Hybrid Simulations of Energetic Particle-driven Instabilities in Toroidal Plasmas

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In collaboration with

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Outline

- M3D code: hybrid model, code development
- Examples of M3D Hybrid Simulations
- NBI-driven TAEs in NSTX
- Summary
- Future Work

M3D XMHD Model

$$\rho \frac{d\mathbf{v}}{dt} + \rho(\mathbf{v}_{\mathbf{i}}^{\star} \cdot \nabla)\mathbf{v}_{\perp} = -\nabla P - \nabla \cdot \mathbf{P}_h + \mathbf{J} \times \mathbf{B} - \mathbf{b} \cdot \nabla \cdot \Pi_i$$

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

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J} - \nabla_{\parallel} P_e / en - \mathbf{b} \cdot \nabla \cdot \Pi_e$$

$$\partial P / \partial t + \mathbf{v} \cdot P = -\gamma P \nabla \cdot \mathbf{v} + ...$$

$$\partial P_e / \partial t + \mathbf{v} \cdot P_e = -\gamma P_e \nabla \cdot \mathbf{v} + ...$$

- Pressure tensor

$$\mathbf{P}_h = P_\perp \mathbf{I} + (P_\parallel - P_\perp)\mathbf{b}\mathbf{b}$$

$$f = \sum_i \delta(\mathbf{R} - \mathbf{R}_i)\delta(v_\parallel - v_{\parallel,i})\delta(\mu - \mu_i)$$

- Gyrokinetic Equations

$$\frac{d\mathbf{R}}{dt} = \frac{1}{B^{\star\star}}\left[v_\parallel(\mathbf{B}^\star - \mathbf{b_0} \times (< \mathbf{E} > -\frac{1}{q}\mu\nabla(B_0 + < \delta B >))\right]$$

$$m\frac{dv_\parallel}{dt} = \frac{q}{B^{\star\star}}\mathbf{B}^\star \cdot (< \mathbf{E} > -\frac{1}{q}\mu\nabla(B_0 + < \delta B >))$$

$$\mathbf{B}^\star = \mathbf{B_0} + < \delta\mathbf{B} > + \frac{mv_\parallel}{q}\nabla \times \mathbf{b_0}, \qquad B^{\star\star} = \mathbf{B}^\star \cdot \mathbf{b_0}$$

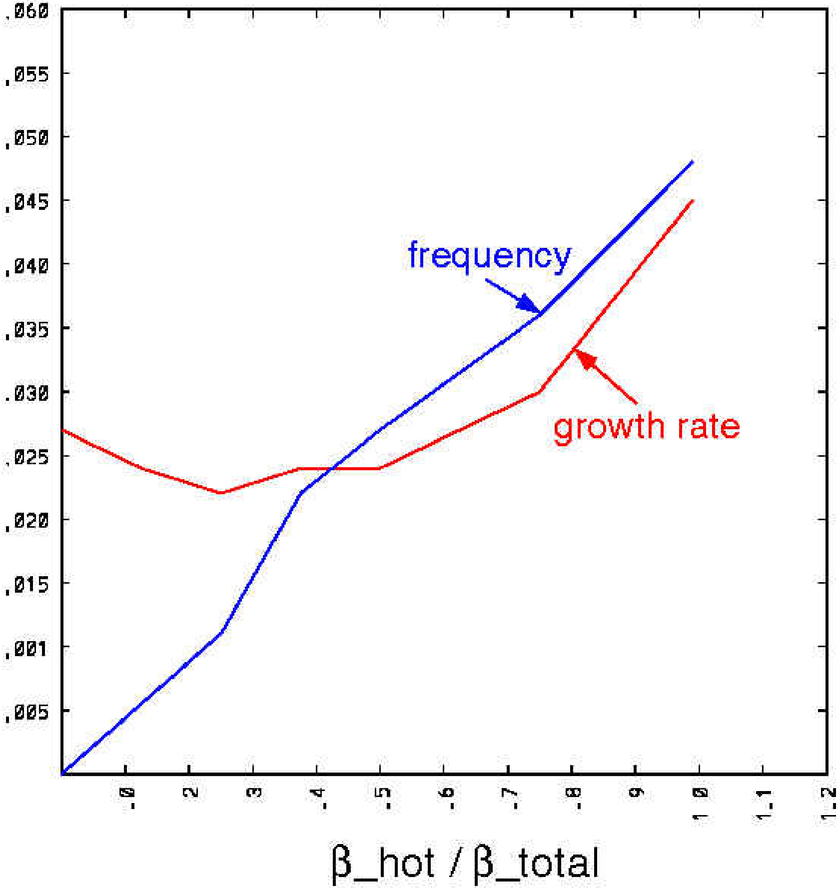
Recent M3D Hybrid Code Development

- extended to 2D domain decompostion for MPI;
- Implemented an anisotropic particle distribution.

Examples of M3D Hybrid Simulations

- Fishbone instability;
- ITER: Alpha particle effects on n=1 kink
- TAE in stellarators.

