Update on EHO modeling: nonlinear cases

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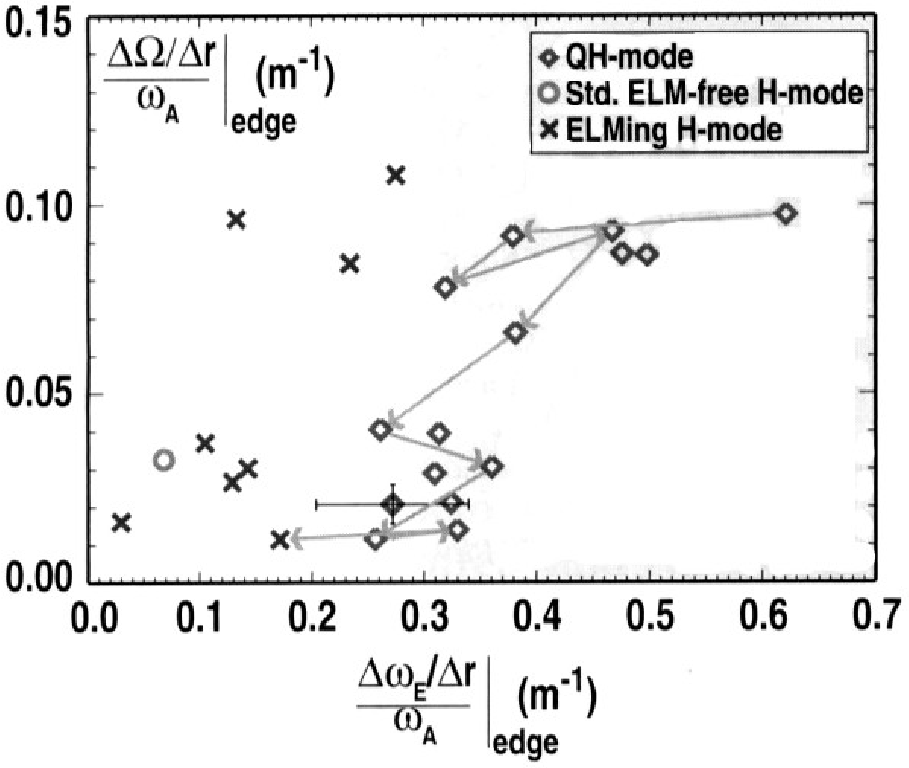
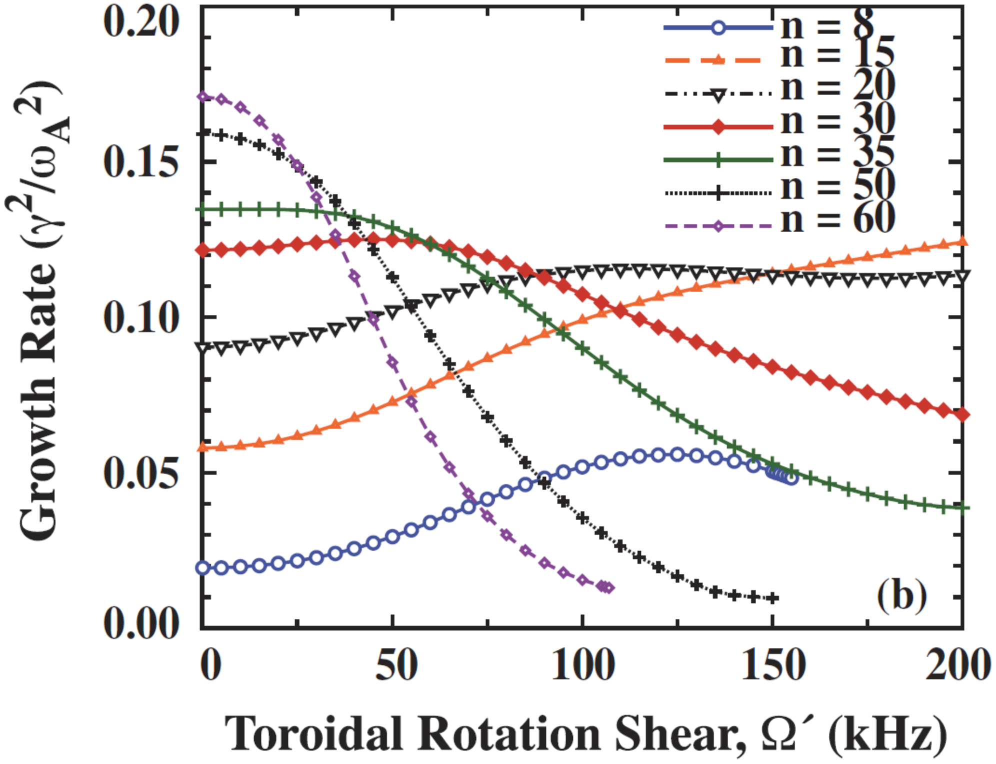
Tokamak operation with edge harmonic oscillations (EHO) provides access to a quiescent H-mode regime [Burrell 2012].

