Anomalous electron transport induced by multiple beam ion driven global Alfvén instabilities

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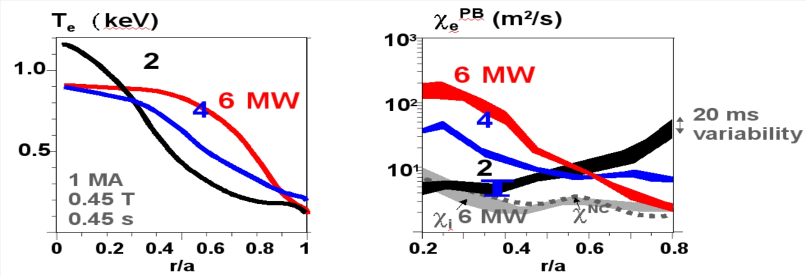
T_e flattens in NSTX H-mode shots as P_b increased



- $\chi_e^{PB} \geq 10m^2/s$ inside $r/a \leq 0.4$, while $\chi_i \sim \chi_i^{NC}$
- Not caused by low-f MHD or fast ion radial distribution
- E-transport correlates with GAE activity (Global shear Alfvén Eigenmode) *(Stutman, et.al. PRL'09)*
- Can GAEs induce electron transport? If yes, under what conditions?

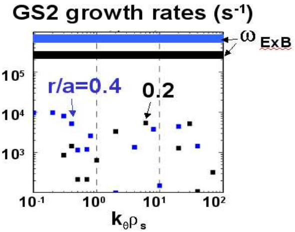
NSTX - spherical tokamak, $B = 0.5T$, $R/a = 0.86m/0.65m$, $P_{NBI} = 6MW$, $\mathscr{E}_{NBI} = 60 - 90keV$.

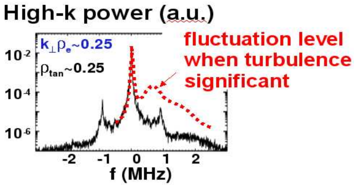
Outline

1. Motivations
   - Evidence of electron transport driven by NBI
2. Numerical modeling
   - GAE observations and theory
   - ORBIT model for e-transport
   - ORBIT analysis with ideal MHD GAEs
   - Parallel electric field effects
3. Discussion and Summary
   - Simulation comparisons with experiments
   - Projection to future reactors
   - Summary

Outline

No ETG instabilities seem to be present (due to ∇T_e)

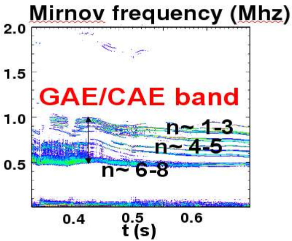




- Weak high-k fluctuations
- Persistent 0.5-1.1 MHz GAE/CAEs

(Global and Compressional Aflven Eigenmodes)

(Gorelenkov et al NF 2003)



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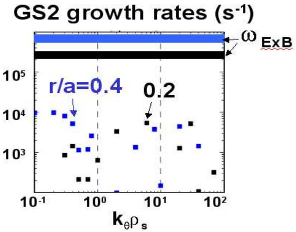

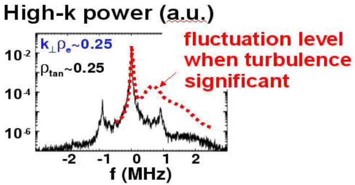

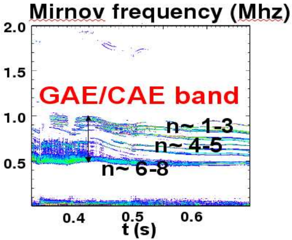

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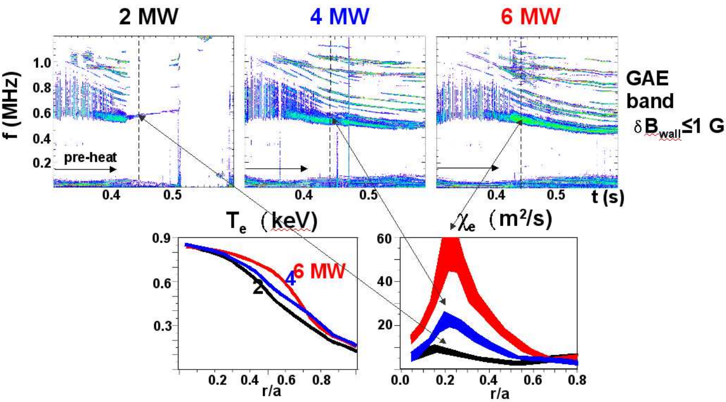
T_e flattening (and inferred χ_e) correlates with GAE activity



