Theoretical and Numerical Studies of Electron Transport Induced by Beam Ion Driven GAEs

N.N. Gorelenkov, E. Fredrickson, S. Kaye, R. White
PPPL, Princeton University
L. Delgado-Aparicio, D. Stutman, K. Tritz
Johns Hopkins University
A. Boozer
Columbia University

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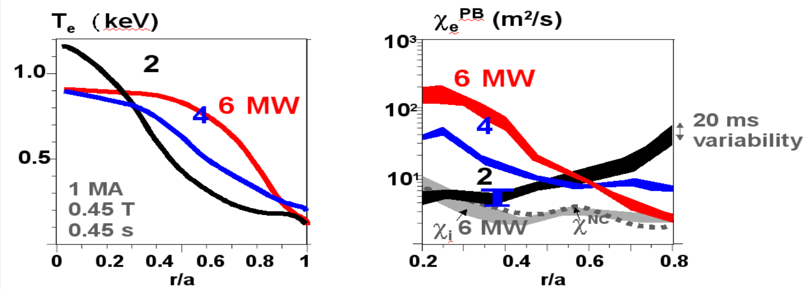
PPPL PRINCETON PLASMA PHYSICS LABORATORY

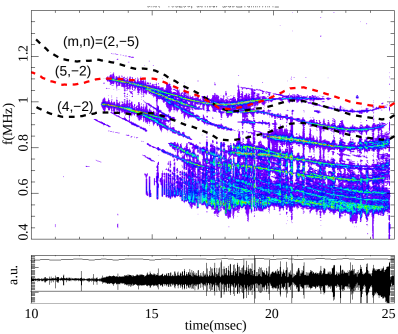
T_e flattens in NSTX H-mode shots as P_b increased



- Not caused by low-f MHD or fast ion radial distribution
- $\chi_e^{PB} \geq 10 m^2/s$ inside $r/a \leq 0.4$, while $\chi_i \sim \chi_i^{NC}$
- Perturbative experiments support PB transport picture with the uncertainties included
  (Stutman, et.al. PRL'09, K. Tritz, T&T session today)

Outline

High-f GAE instabilities were indentified in NSTX



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

GAEs - Global Alfvén Eigenmodes (Appert, 1982):

- 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 and if $\omega < \omega_{ci}$: may expect effects on electrons.

(N.N.Gorelenkov, E. Fredrickson, E. Belova et.al., IAEA'02, NF'03, and Belova later on).

Outline

Characteristic frequencies of electron drift motion are close to GAE's frequencies

- Instabilities at $f_{GAE} \sim 500 - 1000kHz$, 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 $\nu_e/\omega_{ce} = 3 \times 10^{-7}$ $(\omega_{ce} = 0.7 \times 10^{11} sec^{-1})$, e-i collisions double this.
- thermal ion cyclotron frequency $f_{ci} = 3MHz$.

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

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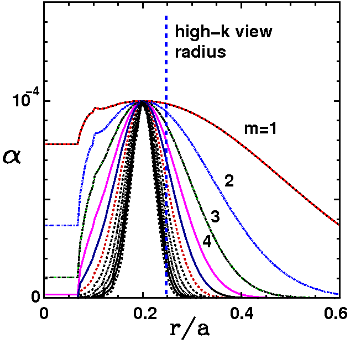
Employ ORBIT to study e-transport due to GAEs

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



ORBIT ideal MHD perturbation, $E_\parallel = 0$:

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

and $\delta B_r/B \simeq i k_\theta \alpha = i\alpha m/r$.
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).
- 16 or 31 GAEs with $n = 1-10$, m is such that $f = 500-1000 kHz$ - observed window.

