Simulations of Neoclassical Tearing Mode Growth with Realistic Wall Boundary Conditions

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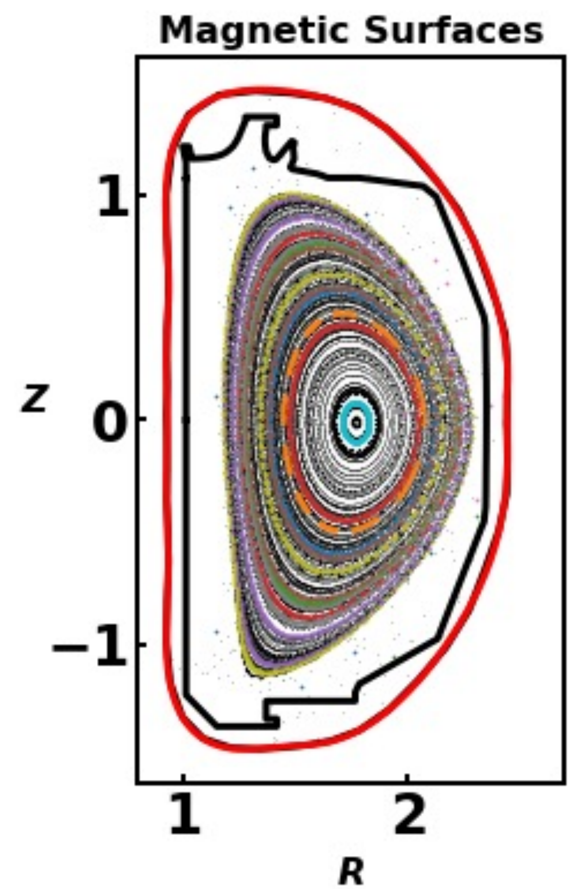
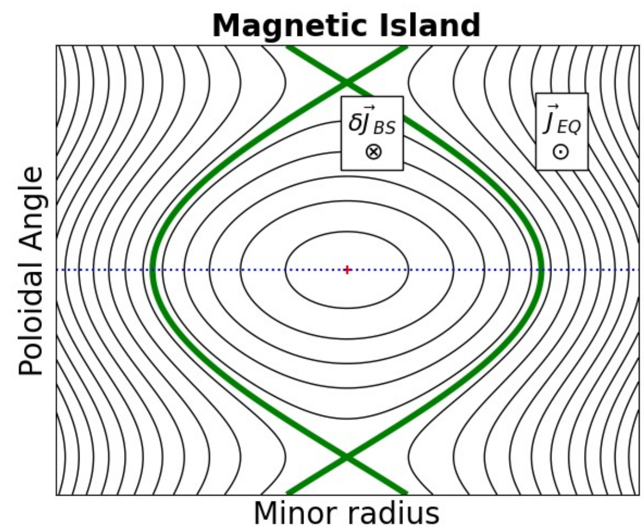
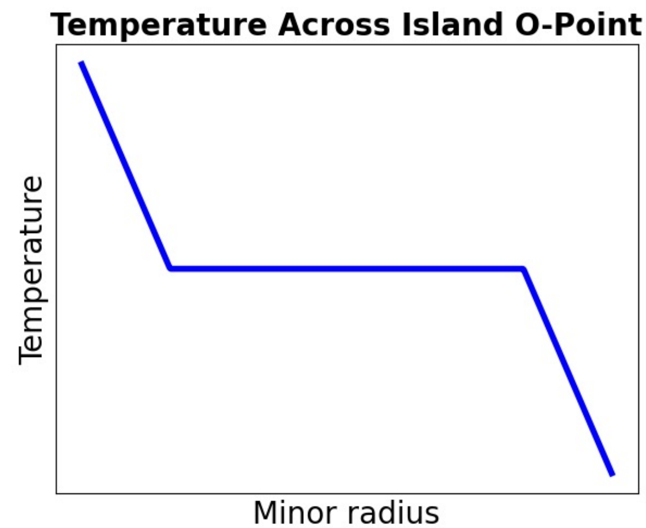


Neoclassical Tearing Modes (NTMs) are a leading physics cause of disruptions

- **Pressure-gradient driven bootstrap current destabilizes NTM**[1]
  - Current caused by drag of passing electrons on trapped electrons
- **Seed Island generated by helical current perturbation**
- **Transport flattens pressure across island**
  - Resulting missing helical bootstrap current perturbation reinforces island current
- **Large islands degrade confinement and trigger disruptions**





[1]E.g. Hegna PoP 5 (1998)

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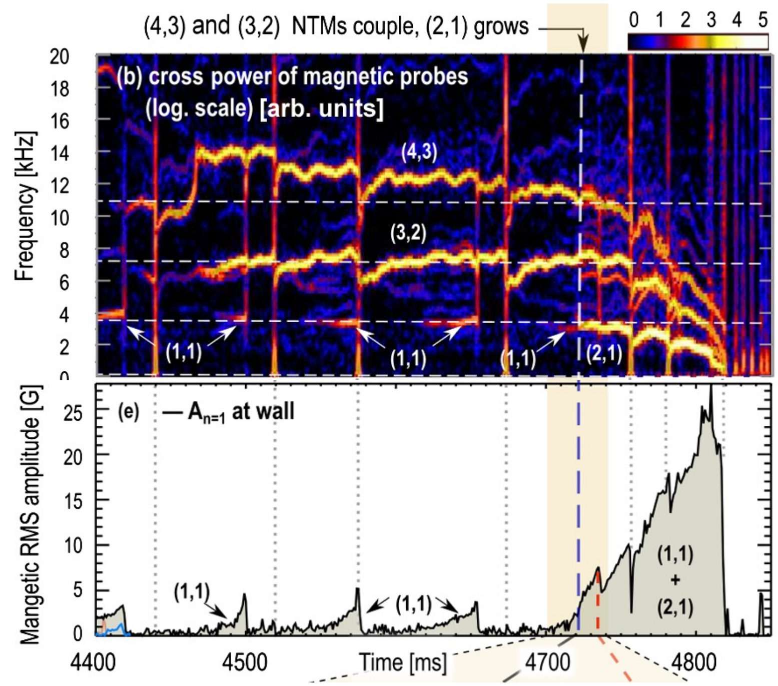
Nonlinear simulations are needed to understand NTM physics

- **Modified Rutherford Equation (MRE): standard tool for understanding NTMs**
  - $\frac{\rho_0}{D_\eta}\frac{dw}{dt} = \rho_0\Delta' + \frac{\rho_0 d_{NTM}}{w} - \frac{\rho_0 w^2_{polF(f_m)}}{w^3} + \cdots$
  - Assumes single helicity thin island

- **Many important issues occur where MRE is insufficient**
  - Transient seeding: sawteeth, ELM's
  - Seeding via 3-mode interactions
  - Disruption trigger via island overlap
  - Island bifurcation impact on ECCD

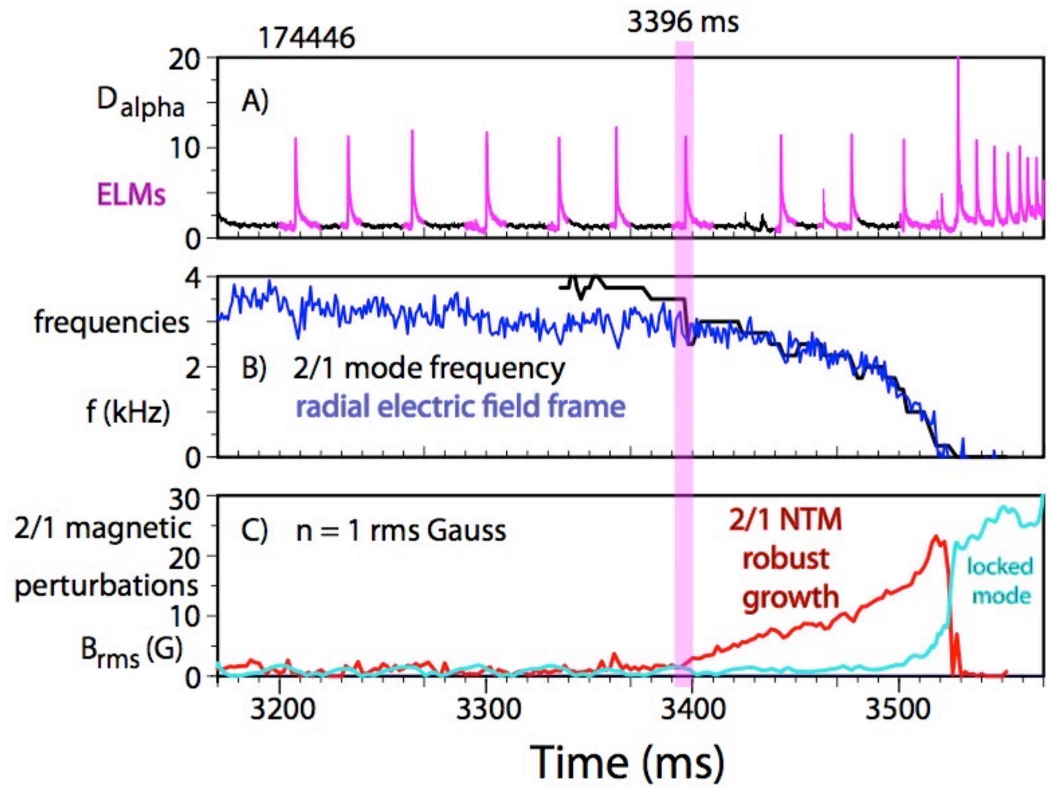
Seeding via 3-mode interactions[1]



