Simulation study of a new kind of energetic particle driven geodesic acoustic mode
新しい種類の高エネルギー粒子駆動型測地的音響モードのシミュレーション研究

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Outline

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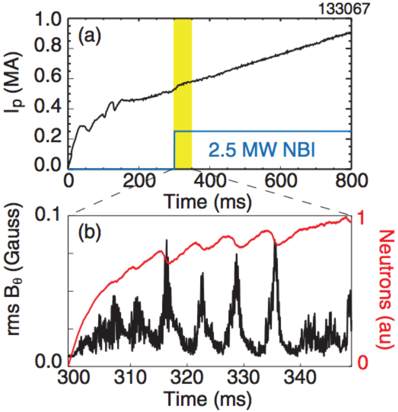
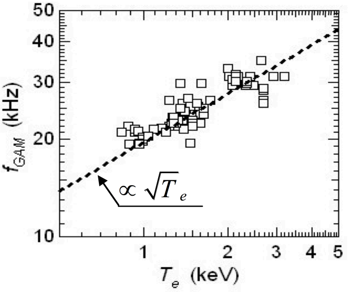
Geodesic acoustic mode (GAM) is a finite frequency oscillatory zonal flow with mode number $m/n = 0/0$.

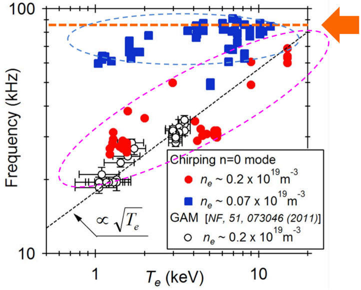


- GAM can be driven by both plasma micro-turbulence, TAE mode[1], and energetic particles.
- In DIII-D, the energetic particle driven GAM (EGAM) causes neutron emission drops[2]. It means the energetic particles are transported by the EGAM.

[1] Y. Todo, *Nucl. Fusion*, (2010)
[2] R. Nazikian, *Phys. Rev. Lett.*, (2008)

Two kinds of EGAMs with similar experimental parameters are observed in LHD





- The traditional EGAM (left) frequency is proportional to the square root of plasma temperature.[3]
- The new kind of EGAM (right) frequency has weak dependence on plasma temperature.[4]

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[3] T. Ido et al., in *23rd IAEA Fusion Energy Conference, Daejon, 2010*

[4] T. Ido *et al*, in *24th IAEA Fusion Energy Conference, San Diego, 2012*, & M. Osakabe, in *the 25th IAEA Fusion Energy Conference, St Petersburg, 2014*

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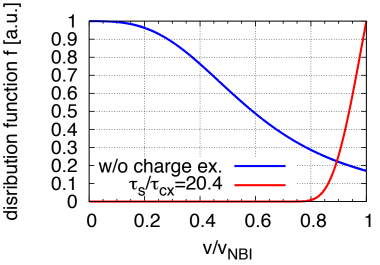
Velocity distribution $f(v)$

$$f(v) = C(v^3 + v_c^3)^{\frac{1}{3}\tau_s/\tau_{cx} - 1} \quad (1)$$

where C is integration constant, v_c is the critical velocity, τ_s is slowing down time, τ_{cx} is charge exchange time.



τ_s/τ_{cx} decides the shape of the distribution function. High τ_s/τ_{cx} value (red curve) causes significant bump-on-tail distribution, while 0 τ_s/τ_{cx} value (blue curve) means typical slowing-down distribution without charge exchange.

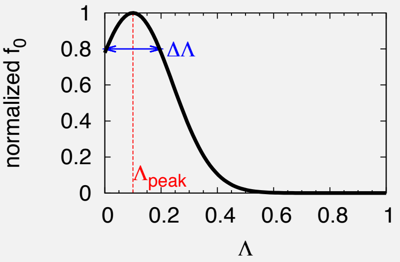
Pitch angle distribution $g(\Lambda)$ is Gaussian type

Analytical form

$$g(\Lambda) = exp(-\frac{\Lambda - \Lambda_{peak}}{\Delta\Lambda}^2) \quad (2)$$

$\Lambda = \mu B_0/E$ where μ is the magnetic moment, B_0 is the magnetic field strength on the magnetic axis, and E is particle energy. $g(\Lambda_{peak})$ is the maximum value of $g(\Lambda)$, and $\Delta\Lambda$ controls the distribution width.

