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

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Abstract
In many tokamaks and helical devices, Alfvén eigenmodes (AEs) driven by energetic ions are intensively studied because of the importance in a fusion reactor. In particular, much attention is paid to the damping rates of AEs. In order to evaluate the damping rate of AEs, AE spectroscopy system was constructed in the CHS. In the system, alternating currents are induced along the magnetic field line using two inserted electrodes. This system was applied to low temperature plasmas produced with 2.45GHz microwaves, for a basic study of damping mechanisms of AEs. The damping rate and AE frequency were derived from an analysis of frequency dependence of a transfer function measured by this system. In low temperature plasma produced at very low toroidal field $B_t < 0.1\,\mathrm{T}$, fairly large damping rates of about $5 \sim 20\%$ were obtained. The AE spectroscopy experiments in low temperature plasmas were carried also for helium and neon gasses by changing electron density and B_t, to study characteristics of the damping rates in the wide range of the ratio of electron thermal velocity to the Alfvén one.

1. Introduction

In a future fusion reactor, energetic alpha particles could destabilize Alfvén eigenmodes (AEs) and in turn AEs would enhance a loss of alpha particles and lead to quench of DT ignition. The stability of energetic-ion driven AEs is determined through competition between the energetic ion drive and various damping mechanisms, such as ion and electron Landau damping, radiative, continuum and collisional damping and so on. These damping mechanisms have been theoretically investigated and several models have been suggested. However, it is difficult to experimentally confirm these models, because the damping rate of AE cannot be estimated in a plasma with fast ions. To obtain pure damping rates of AEs experimentally, it is necessary that stable AEs are excited using external perturbations, and plasma response as transfer function, which includes eigen-frequency and damping rate, are measured, that is the so-called 'Alfvén Eigenmodes Spectroscopy'. This experimental method was applied for the first time to a JET using saddle coils [1]. In helical device, we constructed AE spectroscopy system in the Compact Helical System (CHS), and then, carried out experiments in a low temperature plasma produced with 2.45GHz microwaves [2]. In our system, external magnetic perturbations can be generated by two electrodes inserted into a plasma. Furthermore, magnetic probe array was also inserted into a plasma to obtain a radial profile of transfer function. Since the plasma produced with 2.45GHz microwaves has very low electron and ion beta, that is $\beta_e \ll 1$, $\beta_i \ll 1$, neither electron nor ion Landau damping of background plasma can be effective. Besides, collisional damping with neutrals is also negligibly small because of highly ionized plasma. Therfore, continuum and radiative damping are expected to be dominant in this type of plasma. In this paper, we will report the experimental results and compare them with theoretical results.

2. Experimental Setup

Alfvén eigenmodes spectroscopy system was constructed in the CHS with poloidal and toroidal field period numbers $l = 2$ and $N = 8$, of which major and averaged minor radii are $R \simeq 1\,\mathrm{m}$ and $\langle a \rangle \simeq 0.2\,\mathrm{m}$, respectively [3]. The magnetic configuration of a low beta plasma is determined mostly by external coils (helical and vertical coils), so that the safety factor q profile is well known. This is one of advantages for Alfvén eigenmodes study. In CHS, external coils make a strong magnetic shear $|s| > 1$ at the plasma edge compared with a tokamak device, $s\,(= (r/q)\mathrm{d}q/\mathrm{d}r)$, where q is the safety factor and r is the minor radius. Strong continuum damping is expected in CHS plasmas.

