Linear kinetic analysis of Alfvén eigenmodes in tokamak plasmas
トカマクプラズマにおけるアルヴェン固有モードの運動論的線形安定性解析

Taisei Futakuchi[1)], Atsushi Fukuyama[2)]
二口泰成 [1)], 福山　淳 [2)]

[1)] *Fuculty of Engineering, Kyoto University*
Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan
[2)] *Graduate School of Engineering, Kyoto University*
Kyoto-Daigaku-Katsura, Nishikyo-ku, Kyoto 615-8540, Japan
[1)] 京都大学工学部 *606-8501* 京都市左京区吉田本町
[2)] 京都大学大学院工学研究科 *615-8540* 京都市西京区京都大学桂

The excitation of Alfvén eigenmodes driven by fast ions with anisotropic velocity distribution function is analyzed in tokamak plasma using the full wave code TASK/WM. The dielectric tensor for species with anisotropic velocity distribution function is numerically calculated and complex eigenmode frequency were obtained. The parameter dependence of the eigenmode frequency and growth rate is studied, and the wave structures in real space and frequency space are clarified.

1. Introduction

Various low-frequency modes excited by energetic ions have been observed experimentally in tokamak plasmas. Most of them are attributed to the Alfvén eigenmodes (AE) which have been extensively explored theoretically and numerically [1]. The linear stability and the nonlinear effect on energetic ion confinement are key issues of the analyses. Linear stability analyses [2] have revealed the importance of mode-conversion to the kinetic Alfvén waves and the sensitive dependence on profiles of safety factor, edge density, rotation velocity and energetic ion pressure. Therefore, careful study of AE in present-day tokamaks and fusion device is required.

In this paper, we report on the results of linear stability analyses in the Alfvénic frequency range the kinetic full-wave code TASK/WM [2] with various plasma models. In this code, Maxwell's equation with kinetic dielectric tensor is solved in magnetic flux coordinates. The response of energetic ions is calculated from the drift kinetic equation. With poloidal and toroidal mode expansion, parallel wave number is correctly taken into account to describe the wave-particle resonant interaction. Eigenmode with complex wave frequency is obtained by maximizing the wave amplitude for given external current proportional to the plasma density.

2. Toroidicity-induced Alfvén eigenmodes

First we examine the effect of kinetic Alfvén waves on the toroidicity-indueced Alfvén eigenmode (TAE). We assume a simple tokamak configuration with circular crosssection, flat density profile, peaked temperature profile, and simple parabolic q profile: $q(\rho) = q_0 + (q_a - q_0)\rho^2$, $q_0 = 1$, $q_a = 2$. The Alfvén continuum frequency and the poloidal wave electric field are depicted as a function of minor radius in Fig. 1. Figures 2 and 3 shows the contour of the volume integral of the wave electric field amplitude on the complex frequency plane. The peaks of the contour correspond to eigen modes. The dominant TAE locates in the frequency gap between the two continuum range, while small eigenmodes exist inside of the continuum range. Figure 2 depicts the frequency structure with collisional cold plasma model, while figure 3 with uniform kinetic plasma model. With the kinetic model, the kinetic Alfvén wave contributes the damping of the mode in the continuum region. The damping rate of the damped mode increases with the increase of the frequency. In the case of collisional cold mode, the damping rate depends on the collision frequency assumed. The mode frequency and the damping rate of the TAE mode is $f_r = 81.95\,\mathrm{kHz}$ and $f_i = -20.32\,\mathrm{Hz}$ for central temperature of 5 keV.

