M3D Simulation of Plasma Response to External Field Perturbations

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NSTX Results Review

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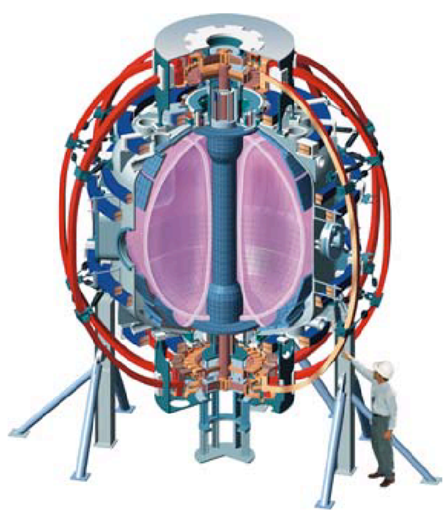
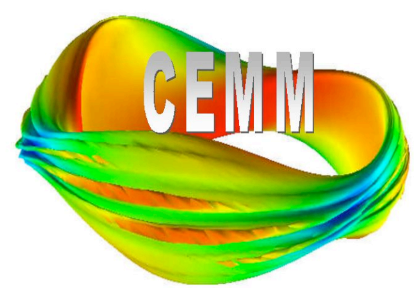
PPPL





Motivation

- Left uncorrected, the NSTX error field produces magnetic islands that can mode lock, braking plasma rotation and destabilizing RWMs.

- Analysis with IPEC has helped to predict these effects and design effective mitigation strategies.

- Analysis with M3D can extend these results to the nonlinear, resistive, rotating plasma regime inaccessible to the ideal linear code.

- M3D analysis should be extensible to other RMP effects, such as potential ELM mitigation or destabilization.

The M3D Resistive MHD Model

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}_i) = 0$$

$$\rho\left[\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v}\right] = -\nabla \mathbf{p} + \mathbf{J} \times \mathbf{B} + \mu \nabla^2 \mathbf{v}$$

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$\mathbf{J} = \nabla \times \mathbf{B}$$

$$\frac{\partial p}{\partial t} + \mathbf{v} \cdot \nabla p = -\gamma p \nabla \cdot \mathbf{v} + \nabla \cdot n \chi_\perp \nabla\left(\frac{p}{\rho}\right)$$

Artificial sound wave model for $\chi_\parallel$:

$$\frac{\partial T}{\partial t} = s \frac{\mathbf{B} \cdot \nabla u}{\rho}$$

$$\frac{\partial u}{\partial t} = s \mathbf{B} \cdot \nabla T + \nu \nabla^2 u$$

M3D representation:

$$\mathbf{B} = \nabla \psi \times \nabla \phi + \frac{1}{R} \nabla_\perp F + \left(R_0 + \tilde{I}\right) \nabla \phi$$

$$\mathbf{V} = \frac{R^2}{R_0} \nabla U \times \nabla \phi + \nabla_\perp \chi + V_\phi \hat{\phi}$$

Calibration with IPEC

- In order to establish a baseline for comparison, we first compared the steady-state predictions of island widths in response to boundary perturbations between codes.

  - Add various low-*m*, *n*=1 perturbations of specified amplitude to initial poloidal flux on plasma boundary:

$$\tilde{\psi}_{boundary}(\theta,\varphi)=\tilde{\psi}_0\cos(\varphi-m\theta)$$

  - Measure plasma displacements, singular currents with IPEC; infer island widths.

  - Solve for instantaneous equilibrium+vacuum field (or evolve M3D nonlinearly until saturation of *n*=1 islands to include plasma response), measure island widths directly, compare to linear results.

