Localized density fluctuation measurements by tangential phase-contrast imaging in the TCV tokamak and comparisons with a synthetic diagnostic

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1. Introduction

A new diagnostic has been installed on the TCV tokamak with the aim of studying plasma density fluctuations arising from the entire variety of electron- and ion-dominated microinstabilities predicted in a tokamak, with very high spatial resolution and across the plasma cross section. The diagnostic is currently in a preliminary configuration and has achieved only part of the design specifications, with full commissioning expected for the near future.

Initial results include the detection and characterization of geodesic acoustic modes and a preliminary comparison of broadband turbulence in plasmas with positive and negative triangularity. A synthetic diagnostic is being developed in parallel to allow quantitative comparisons with nonlinear numerical simulations.

2. The tangential phase-contrast imaging diagnostic on TCV

Phase-contrast imaging is an established technique for measuring plasma density fluctuations, particularly in magnetic-confinement nuclear-fusion devices [1-2]. The technique is akin to imaging interferometry, with the crucial elimination of an external phase reference, replaced by an internal one intrinsic to the probing light beam. The Zernike phase-contrast technique is employed to transform the phase into a measurable amplitude variation. The insensitivity to mechanical displacements engenders excellent sensitivity, at the cost of losing absolute phase information: the technique effectively operates as a high-pass wave-number filter.

In the study of plasma microturbulence in tokamaks, one can make use of its known property of being approximately homogeneous along the magnetic-field lines. As the line integration from interferometry also averages out fluctuations with finite wave number along the propagation direction of the probing beam, it follows that at any location only wave numbers perpendicular to both the magnetic field and the beam direction can contribute to the signal. Spatial filtering in a focal plane can then be employed to select a wave-number direction and localize the measurement to a sub-segment of the beam's line of sight. The effectiveness of this technique, i.e., the achievable degree of localization, is greatly enhanced when the beam propagates approximately parallel to the magnetic field [3].

The tangential phase-contrast imaging (TPCI) system on TCV has adopted precisely this configuration. The system has been designed to cover the wave-number range 0.9-60 cm^{-1}, corresponding to $0.2<k\rho_s<90$ and thus covering the range from ion to electron scale lengths (TEM, ITG, ETG modes). A multi-MHz bandwidth is also planned in order to reach the ETG range. A sensitivity of ~3×10^{15} $m^{-3}/MHz^{1/2}$ can be attained, with a spatial resolution down to 1% of the minor radius. The full radial extent of TCV plasmas can be probed by moving the plasma column vertically within the highly elongated vacuum vessel, as shown in Fig. 1 [4].

In its prototype version, the TPCI diagnostic is currently limited to 9 unevenly spaced chords, to 1.5 MHz bandwidth, and to ion-scale wave numbers. The spatial filtering for localization has not been fully implemented and has been applied only in a few selected experiments. A standard operational verification, using acoustic waves in air, is shown in Fig. 2. An upgrade to 32 to 64 chords, broader bandwidth, and full wave-number range, as well as the full commissioning of spatial filtering, is imminent.

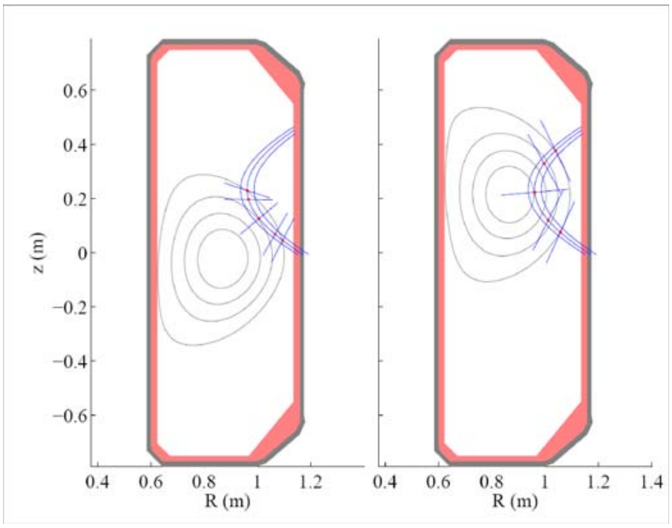

Fig. 1 *Similar plasma at two different vertical positions, illustrating the varying relative location of the TPCI beam relative to the plasma. Segments depict the local wave vectors contributing to the signal.*

As accurate focusing is crucial to the success of the technique, mechanical vibrations must be compensated or damped at the focal plane. Such vibrations are inevitable as several optical elements are mounted on the vessel itself. A feedback control system, replicating a successful earlier design [5], was incorporated in the diagnostic from the outset with the design goal of a maximum deviation of the wave-number transfer function of 1%, corresponding to a maximum shift of 35 μm on the focal plane. As shown in Fig. 3, this goal has not yet been achieved, primarily because of vibrations at higher frequency than expected (100-500 Hz), which are damped less effectively. The upcoming upgrade will also aim to ameliorate this problem.

