17pC34-1

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大阪大学豊中キャンパス

大型ヘリカル装置における測地線音響モードの亜臨界励起現象の実験的検証

Experimental Identification of Subcritical Instability of Geodesic Acoustic Mode in the LHD

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This study has been performed under collaboration with

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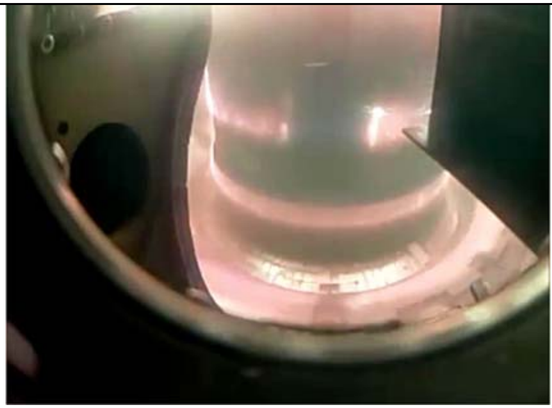
- **Summary**

Background: Abrupt phenomena

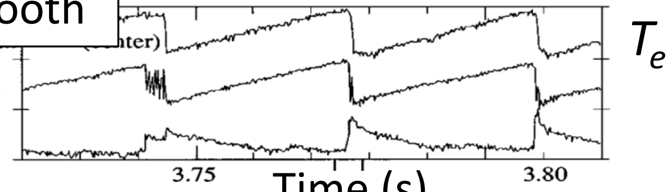
Abrupt phenomena are widely observed in laboratory plasmas and space plasmas.

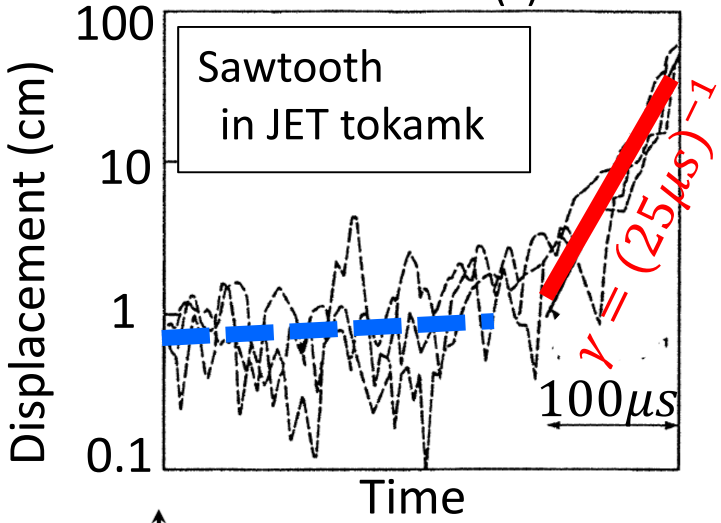
Reviewed in S. -I. Itoh, et al. Plasma Phys. Controll. Fusion 40, 879 (1998)

Disruption in tokamaks (Alcator C-Mod)

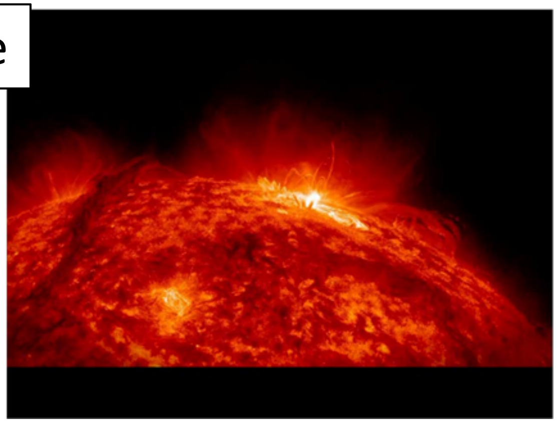


https://www.youtube.com/watch?v=CUfR819hIDg

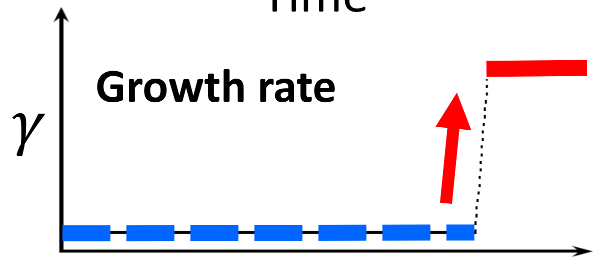




Solar flare



http://www.nasa.gov/downloadable/videos/nasa__twisting_solar_eruption_and_flare.mp4

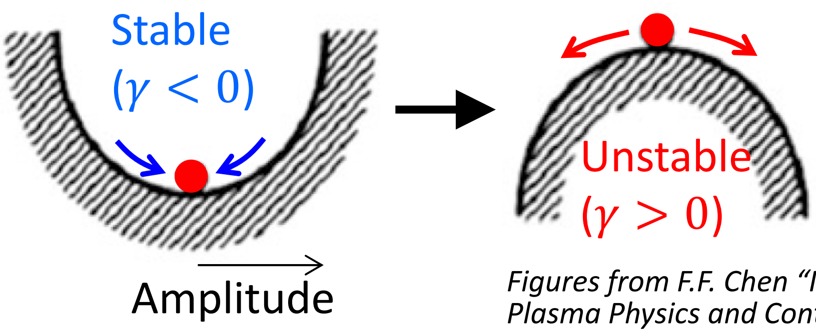


Why does the growth rate increase suddenly and rapidly?

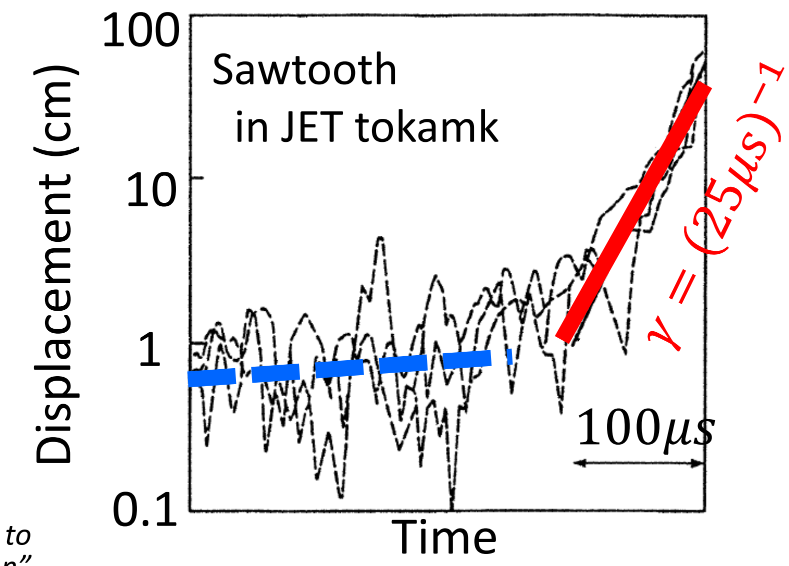
Why does the growth rate increase suddenly and rapidly?

Linear instability

$$\frac{du}{dt} = \gamma u \quad [u\text{: variation}]$$



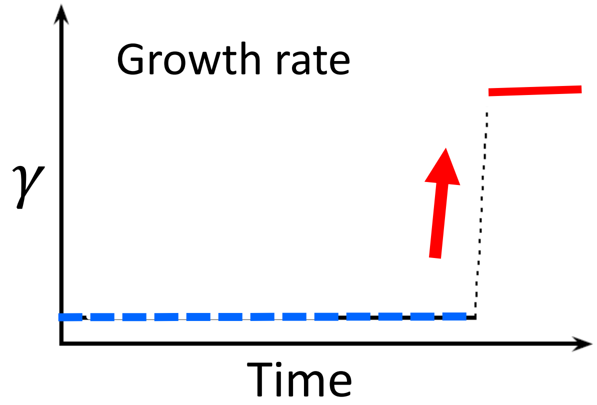
Figures from F.F. Chen "Introduction to Plasma Physics and Controlled Fusion"



The rate of change in the growth rate is determined by the rate of change in driving or damping source, such as ∇p, current profiles, and so on.

$$\frac{\partial \gamma}{\partial t} = \frac{\partial \gamma}{\partial \beta}\frac{\partial \beta}{\partial t} + \frac{\partial \gamma}{\partial q}\frac{\partial q}{\partial t} + \cdots$$

→ The rate of change in linear growth rate is too slow to explain the abrupt phenomena.

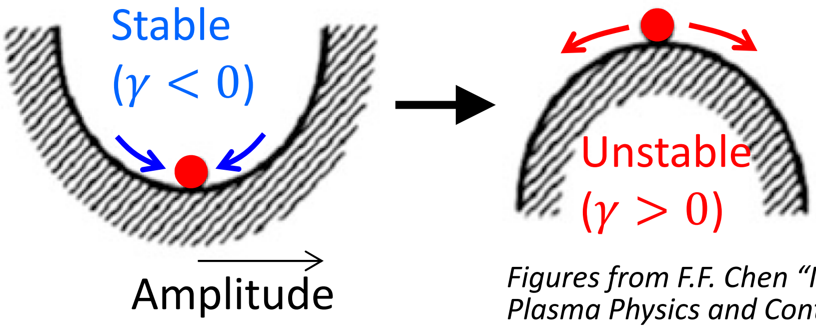


Reviewed in S. -I. Itoh, et al. Plasma Phys. Controll. Fusion 40, 879 (1998)

Subcritical instability

Linear instability

$$\frac{du}{dt} = \gamma u \quad [u\text{: variation}]$$



Figures from F.F. Chen "Introduction to Plasma Physics and Controlled Fusion"

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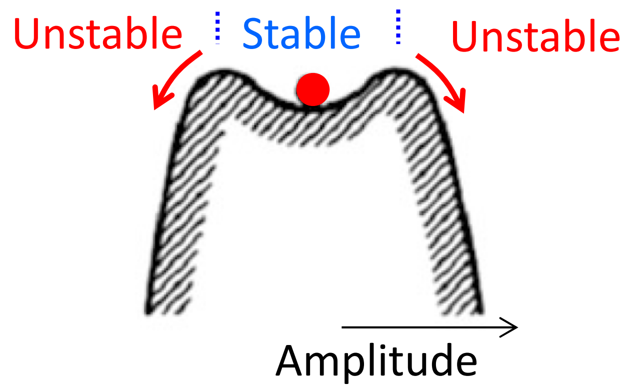
→ The rate of change in linear growth rate is too slow to explain the abrupt phenomena.

