Simulation Study on the Linear Properties and Nonlinear Frequency Chirping of EGAM in LHD

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Outline

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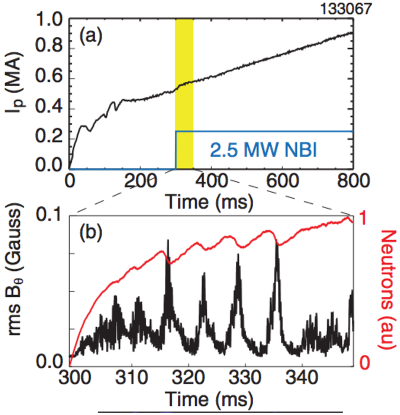
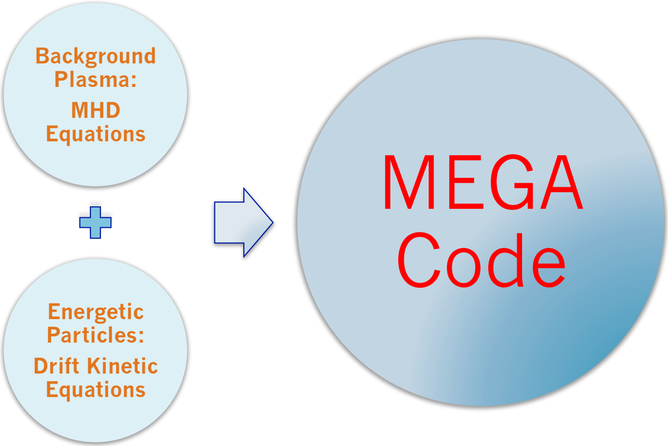
Geodesic acoustic mode (GAM) is a kind of electrostatic mode with $n = 0$, and it is a finite frequency oscillatory zonal flow



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

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

Introduction of MEGA code[1]

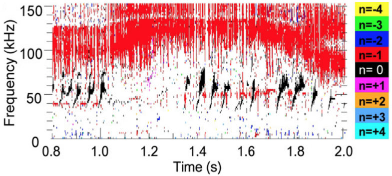


[1] Y. Todo, *Phys. of Plasmas*, (2006)

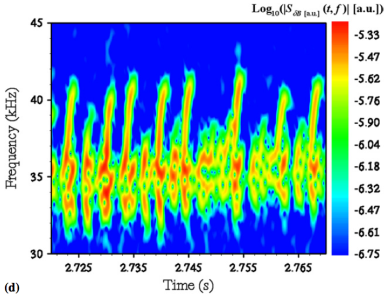
Outline

EGAM experiments in LHD[2] and JET[3]

EGAM in LHD



EGAM in JET



[2] T. IDO *et al*, *Nucl. Fusion*, (2011).
[3] H. L. Berk *et al*, *Nucl. Fusion*, (2006).

Analytical Form of Distribution Function

Velocity distribution $f(v)$ is slowing down type.

$$f(v) = \frac{1}{v^3 + v_c^3} \tag{1}$$

where v is particle velocity and v_c is critical velocity.

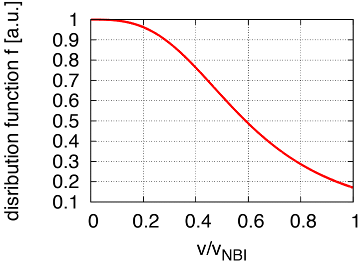
Pitch angle Λ distribution $g(\Lambda)$ is Gaussian type.

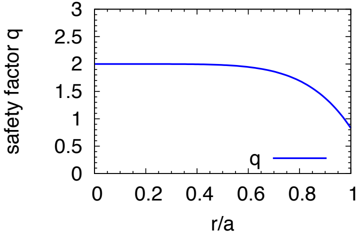
$$g(\Lambda) = exp[-(\frac{\Lambda - \Lambda_{peak}}{\Delta\Lambda})^2] \tag{2}$$

where $\Lambda = \mu B_0/E$, μ is magnetic moment, B_0 is magnetic field strength at the magnetic axis, and E is the energy.

Charge exchange is not considered.

Simulation parameters





- The distribution $f(v)$ is slowing down type.
- q profile is weak shear.
- Simulation parameters based on an LHD experiment[4]: $B_0 = 1.5T$, $n_e = 0.1 \times 10^{19}/m^3$, $T_e = 4keV$, $\beta_0 = 7.2 \times 10^{-4}$, q profiles.

