Nonlinear excitation of energetic-particle-driven geodesic acoustic mode by resonance overlap with Alfvén instability

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- Introduction
- Nonlinear excitation of energetic particle driven geodesic acoustic mode (EGAM)
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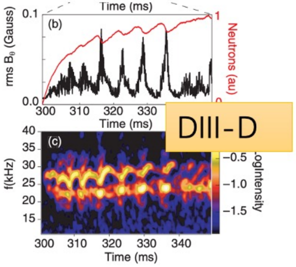
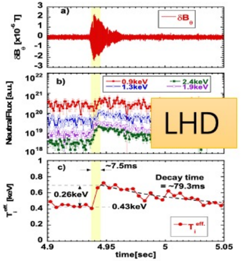
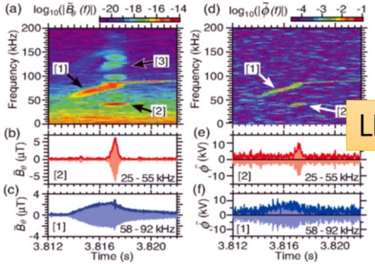
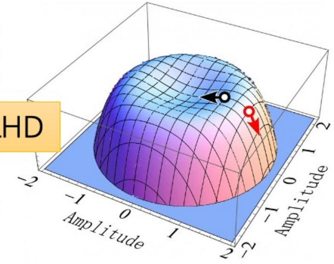
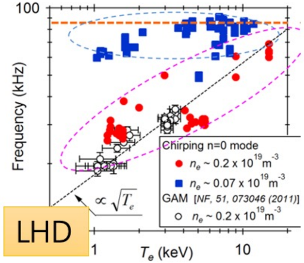
Why Energetic-particle-driven Geodesic Acoustic Mode (EGAM) experiments are important and interesting?





