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Upgrade of far-infrared laser-based Faraday rotation measurement on MST\textsuperscript{a)}

W. X. Ding,\textsuperscript{b)} D. L. Brower, W. F. Bergerson, and L. Lin

Department of Physics and Astronomy, University of California, Los Angeles, Los Angeles, California 90095, USA

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Recently, the far-infrared (FIR) laser ($\lambda_0=432$ $\mu$m) Faraday rotation measurement system on MST has been upgraded. The dc flowing-gas discharge CO\textsubscript{2} pump laser is replaced by a rf-excited, sealed CO\textsubscript{2} laser at 9.27 $\mu$m (GEM select 100, Coherent Inc., Santa Clara, CA), which is subdivided equally into three parts to simultaneously pump three FIR cavities. The total infrared pump power is approximately 80 W on the 9R(20) line required to pump the formic acid molecule. Each FIR cavity produces $\sim$12 mW, sufficient for 11 simultaneous chord interferometry-polarimetry operations. Three key issues [(1) conservation of circularly polarized wave, (2) collinearity of two probe waves, and (3) stability of intermediate frequencies between lasers] affecting the Faraday rotation measurement have been resolved experimentally. © 2010 American Institute of Physics. [doi:10.1063/1.3466898]

I. INTRODUCTION

Understanding plasma equilibrium, stability, and transport requires measurement of magnetic field and its fluctuations in the high-temperature plasma interior. Neutral beam injection based motional Stark effect (MSE) and Faraday rotation effect (FRE) have been utilized to measure the internal magnetic field structure in high temperature plasmas. MSE-based polarimetry has a high spatial resolution and FRE-based polarimetry has a high temporal resolution. They are complementary in measuring magnetic field and magnetic field fluctuations in high-temperature plasmas. Faraday rotation measurements have been conducted over several decades and will be used to measure the magnetic field (current profile) in burning plasmas like ITER as well. It is well known that Faraday rotation in magnetized plasmas originates from circular birefringence as the left-handed circularly polarized wave and the right-handed circularly polarized wave have different phase velocities along the magnetic field. Based on this principle, Dodel and Kunz\textsuperscript{1} proposed to measure the phase difference between these two waves to obtain the Faraday rotation angle as opposed to measuring the small rotation angle of linearly polarized light directly. This technique was previously employed on the RTP tokamak,\textsuperscript{2} is under development to measure the current density profile in the C-Mod tokamak,\textsuperscript{3} and is planned for use on the tangential interferometer and polarimeter system for ITER. The Dodel–Kunz technique is relatively simple, requires no amplitude calibration,\textsuperscript{4} has a very high temporal and phase resolution,\textsuperscript{5} and is less sensitive to elliptization caused by transverse magnetic field in plasmas when Faraday rotation angle is small.$^2$ However, the measurement of very small Faraday rotation angle requires low phase noise and small errors, which presents a challenge for present day and future fusion reactor devices.

A combined FIR polarimetry-interferometry system has been developed to measure plasma density and magnetic field in the reversed field pinch on Madison Symmetric Torus (MST) where only small port hole (3.8 and 5 cm) access is available.\textsuperscript{5} The fast time response ($\sim$4 $\mu$s for simultaneous polarimetry and interferometry measurements, and 1 $\mu$s for Faraday measurement only) allows observation of the interior magnetic field fluctuations. Recently, the far-infrared (FIR) system on MST has been upgraded to improve laser stability and eliminate elliptization of the laser polarization related to polarization-sensitive beamsplitters in the optical system. Critical systematic errors, resulting from laser instabilities, distortion of circularly polarized light, and misalignment, have been studied. Understanding and mitigating these effects are key to obtaining a reliable, high-resolution Faraday rotation measurement using Dodel and Kunz approach.

