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Observation and Measurement of MHD Activity Using Motional Stark Effect (MSE) Diagnostic

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In a new mode of measurement, the amplitude of a tearing mode rotating at frequencies of up to tens of KHz has been obtained using the spectral features of high frequency MSE data. A formulation has been developed to calculate the pitch angle oscillations associated with these instabilities, from the MSE spectrum. Density fluctuations can be simultaneously obtained from MSE measurements if the intensity response to density variation can be calibrated. Examples of observations are given and detection limits are explored.

I. Introduction

The measurement of the structure of magnetohydrodynamic (MHD) instabilities and plasma turbulence phenomena is necessary to understand and control these instabilities and obtain high fusion performance in fusion devices. The instabilities are characterized by spatial variations in the local magnetic field from the equilibrium fields. In tokamaks, this variation is mainly in the poloidal field. When the mode rotates toroidally, the mode appears as an oscillating component of poloidal field and the mode characteristics can be obtained from the measurements at a single toroidal location. In this paper, we report direct local measurements [1] of the poloidal field oscillations using the motional Stark effect (MSE) diagnostic.

The conventional MSE technique [2,3] is applicable only for slow phenomena (~ few kHz) and therefore a new technique of measurement has been developed where the MSE data is digitized at a fast rate and the data is spectrally analyzed. The amplitude of the signals at the beat frequencies of the polarimeter [4] modulation frequency and the mode frequency is used to obtain the pitch angle associated with perturbed field and the MSE intensity perturbations simultaneously. The density perturbations can also be obtained from the intensity oscillations, if the MSE intensity dependence on density can be parametrized. Measurements with a multi-channel high frequency MSE system have been implemented on DIII-D, to measure the profile of MHD instabilities. The limits on sensitivity, upper frequency and time resolution are set by by signal to noise ratio, sampling duration and photon statistics.

II. Measurement of MHD Oscillations Using MSE Diagnostic

The DIII-D MSE diagnostic [2,3] uses the the σ polarization component of the Doppler shifted D_α line emitted by a heating beam. The MSE polarimetry measures the angle of polarization of the σ component with respect to a reference axis which is related to the plasma magnetic and electric fields. The MSE optics gather the light emitted from the beam, which is focused by an objective lens system and then passes through an optical window and a pair of photo-elastic modulators (PEMs), spectrally filtered and then detected by a photomultiplier.

With instrument responses taken into account and including the oscillating component of the different parameters, The expression for the photomultiplier signal is [1],

$$I_{tot} = I + \tilde{I}Cos(\omega t) + [A_S + \tilde{A}_s Cos(\omega t)]\ Cos(\omega_S t)\ Sin[2(\gamma + \tilde{\gamma}Cos(\omega t)]$$

$$+ [A_C + \tilde{A}_c Cos(\omega t)]\ Cos(\omega_C t)\ Cos[2(\gamma + \tilde{\gamma}Cos(\omega t)] + \ldots \quad , \qquad (1)$$

where γ is the MSE pitch angle, A_S and A_C are the amplitudes of the MSE signals associated with the Sin(2γ) and Cos(2γ) terms respectively and $\omega_S/4\pi$ and $\omega_C/4\pi$ are the PEM frequencies. The superscript ~ refers to the component of the parameter that is oscillating at a frequency ω. The oscillating components of intensities ($\tilde{I}$ and $\tilde{A}$) are associated with oscillations of the plasma density and/or the diagnostic neutral beam density. With the assumption that the oscillating component of γ is small and is in phase with intensity oscillations, one obtains the relations for the oscillating component of the pitch angle and signal amplitudes as,

$$\tilde{\gamma} = \frac{R_s - R_c}{Cot(2\gamma) + Tan(2\gamma)} = 0.5(R_s - R_c)Sin(4\gamma)$$

$$, \qquad (2)$$

$$\frac{\tilde{A}_s}{A_s} = \frac{\tilde{A}_c}{A_c} = 2R_s - \tilde{\gamma}\,Cot(2\gamma) = 2[R_s Sin^2(2\gamma) + R_c Cos^2(2\gamma)]$$

with

$$R_s = \frac{S_{\omega s - \omega}}{S_{\omega s}} = \frac{\tilde{A}_s\ Sin(2\gamma) + 2A_s\tilde{\gamma}\ Cos(2\gamma)}{2A_s\ Sin(2\gamma)};\ R_c = \frac{S_{\omega c + \omega}}{S_{\omega c}} = \frac{\tilde{A}_c\ Cos(2\gamma) - 2A_c\tilde{\gamma}\ Sin(2\gamma)}{2A_c\ Cos(2\gamma)}\ .$$