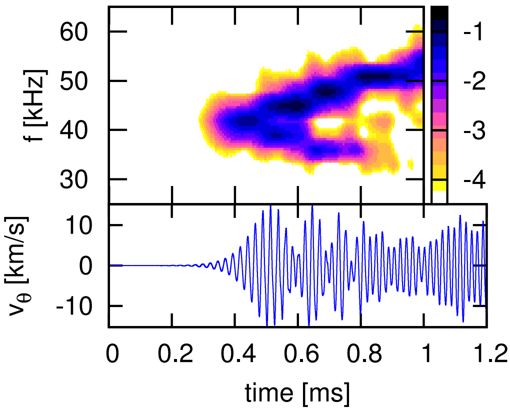
[4]T. IDO et al., in *23rd IAEA Fusion Energy Conference, Daejon, 2010*

Nonlinear frequency chirping

MEGA Simulation

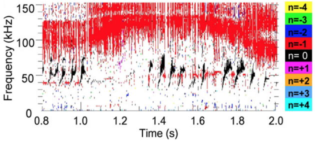
H. Wang, Y. Todo, and C. C. Kim, *Phys. Rev. Lett.* (2013)

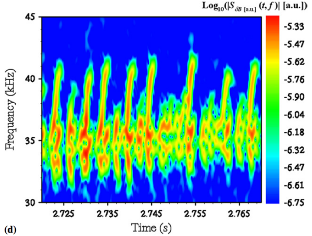
E_{NBI}=170keV, Λ_{peak}=0.3



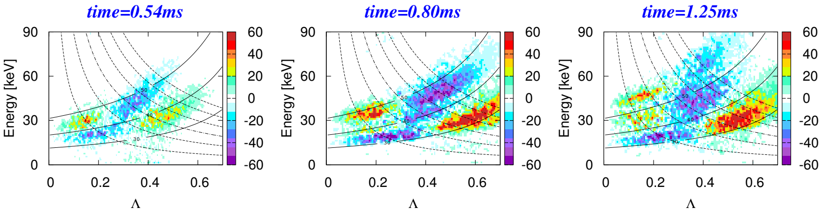
LHD and JET (again)

T. IDO et al., in *23rd IAEA FEC*
H. L. Berk et al., *Nucl. Fusion*, (2006)



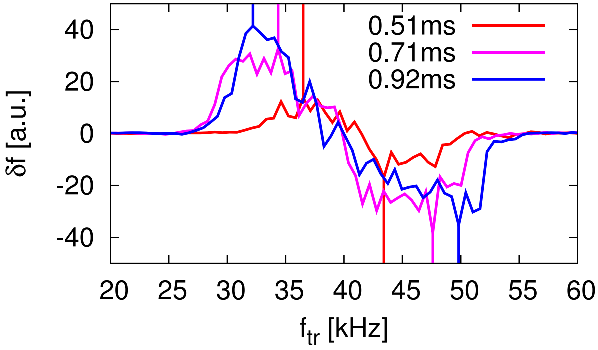


Hole-clump pairs creation: δf distribution



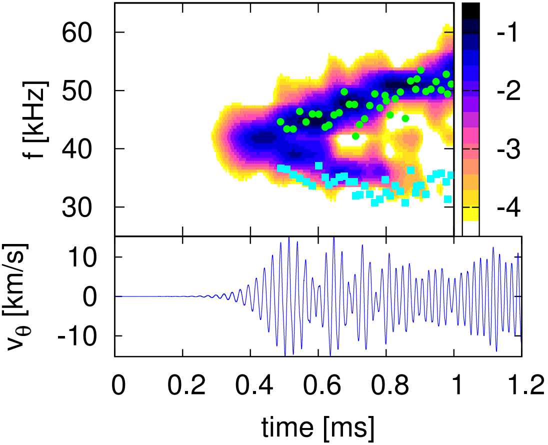
- The figures: δf distribution at t = 0.54 ms, t = 0.80 ms, and t = 1.25 ms.
- Hole-clump pairs are created along the $\mu =$ *constant* curves in the nonlinear phase.
- Particle transit frequency: $f_{tr} = \sqrt{1 - \Lambda} v / (2\pi q R_0)$.
- $q = 2.0$ is a constant in the present f_{tr} calculation.
- The transit frequencies of the holes and clumps shift with the mode frequency chirping.

