Energetic Particle-induced Geodesic Acoustic Mode: Theory and Experiment

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Outline

- Introduction
- DIII-D Experiments
- Analytic Theory and Simulations of EGAM
- Summary

Geodesic Acoustic Mode (GAM)

- GAM is an axisymmetric mode (n=0) in tokamaks and is mostly of m=0 (i.e., electric potential is almost constant on flux surfaces);
- GAM oscillations result from compression of poloidal ExB flow due to geodesic curvature in toroidal geometry;
- GAM frequency ~ v_t/R;
- The mode is usually stable due to n=0 (i.e., no universal drive due to radial gradient). Thus usually it can only be driven nonlinearly by micro-turbulence.
- However, energetic particles could provide instability drive via velocity space gradient for inverted distribution function (dF/dE >0).

Energetic Particle-driven GAM (EGAM)

- An n=0 mode observed in JET and Berk et al's explanation of energetic particle-driven GAM;
- Recent DIII-D results showed count-injected beam ions can excite a n=0 GAM-like global mode (Nazikian et al, 2008, PRL);
- EGAM could be excited in ITER by NBI in reversed shear plasmas;
- EGAM may affect plasma micro-turbulence.
- Alpha-channeling?

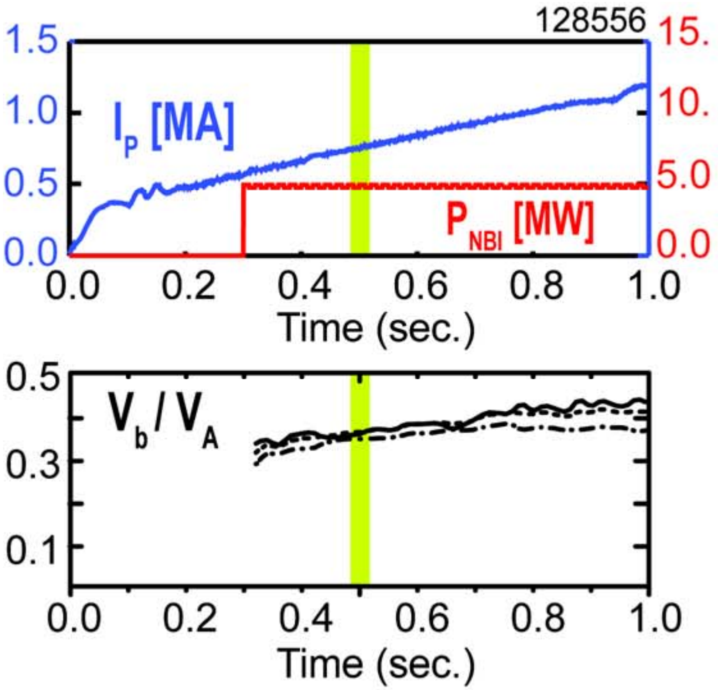
The DIII-D Experiments of beam-driven n=0 GAM-like mode

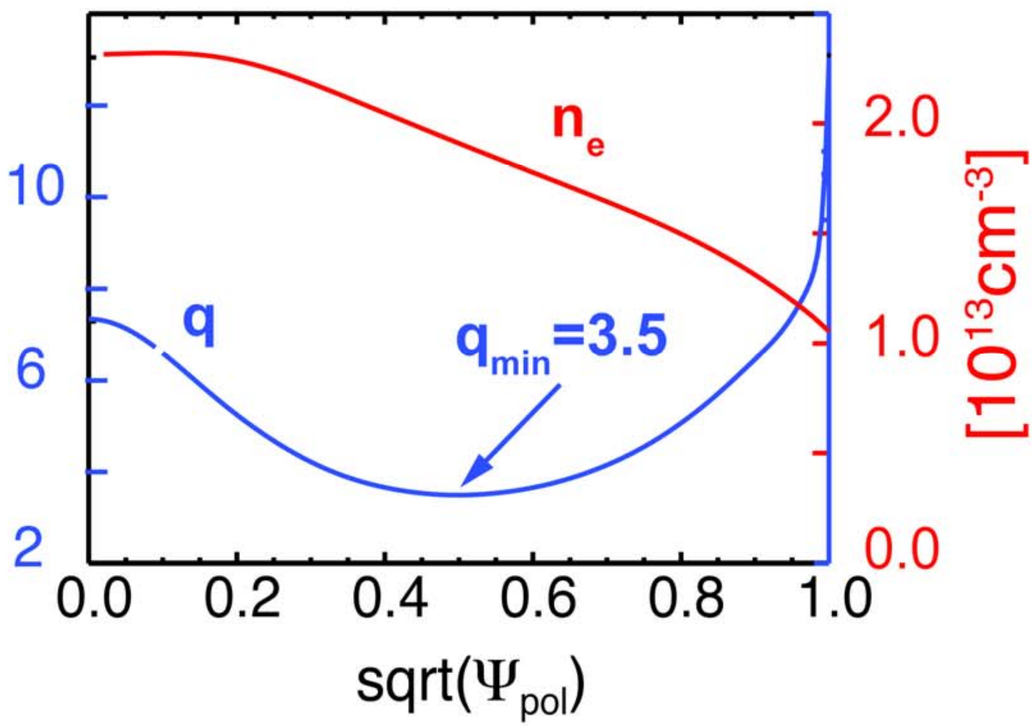
R. Nazikian et al., Phys. Rev. Letts. **101**, 185001 (2008).

Global GAM-like mode observed with counter beam injection in high q_{min} DIII-D Plasmas

- Modes are qualitatively different from GAMs excited by turbulence
  - radially extended n=0 mode excited at high q_{min}(>2)
  - mode frequency inside GAM continuum: not ideal MHD mode and not a continuum mode
  - intense mode bursting, frequency chirping, neutron drops: strong beam ion interaction
- Mode is EPM: no ideal GAM solution found using NOVA

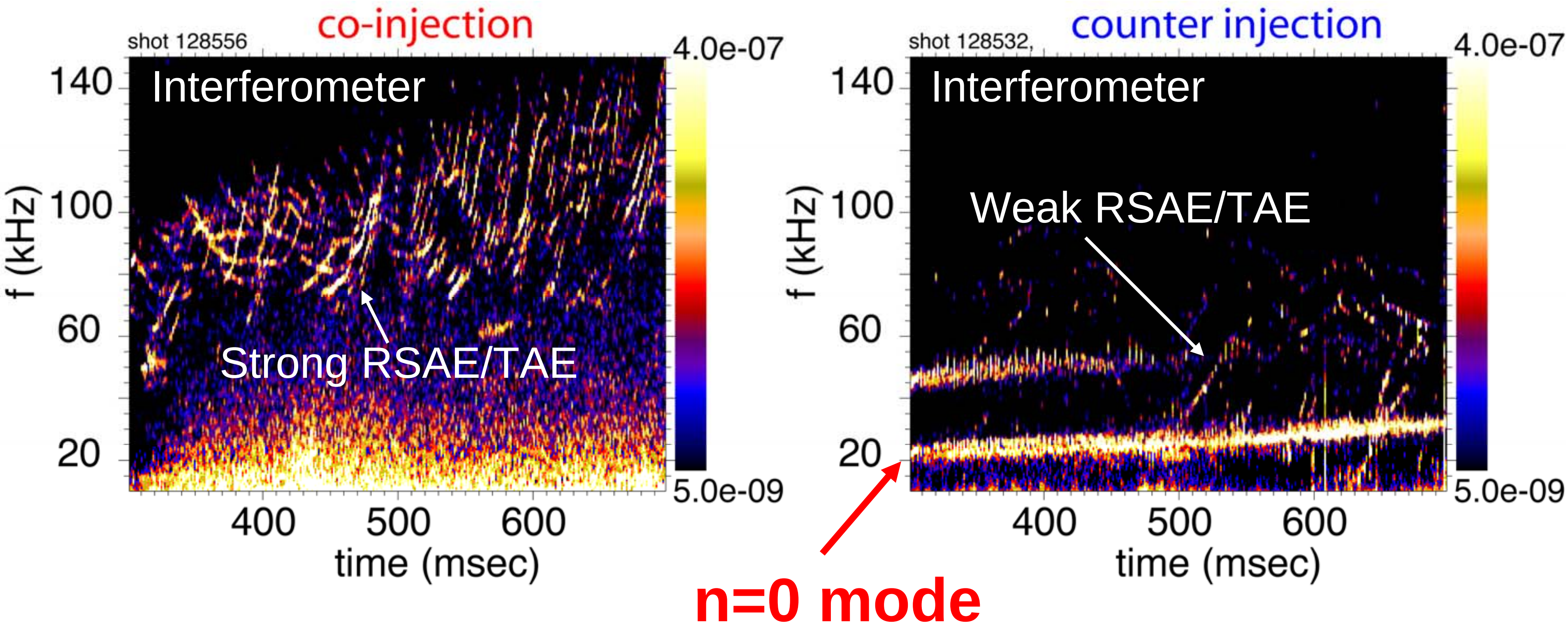
DIII-D target plasmas: early counter beam injection Reverse Magnetic Shear, high q_{min}





