MHD Control of Alfvenic Instability

presented by

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at the

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Structure of Presentation

1. Basics of Toroidal Alfven Eigenmode
2. Discussion of Stability
3. Basic theory in need of development
4. Options for Control
5. Alpha energy extraction through frequency sweeping

Alfvèn-alpha wave particle interaction

1. Alpha particle birth speed somewhat larger than shear Alfvèn; wave will resonate with this wave as alpha slows down
2. This resonance interaction may tap universal instability of alpha particles ($k_{llm}\, \upsilon_A \approx \omega < \omega*_\alpha \propto n E_\alpha$), to induce radial diffusion
3. Especially dangerous is interaction with discrete Alfvèn eigenmode especially the TAE mode
4. TAE mode emerges from continuum mode degeneracy existing in cylindrical approximation that produces TAE gap when toroidicity is accounted for

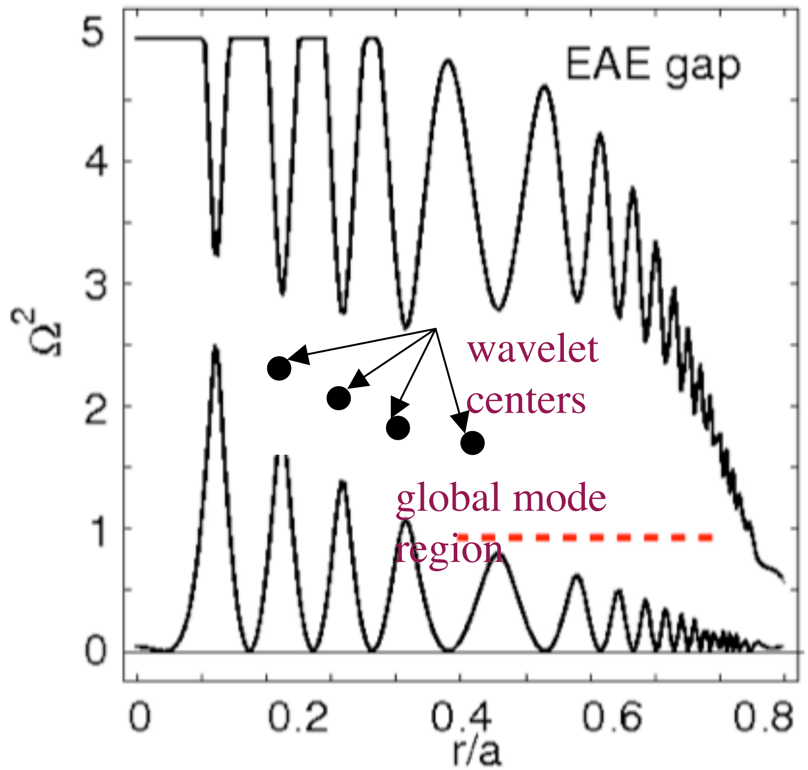
$$\omega_{TAEm} = k_{\|m}\upsilon_A = -k_{\|m+1}\upsilon_A = \upsilon_A / 2q_m R,$$

$$k_{\|m} \equiv \left(n - m / q(r)\right) / R,\ q_m = \frac{2m+1}{2n}$$

5. Toroidal wave numbers for resonance with alpha particles that tap universal instability drive moderately high (n~ 8 -15) and will be difficult to control directly