II. POLARIMETRY-INTERFEROMETER SYSTEM ON MST

As shown schematically in Fig. 1, the MST ($R_o$ =1.5 m, $a=0.52$ m) vertically viewing heterodyne FIR laser interferometer/polarimeter system consists of 11 discrete chords divided between toroidal location $250^\circ$ ($x=\sim$24, $-9$, $-6$, 21, and 36 cm) and $255^\circ$ ($x=\sim$32, $-17$, $-2$, 13, 28, and 43 cm), where $x$ is the impact parameter and $x=0$ is the torus geometric center. An additional beam path which bypasses the plasma is used for a reference. A rf-excited, sealed CO\textsubscript{2} laser ($\sim$80 W) at 9.27 $\mu$m (GEM Select 100, Coherent Inc.) is subdivided equally into three parts to simultaneously pump three FIR cavities filled with formic acid (HCOOH) vapor at 150 mtorr. Each cavity produces approximately...
10–12 mW of FIR power at 432.5 μm (694 GHz) with linear polarization. A half-wave plate in front of cavity number 1 rotates the polarization of beam 90° before being combined with the beam from cavity number 2 at the standing wave polarizer. Thus two linearly polarized, orthogonal, colinear beams with intermediate frequency (IF) offset (IF ~1 MHz) are transported from laser room to the MST device via over-moded waveguide. The beams are then evenly divided into 12 parts via mesh metallic wire mesh beamsplitters. One is used for a reference while the others are the 11 plasma probe beams. The two linearly polarized orthogonal beams are converted to circularly polarized orthogonal (R- and L-waves) beams after passing a quarter-wave plate just before the vessel entrance port for each chord. This configuration is essential to ensure that circular probing waves are launched as, in general, the mesh beamsplitters are polarization sensitive.² Cavity number 3 provides local oscillator beam (also with a small frequency offset from the two probing beams) used to provide rf bias for the mixers used with the 11 probing chords and one reference leg in order to obtain a heterodyne density measurement. A polarizer is placed in front of each mixer to ensure selection of the wave component along the toroidal direction. Each mixer measures the mixing product of the three frequency-offset laser beams. The signal from each mixer is digitized (6 MHz sampling) and stored for offline analysis whereby a software based demodulation scheme is employed to obtain the phase change with respect to the reference mixer.³ Three bands of frequency bands of phase information are multiplexed onto a single time series for each chord.

The phase information can be directly related to electron density and Faraday rotation in the plasma. The difference of refractive index for the right-handed (R-) and the left-handed (L-) circularly polarized waves in a magnetized plasma leads to a relative phase shift, i.e.,

\[ \Phi_I(x) = \Phi(x) + \Psi(x) = c_I \int n_e dl + c_F \int n_e B_T dl, \]

(1a)

\[ \Phi_F(x) = \Phi(x) - \Psi(x) = c_I \int n_e dl - c_F \int n_e B_T dl, \]

(1b)

where \( \Phi(x) = (\Phi_L + \Phi_R)/2 \) is the line-integrated density and \( \Psi(x) = (\Phi_L - \Phi_R)/2 \) is Faraday rotation angle; \( c_I \) and \( c_F \) are constants. Faraday effect \( \Psi(x) \) is much less than \( \Phi(x) \), typically by factor of at least 100. The three mixing products observed in each detector carry the phase information for L-wave, R-wave, and their difference.³ ⁶