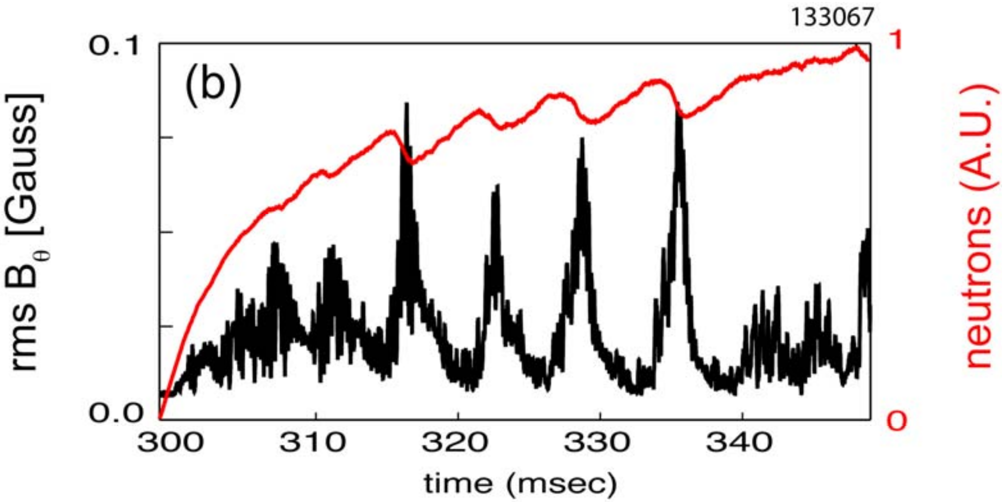
- Early beam heating is used to delay current penetration and create reverse magnetic shear

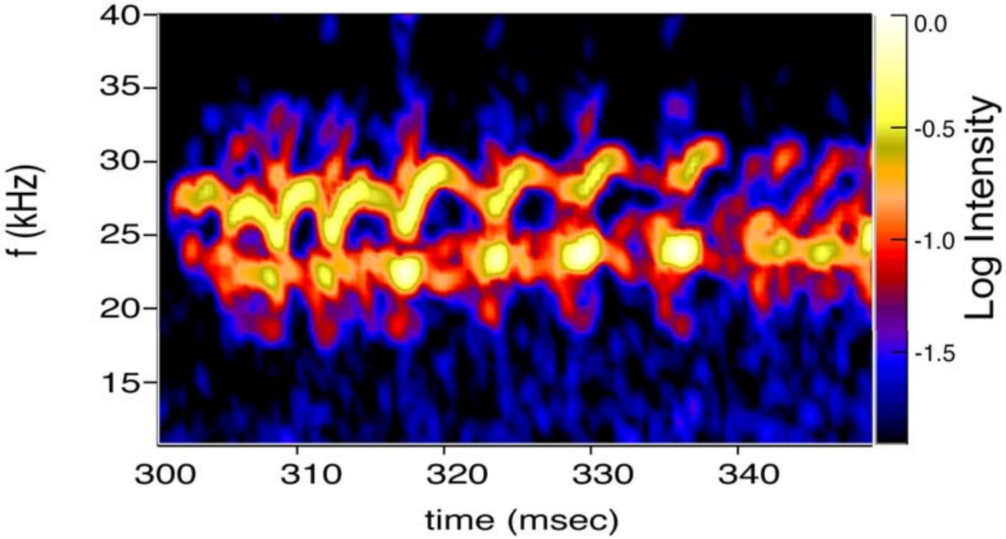
Mode Activity Very Different for 5 MW Co and Counter Beam Injection in DIII-D



- **P_{inj} = 5 MW co/counter injection, starting at 300 ms**
- **weak n=0 transiently observed with co injection**

Neutron Drops with Frequency Chirping, bursting Indicate Intense Beam Ion Interactions

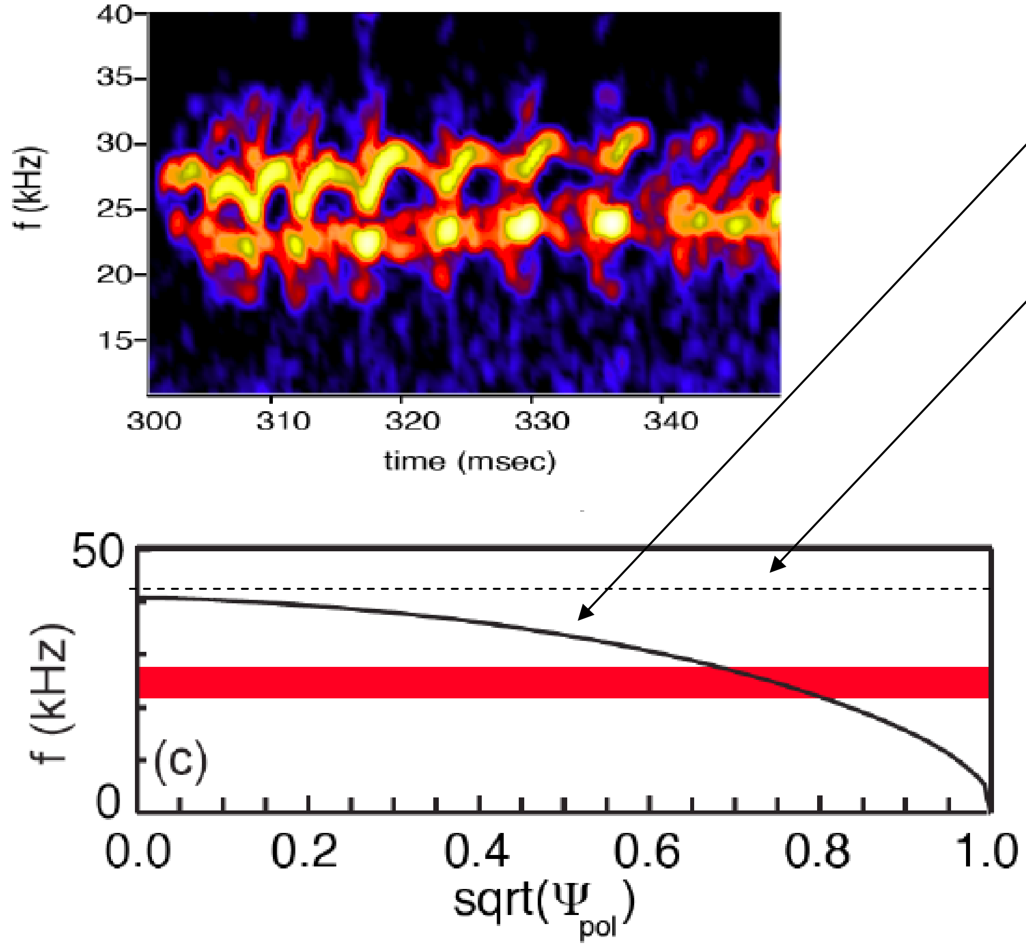




- 10-15 % neutron drops with each burst
- bursting, frequency sweep seen on Mirnov coils
- chirp/burst pattern indicates strong drive, large linear growth rate
- small amplitude at wall $\delta B/B \sim 10^{-5}$