1st Test: DIII-D Equilbrium, q_0=1.07

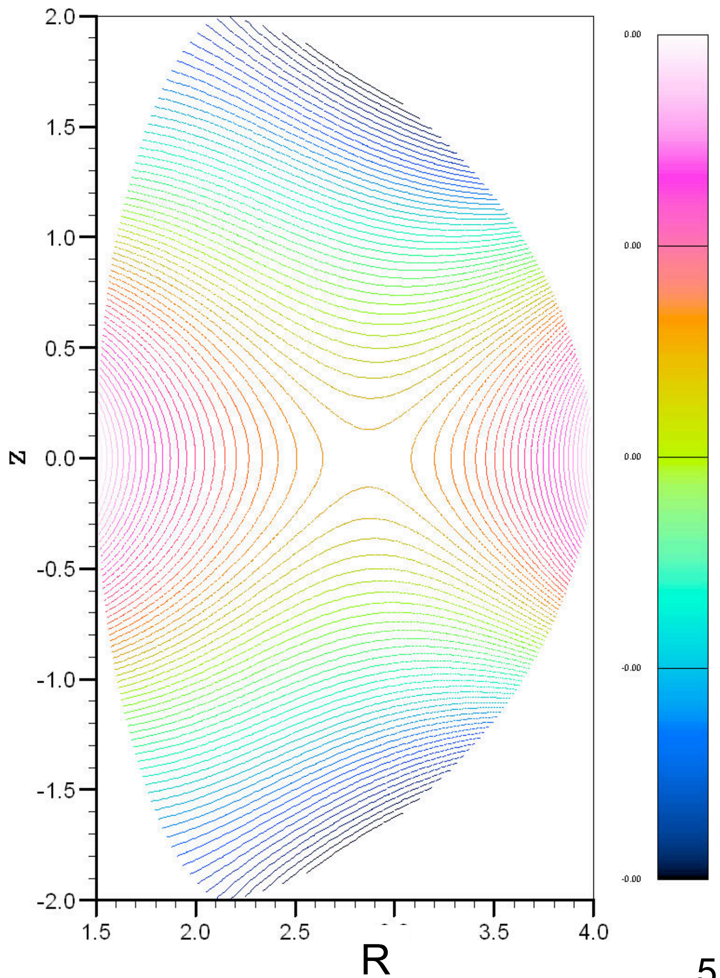
- Begin by solving the Poisson equation

$$\frac{\partial^2\psi}{\partial R^2}-\frac{1}{R}\frac{\partial\psi}{\partial R}+\frac{\partial^2\psi}{\partial z^2}=-RJ_\phi$$

