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# MHD Spectroscopy Using Energetic-Ion-Driven Alfven Eigenmodes in Toroidal Plasmas

# トロイダルプラズマにおける高速イオン駆動アルヴェン固有モードを利用したMHDスペクトロスコピー

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The mode frequencies of various energetic-ion-driven Alfven eigenmodes (AEs) sensitively depend on toroidal magnetic configuration and plasma equilibrium quantities such as ion density and rotational transform (or safety factor) profiles. If the frequency and/or radial locations of AEs are measured by a few diagnostic techniques, the rotational transform (ι/2π ) or safety factor ($q$) profile can be derived with good accuracy, based on well-developed AE theory. This technique is called "*MHD spectroscopy*" using energetic-ion-driven AEs. In this paper, prediction of the rotational transform profile is attempted by monitoring AE frequencies in a beam heated plasma with large Shafranov shift on LHD and in a sawtoothing plasma on the KSTAR tokamak. Global Alfven eigenmodes (GAEs) and reversed shear Alfven eigenmodes (RSAEs) are in particular useful for MHD spectroscopy.

## 1. Introduction and MHD spectroscopy

In deuterium-tritium (DT) burning plasma, energetic alpha particles and energetic beam ions can drive energetic-ion-driven Alfven eigenmodes (AEs). Energetic ion losses would be induced by these AEs and lead to serious damages to plasma facing components of toroidal devices. Efforts to avoid or mitigate these energetic ion losses are being made by controlling AEs. In contrast to the unfavorable impacts of AEs, AEs have favorable aspects. An important application of AEs is to predict equilibrium quantities such as ι/2π profile (or $q$-profile), fuel mass ratio and so on. This technique is called *MHD spectroscopy* [1-3]. Propagation of AEs such toroidicity induced Alfven eigenmodes (TAEs) and RSAEs is determined with the shear Alfven dispersion relation: $\omega^2 = k_\parallel^2 v_A^2$, where $k_\parallel = \frac{m\left(\frac{\iota}{2\pi}\right)-n}{R}$. The parameters $m$, $n$, $R$ and $v_A$ are the poloidal and toroidal mode numbers, plasma major radius and Alfven speed, respectively. Accordingly, the mode frequency and radial mode structure depend on ι/2π, ion density and magnetic configuration, sensitively. In this paper, we investigate a potentiality of *MHD spectroscopy* by applying the idea to neutral beam (NB-) heated plasmas of LHD and KSTAR. The procedure of *MHD spectroscopy* is following: (1) to pre-analyze observed AE frequencies ($f$), (2) to calculate MHD equilibria using VMEC code [4] for both 3D stellarator/helical plasmas and 2D tokamak ones, (3) to calculate shear Alfven spectra by AE3D code [5] using the ι/2π profile calculated at the step (2) and ion density profile inferred from measured electron density profile, (4) to compare the calculated AE frequencies with experimentally observed frequencies, (5) to tailor the ι/2π profile to match both calculated and observed frequencies consistently. This process (5) is iteratively repeated to reach good agreement within experimental errors. In particular, the temporal frequency sweeping of the AEs in a time scale of plasma equilibrium evolution in a plasma with nearly fixed density profile enables us to infer the evolution of ι/2π profile accurately. AEs having this character are RSAEs and GAEs where $f \cong (k_{\parallel} v_A)_{min}$ or $f \cong (k_{\parallel} v_A)_{max}$ and $k_{\parallel}$ depends on the ι/2π profile.