- Plasma & strong GAEs have flat $T_e(r)$, high central $\chi_e > 10m^2/sec$
- Plasma & weak GAEs have peaked $T_e(r)$, low $\chi_e < 10m^2/sec$
- Compressional Alfvén Eigenmodes (CAEs) are also present, but localized at the edge

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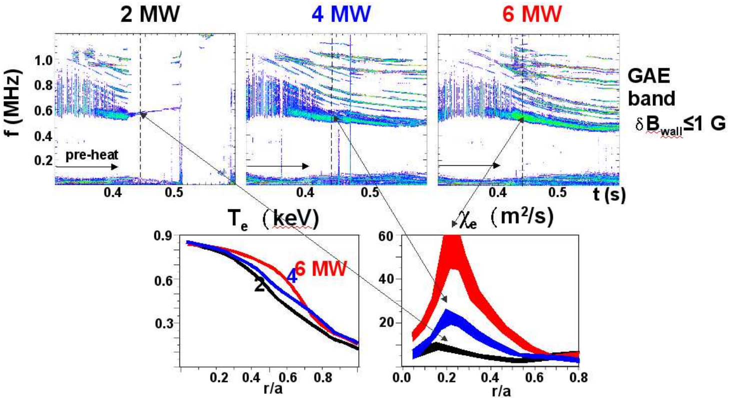

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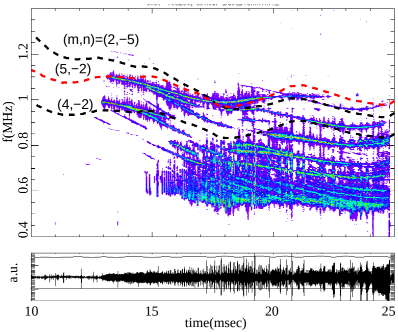
Outline

High-f GAE (Global shear AEs) instabilities were identified in NSTX



Dashed curves are GAE dispersion $\omega_{GAE} \simeq v_{A0}(m - nq_0)/q_0 R$.

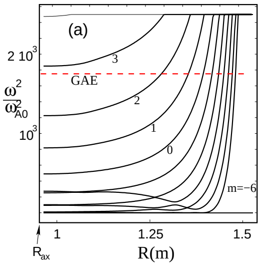
GAEs in NSTX:

- observed spectrum peaks of different (m,n) modes can intersect $\Rightarrow$ characteristic of shear AEs,
- polarization $\delta B_\perp > \delta B_\parallel$,
- GAEs are driven by fast super Alfvénic beam ions, $v_b/v_A \simeq 2-4$,
- multiple modes are often present
- damped on electrons
- at $\omega < \omega_{ci}$ no interaction with thermal ions expected to affect electrons.

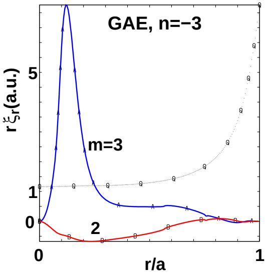
(GAEs reported by Appert, et.al., Pl.Phys.1982; Mahajan.et.al. Phys.Fluids, 1983; GAEs in NSTX, N.N.Gorelenkov, E. Fredrickson, E. Belova et.al., IAEA'02, NF'03).

GAEs have localized structure below each Alfvén continuum (NOVA)

Alfvén continuum



radial structure



$\omega_{GAE} \simeq v_{A0}(m - nq_0)/q_0 R$

- Many radial modes can exist below each A-continuum line
  - Frequencies are shifted downward from the continuum up to 30%.
- Theory is extended to $\omega_A(r)$ having minimum at $r = 0$ *(Gorelenkov, NF'03)*
  - GAE radial mode width is $\sim m^{-1}$, dominant single m harmonic
- nonlinear hybrid code HYM GAE modeling confirms their experimental identification and theory *(Belova,'09)*