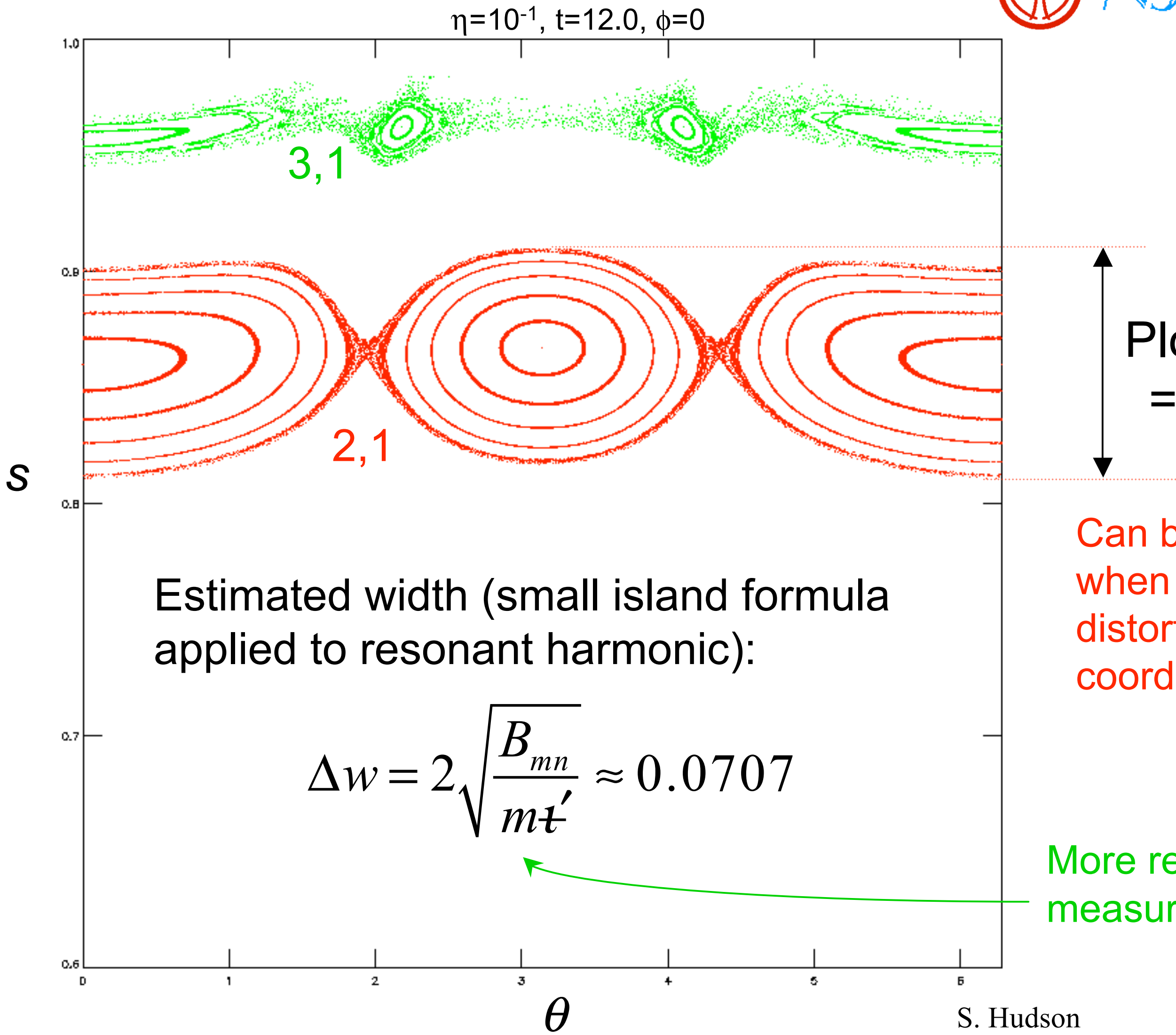
for ψ, subject to the perturbed boundary condition, where J_ϕ is the unperturbed equilibrium toroidal current density.

- Time-evolving from this state with various choices of resistivity, viscosity, etc. will show the effect of the plasma response on the islands.

Instantaneous Perturbed Flux



Island Widths are Characterized using Field-line-following diagnostic



Estimated width (small island formula applied to resonant harmonic):

$$\Delta w = 2\sqrt{\frac{B_{mn}}{m\iota'}} \approx 0.0707$$

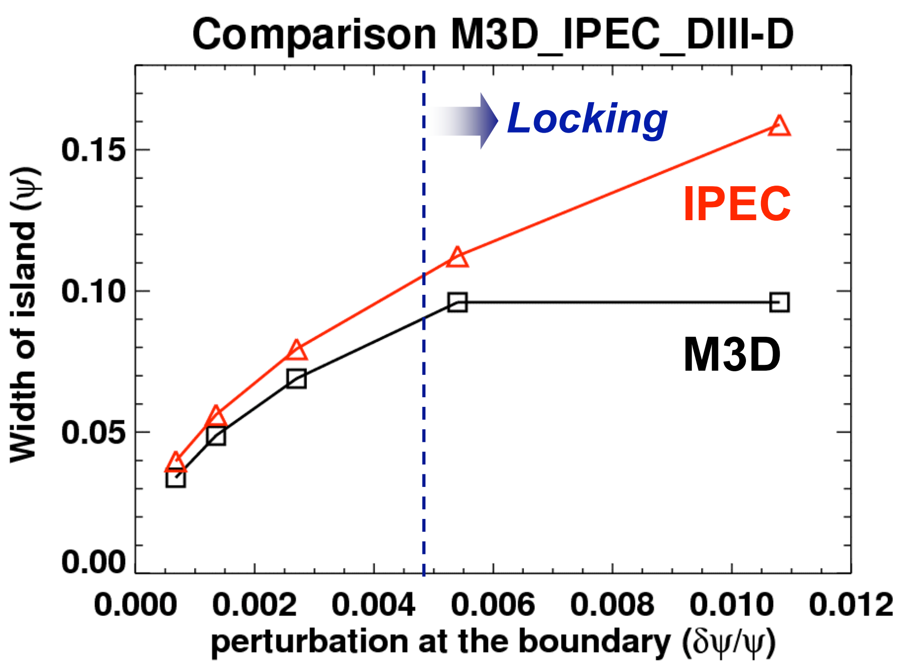
Can be inaccurate when islands are distorted in flux coordinates.

