Simulations of the effect of beam driven Global Alfvén Eigenmodes on electron transport

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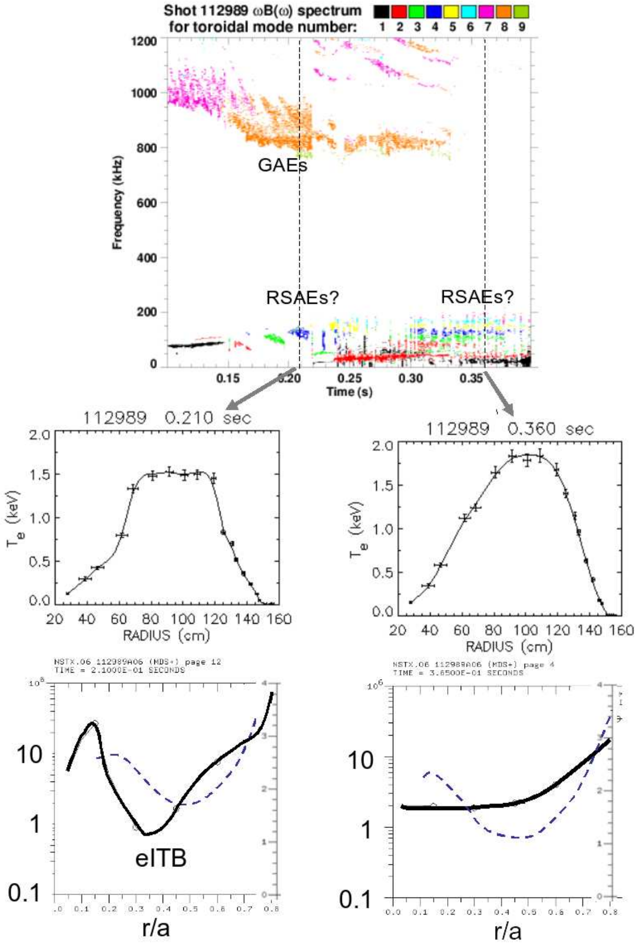
Motivation



- e-transport seems to be driven by sub-cyclotron modes - D. Stutman, recent presentations
  - GAEs are candidates
- location of T_e-flat region is $r/a <\sim 0.25$ inside of q_{min} surface !!!
- can utilize theory developed for GAEs/CAEs, ORBIT
  - aim at heat diffusion coefficient on the order $> 2m^2/sec$,
  - what is required mode amplitude.

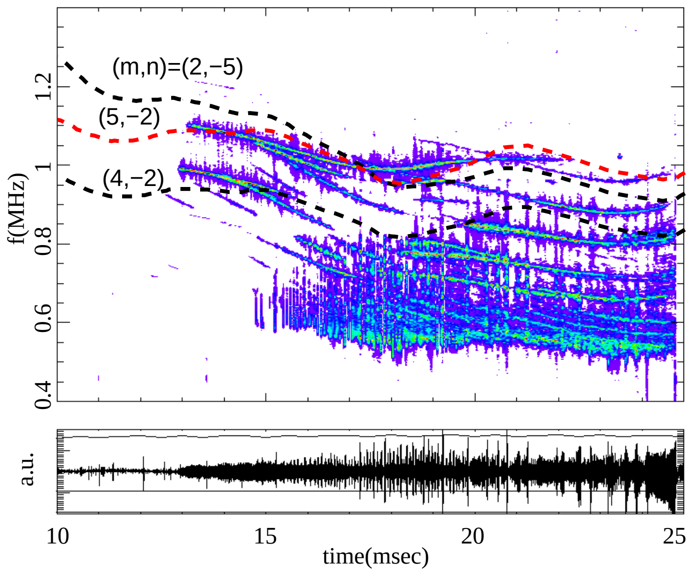
OUTLINE

- Experimental and Theoretical properties of GAE instability
- ORBIT simulation

Experimental Observations and Theory

- Experiment:
  - Multiple sub-ion cyclotron frequency instabilities are observed in NSTX.
  - Frequency typically scales with Alfvén speed and dispersion.
  - Modes are driven by fast super Alfvénic ions.
  - GAE frequencies intersect, polarization $\delta B_\perp > \delta B_\parallel$
  - CAE frequencies do not intersect, polarization $\delta B_\parallel > \delta B_\perp$.
- Theory:
  - GAEs: Appert'82, in NSTX discovered by Fredrickson, with input from HYM (E.Belova).
  - Mode identification: shear and/or compressional (magnetosonic) AEs is easier in NSTX due to instability spectrum peak separation.
  - Instability properties can be used to diagnose plasma: fast ion distribution,
    q-profile.
  - damped on electrons if $\omega < \omega_{ci}$: may expect effects on electrons.