Outline

Characteristic frequencies of electron drift motion

- GAE instabilities at $f_{GAE} \sim 500-1000kHz$, but may go higher.
- transit (passing) frequency $f_{te} = \frac{1}{2\pi}\frac{v_{\|}}{qR} = 1.5MHz \ \ T_e = 1keV$,
- bounce (trapped) frequency $f_{be} = \frac{1}{2\pi}\frac{v_{\perp}}{qR}\sqrt{\frac{r}{2R}} = 430kHz$ at $q=2$, $R=1m,\ a=0.8m,\ r/a=0.2$.
- electron Coulomb scattering frequency $\nu_e/\omega_{ce} = 3\times10^{-7}$ $(\omega_{ce} = 0.7\times10^{11}sec^{-1})$, e-i collisions double this.
- thermal ion cyclotron frequency $f_{ci} = 3MHz$.
- GAEs are driven by Doppler shifted cyclotron resonance of beam ions $\omega - k_{\|}v_{\|} - \omega_{cf} = 0$.

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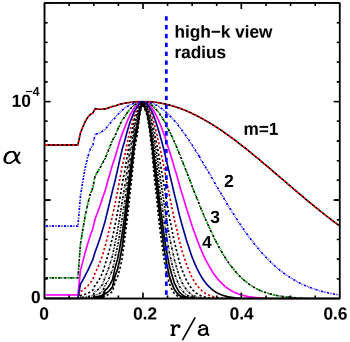
Employ ORBIT (White, Ph.Fl.'84) to study e-transport due to GAEs

Ideal MHD perturbation, $E_{\parallel} = 0$

$\alpha(r)$: $\delta \mathbf{B} = \nabla \times \alpha \mathbf{B}$



Set up test GAE structures

$$\alpha = \alpha_0 e^{-m^2(r-r_0)^2/\delta r^2}.$$

and $\delta B_r/B \simeq ik_\theta \alpha = i\alpha m/r$.

Baseline case:

- $\alpha_0/R = 4 \times 10^{-4} \Rightarrow \delta B_r/B \simeq 0.5 \times 10^{-2}$ at $r/a = 0.2$ (mode's peak),
- up to 31 GAEs with $n = 1 - 10$, m is such that $f = 500 - 1000 kHz$ - observed window,
- localization is close to the center - uncertainty in q-profile exist.

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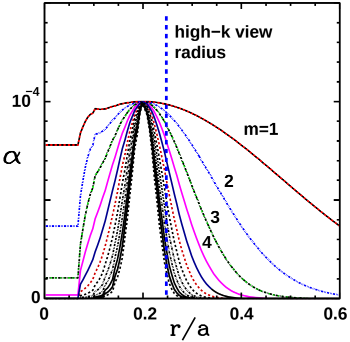

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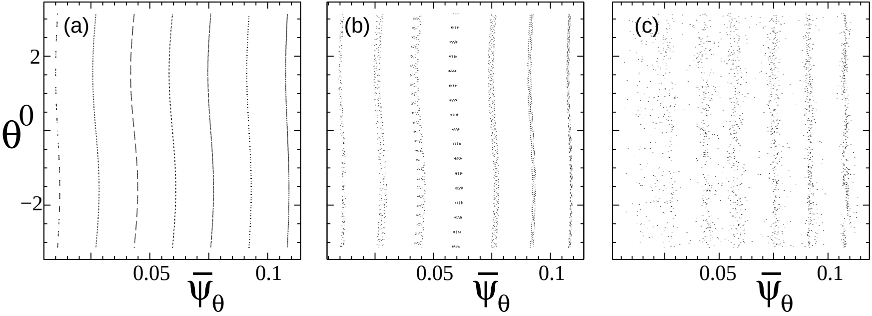
Electrons make radial excursions due to δB_r and $[E_\theta \times B]$ drift

Electron Poincare map in $\{\psi_p, \theta^0 = \omega t + n\varphi\}$ plane.

1 mode, $\xi_{re} \sim \delta B_r / B k_{\|}$ $(m,n) = (-3,1)$; $f_1 = 510 kHz$

2 modes $(f_1 \neq f_2)$

$N = 20$ modes $(f_i \neq f_j)$



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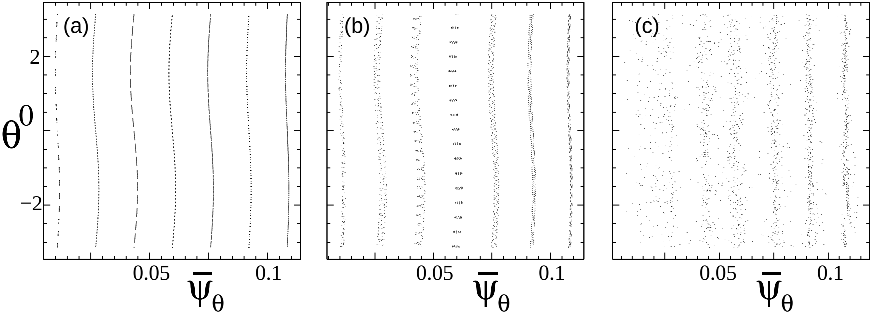