Hot Particle-induced Fishbone Instability: The CEMM hybrid benchmark case



circular tokamak R/a=2.76

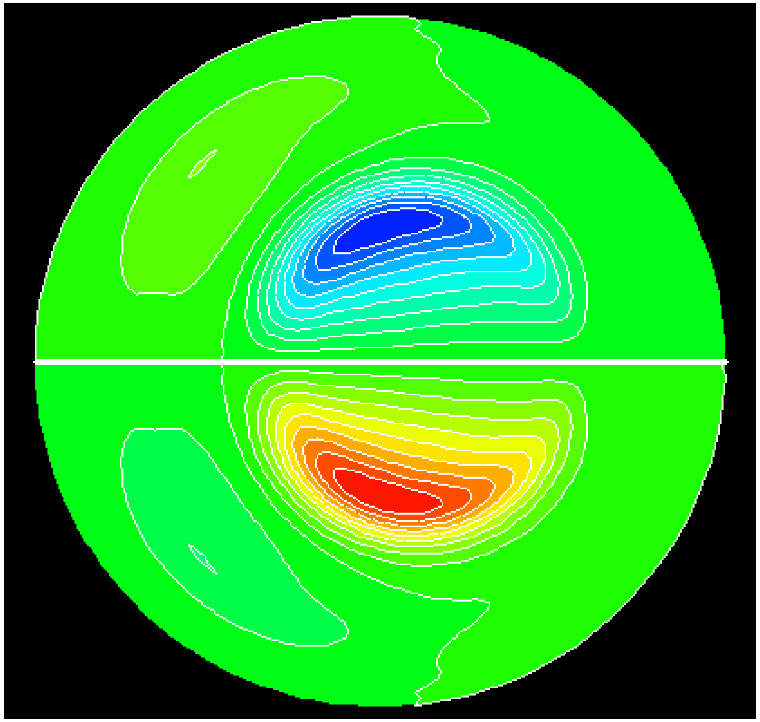
q(0)=0.6, q(a)=2.4

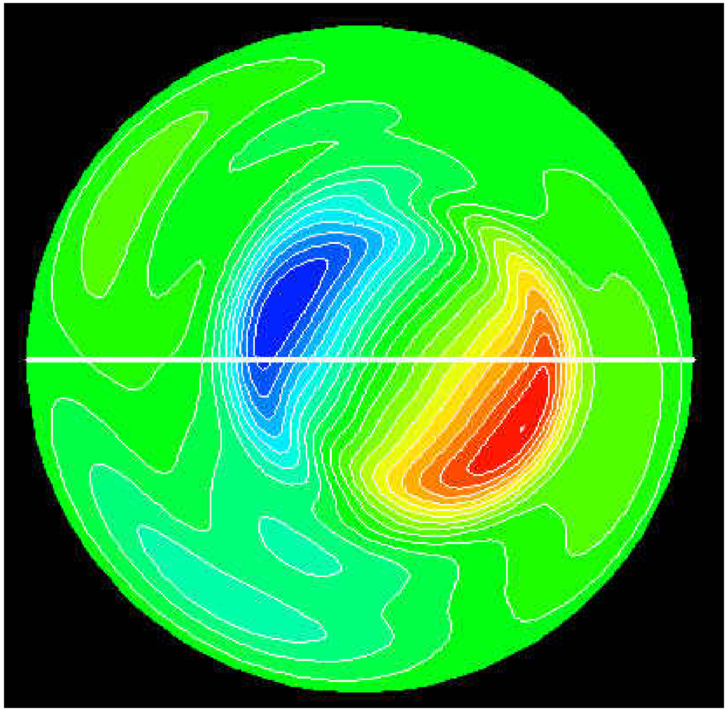
β_total(0) = 8%

v_h/v_A = 1.0, ρ_h/a=0.05

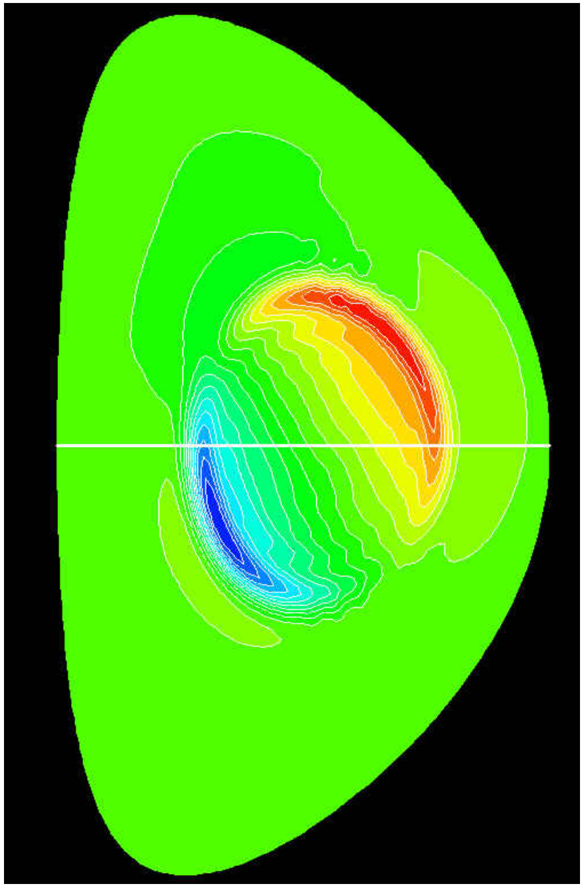
Isotropic slowing-down hot particle distribution

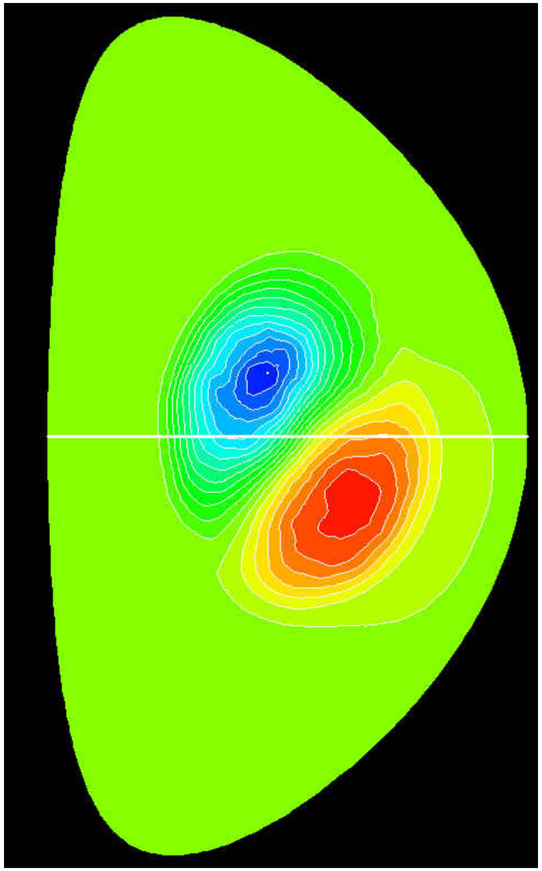
Mode Structure: Ideal Kink v.s. Fishbone



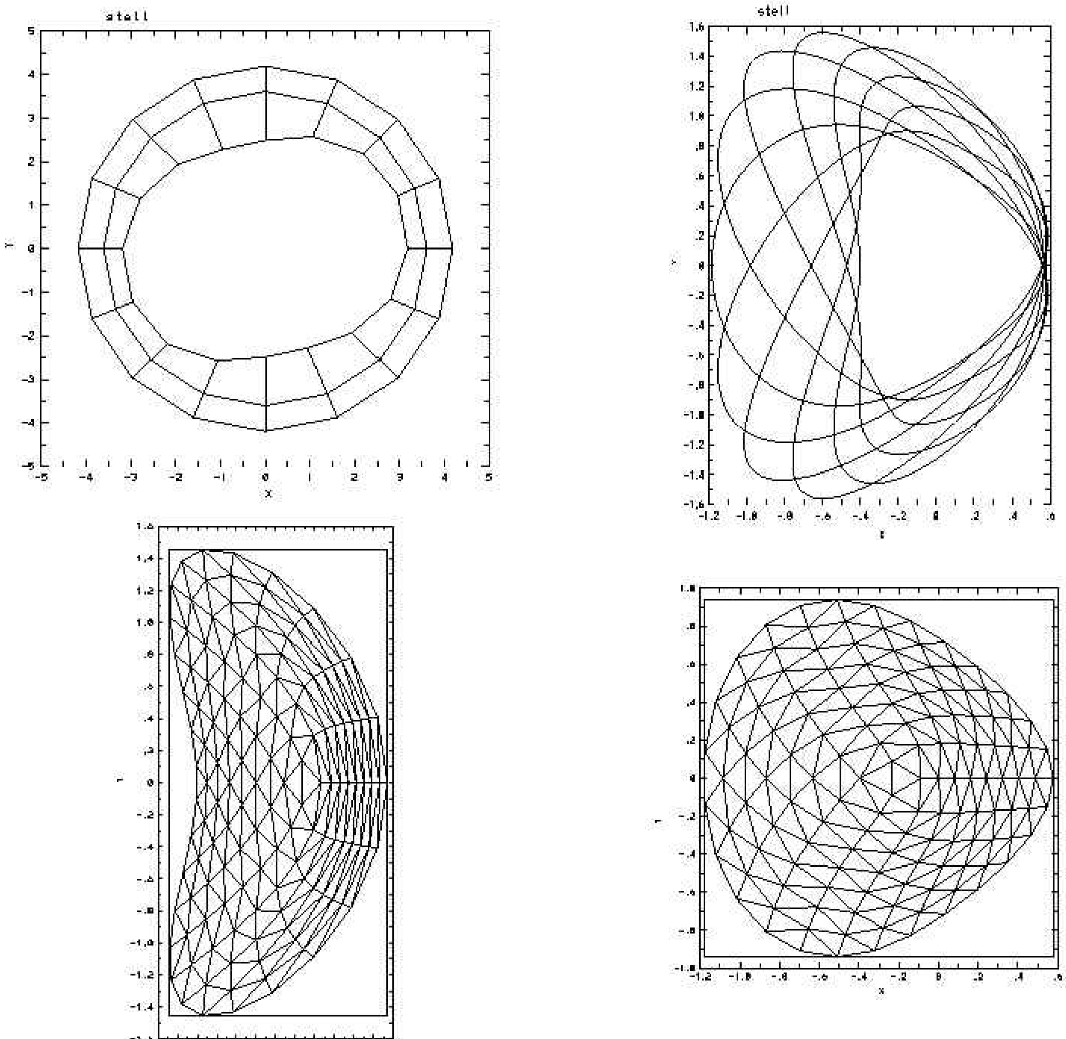


ITER: alpha particle effects are not sufficient to stabilize n=1 internal kink mode (q0=0.7)

