12th IAEA Technical Meeting
"Energetic Particles in Magnetic Confinement Systems"
September 07-10, 2011, Austin, TX

SUMMARY of
THEORY AND MODELING

Boris Breizman

Statistics:

35 presentations = 7(invited)+9(oral) +19(postersl)

Developments and Trends

- Equilibrium and classical transport of energetic ions (Hole, Kurki-Sounio, Kramer, Hamamatsu, Farengo)
- Runaway electrons (Riemann, Papp)
- Linear studies of Alfvénic and acoustic modes (Bass, Lang, Deng, Könies, Gorelenkov, Merle, Lepiavko)
- Nonlinear dynamics of isolated modes (Lilley, Nyqvist, Lesur, Wang, Pinches, Chen, Fu, Lin, Zhang, Zarzoso)
- Anomalous transport due to instabilities (Todo, Yakovenko, Kolesnichenko, Ghantous, Albergante, Schneller, Breizman)
- Progress in code development (Spong, Könies, Vlad, Wong)
- Interpretation of experimental mysteries
- Predictive theoretical work

Highlights of Presentations

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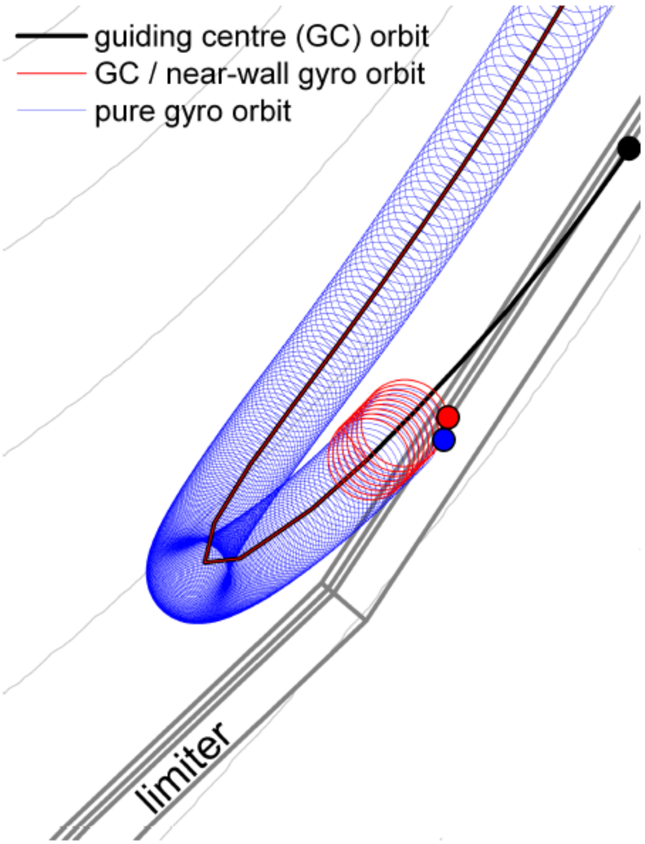
The authors have computed the level of anisotropy from a TRANSP simulation of a neutral beam heated MAST discharge. This showed a large level of anisotropy, with $p_{\perp} / p_{||} \sim 1.7$, sufficient to boost the central safety factor by 15%, well in excess of the change induced by toroidal rotation.

T. Kurki-Suonio *“Orbit-following fusion alpha wall load simulations for ITER including full orbit effects”*

ASCOT simulations



- Test particle following MC code
- Integrates particle's EoM
- MC collision operators affecting particle $\xi = v_{\parallel}/v$ and E
- 3D wall and ***B***-field structures ⇒ ideal tool for modelling fast ion wall loads
- 200000 test particles followed until they hit the wall or cool down $2T_i$
- FO collision model used: close to material surface follow the particles’ full orbits

G. J. Kramer *“Full orbit simulations of fast ion losses in DIII-D and NSTX”*

R. Farengo *“Simulation of alpha particles current drive and heating in small aspect ratio tokamaks”*

K. Hamamatsu *“Fokker-Planck simulation for radial transport of high energy ions”*

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Summary

- 2D model for energy conversion under disruption presented
- earlier qualitative results by other authors confirmed
- substantial conversion of magnetic energy during disruptions
- final RE energies of up to $\sim 100\,\mathrm{MJ}$ possible
- two qualitatively different phases of plasma motion found
- energy mainly consumed by friction in free-motion phase
- strong energy gain by REs during scrape-off phase

RE suppression/control/mitigation is a key topic for ITER!

(submitted to *Physics of Plasmas*)

Conclusions

- Identified a possible RMP configuration for runaway suppression in ITER
  - ➡ RMP enhances the edge (ψ>0.5) particle transport that significantly increases particle losses
  - ➡ Particles get lost while still at low energies
- Can be applied along with other mitigation methods (e.g. pellet or gas injection)
- Fast losses reduce the seed population for avalanche ***but*** **might increase the electric field**
- **Self-consistent calculation of the runaway dynamics is feasible with the ARENA+ code in the near future**

G. Papp ***et al,*** Nuclear Fusion **51** 043004, 2011.
G. Papp ***et al*****,** PPCF **53** 095004, 2011.

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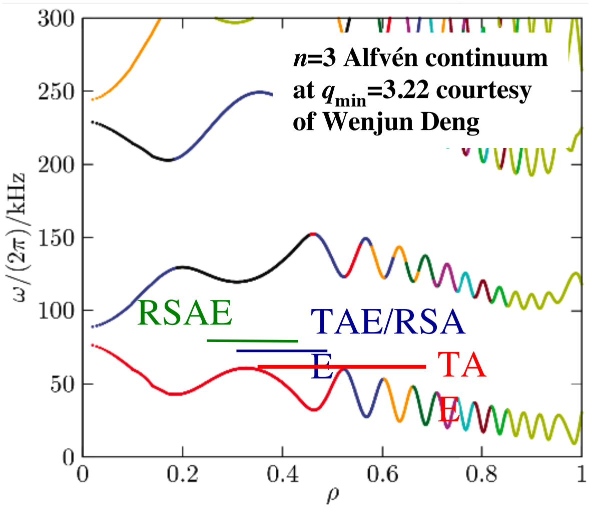
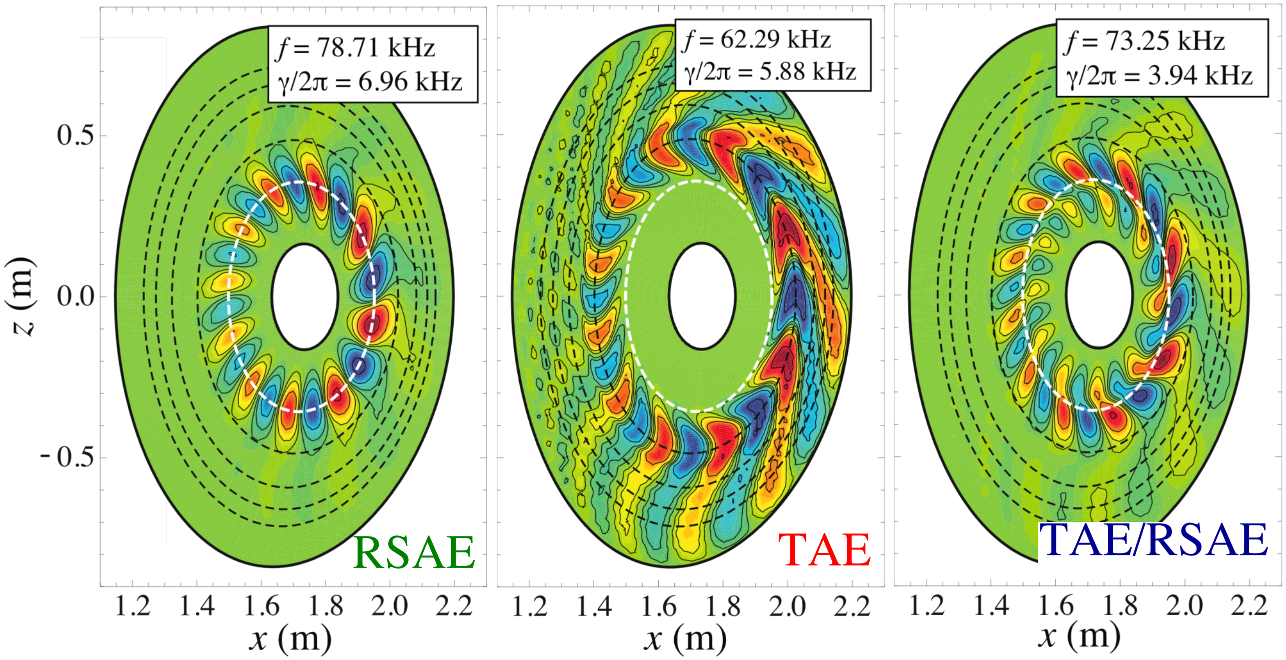
GYRO eigenvalue solver detects three principle unstable AEs.





The **RSAE** lies on the q_{min}=3.22 surface.

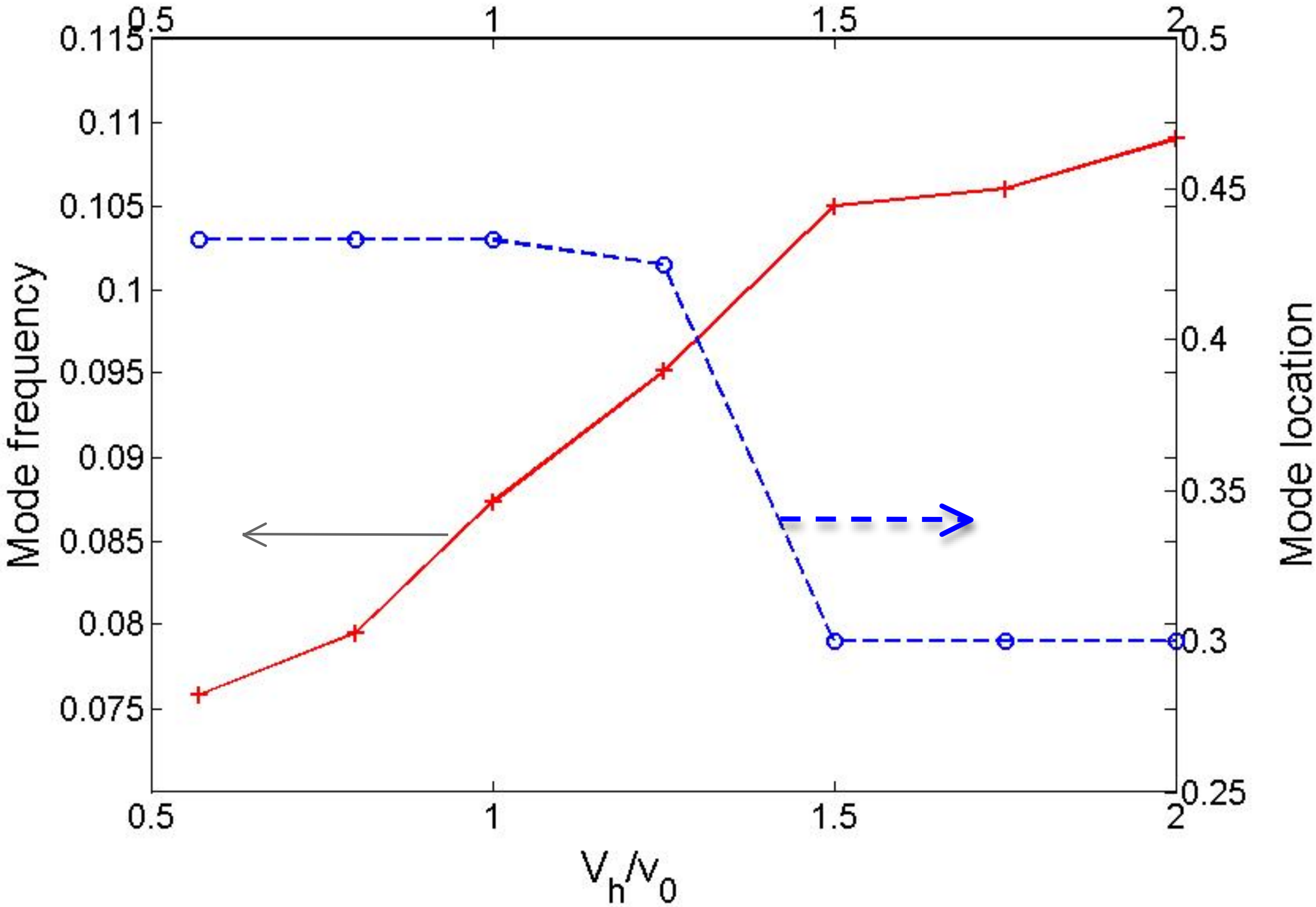
Electrostatic potential ϕ of three GYRO eigenfunctions.