[1] L. Bardóczi, PRL 127 (2021)

Simulations study NTM physics experimentally relevant equilibria

- **Use reconstructions of DIII-D ITER baseline scenario discharge**[1,2]
  - ELM at 3396ms triggers 2/1 NTM
  - NTM locks in ~100ms
- **High resolution measurements enable high fidelity kinetic reconstruction**
  - Realistic n_e, T_e, P, J, Ω profiles
  - ITER shaping



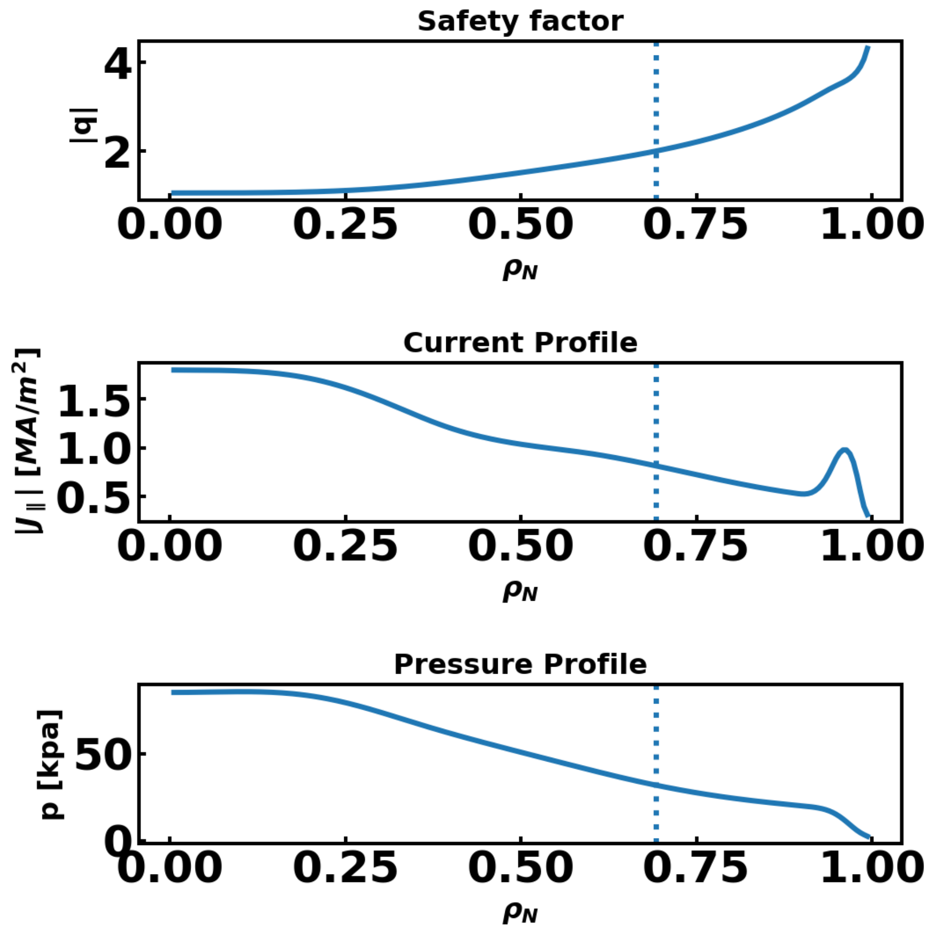
[1]La Haye, NF (2022)

[2]Callen, APS-DPP TI02:00005 (2020)

Simulations initialized with kinetic reconstruction immediately prior to NTM seeding and growth

Parameters at q=2	NIMROD	Experiment
S	2.5×10^6	7.9×10^6
Pr_M	23	11
$(\chi_\parallel/\chi_\perp)^{1/4}$	100	260
$\mu_e/(\nu_{ei} + \mu_e)$	0.55	0.45

- **Normalized parameters are within a factor of 3 at 2/1 surface**
- **Reconstructed toroidal and poloidal flows are required for ELM stability**
- **Fix $|q_0|>1$ to avoid 1/1**



Heuristic Closures Model Neoclassical Stresses in NIMROD[1,2]

- **Closures**[1] **used in resistive MHD**[2]
  - Generalizes to x-MHD
- **Models dominant neoclassical effects**
  - Bootstrap current drive
  - Poloidal ion flow damping
- **Closures depend on quantities available in fluid simulations**

$$\frac{Dn_e}{Dt} = -n_e \nabla \cdot \vec{V}$$

$$\rho \frac{D\vec{V}}{Dt} = -\nabla p + \vec{J} \times \vec{B} - \boldsymbol{\nabla} \cdot \vec{\vec{\boldsymbol{\Pi}}}_{\mathbf{i}} - \nabla \cdot \vec{\vec{\Pi}}_{Classical}$$

$$\frac{n_s}{\Gamma_s - 1}\left(\frac{dT_s}{dt} + \vec{V} \cdot \nabla T_s\right) = -\Gamma p_s \nabla \cdot \vec{V} - \nabla \cdot \vec{q_s}$$

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \left(-\vec{V} \times \vec{B} + \eta \vec{J} - \frac{\mathbf{1}}{\mathbf{n_e e}} \boldsymbol{\nabla} \cdot \vec{\vec{\boldsymbol{\Pi}}}_{\mathbf{e}}\right)$$

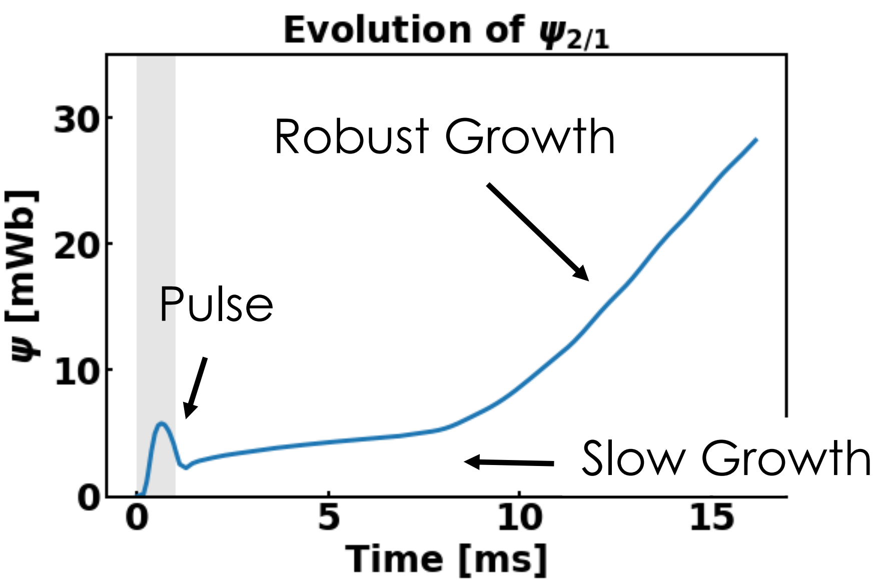
$$\boldsymbol{\nabla} \cdot \vec{\vec{\boldsymbol{\Pi}}}_{\mathbf{i}} = \boldsymbol{\mu_i n_i m_i} \langle \mathbf{B_{eq}^2} \rangle \frac{\vec{\mathbf{V}} \cdot \vec{\mathbf{e}}_{\Theta}}{\left(\vec{\mathbf{B}}_{\mathbf{eq}} \cdot \vec{\mathbf{e}}_{\Theta}\right)^2} \vec{\mathbf{e}}_{\Theta}$$

