Simulations of Neoclassical Tearing Modes Seeded via Transient-Induced-Multimode Interaction

Eric Howell[1], Jake King[1], Scott Kruger[1], Jim Callen[2], Rob La Haye[3] and Bob Wilcox[4]

[1]Tech-X Corporation, [2]University of Wisconsin, [3]General Atomics, [3]Oak Ridge

Virtual Theory and Simulation of Disruptions Workshop

July 19-23, 2021

Work Supported by US DOE under grants DE-SC0018313, DE-FC02-04ER54698, DE-FG02-86ER53218

Outline

- Introduction

- Summarize NIMROD developments that enable NTM modeling
  - Heuristic closures model neoclassical effects
  - External MP generate seed

- Simulations of transient induced NTMs in IBS discharge
  - MP pulse as surrogate model for MHD transient
  - Resulting 2/1 grows in two phase (slow and fast)
  - Slow growth phase sustained by nonlinear 3-wave coupling

- Conclusions and Future Work

NTMs are leading physics cause of disruptions.

- Robustly growing NTMs are more likely in ITER and future ATs
  - Larger f_B, small ρ^*, low rotation
- Qualitatively understood …
  - Seeding -> Locking -> Disruption
- but key details are missing
  - Why do some transients seed NTMs but not others?
  - How do locked NTMs trigger the TQ?
- Avoidance requires understanding details
  - Design NTM resilient scenarios
  - Evaluate proximity to seeding
- **Nonlinear simulations help address knowledge gaps**

What makes NTM simulations challenging?

- NTMs require linear layer thinner than critical island width: $\delta_{VR} < W_D$
  - Large Lundquist number and large heat flux anisotropy

- Bootstrap current is kinetic
  - Self-consistent modeling requires 5D kinetic closures
  - We use heuristic closures

- NTMs growth slow compared to ELMs and Sawteeth
  - Modeling multiple MHD transients is not practical

- NTMs require seed island for growth
  - We apply MP to seed generate island

Outline

- Introduction

- Summarize NIMROD developments that enable NTM modeling
  - Heuristic closures model neoclassical stress
  - External MP generate seed

- Simulations of transient induced NTMs in IBS discharge
  - MP pulse as surrogate model for MHD transient
  - Resulting 2/1 grows in two phase (slow and fast)
  - Slow growth phase sustained by nonlinear 3-wave coupling

- Conclusions and Future Work

Heuristic Closures Model Forces due to Neoclassical Stresses[1]

- Closures model dominant neoclassical effects
  - Bootstrap current drive
  - Poloidal ion flow damping
- Closures use fluid quantities available in simulations

$$\rho\left(\frac{d\vec{v}}{dt}+\vec{v}\cdot\nabla\vec{v}\right)=-\nabla p+\vec{J}\times\vec{B}-\nabla\cdot\vec{\vec{\Pi}}_i$$

$$\vec{E}=-\vec{v}\times\vec{B}+\eta\vec{J}-\frac{1}{ne}\nabla\cdot\vec{\vec{\Pi}}_e$$

$$\nabla\cdot\vec{\vec{\Pi}}_i=\mu_i n m_i\langle B_{eq}^2\rangle\frac{\left(\vec{V}-\vec{\mathrm{V}}_{\mathrm{eq}}\right)\cdot\vec{e}_\Theta}{\left(\vec{\mathrm{B}}_{eq}\cdot\vec{e}_\Theta\right)^2}\vec{e}_\Theta$$

$$\nabla\cdot\vec{\vec{\Pi}}_e=-\mu_e\frac{nm_e}{ne}\langle B_{eq}^2\rangle\frac{\left(\vec{J}-\vec{\mathrm{J}}_{\mathrm{eq}}\right)\cdot\vec{e}_\Theta}{\left(\vec{\mathrm{B}}_{eq}\cdot\vec{e}_\Theta\right)^2}\vec{e}_\Theta$$

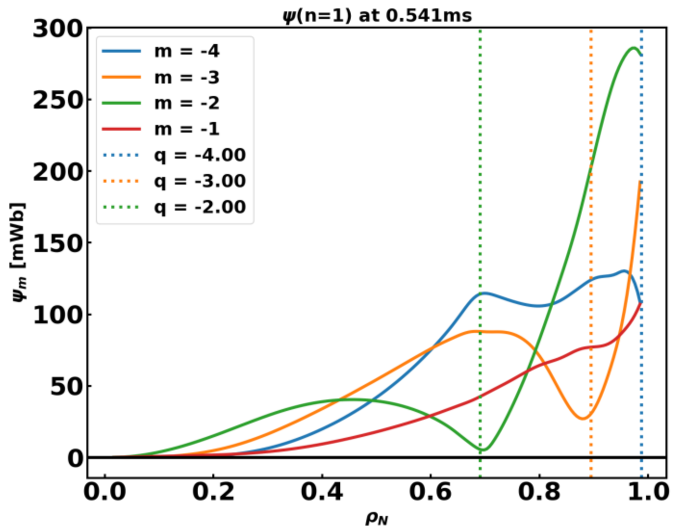
[1]T. Gianakon et al., PoP 9 (2002)

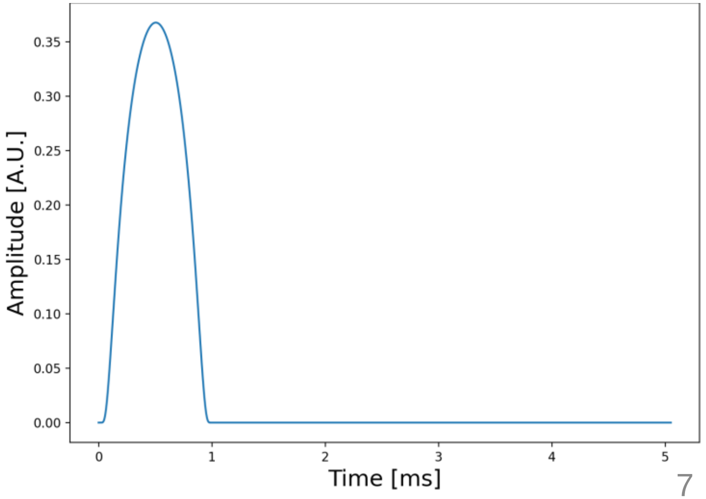
Pulsed magnetic perturbations (MP) surrogate model for MHD transient

- External MP generates seed needed for growth
- MP applied as a 1ms pulse at boundary

$$B_n = B_{ext} \times \mathrm{amp}(t) \times \exp(i\Omega t)$$

- Applied n=1 pulse is designed to excite large 2/1 vacuum response
- MP phase is modulated with flow to minimize screening





