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Polarization Plasma Spectroscopy (PPS) viewed from plasma physics and fusion research

Katsumi Ida

National Institute for Fusion Science, 322-6, Oroshi-cho, Toki, 509-52 Japan
322-6 Oroshi-cho, Toki, 509-52 Japan

Abstract

Recently the measurements of poloidal magnetic field become important in plasma physics and nuclear fusion research, since an improved confinement mode associating with a negative magnetic shear has been found. The polarization plasma spectroscopy is recognized to be a useful tool to measure poloidal magnetic field and pitch angle of magnetic field.

1. Zeeman spectroscopy

At the weak magnetic field the energy levels of ion is split into 2J + 1 sublevels with energy shift given by

$$\Delta E = MgB_0\mu \tag{1}$$

where M has values from -J to +J , J is the total angular momentum number, μ is Bohr magnetron factor,the g is standard Lande splitting factor, and B is the magnetic field strength[1]. A spectral lines is composed a number of component due to the energy splitting of the upper and lower levels. The selection rules for electric dipole and magnetic dipole transition are ΔJ = 0, ±1, ΔM = 0 (π component) and ΔM = ±1 (σ component). When observed from the direction parallel to the magnetic field, the intensity of ΔM =0 line (linearly polarized) is zero and only ΔM = +1 (clockwise [right-hand] circularly polarized) line and ΔM = -1(counterclockwise [left-hand] circularly polarized) lines are present. When observed from the direction perpendicular to the magnetic field, the radiations of ΔM =0, ±1 transition are linearly polarized parallel (ΔM =0) and perpendicular (ΔM =±1) to the magnetic field. The Zeeman splitting in angstrom measured from zero-field wavelength λ_0 for the circularly polarized component is given by

$$\Delta\lambda_B = \pm 4.67\times10^{-13}\ zB\lambda_0^2 \tag{2}$$

where ± refers to the clockwise and counterclockwise circularly polarized component. B is the strength of the magnetic field in Gauss and z is unity for a normal Zeeman triplet. In the high temperature plasma, the Zeeman splitting is much smaller than the the Doppler broadening with the full width of half maximum (FWHM),

$$\Delta\lambda_D = 7.71\times10^{-5}\ \lambda_0(T_i/A)^{1/2} \tag{3}$$

The intensity of right-hand and left-hand circularly polarized component, I_R and I_L , observed from the direction with the angle of γ with respect to the magnetic field, is given by

$$I_{R,L} = \frac{(1 \pm \cos\gamma)^2}{4} I_{\pi+} + \frac{(1 \mp \cos\gamma)^2}{4} I_{\pi-} + \frac{\sin^2\gamma}{2} I_{\pi} \tag{4}$$

where $I_{\sigma+}$ [$= I(\lambda + \Delta\lambda_B)$]and $I_{\sigma-}$ [$= I(\lambda - \Delta\lambda_B)$]are right-hand and left-hand circularly polarized σ component and I_π [$= I(\lambda)$] is linear polarized π component. Because of Doppler broadening, the intensity $I(\lambda)$ has Gaussian profile as

$$I(\lambda) = I_0 \exp\left[-\left(\frac{\lambda - \lambda_0}{\Delta\lambda_D/2/\sqrt{\ln 2}}\right)^2\right] \tag{5}$$

Then the difference in intensity between I_R and I_L is proportinal to $\cos\gamma$ as,

$$I_R - I_L = \cos\gamma \left\{ I_0 \exp\left[-\left(\frac{(\lambda + \Delta\lambda_B - \lambda_0)}{(\Delta\lambda_D/2/\sqrt{\ln 2})}\right)^2\right] - I_0 \exp\left[-\left(\frac{(\lambda - \Delta\lambda_B - \lambda_0)}{(\Delta\lambda_D/2/\sqrt{\ln 2})}\right)^2\right]\right\} \tag{6}$$