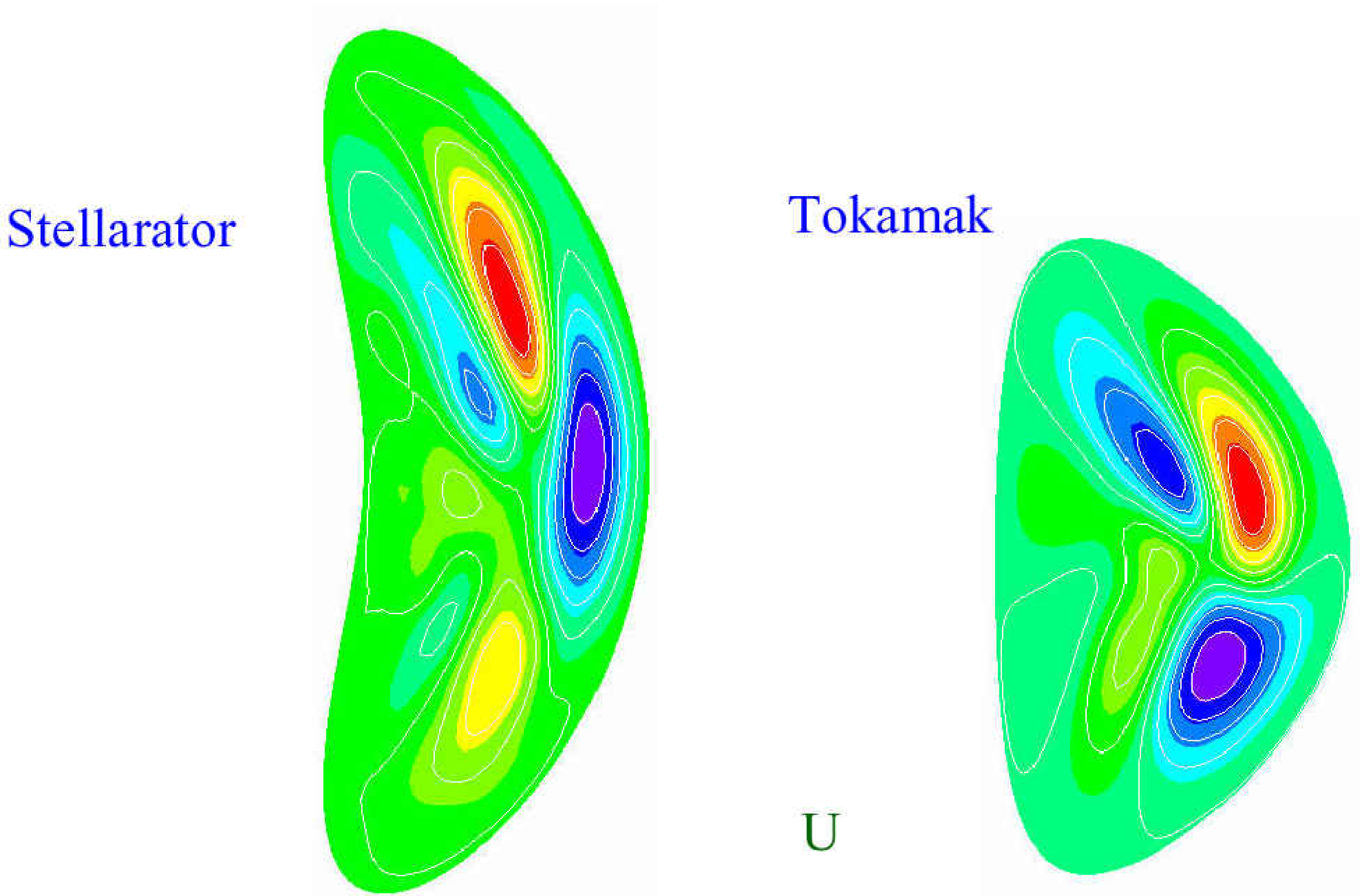




Fast Ion-driven TAE in a Quasi-symmetric stellarator

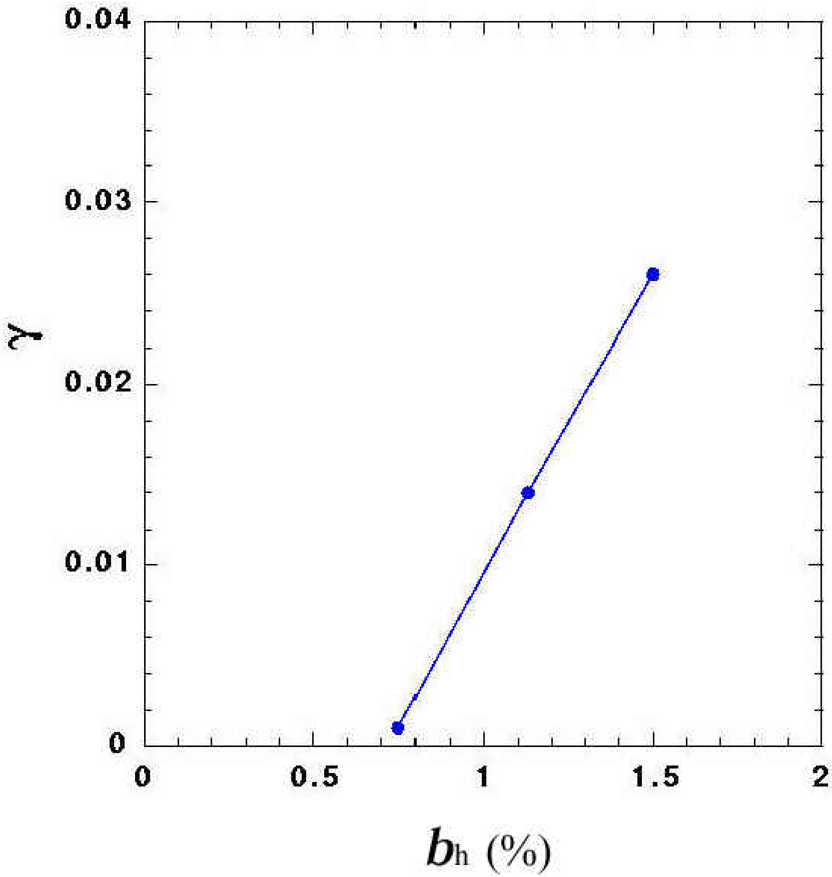


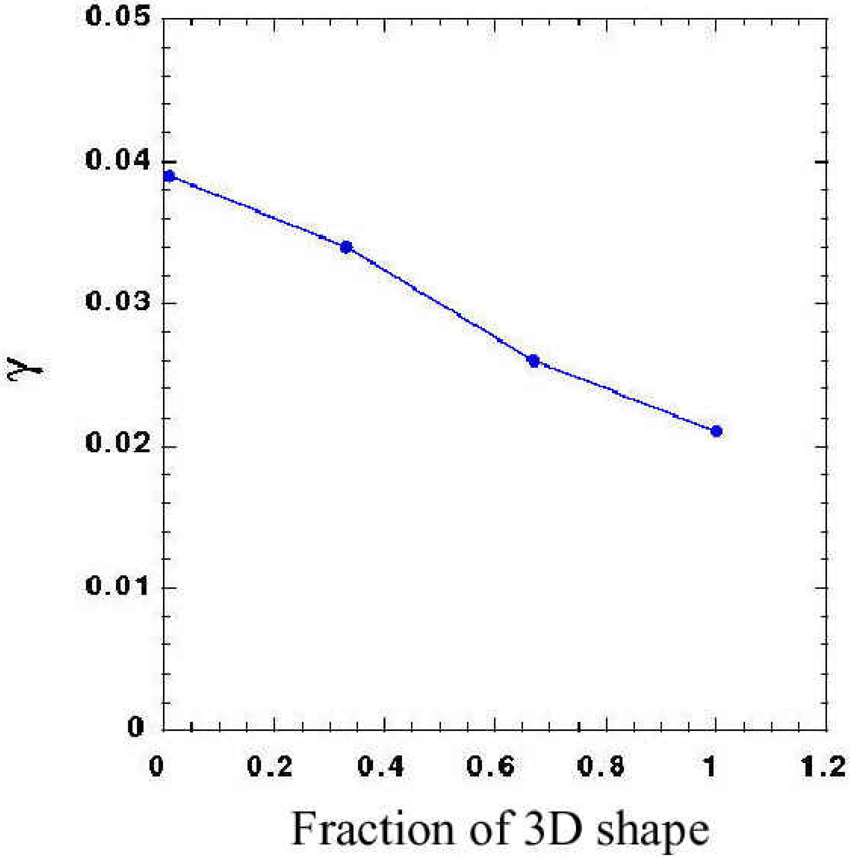
TAE mode structure: tokamak v.s. stellarator



TAE growth versus hot ion beta: the growth rate is linear in hot ion beta.

