9th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems

Alfvén Eigenmode Spectroscopy by Application of External Magnetic-Field Perturbations in the Compact Helical System

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Outline of the talk

- Introduction
- Experimental Setup
- Experimental Results
- Summary

Introduction

In a fusion reactor, energetic particles could destabilize Alfvén Eigenmode(AE).

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Destabilized AEs enhance loss of energetic particles.

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Quench of ignition and damage to the first wall can occur.

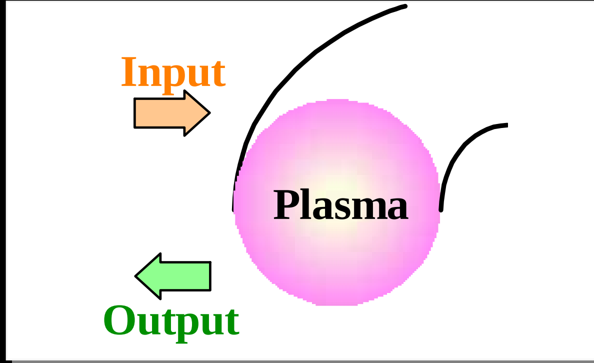
- **Investigation of physics of AEs is important.**
- **The damping mechanisms of AEs should be clarified.**

In order to experimentally clarify the damping mechanism of AEs, we try direct excitation of AEs without fast ions:

"Alfvén Eigenmode Spectroscopy"

Principle of Alfvén Eigenmode Spectroscopy

We apply the linier modal analysis to plasma.



For the first time, it was applied to JET using saddle coils. [A. Fasoli et al. PRL 75, 645 (1995)]

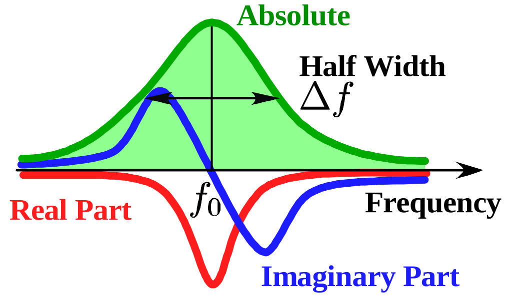
$$\text{Transfer Function} = \frac{\text{Output}}{\text{Input}}$$

- Transfer function provides eigen-frequency and damping rate.
- If we measure the profile of transfer function, the mode structure can be obtained.

Input : Magnetic-field Perturbation by electrodes

Output : Magnetic probe signal

Example for Transfer Function



- Eigen-frequency

$$f_0$$

- Damping rate

$$\frac{\gamma_d}{\omega} = \frac{\Delta f}{2\sqrt{3} f_0}$$

Why is it in the low Temp. and Dens. Plasma?

We carried out these experiments of AE spectroscopy in the low temperature and low density plasma produced by 2.45GHz ECH.

Advantages of the experiments in this plasma.

- **Insertion of electrodes into plasma to excite AEs**
- **Insertion of probes into plasma to measure internal structures of AEs**

Besides, we can focus on specific damping mechanisms;

- **Continuum damping**
- **Radiative damping**

Because of very low βe and βi, electron and ion Landau damping of background plasma are negligible small. Moreover, collisional damping is also small.

$$\frac{\gamma_{\mathrm{Le}}}{\omega} \propto q^2 \beta_{\mathrm{e}} \,, \frac{\gamma_{\mathrm{Li}}}{\omega} \propto q^2 \beta_{\mathrm{i}} \qquad \frac{n_{\mathrm{n}}}{n_{\mathrm{e}}} \ll 1 \,, \frac{\nu_{\mathrm{en}}}{\omega} \ll 1 \,, \frac{\nu_{\mathrm{in}}}{\omega} \ll 1$$

Compact Helical System

- In this type device, magnetic configuration is determined by external coils.
- These coils make a large magnetic shear near the edge.

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- If AE has a broad eigenfunction, it can interact with the Alfvén continuum near the edge.

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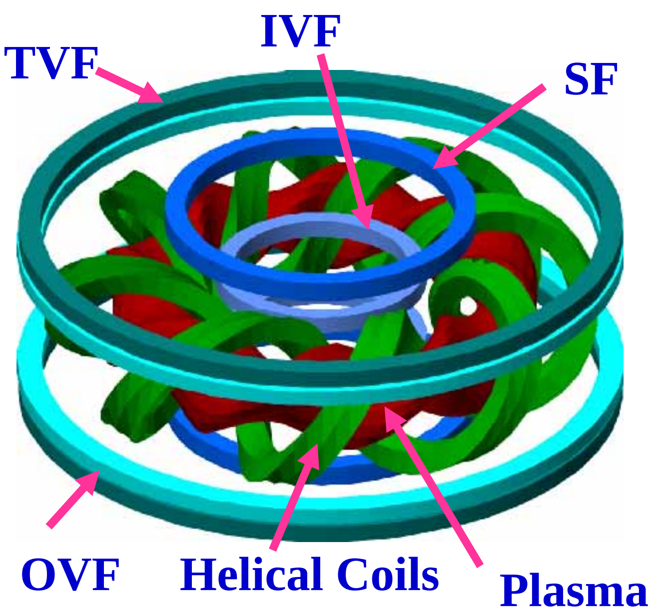
In CHS, continuum damping is expected to be large.



Device Parameters

- Major radius 1.0m
- Miner radius 0.2m
- Aspect ratio 5
- pole number 2
- pitch number 8

AE Spectroscopy System in CHS

- This system is composed of two electrodes.
- Excitation voltage is applied between vacuum vessel and electrodes.

  → Single probe method
- Excitation current is induced along a specific magnetic field line.

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$$\tilde{b}_{\parallel} = 0, \quad \tilde{b}_{\perp} \neq 0$$