The schematic drawing of the newly developed AE spectroscopy in CHS is shown in Fig. 1. This system is composed of two insertable electrodes that are arranged apart from 180 degrees in the toroidal direction to specify the toroidal mode number, that is, even mode such as $n = 2$. An oscillatory voltage in the range of $1 \sim 300\,\mathrm{kHz}$ is applied between each electrode and the vacuum vessel wall, the oscillatory current is induced along a specified magnetic field line as an electron or ion saturation current, depending on the polarity of the applied voltage. That is, each electrode acts as a single Langmuir probe. The peak voltage applied to each electrode is $\pm 75\,\mathrm{V}$, and the electron saturation current reaches in the order of $1 \sim 4\,\mathrm{A}$. The electrode has a metallic plate of $30\,\mathrm{mm} \times 10\,\mathrm{mm}$ size perpendicular to the magnetic field line. One side of the metallic plate is insulated with a block of boron-nitride to specify the path of oscillatory current in the one toroidal direction. The most significant point of this system is that magnetic perturbations induced by the oscillatory current are perpendicular to the equilibrium magnetic field, and would generate shear Alfvén waves very effectively. Moreover, these electrodes can be inserted into a plasma core region up to the normalized radial position $\rho\,(= r/\langle a \rangle) \simeq 0.7$. In addition, detailed internal information of AE fluctuations can easily be obtained by insertion of a magnetic probe array and Langmuir probes.

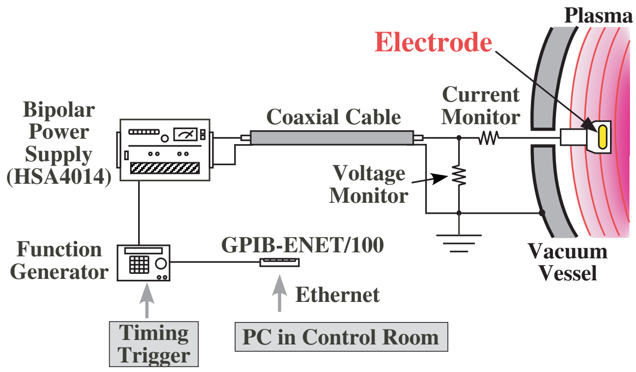

Fig. 1: Schematic drawing of AE spectroscopy system in CHS. An oscillatory voltage is applied between each electrode and the vacuum vessel wall

3. Experimental Results

3.1 Experiment in Low-β Plasma

We have carried out AE experiments in a very low-β plasma produced with 2.45GHz microwaves at very low toroidal field $B_\mathrm{t} < 0.1\,\mathrm{T}$. The line averaged electron density and electron temperature at the plasma edge are in the range of $\bar{n_e} \sim 3 \times 10^{17}\,\mathrm{m}^{-3}$ and $T_e \leq 10\,\mathrm{eV}$, as shown in Fig. 2(b). These are measured by 2mm interferometer and Langmuir probe, respectively.

To investigate the dependence of the AE frequency on Alfvén velocity v_A, the line averaged electron density $\bar{n_e}$ was stepped up three times in one shot by the step-up of microwave power. In this experiment, the electrodes were inserted inside beyond the last closed flux surface (LCFS) up to $\rho \simeq 0.7$ in a low density and low temperature helium plasma. In this plasma an oscillatory voltage is applied in the frequency range $1 \sim 300\,\mathrm{kHz}$ between each electrode and the vacuum vessel wall, since the expected TAE gap frequency is in the range of 50 kHz to 300 kHz. The oscillatory current is dominantly electron saturation current as expected, as shown in Fig. 2(e). This current is stepping up with increasing the electron density.

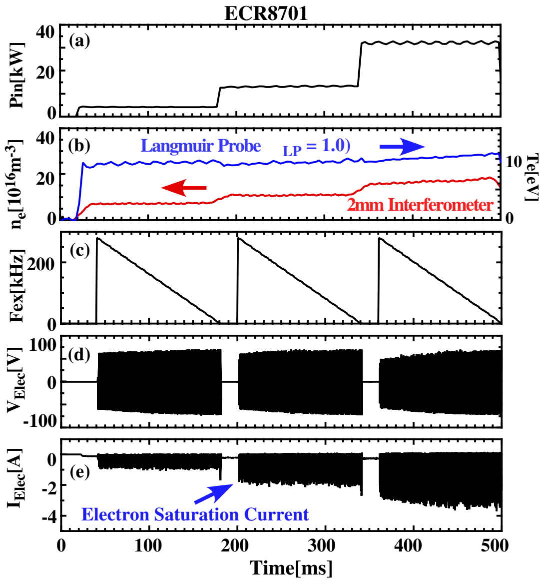

Fig. 2: Typical discharge waveform in the AE spectroscopy experiment. (a) Input microwave power, (b) electron temperature and density, (c) excitation frequency, (d) voltage and (e) current of electrode.