- Small Λ_{peak}: tangential NBI is dominant.
- Large Λ_{peak}: perpendicular NBI is dominant.
- $\Lambda_{peak} = 0.1$ in the present work.



The energetic particle inertia are considered

The energetic particle inertia term is added into the MHD momentum equation to simulate with energetic particle density comparable to the bulk plasma density:

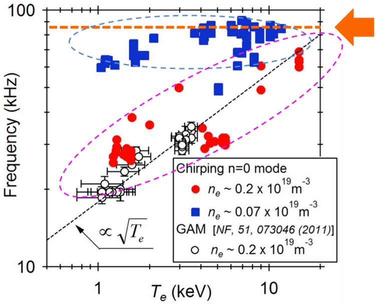
$$\rho_b(\frac{\partial}{\partial t} + \mathbf{v_b} \cdot \nabla)\mathbf{v}_\parallel = -\nabla_\parallel p_b \tag{3}$$

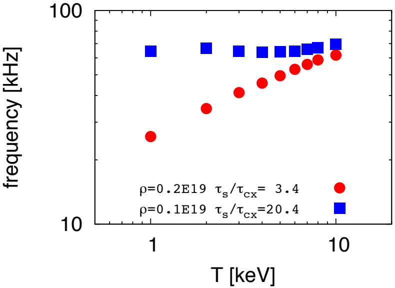
$$[\rho_b(\frac{\partial}{\partial t} + \mathbf{v_b} \cdot \nabla) + \rho_h(\frac{\partial}{\partial t} + \mathbf{v_h} \cdot \nabla)]\mathbf{v}_\perp = -\nabla_\perp p_b + (\mathbf{j} - \mathbf{j_h}) \times \mathbf{B} \tag{4}$$

The inertia term may affect the mode frequency and growth rate.

Outline

The new kind of EGAM is reproduced

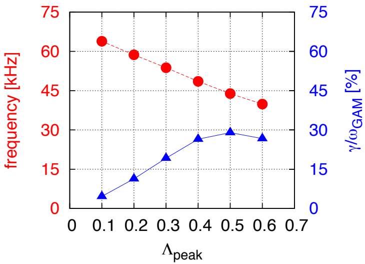




- Left: Experimental observation. [5]
- Right: Two kinds of EGAMs are simulated with $\beta_h = 1\%$.
  - New EGAM: bulk density $\rho = 0.1 \times 10^{19} m^{-3}$, $\tau_s/\tau_{cx} = 20.4$.
  - Traditional EGAM: bulk density $\rho = 0.2 \times 10^{19} m^{-3}$, $\tau_s/\tau_{cx} = 3.4$.

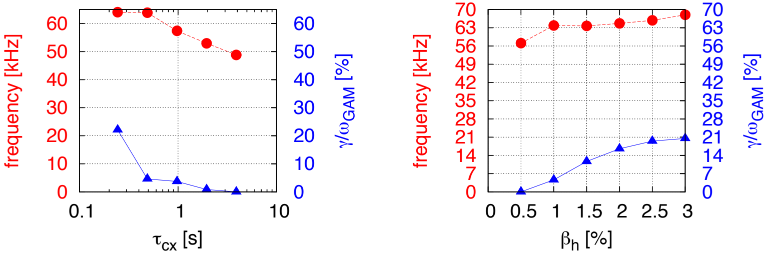
[5] T. Ido *et al*, in *24th IAEA Fusion Energy Conference, San Diego, 2012*, & M. Osakabe, in *the 25th IAEA Fusion Energy Conference, St Petersburg, 2014*

Dependence on pitch angle distribution



- As mentioned in slide 9, small Λ_{peak} means tangential injection is dominant, so energetic particles parallel velocity is higher, then the transit frequency $f_{tr} = \omega_\theta / 2\pi$ will be higher. Also, large Λ_{peak} means lower f_{tr}.
- Frequency decreases with Λ_{peak} increases. This indicates that the new EGAM is a special kind of energetic particle modes (EPM) whose frequency is determined by the energetic particles.
- $\tau_{cx} = 0.488s$ and $\beta_h = 1\%$.