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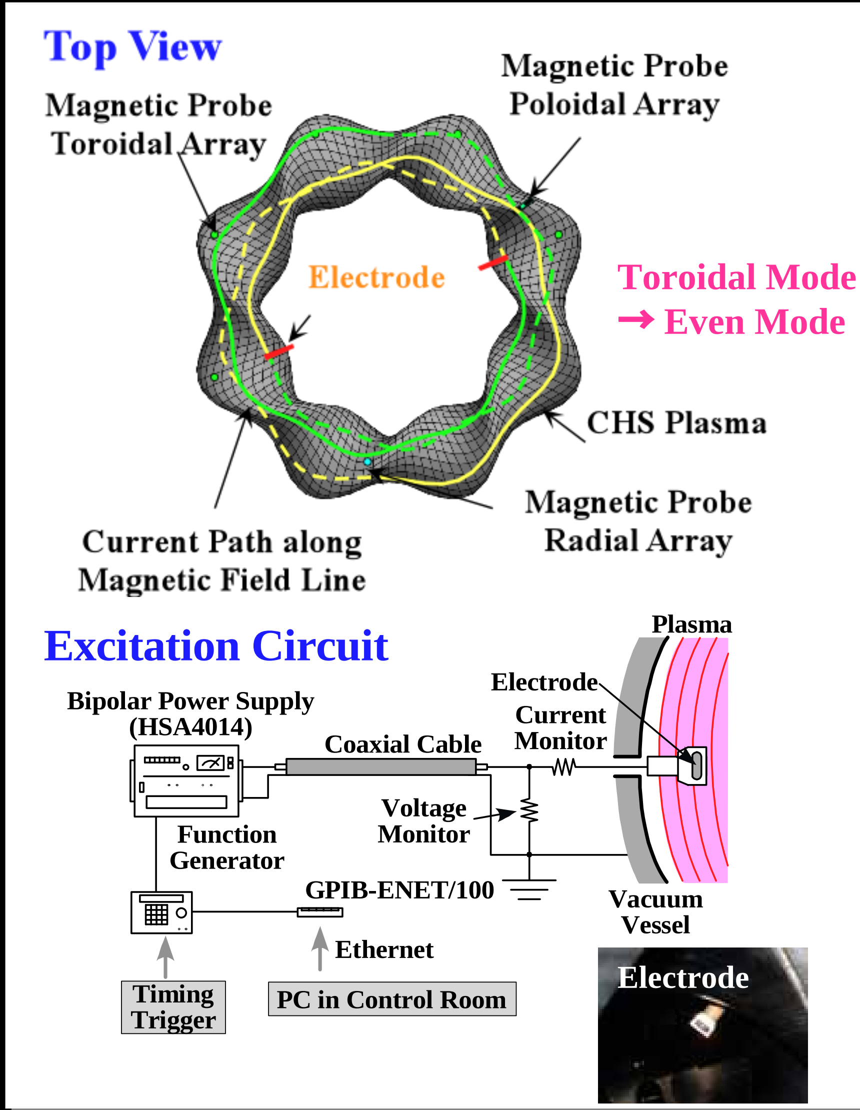
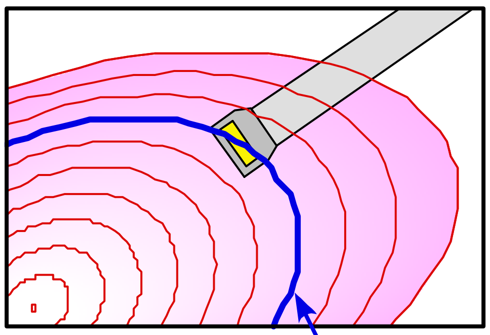
Shear Alfvén waves would be effectively generated.



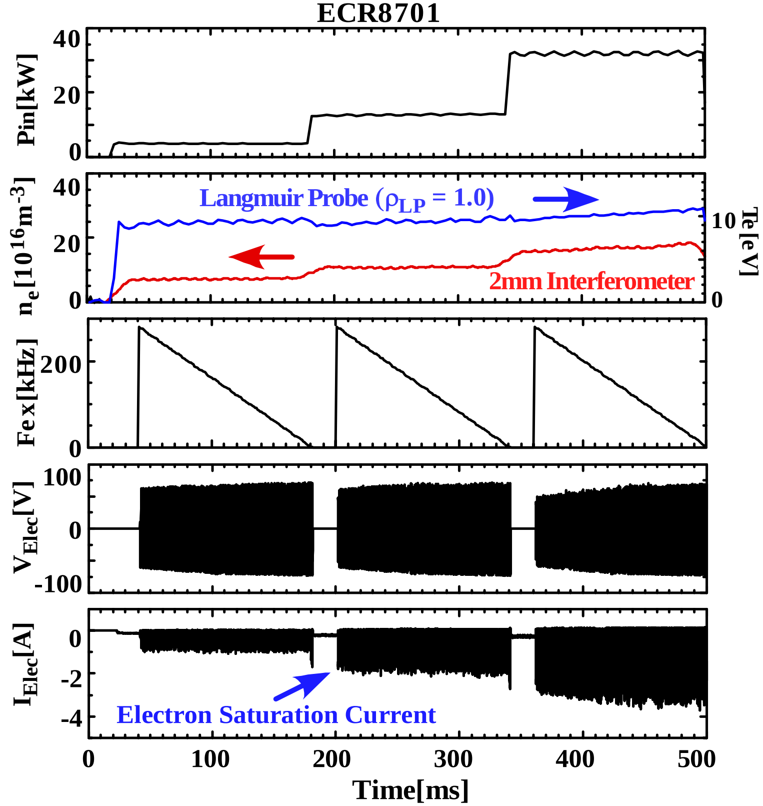
AE Excitation Experiment in 2.45GHz ECH Plasma

- ECH power were 3 times stepped up in one shot to change plasma parameters.
- Electrodes were placed at r/a ~ 0.7.

