NIMROD Modeling of Transient Induced NTM

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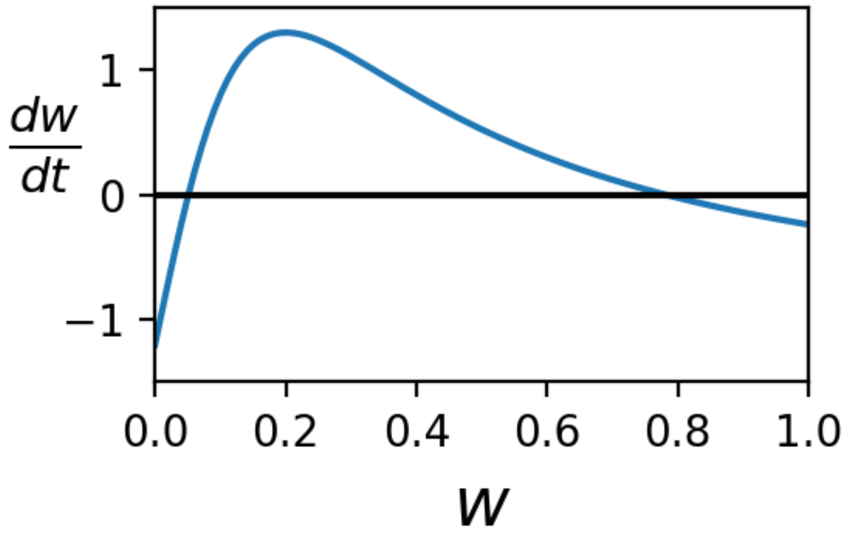
Outline

- Introduction/Motivation
- Simulation Methodology
- Simulation Results using DIII-D IBS Discharge
- Conclusions/Future Work

Forced Reconnection is used to generate seed island for numerical NTM studies

- Modified Rutherford equation models NTM evolution:

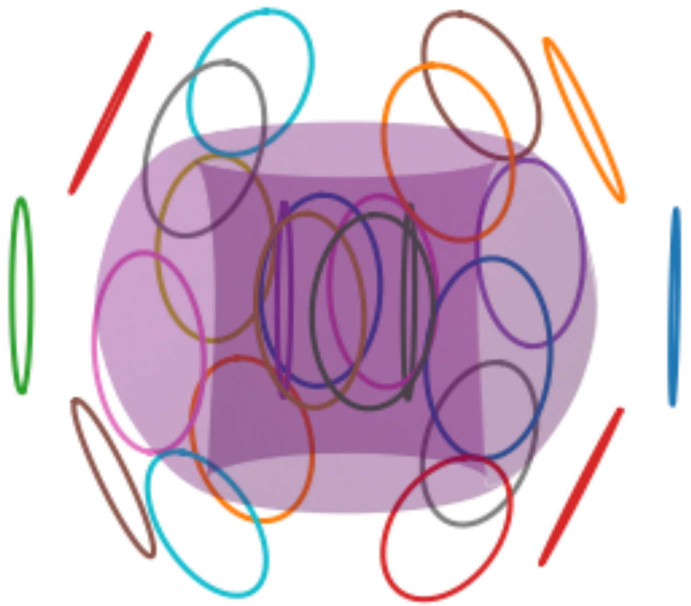
$$\frac{dW}{dt} = k_0\eta^* \left[\Delta' + \frac{D_{NTM}W}{W^2 + W_d^2} - \frac{W_{pol}^2}{W^3} + \cdots\right]$$



- NTMs require seed island for growth
- Transients seed NTMs in experiments
- Simulations require method of generating seed island

External magnetic perturbations generate seed Island

- Perturbation are generated from planar coil array
- Coil configuration is optimized to preferentially excite 2/1 vacuum response



- Perturbations are applied as a slowly varying pulse

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

- Perturbations are modulated with plasma rotation to reduce screening

Heuristic Closures Model the Neoclassical Stresses[1]

- Closures model dominant neoclassical effects
  - Bootstrap current drive
  - Poloidal ion flow damping
  - Polarization current enhancement
- Closures use quantities that are readily available in simulations

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

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

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

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

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

Fourier amplitude of JB_ψ is a proxy for the island width[2]

- Magnetic island width scales with the resonant perturbed flux:

$$W \propto \sqrt{\left|\frac{\tilde{\psi}_{m,n}}{q'}\right|}$$

- Perturbed flux is related to the radial component of the magnetic field:

$$\frac{\partial\tilde{\psi}}{\partial\Theta} = J\tilde{B}\cdot\nabla\psi_0$$

- Poloidal field line integration calculates the cos and sin transforms:

$$\psi_{m,n} = \sqrt{\psi_{cos}^2 + \psi_{sin}^2}, \qquad \psi_{cos} = \oint\oint J\tilde{B}\cdot\nabla\psi_0\, cos(n\phi - m\Theta)d\Theta d\phi$$

[2]M. J. Schaffer et al., NF 48 (2008)

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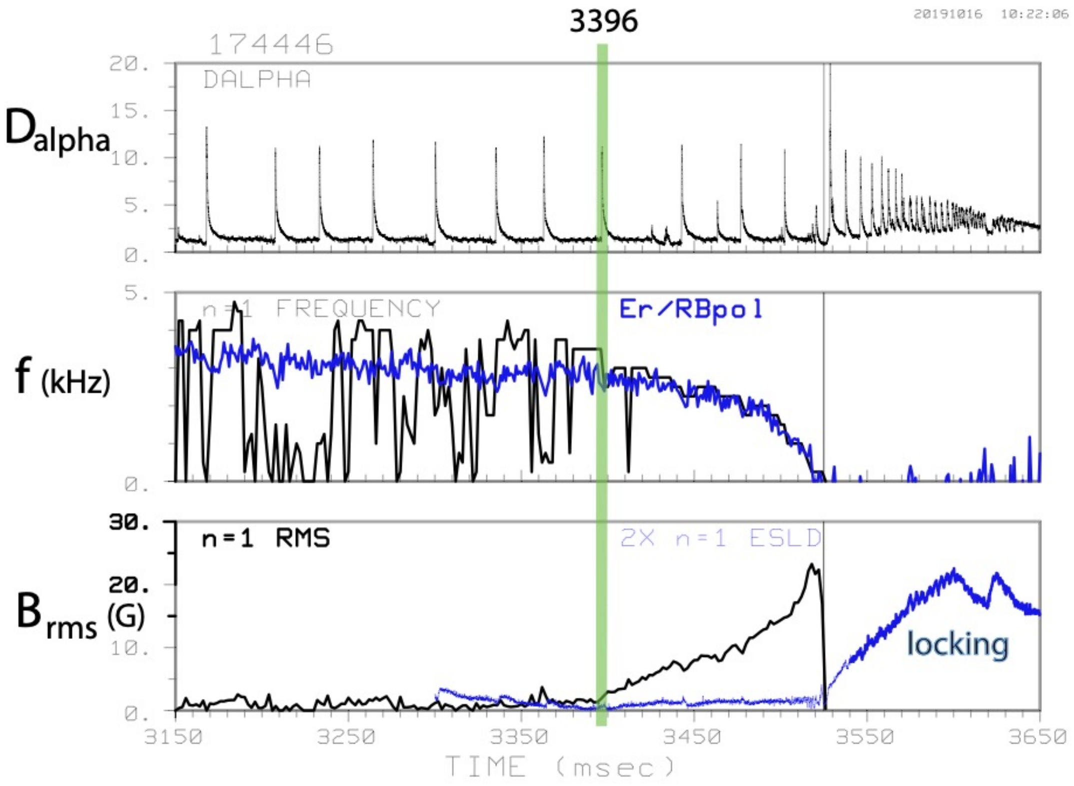
Simulations are based on a DIII-D NTM seeding study[3]

- 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



[3]R. La Haye, B. Wilcox, C. Chrystal, et al.

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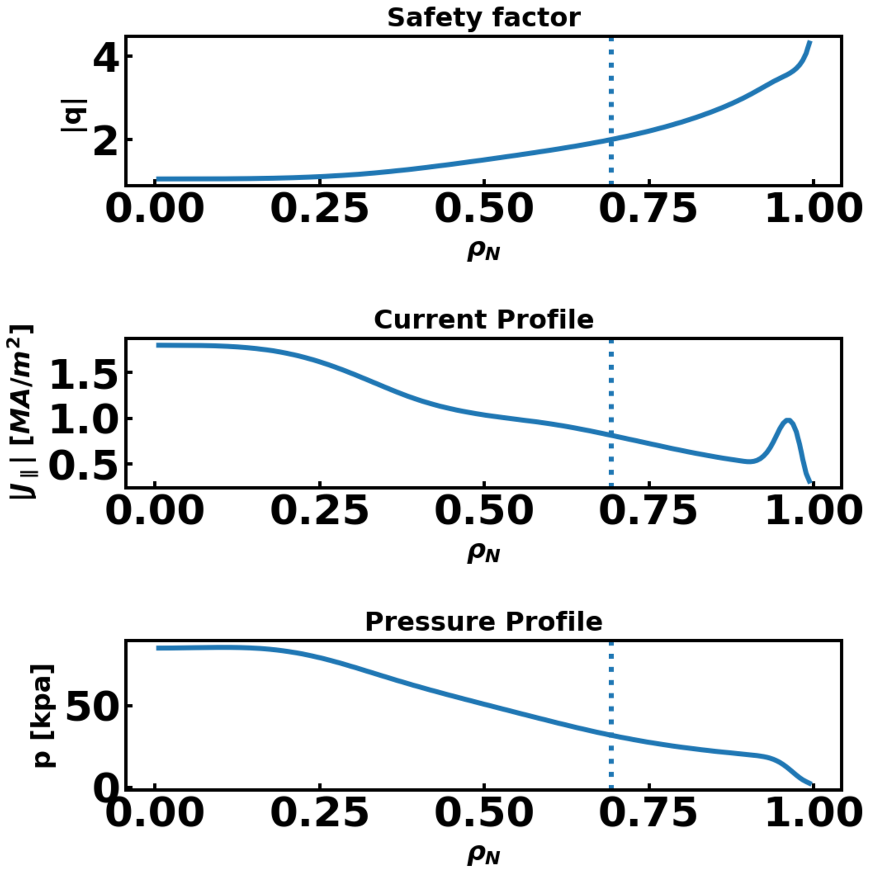
Simulations are initialized with kinetic reconstruction at 3390ms, prior to the 2/1 growth

Simulation Parameters at 2/1 Surface

Lundquist number	2.5×10^6
Prandtl number	23
$\chi_\parallel / \chi_\perp$	10^8
μ_e	8×10^5 [s^{-1}]
μ_i	10^3 [s^{-1}]
$\mu_e / (\nu_{ei} + \mu_e)$	0.55

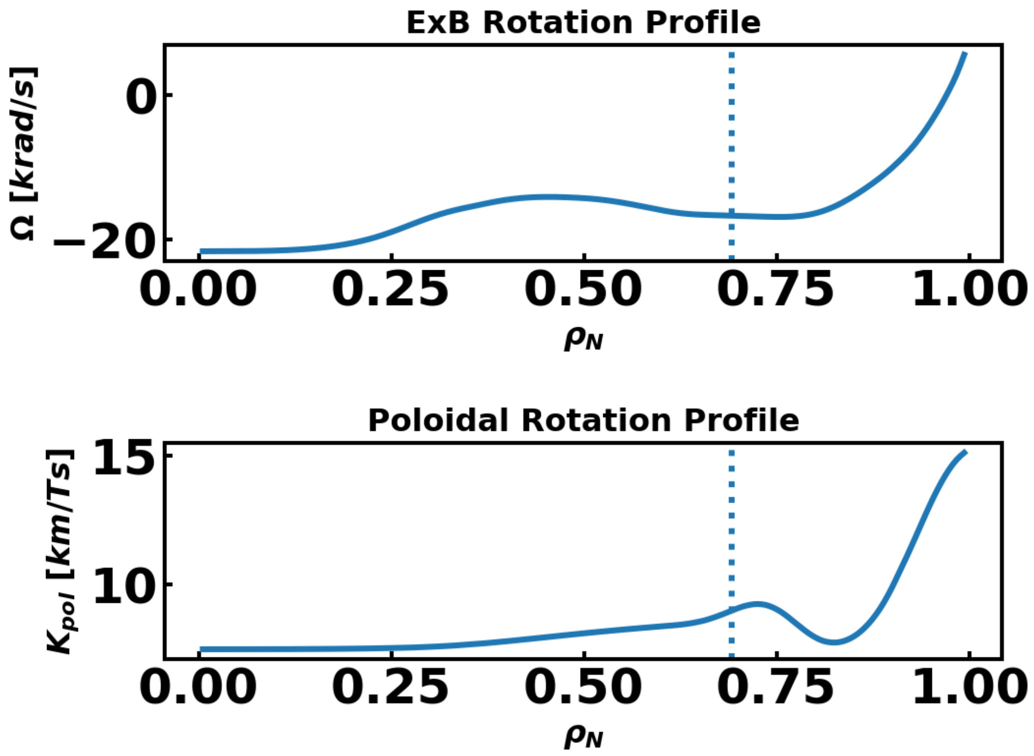
- Reconstructions fix $q_0>1$ to avoid 1/1
- Parameters are within a factor of 5 of experiment at 2/1 surface



