Excitation of Stable Alfvén Eigenmodes by Application of Alternating Magnetic Field Perturbations in the Compact Helical System

T. Ito[a], K. Toi[a,b], G. Matsunaga[c], M. Isobe[b], K. Nagaoka[b], and CHS Group[b]

[a] *Department of Energy Engineering and Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya City, Aichi 464-8601, Japan*

[b] *National Institute for Fusion Science,322-6 Oroshi-cho, Toki 509-5292, Japan*

[c] *Japan Atomic Energy Agency, 801-1 Mukouyama, Naka, Ibaraki 311-0193, Japan*

ito.takafumi@lhd.nifs.ac.jp

In the Compact Helical System (CHS), alternating magnetic perturbations were applied to NBI heated plasmas by using two electrodes inserted near the plasma edge by 180 degree away toroidally, to excite stable Alfven eigenmodes and measure the damping rate. The frequency dependence of the transfer function defined by the ratio of a magnetic probe signal for an electrode current signal shows the presence of a few resonant peaks which would be related to stable Alfvén eigenmodes(AEs) excited. Each observed resonance frequency fo agrees well with the frequency of each corresponding toroidicity induced Alfvén eigenmode of which gap is located in peripheral plasma region, where fast ion drive of AEs would be sufficiently small. The derived damping rates γ are very large, i.e., $\gamma/(2\pi f_0)\sim 10\%$.

1. Introduction

In a D-T fusion plasma, one of the most dangerous MHD modes driven by energetic particle is the toroidicity-induced Alfvén eigenmodes (TAEs)[1]. In this situation, the first wall and various plasma facing components may be seriously damaged by energetic alpha particles lost by TAEs. It is important to assess the stability of energetic-ion driven MHD modes such as TAEs experimentally and compare the theoretical predictions. The stability of TAE is determined by competition between the linear growth rate and various damping rates. The linear growth rate will be expressed as[2],

$$\frac{\gamma}{\omega_0} \approx \frac{9}{4}\left[\beta_\alpha\left(\frac{\omega_{*\alpha}}{\omega_0}-1/2\right)F\left(\frac{\upsilon_A}{\upsilon_\alpha}\right)\right] \qquad (1)$$

Here, the quantities $\omega_{*\alpha}$, β_α, v_A, F and v_α are respectively the diamagnetic drift frequency of an energetic ion, the toroidal beta value of energetic ions, Alfven velocity, the fraction of resonant energetic particles with shear Alfven wave and energetic ion velocity. On the other hand, there are several important damping mechanisms: Landau damping by bulk electron and beam ions, continuum damping, radiative damping and so on. However, the theoretical prediction of these damping rates would include large uncertainty depending on theoretical models because of lack of precise information of eigenfunction of TAE, shear Alfven spectrum and so on. Accordingly, it is necessary to establish the most reliable theoretical model of the damping rates in a future burning plasma through comparison between various theoretical results and experimentally measured ones.

A powerful method to measure the damping rate was developed in the JET tokamak[3] and then has been applied to the Alcator C-Mod tokamak[4]. This method is based on a response analysis of a plasma for applied magnetic perturbations generated by a set of loop antennas arranged in the toroidal direction of a torus. In this method, the frequency of applied fields is swept to search resonance points related to TAE frequencies. Excitation of stable TAEs by application of magnetic perturbations was also attempted in the Compact

Helical System (CHS) where a couple of electrodes inserted into the plasma boundary were adopted to generate magnetic perturbations purely perpendicular to the toroidal magnetic field line [5]. This experiment was carried out in low temperature plasmas produced at the toroidal field less than 0.1T by using 2.45 GHz electron cyclotron waves, where no energetic ions were present. Recently, this method was also applied to a plasma heated by neutral beam injection(NBI). This paper describes the experimental results.