The **TAE** peaks between singular surfaces near the interior, but often extends to the simulation boundary.

A hybrid **TAE-RSAE** manifests when mode frequencies come near each other.

All modes n=3 at q_{min}=3.22.

As beam speed increases, the destabilized mode jumps from EPM to RSAE (DIII-D shot # 142111)

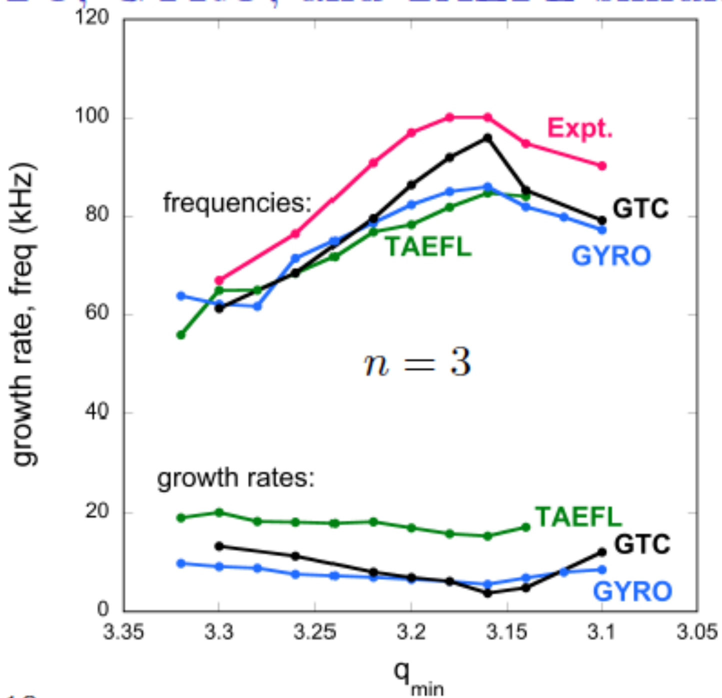


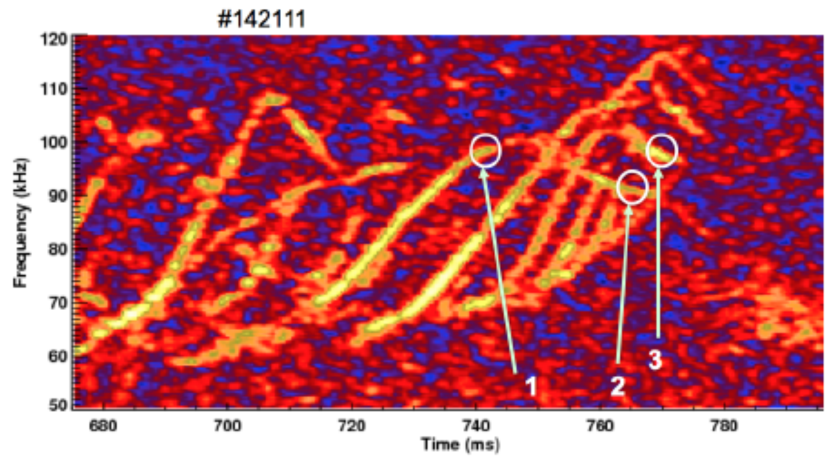
n=2

q_{min}=3.86

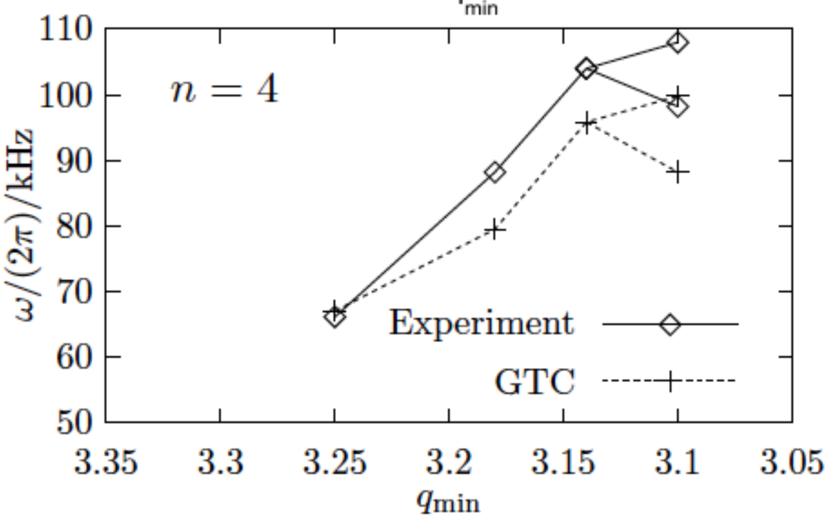
W. Deng *"Gyrokinetic particle simulations of reversed shear Alfvén eigenmode in nonuniform plasmas with equilibrium curent"*

GTC, GYRO, and TAEFL simulations recover RSAE/TAE in DIII-D





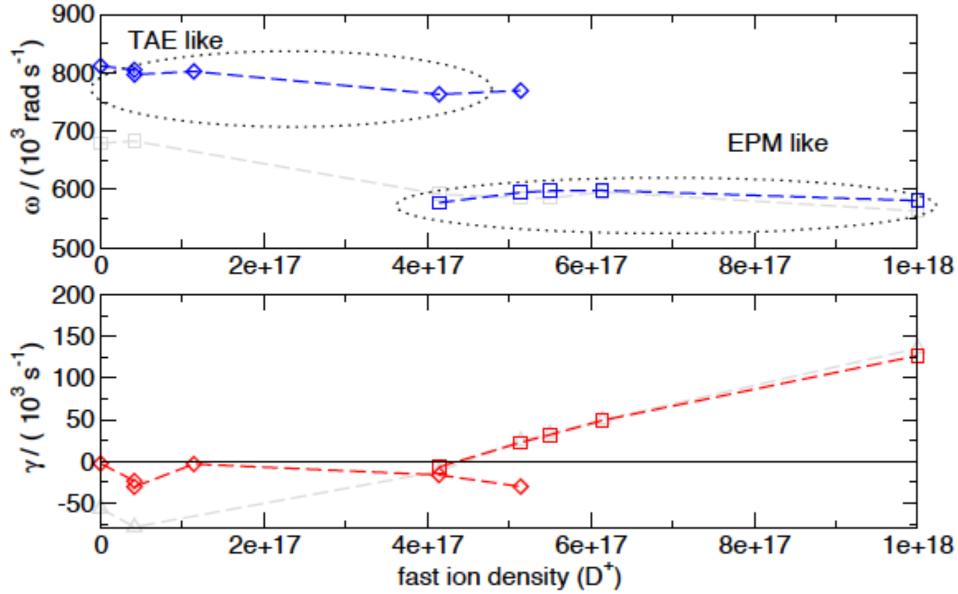
[Van Zeeland *et al.*, PoP 2011; Tobias *et al.*, PRL 2011]

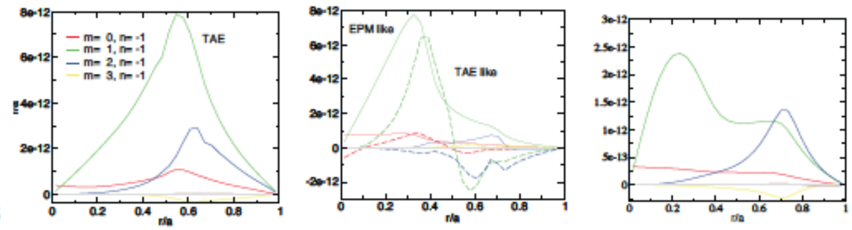


- RSAE/TAE in DIII-D #142111 are simulated by GTC, GYRO, and TAEFL.
- Good agreements in frequency, growth rate, and mode structure are obtained among the 3 codes.
- Simulation frequencies also agree well with experimental values in both up-sweeping RSAE region and RSAE to TAE transition region.

A. Könies *“Particle-in-cell simulations of low n energetic particle driven TAE in low aspect ratio tokamaks”*

GYGLES



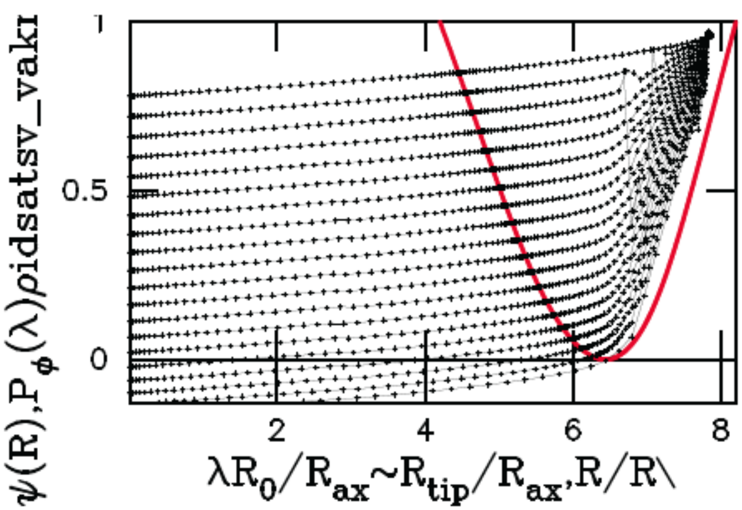


$n_f = 0\mathrm{m}^{-3}$ $\quad$ $n_f = 5 \cdot 10^{17}\mathrm{m}^{-3}$ $\quad$ $n_f = 1 \cdot 10^{18}\mathrm{m}^{-3}$

