Turbulence studies by phase-contrast imaging on TCV and developments towards electron-scale measurements

V. Masson[1], S. Coda[1], E. Devlaminck[1], O. Krutkin[1], and the TCV team[2]

[1] *Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), 1015 Lausanne, Switzerland*

[2] *See C. Theiler et al. 2026 Nucl. Fusion 66 116007.*

Introduction

Turbulent transport remains a major challenge for magnetic confinement, as heat and particle transport in tokamaks is often dominated by small-scale instabilities beyond neoclassical predictions. Modes such as Trapped Electron Modes (TEMs), Ion Temperature Gradient modes (ITG) and Electron Temperature Gradient modes (ETG) tap free energy from density and temperature gradients and generate turbulent structures over a broad range of scales. Understanding these processes is therefore essential for improving plasma performance and predicting transport in future reactors.

The Tokamak à Configuration Variable (TCV), with its flexible shaping and versatile electron cyclotron heating and current drive systems, is well suited for turbulence studies. Tangential Phase Contrast Imaging (TPCI) provides localized measurements of electron density fluctuations using a tangential laser geometry, giving access to fluctuation dynamics relevant to turbulent transport and confinement.

The recent TPCI upgrade aims at extending these measurements towards smaller spatial and temporal scales, in particular to access ETG-driven turbulence, which is suspected of contributing to anomalous electron heat transport [1][2], but has not yet been directly measured in fusion-relevant devices. The upgraded system combines increased CO_2 laser power with a new 64-element photovoltaic detector, enabling spatially resolved measurements at higher frequencies and wavenumbers. While the full detector is being commissioned, preliminary L-mode measurements with a single-element detector allow time-resolved analysis of the fluctuation frequency spectrum.

Tangential Phase Contrast Imaging (TPCI)

Tangential Phase Contrast Imaging (TPCI) is a phase-contrast diagnostic in which the unscattered part of the laser beam acts as an internal optical reference. This configuration makes the diagnostic relatively insensitive to mechanical vibrations, since the reference and phase-modulated components follow nearly the same optical path. However, unlike an interferometer with an external reference beam, TPCI does not provide a direct measurement of the absolute plasma density. Instead, it is sensitive to electron density fluctuations integrated along the laser beam path.

When the laser beam propagates through the plasma, electron density fluctuations induce a small phase shift ϕ, proportional to the line-integrated density fluctuation. The role of the TPCI phase-contrast technique is to convert this phase modulation into an intensity modulation measurable by a square-law detector. To first order in ϕ, the electric field after the plasma can be written as

$$E = E_0 e^{i\phi} \simeq E_0(1 + i\phi),$$

where E_0 is the unperturbed beam. Without any phase-contrast element, the detected intensity is $I = |E|^2 = |E_0|^2$, and is therefore insensitive to the plasma-induced phase shift. To obtain a linear relation between the measured intensity and the density fluctuations, TPCI uses a phase plate placed in the focal plane of the optical system. In this plane, the unscattered component is focused onto a central groove, while the scattered components are displaced from the optical axis, as shown in figure 1.

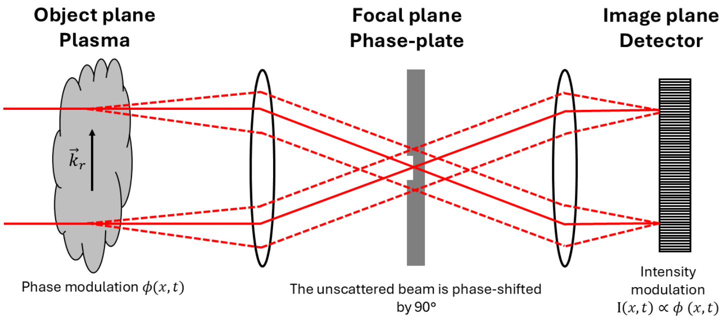

Figure 1: Schematic illustrating the optical principle of TPCI. The reflective phase plate is shown in an unfolded geometry for clarity; in the actual system, the beams are reflected by the mirror rather than transmitted through it.

The groove introduces a 90° phase shift between the unscattered reference beam and the scattered, phase-modulated component. For a reflective phase plate, this corresponds to a groove depth of $\lambda_0/8$, giving an additional round-trip optical path of $\lambda_0/4$. The groove reflectivity can also be reduced by a factor ρ in order to attenuate the much stronger unscattered beam and improve the sensitivity to the weaker scattered component. After the phase plate, the electric field at the image plane can be written as

$$E' \simeq E_0\left(\pm i\sqrt{\rho} + i\phi\right),$$

where the sign depends on the phase-plate convention. The corresponding detected intensity is then

$$I' = |E'|^2 \simeq |E_0|^2\left(\rho \pm 2\sqrt{\rho}\phi\right), \tag{1}$$

where terms of order ϕ^2 have been neglected. The intensity measured at the image plane is therefore linearly proportional to the plasma-induced phase shift, and hence to the line-integrated electron density fluctuation.