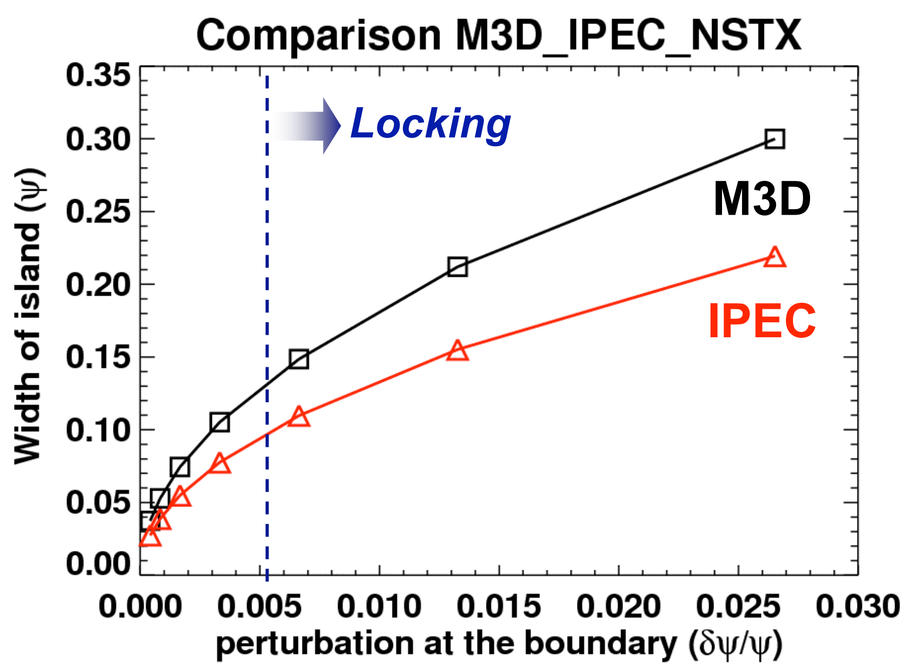
More reliable as a measure of width.

S. Hudson

2,1 Island Widths agree well with IPEC in Linear Regime

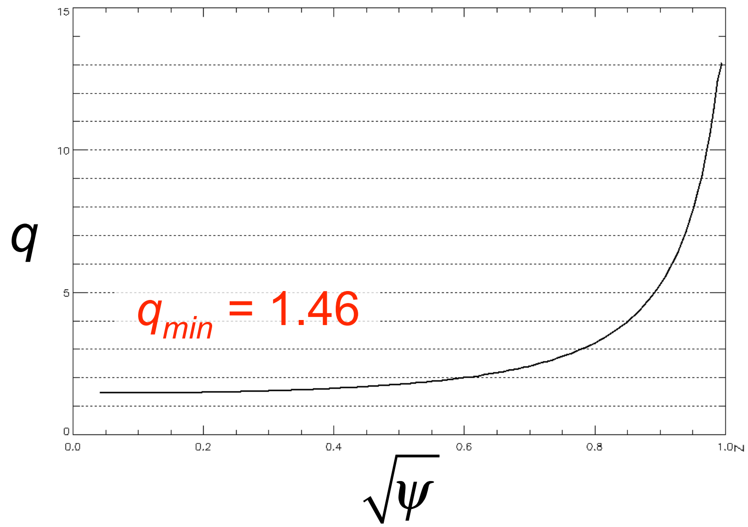
m=2, *n*=1 perturbation applied at boundary