## 2. Prediction of the rotational transform profile in LHD and KSTAR plasmas

Characteristic frequency sweeping of energetic-ion-driven AEs was observed in an NB heated plasma at low toroidal field $B_t$=0.45T on LHD, as shown in Fig.1. In this shot, plasma stored energy increases by repetitive hydrogen ice pellet injection, accompanying large Shafranov shift which is seen from the electron temperature profiles $T_e(R)$ shown in Fig.2. Large Shafranov shift due to increased stored energy $W_p$ is thought to cause the downward sweeping of $n$=-1 mode frequency from t=2.45s taking ~25 ms, which is much longer than the duration of rapid frequency chirping observed in nonlinear evolution of AEs[6] . In the frequency sweeping phase, line averaged electron density is gradually decreasing. This tendency is different from the character of TAE of which frequency depends on ion density but not depend on the ι/2π profile change sensitively. A most like candidate of the observed $n$=-1 mode is RSAE or GAE. Note that the negative value of $n$ means the mode propagation in the co-beam direction. 3D MHD equilibria are calculated using experimental data by VMEC code, changing the radial profile of toroidal current density. In the calculations, the eigenmode frequency (=36.4 kHz) close to the experimental one (~ 35 kHz) is found for the ι/2π profile which is obtained on the assumption of a considerably peaked toroidal current density profile as $j/j(0)=(1-(r/a)^2)^4$. For this case, the calculated shear Alfven spectra and the ι/2π profile are shown in Fig.3. Whether such peaked current density profile driven by energetic tangential neutral beam injection and neoclassical effect is feasible or not should be investigated. Thus peaked current density profile and large Shafranov shift realizes a reversed magnetic shear plasma. As seen from Fig.3, the obtained AE is thought to be $m$=-2 GAE. When Shafranov shift is slightly reduced due to lower plasma pressure and the off-axis minimum of ι/2π increases slightly, the mode frequency is expected to go upward as observed in Fig.1.

In a sawtoothing plasma of KSTAR, an AE of which frequency is swept upward was observed although line averaged electron density increases linearly in time. The AE is also GAE and the time evolution of q-profile was successfully predicted from the frequency sweeping phenomenon.

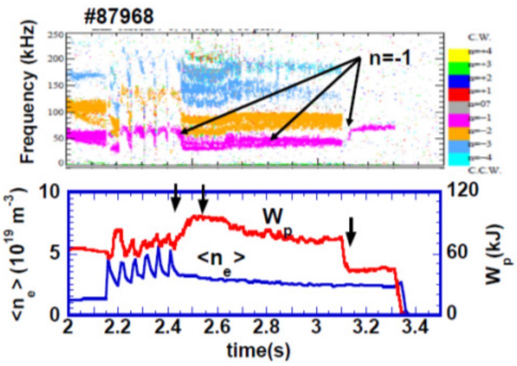


**Fig.1** Spectrogram of toroidal mode number $n$ of magnetic fluctuations (top) and evolution of line averaged density and $W_p$ (bottom).

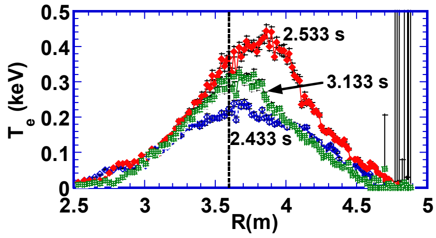


**Fig.2** Evolution of electron temperature $T_e(R)$. The vertical line indicates the magnetic axis position of the vacuum field.

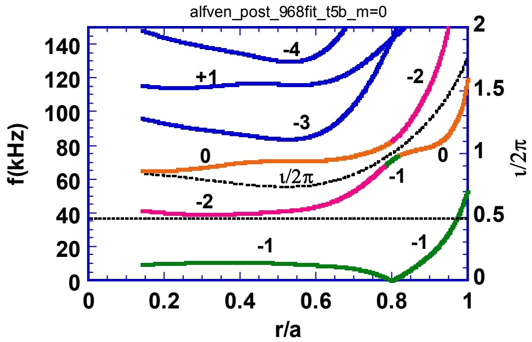


**Fig.3** Shear Alfven spectra and the ι/2π (Broken curve) profile calculated by VMEC code. The horizontal dotted line indicates the mode frequency close to the observed one. The numbers indicate the poloidal mode number $m$.


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