Waves and Energetic Particle Physics and Five Year Plan

Presented by

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PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Collaborative approach to advancing Waves and Energetic particle physics

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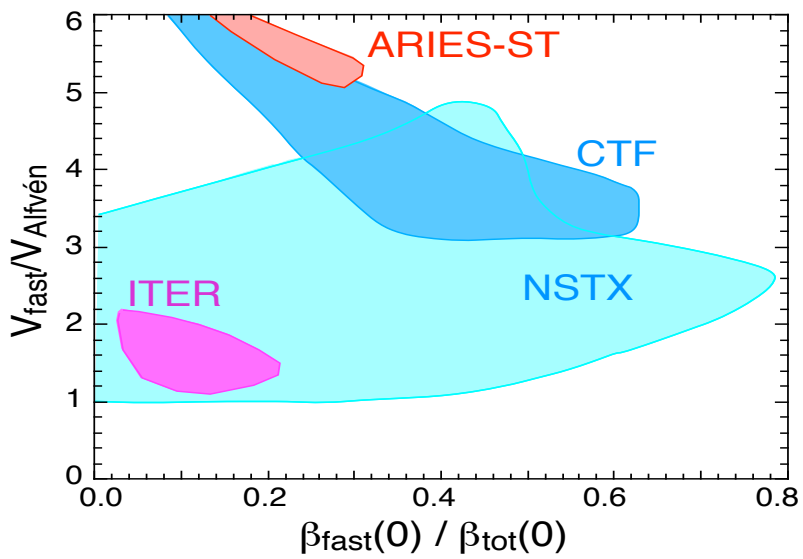
UC Irvine(W.Heidbrink)
UCLA(N.Crocker)
JET (S.Sharapov, M.Mantsinen)
JT-60U(Y.Kusama,K.Shinohara, K. Ozeki, M. Takechi)
DIII-D(M.VanZeeland)
ITER team(A.Polevoi)

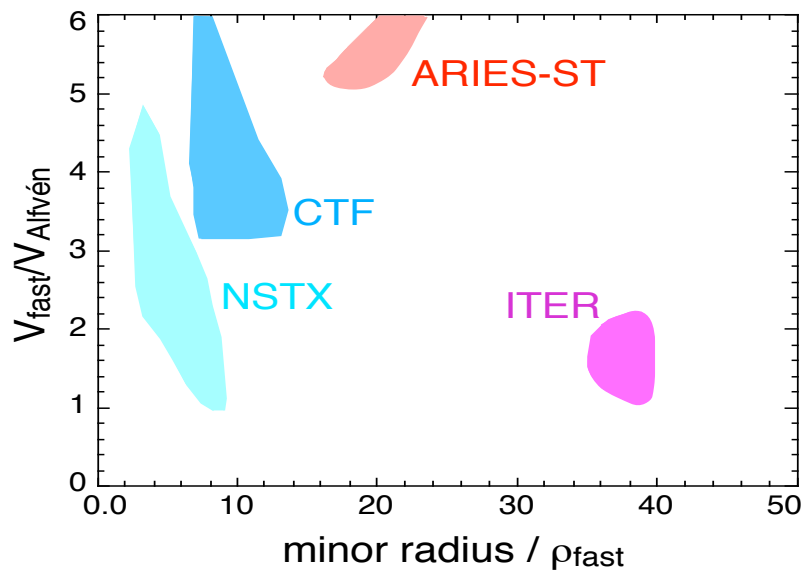
R.Nazikian will address collaboration

Goal is to establish a predictive capability valid for burning plasmas

From FESAC priorities panel:
T12:How do high-energy particles interact with plasma?

Present day plasma vs ITER: ρ_* is different => multiple instabilities are expected



