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POLARIZATION SPECTROSCOPY OF TOKAMAK PLASMAS

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ABSTRACT

Measurements of polarization of spectral lines emitted by tokamak plasmas provide information about the plasma internal magnetic field and the current density profile. The methods of polarization spectroscopy, as applied to the tokamak diagnostic, are reviewed with emphasis on the polarimetry of motional Stark effect in hydrogenic neutral beam emissions.

INTRODUCTION

High temperature plasma is confined in a tokamak by an externally produced toroidal magnetic field (long way around the torus) and a poloidal magnetic field (short way around the torus) associated with the toroidal current induced in the discharge - Figure 1. The resulting helical field forms a set of nested magnetic surfaces. The stability and confinement properties of the plasma depend critically on the distribution of the plasma current density. The current profile may be considered to be one of the most important parameters of the tokamak discharge but it is also one of the most difficult to measure.

In the usual approach, the current distribution is inferred from a measurement of the poloidal magnetic field profile. As the poloidal magnetic field is usually much smaller than the externally produced toroidal field, the measurement error smaller than 1% of the total field, with the spatial resolution of the order of 1 cm, is required to provide a meaningful estimate of the current profile. The time resolution of the order of 10^{-3} sec has been achieved by some of the diagnostics but an extension of this range to 10^{-5} - 10^{-6} sec will be required for the studies of plasma fluctuations and details of magnetohydrodynamic (MHD) instabilities.

With the growing importance of the current profile measurement in the tokamak, a number of measurement techniques has been proposed and implemented. This report concentrates on the polarization spectroscopy methods which take advantage of the polarization properties of spectral lines emitted by a magnetized plasma. The polarization may be due to the Zeeman effect or, in the case of lines emitted by high energy hydrogenic beam particles, to the Stark effect. In particular, the dependence of the polarization on the direction of the local magnetic field and the observation direction is used to determine the direction of magnetic field. For plasmas with circular cross-section and when the modification of the externally produced toroidal field by the plasma is negligible, the current profile may be easily deduced from the polarization measurement. In the case of shaped plasmas with high stored energy density, the MHD equilibrium constraint is invoked to reconstruct the current profile from the magnetic field measurements.

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The success of the polarization spectroscopy in the determination of the plasma current profile depends on the presence of a suitable source of line radiation in the plasma and on a very accurate measurement of its polarization. With the Doppler broadening dominating the line profiles, the net polarization of the most prominent spectral features of a tokamak plasma, located in the UV and XUV parts of the spectrum, is negligible. However, as the ratio of the Zeeman splitting to the Doppler broadening increases with the transition wavelength, the polarization fraction of the visible and near UV lines may be measurable with the use of advanced techniques. Also, the instrumentation capable of measuring the very small polarization effects is not available for wavelengths below the UV range. Thus, only the transitions in near UV or visible range of wavelengths may be employed for the polarization measurements. There is a rather limited number of sources of visible line radiation in the tokamak plasma interior. The types of emissions that have been considered include the spectral lines emitted by the neutral particles injected into the plasma as a high energy neutral beam¹⁻⁵ or a pellet,^{6,7} the forbidden transitions in heavy impurity ion lines,⁸⁻¹⁰ and the charge-exchange recombination lines.¹¹ The hydrogenic emissions from high energy beams, with their spectrum dominated by strong motional Stark effect (MSE), proved to be especially useful for the current profile diagnostic.¹²⁻¹⁴

POLARIMETRY OF ZEEMAN EFFECT

In the weak field approximation, the wavelength separation (in Å) of the Zeeman components of a spectral line is given by (cf. e.g. Ref. 15):

$$\Delta\lambda_B = 4.67 \times 10^{-13} z B \lambda_0^2 \Delta M, \quad (1)$$

where λ_0 is the line wavelength (in Å), and z is the effective splitting factor (intensity weighted average of splitting factors of a blended group of transitions with the same polarization properties¹⁶). There are three types of transitions: $\Delta M = 0$ which are linearly polarized, and $\Delta M = \pm 1$ which, in general, are elliptically polarized. For the observation along the magnetic field direction only $\Delta M = +1$ and $\Delta M = -1$ components are observable and are, respectively, left-hand or right-hand circularly polarized. When observed from a direction perpendicular to the magnetic field the radiation is linearly polarized either parallel to the magnetic field ($\Delta M = 0$) or perpendicular to the magnetic field ($\Delta M = \pm 1$). [The above rules are for the electric dipole transitions. For the magnetic dipole (forbidden) transition the directions of linear polarization vectors should be reversed].

