Compressional Alfvén eigenmodes in NSTX help to explain anomalous ICRH driven fast ion energy diffusion

M.V. Gorelenkova, N.N. Gorelenkov, N.J. Fisch, E.D. Fredrickson

Princeton Plasma Physics Laboratory, Princeton, USA

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Outline

1. Observations of edge Mirnov coil signal of high-/sub- ion cyclotron frequency modes in NSTX and TFTR: ICE, CAEs etc.
2. Paradigm of fast ion energy diffusion in TFTR
3. STs to tokamaks scaling for CAE studies.
4. Studies of CAEs as a way to solve the anomalous energy diffusion problem of beam ions in TFTR as suggested by Clark '00.

Question to answer:
What did we learn from precise measurements of CAEs in NSTX to support Clark and Fisch hypothesis?

Summary of observations of wave-particle interactions via cyclotron instabilities

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1. Many tokamaks (JET, TFTR, TFR...) show Ion Cyclotron Emission (ICE):
   $\omega \simeq l\omega_{ci}$, $l = 1, 2, ...$
   Green, Cottrell...

2. Theory explained ICE as instability of Compressional Alfvén Eigenmodes (CAEs) driven by fusion products (Coppi, Dendy, Gorelenkov):

$$\omega = l\omega_{ci} + \mathbf{kv}$$

   (a) JET shows ICE power scales with the neutron rate over 6 orders of magnitude (Cottrell '93): from DD to DT experiments !!!

3. CAEs in NSTX due to cyclotron instabilities are unique to study individual mode properties.

NSTX allows study of each CAE due to f separation

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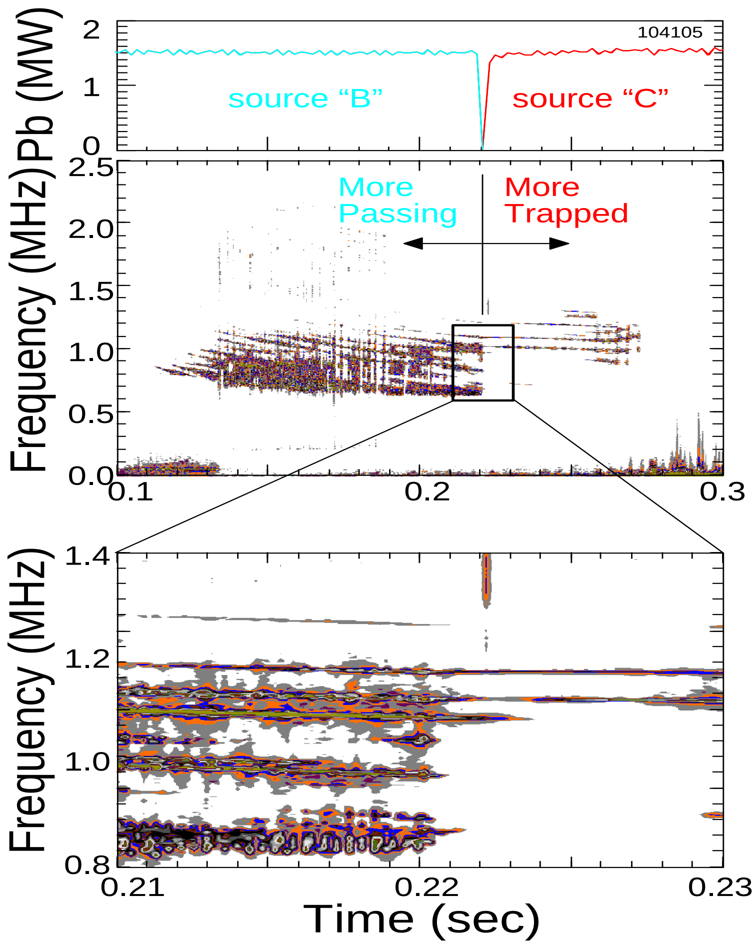

Highlights from obsevations

✓ Instabilities are coherent modes driven by NBI.

✓ Some modes persist through the NBI source switch.

✓ Sensitive to NBI injection angle.

✓ Modes are identified as Compressional Alfvén Eigenmodes $f < f_{ci} \simeq 2MHz$. (Fredrickson '01, Gorelenkov'02)

✓ Modes are driven by fast super Alfvénic ions, $v_{b0} \simeq 3v_A$ due to $80keV$ NBI.