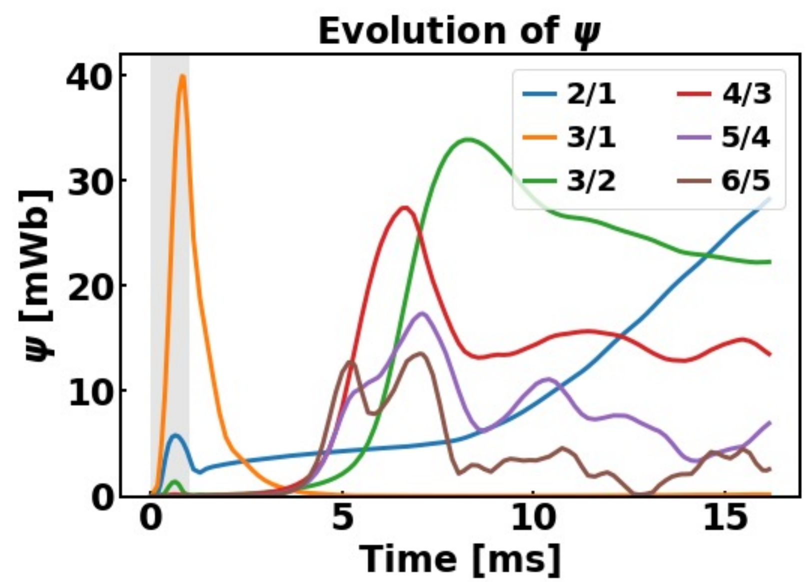
$$\boldsymbol{\nabla} \cdot \vec{\vec{\boldsymbol{\Pi}}}_{\mathbf{e}} = -\boldsymbol{\mu_e} \frac{\mathbf{n_e m_e}}{\mathbf{n_e e}} \langle \mathbf{B_{eq}^2} \rangle \frac{\vec{\mathbf{J}} \cdot \vec{\mathbf{e}}_{\Theta}}{\left(\vec{\mathbf{B}}_{\mathbf{eq}} \cdot \vec{\mathbf{e}}_{\Theta}\right)^2} \vec{\mathbf{e}}_{\Theta}$$

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

[2]C. Sovinec, et al., JCP 195 (2004)

Prior work[1]: NTM grows in two phases following applied perturbation





- Applied 1ms magnetic perturbation (MP) pulse seeds growing NTM
  - Surrogate for MHD transient (e.g. ELMs)
- **Slow growth**: driven by nonlinear multi-mode interactions
  - Pulse excites cascade of n>1 core modes in addition to n=1
- **Robust growth**: standard growth described by MRE

[1]**E.C. Howell, et al., PoP 29 (2022)**

$$\tilde{\Psi}_{m,n} = \oint \oint J\tilde{B} \cdot \nabla\psi_0 \exp(in\phi - im\Theta)d\Theta d\phi$$

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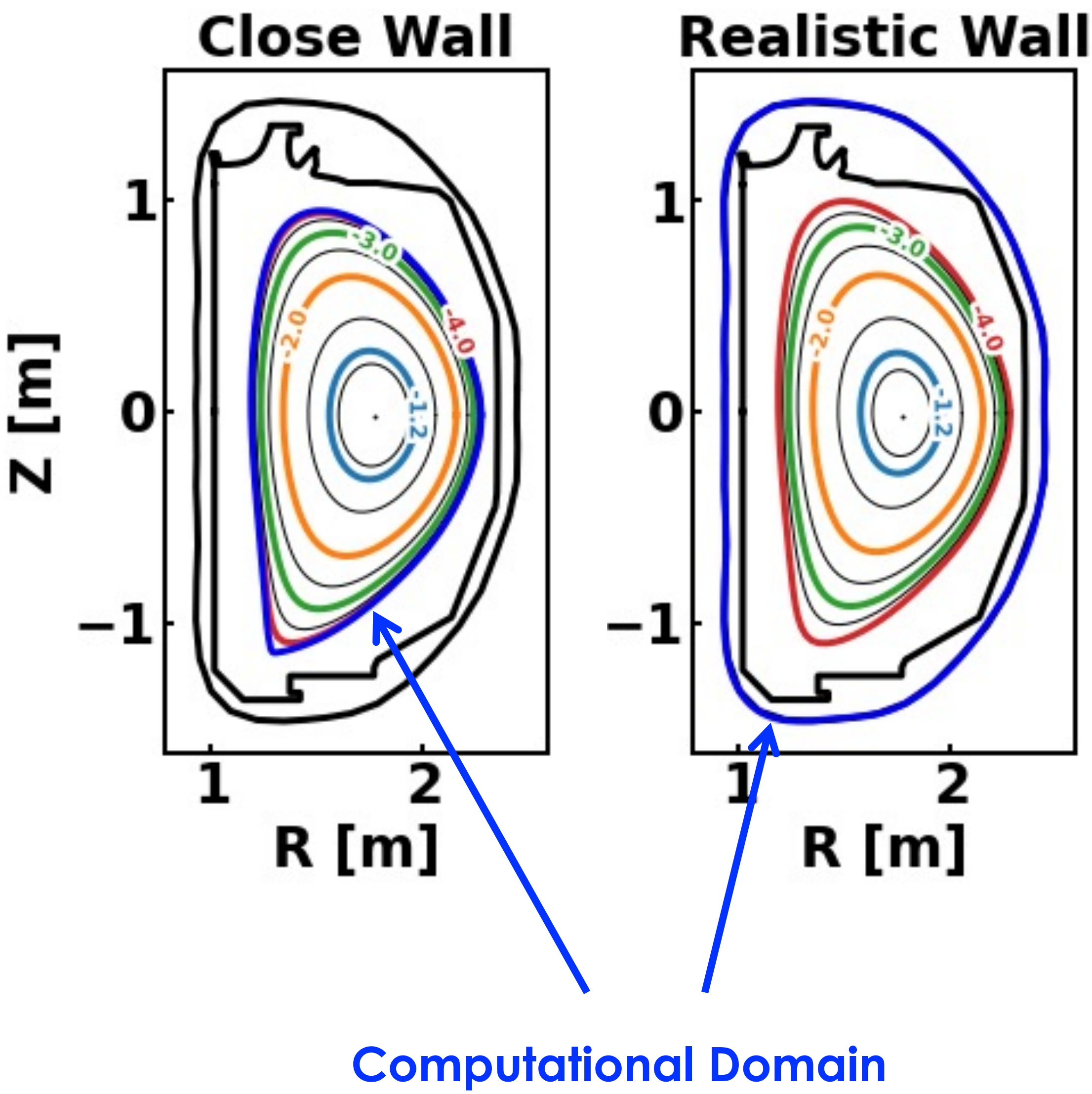
Model improvements enable higher fidelity studies: 1) Realistic Wall

- **Prior Work: Computational domain extends to last closed flux surface**
  - Wall stabilizes edge modes

- **New wall approximates DIII-D's vacuum vessel**
  - Results presented use a perfectly conducting wall boundary (**blue**)
  - Resistive Wall simulations are progressing