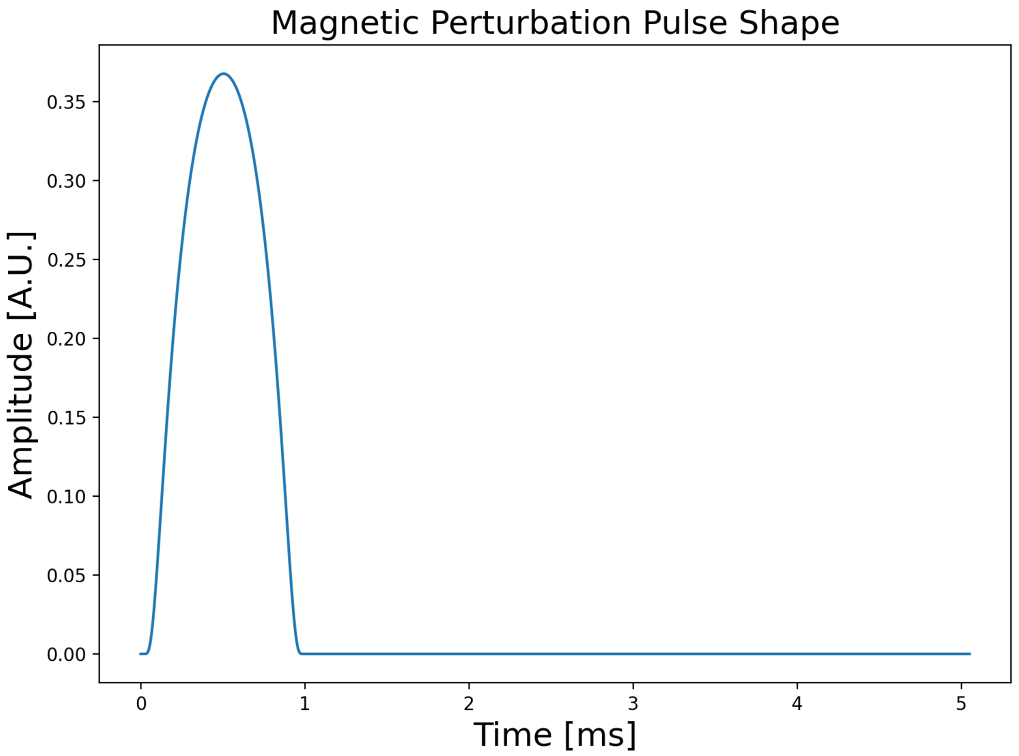
Simulations include rotation inferred from measurements

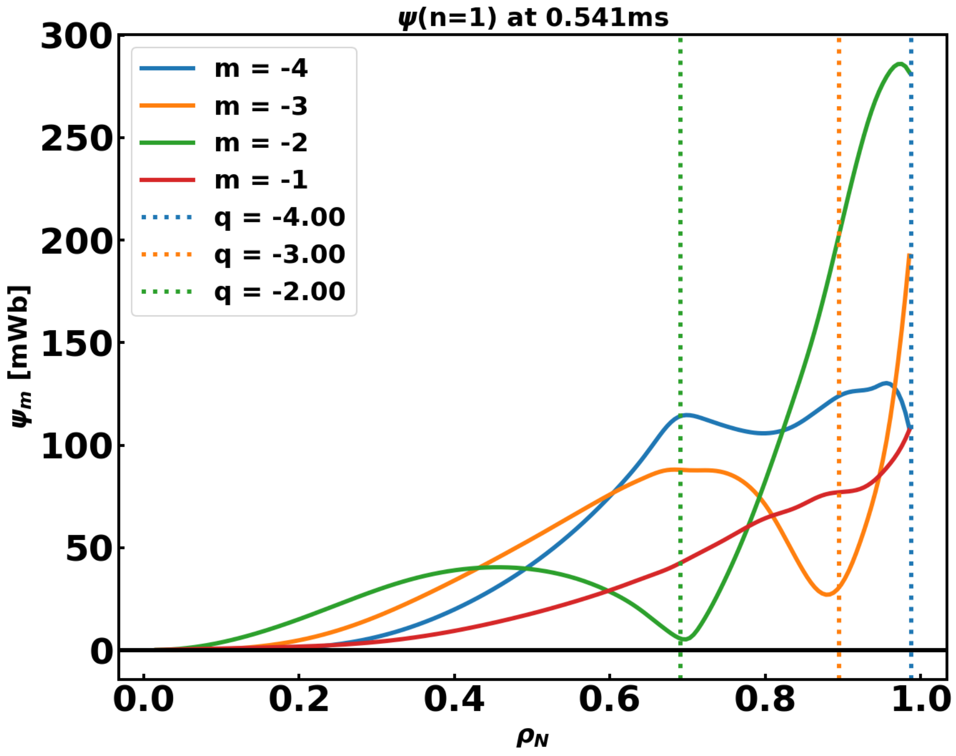
$$\vec{v}_{eq} = K\vec{B}_{eq} + \Omega R^2 \nabla\phi$$

- Experimental rotation profiles are based on CER measurements
- Flow shear stabilizes pedestal peeling-ballooning modes
- Planned locking studies require a realistic flow profile



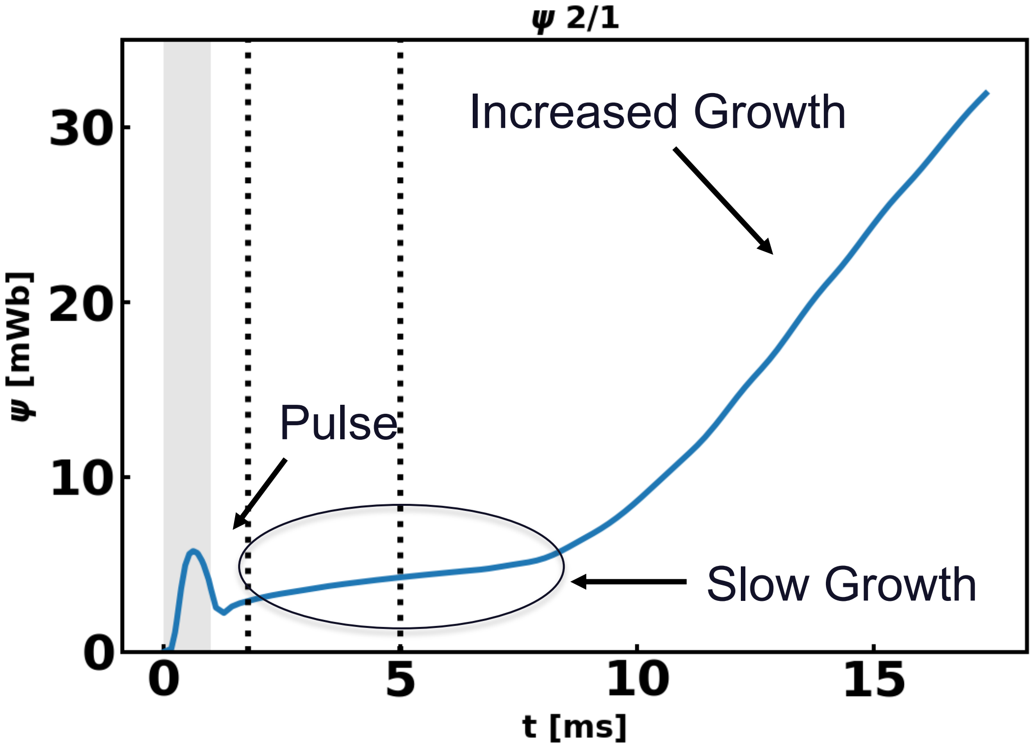
Applied 1ms pulse excites a broad n=1 spectrum