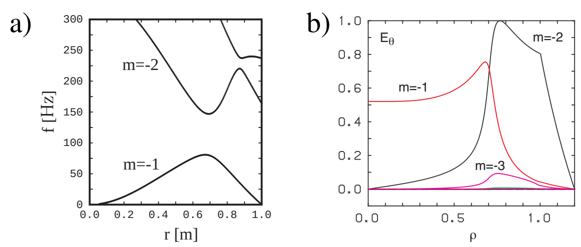

Fig. 1 Typical examples of a) radial profile of Alfvén continuum frequency, and b) radial structure of TAE

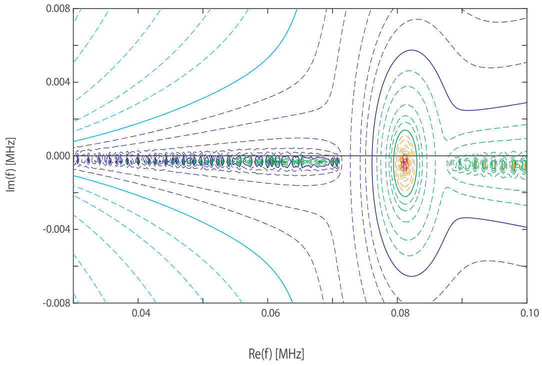

Fig. 2 Contour of $|E|^2$ in complex frequency space with collisional cold plasma model

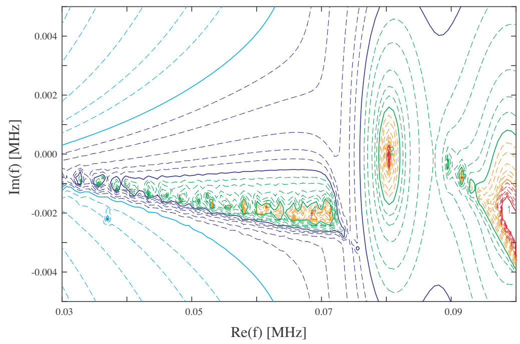

Fig. 3 Contour of $|E|^2$ in complex frequency space with kinetic plasma model

3. Excitation by energetic ions

Energetic ions with a large pressure gradient can excite AEs. Figures 4 and 5 indicate the change of frequency spectrum without and with fast ions. In the presence of fast ions, the damping rate of AE decreases and finally the growth rate becomes positive.

In addition to the case of density gradient, the effects of anisotropic velocity distribution are also examine.

4. Discussion

In the low frequency range, the eigen frequency becomes comparable to the diamagnetic drift frequency, the bounce frequency and toroidal precession frequency. In this frequency region, we have to take account of the particle orbit in a real magnetic geometry, and formulate the drift-kinetic dielectric tensor. The eigenmode analysis with this dielectric tensor will enable us to study the coupling to drift Alfvén waves and fishbone instabilities which have been studied mostly with MHD model.

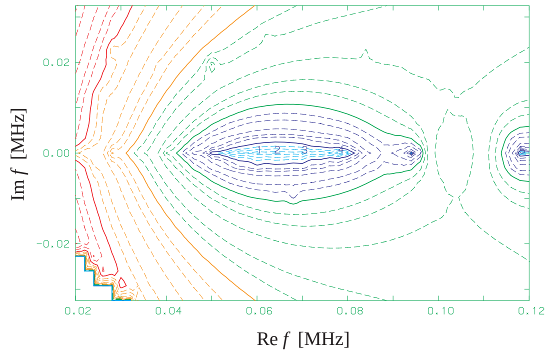

FIg. 4 Frequency spectrum without fast ion components

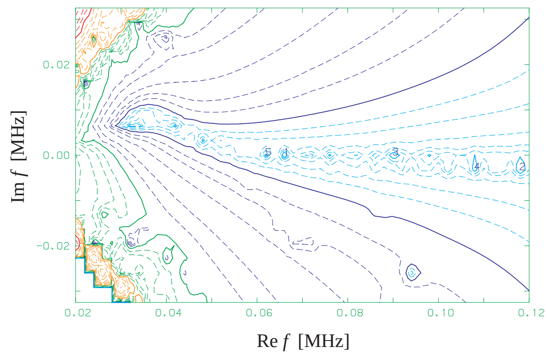

Fig. 5 Frequency spectrum with fast ion component, $n_{F0} = 1 \times 10^{17}\ \mathrm{m}^{-3}$, $T_{F0} = 0.5\,\mathrm{MeV}$

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