Subcritical instability

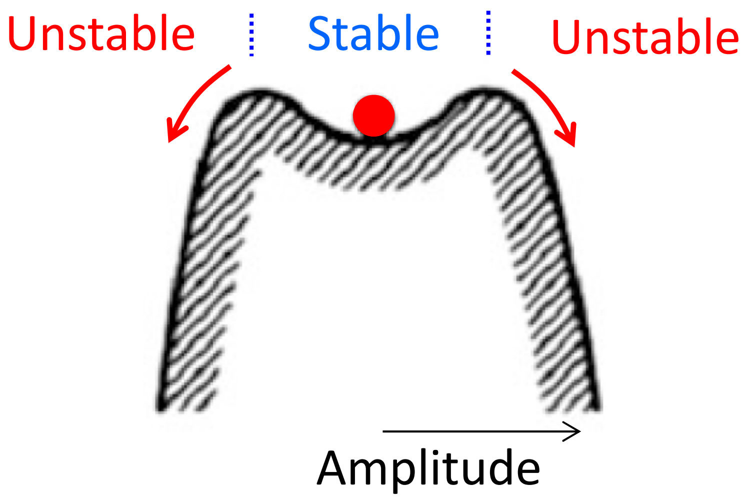
$$\frac{du}{dt} = \gamma u + l u^3 \quad (\gamma < 0, l > 0)$$



The instability is driven when the amplitude exceeds a threshold, even if macro parameters don't change.

→ Although a sufficient trigger is necessary , **sudden** and **rapid** growth is possible, regardless of change in the macro parameters.

Subcritical instability



- Threshold
- Trigger
- Rapid change in the growth rate

Subcritical instabilities appear widely in nature.
(see M. Lesur, J. Plasma Fusion Res. **92**, 665(2016))

Neutral fluid (theory , Experiment)

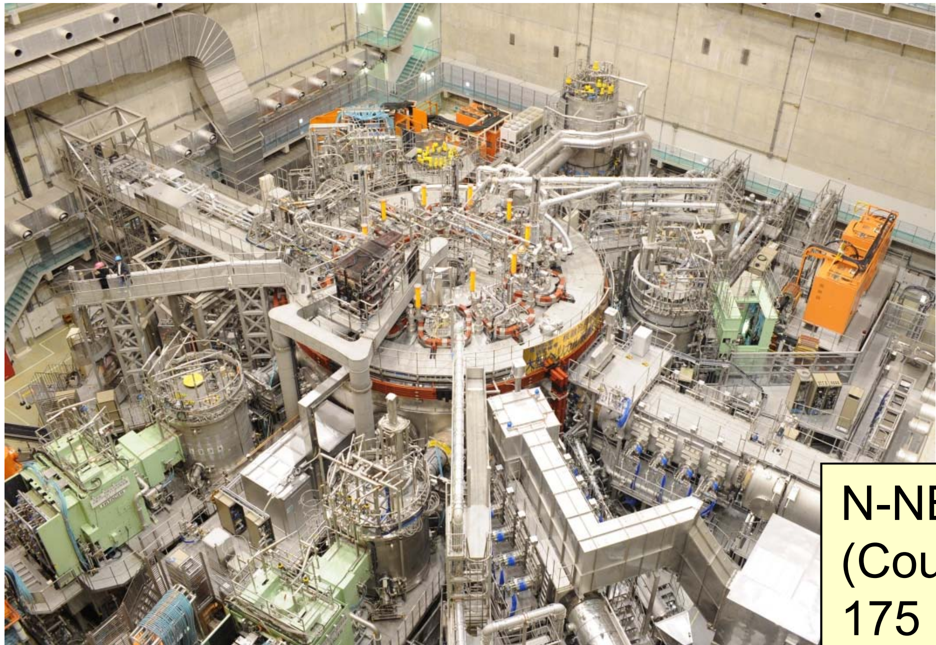
- Planer Couette flow
- Planer Poiseuille flow

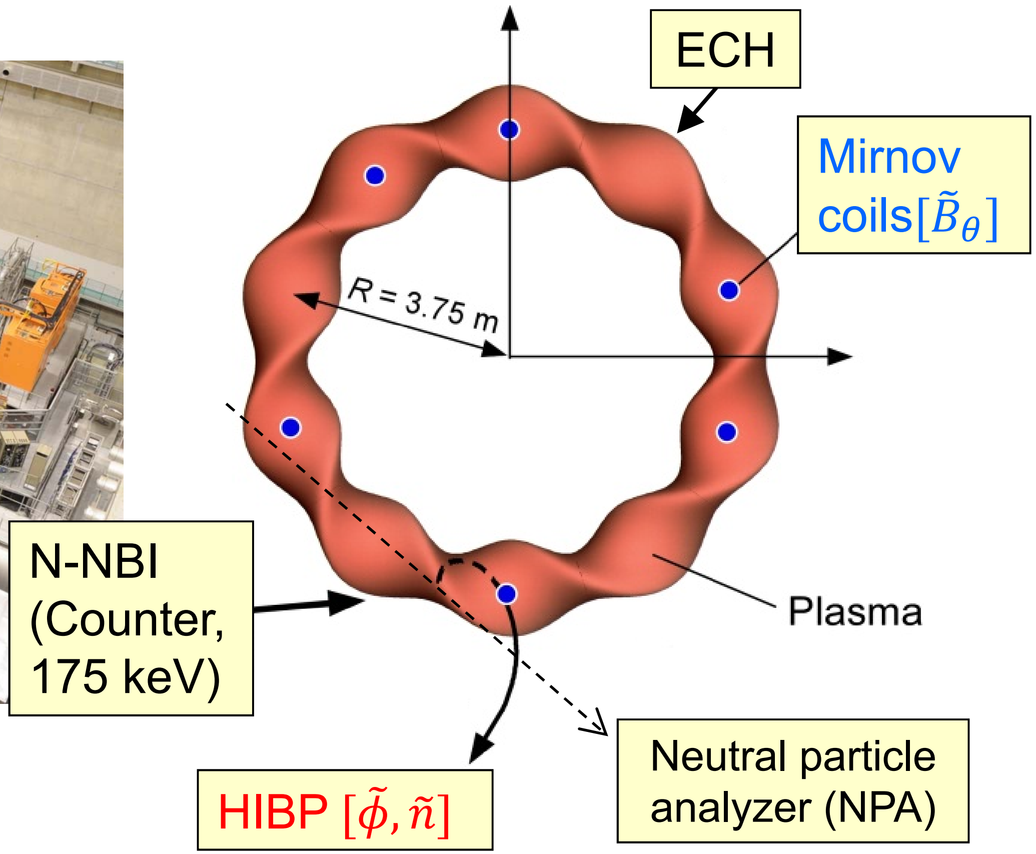
High temperature plasma (theory)

- Current diffusive interchange mode[Yagi, PoP(1995)]
- Neoclassical tearing mode[Carrera, PoF(1986)]
- Energetic particle driven instabilities(e.g. Berk-Braizman model)
- Onset of solar flare [Kusano, Astrophys. J. (2012)]

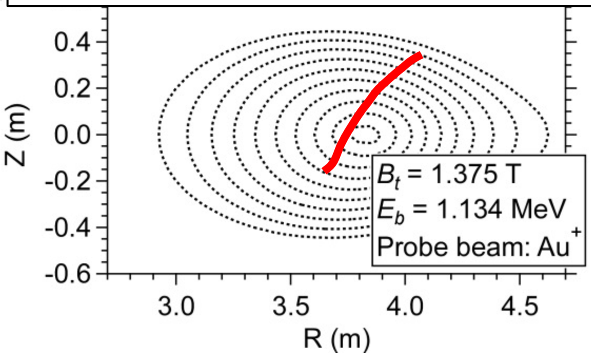
Experiment in the LHD: Experimental setup

LHD





Measurement position of the HIBP



- Mirnov coils array : $\tilde{B}_\theta$ and its toroidal mode structure
- HIBP : $\tilde{\phi}$ and $\tilde{n}$ in the core region
- NPA : Energy spectra of confined ions
- N-NBI : Heating source and energetic particle source