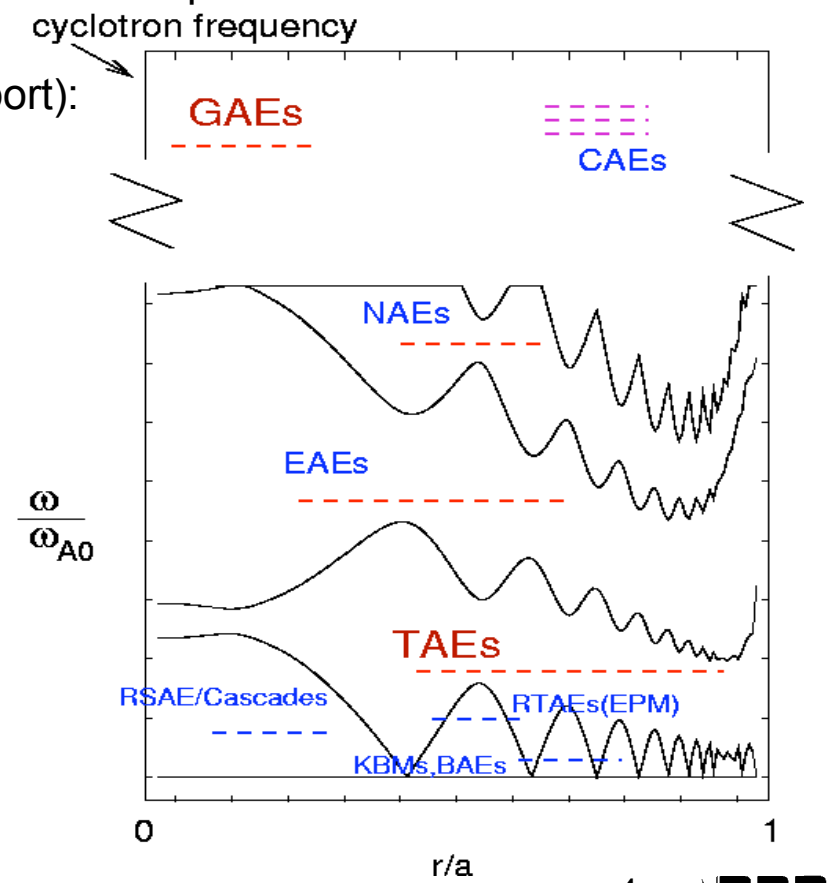


Predicting fast ion confinement is critical for the sustained burning plasma.

A variety of AEs and collective effects due to fast ions

Our research and future plans build upon rich history of physics discoveries at PPPL in the area of EP and Waves, such as ripple diffusion, fishbones, TAEs, etc. and most recently CAE/GAEs.

Rich spectrum of modes in tokamaks



Models and numerical tools:

High frequency modes $\omega \sim \omega_{ci}$, $\omega > \omega_{ci}$(velocity transport):

- Linear MHD NOVA code $\omega < \omega_{ci}$, $\omega > \omega_{ci}$
- Linear wave code TORIC
- Nonlinear HYM initial value, hybrid

Low frequency modes $\omega << \omega_{ci}$ (radial transport):

Linear codes:

- HINST – local nonperturbative ballooning
- NOVA-K –hybrid MHD-kinetic
- NOVA-KN – nonperturbative global hybrid

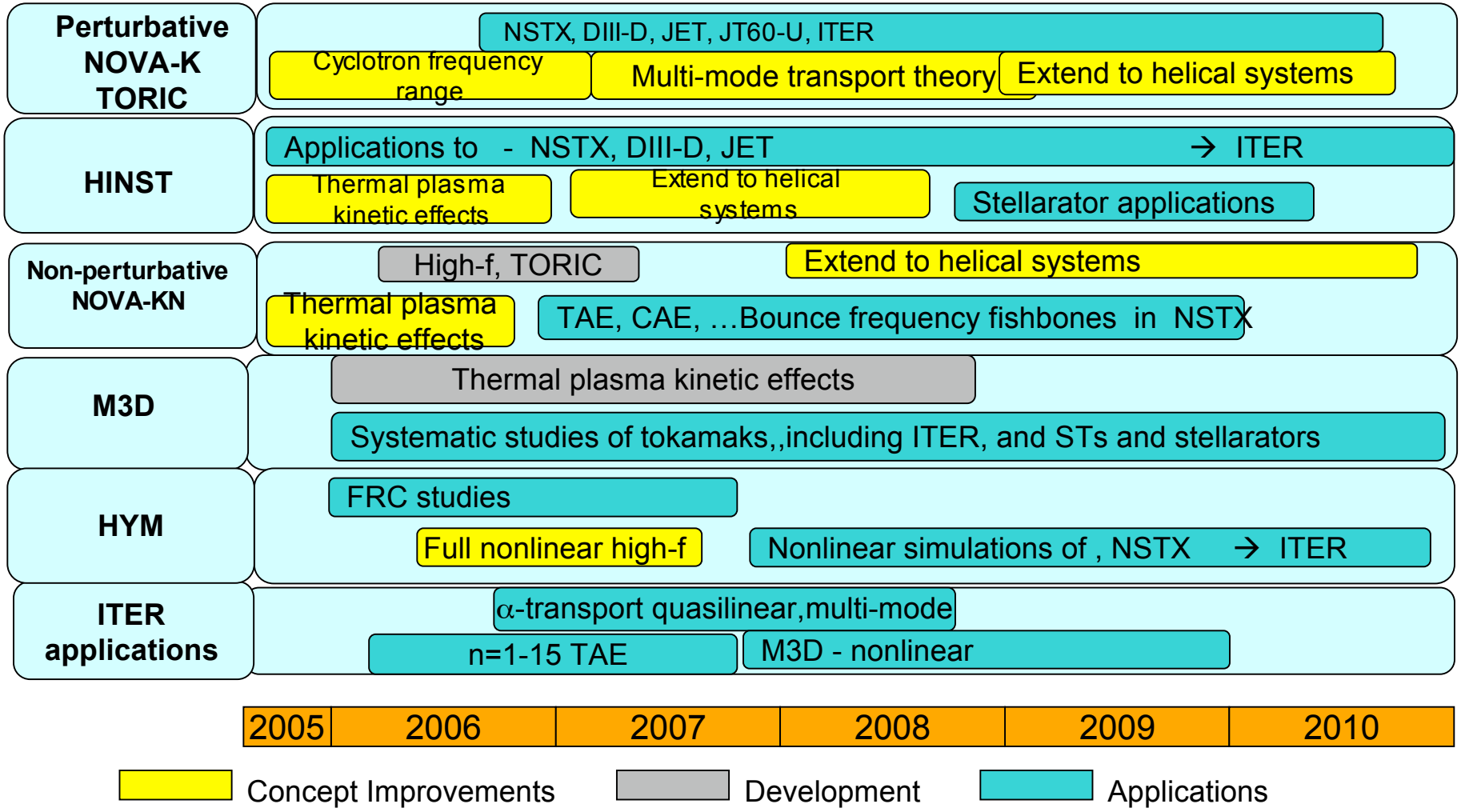
Nonlinear codes:

- M3D – initial value hybrid MHD-kinetic code
- NOVA-K – reduced theoretical model for wave saturation and fast ion transport

Single particle motion:

ORBIT code

A roadmap in the area of waves and energetic particles



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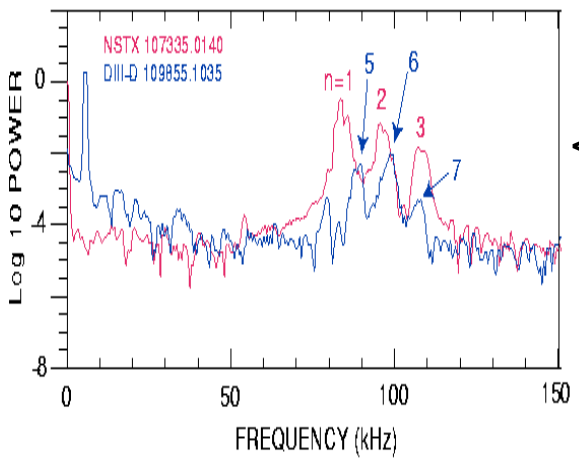
The linear stability of low frequency modes by NOVA-K code is well established

Linear stability calculations predict higher number of modes for larger machines.

Similarity experiments on NSTX and DIII-D of physics validation (Fredrickson, Heidbrink)



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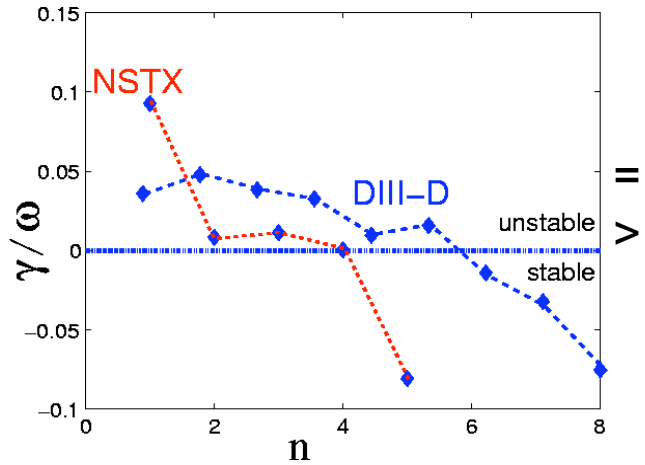
NOVA-K simulations of the most unstable mode for each n



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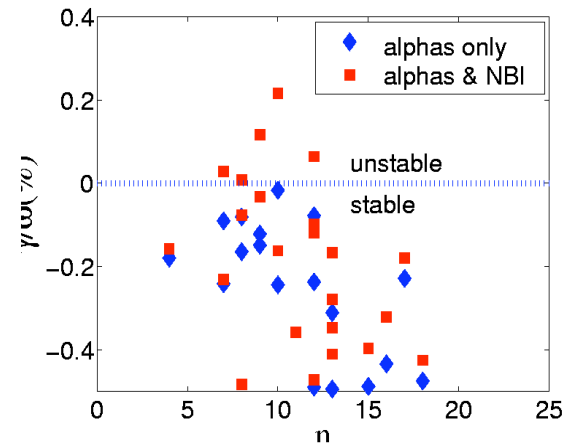
Predictions for ITER



NOVA-K has rich physics and extensively used in many applications.
Plans:
NOVA-K
ITER simulations through ITPA tasks (emphasis on continuum damping, FY06)
DOE milestone in linear TAE stability for FY07 (including NOVA-K, TRANSP, ORBIT)

HINST (non-perturbative) extension for stellarators (FY07-09)