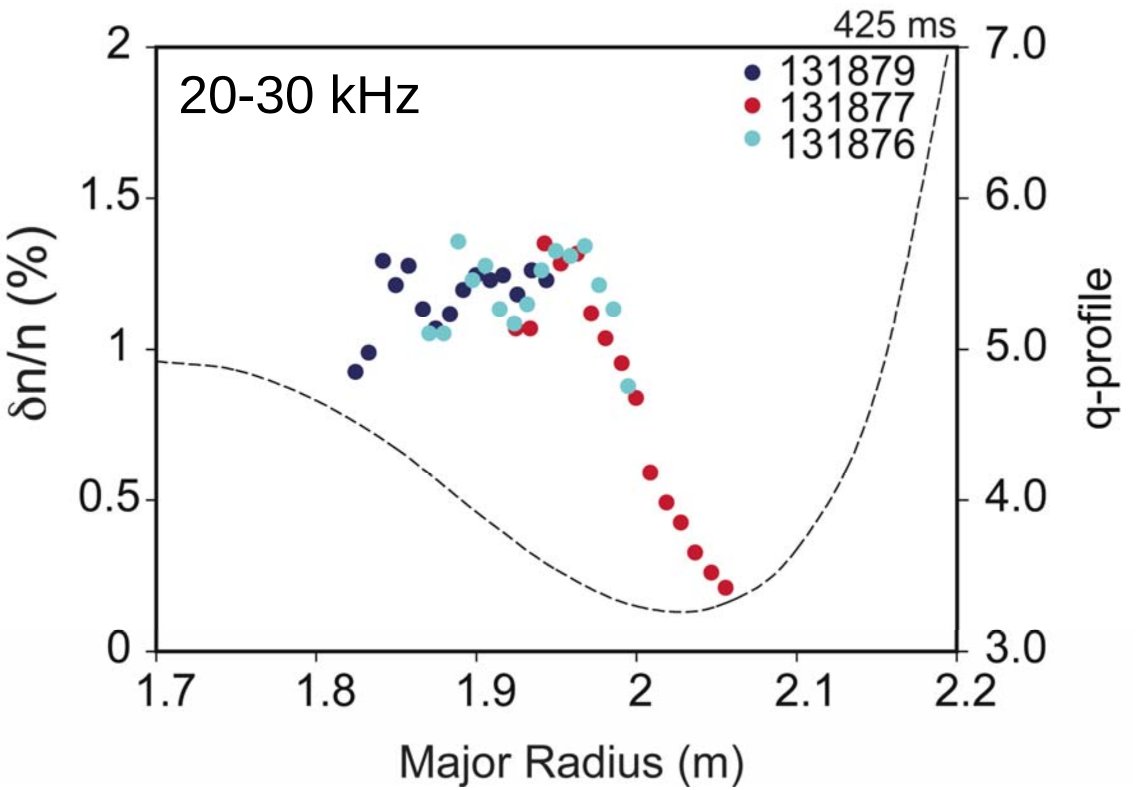
Mode Frequency Well Below ideal GAM frequency

$\delta B/B \sim 10^{-5}$, n=0 at wall



- n=0 GAM continuum
  $\omega \approx 2C_s/R$
- ideal GAM can only exist above the continuum
  - no NOVA solution
- Local GAM continuum (kinetic GAM) can be driven by turbulence
- Mode frequencies well below peak in the continuum
  - not the ideal GAM
- Mode structure is global, not the local kinetic GAM

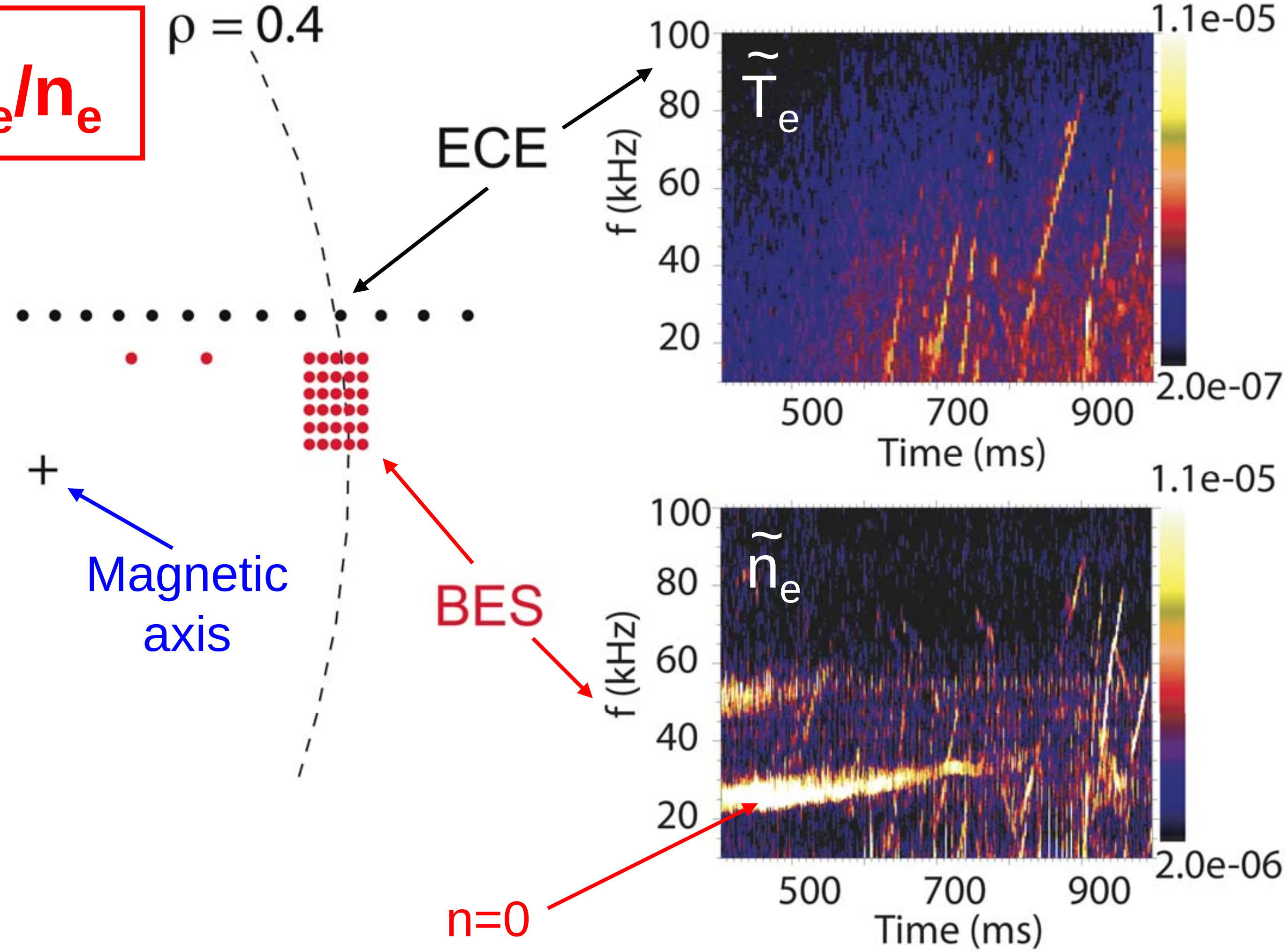
BES Radial Array Resolves Global Mode Structure: Not consistent with localized Continuum Modes



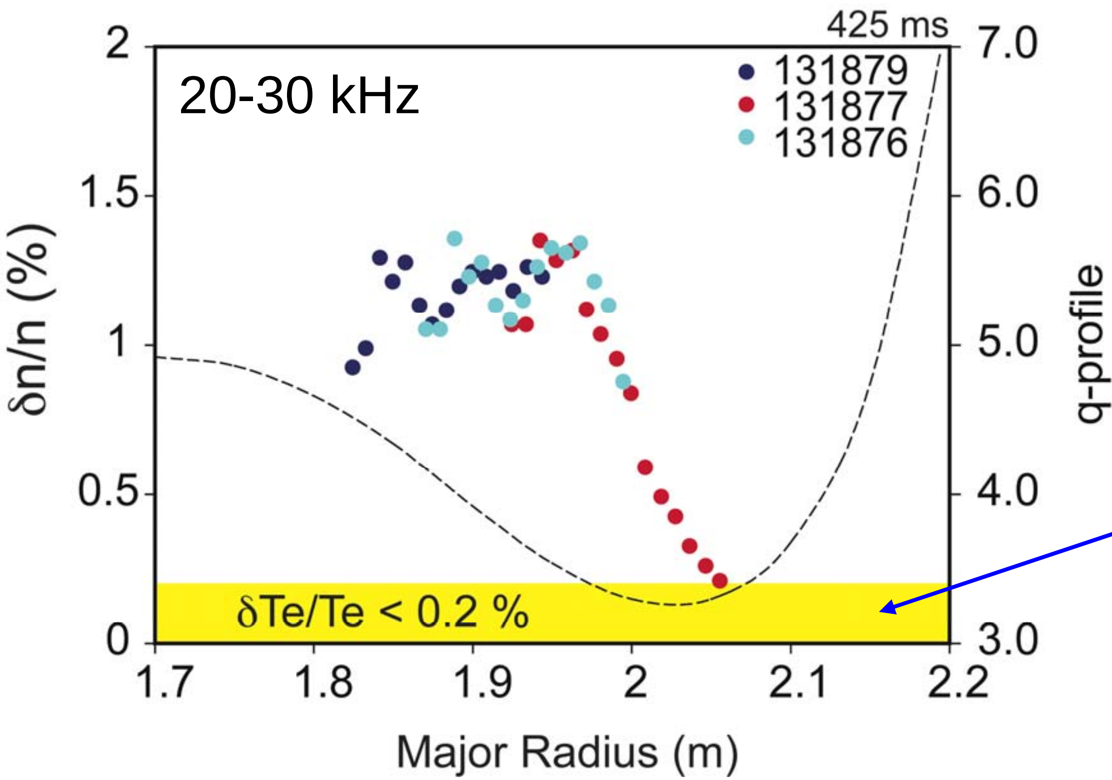
- Profile is a composite of three reproducible discharges
- 16 channel radial BES array shifted between shots
- z=+6 cm above axis

