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

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Alternating magnetic perturbations, generated by external electrodes, are applied to a neutral-beam-heated plasma in the Compact Helical System, to excite stable Alfvén eigenmodes (AEs). Resonant peaks in the frequency range of the toroidal Alfvén eigenmode (TAE) have been observed in a transfer function defined by the ratio between the magnetic probe signal and the alternating electrode current. The resonant frequency f_o agrees well with that of the TAE gap located near the plasma edge, where the strength of energetic ion drive of AEs will be sufficiently low. The damping rates γ derived from the width of the resonant peak are fairly large, i.e., $\gamma/(2\pi f_o) \sim 20\%$.

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There is a serious concern that energetic alpha particle loss and/or redistribution induced by alpha-particle-driven Alfvén eigenmodes (AE) might degrade fusion burn and damage the first wall in a deuterium–tritium (DT) fusion reactor. In existing tokamaks and helical devices, the instabilities of AEs are investigated using energetic ions produced by neutral beam injection (NBI), ion cyclotron resonance heating (ICRH) and DT reaction [1–3]. The stability of an AE is determined by competition between fast ion drive and damping mechanisms, and evaluated by the sign of the net growth rate $\gamma = \gamma_{\rm drv} - \gamma_{\rm damp}$. Here, $\gamma_{\rm drv}$ is the growth rate, and a linear growth rate is adopted for safety in stability evaluation. However, $\gamma_{\rm damp}$ is the total damping rate, which originates from various damping mechanisms involving bulk plasma and beam ions. However, theoretical evaluation of $\gamma_{\rm damp}$ still has appreciable uncertainty. Therefore, it is necessary to measure the AE damping rate experimentally and compare it with theoretical estimates. An active sensing method for measurement of the damping rate, using a set of loop antennas, has been successfully deployed in tokamaks [4, 5]. By this method, AE damping rates have been successfully measured in plasmas without an energetic ion drive, and are fairly small — less than several percent of the angular eigenfrequency.

In the Compact Helical System (CHS), we have tried to excite AEs by applying alternating magnetic field perturbations with a set of electrodes inserted in the plasma edge, and measuring the damping rate. Small magnetic field perturbations perpendicular to the confinement magnetic field line are generated by an alternating current along the magnetic field line induced by a pair of electrodes inserted at the plasma edge [6]. The alternating current induced by the electrode(s) acts an excitation antenna. This electrode technique can excite shear Alfvén waves effectively. Two electrodes are placed 180 degrees apart, in the toroidal direction, at the inner port of the toroidal vacuum vessel to specify the toroidal mode numbers of the applied perturbation fields. This system can excite AEs using a single electrode as well as with two. For a single electrode, the dominant toroidal mode numbers of the applied perturbation field are expected to be $n = 0, \pm1, \pm2, \ldots$. Two electrodes, however, must be operated with same polarity because the alternating current is generated by an electron saturation current using a positively biased electrode. Thus, the toroidal mode number is expected to be an even value such as $n = 0, \pm2, \pm4, \ldots$. In this paper, we describe the experimental results for operation with a single electrode. The driving frequency $f_{\rm ext}$ was swept up to 500 kHz to cover the expected TAE gap frequency. The maximum current of each electrode is ~5 A, and is limited by the capability of the power amplifier. The maximum amplitude of the perturbation field is estimated to be very small ($\sim 5 \times 10^{-6}$ T) at the magnetic axis.