In TFTR CAEs were seen via ICE measurements

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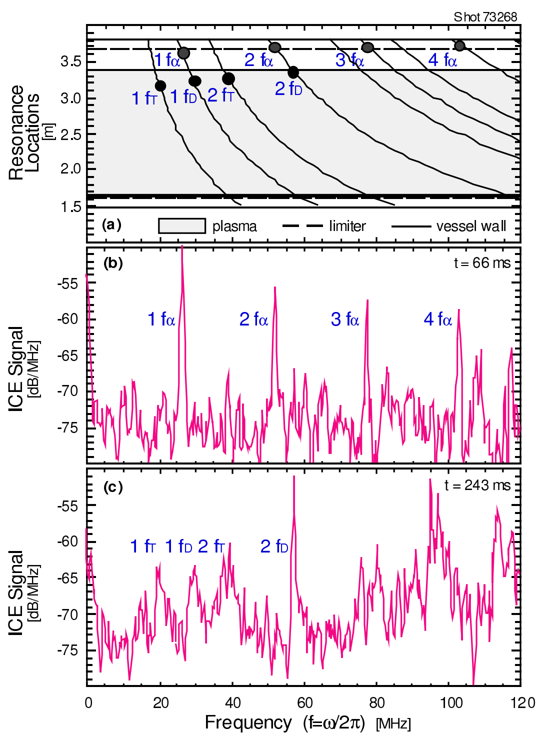

FIG. 1. *Early and late ICE spectra from a DT supershot.* The apparent locus of emission (a) and the spectral structure at 66 ms (b) is distinct from that at 243 ms (c) after the onset of neutral beam injection.

S.Cauffman, NF '95.

Instabilities regular spaced in frequency were observed in TFTR with frequencies $f_{ICE} \sim l f_{cj}$, where f_{cj} is the cyclotron frequency of fast ion specie j, such as fusion products or beam ions.

Spectrum was shaped by the ion cyclotron damping (Gorelenkov'95).

Spacing was too narrow for individual mode study.

CAE poloidal mode numbers data

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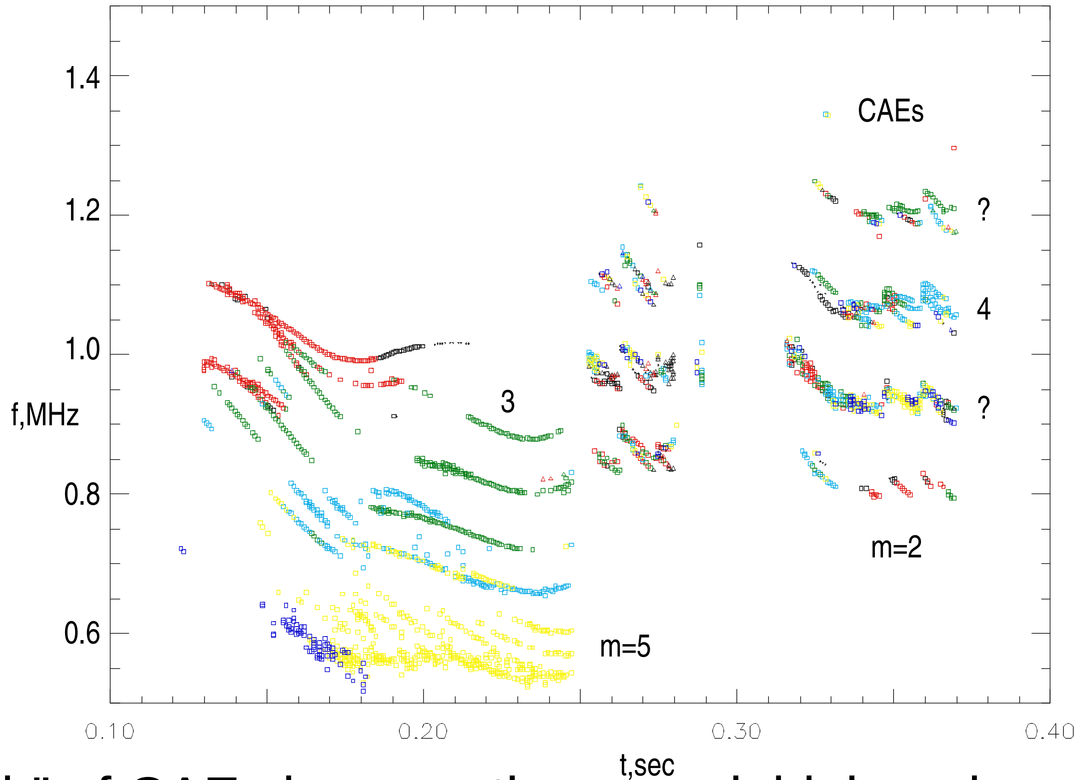
108236 shot with C NBI source. $\omega \simeq v_A \left(\frac{m^2}{r^2} + \frac{n^2}{R^2} + k_r^2 \right)$