Although the measured signal remains integrated along the laser path, TPCI can provide partial localization thanks to its nearly tangential viewing geometry and to an optical filter selecting the direction of the scattered radiation.

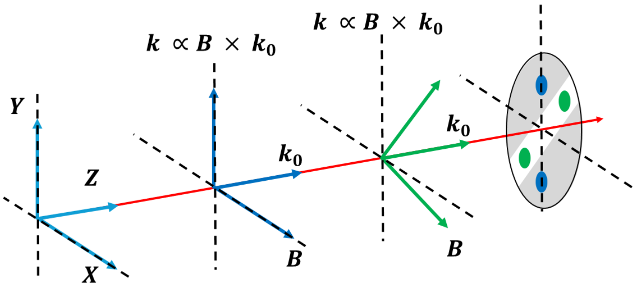

Figure 2: Principle of localization in TPCI.

In a strongly magnetized plasma, turbulent structures are elongated along the magnetic field lines. As a result, the fluctuation wave vector $\mathbf{k}$ is mainly perpendicular to the local magnetic field,

$$\mathbf{k} \cdot \mathbf{B} \simeq 0.$$

In addition, because the phase shift is integrated along the laser beam, fluctuations with a significant wave-vector component along the beam direction are averaged out. The diagnostic is therefore mainly sensitive to fluctuations satisfying

$$\mathbf{k} \cdot \mathbf{k}_{\text{beam}} \simeq 0.$$

At each position along the laser path, the detected fluctuations must therefore have a wave vector approximately perpendicular to both the magnetic field and the beam direction. Since the relative orientation between the beam and the magnetic field varies along the tangential chord, the selected wave-vector direction also changes along the path. As the scattering direction of the laser light is directly related to the fluctuation wave vector, an optical mask can select a given scattering direction and thus favour the region where the corresponding **k** satisfies both perpendicularity conditions. This thus provides spatial localization.

TPCI upgrade

The TPCI diagnostic on TCV has undergone several upgrades to extend its measurement capabilities towards electron-scale turbulence. The CO_2 laser power was increased from 7 W to 50 W in order to improve the signal-to-noise ratio, which is essential for detecting small-amplitude density fluctuations. In parallel, the detector was replaced by a new 64-channel photovoltaic detector with a 10 MHz bandwidth at -3 dB. This detector is designed to provide one-dimensional imaging of the density fluctuations, giving access not only to the temporal evolution of the turbulence but also to its spatial structure.

Together with the upgraded optical system, these modifications are expected to extend the accessible wavenumber range up to approximately $60\,\mathrm{cm}^{-1}$. This range approaches the scales relevant for ETG turbulence. Therefore, the upgrade opens the possibility of directly observing ETG-scale density fluctuations on TCV for the very first time. Such measurements would provide a new experimental window to study electron heat transport and to validate gyrokinetic turbulence simulations.

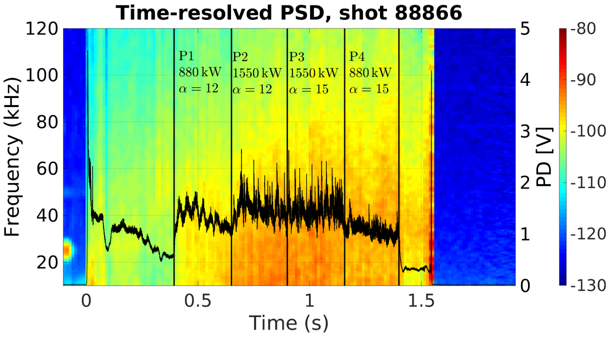

Figure 3: Time-resolved power spectrum of discharge #88866 in negative triangularity with co-current ECCD injection.

First measurement test

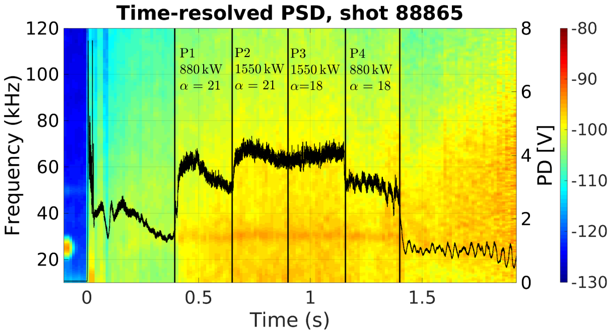

Figure 4: Time-resolved power spectrum of discharge #88865 in positive triangularity with counter-current ECCD injection.