3.2 Transfer Function

We measured the radial profile of magnetic perturbations using magnetic probe array inserted into plasma. Therefore, plasma response with respect to the externally applied field can be obtained as complex function of excitation frequency f_{ex} and radial position r. Now, plasma response is deduced as a transfer function,

$$G_\theta(f_{ex}, r) = \frac{\dot{b}_\theta(f_{ex}, r)}{I_{Elec}(f_{ex})}\,[\mathrm{T}/(\mathrm{A}\cdot\mathrm{s})],$$

where $\dot{b}_\theta$ is the poloidal component of magnetic probe signal and I_{Elec} is the electrode current. In Fig. 3, the real part $\mathrm{Re}[G_\theta]$ and imaginary one $\mathrm{Im}[G_\theta]$ and the absolute value $|G_\theta|$

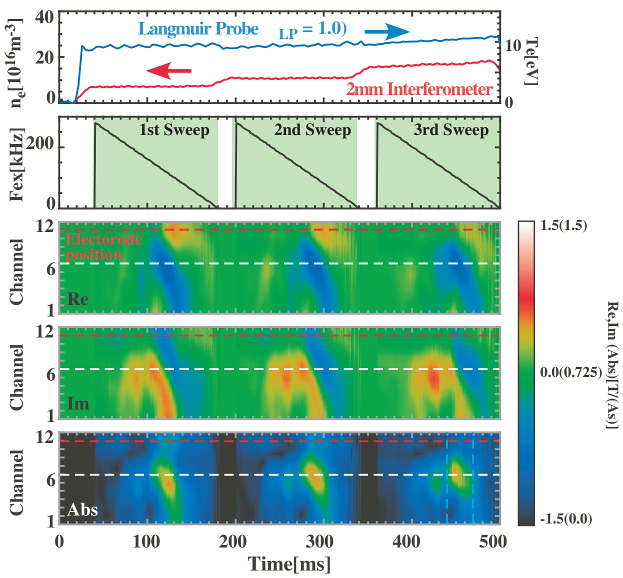

Fig. 3: Real part, imaginary part and absolute value of a transfer function with electron temperature, density and excitation frequency. Electrode position (red dash) and resonance position (white dash) are also shown.

are shown. Note that channel $1 \sim 12$ are corresponding to $r/a = 0.15 \sim 0.75$. When the excitation frequency $f_{\rm ex}$ is swept around 100 kHz, the transfer function $G_\theta(f_{\rm ex}, r)$ at ch.7 ($r/a \simeq 0.5$) would exhibit a character of resonance behavior related to $f_{\rm TAE}$.

3.3 Eigenfunction

In order to determine the location of the excited mode, eigen-function was roughly estimated from ideal MHD equations. The magnetic perturbation vector $\boldsymbol{b}$ will be related to the plasma displacement vector $\boldsymbol{\xi}$ through $\boldsymbol{b} = \nabla \times (\boldsymbol{\xi} \times \boldsymbol{B_0})$, where $\boldsymbol{B_0}$ is the vector of the equilibrium magnetic field. If a cylindrical configuration is assumed for simplicity, the radial displacement ξ_r is evaluated as

$$\begin{aligned}\xi_r(r) &\simeq -\frac{1}{B_\theta(r)}\int_0^r b_\theta(r')\mathrm{d}r' \\ &\propto \frac{1}{B_\theta(r)}\int_0^r G_\theta(r')\mathrm{d}r',\end{aligned}$$

where B_θ is the poloidal magnetic field. In this calculation, the magnitude and phase of G_θ are taken into account. The spatial integration of G_θ is shown in Fig. 4. This indicates that the eigenmode has a peak in the radial location of $\rho \simeq 0.4 - 0.6$.

