Experimental investigation of the mean turbulent structure tilt angle in the ASDEX Upgrade tokamak

J.R. Pinzón[1,2], C. Angioni[1], T. Happel[1], P. Hennequin[3], E. Blanco[4], T. Estrada[4], U. Stroth[1,2]

and the ASDEX Upgrade Team

[1] *Max-Planck Institut für Plasmaphysik,Garching, Germany*

[2] *Physics-Department E28, TUM, Garching Germany*

[3] *Laboratoire de Physique de Plasmas, Ecole Polytechnique, Palaiseau, France*

[4] *Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain*

Introduction

Turbulence determines at a large extent the confinement of energy and particles in magnetically confined plasmas. Therefore optimizations towards a burning fusion reactor require an accurate description and deep understanding of turbulence and its associated transport. In the last years, models and simulations which can predict turbulence in detail have become available, however the further development of such modelling tools has to be accompanied by comparisons of their predictions with fluctuations measurements of the different physical quantities involved. This would validate the models and would provide a better understanding of turbulence and transport in experiments.

Turbulent fluctuations in plasma parameters, e.g. electron density, results in the formation of *turbulent structures* or eddies. The average size and life time of turbulent structures correspond to the correlation length and decorrelation time of the turbulence, quantities commonly used in transport models. Furthermore turbulent structures can be elongated and tilted. The average *tilt angle of turbulent structures* is a physically meaningful quantity; it is a key element for describing the interaction between turbulence and plasma flows, since it quantifies the anisotropy required for Reynolds stress drive and also induced by sheared flows [1]. Moreover the tilting is a quantity also predicted by gyrokinetic simulations, which have demonstrated its dependency with the radial profiles of plasma parameters and the type of dominant microinstability [2].

Despite of the physical relevance of the tilt angle, its direct measurement is challenging, especially in the confined region of fusion plasmas. The experimental methods currently available are limited to the scrape-off layer or to cold plasmas. In this paper, measurements of the tilt angle on the ASDEX Upgrade tokamak are reported. Measurements are performed using a new method based on Doppler reflectometry [3].
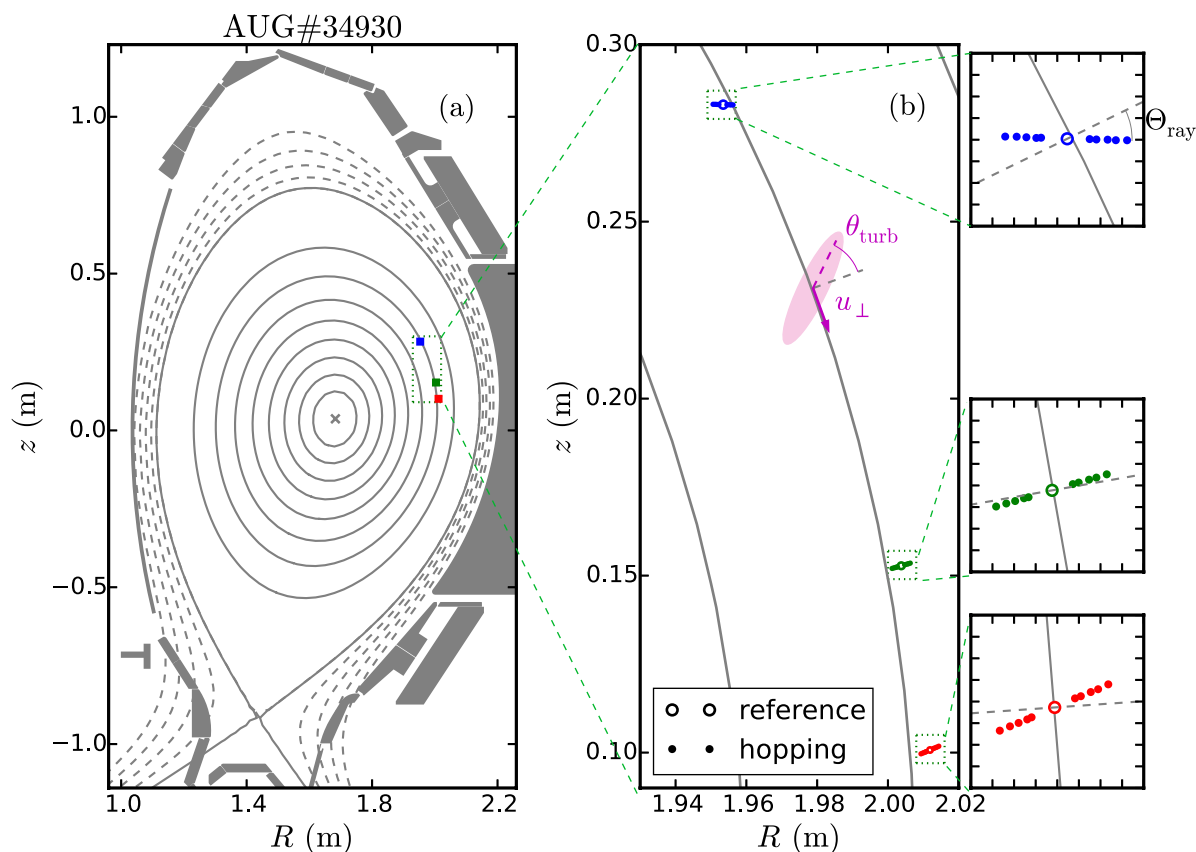
Figure 1: (a) Measurement positions on the poloidal cross-section of AUG and (b) detailed view. Reference and hopping channels are shown with open and closed symbols, respectively. One turbulent structure is schematically depicted. Tilt angle θ_{turb} and propagation velocity $u_\perp$ are indicated.