- EHO is characterized by a small toroidal mode number (n~1-5) perturbation localized to the magnetic separatrix.
- Particle transport is enhanced leading to steady-state pedestal profiles.
- Access to the EHO operation regime requires control of the flow profile.
- The aim of this work is to ascertain the role of the flow shear.
- In particular, experimental observations indicate that the ExB flow shear is a key component in the generation of EHO [Garofalo 2011].



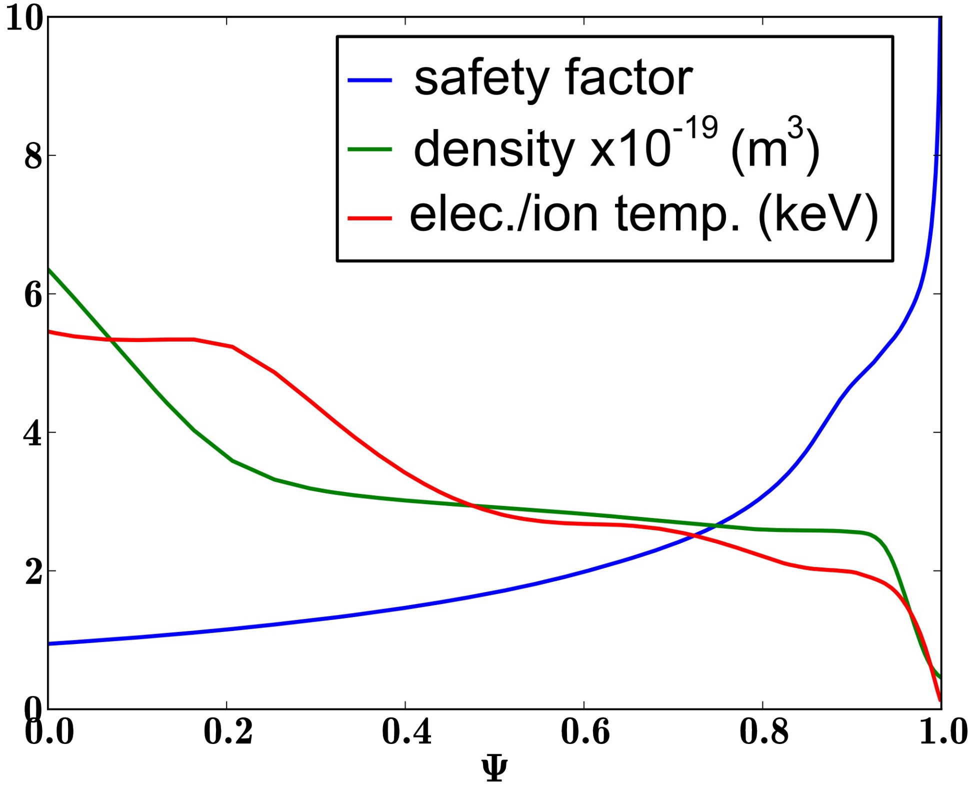
The physical mechanisms of EHO are not fully understood.