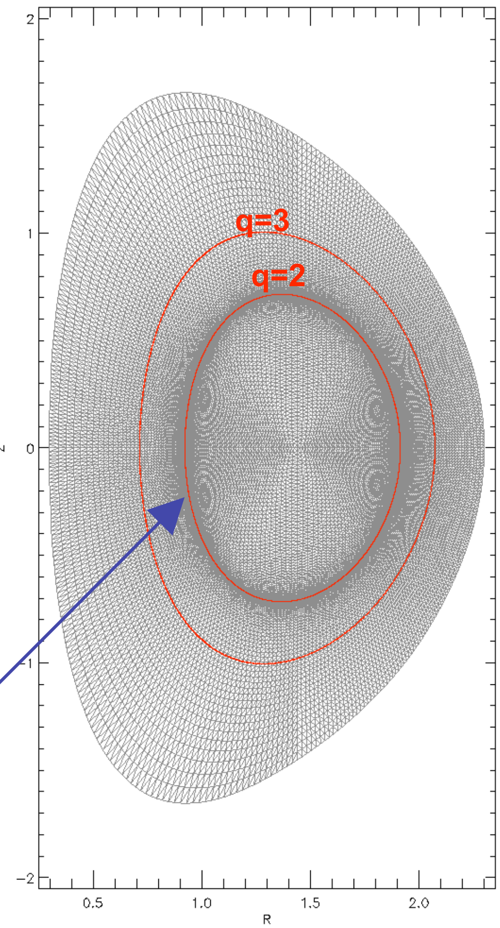


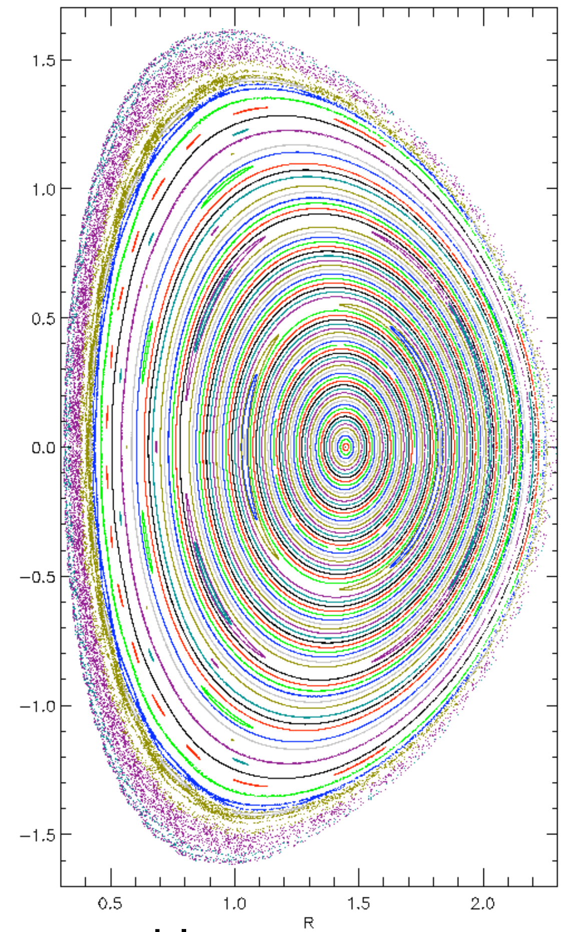


Nonlinear Studies Based on EFIT Reconstruction of NSTX shot 122444

NSTX

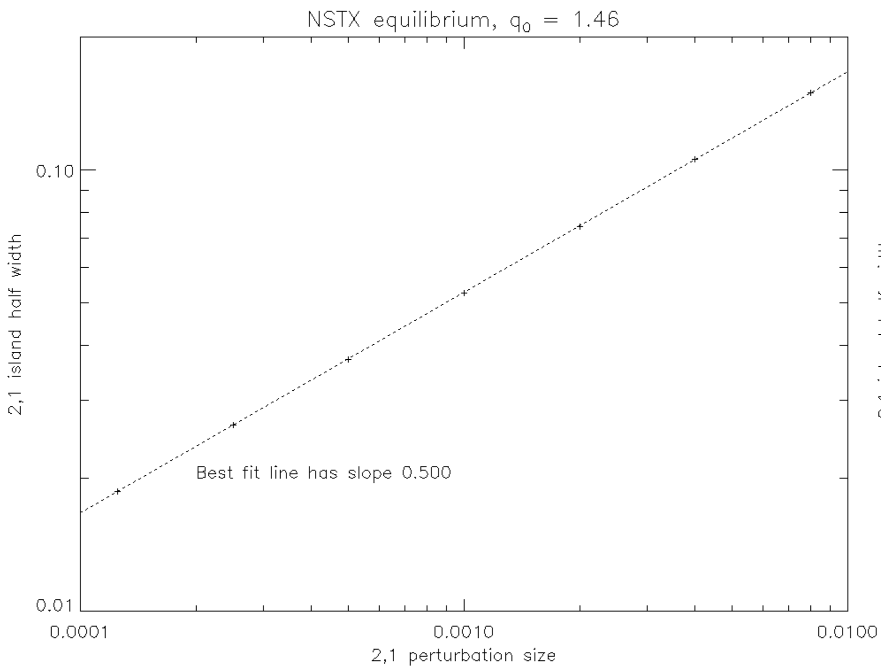