Outline

- Introduction

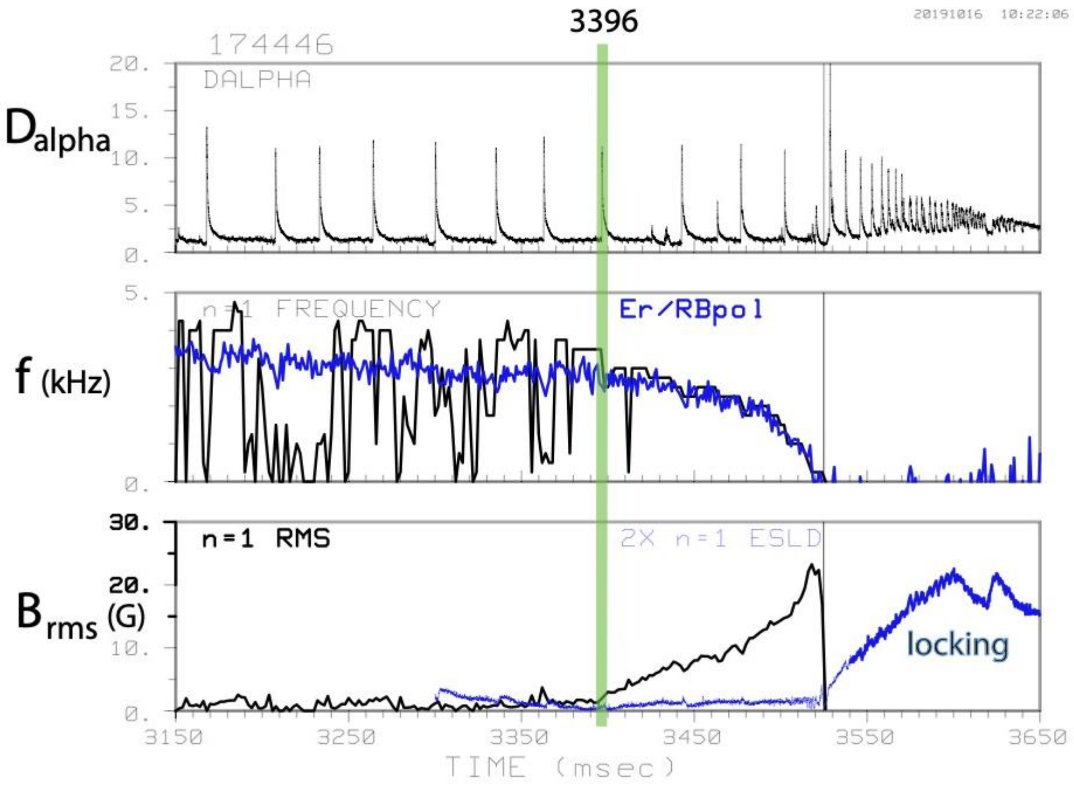
- Summarize NIMROD developments that enable NTM modeling
  - Heuristic closures model neoclassical stress
  - External MP generate seed

- **Simulations of transient induced NTMs in IBS discharge**
  - **MP pulse as surrogate model for MHD transient**
  - **Resulting 2/1 grows in two phase (slow and fast)**
  - **Slow growth phase sustained by nonlinear 3-wave coupling**

- Conclusions and Future Work

Simulations are based on a DIII-D NTM seeding study[1,2]

- Simulations use ITER baseline scenario discharge 174446
- ELM at 3396 ms triggers a 2/1 NTM
- Mode grows to large amplitude and locks in ~100ms
- High resolution measurements enable high fidelity kinetic reconstruction

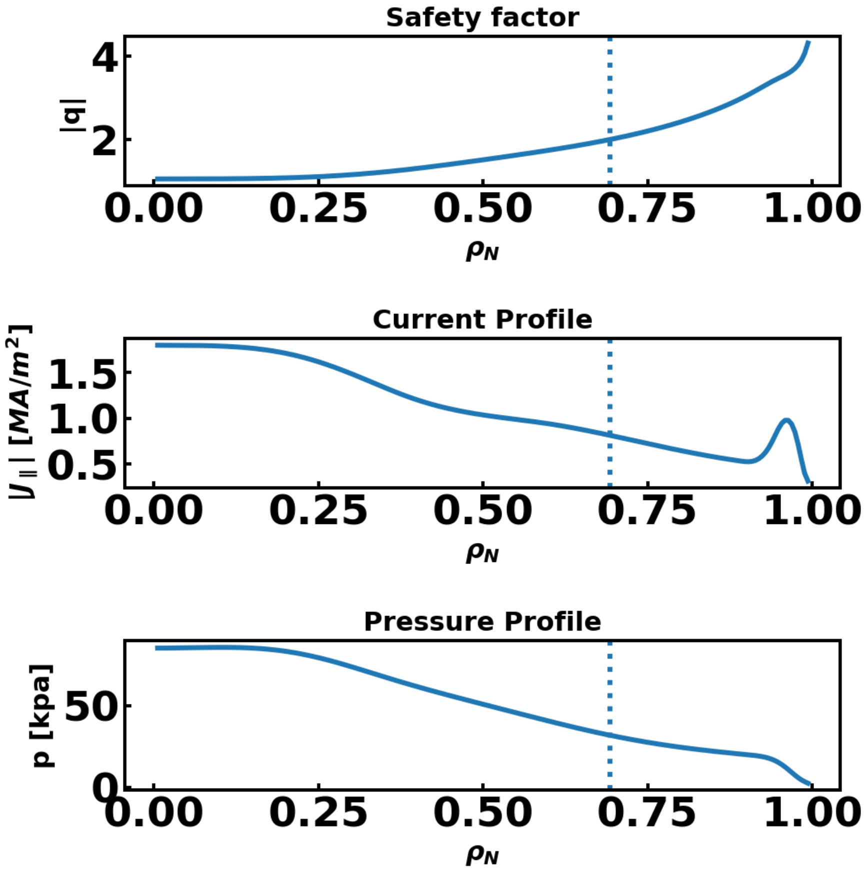


[1]La Haye, IAEA-FEC (2020)
[2]Callen, APS-DPP TI02:00005 (2020)

Simulations initialized with kinetic reconstruction at 3390ms, prior to growth

Parameters at 2/1 Surface	Simulation	Experiment
Lundquist number	2.5×10^6	7.9×10^6
Prandtl number	23	11
$\chi_\parallel / \chi_\perp$	10^8	
$\mu_e / (\nu_{ei} + \mu_e)$	0.55	0.45

- Reconstructed toroidal and poloidal flows are required for ELM stability
- Fix $|q_0|>1$ to avoid 1/1
- Normalized parameters are within a factor of 5 of experiment at 2/1 surface