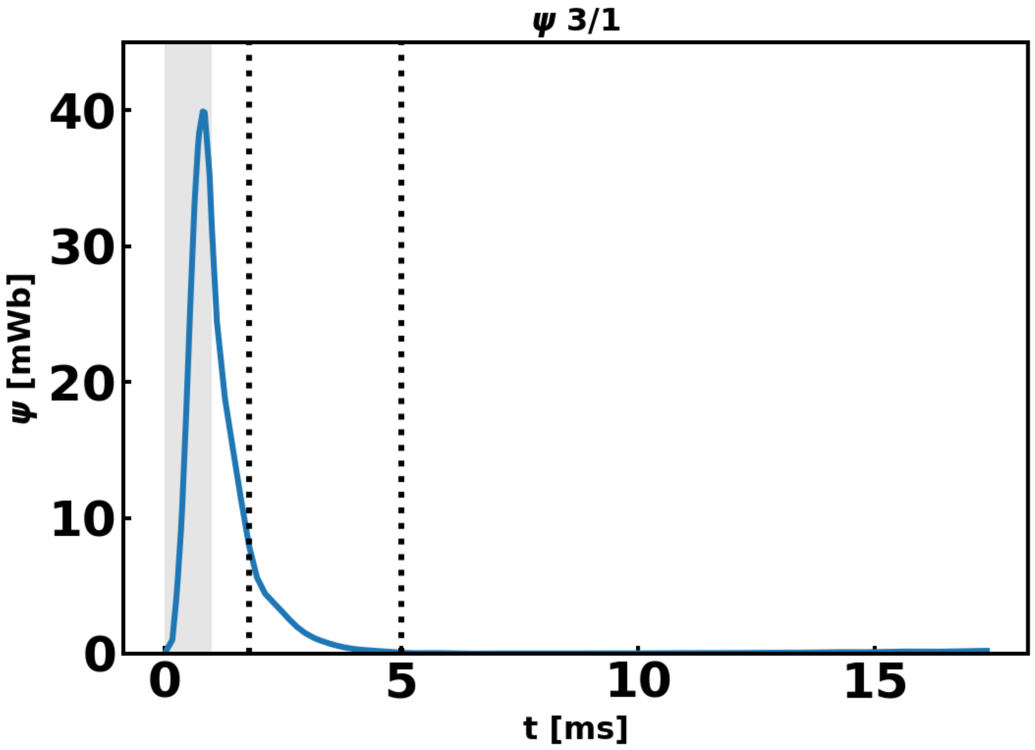




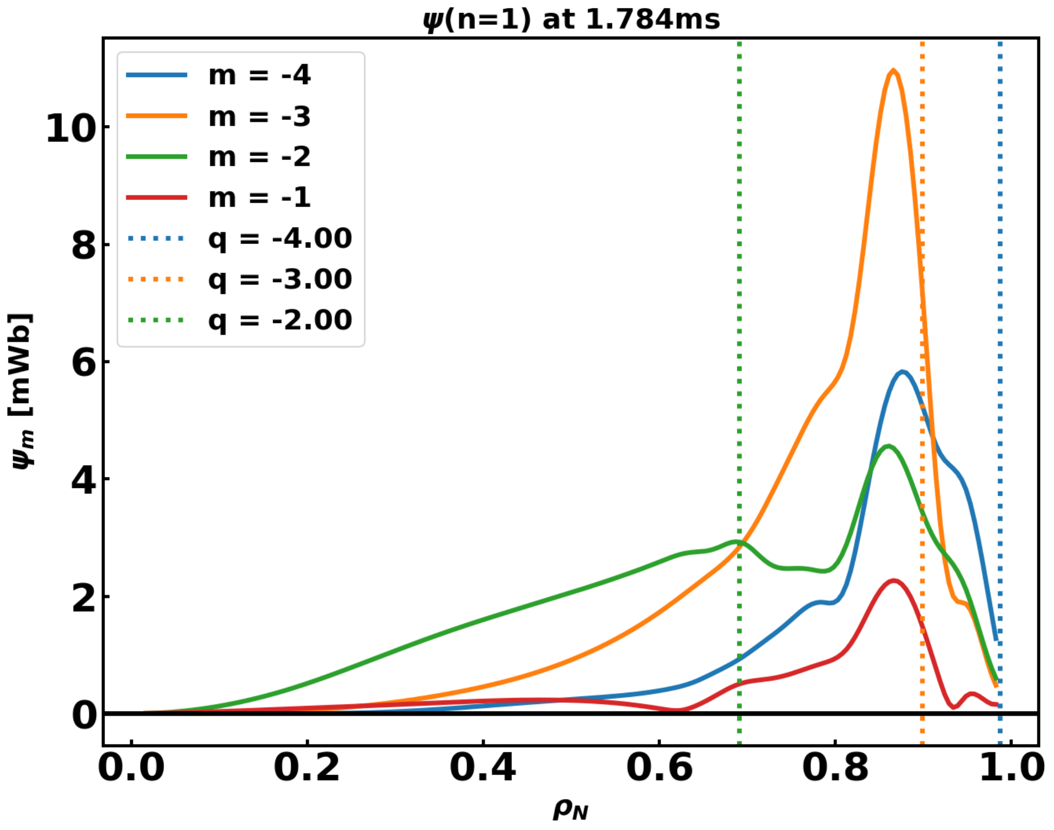
- 2/1 response is strongly screened

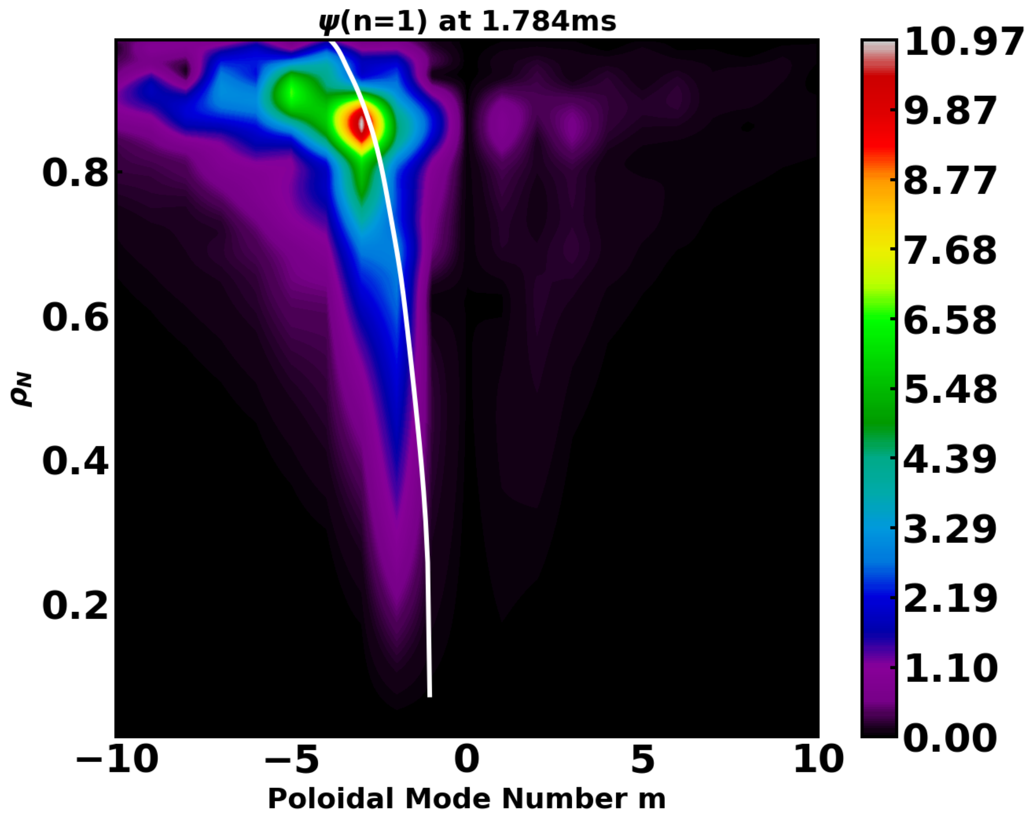
2/1 island grows following applied magnetic perturbation



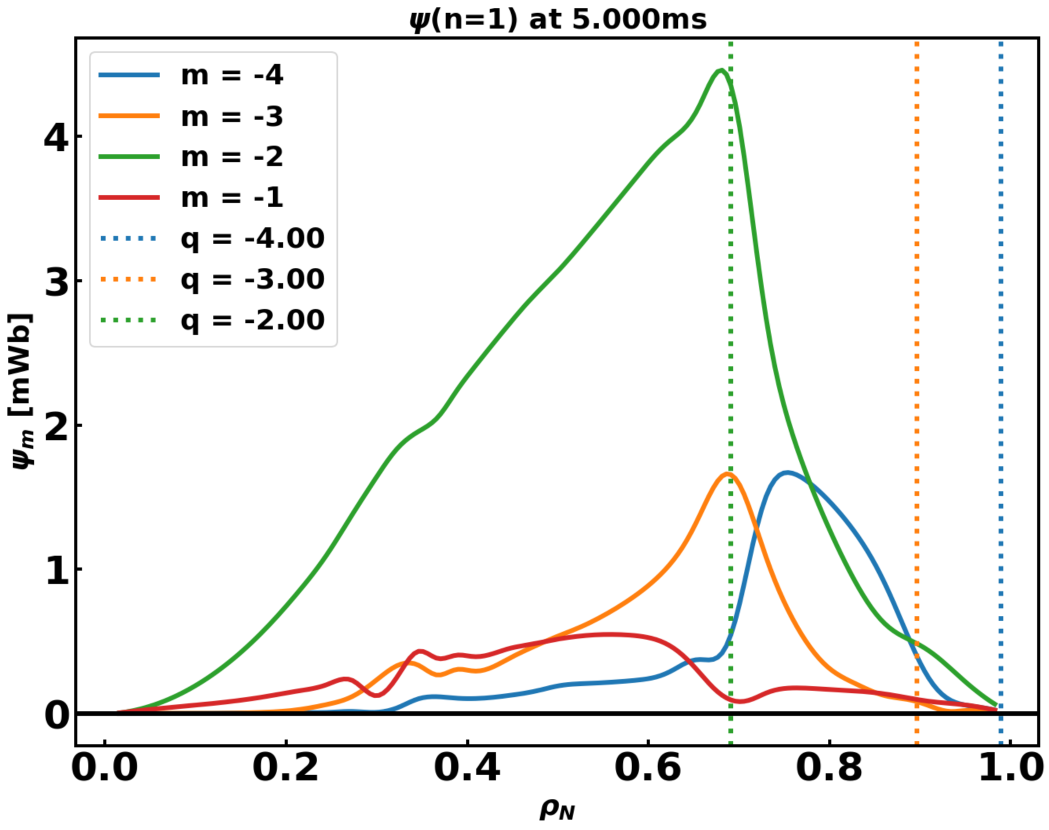


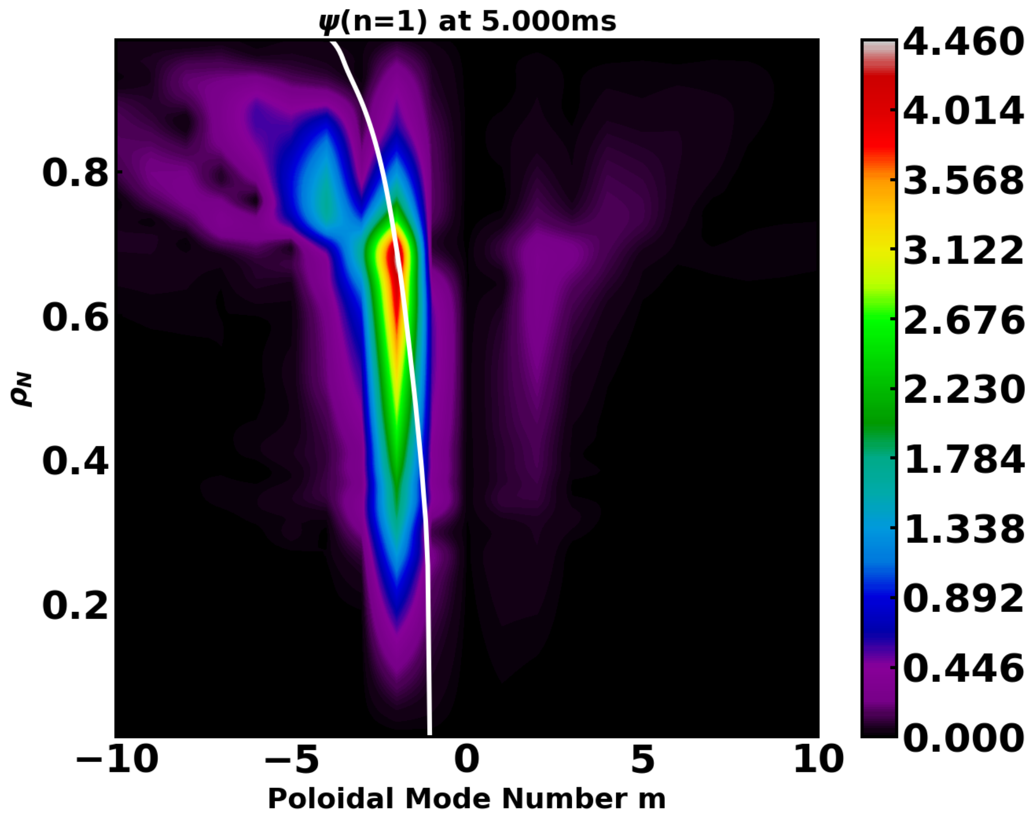
3/1 mode is dominant during the initial decay





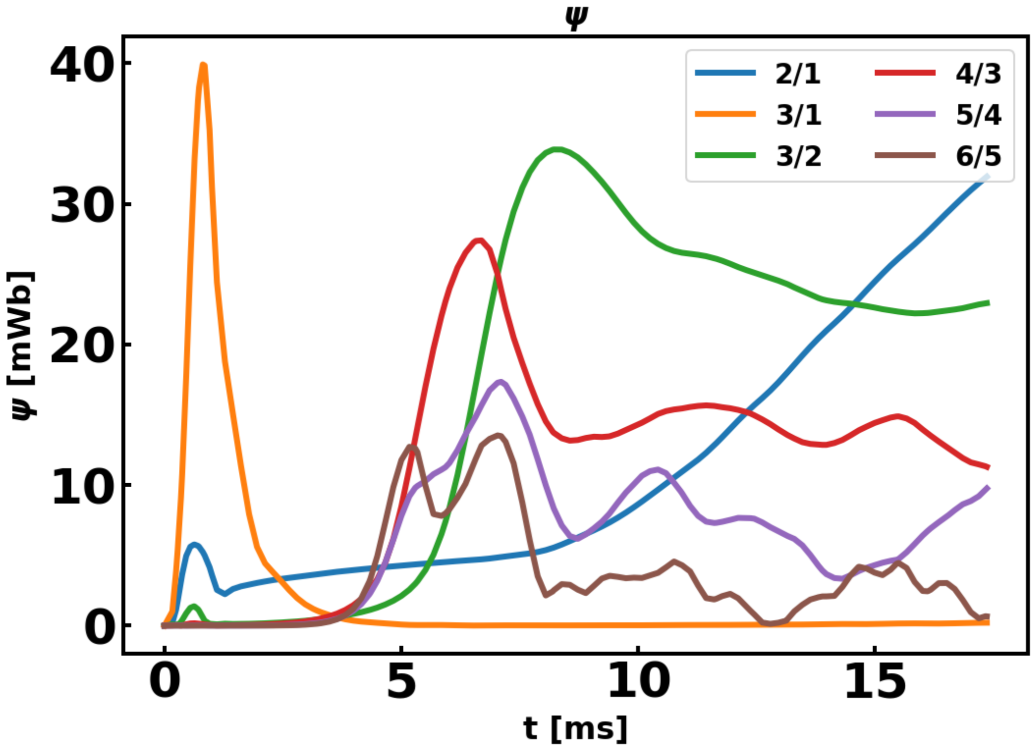
2/1 mode is dominant n=1 mode during slow growth



