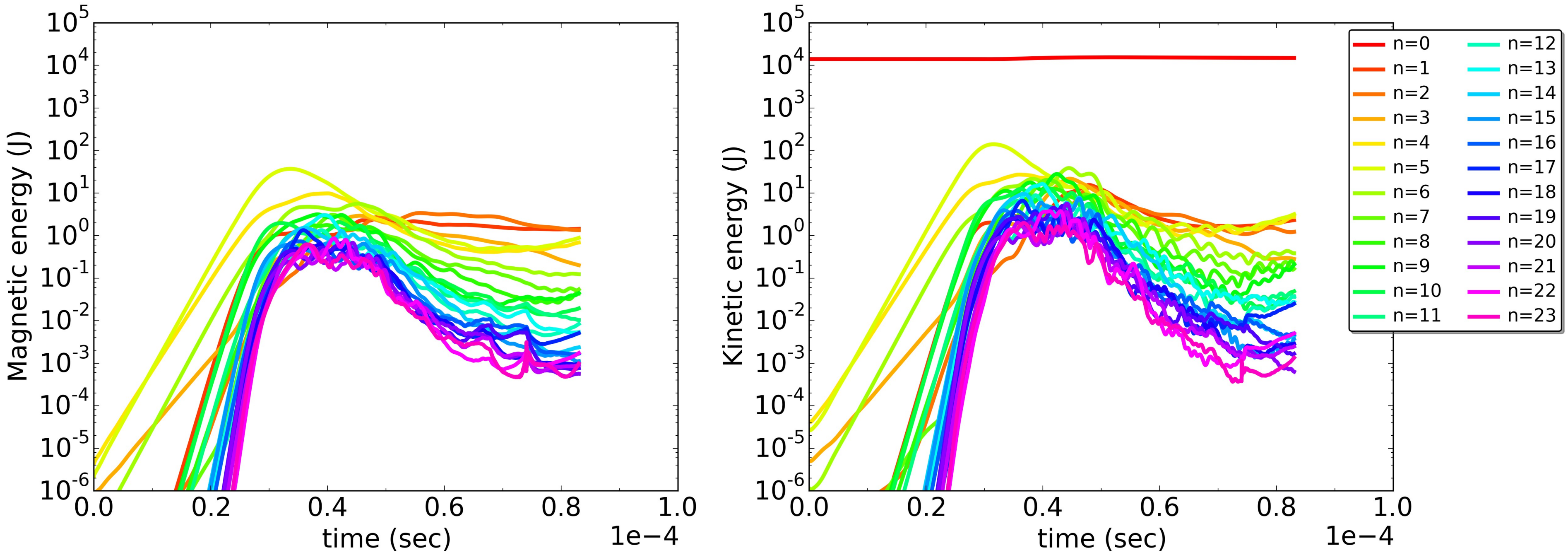
Flow effects are known to be crucial to QH-mode

$$\mathbf{v}_{EQ} = \Omega_{E\times B} R\hat{\phi} + K_p(\psi)\mathbf{B} + \Omega_{\nabla p} R\hat{\phi}$$



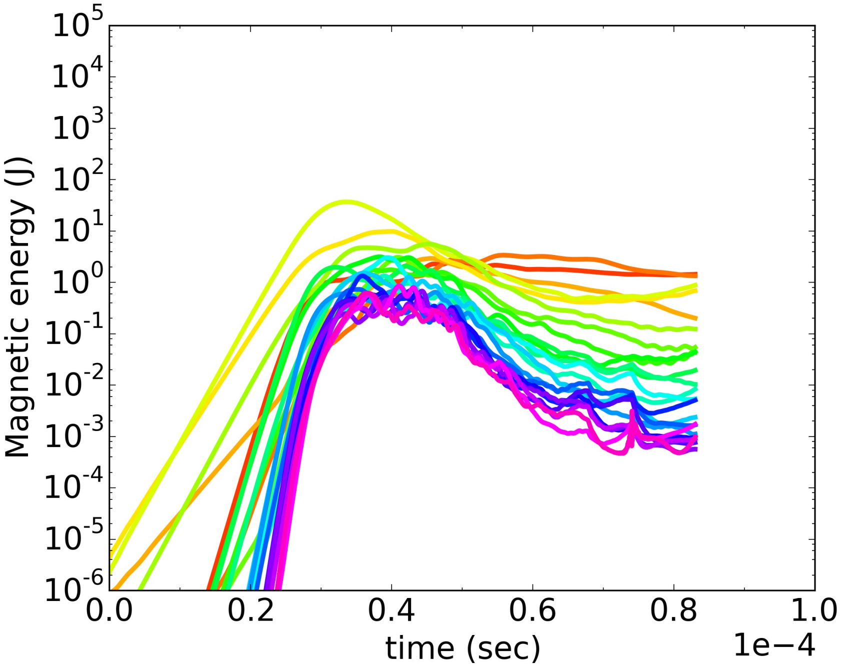
- Flows are specified by the reconstruction up to the separatrix and extrapolated to zero beyond the separatrix at the SOL-current-free interface