Right-hand (I_R) and left-hand (I_L) polarized profiles contain contribution from all Zeeman components but due to their partial circular polarization, the σ components do not contribute evenly, which results in a small shift (~ $\Delta\lambda_B \cos\gamma$)between the polarized profiles as shown in Fig.1. The magnitude of difference between the circularly polarized profiles is proportional to the magnetic field component in the direction of observation in magnetic field [$\Delta\lambda_B/\Delta\lambda_D \ll 1$]. The circularly polarized component of Ti XVII 383.4nm was measured in Texas Experimental Tokamak (TEXT) using Fabry-Perot interferometer and photoelastic modulator (PEM)[2]. Figure 2(a) shows the normalized difference of I_+ and I_-, $(I_+ - I_-)/I_0$, at four position near the plasma axis. The solid lines is least-squares fit to the measured signal (dotted line). The coordinate r is the distance of the line of sight from the center of vacuum vessel. The reversal of the modulation signal indicates null in the poloidal magnetic field. The radial profile of poloidal magnetic field derived with this technique is plotted in Fig.2(b). This data clearly shows the position of magnetic axis (poloidal field is zero) at r = 3cm. The position of magnetic axis is an important issue in plasma physics. Since the shift of magnetic axis is related to the spontaneous current driven by the plasma pressure gradient, the plasma pressure can be estimated from the shift of magnetic axis.

2. MSE spectroscopy

The polarization spectroscopy techniques is applied to emission (H_α lines) from a high energy atomic hydrogen beam injected into a magnetically confined plasma. A strong Lorentz field, E = v x B, (v : neutral beam velocity, B : magnetic field in the plasma) observed in the reference frame of the beam particle produces splitting and polarization of line emissions via the Stark effect. The Doppler shifted wavelength of the beam emission including the first-order Stark effect is obtained from

$$\lambda = \lambda_0 \,(1 + (v/c)\cos\beta)(1 + a_i \lambda_0 v B \sin\zeta) \tag{7}$$

Here, ζ is the intersecting angle of the injected beam and the magnetic field, and β is the angle between the beam and the line of sight.'a(i)' is the coefficient for the line splitting, λ_0 is the H_α wavelength (6562.8 Å) and c is the light velocity.

When observed in the direction perpendicular to the electric field, the Stark σ and π component are linearly polarized, respectively perpendicular (σ component) and parallel (π component) to the direction of the Lorentz field. The spectral intensity through the optics transmitting at φ degree with respect to the mid-plane at the wavelength λ is expressed as

$$I(\phi,\lambda) = I_{\pi l}(\lambda) \cos^2(\alpha_\pi-\phi) + I_{\sigma l}(l) \cos^2(\alpha_\sigma-\phi) + \frac{1}{2} I_{\sigma c}(\lambda) \tag{8}$$

where $\alpha_\pi=\alpha_\sigma+90$, $I_{\pi l}(\lambda)$ [$= I_\pi(\lambda) (\sin^2\theta)/2$]and $I_{\sigma l}(\lambda)$ [$= I_\sigma(\lambda) (\sin^2\theta)/2$] are the linearly polarized π component and the σ component, respectively, $I_{\sigma c}(\lambda)$ [$= I_\sigma(\lambda) (\cos^2\theta)$] is the circularly polarized σ component, θ is the angle between Lorentz field vector and viewing line. When the excitation is isotropic, the total intensity of σ and π+ plus π− component become equal as $I_{\pi+} = I_{\pi-} =(1/2)I_\sigma$. By using the intensity ratio measured with four different optic transmitting angle φ, regardless the intensity ratio between I_π and I_σ and angle θ, the polarization angle of the σ (or π) component α_σ (= α_π − 90) is given by

$$\tan(2\alpha_\sigma) = \frac{\left(I(135,\lambda)-I(45,\lambda)\right)}{\left(I(90,\lambda)-I(0,\lambda)\right)} \tag{9}$$

The pitch angle γ is derived from the polarization angle of α_σ or α_π as

$$\tan\gamma = \frac{\tan\alpha_\sigma}{\cos\beta} = \frac{\cot\alpha_\pi}{\cos\beta} \tag{10}$$

