A combined Phase Contrast Imaging and heterodyne interferometer for multiscale fluctuation measurements in tokamak plasmas

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A Combined Phase Contrast Imaging and Heterodyne Interferometer for Multiscale Fluctuation Measurements in Tokamak Plasmas

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Abstract: An upgrade to the Phase Contrast Imaging (PCI) diagnostic on the DIII–D tokamak has successfully combined PCI with density interferometry to provide electron density fluctuation measurements across an unprecedented range in wavenumber. The combined diagnostic uses a single laser and a single beam path through the tokamak, minimizing machine resources in anticipation of future reactor-scale devices where port access will be at a premium. The PCI multichannel detector provides low-noise, wavenumber-resolved detection of moderate-wavenumber turbulence, while the interferometer channel is sensitive to long-wavelength turbulence, including the peak of ion-scale turbulence and MHD. The overlap in wavenumber range between the two schemes allows for an in situ absolute calibration of the PCI.

Keywords: Plasma diagnostics - interferometry, spectroscopy and imaging

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1 Introduction

Achieving the ultimate goal of tokamak research, maintaining the plasma density and temperature that allows the production of net energy, requires understanding of the transport of energy and particles out of the core plasma. The dominant transport results from fluctuations in plasma density and temperature and in electromagnetic fields generated by an array of instabilities with different driving mechanisms [1]. Dominant processes include electrostatic gradient-driven instabilities such as ion thermal gradient (ITG) and trapped electron modes (TEM) at low wavenumber $0.1 < k \rho_i < 1$ and electron thermal gradient (ETG) modes at moderate to high wavenumber, $k \rho_i > 1$ to $k \rho_e \sim 10$. The transport of highly energetic particles, with energies far above the thermal plasma, is of particular relevance to fusion plasmas, where the confinement of fusion-generated alpha particles is critical to performance. That transport predominantly results from magnetohydrodyanamic (MHD) instabilities with wavelengths similar to the plasma size, tens of centimeter to meters.

The MIT Phase Contrast Imaging (PCI) group has established PCI diagnostics on DIII–D [2], Alcator C-Mod [3], and W7-X [4]. PCI has been used in the study of electrostatic turbulence and transport, with studies of including L-H transitions [5], ELMs [6], QH-mode [7], ITG/TEM instabilities and comparisons with modeling [8–12], I-mode [13], and the effects of ECH heating [14].
PCI has also been used in the study of MHD instabilities [15–17]. The absolutely calibrated PCI has measured the externally launched ICRF heating wave amplitudes [18], as well as mode converted ICW [19] and IBW [20], and the results were found to be in good quantitative agreement with full wave code (AORSA) predictions [21]. Synthetic diagnostics have been developed to allow quantitative comparison between PCI measurements and gyrokinetic simulations [7] and RF simulations [21]. The strengths of the PCI include excellent sensitivity and measurement of the spectrum $S(k)$ over a large range in wavenumber $k_{\text{max}}/k_{\text{min}} \sim 30$. A key limitation is that PCI, like most scattering diagnostics, has a minimum wavenumber, with reduced sensitivity to most ITG and MHD modes. One motivation of this project is to create a combined system with the strengths of the PCI with added capabilities to measure long wavelength modes, including MHD and the largest ITG modes.

On DIII–D, bulk density measurements are made using an external reference interferometer [22, 23]. The DIII–D interferometer, along with other diagnostics, has been used in the study of MHD fluctuations [24, 25], including their effect on the transport of fast particles [26]. A second motivation of this work is to enhance the study of MHD and fast-particle transport by providing a second interferometer chord which can be used with the existing interferometer to diagnose the toroidal structure of MHD modes internal to the plasma.

