Phase Contrast Imaging of Waves and Instabilities in High Temperature Magnetized Fusion Plasmas

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Invited Paper

***Abstract*—Phase contrast imaging (PCI) is an internal reference beam interferometry technique which provides a direct image of line integrated plasma density fluctuations. The method has been used with great success to measure waves and turbulence in magnetically confined high temperature plasmas. The principle of PCI was developed in optics in the 1930s by the Dutch physicist Zernike, leading to the development of phase-contrast microscopy [1], [17]. The technique allows one to detect the variation of the index of refraction of a dielectric medium (such as a plasma) due to the presence of waves or turbulent fluctuations. The image produced by the introduction of a phase plate in the beam path, and subsequently imaging the expanded laser beam onto a detector array can be used to calculate wavelengths and correlation lengths of fluctuations in high temperature plasmas. In this paper, the principle of PCI is summarized and examples of measurements from the DIII-D and Alcator C-Mod tokamak plasmas are given.**

***Index Terms*—Phase contrast imaging, plasmas, tokamak plasmas, turbulence, waves.**

I. Introduction

PHASE contrast imaging (PCI), invented by Zernike [1], [17] in the 1930s, allowed one to observe dielectric type of media as light waves traveled through them. These "phase objects" caused the phase of the light waves to change as the light traversed the object (rather than reflect or absorb it) and by introducing a phase plate in the beam path the phase variations could be transformed into amplitude variations in the microscope, thus making the dielectric object "visible." These were called phase objects to differentiate them from visible amplitude objects that reflect or absorb light. In the 1980s, the technique was adapted to plasma physics by Weisen of the Ecole Polytechnique Federale of Lausanne (EPFL), Lausanne, Switzerland, to image turbulence and driven Alfven waves in the "TCA" magnetically confined plasma experiment [2], [18]. This experiment used an expanded CO_2 laser beam and the "corner-cube" mirror approach to accommodate machine vibrations while maintaining beam alignment on the phase plate and detectors. However, this arrangement was not easy to adapt to larger, higher performance tokamaks with large vibrations during the plasma discharge. Nevertheless, realizing the potential of the method to measure long wavelength fluctuations in plasmas, including radio frequency (RF) waves in tokamak plasmas, Massachusetts Institute of Technology (MIT), researchers have revived the technique and improved on it by developing an optical feedback system in two dimensions to maintain the CO_2 laser beam alignment. The concept was implemented successfully by the MIT group on the DIII-D tokamak at General Atomics, San Diego, CA [3], [19] and the Alcator C-Mod tokamak at MIT [4]. The Alcator C-Mod tokamak is surrounded by concrete shielding, which provides a stable base for mounting optical components and allows operation without the optical feedback system [4].

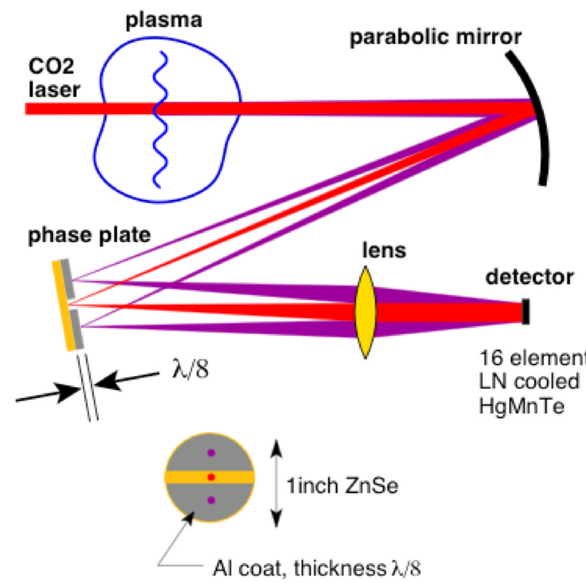

Fig. 1. Conceptual layout of the PCI optics, including the phase plate and detector array. Actual optical design is much more complex.

