New results on edge instabilities

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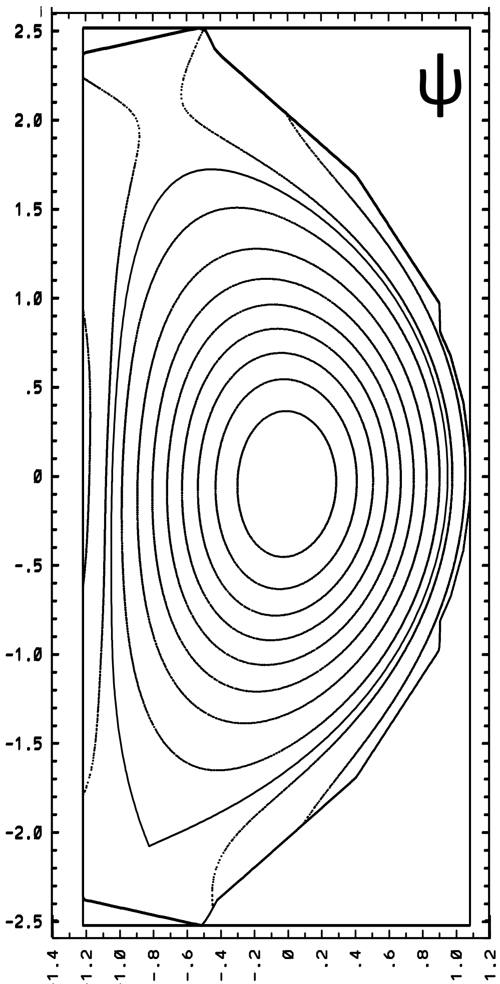
Topics

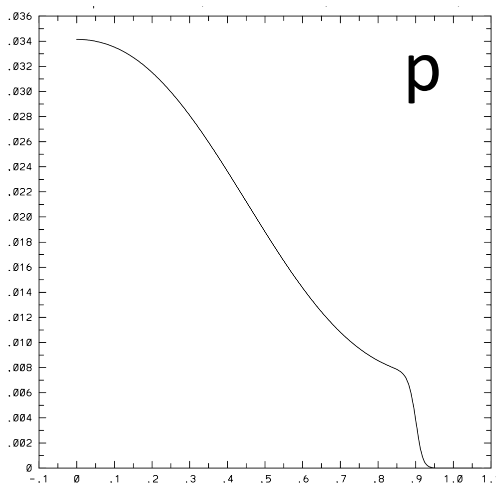
- Nonlinear MHD simulation of plasma edge instabilities find that ELMs and inter-ELM modes have many similar features
- Linear eigenmode spectrum compared to small amplitude nonlinear mode – consistent, large aspect ratio approximation
- Finite amplitude – nonlinear and higher order aspect ratio effects
- Nonlinear mode structure – first comparison to measured 2D/3D perturbations in an edge mode (T_{ECE} in inter-ELM mode in KSTAR) – nonlinear gives much better fit than linear eigenmode

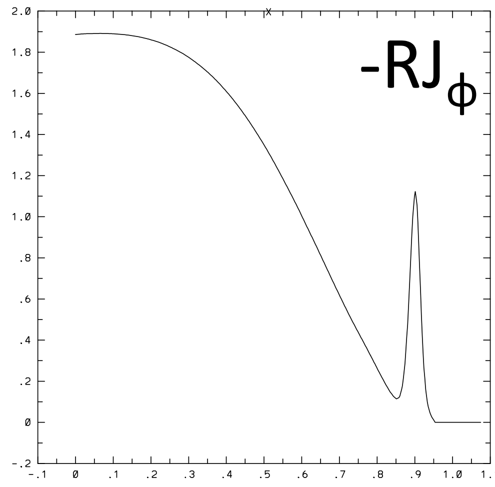
KSTAR inter-ELM mode

- In KSTAR, the 2D and 3D structure of edge instabilities can be measured at high resolution by electron cyclotron emission imaging (ECEI) of the radiation temperature T_{ECE} [1,2]
- The inter-ELM mode in KSTAR is a long-lived, finite amplitude edge instability that exists between ELM crashes, which have different *m,n* structure and behavior
  - Unlike ELM, no strong loss of plasma from the edge
- But, background plasma profiles not well known
- MHD nonlinear simulation of approximate equilibrium for ECEI cases with the M3D code, starting from small perturbation of all $n \le 23$ nonzero toroidal harmonics
  - Parameters $S=10^7$, $\mu=10^{-5}$, $\kappa_\perp=D_n=10^{-5}$, effective $\kappa_\parallel=3R_o v_A$
  - Density profile not measured; simulation uses uniform density $n \equiv n_o$, solves p equation with the thermal conductivities

KSTAR 7328 equilibrium





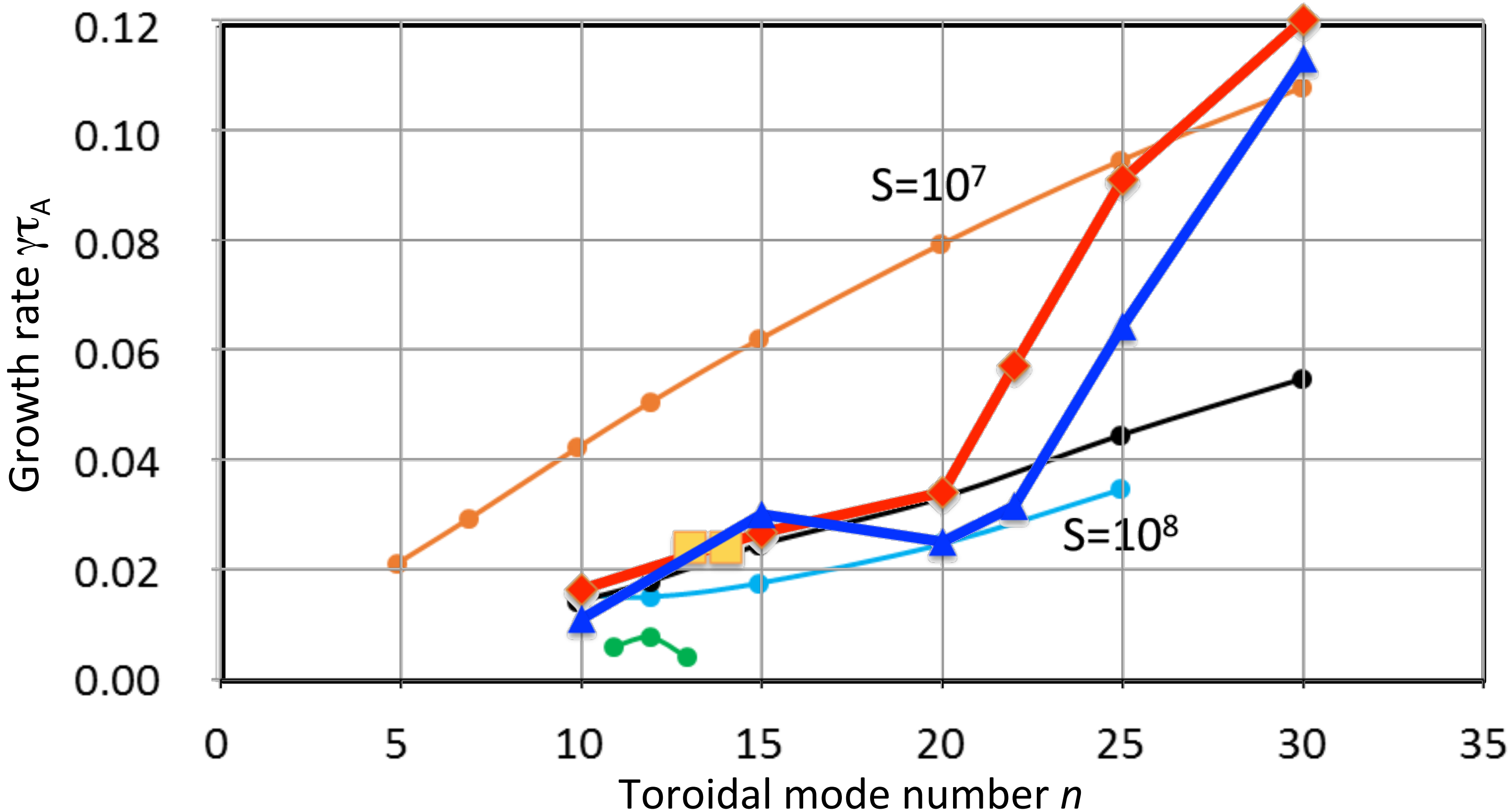


Plasma:

a=0.457m, R_o=1.82m
B_T=1.017 T, I_p=750 kA
P_{NB}~3 MW
q_{95}~5
β_o=1.72%, $\langle\beta\rangle$=0.384%
τ_A=1.6×10^{-7} s