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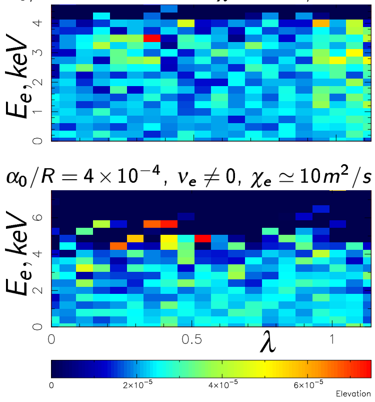
Strong GAEs smears resonances with electrons

Compare phase space map of local ψ deviation: $\left\langle \left| \psi^2 - \langle\psi\rangle^2_{\mathbf{v}^3} \right| \right\rangle_{\Delta \mathbf{v}^3}$.

$\alpha_0/R = 10^{-4}$, $\nu_e = 0$, $\chi_e < 1 m^2/s$

$\alpha_0/R = 4\times 10^{-4}$, $\nu_e \neq 0$, $\chi_e \simeq 10 m^2/s$



Take 31 modes, $\bar{\psi} = 0.05$, $T_e = 1 keV$ $(\lambda = \mu B_0/E)$

Small amplitude GAEs

- Trapped electrons are effected by GAEs ($\lambda \simeq 1$) in a broad energy range.
- Passing electron can resonate via $\omega - (k_\parallel + l/qR)\, v_\parallel = 0$. *(similar to Kolesnichenko, et.al, PRL'05)*
- But χ_e is too small $< 1 m^2/sec$.

Strong amplitude GAEs

- Pitch angle broad response to GAEs
- χ_e is larger $\sim 10 m^2/sec$.

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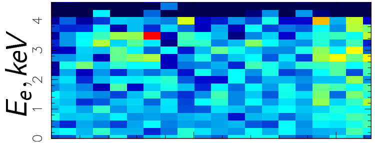

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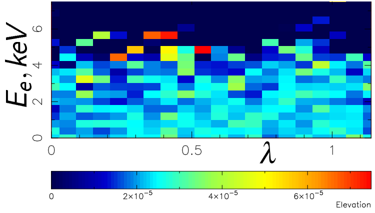

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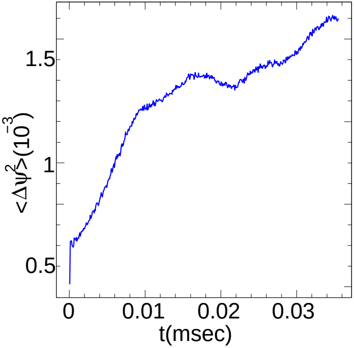
Use particle code ORBIT to simulate electron thermal conductivity

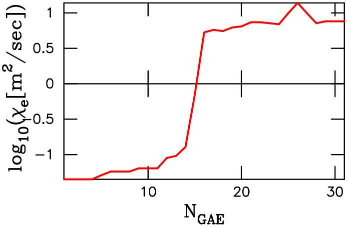
Load particles on one surface & Maxwellian isotropic distribution.
Look for linear "diffusive" dependence of $\langle \psi^2 \rangle_v (t)$ over time $\Delta t \gg qR/v_{\|}, \omega_{GAE}^{-1}, \omega_{dr}$.



- introduce ambipolar potential
$$F_e = n_e \left(\frac{m_e}{2\pi T_e} \right)^{3/2} e^{-(\mathscr{E}+e\phi)/T_e}$$
- electrons are attached to ions, $\Gamma_e = 0$, but can transfer energy
- χ_e is on the same order as D_e
$$\frac{\chi_e}{D_e} = \frac{\langle \mathscr{E}^2 D_e \rangle}{T_e^2 \langle D_e \rangle} - \frac{\langle \mathscr{E} D_e \rangle^2}{T_e^2 \langle D_e \rangle^2}.$$
- $\chi_e = 3D_e/2$ for weakly perturbed Maxwellian

How many modes introduce stochasticity?