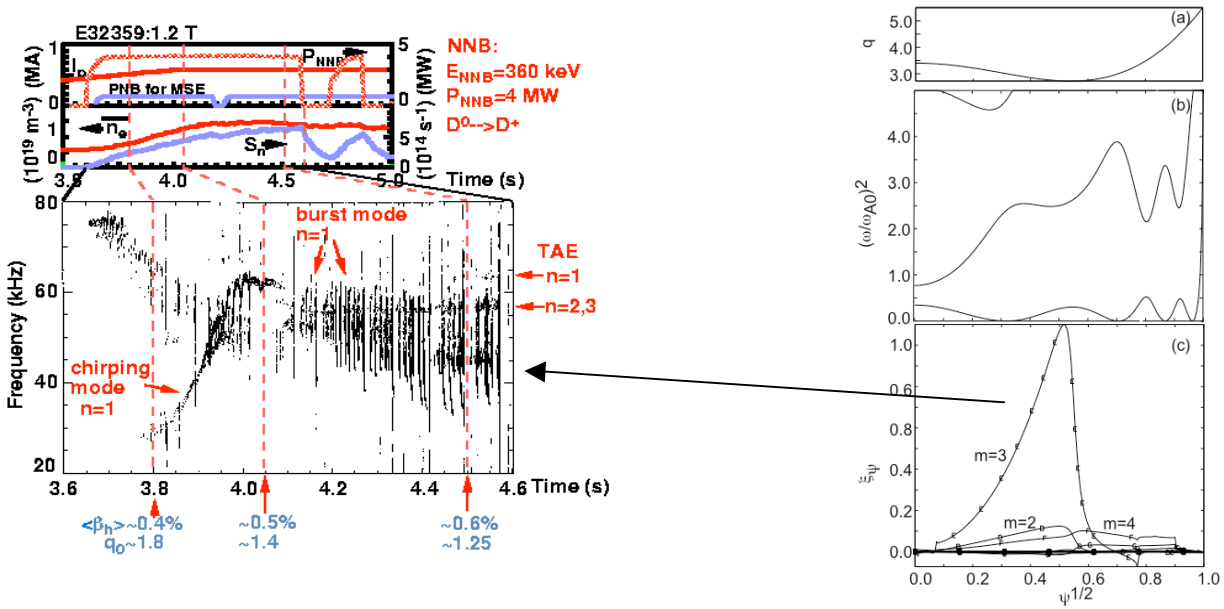
Collaboration plays an important role in theory and code development/validation

NOVA-K is widely used in many experiments around the world (see Nazikian talk)

Application of NOVA family of codes allows to validate its predictions:

JT60-U observed chirping frequency modes (Kusama, Shinohara)

recent NOVA-K analysis identified it as RSAE/cascade



Application of NOVA will be continued.
New collaborations have started with C-Mod (J.Snipes).
Plan to use NOVA-K to check the continuum damping model (FY06-07, see ITER task)

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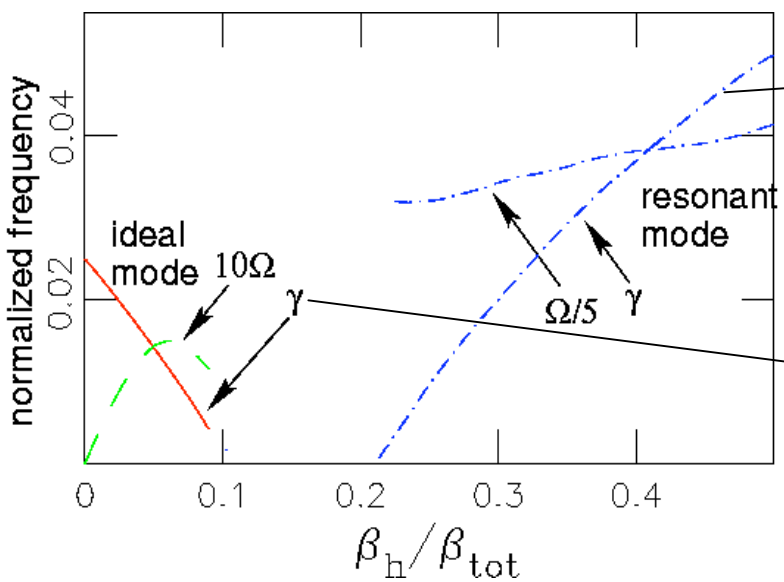
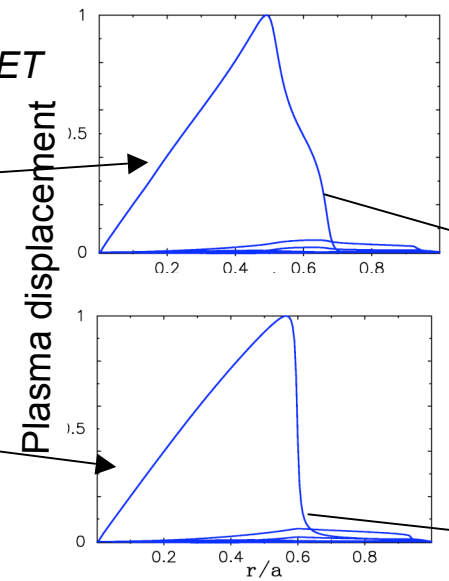
Extending the linear model for nonperturbative studies with NOVA-KN