TAE growth versus the fraction of 3D shape: 3D geometry is stabilizing.



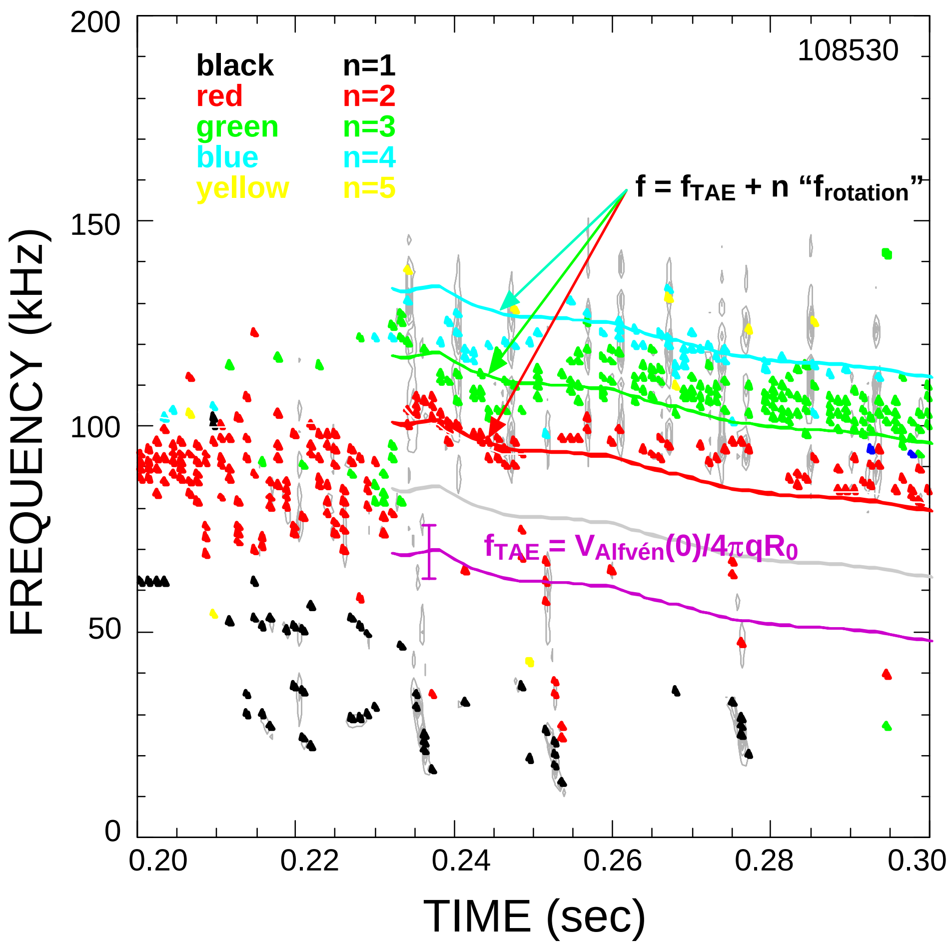


Simulations of Beam-driven Alfven Modes in NSTX

- Recent NSTX experimental observations show rich beam-driven instabilities: fishbone, TAEs, CAEs etc and associated hot particle losses.
- Alfven modes in STs are less understood as compared to those in conventional tokamaks.
- Need to study possible new features of beam-driven Alfven modes associated with ST's unique parameter regime: low aspect ratio, high beta, large energetic ion speed and gyroradius.

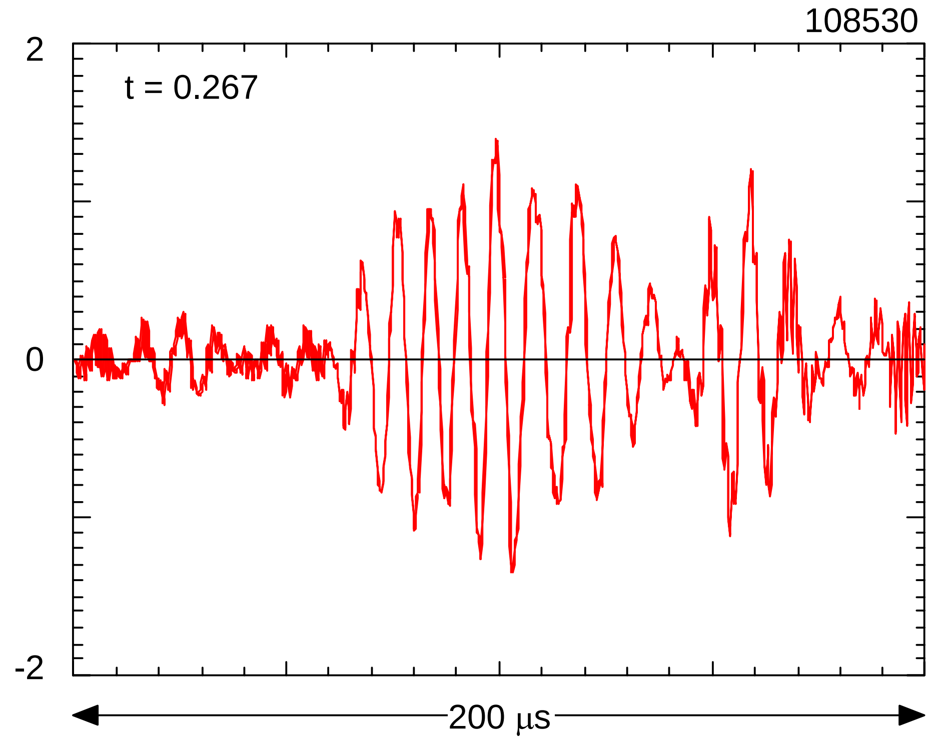
The bursting modes are in the TAE frequency range (NSTX)

- Multiple modes burst at the same time.
- Toroidal mode number, n, ranges from 2 - 5 with the dominant mode being n=2 or 3.
- Mode frequencies in reasonable agreement with expected TAE frequencies.



The final mode growth and decay is very fast

- Some of the mode amplitude modulation represents "beating" of the multiple modes.
- Mode growth and decay times are approximately 50 - 100 μs.

