Turbulent Transport in Fusion Plasmas

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Introduction

Understanding turbulent transport in magnetised plasmas is a subject of utmost importance to optimise experiments in present fusion devices, and to design a future reactor. The importance of this subject is quite clear when analysing the condition for producing a fusion power that is larger than losses (Lawson criterion). This criterion states that the triple product $nT\tau_E$ must be larger than $3.10^{21}m^{-3}keVs^{-1}$, where n is the density, T the temperature, and τ_E is the confinement time defined as the ratio of the energy content to power losses. The confinement time τ_E, which is basically a thermal relaxation time, is mainly determined by conductive losses due to turbulent transport. A vigorous and coordinated effort has been undertaken worldwide to improve our knowledge in this domain. This overview summarises some of the main results. The interested reader can find an overview of the main results obtained in this field in an overview published in 2006 [1]. This summary covers only the most recent advances obtained on the Tore Supra tokamak, covering the period 2007-2010. Also it addresses mainly issues related to core plasmas. The questions related to plasma/wall interaction are addressed in other papers presented in this conference.

I. Towards the development of a transport model

The main instabilities that underlie turbulent transport in fusion plasmas are now well identified. However the resulting turbulent transport remains hard to predict with the adequate accuracy. The most common methodology for addressing this problem relies on an assumption of space and time scale separation between equilibrium and fluctuations. This assumption is the justification for developing a mean field theory of transport. A common recipe for building most models of transport is based on a quasi-linear theory combined with a mixing-length rule. Recently some advances have been made in this direction by comparing the experimental data to numerical simulations of turbulence [2]. It has been found that measurements of density fluctuations done on Tore Supra by reflectometry are in fair agreement with calculations. This turns out to be true for the turbulence intensity (Fig.1), wave number, frequency spectra and also electron heat diffusivities. Incidentally, simulations were done with gyrokinetic codes, which account for resonances and orbit width effects. The development of these codes has mobilised a large number of physicists, mathematicians and experts in computer sciences. Details can be found in the overview [3].

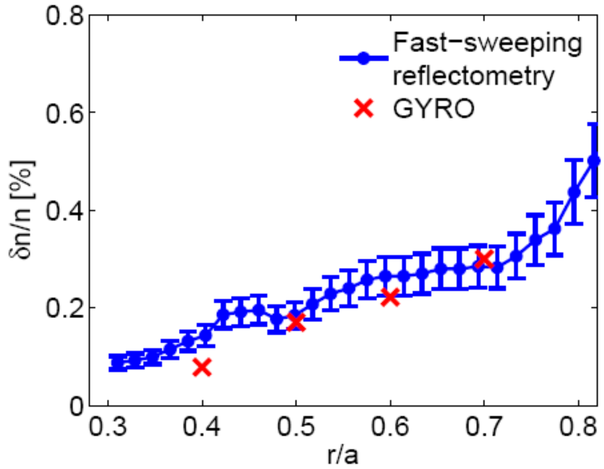

Fig.1: Comparison between turbulence simulations (red crosses) and density fluctuation measurements on Tore Supra (from [2]).

One robust feature of wave number spectra in tokamaks is a power law which behaves as k^{-3} for wave numbers smaller than the inverse of the ion Larmor radius [4]. This was a puzzling result until recently since this spectrum is much flatter than expected.