Current high-performance tokamaks typically have more diagnostics needing windows or feedthroughs than the available port space allows. In future fusion-grade device, this problem will be exacerbated by the complicated labyrinth design required to allow probe beam access while not allowing a direct exit path for fusion products. A further goal of this project is to demonstrate that a density interferometer and PCI diagnostic can share laser, optics, and tokamak windows, making PCI an attractive add-on to the required density interferometer. While combined interferometer-polarimeters have been designed and implemented [27–30], the combination with PCI described herein maximizes the contribution as a diagnostic for turbulence and transport.

2 Theory of Operation

2.1 Phase Contrast Imaging

PCI is an internal reference beam interferometer [31]. The probe beam, typically a 10.6 $\mu$m CO2 laser beam, is passed through a plasma, as shown in figure 1. The index of refraction for the beam is described by

$$N = (1 - \omega_{pe}^2/\omega^2)^{1/2} \approx 1 - \omega_{pe}^2/2\omega^2$$

(2.1)

where $\omega_{pe}$ is the angular electron plasma frequency, $\omega = 2\pi c/\lambda_0$ is the laser frequency, leading to the key result that variation in the index of refraction is proportional to plasma electron density, that is $1 - N \propto n_e$. The initially parallel wave fronts in the probe beam pick up a phase shift proportional to the integration plasma density, which can be written as

$$\Delta \phi(t,x) = \phi_0(x) + \tilde{\phi}(t,x) = -r_e \lambda_0 \int (n_{e0}(x,z) + \tilde{n}_e(t,x,z)) dz$$

(2.2)

where $r_e$ is the classical electron radius, $x$ is a coordinate perpendicular to the laser, and $z$ is the coordinate along the laser path. The subscript 0 is used for slowly varying quantities that can be
Figure 1. The PCI technique operates on a probe beam that has passed through a plasma. The unperturbed portion of the probe beam is focused on the center of the Phase Plate, traversing an extra path length of $\lambda/4$, while the perturbed components of the beam are focused away from the center. The components recombine at the detector.

considered static on the time scales of interest for fluctuations, and a tilde is used for fluctuating quantities with frequencies above roughly 1 kHz. The fluctuations of interest show weak variation along the magnetic field, so the density perturbation can be treated as two-dimensional, although the 3d structure of the magnetic fields can be exploited to provide some localization of the measurement [2]. In practice, $\phi_0$ may be several $\pi$ while $\tilde{\phi} < 10^{-2}$. Furthermore, the $x$ dependence of $\phi_0$ results in weak diffraction which is removed by the PCI beam steering system as described later and can be neglected.

Two key transformations underlie the PCI system. First, a parabolic mirror creates a focal plane, where the laser radiation pattern is essentially a Fourier transform of the beam after the plasma. If the electric field at the plasma exit is described as

$$E_p = E_s e^{i\Delta\phi} = E_s e^{i\phi_0} e^{i\tilde{\phi}(t,x)} \approx E_s e^{i\phi_0} \left(1 + i\tilde{\phi}(t,x)\right), \quad (2.3)$$

the term proportional to unity is focused down to a small spot in the focal plane, while the term proportional to $\tilde{\phi}(t, x)$ forms an extended pattern. The second transformation occurs in the focal plane, where an optical element called a phase plate adds a phase shift of $\pi/2$ to the central spot and reduces the amplitude due to the reflectivity $\rho$ (for ZnSe as used here $\rho = 0.17$). The total beam passes through lenses that create an image plane of the plasma at the detector, where the intensity is

$$I_{\text{pci}} = |E_{\text{det}}|^2 = |E_s e^{i\phi_0} (i\sqrt{\rho} + i\tilde{\phi}(t,x))|^2 \approx |E_s|^2 (\rho + 2\tilde{\phi}(t,x)\sqrt{\rho}). \quad (2.4)$$

