A phase contrast imaging–interferometer system for detection of multiscale electron density fluctuations on DIII-D

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A Phase Contrast Imaging–Interferometer system for detection of multiscale electron density fluctuations on DIII-D\textsuperscript{a}

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Heterodyne interferometry and phase contrast imaging (PCI) are robust, mature techniques for measuring low-\textit{k} and high-\textit{k} electron density fluctuations, respectively. This work describes the first-ever implementation of a combined PCI–interferometer. The combined system uses a single 10.6\,\textmu m probe beam, two interference schemes, and two detectors to measure electron density fluctuations at large spatiotemporal bandwidth (10\,kHz \textless \textit{f} \textless 5\,MHz and 0 cm\textsuperscript{−1} \textless \textit{k} \textless 20 cm\textsuperscript{−1}), allowing simultaneous measurement of ion- and electron-scale instabilities. Further, correlating our interferometer’s measurements with those from DIII-D’s pre-existing, toroidally separated interferometer allows core-localized, low-\textit{n} MHD studies that may otherwise be inaccessible via external magnetic measurements. The combined diagnostic’s small port requirements and minimal access restrictions make it well-suited to the harsh neutron environments and limited port space expected in next-step devices.

I. BACKGROUND AND MOTIVATION

ITER and next-step devices will have harsh neutron environments and limited port space. By combining compatible diagnostics, port space can be conserved, and novel physics can also be investigated. As summarized in Table I, phase contrast imaging (PCI) and interferometry are compatible and complementary, making the two techniques prime candidates for a combined diagnostic.

A combined PCI-interferometer was recently installed on the DIII-D tokamak. The PCI technique excels at detecting fluctuations smaller than the diameter of the probe beam, which, for DIII-D’s pre-existing PCI system and a 1\,keV temperature typical of DIII-D’s pedestal, corresponds to \(k_0\rho_s \gtrsim 0.25\). By diverting a portion of the returned PCI probe beam to a fast detector and employing a heterodyne interference scheme, the minimum detectable wavenumber has been extended to zero, allowing novel investigation of coupling between ion- and electron-scale instabilities and their interaction with MHD.

\begin{table}[h]
\centering
\begin{tabular}{|l|l|l|}
\hline
Parameter & PCI & Interferometer \\
\hline
probe beam & single CO\textsubscript{2} beam & single CO\textsubscript{2} beam \\
frequency bandwidth & 10 kHz \textless \textit{f} \textless 5 MHz & 10 kHz \textless \textit{f} \textless 5 MHz \\
spatial bandwidth & 1.5 cm\textsuperscript{−1} \textless \textit{k} \textless 20 cm\textsuperscript{−1} & 0 cm\textsuperscript{−1} \textless \textit{k} \textless 5 cm\textsuperscript{−1} \\
measured sensitivity & \(1 \times 10^{14}\) m\textsuperscript{−2}/\sqrt{\text{kHz}} & \(1 \times 10^{15}\) m\textsuperscript{−2}/\sqrt{\text{kHz}} \\
\hline
\end{tabular}
\caption{PCI and interferometry have compatible probe beams, comparable frequency bandwidths, and complementary spatial bandwidths. All parameters are for DIII-D’s currently implemented PCI–interferometer system.}
\end{table}

A. Plasma-induced phase fluctuations

For a CO\textsubscript{2} laser beam (\(\lambda_0 = 10.6\)\,\textmu m) in a tokamak plasma, the index of refraction \(N\) is very nearly isotropic and is given as
\[
N \approx 1 - \omega_{pe}^2/2\omega_0^2,
\]
where \(\omega_{pe} = (n_e e^2/m_e c_0)^{\frac{1}{2}}\) is the angular plasma frequency and \(\omega_0 = 2\pi \cdot 28.3\)\,THz is the angular frequency of the incident CO\textsubscript{2} probe radiation. Thus, a CO\textsubscript{2} beam propagating through a tokamak plasma will acquire an absolute phase shift \(\phi = (\omega_0/c) \int N dl\) with the integration performed along the beam path.

Now, electron density fluctuations \(\tilde{n}_e\) scatter a portion of the incident beam and modulate \(\phi\) as
\[
\tilde{\phi} = -r_e \lambda_0 \int \tilde{n}_e dl
\]
where \(r_e = e^2/(4\pi\varepsilon_0 m_e c^2)\) is the classical electron radius. Typically, the fluctuation wavenumber \(k \ll k_0\) such that the scattering process is far-forward, and \(\phi \ll 1\) such that the scattering process can be discussed in terms of a weakly attenuated “unscattered” beam and higher-order “scattered” beams. Both heterodyne interferometry and phase contrast imaging (PCI) are robust, mature techniques for measuring the phase fluctuations \(\tilde{\phi}\) in Eq. (1).

