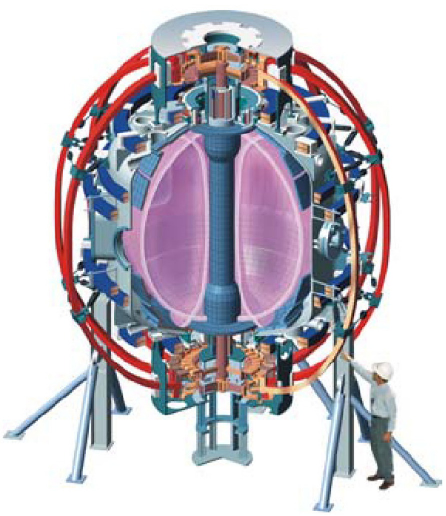
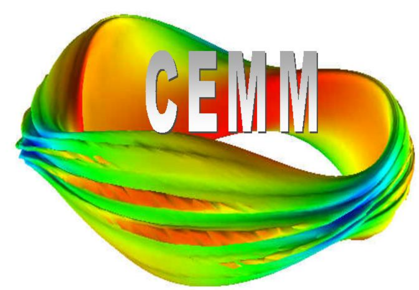
Supported by

NSTX-Related Research Activities:

Modeling Plasma Response to Resonant Magnetic Perturbations

Josh Breslau





NSTX Physics Meeting

June 15, 2009

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.

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:

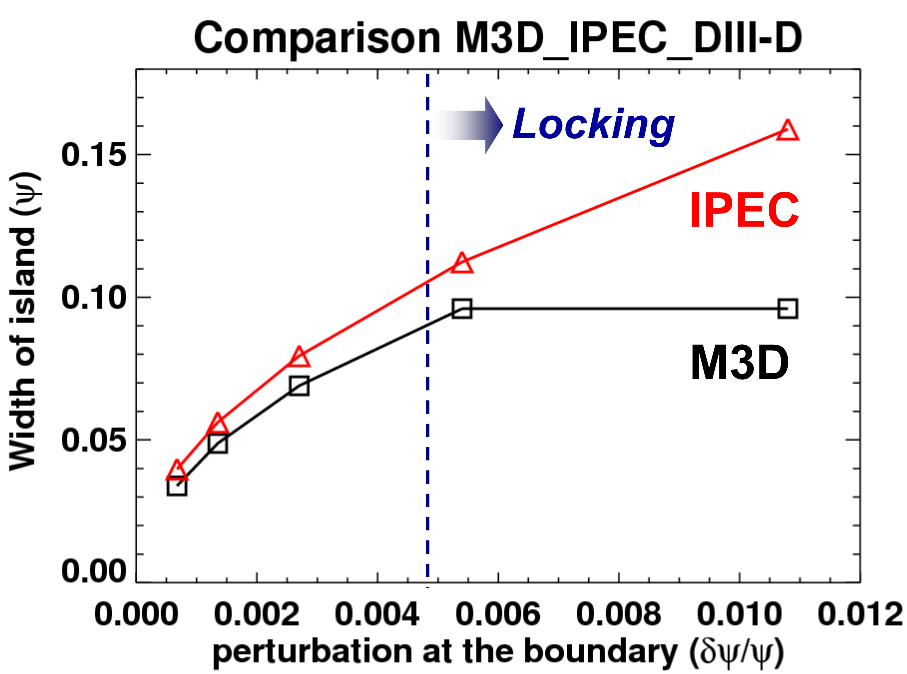
$$\tilde{\psi}_{boundary}(\theta,\varphi)=\tilde{\psi}_0\cos(\varphi-m\theta)$$

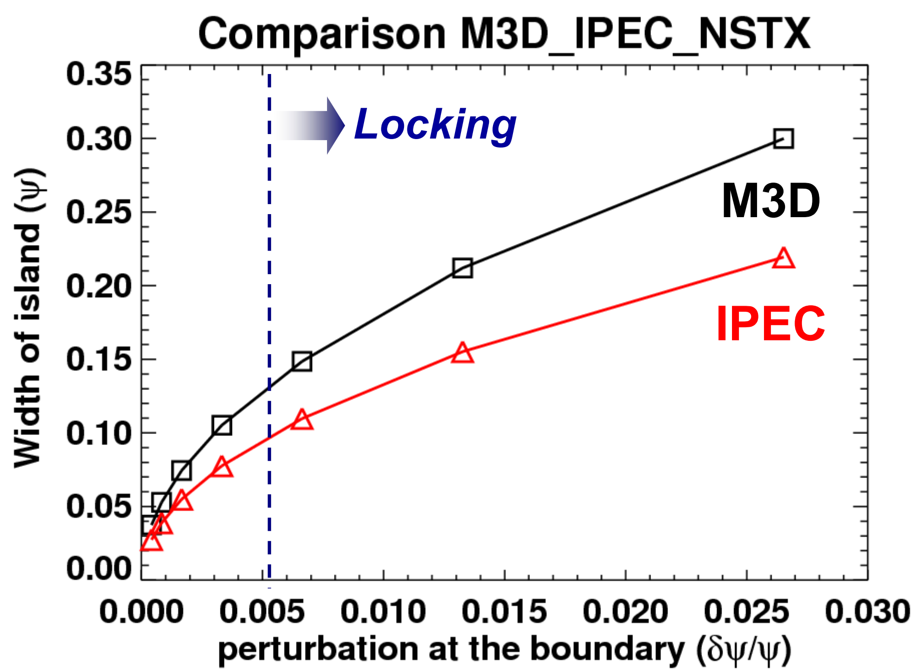
  - Measure plasma displacements, singular currents with IPEC; infer island widths.

  - 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.

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

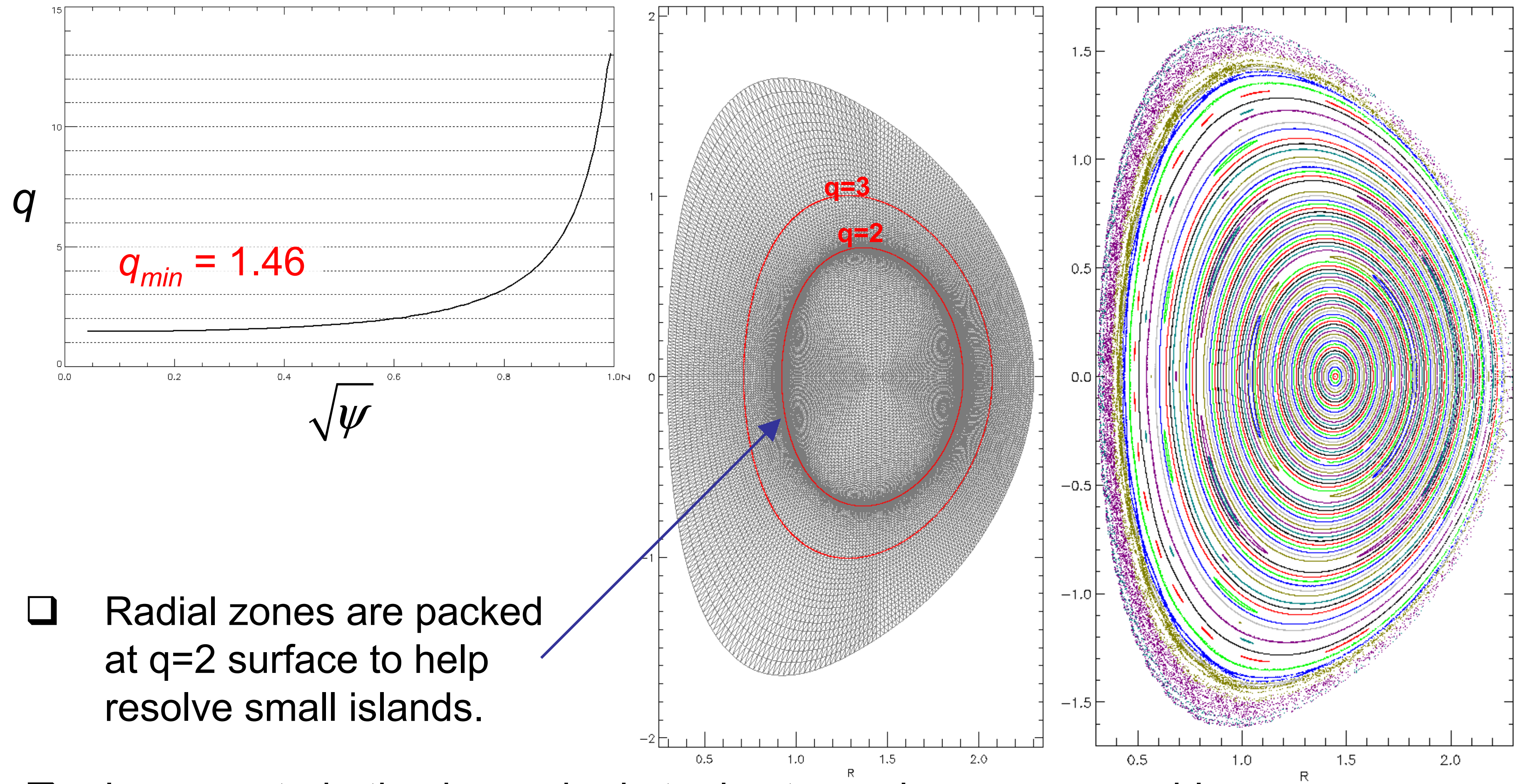
m=2, *n*=1 perturbation applied at boundary





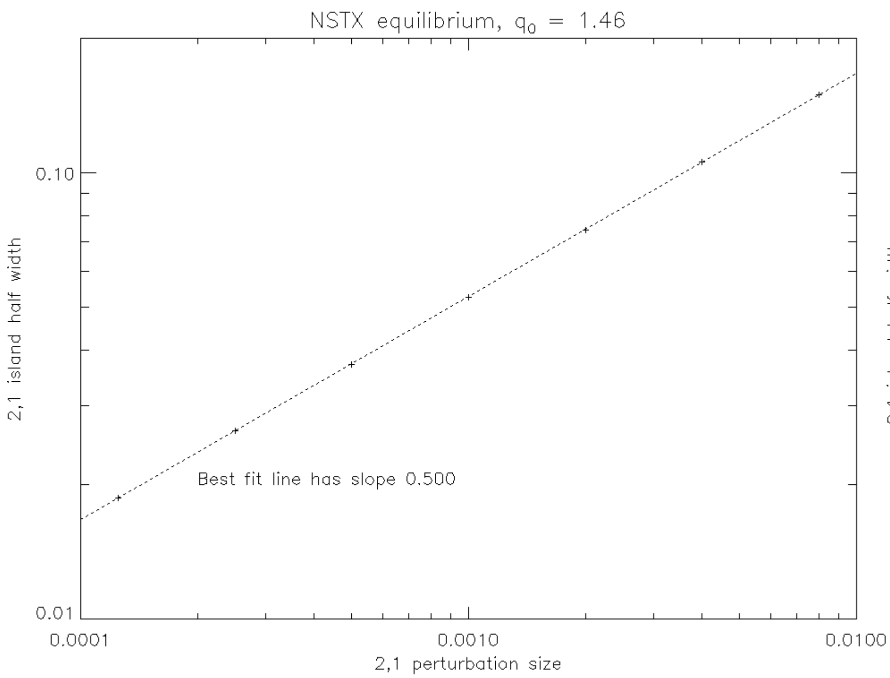
J.K. Park

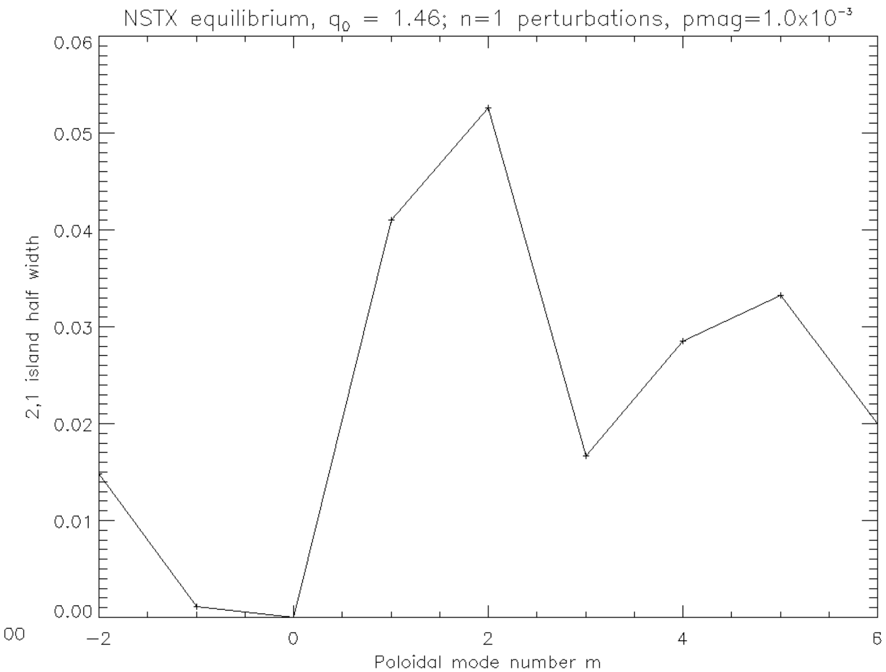
Nonlinear Studies Based on EFIT Reconstruction of NSTX shot 122444



- 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).