Mode amplitudes saturate to a turbulent state

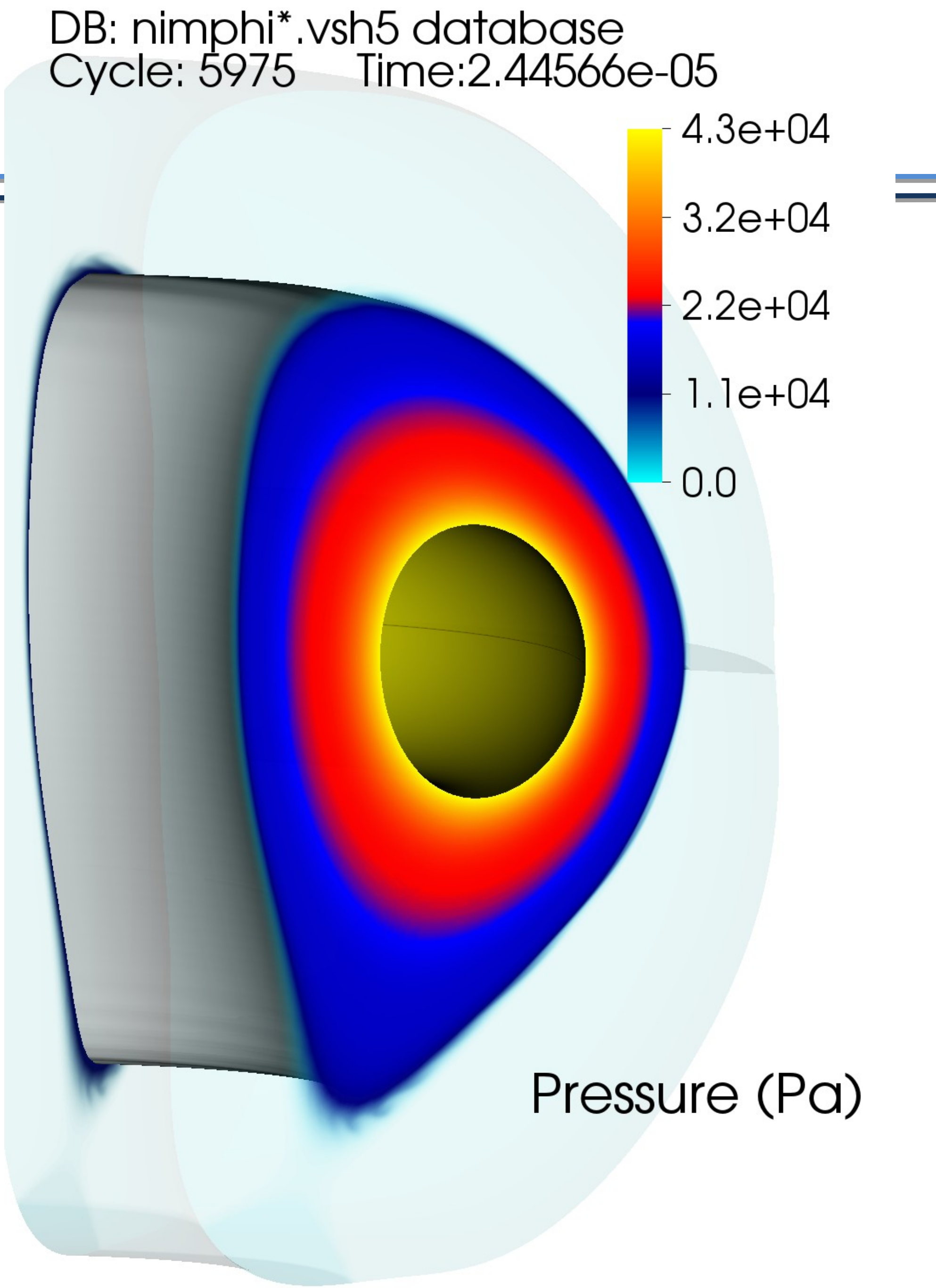


- n=5 dominant (along with n=4) during linear [0-0.3x10^{-4}s] and saturation [0.3-0.5x10^{-4}s] stages
- n=2 dominant (along with n=1) later [0.5-0.9x10^{-4}s]
- Final state of computation has n=1,2,4,5 at comparable amplitudes
- Need to run cases long (ms time scale)
- Still need higher resolution and/or FLR stabilization to resolve higher-n modes