The first diagnostics of the poloidal magnetic field were based on the measurement of the polarization direction of the Zeeman π -component. In this case, the observation direction is perpendicular to the total magnetic field (i.e. along the tokamak major radius) and the change of the polarization direction due to the plasma current gives the magnetic field pitch angle $\gamma = \text{atan}(B_p/B_T)$, where B_T and B_p is the toroidal and the poloidal component of the magnetic field, respectively.

The linear polarization of resonance line of high energy (~ 60 keV) lithium neutral beam was measured in the experiments on ASDEX^{1,2} and TEXT^{3,4} tokamaks. The lithium beam injected into the tokamak plasma produces a strong

resonance line with small Doppler broadening and, because of its low atomic number, causes a negligible perturbation of the plasma. Also, a very good spatial resolution may be achieved if a small diameter beam is used. About 0.1 degree accuracy of the tilt angle measurement was achieved with 50 ms integration time.² Unfortunately, because of the large ionization cross-section and poor penetration, the usefulness of the lithium beam is limited to low density, small size plasmas. In order to avoid the attenuation problem, Levinton proposed to use a helium beam which has much lower ionization cross-section than lithium.⁵

As an low cost alternative to high energy particle beams, a high velocity pellet may be employed. As the pellet travels through the plasma its material is evaporated and excited, and the polarization of spectral lines may be analyzed to yield information about the local magnetic field. Lithium pellets were employed in the experiments on the Alcator C and TFTR tokamaks^{6,7} and polarization measurements could be obtained for the LiII lines ($\lambda \simeq 5484 \text{ \AA}$). The pellet spectroscopy provides a 'snapshot' of the poloidal field profile as the pellet transverses the plasma in few hundred microseconds, followed by a rather large perturbation of the plasma due to the deposition of the pellet material in the plasma interior. Thus, this approach is not useful for continuous monitoring of the plasma current profile.

As the spectral separation of the circularly polarized Zeeman components is twice as large as separation of the linearly polarized components, the measurement of the fractional circular polarization in the lines for which $\Delta\lambda_B/\Delta\lambda_D \leq 1$, where $\Delta\lambda_D$ is the Doppler broadening, may result in better sensitivity than the measurement of the linear polarization. This approach, used extensively in astronomy, takes advantage of the fact that the polarization of σ -components varies from purely linear to purely circular when the direction of observation is changed from perpendicular to parallel to the magnetic field direction. Thus, the relative content of circular polarization is a direct measure of the magnetic field component in the direction of observation. The measured quantity is the difference between the right-hand and the left-hand circularly polarized line profiles:

$$I_L - I_R = \cos\gamma_0 [I(\lambda + \Delta\lambda_B) - I(\lambda - \Delta\lambda_B)], \quad (2)$$

where γ_0 is the angle between the direction of observation and the total magnetic field, λ is the wavelength, and $I(\lambda)$ is the function describing the polarized line profile (a Gaussian for high temperature plasma and/or for lines with simple Zeeman patterns). For $\Delta\lambda_B/\Delta\lambda_D \ll 1$:

$$\max(I_L - I_R) \sim \cos\gamma_0 \frac{\Delta\lambda_B}{\Delta\lambda_D} \sim B \cos\gamma_0 \left(\frac{A}{T_i} \right)^{1/2}, \quad (3)$$

where B is the total magnetic field, T_i is the ion temperature, and the maximum of $(I_L - I_R)$ is at $\lambda - \lambda_0 \approx \Delta\lambda_D/2$. Thus, $\max(I_L - I_R)$ is directly proportional to the component of the magnetic field in the direction of observation. $\Delta\lambda_D$ and $\Delta\lambda_B \cos\gamma_0$ may be determined by fitting the measured $I_L - I_R$ and line profiles, yielding the ion temperature and the component of magnetic field in the direction of observation, respectively.¹⁷ For the poloidal field measurement in a tokamak, the observation must be in the major radial direction (to avoid contribution from

the toroidal field) and tangent to the magnetic surface on which the field is to be measured. In this case, $\cos\gamma_0$ will vary from zero in the plasma center to about 0.1 at the plasma edge.