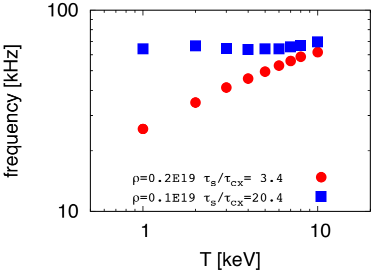
Dependence on τ_{cx} and β_h

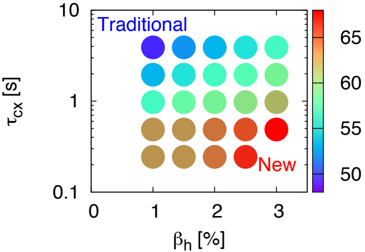


- Left: Frequency and growth rate decrease with τ_{cx} increases, because shorter τ_{cx} value means more energetic particles distribute in the high-energy region in phase space.
  $\beta_h = 1\%,\ T = 4keV,\ \Lambda_{peak} = 0.1.$
- Right: Frequency slightly increases with β_h increases. This property is different from traditional EGAM.[6]
  $\tau_{cx} = 0.488s,\ T = 4keV,\ \Lambda_{peak} = 0.1.$

[6]Hao WANG and Yasushi TODO, *Phys. Plasmas*, (2013) & G. Fu, *Phys. Rev. Lett.*, (2008)

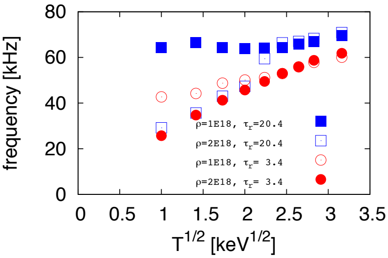
Transition from traditional EGAM to new EGAM (1)





- In the case of $T_e = 4keV$, traditional EGAM frequency is low while new EGAM frequency is high. Then, the frequency with different β_h and τ_{cx} is compared to observe the transition.
- Frequency increases gradually from top left corner (traditional EGAM region) to bottom right corner (new EGAM region) with $T = 4keV$. High β_h and short τ_{cx} (or larger τ_s/τ_{cx} value) are essential for new EGAM excitation.

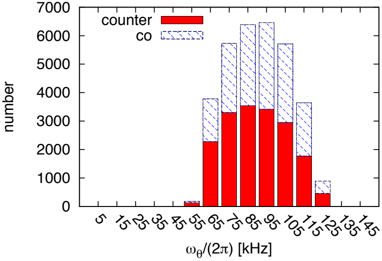
Transition from traditional EGAM to new EGAM (2)

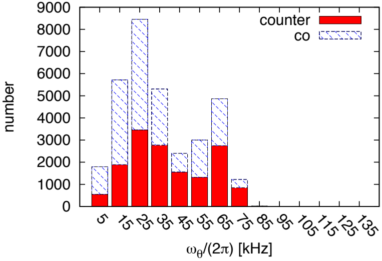


- The distribution function shape is decided by $\tau_r = \tau_s/\tau_{cx}$.
- The open and close squares have same distribution function, but frequencies are different, because of different bulk densities.
- Low bulk density is also essential for new EGAM excitation.

Outline

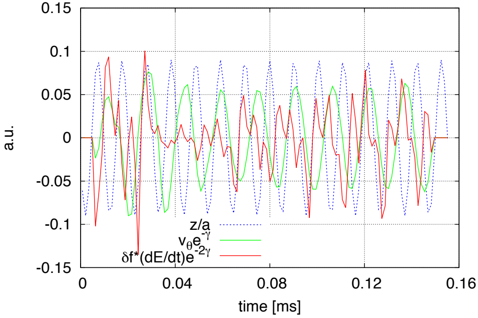
Three types of particles are found to be important for resonance

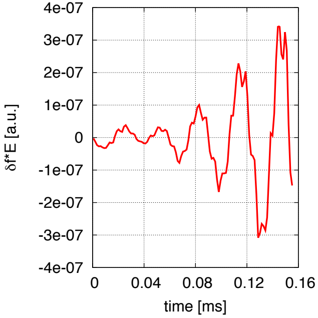




- Left: The distribution of the most strongest 6.25% particles (32768/524288) ordered by absolute δf value.
- Right: The distribution of the most strongest 6.25% particles (32768/524288) ordered by absolute $\delta f/f$ value.
- 3 types of particles will be analyzed by the value of f_{tr}, where $f_{tr} = \sqrt{1-\Lambda}v/(2\pi qR_0)$, q is safety factor and R_0 is plasma major radius.
- Type I: $f_{tr} \approx 95kHz$; type II: $f_{tr} \approx 25kHz$; type III: $f_{tr} \approx f_{EGAM} = 63.86kHz$.