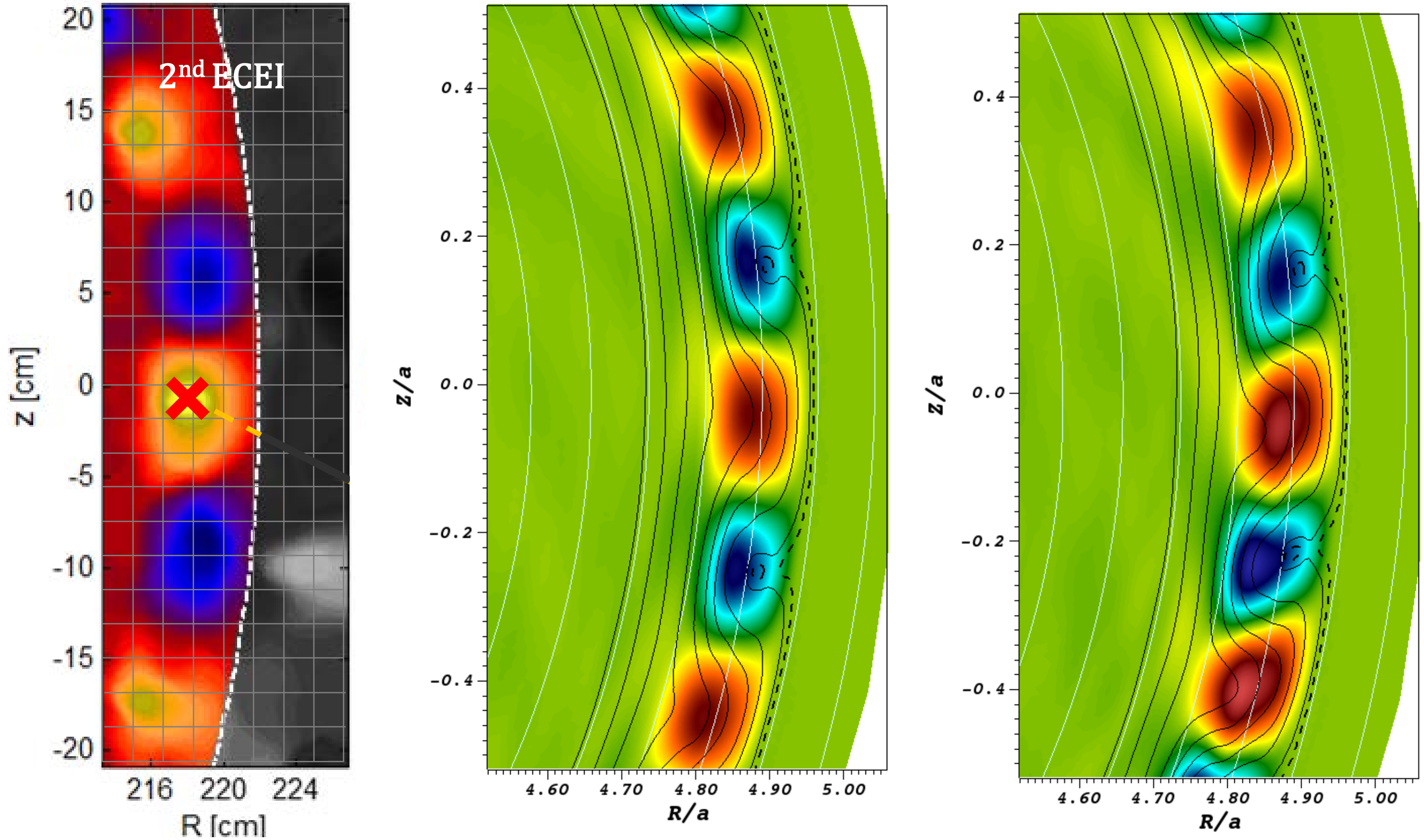
- Equilibrium for edge mode study t=4.400 s – added edge p-pedestal and bootstrap current (A. Pankin, 2014)

Linear eigenmode spectrum



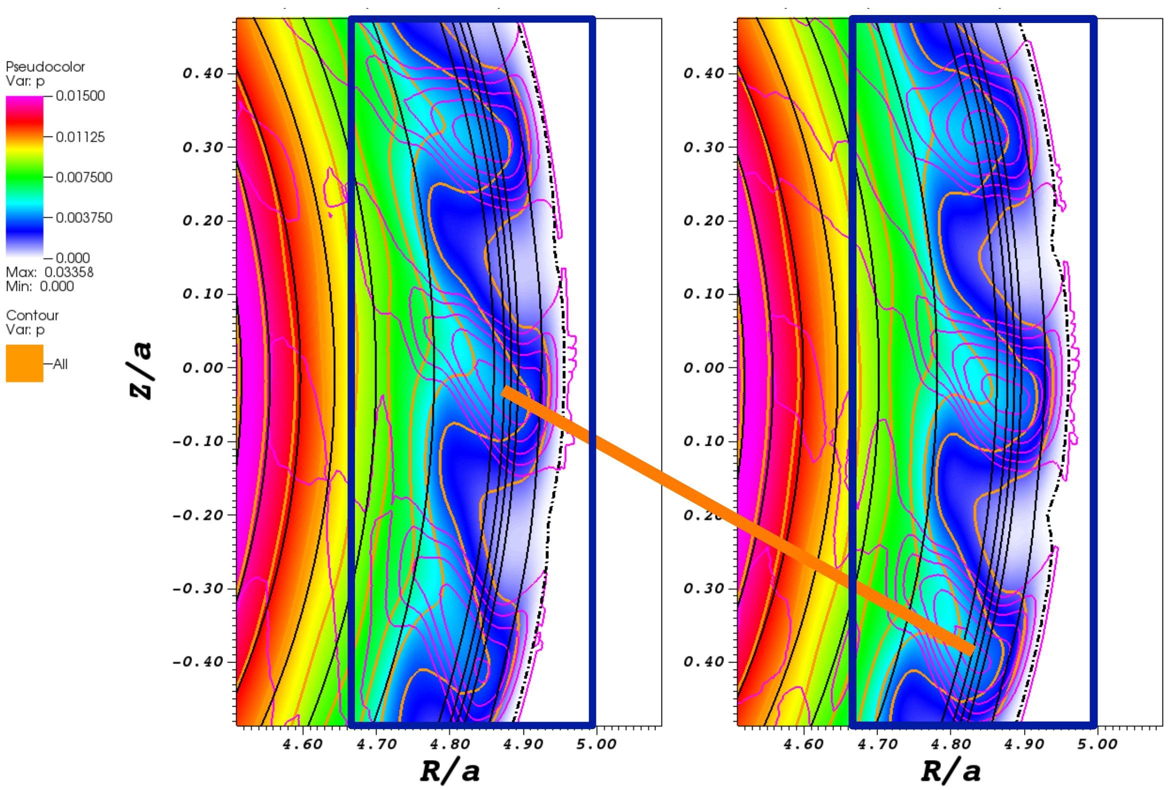
- Linear resistive MHD eigenmodes from BOUT++ (M. Kim, POSTECH)
  - Uniform resistivity $S=10^7$ and $S=10^8$; Black: Spitzer resistivity $(T/T_o)^{-3/2}$
  - Green: with ion diamagnetic correction $\gamma_{MHD}-\omega_{*i}/2$. Peak γ at n=12.
- M3D (Spitzer, $S=10^7$) at two spatial resolutions (red=lower, blue=higher). Smoothing mode at top/bottom of plasma increases γ.

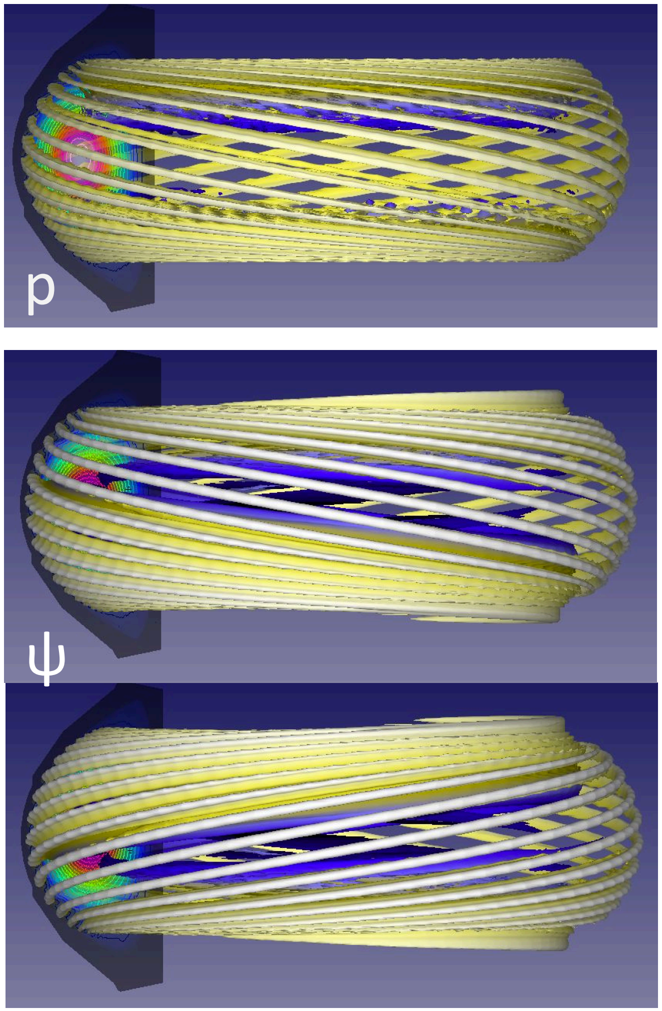
MHD simulation p resembles ECEI T_{ECE}



- Left: ECEI perturbed δT_{ECE} with $n \simeq 10$ (from [2], KSTAR 7328 at t=7.917)
- Middle & right: Non-axisymmetric $\tilde{p}$ from MHD simulation at S=10^7 (Spitzer), with dominant n=13,14. Middle – same poloidal phase as ECEI. Right – at the ϕ with maximum difference in m. Dashed lines are plasma edge. Total p contours 0.08,0.07,0.06,0.05,0.04,0.03,0.02,0.01, 0.001,0.0001; dashed 1.e-05