δ f v.s. transit frequency f_{tr} along $\mu = 15$ keV/T



- The peak and bottom values are marked with straight lines.
- From time=0.51ms to 0.92ms, the f_{tr} of clump decreases and the f_{tr} of holes increases.

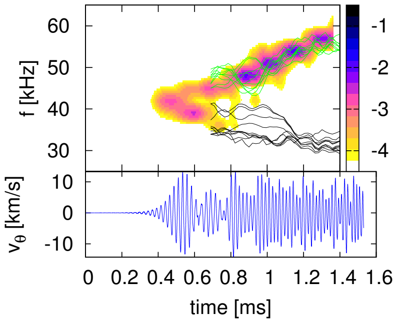
Mode frequency and f_{tr} of the hole and clump



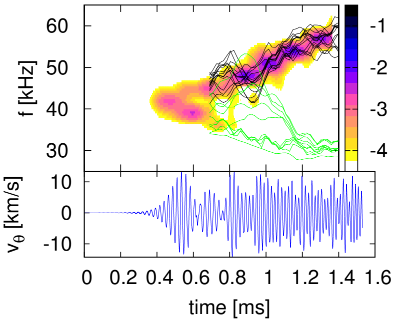
- The green dots represent the f_{tr} of the hole.
- The cyan squares represent the f_{tr} of the clump.
- The transit frequencies of the hole and the clump are in good agreement with the mode frequencies.

f_{tr} evolution of particles in holes and clumps

lower μ



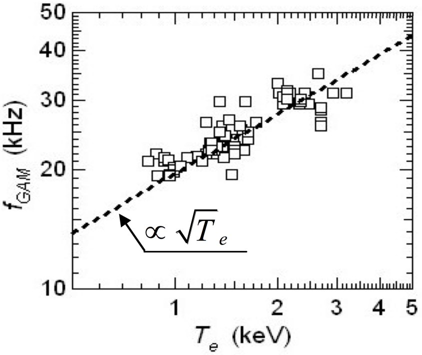
higher μ

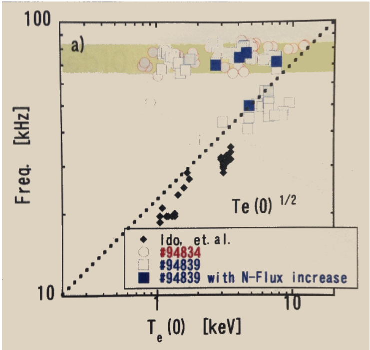


- **BLACK:** particles in the holes.
- **GREEN:** particles in the clumps.
- The f_{tr} of these particles are consistent with mode frequency.
- This indicates the particles in the holes and clumps are kept resonant with the EGAM.

Outline

Two kinds of EGAMs in LHD with similar experimental parameters





- The conventional EGAM (left) frequency is proportional to the square root of plasma temperature.[5]
- The new kind of EGAM (right) frequency is independent of plasma temperature.[6]
- The experimental parameters are similar: $B_0 = 1.5T$, n_e is $1.0 \times 10^{18}/m^3$ and $0.8 \times 10^{18}/m^3$, E_{NBI} is $170keV$ and $180keV$.

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

[6] M. Osakabe, discussion in NIFS.

Analytical form of distribution function

Velocity distribution $f(v)$ is slowing down with charge exchange.

$$f(v) = Ce^{-I(v)} \tag{3}$$

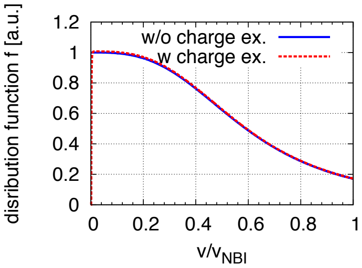
$$I = \int_0^v \frac{3u^2 - u^2\tau_s/\tau_{cx}(u)}{u^3 + v_c^3} du \tag{4}$$

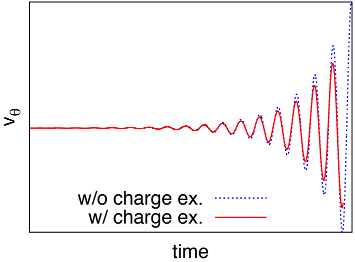
where C is integration constant, τ_s is slowing down time, τ_{cx} is charge exchange time.