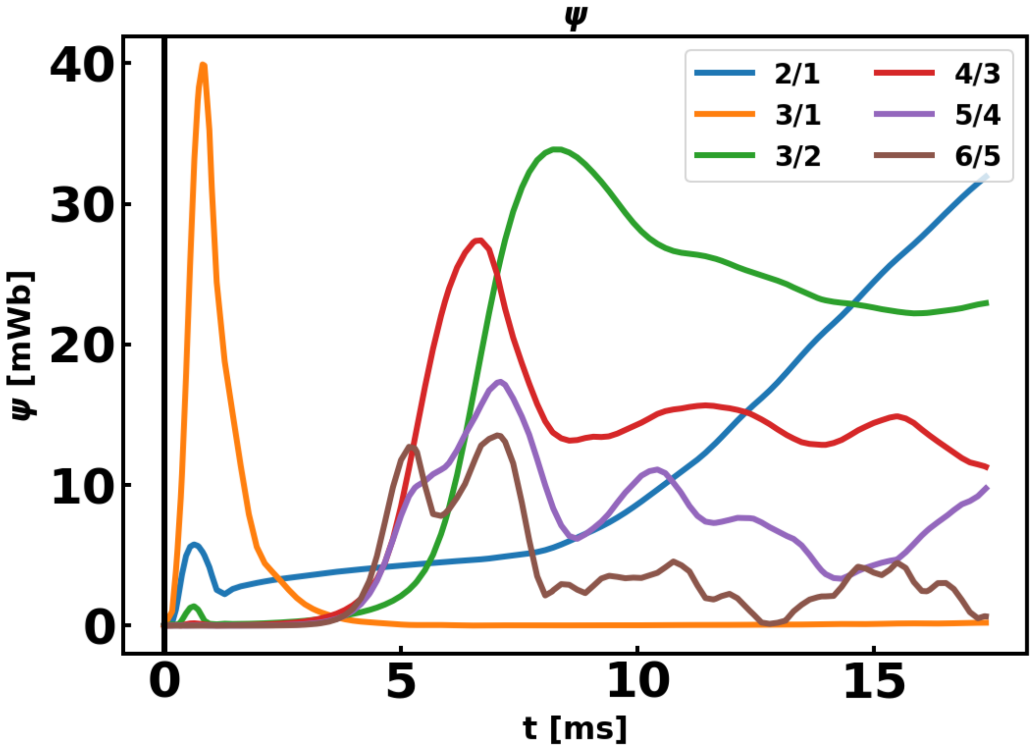


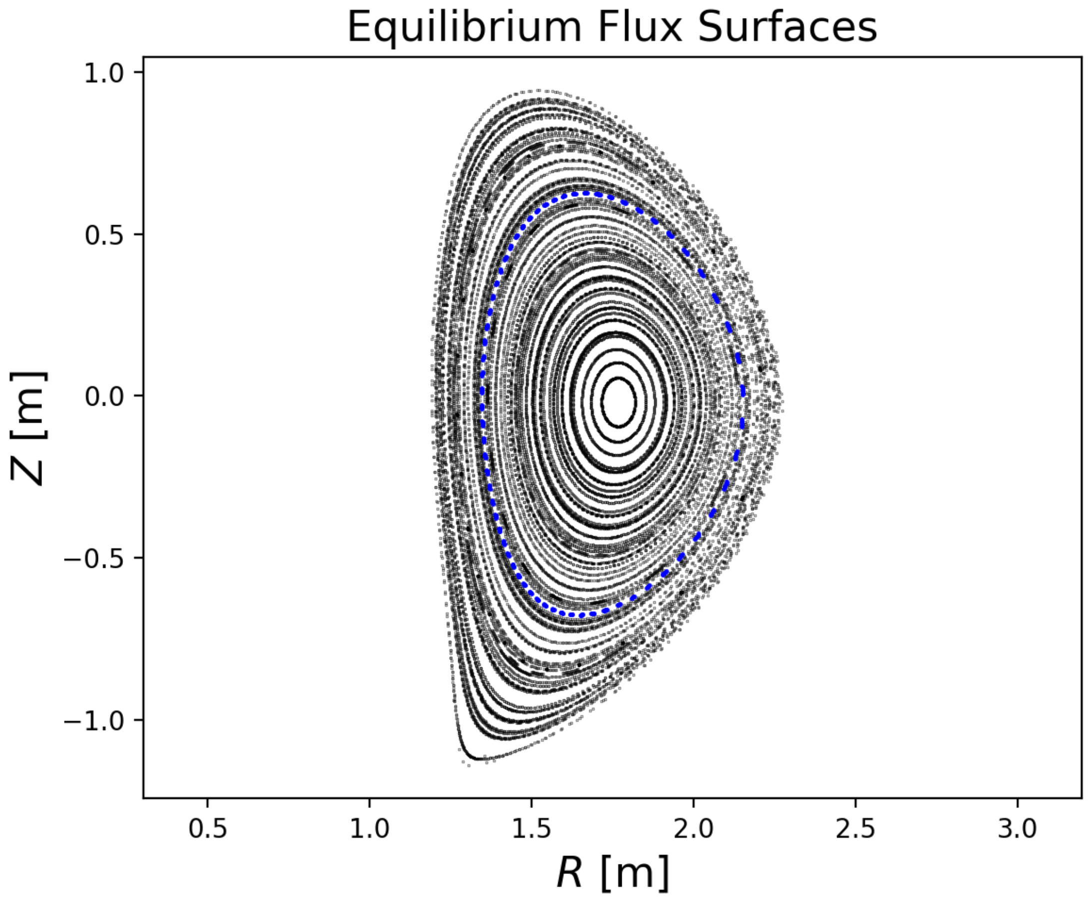
Core modes destabilized at 4ms

- Resonant modes are destabilized in a sequence
  - 6/5, 5/4, 4/3, 3/2, 2/1
- Core modes located in region with weak magnetic shear
- Modes saturate and decay when the next mode in the sequence grows to large amplitude
- Increased growth of the 2/1 mode occurs when the 3/2 mode reaches large amplitude