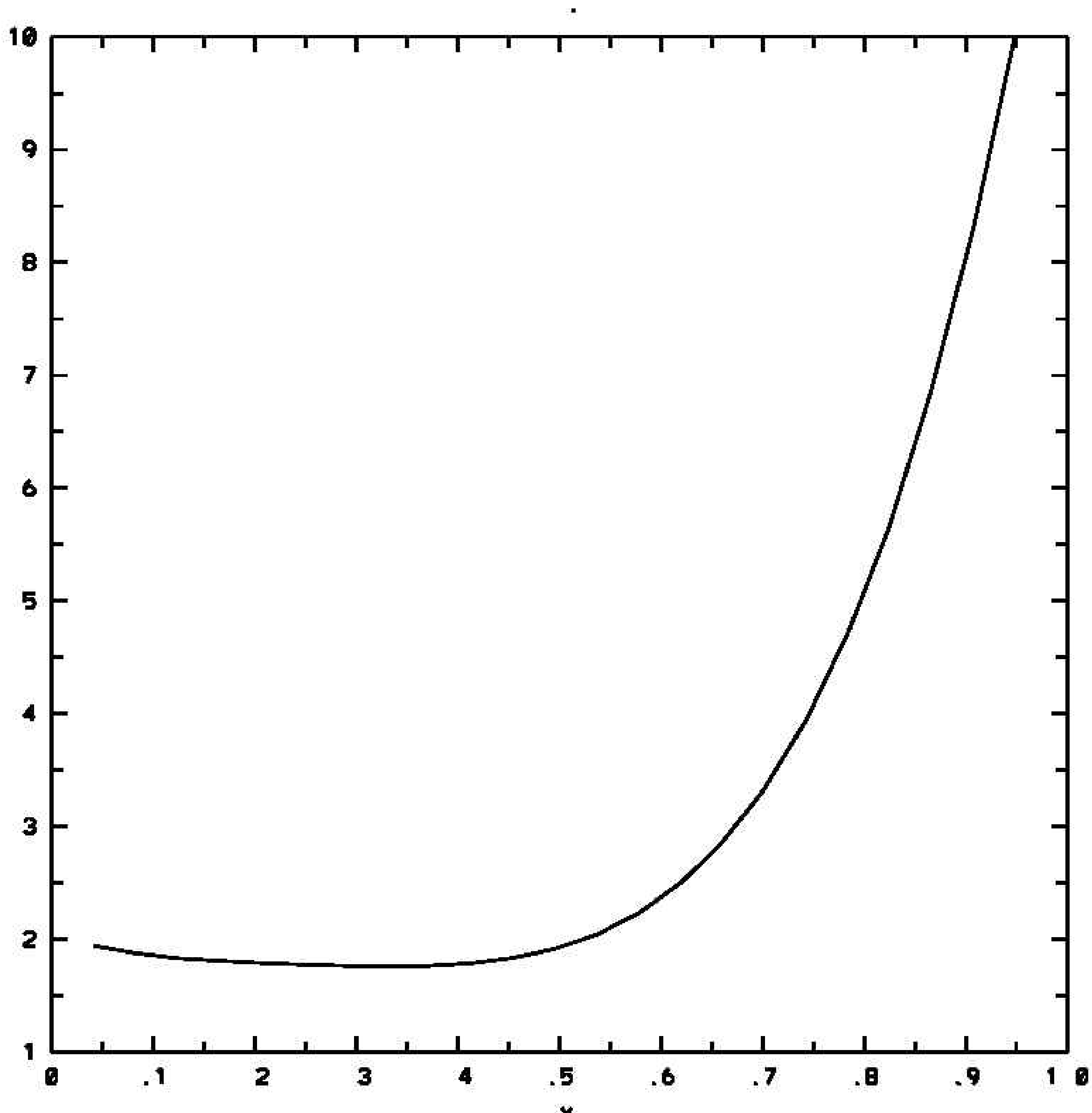


NSTX Parameters and Profiles

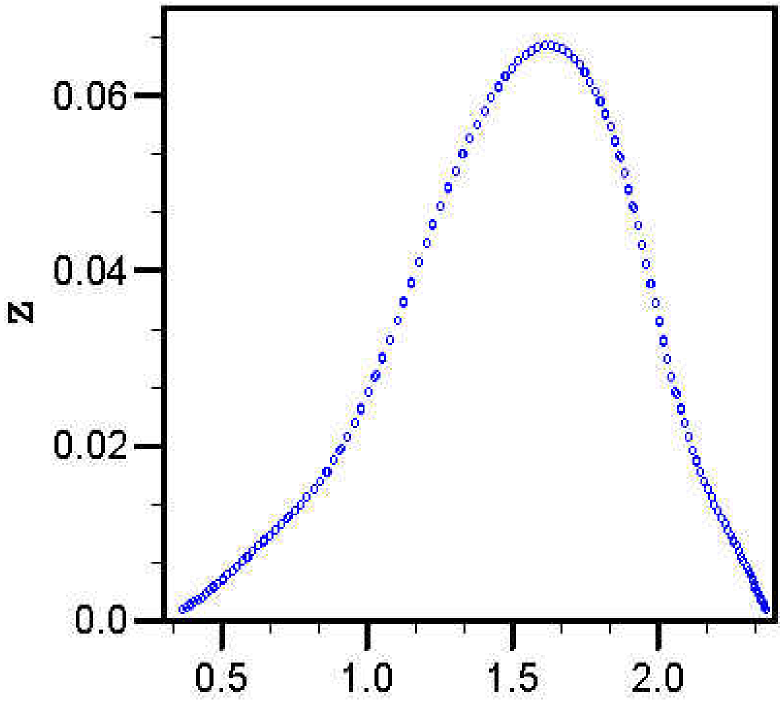
- NSTX shot #108530 at t=0.267sec:

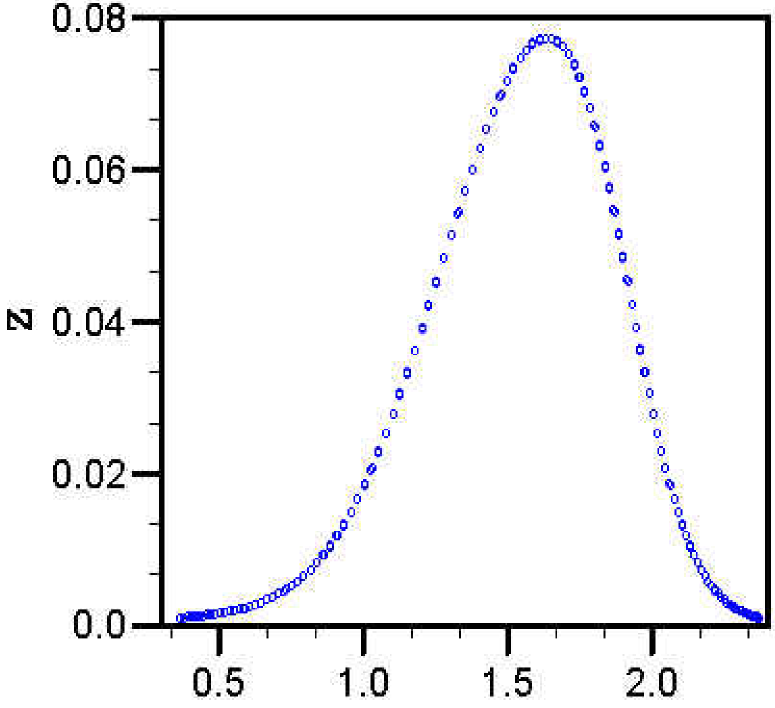
- R=87cm, a=63cm, B=0.43T, $n_e(0)$=2.5e13, Ti=1.7kev, Te=1.4kev;
- q(0)=1.82, q(a)=12.9, weakly reversed;
  $\beta(0)$=21%, $\beta_{beam}(0)$=13%;
- v_{beam}/v_{Alfven} = 2.1, ρ_{beam}/a =0.17