II. Experimental Setup and Results

The layout of the PCI optical setup is shown in Fig. 1. We see that the critical elements include an expanded CO_2 laser beam (typically 10–20 cm wide), a $\lambda/8$ deep groove on a phase plate which causes part of the beam to shift by 90° as it reflects from the groove (traversing it twice so the total phase shift is $\pi/2$, or

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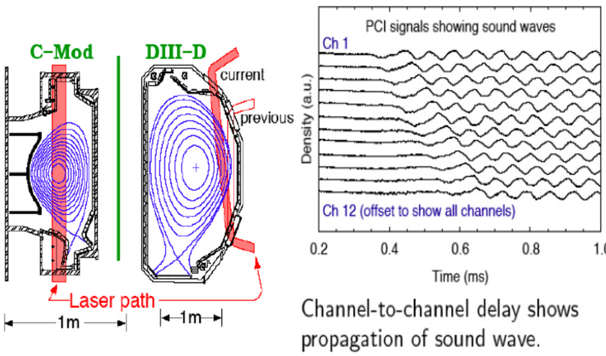

Fig. 2. Laser beam paths in the Alcator C-Mod tokamak (left picture) and in the DIII-tokamak (middle picture). Right side shows sound wave propagation ($k \approx 2$ cm^{-1}) as detected by the PCI diagnostic.

total additional path length is $\lambda/4$), and a liquid nitrogen (LN) cooled detector array is used. In the DIII-D case, the 16 element detector material is HgMnTe while in Alcator C-Mod a 32 element HgCdTe detector is used. Since the index of refraction, N varies as

$$N = \left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)^{\frac{1}{2}} \cong 1 - \frac{\omega_{pe}^2}{2\omega^2} \tag{1}$$

where $\omega_{\rm pe}^2$ is the plasma frequency squared, $(1-N)$ is proportional to the plasma density. The light waves will experience a phase shift as they propagate through the plasma, and it is given by $\Delta\phi(R) \cong \int (N-1)dz \propto \int n(R,z)dz$. It should be noted that localization along the beam is not obtained. After the phase plate, the scattered light wave components are mixed in the detector with the phase-shifted central component. This transforms the phase variation into an amplitude variation. Note that light scattered off sufficiently long-wavelength plasma waves cannot be distinguished from the unscattered light, giving a low k cutoff which is about 0.7 cm^{-1} on both machines. The whole process is described by the following simplified equations.

Wave fields before the phase plate:

$$E_0(1 + i\Delta\phi). \tag{2a}$$

Wave fields after the phase plate:

$$E_0(i + i\Delta\phi). \tag{2b}$$

Field intensity on the detector array:

$$I \propto |E|^2 = E_0^2(1 + 2\Delta\phi). \tag{2c}$$

Thus, the intensities on the detector array vary proportionally with the phase shift of the wave front and hence the line integrated density, with each detector channel corresponding to a different spatial location (radius R perpendicular to the beam) in the plasma, $s_i = \int n(R,z)dz$. With the magnification of the optics, the wavelengths (or correlation lengths) can be obtained from the detector image. In some sense, the detector array intensity variation is an "instant image" of the waves propagating perpendicular to the beam. When a coherent instability or wave propagating perpendicularly to the beam (and partially localized along the beam) is present, the observation and interpretation of such modes is relatively easy. However, in the more general cases of turbulence or coherent waves at an arbitrary direction, the PCI responds only to the spectral components that are perpendicular to the beam. For an externally launched wave, we can model what the detectors should see by integrating the density perturbation (this will be discussed later). Fig. 2(a) and (b) shows the optical layout in the Alcator C-Mod and DIII-D tokamaks. The PCI diagnostic is usually calibrated between shots by launching sound waves with a loudspeaker. Traces of sound waves on individual detectors are shown in Fig. 2(c), where the traces have been displaced vertically to demonstrate the time delay of the waves arriving at different radial positions. Typical sound wavelengths are 3 cm for a sound speed of 340 m/s and a typical frequency of 11 kHz.

The PCI images line-integrated density fluctuations onto a linear array of detector elements. The magnification of the optical layout in chosen depending on the scale length of turbulence of interest. Rarely do the detector elements span the width of the imaged laser beam; rather the detector generally covers only a portion of the center of the beam's Gaussian profile. On DIII-D (C-Mod), the detector element spacing is ~650 (850) μm (see Table I below). The k space Nyquist limit is given by

$$k_{\rm max} = \frac{\pi M}{\delta} \tag{3}$$

where M is the optical magnification and δ is the detector element spacing. This assumes that all system apertures are large enough to accommodate the scattering angle produced by $\mathrm{k_{max}}$. The long wavelength cutoff imposed by the phase plate groove depends on the size of the phase plate groove width (ε). By ignoring diffraction effects (which is valid to a good approximation for our applications presented here; see [2] and [18] for details), we have

$$k_{\rm min} = \frac{\pi\varepsilon}{\lambda_0 f} \tag{4}$$

where f is the focal length of the parabolic mirror. Typical parameters in DIII-D and C-Mod are given in Table I. We see that the Nyquist limit is near 25–30 cm^{-1} in the present experiments, and $k_{\rm min}$ is of the order 0.7 cm^{-1}.