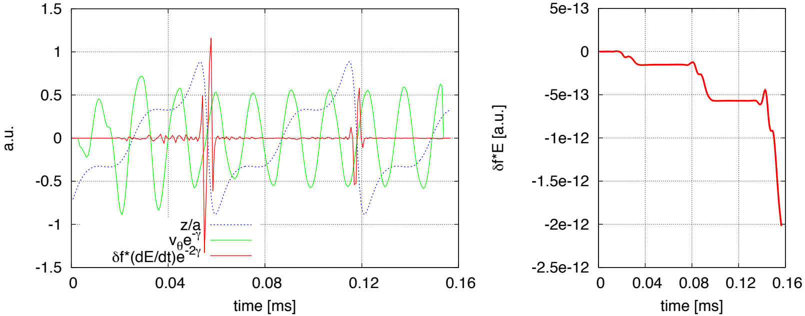
Type I particles don't supply net energy to the mode





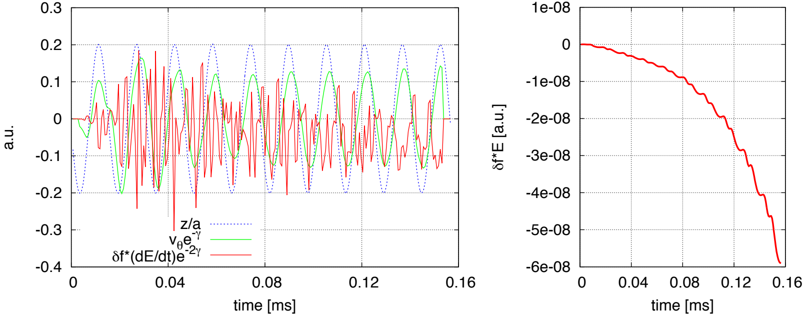
- The particle with the largest absolute δf value is analyzed. This is a type I particle.
- The signal of energy transfer rate changes with time. Sometimes this particle supplies energy to the mode, sometimes it absorbs energy from the mode.
- The signal of $\delta f \times E$ also changes with time.
- Type I particles don't supply net energy to the mode. They don't make contribution for mode destabilization.

Type II particles supply net energy



- The particle with the largest absolute $\delta f/f$ value is analyzed. This is a type II particle.
- Type II particles are trapped particles, not passing particles. The bounce frequency is around 1/4 mode frequency.
- The $\delta f \times E$ value is always negative.
- Type II particles supply net energy to the mode. They make contribution to mode destabilization.

Type III particles also supply net energy



- The particle whose $f_{tr} \approx f_{EGAM}$ is analyzed where f_{EGAM} is the mode frequency. This is a type III particle. The $\delta f/f$ value is large.
- The particle energy transfer rate is often negative, and the $\delta f \times E$ value is always negative.
- Type III particles supply net energy to the mode. They make contribution to mode destabilization.

Outline

1. Introduction
2. Simulation Model
3. Simulation Results: Excitation Condition
4. Simulation Results: Resonance Condition
5. **Summary**

Summary

- Charge exchange and energetic particle inertia are considered.
- The new kind of EGAM emerges under the condition of low bulk density, high β_h, and large τ_s/τ_{cx} value. The mode frequency has weak dependence on plasma temperature.
- The new EGAM frequency increases as the central value of the Gaussian pitch angle distribution decreases. This indicates that the new EGAM is a special kind of EPM.
- The most strongest resonant particles don't supply net energy to the mode. The new EGAM is mainly destabilized by the particles whose transit frequencies are close to the mode frequency. In addition, trapped particles supply very little net energy to the mode.

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Thanks for Your Attention!