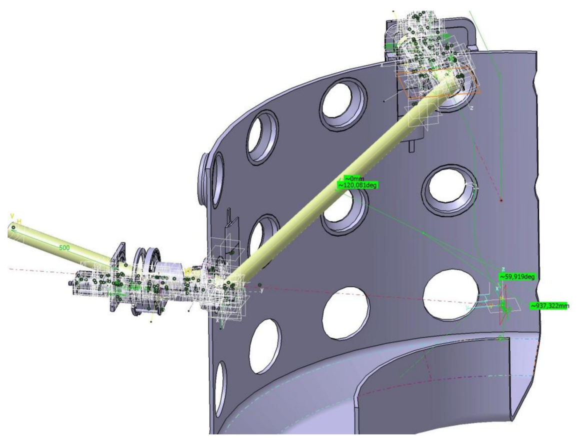
Turbulence studies by Phase Contrast Imaging on TCV and developments towards electron-scale measurements



V. Masson, S. Coda, E. Devlaminck, O. Krutkin, TCV team

Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

Abstract

Turbulence driven by small-scale instabilities governs heat and particle transport in magnetically confined plasmas, limiting confinement times and impeding self-sustained fusion reactions.

While theoretical and numerical models of turbulence are advancing, experimental validation remains essential.

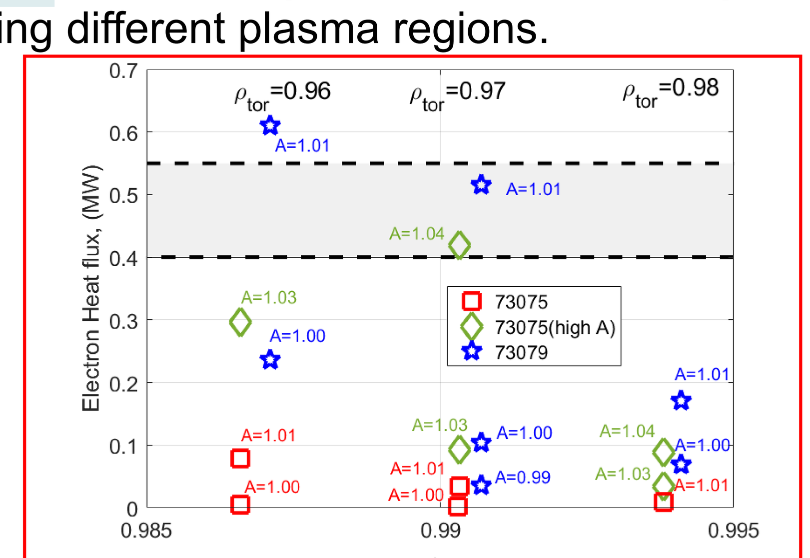
The TCV Tangential Phase Contrast Imaging (TPCI) diagnostic can play a key role, particularly as it has undergone an upgrade, designed to enable it to image for the very first time Electron Temperature Gradient (ETG) driven turbulence. These perturbations are suspected of contributing to significant heat transport in the pedestal [1]. By providing localized, high-resolution measurements of electron density fluctuations, TPCI constitutes a unique tool for validating turbulence models and improving our understanding of turbulent transport in tokamaks.

Introduction

Tangential Phase Contrast Imaging (TPCI) on TCV measures electron density fluctuations using a tangentially injected laser beam, providing spatial localization. It enables spatially resolved turbulence studies, contributing to the understanding of turbulent transport and confinement by probing different plasma regions.

ETG turbulence is suspected of playing a role in anomalous electron transport under certain specific conditions [1], impairing plasma confinement. The TPCI upgrade is intended to provide access to the electron scale and enable ETG imaging.

To date, no direct measurements of these ETG fluctuations have been made in a fusion-relevant device. Observing them would be a world first.



Local nonlinear GENE GK simulations for shots 73075 and 73079. The factor A stretches the density profile, $n_A(\rho_{tor}) = n(\rho_{tor}/A)$, to compare profile-gradient effects between discharges. [1]