Doppler reflectometry

Doppler reflectometry is an established diagnostic technique used for the characterization of density turbulence and plasma flows in magnetic confinement fusion experiments [4]. It uses an obliquely injected microwave beam which is backscattered by density fluctuations. The backscattered signal is proportional (in the linear diagnostic regime) to the density fluctuations at the *measurement position*, at which, the electric field of the wave is maximum.

The radial structure of the density turbulence has been investigated by using two beams probing at radially displaced positions [5]. This technique is often called radial correlation Doppler reflectometry. The measurement position of one beam (refer to as *reference channel*) is kept constant, while the measurement position of the other (*hopping channel*) is scanned. In the standard analysis technique, the correlation level between the Doppler reflectometer channels is used for estimations of the radial correlation length [5]. In this paper, the *time delay* τ_{max} computed at the maximum of the cross-correlation function between the signals is used for measuring the
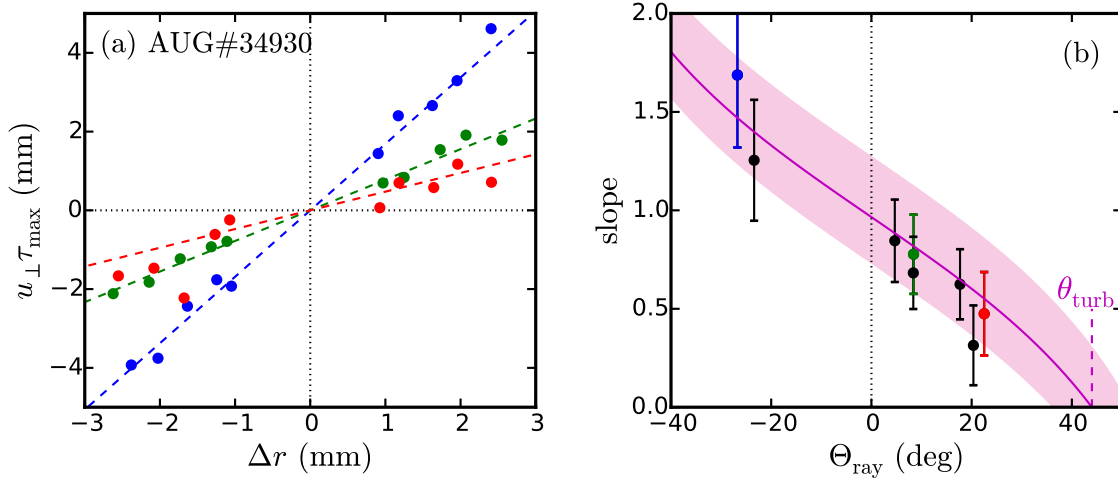
Figure 2: (a) Time delay τ_{max} multiplied with the perpendicular velocity $u_\perp$ as a function of radial separation. Different colours correspond to the measurement positions shown in Fig. 1. The dashed lines depict linear fits to the data. (b) Slope of the fit as a function of Θ_{ray}. Prediction of the model in Ref. [3] is depicted by a magenta line. The tilt angle θ_{turb} is indicated.

tilt angle of turbulent structures.