Internal Measurements Reveal No Electron Response for the n=0 mode

$\tilde{T}_e/T_e \ll \tilde{n}_e/n_e$



Absence of temperature fluctuations consistent with dominant radial electric field (GAM-like mode)



- **electrons are isothermal along field lines (ω_e^{tr} ~ 400 kHz>>ω)**
- **Hence δTe requires radial displacement**

  $\xi_r . \partial Te / \partial r$
- **$\delta T_e << \delta n_e$ for small ω means tangential mode displacement ξ_θ**
  - **weak ξ_r means weak $\delta T_e/T_e$ and B_θ**
- **consistent with $v_\theta = E_r x B$**
  - **compressional δn_e**

Analytic Theory and Simulation of EGAM

G.Y. Fu, Phys. Rev. Letts. **101**, 185001 (2008)

Hybrid Model for GAM

Consider n=0 electrostatic perturbation

$$\rho \frac{\partial}{\partial t}\mathbf{v} = -\nabla \cdot \delta\mathbf{P} + \delta\mathbf{J} \times \mathbf{B}$$

$$\delta\mathbf{P} = \delta P_{\perp}\mathbf{I} + (\delta P_{||} - \delta P_{\perp})\mathbf{bb}$$

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$$

Assume isothermal fluid model for electrons;
Use drift-kinetic equation to describe both thermal ions and energetic ions

Hybrid Equations for Energetic Particle-induced GAM

$$\frac{\partial}{\partial t}\nabla\cdot\rho\frac{\mathbf{v}\times\mathbf{B}}{B^2}=\nabla\cdot\frac{\mathbf{B}\times\nabla\cdot\delta\mathbf{P}}{B^2}+\mathbf{B}\cdot\nabla\frac{\delta\mathbf{J}\cdot\mathbf{B}}{B^2}$$

$$\frac{\partial}{\partial t}<\frac{\rho|\nabla r|^2}{B^2}>E_r=-<G(r,\theta)(\delta P_{||}+\delta P_{\perp})>$$

$$G(r,\theta)=-\frac{B_\phi R}{JB^3}\frac{\partial B}{\partial\theta}$$

$$\delta P_{||}+\delta P_{\perp}=\int d^3v(mv_{||}^2+\frac{1}{2}mv_{\perp}^2)\delta f$$

$$\frac{d\delta f}{dt}=-\frac{dE}{dt}\frac{\partial f}{\partial E}=-(mv_{||}^2+\frac{1}{2}mv_{\perp}^2)\frac{\partial f}{\partial E}G(r,\theta)E_r$$

EGAM dispersion relation: zero orbit width limit

$$\omega^2 = \omega_{GAM}^2 + \frac{< P_{||h} + P_{\perp h} >}{\rho R^2} Q_h(\frac{\omega}{\omega_{b0}})$$

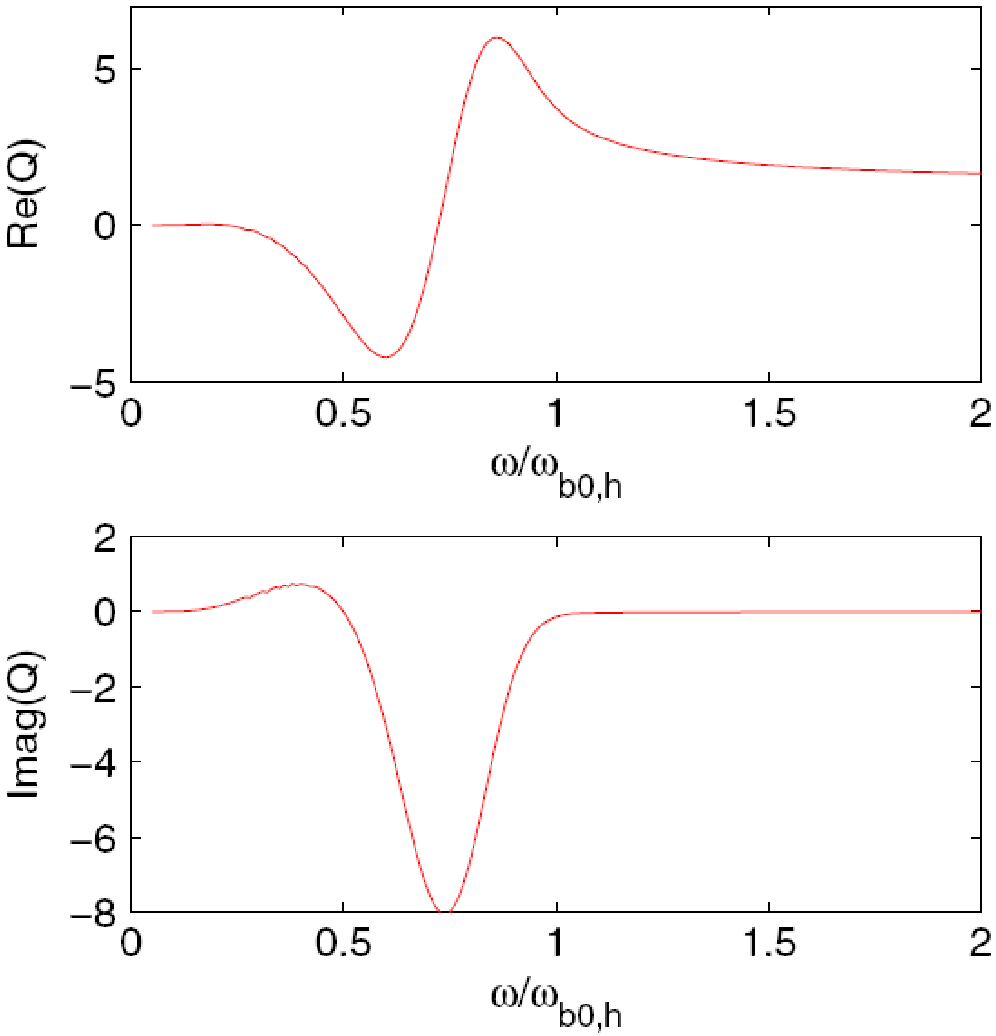
$$Q_h = -\frac{2\int \frac{\partial f}{\partial E} E^3 dE d\Lambda \tau_b H_1^2 \omega^2 / (\omega^2 - \omega_b^2)}{\int f E^2 dE d\Lambda \tau_b < 2 - \Lambda B >}$$

$$H_1 = \frac{1}{\tau_b} \int dt' (2 - \Lambda B) G(r', \theta') sin(\omega_b t')$$