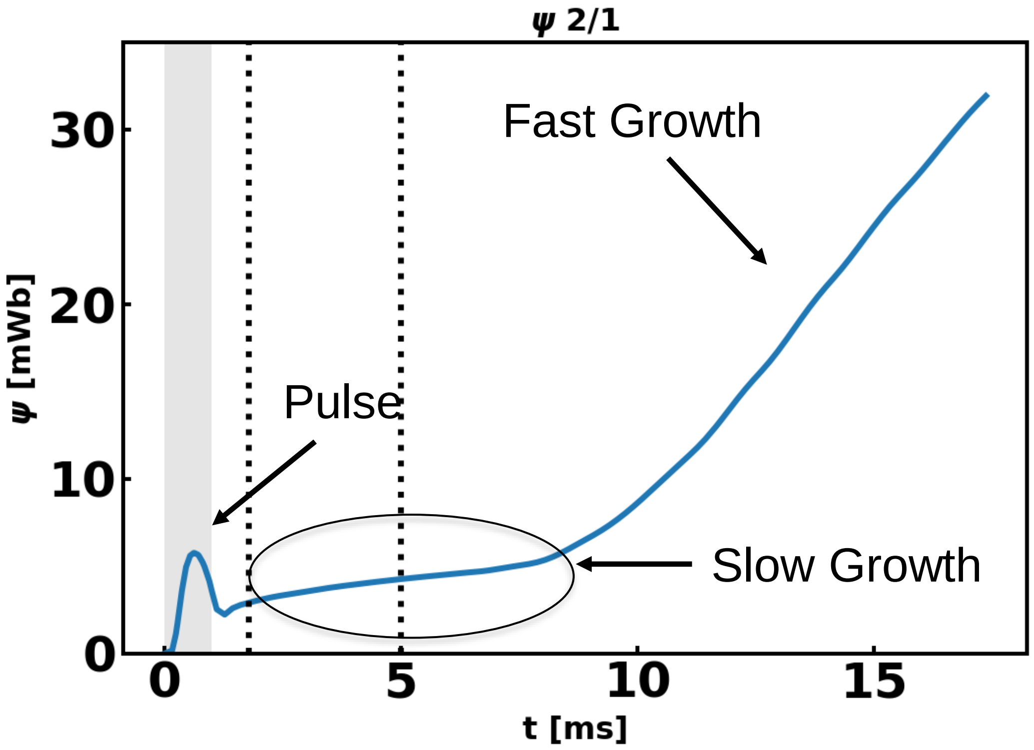


Multiple phases of 2/1 mode following 1ms MP pulse

- 2/1 resonant helical flux grows and decays with initial pulse

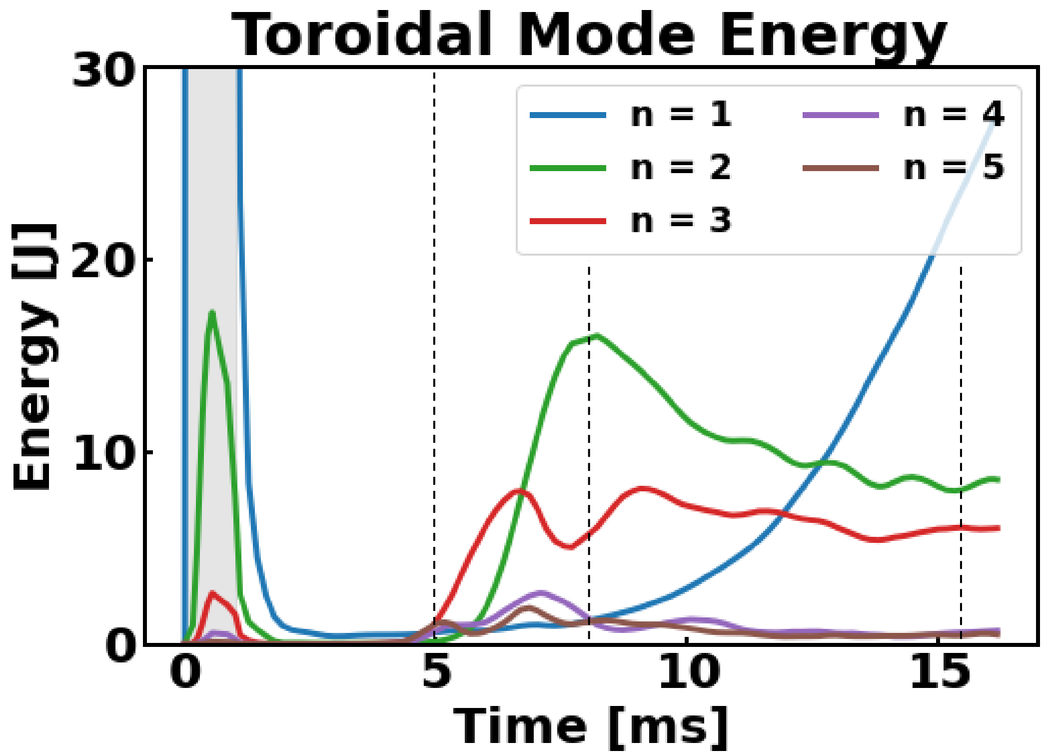
- Robust growth starting at 10ms consistent with MRE
  - MRE: $\frac{d\psi}{dt} \sim 3.3\, Wb/s$
  - Simulation: $\frac{d\psi}{dt} \sim 3.4\, Wb/s$

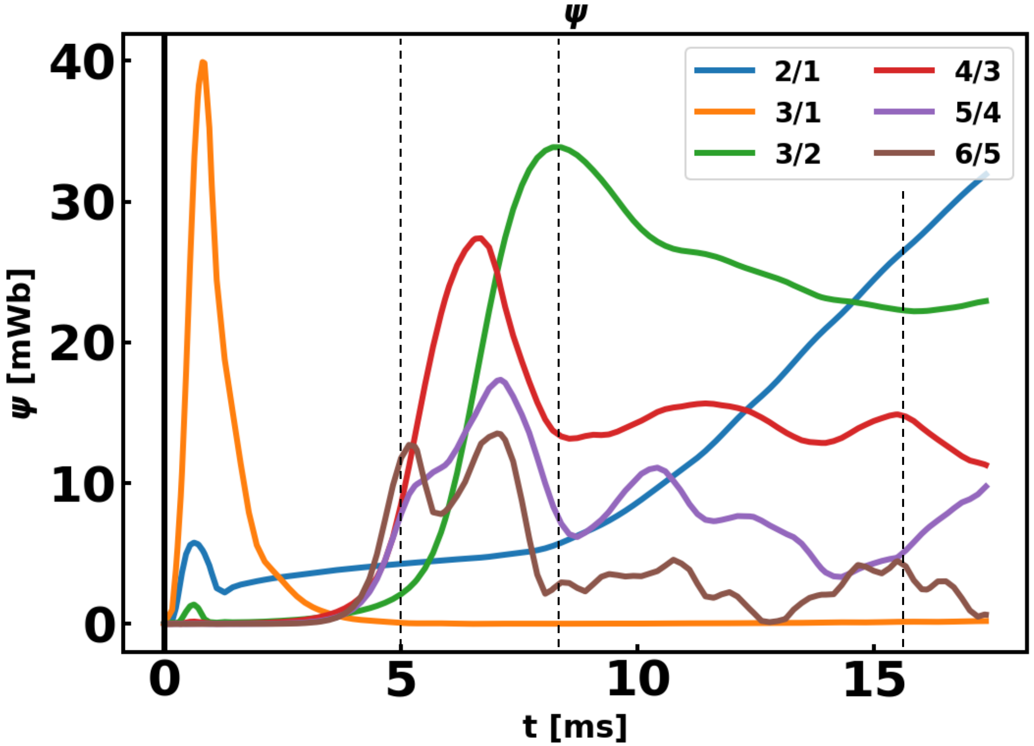
- Origin of slow growth phase subject of the rest of this talk