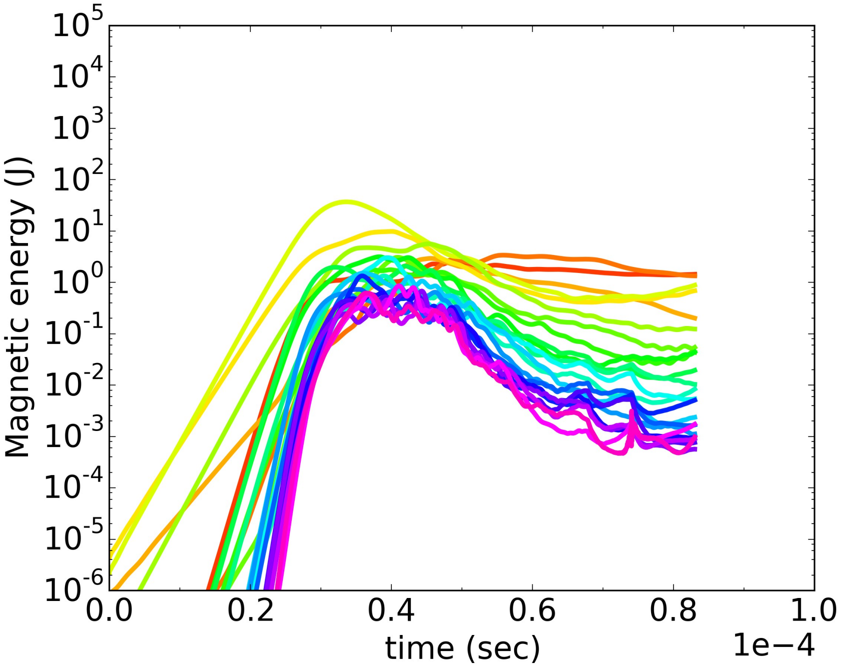
Pressure evolution



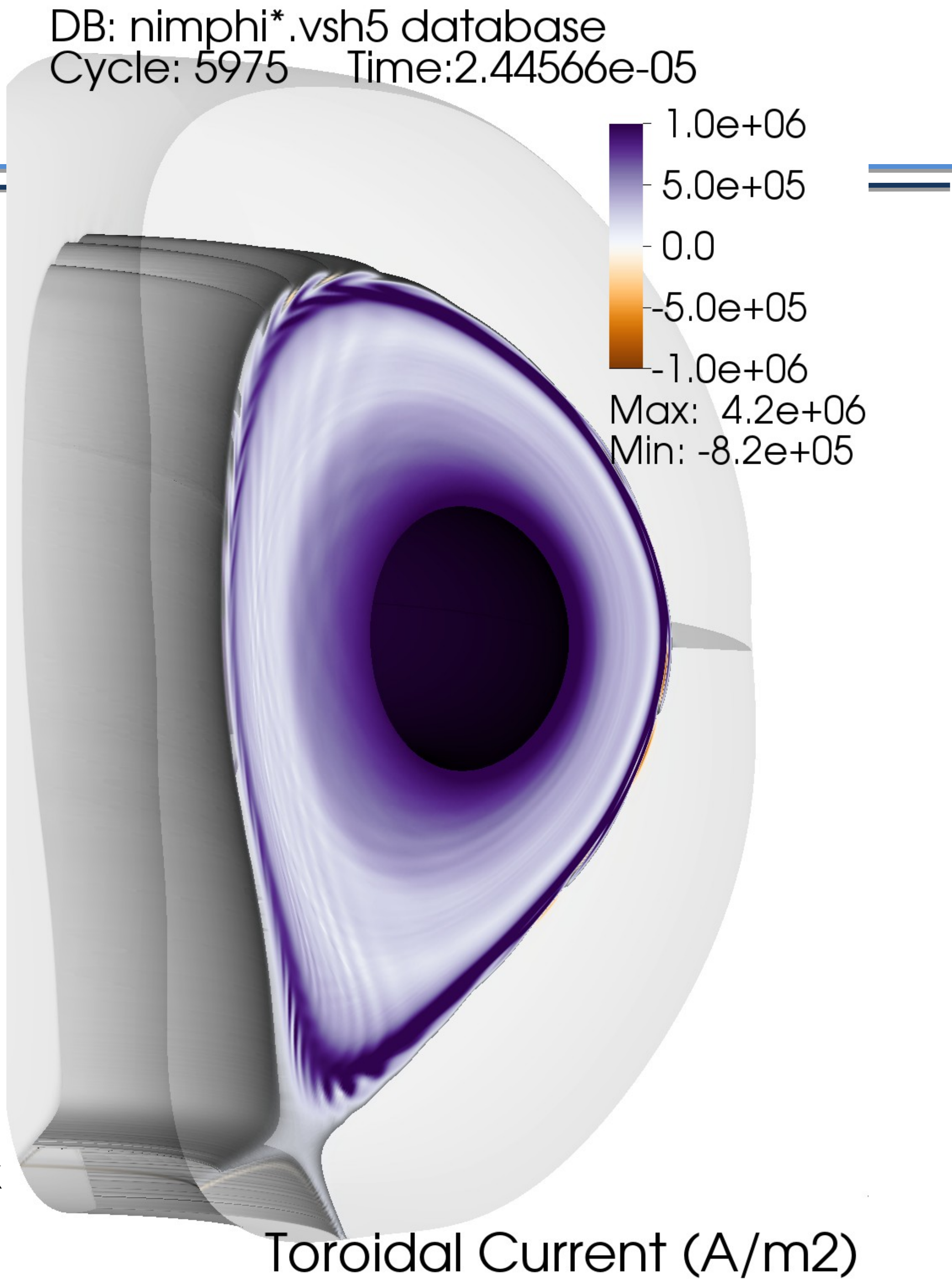
- Movie for t > 2.45×10^{-4}s
- Initially coherent eddies develop
- Turbulent state develops at t > 0.5×10^{-4}s



