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An upgraded interferometer-polarimeter system for broadband fluctuation measurements

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Measuring high-frequency fluctuations (above tearing mode frequencies) is important for diagnosing instabilities and transport phenomena. The Madison Symmetric Torus interferometer-polarimeter system has been upgraded to utilize improved planar-diode mixer technology. The new mixers reduce phase noise and allow more sensitive measurements of fluctuations at high frequency. Typical polarimeter rms phase noise values of 0.05°–0.07° are obtained with 400 kHz bandwidth. The low phase noise enables the resolution of fluctuations up to 250 kHz for polarimetry and 600 kHz for interferometry. The importance of probe beam alignment for polarimetry is also verified; previously reported tolerances of ≤0.1 mm displacement for equilibrium and tearing mode measurements minimize contamination due to spatial misalignment to within acceptable levels for chords near the magnetic axis. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4960731]

I. INTRODUCTION

Diagnosing magnetic and density fluctuations is important for understanding transport phenomena in magnetically confined plasmas. Global tearing mode driven density and magnetic fluctuations in the Madison Symmetric Torus (MST) reversed-field pinch (RFP) have been well-characterized by interferometry and polarimetry.[1,2] Neutral beam heated plasmas and improved confinement plasmas provide a range of phenomena (drift waves, energetic particle modes, Alfvénic modes) at higher frequencies which have been diagnosed primarily by density fluctuation measurements.[3] While the strongest of the observed fast-ion instabilities have been diagnosed through polarimetry,[4] many of these high-frequency instabilities have been too weak to resolve magnetic fluctuations. Additionally, broadband magnetic turbulence may play a role in stochastic transport of particles and energy. Extending the accessible bandwidth of fluctuation measurements is critical for understanding the full range of behavior observed at high frequencies.

The Far-Infrared (FIR) interferometer-polarimeter system on MST offers fast-time response, high-resolution fluctuation measurements.[5,6] The heterodyne detection system provides high bandwidth (up to ~1 MHz) for measurement of dynamic changes in plasma equilibrium as well as high-frequency fluctuations. With such large achievable bandwidths from heterodyning, the primary limit on resolving high-frequency behavior is the detector noise floor. New planar-diode mixers improve on the corner-cube mixers previously used.[7] The MST interferometer-polarimeter system has been upgraded to use planar-diode mixers on all chords, reducing phase noise and allowing measurement of high-frequency fluctuations with small amplitude. The FIR interferometer-polarimeter system is described in Section II. For polarimeter operation, displacements between the probe beams even at scales much smaller than the beam width can have a significant impact on measured fluctuations. In Section III, the alignment tolerances between probe beams are described and found to be within acceptable limits for chords near the magnetic axis. In Section IV, the system performance is characterized up to 250 kHz for polarimetry and 600 kHz for interferometry.

II. HARDWARE

The FIR laser system is comprised of a CO_2 pumped formic acid molecular gas laser operating at 432 μm.[6] Three independent cavities can be tuned with relative frequency offsets on the order of 1 MHz for heterodyne detection. The beams from two of the cavities are directed through the plasma to act as probe beams, while the third cavity provides a local oscillator for density measurements. The two probe beams have orthogonal polarization and are split into 11 chords passing through the plasma plus an additional reference mixer. See Figure 1 for a simplified schematic of the three beam configuration involving only six chords and the reference mixer. Of the 11 chords, five are located at 250° toroidal, while the other six are located at 255°. Mixer signals are digitized at 6 MHz, and density and Faraday rotation values are digitally phase extracted through comparison to the reference signal.

Prior to the upgrade, the mixers were corner-cube whisker-diodes built in-house. All corner-cube mixers have been replaced by commercially available planar-diode mixers from Virginia Diodes, Inc. The planar diode mixers have typical responsivity of 800 V/W and preamplifier gain of 100. The improvement in responsivity compared to the corner-cube

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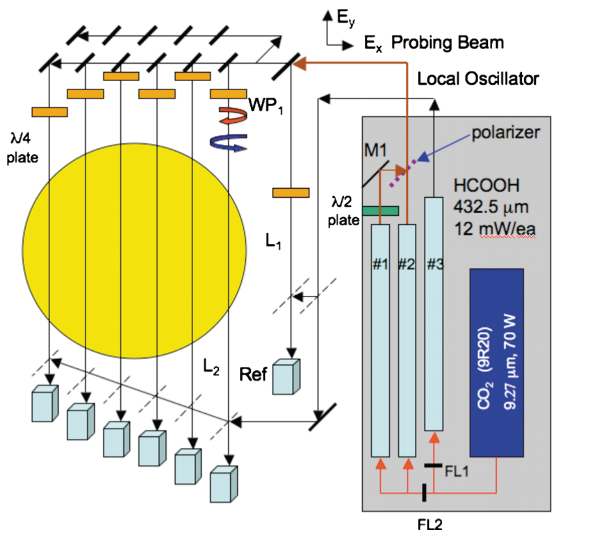