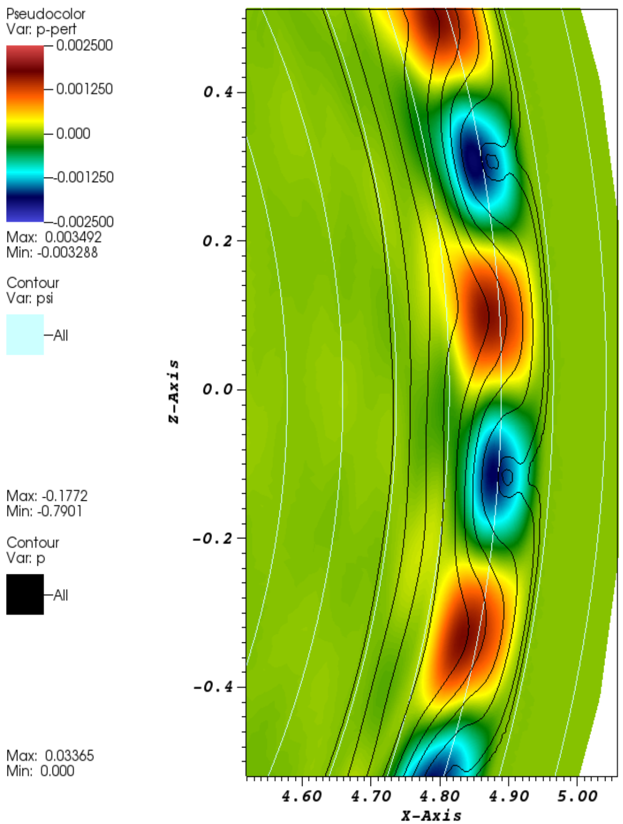
Inter-ELM mode 3D structure

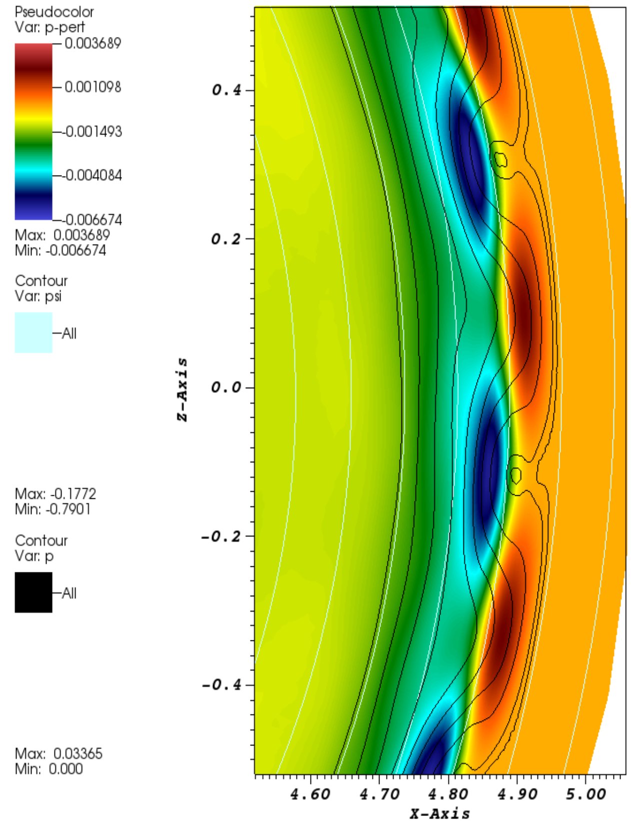




- Views on poloidal planes Δϕ=22.5 deg apart. Orange line shows same filament.
  - Black contours show equilibrium pressure
- Right: 3D asymmetry due to multiple toroidal harmonics, especially low *n*=1,2,3

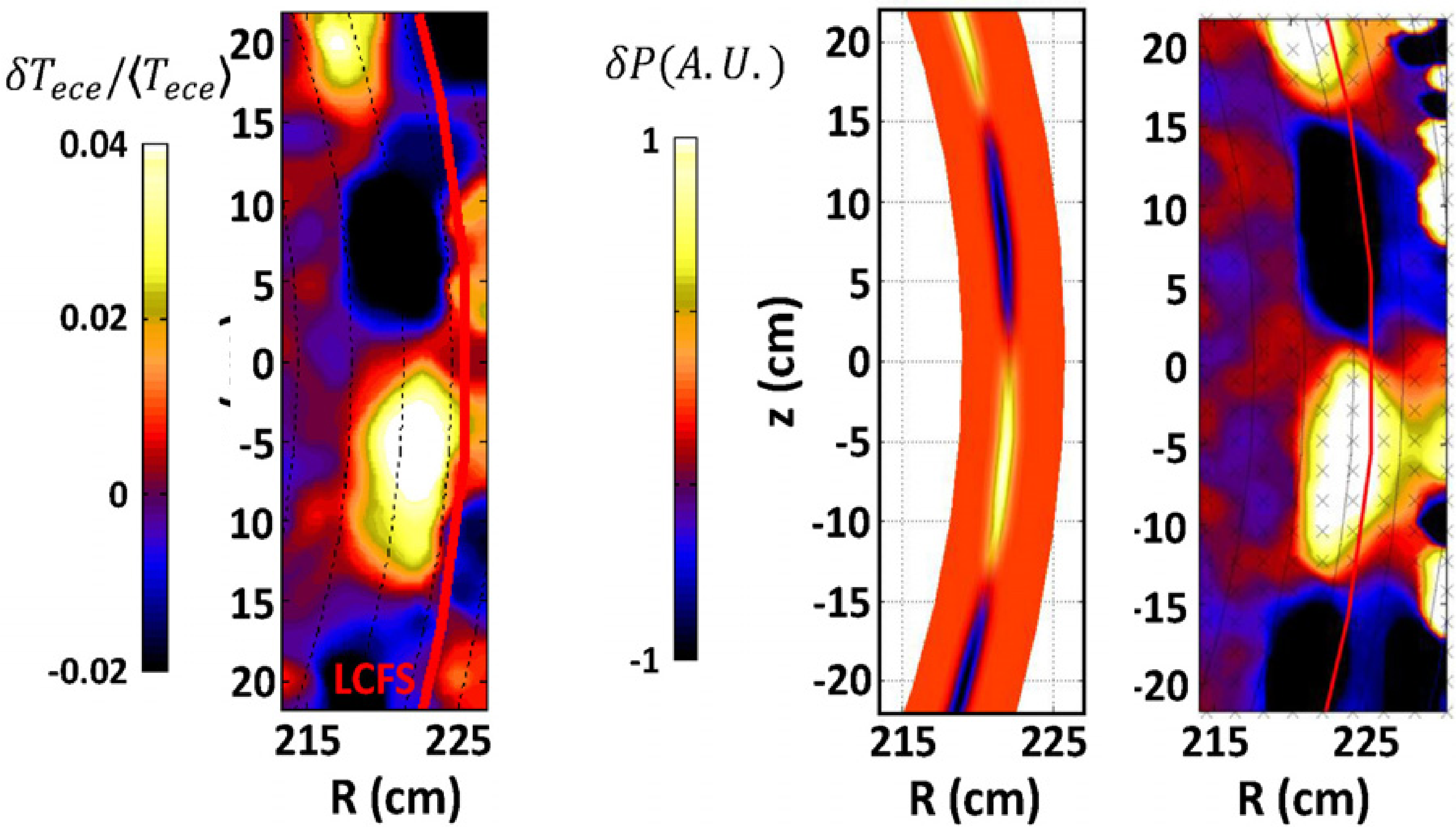
Mode does not resemble perturbation of the original equilibrium