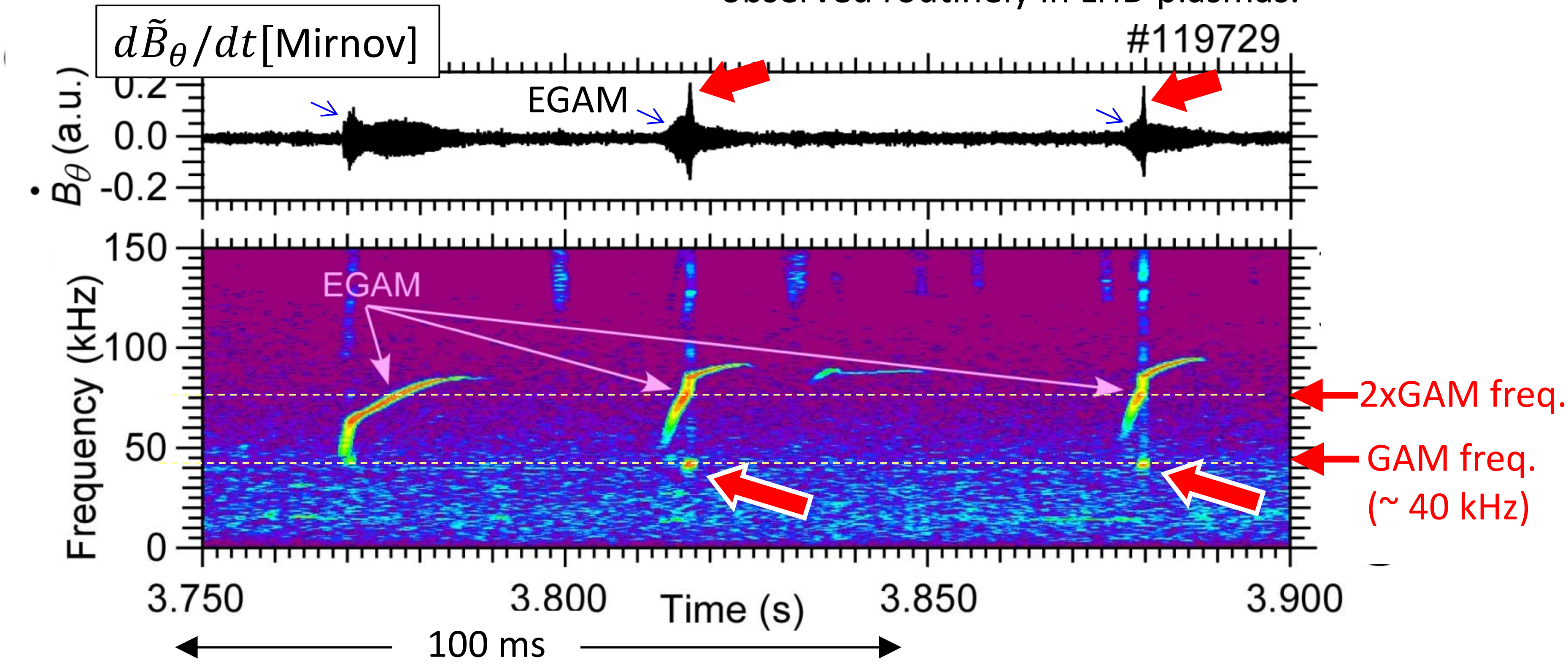
A intense mode is abruptly excited during frequency chirping of an EGAM.

- Tangential Neutral Beam Injection (NBI)
- ECH is applied.
- n_e ~ 0.1 x 10^{19} (m^{-3}), H plasma
- $T_{e,O}$~ 8 keV, $T_{i, NPA}$ ~0.6 keV.

T. Ido, et al. Nucl. Fusion ***55****, 083024 (2015)*

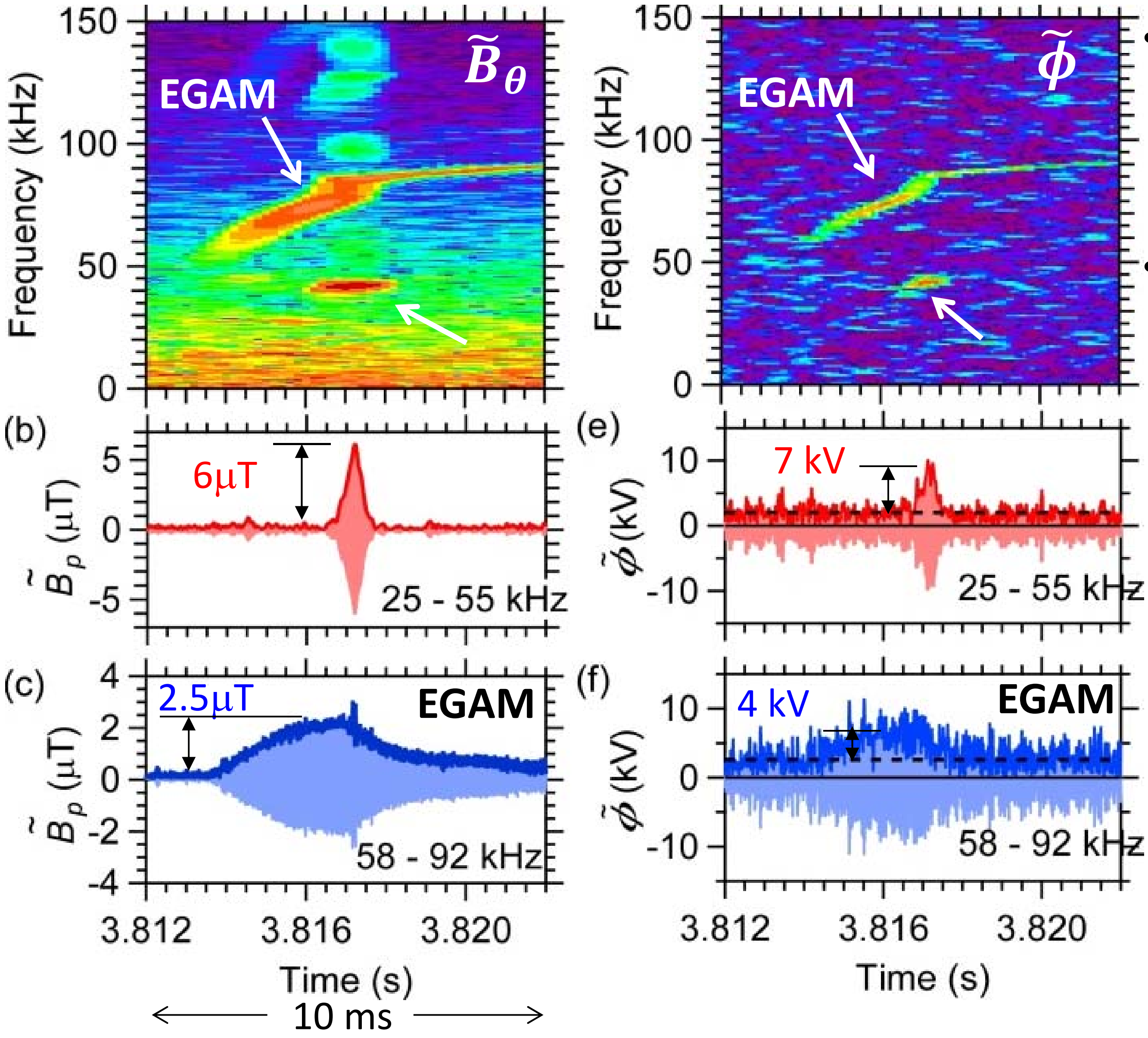
T. Ido, et al., Phys. Rev. Lett. ***116****, 015002 (2016)*

Energetic particle-driven GAM (EGAM) is observed routinely in LHD plasmas.



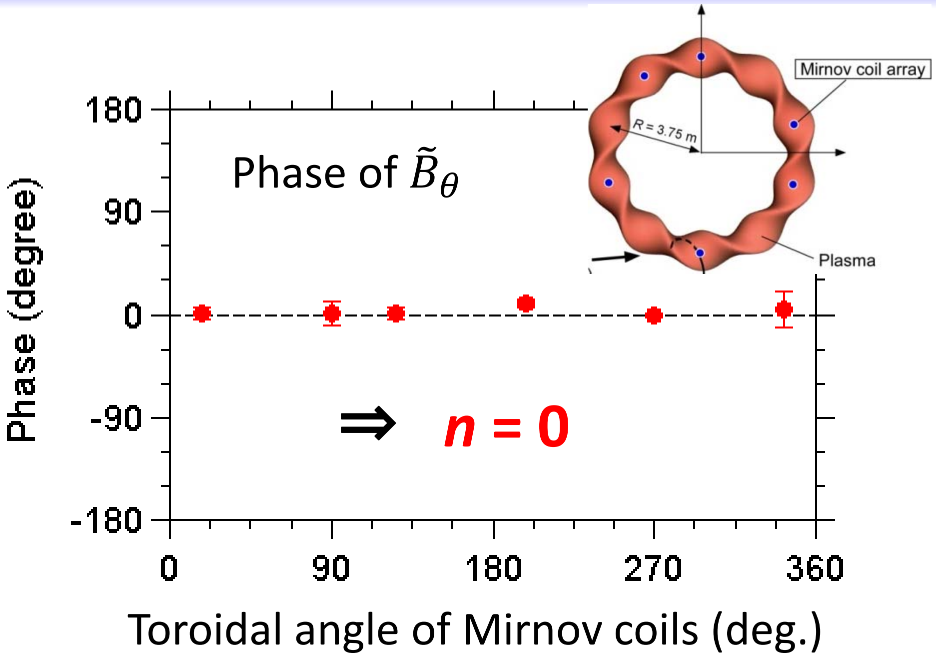
- When the frequency of this chirping EGAM reaches twice the GAM frequency, another strong mode with the GAM frequency is abruptly and transiently excited.