$$B_r[G] = 0.544\, \psi_{2/1}[mWb]$$

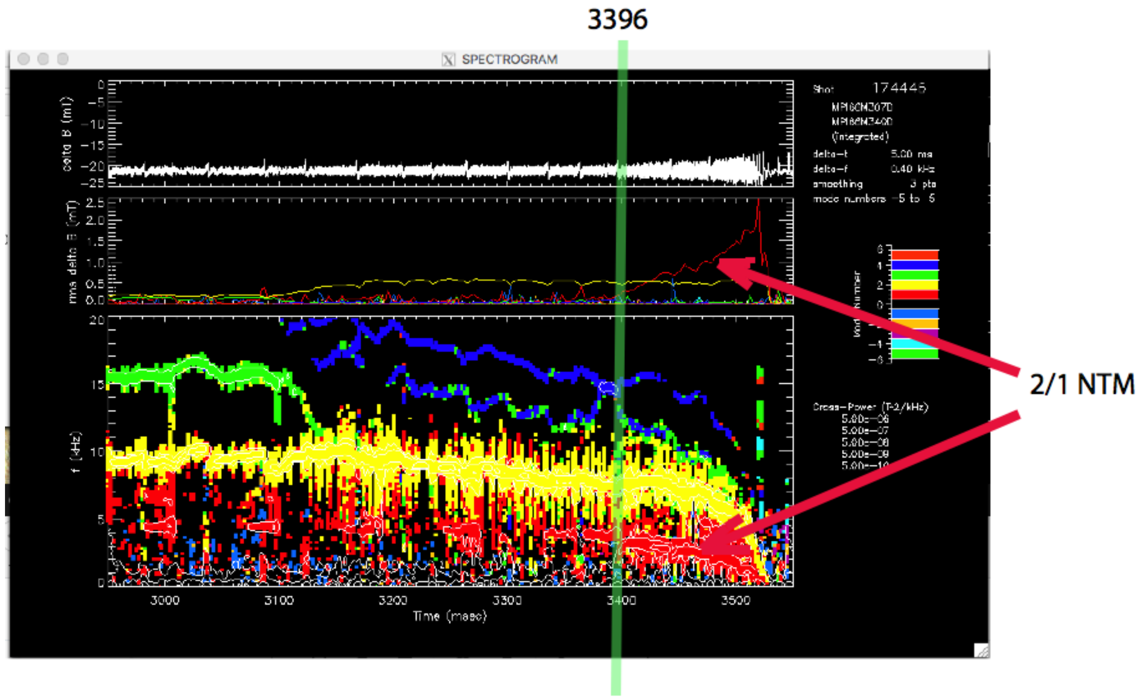
Simulation involve rich multimode dynamics

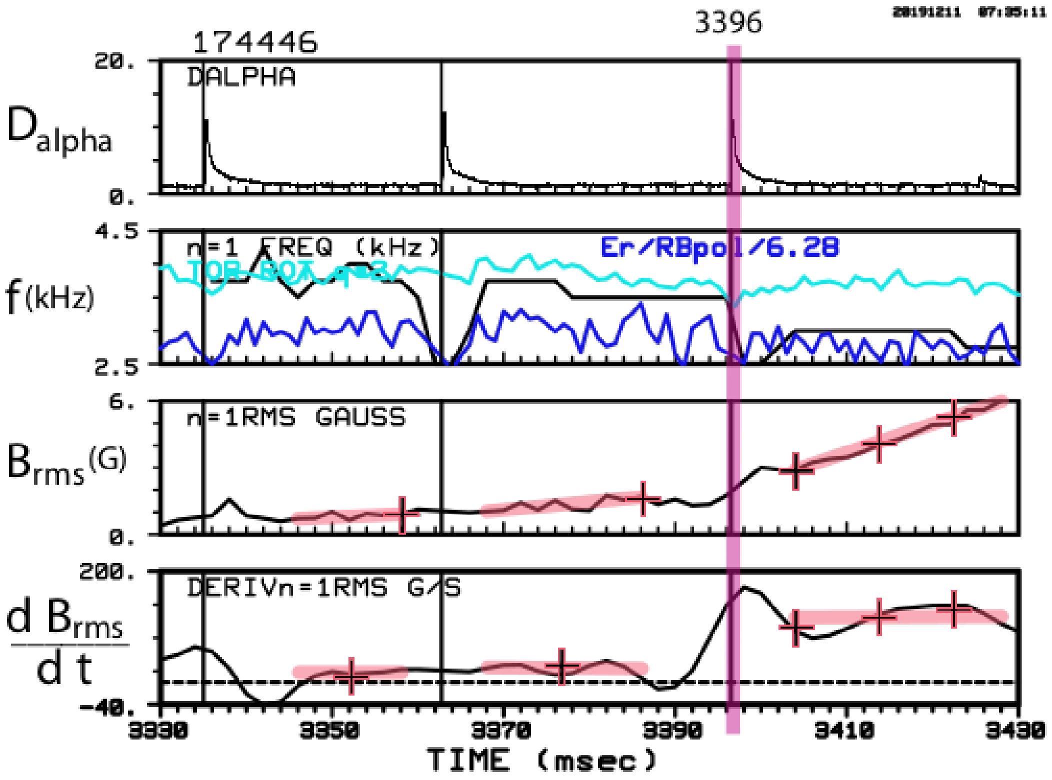




- Robust 2/1 growth follows sequence of core modes
  - High-n (3,4,5) core modes grow up around around 5ms
  - 3/2 takes off when 4/3 reaches large amplitude
  - 2/1 takes off when 3/2 reaches large amplitude

Experiment shows two phases of growth and multiple core modes, but there are differences





- Core mode evolution spans whole discharge
- Red: n=1 (1/1 and 2/1)
- Yellow: n=2 (3/2)
- Green: n=3 (4/3)

Callen, APS-DPP TI02:00005 (2020)

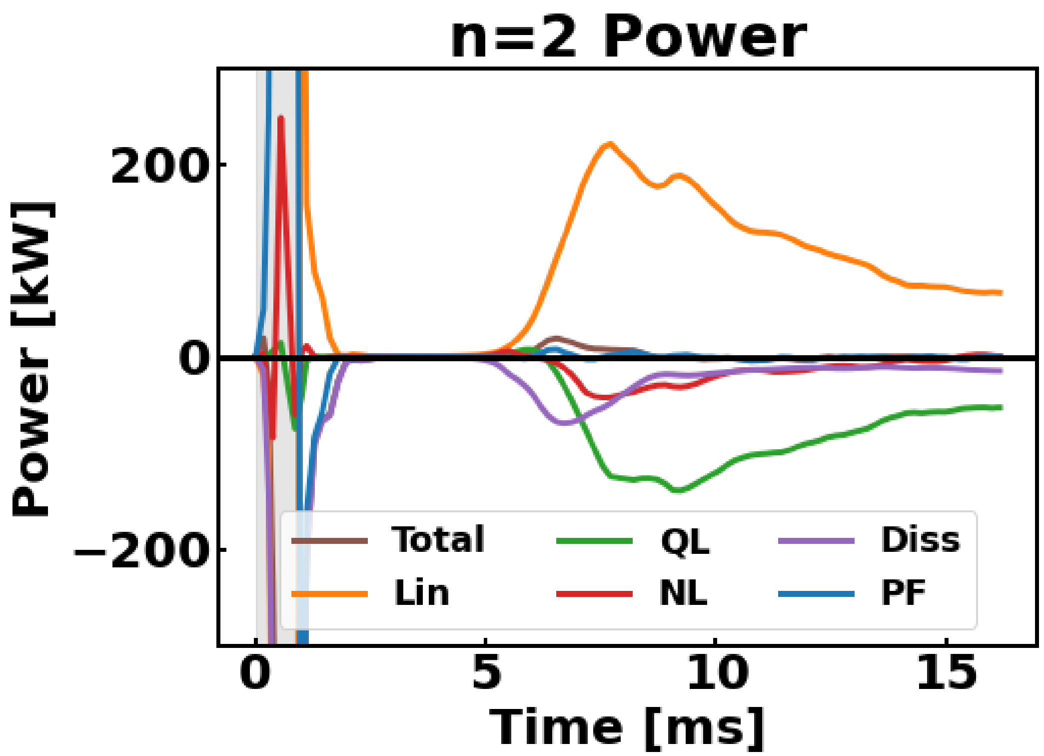
Power analysis quantifies interaction between toroidal modes[1]