2. Experimental setup

Alternating voltage of about 75V was applied to a couple of electrodes inserted into a plasma edge region to produce alternating magnetic perturbations. The detailed structure and arrangement are shown in ref. 5. The driving frequency fext was swept up to 500 kHz to include the expected TAE frequency[6]. The maximum current of each antenna is ~5A, and the maximum amplitude of the perturbation field is estimated to be ~$5\mathrm{x}10^{-6}$T at the magnetic axis position of 0.921m. These electrodes are placed by 180 degrees away in the toroidal direction to specify the toroidal mode numbers of applied perturbation fields. In this experiment, the polarity of two electrode currents were adjusted to be the same. This is called "even" mode operation. The so-called "general" mode operation was also tried by energizing only a single electrode. The dominant toroidal mode numbers of applied perturbation field are n=0, ±2, ±4, ... (n=0, ±1, ±2, ...) for "even" ("general") mode operation by using double (single) electrode. The electrode current and the applied voltage are monitored at the vacuum feedthrough. The magnitude of applied voltage to an antenna and a time-dependent sweeping pattern of fext are created by a function generator controlled with PC in the control room of CHS. The sweeping pattern of signal is amplified by a high-speed bipolar power supply. Typically, the frequency was swept from 1kHz to 300kHz in 100 ms. The response of a plasma for applied magnetic perturbations was obtained with the magnetic probes arranged in poloidal and toroidal directions. The toroidal array of magnetic probes consists of the five probes and is used to determine the toroidal mode number of the response. The poloidal mode number was determined by a poloidal array with 12 probes.

3. Experimental results

A typical discharge waveform of an NBI heated plasma in this experiment is shown in Fig.1. In this shot, the line-averaged electron density rises from $1.0\mathrm{x}10^{19}$ m^{-3} to $4.6\mathrm{x}10^{19}$ m^{-3} by gas puffing, as shown in Fig.1(b). The toroidal current and the volume-averaged toroidal beta value reach about 3kA and 0.25%, respectively, as shown in Figs.1(c) and