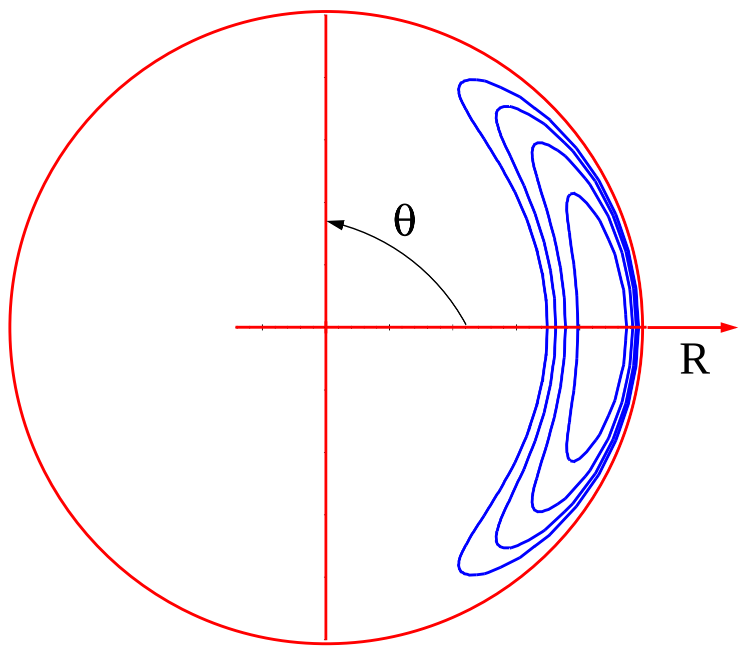
✓ One "bunch" of CAEs has mostly one poloidal mode number.

✓ Toroidal mode number changes within one bunch typically $n = 5, 6$.

✓ CAE may have different poloidal number at the edge (for $m = 3, 5?$).

ICE is suggested to be the cyclotron instability of compressional (fast, magnetosonic) Alfven eigenmodes driven by energetic ions.

Modes are localized radially (Mahajan '83, Coppi '86) and poloidally at the Low Field Side (Gorelenkov '95).



Potential well in R, Z space: $\sim v_A \sim B/\sqrt{n}$

Compressional Alfvén Eigenmode Dispersion

New CAE dispersion gives mode frequency, Gorelenkov'02, PoP.

$$\omega^2_{msn} \simeq \frac{v^2_{A00}}{r_0^2}\left\{\frac{4(m+1/2)^2}{\kappa^2}(\epsilon_0-\alpha_0)+\frac{\kappa^4-1}{\kappa^4}\frac{m^2+m+3/2}{2}\right. \\ \left. + \frac{2(2s+1)(2m+1)}{\kappa}\sqrt{\frac{(\epsilon_0-\alpha_0)(1+\sigma)}{2\sigma}}+n^2\left[\frac{q^2(r_0)}{\kappa^2}+\frac{R_0^2+4r_0^2}{4R_{00}^2}\right]\right\}. \tag{1}$$

m, n, and s - the poloidal, toroidal and radial wave numbers
$\alpha_0 \simeq B_\theta^2/2B_\varphi^2$, $r_0 = 1/\sqrt{1+\sigma}$,
κ - ellipticity, $n_e = n_{e0}(1-r^2/a^2)^\sigma$.