Use ORBIT for the physics *insight* into the driven e-transport

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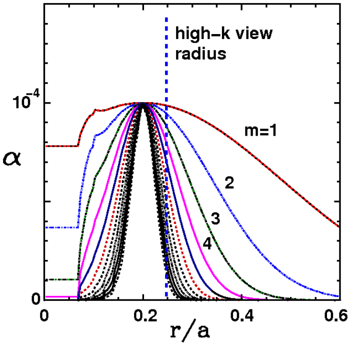

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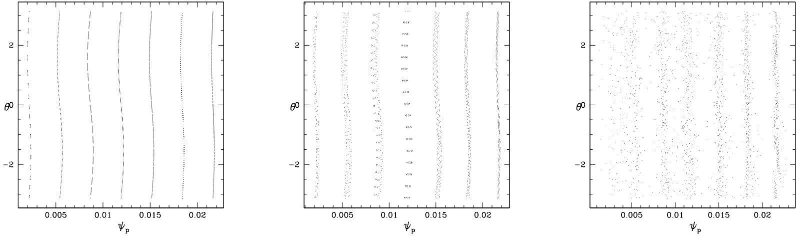
Electrons make radial excursions due to δB_r and $[E_\theta \times B]$ drift

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

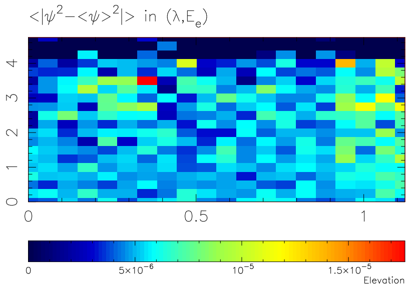
1 mode, $\xi_{re} \sim \delta B_r / B k_\parallel$ $(m,n) = (-3,1)$; $f_1 = 510 kHz$ — 2 modes $(f_1 \neq f_2)$ — $N = 20$ modes $(f_i \neq f_j)$



Multiple GAEs ($>N = 10$) introduce stochasticity in electron drift motion ω_{dr} or f_{GAE} dephase electron-GAE interaction

At weak amplitudes resonant interaction dominates

Take $\alpha_0/R = 10^{-4}$ case, 31 modes, no collisions, $\bar{\psi} = 0.05$



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

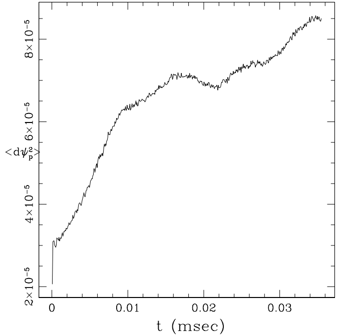
$$\left\langle \left| \psi^2 - \langle\psi\rangle^2_{\mathbf{v}} \right| \right\rangle_{\mathbf{v}},$$

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

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

Use particle code to simulate electron thermal conductivity

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



- introduce ambipolar potential
- electrons are attached to ions, $\Gamma_e = 0$, but can transfer energy
- χ_e is on the same order as D_e

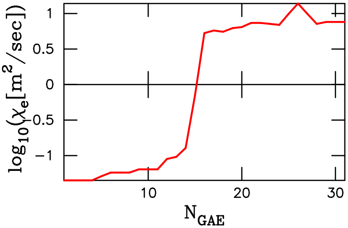
$$\frac{\chi_e}{D_e} = \frac{\left\langle \mathscr{E}^2 D_e \right\rangle}{T_e^2 \left\langle D_e \right\rangle} - \frac{\left\langle \mathscr{E} D_e \right\rangle^2}{T_e^2 \left\langle D_e \right\rangle^2}.$$

- $\chi_e = 3D_e/2$ for weakly perturbed Maxwellian

Outline

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.
Construct the random walk:

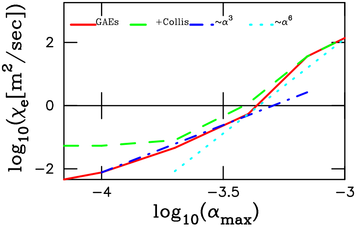
$$\xi_{re}^2 = \left(\frac{\delta B_r}{k_\parallel B}\right)^2.$$

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

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

but this estimate gives $D \sim \alpha^2$??

e-transport strongly growth with GAE amplitude



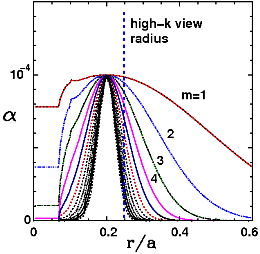
Baseline case $\nu_e/\omega_{ce} = 6 \times 10^{-7}$.
Shown is diffusion at $r/a = 0.22$.

