Hybrid Simulations of Energetic Particle Effects in Tokamaks

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In collaboration with

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The 2rd US-Japan Workshop of CAS on Integrated Modeling
Sept. 21-24, 2004, Princeton Plasma Physics Laboratory

Outline

- Introduction
- M3D code: hybrid model, code development
- Examples of M3D Hybrid Simulations
- Alpha Particle Stabilization of Internal Kink
- NBI-driven Alfven Modes in NSTX
- Future Work

Introduction

- We investigate energetic particle-driven MHD modes in toroidal plasmas by particle/MHD hybrid simulations;
- Our main tool is a 3D global nonlinear extended MHD code M3D.
- Our goal is to understand and predict linear instability and nonlinear dynamics of energetic particle-driven Alfven modes.

Motivation

- In a toroidal plasma (tokamak/stellarator), energetic particles with velocity comparable to Alfven phase speed can resonantly destabilize MHD modes such as TAE and CAE, they can also induce/excite new modes such as fishbone or Energetic Particle Mode(EPM).
- In a magnetic fusion reactor, alpha particle-driven MHD modes can results in alpha particle loss and change alpha heating profile.
- Key issues of alpha physics are alpha effects on sawteeth and alpha particle transport due to multiple Alfven modes.

M3D code

M3D project is part of SciDAC's Center for Extended MHD Modeling

M3D is an extended-MHD (XMHD) code which has multi-level of physics:

Resistive MHD;
Two fluids;
Energetic Particle/MHD hybrid;
Particle Ion/Fluid Electron hybrid

M3D XMHD Model

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

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

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

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

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

- Pressure tensor

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

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

- Gyrokinetic Equations

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

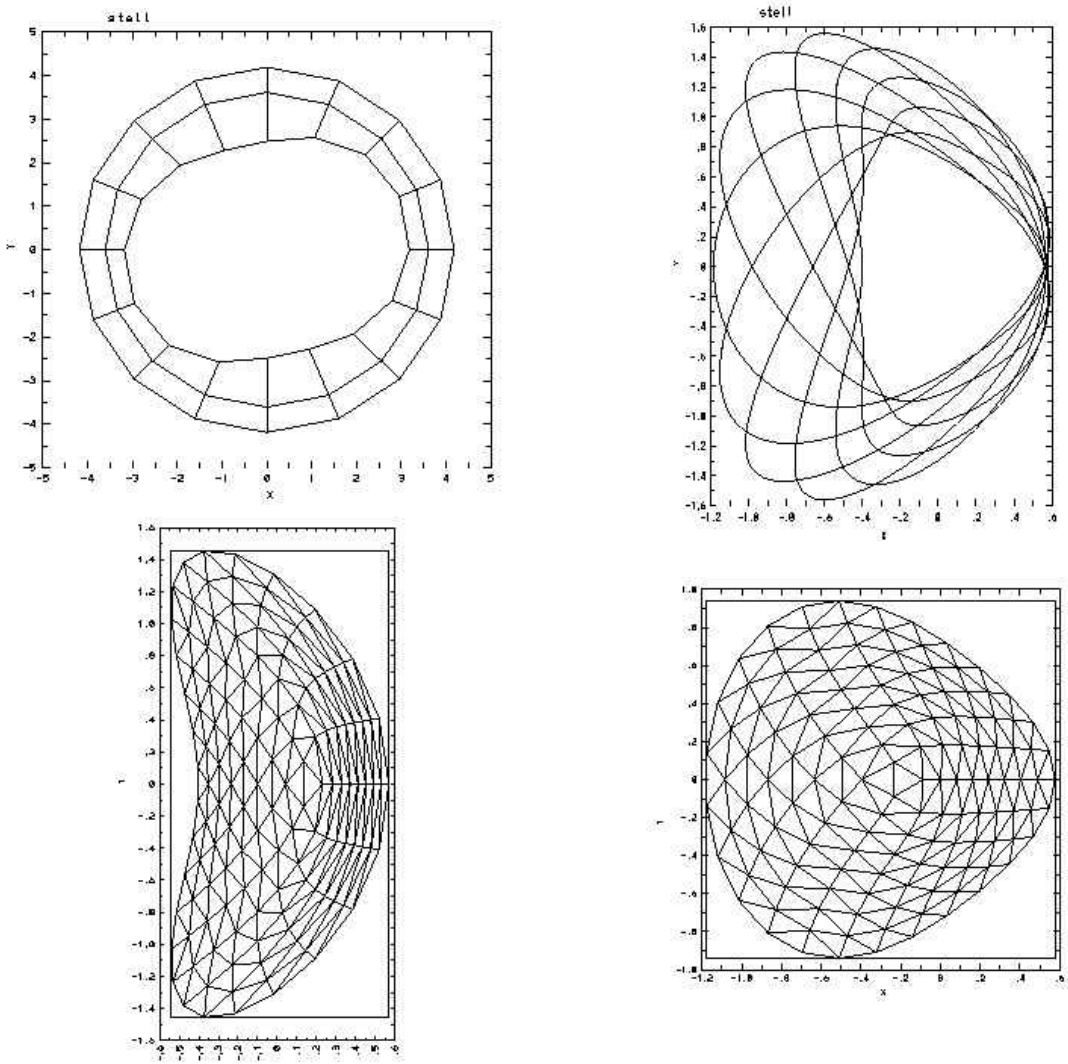
$$m\frac{dv_\parallel}{dt} = \frac{q}{B^{\star\star}}\mathbf{B}^\star \cdot (< \mathbf{E} > -\frac{1}{q}\mu\nabla(B_0 + < \delta B >))$$

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

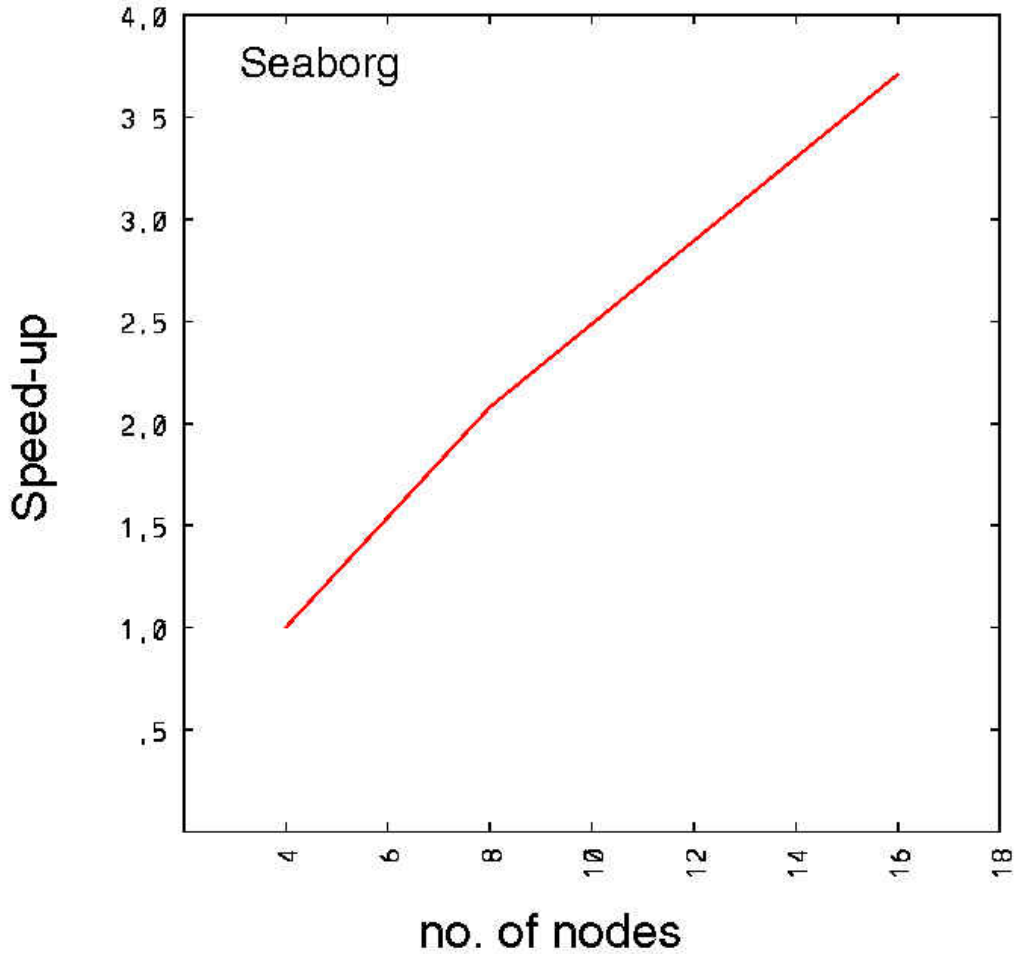
M3D Hybrid Code Development

- extended to general 3D geometry valid for stellarators;
- massively parallelized via MPI;
- benchmarked against NOVA-K code.