A few examples of actual plasma shots under different plasma conditions demonstrate the versatility of the diagnostic. In Fig. 3 we show PCI results from the Alcator C-Mod tokamak as the plasma enters the so-called enhanced D-alpha light (Fig. 3(a), bottom trace) "EDA" high confinement mode (H-mode) when the ion cyclotron resonance frequency (ICRF) power is turned on [4]. The PCI signal detects density fluctuations associated with a saturated instability (a resistive ballooning mode, also called the quasi-coherent (QC) mode) localized in the plasma edge pedestal region. The mode is unstable due to the combination of finite plasma resistivity and the "bad" magnetic field curvature in the outer regions of the plasma (i.e., decreasing magnetic field and outward centrifugal force while the plasma density gradient is pointing inward) [5]. In a diverted tokamak, the mode is called an X-point resistive ballooning mode [6] and the

TABLE I
PCI SYSTEM SPECIFICATIONS (PV MEANS PHOTOVOLTAIC AND PC IS PHOTOCONDUCTIVE)

	DIII-D	C-Mod
Detector	16 element PV HgMnTe	32 element PC HgCdTe
Detector element separation	650 µm	850 µm
Laser diameter in plasma	5 cm	6-12 cm
Phase Plate groove width	450µm	400µm
Optical Magnification	0.125 - 0.62	0.21-0.81
Nyquist k-limit	6.5 – 30 cm^{-1}	8 - 32 cm^{-1}
Low k-cutoff	0.7 cm^{-1}	0.7 cm^{-1}
Laser Power	20 W	60 W

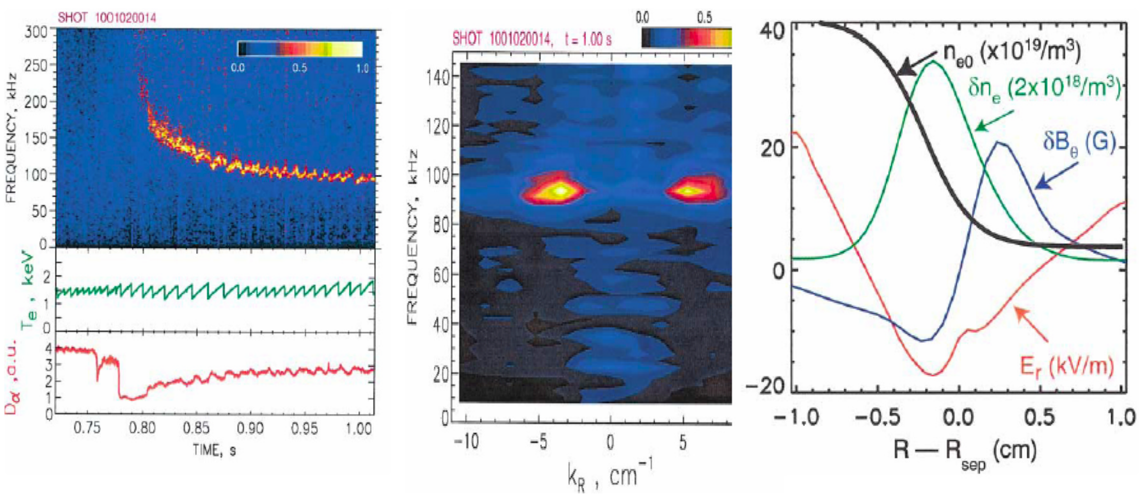

Fig. 3. (a) PCI frequency spectrum showing time evolution of the QC mode and (b) spectrum versus frequency and wavenumber from a 2-D Fourier transform of PCI data as the C-Mod plasma enters the EDA H-mode regime. (c) Theoretical predictions of the mode localization by the BOUT code ([4]).

theoretically predicted quantities [4] are depicted in Fig. 3(c) (based on the BOUT code, [6]).