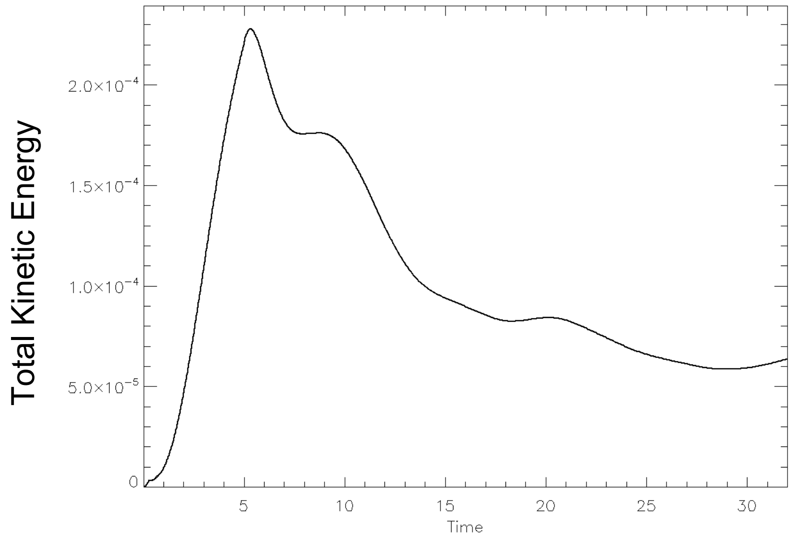
Steady State Response

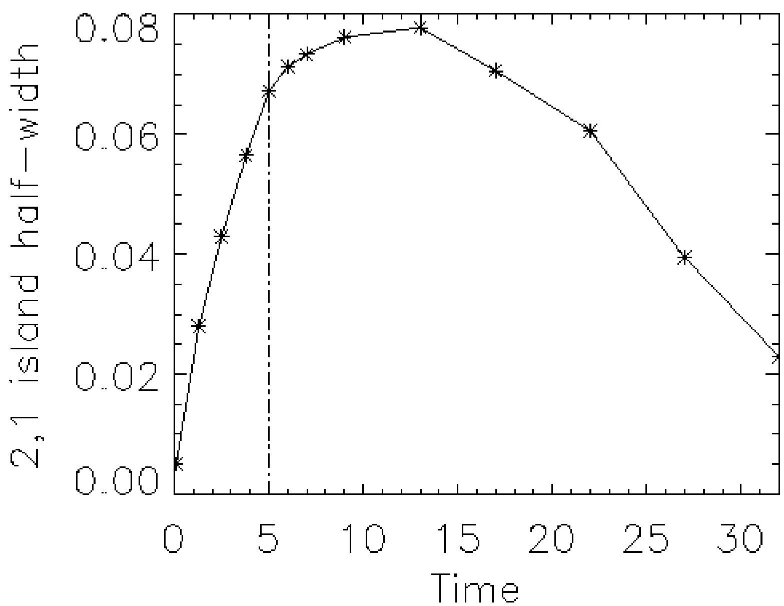




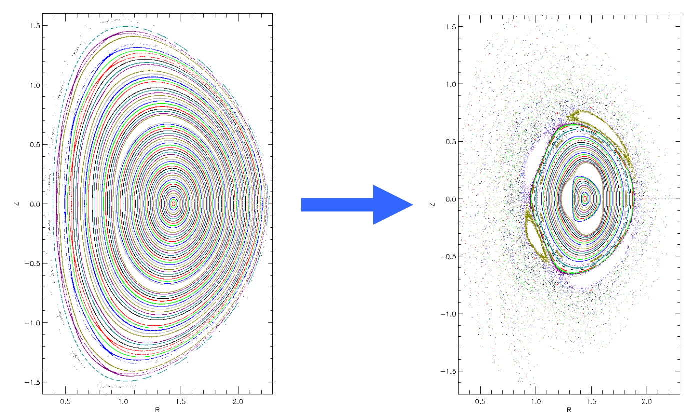
- Island width has expected scaling with perturbation amplitude.
- Peak response is at m=2.

Time-Dependent Response

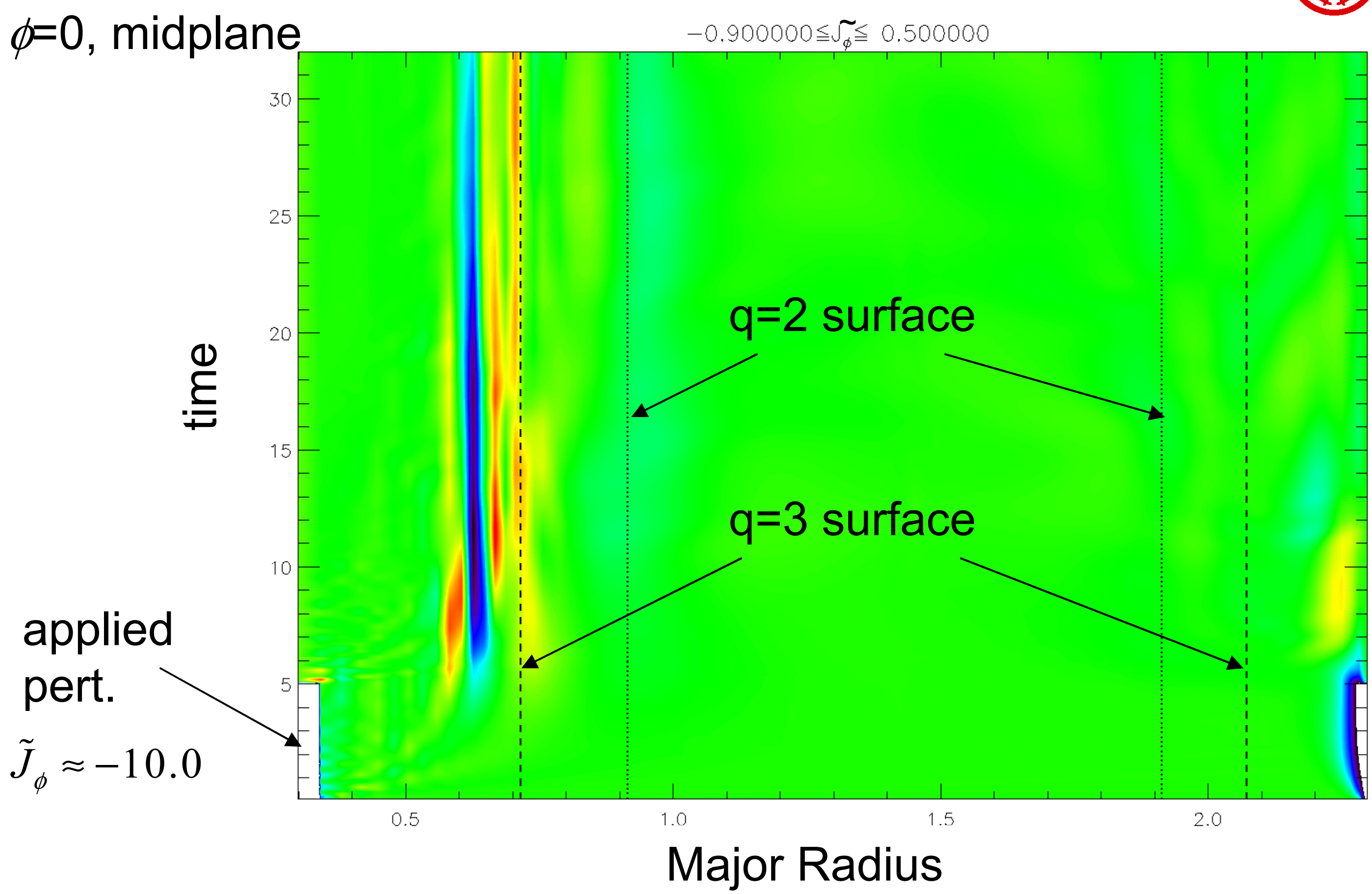




- Start with zero perturbation, ramp up linearly to full size in five Alfvén times to produce current sheets.
- S =2000, Pr =0.02, pmag=7.5×10^{-3}.
- Island size lags perturbation slightly, becomes stochastic on longer timescale.



Sharp current sheets form away from the q=2 surface



Why isn't a singular current seen at the resonant surface as expected?

Isolating Physics Responsible for Current Sheet Formation

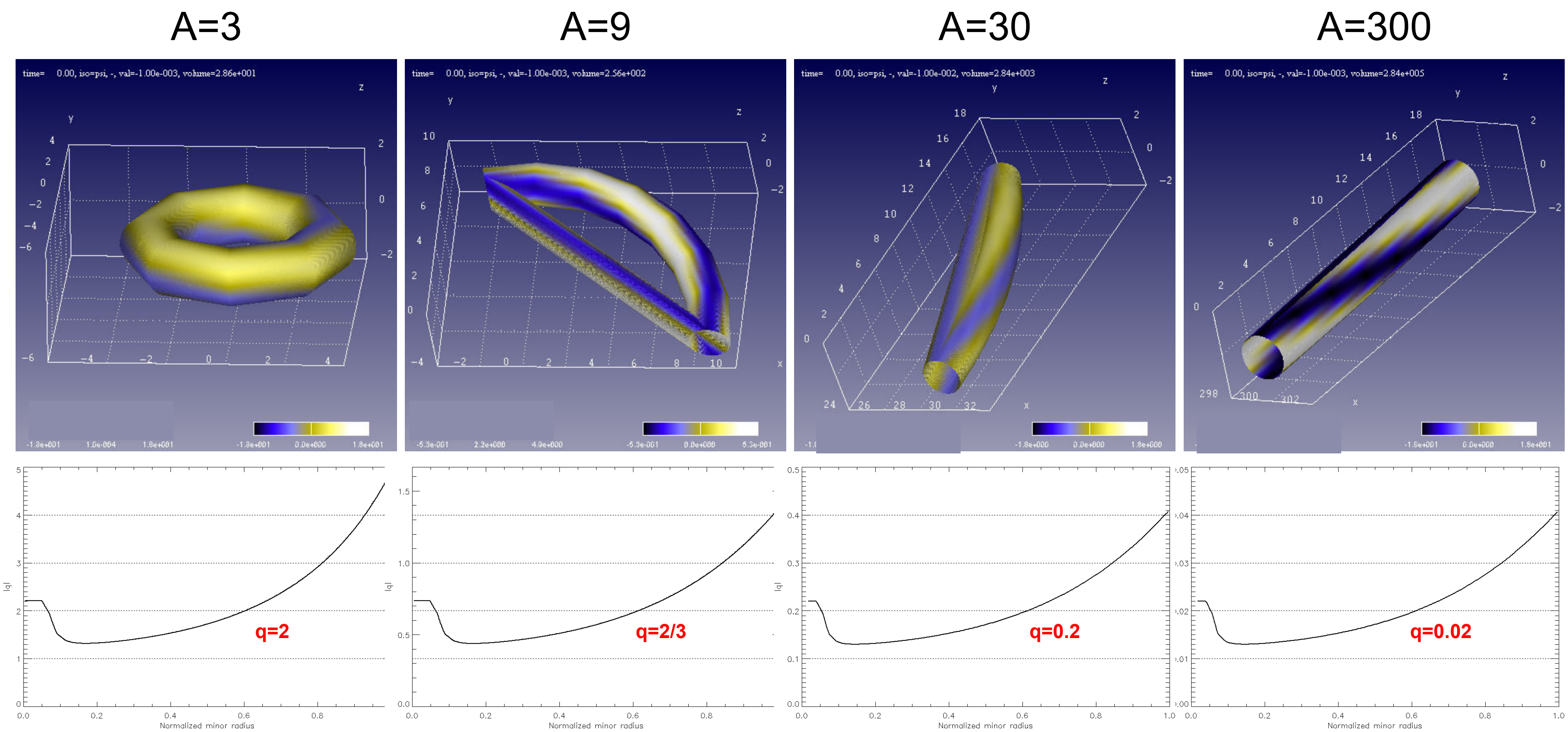
- Connect to analytic theory by approaching straight circular cylinder limit as aspect ratio A$\rightarrow\infty$.