A. Conservation of circularly polarized waves

Realizing a Faraday rotation measurement using the Dodel and Kunz method requires the launching of two circularly polarized, orthogonal waves into plasma. If the circularly polarized beams are produced near the laser source, they become elliptically polarized after passing through the optical system (due to multiple beamsplitters) but before reaching the plasma which consequently leads to large systematic errors.² ⁶ It is well known that metal mesh beamsplitters are sensitive to polarization.⁷ Partially, it is ascribed to the fact that reflectivity (transmission) of meshes depends on the polarization direction. To quantify the deformation of polarization state, we place a rotating (~2–3 Hz) crystal quartz \( \lambda/2 \)-wave plate in front of the vessel entrance port to simulate polarization change in a plasma. One expects the measured phase to be linearly proportional to the rotation angle if two circularly polarized waves pass through the rotating \( \lambda/2 \)-wave plate. Figure 2(a) shows the measured phase versus rotation angle if one launches waves that are circularly polarized near the laser (accomplished by placing \( \lambda/4 \)-wave plate in immediately after polarizing beam-combiner by FIR cavities 1 and 2, see Fig. 1). A strong nonlinear relation between measured phase and rotation angle is observed, thereby implying that the probe waves are
no longer circularly polarized. The ratio of measured phase to quartz rotation angle can be used as a calibration factor to isolate the polarization change due to the plasma effects in real experiments. It is important to note that the calibration factor is dependent on the initial (no plasma) phase. One has to monitor this phase (which can change with any change to the optical system) in order to determine the correct calibration factor. The initial phase dependence varies with the orientation of the main axis of the elliptically polarized wave with respect to the toroidal field. The nonlinear relation between the measured phase and real Faraday effect complicates the polarimetry measurement and leads to increased systematic errors. Measurements show that the wire-mesh beamsplitters do not change the polarization state of linearly polarized waves significantly. With this knowledge, instead of subdividing circularly polarized waves into 11 probing beams, we first divide the linearly orthogonal polarized waves into 11 beams then convert them into circularly polarized orthogonal waves. This ensures that we are sending 11 circularly polarized probe beams into the plasma. In this configuration, the measured phase versus quartz rotation angle becomes linear as shown in Fig. 2(b), implying a calibration factor of 1.00 ± 0.01. (The \( \frac{1}{2} \) part is just a constant and not a calibration factor.)

During recent upgrade of MST FIR system, 11 quartz wave plates were installed just before waves enter plasma to eliminate the deformation of circular polarization caused by metal meshes beamsplitters. Routine calibration is no longer needed for the polarimeter-interferometer diagnostic on MST, although it is always rechecked after replacing or adding any new optical components to confirm proper system response.

**B. Colinearity of two probing beams**

Realizing a Faraday rotation measurement using the Dodel and Kunz method requires the two orthogonal, circularly polarized laser beams be colinear. Any misalignment between two laser beams will introduce extra phase noise along the beam propagation direction. Moreover, a small spatial offset (\( \Delta x \)) between two probing beams also introduces large systematic phase errors due to electron density gradient and path length change in the plasma. To quantify errors related to beam to offset, from Eq. (1) we write

\[
\Phi(x + \Delta x) - \Phi(x) = \Delta \Phi(x) + \Delta \Psi(x),
\]

where the higher order terms for \( \Delta \Psi(x) \) are ignored since \( \Psi \ll \Phi \). Now let us estimate \( \Delta \Phi(x) \) due to small spatial offset. The phase shift due to plasma density is \( \Phi(x) = c_I n_e(r, x) dz \); therefore we have

\[
\Delta \Phi(x) \sim \frac{\Phi(x) \Delta x}{a},
\]

where the MST plasma radius \( a = 0.5 \) m is the assumed scale length for the line-integrated density profile. For typical MST plasma density \( \sim 10^{13} \) m\(^{-3} \), \( \Delta \Phi(x) \sim 1^\circ - 2^\circ \) for beam offset \( \Delta x = 1 \) mm and is comparable to the Faraday rotation phase shift \( (1^\circ - 5^\circ) \) for standard MST plasmas. This offset would lead to a significant error for Faraday rotation measurement even though the misalignment (\( \sim 1 \) mm) is small compared to the FIR beam diameter (\( \sim 40 \) mm). In fact, the phase difference due to beam offset is easily observed as reported in Ref. 7 and has been exploited to measure the equilibrium density profile and its gradient. For Faraday rotation measurement, any spatial offset must be minimized. Tolerance to misalignment along density gradient direction is given by