Small amplitude $\chi_e \sim \alpha^3$.
Large amplitude $\chi_e \sim \alpha^6$.

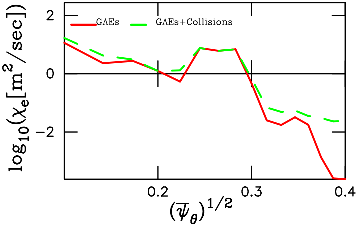
Collisions have small effects at large amplitudes.

Radial dependence of χ_e

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



$\alpha_0/R = 4 \times 10^{-4}$



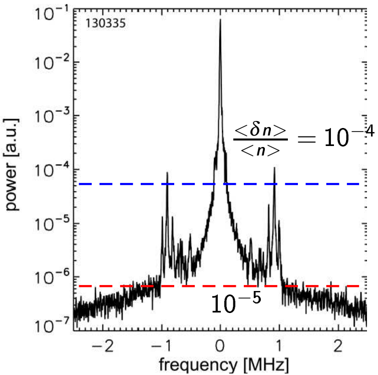
Peak of $D(r)$ is near/outside the mode amplitude peak.
Low-m modes contribute more to the diffusion.

$$\frac{\chi_e}{D_e} = \frac{\langle \mathcal{E}^2 D_e \rangle}{T_e^2 \langle D_e \rangle} - \frac{\langle \mathcal{E} D_e \rangle^2}{T_e^2 \langle D_e \rangle^2}.$$

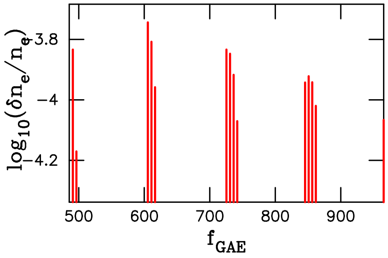
Outline

GAE amplitudes in experiments vs used in the model

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

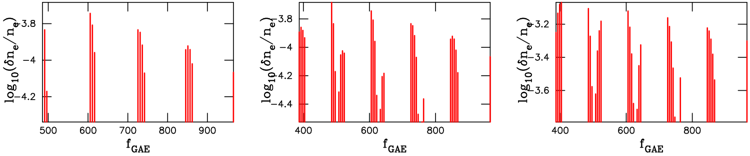


16 modes are shown from simulations $\alpha_0 = 1.5 \times 10^{-4}$.



GAE amplitude spectrum in a model

16 modes, $\langle \delta n \rangle / \langle n \rangle$ 31 modes, $\langle \delta n \rangle / \langle n \rangle$ local $\delta n / n_{max}$



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

This is within measured accuracy (factor 2) of the intermitten GAE amplitudes given the uncertainty in the mode structure.

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
  - resonances of electrons with GAEs at $f = 500 - 1000kHz$.
- overlap of electron radial motion due to $\delta B_r/B$ is the mechanism of e-transport.
- comparison with high-k interferometry shows that the observed GAE amplitudes within the measurement accuracy (2 to 3) and given uncertainty in the mode structure provides the lower end of the inferred electron thermal conductivity, $\chi_e = 10m^2/s$.
- $E_{\parallel}$ strongly enhances radial diffusion. Need to search for $E_{\parallel}$ effects in experiment and theory.
- interaction between GAEs and turbulence has to be studied.