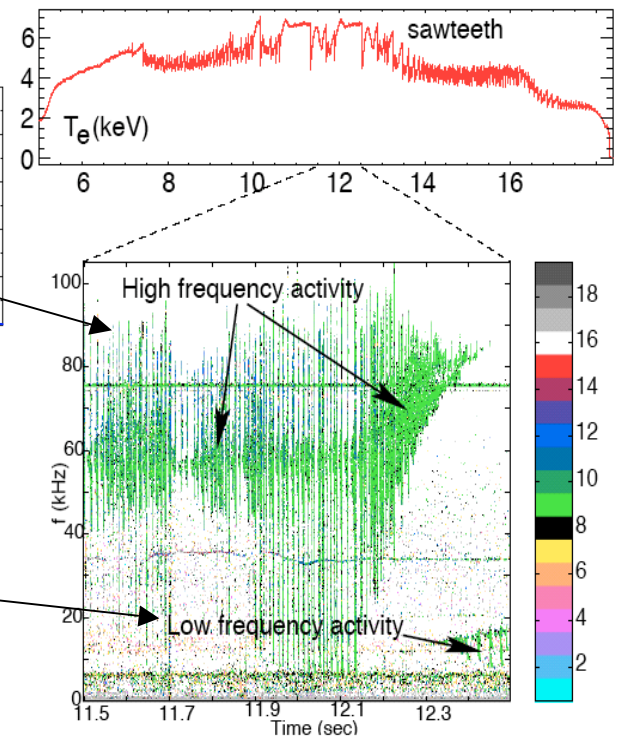
Local HINST indicates importance of non-perturbative modelling: new resonant TAE, other EPM modes emerge when fast ion beta is comparable to the plasma beta.
Global NOVA-KN addresses these modes:

- Fast ions are treated non-perturbatively.
- Capable of studying fishbones, sawteeth stabilization.

NOVA-KN simulates two fishbone branches in JET





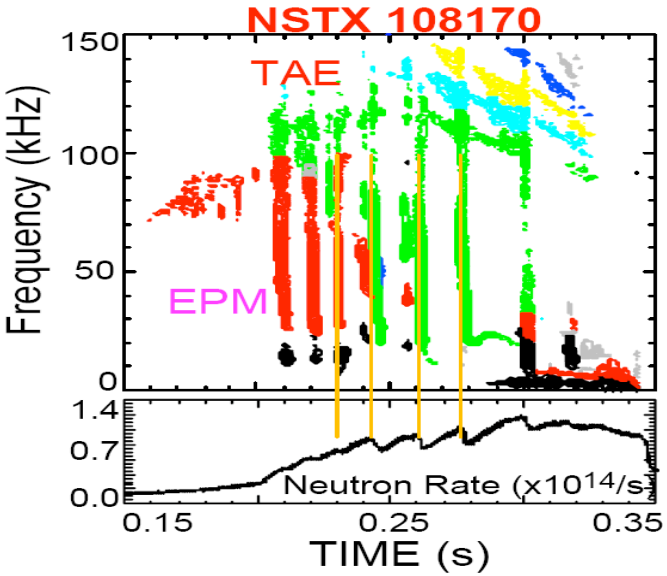


Plans:

Include kinetic effects, FLR, dampings (FY07-10),
model NSTX, JET fishbones and sawteeth (FY06)
model TAEs in ITER (FY08-09)

Multiple mode instabilities in present machines are of relevance to ITER

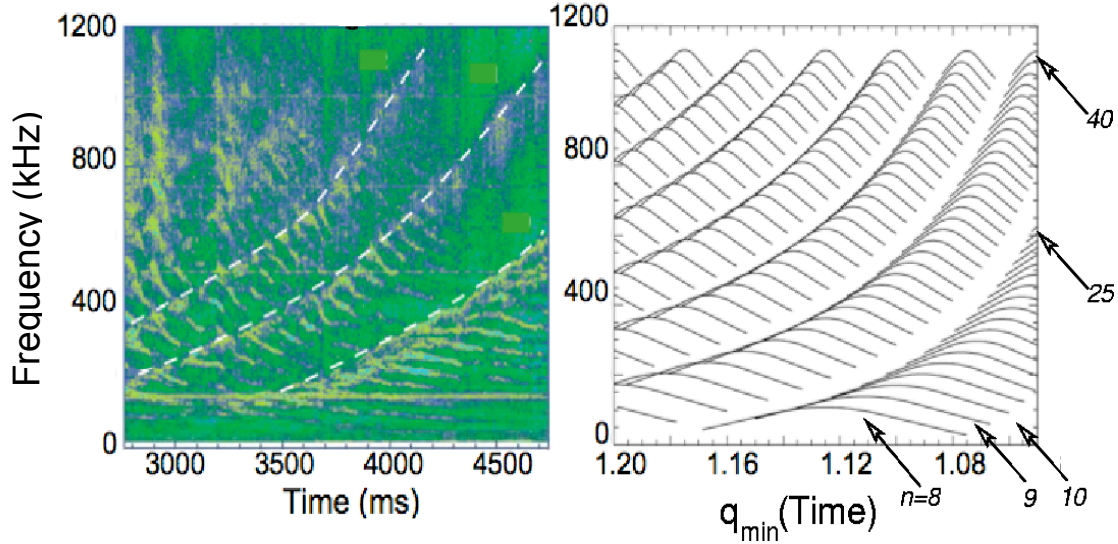
Simultaneous bursting EPMs and TAEs correlate w/largest fast ion loss in NSTX (Fredrickson)



"Sea" of Alfven modes in DIII-D experiments.

Thermal ions determine the instability condition η_i-drive, ITG like RSAE instability in negative shear plasma.