M3D hybrid code has been extended to unstructured mesh valid for 3D geometry



M3D hybrid code has been parallelized using either MPI or OpenMP



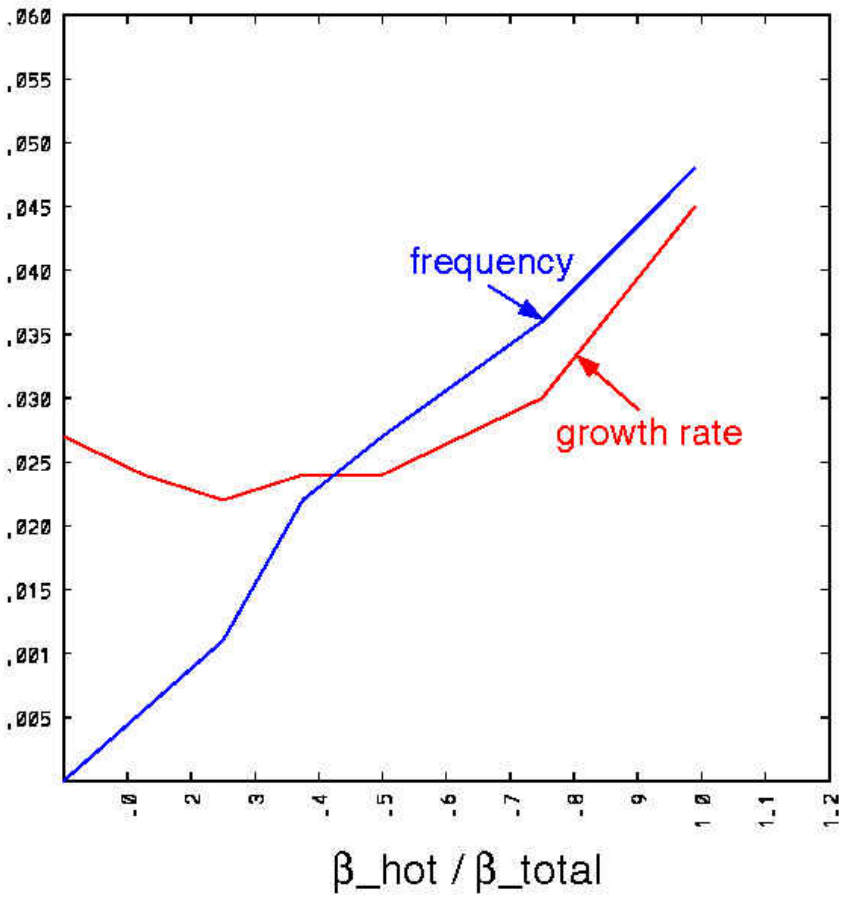
512 poloidal planes
7321 mesh points
32 million particles

1 node = 16 processors

Examples of M3D Hybrid Simulations

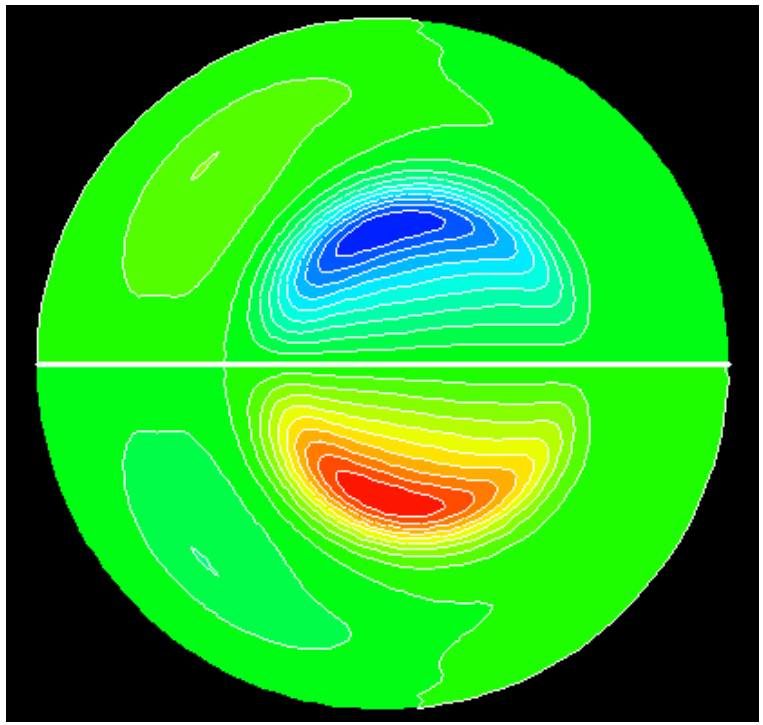
- Fishbone instability;
- TAE in stellarators.

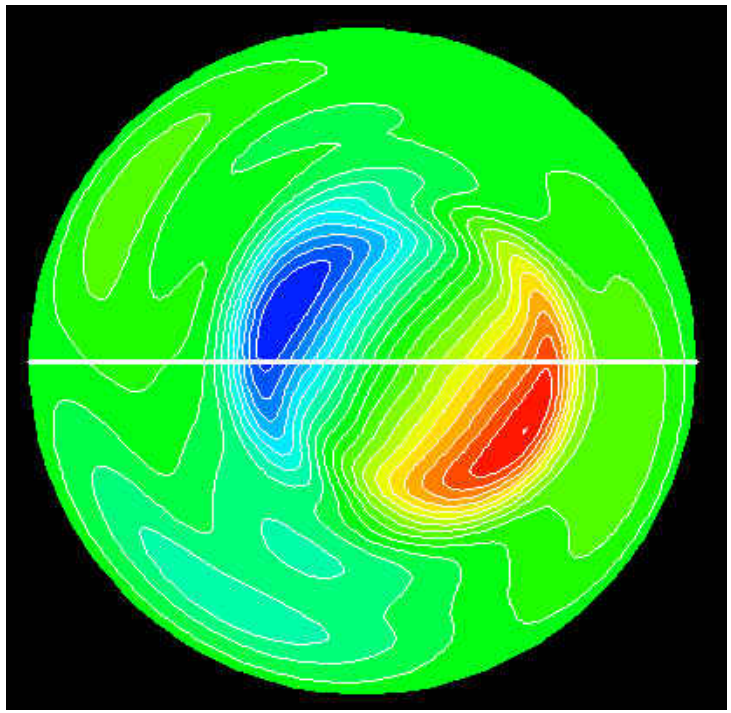
Hot Particle-induced Fishbone Instability



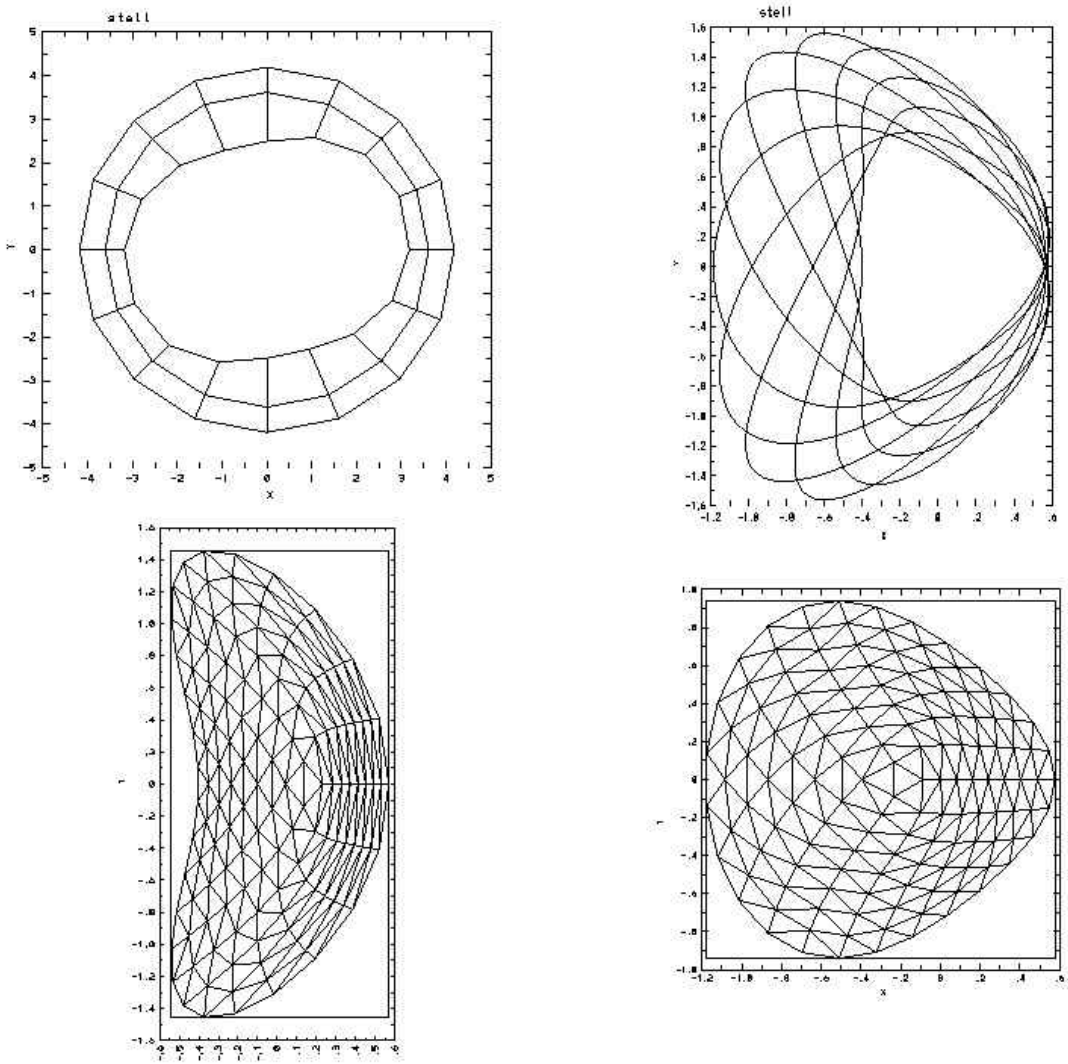
circular tokamak R/a=2.76
q(0)=0.6, q(a)=2.4
β_total(0) = 8%
v_h/v_A = 1.0, ρ_h/a=0.05
Isotropic slowing-down
hot particle distribution