MODE STRUCTURE is localized at the LFS

Poloidal width - $\Theta = 1/\sqrt{\epsilon_0 - \alpha_0}$,

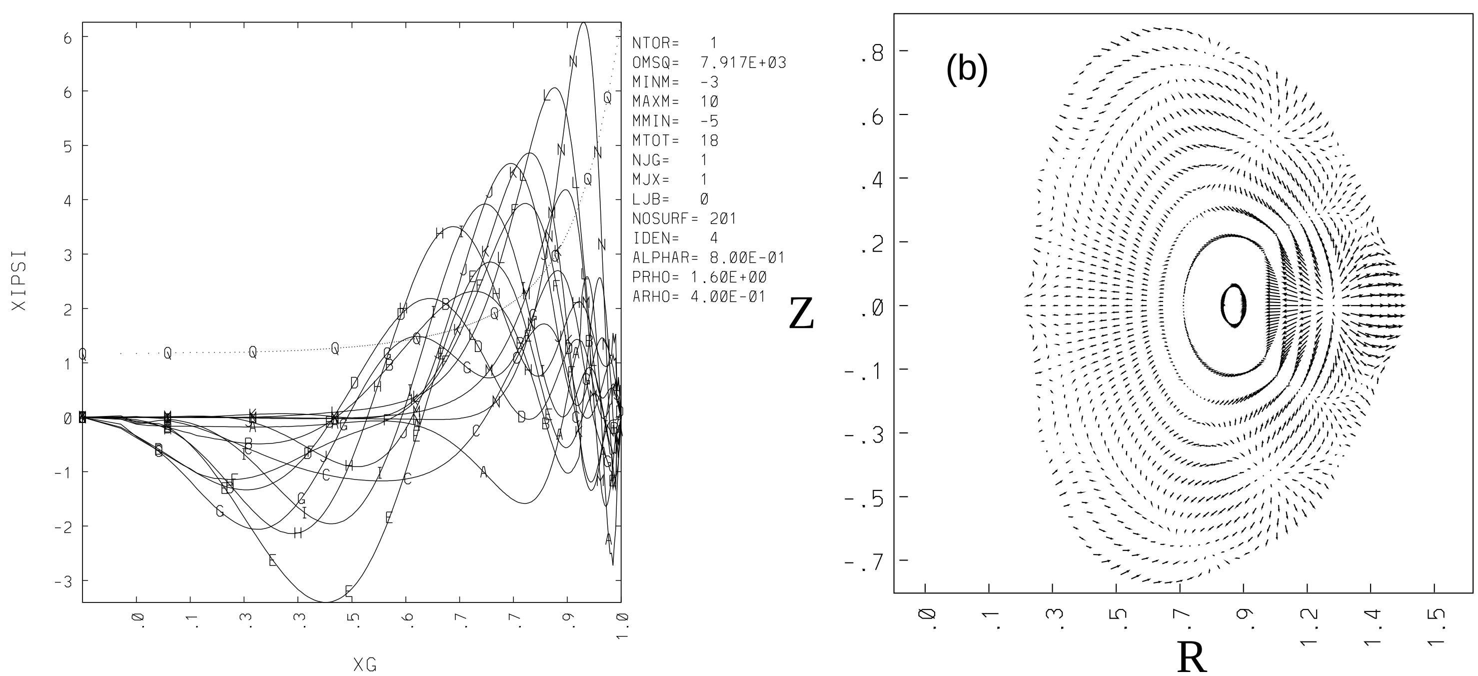
radial width - $\Delta^2/r_0^2 = \kappa\sqrt{2\sigma/(1+\sigma)\,(\epsilon_0-\alpha_0)}/(2m+1)$:

$$E = e\phi_m(\sqrt{2}\theta/\Theta)\phi_s(\sqrt{2}(r-r_0)/\Delta), \tag{2}$$

where $\phi_s(x) = e^{-x^2/2}H_s(x)/\sqrt{n!2^s\sqrt{\pi}}$ and H_s are the $s-th$ order Chebyshev-Hermit functions and polynomials.

NOVA calculates CAE Space Structure

For NSTX shot #103701, CAE structure is obtained using NOVA code. High frequency mode $f = 1.45MHz$ with visible plasma compression at m=-3 to 10, n=1, low beta:



✓ High poloial harmonics dominate near the edge.