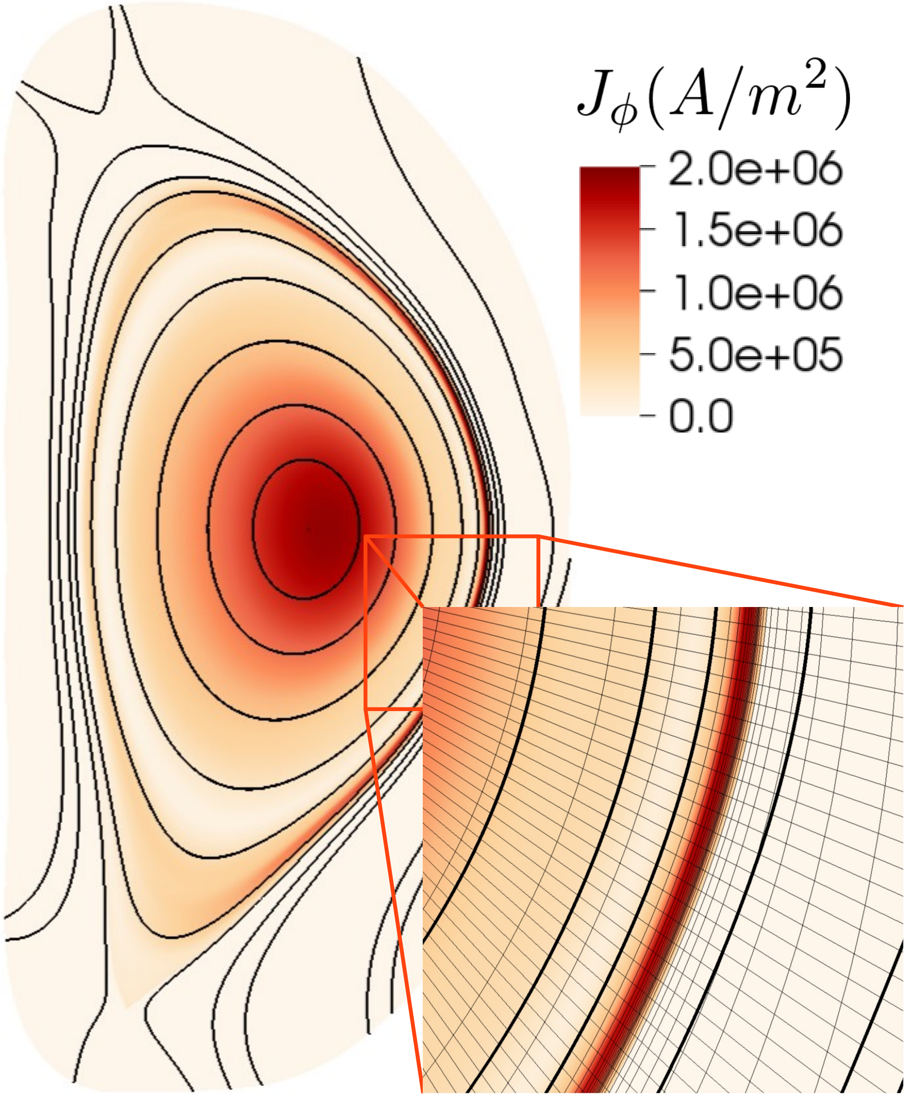
- Linear MHD calculations suggest EHO may be a saturated kink-peeling mode partially driven by flow-profile shear [Snyder 2007].
- It is hypothesized that the saturated mode drives sufficient particle and thermal transport to maintain steady state pedestal profiles.
- Our intent is to investigate the nonlinear physics.



ELITE results from Snyder 2007

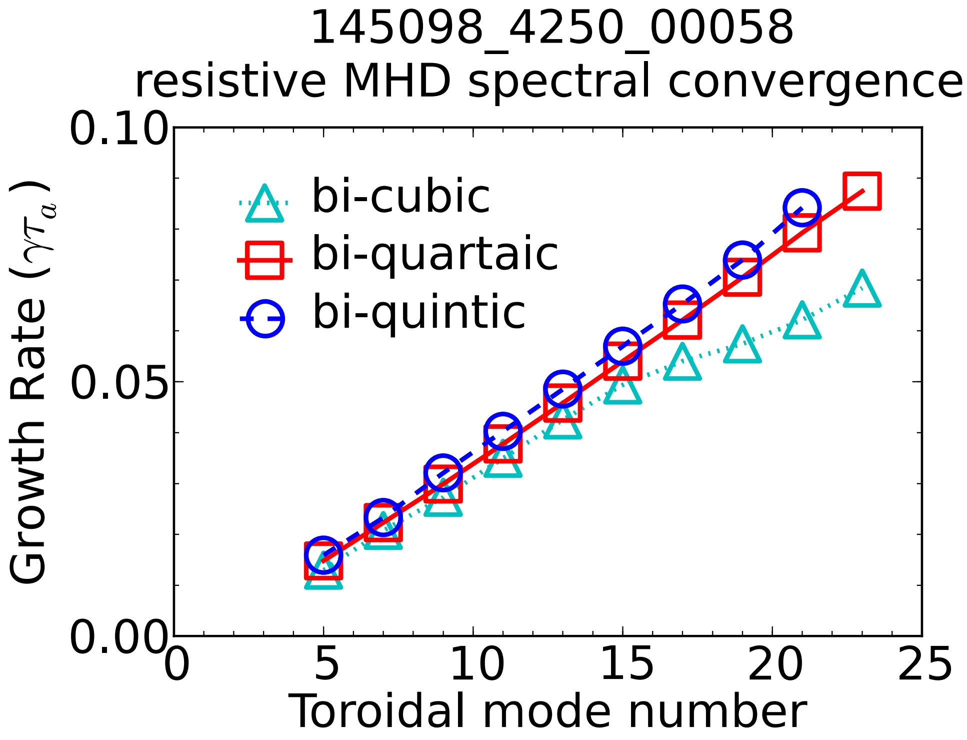
Our studies currently focus on a reconstruction from DIII-D shot 14098 (t=4250 ms).