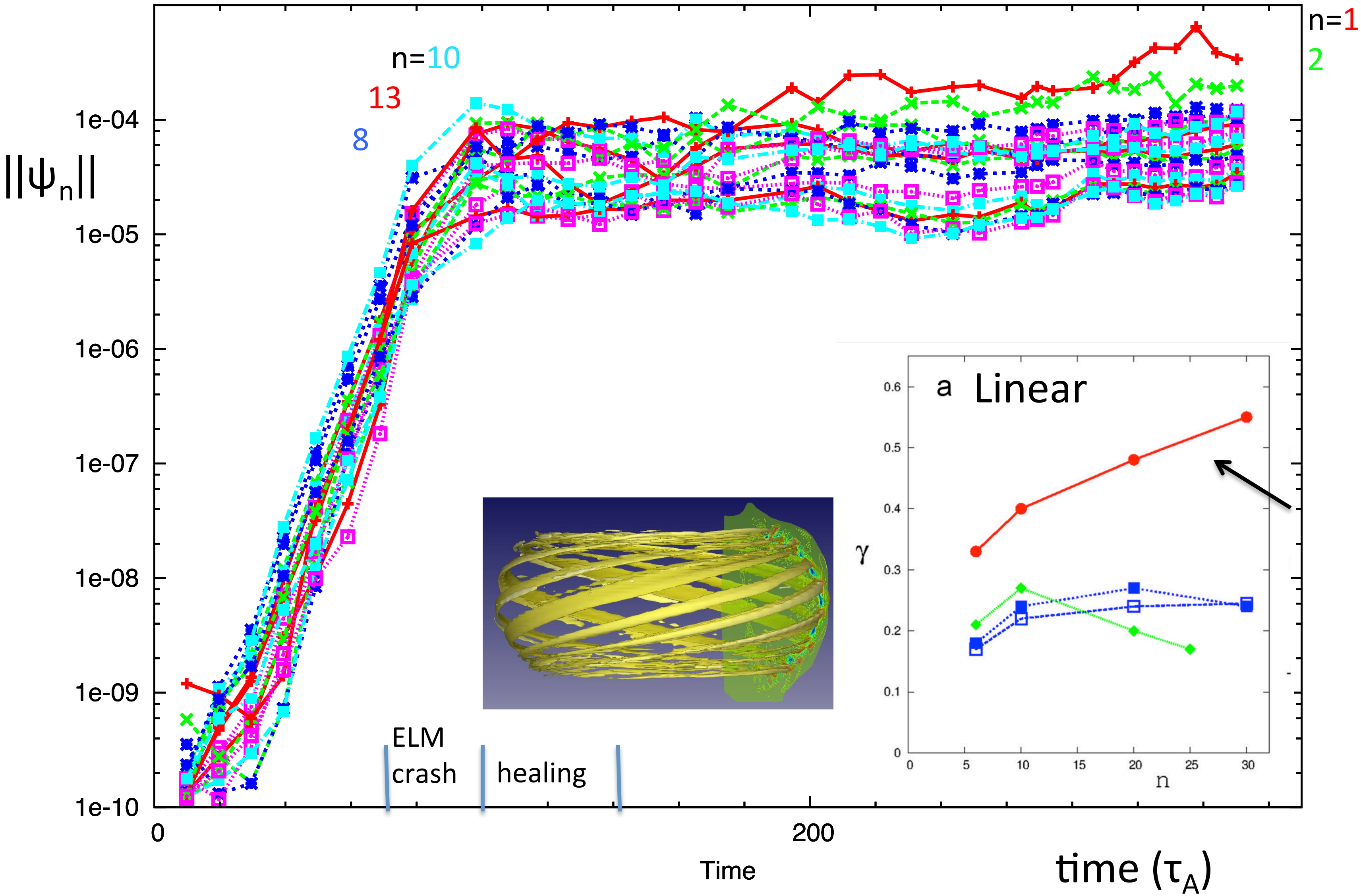
- Mode changes near-edge axisymmetric equilibrium. Plasma expands slightly.
- (Left) Non-axisymmetric pressure (color); black contours show total pressure.
- (Right) Perturbed pressure $\tilde{p} \equiv p - p_{eq}$ defined from the original equilibrium pressure; Positive $\tilde{p}$ is narrow and concentrated at the tips of the ballooning fingers, just outside original plasma edge.
  - ECEI synthetic signal response functions will broaden narrow signals [4]

Linear eigenmode $\tilde{p}$ may resemble ECEI δT_{ECE}

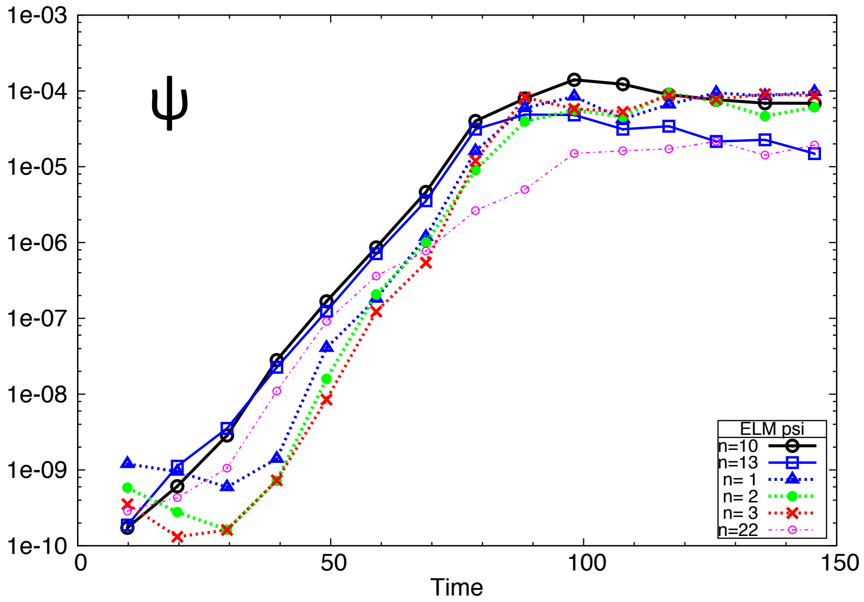


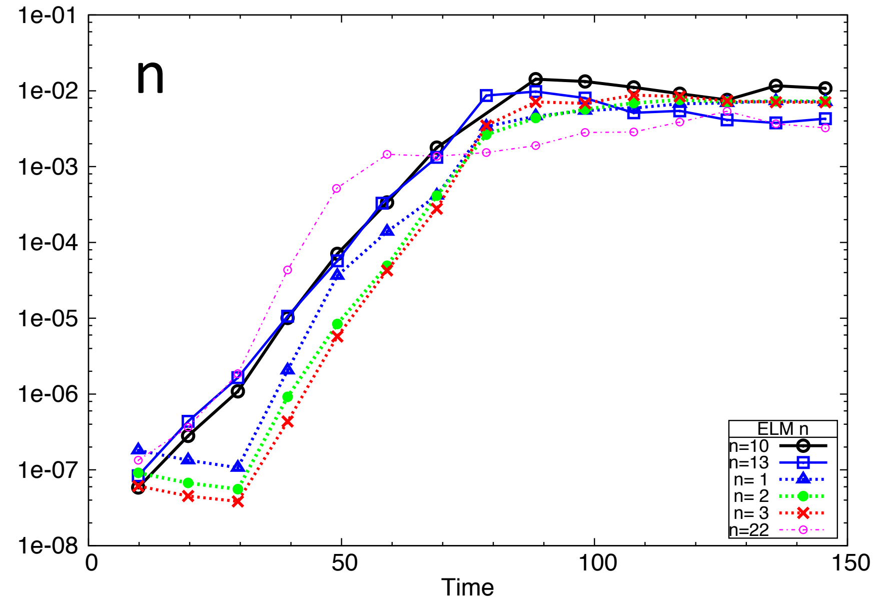
- Left: experimental ECEI perturbed T_{ECE} with n≃8 (t=4.36s, M. Kim, NF (2014) [4]) DIFFERENT EQUILIBRIUM PROFILES than M3D case!
- Middle & right: $\tilde{p}$ from BOUT++ resistive MHD linear eigenmode with n=8.
- Middle: raw eigenmode. Δr=2 cm. Right: Synthetic ECEI signal of the linear eigenmode, including system noise. Matches experimental signal

Time history of Type I ELM in DIII-D (126006)



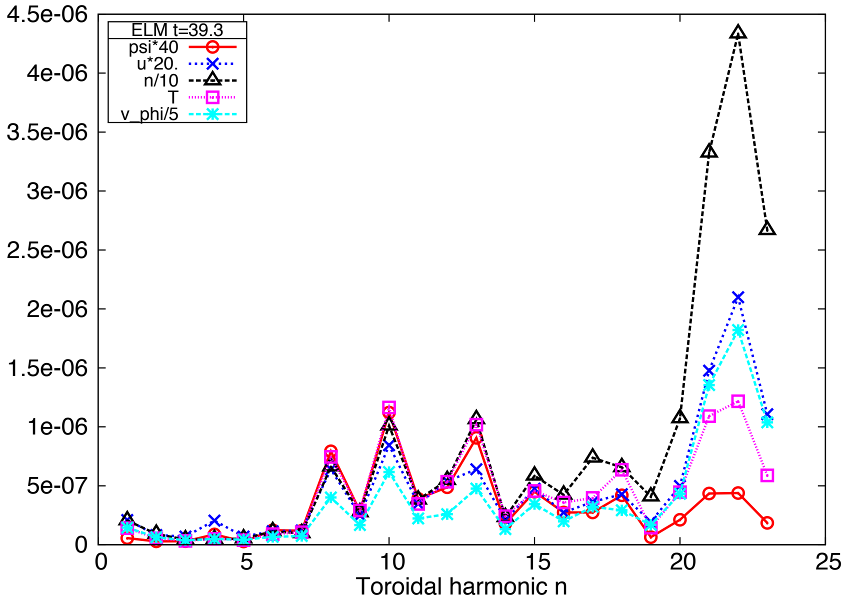
Lowest *n* harmonics grow from mode coupling