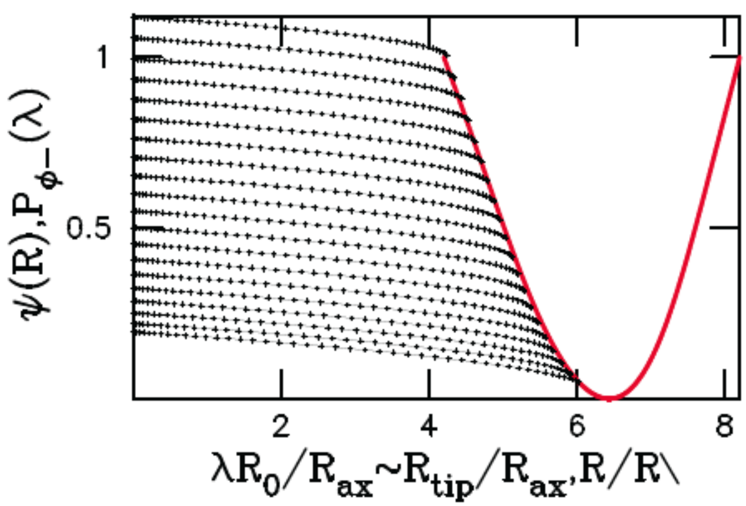
- simulation of TAE for small aspect ratio and low mode number
- simulation allows discrimination of TAE and other modes
- new mode diagnostics (SVD + extended frequency analysis) installed
- discrimination of sub-dominant modes possible

Computing conforming grids for ITER plasma

cogoing/trapped



countergoing



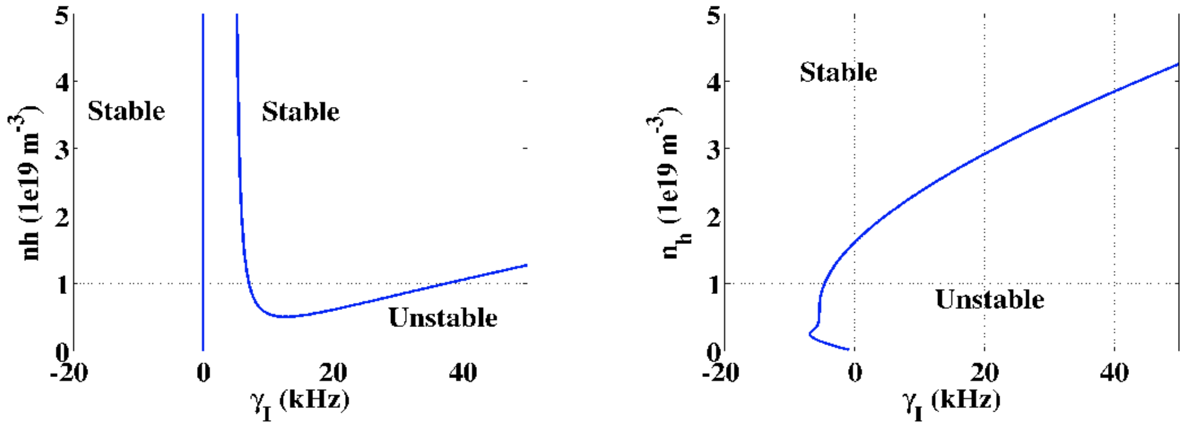
- Grid points are adjusted to the singularities in the transforming Jacobian (ω_b)
  - Non-uniform grid addresses singular point basing on the numerical results.
  - Approaches each boundary with given accuracy ($10^{-5}\psi_0$ in this case)

Linear stability of the electron fishbone mode

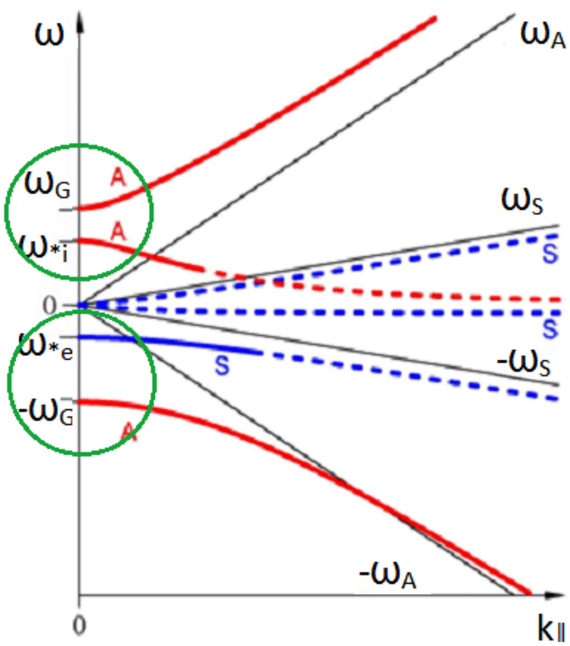
energie atomique • energies alternatives

Association Euratom-Cea

- MIKE, a solver for the fishbone dispersion relation now includes passing particle resonances.
- MIKE was used to study the mode stability with electron distributions modeling ECRH heated plasmas.
- Addition of passing particle resonances can strongly modify the stability of the mode



Stability diagram without (left) and with passing particles (right).



$$\omega_G = \frac{c_{ei}}{R}\sqrt{\frac{2}{\delta_0}\left(1+\frac{7}{4}\tau\right)}$$

- Coupled linear equations for drift-acoustic and drift-Alfvén modes derived for toroidal plasmas.
- These equations are applicable to tokamaks and stellarators.
- Preliminary analysis indicates that the modes observed in HSX can be identified as drift-acoustic modes.

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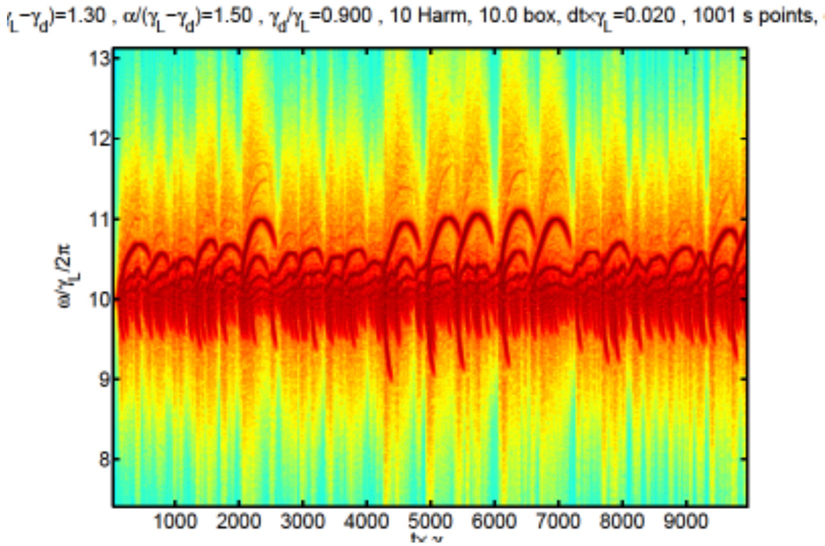
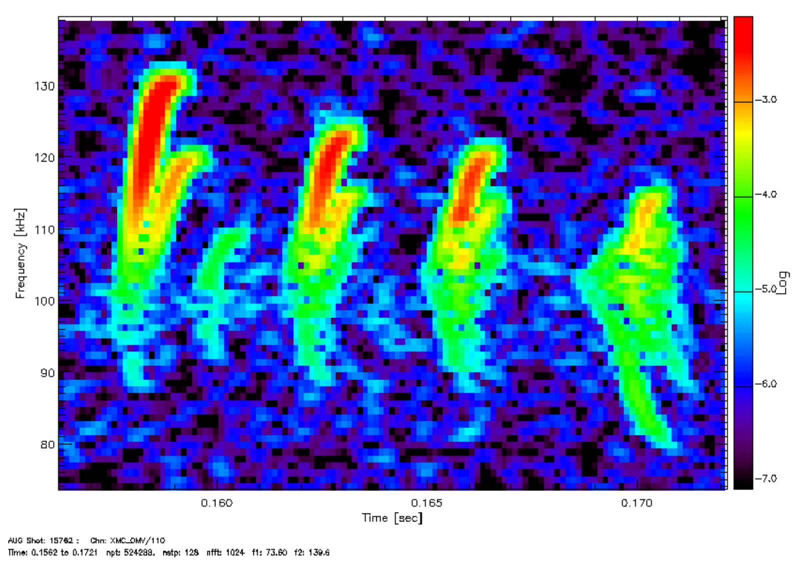
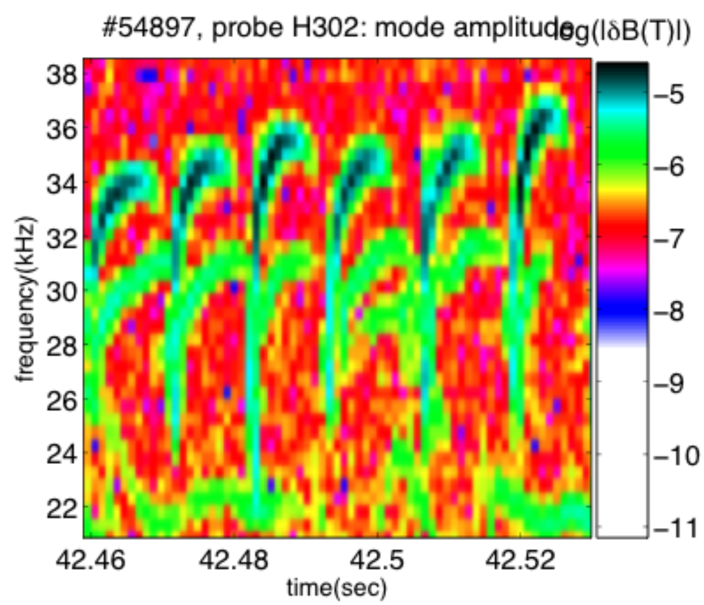
M. Lilley *"Nonlinear energetic particle modes: from bump-on-tail to tokamak plasmas"*



Hooked frequency chirp
seen in BOT simulations.