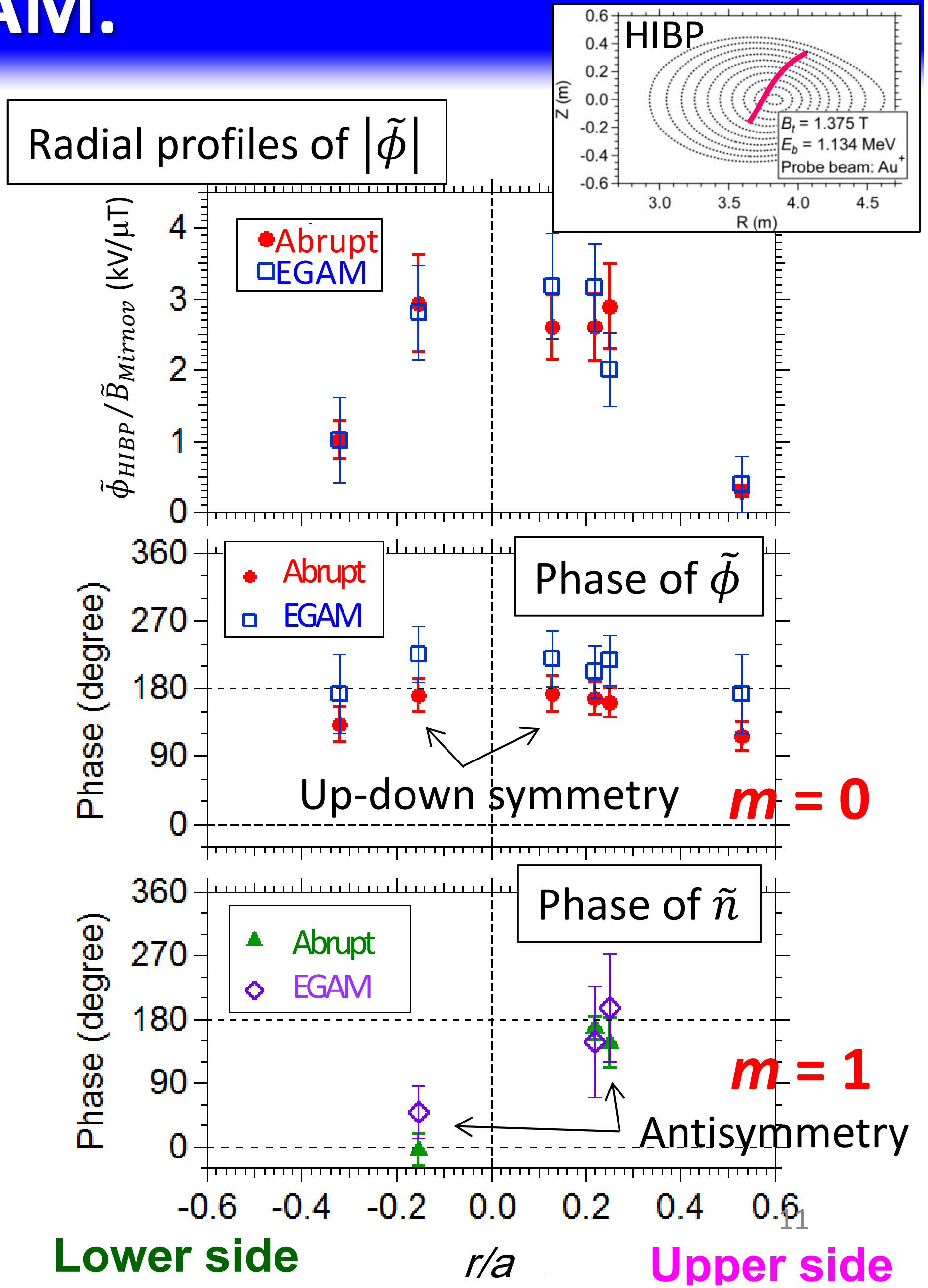
A GAM is abruptly excited during frequency chirping of an EGAM



- Time scale of the abrupt excitation (< 1 ms) << that of the EGAM(a few ms).
- The amplitude of the abruptly-excited GAM is 2-3 times larger than that of the EGAM.

Spatial structures of the abruptly-excited mode agree with those of the GAM.

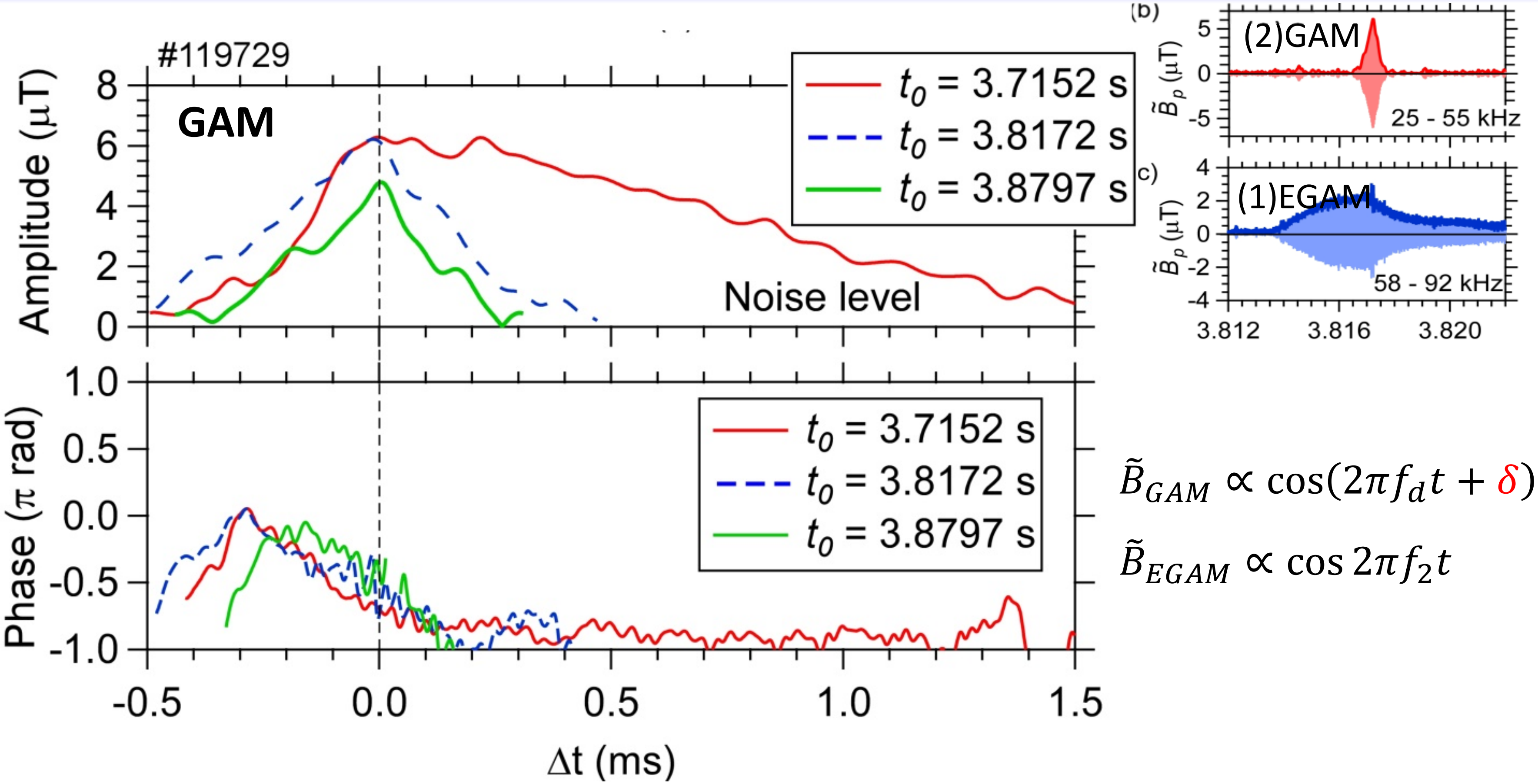




- The GAM exists in the same region as the EGAM.
- Uniform in the toroidal direction (*n* = 0)
- In the poloidal cross section,
  up-down symmetry for $\tilde{\phi}$ (*m* = 0)
  up-down antisymmetry for $\tilde{n}$ (*m* = 1)
- GAM frequency