Note that the large mean phase shift due to the plasma $\phi_0$ cancels; the unscattered radiation acts as the reference path, and only the time-varying portion contributes. Phase plates can be transmissive or reflective, as at DIII–D, where a 5 cm ZnSe blank is coated with Al to a depth of $\lambda_0/8$ except for a central uncoated region with a width of 1 mm. Because the beam pattern is proportional to the transform of the phase shift $\tilde{\phi}(t, k)$, the PCI process can be seen as bandpass filter in wavenumber space; low-$k$ components miss the reflective portion of the phase plate while high-$k$ components miss
the phase plate entirely. The finite size of the laser beam through the plasma translates to finite spot size on the phase plate, which then sets the minimum detectable wave number at $k_{\text{min}} \approx \pi/w_{\text{pl}}$ where $w_{\text{pl}}$ is the radius of the beam in the plasma. Increasing the beam size decreases $k_{\text{min}}$, so the beam is expanded to the largest size that can be accommodated by the available vacuum vessel port without diffraction. At DIII–D, the PCI expanded beam radius is $w_{\text{pl}} = 3$ cm. The full low-$k$ response is calculated by calculating the complete focal plane beam pattern and the applying the effect of the finite phase plate groove width.

### 2.2 Mach-Zehnder interferometry

To form the reference path of the interferometer subsystem, a small portion of the initial laser beam is deflected and shifted in frequency using an acousto-optic modulator (AOM). Including an additional phase shift due to differences in path length, the reference beam can be represented as

$$E_{\text{ref}} = E_s e^{i\omega a t} e^{i\phi_r}. \quad (2.5)$$

The reference beam and plasma beam are combined on a detector. Using eq. (2.2), the intensity can be written

$$I_{\text{int}} = |E_{\text{ref}} + E_p|^2 = |E_{\text{ref}}|^2 + 2\text{Re} \left[ E_{\text{ref}} E_p^* \right] + |E_p|^2 \quad (2.6)$$

$$\text{Re} \left[ E_{\text{ref}} E_p^* \right] = |E_s|^2 \text{Re} \left[ e^{i(\omega a t + \phi_r - \phi_0)} e^{-i\tilde{\phi}(t,x)} \right]. \quad (2.7)$$

A narrow bandpass filter around the AOM frequency $\omega_a$ ensures that DC components and harmonics of $\omega_a$ are blocked. While path lengths are not matched, the radius of curvature of the reference and probe beam is matched, allowing $\phi_r$ to be a constant in $x$.

Often, the entire beam is focused on the detector, giving a spatial response determined by the Gaussian beam profile

$$s = \int |E_s(x)|^2 \tilde{\phi}(t,x) dx. \quad (2.8)$$

On the combined PCI-interferometer system, the detector is at an image of the plasma and the detector is much smaller than the beam

$$s = \int_{-h/2}^{h/2} |E_s(x)|^2 \tilde{\phi}(t,x) dx$$

$$\approx |E_s(0)|^2 \int_{-h/2}^{h/2} \tilde{\phi}(t,x) dx$$

$$= |E_s(0)|^2 \int_{-h/2}^{h/2} dx \int dk e^{-ikx} \tilde{\phi}(t,k)/2\pi$$

$$= (h|E_s(0)|^2/2\pi) \int dk \tilde{\phi}(t,k) \text{sinc}(kh/2) \quad (2.9)$$

where $h = H/M$ is the detector width scaled by the image magnification and $\text{sinc} y = (1/y) \sin y$. This response is valid for rectangular detector elements when the beam is imaged and the image is much larger than the detector. The wavenumber response of this system is adjustable by changing the image magnification.
3 Hardware Implementation

3.1 Tokamak and beampath

DIII-D is a medium-sized \((R = 1.66 \text{ m}, a = 0.67 \text{ m})\) diverted tokamak with a carbon first wall [32]. Auxiliary heating is provided by neutral beams \((P_{\text{inj}} < 16 \text{ MW})\) and ECH \((P < 6 \text{ MW})\). Typical ranges for plasma parameters are \(B_0 = 1.5–2 \text{ T}, I_p = 1–2 \text{ MA}, n_e = 1–5 \times 10^{19} \text{ m}^{-3}, T_{i0} = 2–10 \text{ keV},\) and \(T_{e0} = 1–4 \text{ keV}\).