Baseline case $\nu_e/\omega_{ce} = 6 \times 10^{-7}$, $r/a = 0.245$, $\alpha_0/R = 4 \times 10^{-4}$.



At $N_{GAE} > 16$ there is a plateau in $\chi_e(N)$

Construct the random walk:

$$\xi_{re}^2 = \left(\frac{\delta B_r}{k_\parallel B}\right)^2.$$

If modes are incoherent characteristic time is smallest of ν_{coll}^{-1}, τ_{pr}, $\tau_{transit}/\left(k_\parallel qR\right)$ (confirmed by numerics).
Then the diffusion is ($\delta B_r/B = i\alpha m/r$, $k_\parallel \simeq 2m/qR$, $m = 3$, $\tau_{transit}^{-1} = 1.5\left(v_\parallel/v\right) MHz$)

$$\chi_e = \xi_{re}^2\left(k_\parallel qR\right)/\tau_{transit} = \frac{\delta B_r^2 qR}{k_\parallel B^2}/\tau_{transit} \simeq 25\frac{v_\parallel}{v} m^2/s.$$

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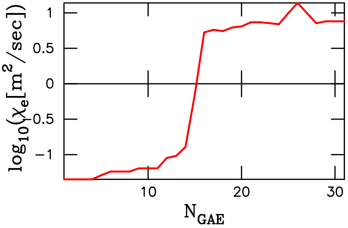

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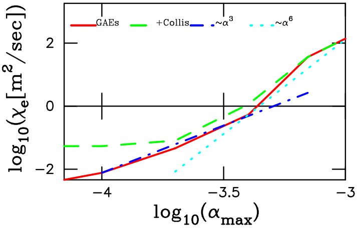
e-transport strongly growth with GAE amplitude



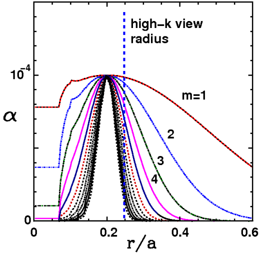
Baseline case $v_e/\omega_{ce} = 6 \times 10^{-7}$ at $r/a = 0.22$.

- Small amplitude $\chi_e \sim \alpha^3$ (deviates from α^2).
- Large amplitude $\chi_e \sim \alpha^6$ intoduces intermittently strong e-transport.
- Time averaged amplitude is lower than peak amplitude, which can be above intermittent threshold.

Collisions have small effects at large amplitudes.

Radial dependence of χ_e

$\alpha(r): \delta\mathbf{B} = \nabla\times\alpha\mathbf{B}$



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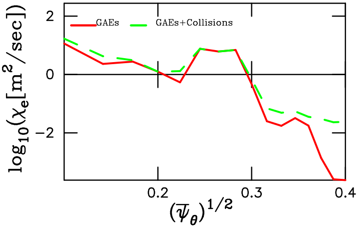


Peak of $D(r)$ is near/outside the mode amplitude peak.

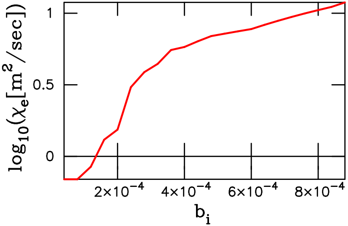
Low-m modes contribute more to the diffusion.

From ORBIT $\chi_e \simeq 10m^2/sec$ diffusion we need $\alpha > 4\times10^{-4}$ or $\delta B_r/B >\sim 0.5\times10^{-2}$, $\frac{\xi_r}{R}\sim\alpha\frac{m}{k_\parallel r}\sim\frac{\alpha}{\varepsilon}\sim10^{-3}$ and $\langle\delta n\rangle/\langle n\rangle \simeq \xi_r/R$

Outline

Parallel electric field can strongly enhance χ_e

Baseline case, $v_e = 0$, $r/a = 0.22$, $\alpha_0/R = 4\times10^{-4}$.



- Ideal MHD GAEs: $E_{\parallel MHD} = 0$,
- Finite $E_\parallel = -\nabla\Psi$ is computed perturbatively via the quasi-neutrality condition due to thermal ion FLR $$\Psi = \phi_{MHD}\frac{b_i}{1+b_i},\ b_i = \frac{k_\perp^2\rho_i^2}{2},$$

  $b_i \simeq 0.5\times10^{-4}$ in NSTX
- Other sources of $E_\parallel$: two fluid effects, compressibility ($\sim b_i$), beam ions: $\Psi/\phi_{MHD} = O\left(\frac{\omega_{ki,e}}{\omega}, b_i\right) \simeq b_i$.