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

It is same as that in the last section.

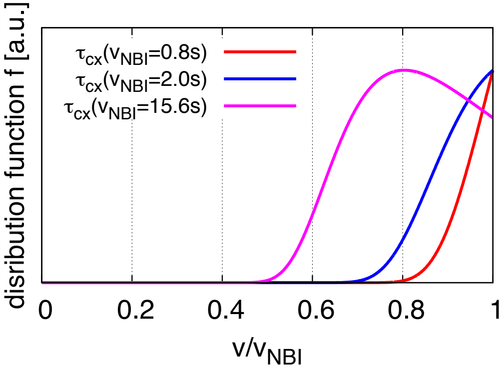
Code validation





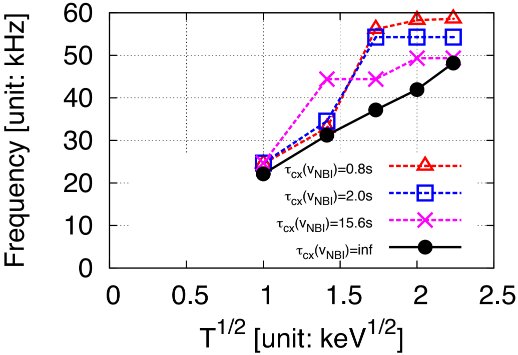
- For the curves w/ charge exchange, $\tau_{cx}/\tau_s \approx 10^{11}$.
- The distribution in these 2 cases are almost same.
- The frequency in these 2 cases are same, and growth rate is close to each other.

Simulation parameters



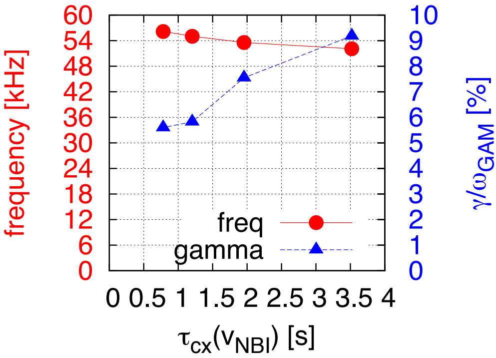
- Various τ_{cx} values are applied to the present work.
- The case with $\tau_{cx}(v_{NBI}) = 0.8s$ is most commonly used. This value is inferred from the experiment, and it is about 10% of slowing down time.
- The other simulation parameters (q, density, T, E_{NBI}, B_0, *etc*) are same as that in the last section.

The relation between frequency and temperature



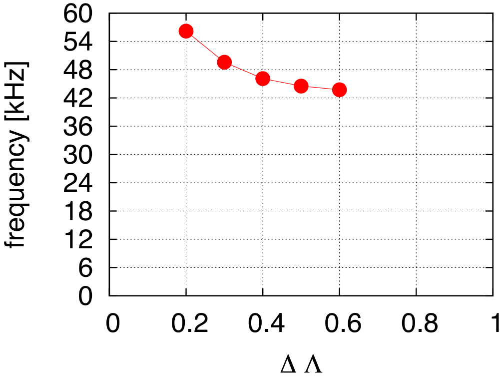
- EGAM frequency is proportional to $\sqrt{T}$ for the case w/o charge exchange.
- EGAM frequency with higher T is independent of T for the case w/ charge exchange.
- EGAM frequency with lower T is similar for both cases w/ and w/o charge exchange.
- $\beta_h = 0.3\%$.

Frequency and growth rate versus $\tau_{cx}(v_{NBI})$



- The distribution is flatter for longer $\tau_{cx}(v_{NBI})$.
- Frequency decreases with $\tau_{cx}(v_{NBI})$ increases.
- Growth rate increases with $\tau_{cx}(v_{NBI})$ increases.
- $\beta_h = 0.3\%$, and $T = 4keV$.