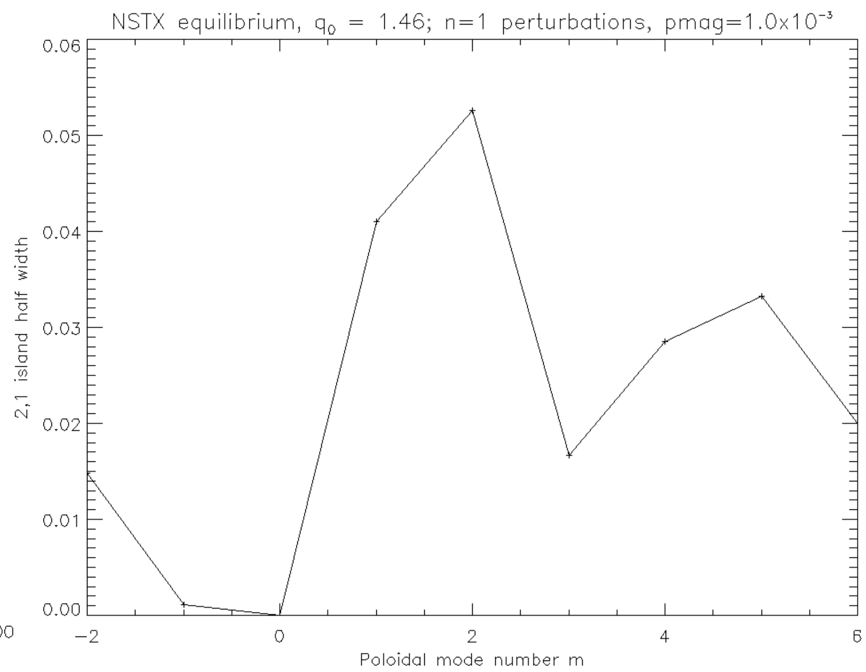




- ❑ Radial zones are packed at q=2 surface to help resolve small islands.
- ❑ Large perturbation is required at edge to produce a measurable island at q=2 (s=0.6).