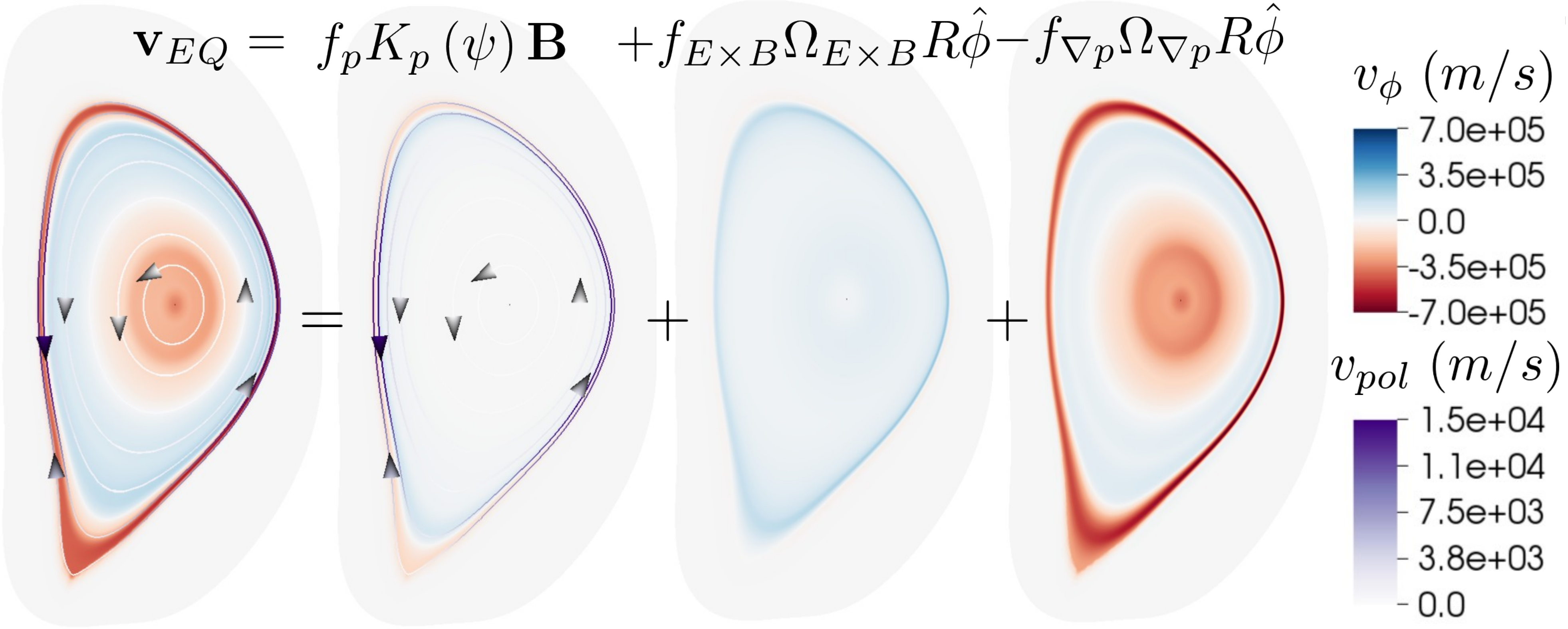
- This case is strongly shaped with an acute angle at the x-point.

Resistive-MHD computations produce a ballooning-like growth-rate spectrum.



- We do not expect uniform-wave initialized nonlinear perturbations with the growth-rate spectrum to produce EHO.
- However, it is known that the flow profile is crucial to EHO.
- These cases use reconstructed density and Spitzer-resistivity profiles with Ti=Te=50 eV at the separatix.