q profile



Pressure Profiles: $P_{thermal}$ and P_{beam}





Beam Particle Distribution

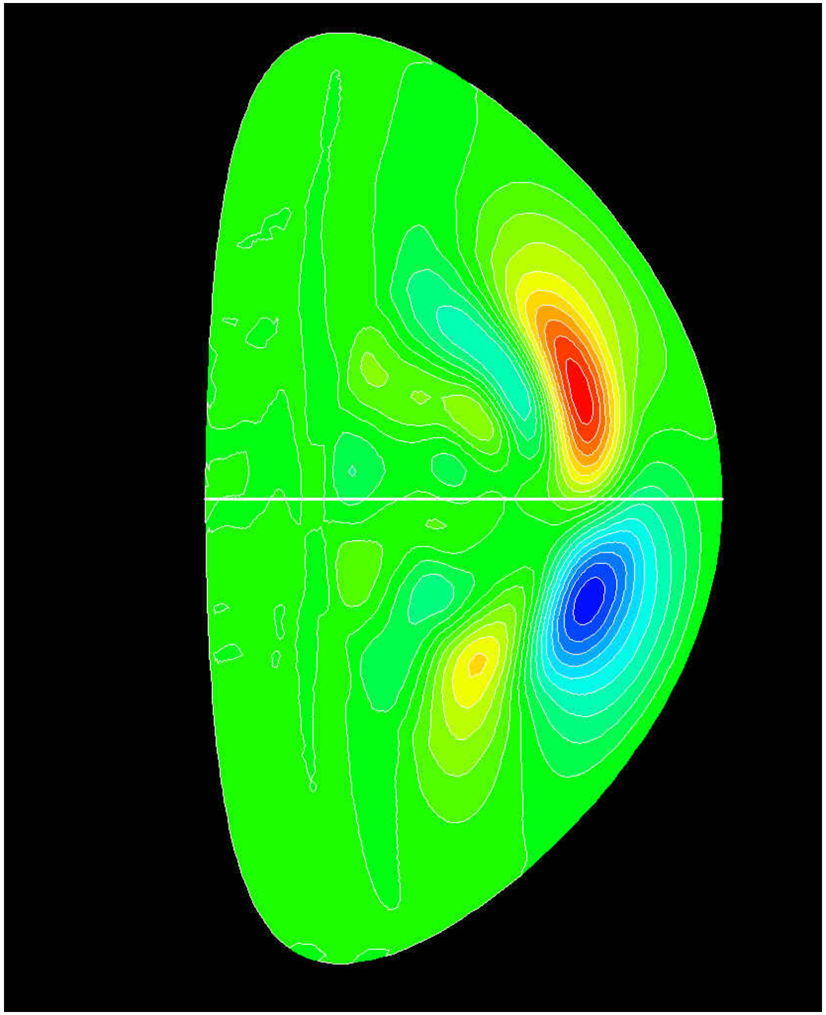
$$f = \frac{1}{v^3 + v_c^3} \exp\left(-\frac{\bar{P}_\phi}{\Delta\Psi}\right) \exp\left(-\frac{(\Lambda - \Lambda_0)^2}{\Delta\Lambda^2}\right)$$

$$\bar{P}_\phi = \frac{P_\phi - P_{\phi,min}}{P_{\phi,max} - P_{\phi,min}} \qquad \Lambda = \mu B_0 / E$$

(1) isotropic distribution;

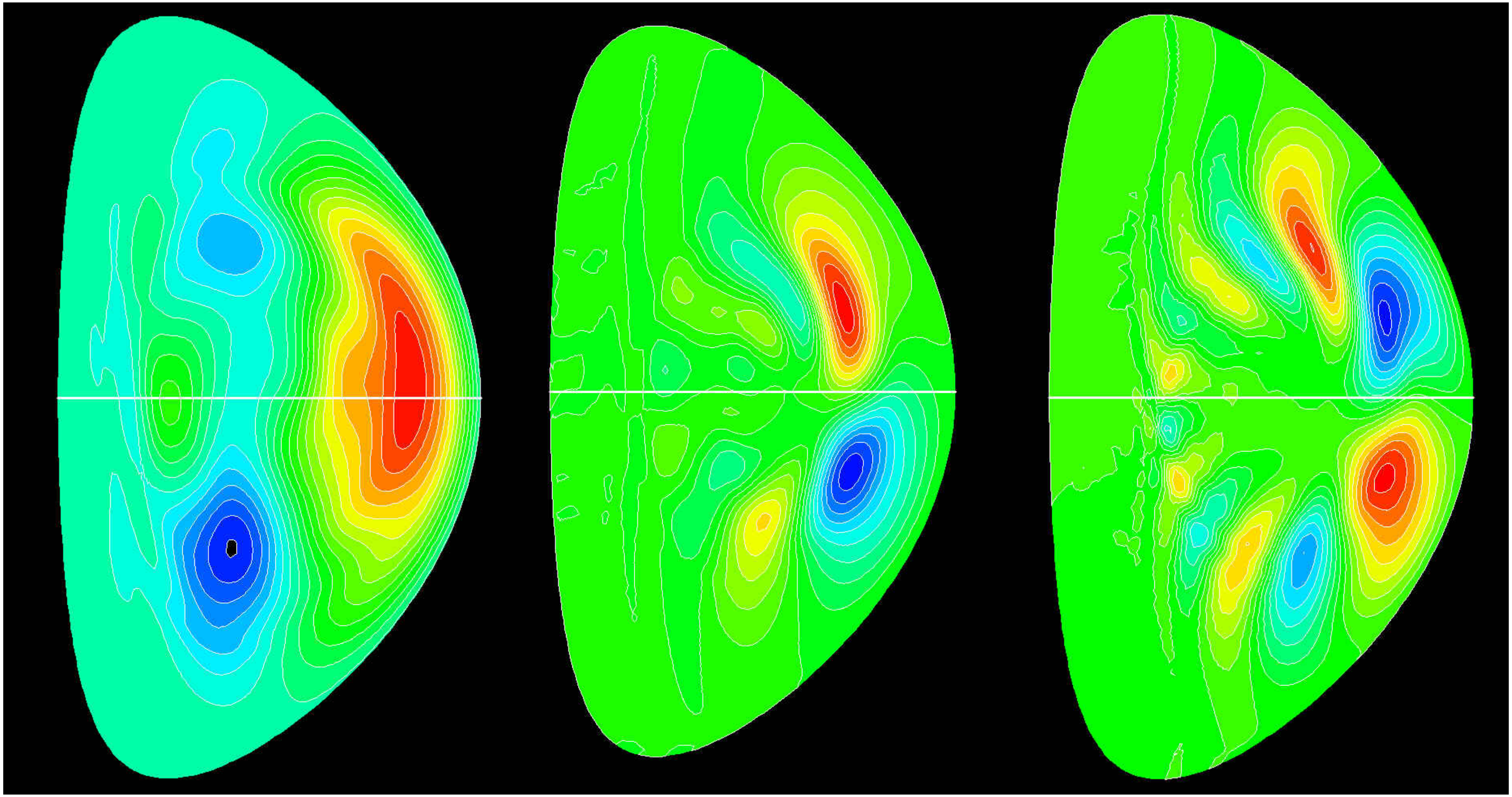
(2) anisotropic distribution.