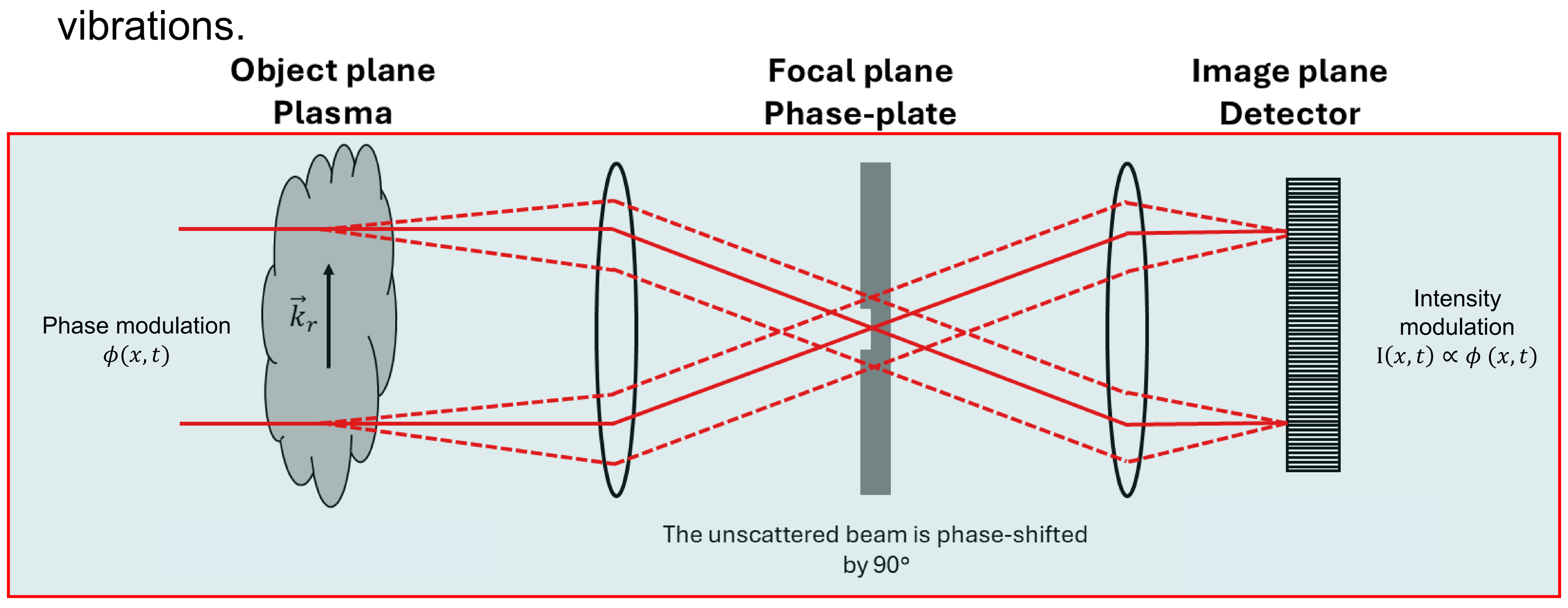
Principles of Tangential Phase Contrast Imaging

- This diagnostic technique is based on the phase shift $\Delta\Phi$ caused by changes in electron line-integrated density within the plasma, allowing it to produce an image of the density fluctuations. [2]

$$\Delta\Phi(\vec{x}) = r_e \lambda_0 \int_{\{\vec{x}_1\}}^{\{\vec{x}_2\}} n_e(\vec{x})\, dl$$

- The intensity I of the resulting image is directly proportional to the beam's phase shift, and thus to the plasma density.
- TPCI is an internal reference system, which makes it highly insensitive to mechanical vibrations.

$$I(\vec{x},t) \approx |E_0|^2[\,1 \pm 2\Delta\Phi(\vec{x},t)]$$

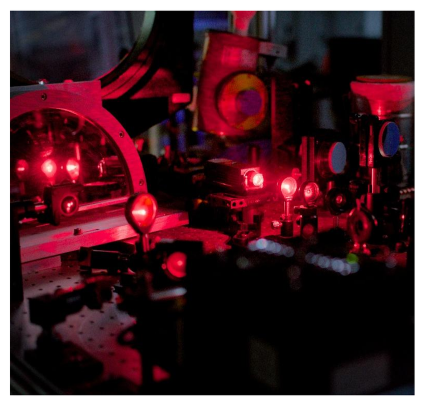


- The half-width d of the phase plate's groove sets a lower limit on the measurable wave number $k_{cutoff} = k_0 d/F$ where k_0 is the laser's wave number and F is the effective focal length of the optical system.
- An upper physical limit on the measurable wave number is imposed by the transition from the Raman-Nath regime to the Bragg regime : $k_{max} = (\pi k_0/L)^{\frac{1}{2}}$.
- Because the laser beam is nearly tangent to the magnetic field, selecting the scattering direction with an optical filter selects a fluctuation wave-vector direction; only the part of the chord where this wave vector is approximately perpendicular to the local magnetic field contributes significantly to the signal, thus providing spatial localization.