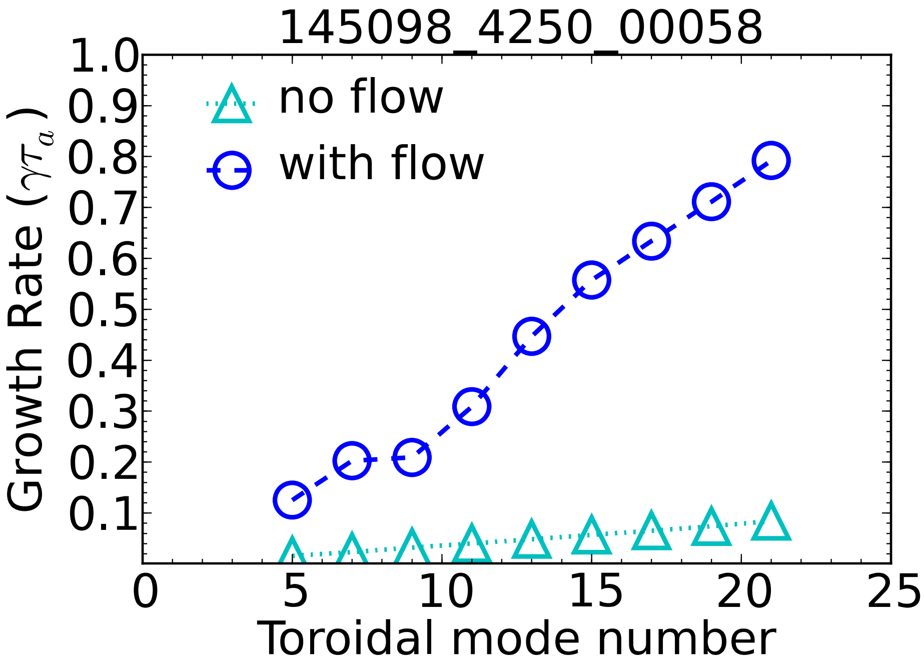
We have the ability to add individual components from the reconstructed flow profile to our nonlinear computations.

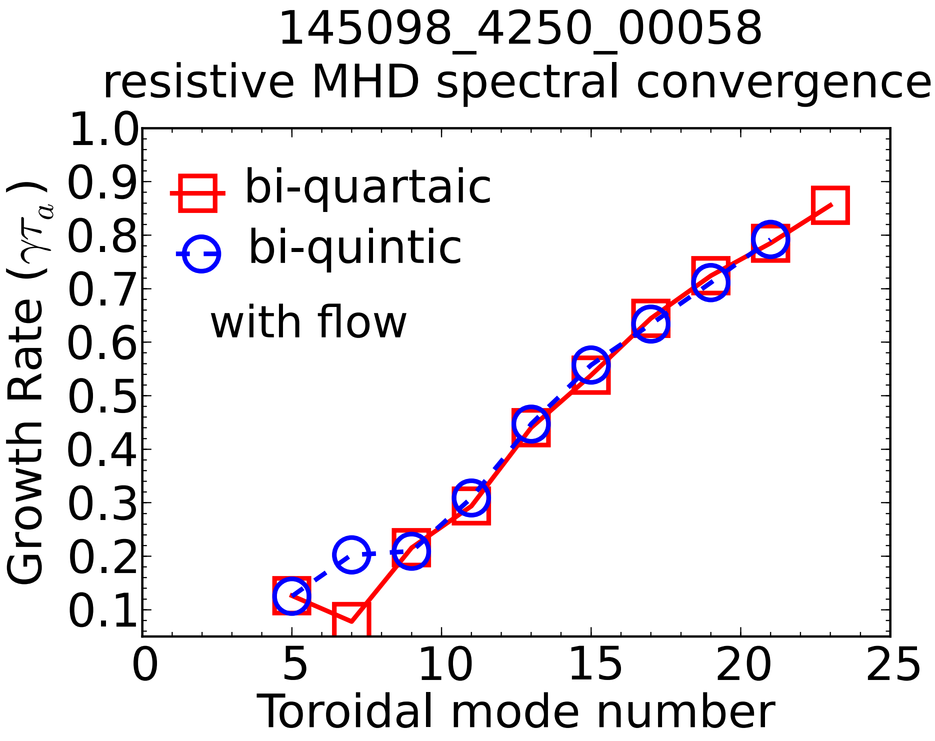


$$\mathbf{v}_{EQ} = f_p K_p(\psi)\,\mathbf{B} + f_{E\times B}\Omega_{E\times B}R\hat{\phi} - f_{\nabla p}\Omega_{\nabla p}R\hat{\phi}$$

- Flow profile control is essential to produce the EHO state [Burell 2012, Garofalo 2011 etc].
- We can vary the each contributions flow profiles.
- Profiles are shown for $f_p = f_{E\times B} = f_{\nabla p} = 1$.