Potential for global coupling of TAE wavelets

Gap centers and continuum in ITER

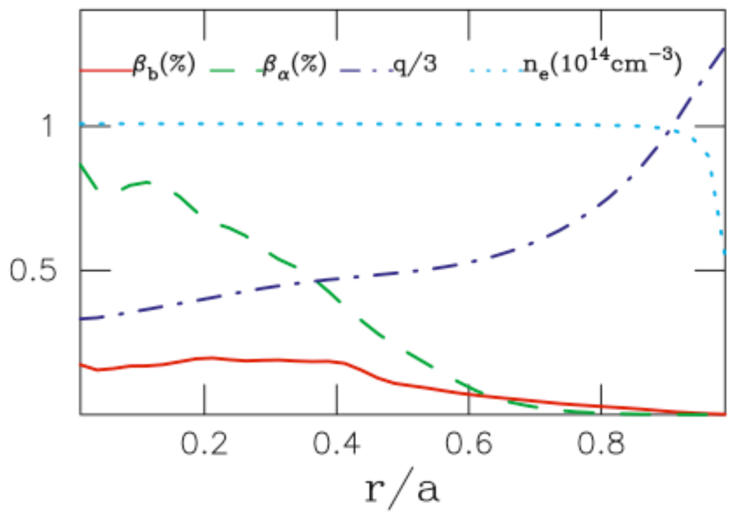


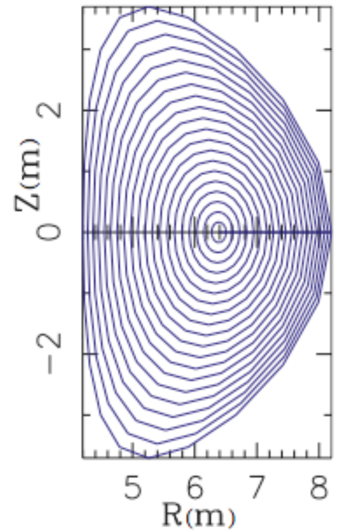
n=10 continuum

- interior: well defined wavelets & continuum region; exterior-continuum fading
- local wavelet pair coupling ($\propto$ *nr/R)* of interact, produces global mode
- wide gap produces global mode, nearly free of continuum interaction
- additional damping, particularly ion Landau damping accounted for perturbatively in typical codes such as NOVA-K and CASTOR

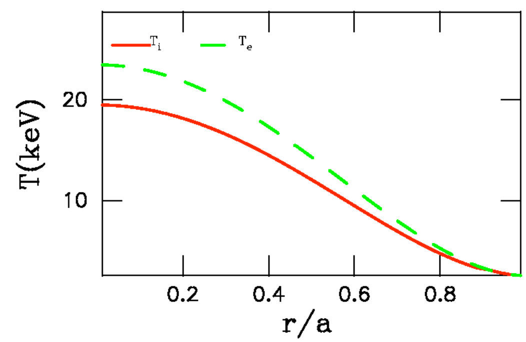
Radial continuum and mode structure

q, *β* & *n* profiles



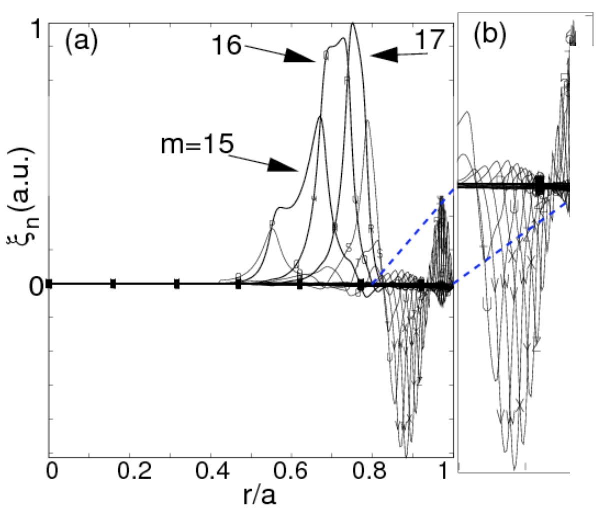


temperature profiles

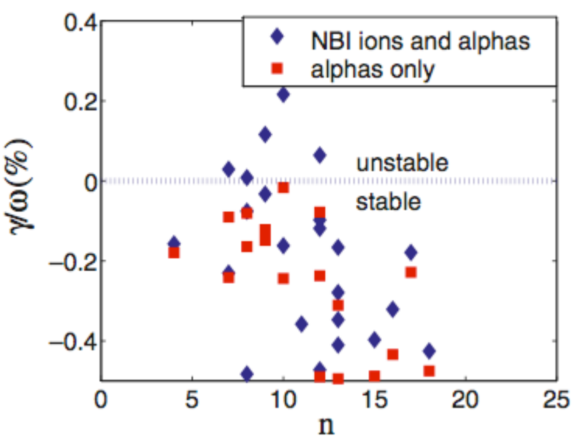


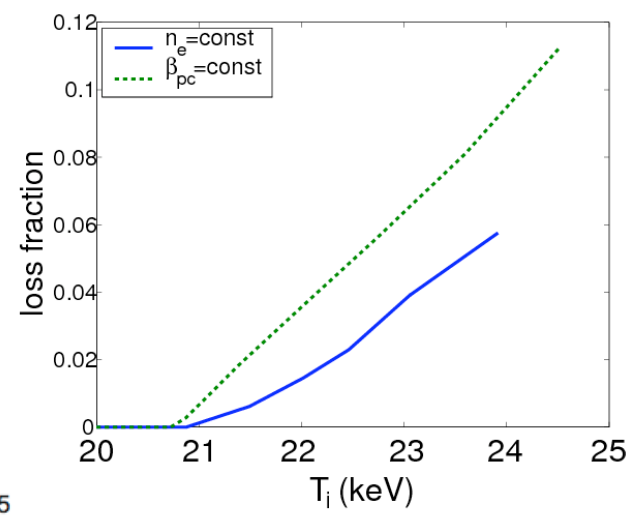
From Gorelenkov et. al. [NF 45 226, (2005)]