Feldman et al.⁸ proposed to measure the circular polarization of the forbidden (magnetic dipole) lines produced by transitions within ground configuration of high ionization stages of heavy impurity ions (Fe, Ti, Cr, etc.). As the ratio $\Delta\lambda_B/\Delta\lambda_D$ increases with wavelength and atomic weight the UV/visible forbidden lines have relatively large fractional polarization. No injection is necessary if an intrinsic heavy impurity is present. A successful measurement of the forbidden line TiXVII 3834 Å (transition $2s^22p^2\ ^3P_2 \rightarrow\ ^3P_1$) was obtained on the TEXT tokamak (University of Texas, Austin). A single sightline, scanning polarimeter was employed to measure both the line and $I_L - I_R$ profiles. Intrinsic titanium originated from the machine limiter. The line showed a substantial brightness throughout the plasma cross section and the whole poloidal field profile could be obtained on shot-to-shot basis. The Abel inversion was used to obtain the local quantities. Figure 2 shows an example of the poloidal field profile measured for a discharge with $B_T=2.0$ T, plasma current $I=200$ kA, and plasma density 10^{-13} cm^{-3} . Each of the data points represents an average of the results obtained from 5 to 10 single measurements. Accuracy of the fractional circular polarization measurement was of the order of 5×10^{-3} with the integration time of the order of 20 ms. About 0.005 T accuracy of the poloidal field measurement was achieved with 50 ms integration time and superposition of 5-10 single measurements.^{10,17}

Similar approach was used to measure the circular polarization of resonance line of the lithium beam.¹⁸ Comparable accuracy of the diagnostic was achieved with the additional advantage of local instead of line integrated measurement.

A measurement of circular polarization of light impurity lines (He, C) was attempted in the DIII-D tokamak. The hydrogenic transitions produced as a result of charge exchange between fully ionized light impurities and high energy neutral beam particles were studied. Even at high plasma temperatures the charge-exchange recombination lines should exhibit a measurable circular polarization fraction ($10^{-2} - 10^{-3}$). In the DIII-D experiments, the charge-exchange lines were found to be overwhelmed by their strong, collisionally excited counterparts emitted from the plasma edge which led to inadequate accuracy of the polarization measurement.¹⁹

MOTIONAL STARK EFFECT

Recently, very encouraging results have been obtained with the use of neutral beam emissions of hydrogenic species.^{12,14} In this case, the polarization is due the Stark effect in the Lorentz ('motional') electric field $E=v \times B$, where v is the velocity of the neutral particle, and B is the tokamak magnetic field. The linear Stark effect is observed in the hydrogenic species (hydrogen or deuterium) leading to large splitting and substantial fractional polarization of beam emitted lines. (The line broadening is due almost entirely to the beam divergence). The Doppler shifted emissions are observed and thus the interference of the strong line emissions from the plasma edge is avoided. Either a high power heating neutral beam or a dedicated low power 'diagnostic' beam may be used. The spatial resolution is determined by the beam size and the measurement geometry.

The Stark effect produces linear polarization only and, similar to the measurements of Zeeman effect linear polarization, direction of the local magnetic field is determined by measuring the direction of linear polarization of the emission.

Figure 3 shows a spectrum of the Balmer- α line emitted by a 75 keV hydrogen beam as observed by a tangentially viewing spectrometer in DIII-D tokamak. The Doppler shifted beam emissions are observed at full, 1/2 and 1/3 beam energy, corresponding to the molecular composition of the beam.²⁰ For a given energy component, three spectral features are resolved which are identified as clusters of Stark σ and π -components.^{20,21} The σ -components are linearly polarized in the direction perpendicular to the electric field direction when observed in the direction perpendicular to the electric field and are not polarized when observed along the field. The π -components are polarized parallel to the electric field when observed in the direction perpendicular to the field and have null intensity for observation along the field. The magnetic field pitch angle is deduced from a measurement of direction of polarization of the full energy σ -components.

MODULATION TECHNIQUES IN POLARIZATION MEASUREMENTS

The polarization measurements require an efficient elimination of the unpolarized background and an accurate relative calibration of measurements of different polarization states. The modulation techniques accomplish that by converting the polarization content information into intensity modulation that may be accurately measured using the phase-sensitive (lock-in) detection. This approach has been widely used in the astronomical applications²² and recently, in the polarimetry of tokamak plasmas.^{10-14,17,18}