Mode Structure: Ideal Kink v.s. Fishbone



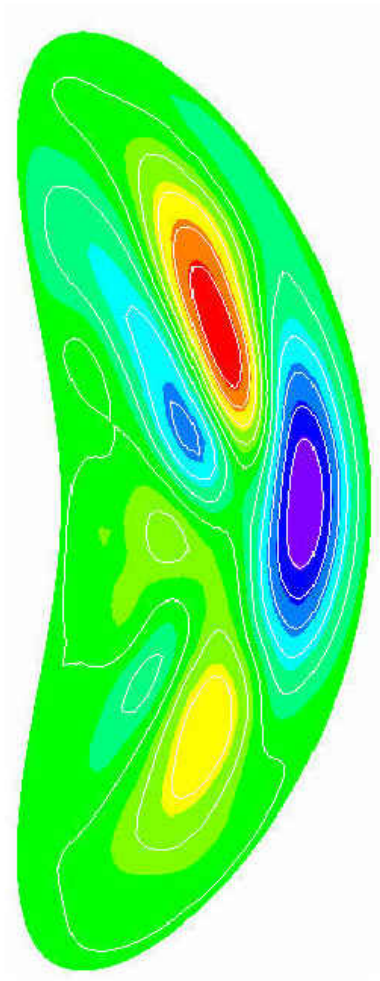


Fast Ion-driven TAE in a Quasi-symmetric stellarator

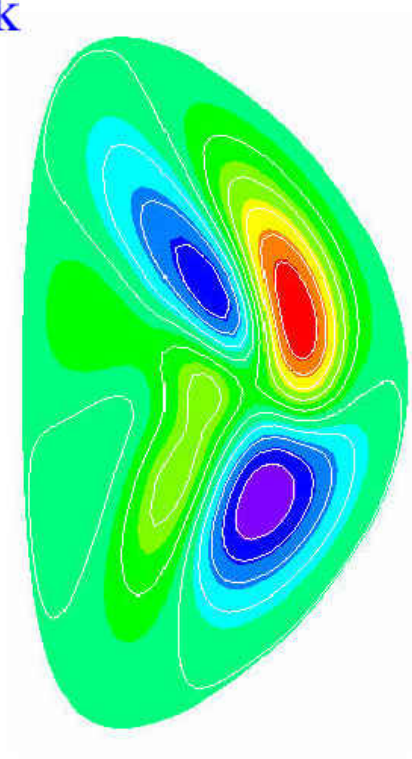


TAE mode structure: tokamak v.s. stellarator

Stellarator



Tokamak



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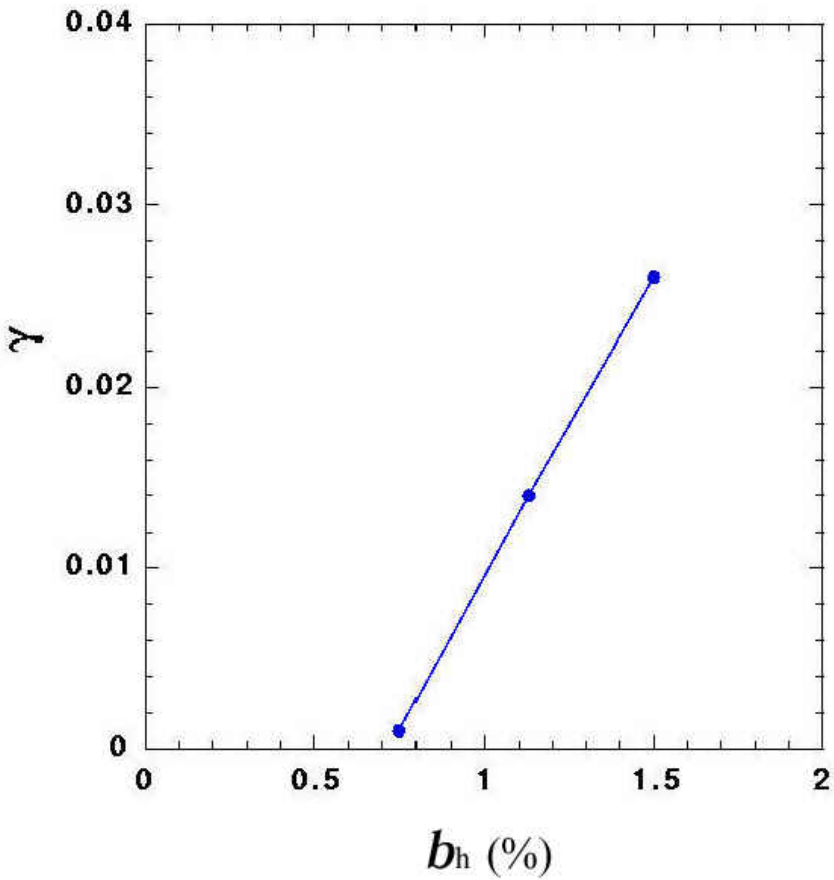
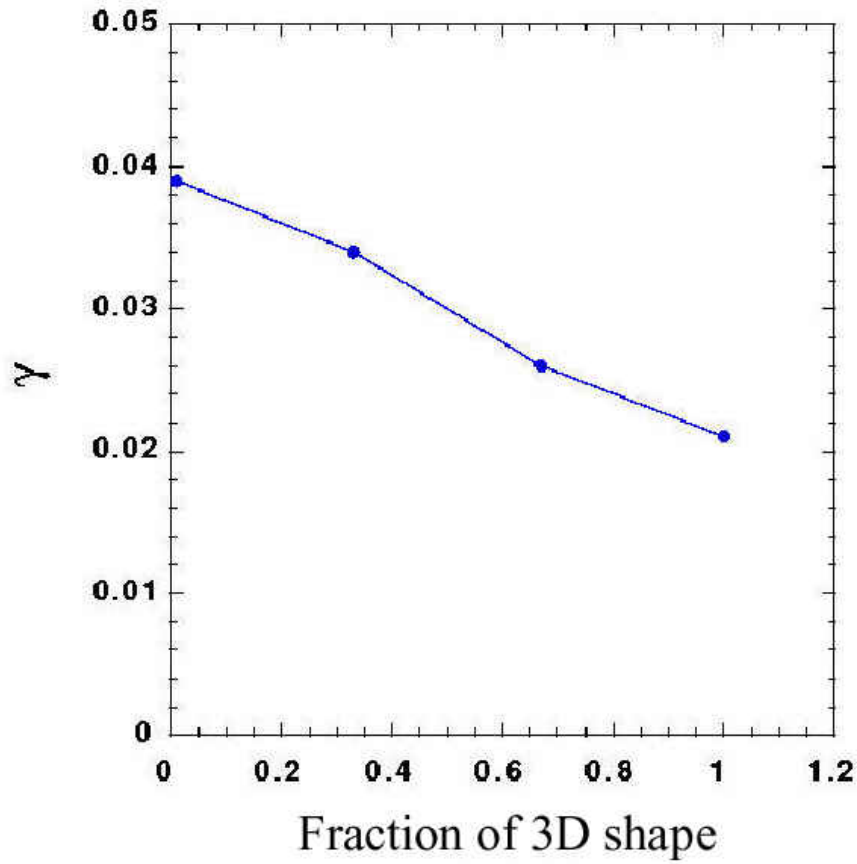
TAE growth versus hot ion beta: the growth rate is linear in hot ion beta.



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



Alpha Particle Stabilization of Internal Kink Mode:
Analytic Model

$$\frac{\gamma}{\omega} = \frac{\gamma_{mhd}}{\omega} - \beta_\alpha(0)\delta W_\alpha$$

$$\delta W_\alpha = \frac{\sqrt{3}\pi}{8 s_1}\sqrt{\frac{R}{r_1}}\int_0^{r_1} dr\left[(0.6 + 3.2(1 - q - 0.5s))\left(\frac{r}{r_1}\right)^{1.5}\frac{d\hat{p}_\alpha}{dr}\right]$$

Alpha Particle Stabilization of Internal Kink:

Numerical Results for a Model Tokamak Equilibrium

Parameters and Profiles:

R/a=3.2, circular flux surfaces;

β_{total} (0) = 3.3%;

q(0)=0.85, q(a)=2.7;

constant density profile;

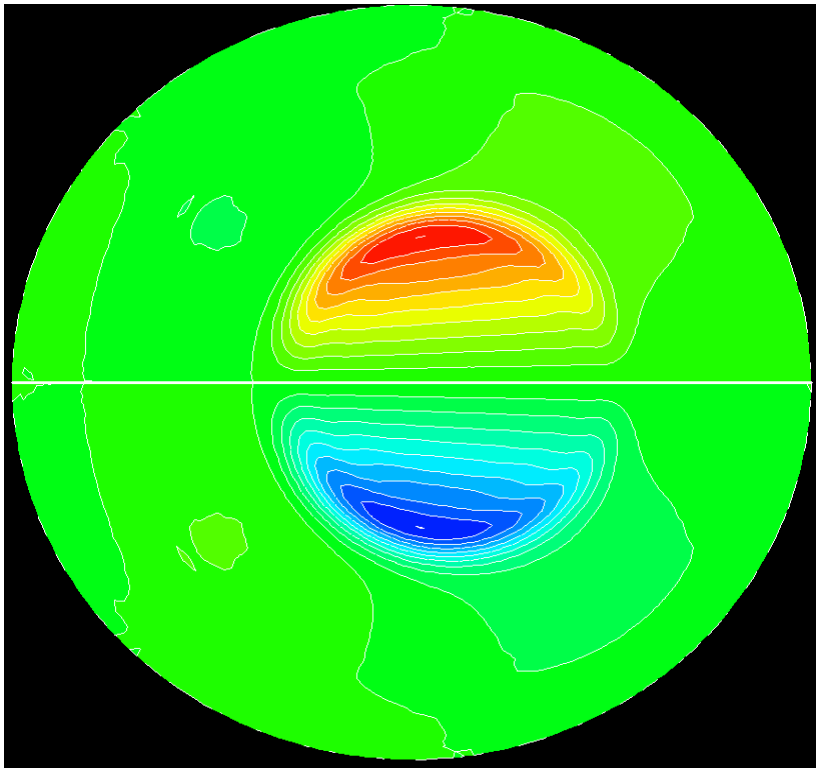
thermal and alpha pressure profiles:

$P(\psi) \sim \exp(-\psi/0.25)$;

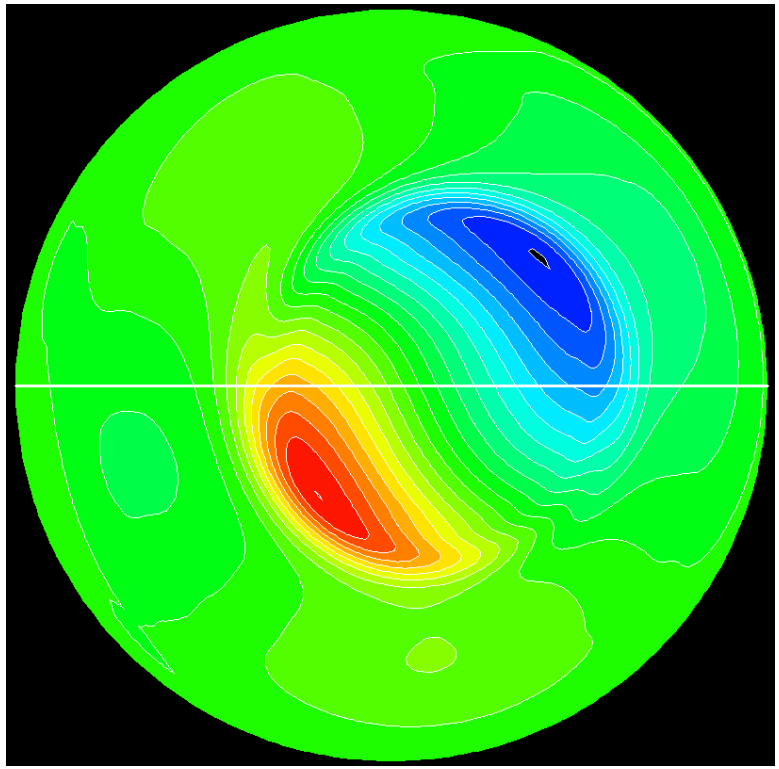
alpha particle beta is varied at fixed total beta.

