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Internal magnetic field measurement in tokamak plasmas using a Zeeman polarimeter

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Abstract. In a tokamak plasma, the poloidal magnetic field profile closely depends on the current density profile. We can deduce the internal magnetic field from the analysis of circular polarization of the spectral lines emitted by the plasma. The theory of the measurement and a detailed design of the Zeeman polarimeter constructed to measure the poloidal field profile in the ADITYA tokamak are presented. The Fabry-Perot which we have employed in our design, with photodiode arrays followed by lock-in detection of the polarization signal, allows the measurement of the fractional circular polarization. In this system He-II line with wavelength 4686 Å is adopted as the monitoring spectral line. The line emission used in the present measurement is not well localized in the plasma, necessiating the use of a spatial inversion procedure to obtain the local values of the field.

Keywords. Tokamak; polarimeter; Zeeman effect.

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1. Introduction

There is a growing interest in developing a reliable method for the measurement of the internal magnetic field in high temperature, magnetically confined plasmas. A special need for such diagnostic arises in the investigation of the tokamak devices in which the measurement of the poloidal field distribution would yield the plasma current density profile. This information is essential for understanding confinement, stability and energy balance of the tokamak plasma. Several methods of the magnetic field measurements have been proposed. Faraday rotation of far-infrared laser radiation is measured in the TEXTOR device [1], laser-light scattering [2], parametric interaction of microwave radiation with the plasma [3]. The various spectroscopic techniques, that have been suggested suffer from excessive line broadening which is due to the strong toroidal field and by the thermal motion of the plasma ions. The other methods require active probing of the plasma by an atomic beam [4].

We consider here the possibility of measuring the poloidal magnetic field from the Zeeman splitting and polarization of the magnetic dipole radiation from He-II ions. The magnitude of the Zeeman effect (splitting of atomic energy levels and associated spectral lines in the magnetic field) is directly related to the strength of the local magnetic field. In principle, the measurement of the wavelength shift between the Zeeman components should provide a measurement of the total magnetic field in the location from which the line is emitted. But in the case of high temperature tokamak plasmas, where the Zeeman splitting is completely obscured by the thermal broadening of spectral lines, the circular polarization associated with the Zeeman effect is measured. The circular polarization effect in several heavy impurity ion lines was measured in TEXT tokamak [5].

The fractional circular polarization of a spectral line is proportional to the component of the magnetic field in the direction of observation. The geometry of the experiment is chosen in such a way that the poloidal component of the magnetic field is measured directly. Estimations of the linewidth and the magnitude of the Zeeman effect show that, with appropriate polarization analyser and the experimental geometry, the poloidal component of the magnetic field can, in principle, be measured.

2. Theory of the magnetic field measurement

As we know that, each level of an atom in a weak magnetic field is split into $2J + 1$ sublevels with energy shifts given by

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

where, M assumes values from $-J$ to $+J$, where J is the total angular momentum quantum number, B_0 is the total magnetic field magnitude, μ is the Bohr magneton, and g is the splitting factor.

Feldman *et al* [6] has discussed the aspects of magnetic field measurements in tokamaks. Transitions between the energy levels that are split by the magnetic field give rise to several components of a spectral line. Owing to the energy splitting of the upper and lower levels of a transition, a spectral line is composed of a number of components whose relative intensities depend on the changes in J and M. The selection rules for the magnetic dipole transitions for J and M are given as

$$\Delta J = 0, \pm 1; \quad \Delta M = 0, \pm 1 \tag{2}$$

where, $J = 0 \to 0$, $M = 0 \to 0$ transitions are not allowed.

The polarization of the radiation depends on ΔM. Intensity is zero for the $\Delta M = 0$ line components. When viewed from a direction parallel to the magnetic field, radiation is circularly polarized clockwise for $\Delta M = +1$ and counterclockwise for $\Delta M = -1$. We cannot resolve the individual components of the Zeeman structure in a high temperature plasma. It is sufficient, if we consider blended group of transitions with the same polarization properties. Then, the wavelength separation (in Å) of the blended polarized Zeeman components of a spectral line is given by

$$\Delta\lambda_B = 4.67 \times 10^{-13} z B_0 \lambda_0^2 \Delta M, \tag{3}$$

where λ_0 is the line wavelength (in Angstroms), B_0 is the total magnetic field in Gauss, z is the effective splitting factor defined as the intensity-averaged g factor of a blended group of transitions with the same polarization properties. The Zeeman splitting is completely obscured by the thermal (Doppler) broadening of spectral lines. The FWHM (full width at half maximum) of the Doppler broadened line emitted from a high temperature plasma is given by [6]

$$\Delta\lambda_D = 7.71 \times 10^{-5} \lambda_0 (T_i/A)^{1/2} \text{ (in Å)}. \tag{4}$$