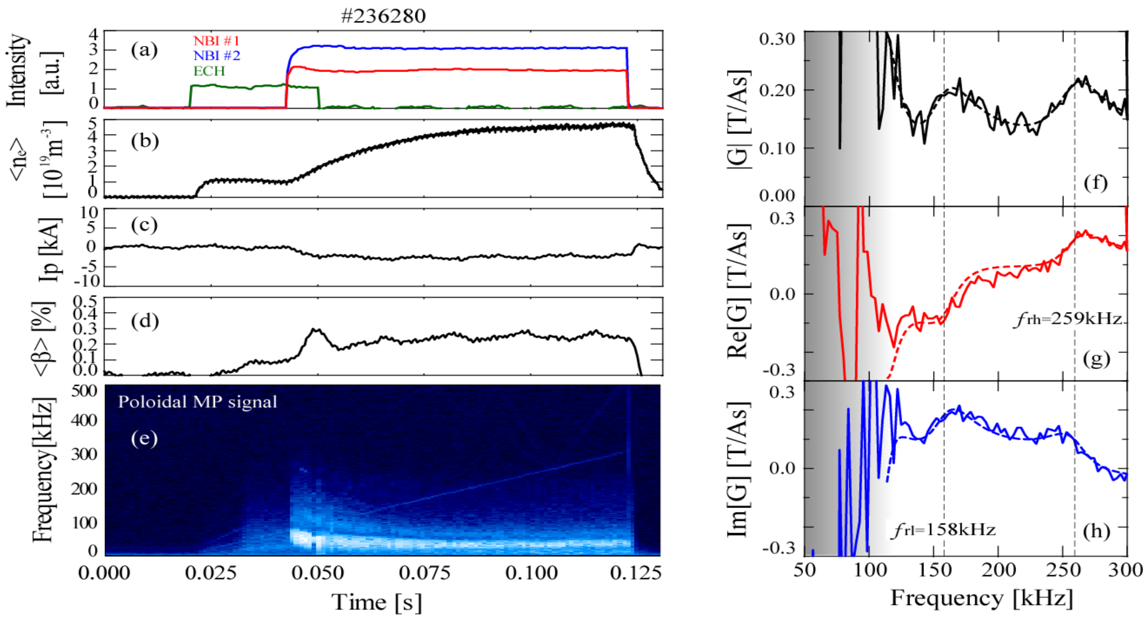

Fig.1. A typical discharge of the AE excitation experiment by using the double electrode(#236280). Time evolution of the power of external heat sources(a), line-averaged electron density(b), net toroidal current(c), volume averaged beta(d), the spectrogam of a magnetic probe signal(e). The absolute value of the transfer function (f), its real part(g) and imaginary part(h) as a function the driving frequency f_{ext} .

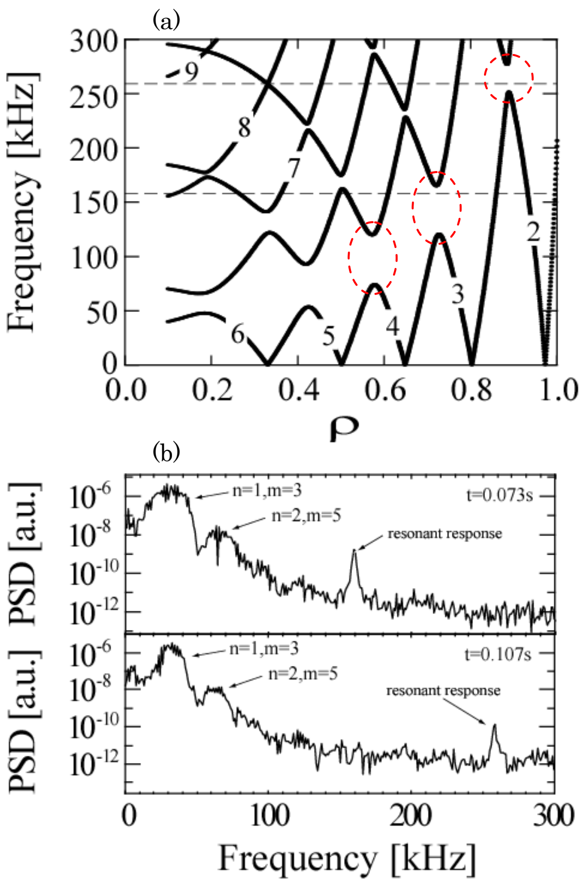

Fig.2(a). The n=2 shear Alfvén spectra calculated for two dimensional approximation of the actual CHS magnetic configuration (a). The dashed and the dot-dashed horizontal lines indicate the observed resonance frequencies of *fo*=158kHz and 259kHz, respectively. (b) The power spectra of magnetic fluctuations in the time windows of t=0.071s to t= 0.075 s and t=0.105s to t=0.109s. The modes in the lower frequency range less than 100 kHz are the energetic ion driven TAE and EPM. The broad spectral peaks of these modes are caused by rapid frequency sweeping.

(d). In Fig.1(e), the spectrogram of a magnetic probe signal is shown. In this figure, strong MHD activities driven by energetic ions are observed together with a weak perturbation signal induced by the electrode current. In this shot, two electrodes were driven with the same polarity, that is, "even" mode operation.

Figure 1(f), 1(g) and 1(h) show respectively the absolute value. the real part and imaginary part of the transfer function as a function of the driving frequency f_{ext}, of which transfer function was derived from the ratio of the magnetic probe signal for the electrode current. Two resonance peaks have been observed in the transfer function. The resonance frequency f_o and the normalized damping rate $\gamma/(2\pi f_o)$ were evaluated by fitting of the transfer function with that of a general viscous damping system . The transfer function of such system is expressed as [7]:

$$G(\omega) = \frac{B(\omega)}{A(\omega)} = \sum_{r=1}^{N} \left\{ \frac{R_r}{i(\omega+\Omega_r)+\gamma_r} + \frac{R_r^*}{i(\omega-\Omega_r)+\gamma_r} \right\} \tag{2}$$

Here, Ω_r, γ_r, R_r, and R_r* are respectively the angular eigenfrequency, damping rate, residue and its conjugate term at r-th resonance. The output signal B(ω) corresponds to the magnetic probe signal and the input signal A(ω) corresponds to the electrode current.