When the pitch angle is derived from π component alone (when π component is completely isolated from σ component), the polarization angle or α_π can be measured from the ratio of I(45,λ) to I(135,λ) as $\tan^2(\alpha_\pi - 45) = I(45,\lambda)/I(135,\lambda)$[3]. However, in many cases, there is a overlap of spectra between π component and σ component as shown in Fig.3[4]. When the magnetic field is weak, the overlapping problem becomes serious and π component and σ components looks like one peak. Therefore the technique to solve the overlapping problems. There are two technique to separate π component from overlapping σ component or linearly polarized σ component from circular polarized σ component. One is the set of four linear polarizer[5] and the other is set of linear polarizer and photo elastic modulator (PEM), which functions as oscillating (~ 50kHz) quarter-wave plate (retardation from -λ/4 to +λ/4). The axes of the PEM are at +22.5 and -22.5 to the transmission axis of the linear polarizer and modulated with different frequency ω_1 and ω_2. The intensity ratio of the modulation amplitude at $2\omega_1$ to that at $2\omega_2$ gives polarization angle as $\tan[2(\alpha_\sigma-22.5)] = I(2\omega_1)/I(2\omega_2)$. The pitch angle measurements using PEM has been widely used in many tokamaks[4,6,7]. The pitch angle measurements with high time resolution was demonstrated in DIII-D tokamak as seen in Fig.4. The periodic oscillations with 10Hz are so-called sawtooth oscillation. The correlation between MSE measurements and soft x-ray (SXR) emission signal, which indicates the change of plasma electron temperature and density, shows that the magnetic field changes at the sawtooth instability as well as temperature. The good correlation between MSE and SXR measurements supports that sawtooth instability is due to the reconnection of magnetic field in the plasma. The measurements of local magnetic field inside the plasma is essential in the research of

MHD activity in the plasma.

Another application of MSE is measurement of radial electric field. When the radial electric field is large enough to comparable to 1% of Lorentz electric field (> 100kV/m), change of polarization angle due to radial electric field will be measurerable[8].

3. Possible application of polarization spectroscopy to plasma diagnostics

In magnetically confined plasma, the polarization of emission is due to the existence of magnetic field through Zeeman and Motional stark effect as described above. Therefore the most application of polarization plasma spectroscopy is the measurements of strength and direction of magnetic field. Another possible application of polarization plasma spectroscopy is the measurement of electron tail using the effect of the anisotropic electron impact on polarization characteristics such as the ratio of π component to σ component. The electron tail appears in the plasma, where the plasma current is driven by waves in the range of lower hybrid resonance[9]. Conventional approach is that the energy of electron tail is estimated from the angular dependence of hard X-ray intensity in the range of 100 - 400 keV measured with sodium iodide NaI detector. However, the parameters fitting the measured hard X-ray are not determined in a unique fashion[10,11]. Then the estimated energy of electron tail has large uncertainty in general.

A preliminary experiment to study the polarization of impurity emission due to electron tail was done for the plasma with lower hybrid resonance current drive (LHCD) in WT-3 tokamak. The ratio of π component to σ component is above unity when LHCD is applied, while it is around unity before the LHCD[12]. This experiment suggests the possibility of measurement of electron tail with polarization plasma spectroscopy. Preliminary experiments to measure the polarization due to anisotropic charge exchange at the beam energy of 30 - 40 keV have been done in JFT-2M[13], JIPP T-IIU[14] tokamaks and CHS heliotron/torsatron devices. However, the intensity ratio of π component to σ component is 1.03 ± 0.02 (in JFT-2M), 0.95 ± 0.03 (in JIPP TII-U), 1.05 ± 0.02 (in CHS) [the error bar is only due to the scatter of data and not including systematic error bar in the measurements], and there is no results that shows the the polarization due to anisotropic charge exchange. The beam energy for these experiments seems to be too low to produce enough polarization to be measured. Higher beam energy using negative ion source will be required for further study.

References

[1] U.Feldman, J.F.Seely, N.R.Sheeley, Jr., S.Suckewer, A.M.Title, J.Appl. Phys. **56** (1984) 2512.

