

POLARIMETRIC LINE DENSITY MEASUREMENTS AT 'W7-AS' USING THE 'COTTON-MOUTON EFFECT'

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Abstract

A polarimeter based on the Cotton-Mouton effect has been developed and installed at the W7-AS stellarator. It is operated in the sub-millimeter wave region at frequencies between 500 and 650 GHz. The change of the polarization state is calculated numerically using Segre's formalism and compared with measurements. The polarimeter demonstrated its capability to perform absolute, robust measurements of the line integrated electron density. An improved version for the future W7-X stellarator is briefly discussed.

1. Introduction

Polarimetry makes use of the birefringence of a magnetized plasma. It can provide a robust measurement of the line integrated density, which is of special importance for long pulse operation as expected for future devices like the W7-X stellarator or for ITER. In this context a Cotton-Mouton polarimeter was proposed for ITER [1].

Both the Faraday and the Cotton-Mouton magneto-optic effects can be used for measurements of the line density. The Faraday effect is caused by circular birefringence which leads to a phase shift between the left- and the right-handed circularly polarized waves, resulting in a rotation of the plane of polarization; the magnetic field is parallel to the direction of propagation.

The Cotton-Mouton effect is observed if the magnetic field is perpendicular to the direction of propagation. The characteristic waves are linear polarized waves with the plane of polarization parallel (o-mode) and perpendicular (x-mode) to the magnetic field. The phase difference caused by linear birefringence leads to a change of the ellipticity. If the magnetic field \vec{B} along the line of sight is known, the line density can be determined by a measurement of this phase difference.

Optimal conditions are provided by the Wendelstein stellarators which offer lines of sight where $|\vec{B}|$ is almost constant and the field component B_{\parallel} in propagation direction of the wave is negligible. In this case the position of the plasma and the density profile need not be known and the Faraday effect is negligibly small.

2. Calculation of the changes in the polarization state

Owing to the small twist of the magnetic field, it is not possible to obtain pure o- and x-modes along the whole line of sight. In addition, a possible misalignment leads to $B_{\parallel} \neq 0$ which provokes an unwanted Faraday effect. A general formalism [2,3] is used to describe the changes of the polarization state along the probing beam path. The polarization state is described by the three Stokes parameters s_1 , s_2 and s_3 , the components of the Stokes vector \vec{s} . The evolution along the line of sight (z -direction) is $d\vec{s}(z)/dz = \vec{\Omega}(z) \times \vec{s}(z)$. The vector $\vec{\Omega}(z)$ describes the plasma-wave interaction. The components Ω_1 and Ω_2 of the vector $\vec{\Omega}$ represent the Cotton-Mouton, while Ω_3 describes the Faraday effect. The quantity Ω_2 is non-zero due to the twist of the magnetic field. The beam path and an example of n_e , \vec{B} and the components of $\vec{\Omega}$ along the chosen line of sight in W7-AS are shown in Figs. 1 and 2.

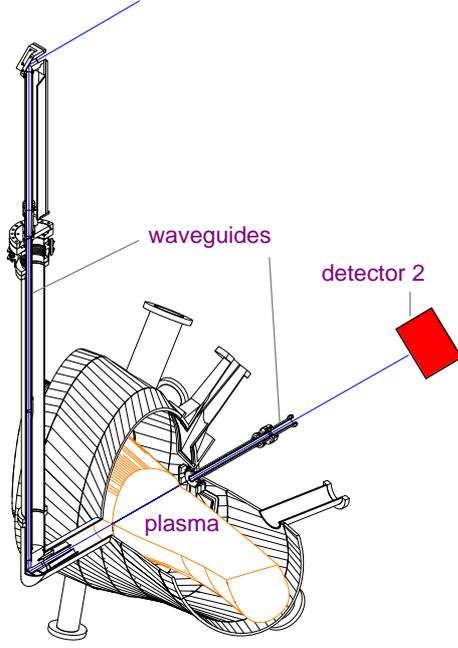


Figure 1. Beam path at the W7-AS stellarator.

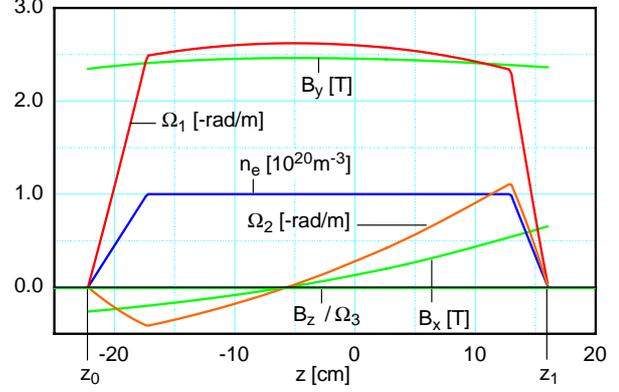


Figure 2. Plasma parameters along the line of sight for a typical configuration of the magnetic field at W7-AS.