Numerical Results for a Model Tokamak Equilibrium:
Internal Kink Mode Structure

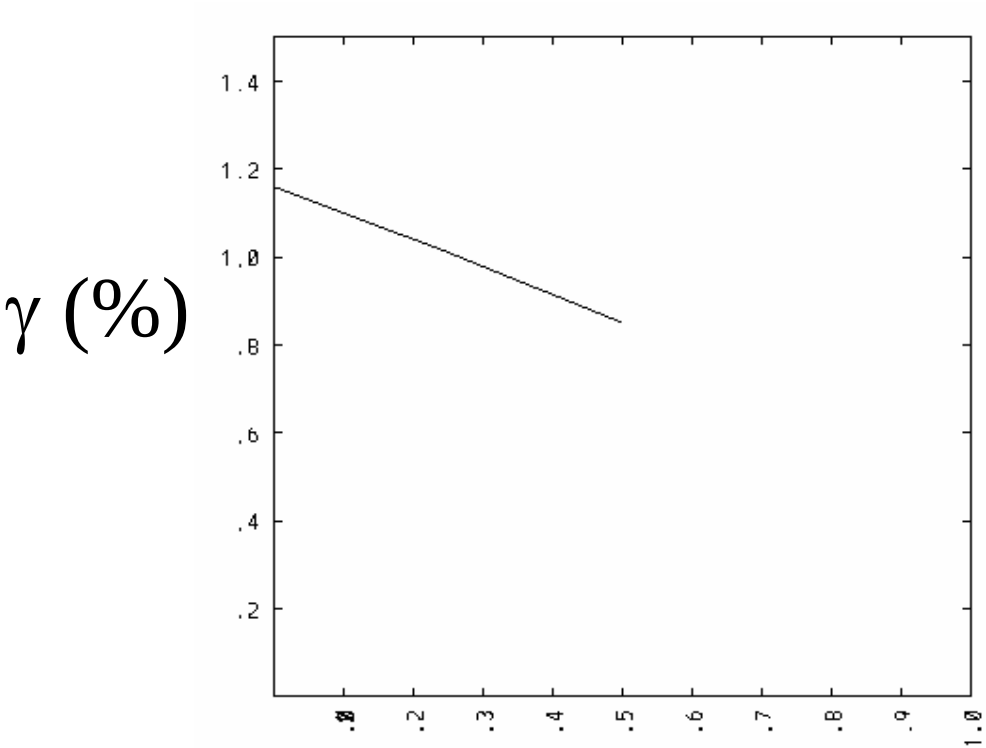
β_α=0.0%



β_α=0.5%



Numerical Results for a Model Tokamak Equilibrium:
Growth Rates agree with Analytic Results



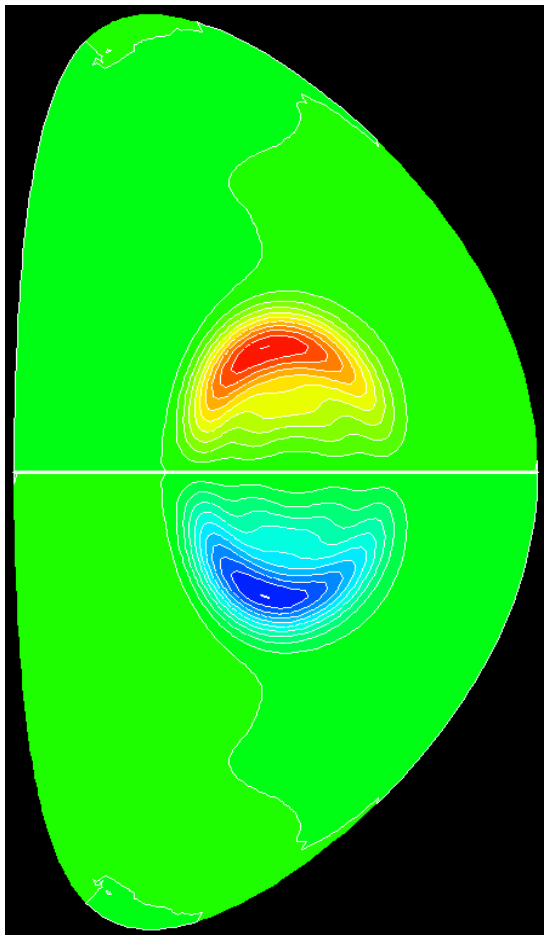
Alpha Particle Stabilization of Internal Kink Mode for ITER: Parameters and Profiles

- R=620cm, a=200cm, B=5.05T, $n_e(0)$=1.0e15, Ti=19kev, Te=23kev;
- q(0) ~ 1, q(a)=3.83;
  $\beta(0)$=6.5%, $\beta_\alpha(0)$=1%;
- v_α/v_{Alfven} = 2.5, ρ_α/a =0.023

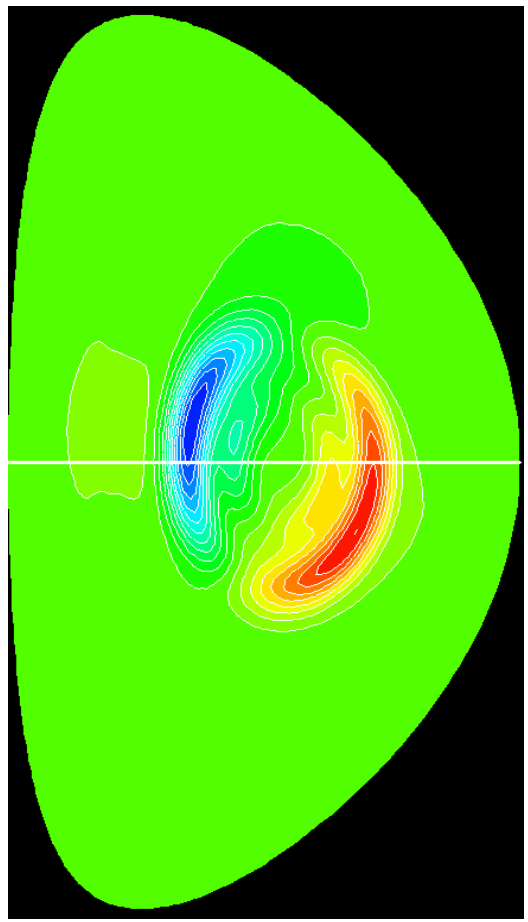
Alpha Particle Stabilization of Internal Kink Mode for ITER:

Internal Kink Mode Structure

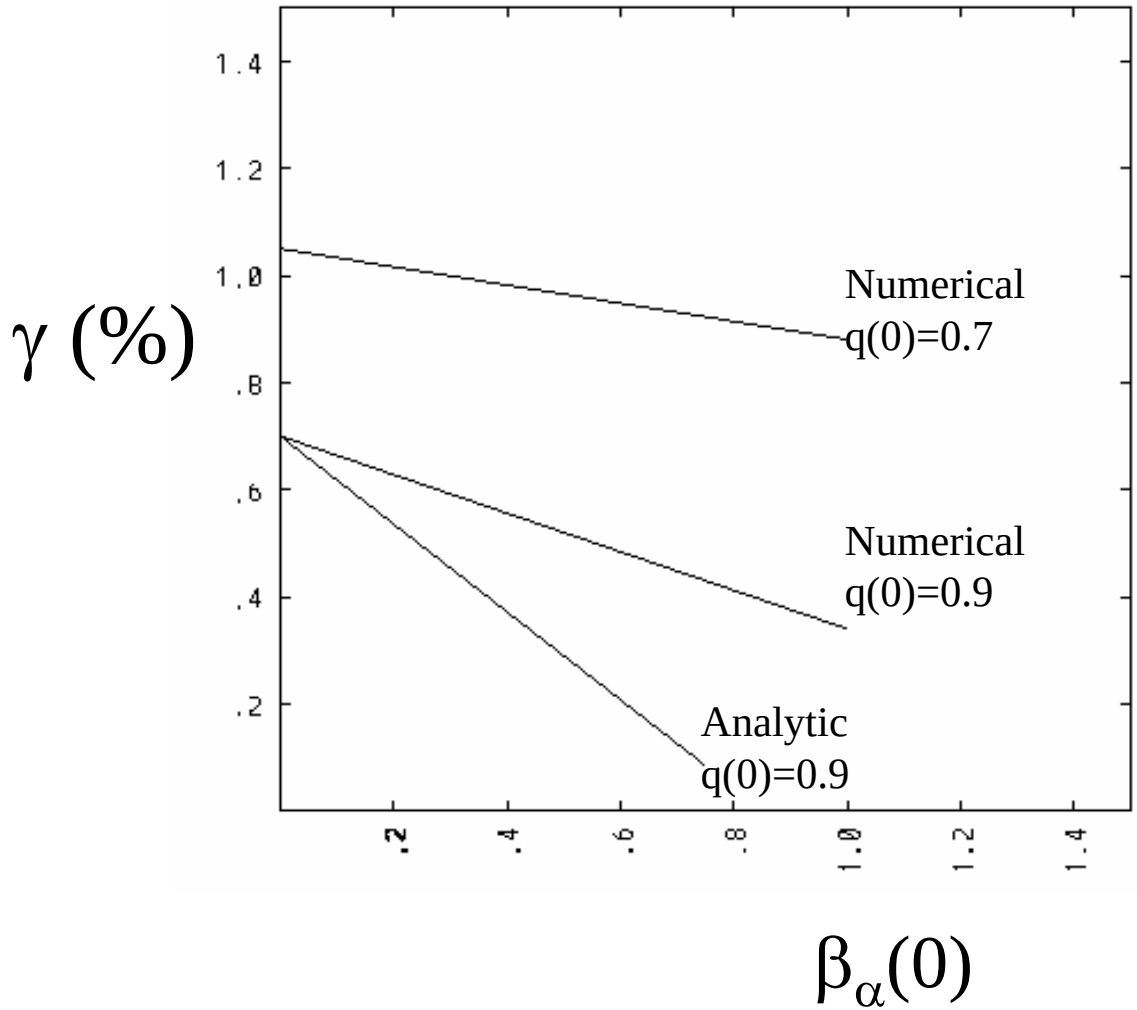
β_α=0.0



β_α=1.0%



Alpha Particle Stabilization of Internal Kink Mode for ITER: dependence on q(0)



Summary I:
Alpha Particle Stabilization of Internal Kink Mode

- We have shown that alpha particles can be strongly stabilizing when q(0) is close to unity or when q profile is flat near the center;

- However, simple analytic results overestimate the alpha stabilization by a factor of two;

- Results indicate that finite orbit width and passing particle's non-adiabatic response are not significant for alpha stabilization, as usually assumed in analytic theory.