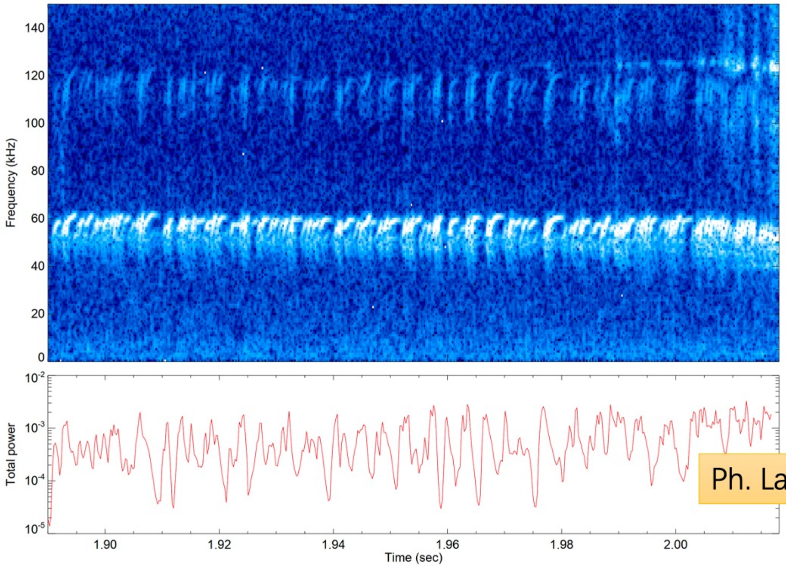




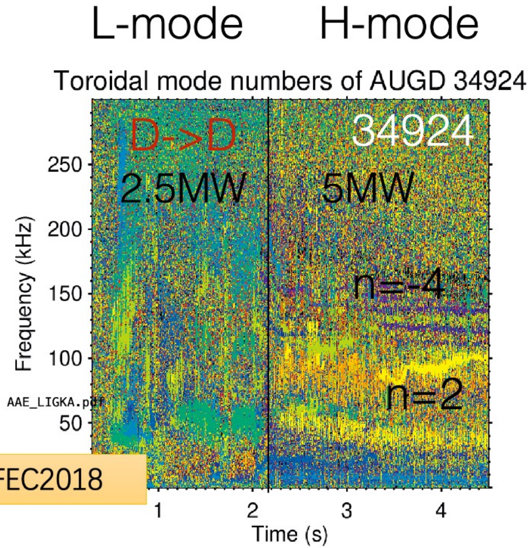


- EGAM causes strong energetic particle (EP) transport in DIII-D. [Nazikian, PRL, 2008]
- EGAM creates energy channel, and causes anomalous bulk ion heating in LHD. [Osakabe, FEC2014]
- EGAM can be a subcritical instability. This instability is linearly stable, but abruptly grows in nonlinear stage in LHD. [Ido, PRL, 2016] [Ido, Eurekalert!, 2016]
- EGAM frequency can be lower or higher than the conventional Geodesic Acoustic Mode (GAM). Previously, the high-frequency EGAM branch was not observed under the condition of slowing-down EP distribution. [Osakabe@FEC2014 and Ido, NF, 2015]

Co-existence of Alfvén instability and EGAM

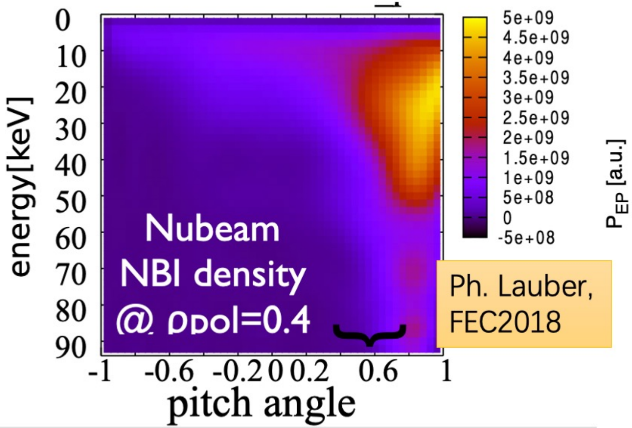


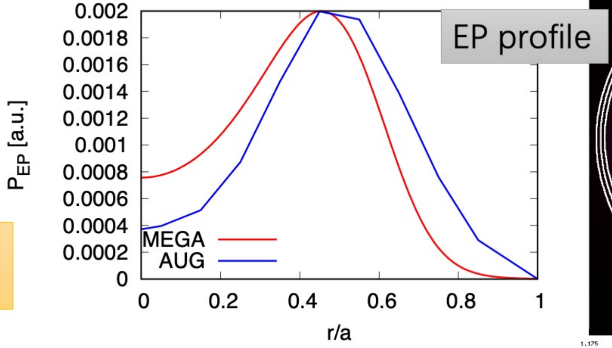
Ph. Lauber et al, FEC2018

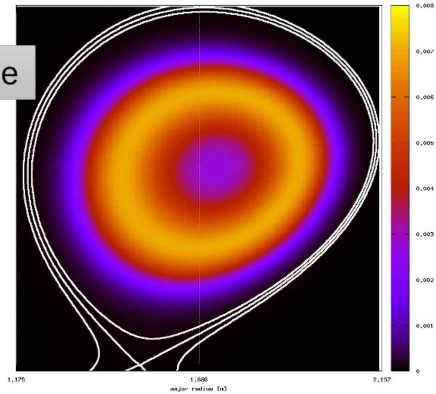


- In ASDEX-Upgrade, Alfvén instability and EGAM exist together in the same shot. This provides a set of experimental reference cases to address different aspects of energetic particle transport and mode properties. [*Ph. Lauber et al, FEC2018*]
- The frequencies and mode numbers of the Alfvén instability and EGAM are different, and a question arises: how the EGAM is nonlinearly excited by Alfvén instability?

Simulation parameters of MEGA code







- MEGA, a hybrid code with MHD bulk plasma and kinetic energetic particles [*Y. Todo et al, PoP 2006*], is used for this work.
- Equilibrium: AUG #34924@1.9s, generated by EFIT code.
- Other plasma parameters: the same as AUG
- EP distribution:
  - Slowing-down in velocity space
  - Gaussian in pitch angle space. It peaks at Lambda=0.4.
- EP profile: off-axis, peaks around r/a=0.5