TPCI upgrade

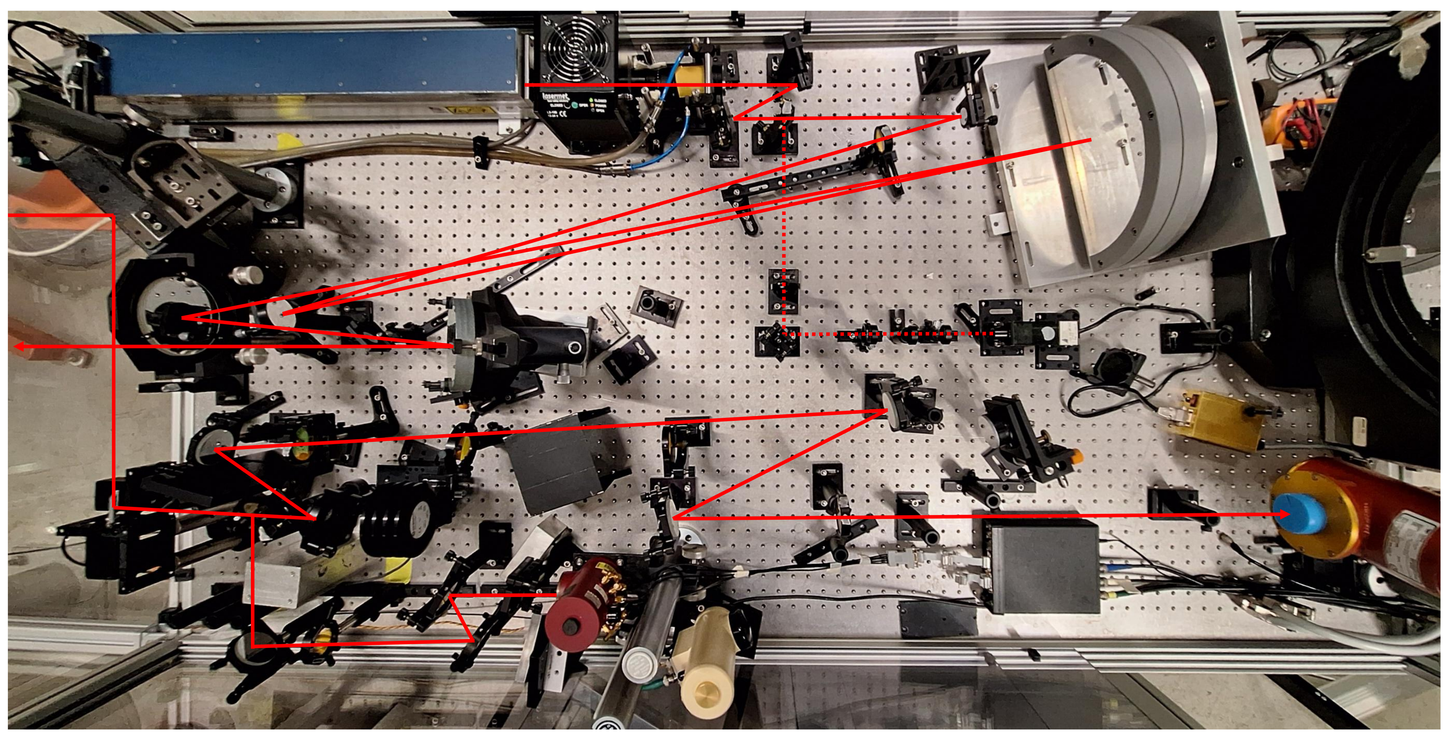
The CO2 laser potential power has been increased from 7 to 50 W to improve the signal-to-noise ratio.
New Judson 64-element photovoltaic detector is designed to have a 3-dB point at 10 MHz.

The optical design was conceived from the beginning to be able to reach high k values, using large enough optics to collect the scattered radiation.



- Laser power: 7 W → 50 W
- Frequency: $0 < f < 1$ MHz → 0 up to 10 MHz
- Wave vector: $1 < k < 13$ cm $^{-1}$ → $1 < k < 60$ cm $^{-1}$

The upgrade is expected to be operational in the immediate future.