The simulation of an NSTX plasma show unstable TAEs consistent with observations

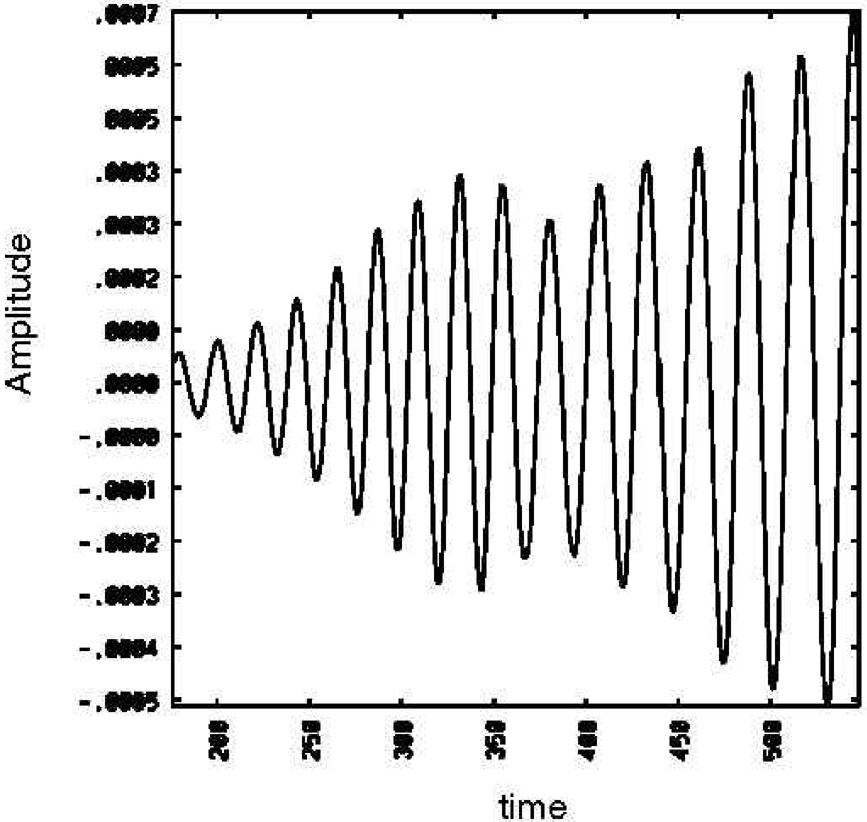


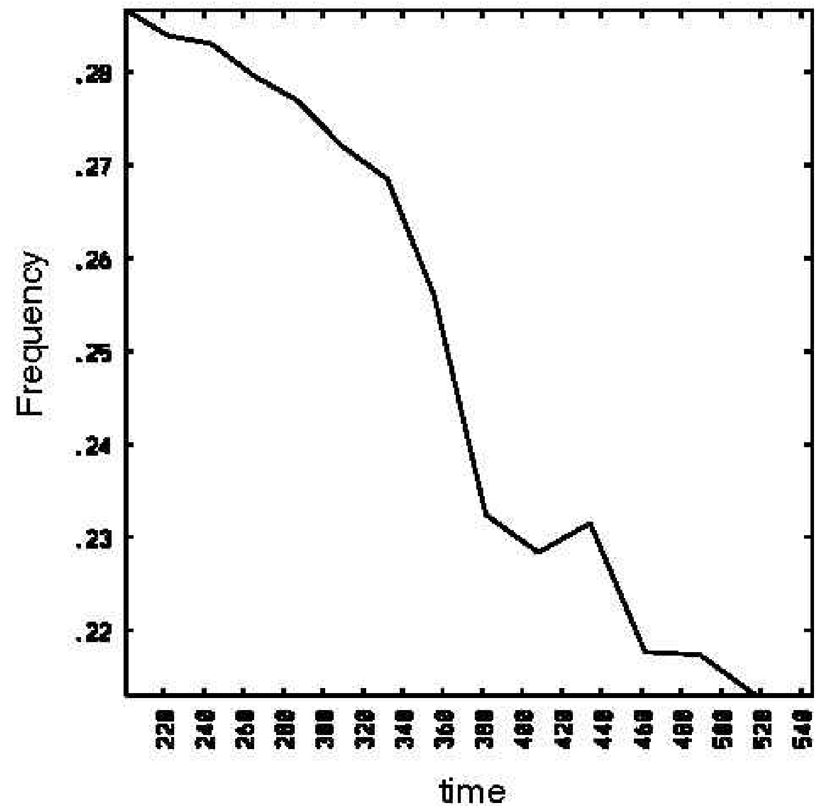
- NSTX shot #108530 at t=0.267sec;
- The calculated n=2 TAE mode frequency is 73 kHz which is close to the experimental value of 70 kHz (assuming 15kHz toroidal rotation)