- Equilibria: minor radius=1, cylinder length=6π, B_{ax} = 10 T, q_{min}=3.75 / A

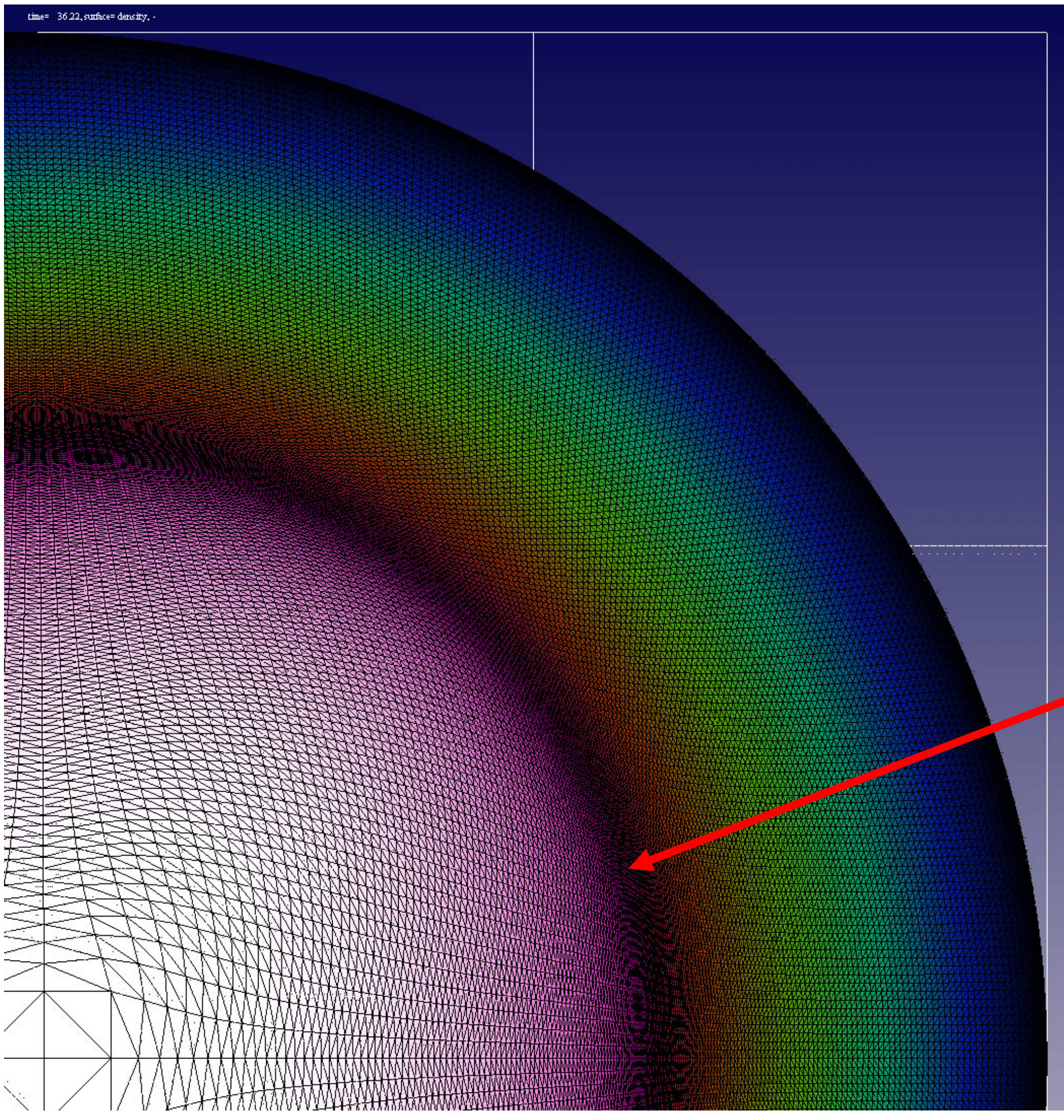
- Perturbations: m=2, n=# of field periods=A/3, `pmag`=7A/3000, t_{ramp} = 4.0 τ_A. (Gives zero-plasma-response island width ~20% of minor radius).

- Parameters: $\eta_{interior}$ =10^{-5}; $\mu_{interior}$=10^{-3}; η_{edge} =10^{-2}; μ_{edge}=1

Equilibria



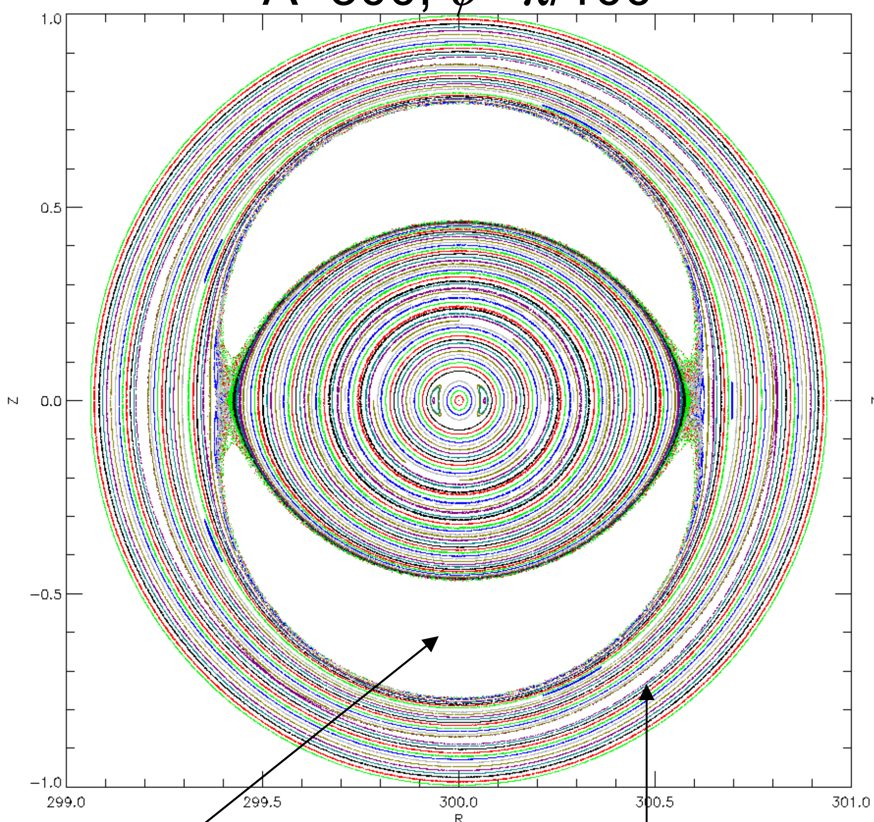
Use High Resolution, Mesh Packing to Resolve Current Sheets