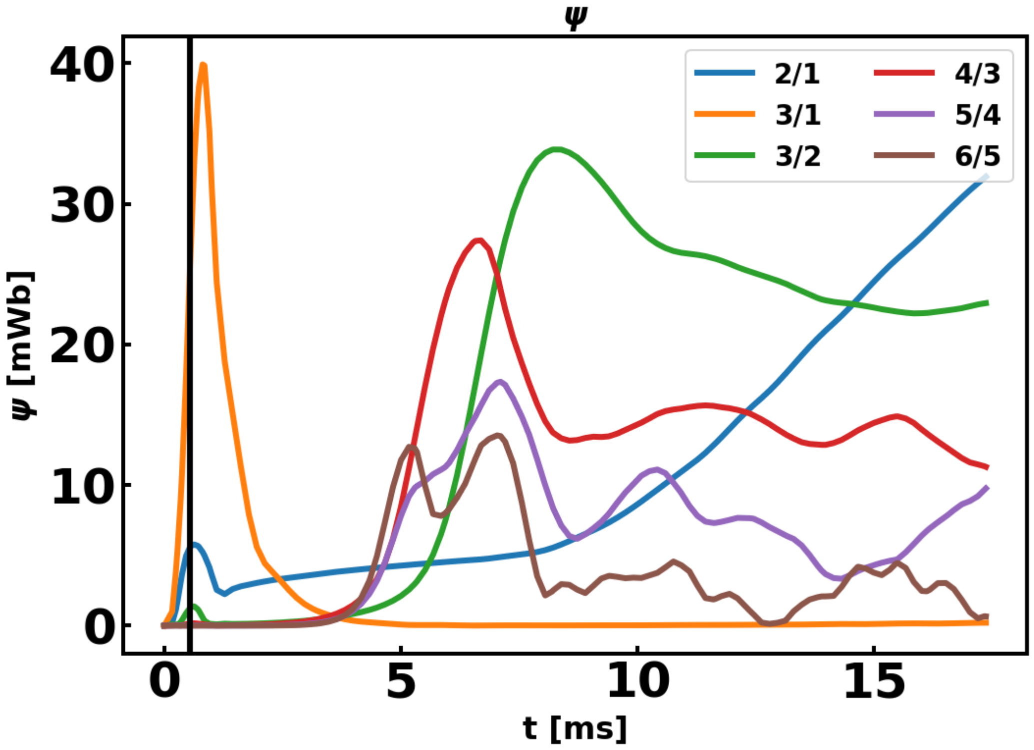


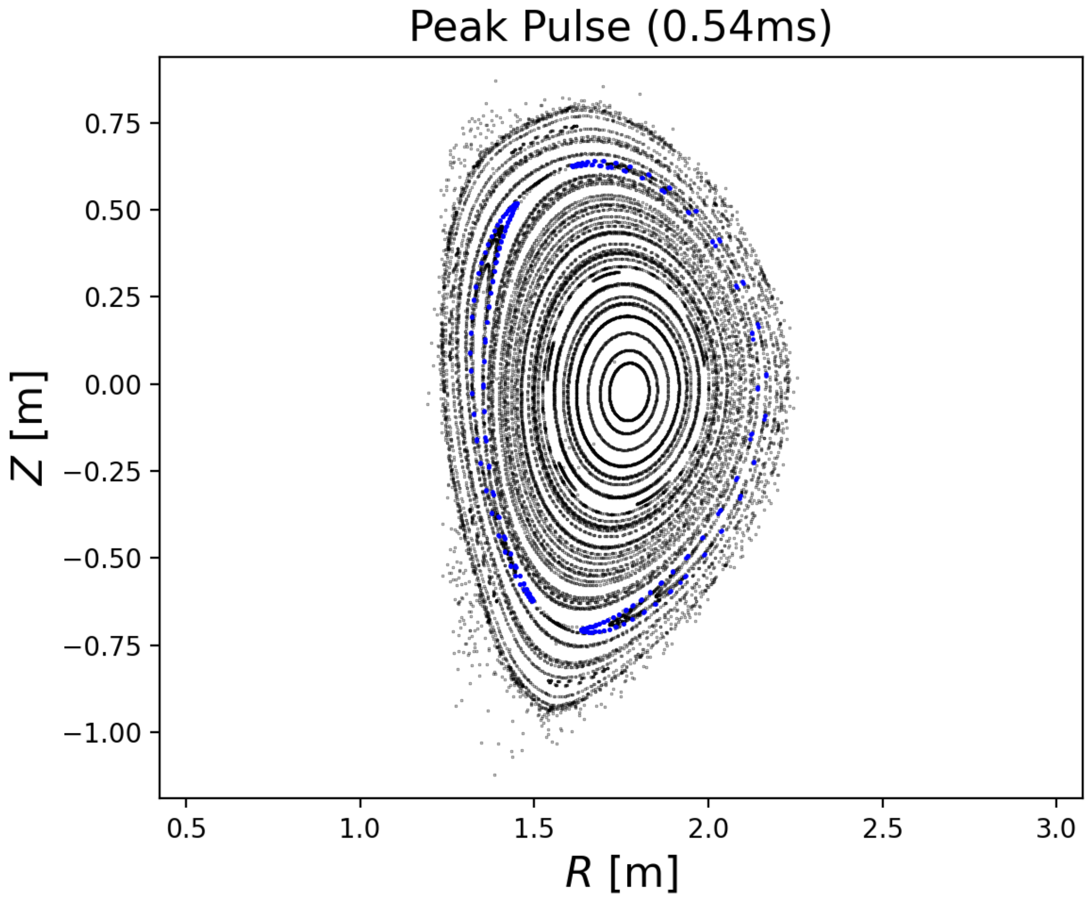
Equilibrium Flux Surfaces



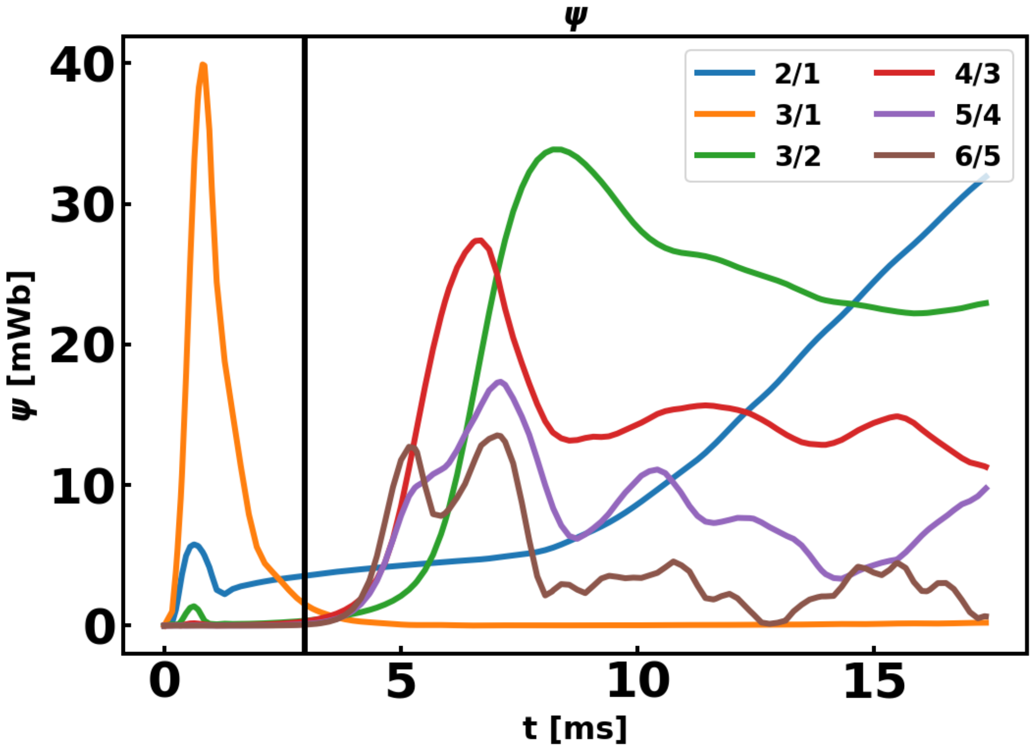


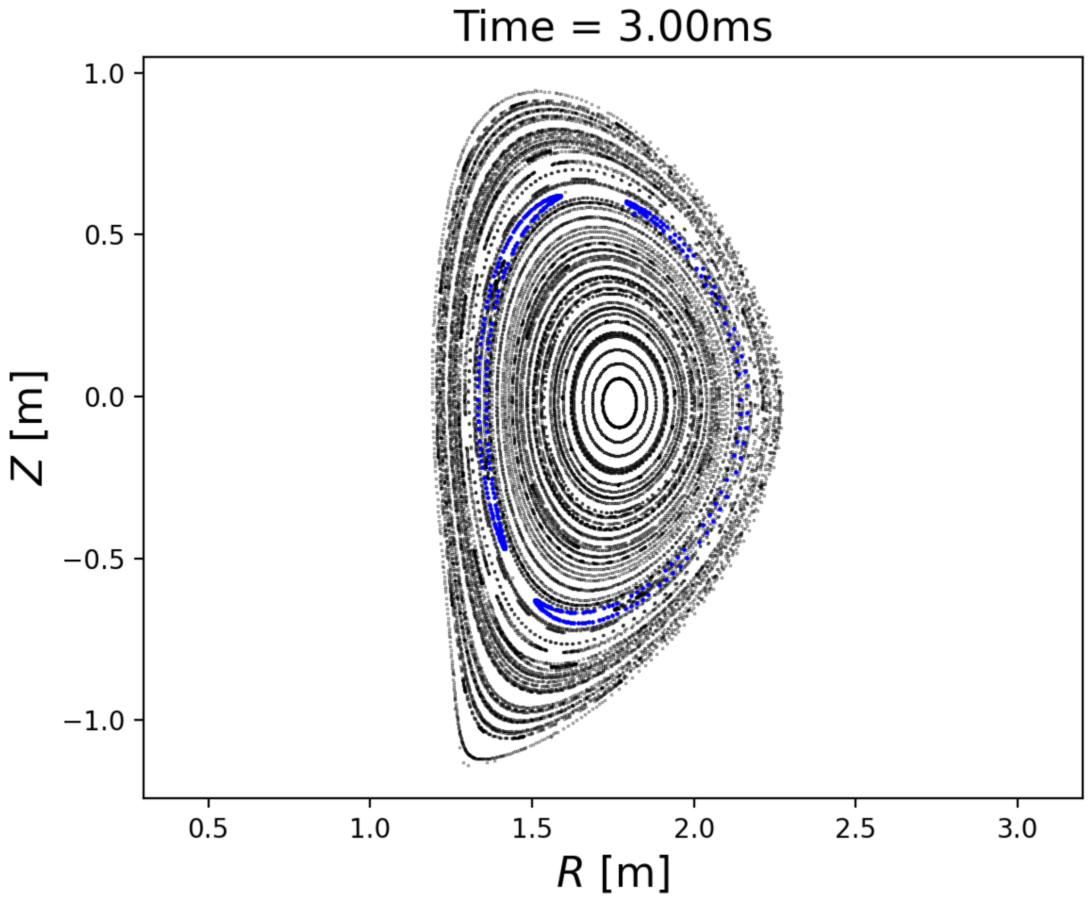
Applied perturbation destroys edge flux surfaces, but core surfaces intact



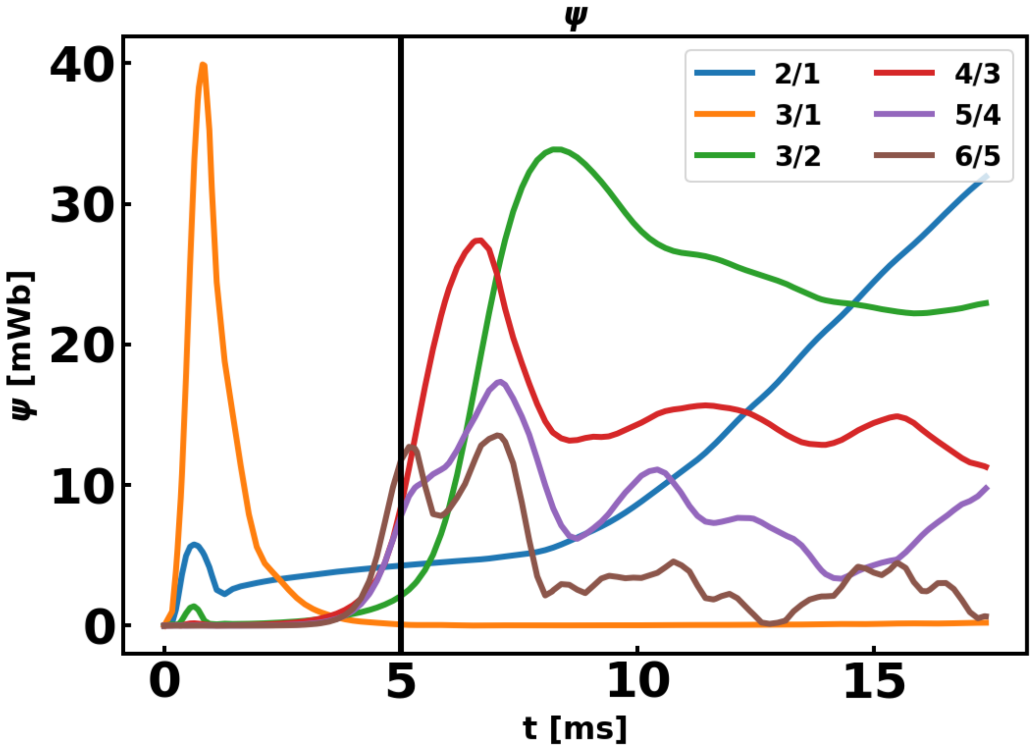


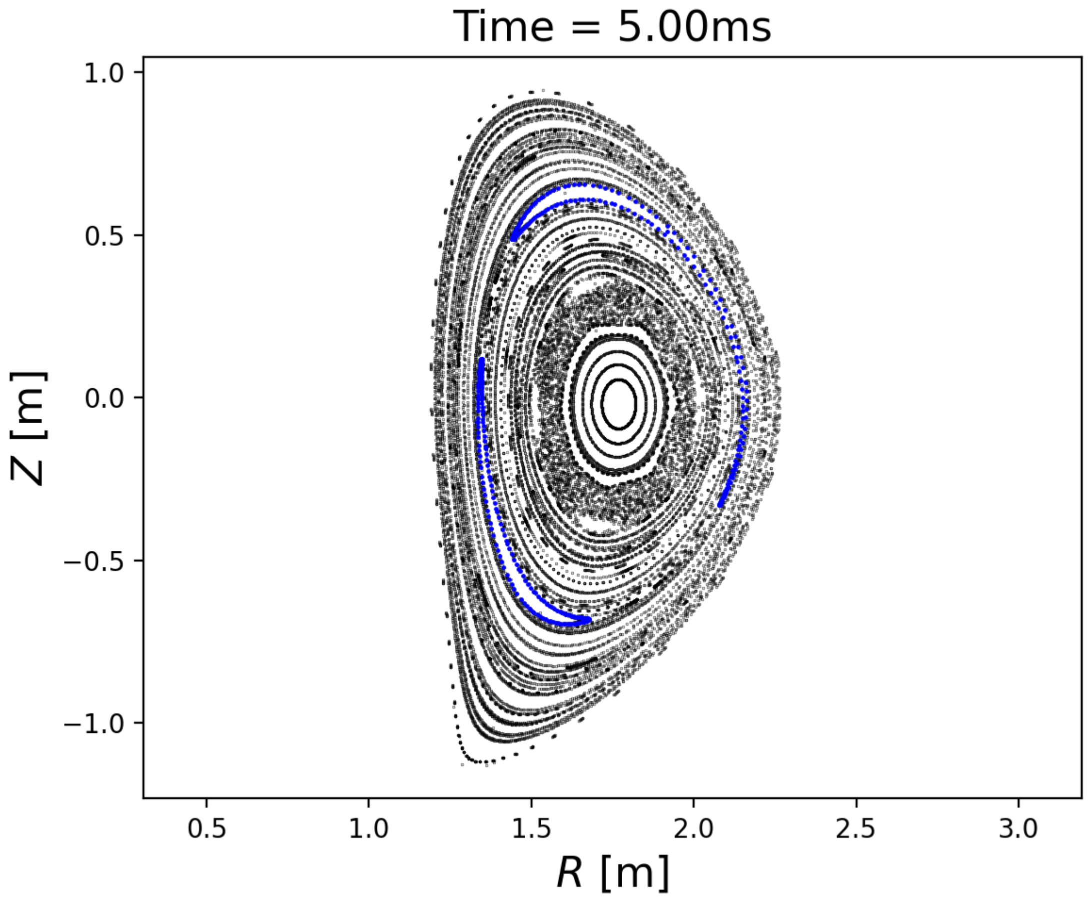
Edge surfaces heal and 2/1 island persists following the pulse