N=1, 2 & 3 Modes in NSTX

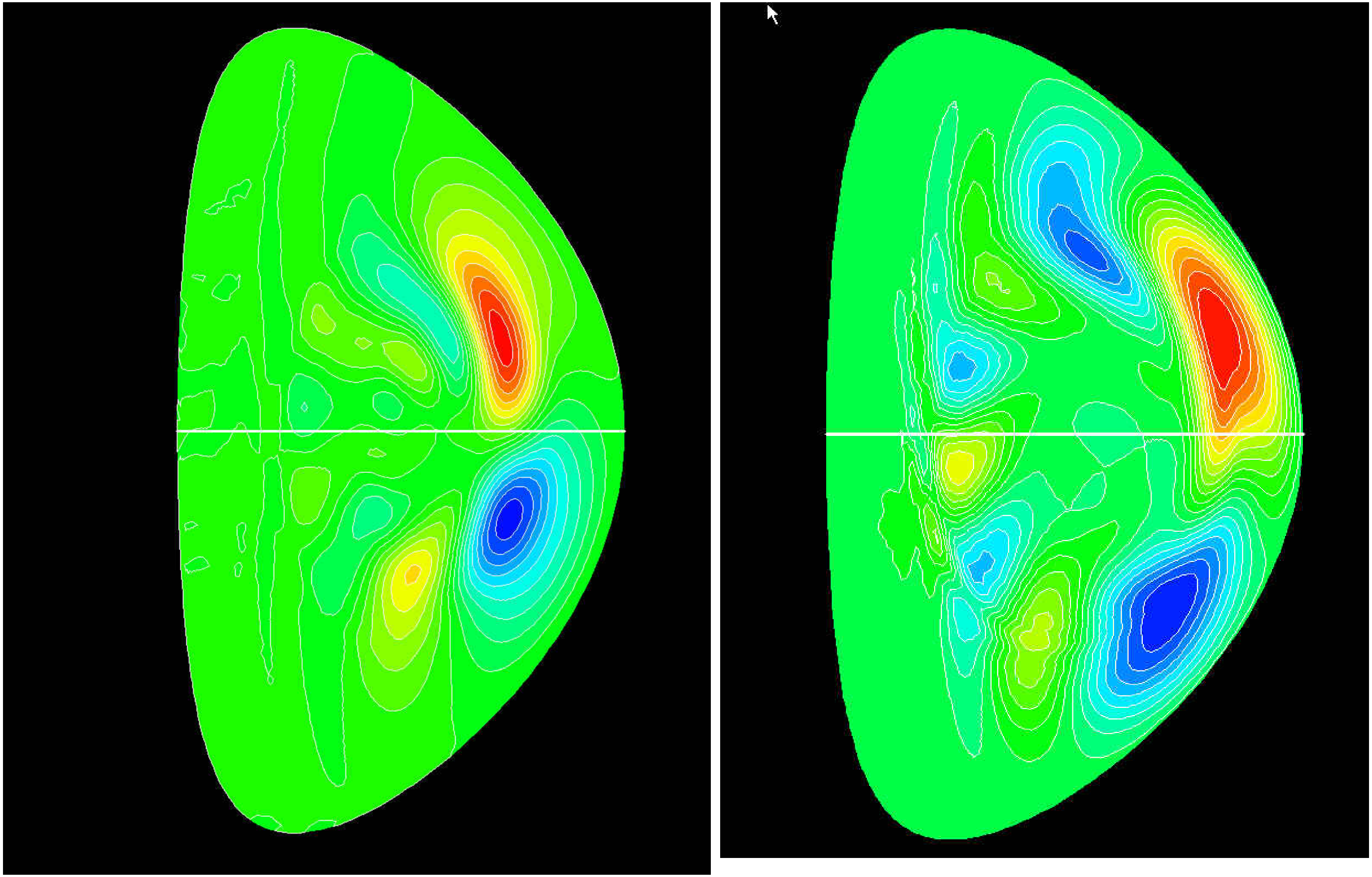


Nonlinear Evolution of n=2 TAE:
Mode Saturation and Frequency Chirping

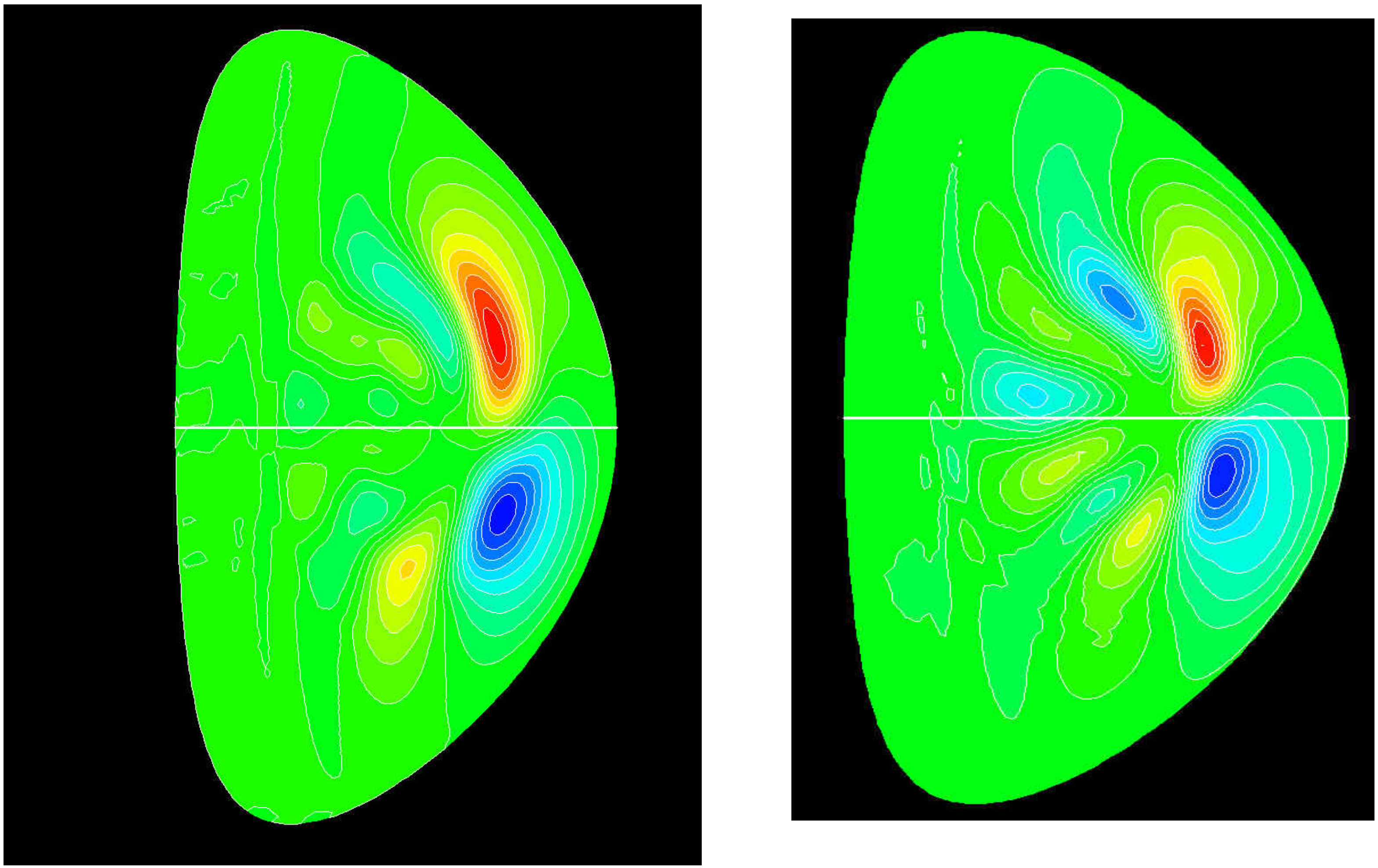




Mode Moving Out After Saturation

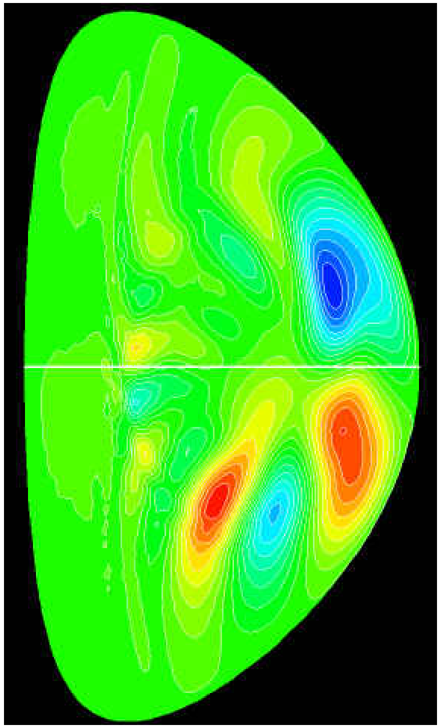


n=2 Mode Structure: Isotropic v.s. Anisotropic distribution

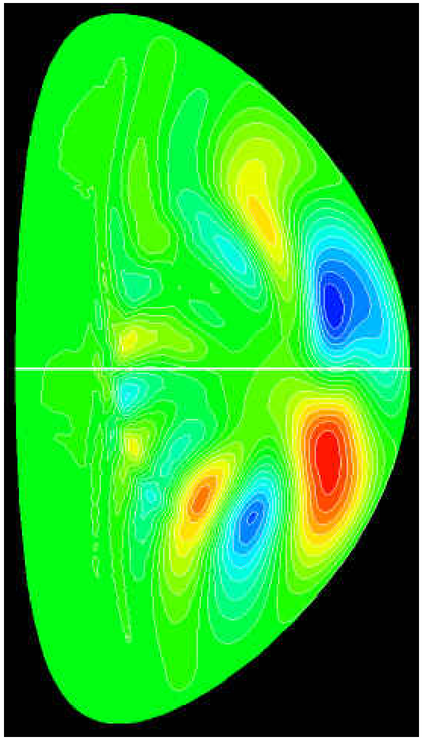


Multiple Mode Simulations (n=1~4)

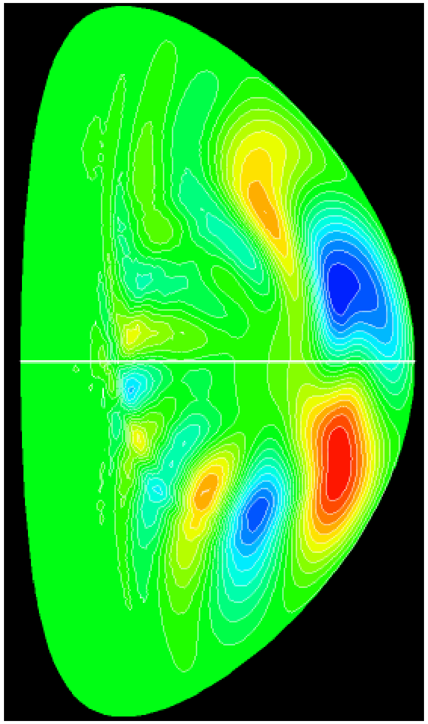
t=139



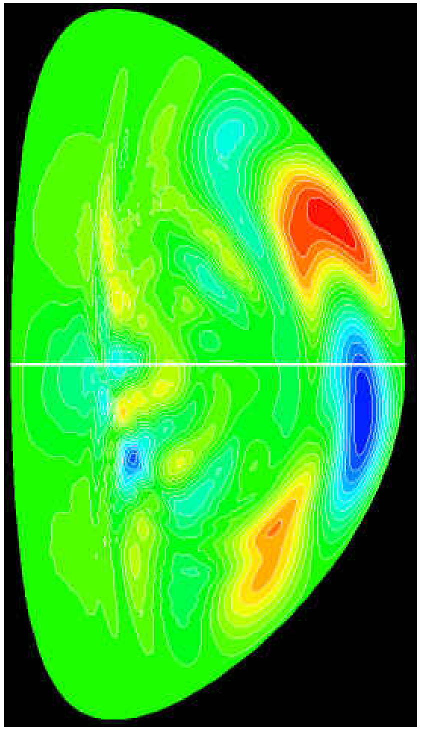
t=180



t=220



t=270



Summary

- Simulations of NBI-heated NSTX plasmas show unstable TAEs with frequencies consistent with experimental observations.
- Initial nonlinear simulations show that the n=2 TAE mode moves out radially and its frequency chirps down during saturation.

Future Work

- Simulations of NBI-driven TAE in NSTX for more realistic distributions;
- Improve M3D for simulations of alpha-driven high-n Alfven modes in burning plasmas: code speed, time step, more physics such as particle collision etc.