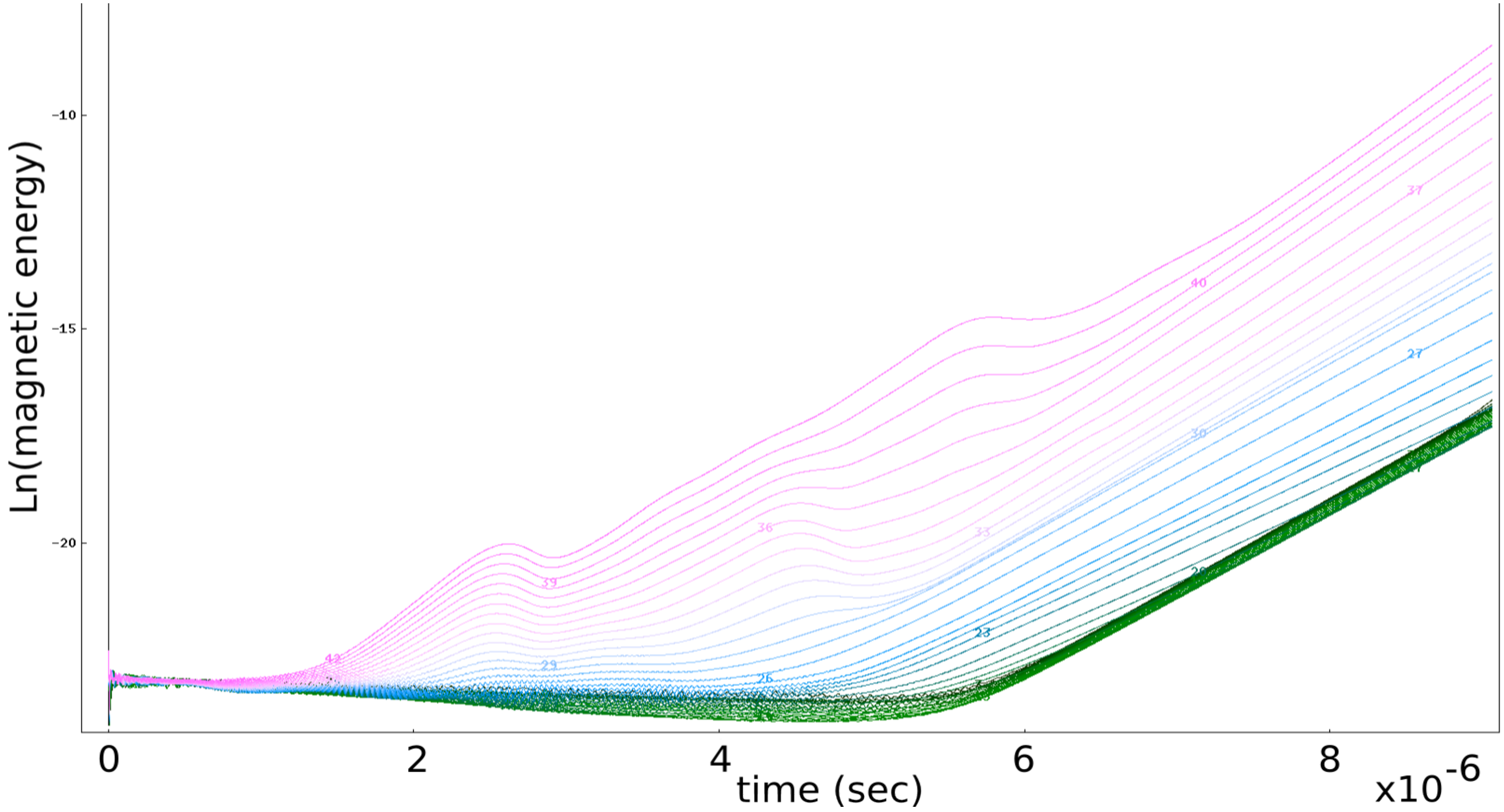
Resistive-MHD computations with flow again produce a ballooning-like growth-rate spectrum and are destabilized relative to cases without flow.