- 8 toroidal planes
- 188 radial zones
- packing factor 4.0 at resonant surface

Zero plasma response, large A: Poincaré plots

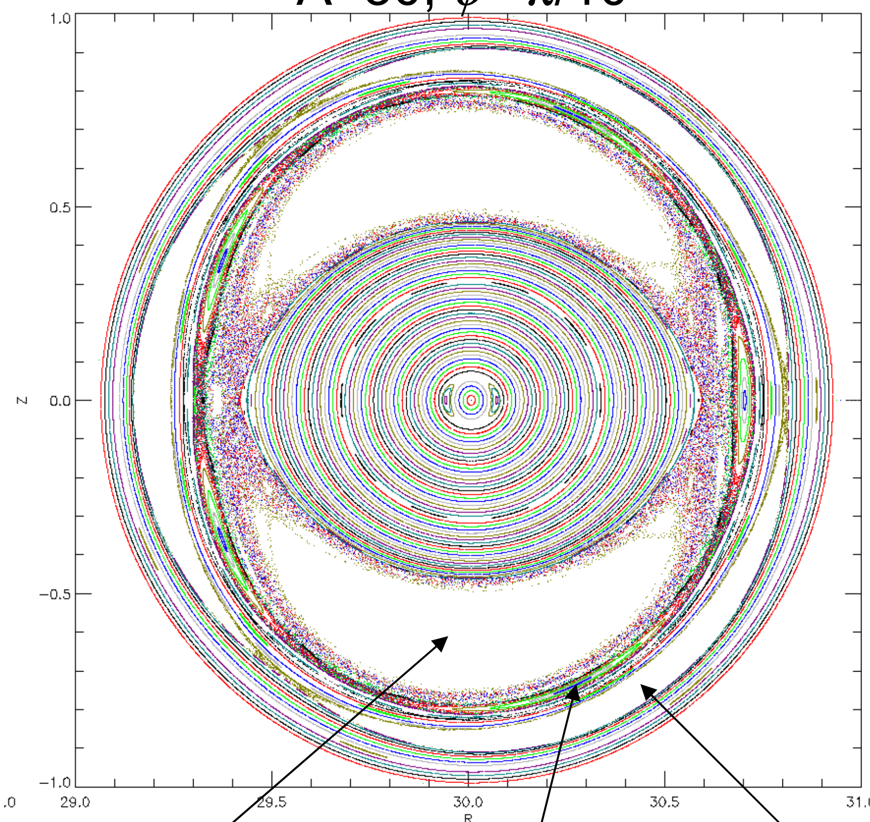
A=300, $\phi=\pi/100$



2,100 island
fw = 0.281

3,100 island

A=30, $\phi=\pi/10$



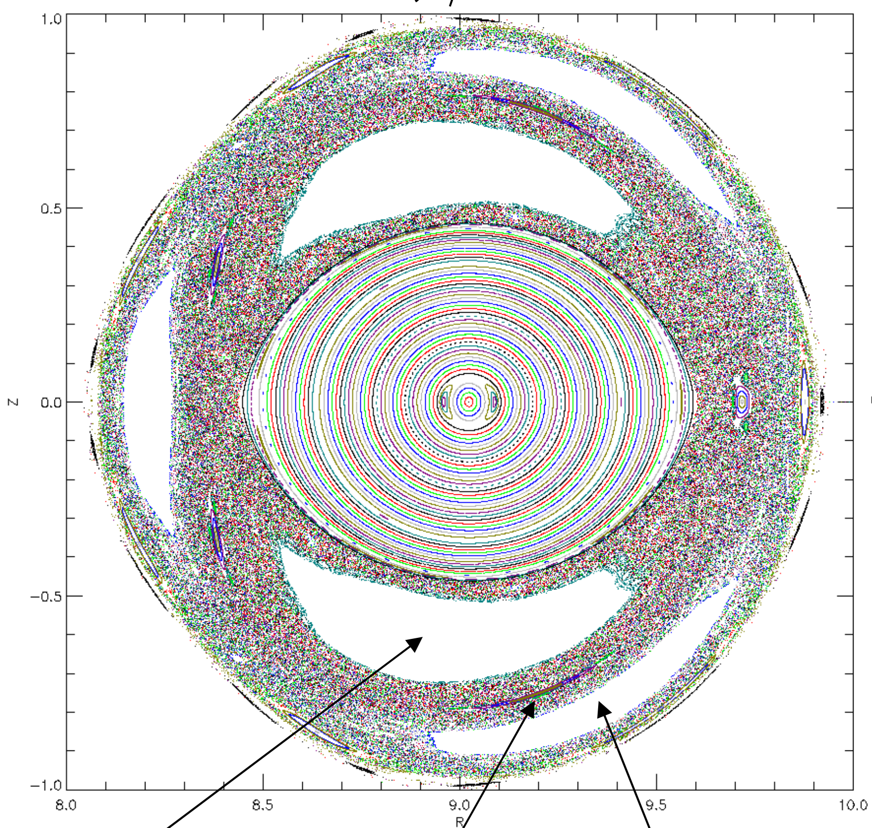
2,10 island
fw = 0.239

5,20 island

3,10 island

Zero plasma response, small A: Poincaré plots

A=9, ϕ =π/3

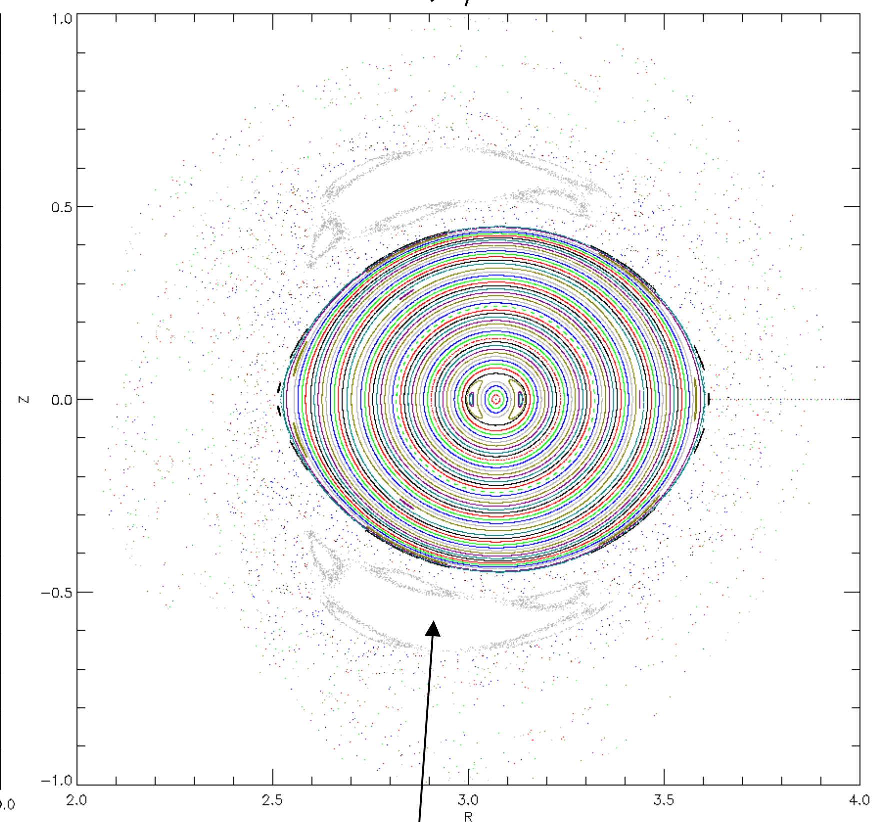


2,3 island
fw = 0.194

5,6 island

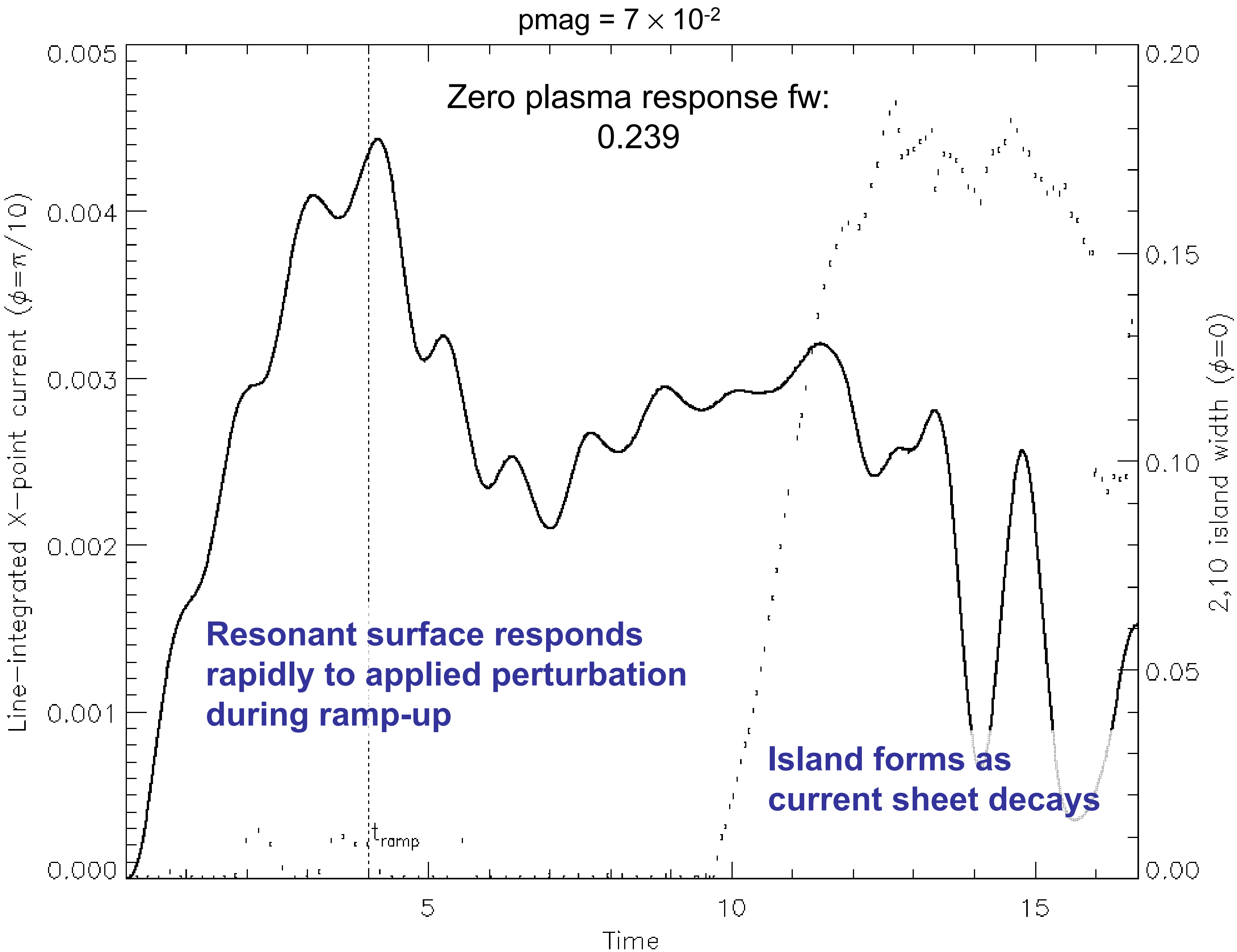