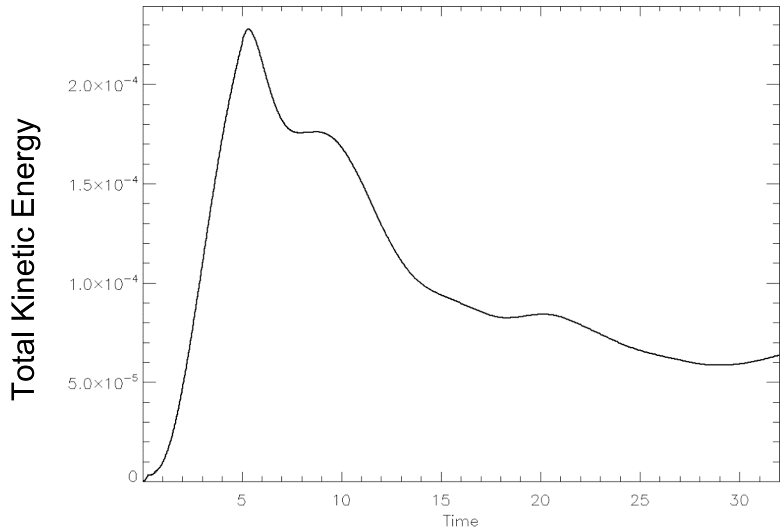
Steady State Reponse

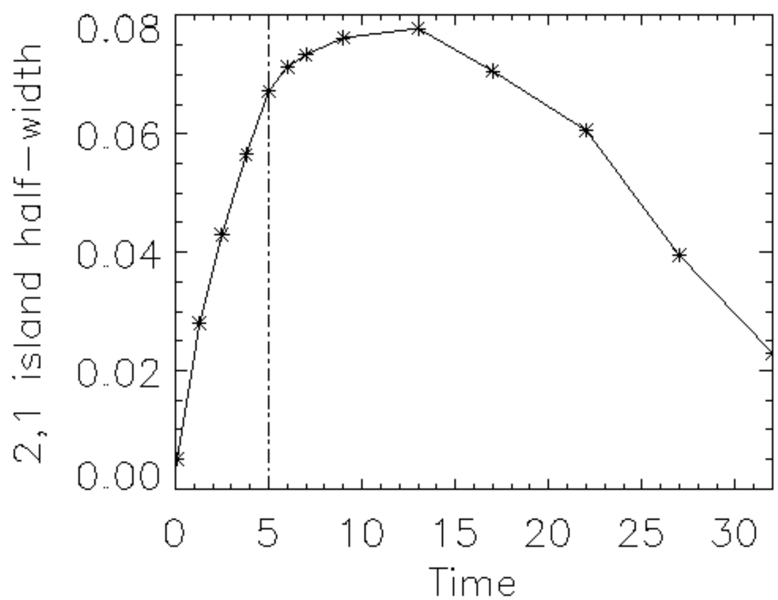




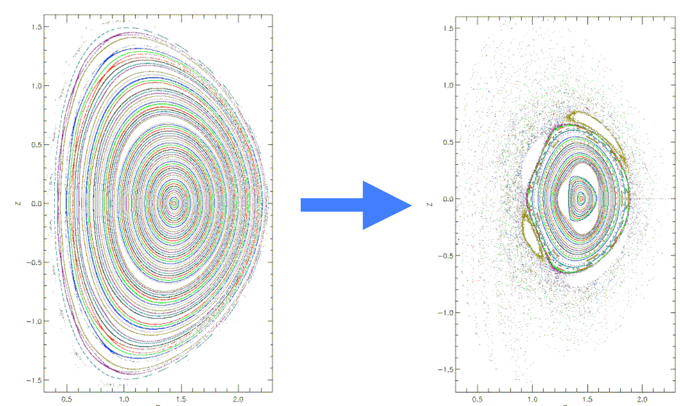
- Island width has expected scaling with perturbation amplitude.
- Peak response is at m=2.