✓ Shear Alfven continuum may occur near for high m modes

TRANSP shows close to "double" single pitch angle NBI distribution function

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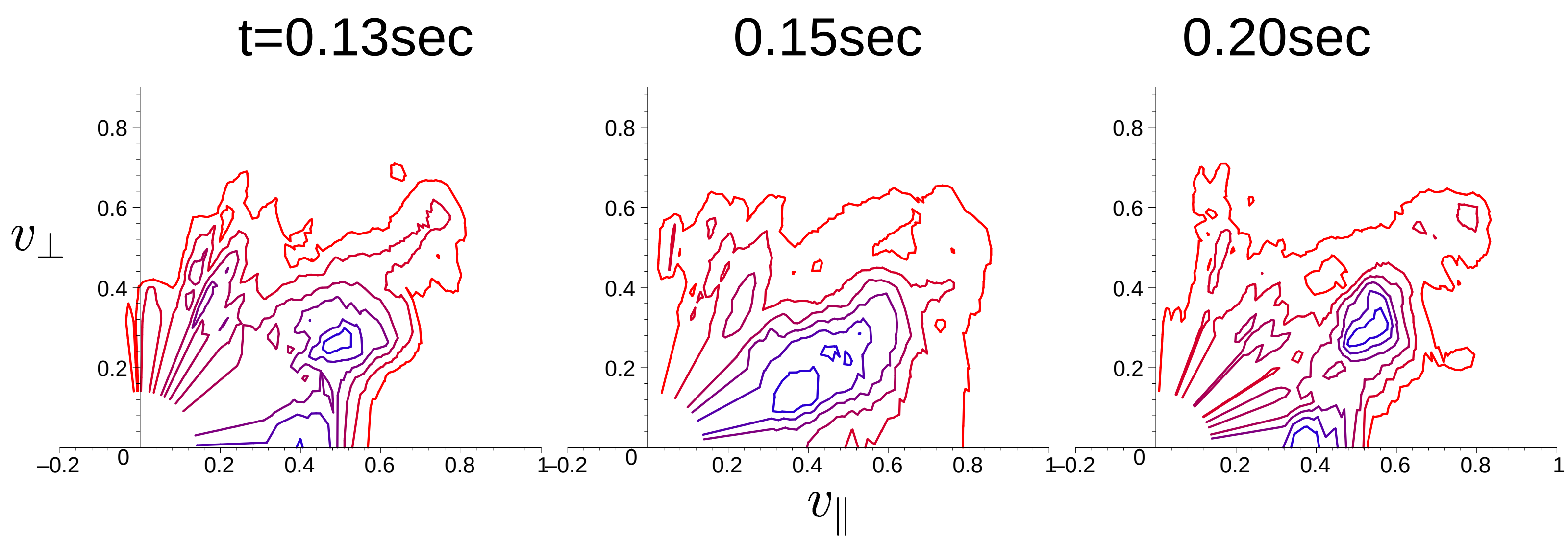


✓ Shown is the distribution function at the LFS, r/a=0.5.

✓ Often distribution function may be casted into the "trapped" and "passing" parts, i.e. confined at the edge and at HFS tangential surface.

✓ At fixed $v_\parallel$ positive velocity space gradient drives instability.

CAE and GAE properties

mode $\rightarrow$	CAE	GAE
dispersion	$\omega = kv_A \simeq mv_A/\kappa r$	$\omega = k_{\|0}v_{A0}$
localization	LFS, plasma edge, $r/a \geq 1/2$	plasma center
resonance $v_\|$	$\frac{v_\|}{v_A} \geq \frac{k_\perp}{k_\|}\left(\frac{\omega_c}{\omega} - 1\right)$	$\frac{v_\|}{v_A} \geq \frac{\omega_c}{\omega} - 1$
$k_\|$	$k_\| \simeq (\omega_c - \omega)/v_{\|b}$, $k_\| > 0$	$k_\| \simeq \omega_c/v_{b0}$, $k_\| > 0$
$v_\perp$	$\frac{v_\perp}{v_A}\frac{\omega}{\omega_c} \geq 1$	$\frac{k_\perp}{k_\|}\frac{v_\perp}{v_A}\frac{\omega}{\omega_c} \geq 2$

Cyclotron resonance with beam ions $\omega - l\omega_{cD} - k_\| v_{\|b} \simeq 0,\ l = \pm 1.$