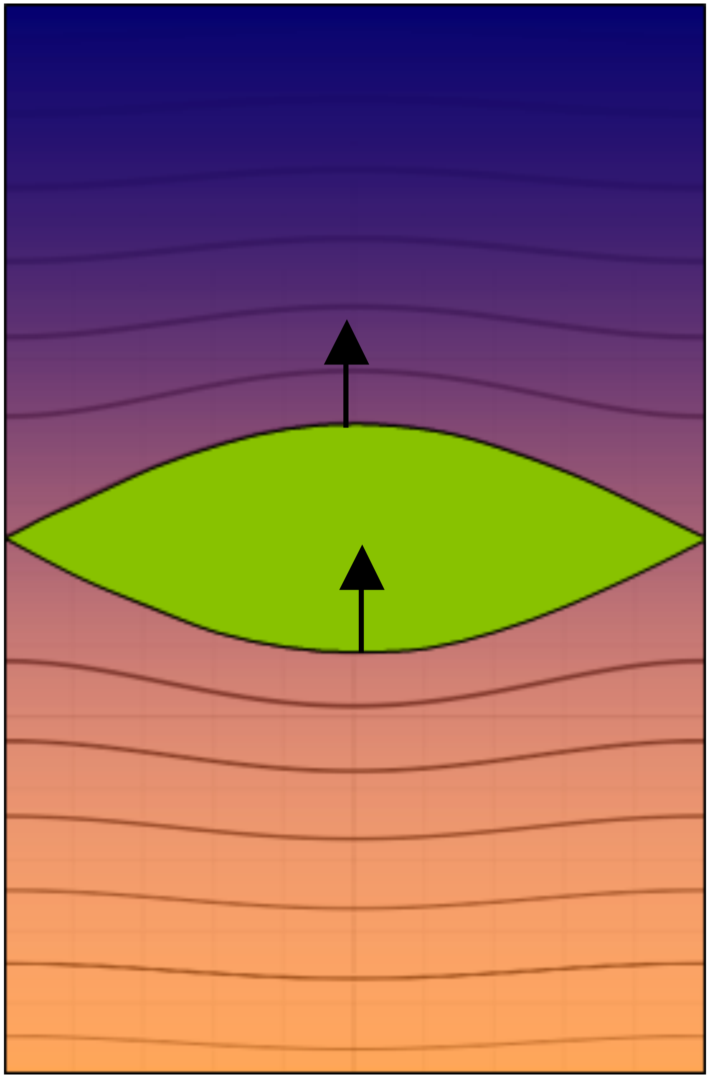
Also seen in MAST (NBI)
and JET (ICRH)





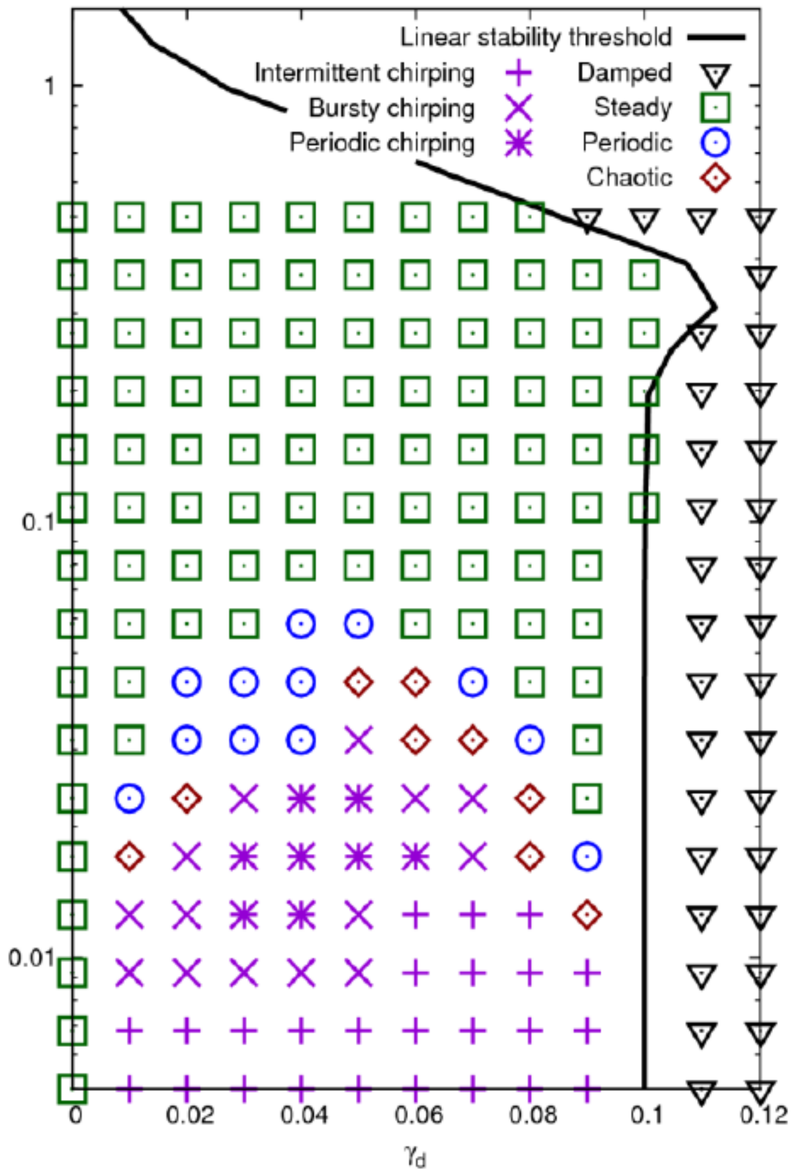
R. Nyqvist *"Adiabatic description of long range frequency sweeping"*

- ❑ New adiabatic code developed for long-range frequency sweeping
- ❑ Only trapped particles are essential in the simulations
- ❑ Adiabatic code accounts for:
  - Fast particle collisions
  - Fast particle trapping and detrapping
  - Nonlinear modification of the wave profile



Separatrix drift in phase space

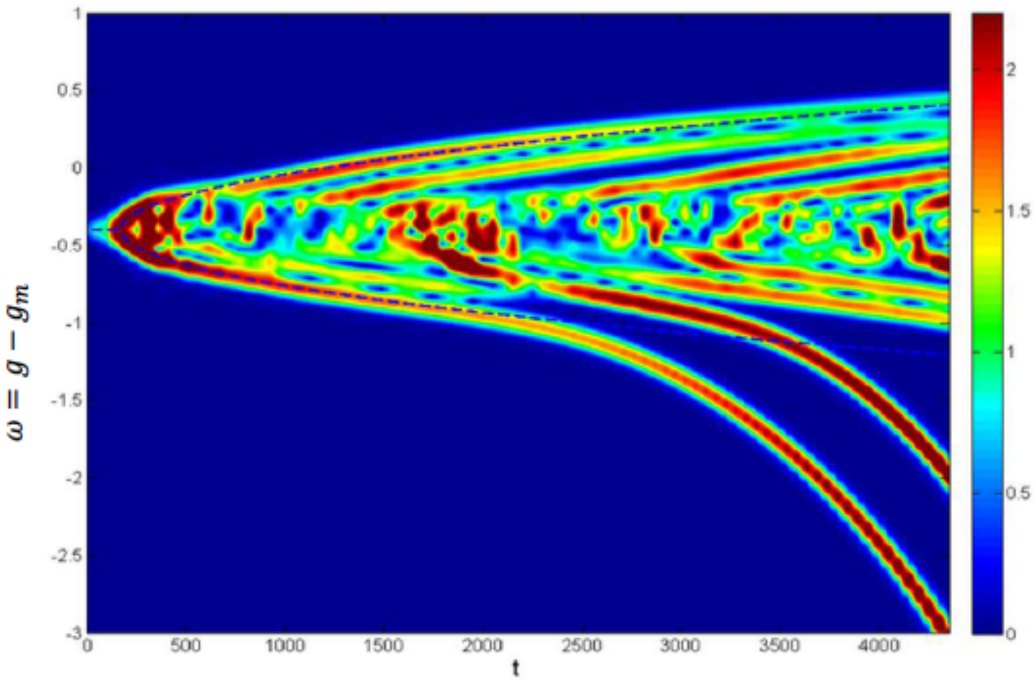
M. Lesur *"Effects of drag and diffusion on nonlinear behavior of energetic particle-driven instabilities"*



Nonlinear bifurcation diagram for a fixed ratio ν_d/ν_f =5, which is relevant for current large tokamaks. Each point represents a simulation.

G. Wang *"Model for spontaneous frequency chirping of an Alfvén wave in a toroidal plasma"*

Spectrogram of TAE signals

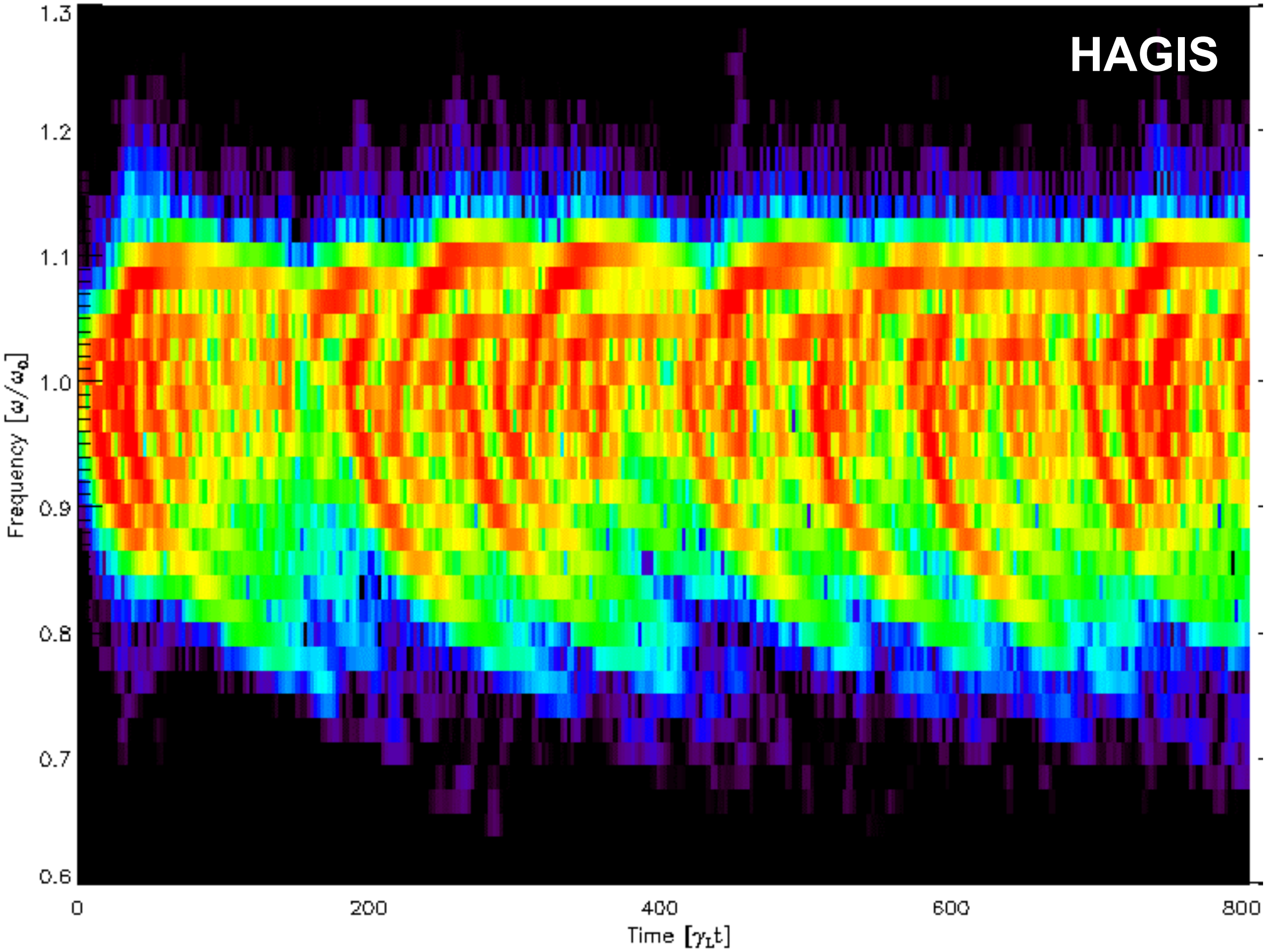


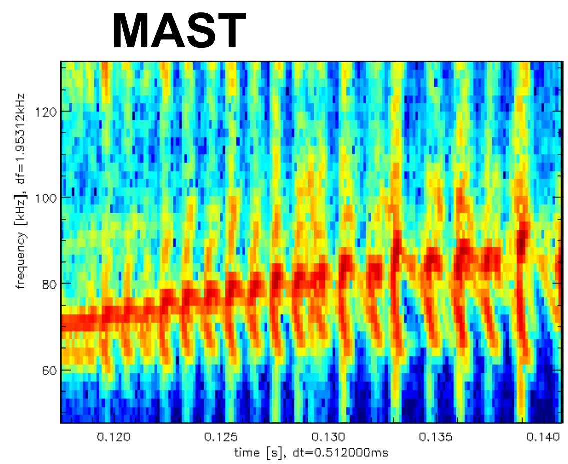
- The robust chirping branch separates from the linearly predicted frequency and approaches the gap-continuum boundary.
- The chirping clump penetrates and continues deep into the continuum.