$z^2 x^2 = 1 + y Q_h(x)$ $x = \omega / \omega_{b0}$

$z = \omega_{b0} / \omega_{GAM}$, $y \sim P_h / P_{th}$

Energetic Particle Contribution

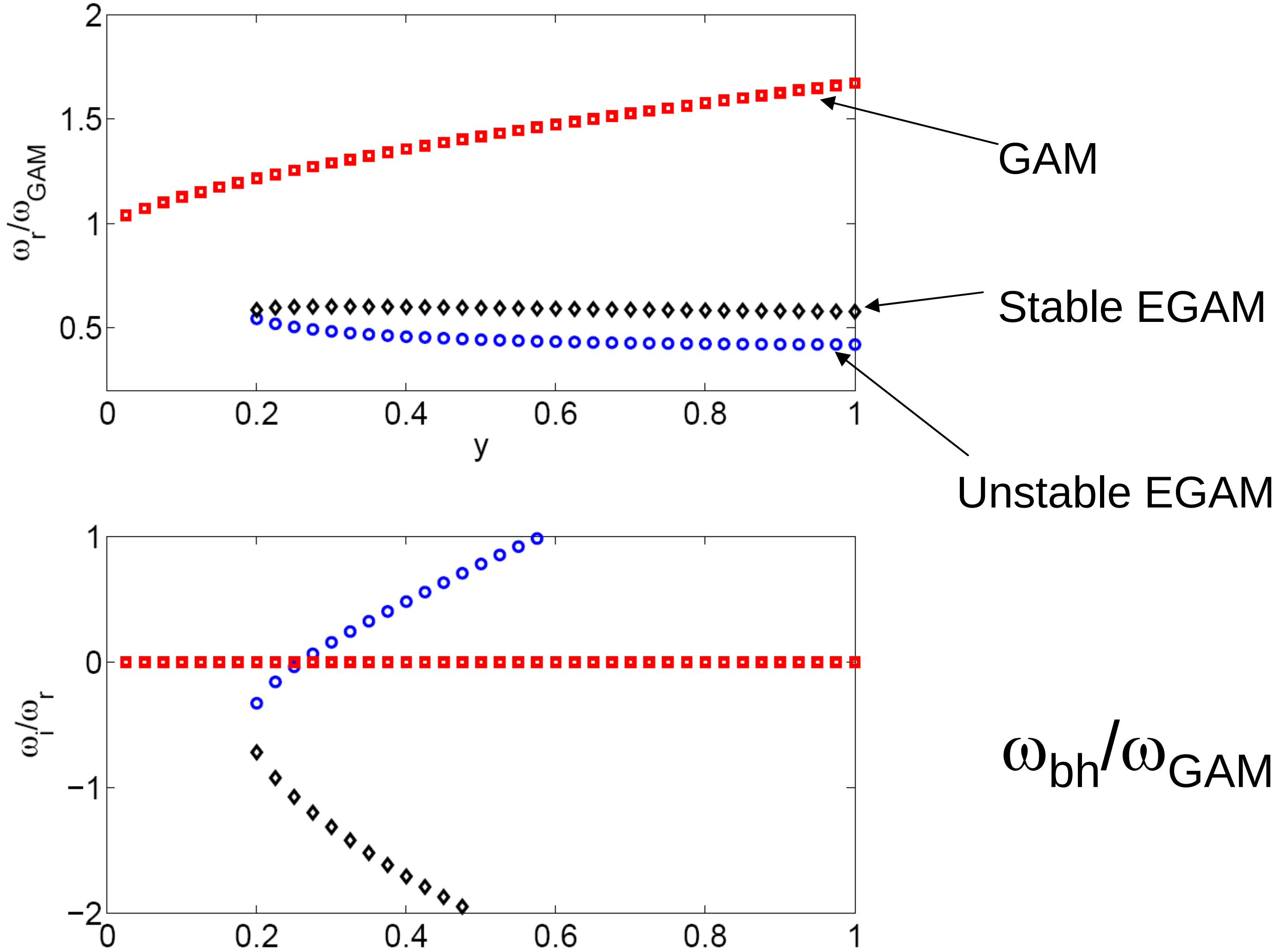


Λ_0=0.5

$\Delta\Lambda$=0.2

$$f = \frac{1}{v^3 + v_{\mathrm{crit}}^3} \exp\left[-\frac{P_\phi}{e\Delta\Psi} - \left(\frac{\Lambda - \Lambda_0}{\Delta\Lambda}\right)^2 \right]$$

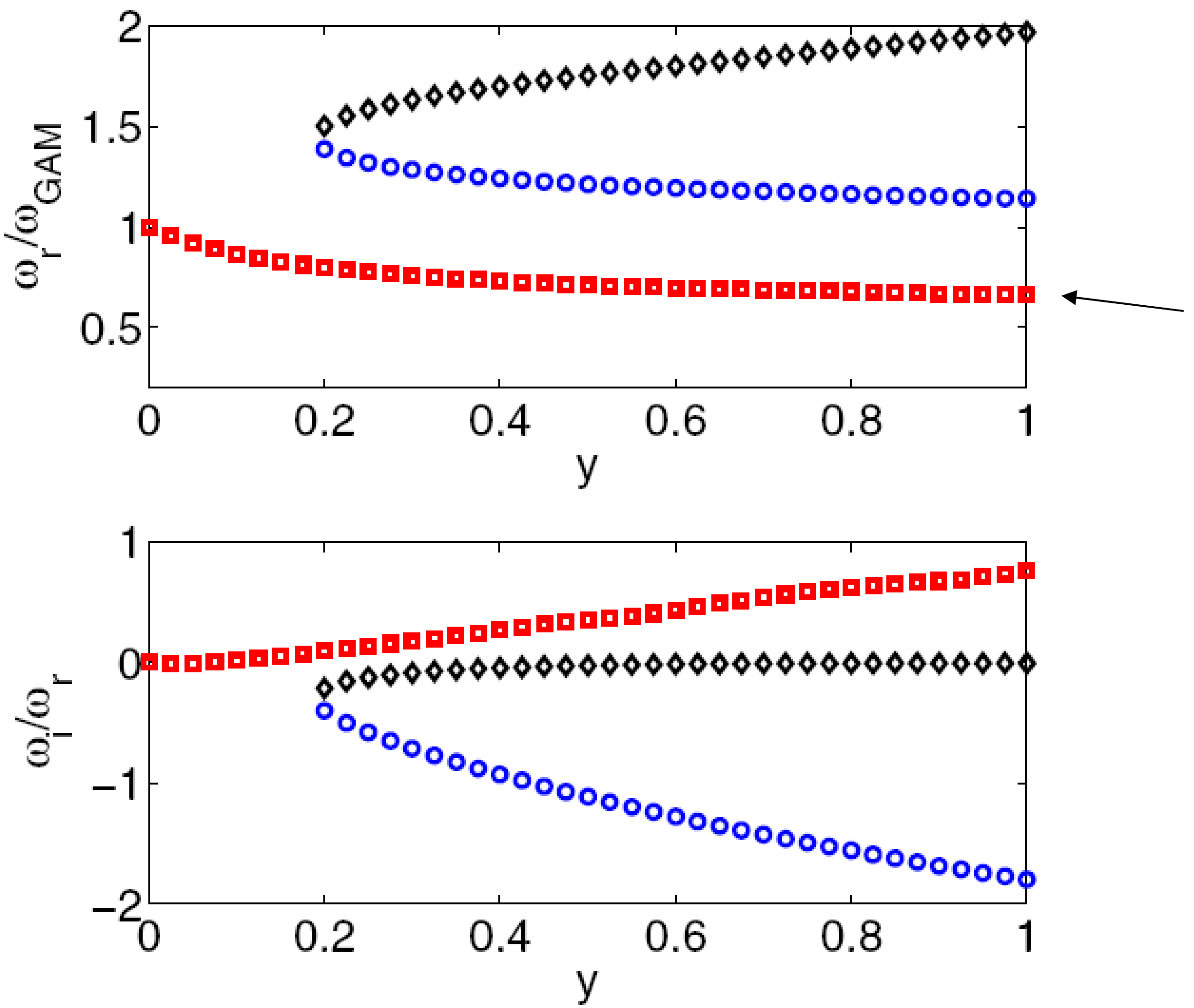
Critical energetic particle beta for EGAM existence and excitation



$\omega_{bh}/\omega_{GAM} = 1$

β_h/β_{th}

Critical energetic particle beta for EGAM existence and excitation



$\omega_{bh}/\omega_{GAM} = 1.8$

β_h/β_{th}

Zero Orbit Width Results

- Energetic particle can contribute negatively to the mode frequency;
- Particle distribution anisotropy allows destabilization of n=0 mode;
- Depending on parameters and distribution, up to three modes can exist.