⇒ **The abruptly-excited mode is a GAM.**

Phase relation between the EGAM and the abruptly-excited GAM



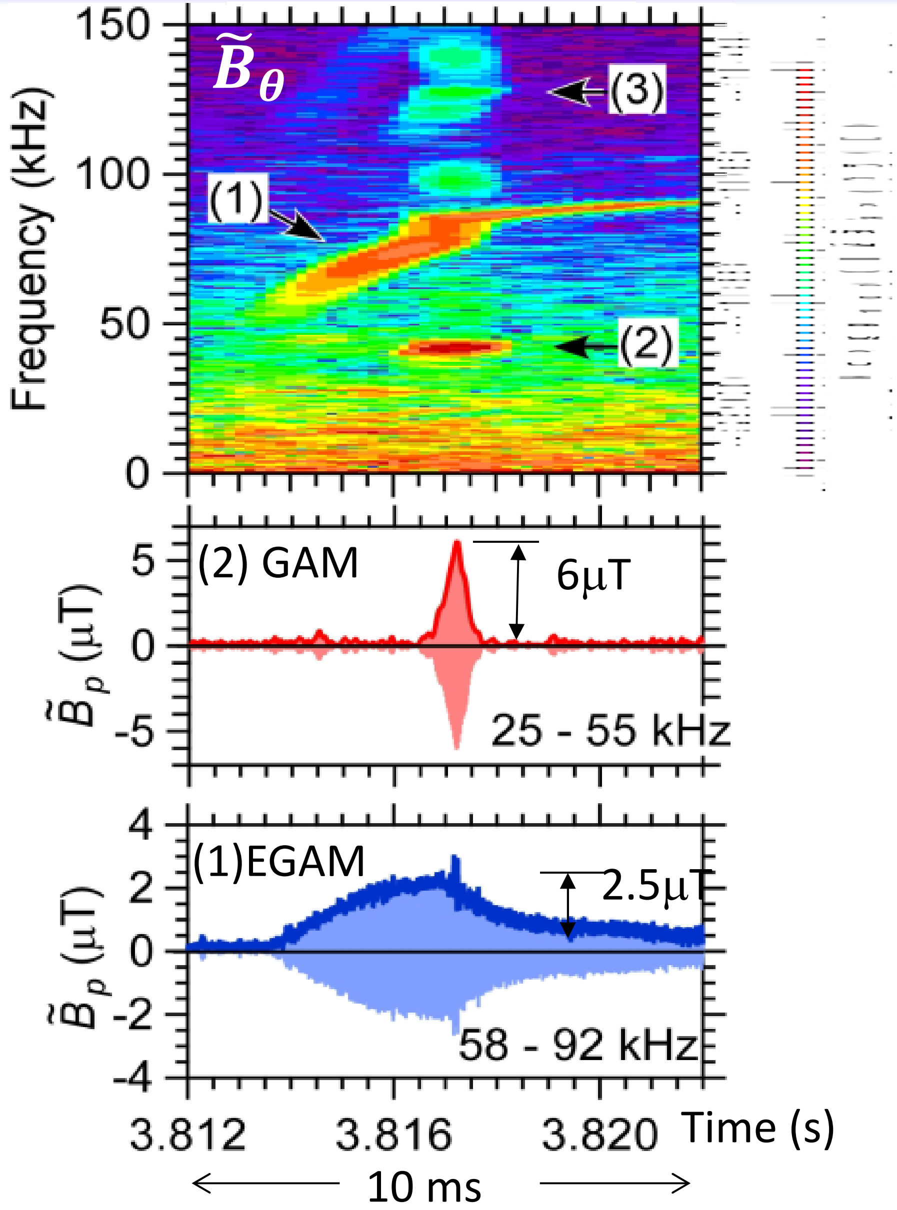
$$\tilde{B}_{GAM} \propto \cos(2\pi f_d t + \delta)$$

$$\tilde{B}_{EGAM} \propto \cos 2\pi f_2 t$$

The phase relation between the EGAM and the abruptly-excited GAM shows a common tendency in the two events (also in the other events).

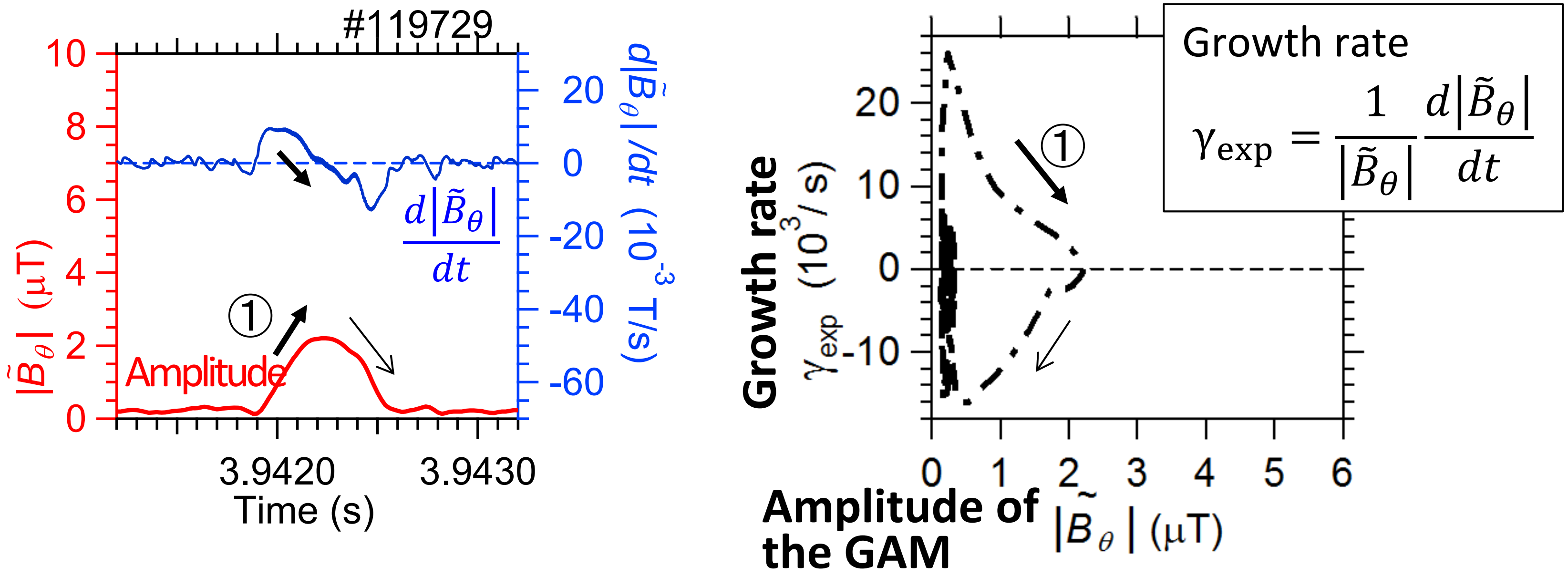
→ **Mode coupling between the EGAM and the abruptly-excited GAM is suggested.**

A GAM is abruptly excited during frequency chirping of an EGAM



- Time scale of the abrupt excitation (< 1 ms) << that of the EGAM.
- The GAM is excited in the same region as the EGAM.
- The phase relation suggests mode coupling between the EGAM and the GAM.
- The amplitude of the lower-frequency GAM is larger than that of the high-frequency EGAM.
  The Manley-Rowe relation is not satisfied:
  $P_1/f_1 \neq P_2/f_2$
  → **Not simple mode coupling**

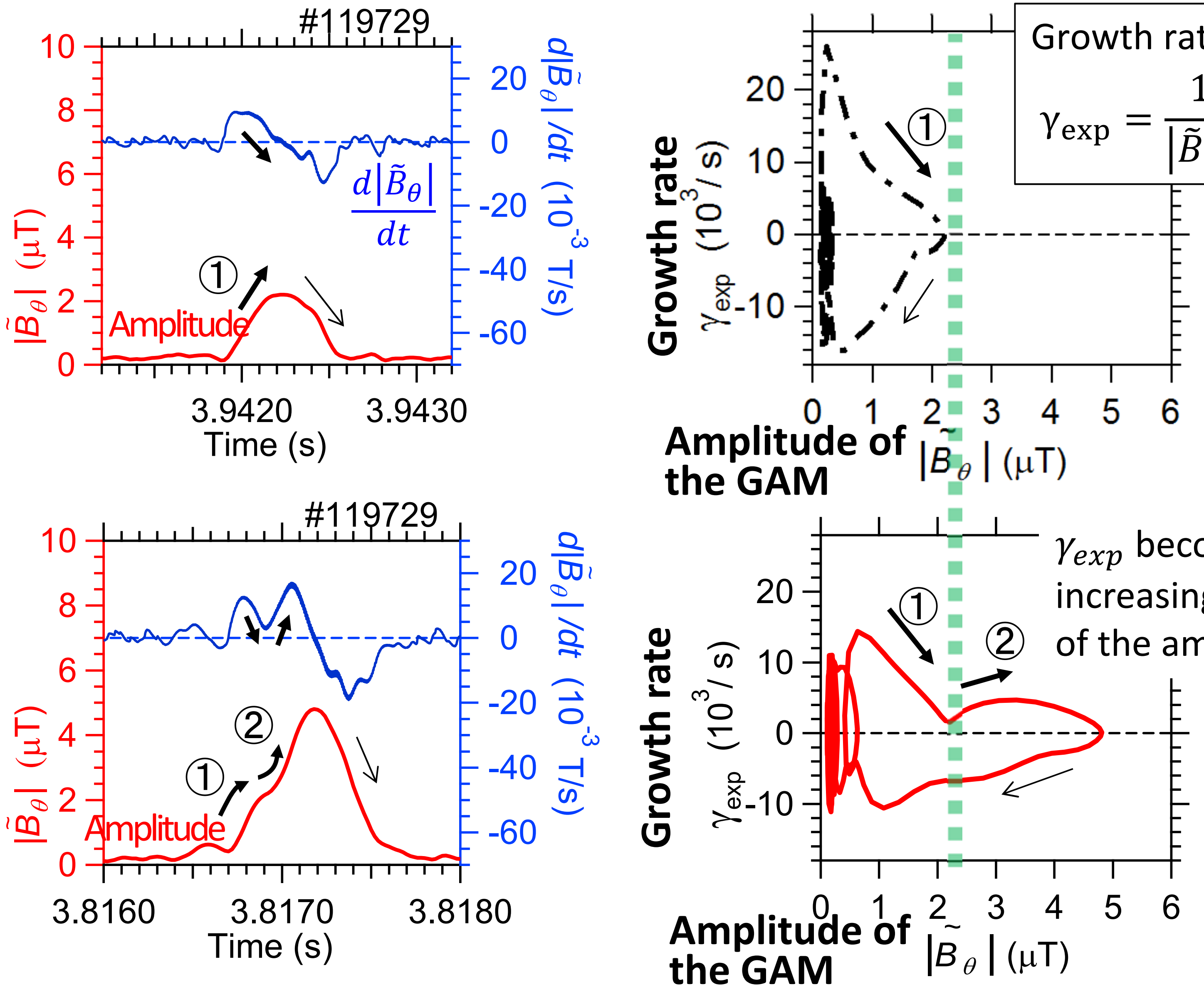
Nonlinear evolution of the abruptly-excited GAM has been observed.