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.

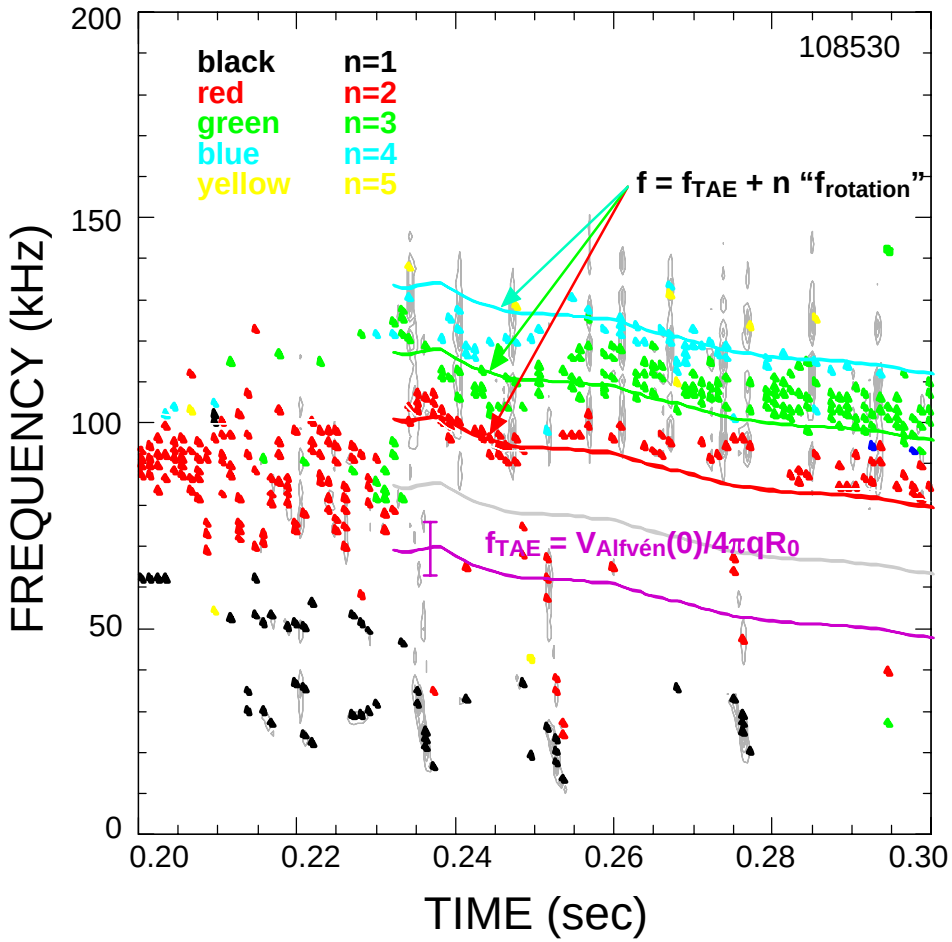
- Alfven modes in STs are less understood as compared to those in conventional tokamaks.

- 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.

E. Fredrickson

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

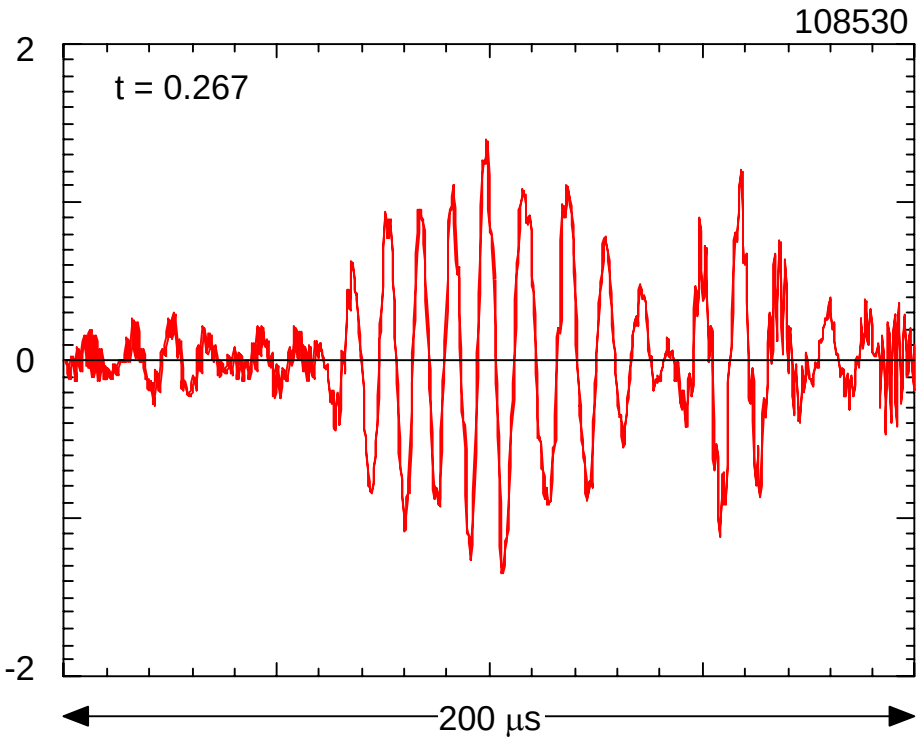
- Multiple modes burst at the same time.
- Toroidal mode number, n, ranges from 2 - 5 with the dominant mode being n=2 or 3.
- Mode frequencies in reasonable agreement with expected TAE frequencies.



E. Fredrickson

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.