Several issues have delayed the first measurements with the upgraded TPCI diagnostic on TCV. Unintended optical convergence was identified along the optical path around the torus, and additional difficulties were encountered in the control electronics and in the active laser beam stabilization system. Tests with the new 64-element detector also showed that, although its sensitivity is in principle sufficient for the targeted measurements, small-amplitude fluctuation signals remain comparable to the numerical noise of the acquisition system. A dedicated amplification stage is therefore being developed in-house. In the meantime, preliminary measurements were performed using a more sensitive single-element detector.

The measurements presented in this section were acquired during a TCV experimental campaign dedicated to the study of turbulent effects on fast electron physics and ECCD scenarios [3]. The present analysis focuses on two L-mode discharges, #88865 and #88866, corresponding respectively to positive and negative triangularity configurations. In discharge #88865, ECCD was injected in the counter-current direction, whereas discharge #88866 used co-current ECCD. In both cases, the injected ECH power was varied between 880 kW and 1550 kW in four phases, together with the ECCD injection angle.

Although these discharges were not specifically designed for TPCI studies, they provide a useful first test case for the upgraded optical system and for the analysis workflow. Since only a single detection element was available, no information on the fluctuation wavenumber could be obtained. The measurements are therefore restricted to the time-frequency domain, allowing the temporal evolution of the fluctuation spectrum to be compared between the two discharges and between the different EC current-drive phases.

The measurements show, in both discharges, an increase in the fluctuation level as the injected ECH power is raised. A comparison between the two discharges also suggests a lower fluctuation level in the counter-current ECCD case. This observation is qualitatively consistent with previous TCV results, where counter-ECCD was shown to modify the current and shear profiles and to contribute, under suitable conditions, to improved electron confinement and the formation of electron internal transport barriers [4][5]. This suggestion is also consistent with the higher value of the normalized electron-temperature-gradient parameter, defined as $\rho^*_{T_e} = \rho_s/L_{T_e}$ [6], where $\rho_s = c_s/\omega_{ci}$ is the ion sound gyroradius, with c_s the ion sound speed and ω_{ci} the ion cyclotron frequency. The electron temperature gradient scale length is defined as $L_{T_e} = -T_e/(\partial T_e/\partial R)$, where R is the major radius. In the present comparison, $\rho^*_{T_e}$ increases from approximately $5 \cdot 10^{-2}$ in discharge #88866 to approximately $7 \cdot 10^{-2}$ in discharge #88865. However, in the present case, this should only be interpreted as an indication of a possible stabilizing effect, since the discharges were not designed to establish or diagnose an ITB.

In discharge #88865, a coherent spectral feature is observed around 31 kHz. Its frequency and spectral signature are compatible with a Geodesic Acoustic Mode (GAM) [7]. A comparison with TCV magnetic fluctuation measurements was performed, but the corresponding MHD signature remains too weak to allow a definitive identification.

Conclusions

TPCI is a powerful diagnostic for measuring electron density fluctuations with spatial localization along a tangential laser chord. The recent upgrade of the TCV TPCI system, including increased CO_2 laser power and a new 64-element detector, is designed to extend these measurements towards higher frequencies and wavenumbers, with the objective of accessing ETG-scale turbulence. Such measurements would constitute the first direct observation of these fluctuations.

While the full upgraded system is still being commissioned, preliminary measurements with a single-element detector already provide useful time-frequency information. These first results demonstrate the capability of the diagnostic to detect physically relevant fluctuation features and represent an intermediate step towards future spatially resolved measurements with the 64-element detector.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium, partially funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). The Swiss contribution to this work has been funded in part by the Swiss State Secretariat for Education, Research and Innovation (SERI). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, the European Commission or SERI. Neither the European Union nor the European Commission nor SERI can be held responsible for them.

References

[1] A. Mariani et al., “Investigation of the role of electron temperature gradient modes in electron heat transport in TCV plasmas”, Nuclear Fusion **59**, 126017 (2019).
[2] O. Krutkin et al., “Modelling of ETG turbulent transport in the TCV pedestal”, Plasma Phys. Control. Fusion **67** (2025).
[3] E. Devlaminck et al., “A multidiagnostic and model-informed approach to suprathermal electron radial transport in a fokker-planck framework”, EPS Plasma Physics Conference (2026).
[4] T. P. Goodman et al., “An overview of results from the TCV tokamak”, Nuclear Fusion **43** (2003).
[5] J. Cazabonne et al., “Experimental and numerical investigations of electron transport enhancement by electron-cyclotron plasma-wave interaction in tokamaks”, Plasma Phys. Control. Fusion **65** (2023).
[6] G. Tresset et al., “A dimensonless criterion for characterizing internal transport barriers in JET”, Nuclear Fusion **42** (2001).
[7] Z. Huang et al., “Experimental observations of modes with geodesic acoustic character from the core to the edge in the tcv tokamak”, Plasma Physics and Controlled Fusion **60** (2018).