B. Heterodyne interferometry

Interfering the exiting probe radiation \(E_0 e^{i\phi}\) with a reference beam of known phase \(E_R e^{i\phi_R}\) produces measurable intensity variations on a square-law detector. To avoid the challenges associated with homodyne interferometry, \(\phi_R\) can be linearly ramped in time \((\phi_R = \Delta\omega_0 t)\) such that the intensity \(I_{\text{het}}\) becomes
\[
I_{\text{het}} \propto E_R^2 + E_0^2 + 2E_R E_0 \cos (\Delta\omega_0 t - \phi)
\]
This approach is known as heterodyne interferometry, as the desired baseband phase information is shifted to an
intermediate frequency $\Delta \omega_0$ satisfying $\omega_{\text{max}} \ll \Delta \omega_0 \ll \omega_0$. Practically, the $\phi_R$ ramp is accomplished by modestly Doppler shifting the reference beam relative to the plasma beam. Quadrature heterodyne detection can then be used to extract an absolute measurement of $\phi$. While vibrations in large fusion experiments can make substantial contributions to the measured phase $\phi$, such vibrations occur on slow time-scales (e.g. $f_{\text{vib}} \lesssim 5$ kHz), and phase measurements at a single wavelength are sufficient to quantify plasma-induced phase fluctuations $\phi$ at frequencies above $f_{\text{vib}}$.

C. Phase contrast imaging (PCI)

In contrast to heterodyne interferometry, phase contrast imaging (PCI) uses an internal reference beam to measure $\phi^5$. Assuming $\phi \ll 1$, as is typical for a CO$_2$ probe beam in a tokamak plasma, the exiting probe radiation can be decomposed as: $E_0 e^{i\phi} = E_0 e^{i(\phi + \theta)} \approx E_0 e^{i\phi}(1 + i\theta)$, with the first and second terms in the parentheses corresponding to the unscattered and scattered components of the beam, respectively. Note that the scattered beams are out-of-phase with the unscattered beam and that the scattering angle $\theta$ is given by the Bragg condition: $\theta \approx \pm k_0 / \omega_0$.

The exiting radiation is passed through a focusing optic. At the resulting focal plane, the radiation is spatially localized by scattering angle $\theta$, and the unscattered beam is forced to acquire an additional $\pi/2$ phase delay (typically, by centering the unscattered beam on the $\lambda_0/8$-deep groove of a reflective optical element known as the “phase plate”). Following this spatial filtering, the beams are recombined and imaged on a detector array, where they interfere to produce an electric field $E_{\text{PCI}}(i + i\theta)$ and corresponding intensity

$$I_{\text{PCI}} \propto |E_{\text{PCI}}|^2 \approx E_0^2 \left(1 + 2\phi\right)$$

(3)

The response is linear in $\phi$ and independent of the equilibrium phase $\phi$. However, this spatial filtering also incurs a low-$k$ cutoff, which, in the ideal, diffraction-limited case, corresponds to $k_{\text{PCI}}^0 = 2/w$, where $w$ is the 1/e electric field radius of the probe beam. Typically, the realized $k_{\text{PCI}}^0$ is $\sim 2 - 3$ times larger than the diffraction limit.

III. IMPLEMENTATION & OPERATION ON DIII-D

The DIII-D PCI system is thoroughly described elsewhere. The system is currently configured in the “Phase II” geometry, with the probe beam propagating vertically downwards from the 285° R+2 to R-2 ports. The 1/e electric field radius of the in-vessel beam is $w = 3.4$ cm, and the beam center sits at $R = 1.98$ m. A pair of fast steering mirrors dynamically centers the unscattered beam on the phase plate groove, compensating for vibrations. The system has $k_{\text{min}} = 1.5$ cm$^{-1}$.


A. Interferometer implementation

As indicated in Fig. 1, a heterodyne interferometer was constructed by adding a few compact optics to the existing PCI optical table, with the PCI and interferometer sharing the probe beam. A series of beam splitters deflect $\sim 20\%$ of the returned probe radiation to the interferometer’s plasma arm; two lenses are subsequently used to image the tokamak midplane. The interferometer’s reference arm is generated by deflecting and Doppler shifting a portion of the probe beam with a 27 MHz Germanium acousto-optic modulator (AOM). The laser is sufficiently stable ($\Delta f < 300$ kHz over 0.1 s) that the $\sim 10$ m path-length difference between the plasma and reference arms minimally alters the interferometer’s noise floor.