Experimental features of GAE instabilities

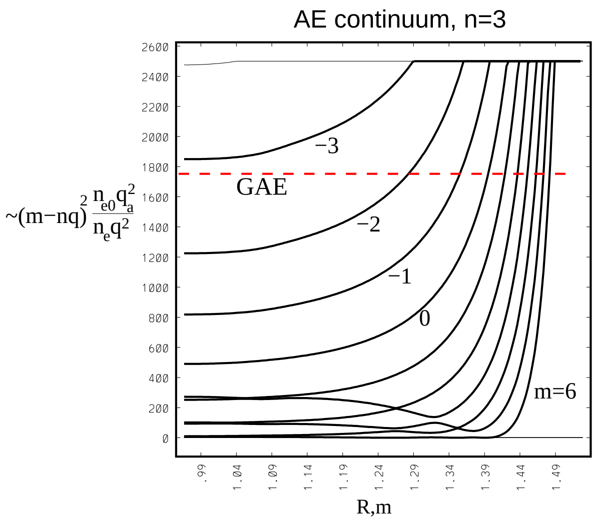


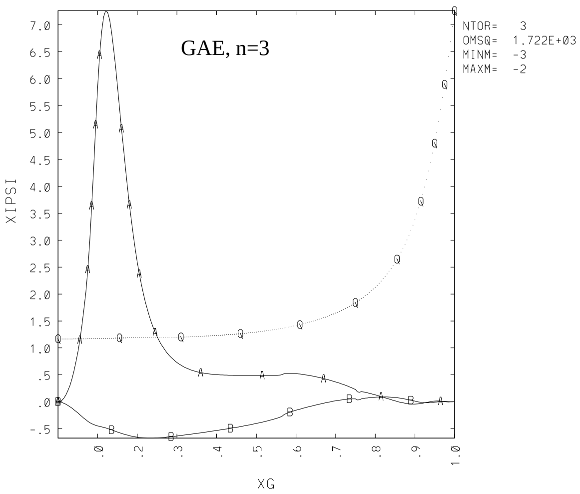
Dashed curves are GAE dispersion $\omega_{GAE} \simeq v_{A0}(m - nq_0)/q_0 R$.

- Observed frequencies of different (m,n) modes intersect
  $\Rightarrow$ characteristic of shear Alfvén Eigenmodes.
- We identified them as Global Alfvén Eigenmodes (GAE), (APPERT, 1982).
- GAEs (center) become stable after sawtooth, whereas CAEs (edge) become unstable.

N.N.Gorelenkov, E. Fredrickson, E. Belova et.al., iaea'02, NF'03.

Alfvén continuum and GAE structure from NOVA

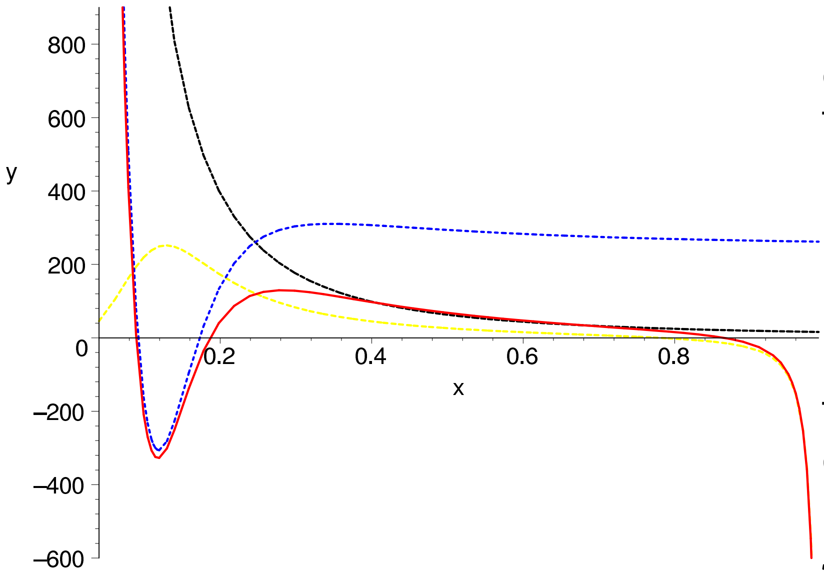




$\omega_{GAE} \simeq v_{A0}(m - nq_0)/q_0 R$.