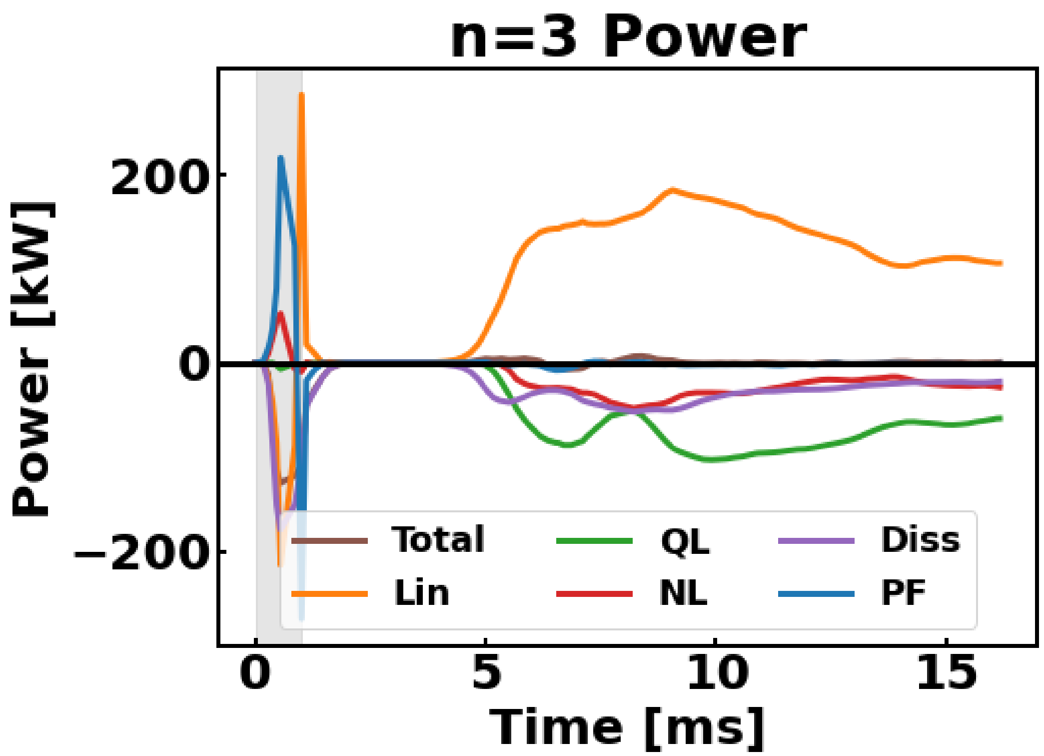
- $n \neq 0$ Fourier mode energy is sum of kinetic energy and magnetic energy
- Powers grouped to highlight transfer between n's

Linear	$(\vec{V}_{eq} \times \vec{B}_n + \vec{V}_n \times \vec{B}_{eq}) \cdot \vec{J}_n^* + (\vec{J}_{eq} \times \vec{B}_n + \vec{J}_n \times \vec{B}_{eq}) \cdot V_n^* - \nabla p_n \cdot \vec{V}_n^*$
Quasilinear	$(\tilde{V}_0 \times \vec{B}_n + \vec{V}_n \times \tilde{B}_0) \cdot \vec{J}_n^* + (\tilde{J}_0 \times \vec{B}_n + \vec{J}_n \times \tilde{B}_0)_n \cdot V_n^*$
Nonlinear	$(\tilde{V} \times \tilde{B})_n \cdot \vec{J}_n^* + (\tilde{J} \times \tilde{B})_n \cdot V_n^*$
Dissipative	$-\eta J_n^2 + \frac{1}{n_0 e} \nabla \cdot \vec{\vec{\Pi}}_{en} \cdot \vec{J}_n^* - \nabla \cdot \vec{\vec{\Pi}}_{vn} \cdot \vec{V}_n^*$
Poynting Flux	$-\nabla \cdot \frac{\vec{E}_n \times \vec{B}_n^*}{\mu_0}$

- **Linear**: transfer with n=0 equilibrium
- **Quasilinear**: transfer with n=0 perturbations
- **Nonlinear**: power transfer with n≠0 perturbations
- **Dissipative**: Collision transfer to n=0 internal energy
- **Poynting Flux**: Conservative redistribution of energy
- **Advective**: Small

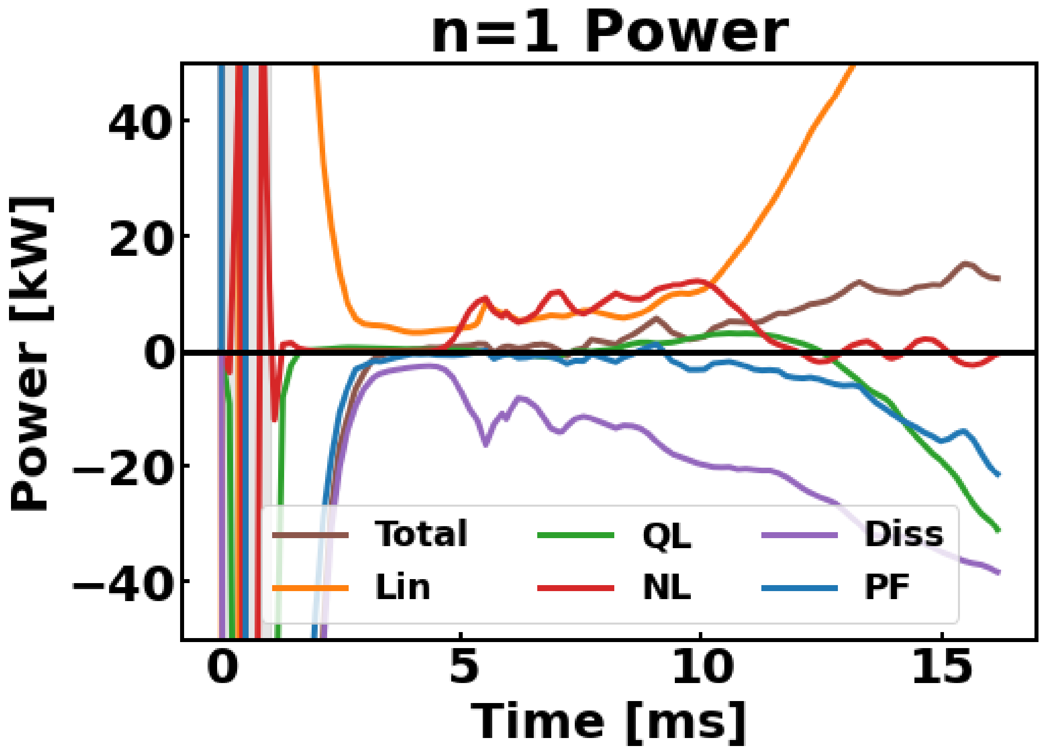
Linear powers are main drivers of n=2 and n=3 growth

