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低磁気シアヘリカルプラズマにおける高速イオン励起MHD不安定性研究
Studies of energetic-ion-driven MHD instabilities in helical plasmas with low magnetic shear

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The features of energetic-ion-driven MHD instabilities such as Alfvén eigenmodes (AEs) in three-dimensional magnetic configuration with low magnetic shear and low toroidal field period that are characteristics of advanced helical plasmas are introduced. Moreover, the external control of AEs and the effects of AEs on energetic ion transport/loss in low magnetic shear helical plasmas are also introduced.

Most concepts of advanced helical plasmas have a low magnetic shear in combination with a magnetic well for good stability against pressure-driven MHD instabilities and low toroidal field period for both good transport and MHD stability. The existence and stability of energetic-ion-driven MHD instabilities, which would affect the transport of energetic ions including alpha particles in a fusion reactor, are characterized by the magnetic configuration including the magnetic shear. We have experimentally and numerically investigated the energetic-ion-driven MHD instabilities in helical-axis heliotron Heliotron J with low magnetic shear and medium rotational transform (iota). And we have compared the results of Heliotron J with results of TJ-II, which has low magnetic shear and high iota. We have effectively utilized the similarities and differences between both devices to clarify the characteristics of AEs in helical plasmas with low magnetic shear.

Characteristics of AEs in low shear helical plasmas: The MHD instabilities destabilized by the energetic ions are observed in NBI-heated plasmas of Heliotron J [1] and TJ-II [2]. The frequency of observed modes is in the range of Alfvén frequency and inversely proportional to the square root of electron density n_e. In order to identify the observed mode, we have compared the experimental results and numerical simulations by STELLGAP and AE3D code [3] where we took into account three-dimensional magnetic configuration which leads to both the poloidal and toroidal mode coupling of each shear Alfvén wave. In the case of Heliotron J, we only found the GAE, whose frequency lies just below the shear Alfvén spectra of m=2/n=1 as shown in Fig.1. The frequency, mode number and radial structure of calculated GAE agree with the experimental results obtained from Mirnov coils and soft X-ray (SX) measurements. The observed modes are identified as GAE in the Heliotron J. It is assumed that the effect of toroidal mode coupling for GAE is fairly weak although N_p is small. HAE frequency is predicted to be above 500 kHz in the Heliotron J because of medium iota. On the other hand, in the

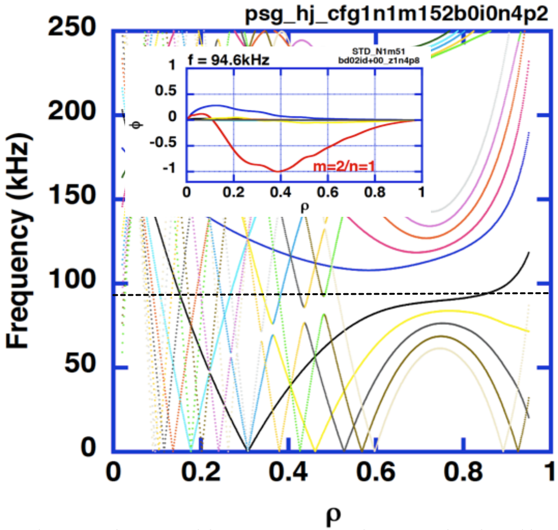

Fig.1. Shear Alfvén spectra for mode family N_f=1 of Heliotron J. Inserted plot means profile of GAE whose frequency corresponds to broken line in spectra.

case of TJ-II, we found GAEs and HAEs, whose frequency is similar to the observed frequencies, in simulations. It seems that the observed mode in the TJ-II is HAE although there are uncertainties in both toroidal and poloidal mode numbers. Moreover, we also observed energetic particle modes (EPMs) whose frequency does not depend upon the square root of electron density. The observed EPMs are localized at plasma edge region obtained from beam emission spectroscopy (BES) [4] and SX. The observed frequency, which is determined by the characteristic frequency of passing energetic ions, intersects with shear Alfvén continua at plasma edge region.