- Many radial modes can exist below each A-continuum line
  - Frequencies are shifted downward from the continuum up to 30%.

GAEs are localized in the core due to density and q-profiles



GAEs are localized near the center. Potential well is

$$V(x) \simeq V'(x) = \left(m^2 - 1/4\right)/x^2$$
$$+2\sigma\omega_{A0}^2/D\left(g - x^\delta\right) + C$$

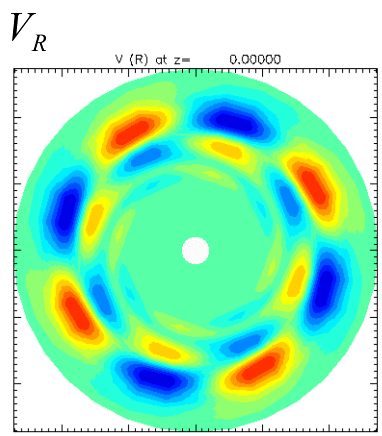
for the Alfvén continuum $\omega_A^2 = \omega_{A0}^2 + Dx^\delta$. GAE dispersion

$$J_{m-1}\left(\left(\frac{-2\sigma\omega_{A0}^2}{Dg} - C\right)^{1/2}(-g)^{1/\delta}\right) = 0$$

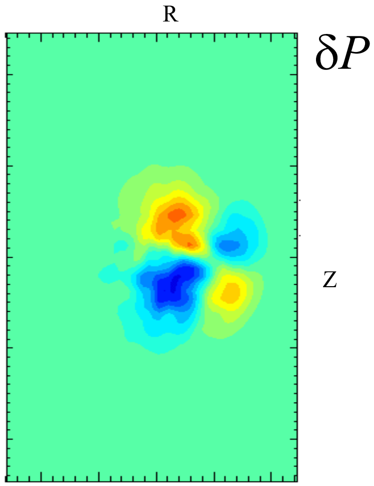
Standard continuum damping calculation produces damping rate to the order of magnitude $\Im\delta\omega/|\omega_0| \sim (x_2/x_s)^{2m+\delta}$ is small for large to medium m's (Gorelenkov, NF, '03).

GAE mode radial width is proportional to m^{-1}.

HYM simulations show localized GAEs at low-n (E.Belova)



Contour plot of radial component
of fluid velocity at equatorial plane.



Contour plot of perturbed fluid
pressure in poloidal plane.

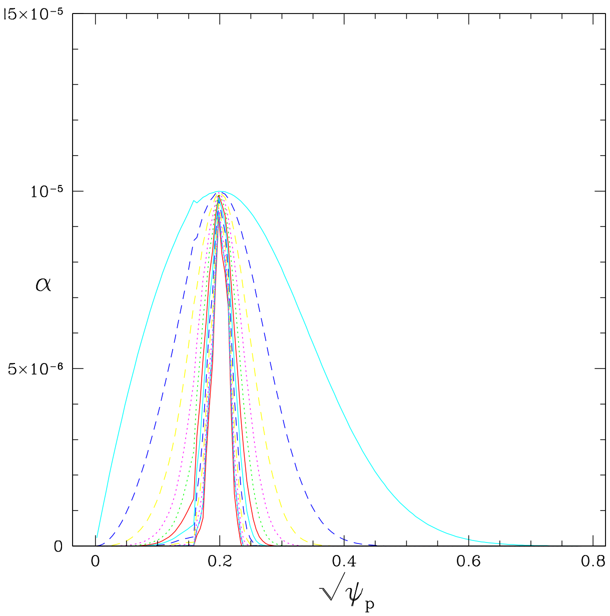
- Mode has characteristics of GAE with $n = 4, m = 2$, frequency is consistent.
- Large $k_{\|}$, significant compressional polarization: $\delta B_{\|} \sim \delta B_{\perp}/3$
- Qualitatively the same poloidal, radial structure as in NOVA