(Nazikian, Kramer)

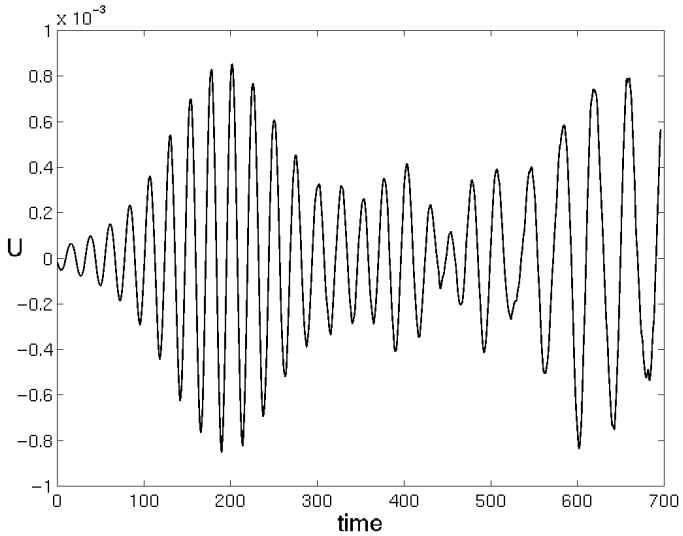


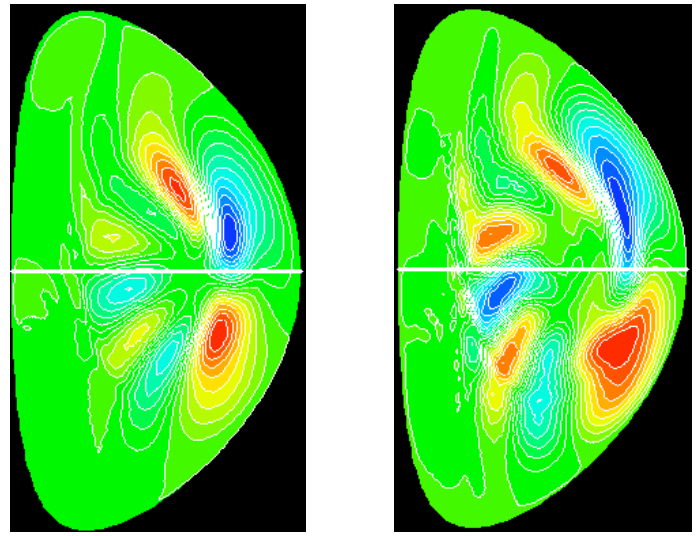
Multiple large-amplitude TAE modes are expected to show wave-particle resonance overlap similar to that expected in ITER.

Multiple instabilities driven fast ion transport has to be addressed by both theory and nonlinear codes such as M3D.

M3D nonlinear hybrid simulations of low frequency modes enable the study of particle confinement

M3D simulations of beam-driven modes in NSTX shows a bursting n=2 TAE as the mode moves out radially => radial fast ion transport (G.Y.Fu):





t=0.0 t=336

Great challenge for the nonlinear physics is multimode excitation (ITER-like).

M3D extension of damping physics (FY06-07),

application to ITER (FY06-09)

modeling of multiple mode instabilities (FY08-10)

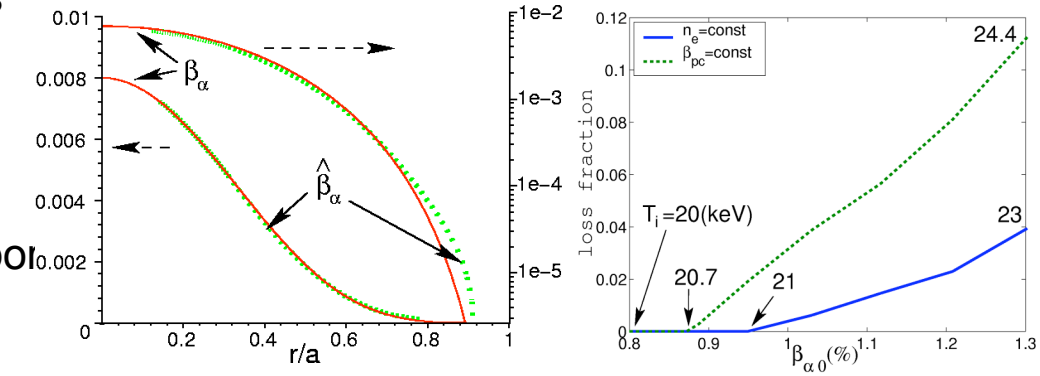
We will apply M3D code for sawtooth, fishbones modeling in NSTX, JET, DIII-D, JT-60U.

Reduced models for fast ion transport in the presence of multiple instabilities

Quasilinear simplified model for multiple instabilities - driven transport (collaboration with IFS, H.Berk within ITPA task):

Based on assumption of multiple TAEs
Based on local transport model
Predicts alphas profiles
Predicts transport beyond initially unstable region
Easy to be incorporated into the transport codes to see the effect on burning.

Predicted alpha profiles and alpha losses for different thermal ion temperatures



Shortcomings:
Does not include realistic global mode structure
Assumes infinite number of localized modes.