3,3 island

A=3, ϕ =π



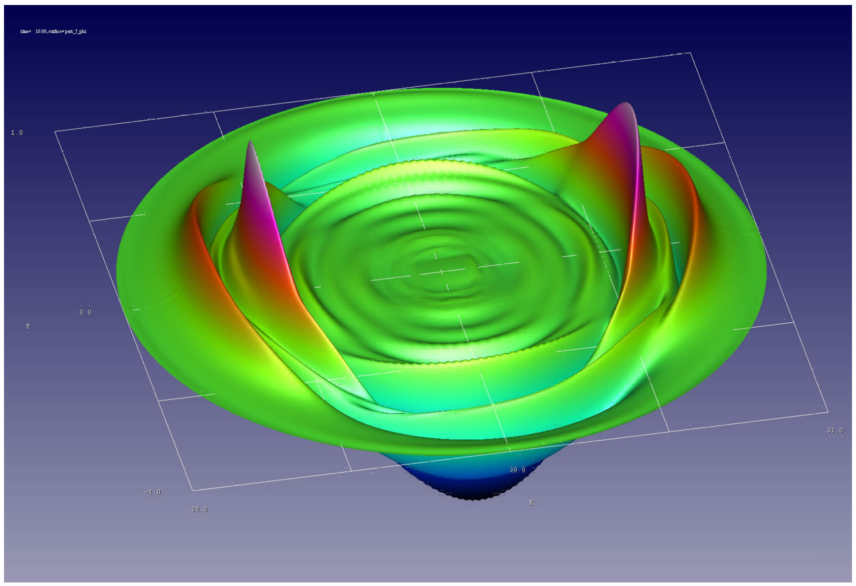
2,1 “island”
fw = 0.116

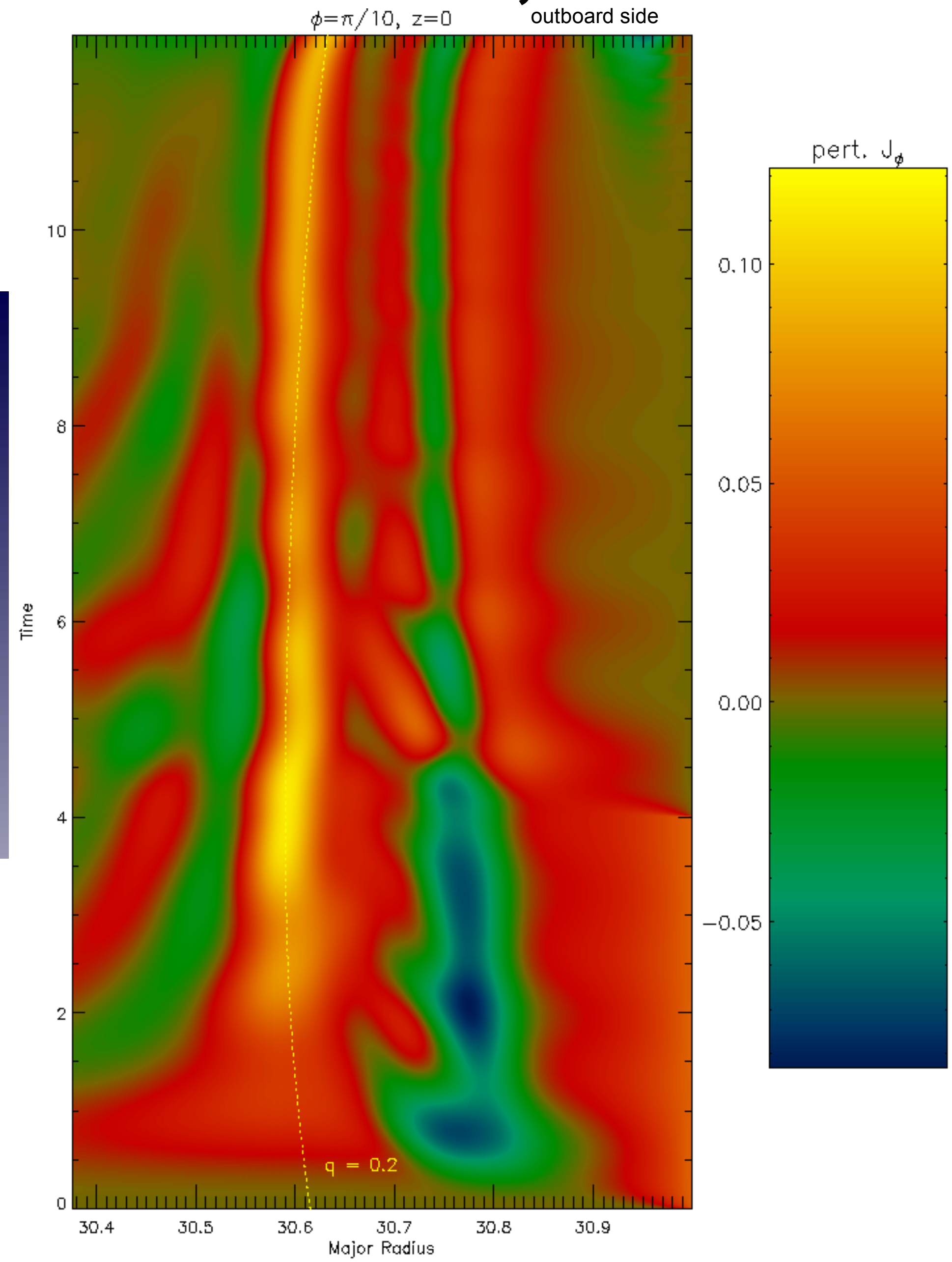
Plasma Response: A=30



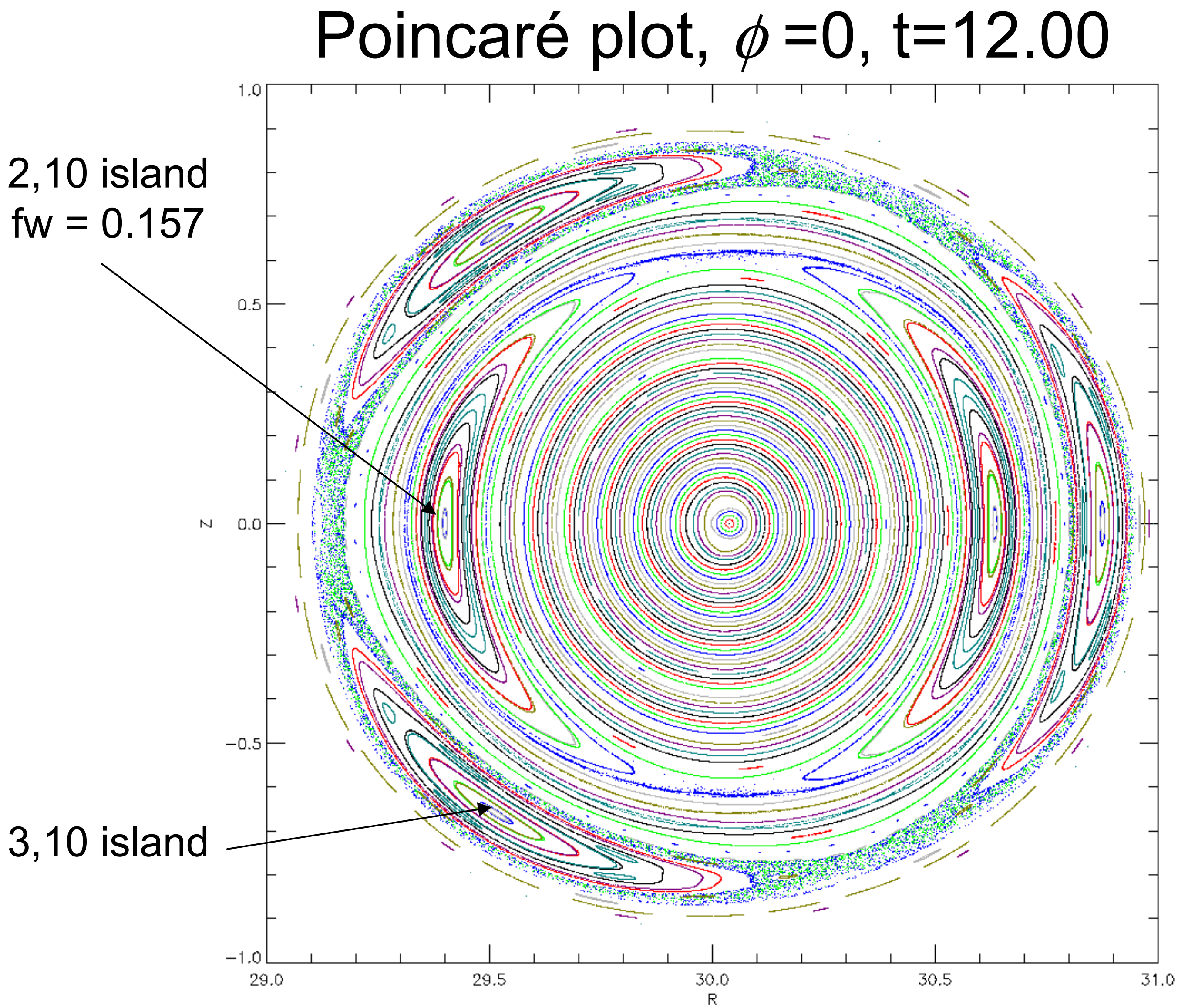
Current sheet formation, A=30

Perturbed component of J_ϕ,
$\phi = \pi/10$, $t = 10.00$



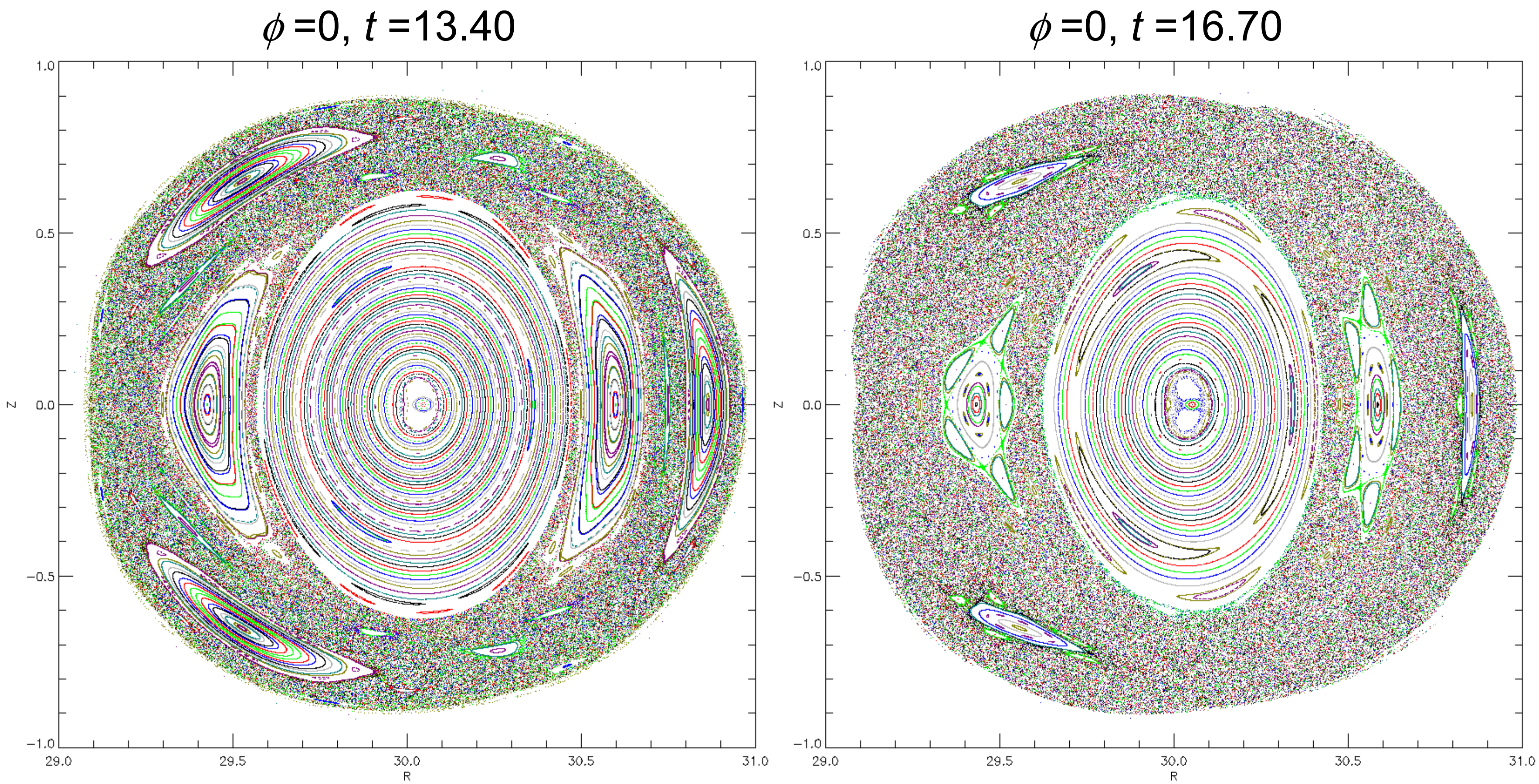


Island formation, A=30

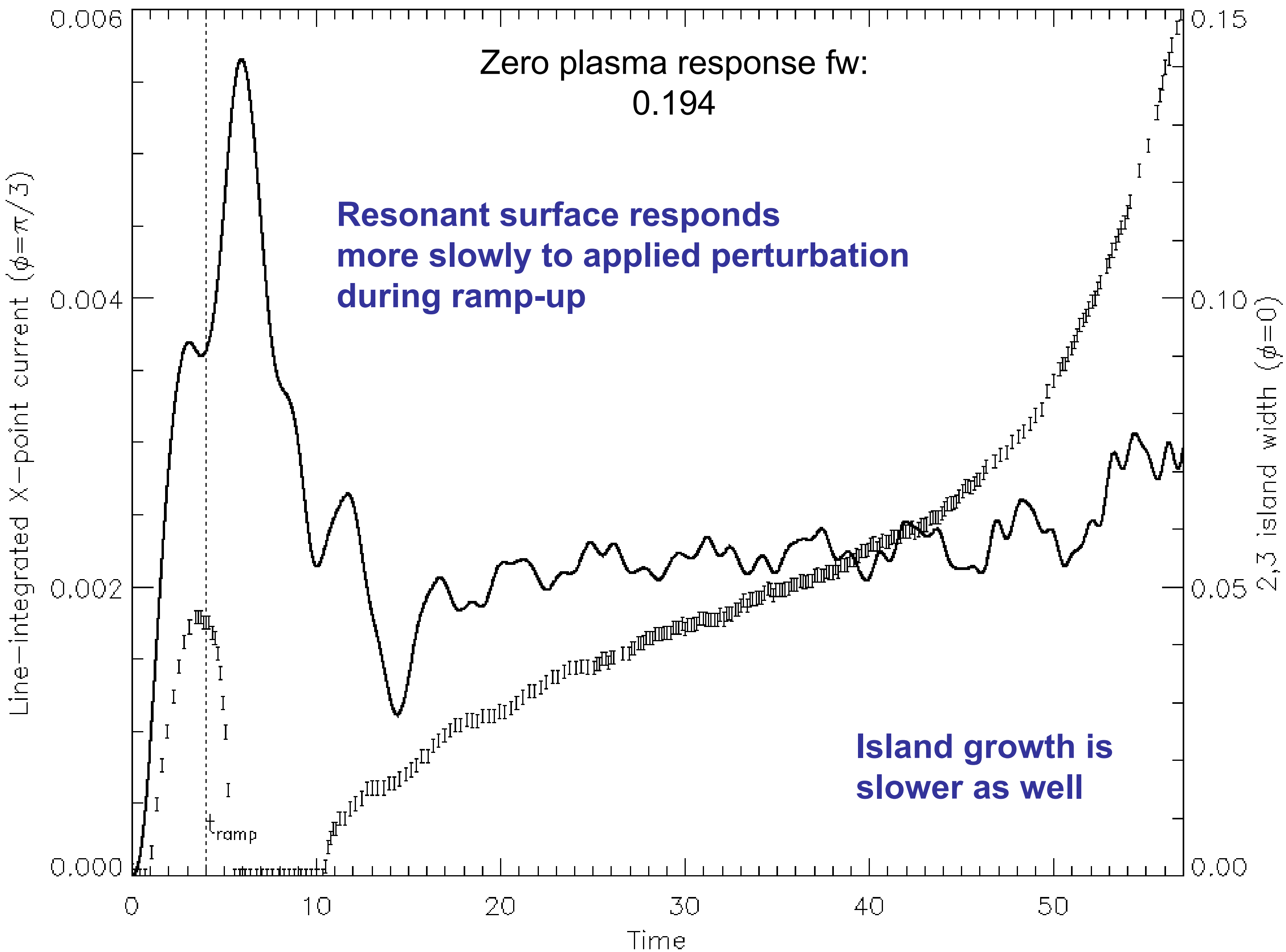


- Plasma response reduces island width compared to equilibrium value.
- Width at later times is limited by overlap, stochasticity.

