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GENERAL ATOMICS

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ABSTRACT

A tangential viewing, 10.59 μm CO_2 laser polarimeter for electron density measurements based on plasma induced Faraday rotation has been installed on DIII-D. The system uses co-linear right and left-hand circularly polarized beams with a difference frequency of 40 MHz to generate the necessary signal for heterodyne phase detection. The high-resolution phase information required to adequately resolve degree level polarization rotation is obtained using an all-digital "real-time" phase demodulation scheme based on modern Digital Signal Processing techniques. Initial application of the system to DIII-D disruption mitigation experiments utilizing "massive gas jet" injection exhibits reliable operation and excellent agreement with CO_2 interferometer measurements; interestingly, the obtained Faraday rotation angles are in the range of those expected in ITER plasmas.

I. INTRODUCTION

Reliable real-time measurements of electron density in tokamak plasmas and other fusion devices are essential for discharge control and optimization. Typically, the technique employed is some type of interferometric measurement of the plasma index of refraction where the specific probing wavelength is dependent on the density, size, and time-scales involved. For fusion plasma applications, low frequency interferometers operating in the microwave range often suffer from refraction off plasma density gradients as well as rapid fringe shifts from sudden density changes. Visible laser interferometers require sensitive alignment, are severely affected by optical component degradation as well as vibration and, in order to separate plasma from mechanical vibration effects, typically are required to operate simultaneously with a path sharing longer wavelength interferometer. While more complicated and inherently less sensitive, this well-established technique, known as two-color vibration compensated interferometry (TCI), does not suffer from refraction and can reliably follow rapid plasma density changes [1,2]. For these reasons, two-color interferometers are often used for feedback control of plasma density in current tokamaks. The major problem with standard two-color interferometry, however, is the inherent susceptibility to fringe counting errors, i.e. “fringe skips”. This susceptibility to fringe-skip errors is an unacceptable drawback of TCI when being considered for application to the steady-state plasmas in next step fusion devices such as ITER; alternate real-time density measurements as well as mitigation techniques, should fringe skip errors occur, will be required.

A promising method for fulfilling the line-density measurement requirements in ITER is standard TCI implemented in combination with a polarimetry measurement of the plasma induced Faraday rotation of the longer wavelength beam, where the longer wavelength is envisioned to be 10.59 μm from a CO_2 laser [5,8,11]. Faraday rotation in a magnetized plasma results from the difference in index of refraction between left-hand (LH) and right-hand (RH) polarized radiation and means a linearly polarized electromagnetic wave will see its plane of polarization rotated by and angle (α); where

$$\alpha = k\lambda^2 \int n_e B_{||} dL \quad , \tag{1}$$

where $k = 2.62 \times 10^{-13}$ Radians/T, λ is the wavelength, n_e is the electron density, and $B_{||}$ is the magnetic field component in the direction of propagation [7,8]. As such, a measurement of Faraday rotation is a measure of the line-integrated electron density weighted by the local parallel magnetic field strength. The rationale behind adding a polarimetry measurement to standard TCI is that for the majority of operating conditions the expected Faraday rotation of 10.59 μm radiation will always be less than 2π making fringe skips irrelevant. This additional measurement can then be used for re-normalizing TCI measurements, should a fringe skip occur, as well as possibly for density feedback control by itself [5].

This paper describes the design, layout, and initial use of a tangentially viewing 40 MHz CO_2 laser polarimeter on the DIII-D tokamak. In the interest of application to future real-time measurements, the system utilizes the same phase demodulation electronics as the existing real-time TCI system. Measurements of high-density gas-jet injection plasmas are demonstrated which take advantage of the polarimeter's large bandwidth and inherent dynamic range. The obtained line-density values are in agreement with a radially viewing TCI chord and, interestingly, are in the range of those expected in typical ITER plasmas. Extension to a simultaneous polarimeter/two-color interferometer is straightforward.

II. POLARIMETER LAYOUT

The polarimeter optical component layout is shown in Fig. 1. The basic principle of operation is that radiation from a 10.59 μm, 8 W, CO_2, fixed grating, waveguide laser is used to create both RH and LH circularly polarized radiation with a difference frequency of ω_1 = 40 MHz. Combined, these two beams form a linearly polarized wave with its plane of polarization rotating at $\omega_1/2$. This composite beam is split and a fraction is sent through a polarizer to a reference detector (Detector 1) and the other fraction is sent through the magnetized plasma and back, then through a polarizer and to a separate detector (Detector 2). Detector 1 sees an intensity signal given by $I_1(t) = A_1 \sin[\omega_1 t + \phi_v(t)]$ and Detector 2 sees $I_2(t) = A_2 \sin[\omega_1 t + \phi_v(t) + 2\alpha(t)]$. Therefore, heterodyne detection can be applied to determine the Faraday rotation (α) where the LO signal is I_1 and the IF signal is I_2. Techniques similar to this have been applied at CO_2 wavelengths [13] as well as longer FIR wavelengths [6] with success.

