Study of plasma-edge turbulence reduction in negative triangularity plasmas using Thermal Helium Beam diagnostic in the TCV Tokamak

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A thorough understanding of the plasma edge is crucial for improving both confinement and stability in fusion reactors. Several strategies are currently being investigated to mitigate edge turbulence and minimize its impact on transport. Recent studies suggest that negative triangularity (NT) plasmas may offer significant advantages over conventional positive triangularity (PT) configurations. These include enhanced confinement, reduction of core turbulence-driven transport, and the elimination of edge-localized modes (ELMs), which are known to cause significant stress on reactor walls. As a result, NT is increasingly being considered a promising alternative for next-generation fusion devices [1][2].

This contribution presents recent experimental results obtained using the upgraded Thermal Helium Beam (THB) diagnostic on the TCV tokamak. A key focus of the study is the influence of plasma geometry on edge profiles and fluctuations, particularly in relation to turbulence suppression mechanisms. Special attention is given to the differences observed between PT and NT plasmas. The analysis highlights the substantial reduction in edge turbulence observed in NT configurations, reinforcing the potential benefits of this shaping approach for improved confinement [3][4]. New insights are obtained thanks to the fact that THB diagnostic can measure profiles and fluctuations across the last closed flux surface.

Thermal Helium Beam diagnostics: upgrades

One of the most valuable diagnostic tools for characterizing edge plasma parameters is the Thermal Helium Beam (THB). This diagnostic technique has gained increasing significance due to its capability to simultaneously measure edge electron temperature T_e and density n_e profiles, along with their fluctuations. The THB system relies on the measurement of selected helium spectral line emissions, which, using Collisional-Radiative models, provide crucial information about plasma parameters with high spatial and temporal resolution.

The original THB diagnostic from the RFP RFX-mod experiment has been upgraded [5] and recently installed at the outer mid-plane of the Tokamak à Configuration Variable (TCV) [6]. This optimized diagnostic will be mounted in the RFX-mod2 experiment, thanks to EU funding for the NEFERTARI project, under the Italian National Recovery and Resilience Plan (NRRP). The key upgrade involves the measurement of an additional HeI emission line beyond the standard three-line approach, which accounts for radiation re-absorption [7]. Photon re-absorption occurs when part of the radiation emitted by the He injected into the plasma is re-absorbed by the He cloud itself, introducing errors in the estimation of plasma properties. This upgrade has led to notable improvements in diagnostic precision, with a spatial resolution of 4 mm and a temporal resolution of up to 0.5 ms. The MPPC detectors mounted on the THB system enable the investigation of plasma edge turbulence with a time resolution of 400 kHz, making it a powerful tool for analysing rapidly evolving plasma phenomena.

Experimental results: triangularity dependence

In 2024, the THB was used to measure a wide range of pulses in NT, exploring different plasma configurations, triangularity, and elongation. Figure 1 shows the trend of turbulence levels in the emissivity of the brightest He line as a function of the triangularity δ. This estimate was obtained by calculating the ratio between the

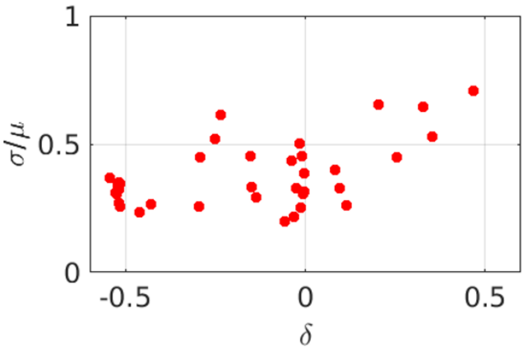

Figure 1 Fluctuation levels estimated as the ratio between the standard deviation and the mean value of the signals at the separatrix as a function of the total triangularity.

standard deviation and the mean value of the signals at the separatrix. For each pulse, a σ/μ value was calculated for each He puff (typically 1 or 2 during the pulse).