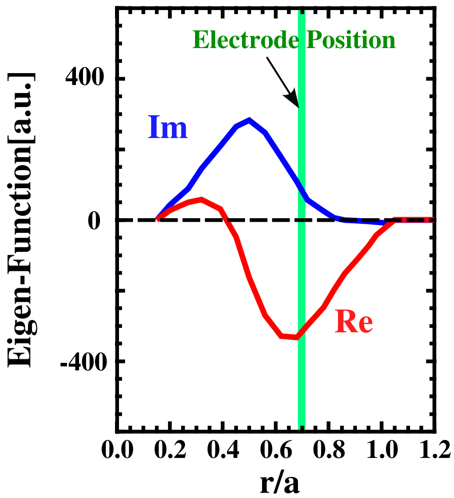

Fig. 4: Roughly estimated eigen-function at the resonance. Integration of real part and imaginary part of the transfer function.

3.4 Eigen-frequency and Damping Rate

In a low-β plasma without fast ions, the effective damping rate $\gamma_{\rm eff}$ $(= \gamma_{\rm d} - \gamma_{\rm f})$ is equivalent to the damping rate $\gamma_{\rm d}$ because the fast ion drive $\gamma_{\rm f}$ is zero. Therefore, the damping can be derived from the shape of the transfer function $|G_\theta|$ at frequency $f_{\rm obs}$ where the absolute value of G_θ has a resonance peak. That is, $\gamma_{\rm d}^{\rm exp}/\omega_0 \propto \Delta f / f_{\rm obs}$, where Δf is the full width at the half maximum of the resonance peak and $\omega_0 = 2\pi f_{\rm obs}$. Plasma parameters related to the Alfvén velocity, that is, the toroidal field $B_{\rm t}$, the electron density $n_{\rm e}$ and the mass of the fuel ion $A_{\rm i}$ are varied in order to confirm that this resonance is related to AEs. Dependence of the observed resonance frequency $f_{\rm obs}$ on $v_{\rm A}$ and the estimated damping of excited modes are shown in Fig. 5. This

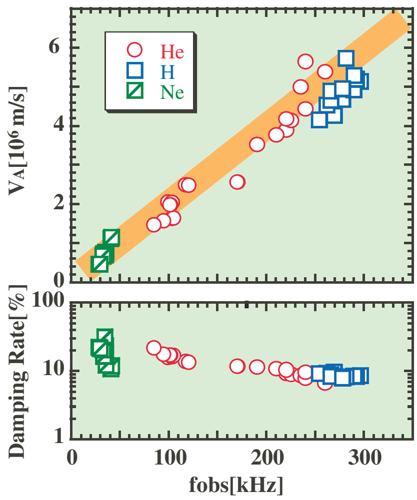

Fig. 5: Dependence of observed resonance frequency on $v_{\rm A}$ and damping rate of excited modes.

figure clearly indicates that the resonance is related to AEs and the damping is fairly large up to $\sim 20\%$.

3.5 Discussion

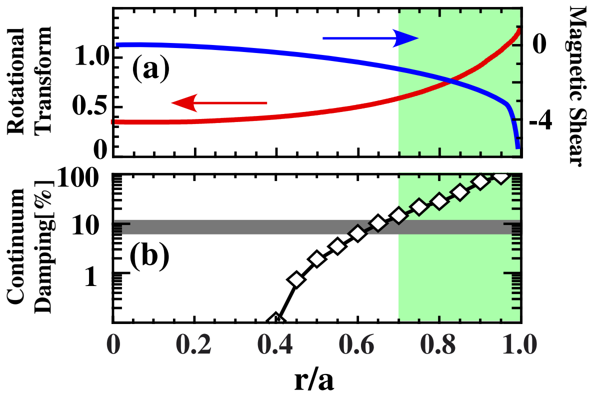

Fig. 6: Profile of (a) rotational transform ($= 1/q$), magnetic shear and (b) continuum damping rate calculated from Ref.[4].