Global eigenmode extended
- individual m-number localized



Instability
T_i= 19.5kev
T_e= 23.5kev
β_0=6.7%





Comments

- Instability drive in middle of plasma (r/a $\sim$ 0.5) but eigenmode extends to wall
- Activity near the walls can lead to losses from central region with just a few modes
- Higher temperatures enhances instability due to longer slowing down time and increased reaction rate that beat increased ion Landau damping
- Some basic improvements in theory still needed:

a. Breakdown of ideal MHD at shorter wavelength; transition to kinetic Alfven wave

b. Especially important effect near edge with accumulation of high m modes may lead to enhanced damping

c. Issue how to include this effect:

NOVA ignores effect while CASTOR can partially capture effect but usually avoids doing so

LIGKA attempting to implement kinetic Alfven physics

Particle Simulation: Goals of PEPSC (PPPL),GTC (Irvine), Gyro (GA) to capture kinetic Alfven physics

d. Appropriate boundary conditions needed (correct equations are highly kinetic)

e. Effect of separatrix (generally ignored)

f. Improved degenerate perturbation theory needed which may cause enhanced drive with mode amplitude peaking at peak drive region (offset edge stabilization?)

Concluding Statement of First Part

- Though we know a great deal about TAE mode experimentally and theoretically, Alvenic instability in ITER, which may be excited at moderately high n-numbers, is difficult to quantitatively assess

a. Improvement in linear modeling needed especially at edge where non-MHD effects become important

b. Difficulty of extrapolating implication of results from smaller machines to larger machines

c. Need to implement degenerate perturbation theory in codes such as NOVA and CASTOR or wait for new generation of codes to emerge (e.g. LIGKA, and simulation codes)

Active MHD control of TAE or something else?

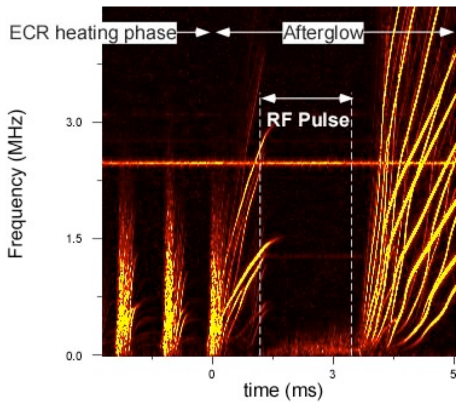
- High frequency and relatively short wavelength make direct feedback control of TAE unlikely
- Better strategy would be to arrange to have alpha population well below threshold for instability
- Mechanisms that limit alpha particle population is desirable but what could that be?

1. Choose lower reactivity rate and faster alpha slowing down plasma conditions

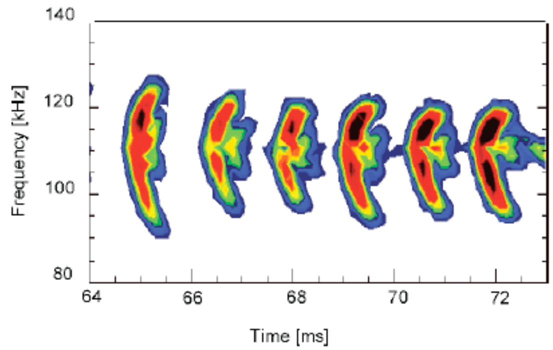
   a. Greenwald density limit makes most likely makes lower temperature - higher density regime inaccessible

   b. Fusion reactor designs want higher T_e to improve Q
2. Optimize coupling to continuum damping (fade out a concern)
3. Attempt to implement Fisch-Rax alpha channeling concept to enhance energy transfer of alpha energy to plasma background
4. Modify originally suggested Fisch-Rax quasi-linear approach through the generation of frequency sweeping phase space structures which extract energy from alpha particles