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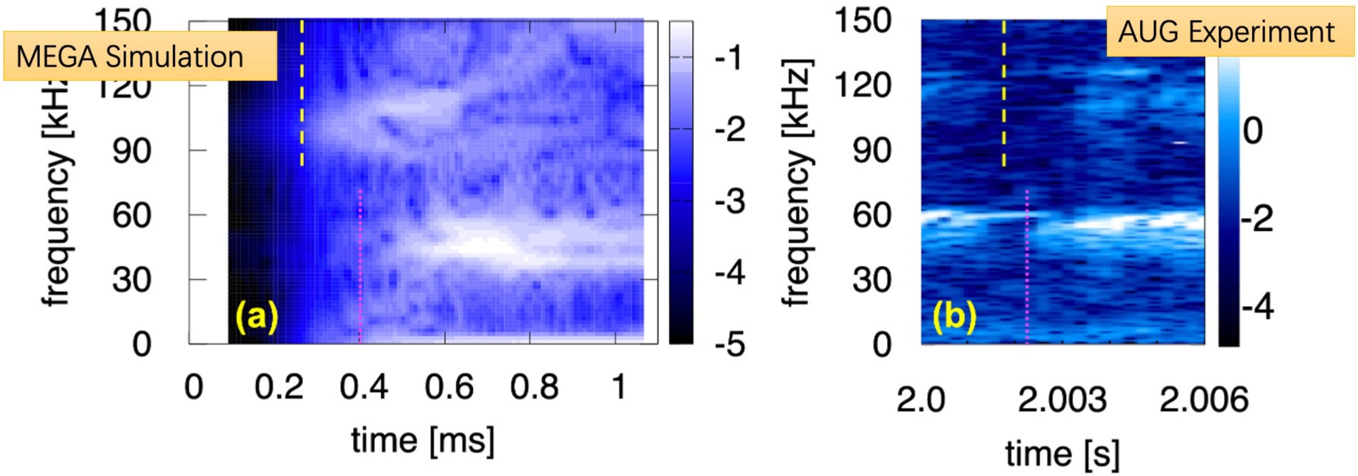
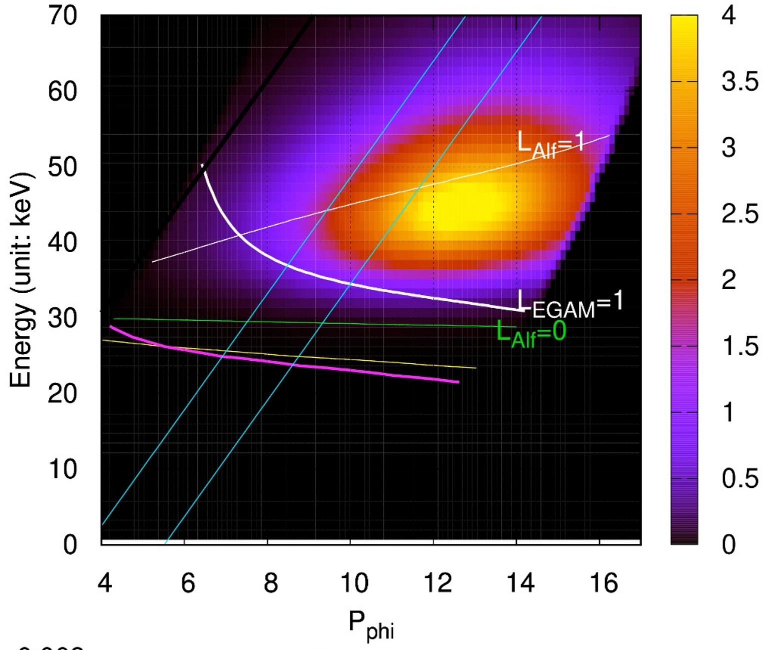
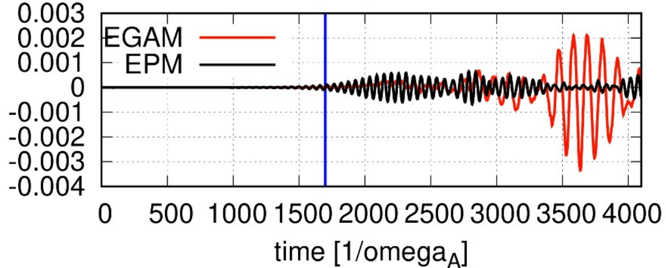
The co-existence of multi-modes is reproduced



- Alfvén instability: m/n=**3/-1**, r/a~0.6, frequency is $0.12*\omega_A$ or 103.5 kHz.
- EGAM: m/n=**0/0**, r/a~0.5, frequency is around 50 kHz.
- EGAM is very weak in linear stage (0~0.3 ms), and becomes stronger than Alfvén instability in nonlinear stage, which is consistent with experimental observation.
- Good validation is obtained.