A typical discharge waveform of an NBI-heated hy-

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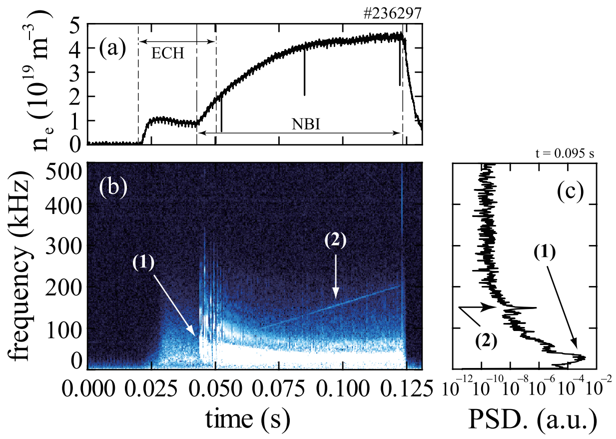

Fig. 1 (a) Time evolution of line-averaged electron density in an NBI-heated hydrogen plasma, where B_t = 0.9 T. (b) Contour plot of poloidal magnetic fluctuations detected by a magnetic probe, where only a single electrode is employed for AE excitation. (c) Power spectrum of magnetic fluctuations calculated in the time window of t = 0.095-0.096 s. The arrows (1) and (2) in Figs. 1 (b) and 1 (c) indicate energetic-ion-driven modes and response to the externally applied perturbations, respectively.

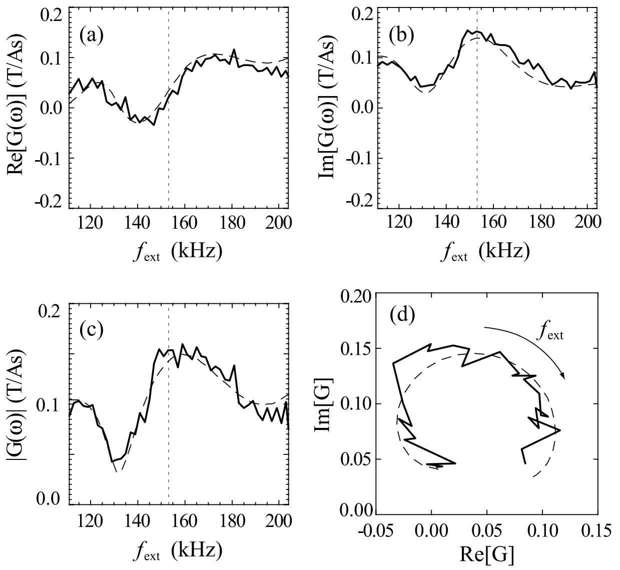

Fig. 2 Experimentally obtained (solid curve) and fitted (broken curve) transfer functions, shown as a function of the driving frequency f_{ext}. (a) Real part, (b) imaginary part, and (c) absolute value of the transfer function. (d) Nyquist plot drawn around the resonance peak from f_{ext} = 120 kHz to f_{ext} = 180 kHz.

drogen plasma is shown in Fig. 1 (a), where the toroidal magnetic field is B_t = 0.9 T, and the magnetic axis position of the vacuum field is R_{ax} = 0.921 m. The line-averaged electron density increases to ~4.5×10^{19} m^{-3} to minimize the strength of energetic ion drive of AEs. The applied external perturbation was swept from 10 to 200 kHz in 0.1 s to search for expected TAE frequencies, as shown in Fig. 1 (b). The volume-averaged total beta value, including the energetic ion component, is about 0.5%. In this shot, the rotational transform profile is dominantly determined by the finite beta effect, because the NBI-driven plasma current is small ($\leq$ 3 kA). The transfer function $G(\omega)$ that expresses a plasma response to applied alternating magnetic field perturbations was derived from the ratio between the magnetic probe signal and the electrode current. It is indicated by a solid curve in Fig. 2 (a) to (c) as a function of the driving frequency f_{ext} of the electrode current. Some resonant effects are found in the transfer function. These resonant peaks were obtained by numerical fitting of $G(\omega)$ using the following model transfer function $G(\omega)_{model}$, which characterizes a general viscous damping system similar to that shown in [7]:

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

Here, ω, Ω_r, γ_r, R_r, and R_r^* are driving angular frequency, angular eigenfrequency that characterizes the resonance, damping rate, and residue and its conjugate term at r-th resonance, respectively. The quantities $B(\omega)$ and $A(\omega)$ denote the Fourier transform of a magnetic probe signal and the electrode current, respectively. Note that the absolute value of the transfer function $|G(\omega)|$ has a peak at f < 130 kHz, which is in part due to energetic-ion-driven Alfvén eigenmodes. On the other hand, an offset caused by an unknown peak located in the high-frequency region is seen in the range of f > 190 kHz. The parts at f < 130 kHz and f > 190 kHz should be removed to derive a resonant peak excited purely by the electrode current. The broken curve shown in Fig. 2 is a fitted curve based on $G(\omega)_{model}$. As seen from Fig. 2, the transfer function fits very well. The resonant frequency thus derived is f_o = 153 ± 6 KHz. As seen in Fig. 3, the frequency is very close to the lower bound of the TAE gap in the plasma peripheral region of the n = 1 shear Alfvén spectra calculated for the plasma shown in Fig. 1, where a single electrode was employed for AE excitation and the lowest expected toroidal mode number was n = 1. The n = 1 and m ~ 3 coherent mode, excited by energetic ions, was also observed in the plasma. From Fig. 3, this is thought to be a GAE-like mode, because the observed frequency is just above the maximum of the calculated shear Alfvén spectrum near the plasma center. This suggests that the calculated Alfvén spectra are consistent with the experimental results, although the radial profiles of the rotational transform and those of the density have certain uncertainties. The normalized damping rate $\gamma/(2\pi f_o)$ of the TAE excited by an electrode is evaluated at 18±5%. In the experiments, the measured damping rates $\gamma/(2\pi f_o)$ are fairly large compared with those obtained in tokamak experiments. This is thought to be due to differences in the magnetic configurations, such as in the rotational transform or shear profiles.

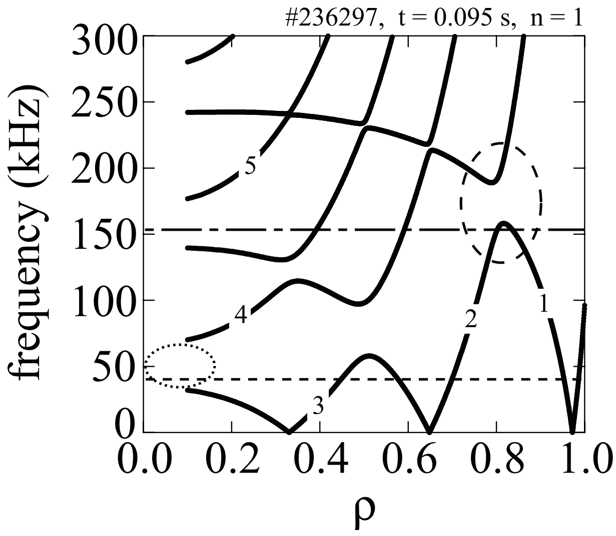

Fig. 3 Shear Alfvén continua, including the effect of toroidicity for $n = 1$ at $t = 0.095$ s, of the plasma shown in Fig. 1 as a function of the normalized radius ρ. The horizontal broken line and dot–dashed line indicate the frequency of the mode driven by fast ions, and that excited by the electrode, respectively. The circle drawn with broken curves indicates the relevant gap for the TAE excited by an electrode. The dotted circle indicates the maximum of the shear Alfvén spectra relevant to the energetic-ion-driven m ~ $3/n = 1$ GAE-type mode.

In particular, continuum damping in the plasma edge and scrape-off layer may play a dominant role in these results, as discussed in the AE excitation experiments performed in a low-temperature CHS plasma produced at very low B_t (< 0.1 T) [6].

In conclusion, application of alternating magnetic field perturbations to NBI-heated plasmas in CHS successfully excited TAEs (whose gaps reside near the plasma edge) without fast ion drive. The derived TAE damping rates were ~20%. Comparison of these results with theoretical predictions is left for future work.

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