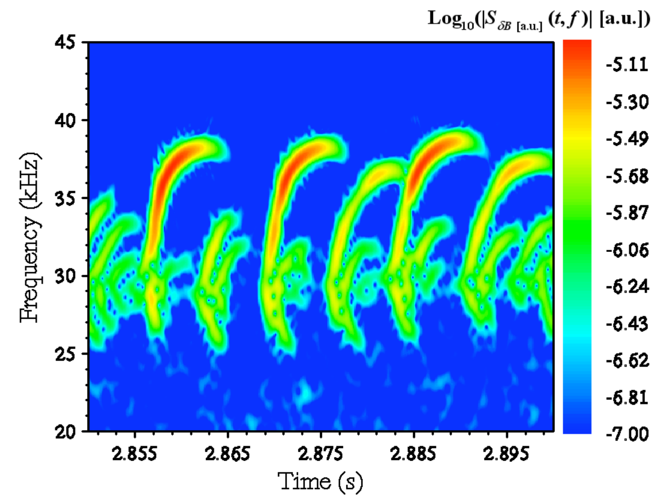
Fast chirping events in confined long mean free path plasmas a characteristic occurrence for many different waves and different resonances



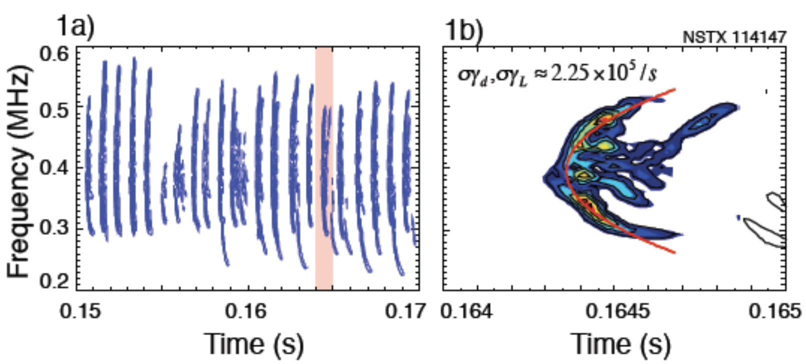
TERELLA: Hot Electron Interchange (electron drift resonance)



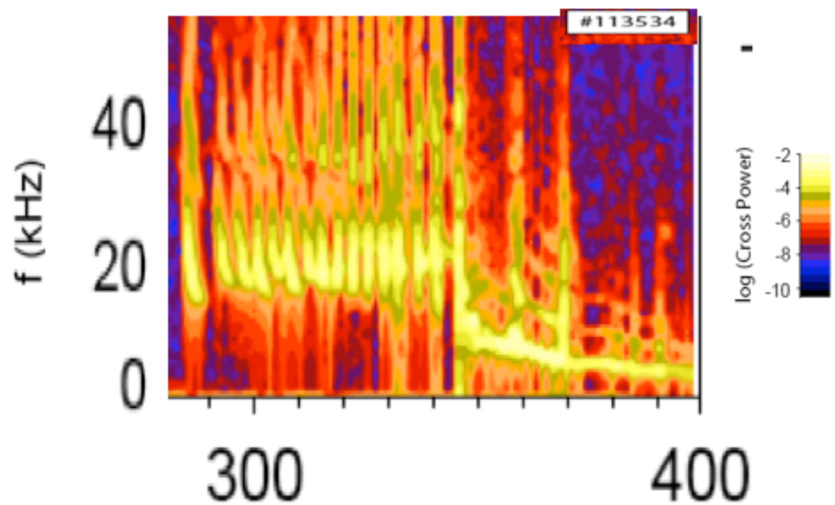
MAST: TAE (passing ion transit resonance)



JET: GAM (trapped ion bounce resonance)



NSTX; Compression Alfven Wave (doppler shifted cyclotron resonance)

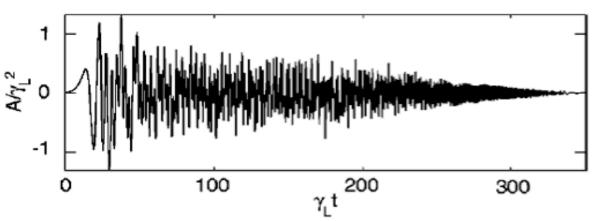


NSTX :Internal kink (fishbone); drift resonance

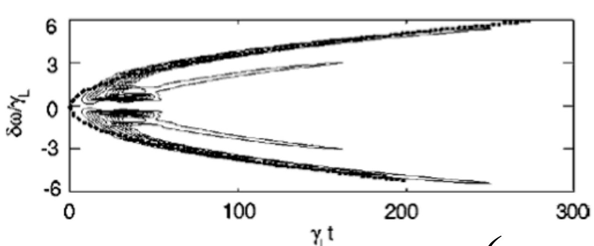
Frequency sweeping from single resonance