Figure 4 shows a schematic of modulated analyzer of linear polarization. The system consists of two photoelastic modulators (PEM₁ and PEM₂) and the linear polarizer (or beam splitting polarizer). The photoelastic modulator²³ is a fused silica plate in which a time-dependent birefringence is produced by a resonant, standing compression wave. The device offers large usable aperture and very large acceptance angle. For the linear polarization measurements, the modulators act as oscillating half-wave plates, i.e. the retardation is varied between approximately $+\lambda_0/2$ and $-\lambda_0/2$, at frequencies ω_1 and ω_2 (e.g. 42 and 47 kHz for the present DIII-D system), leading to a modulation in the direction of linear polarization of the transmitted radiation. The conversion to the intensity modulation is accomplished by the linear polarizer. With a proper orientation of the polarizing elements (axes of the modulators at -22.5 and $+22.5$ deg. with respect to the polarizer axis) the amplitudes of intensity modulation at the second harmonics of the modulators frequencies are given by:

$$I_{\pm}(2\omega_1) = \pm \frac{I_{\sigma} - I_{\pi}}{\sqrt{2}} J_2(\phi_1) \sin 2\gamma_m, \quad (4)$$

$$I_{\pm}(2\omega_2) = \pm \frac{I_{\sigma} - I_{\pi}}{\sqrt{2}} J_2(\phi_2) \cos 2\gamma_m, \quad (5)$$

where: $I_{\sigma}(\lambda)$ and $I_{\pi}(\lambda)$ are the intensities of Stark σ and π features, respectively, J_2 is the Bessel function of the first kind, ϕ_1, ϕ_2 are the retardation maxima

($\approx 3.1(\approx \lambda/2)$), and γ_m is the measured magnetic field tilt angle. The " $\pm$ " sign indicates that I_- and I_+ signals are out of phase. Thus, the magnetic field tilt angle is obtained as a ratio of modulation amplitudes detected at frequencies $2\omega_1$ and $2\omega_2$:

$$\tan 2\gamma_m = \frac{I_+(2\omega_1) - I_-(2\omega_1)}{I_+(2\omega_2) - I_-(2\omega_2)} = \frac{I_+(2\omega_1)}{I_+(2\omega_2)}. \quad (6)$$

The modulation amplitudes are measured by two lock-in amplifiers referenced to the resonant frequencies of the modulators. Note that a single detector may be used to measure the signals at both modulation frequencies and that only the polarized light (with intensity $\sim (I_\sigma - I_\pi)$) contributes to the signal. In order to increase the number of collected photons, two detectors are used to measure both I_- and I_+ signals, which are later combined in the detection circuit.

MSE POLARIMETRY IN DIII-D

The measurement geometry used by the DIII-D polarimeter is shown in Figure 5. Up to 8 high power neutral beams are injected on the machine midplane at an angle oblique to the toroidal magnetic field. The H_α radiation is collected from a 2–6 cm diameter volume at the intersection of one of the neutral beams and the polarimeter sightline. The sightline may be moved within the region indicated approximately on the figure to provide a shot-to-shot profile measurement. In the absence of plasma current the motional electric field is vertical. By measuring the change of the polarization direction of the Stark σ -components when the plasma current is introduced, the magnetic field pitch angle may be determined.

In the polarimeter employed on the DIII-D tokamak the polarization analyzer is placed on the tokamak viewing port and the modulated light is transmitted by a fiber optic link to the interference filter spectrometer. There, a narrow bandpass (3 Å) interference filter is used to select the wavelength of the Doppler shifted σ -components. The peak transmission wavelength of the filter may be tuned over a limited range (to match the Doppler shift) by changing the incidence angle. Two photomultiplier tubes are used to detect the I_- and I_+ intensities.¹⁴

An example of high quality data that may be obtained from the MSE measurement is demonstrated in Figure 6 which shows a fragment of the time history of 1.65 MA, 2.0 Tesla beam heated discharge. In the time interval shown the plasma density increases leading to a decrease in the neutral beam penetration and deterioration of the polarimeter signals. Nevertheless, an accurate measurement of the tilt angle in the plasma center is obtained for the line average plasma density up to $6 \times 10^{13} \text{ cm}^{-3}$. The trace labeled SXR shows the intensity of soft x-ray emissions as observed by a sightline close to the plasma center. This trace indicates a presence of the 'sawtooth' instability, manifested as plasma disruption in the central part of the discharge, leading to a flattening of the density and temperature profiles, and redistribution of the plasma energy from the center to the outside. Note the correlation between the SXR signals and the measured magnetic field tilt angle indicating that a change in the current profile is associated with the instability.