The PCI-interferometer beam passes vertically through the vacuum vessel at \(r/a = 0.4\) at the midplane, as shown in figure 2. The beam enters and exits through large ZnSe windows and has a constant \(1/e^2\) radius in intensity of 3 cm in the vessel. A DIII–D density interferometer chord passes vertically through the plasma at nearly the same radial location but 45° distant toroidally.

3.2 Phase Contrast Imaging

The PCI-interferometer systems are contained on an optical table mounted vertically at the level of the lower ports (see diagram in figure 3). The output of a 10–50 W cw CO2 laser is expanded to a large parallel beam using a lens and an off-axis parabolic mirror. Large mirrors steer the expanded parallel beam to the vacuum vessel. The beam returns to the optics table and is focused on the phase plate, described above, using another off-axis parabolic mirror. A fraction of the beam power, about 5%, is directed to a four-element detector at an image of the phase plate and is used to calculate the beam location on the plate. Galvanometers and an analog feedback system are used to steer the beam to the center of the detector and hence the phase plate. This results in the beam spot being held centered on the phase plate to well within 0.01 mm rms. The feedback system removes the effects of movement.
of the tokamak when the toroidal field is applied, both a drift and a 30 Hz vibration, as well as the
diffraction of the beam passing across the density gradient of the plasma.

The PCI detector, at an image plane of the plasma, is a 32-element HgCdTe photoconductive
detector with a 1 MHz bandwidth (Infrared Associates Inc., Stuart, FL; 0.5 × 1 mm elements with
50 µm separation). The detectors and a bank of custom-built active filters are powered by batteries to
reduce noise. Signals are transferred to the digitizers over fiber optic links.

3.3 Combined Interferometer

The interferometer subsystem design [33] reuses the laser and most of the optics of the PCI system, as
can be seen in figure 3. The first component of the interferometer detection is the germanium AOM
(Gooch & Housego, Ilminster UK) which splits 10% of the initial laser power with a 30 MHz upshift to
form the reference path of the detector. A lens is used to set the beam diameter and phase front radius
of curvature at the detector. After the beam passes through the plasma, 25% of the power is separated
before the phase plate. Lenses set the image location and magnification. The beam is combined with
the reference beam on the detector (single 1 × 1 mm photovoltaic element, thermo-electrically cooled;
VIGO System S.A., Poland).

Two considerations dictated design decisions. First, the system was optimized for fluctuations
while measurement of the background plasma density was neglected. A cooled detector was chosen
to reduce noise. Vibration compensation, such as in two-color interferometers, is required for accurate
measurement of the background density but is not needed for fluctuation detection at \( f > 1 \) kHz.
Second, the design of the system was simplified to the extent consistent with making fluctuation
measurements. Extensive noise studies were made during the design to determine which optimizations
were required.

One question of interest was beam path length matching. Testing showed that matching the path
length did not improve the signal to noise, suggesting that, as expected from the specifications, the
correlation length of the scientific-grade laser was longer than the roughly 7 m path through the vessel
and back to the table. Careful matching of the phase front radius of curvature between the reference
and plasma beams is required without matched paths.

The greatest problem was found to be with the AOM. The commercial AOM driver had very
low stability, such that small temporal mismatches between the local oscillator and signal into the
I-Q demodulator reduced output signal by an order of magnitude. A delay line improved the signal
significantly, but was no longer necessary after the commercial AOM driver was replaced with an
oven-controlled crystal oscillator and high-quality RF amplifier. Analog I-Q demodulation was found
to be adequate for fluctuation measurements, and much simpler to implement compared to digital
systems. Achieving adequate signal to noise was found to require an automatic gain-control (AGC)
amplifier (Palomar Scientific Instruments, San Marcos, CA, USA) before the demodulation stage.
While the output of demodulation depends on the phase of the signal in eq. (2.6), not the amplitude,
a signal near the maximum amplitude was needed for good signal-to-noise. The AGC effectively
corrected changes in signal level during the plasma discharge leading to an improved signal to noise
ratio. Similarly, the laser power at the detector should be near the maximum allowing linear operation.
The PCI, using fully optical demodulation, allows for more effective use of the dynamic range of components and has inherently better signal to noise.