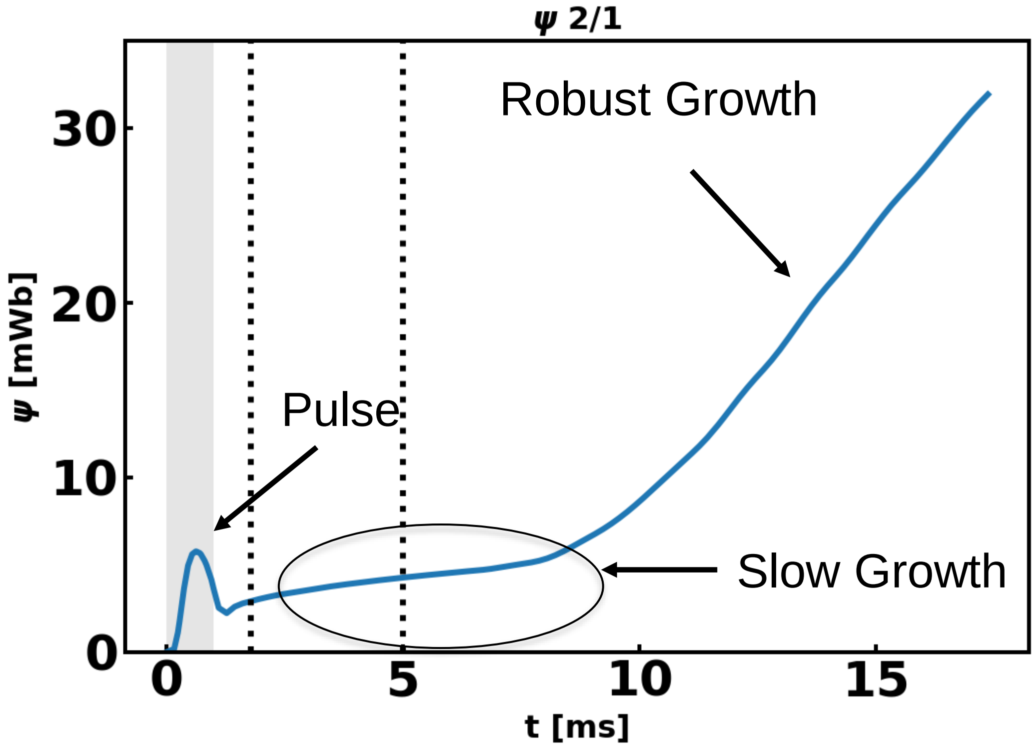




- Linear powers quantify transfer with equilibrium fields
- Growth results from small imbalance between drives and sinks
- n=2 saturation dominated by quasilinear terms
- Nonlinear and dissipative terms contribute more to n=3 saturation

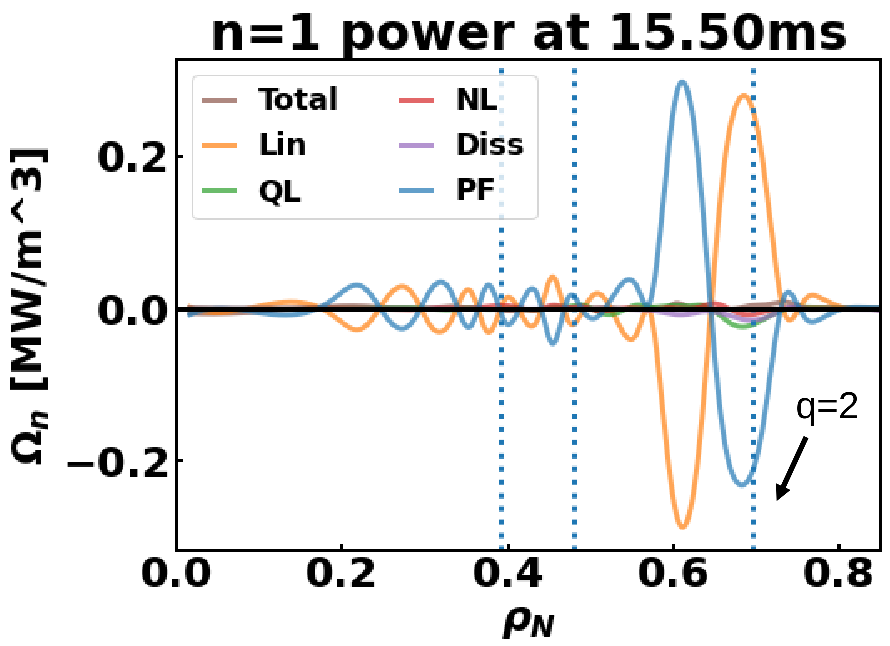
Linear and nonlinear powers drive n=1 during slow growth phase

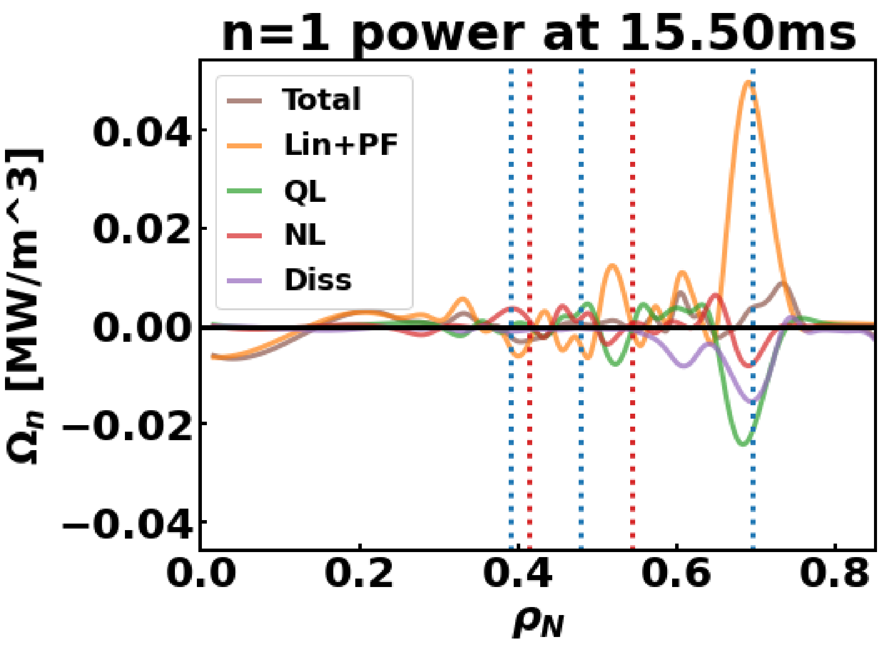




- Linear power terms are main drive during fast growth phase
  - Fast growth phase is described by MRE analysis
- Small positive QL drive prior to transition to fast growth