The signals at the frequencies (ω_S+ω) and (ω_c–ω) are also related in a similar fashion. The above analysis was applied to new measurements on a rotating tearing mode in the DIII-D tokamak [1]. Figure 1(a) shows the results of the mode analysis of the signals from magnetic (Mirnov) probes at the wall. In this first ever measurement of the local magnetic field perturbation associated with a tearing mode, the photomultiplier signal of the MSE channel at R = 2.14 m was digitized at 1 MHz and a spectrum analysis was carried out. Figure 1(b) shows the contours of power spectrum of the MSE signal. The feature at ~40 kHz corresponds to $\omega_S/2\pi$ and the feature at ~46 kHz corresponds to $\omega_C/2\pi$. In addition to basic frequencies produced by PEM modulation of the polarized light, one can clearly see the beat frequencies (ω_S-ω)/2π, (ω_C+ω)/2π, (ω_S+ω)/2π and (ω_C-ω)//2π. The oscillation at the mode frequency ω corresponds only to intensity oscillation [Eq. (1)] and has no contribution from pitch angle ocillation. The frequencies are in excellent agreement with Mirnov signals and the results of the spectrum analysis of ECE signals viewing at R = 2.1 m. One other channel at R = 2.21 m from the same MSE array, does not register the MHD mode, showing that the measurement at R = 2.14 m is a local measurement. Using the expression (3) $\tilde{\gamma}$ is determined to be 0.16 deg (peak to peak) corresponding to a RMS oscillating poloidal field $B_z\sim$ of ~83 Gauss, at 3100 ms. This is in good agreement with the magnetic probe measurement of ~23 Gauss at the wall in a vacuum approximation that mode amplitude varies as $r^{-(m+1)}$.

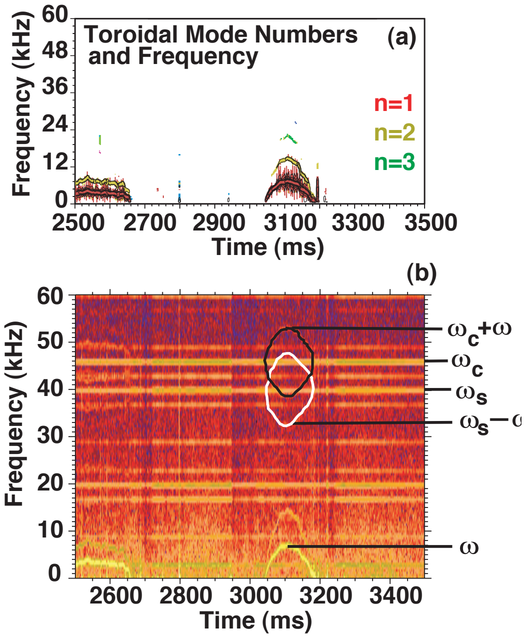

Fig. 1. (a) 2/1 tearing mode characteristics from magnetic probe data analysis, (b) 2/1 mode spectrum obtained from the analysis of MSE data.

The MSE intensity obtained from oscillation in the quantity $\sqrt{(S_{wc}^2 + S_{ws}^2)}$ which is independent of the pitch angle, can be used for determining the plasma density oscillations. However, because of the dependence of this intensity on the beam density, the beam attenuation has to be known. The parametric dependence of this quantity (normalized to peak value) on equilibrium plasma density (normalized to peak) over the duration of a DIII-D discharge is shown in Figs. 2(a) and 2(b). This indicates that after taking into account the beam attenuation, the MSE intensity is proportional to the plasma density in the DIII-D regime of density. This accounts for the equilibrium behavior of the beam density, but any imprinting of oscillations on the beam needs to be determined separately. The feature at the mode frequency (varying over a range of 0–8 kHz) is due only to the oscillations of the total intensity I (which includes back-