$\chi_e \sim E_\parallel^2 \sim b_i^2$ at $b_i < 3\times10^{-4}$
$\chi_e \sim E_\parallel \sim b_i$ at $b_i > 3\times10^{-4}$ as $\tau_\parallel^{-1} = \left(v_\parallel + eE_\parallel\tau_{transit}/m_e\right)/2\pi qR$.

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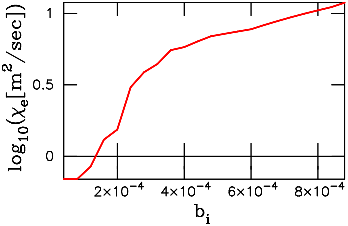

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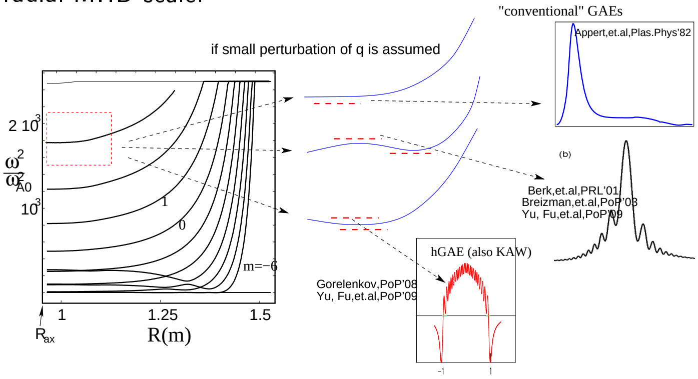

Existence condition for GAEs coupled with KAW

Given $z^2=(r-r_0)^2 m^2/r_0^2 S$, $\varepsilon>0$, $q=q_{min}/\left(1-(r-r_0)^2/w^2\right)$,
GAE equation at $\omega>\omega_A$:

$$\lambda^{-2}\frac{\partial^4}{\partial z^4}\phi+\frac{\partial}{\partial z}\left(1-z^2\right)\frac{\partial}{\partial z}\phi-S\left(1-z^2\right)\phi+Q\phi=0$$

Denoting $\bar{\omega}=\omega R/v_A$, $k_{00}=k_{\|}R_{|q=q_{min}}$ *(Fu, et.al, PoP'06, Gorelenkov et.al, PPCF'06)*:

$$S=\frac{mq_{min}w^2}{r_0^2}\left(\bar{\omega}-|k_{00}|\right);\ Q\simeq\frac{w^2}{4r_0^2}\left[\frac{\alpha^2}{2}-\Delta'\alpha+\alpha\varepsilon\frac{q^2-1}{q^2}-\frac{\varepsilon}{2}\left(\varepsilon+2\Delta'\right)\right].$$

hGAEs (hybrid, global/kinetic, GAE coupled to KAW) exist with $\omega>\left|k_{\|}\right|$ is $Q>2$ *(Gorelenkov, PoP'08 on RSAEs)* $\Rightarrow$ flat q-profiles, low shear, <u>$w>\sqrt{8}R$.</u>

Another branch is similar to sweeping up RSAEs if the continuum has a "hump", $Q>1/4$ *(Berk, PRL'01)* or <u>$w>R$ less restrictive</u>.

Existence condition for GAEs coupled with KAW

Given $z^2 = (r - r_0)^2 m^2 / r_0^2 S$, $\varepsilon > 0$, $q = q_{min} / \left(1 - (r - r_0)^2 / w^2\right)$,
GAE equation at $\omega > \omega_A$:

$$\lambda^{-2} \frac{\partial^4}{\partial z^4} \phi + \frac{\partial}{\partial z} \left(1 - z^2\right) \frac{\partial}{\partial z} \phi - S \left(1 - z^2\right) \phi + Q\phi = 0$$

Denoting $\bar{\omega} = \omega R / v_A$, $k_{00} = k_\parallel R_{|q=q_{min}}$ *(Fu, et.al, PoP'06, Gorelenkov et.al, PPCF'06):*

$$S = \frac{m q_{min} w^2}{r_0^2} \left(\bar{\omega} - |k_{00}|\right);\ Q \simeq \frac{w^2}{4 r_0^2} \left[\frac{\alpha^2}{2} - \Delta' \alpha + \alpha \varepsilon \frac{q^2 - 1}{q^2} - \frac{\varepsilon}{2} \left(\varepsilon + 2\Delta'\right) \right].$$

hGAEs (hybrid, global/kinetic, GAE coupled to KAW) exist with $\omega > \left|k_\parallel\right|$ is $Q > 2$ *(Gorelenkov, PoP'08 on RSAEs)* $\Rightarrow$ flat q-profiles, low shear, $w > \sqrt{8} R$.