Tilt angle measurements

Doppler reflectometry measurements have been performed at the ASDEX Upgrade tokamak (AUG). The plasma under investigation corresponds to the L-mode discharge AUG#34930 in the time interval 1.8–2.4 s. The line integrated plasma density is $1.6 \cdot 10^{19}$ m^{-3}. 0.8 MW of neutral beam injection heating have been applied. Measurements have been performed with the steerable mirror system and two V-band reflectometry channels (50–75 GHz) probing in the extraordinary (X) mode polarization.

The measurement positions for three angles of incidence is shown on the AUG cross-section in Fig. 1a. Closed and open flux surfaces are depicted by solid and dashed grey lines, respectively. The magnetic axis is indicated with an "x" and vessel elements are plotted. Fig. 1b shows the zoom to the region of interest. Each measurement position of the reference channel (empty symbols) is accompanied by multiple measurement positions of the hopping channel (full symbols). The insets show different alignment of the measurement positions defining and angle Θ_{ray} with respect to the radial direction.

The time delay τ_{max} has been determined from the Doppler reflectometry data. The results are multiplied times the perpendicular velocity $u_\perp$ and are displayed as a function of the radial separation Δr in Fig. 2a. The three cases correspond to the measurement positions depicted in Fig. 1 by the same colours. A linear dependence is observed for the three cases.

The tilt and the propagation direction of the structure depicted in Fig. 1b are consistent with the time delays presented in Fig. 2a. The structure is strongly miss-aligned with respect to the blue measurement positions, hence it is "seen" later by the hopping channel with respect to the reference channel (positive time delay) for positive Δr while it propagates downwards with velocity $u_\perp$. The miss-alignment between structure and measurement positions decreases for the measurements depicted in green and red, consistently with the smaller time delays experimentally obtained.

The data in Fig. 2a have been fitted with linear functions; $u_\perp \tau_{\text{max}} = m\Delta r$. The slope m obtained from all the measurements in the range $\rho_{\text{pol}} = 0.70\text{–}0.84$ is plotted as a function of Θ_{ray} in Fig. 2b. The data show a clear trend of m with Θ_{ray}. The data have been fitted to using a mathematical model presented in Ref. [3], whose only fitting parameter is the tilt angle of the turbulent structures θ_{turb}. The fit depicted by a magenta line reproduces well the experimental data, showing the suitability of the model for describing the experimental data. The tilt angle is

$$\theta_{\text{turb}} = (44 \pm 6)^\circ, \tag{1}$$

which is indicated in the figure as the value of Θ_{ray} at the intersection with the $m = 0$ axis, at which the structure would be aligned with the measurement points. The error bar is illustrated as shadowed areas around the fit. One structures with this tilt is schematically depicted in Fig. 1b.

Conclusions

The tilt angle method based on Doppler reflectometry has been applied successfully in the ASDEX Upgrade tokamak. The time delays measured in the experiment are well described by the model proposed in Ref. [3], making possible a determination of the tilt angle of the turbulence structures. The method assumes that the passing time of the structures in front of the probing beam is shorter than the decorrelation time of the turbulence. Although this condition is fulfilled in the measurements here presented, further studies on the applicability in more general conditions is required.

The tilt angle measurement offers new possibilities for turbulence studies in fusion plasmas. It will be exploited in future for comparisons with physical models and simulations.

References

[1] U. Stroth *et al*, Plasma Phys. Control. Fusion **53**, 024006 (2011)

[2] Y. Camenen *et al*, Nucl. Fusion **51**, 073039 (2011)

[3] J.R. Pinzón, "Modelling and application of Doppler reflectometry for advanced turbulence studies on the ASDEX Upgrade tokamak and the TJ-II stellarator", PhD thesis, Technische Universität München (2018)

[4] M. Hirsch *et al*, Plasma Phys. Control. Fusion **43**, 1641 (2001)

[5] J. Schirmer *et al*, Plasma Phys. Control. Fusion **49**, 1019 (2007)