Stochasticity at later times

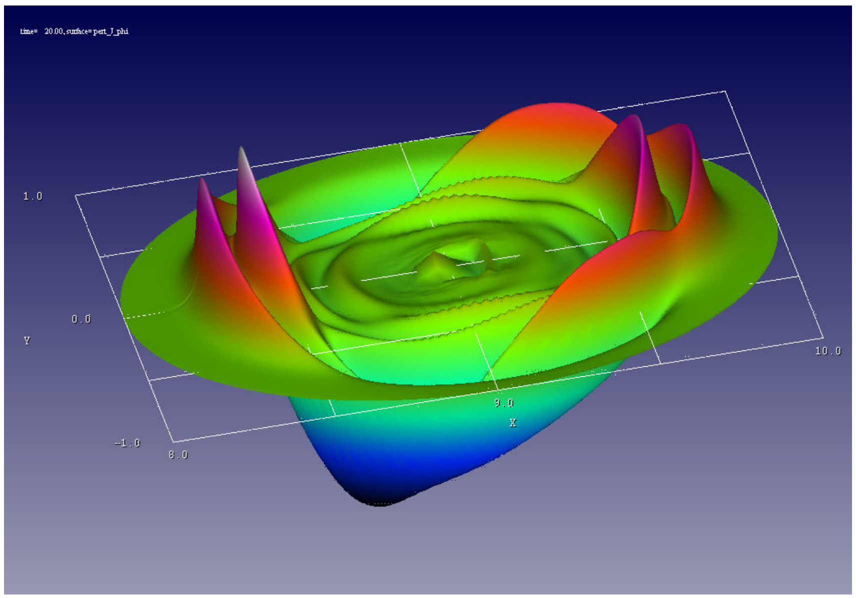


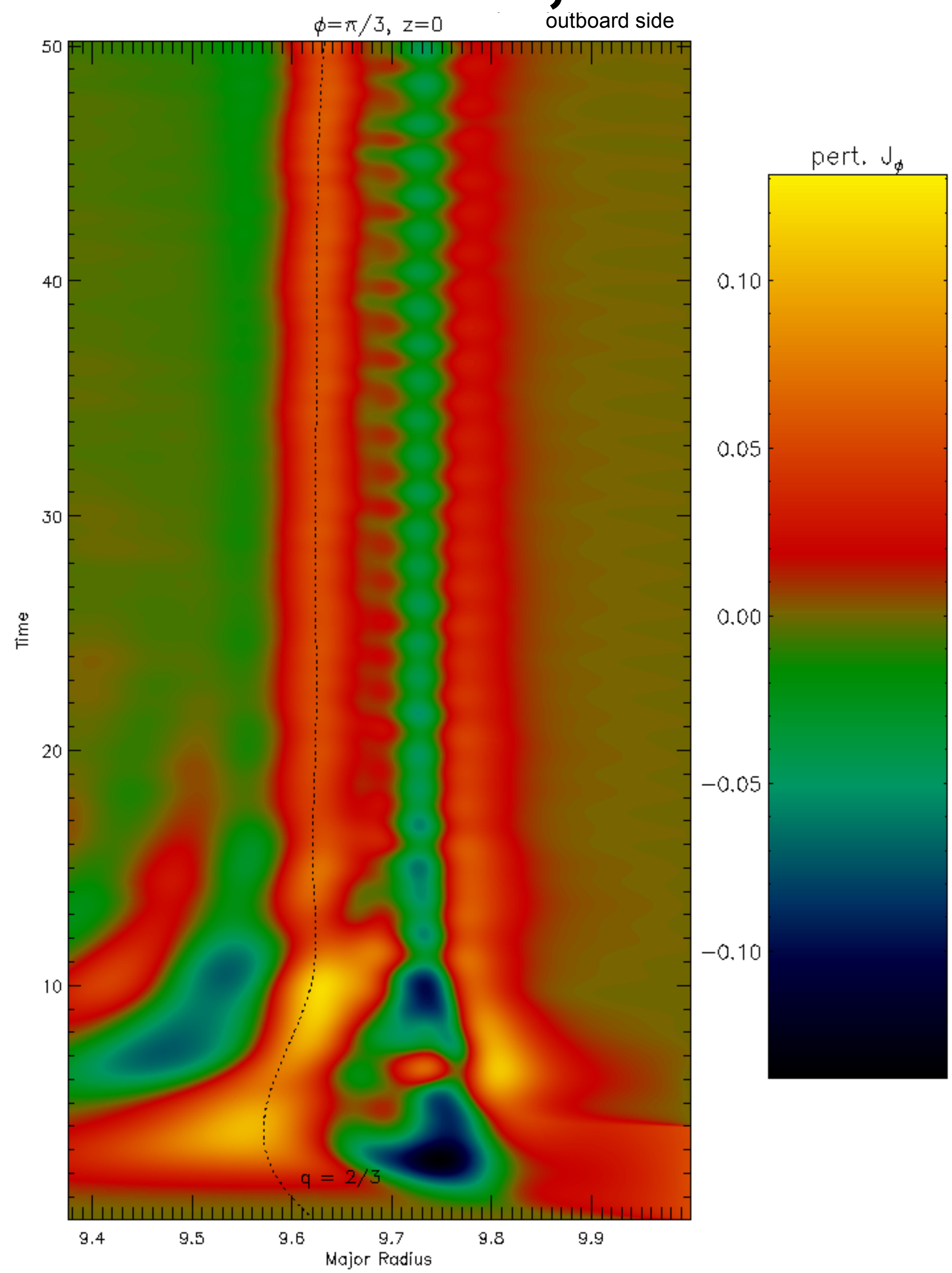
Plasma Response: A=9



Current sheet formation, A=9

Perturbed component of J_ϕ,
ϕ=π/3, t =20.00

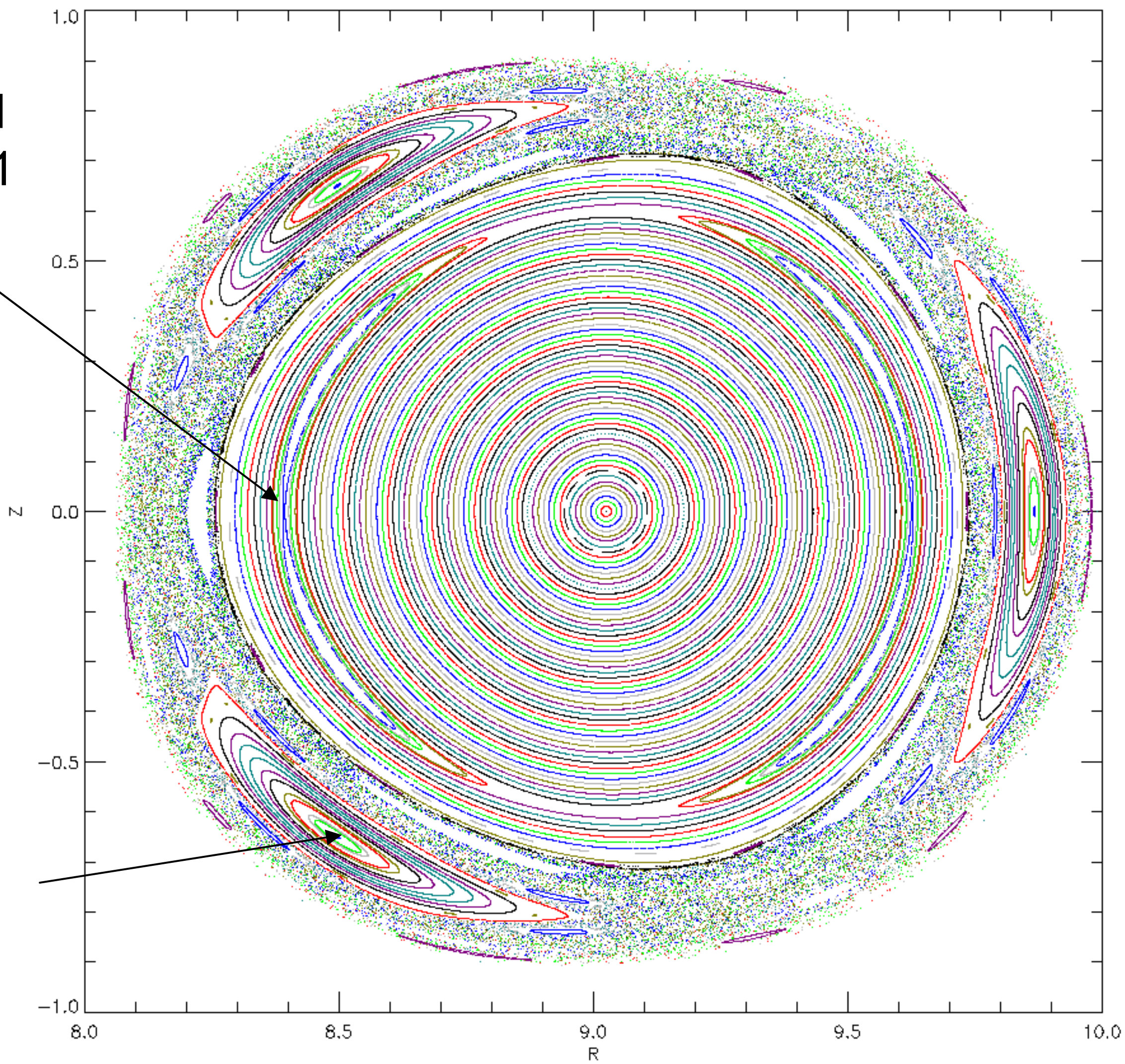




Island formation, A=9

Poincaré plot, ϕ =0, t=36.22

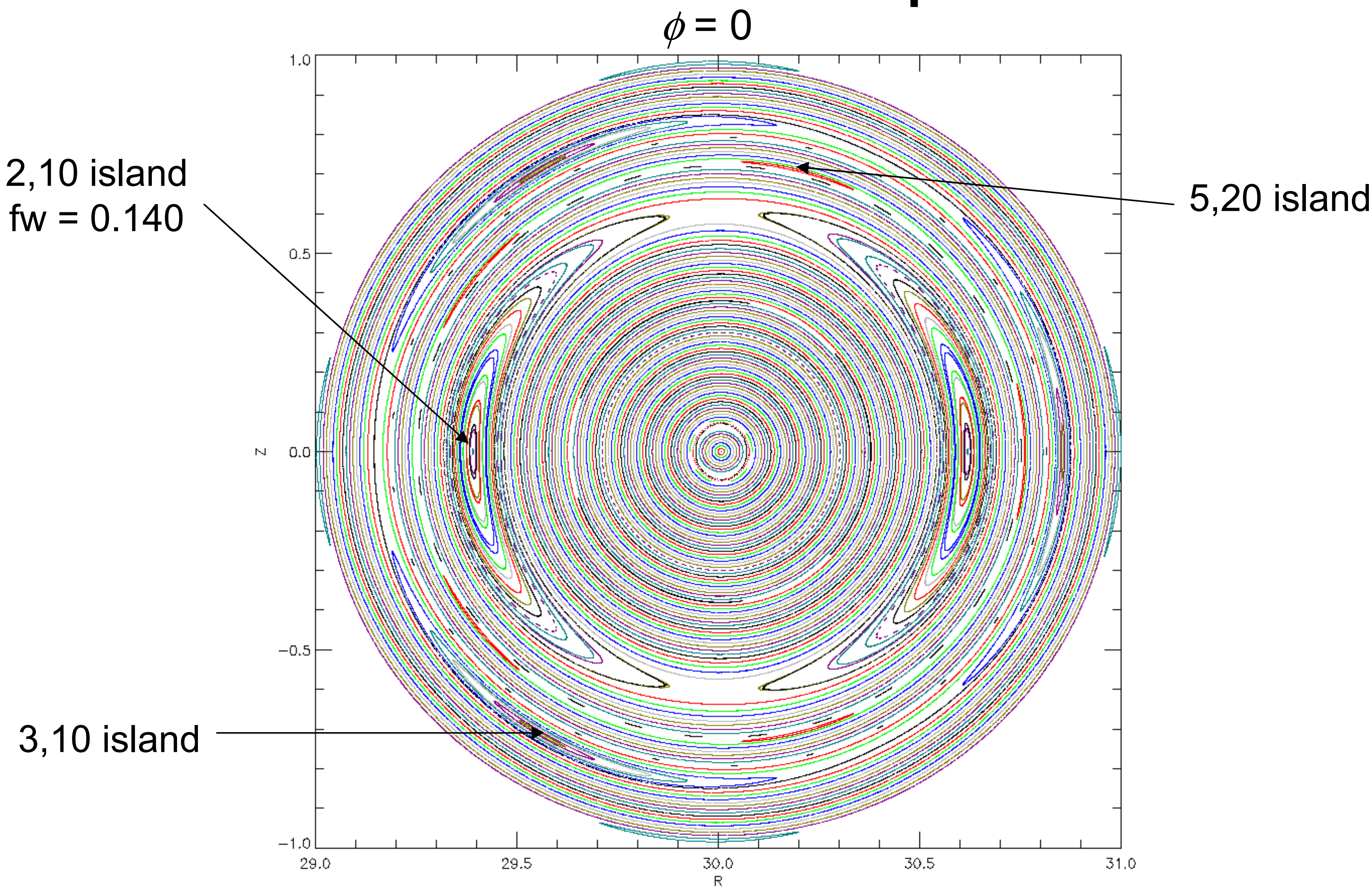
2,3 island
fw = 0.051



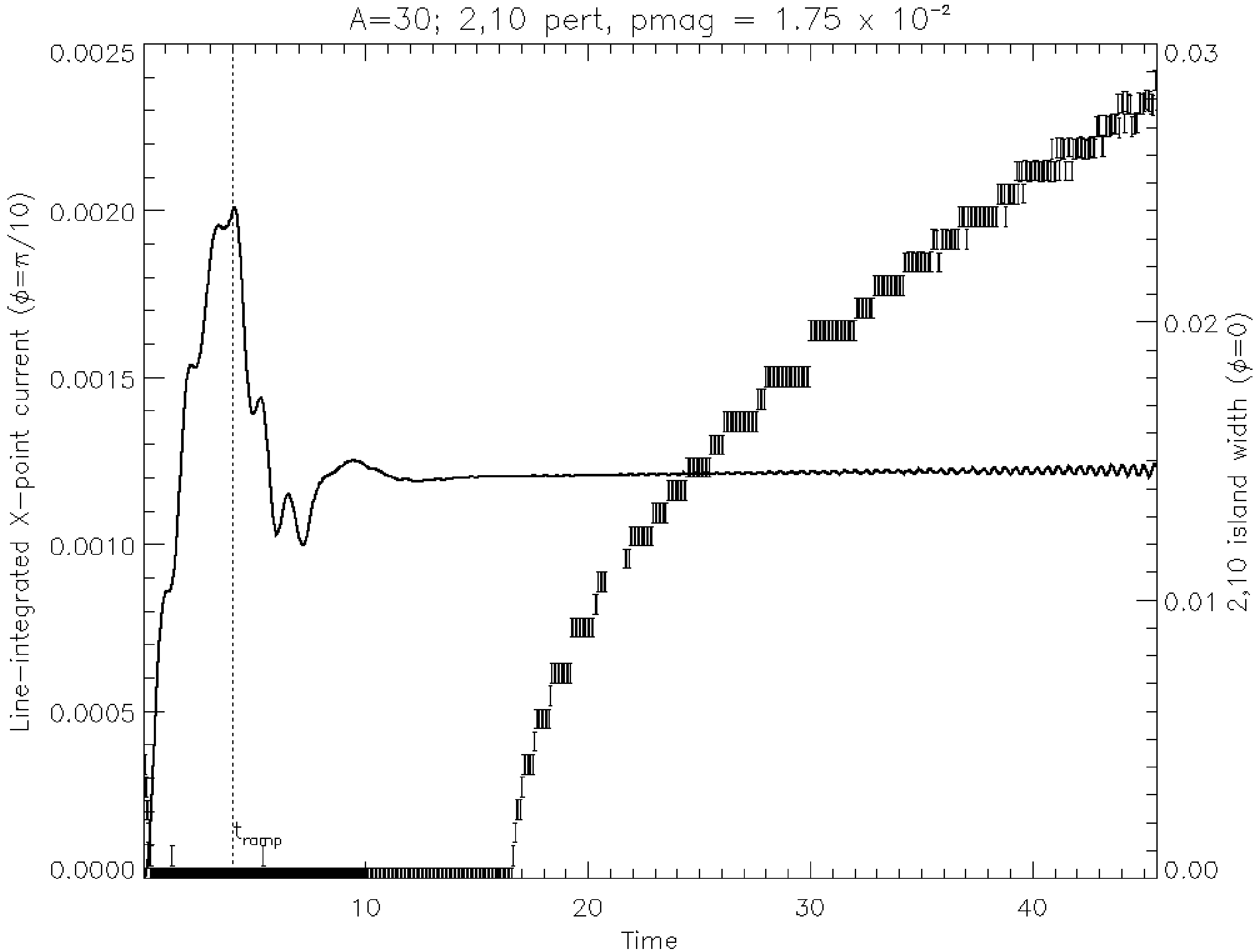
3,3 island

- At lower aspect ratio, toroidal coupling causes non-resonant 3,3 island to respond more strongly than 2,3 island to 2,3 perturbation.

