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MSE Spectroscopy in CHS Heliotron/Torsatron

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Abstract

Pitch angle of the local magnetic field line is measured from the polarization angle of the σ and π components of H_α emitted from the neutral beam. The pitch angle estimated from the π component agrees with the pitch angle estimated from the external coil current (vacuum magnetic field).

Keyword:
motional Stark effect (MSE), local magnetic field line, pitch angle measurement

1. Introduction

In heliotron/torsatron devices, the pitch angle of the vacuum magnetic field line is determined by the external coil current. However, when the plasma pressure increases, the bootstrap current and the Pfirsch-Schlüter current change the poloidal magnetic field in the plasma from the vacuum magnetic field.

The spectroscopic measurement using the motional Stark effect (MSE) has been recognized to be a useful tool for measuring the direction of the magnetic field inside the plasma[1-4]. The MSE arises from the Lorentz Electric Field, $\boldsymbol{E}=\boldsymbol{v}\times\boldsymbol{B}$, in the atom's rest frame, which is induced when the neutral beam, having the velocity $\boldsymbol{v}$, crosses the magnetic field $\boldsymbol{B}$. The MSE spectrum in the H_α emission consists of 15 components, and components having the considerable intensity are categorized into three groups[3]. The σ group (0σ, $+1\sigma$, and -1σ lines) is circularly polarized perpendicular to the Lorentz field, while the $\pi+$ ($+2\pi$, $+3\pi$, and $+4\pi$ lines) group and the $\pi-$ (-2π, -3π, and -4π lines) group are linearly polarized parallel to the Lorentz field, namely perpendicular to the magnetic field. The $\pi+$ and the $\pi-$ groups are red- and blue-shifted, respectively, from the 0σ line, which is not shifted due to the Stark effect. The spectral intensity through the optics transmitting at ϕ degree with respect to the midplane at the wavelength λ is expressed as

$$I(\phi,\lambda)=I_{\pi l}(\lambda)\cos^2(\alpha_\pi-\phi)+I_{\sigma l}(\lambda)\cos^2(\alpha_\sigma-\phi)+\frac{1}{2}I_{\sigma c}(\lambda), \tag{1}$$

where $\alpha_\pi=\alpha_\sigma+90$, $I_{\pi l}(\lambda)$ and $I_{\sigma l}(\lambda)$ are the linearly polarized π component and the σ component, respectively, while $I_{\sigma c}(\lambda)$ is the circularly polarized σ component. The polarization angle of the σ component α_σ is given by

$$\tan(2\alpha_\sigma)=\frac{I(135,\lambda)-I(45,\lambda)}{I(90,\lambda)-I(0,\lambda)}, \tag{2}$$

using the four set of intensity, $I(\phi,\lambda)$, with different ϕ [=0, 45, 90, 135]. The pitch angle γ, defined as $\tan^{-1}(B_p/B_t)$ (B_p: the poloidal magnetic field, B_t: the toroidal magnetic field), is derived from the polarization angle α_σ or α_π as

$$\tan\gamma=\tan\alpha_\sigma/\cos\beta=\cot\alpha_\pi/\cos\beta, \tag{3}$$

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where β is the intersection angle between the beam and the sightline.

2. The Diagnostic System

Figure 1 shows a schematic view of the experimental arrangement of the MSE spectroscopy. The diagnostic neutral beam (DNB) is injected almost perpendicularly into the Compact Helical System (CHS) heliotron/torsatron device in order to minimize the integration along the toroidal angle, where the poloidal magnetic field changes its sign every 22.5 degrees. The acceleration voltage of the DNB is set to be 45 kV with a beam current of 3.7 A, and a beam divergence angle of 0.65 degrees. The optical system consists of two sets of optics, each of them consisting of a polarizer and a ferroelectric liquid crystal (FLC) cell (Fig. 1 (b)). The FLC cell functions as half-wave retarder, whose optic axis is oriented at 45 degrees (by applying +5 V) with respect to the transmission axis of the polarizer. By using two sets of the FLC, the spectral intensity having polarization angles of 0, 45, 90 and 135 degrees with respect to the mid-plane can be measured. Each set of optics has a 24 optical fiber-array viewing the plasma from R=0.72 to 1.13 m along the beam line. Sightlines of the fiber-arrays are oriented with viewing angle of 37.05±21.55 degrees with respect to the direction of the beam to yield enough Dopper shift and spatial resolution. The typical spatial resolution of each optical fiber is about 12 mm in the horizontally elongated poloidal cross section. The light from the fibers is simultaneously led to the entrance slit of the 0.5 m spectrometer and the spectra for each fiber are detected with a two-dimensional (384×576 pixel) cooled charge-coupled device (CCD) detector system at the exit slit of the spectrometer. A 2160 lines/mm grating is used and the wavelength resolution of the spectrometer is 1.7 nm in the wavelength region of interest.