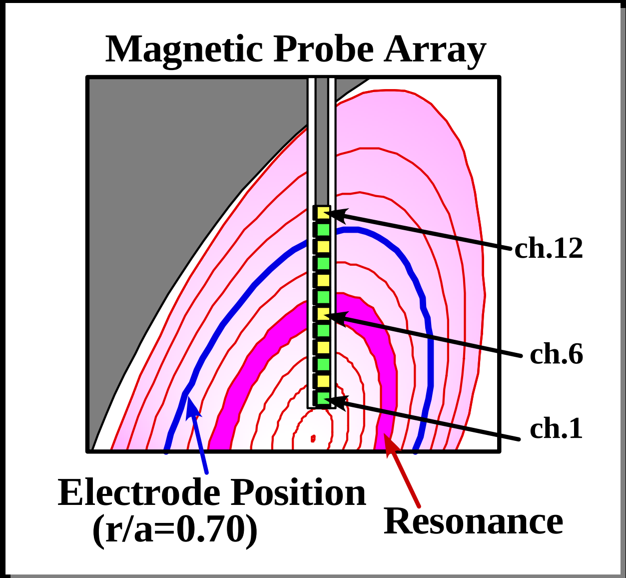


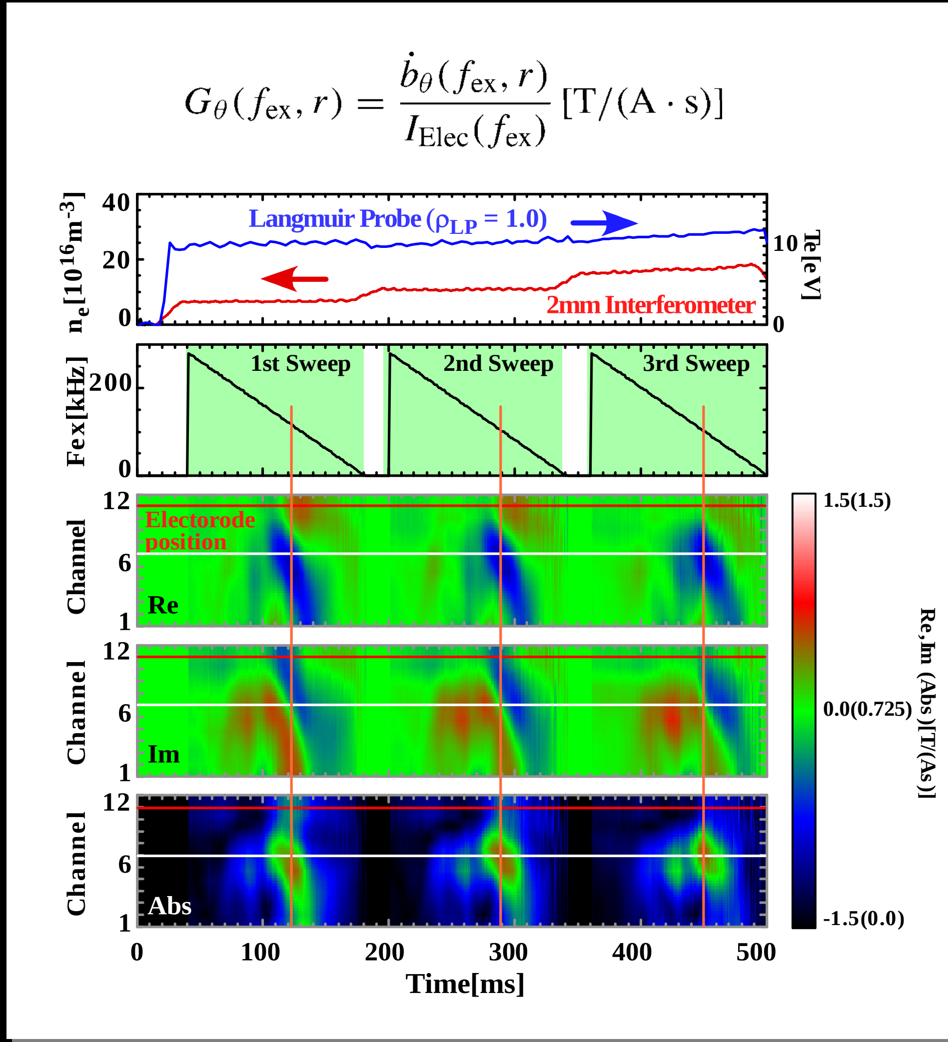
- During the constant density phase, excitation frequency is swept in the range of 1-300kHz where AE gap is expected.

Gas	:	He
Magnetic Axis	:	$R_{ax} = 97.4$ cm
Magnetic Fielld	:	$B_{tor} = 0.0613$ T
Ele. Temp. (at edge)	:	$T_e \simeq 10$ eV
Ele. Dens. (average)	:	$n_e \simeq 2 \times 10^{17}$ m^{-3}



Profiles of Transfer Functions





- Transfer function can be obtained as complex function of frequency and position.
- The transfer functions clearly show eigenmode at r/a ~ 0.5 and f ~ 100kHz.

Eigen-function

- To determine the mode position, eigen-function ξr can be roughly estimated from the radial profile of transfer function.

From ideal MHD equations

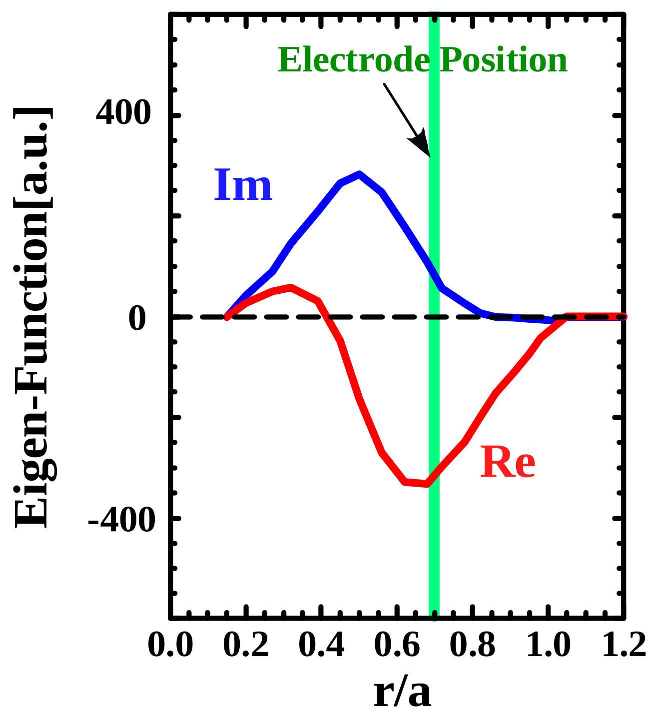
$$\boldsymbol{b} = \mathrm{rot}(\boldsymbol{\xi} \times \boldsymbol{B_0})$$