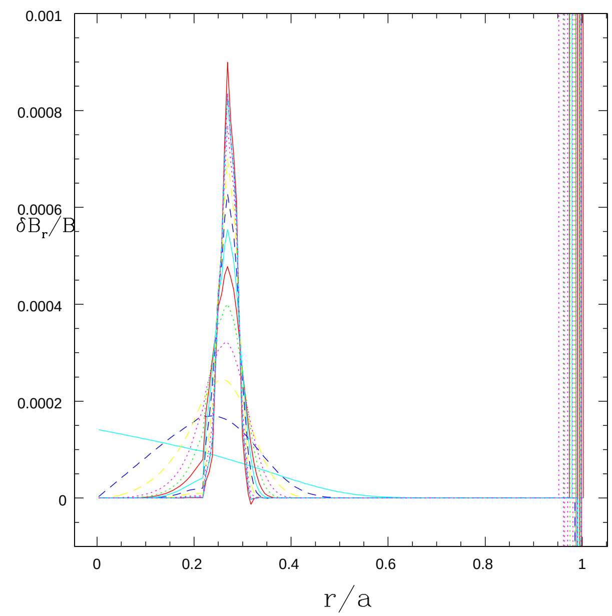
Comparison CAE/GAE instability properties

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

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

Employ ORBIT to study e-transport due to GAEs





ORBIT ideal MHD perturbation:

$$\delta B = \nabla \times \alpha \mathbf{B}, \ \alpha = \alpha_0 e^{-m^2(r-r_0)^2/\delta r^2}.$$

Baseline case:

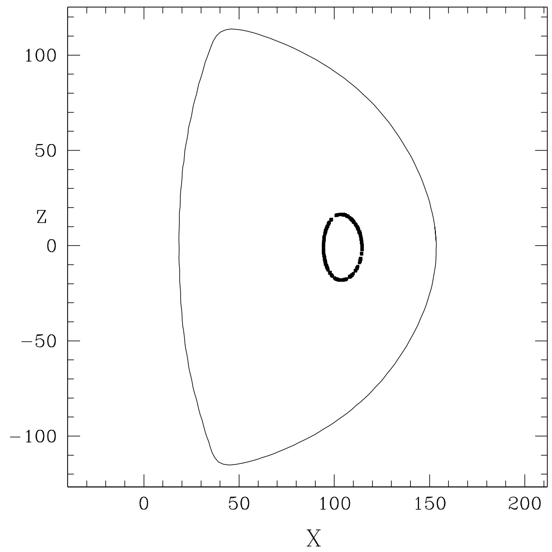
- $\alpha_0 = 10^{-5} \Rightarrow \delta B_r/B = 10^{-4}$ at $r/a = 0.14$.
- 12 GAEs with $n = 1-10$, m is such that $f = 400-600kHz$.

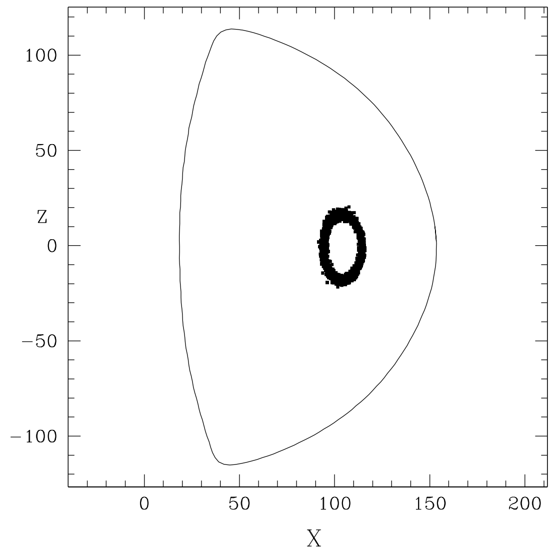
Characteristic frequencies

- $f_{GAE} \sim 400 - 600kHz$, may go higher.
- transit (passing) frequency $f_{te} = \frac{1}{2\pi}\frac{v_{\parallel}}{qR} = 1.5MHz\ T_e = 1keV$,
- 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 $\omega_{ce} = 0.7 \times 10^{11} sec^{-1}$, $\nu_e/\omega_{ce} = 3 \times 10^{-7}$, but e-i collisions may double this.
- thermal ion cyclotron frequency $f_{ci} = 3MHz$.