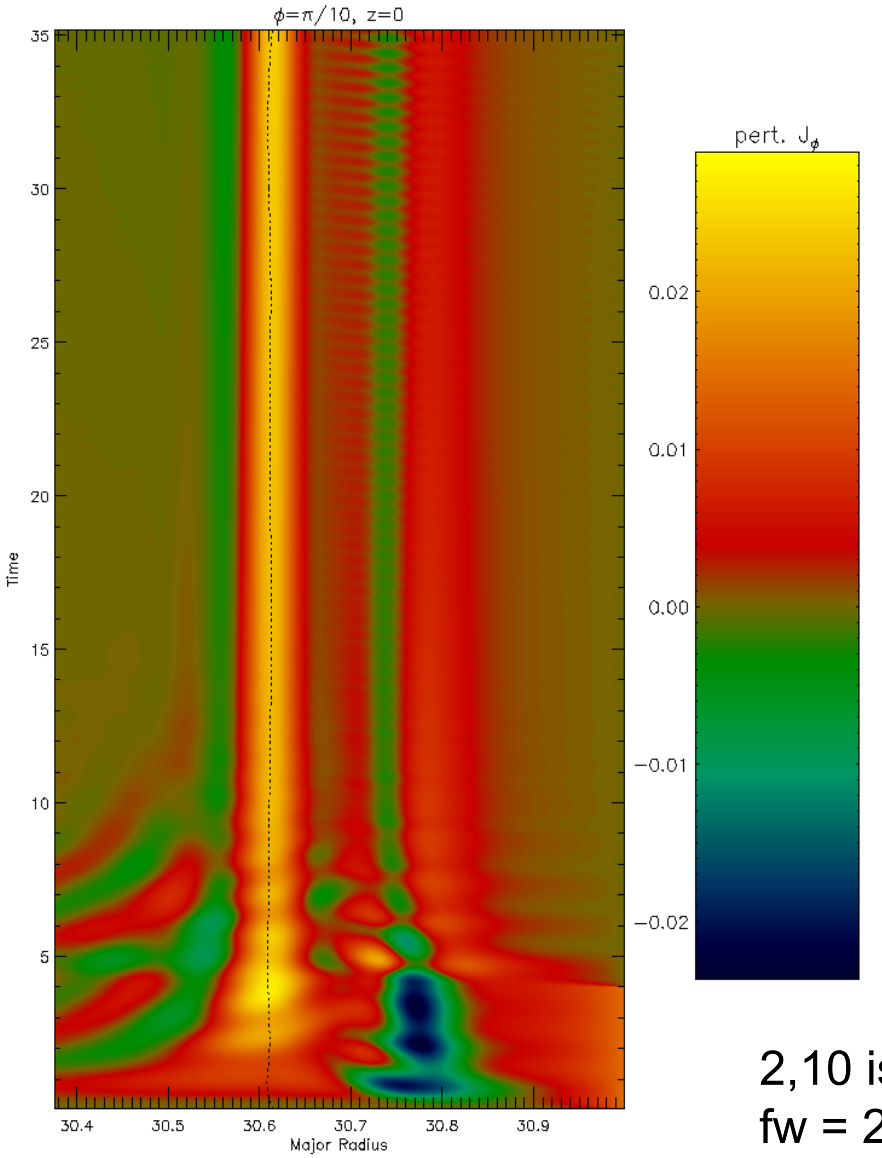
A=30, Perturbation reduced x4: Zero Plasma Response



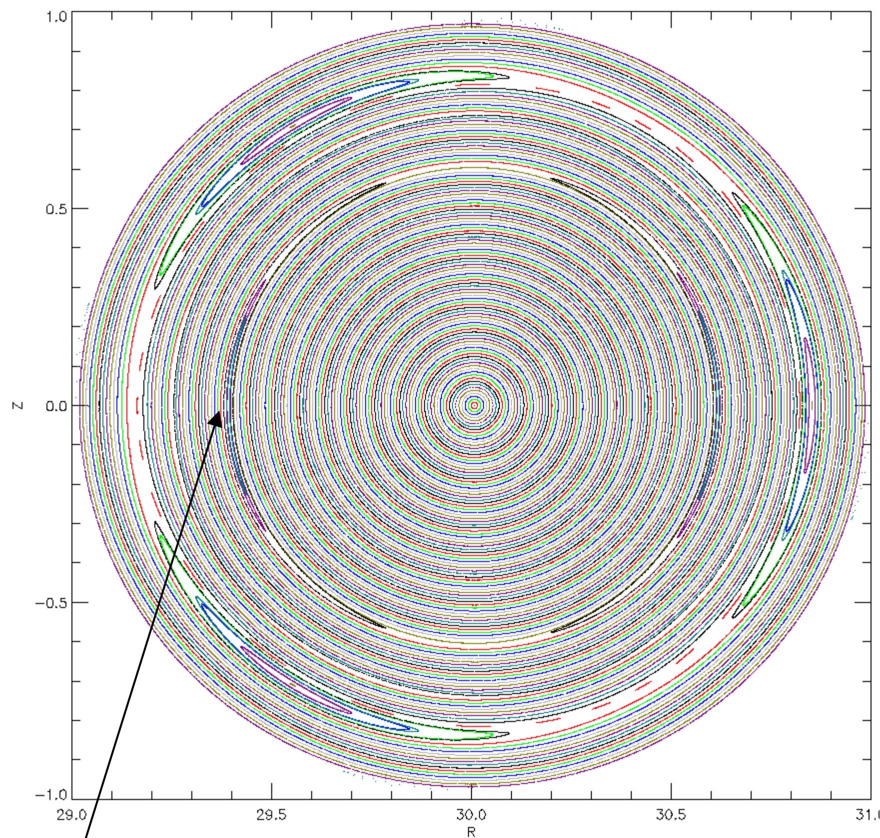
A=30, Smaller Perturbation: Plasma Response



A=30, Smaller Pert.: Sheet, Islands



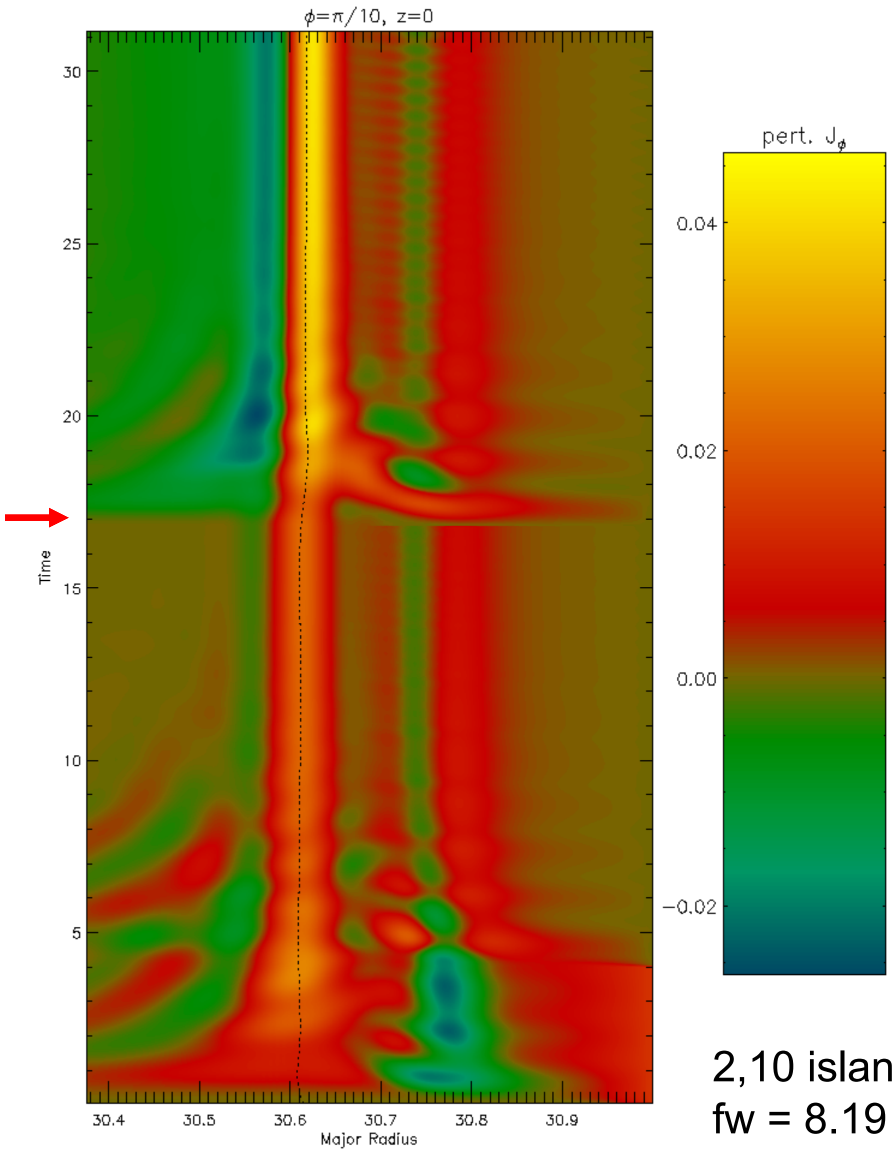
t = 35.18, ϕ = 0

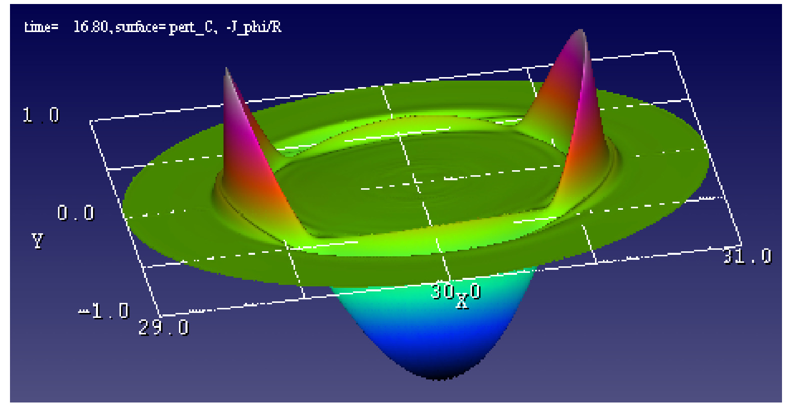


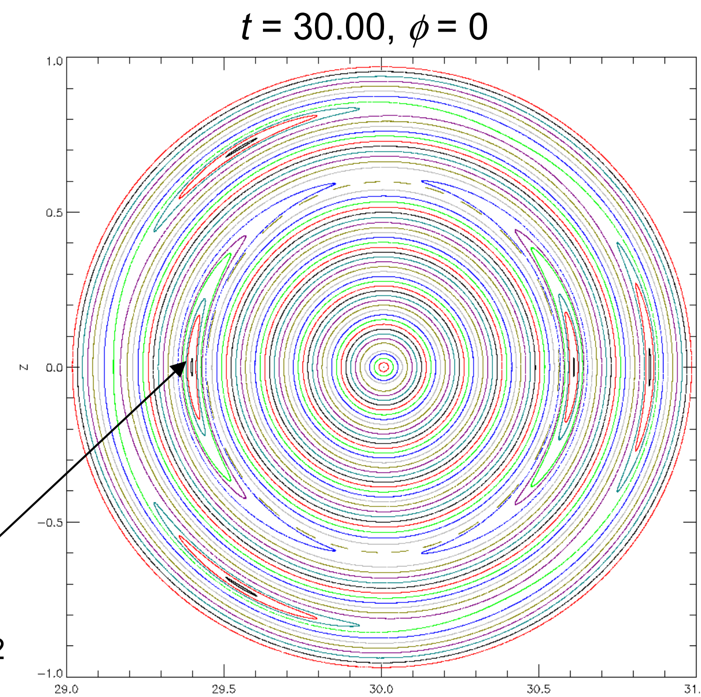
2,10 island
fw = 2.22×10^{-2}

Not stochastic!