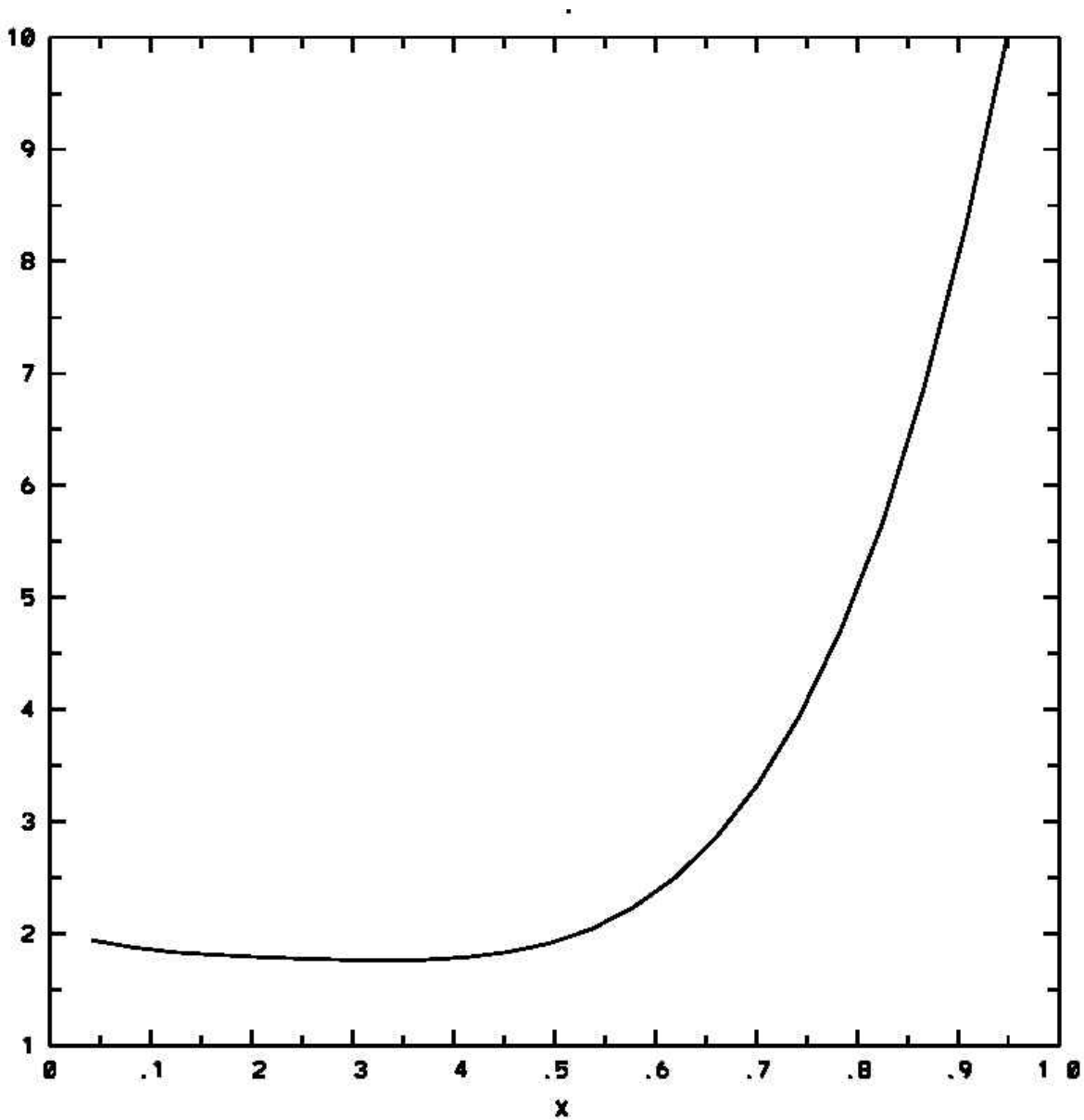


NSTX Parameters and Profiles

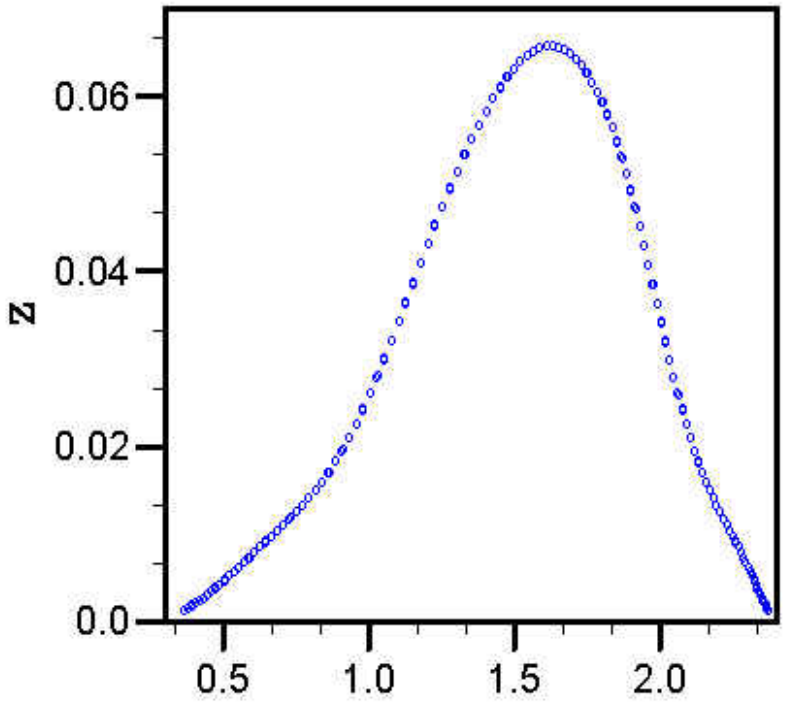
- NSTX shot #108530 at t=0.267sec:

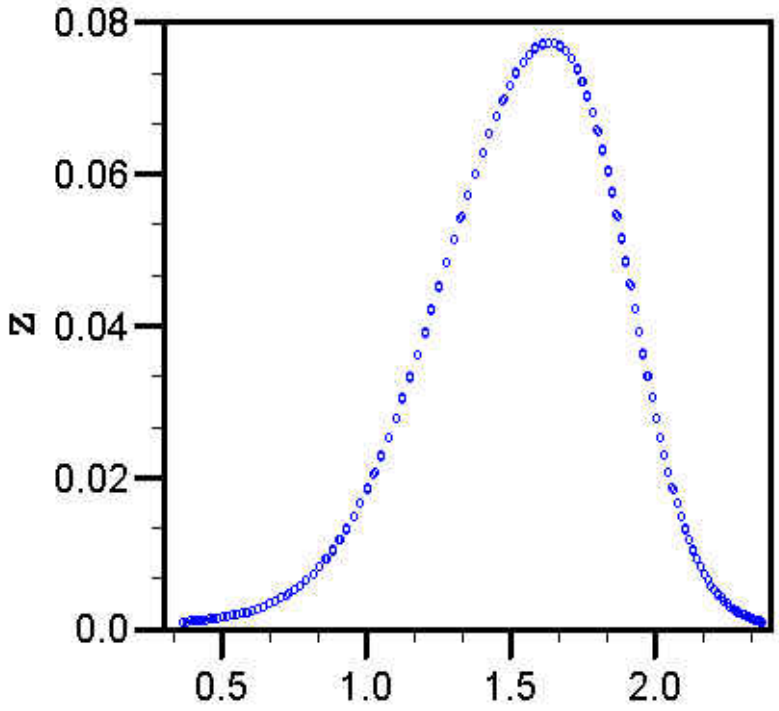
- R=87cm, a=63cm, B=0.43T, $n_e(0)$=2.5e13, Ti=1.7kev, Te=1.4kev;
- q(0)=1.82, q(a)=12.9, weakly reversed; $\beta(0)$=21%, $\beta_{beam}(0)$=13%;
- v_{beam}/v_{Alfven} = 2.1, ρ_{beam}/a =0.17

q profile



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





Beam Particle Distribution

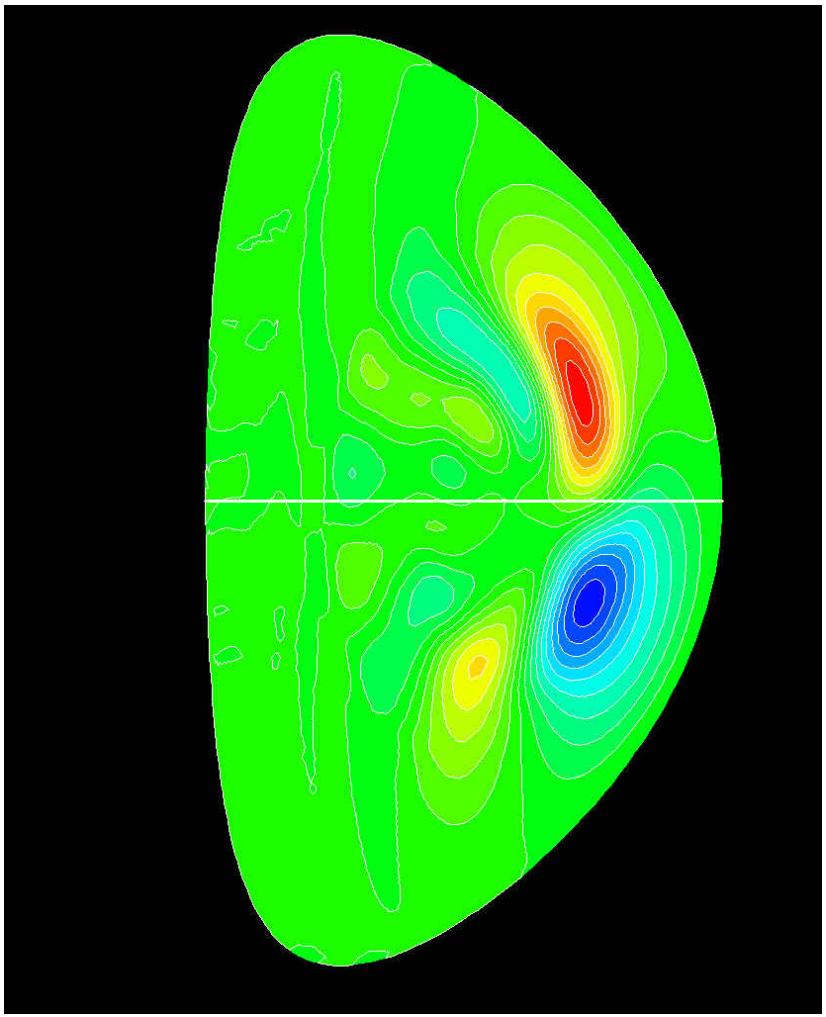
$$f = \frac{1}{v^3 + v_c^3} \exp\left(-\frac{\bar{P}_\phi}{\Delta\Psi}\right) \exp\left(-\frac{(\Lambda - \Lambda_0)^2}{\Delta\Lambda^2}\right)$$

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

(1) isotropic distribution;

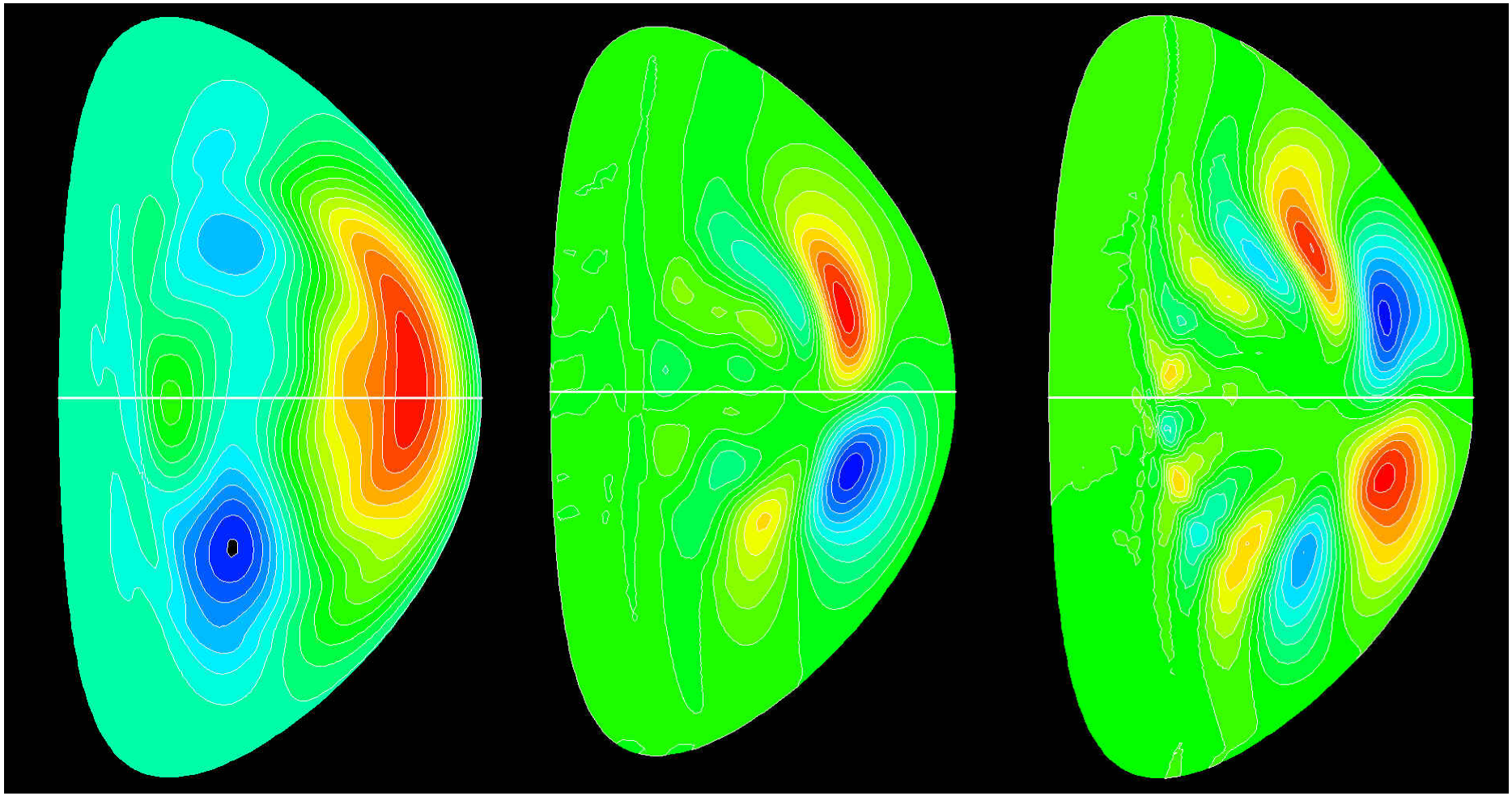
(2) anisotropic distribution.