Eigenmode Equation for Global EGAM: finite orbit width effects

$$\frac{d}{dr}[\frac{< P_{||} + P_{\perp} >}{\rho R^2}(q\rho_h)^2 W(\frac{\omega}{\omega_{b0}})]\frac{d}{dr}E_r + (\omega^2 - \omega_{EGAM}^2)E_r = 0$$

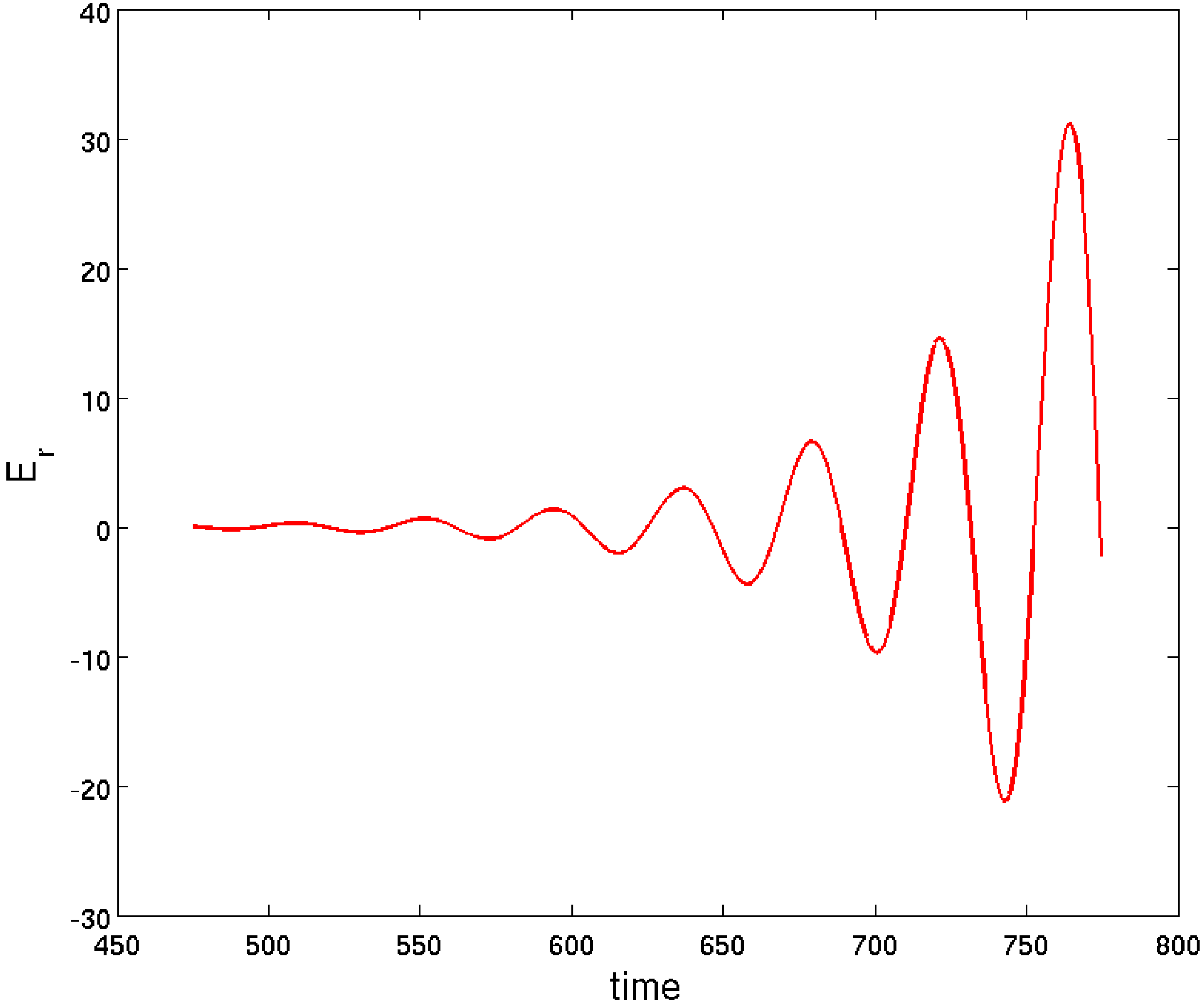
$$\omega_{EGAM}^2 = \omega_{GAM}^2 + \frac{< P_{||h} + P_{\perp h} >}{\rho R^2}Q_h(\frac{\omega}{\omega_{b0,h}})$$

➔Radial width of global EGAM scales as $\sqrt{P_h / P_{th}}\, q\rho_h$

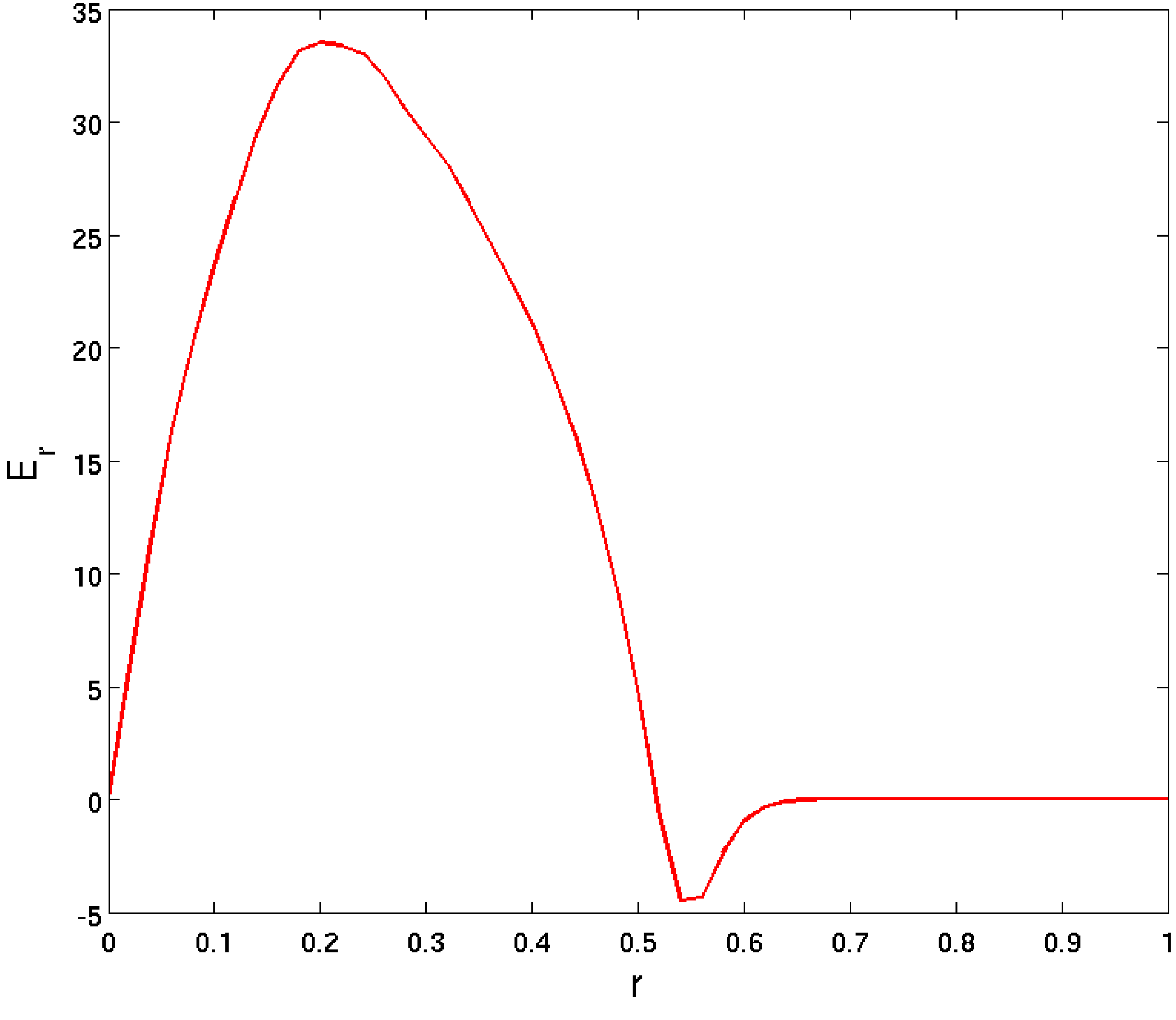
➔q dependence!

•This radial scale length is typically much larger than thermal ion orbit width.