Alfven cascades (AC) are another interesting phenomena that have been detected by the PCI diagnostic in the Alcator C-Mod tokamak during ramping the plasma current while applying intense ICRF power. AC are present only in "reversed shear" plasmas, or plasmas with an inverted current gradient in the inside core plasma region [7]. The drive for these cascade modes is the pressure gradient of the ICRF power driven fast ions. The eigenmodes are localized radially near the minimum value of the safety factor $q(r)$, $(q = rB_T/B_\theta R)$, and as the $q_{\min}$ value evolves in time, modes with different (m, n) values sweep (chirp) upward in frequency as [7]

$$\omega(t) = \left| \frac{m}{q_{\min}(t)} - n \right| \frac{V_A}{R_0} + \Delta\omega. \quad (5)$$

Here, V_A is the Alfven speed, R_0 is the plasma major radius, (m, n) are the poloidal (toroidal) mode numbers, respectively, and $\Delta\omega$ is a frequency offset associated with finite temperature (sound) modifications of the ideal MHD equations [8].

Modeling of mode frequencies as observed by either magnetic pickup loops or the PCI diagnostic shows good agreement with the above formula. In Fig. 4(a), we show experimental measurements of AC using the PCI diagnostic, and in Fig. 4(b), we show predictions by the MISHKA MHD code. These figures show that the theoretically predicted frequencies match the experiment. More recent results using the Nova-K code, including finite pressure, show matching even the initial starting frequency [9].

Another interesting application of the PCI diagnostic is to measure high power launched RF waves in the ion cyclotron resonant frequency (ICRF) regime. To measure RF waves in the plasma, the PCI laser is modulated using two acoustic-optical modulators (AMOs) so that the RF waves appear in the PCI signal at the beat wave frequency with good detector response. In a typical two ion species plasma, a resonance occurs at the ion–ion hybrid frequency, signifying mode conversion of the long wavelength injected Fast Alfven waves (FW) into shorter wavelength kinetic ion cyclotron (ICW) or ion Bernstein waves (IBW) [10], [11]. Both short and long wavelength RF waves have been detected in C-Mod plasmas. For example, the spatial variation of the perpendicular index of refraction is depicted in Fig. 5(a), where the magnetic field increases from the right to the left, as is appropriate to a tokamak geometry. The full wave code TORIC was used [see Fig. 5(b)] to calculate the electric field structure during mode conversion [10], [12]. PCI was used successfully to measure these waves, and the measurements have clarified the physics of the mode conversion process. The wave number calculated from the model agrees with the PCI data [Fig. 5(c)].

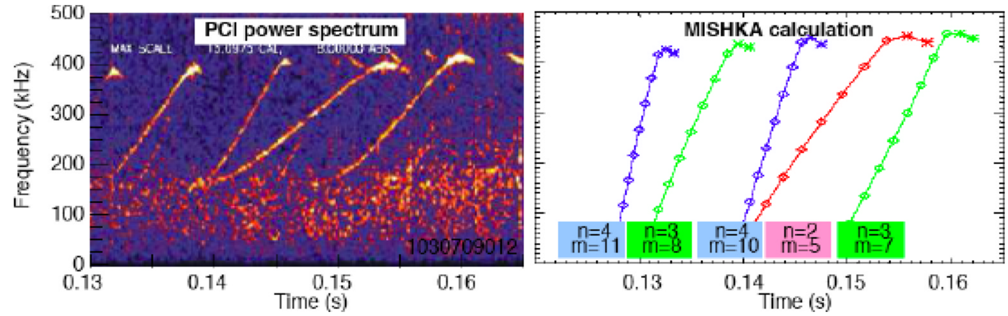

Fig. 4. (a) Alfven wave cascade as observed by the PCI diagnostic. (b) Modeling of the modes by the MISHKA code.

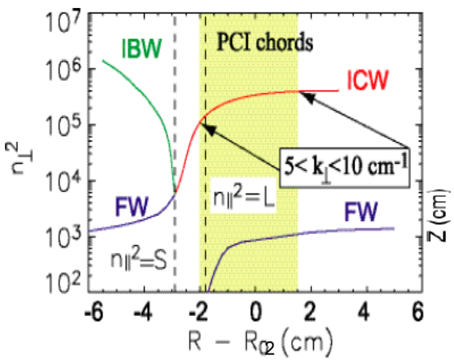

Fig. 5(a). Variation of the index of refraction ($n_\perp = ck_\perp/\omega$), showing the fast wave (launched from the right) converting into the ICW and/or IBW near the resonance layer $n_\parallel^2 = S$, where S is the perpendicular index of refraction (see T. H. Stix, *Waves in Plasmas*, Melville, NY: AIP, 1992). Also see [9].