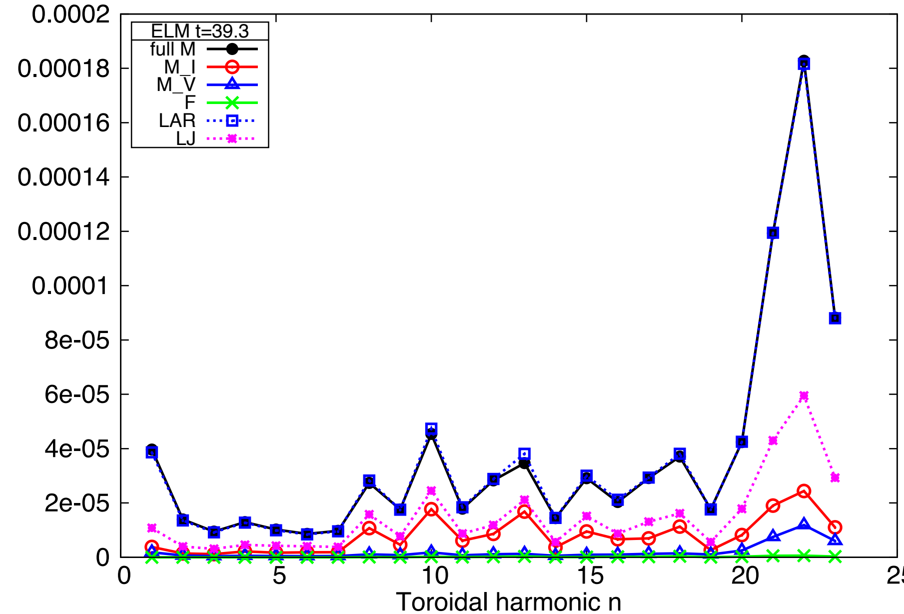




- Time history of initial growth to the ELM crash for the main *n*=10,13 harmonics, next-to-highest *n*=22, and lowest *n*=1,2,3 for poloidal magnetic flux and density
- Different growth rates within general exponential growth
- Lowest-*n* grows later and faster, consistent with origin from mode-beating of higher *n* (*n*=1 also follows strong *n*=22)

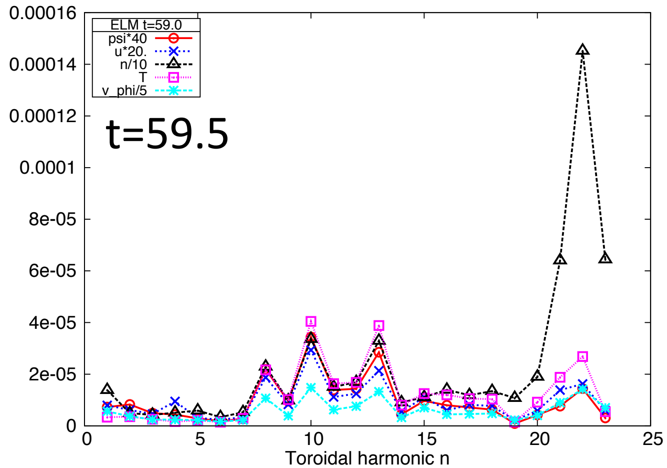
Small amplitude, early time

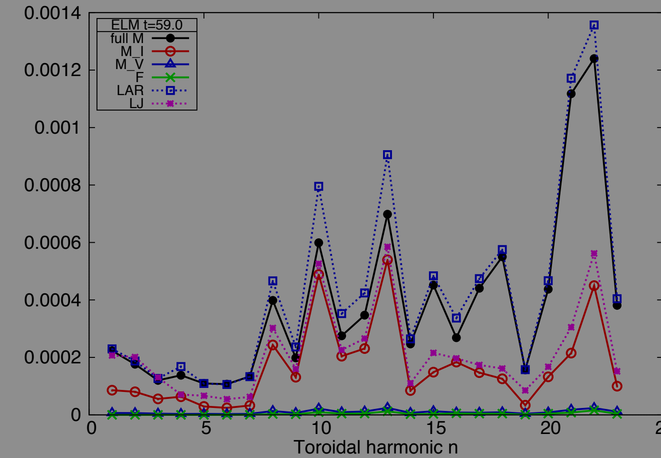




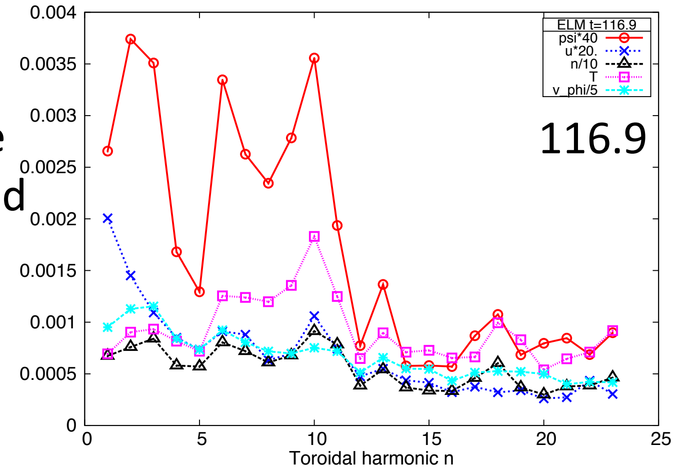
- Spectra at early time t=39.3 (very small amplitude)
- Left: MHD variables (scaled). Right: Radial momentum terms
- Highest harmonics *n*=21-23 are largest, in agreement with the linear ballooning-like growth rate spectrum
- Momentum full M ≃ lowest order in large aspect ratio M_{LAR}