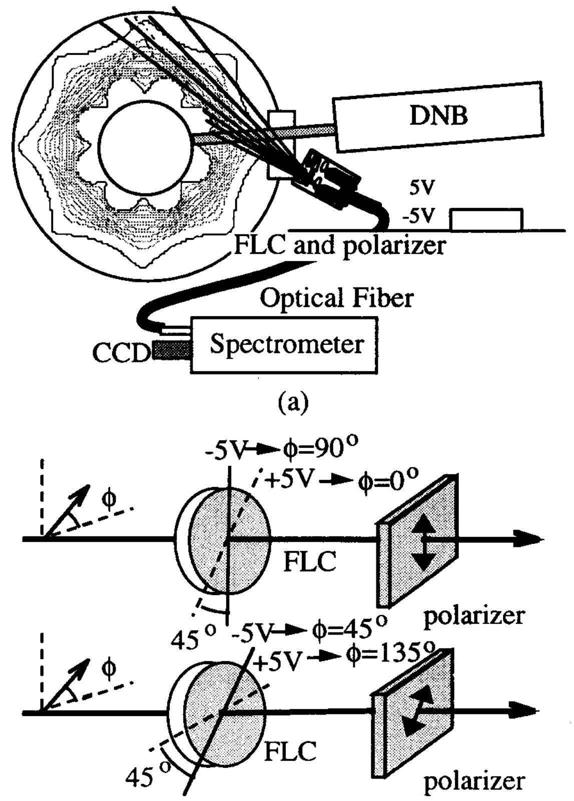

Fig. 1 (a) The schematic arrangement of the experimental system. (b) The ferroelectric liquid crystal (FLC) and the polarizer are rotated by an angle of 45 degrees around the optical path with respect to each optics.

3. Experimental Results

The radial profile of a pitch angle of a local magnetic field line is measured for a CHS plasma at the magnetic field of 0.8 T.

Figure 2 shows the comparison of the measured four spectra of the full energy, half energy and one-third energy beam components at R=93.3 cm with the predictions calculated from the vacuum magnetic field. Although the full energy component has the largest motional Stark splitting and separation in wavelength between the σ and π groups, the intensity of the full energy component is not sufficient to determine the pitch angle with a reasonable accuracy. Therefore, the one-third energy component which has the largest intensity is used to derive the pitch angle. The height of the peak in the calculated spectra for the two systems, $I(0,\lambda)$, $I(90,\lambda)$ and $I(45,\lambda)$, $I(135,\lambda)$ is adjusted to yield the best fit in the measured $I(0,\lambda)$ and $I(45,\lambda)$ spectra for each energy component, respectively. The shape of the measured spectra shows reasonable agreement with the calculated ones.

The wavelength averaged polarization angle $\bar{\alpha}_i$ is given by

$$\bar{\alpha}_i = \frac{1}{2}\tan^{-1}\left\{ \frac{1}{2\Delta\lambda} \int_{\lambda_i-\Delta\lambda}^{\lambda_i+\Delta\lambda} \left[\frac{(I(135,\lambda)-I(45,\lambda))/(I(135,\lambda)+I(45,\lambda))}{(I(90,\lambda)-I(0,\lambda))/(I(90,\lambda)+I(0,\lambda))} \right] \mathrm{d}\lambda \right\} + \delta_i \quad (4)$$

where $i = \pi-$, σ, $\pi+$ and $\delta_\sigma = 0$, $\delta_{\pi-} = \delta_{\pi+} = 90$. $\Delta\lambda$ is the wavelength region for averaging, which is determined as one time the standard deviation of