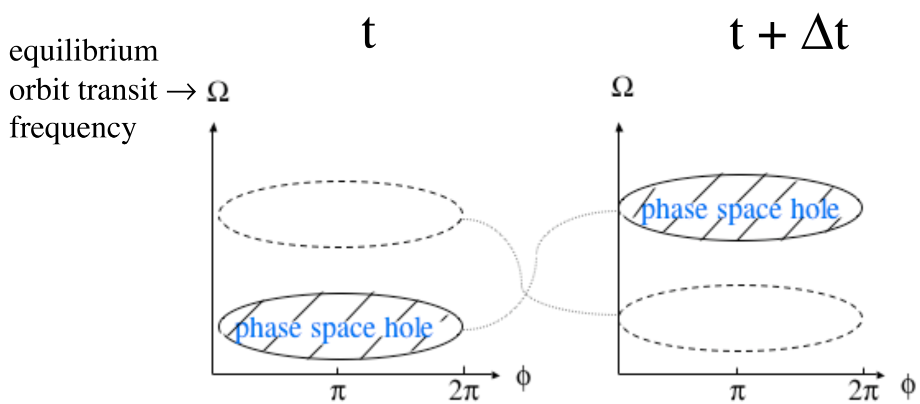
- Simulations of bump-on-tail instability (an example of a single resonance) by Petviashvili shows emergence of phase space structures locked to the chirping frequency
- Chirp is induced because of background dissipation, phase space configurations then continually seek lower energy states
- Clumps move to lower energy regions and holes move to higher energy regions

Time evolution of normalized mode Amplitude.



Frequency Sweeping .





Interchange of phase space to lower energy state during sweep

$$\omega_b \simeq .54\gamma_L$$

$$\delta\omega \cong .44\gamma_L(\gamma_d t)^{1/2}$$

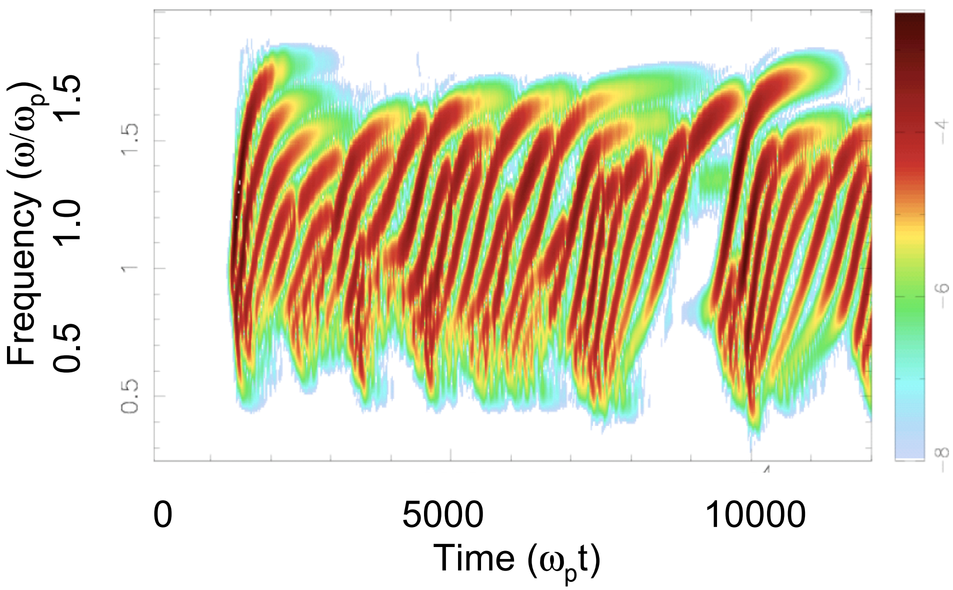
$$\left(\omega_b^2 = \frac{ek|E|}{m} \quad \text{electrostatic wave}\right)$$

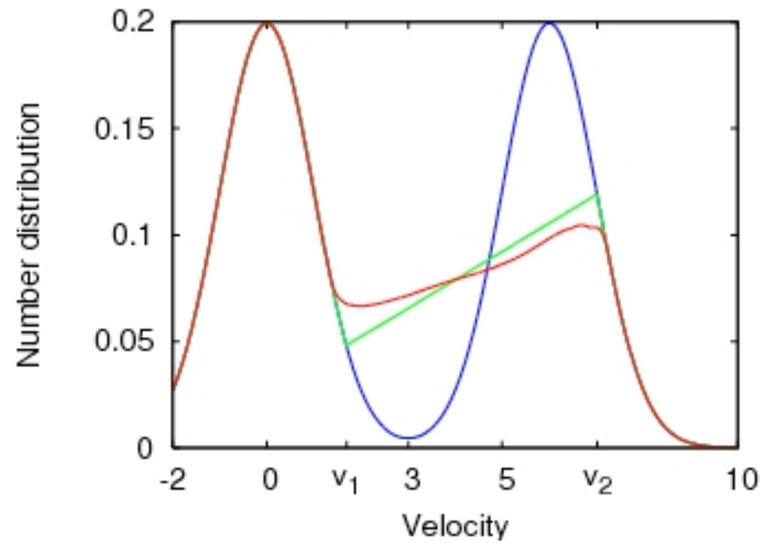
In terms of trapping frequency, ω_b, theoretical description quite similar for nearly any plasma system