As mentioned above, electron and ion Landau damping of background plasma are negligibly small in the present plasma condition. Besides, collisional damping with neutrals is also negligible because the ionization degree is not fairly low [5]. Since CHS has a large magnetic shear near the plasma edge, continuum damping, which occurs as the resonant power absorption at the intersection of the eigenfrequency with a shear Alfvén continuum, is expected to be large. Here, the profiles of rotational transform $= 1/q$ and magnetic shear s in CHS are shown in Fig. 6(a). The magnetic shear is high, that is, $|s| > 1$ in the region of $\rho > 0.7$. The continuum damping is estimated by the equation in Ref.[4], as shown in Fig. 6(b). As shown in Fig. 4, the eigenfunction estimated from the experimental data seems to be broadened and then interact with Alfvén continuum near the edge. This eigenmode would suffer from large continuum.

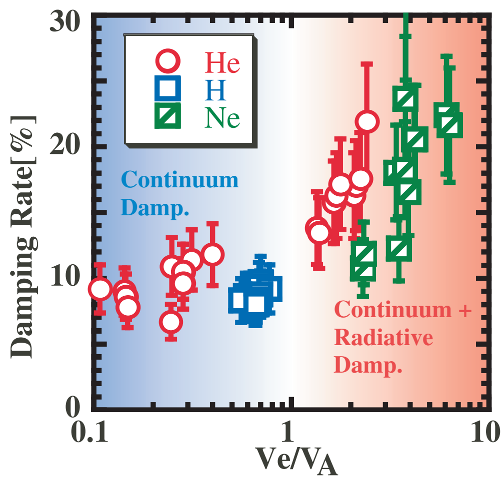

Fig. 7: The estimated damping rate versus the ratio between electron thermal v_e and Alfvén velocity v_A.

Another important damping mechanism is radiative damping in this experimental condition. Radiative damping takes place within the gap region through mode coupling between AE and kinetic Alfvén wave (KAW) under $v_e > v_A$, where v_e is the electron thermal velocity. KAW transfers the wave energy of AE to the plasma core region from the gap region[6, 7]. Note that the radiative damping is effective under $k_\perp \rho_s \geq 1$, where $k_\perp$ and ρ_s are the wave number perpendicular to the magnetic field and the ion Larmor radius evaluated with the electron temperature. It expected that the radiative damping can be effective with the increase in ρ_s. Here, a dependence of the estimated damping rate on the ratio between electron thermal v_e and Alfvén velocity v_A is shown in Fig. 7. As shown in Fig. 7, the damping rates become larger in the range of $v_e > v_A$. It is qualitatively consistent with the radiative damping. The radiative damping is estimated by the equation in Ref.[6], that is,

$$\frac{\gamma_{\mathrm{k}}}{\omega} = 3\left\{\frac{m(m+1)}{2m+1}\left(\frac{s}{\sqrt{2}}\right)\frac{\rho_{\mathrm{s}}}{r}\right\}^{2/3}.$$

In the rang of $v_{\mathrm{e}} \simeq v_{\mathrm{A}}$, ρ_{s} and the radiative damping is about 1 cm and $5 \sim 20\%$, respectively.

In addition, other damping mechanisms are still possible candidates. This plasma is more resistive compare with those of large tokamaks. Alfvén wave can be damped by the resistivity having a functional dependence of $T_{\mathrm{e}}^{-3/2}$. However, the damping rates would be very large and the mode becomes purely damped wave without an oscillatory character, if resistive damping is dominant. At the moment, it is thought that continuum and radiative damping are dominant in this plasma condition.

4. Summary

In conclusion, AE spectroscopy using electrodes was successfully carried out in a low temperature plasma produced by 2.45GHz ECH on CHS. In this experiment, the eigen-frequency and damping rate of AEs were successfully derived from the resonant character of the transfer function G_θ. Transfer functions show that the eigenmode which agrees well with AE gap frequency is located around $r/a \sim 0.5$. The derived damping rate of $\sim (5-20)\%$ is thought to be dominated by continuum damping. Moreover, in the regime of $v_{\mathrm{A}} \leq v_{\mathrm{e}}$, the damping rates are enhanced. Radiative damping may be responsible for the enhanced damping.

Application of this newly developed electrode technique to a low temperature and low density plasma will make the detailed investigation of the excitation and damping of AEs easier in three-dimensional magnetic configuration such as various types of stellarators or helical devices.

Acknowledgments

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