The part of G(ω) less than 120 kHz will be affected by the energetic ion driven instabilities. Accordingly, the fitting was carried out over the frequency range from 120 kHz to 300 kHz on the assumption that four resonances exist. The lowest peak corresponds to the peak of energetic ion driven TAE, which should be ignored. Moreover, the highest resonance much larger than 300 kHz was also obtained by this fitting, but was also ignored because of a virtual resonance. The second and third resonance frequencies f_{o2} and f_{o3} derived from the fitting are 158kHz and 259kHz, respectively. The corresponding damping rates are $\gamma/(2\pi f_{o2})$=6% and $\gamma/(2\pi f_{o3})$=12.5%, respectively. These damping rates are considerably larger than those obtained in JET experiments.

The toroidal and poloidal mode numbers for these resonant components were attempted to determine using the magnetic probe arrays. However, the mode numbers for these resonant fluctuations induced by the applied perturbations were not derived because of irregular phase relations among magnetic probes. The reason is not clarified yet, but may be due to the presence of bi-directional perturbations along the toroidal line of force. Here, the lowest and non-zero toroidal mode was assumed to be n=2 for these oscillations excited by the applied magnetic perturbations. An n=2 shear Alfven spectra calculated with two dimensional approximation of the CHS configuration is shown in Fig.2(a), where a hydrogen plasma with fully ionized carbon impurity was taken into account to be the effective charge of Z_{eff}=3. The frequencies of excited resonant magnetic perturbations agree well with the gap frequencies in the plasma peripheral region. That is, the mode of f=158kHz will correspond to the n=2 TAE due to m=3 and m=4 coupling, and that of f=258 kHz the n=2 TAE due to m=2 and m=3 coupling. In this shot, two types of energetic ion driven modes were observed in the lower frequency range less than 100 kHz, as seen from Fig.1(f) and Fig.2(b). In contrast to the excited modes by applied field perturbations, the mode numbers of them were clearly determined to be m~5/n=2 for the mode of f=65 kHz and m~3/n=1 for the mode of f=30 kHz. The former agrees very well with the n=2 TAE due to m=5 and m=6 coupling. The latter mode with n=1 is thought to be energetic particle mode (EPM) because the frequency is well below the expected minimum gap frequency. From this comparison, the above-mentioned resonant modes driven by electrodes are thought to be stable TAE near the plasma peripheral region where the fast ion drive will be too small to destabilize. So far, it is not clear whether or not the TAE resides more interior region was excited by applied magnetic perturbations. More larger magnetic perturbations will be necessary for the excitation of stable TAEs in more interior region.

4. Summary

An active diagnostic method for measuring the damping rate of Alfven eigenmodes by using external magnetic perturbations induced by a couple of electrodes has been developed in CHS. The single or double electrode inserted into a plasma edge was successfully applied to NBI heated plasmas. Several resonant responses are clearly observed at both of the single and double electrode operations. Some resonant peaks observed in the transfer function agree well with those of the low n TAEs of which gap locate near the plasma edge. The identification of the toroidal mode number of the excited stable TAEs is difficult in most of cases, which may be caused by simultaneous excitation of bi-directional waves and/or several modes having different toroidal mode number. Measured damping rates of excited TAEs are fairly large in the range of about 10% for the eigen-angularfrequency. Excitation of stable AEs by application of magnetic perturbations is being tried in the Large Helical Device (LHD).

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