T_i is the ion temperature (in eV), and A is the ion atomic weight. The magnetic field measurement is based on the determination of the intensity difference between two circularly polarized profiles of a visible spectral line. The polarization of the σ components varies from purely linear to purely circular when the viewing direction is changed from a direction perpendicular to the magnetic field to a direction parallel to it. The relative content of circular polarization gives the direct measure of the magnetic field component in the direction of observation. The maximum of the intensity difference between left hand $I_{\mathrm{L}}(\lambda)$ and right hand $I_{\mathrm{R}}(\lambda)$ circularly polarized profiles for the wavelength is given by

$$\max_{\lambda}(I_{\mathrm{L}} - I_{\mathrm{R}})/I_0 = C \cos\gamma \Delta\lambda_B/\Delta\lambda_D, \tag{5}$$

where γ is the angle between the line of sight and the magnetic field direction, C depends on the fine structure of the spectral line. Thus, the difference between the intensities of the circularly polarized profiles is directly proportional to the component of the magnetic field along the line of sight i.e. $B \cos\gamma$. When viewed in the field direction, the poloidal magnetic field can be directly derived from this method.

3. Experimental set-up

3.1 *Zeeman polarimeter*

This experiment has been proposed in ADITYA [7] tokamak, which is a medium sized tokamak with the major radius $= 75$ cm and minor radius $= 25$ cm. The toroidal field at the center is 1.5 T, with a plasma current of 100 KA, chord averaged density of 3×10^{13} cm^{-3} and a peak temperature of 100 eV. He-II line is selected for mainly two reasons. Firstly, the performance of plasma is not much effected and secondly, this line has enough strength in a wider peripheral region. The region of interest in our case is $0.8 \leq r/a \leq 1.0$, since we have enough signal strength in this region. A polarimeter is constructed to measure the poloidal field profile. The instrument measures the difference between the left-hand and right-hand circularly polarized line profiles, a quantity directly proportional to the magnetic field component in the direction of observation.

As shown in figure 1, this system consists of a photoelastic modulator (PEM) [8], band pass filter, polarizing beam splitter, Fabry-Perot interferometer and photodiode array (PDA) detectors. Apart from this we have some light collection and transfer optics. The Fabry-Perot etalon provides the necessary spectral resolution. In the etalon the distance between the mirrors is not varied. This type of an etalon is a very sensitive angle dependent filter. The analysis of the fringes thus formed, which are recorded electronically using PDA's, provide us the required information. The use of PDA's is quite new in this field. A PDA is a linear array of silicon photo detectors. The array video output, is a train of charged pulses having an amplitude proportional to the light intensity sensed by the corresponding photodiode and the line scan time. The PEM and the beam splitter are mounted with their optic axes at 45° to each other. PEM acts as an oscillating quarter wave plate (retardation from $-\lambda/4$ to $+\lambda/4$). The oscillating retardation is due to birefringence induced in a quarter wave plate by a standing compression wave and it is only weakly

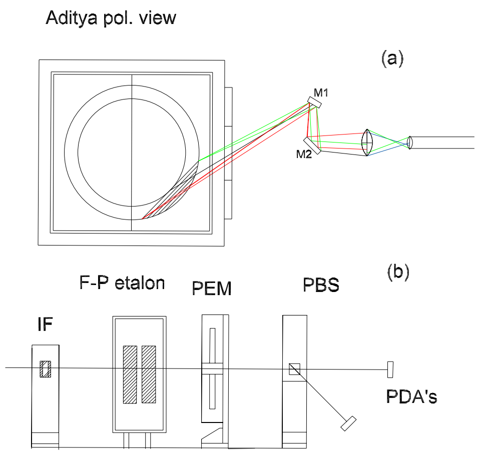

Figure 1. (**a**) Arrangement of the mirrors. M1, M2 are the mirrors of different dimensions. (**b**) Components of the Zeeman polarimeter. IF is the interference filter, F-P is the Fabry-Perot etalon, PEM is the photoelastic modulator, PBS is the polarization beam splitter and finally PDA's are the photodiode array detectors.

dependent on the incident angle. This is important since we are working with poorly collimated beams. The beam splitter splits the incident light beam into two orthogonal linearly polarized beams. The detector array must be placed either in the focal plane or in the conjugate plane of auxillary dispersing equipment. The two output signals from this system are expressed as

$$I_{\pm} = 1/2(I_{\rm L} + I_{\rm R}) \pm (I_{\rm L} - I_{\rm R}) \sin \omega_m t, \tag{6}$$

where t is time and ω_m is the modulation angular frequency of retardation in the PEM.