S. D. Pinches *"Fast ion driven instabilities in MAST"*

Nonlinear Behaviour: Drag + Krook

$n_p = 262{,}500$, $\gamma_L/\omega_0 = 6.12\%$, $\gamma_d/\omega_0 = 6\%$, $\nu_{ei}/\omega_0 = 0.3\%$, $\nu_{eff}/\omega_0 = 1\%$

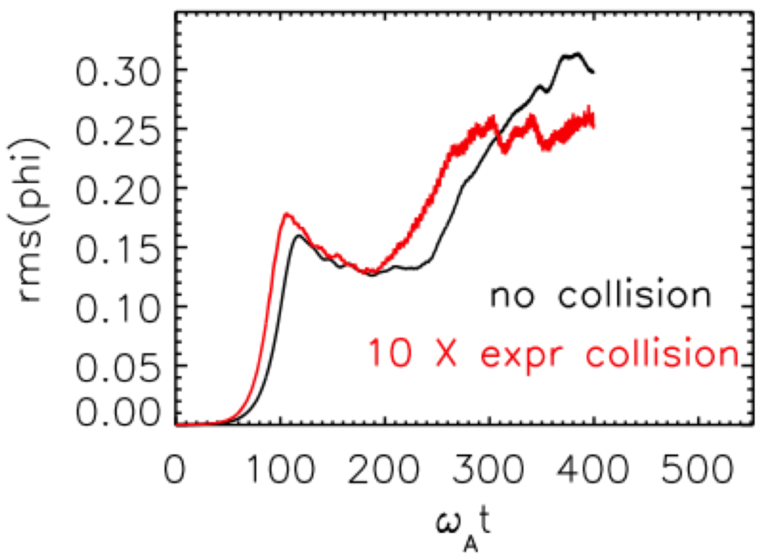




Frequency sweeping TAE in MAST #22807

Asymmetric, repetitive, frequency sweeps: $\delta\omega/\omega_0 \sim \pm 30\%$

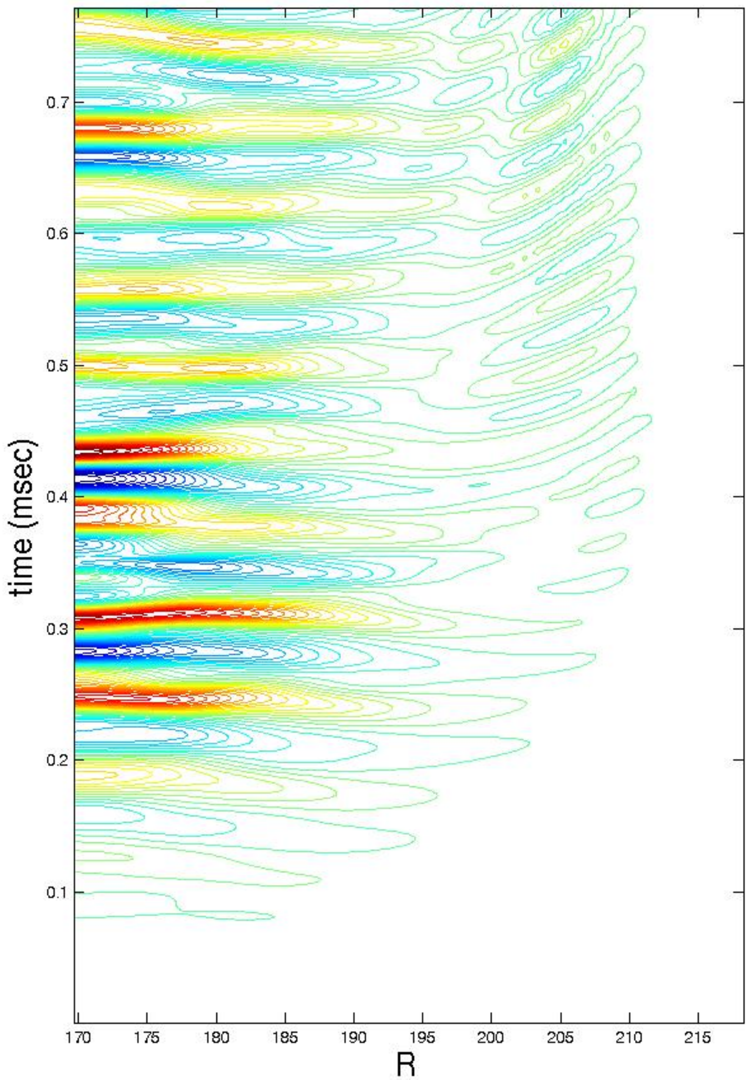
Use GEM to calculate RSAE saturation level



DIII-D #142111 t=725ms
qmin=3.32
$P_{beam}(0)$=7KPa
Only beam nonlinear

- Mode sustained for time >> $1/\gamma_d$
- At saturation (t=100), $\delta B_r/B \sim 4\times10^{-4}$ at r/a=0.4
- Collisions make little difference on the time scale of 1ms, suggesting the nonlinear state is not a BB steady state with $\nu_{eff} > \gamma_d$

Evolution of density fluctuation of EGAM in a DIII-D plasma



Nonlinear hybrid simulations with realistic beam distribution function yield mode frequency, mode amplitude and outward radial propagation consistent with experimental measurement of density fluctuation from BES.

Z. Lin *"Nonlinear gyrokinetic particle simulations of Alfvén eigenmodes and energetic particle transport"*

Nonlinear simulations show that the unstable BAE saturates due to nonlinear wave-particle interaction with both thermal and energetic particles. The saturated amplitude exhibits coherent oscillations. Wavelet analysis shows that the mode exhibits strong chirping associated with nonlinear evolution of coherent structures in the energetic particle phase space . Thermal particle nonlinearity plays a key role in controlling the saturation amplitude.

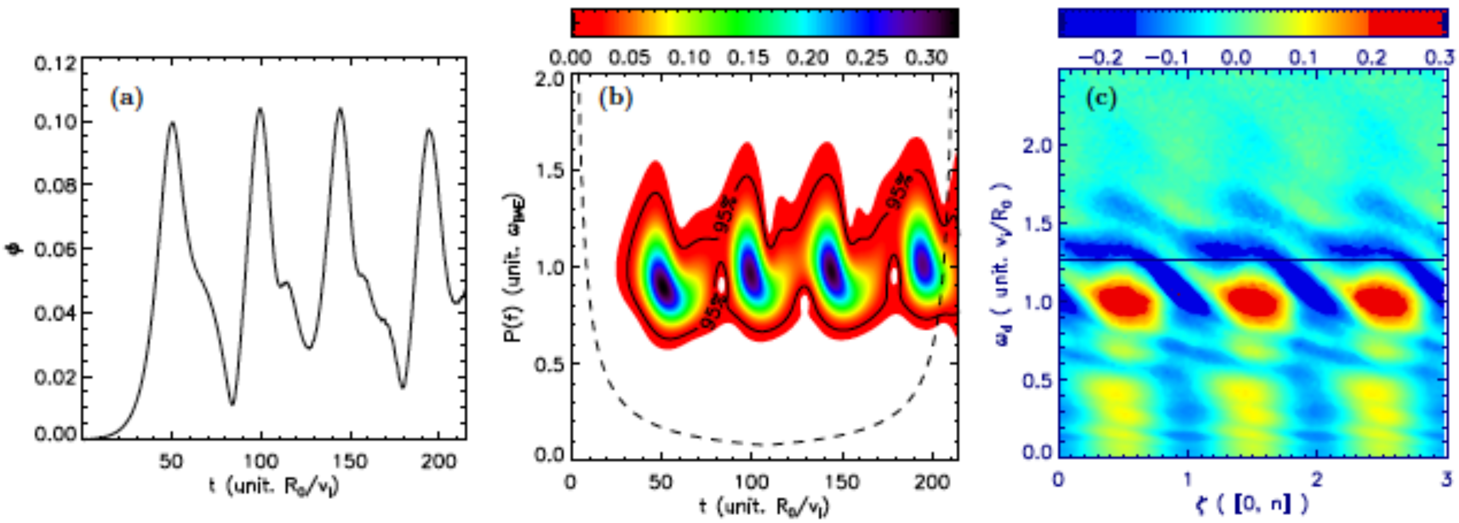
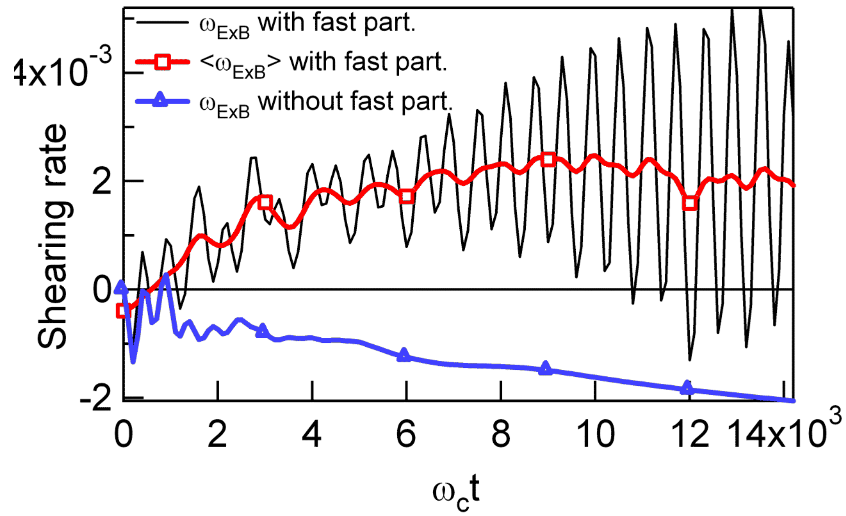


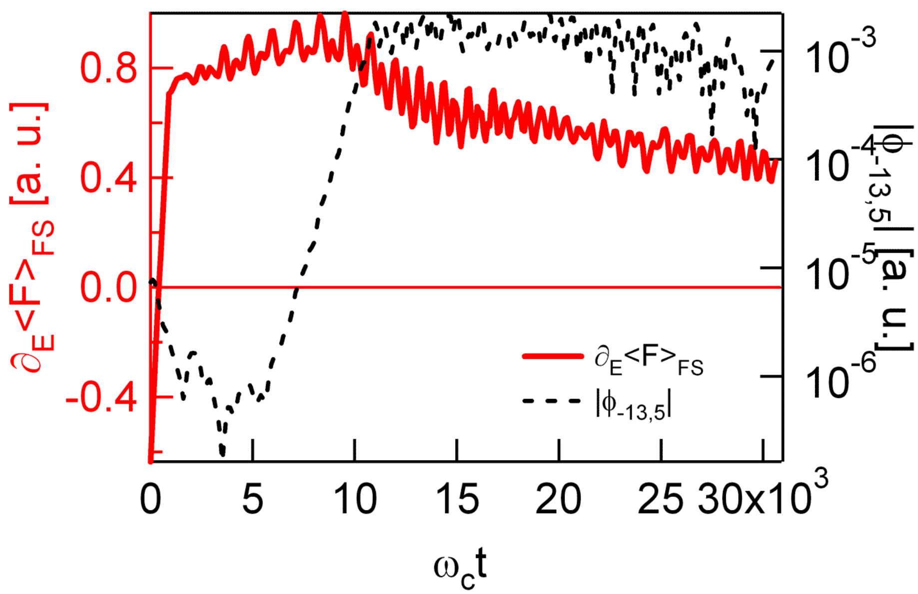
Fig. 1: Nonlinear gyrokinetic simulation of BAE. (a): Time evolution of the BAE amplitude; (b): Wavelet analysis showing frequency chirping; (c): Perturbed distribution function showing wave-particle coherent phase-space structures at $t = 71R_0/v_i$(toroidal precession frequency vs. toroidal angle).