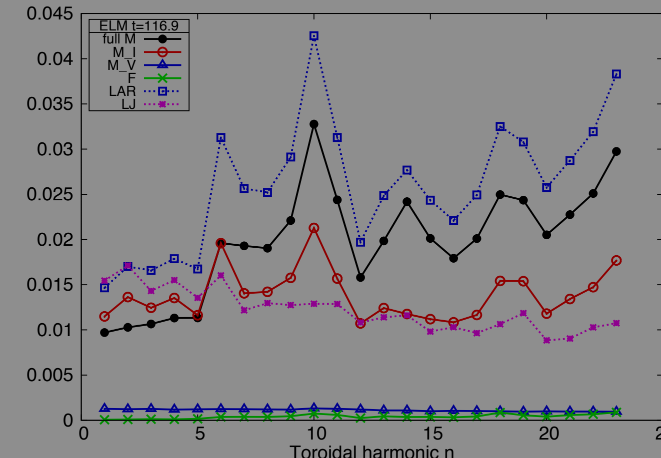
Just before ELM crash



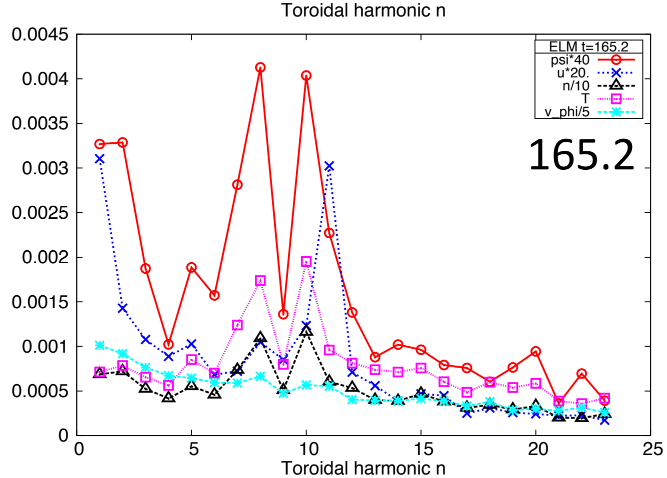


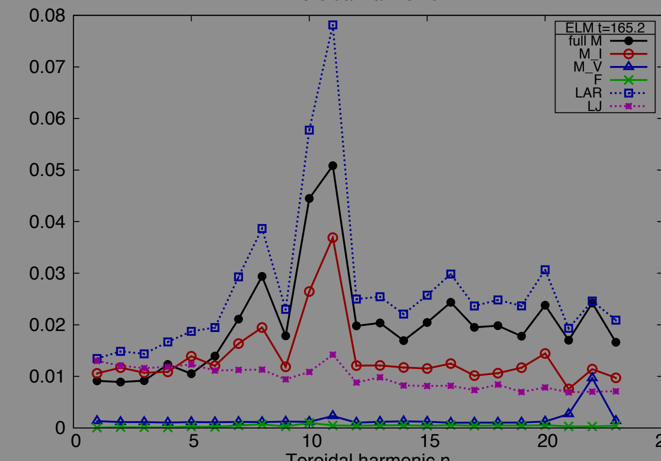
Height of crash; edge ∇n reduced



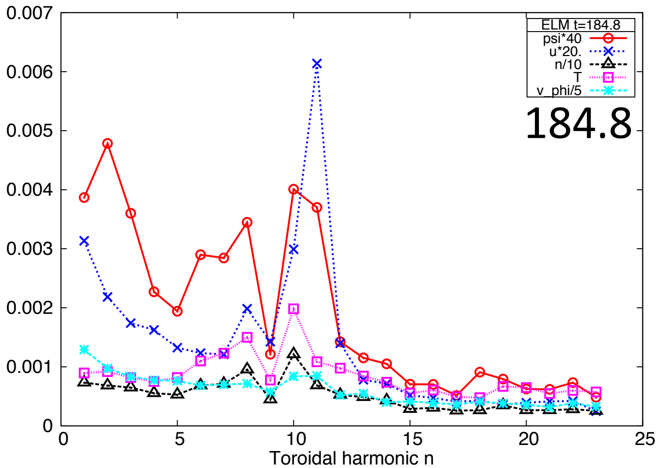


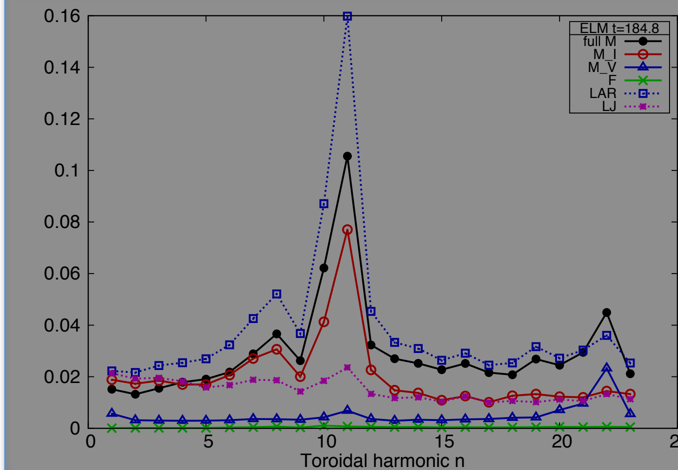
Outboard healing



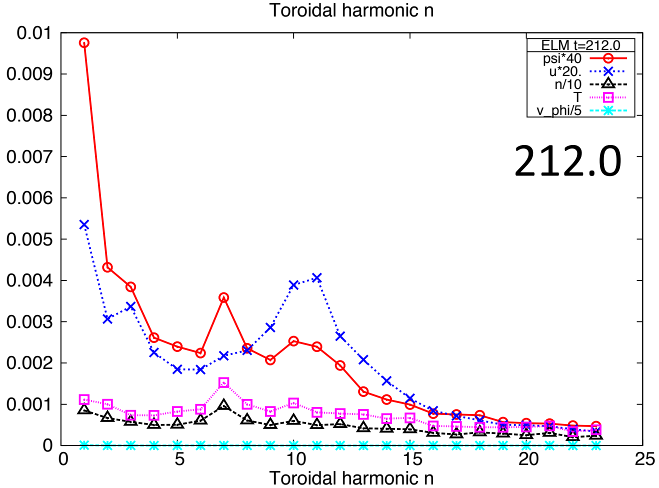


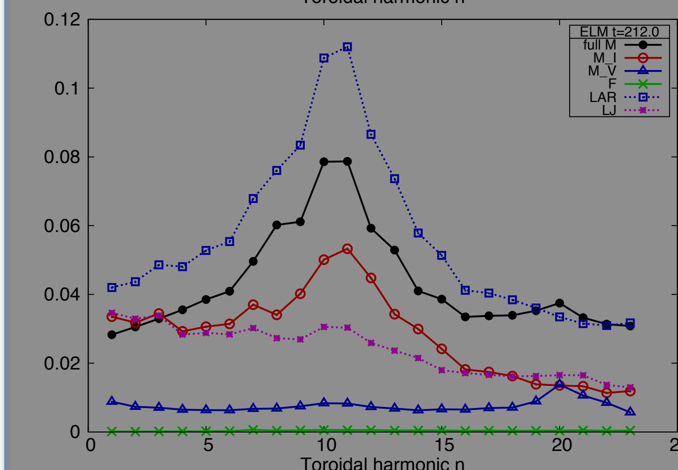
Phase 2: poloidal velocity begins to grow



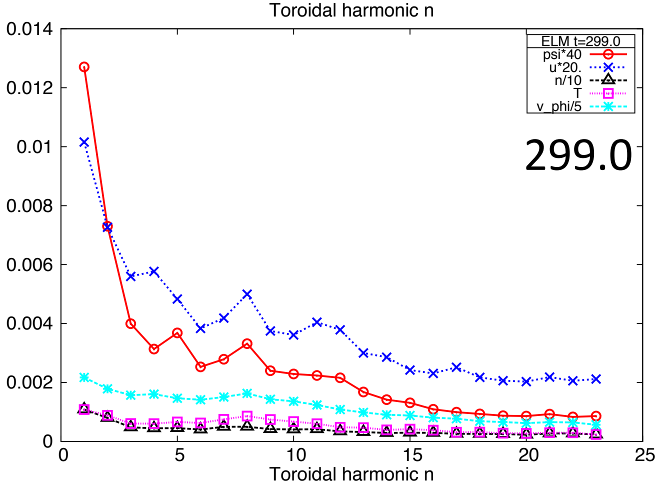


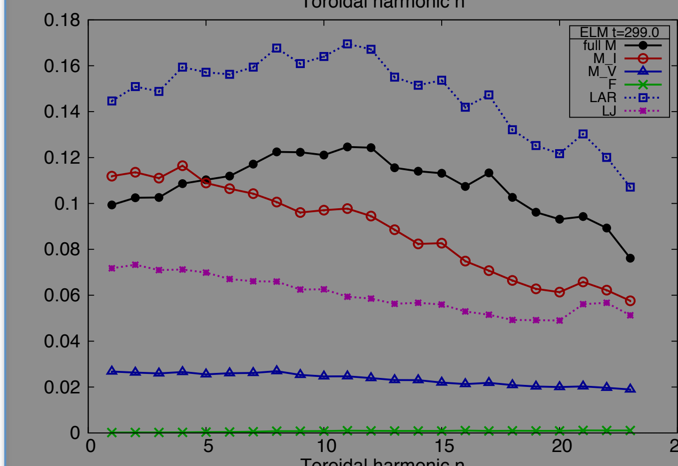
End of v_θ rise



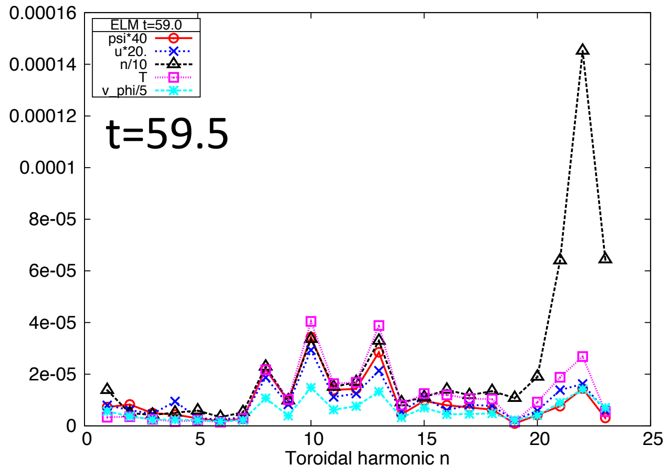


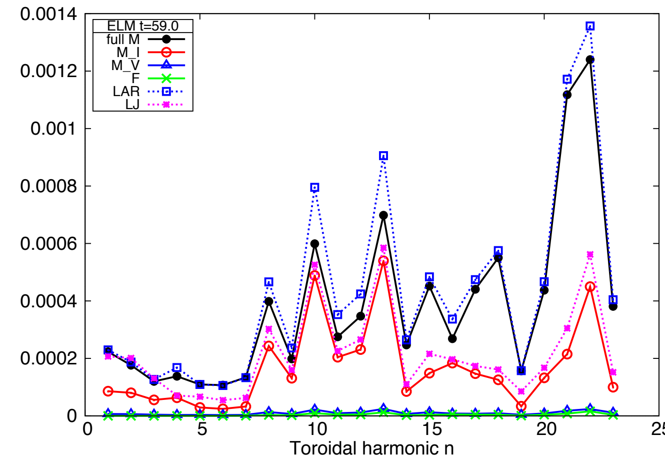
Long time, large interior n=1,2 mode





Just before ELM crash





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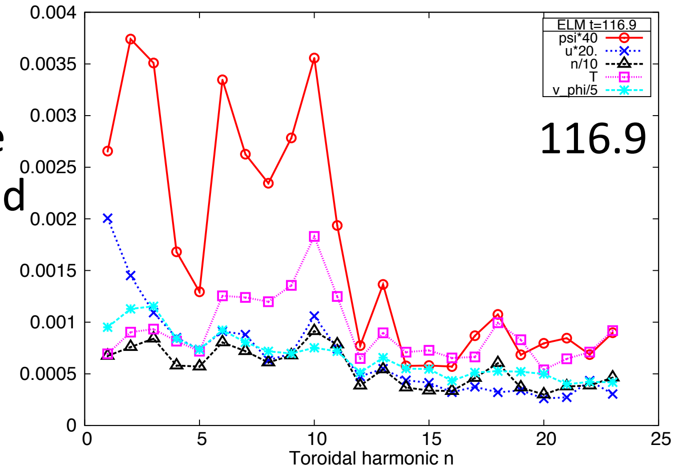