$$\xi_r(r) \simeq -\frac{1}{B_\mathrm{p}(r)} \int_0^r b_\theta(r')\mathrm{d}r'$$

$$\propto \frac{1}{B_\mathrm{p}(r)} \int_0^r G_\theta(r')\mathrm{d}r'$$

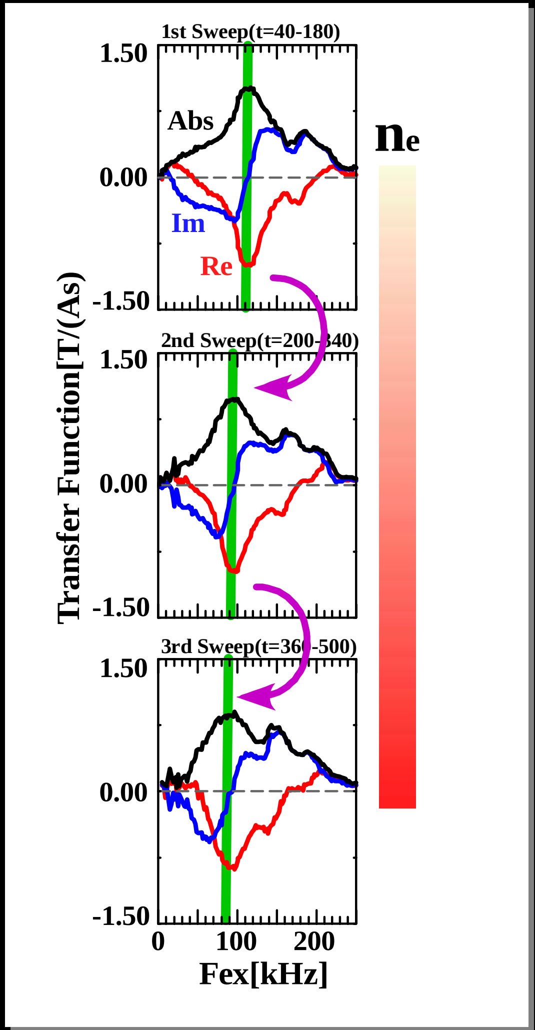
Assumption

$$\xi_r(a) = 0$$

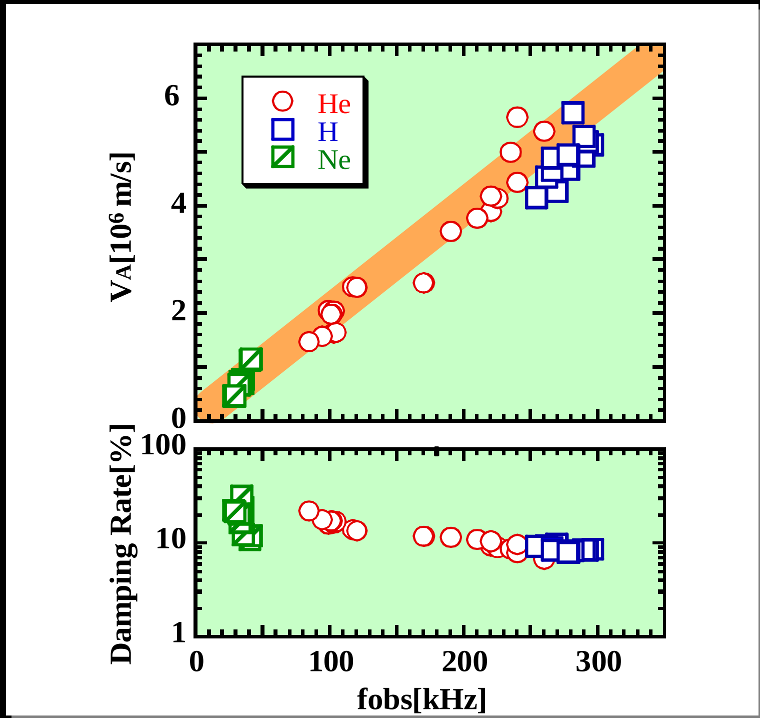


- ξr has a peak in the radial location 0.4 < r/a <0.6 where AE gap predicted.
  → this mode is located in this region.

Eigen-frequency & Damping rate



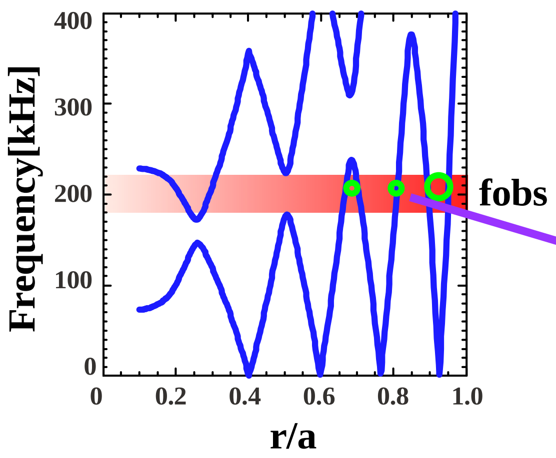
- To confirm that these modes are related to AEs, plasma parameter were varied.



- The observed frequency clearly depends on VA.
  → Alfvén Eigenmode
- Damping rates are about 5 ~ 20%.

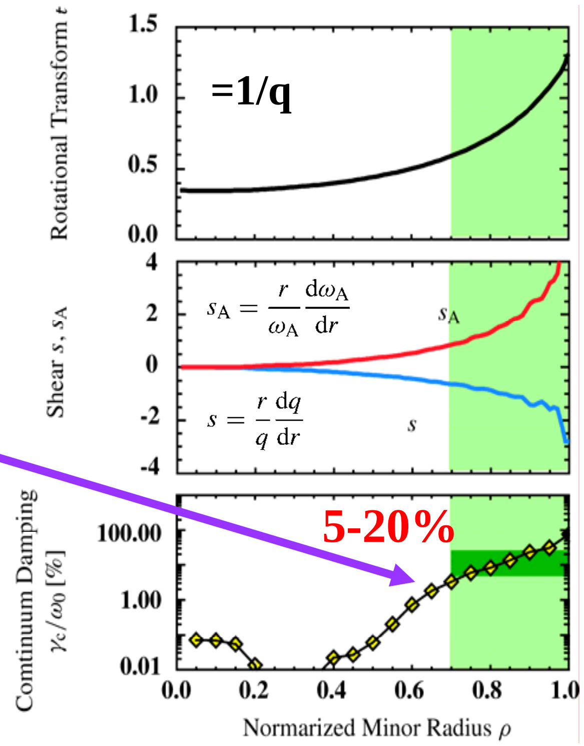
Continuum damping

- In CHS, the magnetic shear is large (|s|~4) near the edge.
- In this plasma, continuum damping is predicted to be large.
- Around r/a > 0.7, the damping rate is estimated to be ~ 5-20%. It is consistent with experimental result.



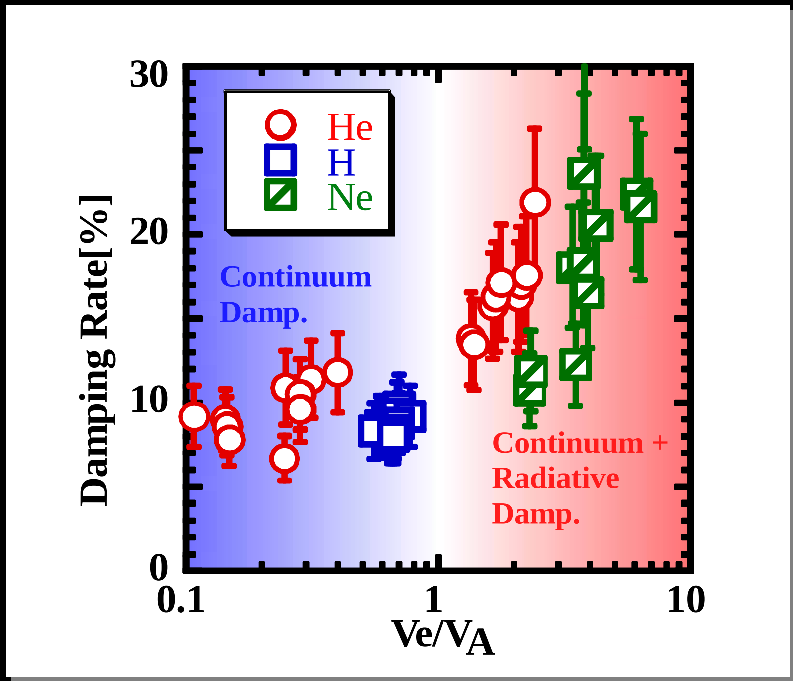
Continuum damping was estimated using equation of Ref. (M. N. Rosenbluth et al. PRL 68, 596, 1992).

$$\frac{\gamma_c}{\omega} = \frac{\epsilon}{2}\left\{\frac{1}{g_0(s)} + \frac{1}{g_\infty(s)}\right\}^{-1}$$



Damping rates v.s. Ve/VA

- Electron pressure converts shear Alfvén wave into kinetic Alfvén wave in the range of $V_e > V_A$.
- KAW propagates away from AE gap and is damped by Landau damping. → Radiative Damping
- It is expected that radiative damping can be effective with increasing T_e.
- In the range of $V_e > V_A$, the damping rates become larger.