[2] D.Wroblewski, L.K.Huang, H.W.Moos, Rev.Sci.Instrum. **59**, (1988) 2341.

[3] W.Mandl, R.C.Wolf, M.G.von Hellermann, H.P.Summers, Plasma Phys. Control. Fusion 35 (1993) 1373.

[4] D.Wroblewski, L.L.Lao, Rev.Sci.Instrum. **63**, (1992) 5140.

[5] J.Xu, K.Ida , et al., Fusion Engineering and Design, B23 (1997) 293.

[6] F. M. Levinton, Rev.Sci.Instrum. **63**, (1992) 5157.

[7] F. M. Levinton, G. M. Gammel, R. Kaita, H. W. Kugel, D. W. Roberts, Rev.Sci.Instrum. **61**, (1990) 2914.

[8] B.W.Rice, K.H.Burrell, L.L.Lao, Nucl. Fuion 37 (1997) 517.

[9] S.Bernabei, et al., Phys. Rev. Lett. 49 (1982) 1255.

[10] S.VonGoeler, et al., Nucl. Fusion 25 (1985) 1515.

[11] S.Texter, et al., Nucl. Fusion 26 (1986) 1279.
[12] T.Fujimoto, et al.Phys. Rev. E 54 (1996) 2240.,
[13] J.Xu, K.Ida, T.Kawachi, H.Ogawa, J.Fujita, JFT-2M group, in Controlled Fusion and Plasma Physics, (Proc. 22th Europ. Conf., Bournemouth 1995), 19C, Part III, European physical Society (1995) p417
[14] K.Ida, J.Xu, et al., UV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas, (Proc. 11th Colloquium on UV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas, May 29 - June 2, 1995, Nagoya), Edited by K.Yamashita T.Watanabe, University Academy Press, Tokyo, (1996).p503

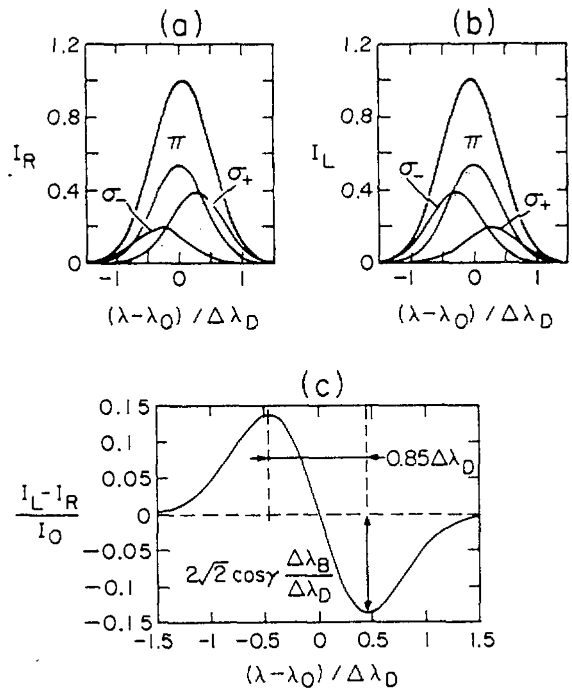

Fig.1.(a),(b) right-hand (I_R) and left-hand (I_L) polarized profiles of a Doppler broadened spectral line and (c) The magnitude of difference between the circularly polarized profiles (quoted from [2]).