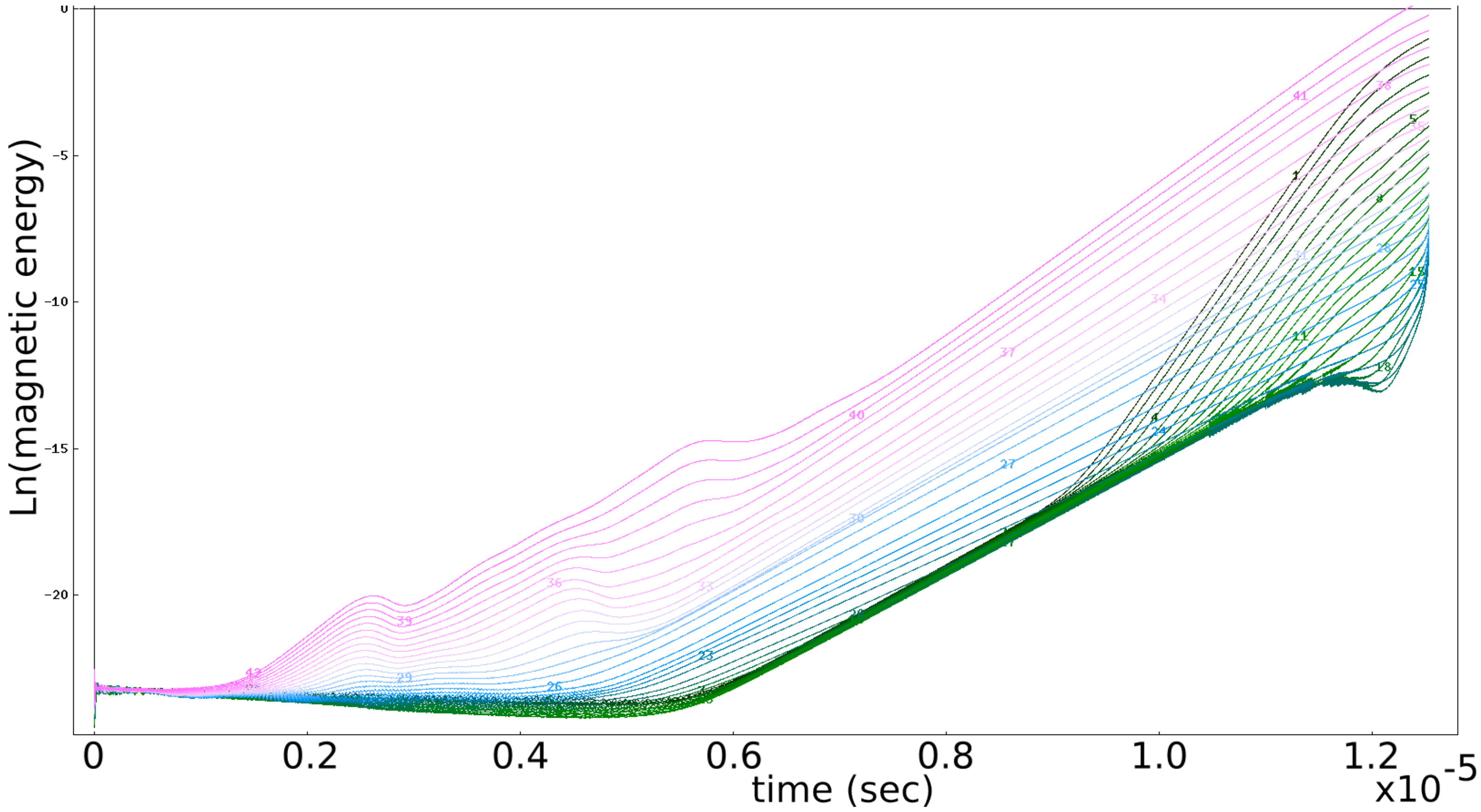
Preliminary nonlinear computations

Nonlinear computations from small-wave perturbations initially produce ELM-like dynamics at large wavenumbers.



- The most unstable mode is at the limit of the computation's toroidal resolution.
- Self-consistent computations require a combinations of additional resolution and more advanced model equations (two-fluid and FLR effects).

During saturation this case drives low-n perturbations to significant amplitude.