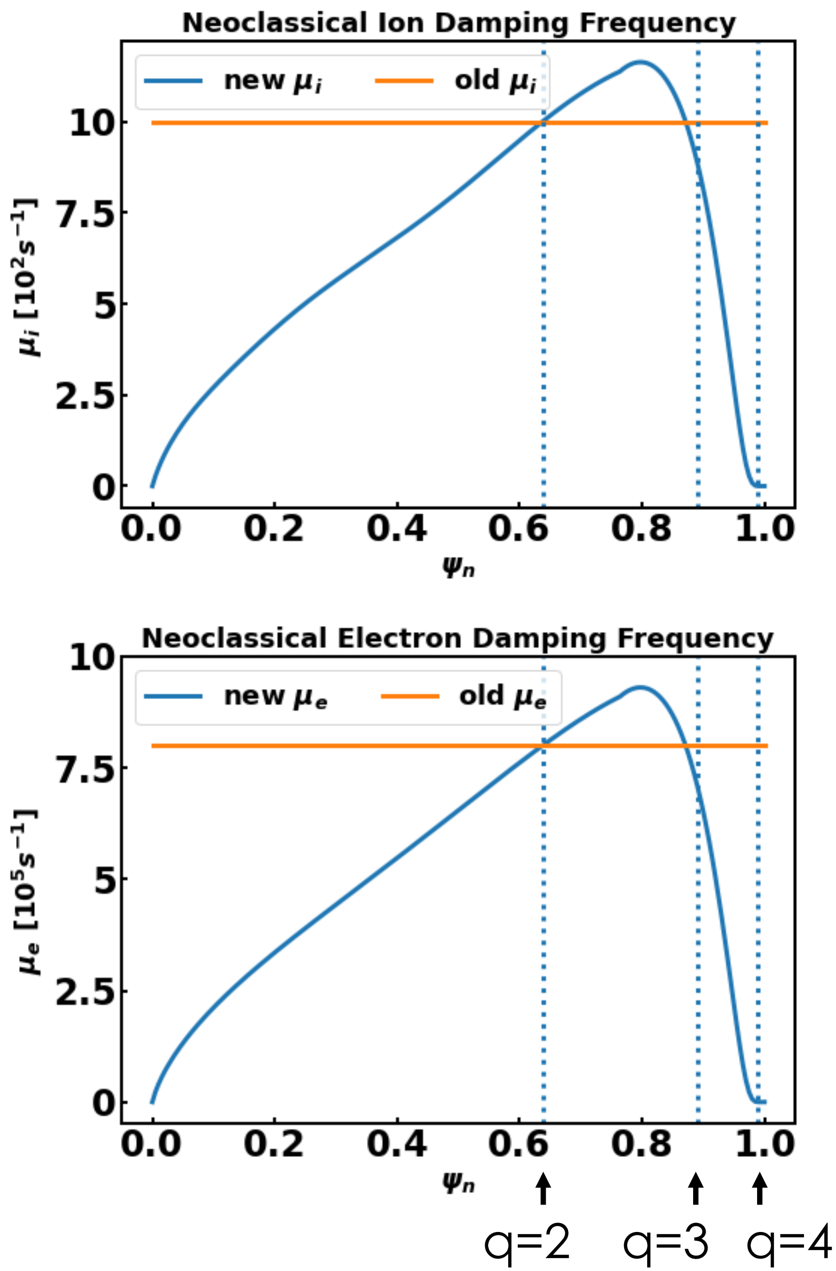
Model improvements enable higher fidelity studies: 2) Spatially dependent neoclassical damping profiles

- **Previous: uniform μ_i and μ_e**
  - Overestimates bootstrap current drive near axis

- **Radial μ_s formula[1,2] extrapolates across collisionality regimes**

$$\mu_s = \frac{\nu_s (f_t/f_c) K_s^B}{\left[1 + \nu_{*s}^{1/2} + 2.92\nu_{*s}\frac{K_s^B}{K_s^P}\right]\left[1 + \frac{2K_s^P}{3\omega_{ts}\tau_{ss}K_s^{PS}}\right]}$$

- **Profiles smoothly fit to zero outside q~2.5 to avoid large μ_s gradients in the pedestal**

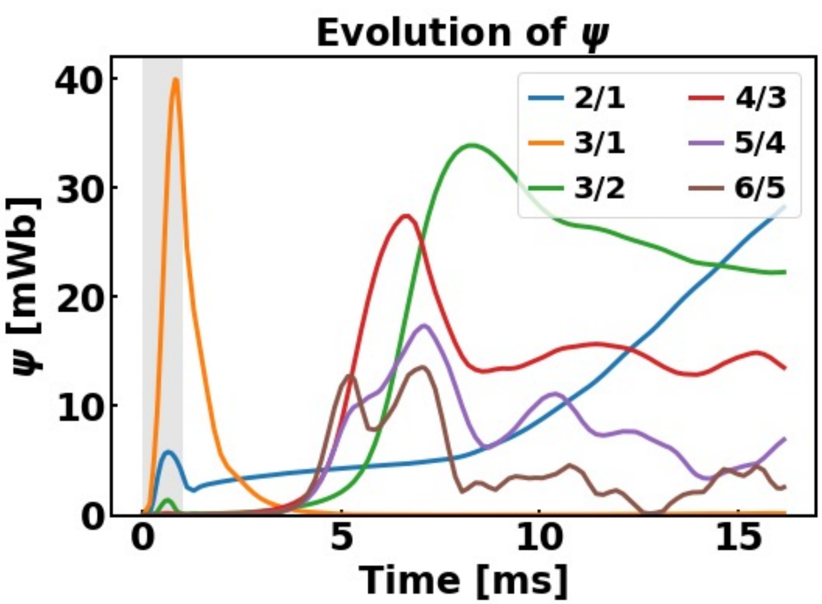


[1]Y.B. Kim et al., PFB 3 (1991); errata 4

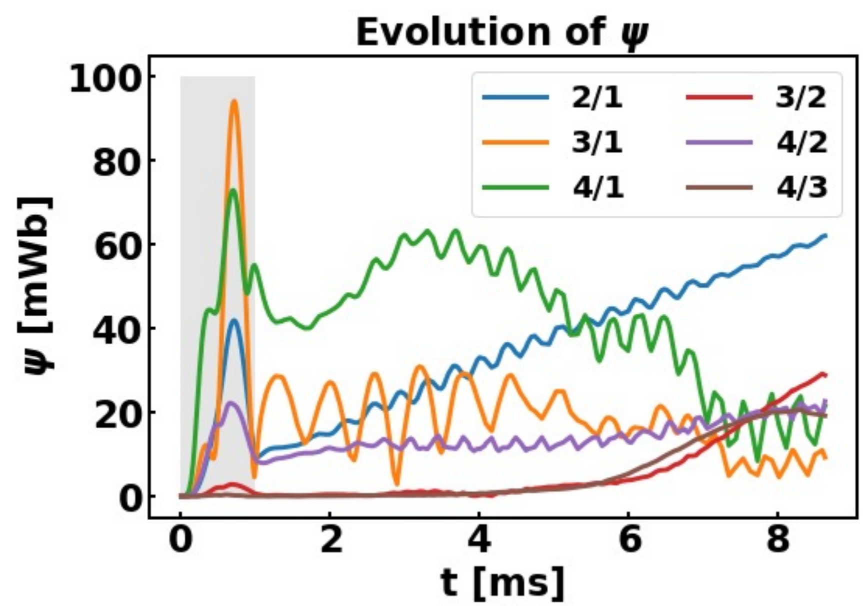
[2]Callen CPTC report 096-rev1 (2010)

Applied perturbation excites larger n=1 response in realistic wall simulations compared to close fitting wall simulations