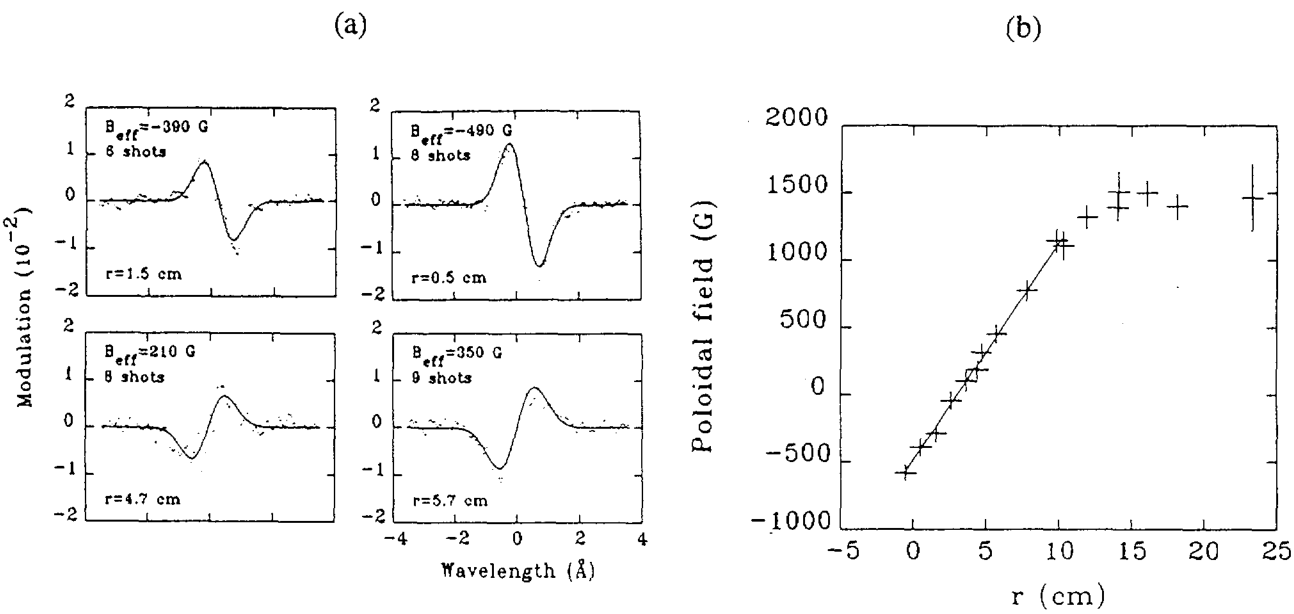

Fig.2 (a) Difference of intensity between clockwise ($\Delta M = +1$) and counterclockwise ($\Delta M = -1$) circularly polarized spectral line of Ti XVII 383.4nm. Solid line is the least squares fit to the measured signal (dotted line). (b) Measured poloidal magnetic field profile. Toroidal field B= 2.0T, plasma current, producing poloidal magnetic field, I_p = 200kA. Solid line is the least squares liner fit to central points (quoted from [2]).