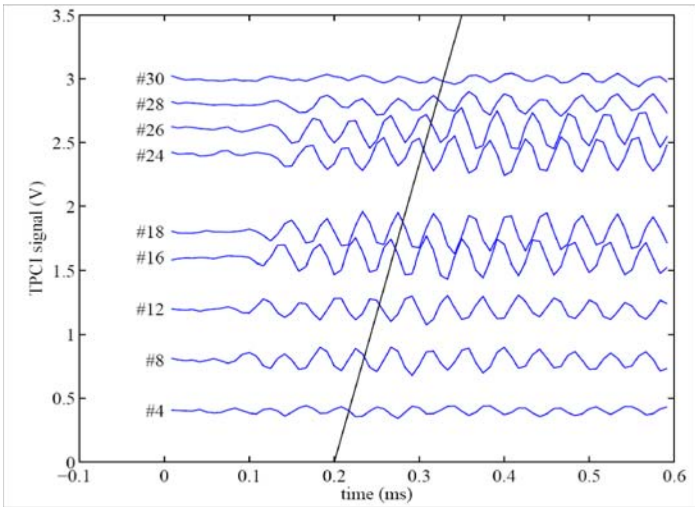

Fig. 2 *TPCI signals in response to an acoustic wave propagating in air perpendicularly to the probing beam. Each signal is offset proportionally to its respective chord location to facilitate visualization of the wave propagation.*

2. First results

An early success of the new TPCI diagnostic was the identification of the geodesic acoustic mode (GAM) on TCV for the first time. The mode is detected in a broad range of conditions, is found to peak close to the last closed flux surface but to extend well into the core, and to be a single-frequency global eigenmode. The radial wave number and direction of propagation are readily measured with the current TPCI setup. The GAM has since been detected by a variety of other diagnostics, as discussed in a companion paper [6].

We also sought to perform a comparison of microturbulence in similar plasmas with opposite signs of the triangularity δ, to address the long-standing question of the cause of the sharply increased confinement in negative- relative to positive-triangularity configurations [7]. Although local flux-tube gyrokinetic simulations have shown that turbulence is suppressed for δ<0, the suppression is observed only at the plasma edge; as triangularity penetration in the core is quite limited, the effect disappears in the inner half of the plasma [8].

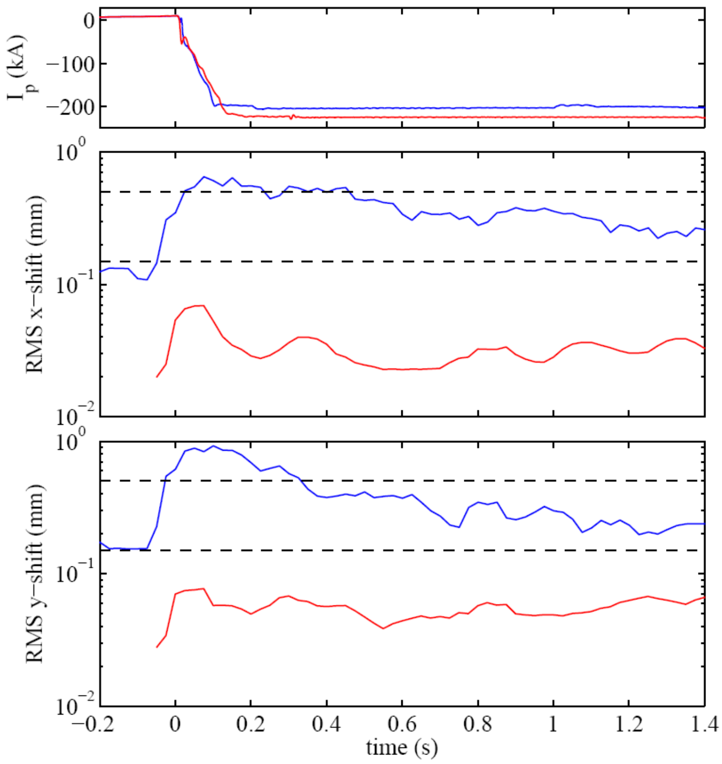

Fig. 3 *Root-mean-square focal-plane displacements along two perpendicular axes, undamped (blue) and feedback-damped (red). The (negative) plasma current is shown at the top.*

Plasmas with δ=-0.4 and +0.4 were studied, with a plasma current of 220 kA, each featuring a vertical sweep of the plasma position to allow the TPCI diagnostic to access different radial locations; 0.9 MW electron-cyclotron heating (ECH) was applied in the center. The mean square signals from the central TPCI chord are compared in Fig. 4. A dramatic decrease in fluctuation level is clearly observed at δ<0 throughout the sweep [4]. Because of the different geometries, the innermost location (point of beam tangency to the flux surface) is different in the two cases: 0.32<ρ<0.59 for δ=-0.4, 0.37<ρ<0.79 for δ=+0.4 (ρ here denotes the normalized square root of the plasma volume). Also, as the high-localization spatial filter was not implemented in this study, the signals are strictly line-integrated and contain contributions from the tangency point to the plasma edge. However, the data are suggestive of a strong suppression of microturbulence for δ<0, even after normalizing by the effective integration length to extract an average density fluctuation level. More studies are planned with the fully upgraded diagnostic.