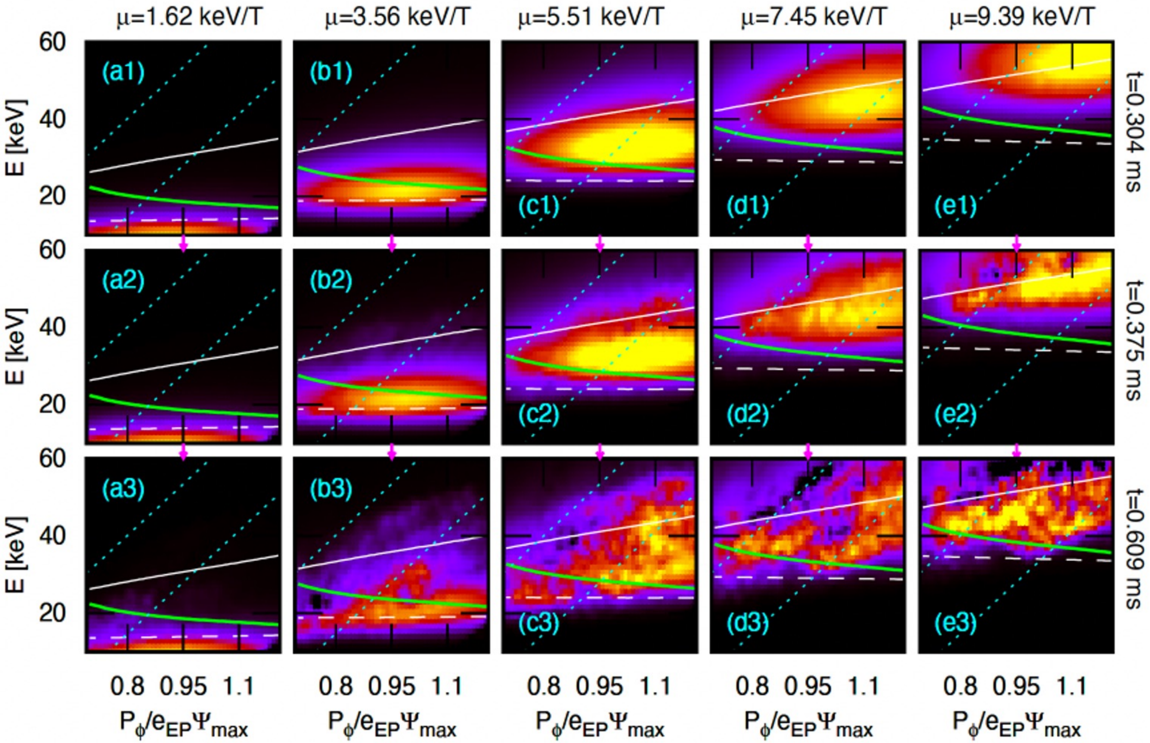




The f_{total} distribution: mu~7.45keV/T (high)