Recurrent Chirping Events Maintain Marginally Stable Distribution

Relaxation of unstable double-humped distribution, with source,sink, and background plasma dissipation.

R.Vann, et al., PRL (2007)





Instability reduces stored energetic particle energy but does not alter power deposition into the plasma.

This is just how we would like to deal with alpha particles, i.e. keep stored alpha particle energy low without affecting power to plasma

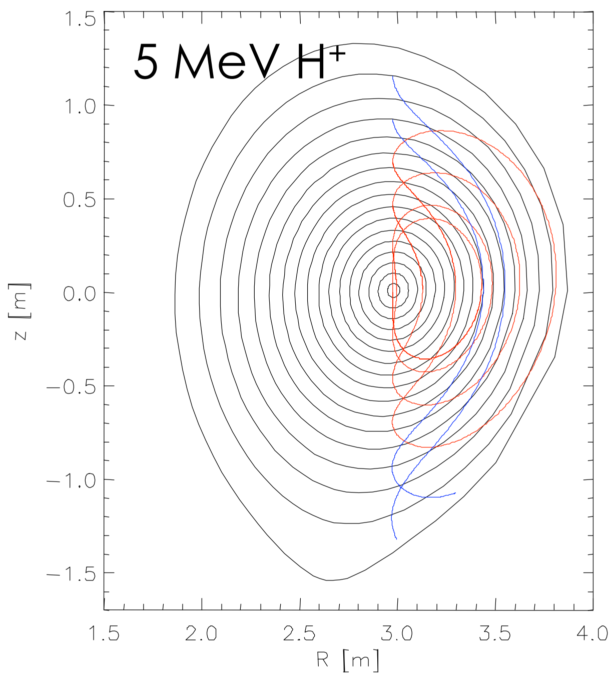
How does simple 1-D problem 'translate' to tokamak?

Resonant ICRH ions (S. Pinches with JET group)

- Track resonances in phase space
- $\omega(t) = \Omega_{p,l,n}(H,\mu,P_\phi) = p\bar{\omega}_\theta(H,\mu,P_\phi) + n\bar{\omega}_\phi(H,\mu,P_\phi) + l\bar{\omega}_{ci}(H,\mu,P_\phi)$

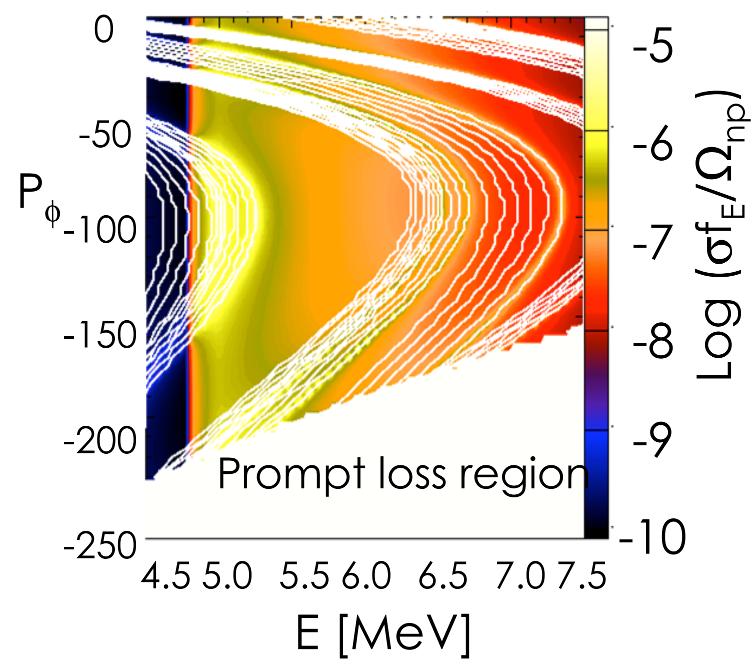
changing resonance due to sweeping

$$\frac{d}{dt}\begin{pmatrix} H \\ P_\phi \\ \mu \end{pmatrix} = \frac{\dfrac{d\omega}{dt}}{\left(\dfrac{\partial}{\partial H} + \dfrac{n}{\omega}\dfrac{\partial}{\partial P_\phi} + \dfrac{l}{\omega}\dfrac{\partial}{\partial \mu}\right)\Omega(H,P_\phi,\mu)}\begin{pmatrix} 1 \\ n/\omega \\ l/\omega \end{pmatrix},$$