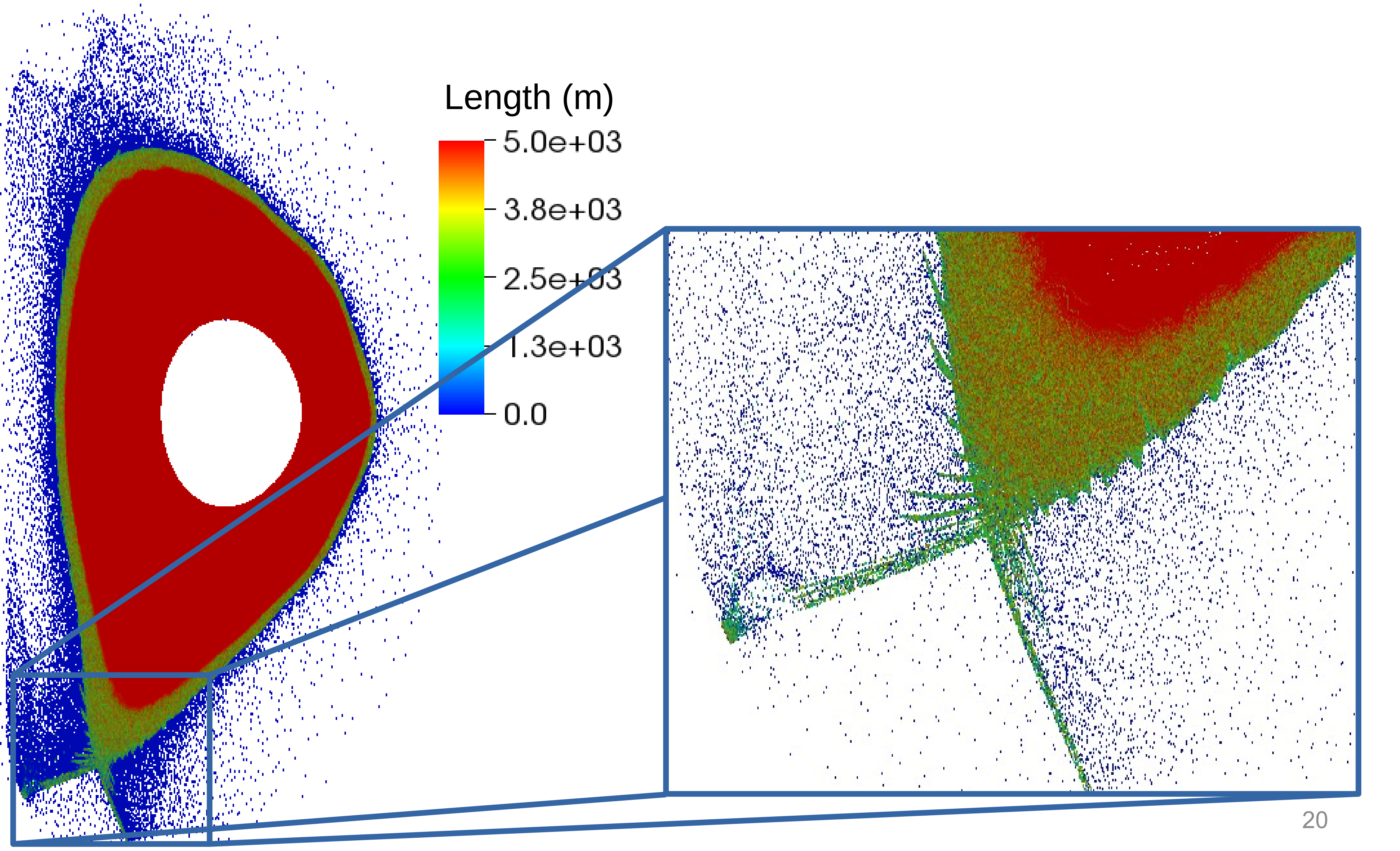
Current evolution



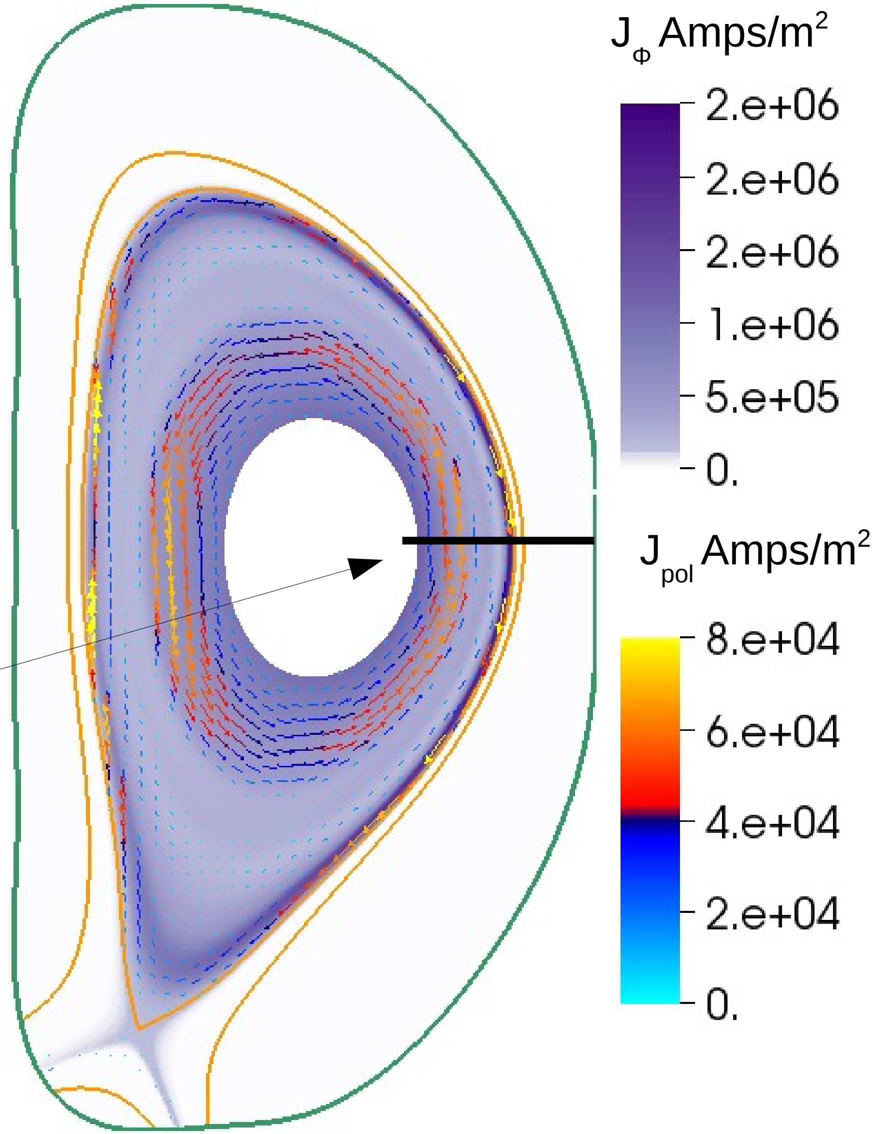
- Movie for t > 2.45×10^{-4}s
- Significant current-density dynamics with reversed current regions
- More resolution is needed to capture dynamics during the peak amplitudes saturation phase