FIG. 1. Schematic of three-wave FIR polarimeter-interferometer. Two probe beams with orthogonal polarization pass through the plasma for polarimeter operation, while a third beam serves as the local oscillator for interferometer operation. Only six chords are shown for simplicity.

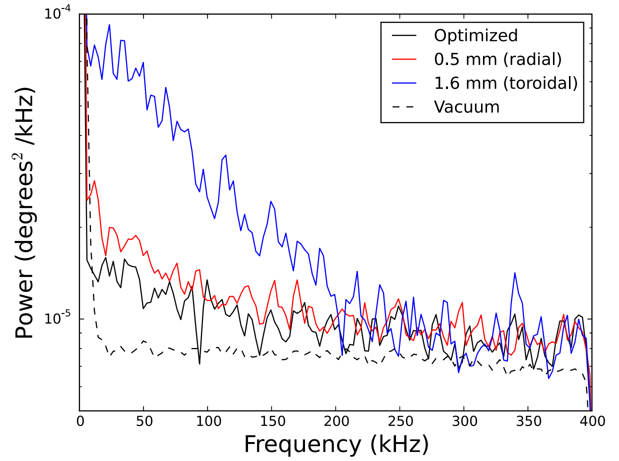

FIG. 2. Power spectra for the chord closest to the magnetic axis ($R - R_0$ = 6 cm) with both probe beams in the same polarization state. Displacements of 1.6 mm (toroidal) and 0.5 mm (radial) are compared to the optimized spectrum (≤0.1 mm).

mixers is roughly a factor of 5, with similar gains seen in the noise floor of signal power spectra.[7] Typical polarimeter rms phase noise is 0.05°–0.07° for 400 kHz bandwidth.

III. ALIGNMENT

Despite beam diameters of 2–3 cm, the alignment of the two probe beams for polarimetry is technically demanding. Typical tolerances for acceptable alignment are ≤0.1 mm displacement between the two beams. Previous work has established a method for aligning the probe beams to within 0.1 mm displacement using a dielectric wedge as well as confirming the importance of aligning to this tolerance for measurements of both the equilibrium and tearing mode correlated fluctuations.[8] Tolerances for broadband fluctuations, however, have not been addressed.

While the dielectric wedge technique offers high precision, the potential for feedback to drive the laser unstable and the intensive labor required motivated an alternative technique for this work. The relative alignment between the two probe beams can be determined by converting both beams to the same polarization state. The Faraday rotation angle for orthogonally polarized beams is given by half the line-integral of the difference in index of refraction experienced by each beam. For beams with the same polarization, the index of refraction is the same and the only phase difference accumulated between the beams is due to spatial misalignment—well-aligned beams should have mean of zero and phase noise equivalent to vacuum measurements.

Alignment tests were conducted with plasmas, iterating over multiple discharges to first minimize the equilibrium signal (using radial displacements) and then to eliminate residual fluctuation power by scanning toroidal displacements. This approach allows similar precision in minimizing displacement between the beams but does not yield the same degree of precision in controlling the divergence between beams that the dielectric wedge offers. Particularly for radial alignment, small-angle crossing between the probe beams may be obscured by uncertainty in the equilibrium measurement. Power spectra with the probe beams in the same polarization state depend strongly on the relative alignment between the two beams, see Figure 2. Fluctuation power at displacements of 1.6 mm can match power observed at low frequencies, while even a 0.5 mm displacement produces fluctuation power comparable to the Faraday rotation fluctuations at higher frequencies. For a given displacement, a similar level of fluctuation power is seen in both the radial and toroidal directions. While low-amplitude fluctuations are observed even up to a few hundred kHz for optimized alignment, the measured spectra for Faraday rotation can exceed the co-polarized spectra up to frequencies of ∼150 kHz for core chords. These measurements indicate that the same tolerance (≤0.1 mm) for equilibrium and tearing mode measurements is sufficient for fluctuation measurements at a range of frequencies above the tearing modes. Further work is required to determine the divergence between the probe beams, and to improve alignment for fluctuations above 150 kHz. Co-polarization spectra for edge chords are much stronger, suggesting that measured Faraday spectra are dominated by density gradient contamination. Tighter alignment tolerances are required to obtain usable Faraday rotation measurements from these chords.