In the case of a dominating Cotton-Mouton effect and sufficiently small twist of the magnetic field ($\Omega_1 \gg \Omega_2, \Omega_3$), the phase shift between the x - and the y -components of a launched wave with the direction of the magnetic field being mainly in y -direction is given by the quantity $W_1 = \int_{z_0}^{z_1} dz \Omega_1(z)$. For $\omega^2 \gg \omega_p^2$ and $\omega^2 \gg \omega_c^2$, where ω_p and ω_c are the plasma- and the electron cyclotron angular frequencies and $\omega = 2\pi f$ is the probing beam frequency, the approximation $\Omega_1 = (e^2/(2c m^2 \omega^3)) \cdot \omega_p^2 (B_x^2 - B_y^2)$ can be made. In this approximation, the quantity W_1 is exactly proportional to the electron line density $\rho_e = \int_{z_0}^{z_1} dz n_e(z)$. In the case of an almost constant magnetic field B , W_1 becomes independent on the shape of the density profile. An extensive discussion is given in [4].

3. Measurement of the Cotton Mouton effect

The quantity W_1 contains the line density ρ_e . Knowledge of the B -field allows the dependence of W_1 on ρ_e to be determined. To measure W_1 , a modulation technique as proposed in [3] is used. The probing wave is composed of two orthogonal linear polarized waves. The phase between these waves is linearly shifted with a modulation frequency ω_m , leading to an elliptical modulation of the probing wave. The Stokes parameters before entering the plasma are $s_1(z_0) = 0$, $s_2(z_0) = \cos(\omega_m t)$ and $s_3(z_0) = \sin(\omega_m t)$, assuming identical intensity of the probing wave components.

The Stokes parameter $s_2(z_1)$ after passing the plasma becomes $s_2(z_1) = \cos(\omega_m t + W_1)$ [4]. In this way, W_1 is just the phase difference between the Stokes parameters $s_2(z_0)$ and $s_2(z_1)$.

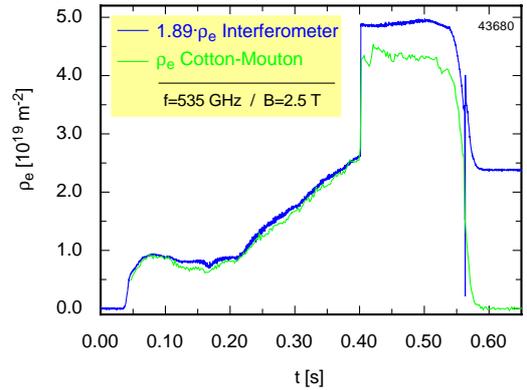


Figure 3. Plasma discharge with pellet injection. The interferometer shows fringe jumps.

The given expression for Ω_1 is valid for high frequencies, but can lead to errors up to about 10 % for the set-up at W7-AS. Therefore more exact calculations using an expression for Ω_1 as given in [2] are conducted to obtain the line density ρ_e [4]. An example for a measurement of ρ_e is shown in Figure 3. By performing systematic scans of the magnetic field at two different frequencies (535 and 627 GHz) and comparing the measured phase differences with calculated values, it could be verified that the Faraday effect, which depends on $\omega^{-2} \cdot B_{\parallel}$, is negligible. More results are discussed in [4].

4. Experimental set-up

The total experimental set-up is sketched in Figure 4. A backwardwave oscillator (BWO) is used as a tunable radiation source in the frequency range 500–650 GHz. Oversized waveguides ($\phi = 24$ mm) are used throughout in the guided wave sections. The modulation of the wave ellipticity is accomplished in a way as described in [5]. A polarizing wire grid reflects the y -polarized component of the wave, whereas the x -component is guided to a delay line. After reflection at two mirrors which rotate the polarization plane by 90° this component is added to the reflected one. The phase difference of the two components depends on the wave frequency and the length of the delay line. A BWO-frequency modulation with $\omega_m/(2\pi) = 47$ kHz and $\Delta f = 300$ MHz then transforms to an ellipticity modulation of the probing wave. Detectors 1 (reference detector) and 2 (signal detector) with 45° analyzers deliver signals proportional to $s_2(z_0)$ and $s_2(z_1)$ respectively. Their phase difference is the quantity of interest which is evaluated digitally. Errors introduced by unwanted amplitude modulation of the BWO are eliminated by the interpretation code with data from a monitor detector at the BWO output.