Numerical Results: amplitude evolution

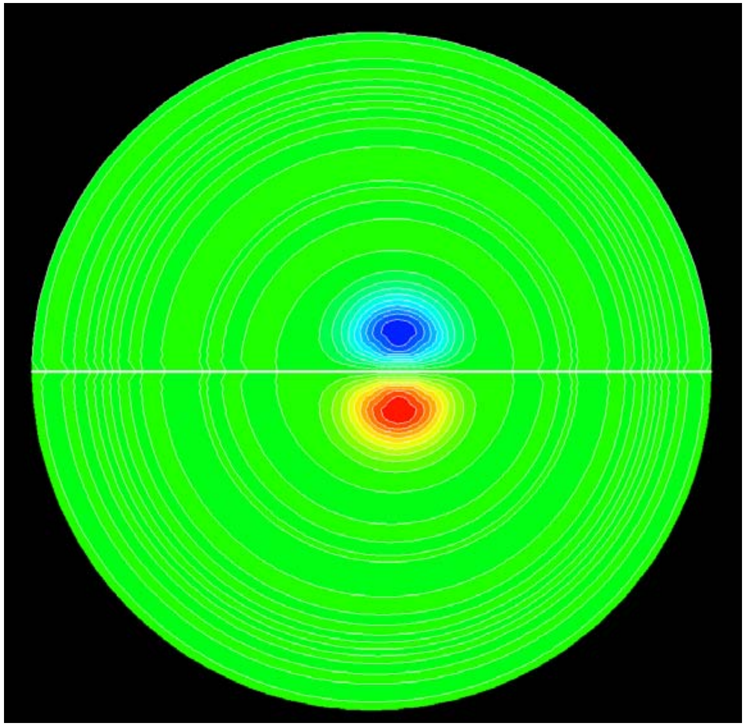


Numerical Results: Existence of global mode

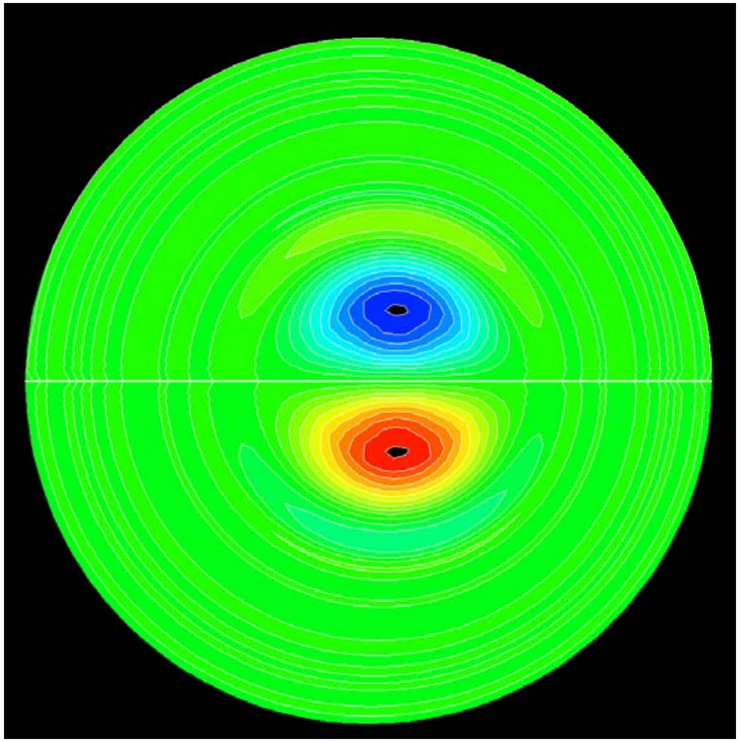


The mode width is determined by the particle orbit width

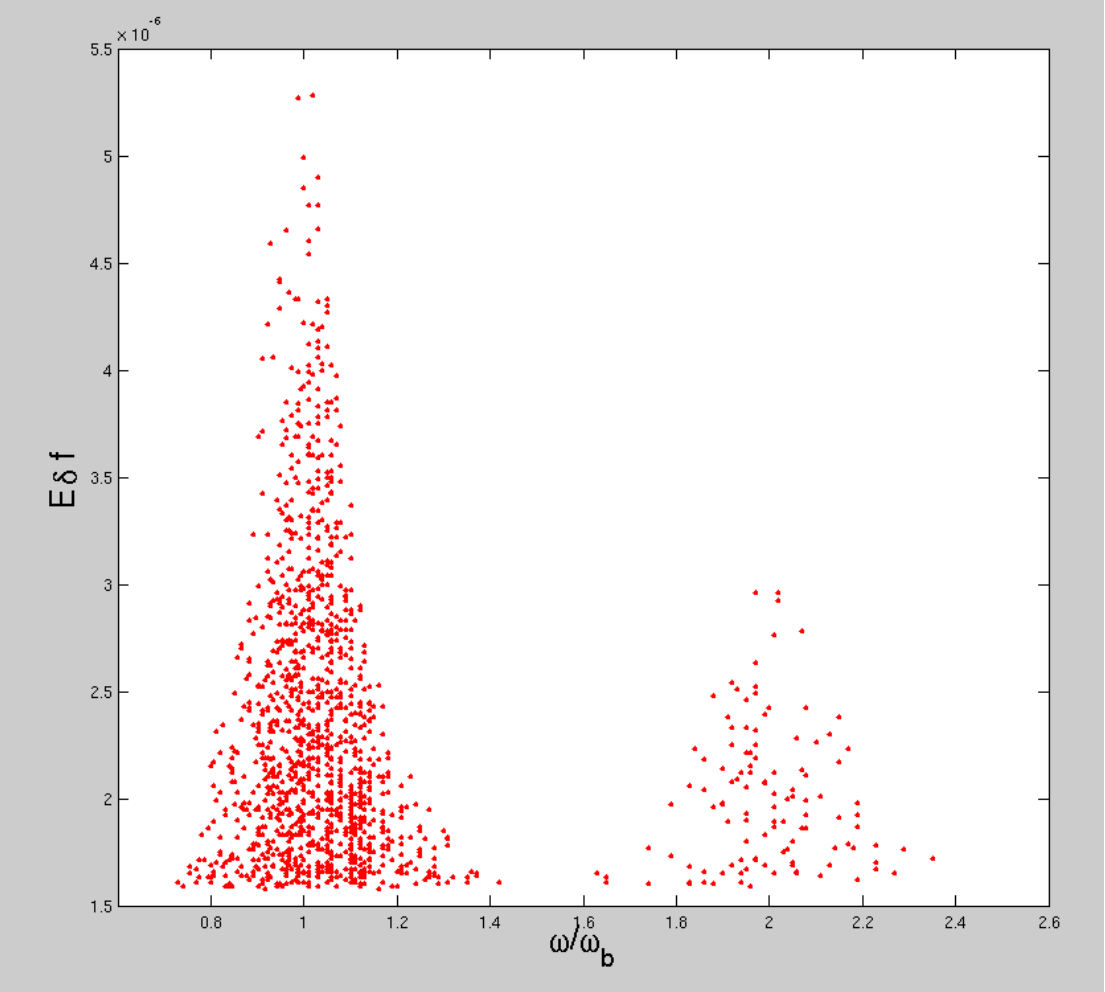
$\rho/a=0.006$



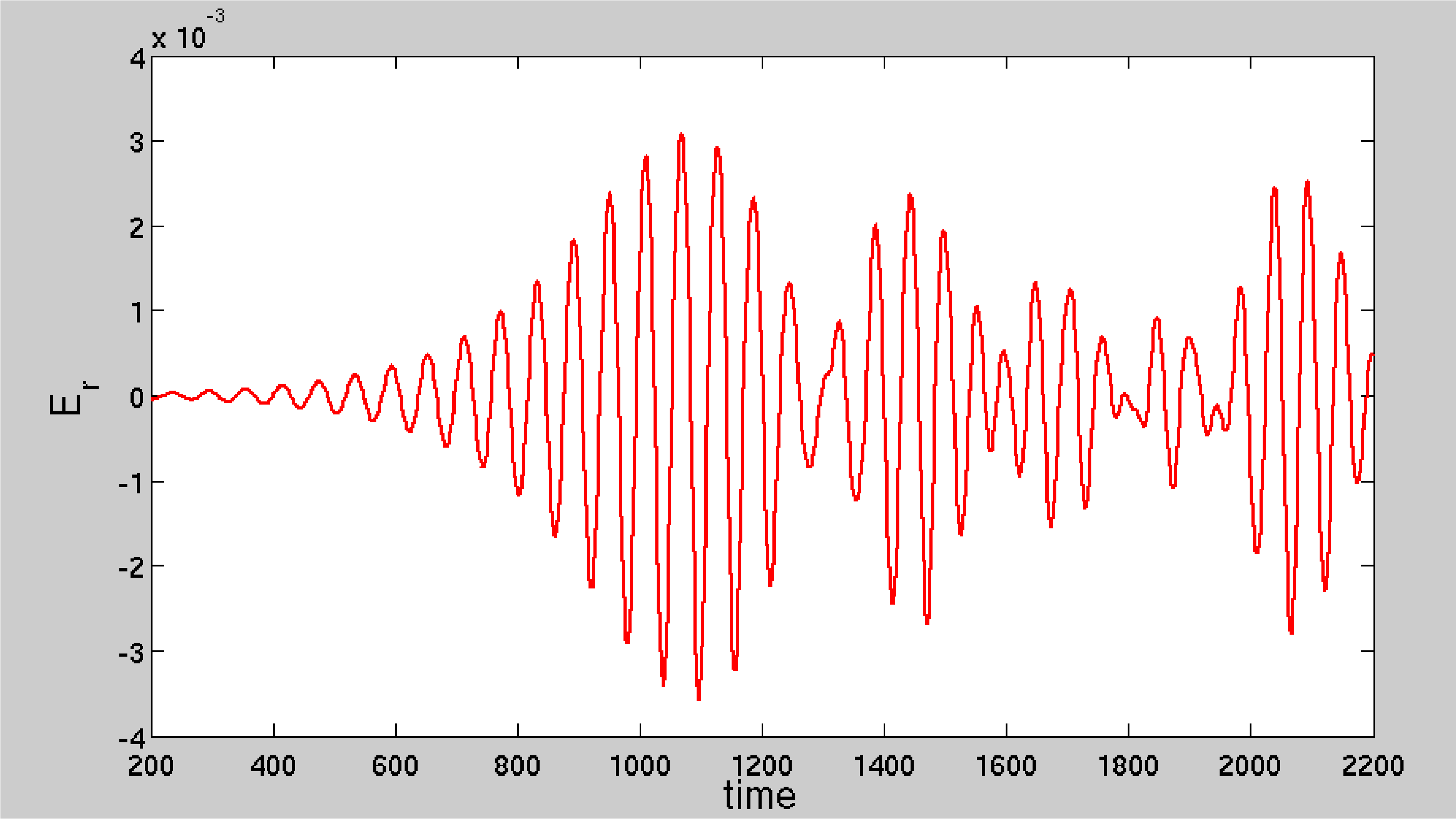
$\rho/a=0.016$



Wave-Particle Resonances



Nonlinear simulations show bursting behavior

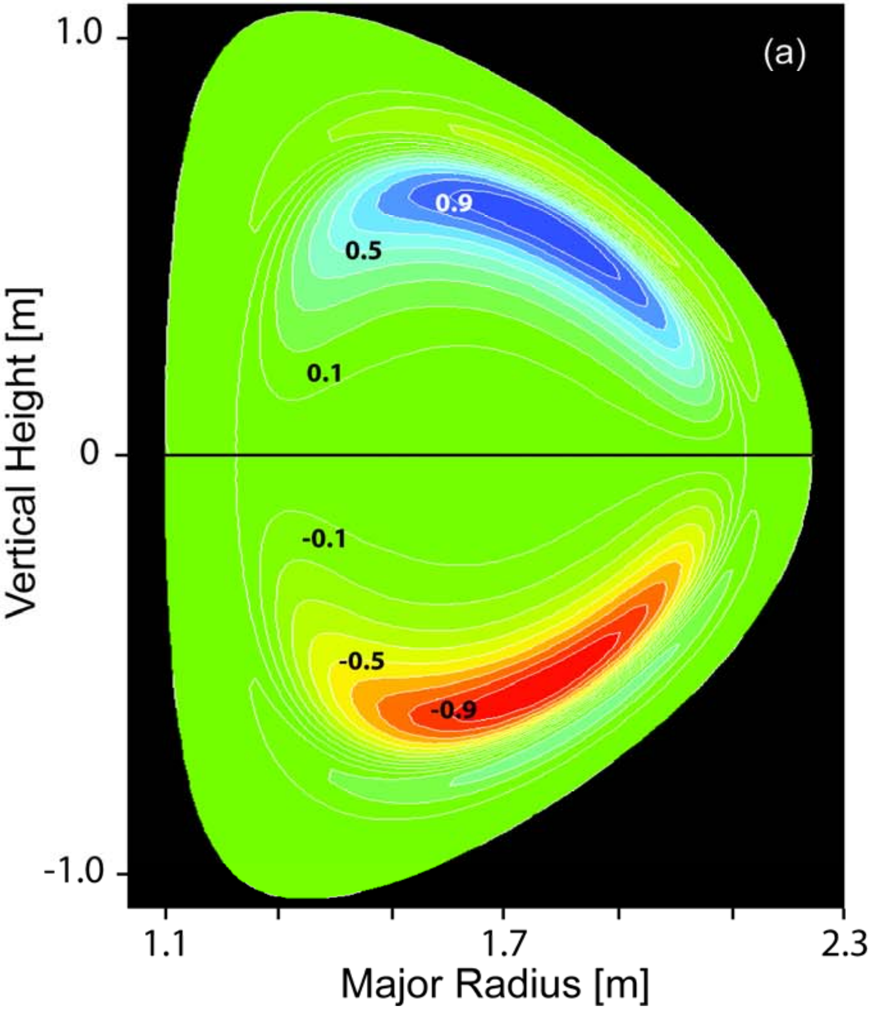


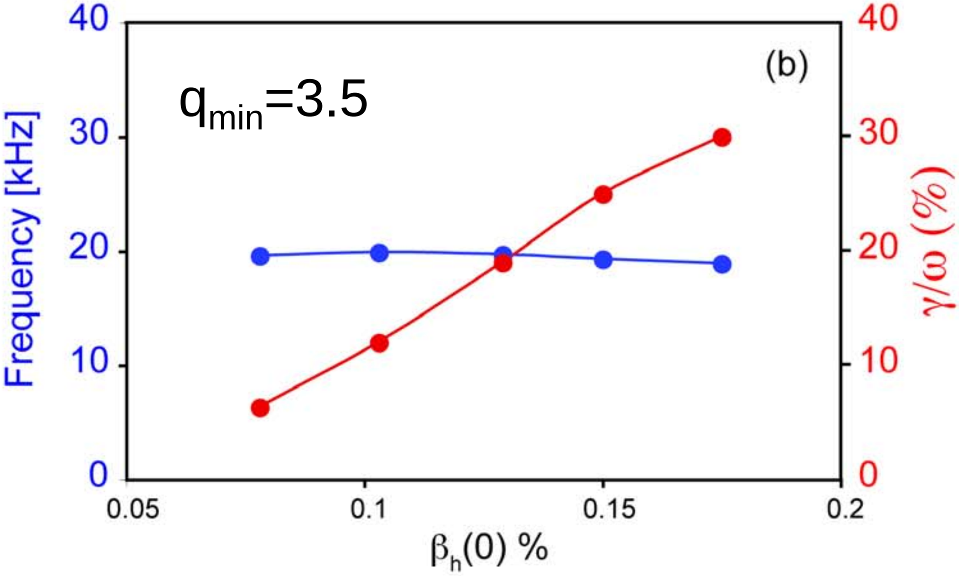
Comparison between theory and D3D observation

- We have qualitative agreement in mode frequency, mode structure, and mode stability.

- Calculated mode frequency is significantly below the local GAM frequency at the axis;
- The calculated density fluctuation scales as $\sin(\theta)$;
- The calculated radial electric field has global mode structure extended between r=0 and r ~ 0.6. The radial scale length is on order of $q^*\rho_h$;
- The calculated growth rate is very large (comparable to mode frequency) indicating very low threshold in energetic particle beta;

The Results of EGAM simulations are consistent With DIII-D experimental observation





- global compressional density
- correct frequency range ≈ 20 kHz
- large growth rate, low threshold consistent with early onset

Summary

- DIII-D experiments revealed an intensive beam-ion driven GAM-like n=0 mode with global mode structure;
- We show both analytically and numerically the existence of energetic particle-induced GAM (EGAM);
- The energetic particle effects determine the mode frequency, mode destabilization and mode radial structure;
- The analytic and numerical results of EGAM are consistent with the DIII-D experimental observations.
- EGAM may be important in burning plasmas (effects on micro-turbulence and alpha-channeling?)