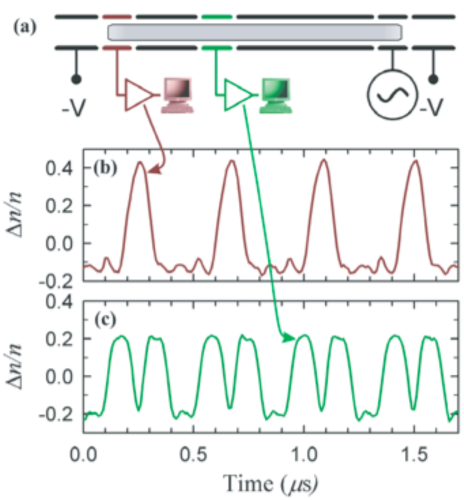
S. D. Pinches *et al.*, Comput. Phys. Commun. **111** (1998)

All resonances, n = 3 - 7

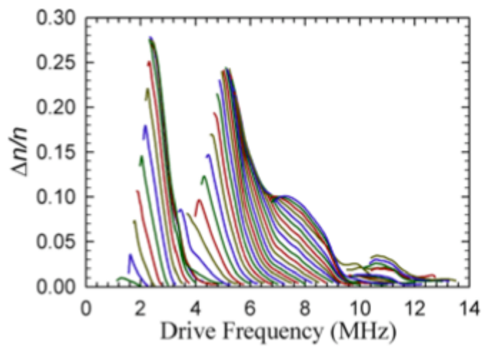


Driven Sweeping Experiments(Bertsche,Fajans, Friedland (PRL, 2005)

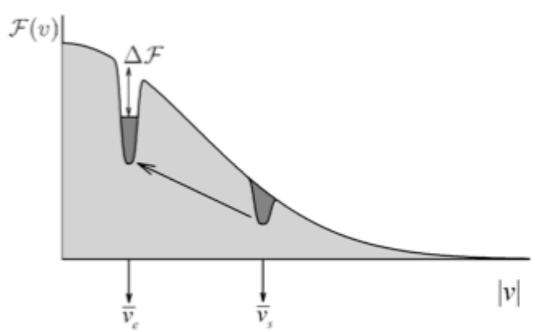
- Experiment performed on a non-neutral plasma which excites Gould-Trivilpiece electrostatic wave [plasma wave with finite $k_{||}(r)$]
- External oscillator excites a natural mode and driving frequency is slowly decreased
- Stronger coupling is observed throughout the external frequency sweep with larger perturbations being generated.
- Phenomena is interpreted as due to the formation of a hole in phase space that is driven into the 'heart' of the distribution function to form a BGK solution
- several modes can be excited simultaneously as long as mode overlap does not arise



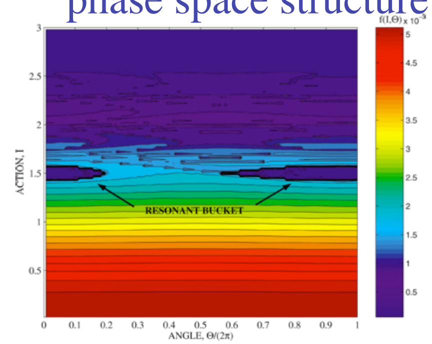
geometry of experiment and observations



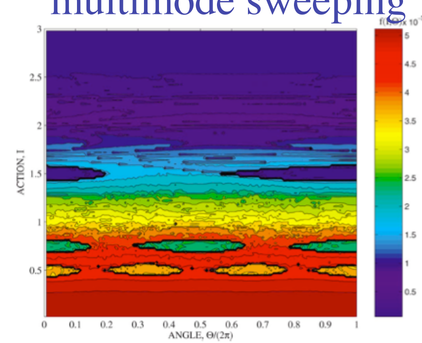
perturbed density with frequency sweeping



Initial formation of phase space structure



multimode sweeping



Friedland, Peinetti, Bertsche, Fajan, Wurtele, (Phys.Plas. (2004)

Driven or Spontaneous Frequency Sweeping?