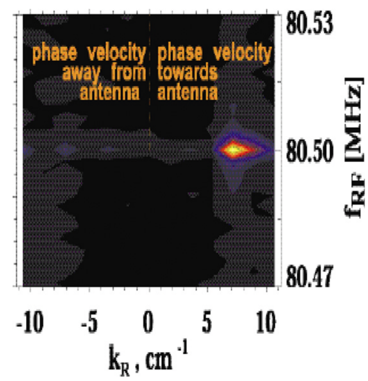

Fig. 5(c). Wave number measurement of the mode converted wave, showing propagation back toward the antenna, verifying that it is the ICW, not IBW that is observed ([10], [11]).

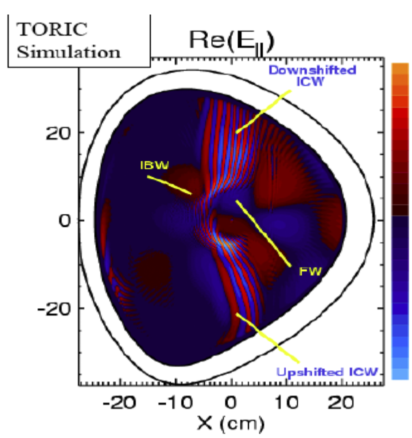

Fig. 5(b). Modeling of the mode conversion process by the full wave code TORIC (after [9], [11]).

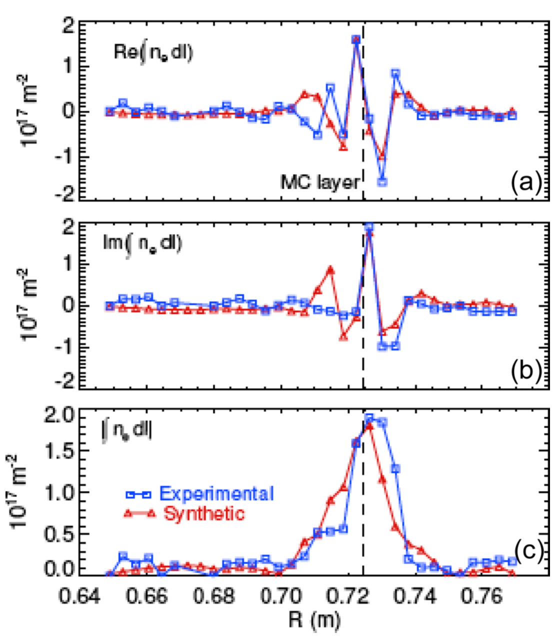

Fig. 6. Comparison of experimental (blue) and synthetic (red) PCI line integrated density fluctuations. $n(\mathrm{He3})/n_e = 0.11$, $n_D/n_e = 0.75$, $n_H/n_D = 0.04$, $n_e = 2 \times 10^{20}\ m-3$, $I_p = 1.0$ MA, $B = 5.57\ T$, $T_e = T_i = 2.1$ keV, $f_{\mathrm{RF}} = 50$ MHz (after [13]).

More recent studies calculated the scattering of the PCI laser beam by the two dimensional (2-D) RF density fields as predicted by TORIC and this kind of modeling (synthetic PCI) was compared with experimental results [12], [13]. As shown in Fig. 6, excellent agreement was obtained between experiment and theory, verifying the importance of two dimensional modeling for a realistic assessment of RF wave fields in tokamak plasmas.