Time-Dependent Response

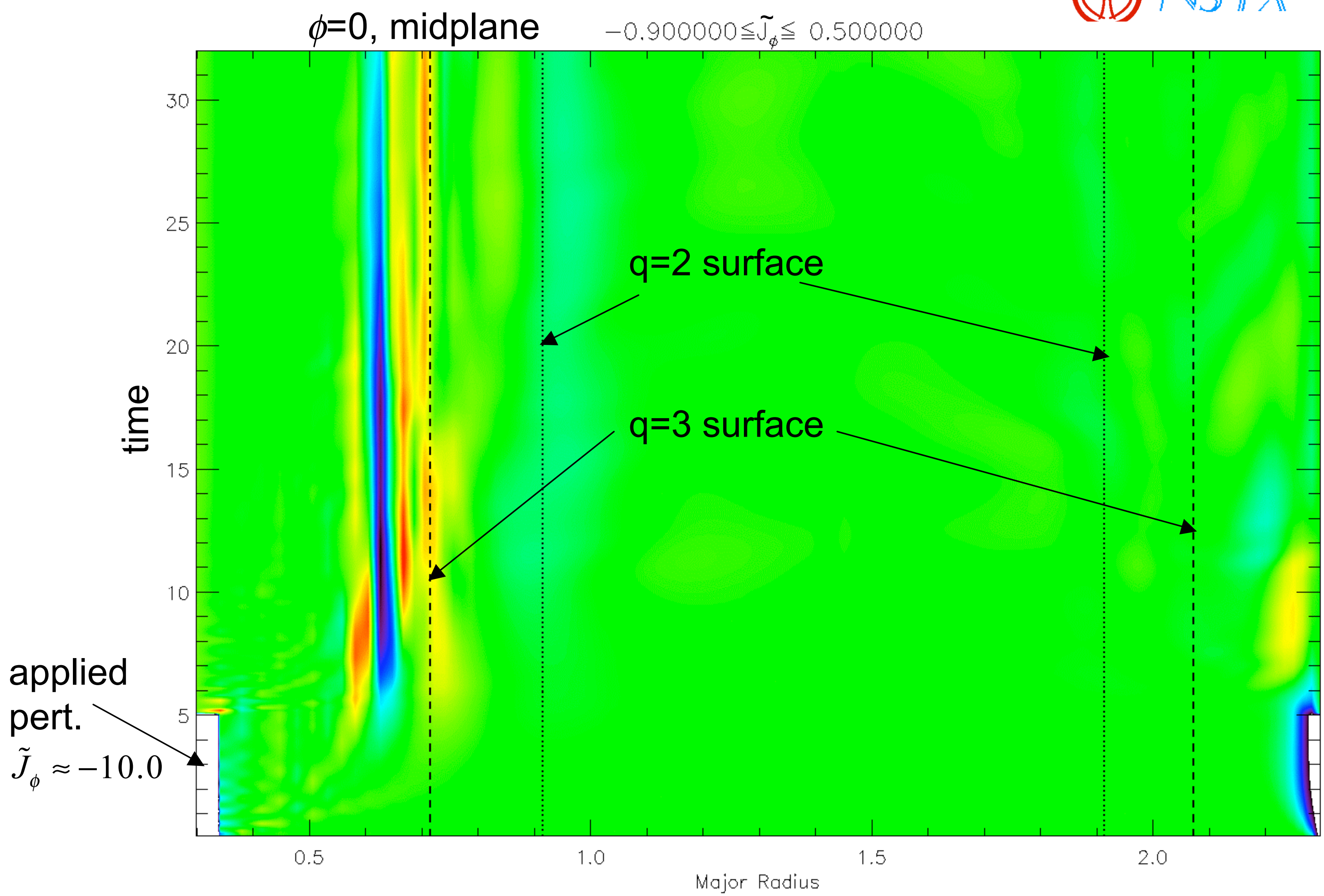




- Start with zero perturbation, ramp up linearly to full size in five Alfvén times to produce current sheets.
- S =2000, Pr =0.02, pmag=7.5×10^{-3}.
- Island size lags perturbation slightly, becomes stochastic on longer timescale.



Sharp current sheets form away from the q=2 surface



Summary & Future Plans

- M3D agrees reasonably well with IPEC on steady-state island width reponses to model perturbations.

- More scans (with smaller perturbation) are needed to understand nonlinear behavior with regard to current sheet formation/decay and island saturation.

- Scans to follow shortly will also include rotation effects, and may make use of the new linear M3D-C^1 code for greater computational efficiency.

- More accurate models of the NSTX error (or applied RMP) fields will give better predictive capability.