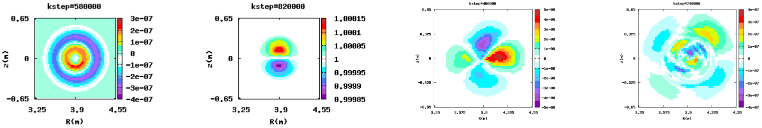
Frequency versus $\Delta\Lambda$



- Frequency decreases with $\Delta\Lambda$ increases.
- $\tau_{cx}(v_{NBI}) = 0.8s$ and $\beta_h = 0.3\%$.
- This tendency is stronger than the previous result w/o charge exchange.[7]

[7] H. Wang and Y. Todo, *Phys. Plasmas* (2013)

Poloidal mode profiles

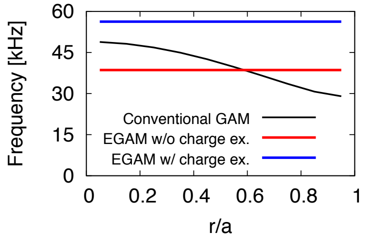


- The poloidal mode number for v_θ, density, δB_r and δB_θ is 0, 1, 2 and 2, respectively.
- $\tau_{cx}(v_{NBI}) = 0.8s$, $\beta_h = 0.3\%$, $T = 4keV$ and $\Delta\Lambda = 0.2$.
- It is similar with the previous result w/o charge exchange.[8]

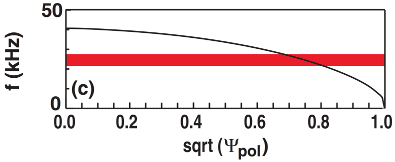
[8] H. Wang and Y. Todo, *Phys. Plasmas* (2013)

EGAM is global

MEGA Simulation



DIII-D Observation



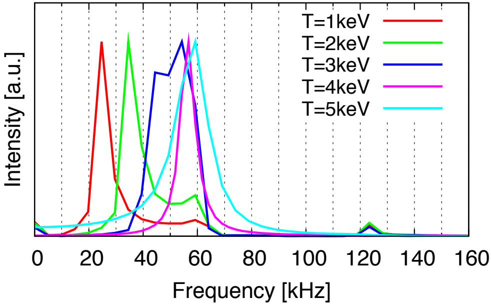
EGAM w/o charge exchange:

- The EGAM frequency is spatially constant: global mode.
- It is consistent with theoretical prediction [a] and experimental observation[b].

[a] G. Y. Fu: *Phys. Rev. Lett.* (2008)
[b] R. Nazikian: *Phys. Rev. Lett.* (2008)

The results of EGAM w/ charge exchange is similar.

Frequency spectrum



- For the red and green curves, frequency is proportional to the $\sqrt{T}$. The modes are stable in these 2 cases.
- For the other curves, frequency is independent of temperature.
- $\tau_{cx}(v_{NBI}) = 0.8s$, $\beta_h = 0.3\%$ and $\Delta\Lambda = 0.2$.

Outline

Summary: Nonlinear frequency chirping [9]

- Nonlinear frequency chirping takes place with hole-clump pairs created in the energetic particle distribution function along $\mu =$ *constant* curves.
- The transit frequencies of holes and clumps are in good agreement with the mode frequency indicating the particles in the holes and clumps are kept resonant with the EGAM.
- The hole-clump pairs structure is investigated in a more realistic system than the previous work.

[9] H. Wang, Y. Todo, and C. C. Kim, *Phys. Rev. Lett.* (2013)

Summary: Linear properties

New EGAM (w/ charge exchange)

- Frequency is independent of $\sqrt{T}$.
- Frequency decreases and γ increases with $\tau_{cx}(v_{NBI})$ increases.

Conventional EGAM (w/o charge exchange)

Frequency is proportional to $\sqrt{T}$.[a].

[a] H. Wang and Y. Todo, *Phys. Plasmas* (2013)

Both (w/ and w/o charge exchange)

- Frequency is spatially constant.
- Frequency decreases with mode distribution width $\Delta\Lambda$ increases.
- The poloidal mode number of v_θ, density and δB is 0, 1 and 2.

Future work

- Clarify the properties of new EGAM.
    - Dependence on Λ_{peak} (relation of EGAM frequency and EP transit frequency).
    - Condition for the transition between new and conventional EGAMs.
- Reproduce EGAM with the frequency observed in the LHD experiment.

Thanks for Your Attention!