Close Fitting Wall

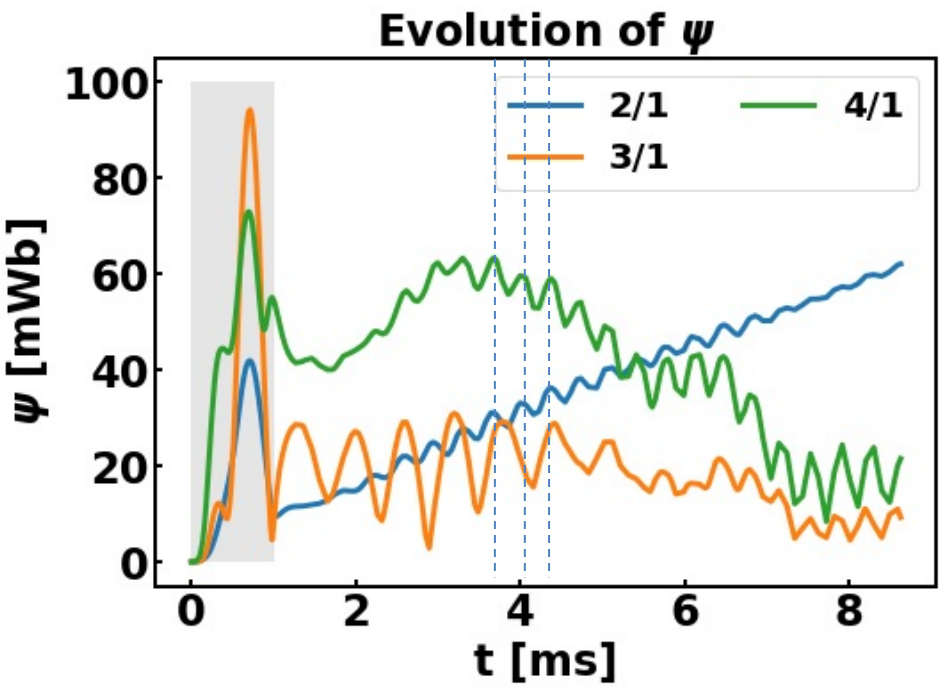


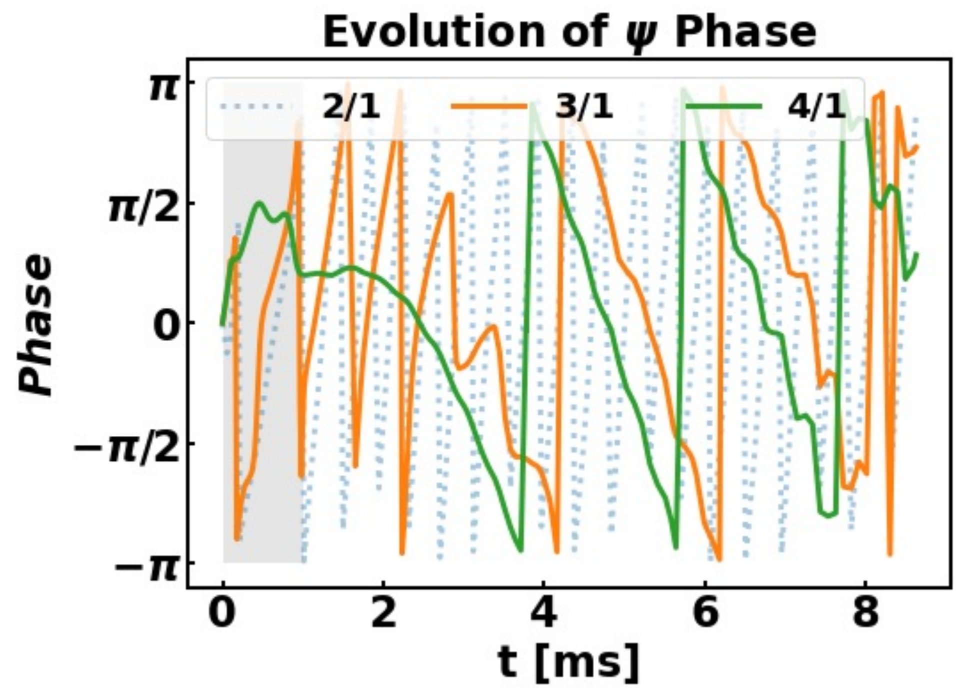
Realistic Wall



- **Applied perturbation calculated using identical coil currents**
- **Enhanced response illustrates the larger response for a realistic wall**
- **Robust 2/1 growth occurs <u>immediately</u> after pulse with realistic wall**
  - **Core modes grow large after 2/1 is large**

Modulations in n=1 resonant flux magnitude highlights nonlinear poloidal mode interactions



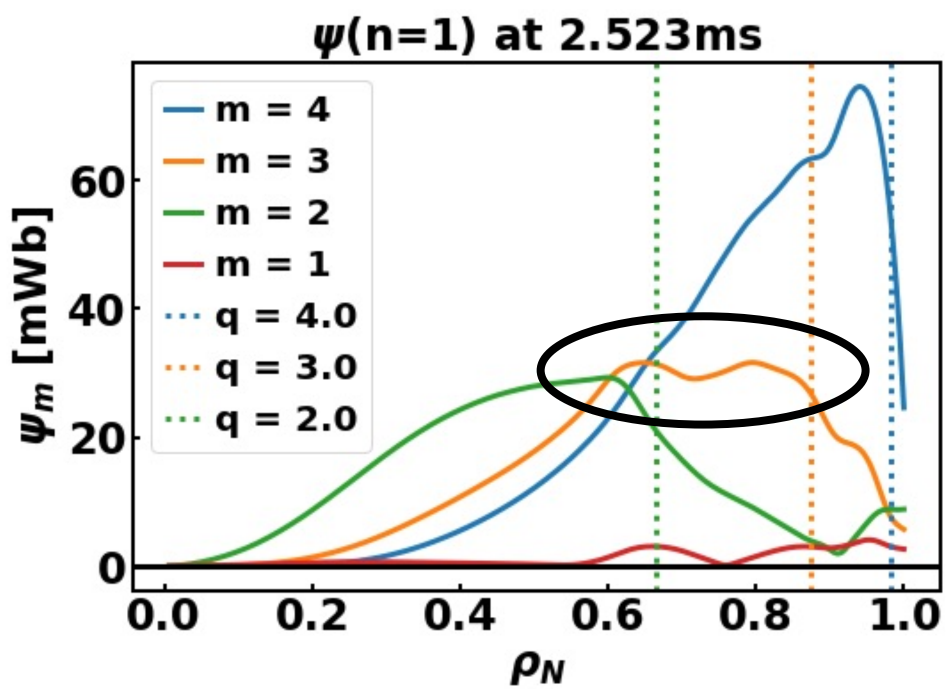


- **Oscillations have little impact on linear 2/1 growth**
- **Early modulations in 4/1 and 2/1 resonant flux magnitude are in sync**
  - Differential rotation modulates coupling between unstable islands[1]
- **4/1 and 3/1 lock starting around 2.5 ms**
  - 4/1 amplitude decays after locking to 3/1

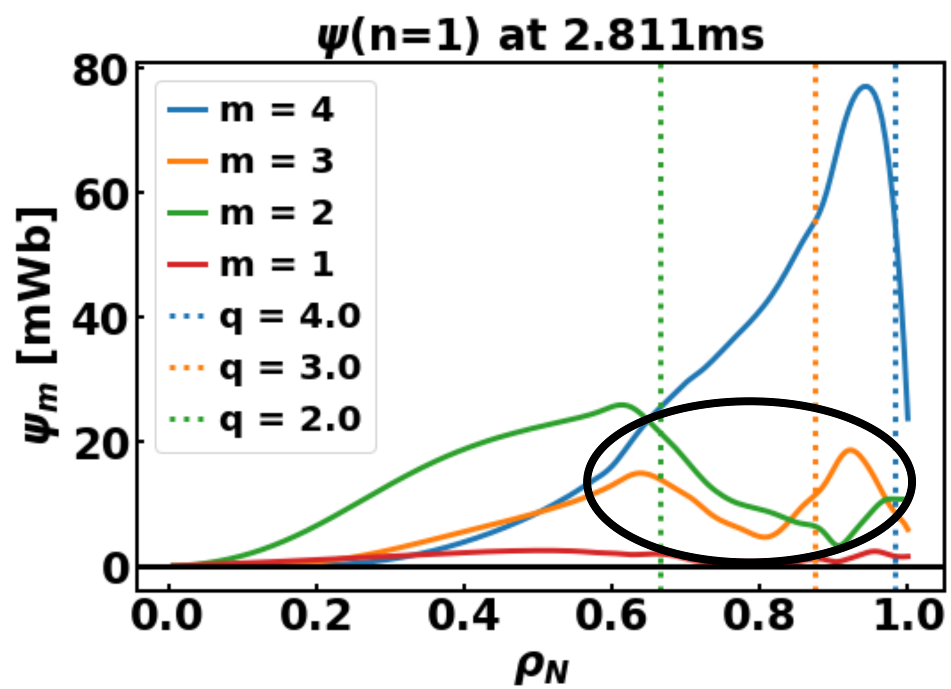
[1]R. Fitzpatrick, et al., NF 33 (1993)