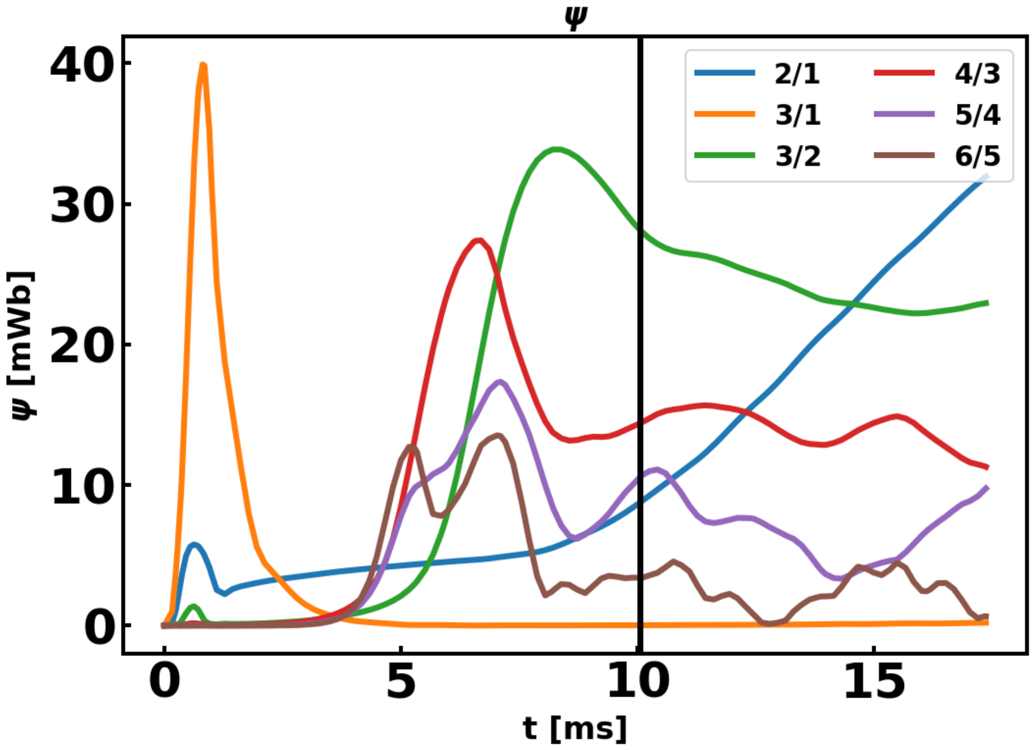


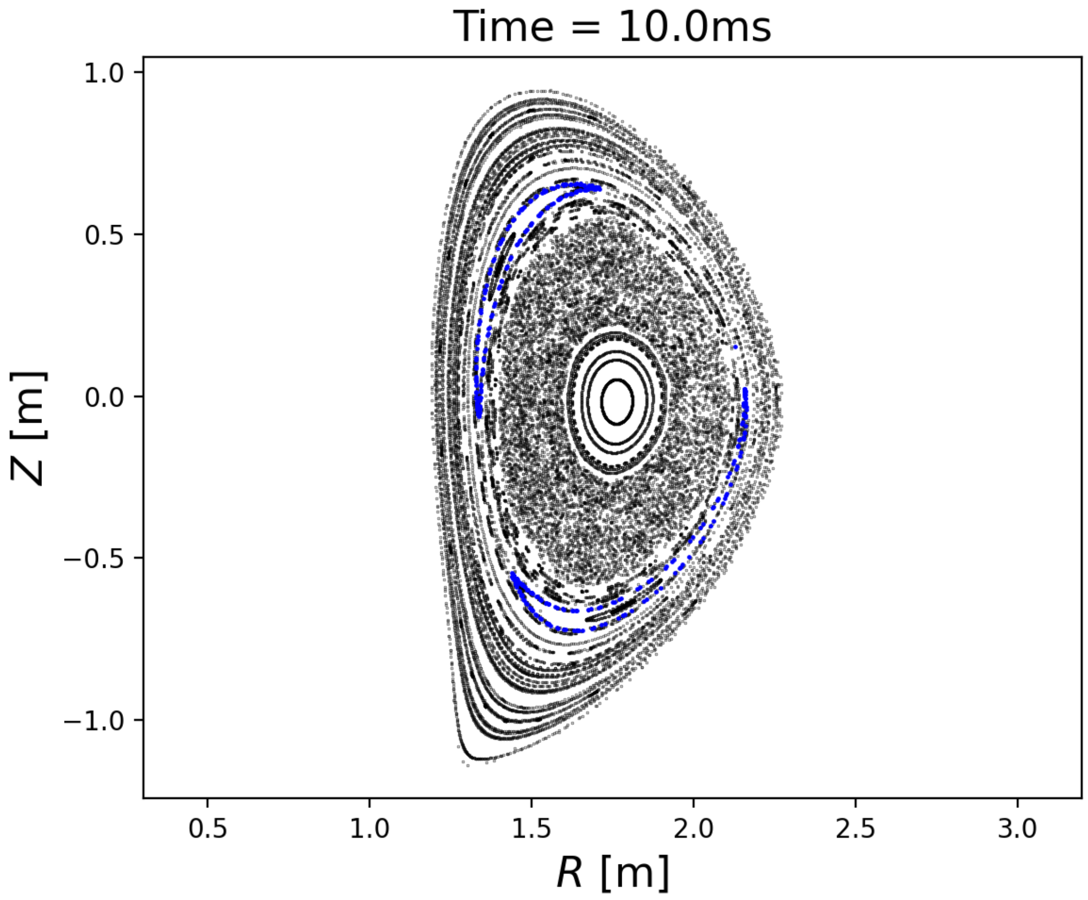
Inner stochastic region forms as core modes grow



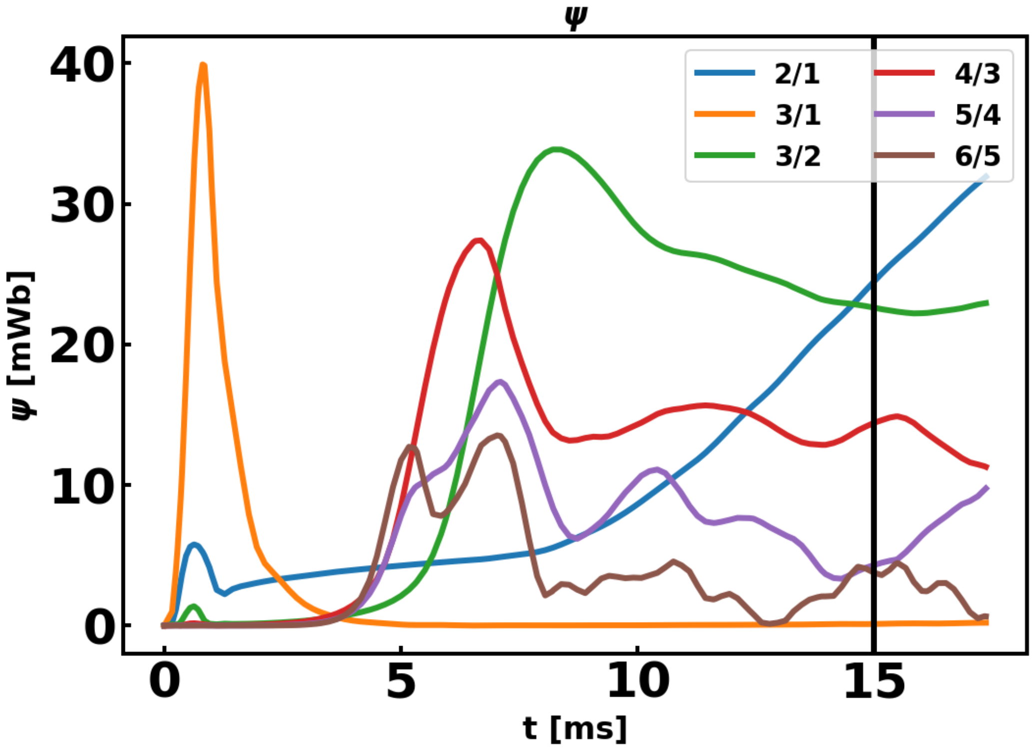


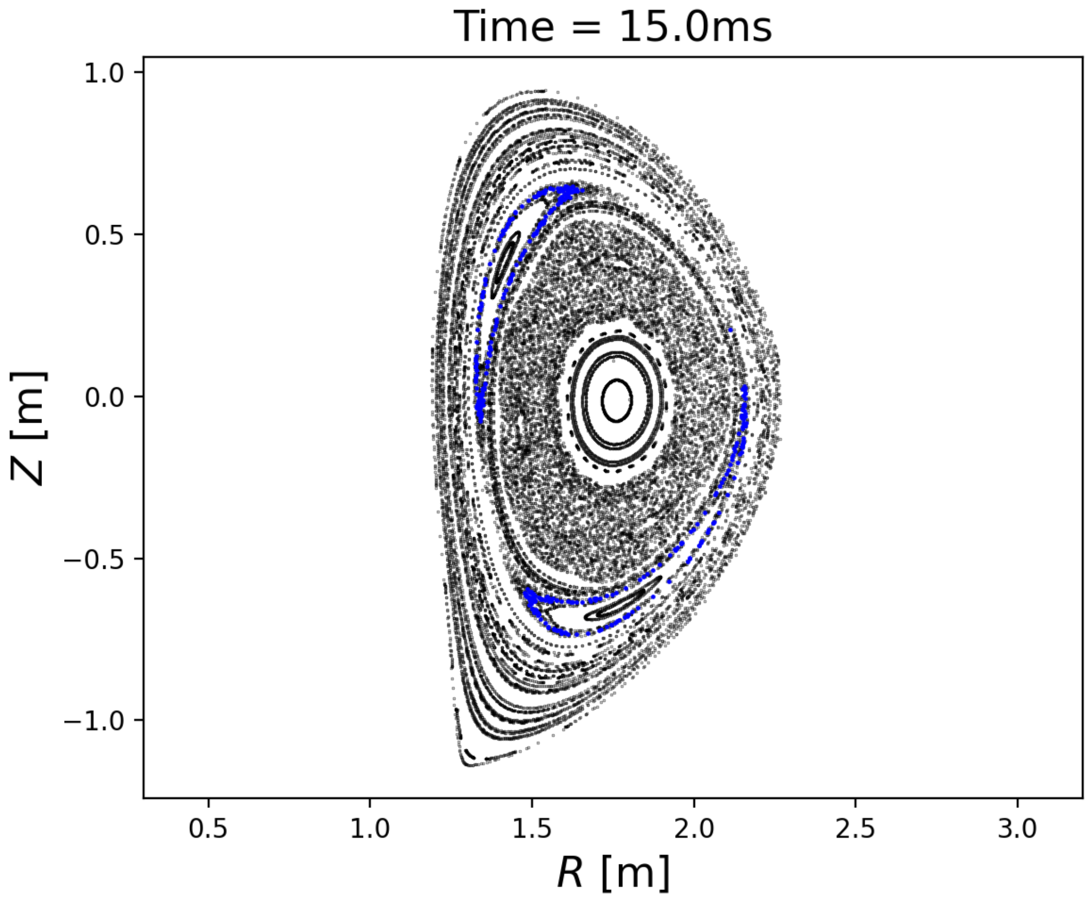
Stochastic region expands outwards as lower order modes grow to large amplitude





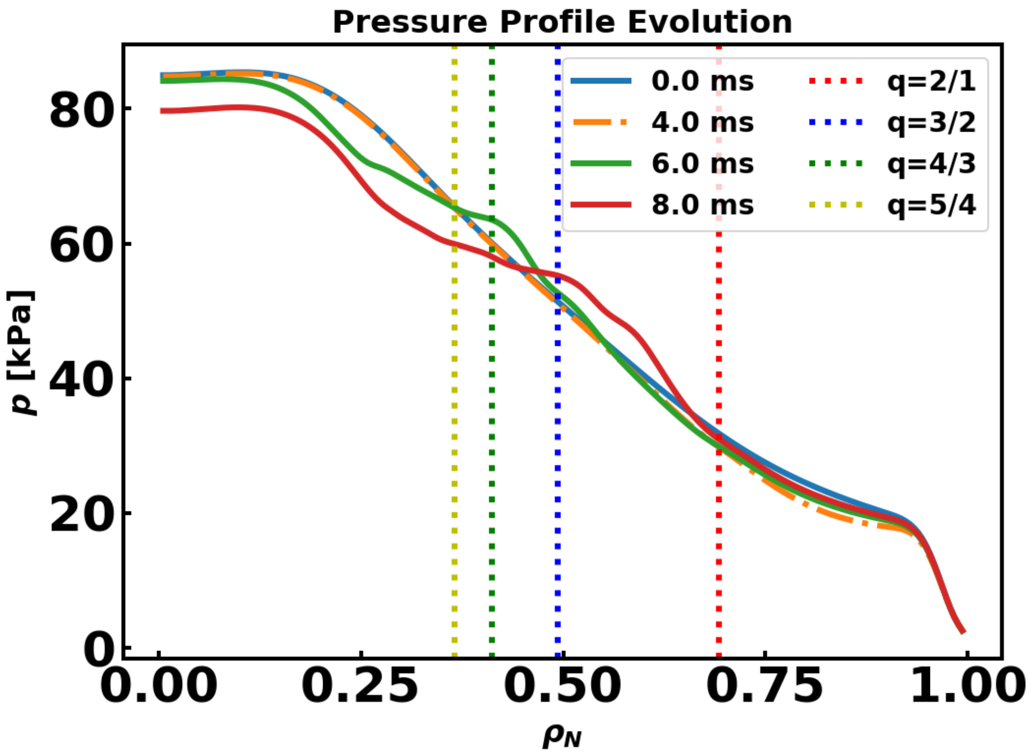
Degradation of core surfaces persists throughout the simulations





Growth of cores modes results in a steeping of the pressure profile outside the stochastic region

- Temperature flattening across the stochastic region steepens pressure gradient outside the region
- The pressure gradient propagates outwards as region grows, eventually destabilizing the next mode in the sequence
- Pressure gradient outside island drives bootstrap destabilization



A similar chain of modes is observed experimentally (on longer time scales)

- 4/3 mode at 2000ms (green)
- 3/2 mode appears later around 2250ms (yellow)
- 4/3 mode disappears around 3100ms after 3/2 mode reaches large amplitude
- 2/1 mode persists at 3400ms (red)