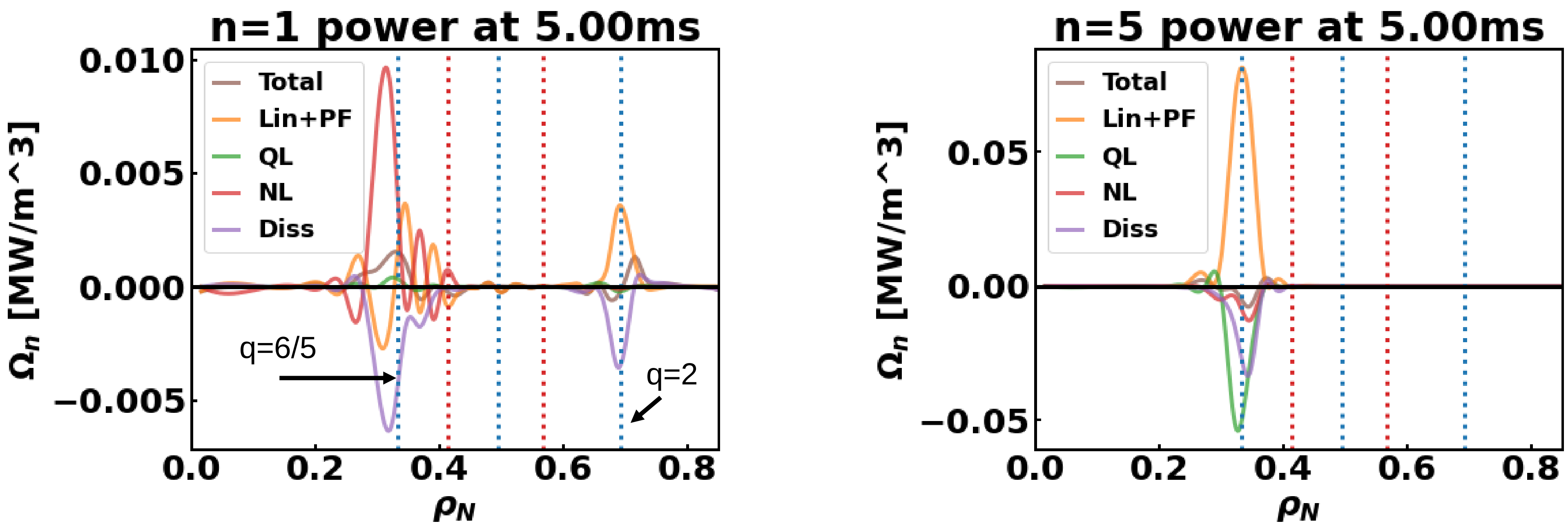
Flux surface averaged power density shows radial deposition





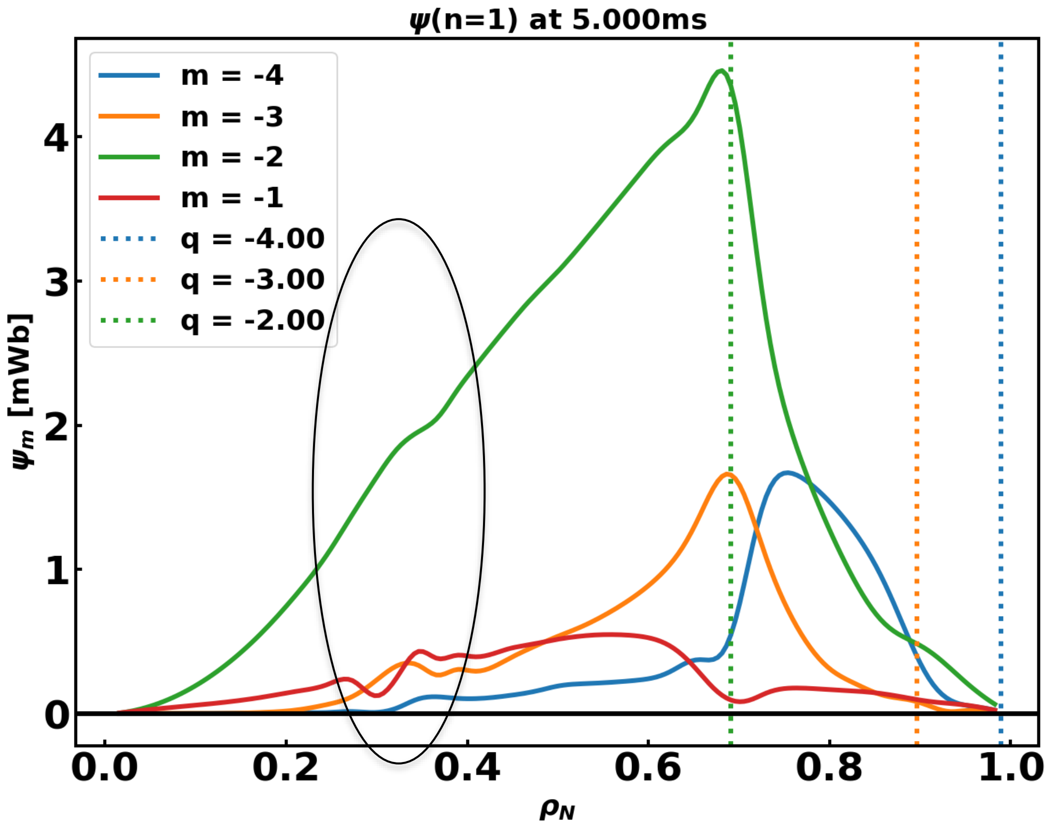
- During robust growth, linear terms inject power into n=1 near q=2
- Poynting flux radially redistributes magnetic energy radially inwards
- Linear terms strongly damp n=1 near $\rho_N \approx 0.6$
- Small imbalance between PF and linear terms results in power deposition