3.2 *Signal detection*

The line profile signal $(I_{\rm L} + I_{\rm R})$ is detected by adding output signals I_+ and I_-. The modulation signal $(I_{\rm L} - I_{\rm R})$ sin$\omega_m t$ is detected by subtracting the output signal. As seen from eq. (5), the magnetic field strength along the line of sight is proportional to the maximum of the difference between the left hand and the right hand circularly polarized profiles and to the FWHM of the line, and is inversely proportional to the maximum intensity of the line profile.

The two beams behind the circular polarization filter are focussed on two PDA's. The signal detection channel consists of two channels, one is the signal which is the sum of the PDA outputs amplified by a dc amplifier to yield a signal proportional to the unpolarized line profile, $(I_{\rm L} + I_{\rm R})$, which is well described by a Gaussian, and the second one is the signal, $(I_{\rm L} - I_{\rm R})$, which is described by the difference between two shifted Gaussians as shown in figure 2. The maximum intensity and the FWHM of the line are determined by fitting the sum signal, and the maximum of the difference between the left hand and the

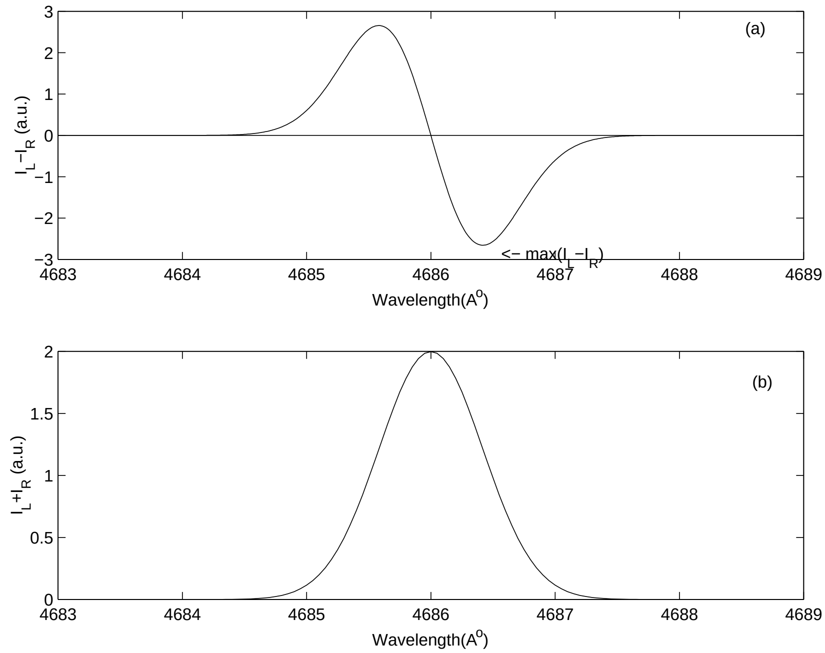

Figure 2. (**a**) Modulation $(I_{\rm L} - I_{\rm R})$ (arbitary units) of the spectral line for ADITYA parameters. (**b**) Line profile signal $(I_{\rm L} + I_{\rm R})$ (arbitary units).

right hand polarized profiles, $\max(I_{\rm L} - I_{\rm R})$ is determined by fitting the difference signal. The expected measurement range of the magnetic field in our case is 0.07–0.1 tesla. In this method the measured poloidal field is intrinsically averaged along the line of sight, and an Abel inversion procedure is required to obtain the local values of the field. We will be performing this experiment on ADITYA and hope to get some favourable results.

4. Conclusion

In this paper, we have proposed a method to measure the poloidal magnetic field in a tokamak plasma. The Zeeman splitting and the polarization of magnetic dipole transitions, for He-II line are analysed for ADITYA parameters. When viewed from a direction perpendicular to the toroidal field, the circular polarization due to the presence of the poloidal field can be detected using Zeeman polarimeter which is applicable to the peripheral region. Its performanance does not depend crucially on the strength of the toroidal magnetic field. The basic idea behind using PDA's in this field is to avoid scanning so that the system is rugged and reliable. The extraneous noise is effectively reduced by phase sensitive detection using lockin amplifiers. All the components of the polarimeter are commercially available. We can also study the formation of skin current [9] and the penetration of the skin current into the inner plasma region. It is also possible to measure the poloidal magnetic field using several spectral lines from ions that occur over a range of plasma temperatures, specifically the impurities that already exist in the plasma environment. This technique holds a very good future as far as magnetic field measurements are concerned.

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