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Radiative Damping may be a possible candidate of damping mechanisms.

Summary

- AE Spectroscopy using electrodes was successfully carried out in a cold plasma produced by 2.45GHz ECH on CHS.
- Transfer Function of AE was successfully obtained.
- Transfer Functions show that the eigenmode which agrees well with AE frequency is located in r/a ~ 0.5.
- The damping rates of AE are about 10%. This large damping rate would be dominantly caused by continuum damping.
- In the regime of $V_e > V_A$, the damping rates are enhanced. Radiative damping may be responsible for the enhanced damping.

Thank you!

Alfvén Wave + Electron Dynamics

$$m_e \frac{\partial v_e}{\partial t} = -eE_\parallel + T_e \frac{\partial n_e}{\partial z}$$

$$\omega = v_A k_\parallel \quad \Rightarrow \quad \omega = v_A k_\parallel \sqrt{\frac{1+\rho_s^2 k_\perp^2}{1+\delta_e^2 k_\perp^2}}$$

$$\delta_e = \frac{c}{\omega_{pe}}$$

$$\rho_s = \rho_i \sqrt{\frac{3}{4} + \frac{T_e}{T_i}} = \delta_e \left(\frac{v_e}{v_A}\right)$$

KAW $v_A < v_e$

$$\omega = v_A k_\parallel \sqrt{1 + \rho_s^2 k_\perp^2}$$

$$\rho_s > 1/k_\perp = r/m$$

$$\omega = v_A k_\parallel \rho_s k_\perp$$

IAW $v_A > v_e$

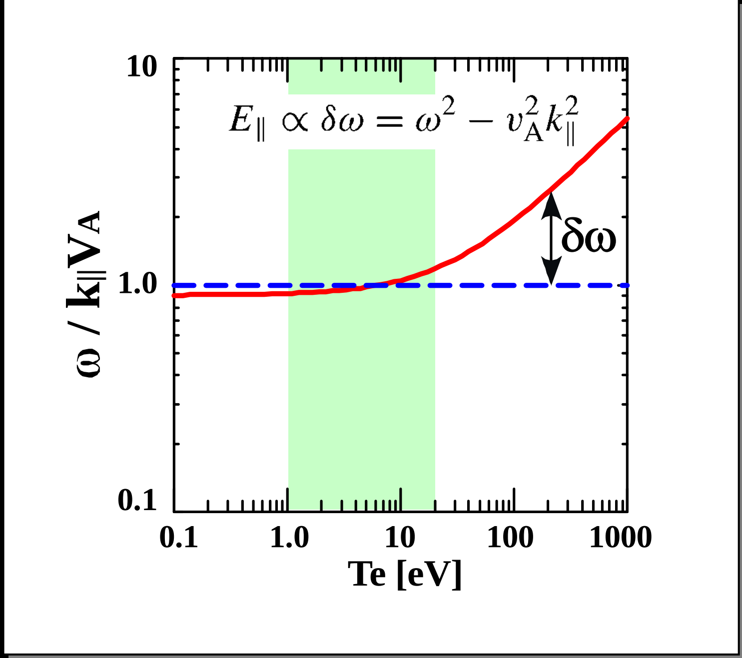
$$\omega = \frac{v_A k_\parallel}{\sqrt{1+\delta_e^2 k_\perp^2}}$$

$$\delta_e > 1/k_\perp = r/m$$

$$\omega = \frac{v_A k_\parallel}{\delta_e k_\perp}$$

Parallel Electric Field

$$\frac{E_\parallel}{E_\perp} = \frac{\omega_{pe}(\omega^2 - v_A^2 k_\parallel^2)}{c^2 k_\perp k_\parallel v_A^2}$$



If the characteristic length of the mode is smaller than ρ_s, electric field parallel to the magnetic filed become larger.

Radiative Damping

Eq.(1) by Mett R. and Mahajan S.

$$\frac{\gamma_k}{\omega} = 3\left\{\frac{m(m+1)}{2m+1}\left(\frac{s}{\sqrt{2}}\right)\frac{\rho_s}{r}\right\}^{2/3}$$

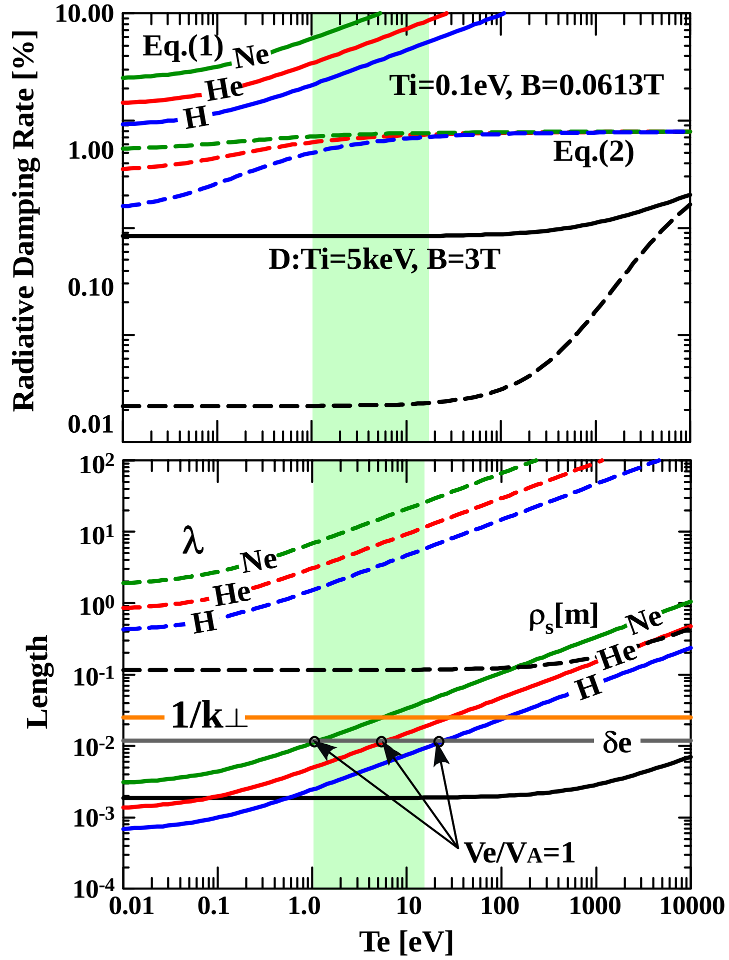
Eq.(2) by Sharapov S.

$$\frac{\gamma_k}{\omega} = \frac{\pi^2}{8}\epsilon s^2 \exp\left(-\frac{\pi^3 s^2}{2^{7/2}\lambda}\right)$$