The plasma and reference arms are combined and then interfered on a single 1 mm $\times$ 1 mm thermoelectrically-cooled HgCdTe photovoltaic detector ($D^* = 5.35 \times 10^7$ Jones); thermoelectric cooling reduces noise but also allows operation up to 50 MHz. The detector is located at the plasma arm’s image plane, and the beams’ radii of curvature are sufficiently matched to ensure less than 5° phase variation across the face of the detector.

The interference (IF) and local oscillator (LO) signals are carried out of the machine hall via coaxial cable. To account for LO drift, the LO cable run was extended by $\sim 500$ m, delaying the LO relative to the IF by the AOM’s coupling time. The IF and LO signals are bandpass filtered and I&Q demodulated with analog electronics. The resulting I&Q signals are low-pass filtered, amplified, and digitized. Phase fluctuations are computed in software, where demodulator imperfections can be compensated.
B. Interferometer wavenumber response

Finite-sampling-volume effects dictate the interferometer’s wavenumber response\(^9\). Imaging a fluctuation \(\phi = \phi_0 \exp(ikx)\) on a square \(s \times s\) detector element with a beam of size \(M \omega \gtrsim s\) yields an amplitude response \(R(k)\)

\[
R(k) \propto \frac{1}{s^2} \int_{\text{det}} \hat{\phi}_0 \exp\left(\frac{ikx}{M}\right) dA = \hat{\phi}_0 \frac{k}{k_c} \sin\left(\frac{k}{k_c}\right)
\]

(4)

where \(\sin(x) = \sin(\pi x)/\pi x\), \(M\) is the magnification of the image relative to the object in the midplane, and

\[
k_c = \frac{2\pi|M|}{s} \equiv k_{\text{int}}^{\max}
\]

(5)

is the first zero of \(R(k)\), defined as being the interferometer’s maximum detectable wavenumber. Magnification \(|M| = 0.08\) was selected, yielding \(k_{\text{int}}^{\max} \approx 5\) cm\(^{-1}\). The interferometer’s mid-\(k\) overlap with the PCI can be used to cross-validate each system’s measurements.

The interferometer’s response has been empirically characterized via sound-wave calibration, as summarized in Fig. 2. At ambient conditions characteristic of San Diego (\(T \approx 20^\circ\text{C},\) modest humidity), swept frequency sound waves were shot through the interferometer’s plasma arm, inducing phase fluctuations\(^8\)

\[
\tilde{\phi} \approx \int \tilde{N}_\text{air} dl \approx 2.7 \times 10^{-9} \int (\tilde{\rho} \text{[Pa]}) dl
\]

(6)

where \(\tilde{\rho}\) is the sound wave pressure, and the perturbation wavenumber is related to the sound wave frequency via the well-known sound-wave dispersion relation \(c_s = 2\pi f/k \approx 343\) m/s. The expected response is determined from multi-dimensional measurements of \(\tilde{\rho}\) with a calibrated microphone. Tests with additional transducers have confirmed the interferometer’s response up to the expected cutoff of 5 cm\(^{-1}\).

C. Interferometer-measured plasma fluctuations

The interferometer’s sensitivity is sufficient to detect microinstabilities, such as suppression of low-\(k\) turbulence following an L-H transition, while its finite response at \(k \approx 0\) cm\(^{-1}\) allows detection of MHD. Further, DIII-D’s pre-existing, toroidally separated interferometer has a vertical chord at \(R = 1.94\) m\(^2\); correlating measurements from the two interferometers allows identification of low-\(n\) MHD, as demonstrated in Fig. 3. These unique multiscale capabilities will allow novel studies of the interaction between MHD and microinstabilities.

![FIG. 2. Sound-wave characterization of interferometer response shows good agreement with expectations. Note that the increased noise floor below 1 cm\(^{-1}\) is attributable to low-frequency (\(f < 5\) k\(\text{Hz}\)) vibrations in the machine hall.](image)

![FIG. 3. Toroidally correlated interferometers probe the plasma core, identifying modes invisible to magnetics! Where the interferometers and magnetics see the same modes, the agreement is excellent!](image)

IV. ACKNOWLEDGMENTS

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