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

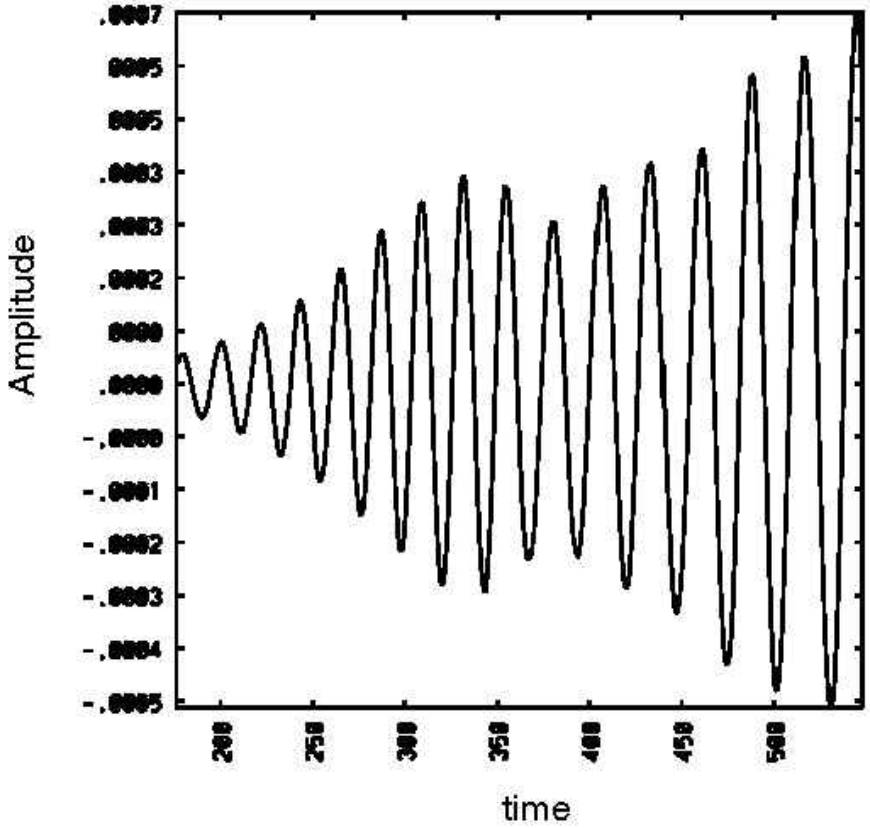


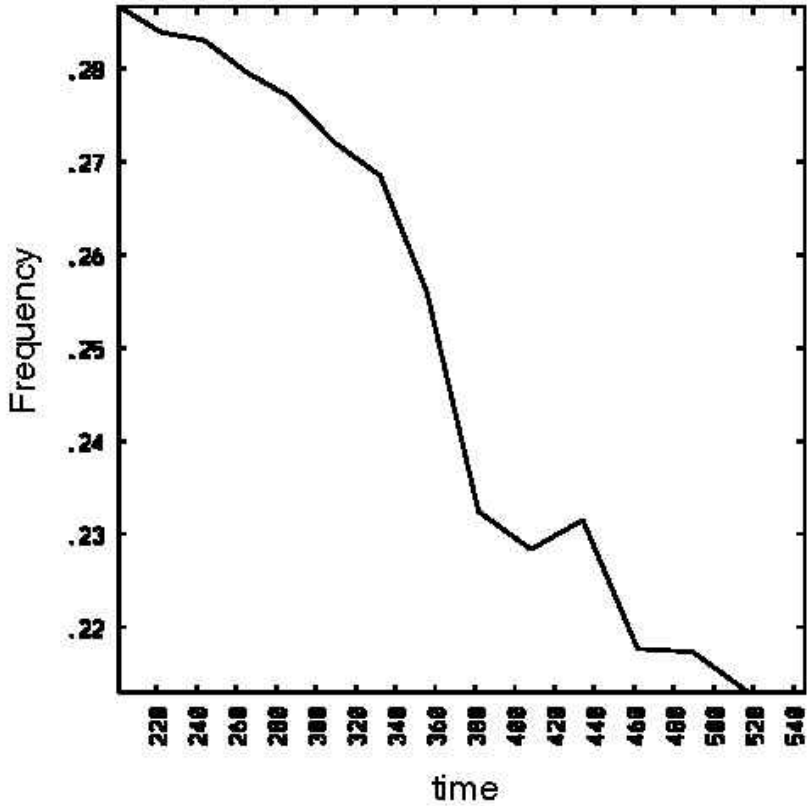
- NSTX shot #108530 at t=0.267sec;
- The calculated n=2 TAE mode frequency is 73 kHz which is close to the experimental value of 70 kHz (assuming 15kHz toroidal rotation)