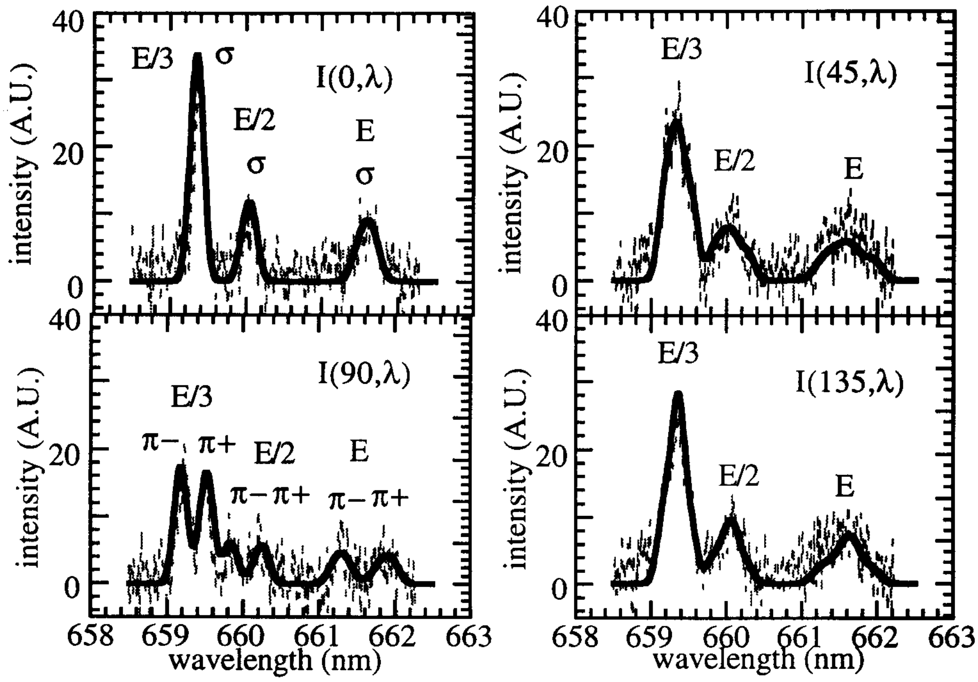

Fig. 2 Comparison of the measured four spectra with the calculated ones at R= 93.3 cm where the pitch angle is expected to be almost zero. The peak of $E/3$ beam component in the $I(0,\lambda)$ spectrum represents the σ group, and the two peaks in the $I(90,\lambda)$ spectrum represent the $\pi-$ and $\pi+$ groups.