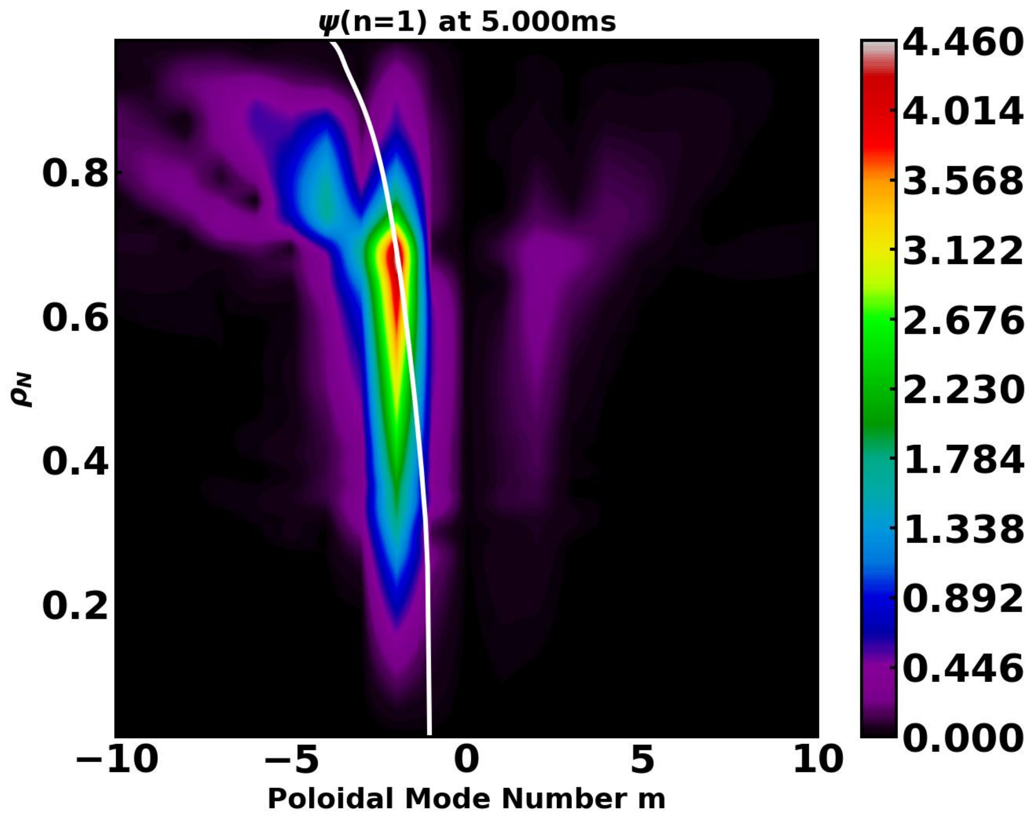
Nonlinear drives deposit energy into n=1 near 6/5 surface at 5ms



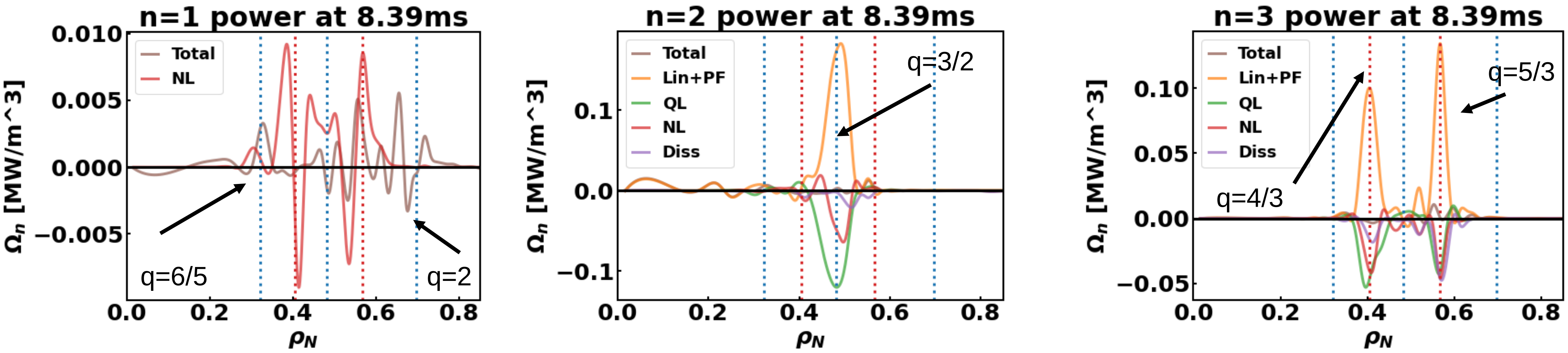
- Power deposition is driven by 6/5 beating with 7/6
- Diss & Linear terms grow with NL drive and damp energy around q=6/5
- PF radially redistributes energy injected around q=6/5 to q=2

Nonlinear power transfer into n=1 has visible impact on mode





At 8ms n=1 nonlinear power deposition spans a large radius



- Multiple peaks in NL power suggests multiple 3-wave interactions
  - Largest peaks occur near q=3/2, q=4/3, and q=5/3 surfaces
  - n=2 power consistent with 3/2
  - n=3 power indicates 4/3 and 5/3

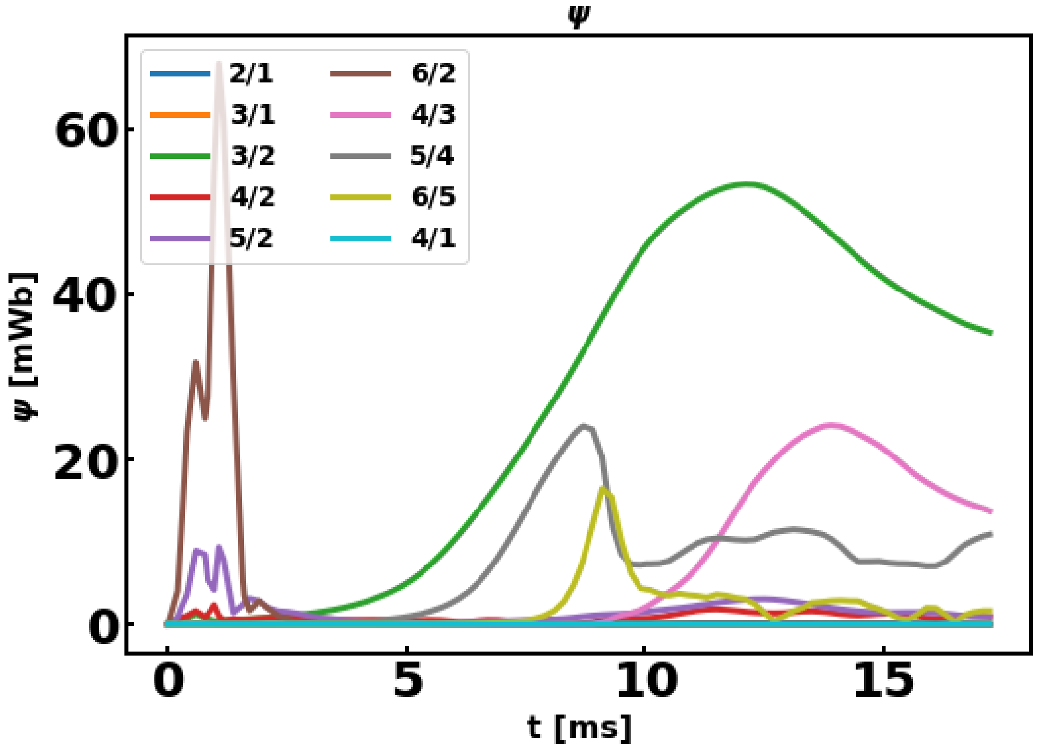
Conclusions

- Recent code developments enable NTM modeling in NIMROD
- Rich nonlinear dynamics results from the application of MP
- 2/1 island grows in two phases
    - Late in time robust growth is well described by MRE
- 2/1 slow growth phase sustained by multiple nonlinear three-wave interactions
    - Initially, one interaction dominates (n=1,5,6)
    - Later, multiple interactions are important

Future work

- Continue seeding studies using more sophisticated pulses
  - Use n=5+6 MP to better mimic ELMs
  - Start with existing 3/2 or 4/3 islands

- Use model to study other NTM physics:
  - How do 4/3 and 3/2 modes interact to seed 2/1?
  - How do locked modes trigger TQ?



Preliminary: Saturated(?) 3/2 and 4/3 islands result from n=2 MP pulse