\[
\Delta x_{\text{max}} = \frac{a}{\Phi(x)} \Delta \phi_{\text{noise}},
\]

where \( \Delta \phi_{\text{noise}} \) is the system phase noise. Misalignment-associated systemic errors must be less than the intrinsic phase noise (electronics noise, etc.) in order to optimize the diagnostic sensitivity. It is evident from Eq. (4) that misalignment errors are sensitive to and increase with the density gradient. For the upgraded FIR system on MST, random phase noise is about \( 0.1^\circ - 0.2^\circ \) (50 kHz bandwidth), which can be further reduced using correlation techniques.\(^5\) This phase resolution requires probe beam offset less than 0.1 mm.

The laser beam profiles have a Gaussian shape with beam width of \( \sim 4 \) cm as measured using a scanning pyrodetector (see Fig. 3). It is extremely difficult to distinguish a 0.1 mm spatial offset between the two probe beams using the profile measurement. Instead, we have developed an empirical alignment procedure to minimize the density gradient effects due to spatial offset, which is discussed elsewhere.\(^9,10\)
Any offset between two beams along toroidal direction does not lead to a large systemic error since the density gradient along toroidal direction in a torus is negligible. However, it may still lead to large phase noise due to the vibration. Accurate alignment of the two probe beams is critical to successfully implementing the Dodel and Kunz method.

C. Stability of intermediate frequencies

A typical power spectrum of mixing products among three waves (FIR laser beams) is shown in Fig. 4. The IF of L-wave (R-wave) is due to the mixing between L-wave (R-wave) and local oscillator (LO). These two frequency bands contain information on the R- and L-wave refractive indices. The lowest IF (L-R) results from direct mixing between the two probing beams, L and R waves, and carries Faraday rotation information. IF stability is important for operation and phase noise. Any IF drift will reduce measurement bandwidth and increase crosstalk between the IF carriers. Slow (minutes or hours) IF drift due to CO\textsubscript{2} laser instability has been improved by replacing dc-discharge CO\textsubscript{2} laser with new rf-excited, sealed CO\textsubscript{2} laser (~74 W) at 9.27 μm (GEM Select 100, Coherent Inc.). In addition, slow IF drift due to the FIR and IR cavity length changes has been improved by controlling laser room temperature.

Long-term IF drift is observed to be 100–200 kHz after 3 h of free-running the FIR lasers without any feedback control. During plasma operations, remote tuning of infrared and FIR laser cavities is easily accomplished between shots (every 5 min), thereby negating the need for direct feedback control. However, the IF often exhibits a ±3 kHz oscillation at 100 Hz which can increase to ±10 kHz during plasma discharges, as shown in Fig. 5. The enhanced frequency oscillation with plasma most likely comes from vibrations coupling to the optical system and sources.

IF change with plasma likely introduces extra phase error for the Faraday measurement. The mixing product between L-wave \((f_{L})\) and R-wave \((f_{R})\) for signal and reference mixers are

\[
I_{\text{sig}} \sim E_{L}E_{R} \cos \left[ 2\pi(f_{L} - f_{R})t + 2\Psi(t) + 2\pi \left( \frac{f_{L} - f_{R}}{c} \right) L_{2} + \phi_{L0} - \phi_{R0} \right],
\]

respectively, where \(L_{1}\) and \(L_{2}\) are path lengths for signal path and reference path, \(f_{L0}\) and \(f_{R0}\) are initial phases of L-wave and R-wave. The measured phase difference between \(I_{\text{sig}}\) and \(I_{\text{ref}}\) is

\[
\phi(t) = 2\Psi(t) + 2\pi \frac{\Delta f}{c} \Delta L,
\]

where \(\Delta f = f_{L} - f_{R}\) and \(\Delta L = L_{1} - L_{2}\). The second term on the right hand side is extra phase due to IF instability. From Eq. (7), the Faraday rotation angle \(\Psi(t)\) can be easily determined by subtracting dc phase offset before discharge only if the IF is constant (\(\Delta f = 0\)). On MST, mixers are arranged so that \(\Delta L\) is less than 1 m. The maximum phase error (due to frequency oscillation) is estimated to be 0.01°. Therefore, IF instability does not contribute to phase errors significantly. Improving the stability of the entire laser system and optical support structure is being considered to further reducing noise levels.