Plans:
Develop quasilinear fast ion transport model to be coupled with NOVA-K linear calculations
(FY06-FY09, single TAE saturation is already in place)
Apply to existing experiments on NSTX, DIII-D (FY08-09)

Theory in collaboration with NSTX has identified new high frequency modes: GAEs and CAEs due to low Alfven velocity

CAEs:

Discovered in NSTX

Understood within PPPL theory of ICE

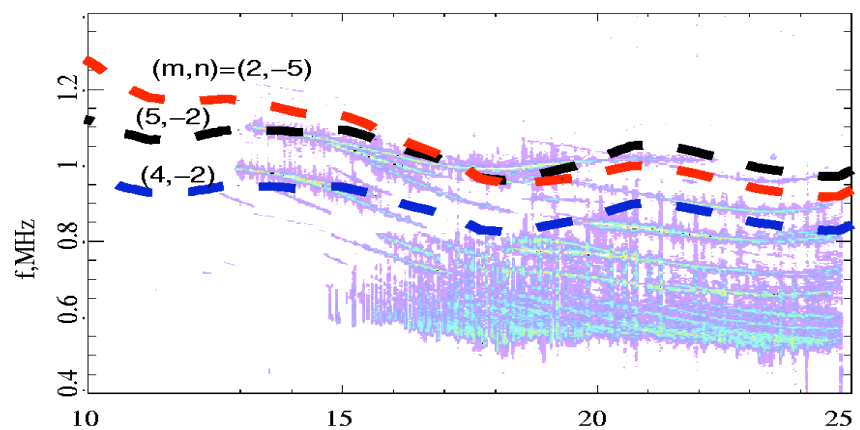
GAEs:

Predicted by HYM code

Found in NSTX plasma

Polarization and dispersion agree with predictions.

GAEs spectra follows Alfven dispersion $\omega = v_A(m-nq)/qR$



Time(msec) as q is evolving

Goal is to have full nonlinear modelling to predict the effect on thermal ions.

Linear wave particle interaction physics (CAEs) is to be addressed with wave codes

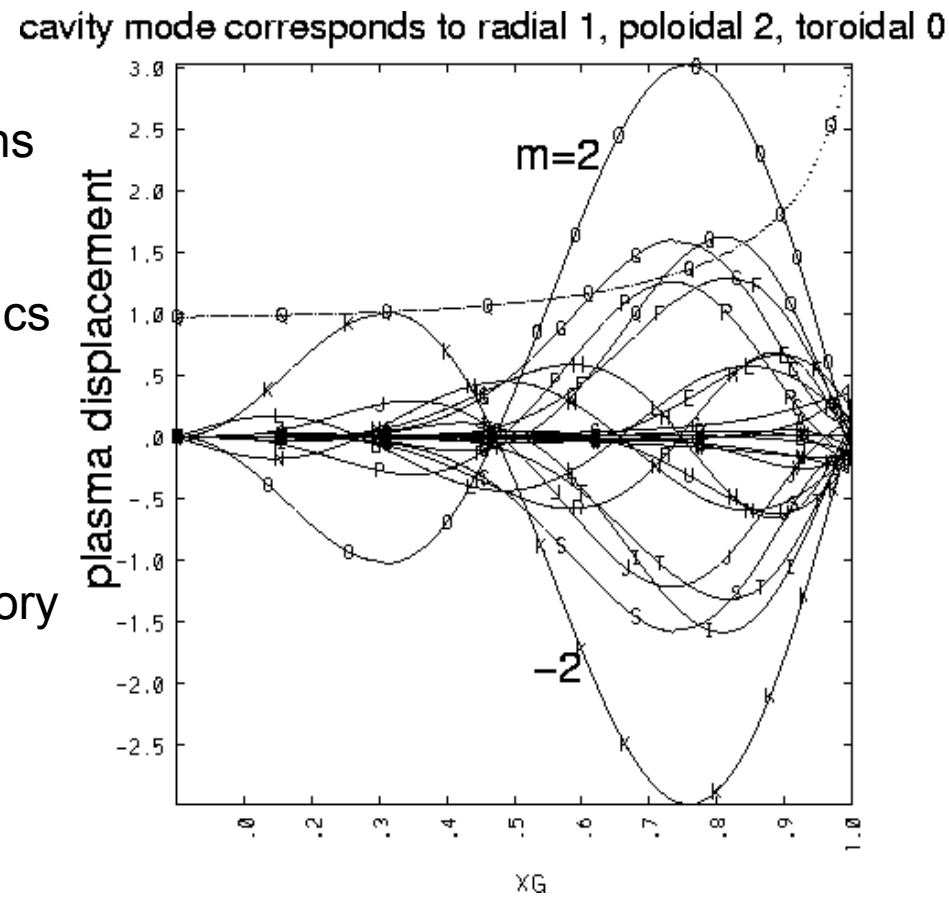
Outstanding physics issues:
FLR, finite ω/ω_c effects, cyclotron resonances, full toroidal geometry, self-consistent fast ion velocity distributions

Approach:
Utilize full wave RF codes to study dynamics of driven modes in the linear regime
>> <u>part of RF SciDAC project</u>

Short term goal (FY06-07):
Recover MHD results from NOVA and theory predictions for CAE/ICE instabilities