①After the growth rate increases, it decreases as the amplitude increases because the driving source is consumed by the mode excitation.

(This behavior is common for linear instabilities.)

Nonlinear evolution of the abruptly-excited GAM has been observed.



Growth rate

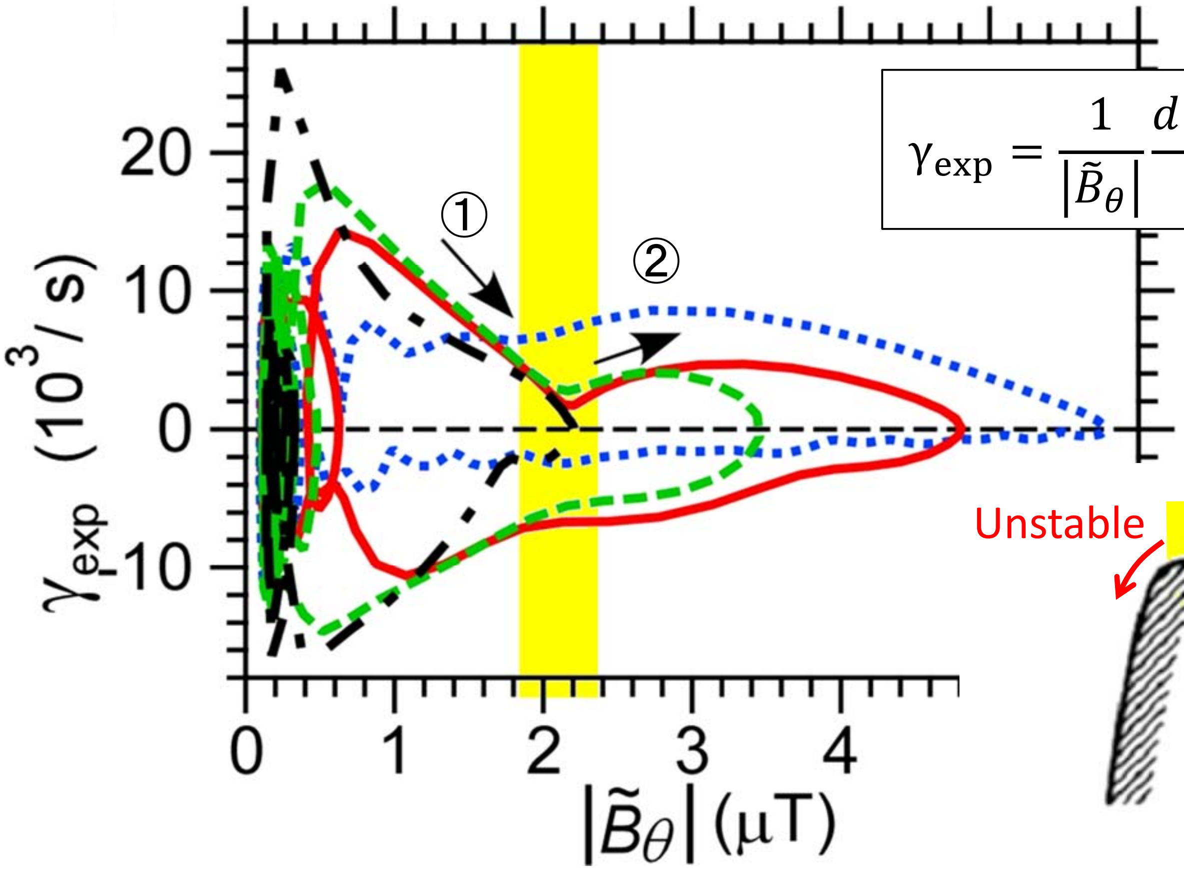
$$\gamma_{\mathrm{exp}} = \frac{1}{|\tilde{B}_\theta|}\frac{d|\tilde{B}_\theta|}{dt}$$

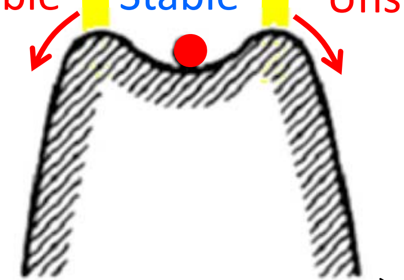
γ_{exp} becomes an increasing function of the amplitude.

Nonlinear evolution of the abruptly-excited GAM has been observed.

T. Ido, et al., Phys. Rev. Lett. ***116****, 015002 (2016)*

(4 bursts are plotted.)





①After the growth rate increases, it decreases as the amplitude increases because the driving source is consumed by the mode excitation.

②When the amplitude exceeds a threshold, the growth rate becomes an increasing function of amplitude. (**nonlinear growth**)

Theoretical model of the abrupt excitation of the GAM

M. Lesur, Phys. Rev. Lett. **116**, 015003 (2016), K. Itoh, Plasma Phys. Reports **42** 428 (2016)

- GAM (Freq. $\omega_1 \sim \omega_{GAM}$, Amplitude Z_1) $\quad \zeta_j \equiv k_j x - \omega_j t$

$$\frac{dZ_1}{dt} = -\gamma_d Z_1 - \frac{m\omega_1^3}{4\pi q m_0}\int f(x,v,t)e^{-i\zeta_1}dxdv - i\frac{V}{\omega_1}Z_2 Z_1^* e^{-i\theta t}$$

Kinetic nonlinearity

Fluid nonlinearity

M. Sasaki, Phys. Plasma (2009)

K. Itoh, Phys Plasma (2005)

→ **Parametric instability**

- EGAM (Freq. $\omega_2 \sim 2\omega_{GAM}$, Amplitude Z_2)

$$\frac{dZ_2}{dt} = -i\frac{V}{\omega_2}Z_1^2 e^{i\theta t}$$

$\theta \equiv \omega_2(t) - 2\omega_1$ (frequency mismatch)

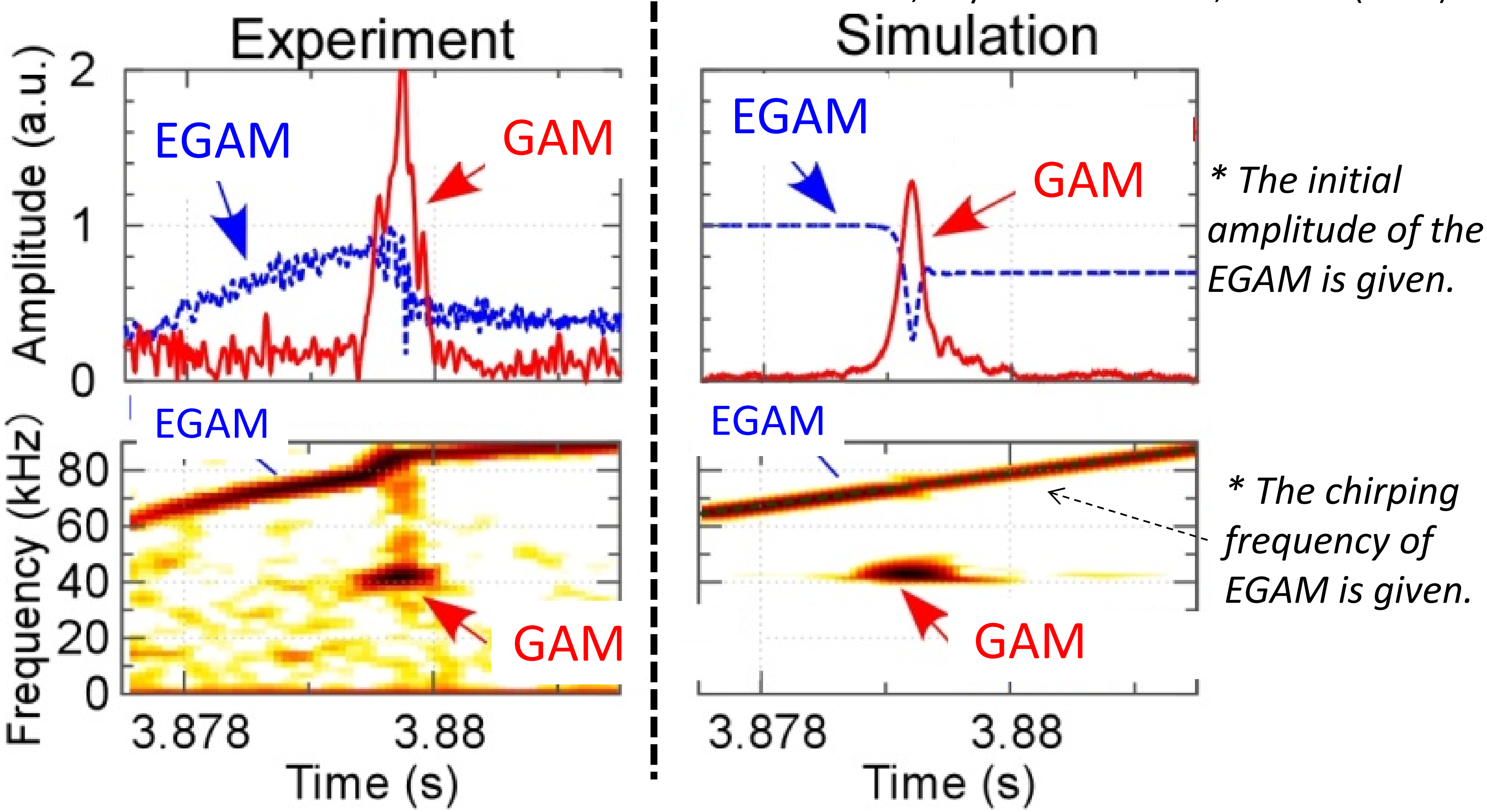
- Distribution function

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} + \frac{qE_1}{m}\frac{\partial f}{\partial v} = \frac{v_f^2}{k_1}\frac{\partial \delta f}{\partial v} + \frac{v_d^3}{k_1^2}\frac{\partial^2 \delta f}{\partial v^2}$$

$$\gamma_{L,0} = \frac{\pi\omega_1^3}{2k_1^2 n_0}\frac{\partial f_0}{\partial v}$$

The simulation reproduces the observed temporal behaviors.