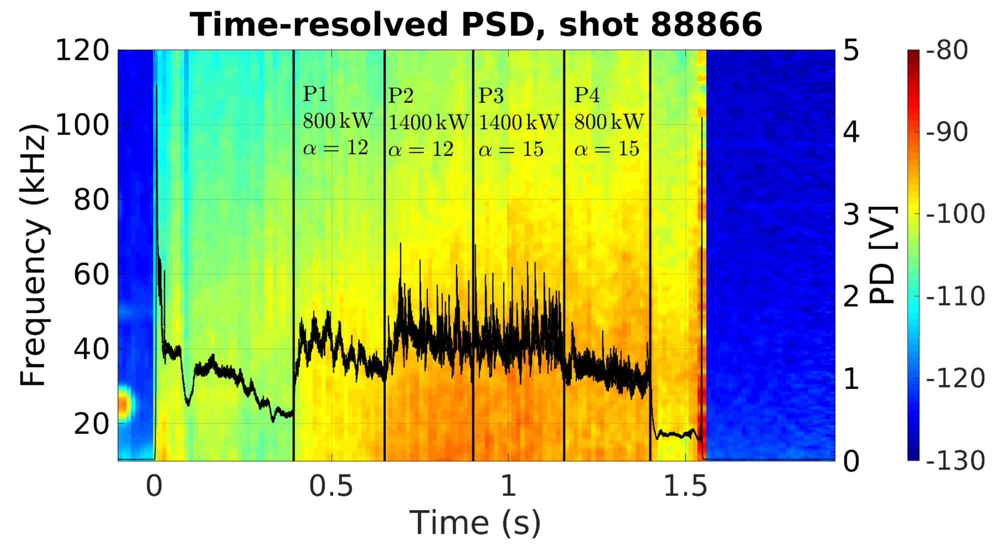


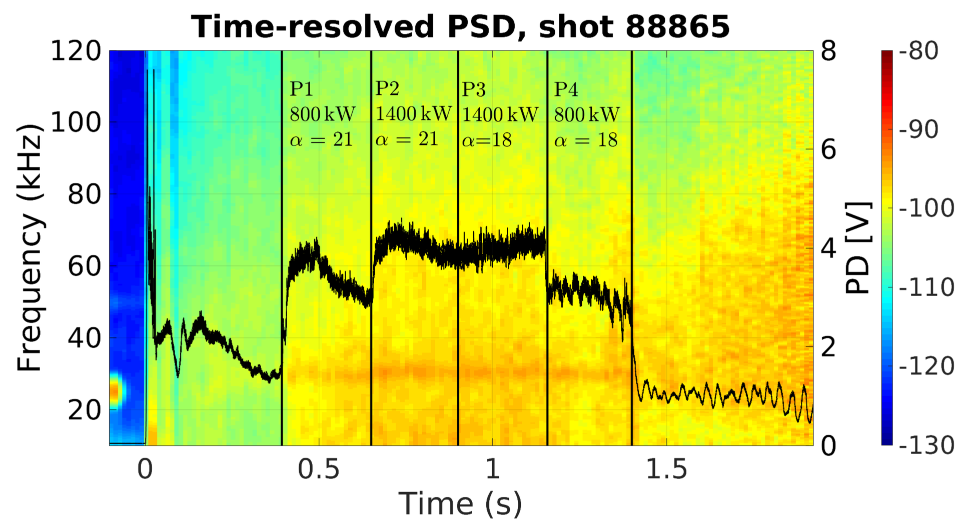
Measurements

While the 64-element detector is being commissioned, first measurements were carried out on L-mode discharges with a single-element detector.

The use of a single detection element precludes direct measurement of the wavenumber k, but still enables analysis of the fluctuation frequency spectrum.

Time-resolved power spectrum density of :
- Negative-triangularity plasma discharge
- ECH power between 880 and 1550 kW in 4 phases
- Varying ECCD co-current injection angle





Time-resolved power spectrum density of :
- Positive-triangularity plasma discharge
- ECH power between 880 and 1550 kW in 4 phases
- Varying ECCD counter-current injection angle

In discharge 88865, a spectral feature around 30 kHz is detected and may be compatible with a geodesic acoustic mode. However, the corresponding MHD signature is too weak to allow a conclusive identification [4].

The decrease in turbulence between the 2 discharges also suggest an indirect stabilizing effect associated with counter-current ECCD injection [5].

This preliminary time–frequency analysis already reveals several physically relevant features. The 64-element upgraded detector will enable the spatial dimension to be incorporated into these analyses. In its previous configuration, TPCI was already extensively used on TCV to study GAMs, TEMs, and ITG modes [6,7].

Conclusions

The recent upgrade of Tangential Phase Contrast Imaging (TPCI) on TCV will extend turbulence studies on TCV into the ETG regime for the very first time. By providing 1D image of electron density fluctuations, TPCI offers critical insights into turbulent transport and plasma confinement. These improvements will help bridge the gap between theoretical predictions and experimental validation, contributing to a deeper understanding of turbulence in magnetically confined plasmas.

References
[1] O. Krutkin et al. (2025). Plasma Phys. Control. Fusion, 67, 025029.
[2] S. Coda et al. (1992). Rev. Sci. Instrum, 63, 4974.
[3] S. Coda. (2024). J. Instrum, 19, C01046.
[4] Z. Huang et al. (2018). Plasma Phys. Control. Fusion, 60, 034007
[5] T. P. Goodman et al. (2003). Nucl. Fusion, 43, 1619.
[6] A. Iantchenko et al. (2023). Plasma Phys. Control. Fusion, 65, 025005.
[7] Z. Huang et al. (2019). Plasma Phys. Control. Fusion, 61, 014021.

This work was supported in part by the Swiss National Science Foundation.

Download the poster

Swiss Plasma Center

EUROfusion

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 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.