Oscillations in ψ_{31} profile coincide with resonant ψ_{31} modulations

Time when resonant ψ_{31} local max

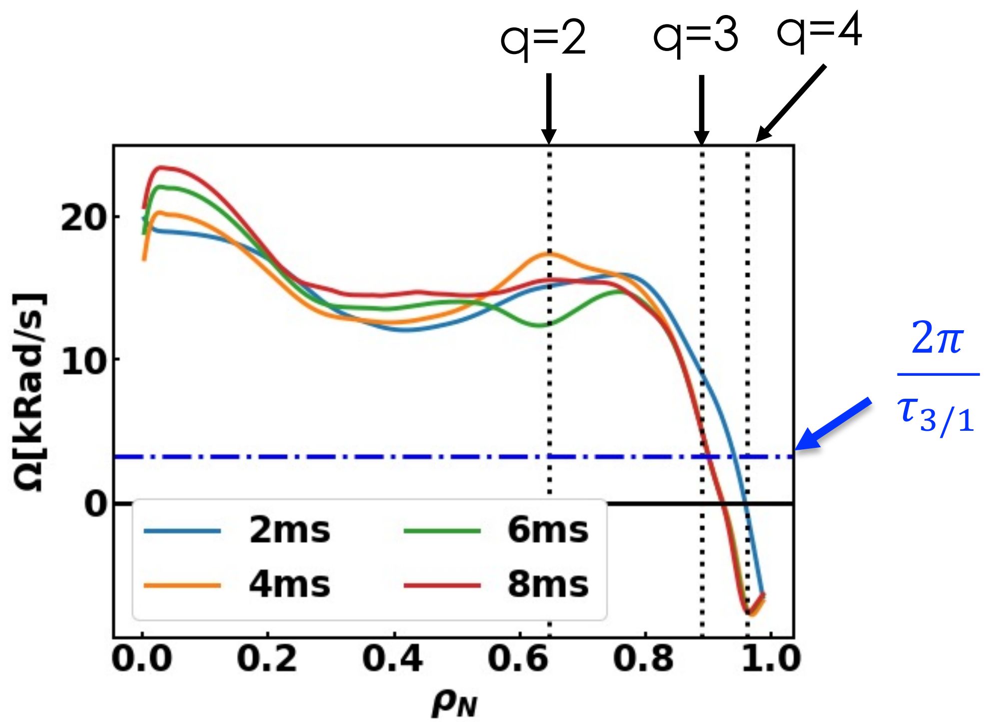


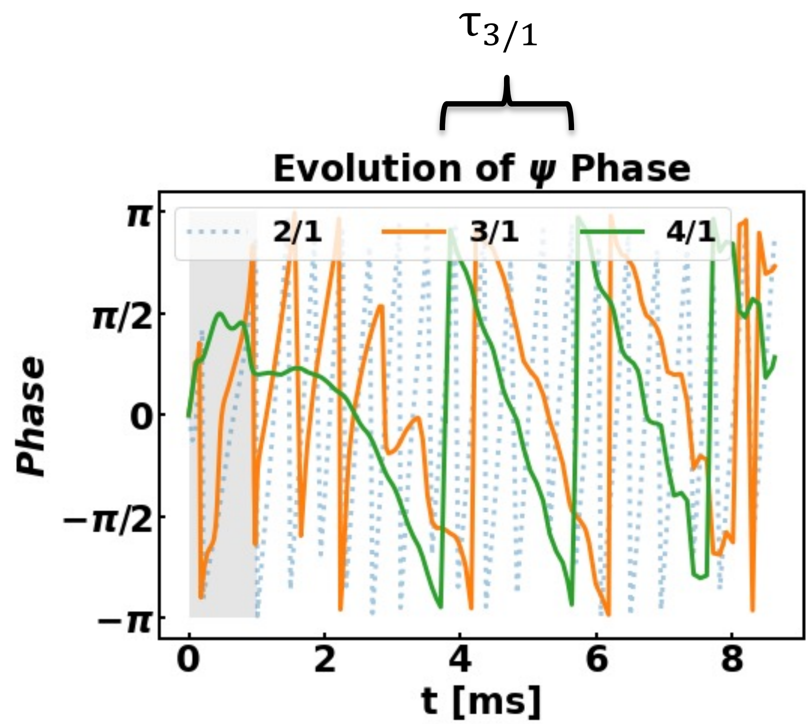
Time when resonant ψ_{31} local min



- Local max: ψ_{31} profile spans region between q=2 and q=3
- Local min: ψ_{31} profile has two peaks at q=2 and q=3
- Similar profile oscillations observed in ψ_{41} radial profile at q=2 and q=3

Torque induced by interaction with 3/1 accelerates the 4/1

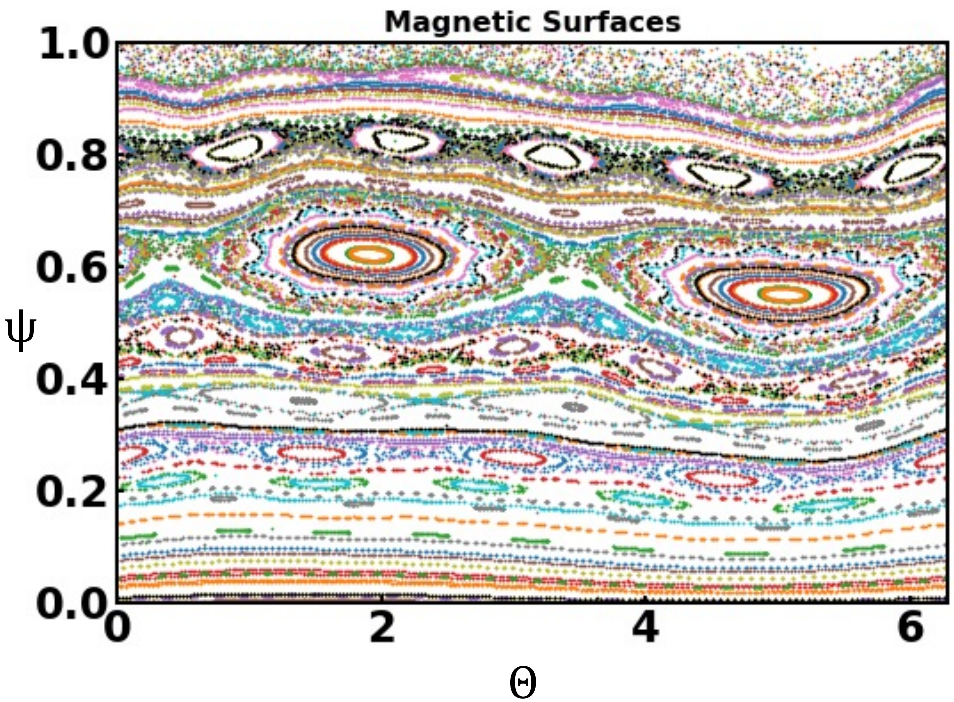




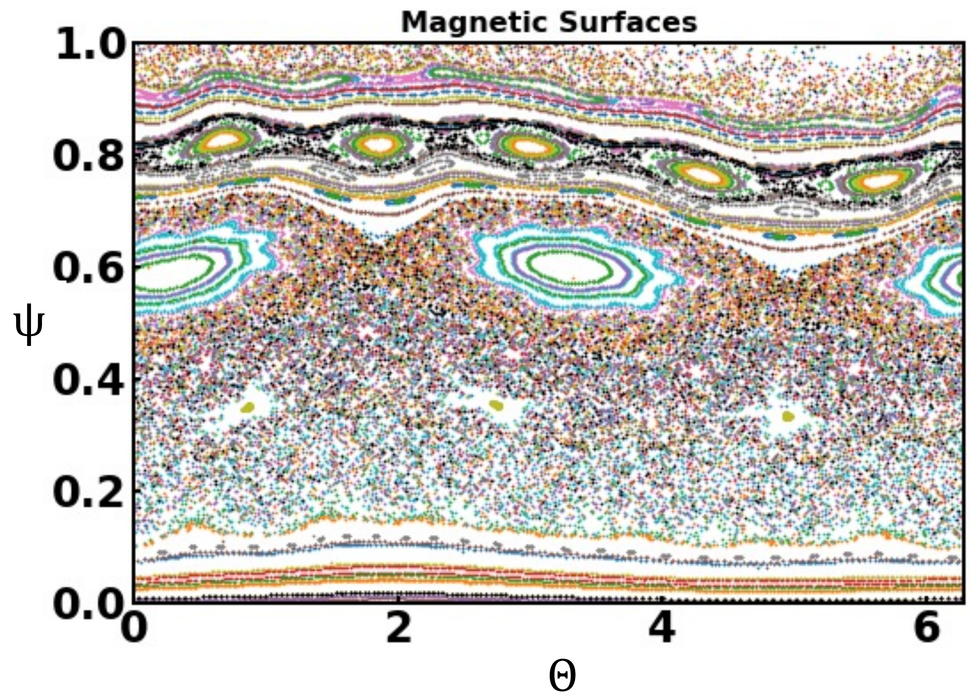
- **Following the pulse, q=3 flow rotation frequency decays to 5 kRad/s**
  - Slowing down consistent with decreased 3/1 phase frequency
- **After locking both 3/1 and 4/1 rotate at local rotation frequency at q=3**
  - Torque not strong enough to pull the n=0 plasma rotation