$f_{GAE} \sim f_{be}$ and may be $\sim f_{te}$!!!

Initial and final e-distributions

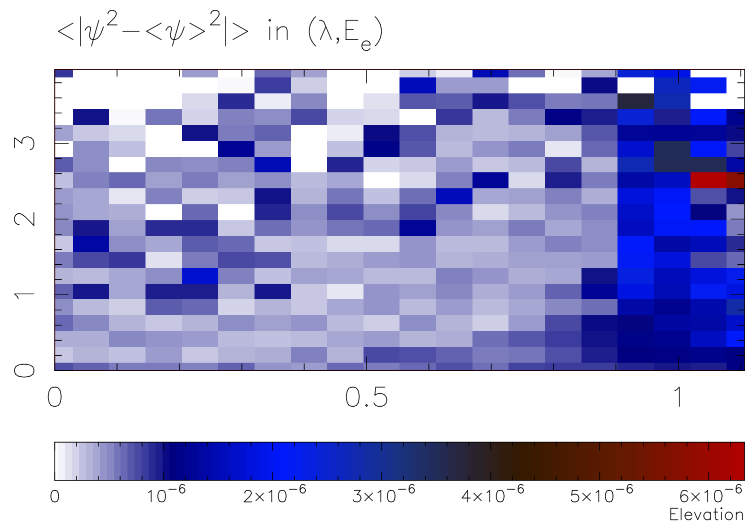




Initial ring distribution of electrons on one surface.

ORBIT run for $3ms$ with Maxwellian electrons with $T_e = 1keV$.

Which electrons are interacting?



Evaluate characteristic displacement for different electrons $T_e = 1keV$

$$\left\langle \left| \psi^2 - \langle \psi \rangle^2 \right| \right\rangle,$$

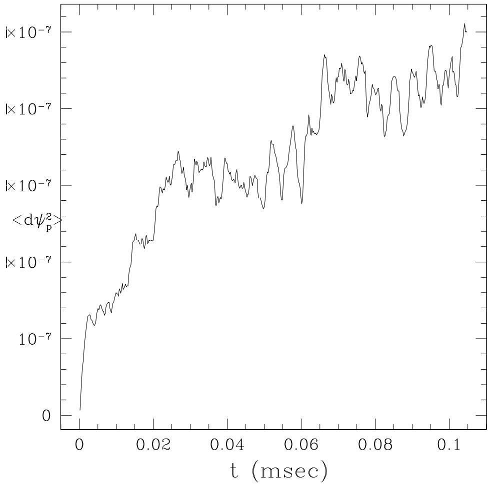
in $\lambda = \mu B_0 / E$, E plane.

Trapped electrons as opposite to passing ones are mostly effected by GAEs $\lambda \simeq 1$. Weak passing electron interactions are due to $\omega - k_\| v_\| = 0$ or $\omega = k_\| \sigma_\| \sqrt{2E}\sqrt{1-\lambda}$.

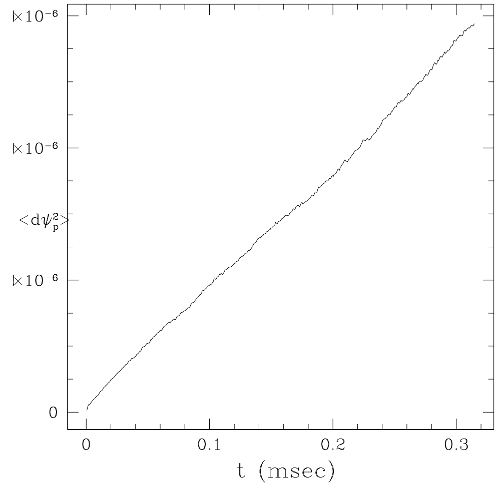
Electrons diffuse in radius w/out and with collisions