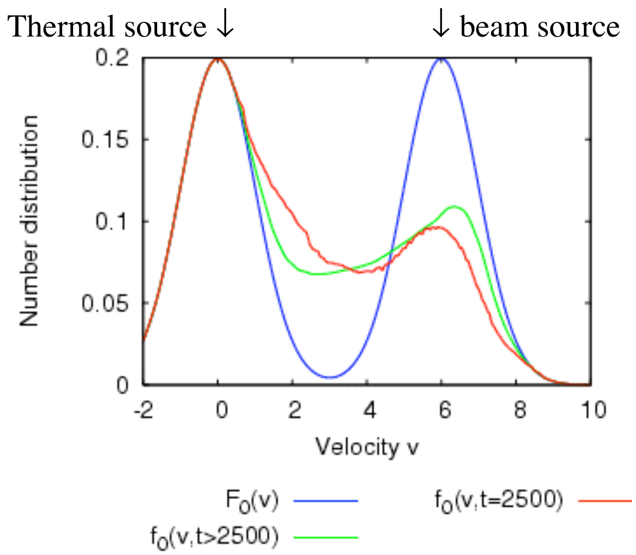
- Driven Frequency mode in stable system requires energy input from source
- Spontaneous frequency sweeping develops in an unstable system. Likely to be too un-tame to control but may work when there is limited modes of excitation (as in Vann's simulation, where there was only one mode)
- Sub-critical burning plasma has potential free energy to release but is inhibited by core plasma dissipative processes
- External antennas can excite a stable mode, a phase space structure can then be formed by initiating sweeping process. External control can then be terminated while 'natural sweeping' process to evolve to extract energy from alphas.
- Once phase space structure evolves spontaneously, the chirping rate automatically adjusts so that energy released from alphas is balanced by the dissipative rate that heats the background plasma
- Mode amplitude is determined by BGK wave conditions that need detailed evaluation
- Thus MHD control achieved by preventing build-up of alpha population that could excite linearly driven instability
- Success would allow the further goal improving the burn characteristics by achieving higher ion temperature and lower electron temperature - the goal of original Fisch- Rax alpha channeling concept

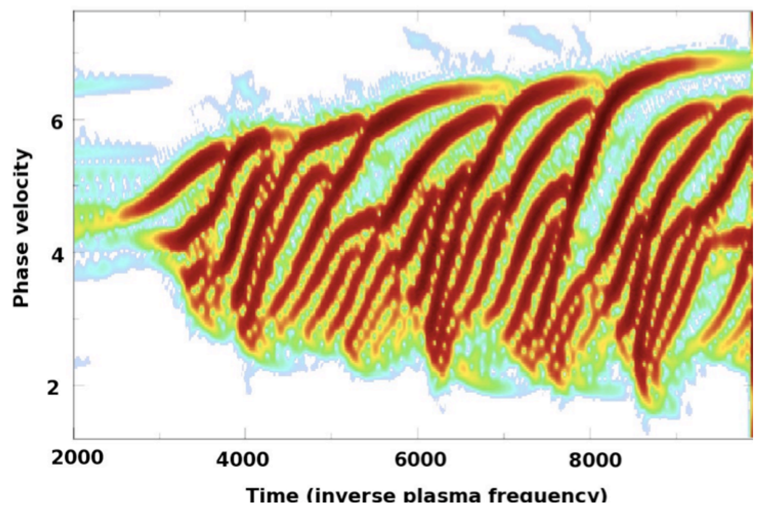
Other Issues

1. Limitation of low frequency resonance for extraction of energy
   a. If frequency ω less than ω^*_{alpha} , momentum rather than energy primarily extracted
   b. If frequency much less than cyclotron frequency, just parallel energy extracted while magnetic moment conserved
2. Fredrickson has shown on NSTX that Doppler shifted ion cyclotron resonance chirp spontaneously excited and extracts perpendicular energy
3. Need to demonstrate external excitation of chirp in linearly stable system!
4. Develop studies for the determination of power extraction rates, maximum frequency shifts, number of simultaneously permissible chirping structures, etc.
5. Design chirps that do not lose particles to boundary (or alternatively lose low energy group to prevent He ash build-up)
6. This is a highly speculative suggestion, time will tell if it has substance

Finis

Benign amelioration of instability drive from frequency sweeping (Vann, et. al.)





Numerical simulation of double humped distribution, with source, sink, and background plasma dissipation. System evolves to a marginal stable state, maintained by continual chirping. Power being transferred independent of stored energetic particle distribution even though stored energetic particle energy considerably lower due to frequency sweeping (compare green curve to blue curve).

This is just how we would like to deal with alpha particles, i.e. keep stored alpha particle energy low without affecting power to plasma