IV. FLUCTUATION MEASUREMENTS

The line-integrated electron density measurements from interferometry are given by

$$\Phi = c_I \int n_e dz, \tag{1}$$

where $c_I = e^2\lambda/4\pi c^2\epsilon_0 m_e$ and z is the path length along the vertical laser chord. The Faraday rotation measurement from polarimetry is

$$\Psi = c_F \int n_e \vec{B} \cdot d\vec{l}, \tag{2}$$

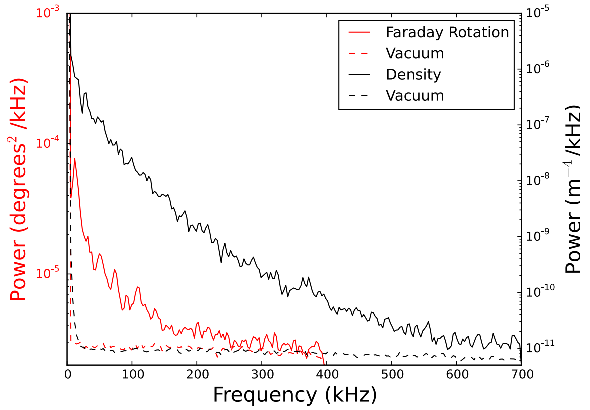

FIG. 3. Power spectral density for Faraday rotation and density between sawtooth events for a central chord near the magnetic axis ($R-R_0=-2$ cm).

where $c_F = e^2\lambda^2/8\pi^2c^3\epsilon_0 m_e^2$. For fluctuation measurements, $\tilde{\Phi}$ is proportional to line-integrated fluctuations in density,

$$\tilde{\Phi} = c_I \int \tilde{n}_e dz, \tag{3}$$

but $\tilde{\Psi}$ is proportional to terms with both density and magnetic fluctuations. Ignoring second order fluctuating terms, Faraday rotation fluctuations can be expressed as

$$\tilde{\Psi} = c_F \int \left[\tilde{n}_e B_{z,0} + n_{e,0}\tilde{b}_z\right] dz. \tag{4}$$

For chords near the magnetic axis, the equilibrium magnetic field is largely perpendicular to the chord and the term proportional to density fluctuations becomes negligible. In this way, the magnetic fluctuation contributions to Faraday rotation can be isolated from the density fluctuations. The radial component of the magnetic perturbations, rather than the poloidal component, will be the dominant contribution to $\tilde{b}_z dz$ near the magnetic axis. As the radial magnetic perturbation is responsible for particle and energy transport, resolving broadband radial magnetic fluctuations is crucial for understanding contributions to transport at high frequencies. Fluctuation measurements from a single chord near the magnetic axis ($R-R_0=-2$ cm) are shown in Figure 3 for typical RFP discharges with $I_p = 400$ kA and core electron density of $1\cdot 10^{19}$ m^{-3}. The Faraday rotation spectra in between sawtooth events show resolvable fluctuations up to approximately 250 kHz—the previous limit was approximately 150 kHz with the corner-cube mixers (information on density gradient contamination is unavailable for corner-cube mixer data at high frequencies). This demonstrates a substantial expansion of the range of frequencies over which radial magnetic perturbations can be resolved. Spectra for density fluctuations (also between sawtooth events) show resolvable fluctuations up to at least 600 kHz (previously only 400 kHz with corner-cube mixers).

V. CONCLUSION

Planar-diode mixer upgrades to the MST interferometer-polarimeter system have been demonstrated to substantially reduce the noise floor. The reduction in phase noise allows measurement of low amplitude fluctuations across a wider range of available bandwidth, with Faraday rotation measurements resolved up to 250 kHz and density fluctuations up to 600 kHz in the core. Faraday fluctuation measurements are above density gradient contamination levels for frequencies up to 150 kHz. Further work is necessary to improve alignment tolerances for higher frequency fluctuations. Additionally, two-mixer correlation techniques are expected to further reduce phase noise and make possible high-wavenumber measurements, while the small (2–3 mm) aperture of the planar diode mixers may be utilized to resolve small spatial scale fluctuations.

SUPPLEMENTARY MATERIAL

See supplementary material for the digital format of the data shown in this paper.

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