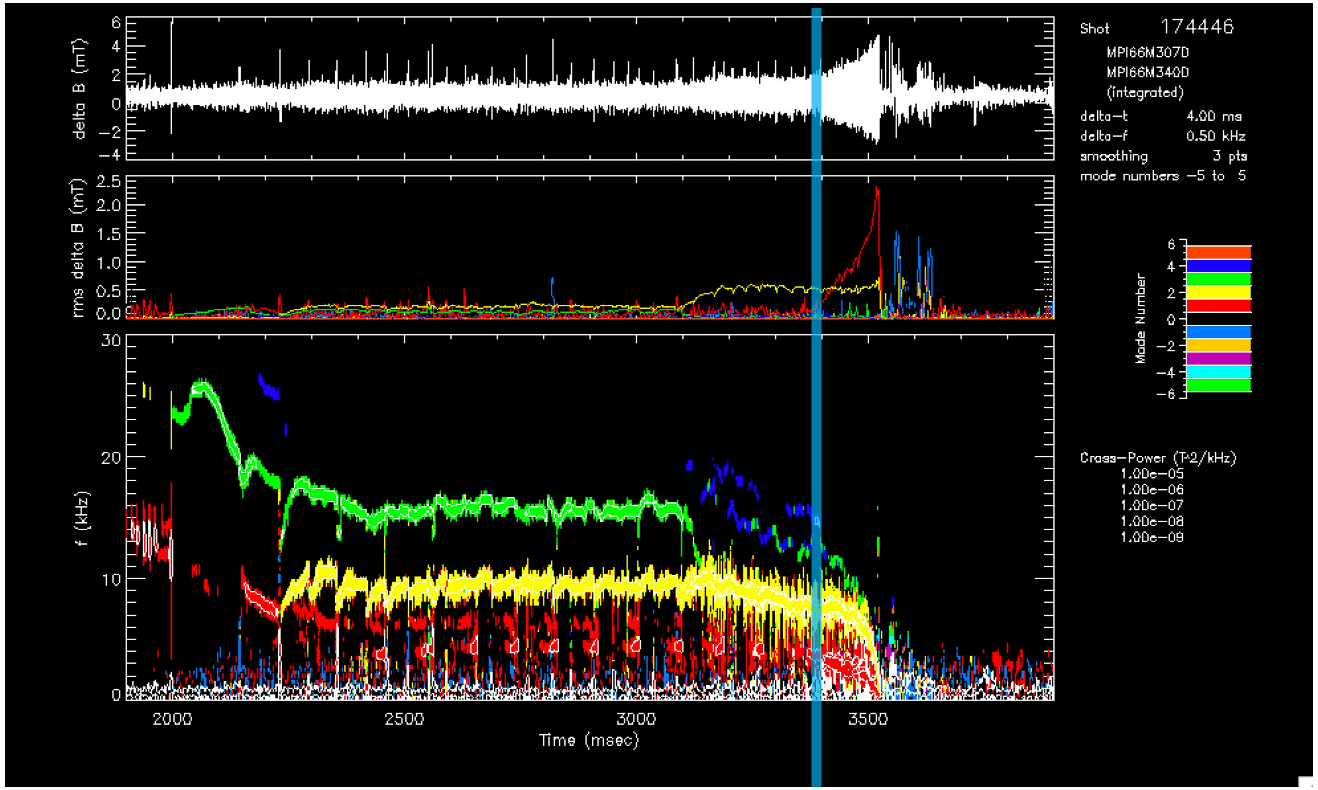


Image curtesy R. La Haye

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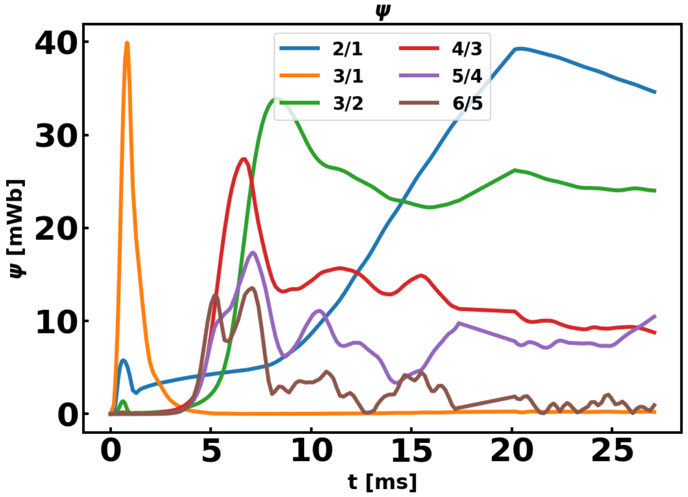
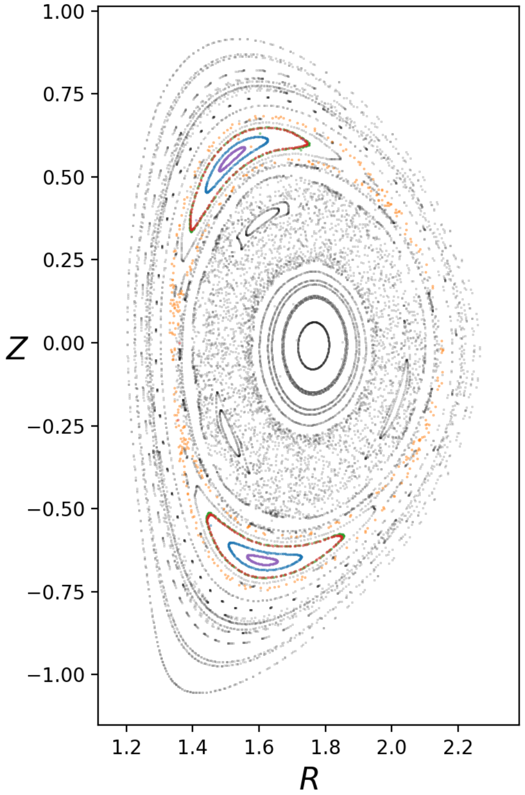
Conclusions

- Demonstrate ability to excite NTM using an external perturbation in a classical tearing mode stable case
- Rich nonlinear coupling leads to destabilization of 2/1 mode from an external perturbation
- Growth of core resonant modes leads to a chain of events
  - Steeping pressure profile inside 2/1 surface
  - Enhances bootstrap current drive
  - Increased 2/1 NTM growth

Future Work: Can we produce a saturated 2/1 island at modest amplitude?

- Goal: Study locking of 2/1 NTM due to error fields and resistive wall
- Reducing μ_e decreases the bootstrap current drive
  - Smaller saturated islands
- Here reducing μ_e by ½ at 20ms cause core modes to decay



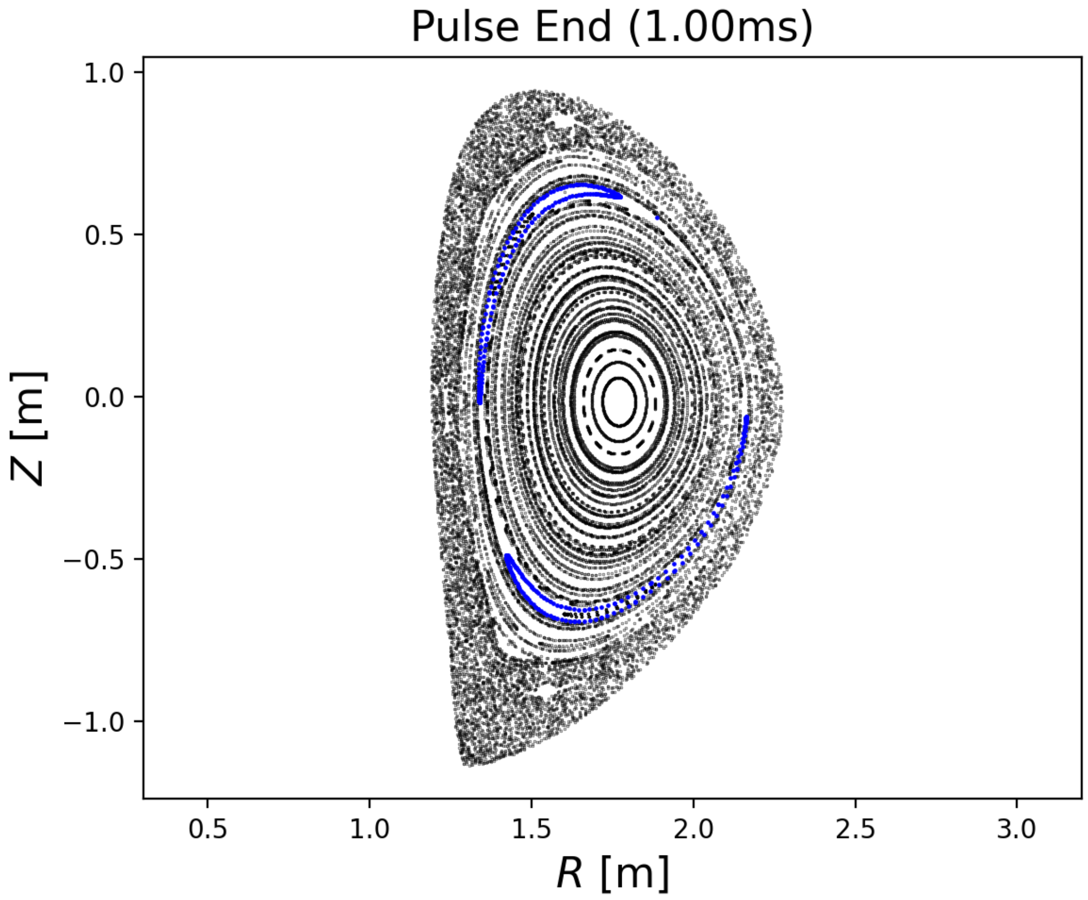


Discussion

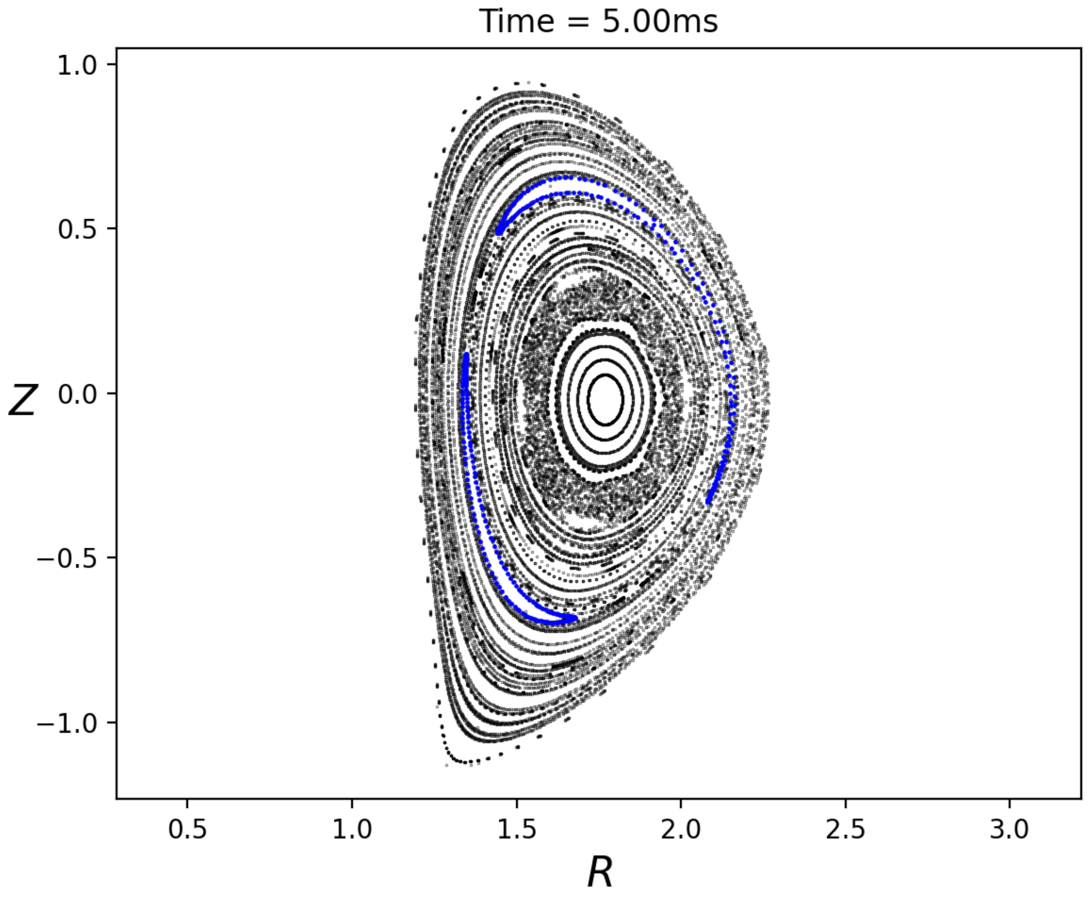
- Relate work to continuum kinetic closures?
  - Run DKE calculation of $\nabla \cdot \overleftrightarrow{\Pi}$ from static MHD perturbation and compare with closures