typical radial diffusion vs time

$\overline{\nu}_e = 0$
$D = 10^{-2} m/sec$



$\overline{\nu}_e = 3 \times 10^{-7}$
$D \simeq 10^{-1} m/sec$

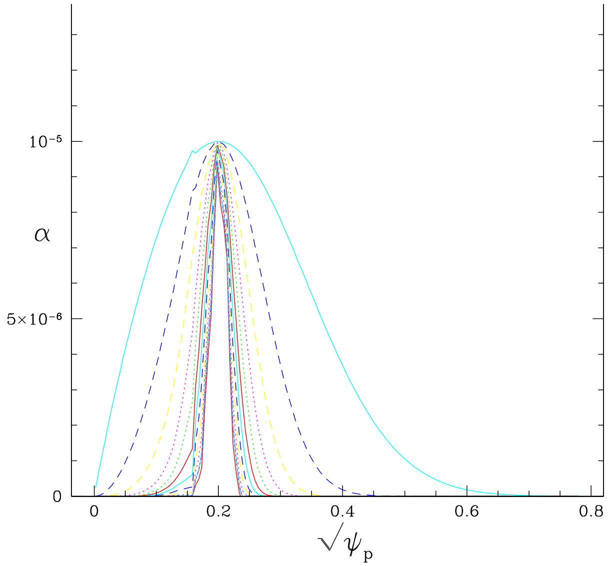


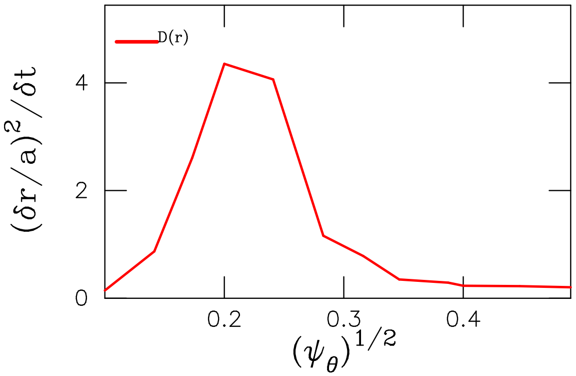
Here $\alpha = 10^{-5}$.

Typical run is for $1 - 3 ms$.

Radial dependence of electron diffusion

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



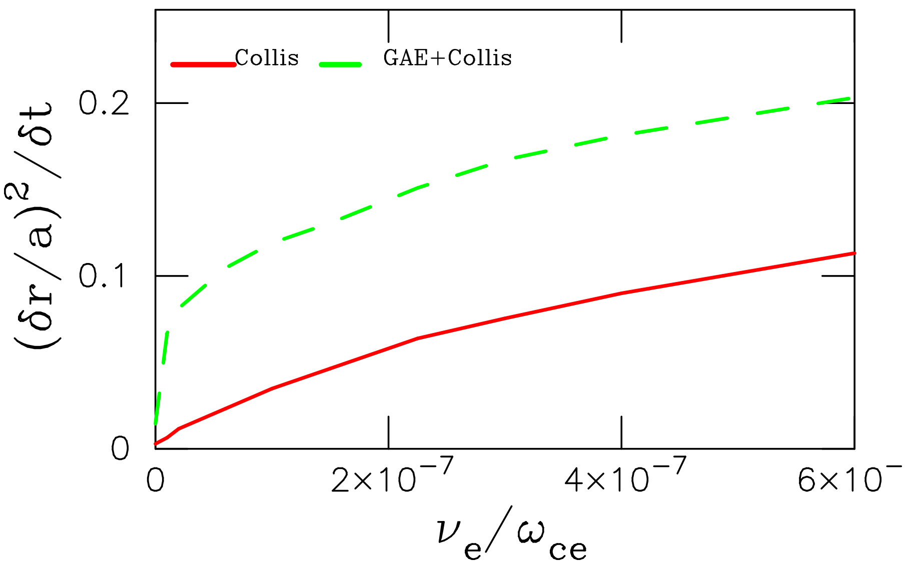


Peak of $D(r)$ is near the mode amplitude peak.

Low-m modes contribute more to the diffusion.