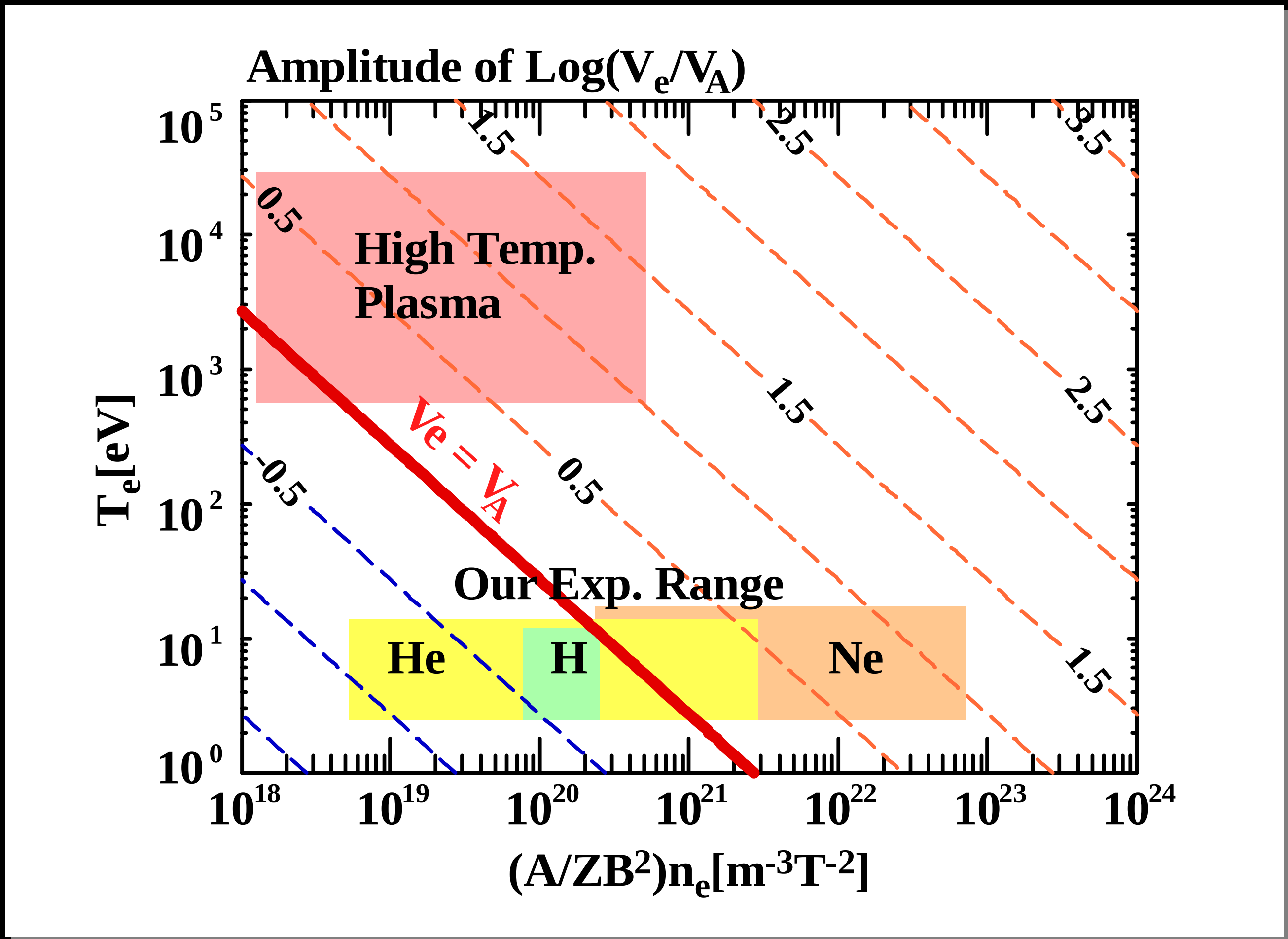
$$\text{Kinetic Parameter} : \lambda = 4\frac{ms}{r\epsilon^{3/2}}\rho_s$$

$$s = \frac{r}{q}\frac{dq}{dr}$$

$$\epsilon = \frac{5}{2}\frac{r}{R}$$



Amplitude of V_e/V_A



Damping Mechanisms of AE

- Collisionless Damping
  - Electron Landau Damping
  - Ion Landau Damping
  - Radiative Damping (Conversion to Kinetic Alfvén Wave)
  - Continuum Damping (Alfvén Resonance)
- Collisional Damping
  - Ion - Neutral
  - Electron - Ion (Resistivity)

Estimation of Damping Rates

- Landau Damping
  - Electron $\beta_e \sim 0.001\% \longrightarrow \gamma_e/\omega_0 \sim 0$
  - Ion $\beta_i < 0.001\% \longrightarrow \gamma_i/\omega_0 \sim 0$
- Collisional Damping
  - Ion-Neutral $n_n < n_i \longrightarrow \gamma_n/\omega_0 \sim 0$
    - Neutral density is small
  - Electron-Ion (Resistivity)

    $n_n < n_i \longrightarrow \gamma_n/\omega_0 \sim 0$
- Radiative Damping

  $v_e < v_A \longrightarrow \gamma_r/\omega_0 \sim 0$
- Continuum Damping

  Large Magnetic Shear near the Edge

Continuum damping

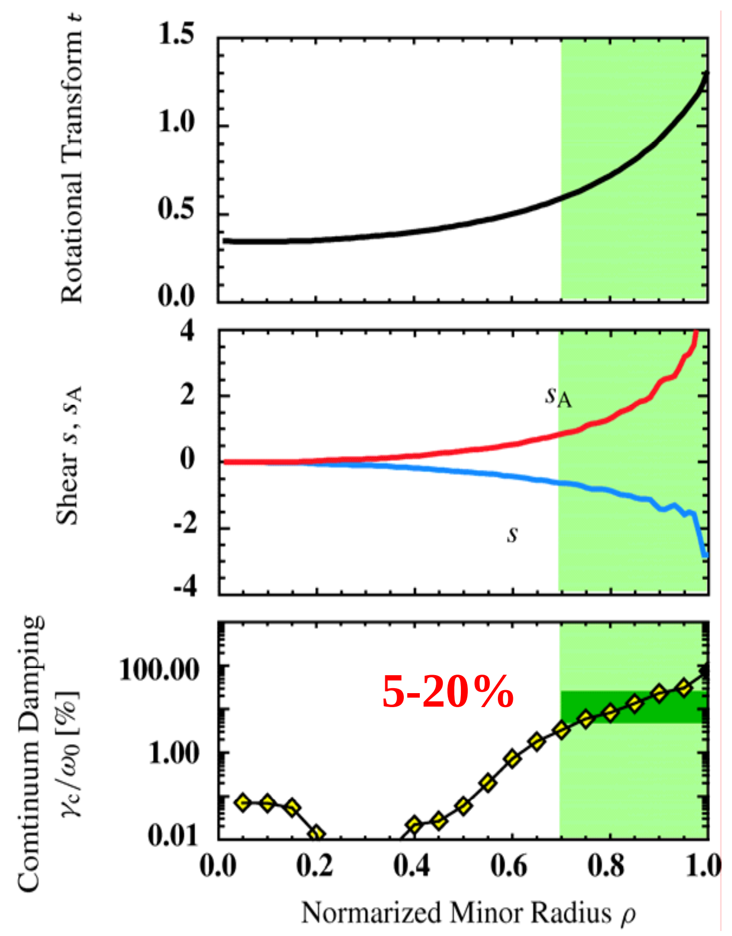
Continuum damping is estimated using equation of Ref. (M. N. Rosenbluth et al. PRL 68, 596, 1992).