M. Lesur, Phys. Rev. Lett. **116**, 015003 (2016).

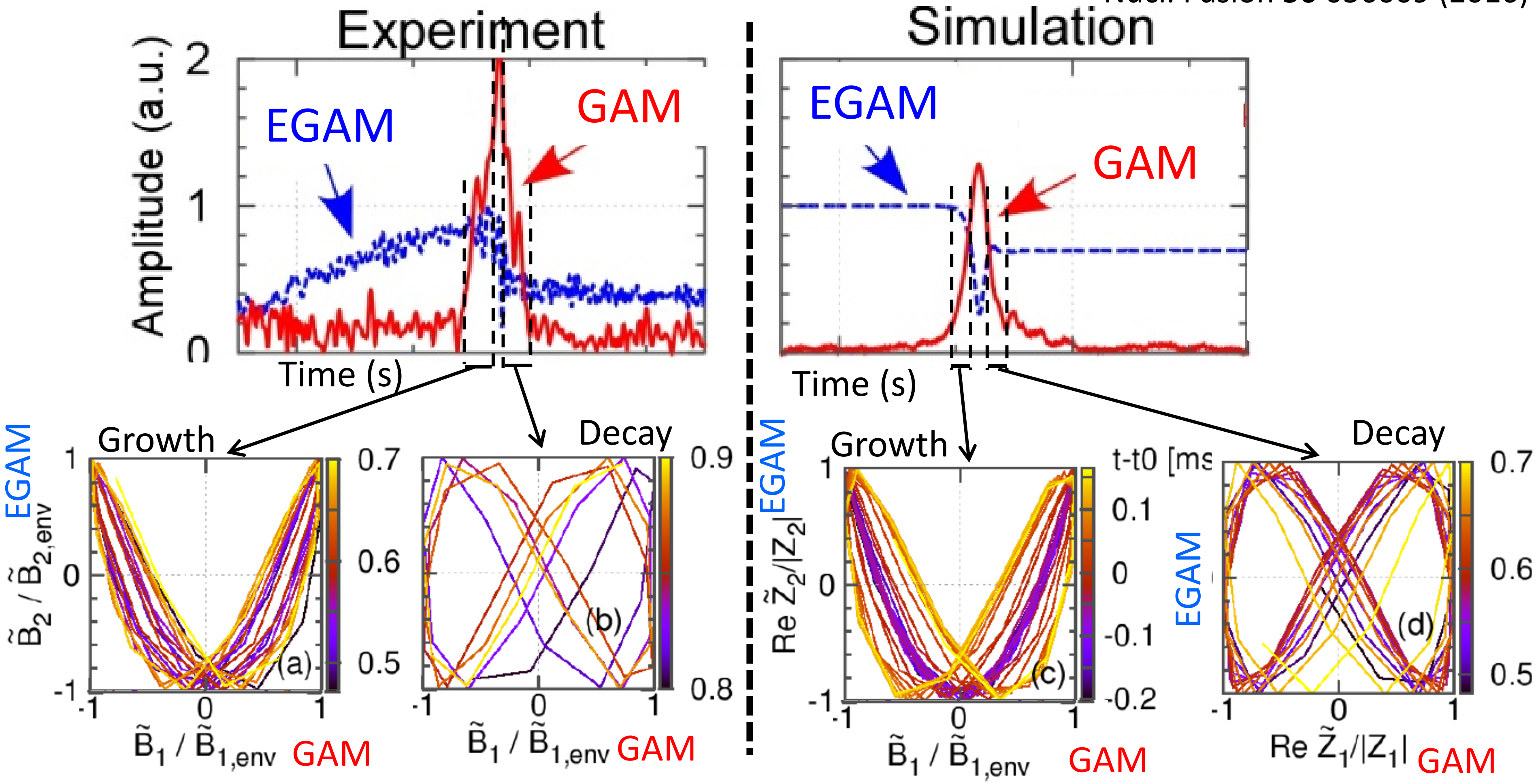


The simulation reproduces the experiment:

- The GAM is excited when the frequency of EGAM approaches twice the GAM frequency.
- Time constant of the evolution of the GAM.
- The amplitude of the GAM becomes larger than that of the EGAM.

The simulation also reproduces the observed phase relation.

M. Lesur, Phys. Rev. Lett. **116**, 015003 (2016)
Nucl. Fusion **56** 056009 (2016)



The phase relation between GAM and EGAM is also simulated by the proposed theoretical model.

MEGA code may simulate a kinetic coupling as the trigger.

MEGA code [Y .Todo, Nucl Fusion(2010)084016]

- MHD fluid
- Kinetic energetic particle

→ EGAM can also be simulated.

H. Wang, 26th IAEA Fusion Energy Conference (2016) TH/P4-11
(Lecture of Young Scientist Award of Physical Society of Japan(2017) 20aC34-11)

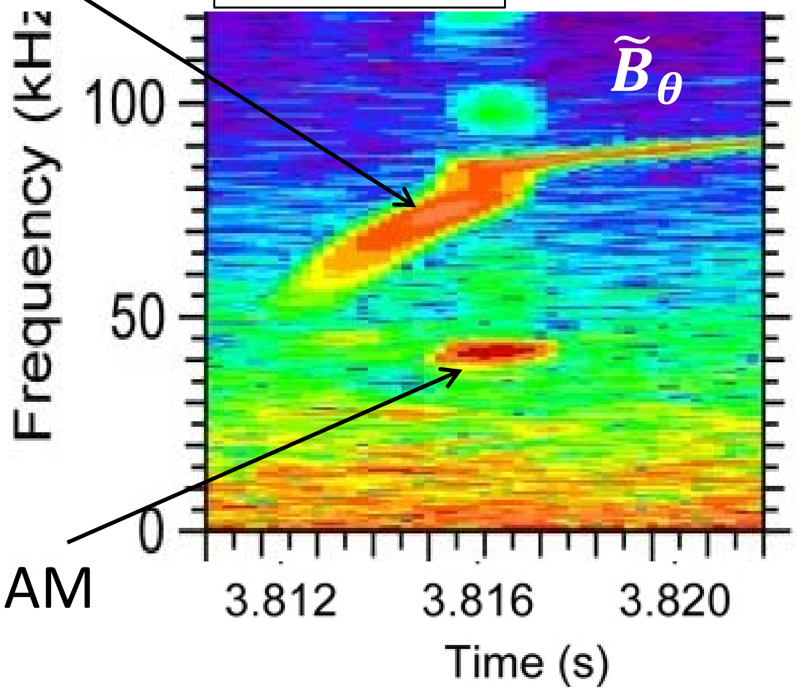
Simulation

See Fig. 4(a) in https://conferences.iaea.org/indico/event/98/session/22/contribution/565/material/paper/0.pdf