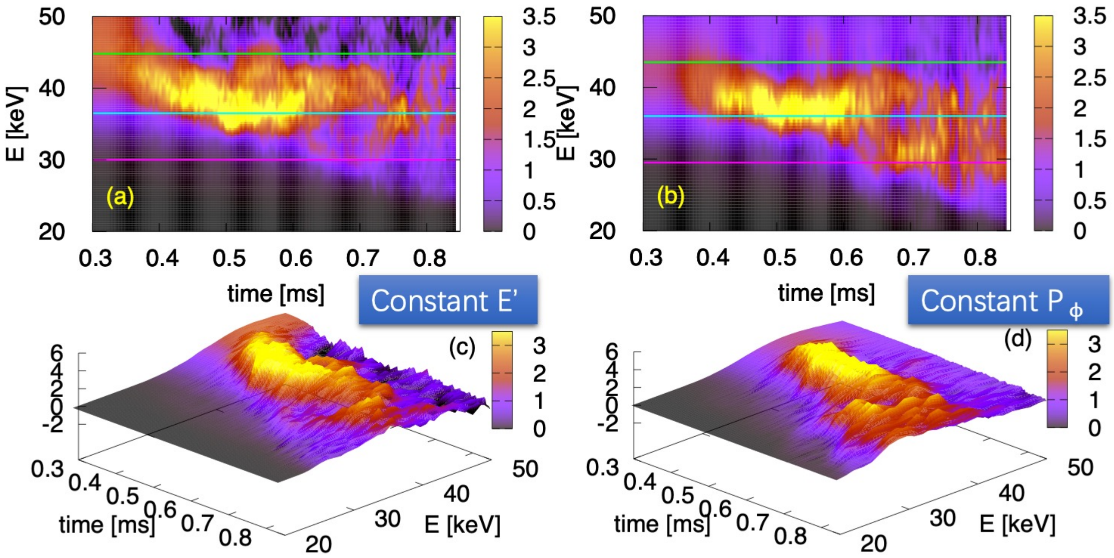
- $f_{total} = f_0 + \delta f$.
- The black color represents the minimum f_{total} value 0. The bright yellow color represents the maximum f_{total} values.
- The straight lines represent constant E prime ($E' = E - \frac{\omega}{n} P_\phi$), which is a conserved quantity for Alfvén instability.
- The solid and dashed white curves represent respectively $L_{Alf} = 1$ and 0, and the green curve represents $L_{EGAM} = 1$. The integer L is an important parameter for resonance condition, $\omega_{mode} = n\omega_\phi + L\omega_\theta$.
- The redistribution is weak in linear phase, but very strong in nonlinear phase.
- **Alfvén instability is destabilized** in the beginning. Then, **EGAM is destabilized**.

EP distribution f_{total} in (P_ϕ,E) phase space



- The black color represents the minimum f_{total} value 0. The bright yellow color represents the maximum f_{total} values, and in the five columns from the left to the right, they are 30, 12, 5, 4, and 2.5, respectively.
- The solid and dashed white curves represent respectively $L_{Alf} = 1$ and 0, and the green curve represents $L_{EGAM} = 1$. The integer L is an important parameter for resonance condition, $\omega_{mode} = n\omega_\phi + L\omega_\theta$.
- The two cyan dotted lines represent two constant E′ values. $E' = E - (\omega/n) \times P_\phi$ is a conserved quantity for the Alfvén instability.

EP distribution f_{total} with detailed time evolution

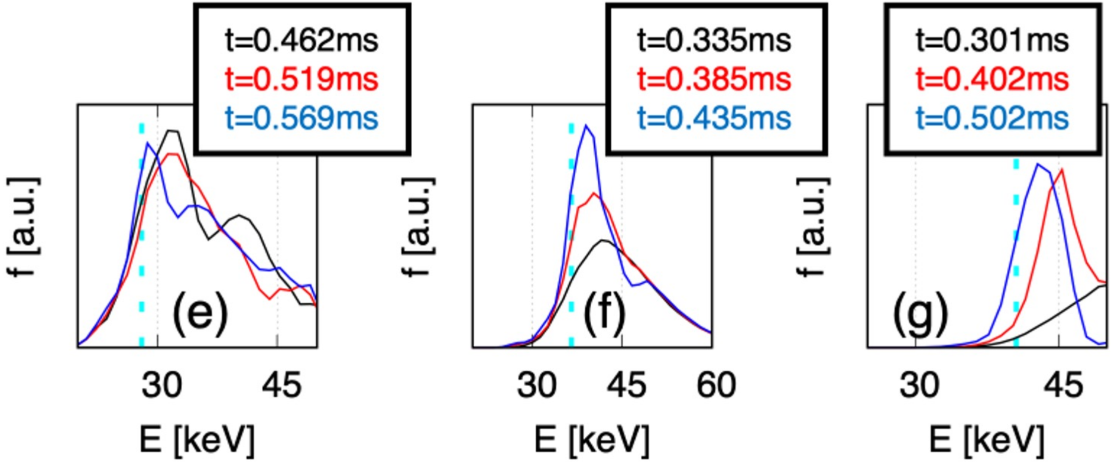


Resonance overlap: Initially, particles resonate with Alfvén instability, and as the mode amplitude grows, the size of the resonance region expands in phase space. Eventually, the Alfvén instability resonance region becomes very large, and reaches the EGAM resonance region. The Alfvén instability resonance region overlaps with the EGAM resonance region, and EGAM is excited.