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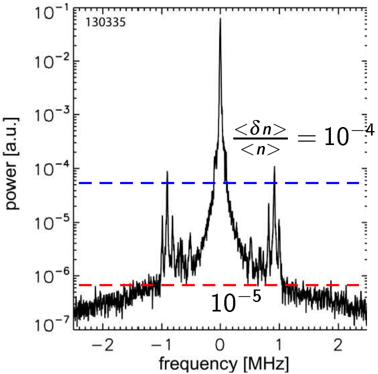
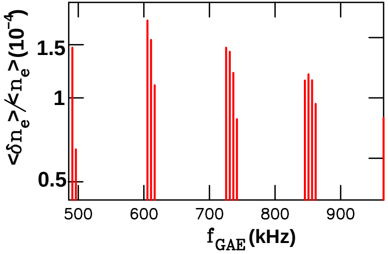
Outline

GAE amplitudes in experiments vs used in the (MHD) model

High-k interferometer line averaged density fluctuation spectrum, $r/a = 0.25$, $10 msec$ averaged

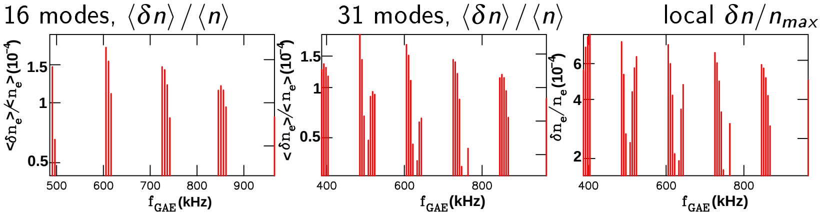


16 modes are shown from simulations $\alpha_0 = 1.5 \times 10^{-4}$. Synthetic diagnostic.



Test spectrum is different from the high-k interferometer spectrum. Further studies are required to refine the simulations.

GAE amplitude spectrum in a model



- Local density fluctuation is up to 5 times higher than line averaged.
- Resulting uncertainty can lead into even bigger uncertainty in χ_e simulations.
- From ORBIT $\chi_e \simeq 10m^2/sec$ diffusion we need $\alpha > 4\times10^{-4}$ or $\delta B_r/B >\sim 0.5\times10^{-2}$, $\frac{\xi_r}{R} \sim \alpha \frac{m}{k_\parallel r} \sim \frac{\alpha}{\varepsilon} \sim 10^{-3}$ and $\langle\delta n\rangle/\langle n\rangle \simeq \xi_r/R$.

This is within the measured accuracy (factor 2 higher) of GAE amplitudes.

Outline

*Qualitatively e-transport due to GAE (other *AEs?) is expected in ST-like plasma*

Essential elements of the GAE driven electron transport in NSTX

- Strongly driven modes $\gamma/\omega = 1 - 10\%$.
- Strong anisotropy: beams, alphas in ST.
- Large ratio $v_f/v_A = 2 - 4$ (ST typical).
- Weak damping.
- Multiple instabilities, $N \geq 10$
- / $\Rightarrow$ high β_f and β_f/β_{pl} are required (STs).

Need more experimental and theoretical studies before making quantitative projections: *Mode structure, inner polarization, small scale structures.*

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Outline

Summary

- GAEs with sufficiently strong amplitudes can induce electron transport in NSTX.
- Electron transport is due to
  - $\delta B_r/B$ caused deviation from the magnetic surface for both particles
  - multiple modes introduce stochasticity in electron motion.
- overlap of electron radial motion is the mechanism of e-transport.
- comparison with high-k interferometry shows the deficit of the observed GAE amplitudes by factor of 2 to 3 required to match the lower end of the inferred electron thermal conductivity, $\chi_e = 10m^2/s$.
- $E_{\|}$ coming from KAW to GAE coupling can strongly enhance radial diffusion. Need to search for $E_{\|}$ effects (ρ_i^{-1} scales) in experiment.