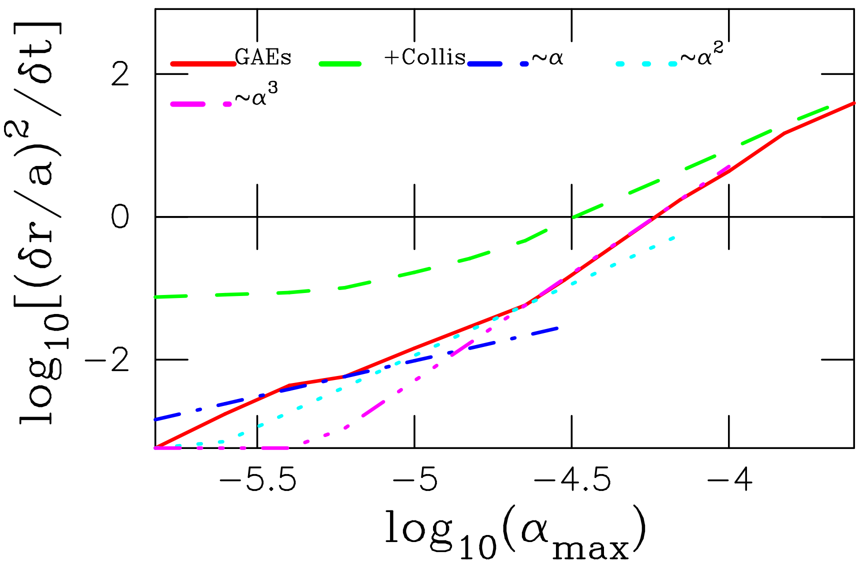
Baseline radial point is at $r/a = 0.14$.

ν_e dependence of electron diffusion



Baseline case $\alpha = 10^{-5}$, $\nu_e/\omega_{ce} = 3 \times 10^{-7}$, and $r/a = 0.14$.

GAE amplitude dependence of electron diffusion



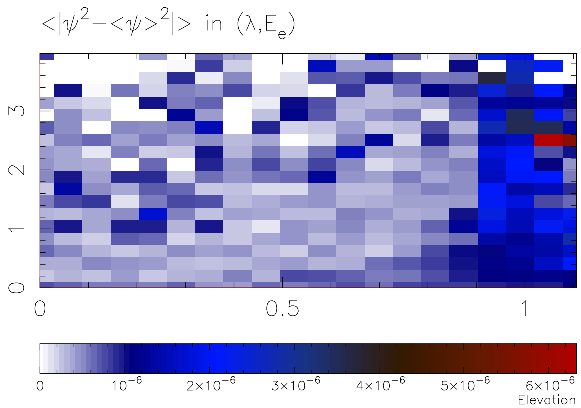
Baseline case $\alpha = 10^{-5}$ and $\nu_e/\omega_{ce} = 3\times10^{-7}$. Shown is diffusion at $r/a = 0.14$. D is higher at peak by ~ 4 times.

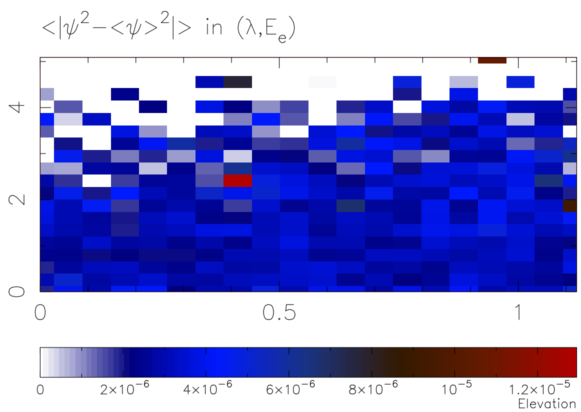
Expected diffusion at resonance island overlap is $D\sim\alpha$. $\Rightarrow$ if $D \sim \alpha^2$ then secondary islands generations/overlaps are expected.

Summary

- GAEs with sufficiently strong amplitude can induce electron transport in NSTX.
- Electron transport is due to resonances of trapped electrons with GAEs at $f = 400 - 600kHz$.
- Phase space resonance overlapping is the mechanism of e-transport.
- Although for trapped electrons $E_{\|}$ is not important it maybe important for passing electrons diffusion. ORBIT may not have exact cancellation of parallel electric field. This should be worked out in detail.

frequency dependence of GAE driven e-diffusion





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