Nonlinear Evolution and Radial Propagation of the Energetic Particle Driven GAM

by
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Outline

- Mode excitation/structure
- Comparison to linear E-GAM theory
- Nonlinear E-GAM evolution
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Recipe for E-GAM Excitation in DIII-D: Counter Tangential Beam Injection with High $q_{\text{min}}$

- 80 keV beam ions, $\beta_{\text{fast}} \sim \beta_{\text{thermal}} < 1\%$

![Graph showing I_p (MA) and P_{NBI} (MW) vs. Time (sec.)](image1)

![Graph showing V_b/V_A vs. Time (sec.)](image2)

![Graph showing q and $n_e$ vs. sqrt($\Psi_{\text{pol}}$)](image3)
Intense Bursting observed with Counter beam injection in DIII-D

- 10-15% neutron drops with each mode burst
- Possible evidence for hole/clump formation

(H.L. Berk and B. Breizman)
Radially Resolved BES Measurements Reveal Global n=0 mode, no Te fluctuations

- Peak density mode amplitude near midplane can be as high as 5-8 %
- Upper bound on temperature fluctuation set by ECE photon noise
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Theory Predicts Global nonperturbative GAM Driven via Beam Ion Bounce Resonance

- Mode exists for $\omega_b \sim \omega_{GAM}$
- pure zonal flow, no $T_e$ component
- Large linear growth rate (30%) consistent with bursting/chirping
Up/Down Standing Wave Prediction Confirmed Using Vertical BES Detector Array

- flip of sign observed across midplane, consistent with standing wave pattern
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Nonlinear Perturbed Density Associated with the E-GAM

\[
\frac{\delta \rho}{\rho} = -\frac{r}{R} \left[ 2 \hat{E}_r \sin(\theta) \sin(\omega t) + \frac{1}{2} \hat{E}_r^2 \cos(\theta) (1 - \cos(2\omega t)) \right]
\]

- Where \( E_r \) is the normalized radial electric field.

- Note that the second term is always negative and the first term can have either sign.

\[ \sin(\theta) > 0; \text{ above midplane} \]
\[ \sin(\theta) < 0; \text{ below midplane} \]
Hybrid Simulation of E-GAM Burst Consistent with Observation on DIII-D

G. Fu, J. Plasma Phys. 2010

- DC density component is negative on midplane
- Second harmonic peaks on midplane, while fundamental goes through zero
Nonlinear Perturbed Density Associated with the E-GAM

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\[ \sin(\theta) > 0; \text{ above midplane} \quad \text{and} \quad \sin(\theta) < 0; \text{ below midplane} \]
DC and Second Harmonic Stay in Phase, Fundamental Flips Phase, Across Midplane

- Some third harmonic is also contributing
Nonlinear Model Predicts Amplitude of Electric Field Fluctuation and peak density fluctuation

\[
\frac{\delta \rho}{\rho} = -\frac{r}{R} \left[ 2 \hat{E}_r \sin(\theta) \sin(\omega t) + \frac{1}{2} \hat{E}_r^2 \cos(\theta)(1 - \cos(2\omega t)) \right]
\]

\[
\left( \frac{\delta \rho_{2\omega}}{\rho} \right)_{\theta=0} = \frac{r}{2R} \hat{E}_r^2
\]

\(\hat{E}_r\) : normalized radial electric field

- Next step is to infer \(E_r\)
- In principle can compare with BES measured advection of microturbulence
Outward and Inward Radial Propagation of E-GAM Observed in Reverse Magnetic Shear Plasmas

- $q_{\text{min}}$ is not aligned with reversal of propagation
Outward Radial Propagation Predicted Analytically, Inward Propagation Needs Understanding

- Theory predicts GAM standing wave in region of energetic particle induced potential well
- Outward propagating solution due to tunneling out of well
- Does reverse magnetic shear induce inward propagation?
- More realistic model required.
Recent Electrostatic Hybrid Full-f Simulation Reveals Outward Propagation Consistent with Experiment – G. Fu

- Mode exists at 15 kHz, close to experimental value

- Outward propagation and increasing $k_r$ with radius consistent with experiment

- No inward propagation seen in simulation
  - note, inward propagation comes late in experimental data

- More realistic simulation required using actual beam deposition profile
  - currently using analytic beam
Summary

• Key nonlinear predictions on E-GAM structure validated with experiment
  - DC, second harmonic coupling
  - outward radial propagation

• Nonlinear theory and simulation can help infer $E_r$ from second harmonic amplitude
  - compare to turbulent advection due to ExB

• Outstanding issues:
  - is inward propagation a property of strong negative magnetic shear?

• More realistic analytic and numerical modeling required