EGAM

GAM

Experiment

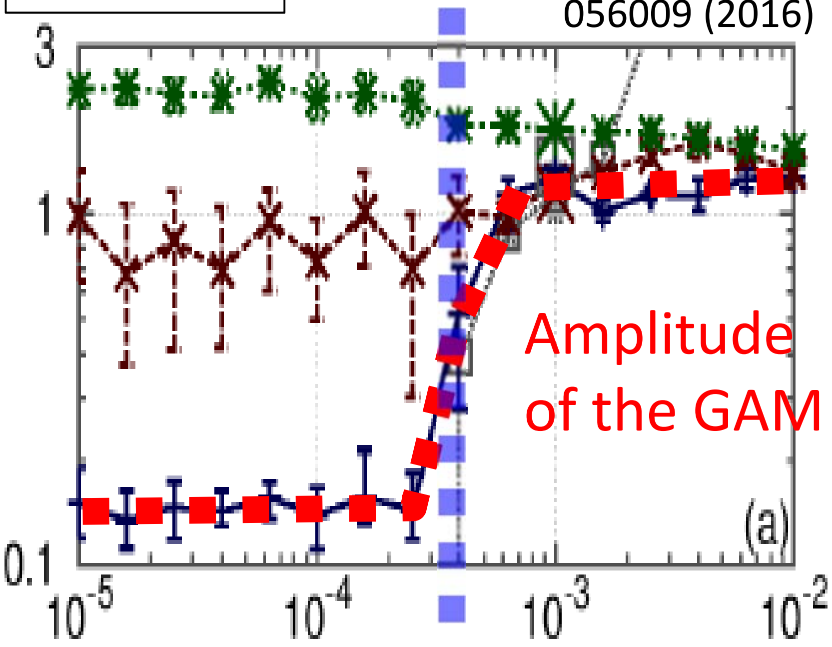


Interaction between the EGAM and the GAM via energetic particles

Threshold in the amplitude of the EGAM

Simulation

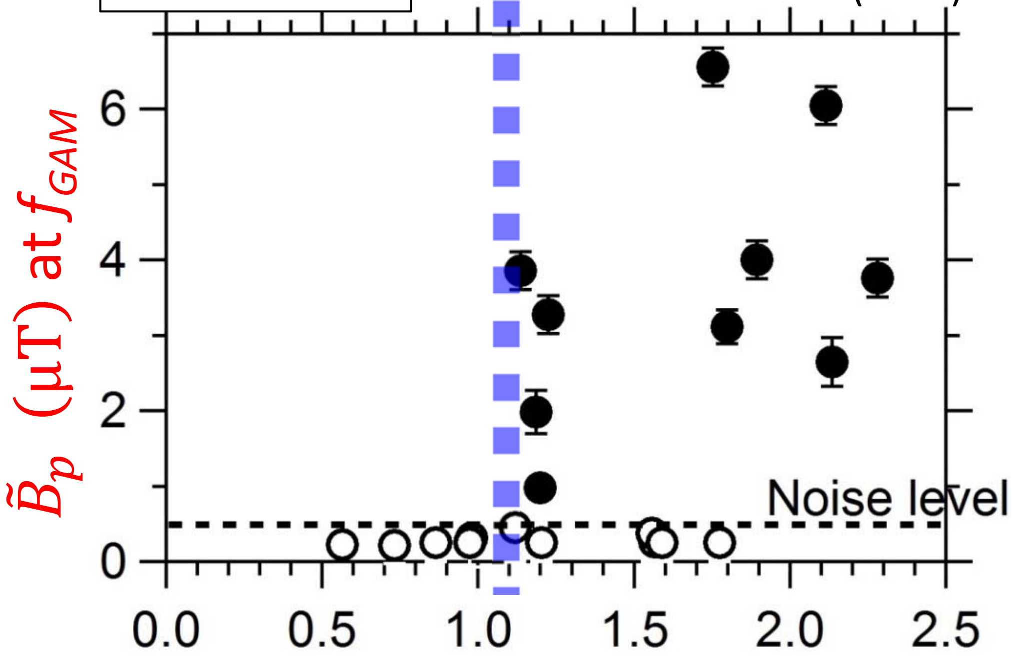
M. Lesur, Nucl. Fusion **56** 056009 (2016)



Amplitude of EGAM
[just before the GAM excitation]

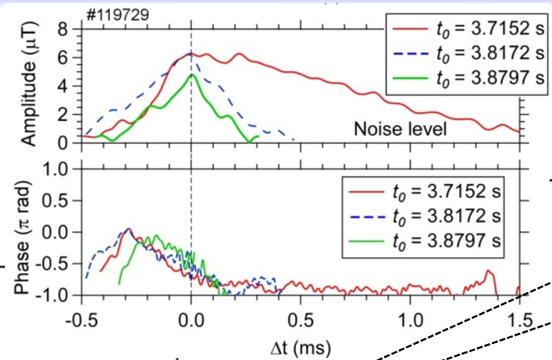
Experiment

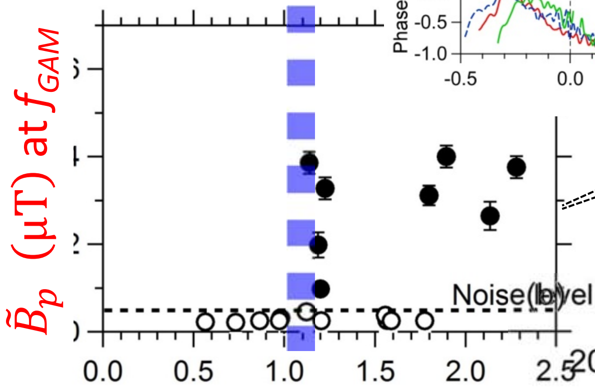
T. Ido, Nucl. Fusion, **57**, 072009(2017)



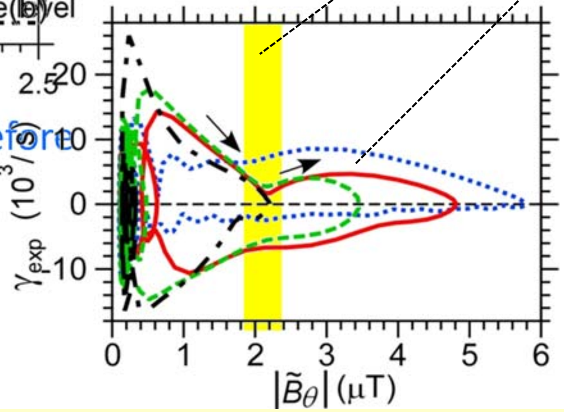
Amplitude of EGAM (μT)
[just before the GAM excitation]

Subcritical instability of the GAM



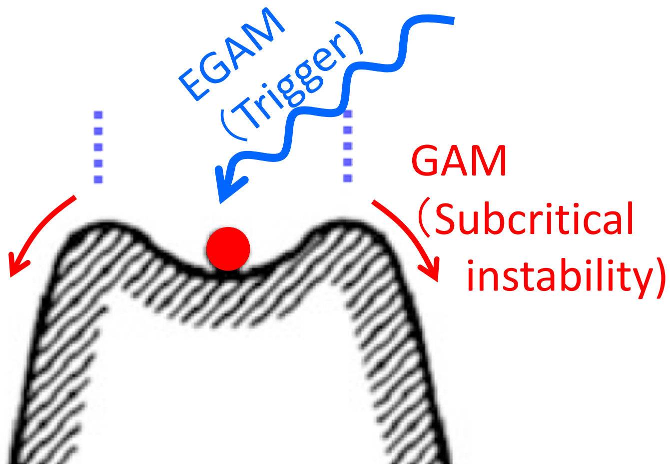


Amplitude of EGAM just before the GAM excitation (μT)



<u>Subcritical instability</u>

- Trigger
- Threshold
- Rapid change in the growth rate



The EGAM triggers the GAM through parametric coupling (and/or kinetic coupling).

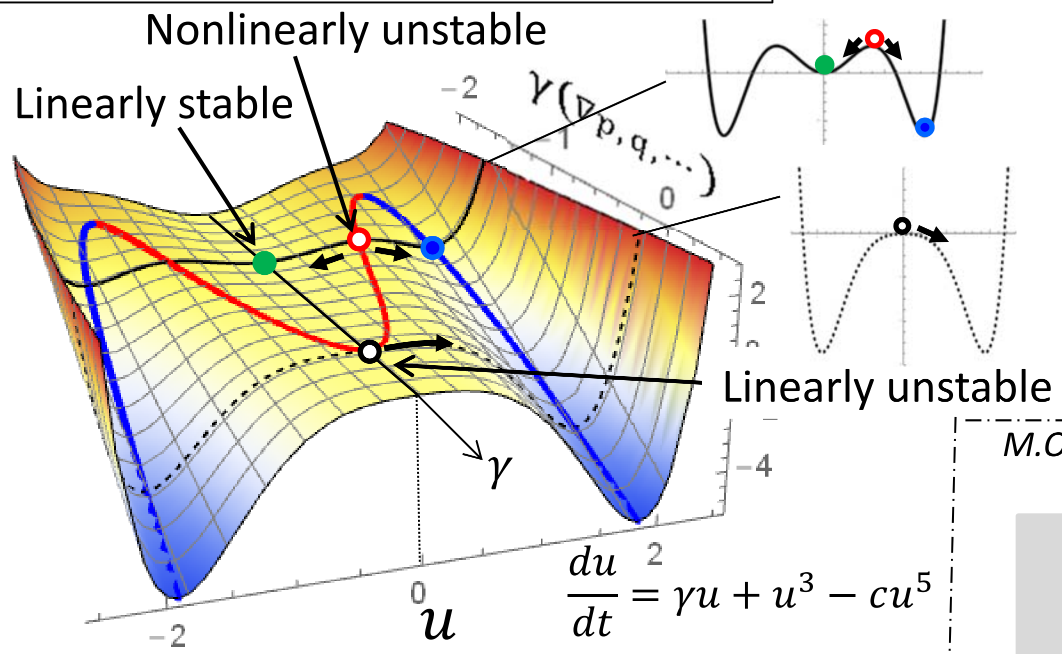
↓

Once the amplitude of the GAM exceeds a threshold, kinetic nonlinearity and fluid mode coupling make the GAM unstable.

Subcritical instability

Impact of this study

Onset of abrupt phenomena, Stability



- This study show an experimental path to explore the trigger problem of abrupt phenomena.
- Even if the system is linearly stable and global parameters don't change, it can be abruptly destabilized by a trigger.

M.Osakabe, IAEA-Fusion Energy Conference, EX/10(2014)

See Fig. 1 in
http://www.nifs.ac.jp/report/IAEA2014/EX-10-3_Osakabe.pdf

Wave-particle interaction

Lower frequency(slower v_{phase})
Larger amplitude

⇩

Larger effect on bulk plasma
(e.g. GAM channeling (M. Sasaki, PPCF, 085017 (2011)))

Summary

- **Abrupt excitation of a GAM is found in the LHD**.
- **The characteristics of the abruptly-excited GAM have been investigated**:
  - The abruptly-excited GAM appears when the frequency of the chirping EGAM reaches twice the GAM frequency.
  - The growth rate and amplitude are larger than those of the EGAM.
  - The phase between the GAM and the EGAM suggests the mode coupling between the GAM and the EGAM.
  - The behaviors of the growth rate suggests that the GAM grows through nonlinear process.
- **Newly proposed theoretical model**, which take into account fluid nonlinearity and kinetic nonlinearity, **can reproduce the experimental results** (phase relation, amplitude, and time scale of the abrupt excitation), **quantitatively**.
- **The abrupt excitation phenomenon observed in the LHD is interpreted as the excitation of subcritical instability**.
- **This study show an experimental path to explore the trigger problem of abrupt phenomena**.