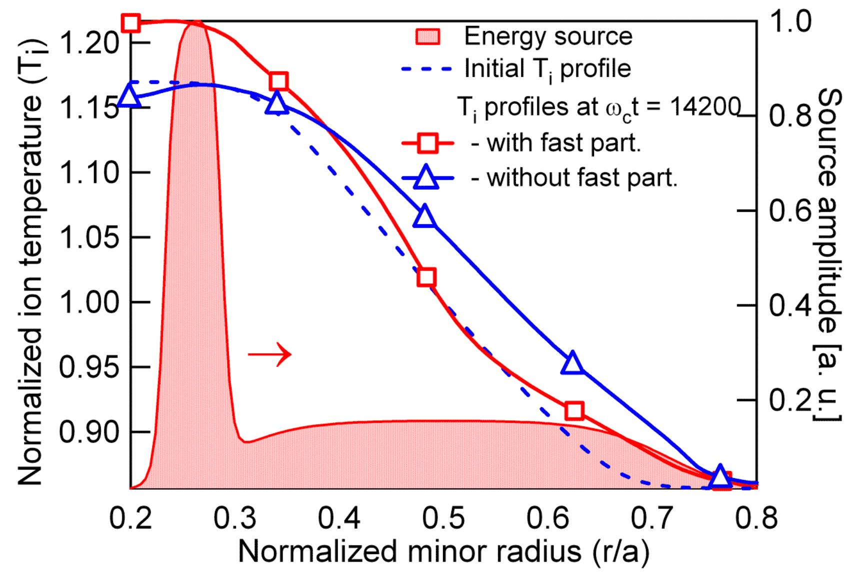
H. S. Zhang *"Nonlinear frequency chirping of beta-induced Alfvén eigenmode"*

Fast ions & turbulence in full-f global GYSELA-5D simulations

Fast ions $\Rightarrow$ **EGAMs** $\Rightarrow \uparrow \omega_{ExB} \Rightarrow \downarrow \chi_{neo} \Rightarrow \uparrow T_i \Rightarrow$ **ITG turbulence** $\Rightarrow$ EGAM saturation







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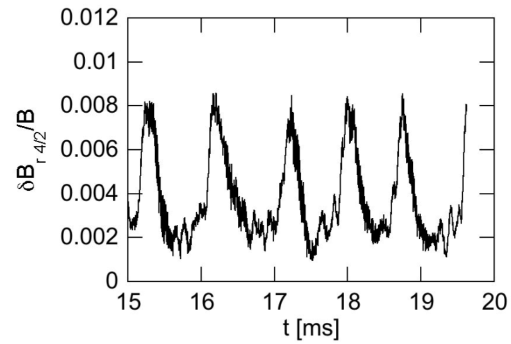
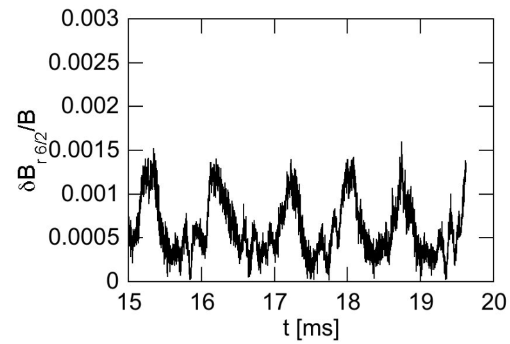
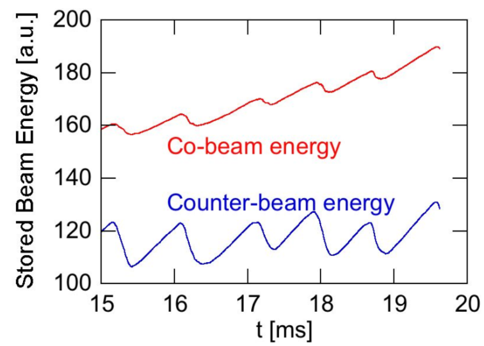
TAE bursts have been simulated with NL MHD effects and source+collision+loss

- Saturation amplitude of the dominant harmonic with significant beam ion loss: $\delta B/B \sim 5\text{-}8\times10^{-3}$ at the mode peak location and 10^{-3} at r/a=0.8 (comparable to the TFTR experiment)

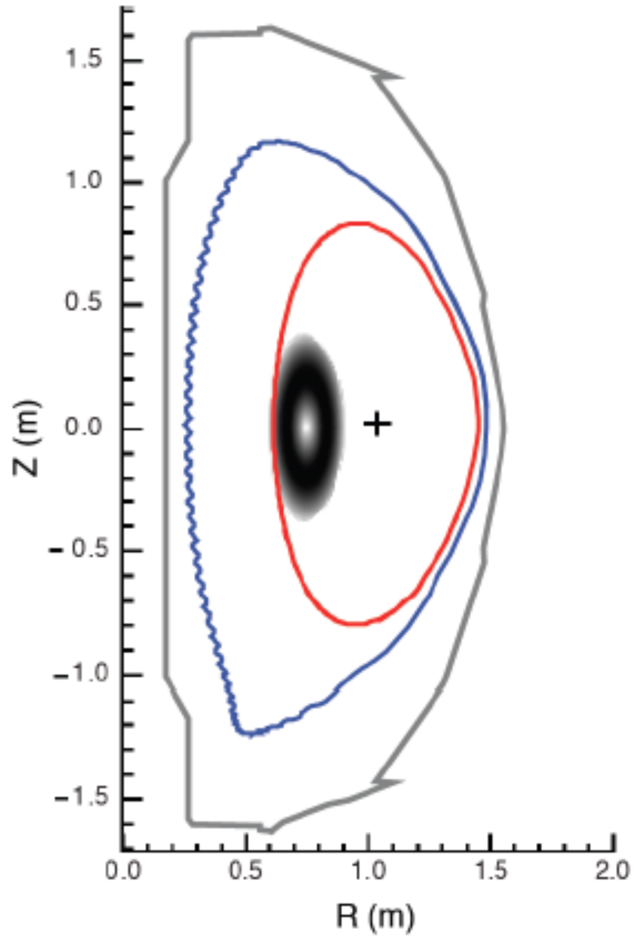
- Nonlinear MHD effects reduce saturation amplitude and beam ion losses







- An explosive instability of two Alfvén eigenmodes can arise due to Compton scattering of the modes on fast ions.
- The explosive instability of two modes is likely to include additional Alfvén modes in the course of its development.
- Preliminary estimates show that this explosive instability may be the mechanism of Alfvén avalanches in NSTX; however, numerical simulation is required to reach a final conclusion.



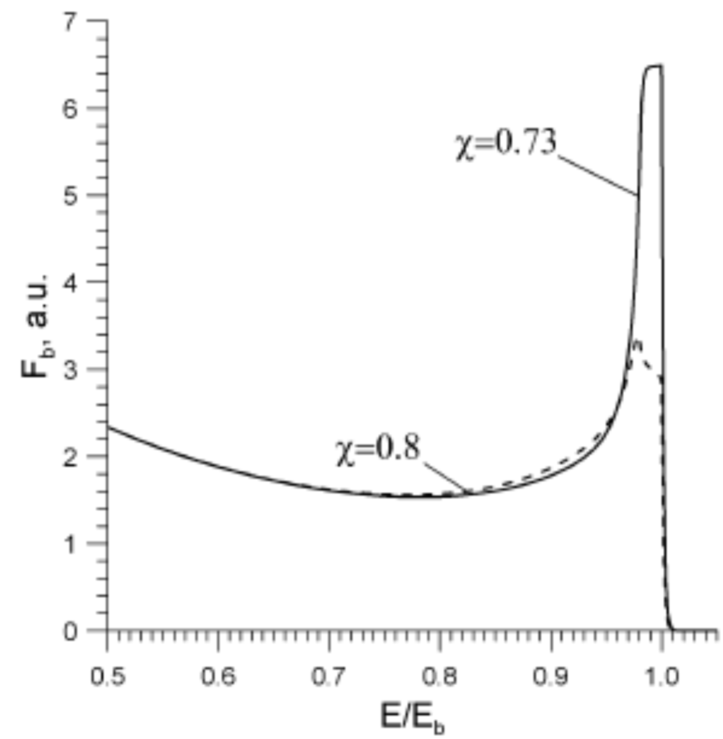
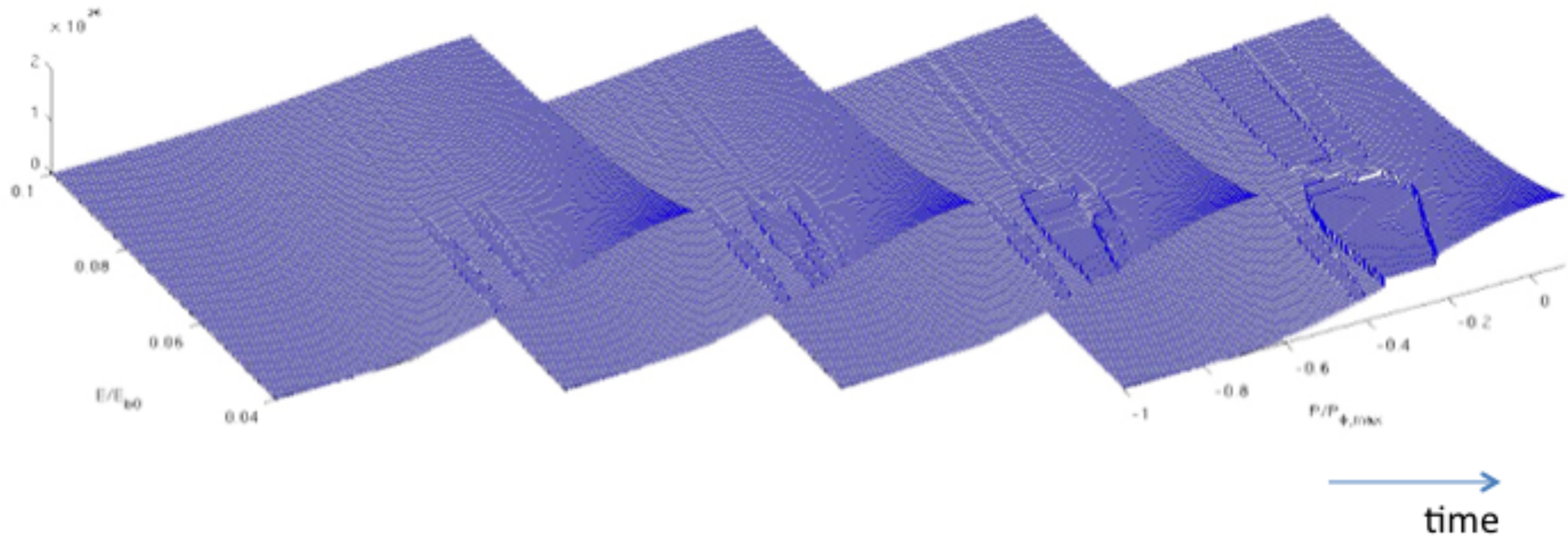


Fig. 1. A bump on the tail of $F_b(E,\chi,r)$ formed due to quasilinear relaxation caused by instabilities with frequencies 800 - 1000 kHz in NSTX.