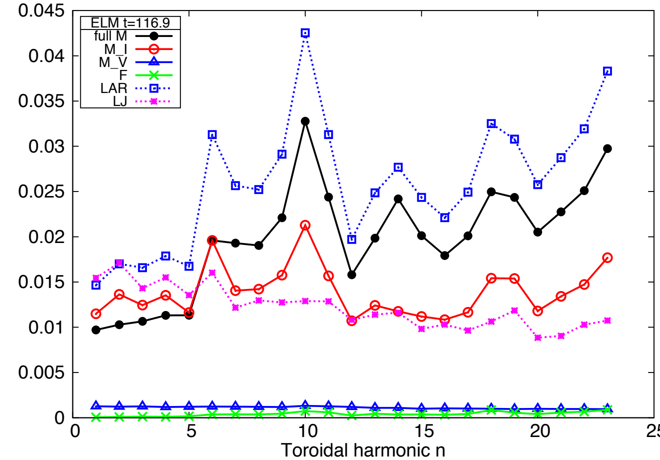

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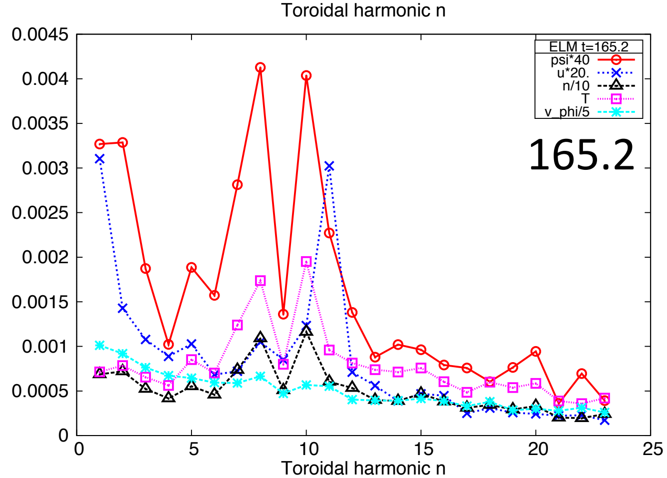

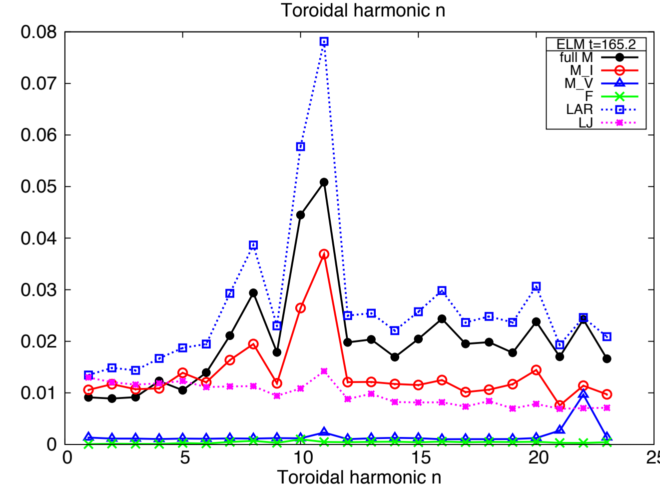

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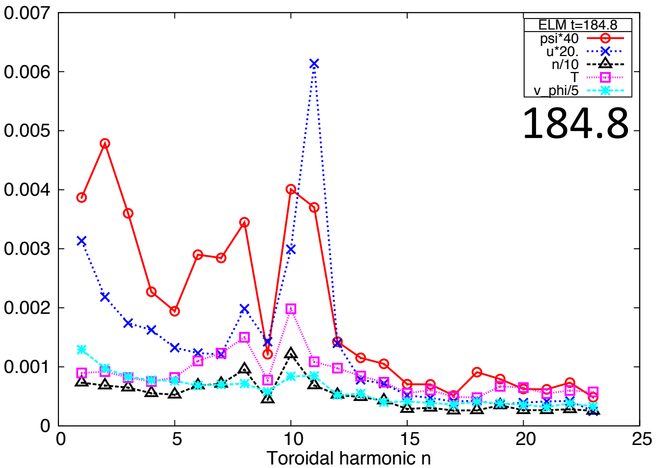

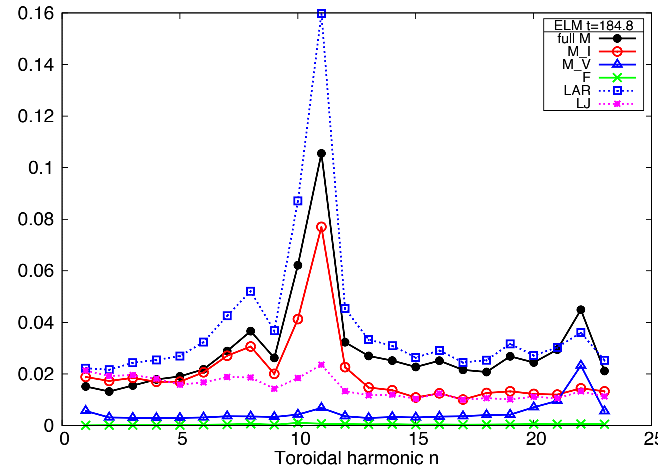

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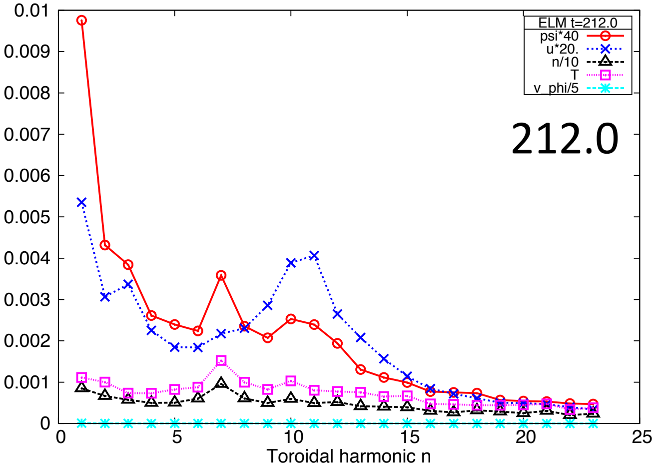