Forcibly remove spurious shielding current

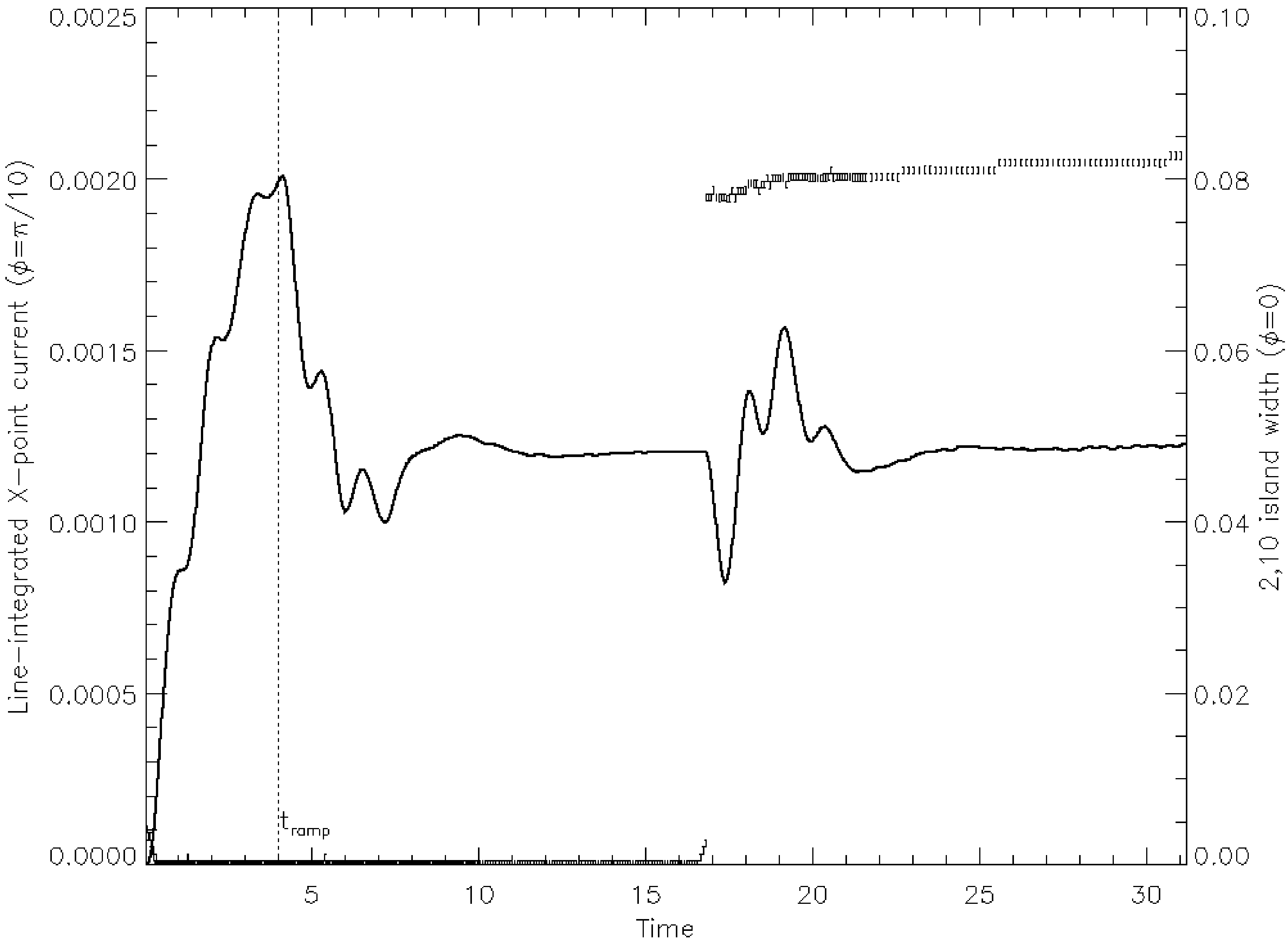






2,10 island
fw = 8.19×10^{-2}

Plasma response



Comparison with theory

- For an m=2 perturbation in a straight cylinder (∞ aspect ratio limit),

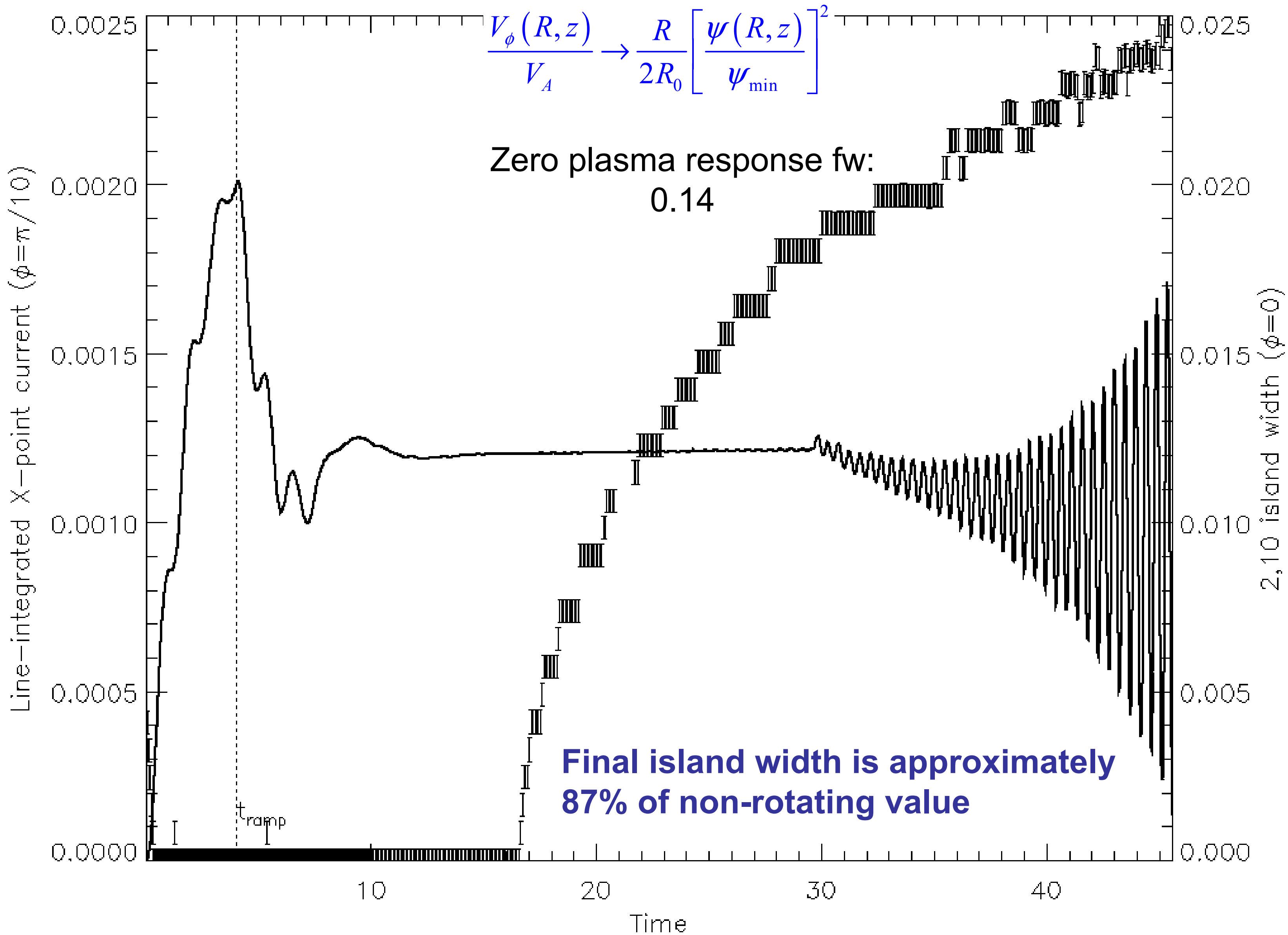
$$\left|B_r\right|_{m=2} = \left|\frac{1-r_2^4}{2}\sigma_{m=2}\right| \quad \text{and} \quad w = \sqrt{2B_r / \iota'}$$

where r_2 is the minor radius of the singular surface, $\sigma_{m=2}$ is the singular sheet current density, w is the island width, and $\iota' \equiv d(1/q)/d\psi$.

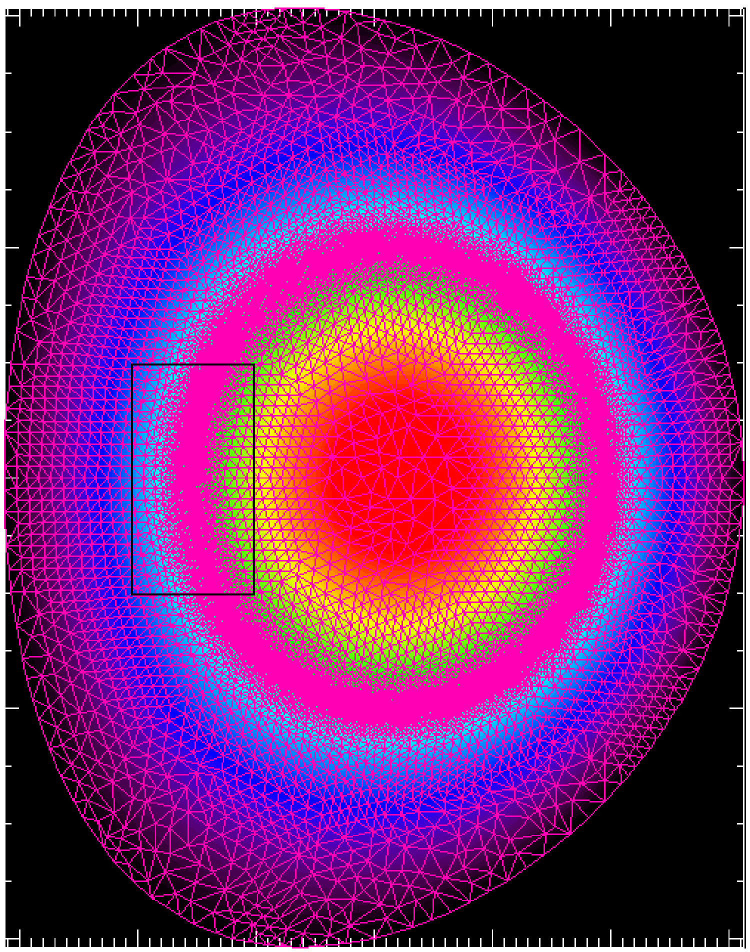
- Rational surface field line aspect ratio is 10.

	Measured induced *m*=2 surface current density	Theoretical $B_{r,m=2}$ at rational surface (infinite aspect ratio straight cylinder)	Measured B_r at rational surface	Theoretical island width	Measured island width
A=30 `pmag` = 0.07	2.81×10^{-3}	1.50×10^{-3}	3.01×10^{-3}	3.26×10^{-2}	1.86×10^{-1}
A=9 `pmag` = 0.021	2.14×10^{-3}	1.61×10^{-3}	3.08×10^{-3}	5.91×10^{-2}	1.48×10^{-1}
A=30 `pmag` = 0.0175	1.20×10^{-3}	1.72×10^{-4}	1.41×10^{-4}	7.05×10^{-3}	2.80×10^{-2}
A=30 `pmag` = 0.0175 *“surface” current killed*	1.57×10^{-3}	1.70×10^{-5}	5.51×10^{-4}	1.39×10^{-2}	8.19×10^{-2}

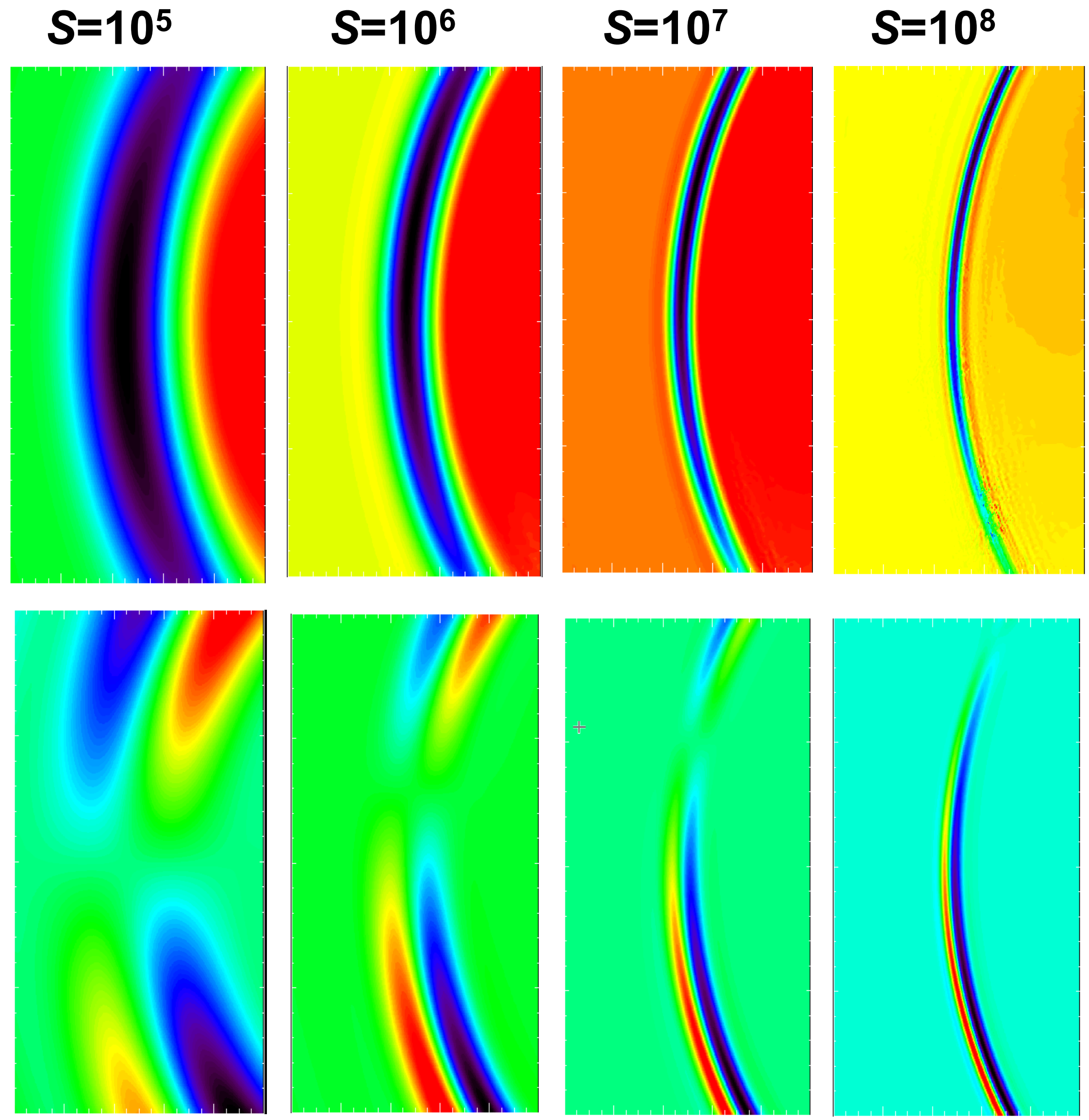
Suppressing Island Growth with sheared toroidal rotation (A=30)



M3D-C^1 code has higher resolution and implicit time stepping. This will allow studies at higher S values.



Perturbed current density (top) and vorticity (bottom) for (1,1) tearing mode at different S



Conclusions

- M3D island width predictions agree reasonably well with IPEC for tokamak test cases with 2,1 perturbation.
- Observing current sheet responses requires high resolution, suppression of edge response (surface currents).
- Toroidal effects couple modes at low aspect ratio even with a circular cross-section, leading to preferential induction of islands closer to the plasma edge.
- Large aspect ratio straight cylinder theory with m=2 only does not agree well with observed B_r or island sizes; curvature effects, higher harmonics are likely.
- Rotation suppresses island growth somewhat; more systematic study is needed.

Future Work

- Repeat theory comparison using a more accurate and complete analytic model.

- Investigate plasma rotation effects more systematically by implementing a parallel viscosity model, performing parameter scan over v_ϕ.

- Repeat these studies with NSTX equilibria.

- Compare results with those of M3D-C^1 code, then use C1 for higher-resolution, higher-S convergence studies.