Stochastic fields with homoclinic tangle are present in the simulation

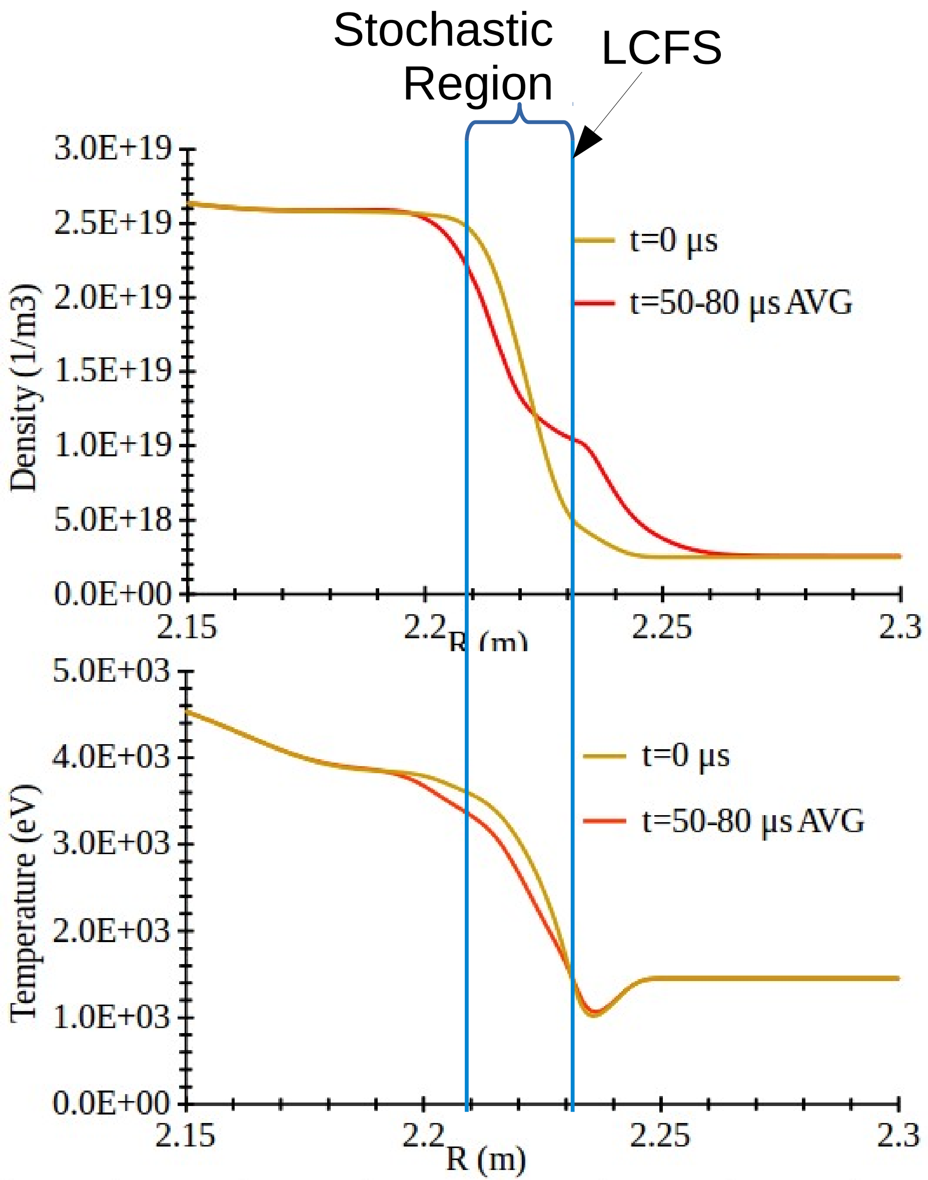


Dynamic profiles are computed with a n=0 line-out on the outboard midplane



Line out for axisymmetric profile plots

Final density transport is large compared to temperature transport

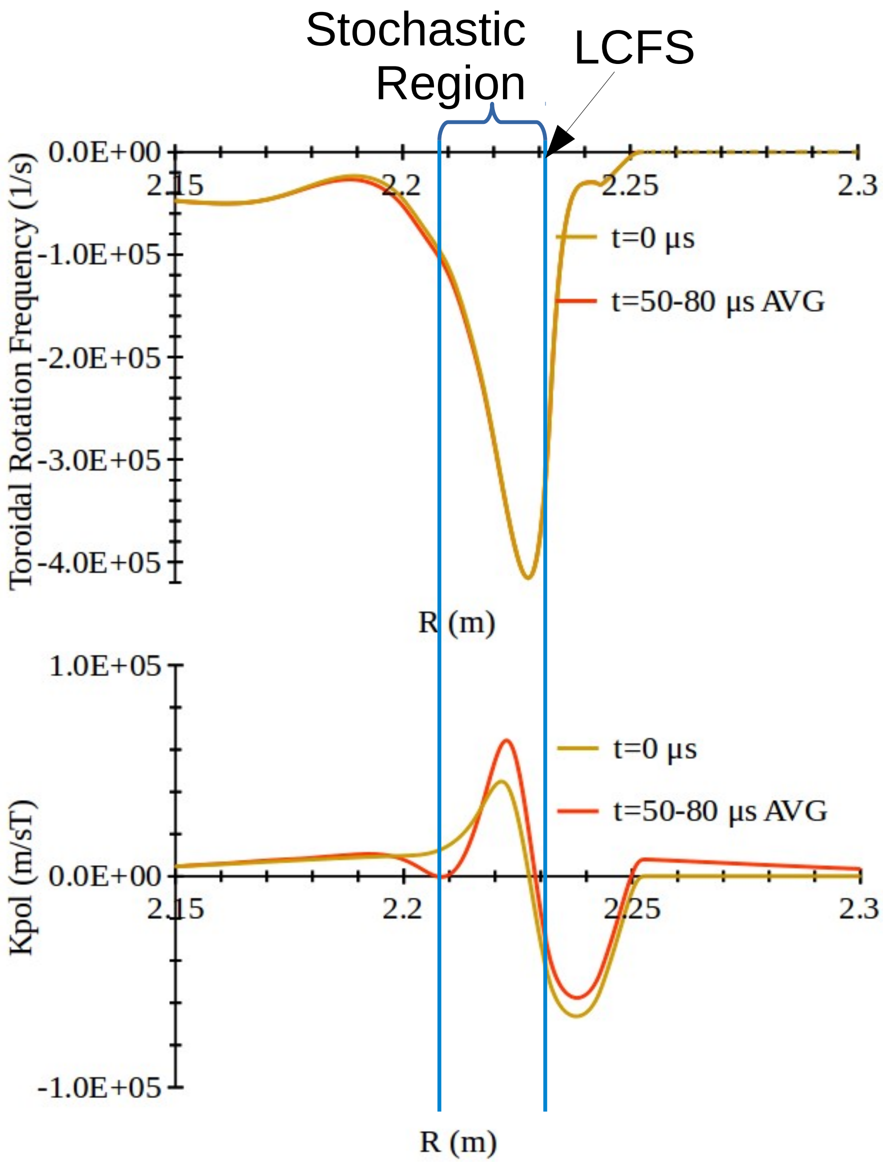


- Result is surprising with stochastic fieldlines and large anisotropic thermal conduction
  - Qualitatively consistent with observations
- Need to investigate phase correlation effects:

$$\Gamma^n = < \tilde{n}\tilde{\mathbf{v}} >$$

$$\Gamma^T = < \tilde{T}\tilde{\mathbf{v}} >$$

Modifications to the flow profiles are small



- Toroidal rotation profile is essentially unchanged
- Poloidal rotation is modestly modified during the peak amplitude phase, but returns to nearly the initial state for $t \geq 7\text{x}10^{-5}$s