3. Synthetic TPCI diagnostics

Synthetic diagnostics are powerful tools for meaningful, quantitative comparisons between numerical simulations and measurements. Even with simple analytical models of turbulence spectra, performing the line integration numerically has permitted us to constrain the interpretation effectively, particularly in the interpretation of the GAM measurements [4]. A TPCI synthetic

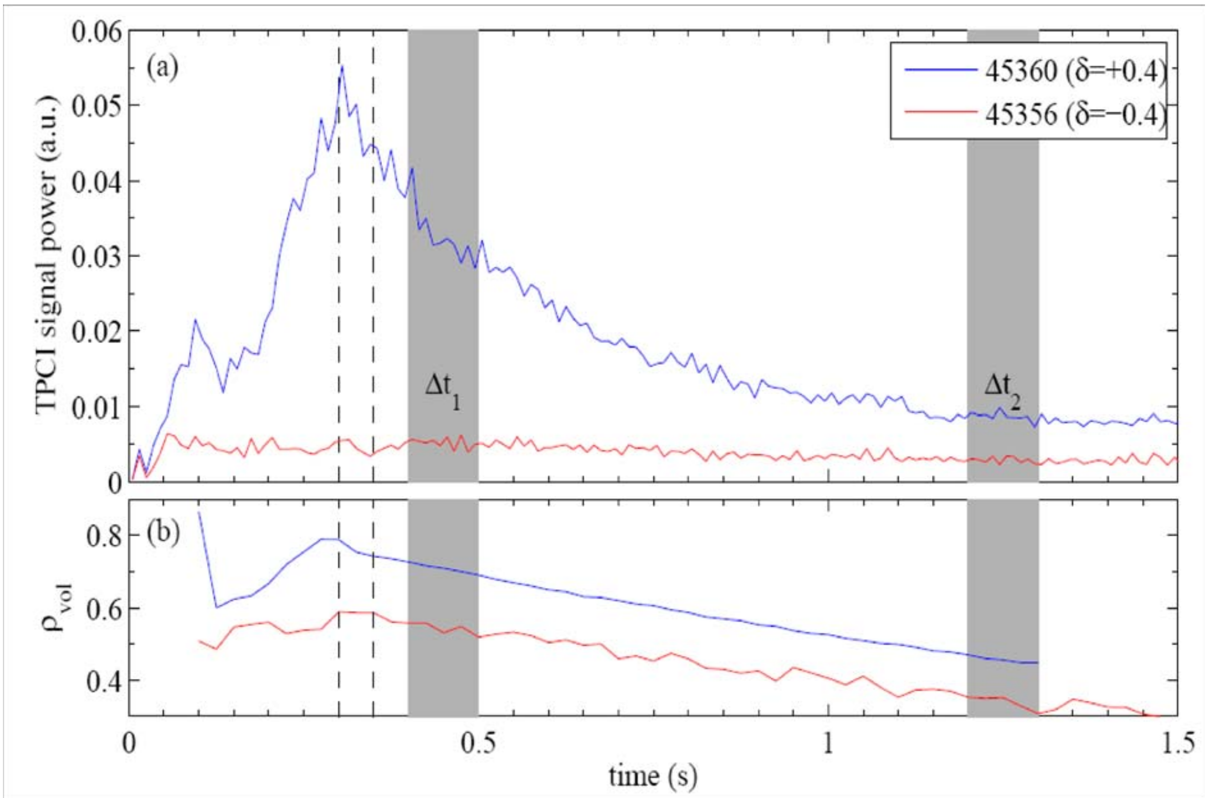

Fig. 4 *(a) Mean-square TPCI signal (bandpass-filtered from 35 to 800 kHz) from the central chord in two discharges with opposite signs of the triangularity; (b) minimum normalized radius reached by the chord. The dashed vertical lines denote the start of the ECH phase (50 ms later in the δ=-0.4 case).*

diagnostic is being developed [9] as a post-processing module for the nonlinear gyrokinetic code GENE [10], applicable to both its flux-tube and global versions. Initial local nonlinear GENE runs were carried out on experimentally relevant scenarios and the applicability of the flux-tube approximation to the synthetic diagnostic problem was verified. The comparison of synthetic-diagnostic and experimental results for these scenarios is the next step and is planned for the near future.

Acknowledgment

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