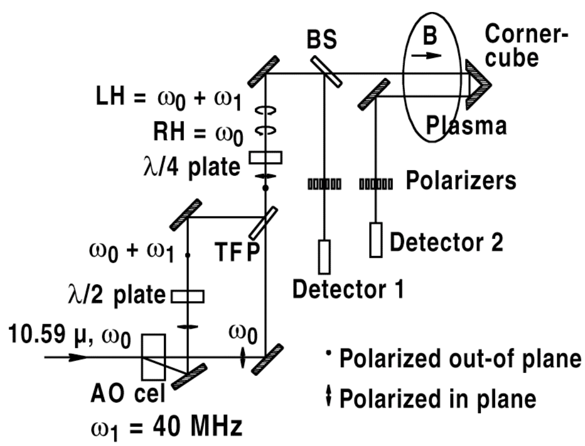

Fig. 1. Optical component layout for polarimeter.

The formation of the separate frequency RH and LH radiation is accomplished by using a single acousto-optic frequency shifter (AO). The AO cel splits the incident beam into equal amplitude components with linear polarization in the plane of the paper. The frequency-shifted component is then passed through a CdS $\lambda/2$ waveplate and its polarization is rotated by 90 deg. The two separate frequency, orthogonally polarized beams are then re-combined using a ZnSe thin film polarizer/combiner (TFP) operating at Brewster's angle. The composite beam is then passed through a CdS $\lambda/4$ waveplate with its axis at 45 deg with respect the polarization vector of each frequency component forming the superimposed RH and LH waves at ω_0 and $\omega_0 + \omega_1$ respectively (i.e. rotating linearly polarized wave). It should be noted that the additional phase term $\phi_v(t)$ present in the expression for I_1 and I_2 is relative to the 40 MHz AO drive signal and results from any vibration or path length variation introduced between the AO cel and the TFP. This additional phase shift leads to errors in the measurement of α if one were to use the AO driver signal as the LO and is the primary reason for including a separate reference detector.

In practice, the relative phase between I_1 and I_2 ($2\times$Faraday rotation angle) is obtained by carrying out a separate demodulation of each signal relative to the AO cel drive frequency and taking the difference. The 40 MHz phase demodulation is accomplished by an all-digital scheme based on modern digital signal processing techniques implemented using a PCI card field programmable gate array and high speed (53.33 MS/s) analog-to digital converters. The real-time system is the same used for day-to-day operation of the DIII-D TCI system and is capable of better than 1/3 degree phase detection accuracy with 8 MHz bandwidth independent of IF amplitude variations up to 20%. The 16-bit phase data are stored at a sampling rate of 1.667 MS/s as well made available in "real-time" via analog outputs [3].

Calibration and noise floor tests of the polarimeter have been carried out using a rotating $\lambda/2$ waveplate in the beam path to simulate Faraday rotation. The measured response is linear with waveplate rotation angle, as expected, with the actual polarization rotation angle being twice that of the waveplate [6,12]. Phase noise tests show approximately 0.08 deg and 0.28 deg, phase noise with a bandwidth of 100 Hz and 1 kHz, respectively.

III. INSTALLATION AND MEASUREMENTS ON DIII-D

The polarimeter's viewing trajectory on DIII-D is shown in Fig. 2 along with that of a radially viewing CO_2 interferometer chord. The beams from both systems enter through a midplane BaF_2 window after which the polarimeter beam is steered tangentially via a solid copper mirror installed inside of the vacuum vessel. Copper was chosen due to its high conductivity in order to reduce the relative phase shift between S and P components resulting from large AOI ($\approx$70 deg) effects. Due to its relatively low cost and transparency in the visible spectrum as well as infrared, BaF_2 is an attractive alternative to other choices for window material such as ZnSe and CVD diamond. It is well known that ZnSe has a large Verdet constant at 10.59 μm which can severely affect polarimetry measurements [10]. While CVD diamond has a negligible Verdet constant, windows of the required diameter (3.6 in.) are prohibitively expensive [10]. An exhaustive literature search has failed to produce the Verdet constant of BaF_2, however, estimates indicate it is as much as an order of magnitude less than ZnSe. The retroreflector for each system is approximately 2.5 in. diameter and constructed out of three orthogonal solid titanium mirrors [2].

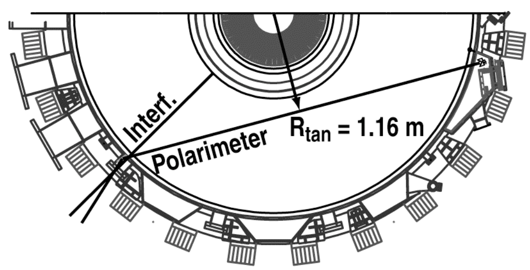

Fig. 2. Polarimeter and Interferometer chord layout on DIII-D midplane. Both are double pass.