CAE/GAE cyclotron excitation by beam ions

- ✓ Use passing $f_{bp} = 3B^2\beta_b(1-\eta)e^{-\lambda/\delta\lambda_p}/v^3\delta\lambda_p^2 2^3\pi\mathcal{E}_{b0}$ and
- ✓ trapped bump-on-tail in $v_\perp$ direction
  $f_{bt} = 3B^2\beta_b\eta\sqrt{1-\lambda_0^2}e^{-(\lambda-\lambda_0)^2/\delta\lambda_t^2}/v^3\delta\lambda_t\lambda_0 2^3\pi^{3/2}E_{b0}$
  distribution functions of beam ions, $\lambda = \mu B_0/\mathcal{E}$.
- ✓ Perturbative drive for GAE/CAEs

$$\frac{\gamma_{bGAE}}{\omega} = \frac{-T_i\beta_b}{E_{b0}\beta_i}\frac{3\pi\omega_{cb}\left(l\omega_{ci}+\omega\right)}{2\omega^2}\left\{2\left(1-\eta\right)\left[1-3\delta\lambda_p^2\frac{\omega}{l\omega_{cb}}\right]+\eta\left[\frac{\partial\left(v_\perp^2 g_t\right)}{v_\perp\partial v_\perp}-\frac{\omega\lambda_0^2 g_t}{l\omega_{cb}}\right]\right\},$$

- ✓ Typical growth rate is $\gamma/\omega \simeq n_b/n_i \simeq 1\%$.

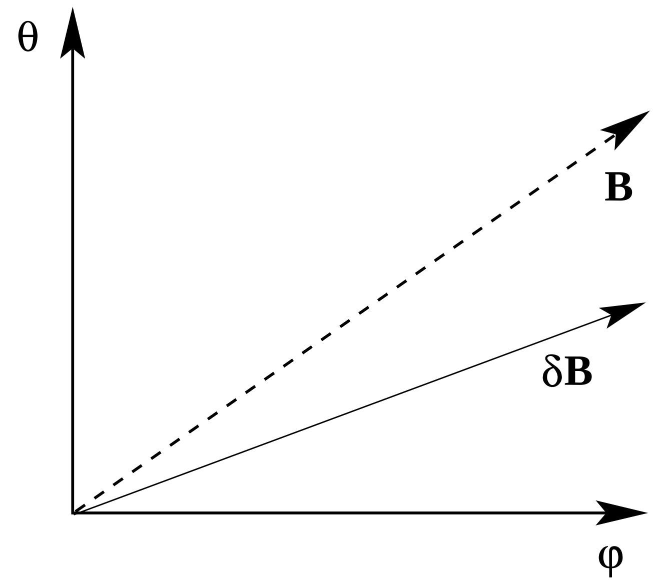
CAE polarization is observed to be compressional

NSTX discharge $\#108236$ at $t = 0.35sec$.

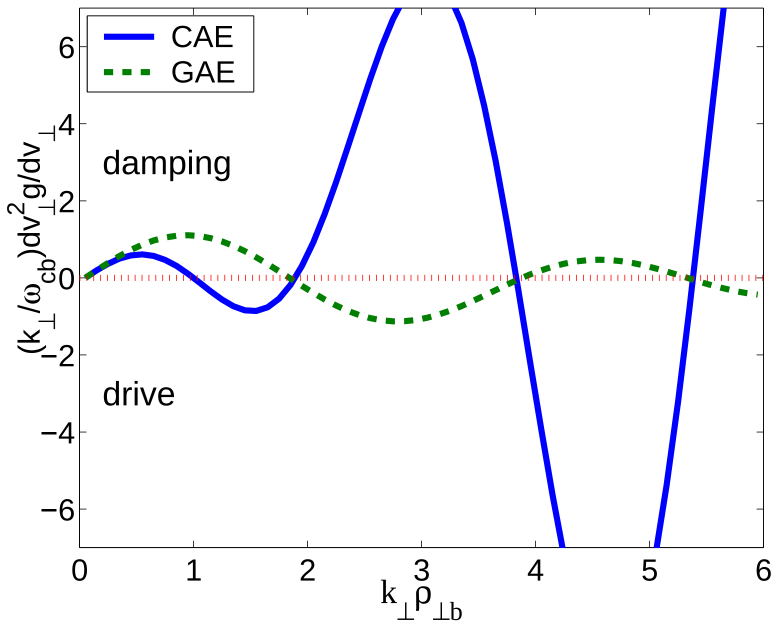
✓ Use Mirnov coils $R \sim 1.6m$ for $f \leq 2Mhz$

✓ Shown $\delta\mathbf{B}$ is the perturbed field of one CAE mode measured near the edge by the Mirnov coils. $\mathbf{B}$ is the equilibrium magnetic field

✓ $\delta\mathbf{B}$ is almost parallel to $\mathbf{B}$.