The particles observed by NPA at $R = 78$ cm, $\vartheta = \pi$ and having Larmor radius $\rho \sim 10$ cm reach the limiter (*R=155 cm*), if they are displaced by $\Delta r \sim 10$ cm.

Line Broadened Quasi-linear Theory



The LBQL model predicts the analytic saturation levels for single modes,

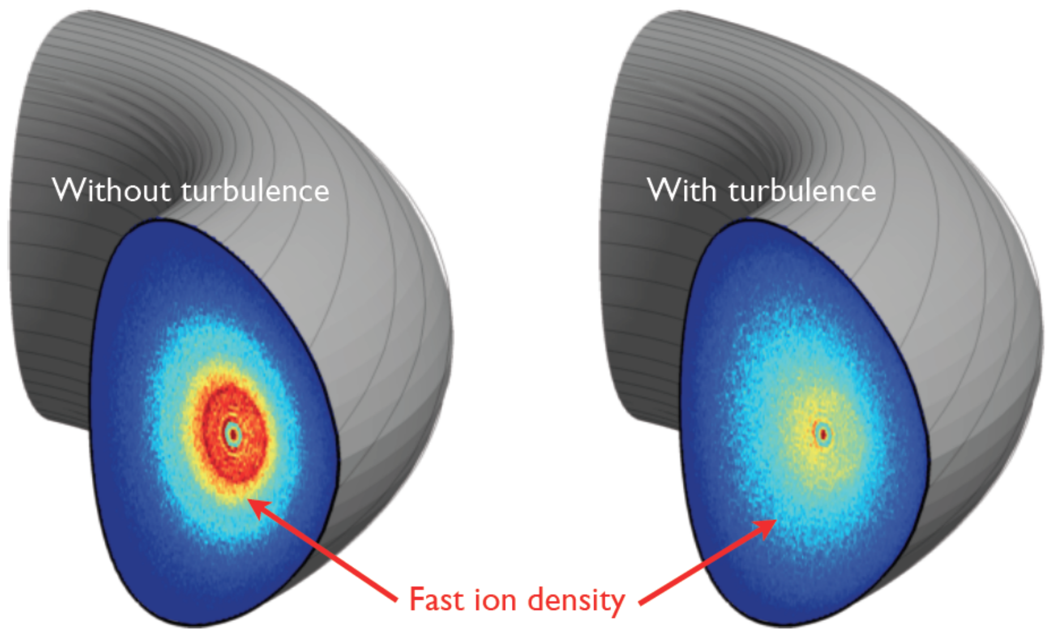
$$\frac{<\omega_b^4>}{<\omega_b^3>} = 3.2\gamma_L \qquad <>= \int \tau dE \frac{1}{|\partial\Omega/\partial P_\phi|^3}\frac{\partial f}{\partial P_\phi}$$

bridging the gap between single and multiple mode regimes allowing for a full description of the time-dependent TAE modes effect of an EP distribution in (E,Pf) phase space.

M. Albergante *"Anomalous fast ion redistribution in burning plasma experiments"*

This work presents a numerical platform to study interaction between energetic ions and micro-turbulence. A beam deposition module in a single particle code (VENUS) is coupled to a gyro-kinetic code (GENE). The energetic ion motion is calculated in the VENUS code with the inclusion of unperturbed drifts, collisions and anomalous radial transport.

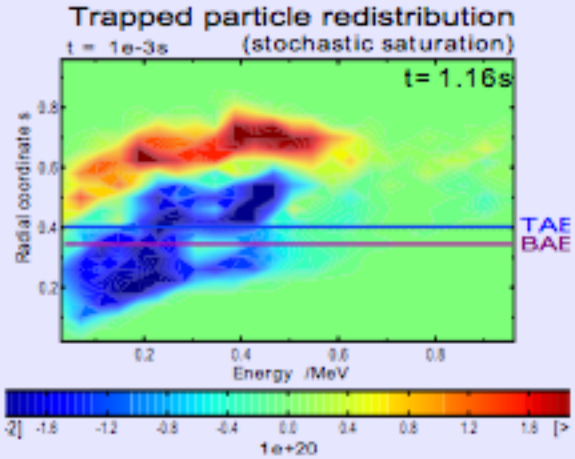
NBI redistribution in DEMO

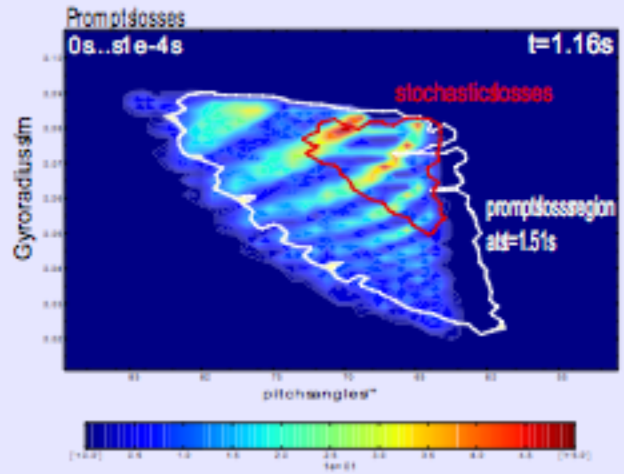


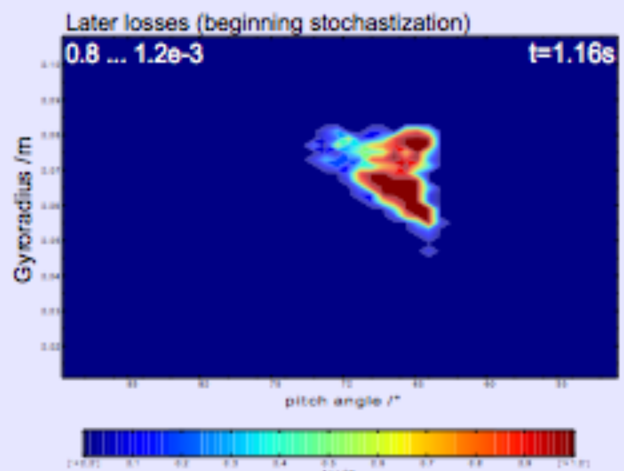
Particle losses do not change: they are negligible
Particles are moved from core to mid-radius

M. Schneller *“Investigation of Alfvénic transport mechanisms with HAGIS”*

ASDEX Upgrade



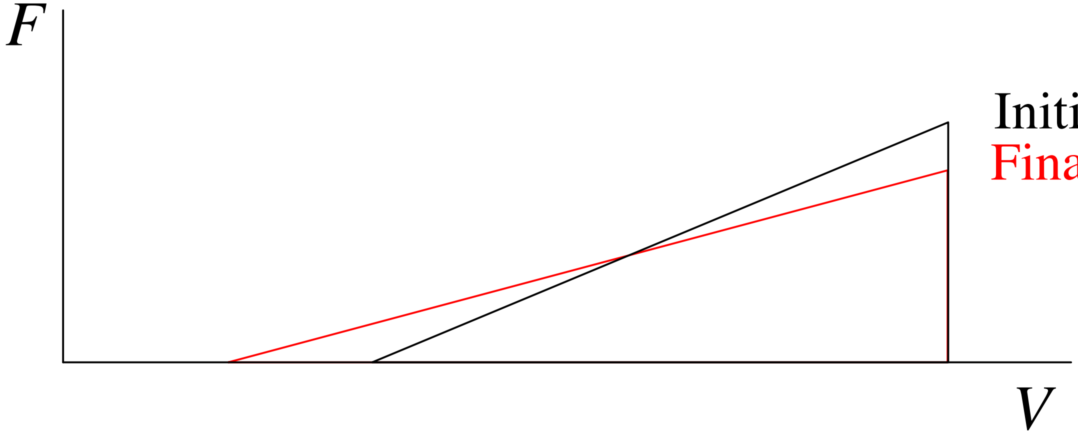




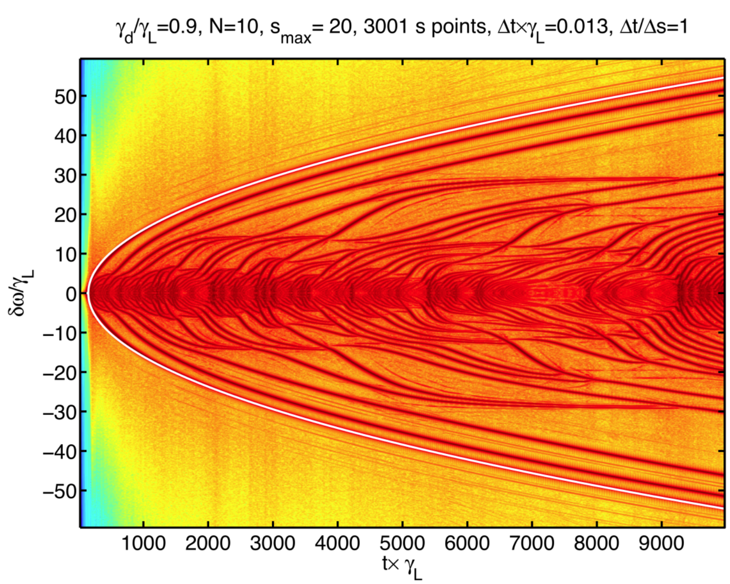
Fast particle losses:

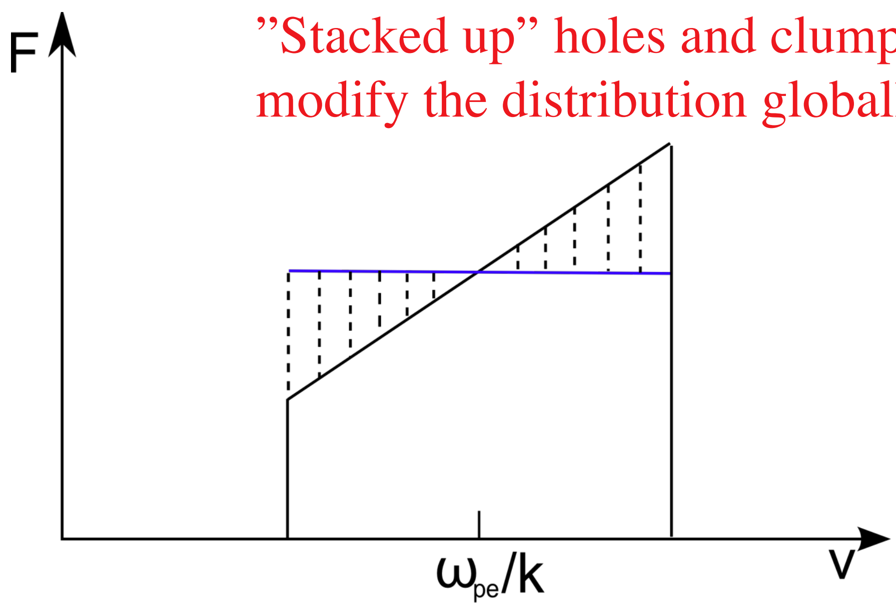
- inverted q profile leads to **enhanced prompt losses**
- **prompt losses spread widely** over phase space
- phase space position of resonant losses **matches with loss boundary**
- **stochastization** enhances losses and leads to a broadening in phase space
- for monotonic q profile, in late phase ($> 3 \cdot 10^{-3}$ s) stochastization occurs as well (similar mode amplitudes), however no significant losses appear

Near-threshold quasilinear relaxation



Global relaxation via recurrent sweeping events





"Stacked up" holes and clumps modify the distribution globally

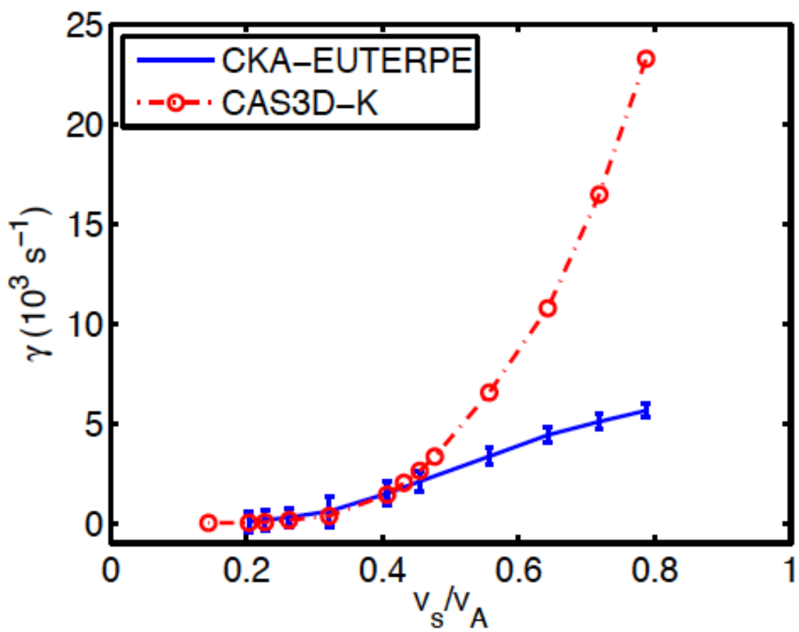
Developments and Trends

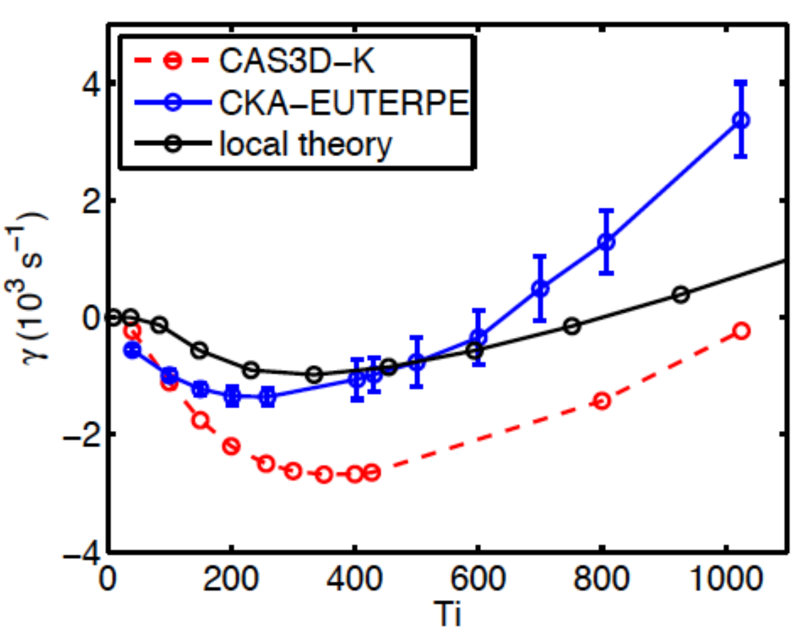
- Equilibrium and classical transport of energetic ions (Hole, Kurki-Sounio, Kramer, Hamamatsu, Farengo)
- Runaway electrons (Riemann, Papp)
- Linear studies of Alfvénic and acoustic modes (Bass, Lang, Deng, Könies, Gorelenkov, Merle, Lepiavko)
- Nonlinear dynamics of isolated modes (Lilley, Nyqvist, Lesur, Wang, Pinches, Chen, Fu, Lin, Zhang, Zarzoso)
- Anomalous transport due to instabilities (Todo, Yakovenko, Kolesnichenko, Ghantous, Albergante, Schneller, Breizman)
- Progress in code development **(Spong, Könies, Vlad, Wong)**
- Interpretation of experimental mysteries
- Predictive theoretical work

- **Important issues for energetic particle physics**
  - Equilibria: flux surface geometry, ripple amplification, islands
  - Focused losses on plasma-facing-components
    - ITER, DIII-D with TBM's; ELM control coils
  - Alfvén instabilities in 3D systems
    - Modes unique to stellarators (helical, mirror Alfvén modes)
    - Finite orbit width effects
    - Ripple induced gaps, continuum crossing gaps
- **Computationally demanding nature of 3D systems motivates**
  - **Efficient, scalable methods**
    - Windowed frequency solution for stable eigenmodes (AE3D)
    - Well adapted for targeting experimentally observed modes
    - Can be made parallel
    - **Wave-energy particle transfer method for finite orbit width effects**
  - **Reduced dimensionality models**
    - Gyro-Landau fluid method has been adapted to stellarators
    - Initial testing underway for eigenvalue solver

A. Könies (for T. Fehér) *"Simulation of the interaction between Alfvén waves and fast particles in stellarators"*

CKA-EUTERPE W7-AS #39042

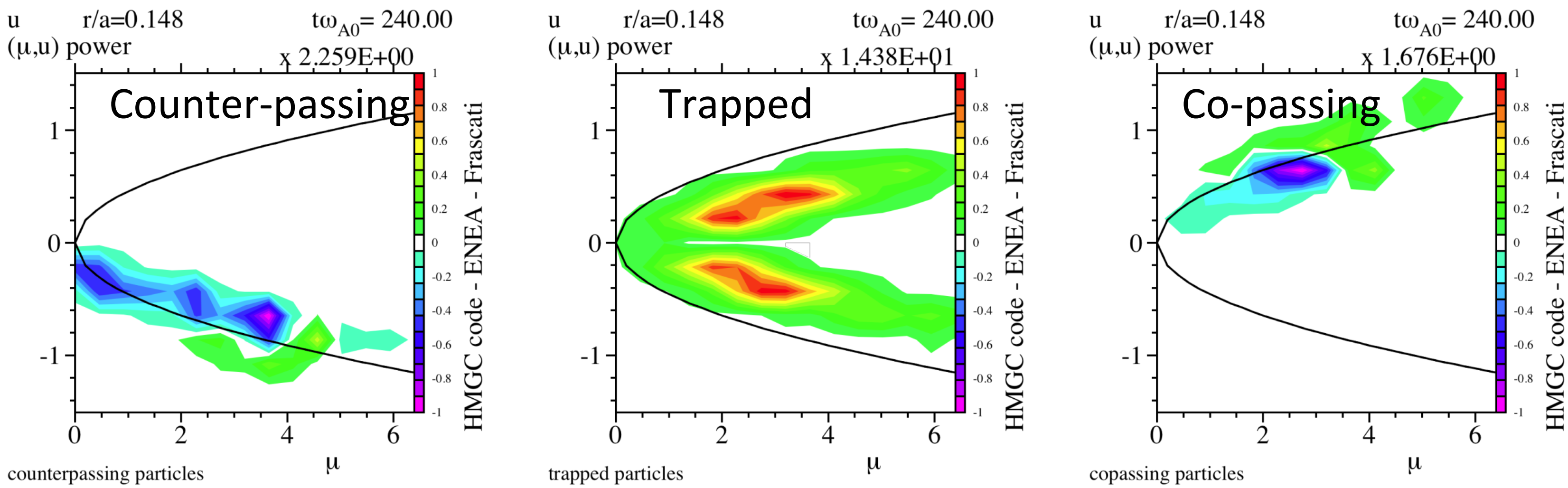




Electron fishbone instability simulated using eXtended HMGC:

- highly anisotropic energetic electrons with mostly perpendicular energy;
- thermal ions treated kinetically (Landau damping and finite compressibility retained);
- detailed description of power exchange between particles and wave in (u, μ) plane (u: parallel velocity, μ: magnetic moment);
- precession frequency of energetic electrons crucial in driving the mode unstable

Benchmark of gyro-kinetic module of new code HYMAGYC vs. HMGC and analytical solution



Wave-particle power exchange in (u, μ) plane

(from green to red: drive, from light blue to violet: damping)

V. Wong *“Simulation of the toroidal geodesic-acoustic mode destabilized by energetic particles”*

With velocity transformation $v_j \rightarrow v_j + \mathcal{V}_{\|} b_j + V_j^E$, where $\mathcal{V}_{\|}$ is ARBITRARY,

DRIFT KINETIC EQUATION is derived :

$$\frac{\partial}{\partial t} BF + \frac{\partial}{\partial x_j} B\dot{X}_j F + \frac{\partial}{\partial v_{\|}} B\dot{V}_{\|} F + \frac{\partial}{\partial \mu} B\dot{\mu} F = 0$$

Linear and Non-linear δF codes for EGAM modes completed.

MOMENT-KINETIC LIMIT $\rightarrow \mathcal{V}_{\|} = \overline{V}_{\|}$ and F is subject to the constraint $\int d^3v \, F \, v_{\|} = 0$

N and $\mathcal{V}_{\|}$ are determined by the continuity and parallel momentum equations.

Challenge is to time integrate the equations for δN, $\delta \mathcal{V}_{\|}$, and δF SELF CONSISTENTLY.

Linear δF code completed —— results are consistent with KINETIC CODE.

Non-linear δF code being developed —- will be compared with KINETIC CODE

MOMENT-KINETIC FORMALISM —- SELF-CONSISTENT inclusion of KINETIC effects in "FLUID" codes

Developments and Trends

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