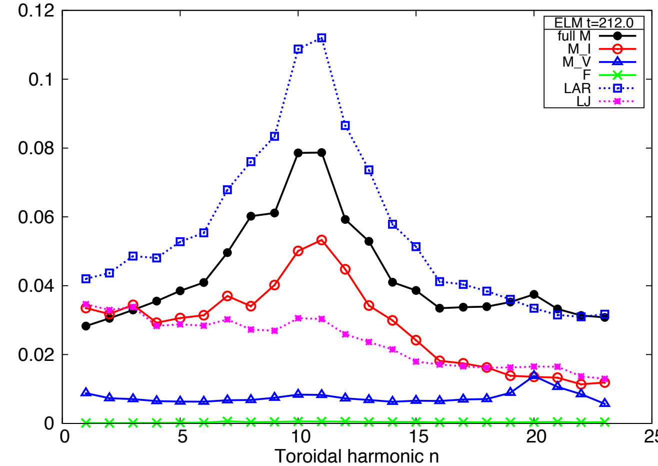

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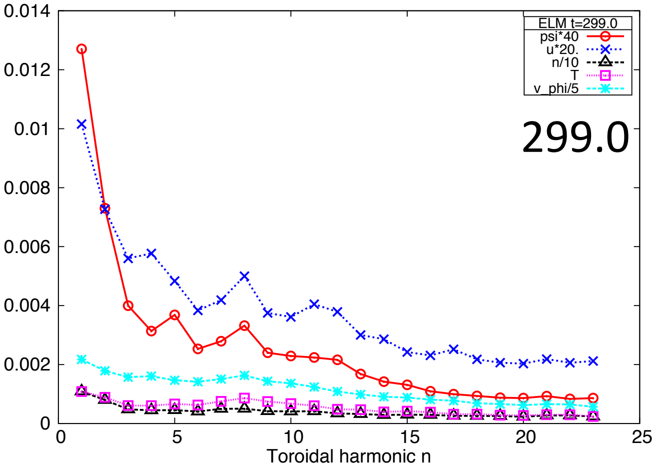
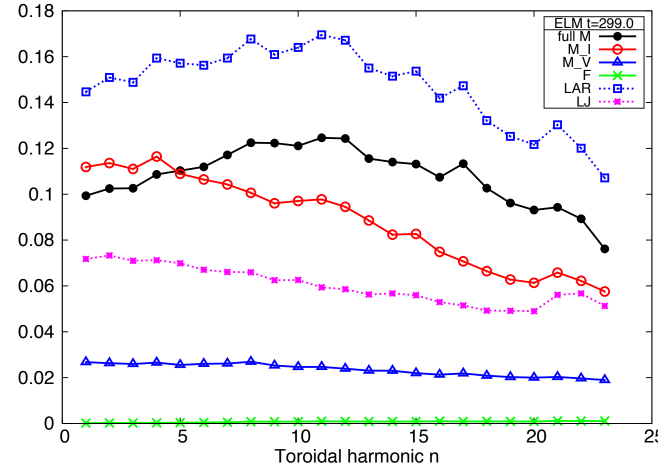
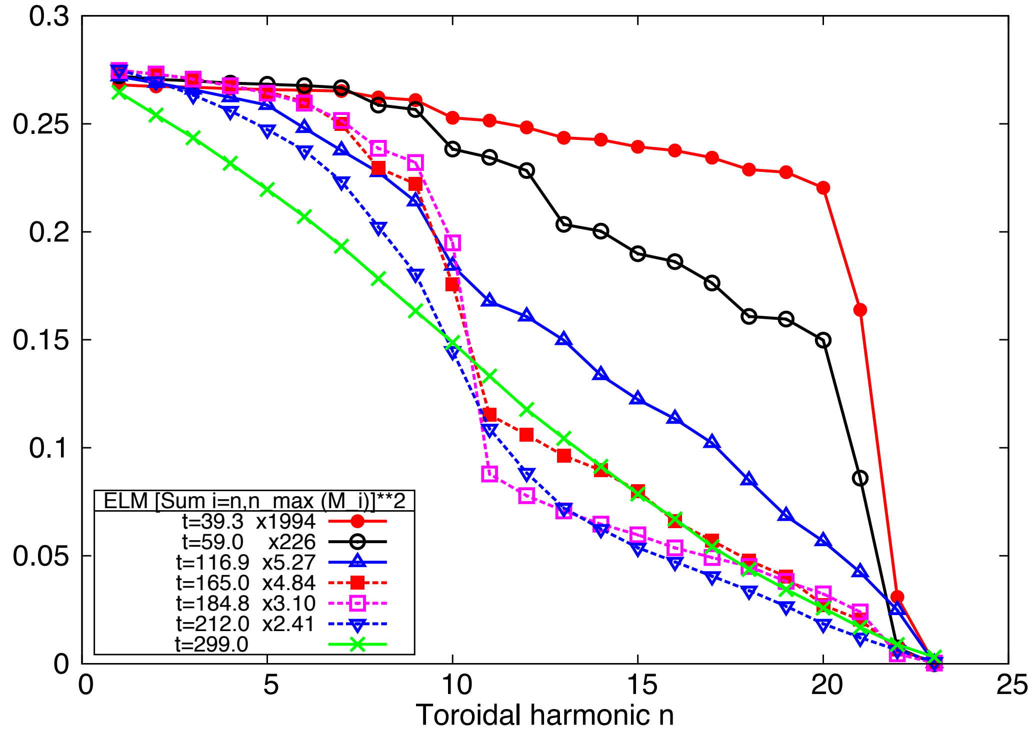


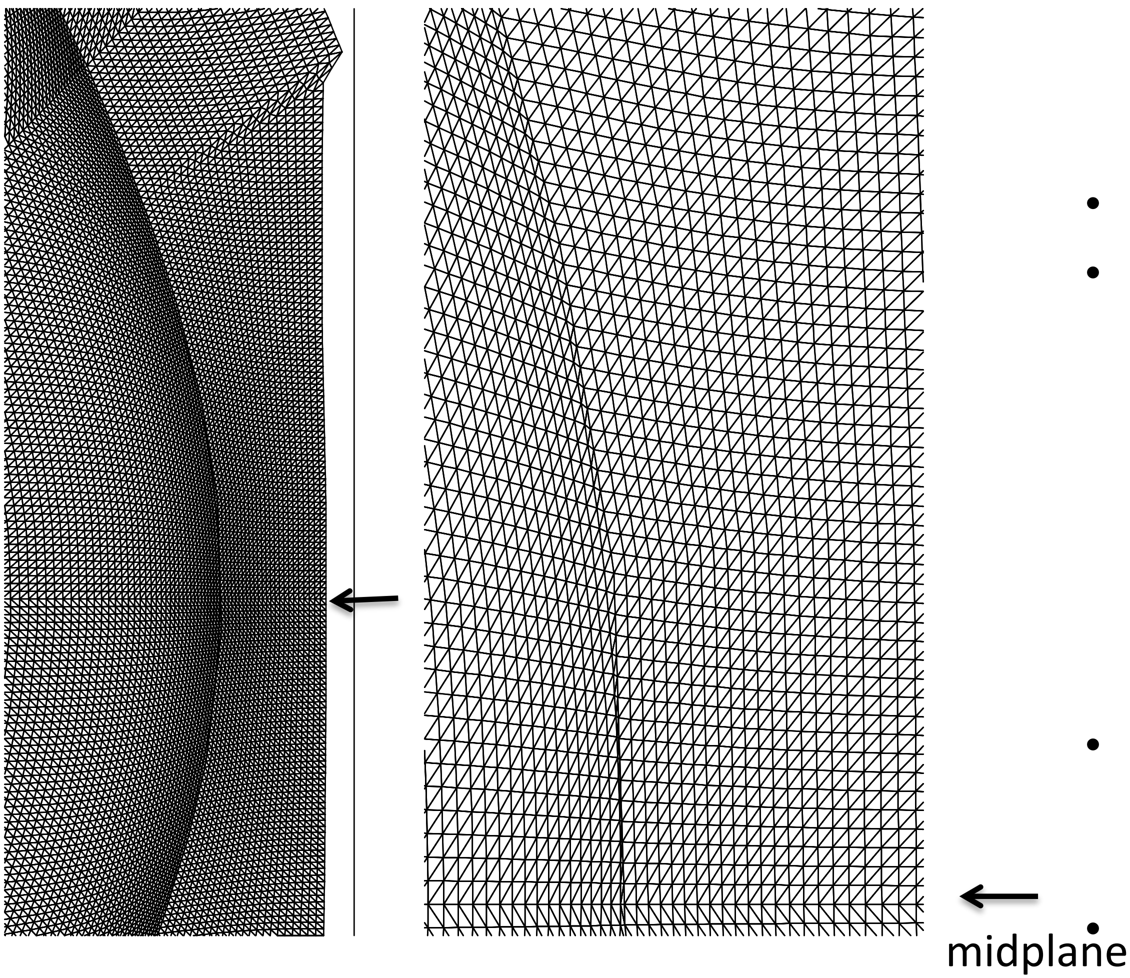


Momentum – evolution of harmonics and v_θ



- Rate of change "Energy" for full MHD M that is contained in harmonics larger than *n* ($\sum_{i=n}^{n\_max}|M_i|^2$, scaled to unity)
- Shifts from high to moderate harmonics during the initial growth of ELM crash; strong loss of higher *n* during outboard-side healing after crash
- Poloidal flow generation for finite amplitude edge instabilities

DIII-D Large ELMs: GEQDSK inaccuracy



M3D (R,Z) mesh on outboard side

- M3D mesh, using a improved interpolation of the GEQDSK psirzIR$_i$,Z$_j$] based on bi-cubic splines
- Separatrix curve from GEQDSK
- Mismatch to the rest of the simulation grid, which is interpolated from psirz(R$_i$,Z$_j$) and the limiter curve (= sim. outer boundary) → uneven radial spacing on outboard, near midplane (similar below midplane)
- 129x129 EFIT output (even 257x257 barely resolves pedestal, J_{BS} layer
- Worse at finer grid spacing
- Causes numerical instability and/or larger ELM growth rates

Summary

- Nonlinear MHD simulation of plasma edge instabilities find that ELMs and inter-ELM modes have many similar features
- Linear eigenmode spectrum compared to small amplitude nonlinear mode – consistent, close to large aspect ratio
- Finite amplitude - nonlinear, and aspect ratio effects give different mode
- Nonlinear mode structure – first comparison to measured 2D/3D perturbations for an edge instability (T_{ECE} in inter-ELM mode in KSTAR) – nonlinear gives much better fit than linear eigenmode
- Poloidal "zonal flow" for edge instabilities?

ICNSP US-Japan JIFT meetings, August 2015

- ICNSP meeting August 12-14, 2015 in Golden CO
  - Organizer: Scott Parker, Univ. Colorado, Boulder
  - Abstracts due June 19, 2015
  - http://www.icnsp.org
- US-Japan JIFT workshop on "Recent studies of extended MHD and MHD simulations" in Golden before ICNSP
  - I am local organizer