Drive condition and stabilization due to finite pitch angle width



For instability one needs:

✓ $1 < k_\perp \rho_{\perp b} < 2$ or $1 < (l\omega/\omega_{cb})(v_{\perp b0}/v_A) < 2$ for CAEs and $2 < (l\omega/\omega_{cb})(v_{\perp b0}/v_A)(k_\perp/k_{||}) < 4$ for GAEs.

✓ and perpendicular width should be less then $\delta v_{\perp bt} > -v_A \omega_{cb}/\omega$ for CAEs, and $\delta v_{\perp bt} > -2 v_A \omega_{cb}/\omega$ for GAEs.

Why in STs CAEs were observed in new regimes $f \sim f_{ci}/2$?

We construct three conditions for CAE excitation based on the cyclotron resonance with beam ions

$$\omega = l\omega_{ci} + \mathbf{k}\mathbf{v_b}$$

1. Low electron damping (assume $\beta_e(\%) \sim 10/\left(R/r\right)$):
   assume $\gamma/\omega < 1\%$
   $\omega/k_{\|}v_{\|} \ll 1$ or $\gg 1$, i.e.
   $\zeta_e = \left(k_{\perp}/k_{\|}\right)\sqrt{m_e/m_i\beta_e} > 1.5$ (curve 1) or $\zeta_e < 0.45$ (curve 2).
2. Low continuum damping (curve 3):
   $\omega_{CAE} = \omega_{KAW} \Rightarrow k_{\|}/k_{\perp} \simeq v_A/v_{Aedge}$
   assume also $v_{\|}/v_A \simeq 4a/R$ (TFTR to NSTX)
   $\Rightarrow \omega > \omega_c/(1 + a/R)$

Low Alfven velocity results in broader range of unstable frequencies in STs

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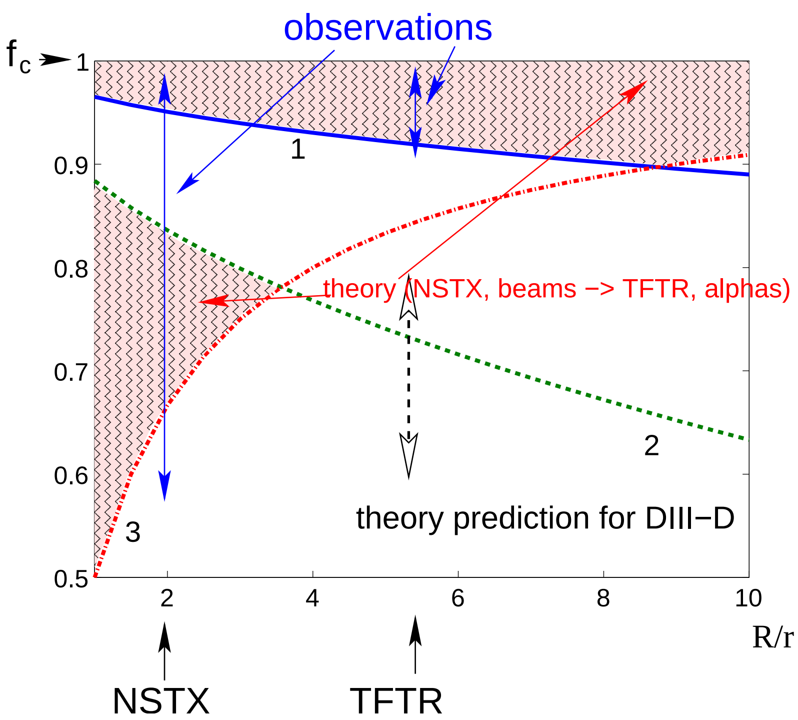

- ✓ Compressional mode dispersion: $\omega^2 = k_\perp^2 v_A^2 = \left(\frac{m^2}{r^2} + \frac{n^2}{R^2}\right) v_A^2 \Rightarrow$.
- ✓ To measure separate mode need to go to smaller tokamaks or low v_A/v_b condition.
- ✓ In contrast in DIII-D $v_\parallel/v_A \simeq 1$ but CAEs are seen (W.Heidbrink, [NP1.014]) drive is large.
- ✓ The drive in TFTR was much smaller due to orders of magnitude lower fusion ion betas.