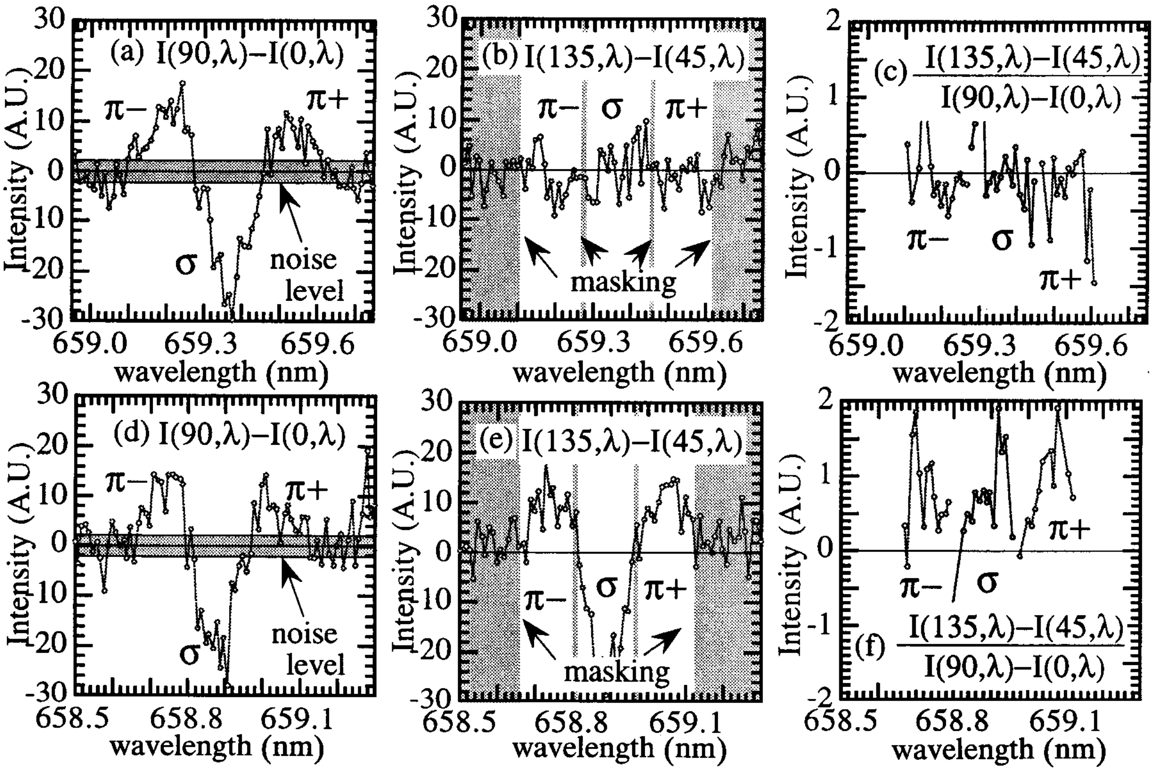

Fig. 3 The $I(90,\lambda)-I(0,\lambda)$, $I(135,\lambda)-I(45,\lambda)$, and $(I(135,\lambda)-I(45,\lambda))/(I(90,\lambda)-I(0,\lambda))$ estimated at R= 93.3 cm ((a) (b) (c)) and R= 115.3 cm ((d) (e) (f)) at H_α emission for the one-third energy. The noise level in Figs.(a) and (d) is determined to be one time the standard deviation. The data where $I(90,\lambda)-I(0,\lambda)$ is smaller than the noise level are masked.

$|I(90,\lambda) - I(0,\lambda)|$ where there are no σ and π lines.

Figure 3 shows the value $I(90,\lambda)-I(0,\lambda)$, $I(135,\lambda)-I(45,\lambda)$ and $(I(135,\lambda)-I(45,\lambda))/(I(90,\lambda)-I(0,\lambda))$ estimated at the R=93.3 cm ((a) (b) (c)) and R=115.3 cm ((d) (e) (f)). The data where $I(90,\lambda)-I(0,\lambda)$ is smaller than the noise level are masked.

Figure 4 shows the radial profile of the magnetic field pitch angle estimated by Eq.(4) from the $\pi-$, σ and $\pi+$ groups. The intersection angle β between the beam path and the sightlines of the fiber-arrays is oriented between 15.5 and 58.6 degrees. The values of the pitch angle derived from the $\pi-$ group agree with that of the vacuum magnetic field (solid line) calculated from the external coil current. The data derived from the $\pi+$ group are scattered around the calculated line. This scattering may be due to the overlap of the spectra between the one-third and half energy components. The pitch angle derived from the σ group shows slight disagreement with that of the vacuum magnetic field. The cause of this discrepancy will be investegated in near future. The shift of the magnetic axis estimated with VMEC code is 25 mm for the plasma beta value of 0.4% in this experiment[5]. However, the position of the major radius where the pitch angle is zero, $R_{\gamma=0}$, shifts outward only by 8 mm, because of the helicity of the magnetic axis. Therefore, the measurement of the $R_{\gamma=0}$ shift due to the finite beta requires small uncertainty of the pitch angle less than 0.7 degrees.

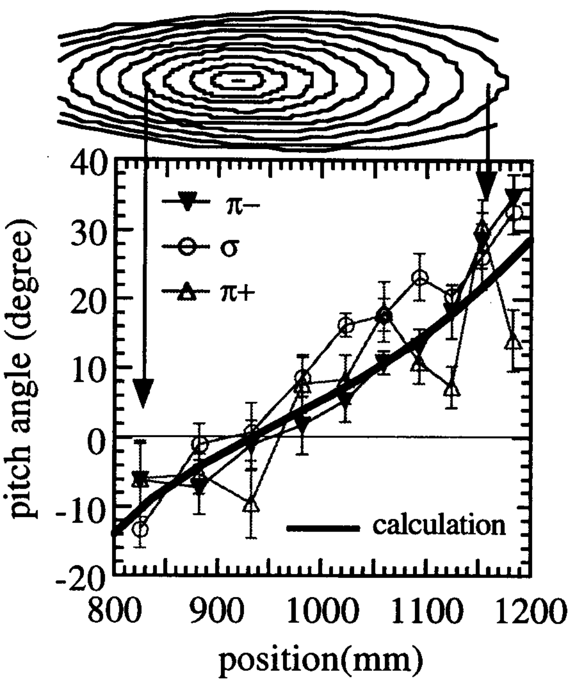

Fig. 4 The radial profile of the magnetic field pitch angle estimated by Eq.(4) from the $\pi-$, σ and $\pi+$ groups. The solid lines represent the calculated pitch angle of the vacuum magnetic field.

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