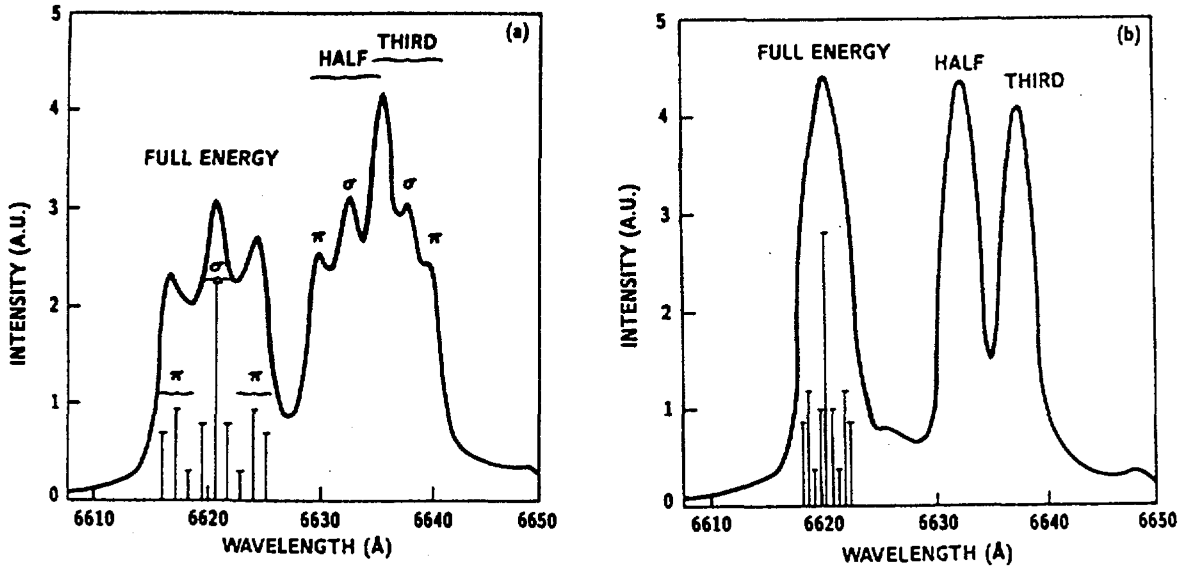

Fig.3. Spectrum of Balmer-α line emitted by the DIII-D neutral beam. Beam energy is 74keV; (a) B = 2.1T, (b) B = 0.9T (quoted from [4]).

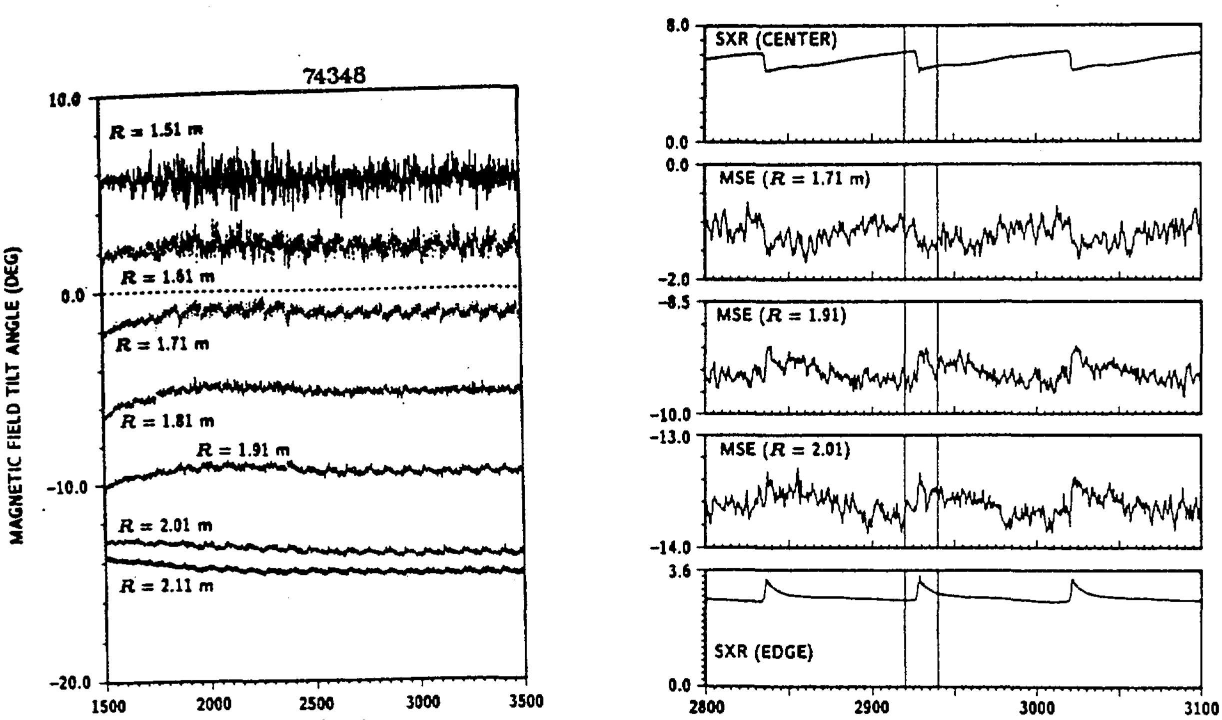

Fig.4. The magnetic field tilt angle measured by the MSE polarimeter at seven spatial locations and correlation between magnetic field tilt angle measured in the plasma interior (MSE) and the soft x-ray emission signal (SXR) during the sawtooth instability (quoted from [4]).