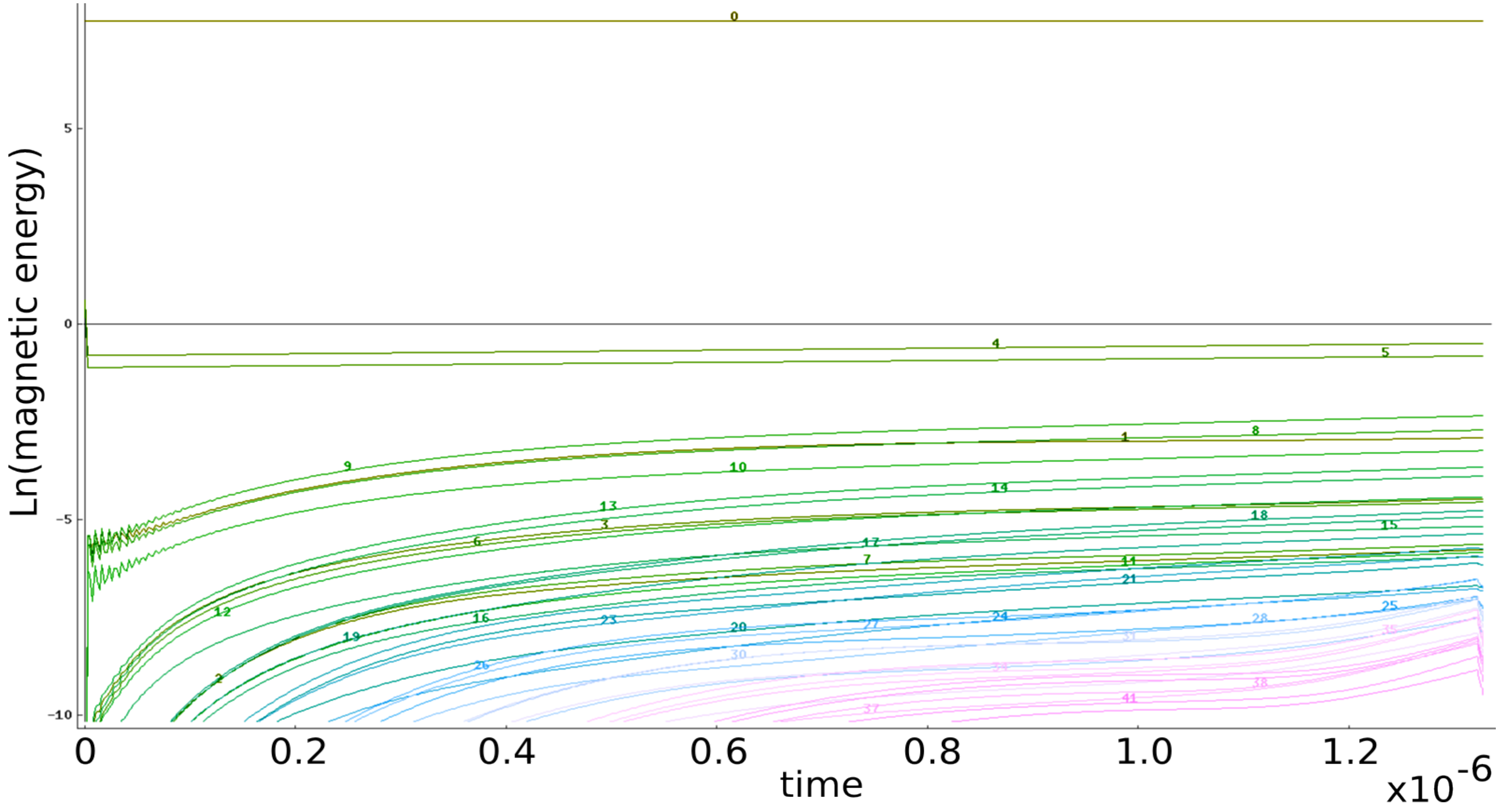


- However, the amplitude of these low-n perturbations does not exceed that of the high-n perturbations.
- What is the effect of inclusion of two-fluid and FLR effects in this computation?

If the EHO state is responsible for ELM suppression, is there an alternative way to access this nonlinear state?

- We can to chose our initial perturbation carefully. We propose using modest amplitude n=4 and n=5 perturbations from the linear spectrum.
- This method of study is not intended to (immediately) produce a predictive model, i.e. given the reconstructed axisymmetric state at t=3000ms it will not predict at EHO state at t=3800ms.
- However, there are still a number of interesting questions it can answer:
    - What is the effect of EHO on transport and what is the quasilinear modification by the EHO to the flow, current and pressure profiles?
    - How does EHO stabilize the high-n perturbations and produce an ELM-free state?

These large initial perturbation computations produce a potential EHO-like state.



- This computation requires higher toroidal resolution in order to run longer in time.
- This initial result is promising, but need to be run out 10-50x longer to be compelling as a state of ELM stabilization.

Recent interfacing of NIMROD with the MUMPS external solver permits larger runs.

- Our tests show MUMPS has a smaller memory footprint than SuperLU_DIST for NIMROD matrices.
- MUMPS also has OpenMP thread support and tests show slightly better time-to-solution as a result of slightly better parallel scaling than SuperLU_DIST for runs with 100s on cores.
- The cases presented are close to converged, increasing the mesh resolution by a factor of 3-6 should be sufficient to fully resolve all dynamics.
- We are actively pursuing a computational hours allocation for these higher-resolution runs.

Summary

- Linear case with and without flow produce a toroidal-mode growth-rate spectrum that is peaked at large n.
- Preliminary nonlinear computations from small-wave perturbations demonstrate high-n perturbations can drive low-n activity during saturation.
- We also explore nonlinear computations where the intent is to access the nonlinear state by carefully choosing our initial condition.
- Preliminary results here are promising, and we are applying for computational time to continue these studies.
- We also intend to study the linear and nonlinear effect of including additional physics (two fluid, FLR) in the model.

Why is NIMROD a suitable code for modeling EHO?

- Experimental observations show EHO is a low-n perturbation and thus global computations are necessary.
- In addition to the capability to model of flow-profile effects, NIMROD also retains important two-fluid and FLR terms.
  - Two-fluid effects are predicted to enhance the growth rate at intermediate wavenumbers and cut it off at large wavenumbers though diamagnetic effects [Hastie, Ramos, Porcelli 2003].
- Even if the high wavenumber modes are stabilized by two-fluid effects, they may be driven nonlinearly. Nonlinear modeling of EHO saturation requires resolution of a large toroidal mode spectrum.
- NIMROD is capable of modeling a realistic x-point geometry.

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