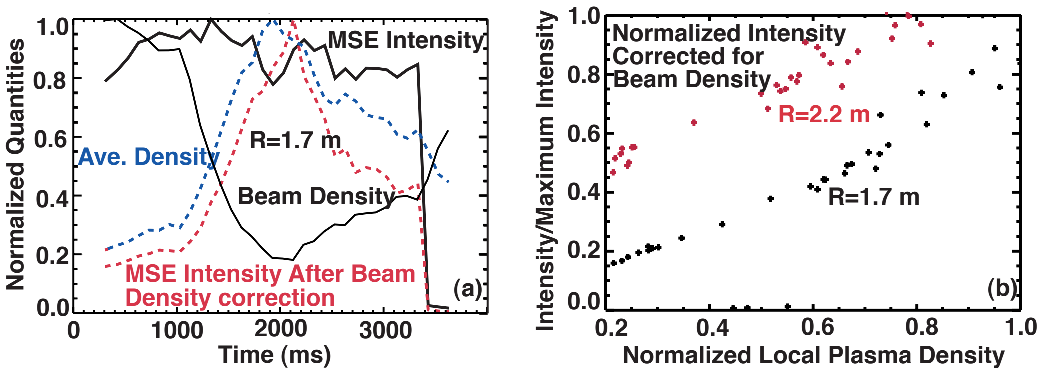

Fig. 2. (a) Observed signal (intensity) for an MSE channel (R = 1.7 m) which includes beam attenuation, computed local beam attenuated density and MSE signal without beam attenuation. For reference, the average plasma density measured by Thomson scattering is also plotted. All quantities are normalized to their peak value during the discharge. (b) Variation of the normalized MSE signal (intensity) as a function of local, normalized (to peak value during the discharge) density (measured by Thomson scattering) for two channels.

ground) and is therefore redundant information. It may be used for determining the density oscillations independently, if the dependence of this total intensity on density can be determined.

The frequency spectrum is obtained by taking a sample of data over a duration and the frequency of the phenomenon can be determined with high accuracy if large number of cycles are obtained. Photon statistics also requires that a certain number of photons should be accumulated. In DIII-D, a typical channel receives about 10^7–10^8 photons per second. The noise level due to electronic noise and radiation noise corresponds to about 1% of the signal. Noise simulation (white noise) and photon statistics have been modeled with poloidal field oscillation and intensity oscillations. The simulated spectrum with photon statistics and a noise level of 1% shown in Fig. 3. The pitch angle oscillation of 0.1 deg with no intensity oscillation is simulated, and the signal is accumulated for 100 ms with a sampling frequency of 250 kHz. The mode and the two PEM frequencies are 22, 20 and 23 kHz respectively. The beat frequencies of 18, 24, 62 and 68 kHz can be seen. It is clear that the photon statistics determines the sensitivity in this range. For the latter case, a five fold noise increase still allows a robust determination of the pitch angle oscillation. It is to be noted that additional intensity oscillations will enhance signal at two beat frequencies and depress it at the other two beat frequencies. A signal at the mode frequency will also appear.

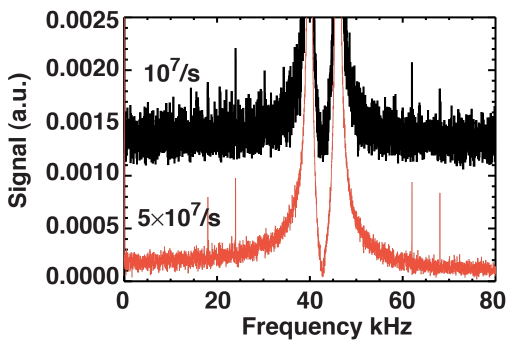

Fig. 3. Simulated spectrum of MSE signal for a pitch angle oscillation of 0.1 deg and no intensity oscillation for two photon rates.

The technique and the formulation for using the MSE diagnostic for observing and measuring characteristics of poloidal field oscillations has been developed. The method was applied for the determination of a 2/1 tearing mode amplitude. Data analysis taking into account calculated neutral beam attenuation shows that the MSE intensity is linearly dependent on the local density and this information can be used for the determination of density oscillations. Results of noise analysis shows that in DIII-D photon statistics determines the sensitivity of the measurement and a pitch angle oscillation of 0.1 deg can be detected well.

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