$$\frac{\gamma_c}{\omega} = \frac{\epsilon}{2}\left\{\frac{1}{g_0(s)} + \frac{1}{g_\infty(s)}\right\}^{-1}$$

$$\epsilon = \frac{5}{2}\frac{r}{R}, \quad s = \frac{r}{q}\frac{dq}{dr}$$

$$g_\infty(s) = \frac{G(s)}{(m\hat{\epsilon})^{3/2}}\left\{e^{-m\hat{\epsilon}H_+(s)} + e^{-m\hat{\epsilon}H_-(s)}\right\}$$

$$\hat{\epsilon} = \epsilon\frac{s}{s_A}, \quad s_A = \frac{r}{\omega_A}\frac{d\omega_A}{dr}$$



Radiative damping

Radiative damping is expected to be sensitive to ion gyroradius, but the damping rates for hydrogen and helium plasmas are almost same.

$$\frac{\gamma_k}{\omega} = 3\left\{\frac{m(m+1)}{2m+1}\left(\frac{s}{\sqrt{2}}\right)\frac{\rho_s}{r}\right\}^{2/3} \qquad \rho_s^2 = \rho_i^2\left(\frac{3}{4}+\frac{T_e}{T_i}\right)$$

(R. R. Mett et al. Phys. Fluids B4 9,2885, 1992)

It is thought that the radiative damping is not important in this experimental condition.

Electron thermal velocity is less than the Alfvén velocity in the whole plasma, so that conversion to kinetic Alfvén wave (KAW) is not occurred, but it is possible to convert to inertial Alfvén wave (IAW) propagating in the opposite direction of KAW.

Current AE's Researches

- AE excitation by NBI- or RF- produced energetic ions

  Simulation alpha particles

  - Effect to Plasma
  - Unstable Conditions

- Direct excitation using external antennas without energetic ions

  Measurement of damping rates

Tokamak Plasma

- Fast Ion Drive

  TFTR, DIII-D, JET, JT-60U, ...

- External Excitation

  JET

Helical Plasma

- Fast Ions Drive

  CHS, LHD, W7-AS, ...

- External Excitation

  CHS

Stability of AEs

(Effective Growth Rate)=
(Growth Rate)=(Damping Rate)

$$\gamma = \gamma_{\mathrm{g}} - \gamma_{\mathrm{d}}$$

$\gamma < 0$ **<--- Stable**

$\gamma > 0$ **<--- Unstable**

Growth Rate due to alpha particles

Diamagnetic Drift Frequency

Condition on Velocity Space

$$\frac{\gamma_\alpha}{\omega_0} \propto \beta_\alpha \left(\frac{\omega_{*\alpha}}{\omega_0} - \eta \right) F\left(\frac{v_{\mathrm{A}}}{v_\alpha} \right)$$

Condition on Real Space

$$1/2 \leq \eta \leq 1$$

Excitation Conditions

$$\begin{cases} v_\alpha \sim v_{\mathrm{A}} \\ \omega_{*\alpha} > \eta\omega \end{cases}$$

Damping Mechanisms

(a)Electron, Ion Landau Damping

$$\frac{\gamma_{\mathrm{e}}}{\omega} \propto q^2 \beta_{\mathrm{e}} \qquad \frac{\gamma_{\mathrm{i}}}{\omega} \propto q^2 \beta_{\mathrm{i}}$$

(b)Continuum Damping

(Alfvén Resonance)

Increase as the magnetic shear is large

$$\frac{\gamma_{\mathrm{c}}}{\omega} \propto F(s)$$

(c)Radiative Damping

(If $v_{\mathrm{e}} > v_{\mathrm{A}}$,AE would be converted to kinetic Alfvén wave)

$$\frac{\gamma_{\mathrm{k}}}{\omega} \propto (ms)^{2/3}$$

Why is the external excitation of AEs needed?

Effective Growth Rate of AEs

(Effective Growth Rate)=
(Growth Rate)-(Damping Rate)