III. Recent Upgrades on the PCI Diagnostic

As discussed previously, the PCI is inherently a line integrated measurement. However, certain characteristics of the turbulence and magnetic field structure in tokamaks allow some resolution of the measurement along the path of the beam to be obtained. Such a system is currently installed on DIII-D, and initial observations have been made. The PCI is sensitive to waves (or the spectral components of waves) propagating perpendicular to the laser beam. In a tokamak, most waves of interest

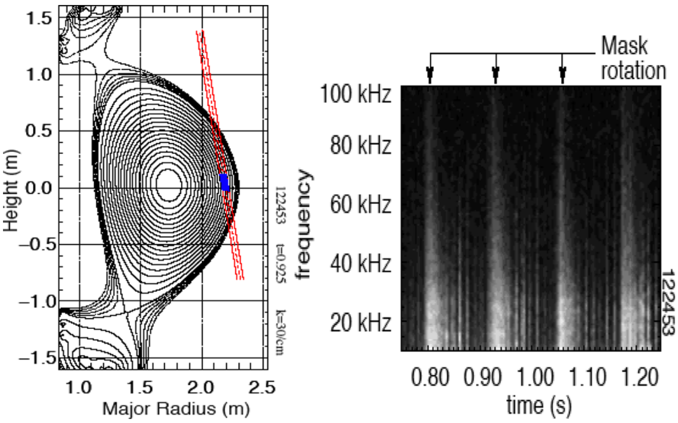

Fig. 7. (a) Modeling of the localization of fluctuations with $k = 30$ cm^{-1} in the DIII-D geometry along the beam using the masking plate. The red lines depict the laser beam and the blue region is the localization of the fluctuations. (b) Power spectrum calculated from the data taken by a slowly rotating mask.

travel perpendicular to the magnetic field. The magnetic field is primarily toroidal, but it has a small radial component that changes with height in the tokamak. The direction of the laser light scattered off the density perturbations is thus slightly different depending on the location in the plasma where the scattering occurred. By filtering the scattered radiation in the PCI system, the measurement can be restricted to small regions of the plasma. This approach has been used with the traditional laser scattering measurements on the Tore Supra tokamak [14]. Unlike with PCI, the scattering angle must be large enough to separate the components, and, therefore, a large exit window is needed. This technique has also been used on toroidal non-tokamak plasmas: on Heliotron-E using a mask [15] as we are doing on DIII-D and on LHD using a 2-D detector [16]. On these machines, the radial field was comparable to the toroidal field, greatly increasing the change in scattering angle and hence resolution. The installation on DIII-D (and recently on C-Mod) is the first use of this technique with PCI on a tokamak plasma. The filtering is performed by placing a mask with a narrow slit into a position in the imaging optics chain where the laser waist occurs. The width of the slit is approximately the diameter of the beam waist. The slit permits only light scattered from a part of the plasma to pass through along with the unscattered radiation. The mask is rotated at speeds from 60 r/min to 1000 rpm. The slower speeds provide better measurements at low frequencies, while the higher speed gives more frequent samples. The mask is mounted on a 2-in aperture bearing driven by a stepper motor. The resolution improves for higher wave-number modes. As shown in Fig. 7(a) for modes in the ETG range with wave-numbers 30–60 cm^{-1}, the resolution is 10–20 cm (see blue region). For ITG range turbulence, the resolution is greater than the machine size, so at best contributions from the top and bottom of the tokamak may be differentiated. Fig. 7(b) shows a power spectrum calculated from data taken with the mask rotating slowly. As the mask rotates, the change in amplitude with time records a change in the amplitude along the beam. Analysis is underway that uses the magnetic geometry and the distribution of scattered laser light on the phase plate to quantify the interpretation.

IV. Summary

In this paper, we gave a brief summary of the principle of phase contrast imaging as deployed in studying plasma waves and turbulence in magnetized fusion plasmas. The diagnostic has been used on DIII-D and Alcator C-Mod to measure a wide variety of phenomena. We have highlighted here contributions of PCI to several important areas of tokamak research. The PCI is a key diagnostic in observing the QC mode which accompanies a particularly enticing regime (the EDA H-mode) of controlled particle transport while maintaining good core energy confinement. PCI measurements of Alfven Cascades are used to infer the magnetic shear in the core plasma in regimes where the shear reduces core energy transport. The PCI is also used to make quantitative measurements of the propagation and interaction of RF waves needed for tokamak heating. The PCI is already a valuable tool for turbulence measurements, and this capability is being improved by adding resolution along the beam. Besides being a relatively inexpensive diagnostic to set up, it is an excellent tool for Ph.D. theses of graduate students.

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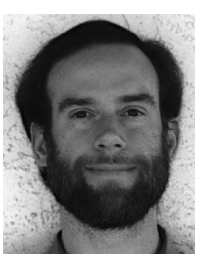

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