All the data shown were obtained without additional heating. Although the data are scattered due to the variety of plasma regimes in the explored configurations, a clear trend of reducing fluctuations with decreasing triangularity is evident. Similarly, as δ becomes more negative, the autocorrelation width of the signals increases, indicating the presence of larger, slower structures and enhanced stability. This is consistent with results previously observed with other diagnostics in TCV [8].

To explore the dependence of plasma edge turbulence on the plasma shape more in details, two identical pulses in USN configuration, having the same δ_{top} but opposite δ_{bottom}, are compared ($\delta_{bottom} < 0$ NT, δ_{bottom}>0 PT). T_e and n_e profiles are very similar in these two pulses, while the turbulence level is different. In Figure 2, the PDFs of the brightest emission line for the two plasma configurations and different radial positions are shown. On the right, the skewness and kurtosis of the distributions are also presented. A higher skewness and kurtosis outside the separatrix are measured in NT compared to PT. A non-symmetric PDF is evident in the NT data around the separatrix, suggesting different mechanisms in the generation of blobs in NT and PT configurations. This finding is further supported by a power spectrum (PSD) comparison, which shows a shift towards lower frequencies in NT plasma outside the separatrix, while the same PSDs are measured inside the separatrix in the two configurations.

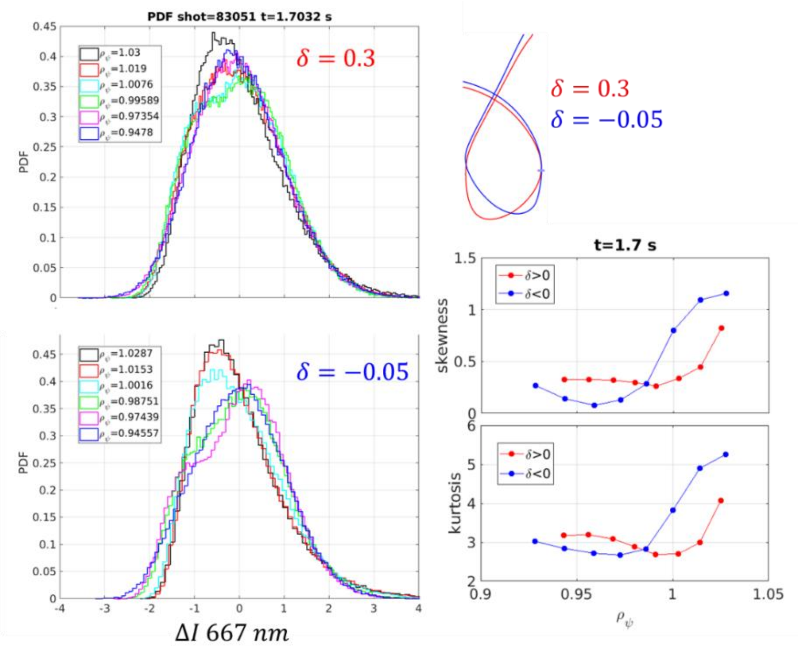

Figure 2 PDF of the the brightest line, in the two plasma configurations and for different radial positions. On the right, the skewness and kurtosis of the distributions.

This is an indication that the change in plasma shape affects particularly the plasma edge, influencing the turbulence level and behavior. This study is extended in different negative triangularity shapes, trying to highlight similarities and differences between the various machines and with expected scaling laws. It is further supported by the data from other plasma turbulence diagnostics (Langmuir probes and Gas Puff Imaging for turbulence studies, Doppler Backscattering to evaluate edge velocity, magnetic probes to study plasma modes). By examining the effects of plasma shaping on edge transport properties, this work contributes to the ongoing efforts to optimize plasma performance in fusion reactors. The results obtained with the upgraded THB diagnostic provide valuable insights into the interplay between geometry, turbulence, and transport, which are crucial for future experimental and theoretical studies.

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