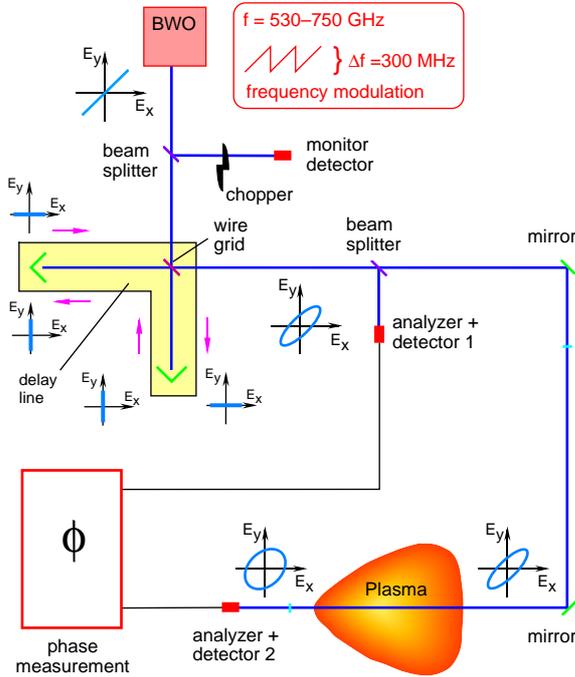


Figure 4. Experimental set-up at the W7-AS stellarator.

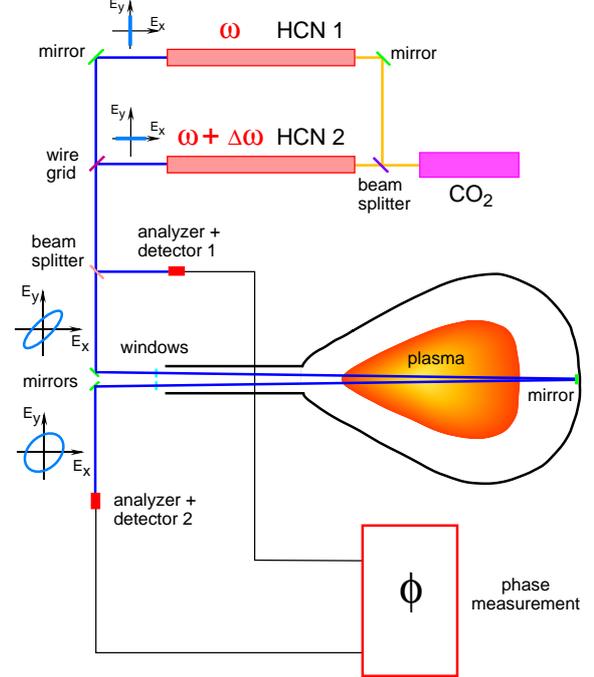


Figure 5. Proposed experimental set-up for the W7-X stellarator.

Small changes of the polarization in the transmission line cause errors in the W_1 measurement of about 1 %. Considering also misalignments in the probing beam path, numerical calculations result in maximum errors between -3% and $+2\%$ for the lowest B -field (1.25 T) where the

effect is smallest. Another error results from different phase shifts for the x - and y -components in the transmission line in combination with BWO instabilities which lead to phase errors of about 1° . Other errors include amplitude modulation caused by the frequency dependent vacuum window transmission, plasma diamagnetism and uncertainties in the probing beam frequency. Errors owing to refraction effects, which could lead to a path length difference for the x - and the y -polarized components of the probing beam, are negligible as proven by ray tracing calculations. The relative errors sum up to an error range of -5.5% to 5.6% for $B = 1.25\text{ T}$ and -4.5% to 5.1% for $B = 2.5\text{ T}$ in maximum, including maximum misalignment of the probing beam.

5. Proposal for an optimized set-up at W7-X

Based on the experience, an optimized set-up for W7-X is proposed. It is sketched in Figure 5. Owing to the larger beam path in the plasma and the double-pass of the probing wave, the optimum frequency is about 900 GHz. In this case, the measured phase shift remains below 360° and the line density derived is unambiguously connected with the phase measurements. Therefore, HCN lasers with 890 GHz (preferably CO_2 -pumped) are well suited as radiation sources. Two lasers with a small frequency offset ω_m of the order of 1 MHz deliver an elliptically modulated wave with a modulation frequency of ω_m by combining the orthogonal polarized beams. The two windows to the vacuum vessel are slightly tilted to avoid reflections. The transmission line should be fully quasi-optical to avoid polarization changes.

With an output power of the order of 10 mW, high signal-to-noise ratios can be reached. This enables a time resolution of about $1\ \mu\text{s}$ and a phase resolution of 0.1° simultaneously. Systematic errors also could be in the region of 0.1° . The corresponding density resolution is about $n_e = 10^{17}\text{ m}^{-3}$ for $B = 2.5\text{ T}$ and $n_e = 4 \cdot 10^{17}\text{ m}^{-3}$ for $B = 1.25\text{ T}$.

6. Conclusions

The capability of the Cotton-Mouton effect for a robust measurement of the line integrated density at W7-AS has been demonstrated. This is of great importance for long pulse machines like the future W7-X. Both W7-X and W7-AS offer a favourable magnetic field topology for the method.

The main problem of the W7-AS set-up are the transmission properties of the oversized waveguides with respect to conservation of the polarization state; this is not discussed in this short contribution. Changes of the polarization state could be avoided in an advanced experimental set-up by using quasi-optical transmission techniques if space allows.

References

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