Evolution of core flux surfaces indicates inside-out confinement loss

5.8ms



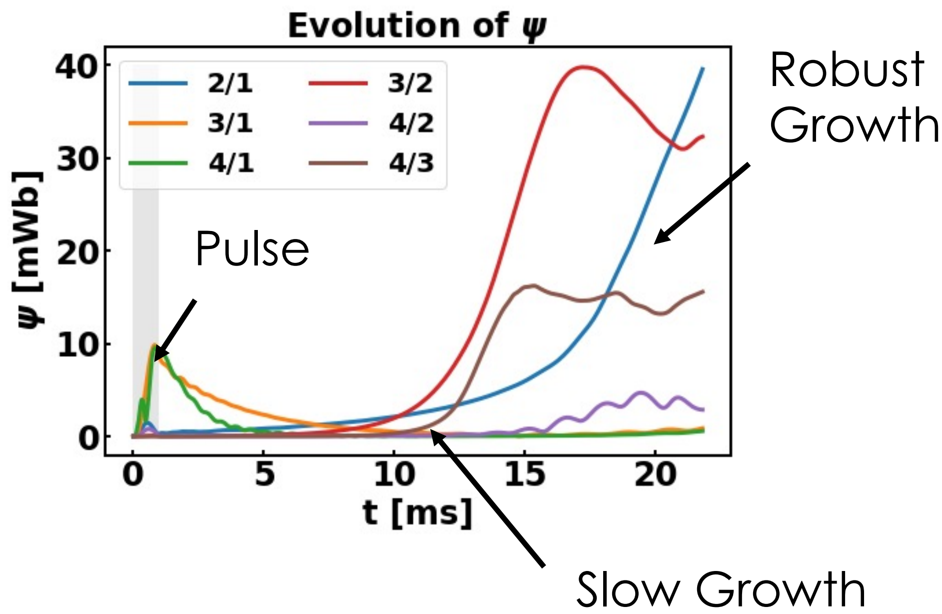
7.7ms



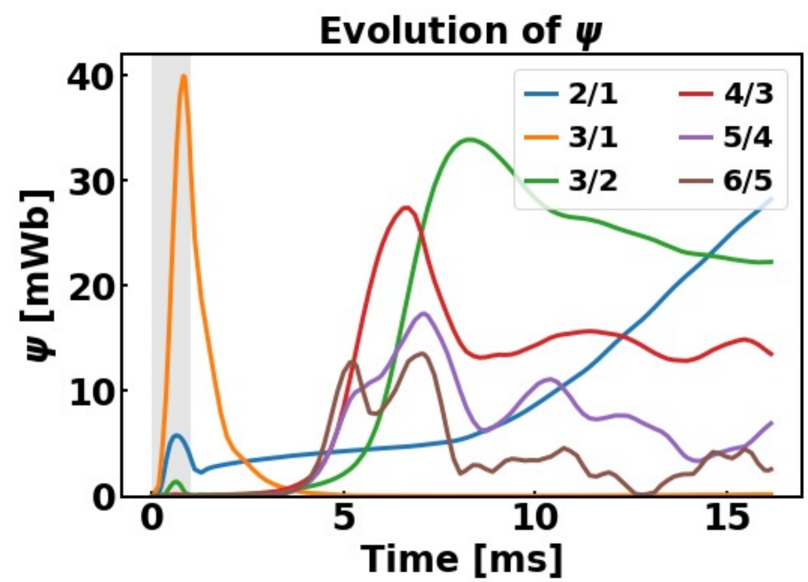
- **Core flux surfaces are destroyed as 2/1 grows large**
- **Surface topology outside of 5/2 island largely unchanged**
- **Simulations and Poincare map are computed in toroidal geometry**
  - Poincare map is mapped to straight field line coordinates

Weak Pulse: Reducing the MP amplitude qualitatively reproduces close fitting wall dynamics

Weak pulse realistic wall



Close fitting wall



- **2/1 grows slowly following applied MP**
- **(n+1)/n core modes are observed starting around 7-8 ms**
  - Modes resonant in region of weak magnetic shear
- **2/1 transition to robust growth after 3/2 grows grows to large amplitude**

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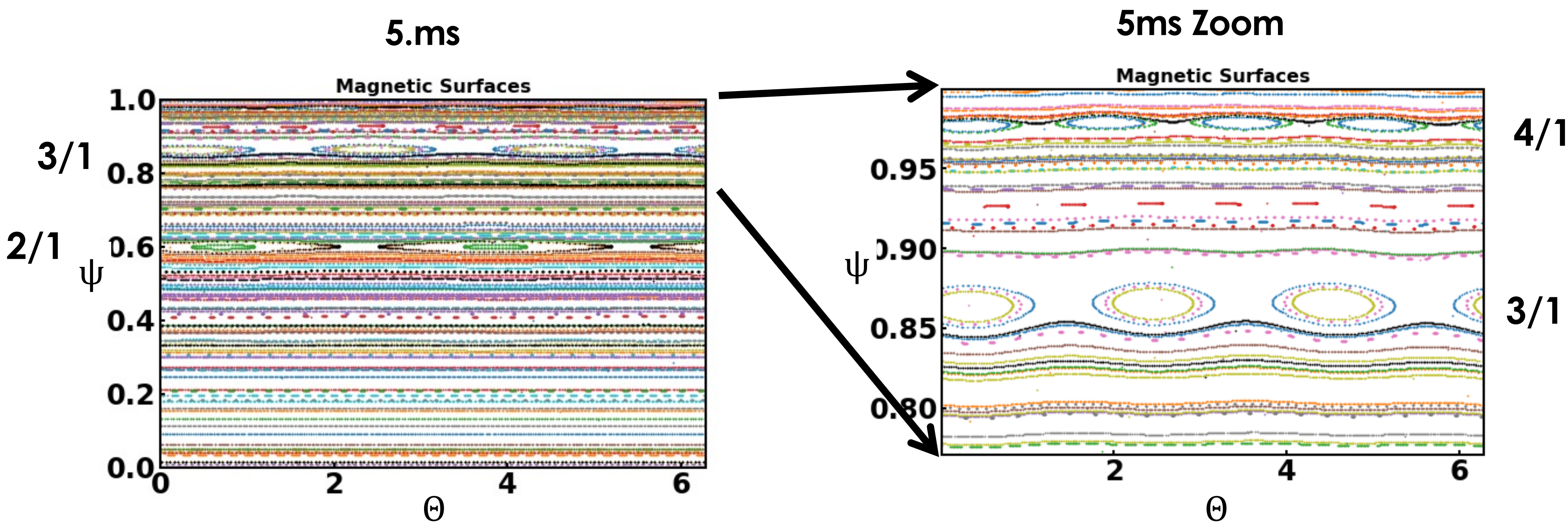
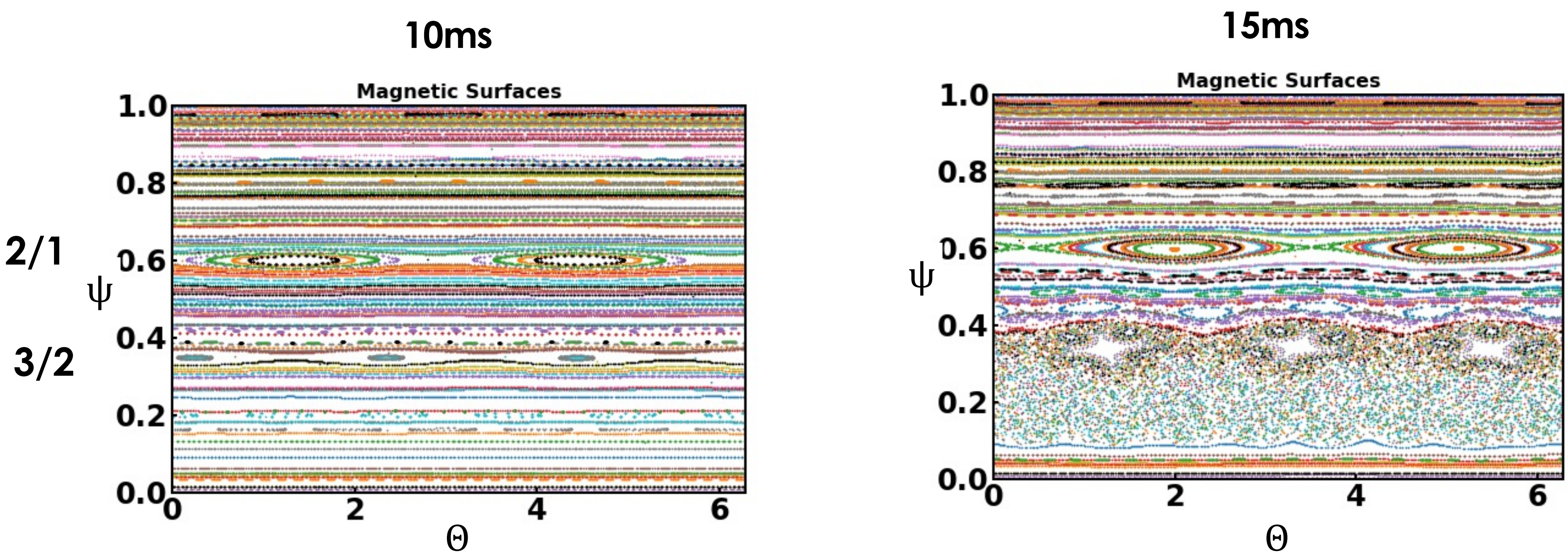
Weak pulse: Good flux surfaces following MP with small 2/1, 3/1, and 4/1 island chains



Weak pulse: Evolution of core flux surfaces indicates inside-out confinement loss