Shown in Fig. 3 are polarimeter and radial interferometer data from DIII-D discharge 128645 in which massive gas jet injection (~ 550 Torr – Liters H_2) occurs at t=1915 ms and the line averaged density ($\bar{n}_e$) rapidly increases from $\bar{n}_e = 6.6\times10^{13}$ cm^{-3} to a maximum of $\bar{n}_e \approx 1.5\times 10^{15}$ cm^{-3}. The line-averaged density from the polarimeter measurements is approximated by using the average parallel magnetic field along the ray path ($\bar{B}_{||}$ = 2.38 T) as calculated from an EFIT equilibrium reconstruction before gas jet injection and the total double-pass path length L = 7.9 m from LCFS to LCFS; giving

$$\bar{n}_e \approx \frac{\alpha}{k\lambda^2 \bar{B}_{||} L} \quad . \qquad (2)$$

Using an average parallel magnetic field value is essentially the only way to arrive at a density measurement without explicitly knowing the profile shape itself. While they are not expected to be identical owing to different sightlines, magnetic field weighting, profile asymmetries, etc., the radial interferometer chord provides an excellent check as to the accuracy of the polarimeter measurement. The temporal behavior of both measurements are qualitatively similar and the relative magnitudes of line-averaged density are in rough quantitative agreement. The actual onset of the initial gas jet density pulse is slightly different on the two different measurements due to their different average toroidal location and the finite propagation time of the pulse itself. Additionally, one can see the relative density difference before gas injection and long after is essentially the same for the polarimeter and interferometer and is an indication of the polarimeter's ability to measure the ambient $\bar{n}_e = 6.6 \times 10^{13}\ \mathrm{cm}^{-3}$ plasma.

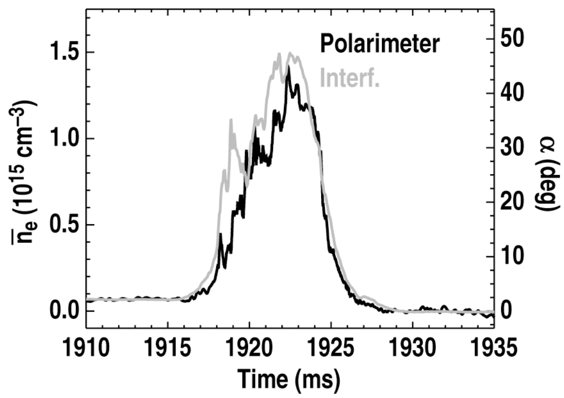

Fig. 3. Discharge 128645, polarimeter and interferometer measurements during gas jet injection. Line-averaged density on left axis (both) and Faraday rotation angle on right axis (polarimeter only).

The actual polarimeter measured Faraday rotation angle (α) is also shown in Fig. 3. It is interesting to note that the large rotation angles during gas injection ($\approx$50 deg) are of similar magnitude as those predicted for tangentially viewing polarimeter chords operating at CO_2 wavelengths in steady state ITER plasmas [5]. A simple estimate of this can be made by assuming $L_{\mathrm{ITER}} / L_{\mathrm{D3D}} \approx 4$, $B_{\mathrm{ITER}} / B_{\mathrm{D3D}} \approx 2.75$, $n_{\mathrm{ITER}} / n_{\mathrm{gasjet}} \approx 1/15$, giving $\alpha_{\mathrm{ITER}} / \alpha_{\mathrm{gasjet}} \approx 0.73$.

IV. POTENTIAL ISSUES

While gas jet injection experiments clearly show the utility of CO_2 polarimeter measurements in DIII-D and these results extrapolate well to steady-state ITER plasmas the polarimeter system described in this article, as implemented, does not have sufficient line-density resolution for measurements of typical DIII-D plasmas. This can be seen by looking at the time periods in Fig. 3 before and after gas jet injection (t < 1915 ms and t > 1930 ms). The low frequency oscillations apparent in the Faraday Rotation signal are a result of optical component motion and highlight the need for real time feedback alignment to obtain sub-degree resolution. Measurements of the error induced by beam motion transverse to the propagation direction indicate that approximately 1 mm motion across the detector can introduce errors as large as 1 deg in the measured Faraday rotation angles. This is consistent with measurements of the same error source in Ref. [12]. The magnitude of this error is extremely dependent on the degree to which the RH and LH wave are co-linear. Indeed, any offset in the presence of a non-uniform density profile will exacerbate the error by forming essentially a differential interferometer. Obtaining and preserving such precise alignment, however, is difficult and further development is required in this area along with feedback alignment.

V. CONCLUSIONS

A CO_2 laser polarimeter operating at 10.59 μm which uses a “real-time” phase demodulation system has been installed and operated on the DIII-D tokamak. The line-density obtained through measurements of Faraday rotation during gas jet injection experiments show agreement with a radially viewing CO_2 interferometer chord and the obtained rotation angles are in the range of those expected in ITER plasmas. Future work will include the construction of a feedback alignment system and the addition of a common path vibration compensated interferometer measurement to make the system more robust and applicable to typical DIII-D plasmas.

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