3.4 Audio Calibration and Testing

Both the PCI and the interferometer channel are sufficiently sensitive to perturbations in index of refraction to allow detection of sound waves in air, allowing for extensive testing and calibration. Several sources of sound waves are used. For testing the PCI, single-frequency ultrasonic transducers provide the most stable, repeatable source. High-\( k \) testing up to \( k = 40 \text{ cm}^{-1} \) is performed with an ultrasonic speaker. Calibrating the PCI from the interferometer requires a source in the overlapping region of response \( 1.5 < k < 4 \text{ cm}^{-1} \), which is best achieved using a standard stereo tweeter. Note that the PCI depth of field encompasses the entire plasma in the wavenumber overlap region.

The wavenumber response of the two systems around the overlap region is calculated as described above. As the interferometer is inherently absolutely calibrated, this allows for an in situ absolute calibration of the PCI by continuously ramping the audio frequency across the overlap range, as shown in figure 4. This testing showed that the response of the PCI is indistinguishable from the expected value based on known values for detector response, amplifier gains, and laser power.

4 Initial Results

4.1 Turbulence across L-H transitions

The benefit of expanding PCI turbulence measurements to lower wave number can be seen by examining results from the changes in turbulence across a transition from L-mode to H-mode. Figure 5 compares autopower spectra from the traditional PCI system to that from the new interferometer detection, with the time-dependent spectra \( S(f, t) \) demonstrating the evolution as well and the power spectra \( S(f) \) at several time slices for quantitative comparison. The dominant feature of the spectra is the L-H transition at \( t = 1.448 \text{ s} \). Note that the PCI and interferometer \( S(f) \) spectra are identical from 100 kHz to 200 kHz (in L-mode), indicating that the turbulence in that frequency range arises from fluctuations in the wave number range 1.5–4 cm\(^{-1}\) where the two systems overlap in response. The spectra also demonstrate that the noise level for the interferometer is almost 3 orders of magnitude higher (in power) than that of the PCI, a reflection of advantage of the optical mixing used by the PCI technique. The turbulence power is shown to decrease by a factor of 10 at the H-mode transition. In all phases, the low-frequency power is larger in the interferometer channel, indicating that the largest fluctuations are at \( k < 1 \text{ cm}^{-1} \), as expected for ITG turbulence which peaks around \( k \rho_i = 0.2 \). As the H-mode evolves and the pedestal height increases, higher-frequency turbulence is seen to increase as well. This increase is at \( f > 150 \text{ kHz} \) for the PCI and at \( f > 80 \text{ kHz} \) for the interferometer. Assuming a constant lab-frame phase velocity \( v_{\phi} = 2\pi f / k \) and noting that the PCI measured turbulence extends to the PCI minimum wavenumber, we can estimate the minimum wavenumber of the turbulence observed by the interferometer as \( k \sim (k_{\text{pci,min}} / f_{\text{pci,min}}) f_{\text{int,min}} = 0.5 \text{ cm}^{-1} \).
4.2 Large scale and short wavelength turbulence during ELMs

The capabilities contributed by the interferometer channel aid in the study of the interaction between large-scale MHD instabilities and short wavelength turbulence. An example of increased turbulence seen during the edge collapse during an Edge Localized Mode (ELM) is shown in figure 6. Type 1 ELMs are magnetic instabilities driven by the large pressure pedestal and edge current in ELMy H-mode [34] and result in near instantaneous collapse in the edge pedestal, which recovers over typically tens of ms until the next ELM [35]. Figure 6 shows a very short time slice of 1 ms covering the period of the magnetic perturbation and collapse. The PCI spectra $S(f, t)$, calculated with 10 $\mu$s data windows, shows bursts of turbulence separated by a few tens of $\mu$s. The interferometer channel records the large density perturbation caused by the magnetic perturbation along the PCI beam path with a periodicity similar to that of the bursts seen on the PCI. Determination of the phase relationship between the
4.3 Measurement of MHD toroidal mode number