- Core flux surfaces are destroyed as 3/2 and then 2/1 grow large
- Surface topology outside of 2/1 island largely unchanged

Conclusions and Future Work

- **NIMROD model improvements enable NTM modeling in experimentally relevant shaped diverted equilibria**

- **Applied MP excites robustly growing 2/1 NTM in both strong and weak pulse simulations**
  - Strong pulse: NTM robustly grows immediately following pulse
    - (n+1)/n core modes activity arises after 2/1 grows
  - Weak pulse: NTM initially grows slowly following pulse
    - (n+1)/n core modes activity triggers 2/1 robust growth

- **Both cases: Core mode activity results in inside-out confinement loss**

- **Future Work: Use model improvements to study locked mode disruptions**
  - Core activity undesirable for these studies
  - Modeling simplifications designed to get things working exacerbate core mode stability issues (next slide)

Simplifications used to get simulations going enhance core mode growth

Increased resistivity increases growth rate

Parameters at q=2	NIMROD	Experiment
S	$2.5\text{x}10^6$	$7.9\text{x}10^6$
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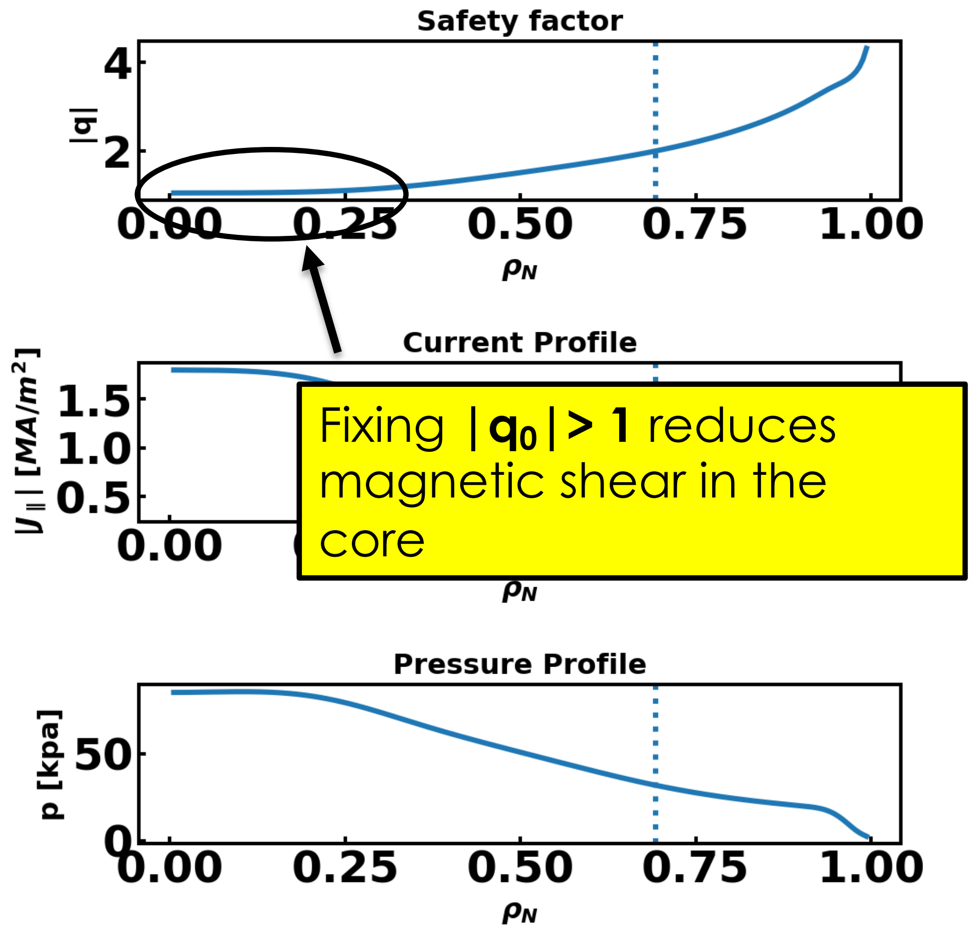

Fixing $|q_0|>1$ reduces magnetic shear in the core

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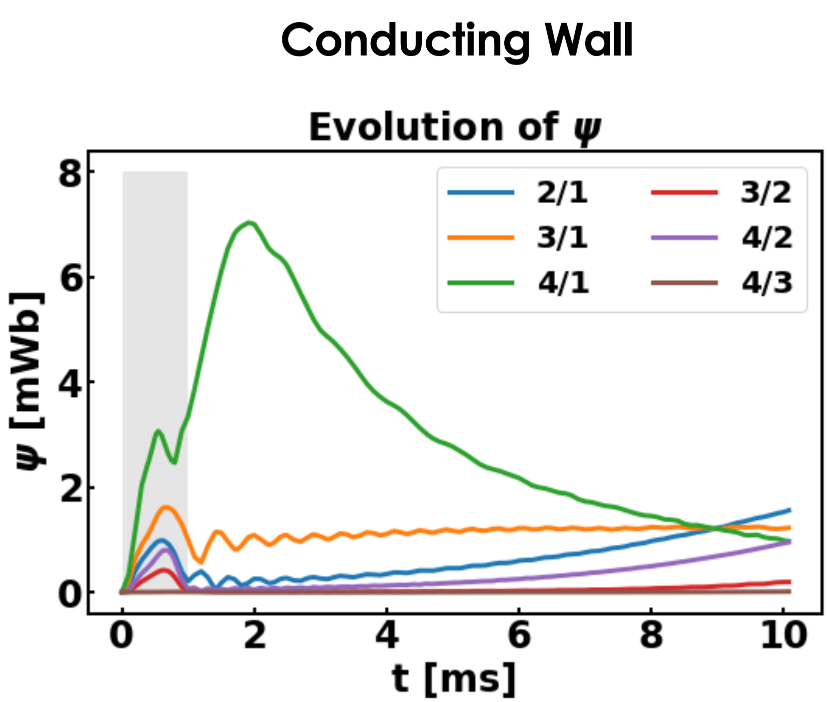
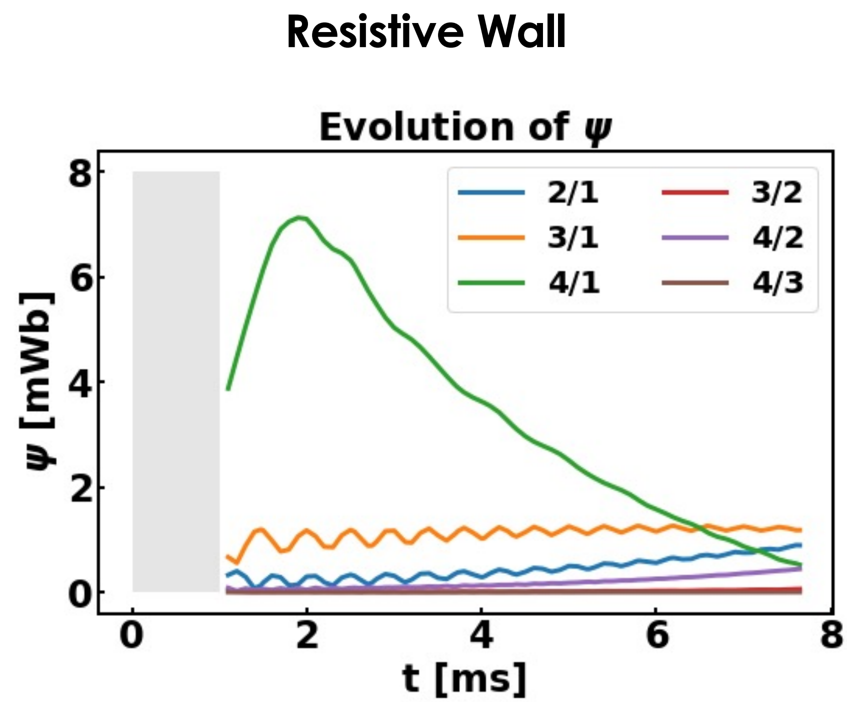
Teaser: Simulations with experimental resistivity and μ_s profiles





- **Both conducting wall and resistive wall simulations are progressing**
  - Resistive wall turned on after applied MP
- **Both cases: Slowly growing 2/1**
  - (n+1)/n core mode activity absent … so far
  - Need to run longer due to increased τ_{VR}
- **Resistivity and μ_s calculated assuming Z_{eff}=3**

Contact Information

- **Feel free to email me if you want to schedule an in-person of virtual meeting to discuss these results**

- **Email: ehowell@txcorp.com**