Conundrum of strong fast ion energy diffusion in TFTR

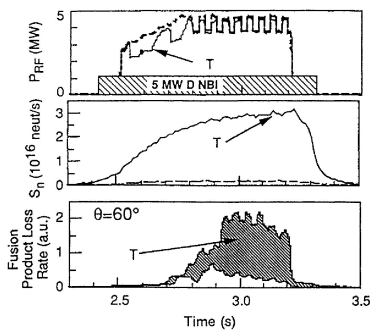

FIG. 5. Comparison of the ICRF power, neutron rate and loss rate at the 60° detector for two plasmas, one with tritium gas puffing and one without. The loss during the shot with tritium puffing is about 5 times larger than that in the other shot, suggesting that DT alpha particles are being lost to this detector under these conditions.

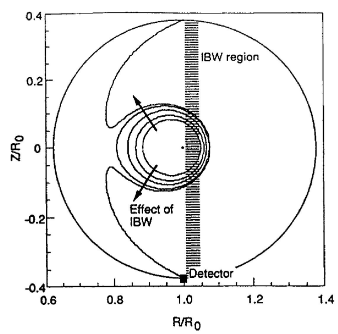

FIG. 6. Poloidal cross-section of orbit of a countergoing triton interacting with a mode converted IBW. The magnetic axis is at (1,0).

D.Darrow, NF '96.

✓ TFTR was measuring T losses above injection energy.

✓ Deducted fast ion diffusion was unexpetedly strong $10-100$ times values expected from IBW generated perturbations (Herrmann '98).

Theory suggests that CAEs may induce strong fast ion energy diffusion

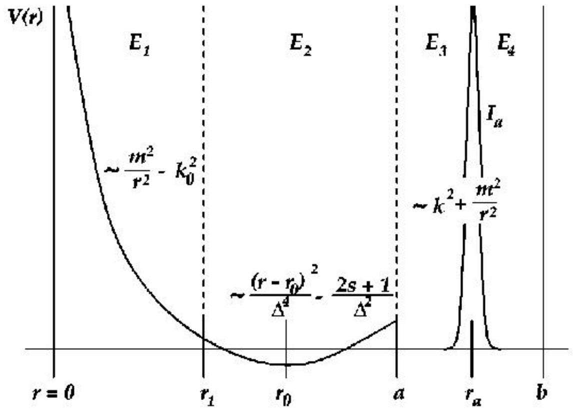

FIG. 1. Piece-wise approximate contained mode potential.

$$V(r)=\begin{cases} -k_0^2+\dfrac{m^2}{r^2}, & 0<r<r_1 \\ -\dfrac{2s+1}{\Delta^2}+\dfrac{(r-r_0)^2}{\Delta^4}, & r_1<r<a, \\ \dfrac{m^2}{r^2}+k^2, & a<r<b \end{cases}$$

1. Hypothesis was proposed of IBW - CAE interactions and strong magnification of the IBW perturbations (D.Clark and Fisch, '00)
2. External antenna launches the fast wave at the edge, wchich are coupled to CAEs in the plasma.
3. Estimates show that CAE amplitudes may be as large as $10-30$ times of expected ICRH amplitudes.

Discussion and summary

- ✓ Unabiguous identification of compressional Alfvén Eigenmodes became possible in STs (NSTX).
- ✓ Analysis of the spectra shows qualitative agreement with theory.
- ✓ As eigenmodes CAEs can be excited externally by the ICRH antenna to large amplitudes.
- ✓ CAE observations and identifications help to validate hypothesis that fast ion strong energy diffusion in TFTR as driven by CAEs.
- ✓ Strong energy diffusion is a key to controlled energy extraction from alpha particle in a reactor - alpha channeling.