N=1, 2 & 3 Modes in NSTX

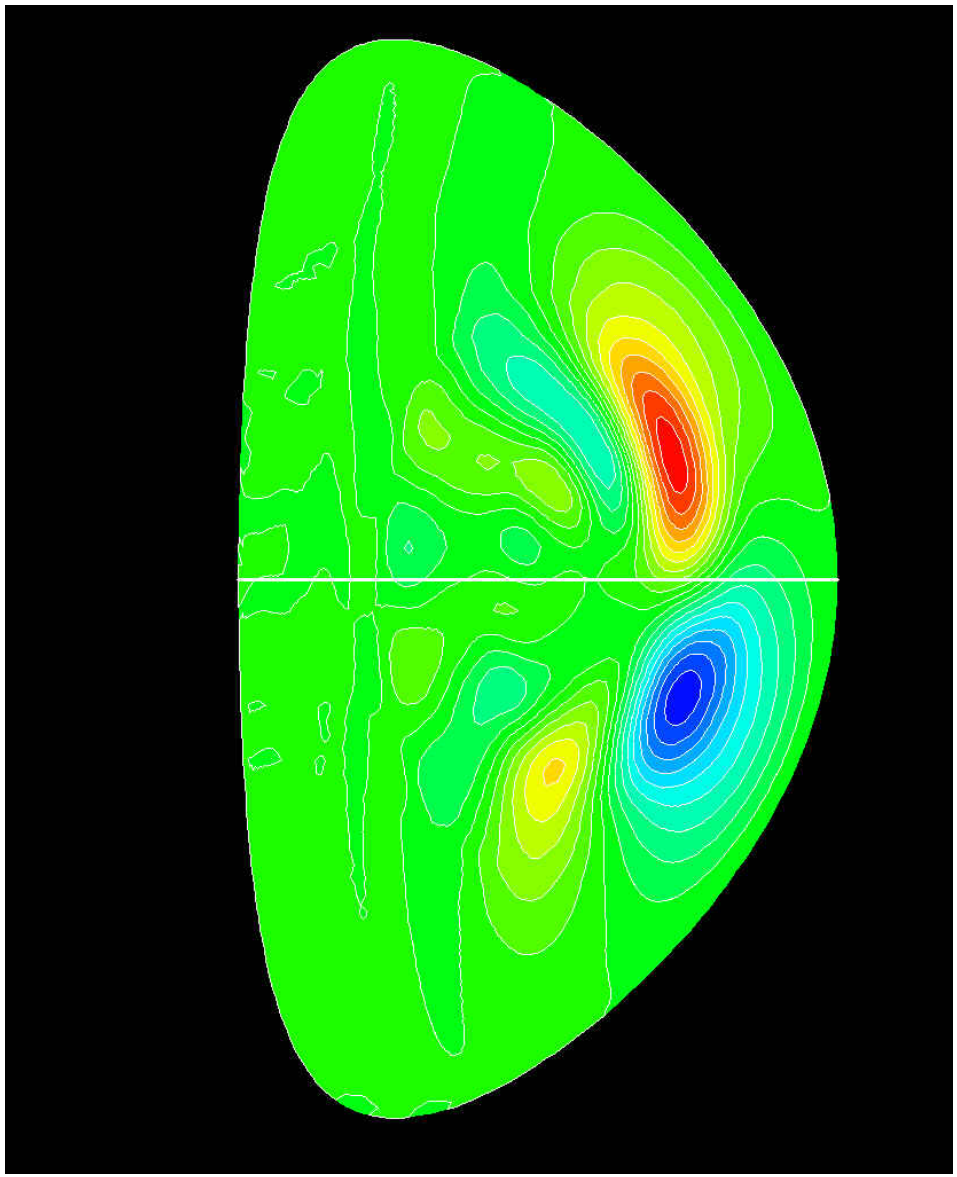


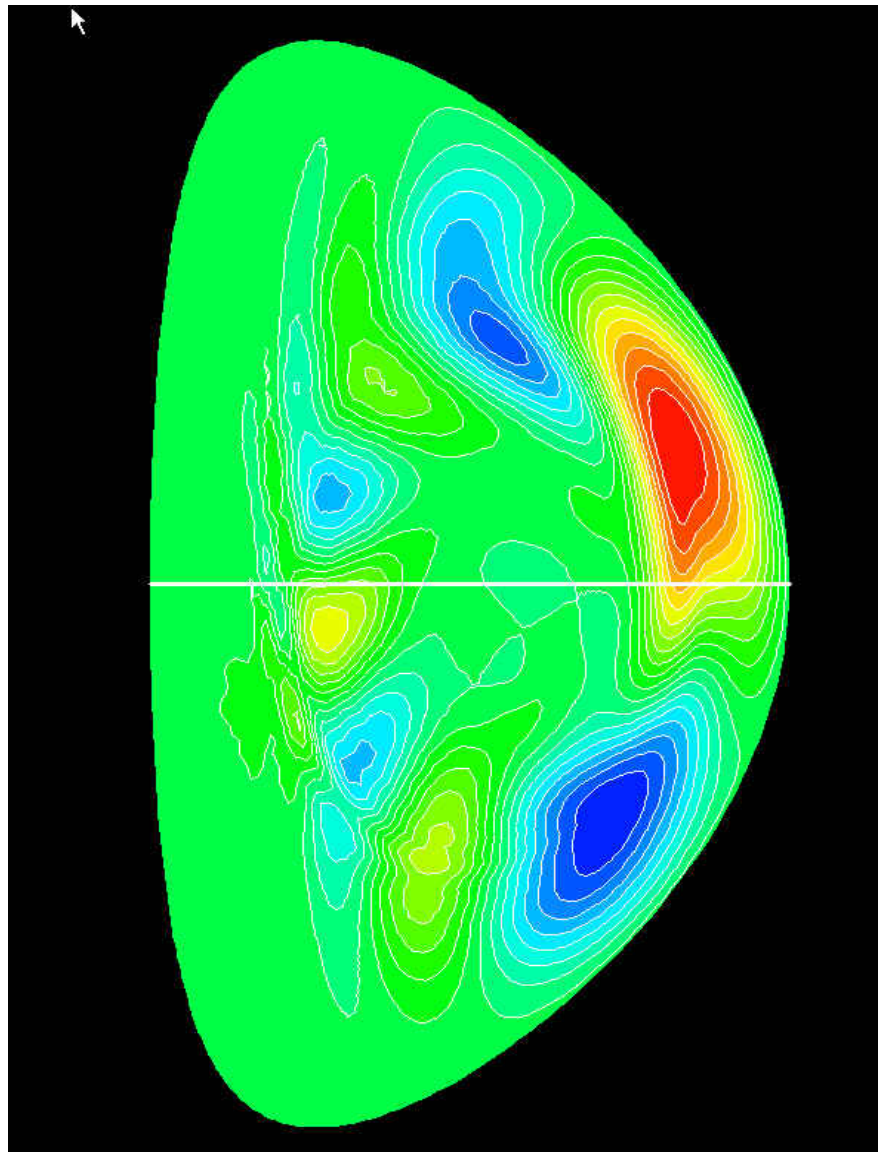
Nonlinear Evolution of n=2 TAE: Mode Saturation and Frequency Chirping



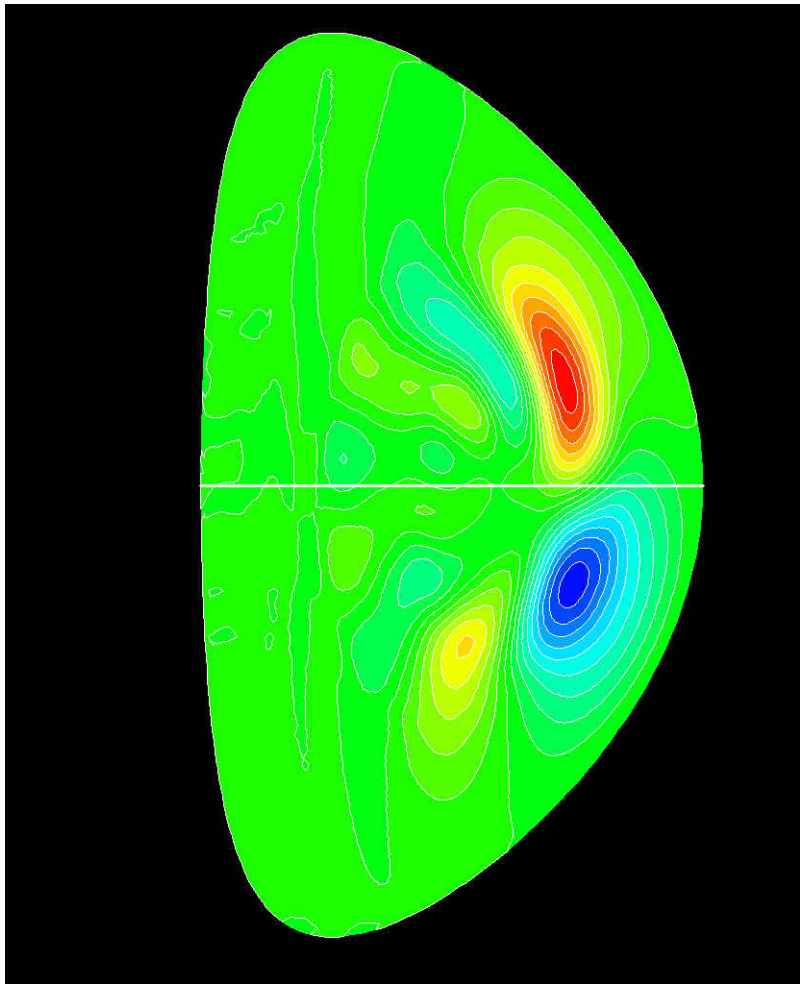


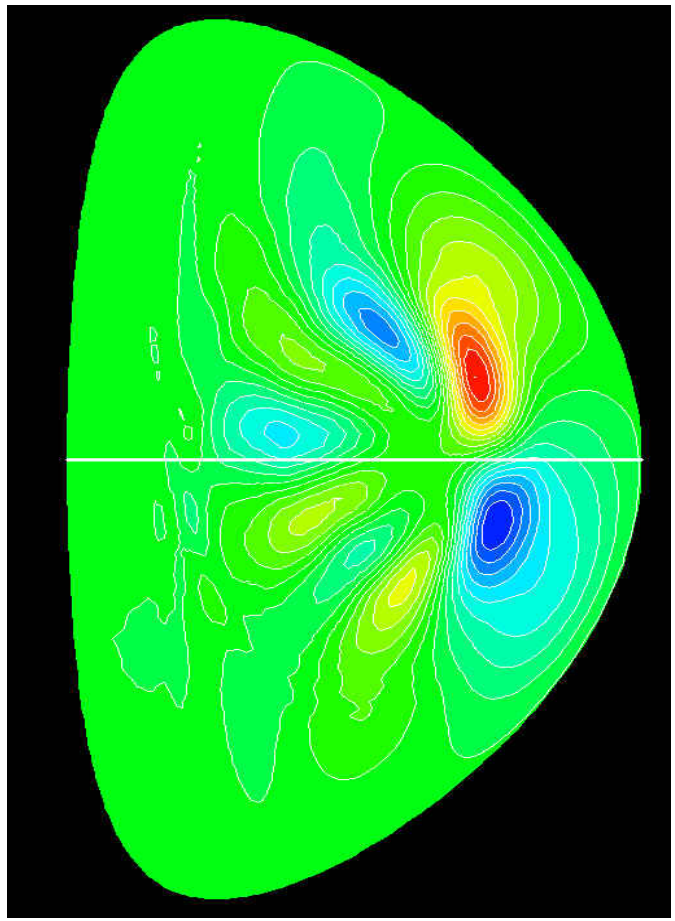
Mode Moving Out After Saturation





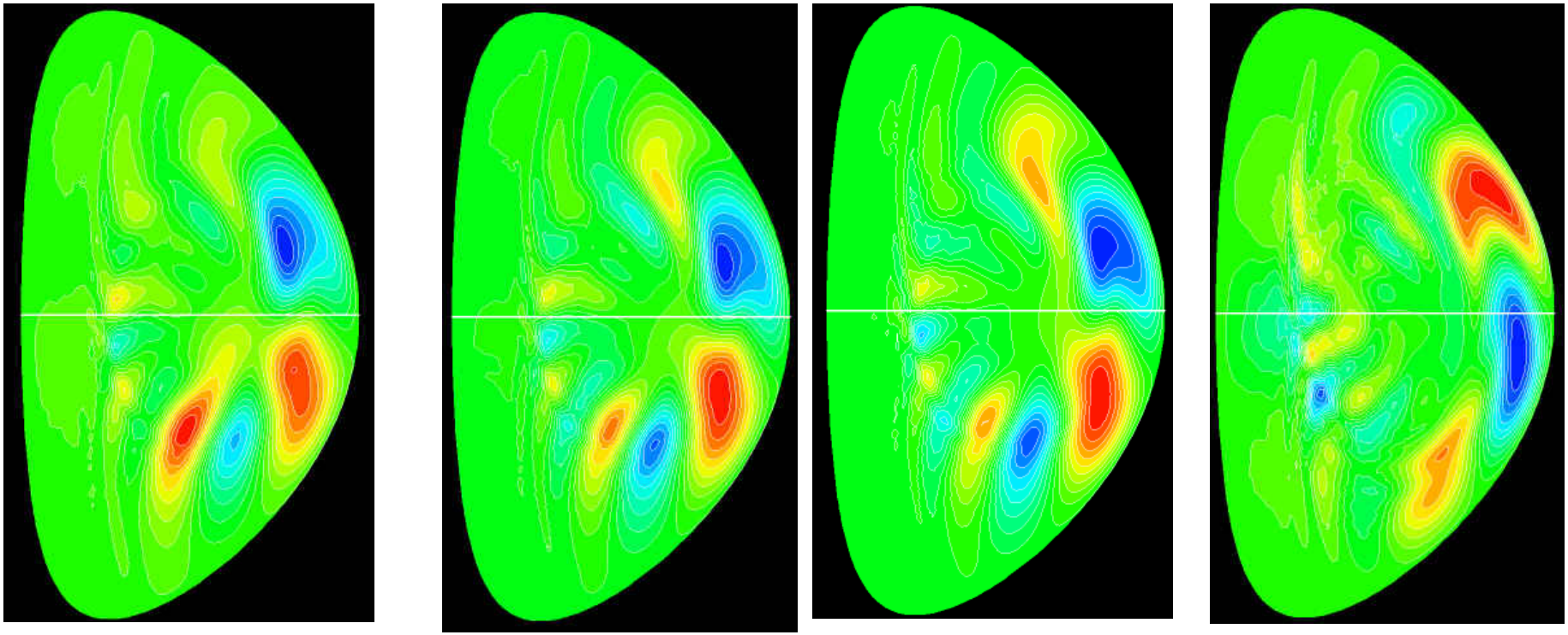
n=2 Mode Structure: Isotropic v.s. Anisotropic distribution





Multiple Mode Simulations (n=1~4)

t=139 t=180 t=220 t=270



Summary II:
NBI-driven Alfven Modes in NSTX

- M3D hybrid code has been extended to general 3D geometry and massively parallelized.

- Simulations of NBI-heated NSTX plasmas show unstable TAEs with frequencies consistent with experimental observations.

- Nonlinear simulations show that the n=2 TAE mode moves out radially and its frequency chirps down during saturation.

Future Work

- 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.
- Simulations of Neo-Classical Modes using particle closure.