To make more clear the effect of iota on AEs, we have performed iota scan experiments in both devices where the iota is scanned in the range of 0.47~0.63 in Heliotron J and 1.53~1.85 in TJ-II. Figures 2 (a) and (b) respectively show the GAE frequency obtained from numerical simulations and experiments as a function of iota in Heliotron J. Experimental results show that the GAE frequency increases with an increase of iota. This is the same tendency found in the numerical simulations. In the case of TJ-II, we did not see the clear dependence of the observed frequency on iota. However, GAE and HAE can exist in the frequency range of observed mode.

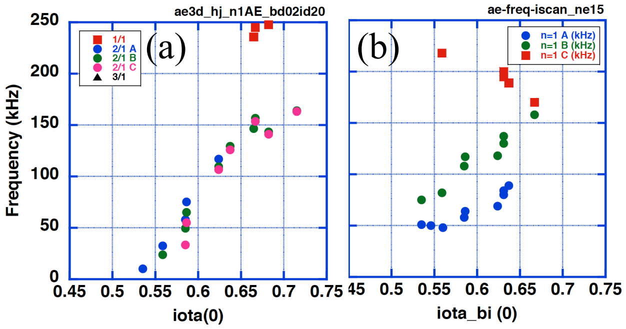

Fig.2. Frequency of GAE obtained from (a) numerical simulations and (b) experiments in Heliotron J.

External control of AEs in low shear helical plasmas: Some way of external control of MHD instabilities destabilized by energetic ions will be required for a fusion reactor. We choose ECH/ECCD to control energetic ion driven MHD instabilities because ECH/ECCD is an ideal tool to control MHD instabilities since it can provide highly localized ECH power /EC current with a known location and good controllability. In Heliotron J, we have attempted to control the mode amplitude of the observed EPMs by the change of plasma current induced by ECCD. EPMs with *n*=0, 1 and 2 are observed in NBI-heated plasma in the range of $n_e < 1\text{x}10^{19}$ (m^{-3}) where the ECCD can successfully drive plasma current. When the refractive index of ECH $N_{//}$ is changed in order to induce ECCD, the mode amplitude of the observed EPMs with *n*=0 and 1 is decreased as the EC induced plasma current increases as shown in Fig. 3. The mode amplitude is strongly linked to the magnetic shear because the continuum damping rate, which is the main damping mechanism of EPMs, is related to the magnetic shear. The magnetic shear of Heliotron J is low in low beta plasma where energetic ion beta is comparable to bulk plasma beta and we often observed EPMs. Therefore the control of EPMs is successfully demonstrated by the plasma current control due to the ECCD in Heliotron J [5].

In TJ-II, when ECH is applied into NBI-heated plasmas, the initially continuous AEs display bursting behavior with rapid frequency chirping. The mode amplitude of the bursting AEs is weaker than that of the continuous AEs. The ECH power and ECH deposition profile affect the mode amplitude of the observed bursting AEs. A candidate to explain the mitigation of AE by ECH in TJ-II is the increment of Landau and/or collisional damping whose damping date is related to the electron temperature.

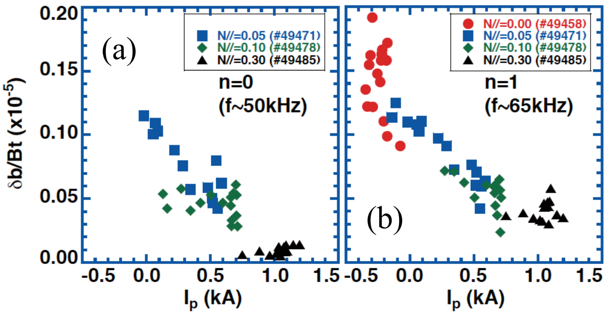

Fig.3. Dependence of (a) *n*=0 and (b) 1 EPMs on plasma current induced by ECCD in Heliotron J.

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