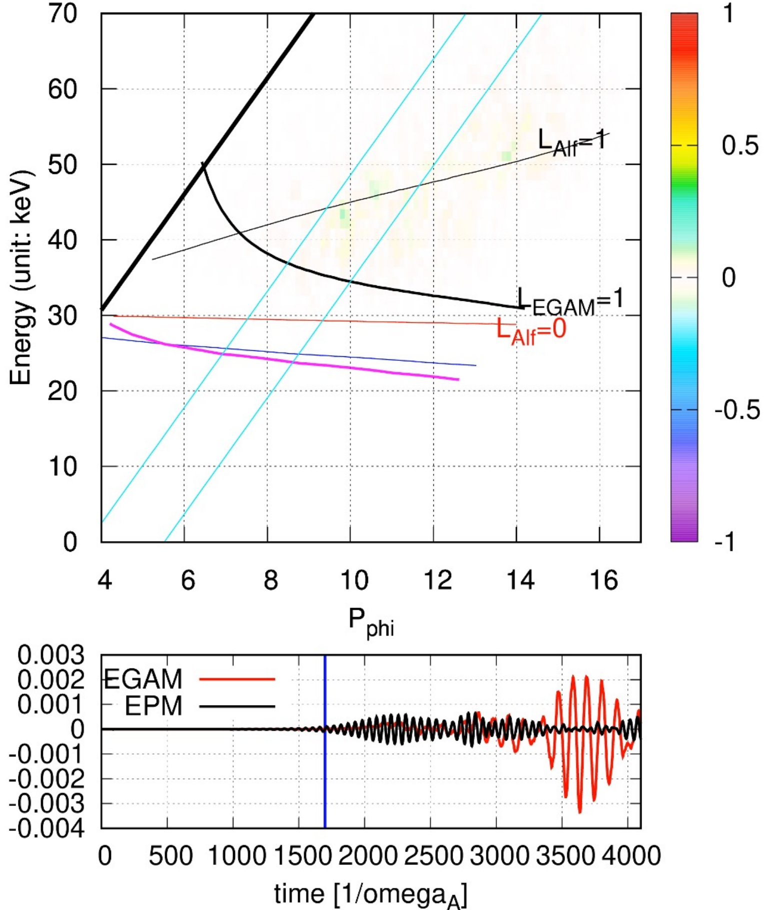
- The time evolution of f_{total} along (left) the right E' line and (right) the vertical line with a P_ϕ value of 11 in the last slide figure. The particle μ value is 7.45 keV/T.
- These three horizontal lines represent resonant layers of $L_{Alf} = 1$, $L_{EGAM} = 1$, and $L_{Alf} = 0$.
- Bottom: the bird's-eye view 3-dimensional figures.

EP distribution f_{total} in 1-dimensional figure

H. Wang et al, Sci. Rep. (2025)



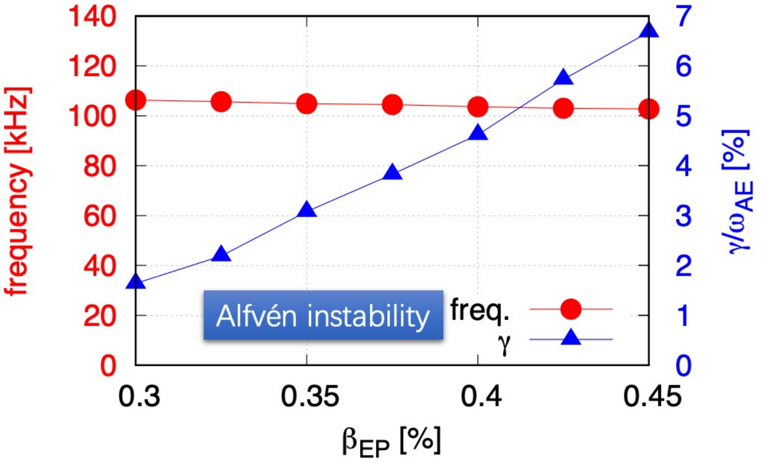
- The f_{total} along P_ϕ = const. at different times, the $P_\phi / e_{EP}\Psi_{max}$ values are 0.994, 0.778, and 0.804, the maximum values of the vertical axis are 6.5, 3.5 and 3.5, and the particle μ values are 5.51, 7.45 and 9.39 keV/T, respectively.
- The vertical dotted lines represent the resonant layers of L_{EGAM}=1.