Many classes of MHD instabilities exhibit a global eigenmode structure with a well-defined toroidal mode number \( n \). Many such instabilities have magnetic fields that extend well outside the plasma...
Figure 6. Narrow time window of 1 ms around ELM transition showing bursts of broadband turbulence coincident with large fluctuations in density recorded on PCI interferometer channel, suggesting that 3d electromagnetic perturbation of ELM may drive toroidally localized turbulence.

and are easily detected using arrays of magnetic pickups, however some are fully internal to the plasma and the toroidal $n$ can not always be inferred. Direct measurement of $n$ can be achieved by cross-correlating the PCI interferometer channel with a corresponding channel of the DIII–D primary density interferometer, which has beams separated from the PCI beam by $45^\circ$ toroidally. Radially, the beam paths overlap but with centers displaced by several cm. The example shown in figure 7 includes modes below 100 kHz which are visible on the magnetics array, which can determine the $n$, demonstrating the success of the correlation technique. Modes above 100 kHz are seen on the interferometers and a fast magnetic probe (available at one toroidal location, which does not allow $n$ reconstruction). Starting at 1.80 s, coherent modes with odd $n$ are seen around 200 kHz which are fully internal to the plasma and are not detected on the magnetic probes, demonstrating the capability of the system to measure the $n$ of internal modes not seen on the magnetics. Note that the cross-correlation depends on sub-µs timing accuracy. While the systems share a 4 MHz clock, the primary DIII–D
Figure 7. Toroidal mode number $n$ spectrum calculated by correlating PCI interferometer with DIII–D density interferometer. Spectrum of low-frequency modes from magnetic probe array confirms proper operation. Modes around 200 kHz after 1.8 s are internal modes, not appearing on magnetics, and can only be studied by such diagnostics.

Interferometers are fully digital and the PCI interferometer channel is analog leading to a slight offset in trigger time that must be corrected for; the trigger offset can be uniquely determined using the time period 1.2–1.3 s where the mode frequency ramps with constant $n$. The small radial difference in measurement locations results in a phase shift of the measurement for a subset of eigenmodes where velocity shear distorts the radial structure.

5 Conclusions

This prototype has demonstrated the successful operation of a diagnostic combining the proven PCI technique with a density interferometer. Such a combination diagnostic is expected to become necessary in the future due to the limited port access on fusion-scale devices. New physics capabilities
have been demonstrated due to significantly enhanced low-\(k\) sensitivity over that of standard PCI which allows more complete diagnosis of the instabilities responsible for energy and particle transport and correlating transport events with MHD events. By correlating with the existing DIII–D density interferometry, the added channel can be used to measure directly the toroidal mode number of coherent fluctuations, a valuable measurement for modes restricted to the plasma interior.

Optimization of the system for fluctuation measurements has shown which components are critical to achieving adequate signal to noise. First, maintaining a signal level at the maximum allowing linear operation of all electronics is necessary to make full use of the dynamic range. This includes careful tuning of the laser powers in the reference and plasma arms and the use of an automatic gain control amplifier to stabilize signal levels. Second, the system was found to be extremely sensitive to inadequacies in the commercial AOM driver. Replacement with higher quality components was necessary to allow measurement of broadband plasma turbulence, which requires better signal to noise than detection of coherent modes.

A future improvement that offers the largest increase in capabilities would be to replace the single-channel interferometer detector with a linear array. No change is required to the optical configuration, which images the plasma on the detector. An array with even as few as four or eight elements would allow separation of the signal into large scale MHD and ITG turbulence. Such a system should be considered as an enhancement to existing designs for interferometers on future devices.

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