It should be noted that in Eq. (7), the Faraday rotation measurement is independent of the initial phases of the L-wave and R-wave because a reference signal is used. It is not necessary for the L-wave and R-wave to have a fixed initial phase for Faraday rotation measurement. Consequently, the FIR cavities can be pumped by independent CO\textsubscript{2} lasers as long as the IF remains stable.\textsuperscript{3}

III. MEASUREMENT RESULTS

The recently upgraded FIR system is now being routinely operated on MST. A typical example of simultaneously measured Faraday rotation [(a) and (b)] and density [(c) and (d)] phase is shown in Fig. 6. Faraday rotation angle changes

\[
\text{FIG. 4. A typical signal power spectrum showing IF carrier frequencies. The separation between these IFs limits the bandwidth. L-R, R-wave, and L-wave indicate different wave beat frequencies, respectively.}
\]

\[
\text{FIG. 5. (a) IF vs time from reference mixer without plasma discharge showing 100 Hz oscillation. (b) IF vs time from reference mixer with plasma discharges showing an increase in the oscillation.}
\]
sign across magnetic axis \((x=6 \text{ cm})\) as expected since poloidal magnetic field changes direction. Faraday rotation angle reaches a maximum value at \(x=-17 \text{ cm}\) and \(x=28 \text{ cm}\), where the poloidal magnetic field is largest. By using precise measurement of Faraday rotation and density, the current density profile can be obtained through equilibrium reconstruction as has been previously discussed.\(^{1,12}\)

The FIR system on MST not only measures equilibrium magnetic field and density but also, due to fast time response and low phase noise, measures magnetic field and density fluctuations. Expanding the time axis of Fig. 6 about magnetic field and density but also, due to fast time response with expanded time scale. All 11 chords show oscillations with frequency which is identified as \((m=1, n=5)\) resistive tearing mode.

Faraday rotation fluctuations for the six central chords \((x=-17, -9, -2, 6, 13, \text{ and } 21 \text{ cm})\) are dominated by magnetic field fluctuations while the remaining chords are dominated by density fluctuations. The central Faraday chord \((x=6 \text{ cm})\) measures line-integrated internal radial magnetic fluctuations, \(\int n\vec{B}_r dl\). Density fluctuations for inboard chord \((x=-32 \text{ cm})\) and outboard chord \((x=43 \text{ cm})\) have \(\pi\) phase change which is consistent with an \(m=1\) mode nature. Detailed physical interpretations of these density and Faraday rotation fluctuations have been published.\(^{13,14}\)

### IV. SUMMARY

Phase measurement of Faraday rotation using the Dodel and Kunz method and continuous laser sources provides reliable information on the plasma internal magnetic field structure and fluctuations. This approach is not sensitive to signal amplitudes and requires no beam modulation techniques. Three criteria required to properly implement this technique have been addressed. They are the conservation of circularly polarization, colinearity of probe beams, and stability of intermediate frequency. Experimental verification that these three criteria are satisfied is necessary to accomplish a successful Faraday rotation measurement. Rms noise from the fundamental mixers and electronics eventually determines the lower limit of the detection sensitivity. Further efforts are needed to reduce rms noise to achieve bandwidth up to a few megahertz with low phase noise in order to measure higher-frequency internal magnetic and density fluctuations.

\(^{1}\) G. Dodel and W. Kunz, Infrared Phys. 18, 773 (1978).