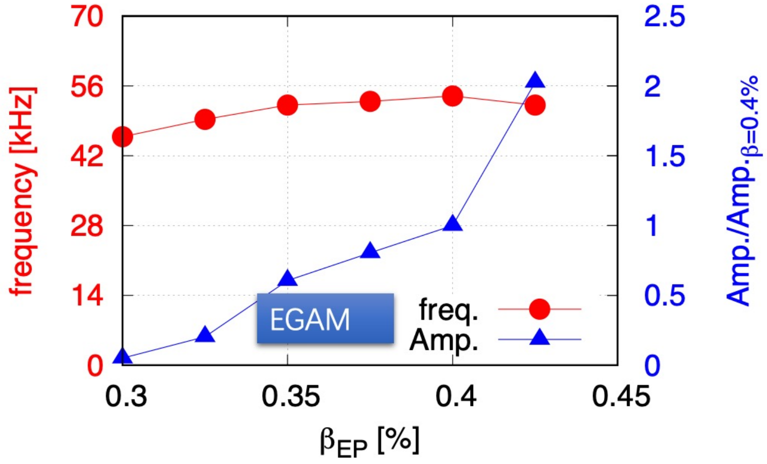


The δf distribution: mu~7.45keV/T (high)

- Red color represents positive δf, and purple color represents negative δf.
- The straight lines represent constant E prime ($E' = E - \frac{\omega}{n} P_\phi$), which is a conserved quantity for Alfvén instability.
- The redistribution is weak in linear phase, but very strong in nonlinear phase.
- **Alfvén instability is destabilized** with L=1 in the beginning. Then, **EGAM is destabilized** with L=1.
- The purple and red region moves along constant E prime line in the beginning, then, moves downward along constant P_{phi}.

The dependence on EP pressure [H. Wang *et al*, Nucl. Fusion 2024]





- The dependence of (left) Alfvén instability and (right) EGAM properties on EP pressure β_{EP}. The red circles represent the mode frequencies, and the blue triangles represent the mode growth rate (Alfvén instability) or maximum amplitude (EGAM).
- The EGAM frequency is higher than the GAM frequency (~ 42 kHz), and the frequency increases with EP pressure.
- The nonlinearly excited EGAM is a high-frequency branch that appears even under the condition of a slowing-down EP distribution.

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Summary

- Under the condition of slowing-down distribution, the coexistence of Alfvén instability and energetic particle driven geodesic acoustic mode (EGAM) in linear stage (and nonlinear stage) is reproduced.
- The mode numbers, mode locations, and mode frequencies are consistent with experiment.
- The nonlinearly excited EGAM is a high-frequency branch that appears even under the condition of a slowing-down EP distribution.
- The conclusive evidence of nonlinear excitation mechanism of EGAM is found in (P_{φ},E) space for the first time.

mu [keV/T]	Alfvée instability	L	EGAM	L
9.392 (very high)	**Destabilized**	1	Weak	1
7.450 (high)	**Destabilized**	1	**Destabilized**	1
5.509 (medium)	Stabilized	1	**Destabilized**	1
3.561 (low)	**Dest.** & Stab.	0 & 1	Stabilized	1
1.620 (very low)	Stabilized	0	Weak	1 & 2

- H. Wang et al, Nucl. Fusion (2024)
- H. Wang, ICPP2024, invited.
- H. Wang et al, Sci. Rep. (2025)

Thank you!