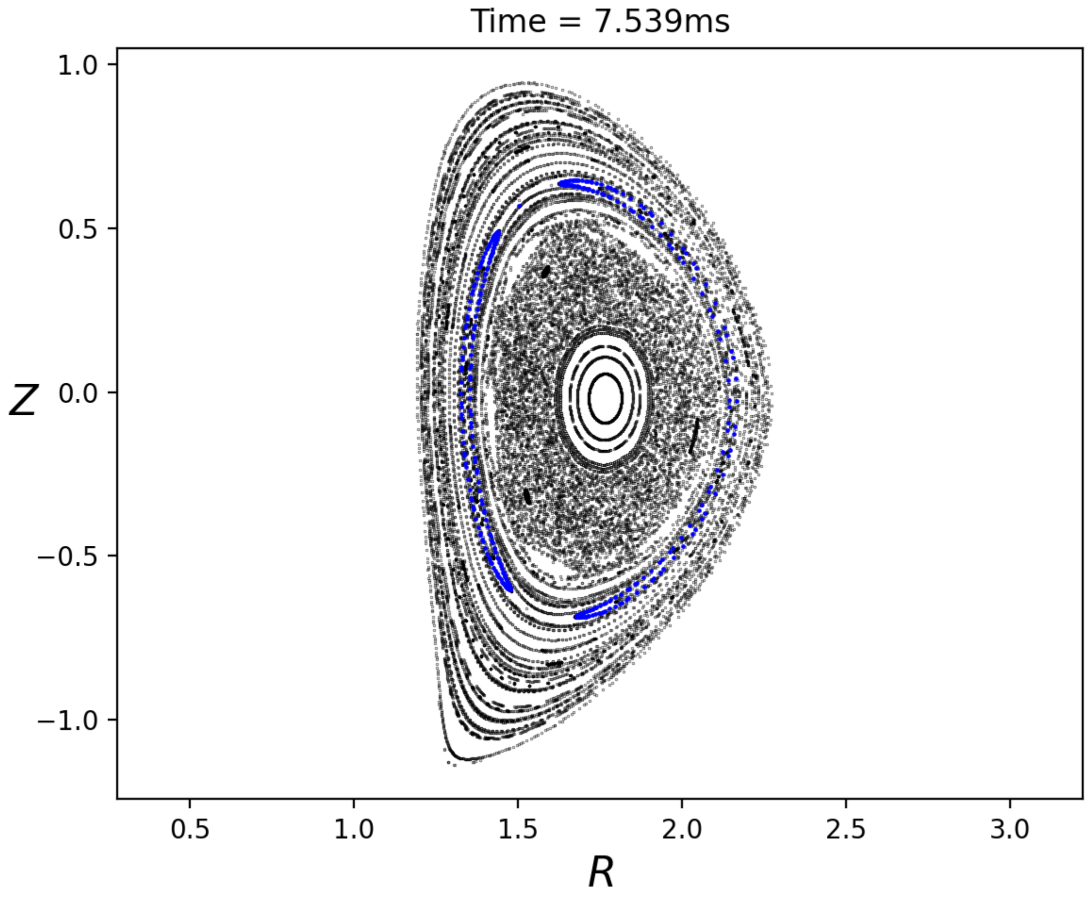
Extra Slides

Applied perturbation destroys edge flux surfaces, but core surfaces intact



Degradation of core surfaces persists throughout the simulations





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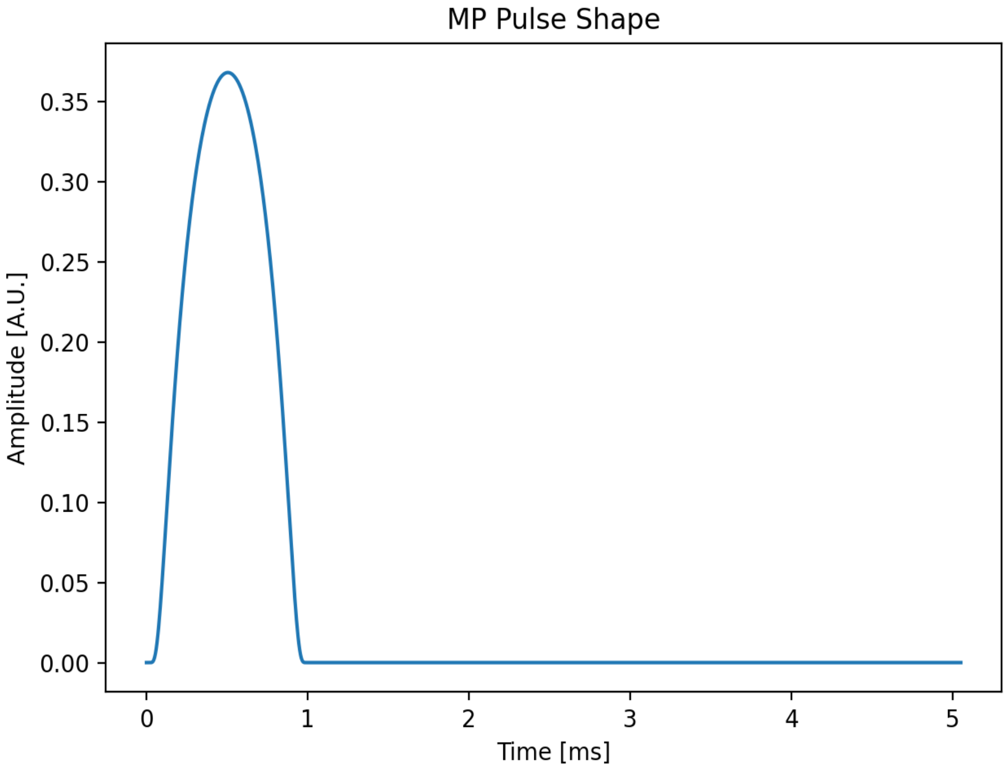
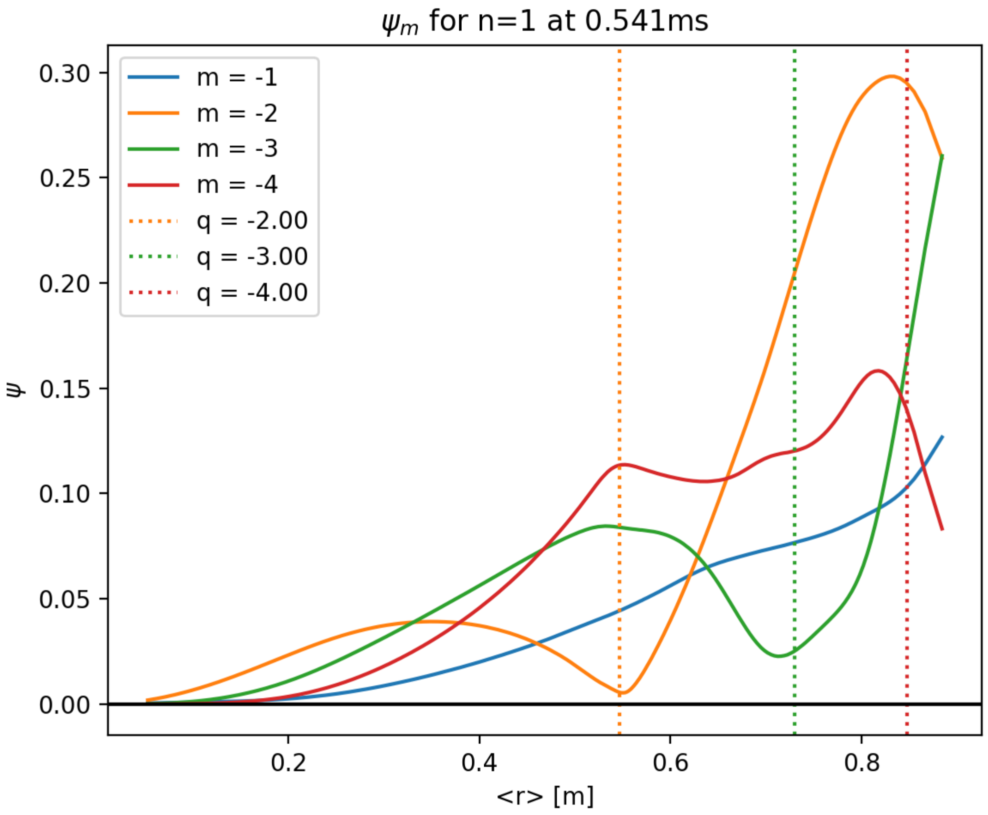
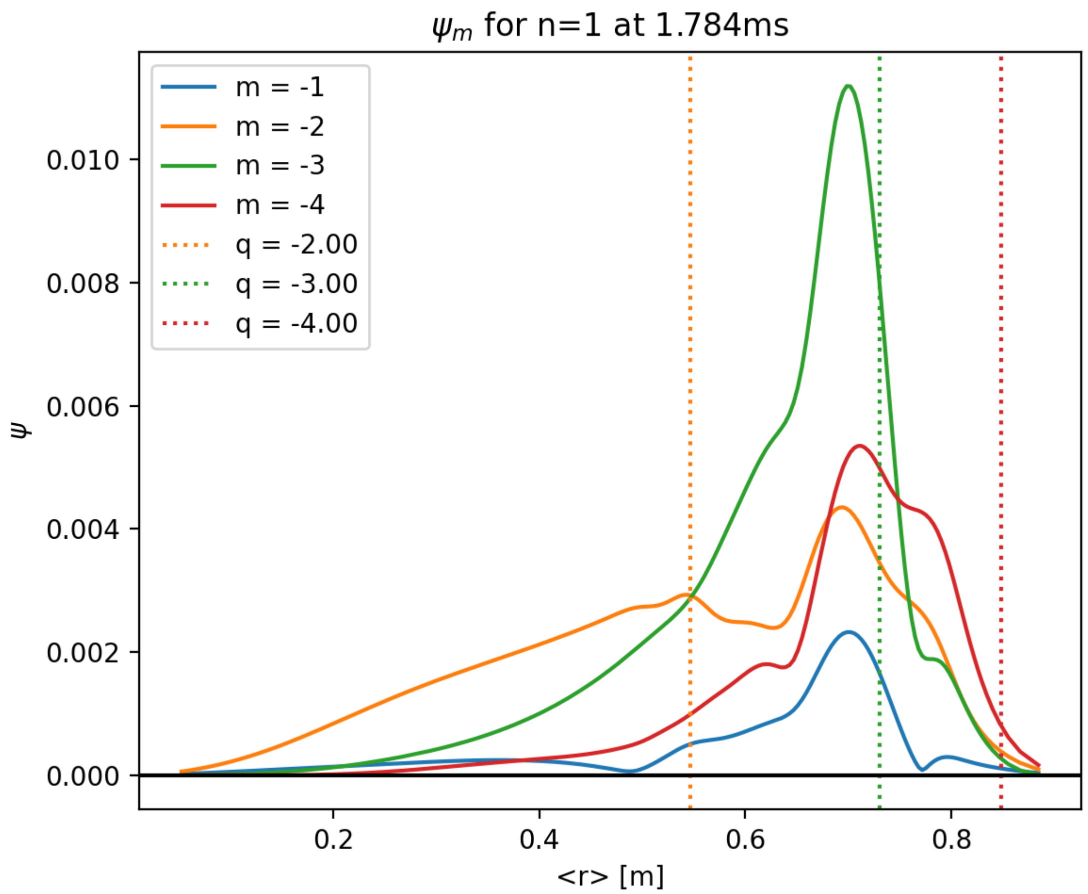
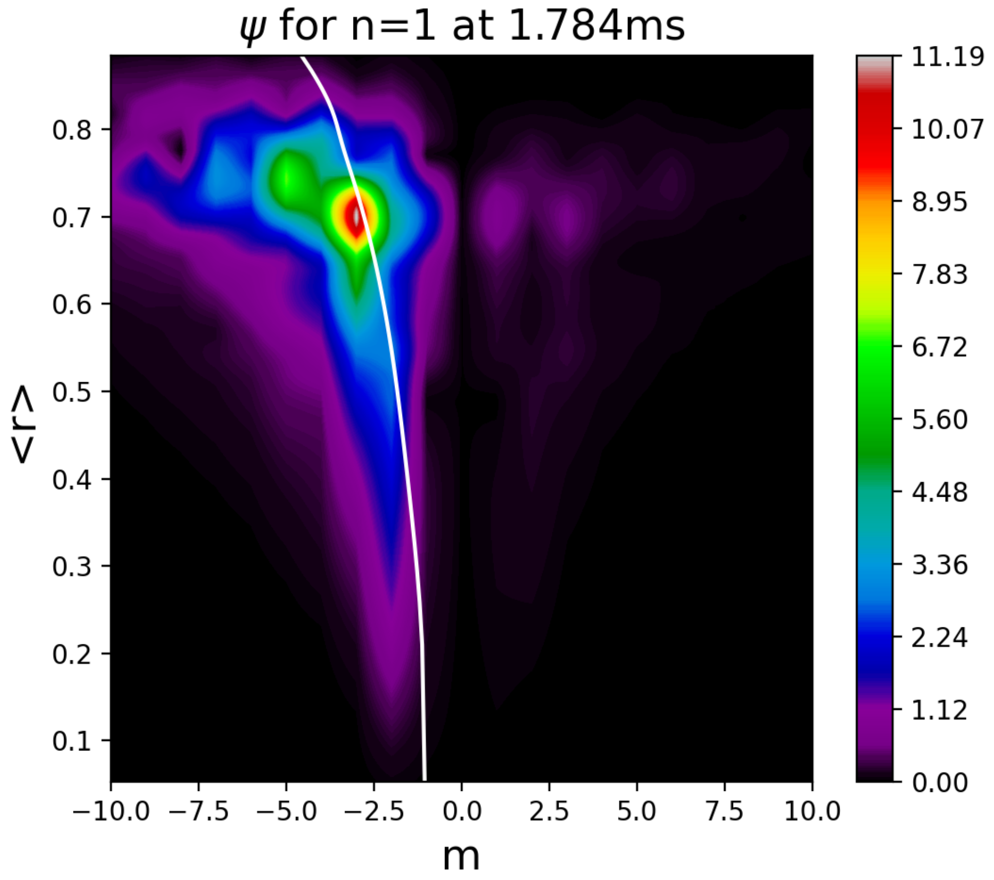




- 2/1 response is strongly screened

3/1 mode is dominant during the initial decay





2/1 mode is dominant n=1 mode during slow growth