$$\gamma = \gamma_{\mathrm{g}} - \gamma_{\mathrm{d}}$$

@with Fast Ions
Cannot separate both rates

$$\gamma_{\mathrm{g}} \neq 0$$

@without Fast Ions

$$\gamma_{\mathrm{g}} = 0$$

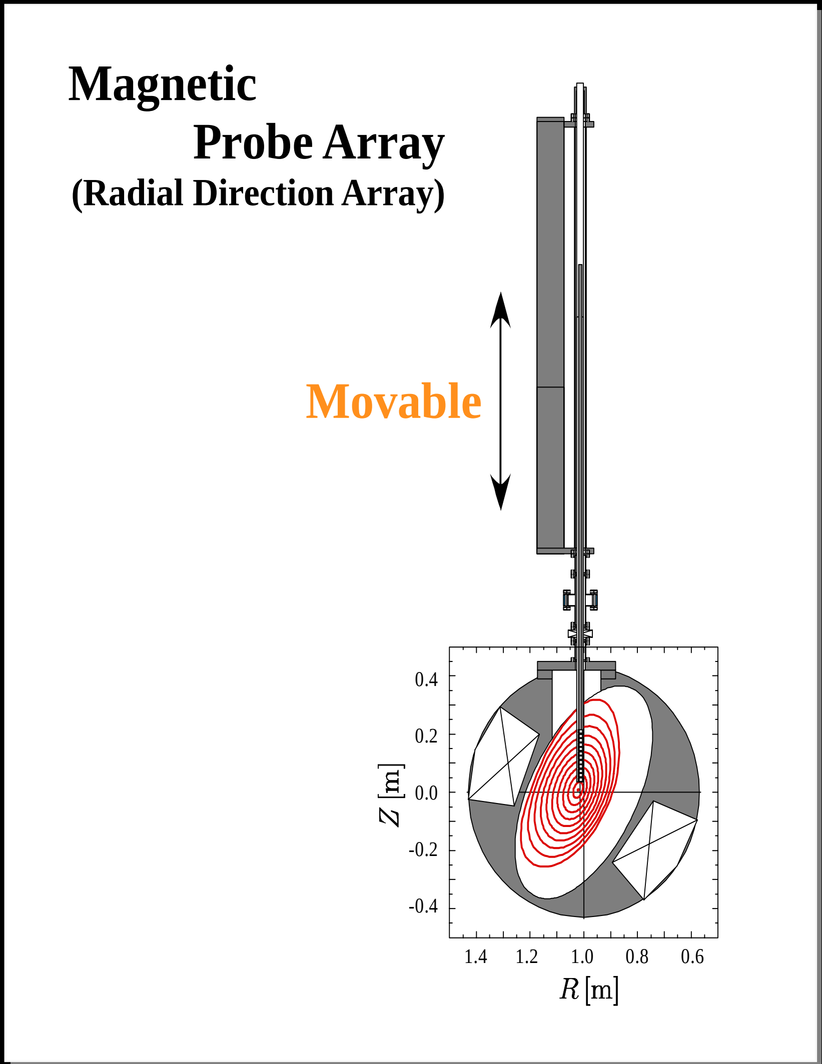
$$\gamma = -\gamma_{\mathrm{d}}$$

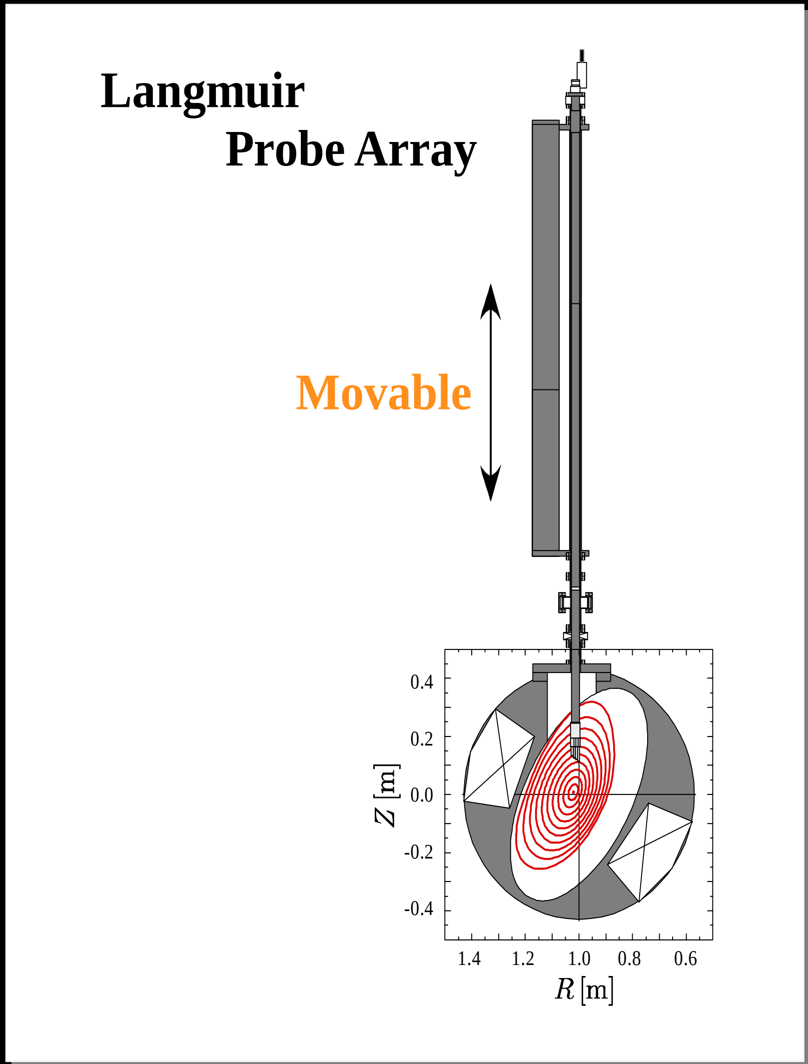
Be able to estimate the damping rate

This approach contributes to develop and improve the numerical codes.

Thus developed numerical codes would accurately predict the stability of AEs in a future fusion plasma.

Arrangement of Magnetic and Langmuir Probe Array



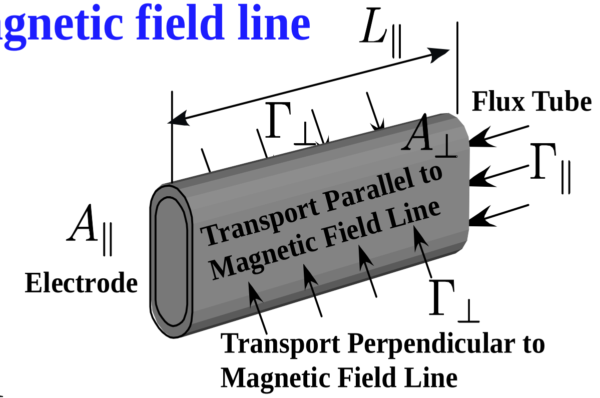


Excitation Current

Estimation of the current path along the magnetic field line

Particle Balance in Magnetic Flux Tube

$$\Gamma_{\parallel} A_{\parallel} + \Gamma_{\perp} A_{\perp} = 0$$



Length of Current path

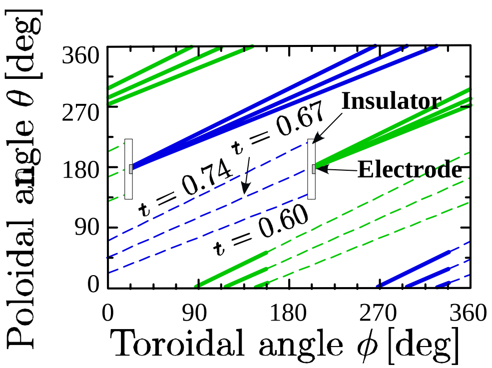
(Assume Bohm Diffusion)

$$L_{\parallel} = \frac{V_{\parallel} A}{16 D_{\perp}}$$

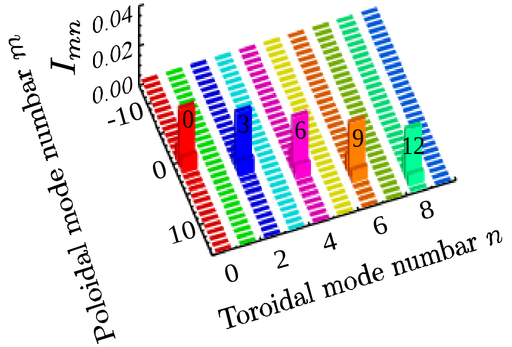
$$L_{\parallel \mathrm{e}} \simeq \lambda_{\mathrm{e}} \simeq 5.5\,\mathrm{m}$$

$$L_{\parallel \mathrm{i}} \simeq \lambda_{\mathrm{i}} \sim 20\,\mathrm{mm}$$

Current path



Fourier Component of Currents



Toroidal Effect $m \pm 1$

Numerical Result (TASK/WM)

- It can be no result !