For the highly shaped DIII-D plasmas, the current profile cannot be deduced from the internal magnetic field measurements only. The MSE data is incorporated into the magnetic field equilibrium code EFIT²⁴. The code uses the data from an array of external magnetic measurements and, by invoking the force balance equation and the toroidal symmetry, calculates the global plasma parameters (current, energy content, position and shape of the last closed surface, etc.). The incorporation of the internal magnetic field measurements allows us to calculate also the shape of internal magnetic surfaces and the current profile. Optionally, the measured plasma pressure profile or the soft x-ray emission profile may be used in the equilibrium calculation to provide a reconstruction of the current density profile consistent with all available diagnostics.

Figure 7 shows an example of the equilibrium reconstruction obtained with the use of shot-to-shot MSE profile measurement. External magnetic data from six discharges similar to the one shown in Figure 6 were averaged for the timeslices before and after the sawtooth disruption. The figure shows a poloidal cross-section of the tokamak with the reconstructed flux surfaces and the positions of the MSE measurements indicated by '+'. The current profile obtained from this analysis shows the expected flattening in the center of the discharge as a result of the sawtooth disruption.

SUMMARY AND CONCLUSIONS

Rapid progress in the accuracy and reliability of the polarization spectroscopy diagnostics has been achieved in recent years. The spectroscopic techniques are based on well understood physical principles and share the advantage of employing visible lines, for which easily available, relatively simple to operate and inexpensive instrumentation may be used. The modulation techniques, used before in similar astronomical applications, were found to be extremely useful for the tokamak diagnostic.

The presence of a suitable source of polarized radiation in the plasma interior is one of the prerequisites for a successful diagnostic. Although a number of results important for the tokamak physics has been obtained with the use of high energy lithium beams, pellets, and heavy impurity ion lines, the usefulness of these emissions seems to be limited to particular plasma conditions (low density, large magnetic field, etc.). Presently, the polarimetry of the motional Stark effect appears to be the diagnostic of choice, specially for large size tokamaks. Very good accuracy of the measurement was demonstrated with prototype instruments^{12,14,25} (e.g. about 0.1 deg. accuracy in the tilt angle measurement with 10 ms integration time in DIII-D). The major advantages of the beam emitted hydrogenic lines are their large partial polarization, reduction of thermal background by observation of Doppler shifted emissions, and generally strong emissivities from the plasma center. As the high energy neutral beams are routinely employed for plasma heating, the source of radiation is in most cases readily available although large size of a heating beam may lead to deterioration of the spatial resolution of the diagnostic. With the advance of the motional Stark effect approach the measurement of tokamak current profile, not long ago thought to be almost impossible, has been demonstrated as a routine diagnostic and has provided valuable insights into the physics of tokamak plasmas.

The time resolution obtained to date is still not sufficient for the studies of plasma fluctuations and details of MHD instabilities. The presently used modulation techniques limit the time resolution to about 0.1 ms (much longer than the time scale of the modulation cycle). The polarization measurement accuracy is ultimately limited by the photon flux available for analysis and some improvement may be obtained by employing more efficient collection and polarization optics.

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FIGURE CAPTIONS

- Figure 1. View of the DIII-D tokamak at General Atomics in San Diego, showing the magnetic field coils and the directions of magnetic field components.
- Figure 2. Poloidal field profile in the TEXT tokamak deduced from the circular polarization measurement of the titanium impurity line. Dashed line is a fit to the measured profile and solid line (INV) shows the result of Abel inversion. Here, a is the plasma minor radius and r/a is the normalized radius.
- Figure 3. Spectrum of the Balmer- α line emitted by hydrogen neutral beam in DIII-D. Observation geometry as shown in Figure 5, $R=2.14$ m.
- Figure 4. Schematic of the linear polarization analyzer employing the photoelastic modulators.
- Figure 5. Top view of the DIII-D tokamak showing the location and spatial coverage of the MSE diagnostic. Tokamak major radius $R_0=1.67$ m, the polarimeter covers the range $R=1.5-2.3$ m.
- Figure 6. Time history of a tokamak discharge showing the line integrated density, polarimeter signals ($I(\omega_1) \sim \sin\gamma_m$, and $I(\omega_2) \sim \cos\gamma_m$), soft x-ray emission, and the magnetic field tilt angle measured at $R=1.7$ m and $R=1.8$ m. The timeslices used for the analysis in Figure 7 are indicated by the vertical lines. The last trace is from a different but similar discharge, where the analyzed sawtooth collapse occurs somewhat later.
- Figure 7. The profile of flux surface averaged current density and the magnetic surfaces obtained from the equilibrium reconstruction using external magnetic field measurements and a 6 point MSE scan.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

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 $I=1.65$ MA, $B_t=2.0$ Tesla

Figure 6

Figure 7

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