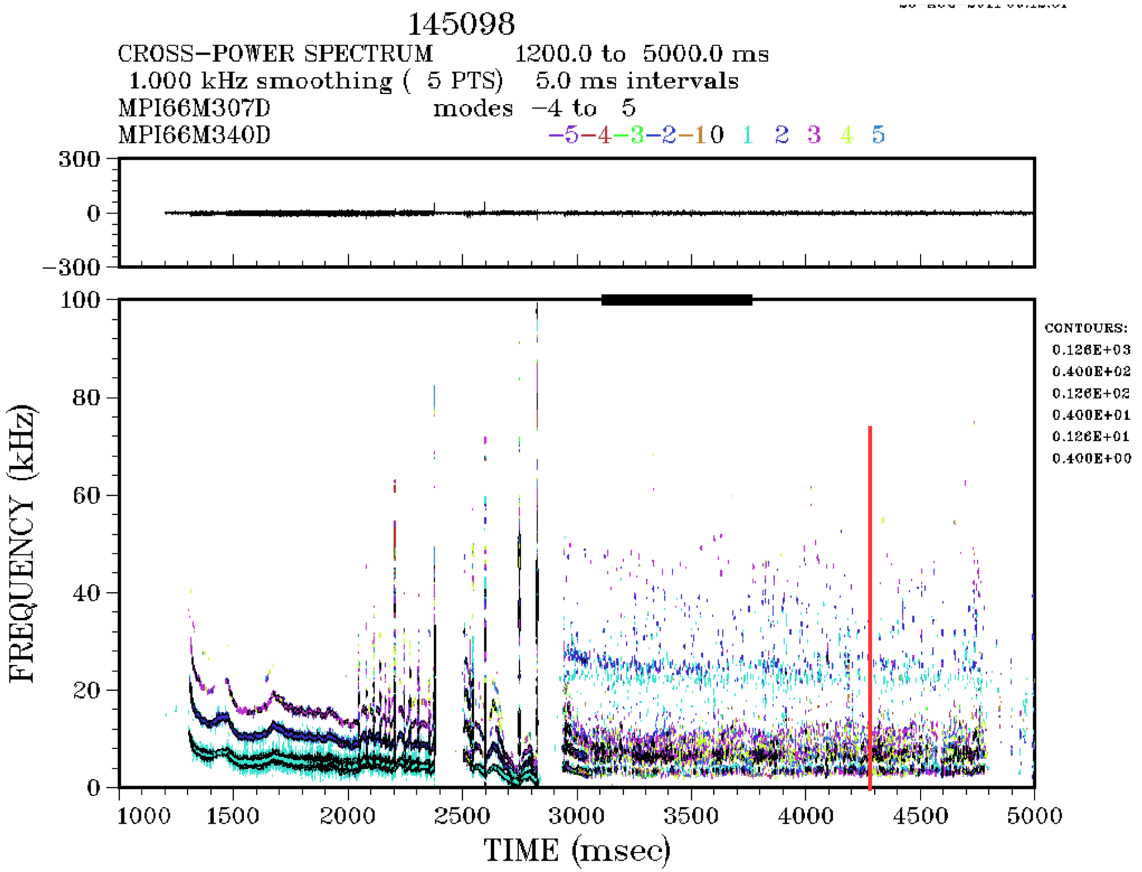
Open questions

- What is the saturation mechanism?
  - Profile modification through relaxation?
  - Coupling to higher-n modes? [Do we need to include FLR drift stabilization?]
- How does the modeled perturbation compare with measurements?
  - Near term: Compare with magnetic coil measurements
  - Long term: Compare with BES measurements
- Can we model the transport caused by the broadband MHD?
  - Related to the saturation mechanism through profile modification
  - Many subtleties here: next slides

Transport effects are subtle but critical

- Reconstructed profiles include the effects of MHD transport
- Implicit transport contained within the reconstruction:

$$\frac{\partial X}{\partial t} = -\nabla \cdot (\Gamma^X_{neoclassical} + \Gamma^X_{turbulence} + \Gamma^X_{MHD}) + S^X = 0$$



Need future studies to characterize MHD transport

- NIMROD models the evolution of 3D, nonlinear perturbations with the extended-MHD model around 2D state
  - These perturbations self-consistently modify the axisymmetric state
  - Major complication: the reconstructed state includes transport from the 3D perturbations
- Currently, we are double counting Γ_{MHD} (once from NIMROD and once in the reconstruction)
- Cancel out Γ_{NIMROD} with an ad-hoc source for a consistent model?
  - Does this preclude saturation through profile modification?
- Can we check that $\Gamma_{NIMROD} = \Gamma_{MHD}$?
  - Need to know all other sources and fluxes to test

Summary

- Initial state is based off an EFIT reconstruction
  - We re-solve the Grad-Shafranov equation with open fieldlines consistent with NIMROD's basis functions
  - Modeling with a SOL eliminates edge current/flow discontinuities
- Preliminary QH-mode results are tantalizing:
  - Nonlinear modeling produces a saturated turbulent-like state
  - Mode preferentially produces density transport
  - Need to run simulation longer and at higher resolution
- Much more to study:
  - Experimental (magnetic coil) comparisons
  - Saturation mechanism
  - MHD transport