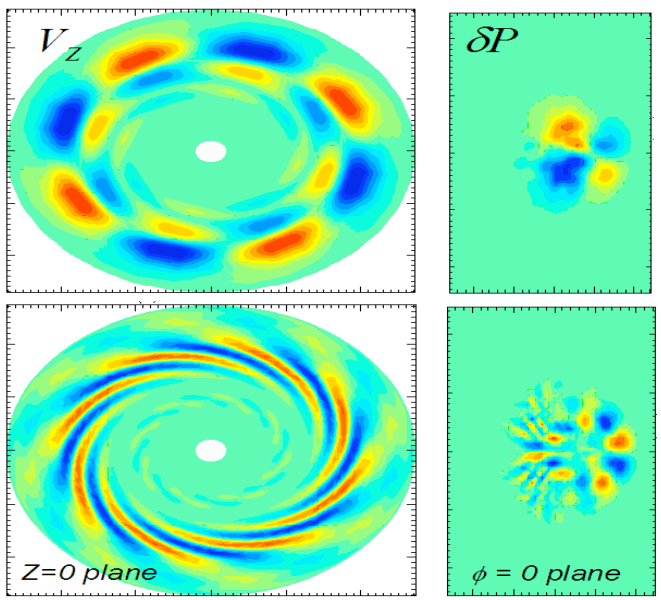
Long term goal (FY07-08):
Simulate CAEs/ICE in STs, ITER
Compare with HYM, NOVA-K

NOVA computes CAEs



CAE modelling enables study of fast ions confinement and plasma heating

HYM - initial value hybrid code is designed to study high frequency modes with anisotropic equilibrium, and distr. function (synergy with FRC study, see Belova talk)



GAE mode

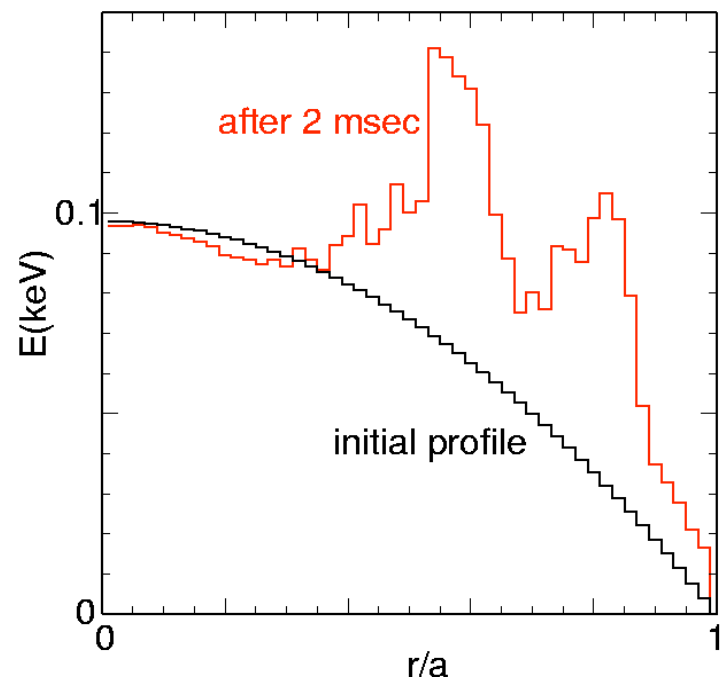
CAE mode

HYM predicted GAEs subsequently observed in NSTX.

Good agreement with theory.

Will have nonlinear CAE/GAE study (FY07) and multi-mode excitation and interactions (FY08-09).

If CAE are large enough:
thermal ions can be heated stochastically
=> alpha/energy channelling?
(Gates, Gorelenkov, White, PRL '01)



ORBIT particle code has been used

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Single particle models are an efficient way to gain insight into wave-particle interactions

ORBIT is guiding center following code (R.B.White)
ORBIT-XY is full orbit following code

ORBIT was extensively used to model ripple effects, interaction with TAEs,
sawteeth, fishbones,
and CAE stochastic thermal ion heating.
ORBIT has been extended for stellarators using PIES equilibrium.

Plans, applications:
For NSTX: fishbone dispersion simulation (FY06-07)
For ITER: on multiple mode effects on fast ions –this will benchmark
quasilinear theory using NOVA TAE structures (FY07)
For TAE: – ripple induced transport in ITER (part of ITPA task, FY06-07)

Wave particle physics plans organized to get predictive capability for burning plasma regimes

Linear, low frequency AE physics:

- NOVA-K further validation through application to existing machines
  application to ITER through ITPA tasks
- HINST (non-perturbative) extension and applications for stellarators
- NOVA-KN physics model extension and applications

Linear, high frequency AE physics:

- NOVA-K application for DIII-D and NSTX CAE/GAE experiments
- TORIC wave code application for comparison with NOVA-K and theory

Nonlinear modeling of wave-particle interaction

- M3D is main numerical tool to be extended and applied to existing experiments and to ITER burning plasma conditions.
- Developing reduced models for fast ion transport
  - Reduced model for multiple mode transport in collaboration with IFS, including the use of ORBIT and NOVA-K codes for verifying predictions.

Long term goal:

- Integrated modeling for BP/ITER to predict alpha particle profiles.
- Theoretical approach has to be developed to address the integration based on both M3D and reduced transport models.