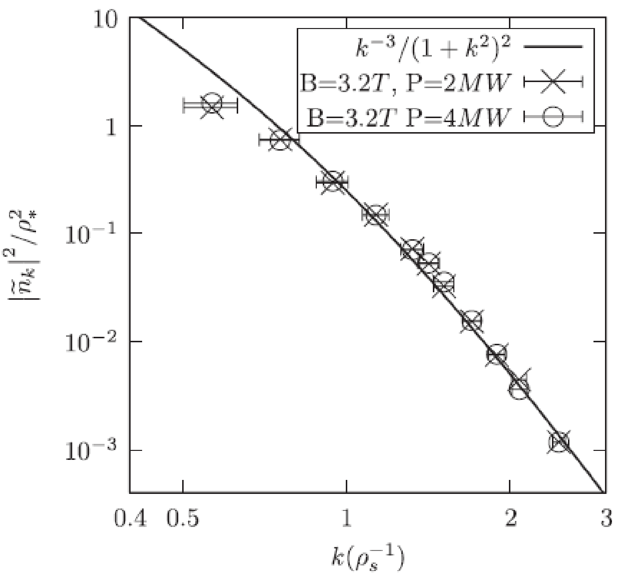

Fig.2: Comparison between measurements of the spectrum of density fluctuations on Tore Supra and the prediction of a shell model (from [5]).

It was shown recently that it is possible to recover these spectra by using a shell model that incorporates the interaction of the background fluctuations with zonal flows on top of the conventional mode-mode coupling (Fig. 2). Local mode coupling underlie most conventional theories and lead to energy or enstrophy cascade. These models predict spectra which are too steep compared k^{-3} [5]. When the non local (in k space) interaction between fluctuations and large scale flows overcomes the local interaction due to quadratic non linearities, the correct slope is recovered. Finally, it was also shown that the fluxes calculated from turbulence simulations agree with the predictions of the quasi-linear theory [6].

This progress has allowed the development of a rather accurate version of the mixing length theory. When combined with quasi-linear expressions of fluxes, which have also been tested against simulations [7], it leads to a transport model that is currently being tested (see [8] for an early version of this model). Comparison between predicted and measured profiles has given encouraging results.

II. Interplay between large scale flows and turbulence

Tremendous progress has also been done in the understanding of momentum transport in tokamaks. A fascinating observation in tokamaks is that the plasma rotates without external sources of momentum. This is quite important since rotation is beneficial for stability and confinement. 3 quantities matter: the radial electric field, and the poloidal and toroidal velocities. Their values result from a competition between the collisional friction, as predicted by the neoclassical theory, and turbulent flow generation due to the Reynolds stress.

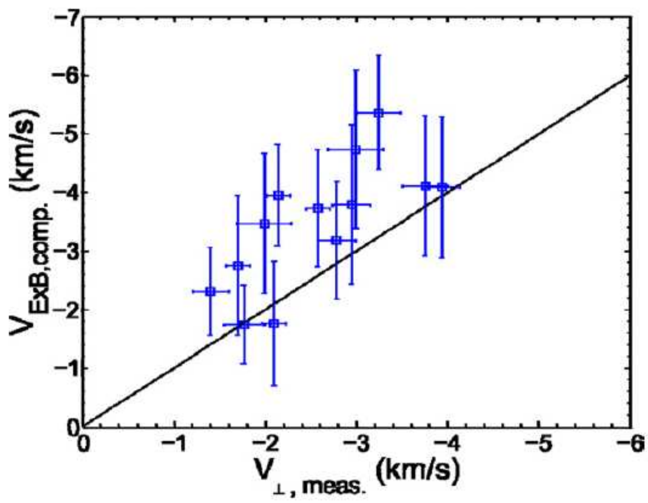

Fig.3: Comparison between measurements of the ExB drift velocity associated to the radial electric field in a tokamak and the neoclassical value (from [9]).

It turns out that the radial electric field in the Tore Supra tokamak is consistent with the neoclassical value, when magnetic corrugations due to the finite number of coils (ripple) are accounted for [9] (fig.3).

Regarding the poloidal velocity, a similar result has been found in simulations, i.e. the value is close to the one predicted by the theory of collisional momentum transport [10]. However, it turns out that the radial profile of the poloidal velocity is not smooth, due to the effect of the Reynolds stress [11]. Hence the shear flow rate is not in line with the neoclassical value. Since it is the one that matters for turbulence self-regulation, it appears that turbulent effects are much more important than one would guess at first sight.

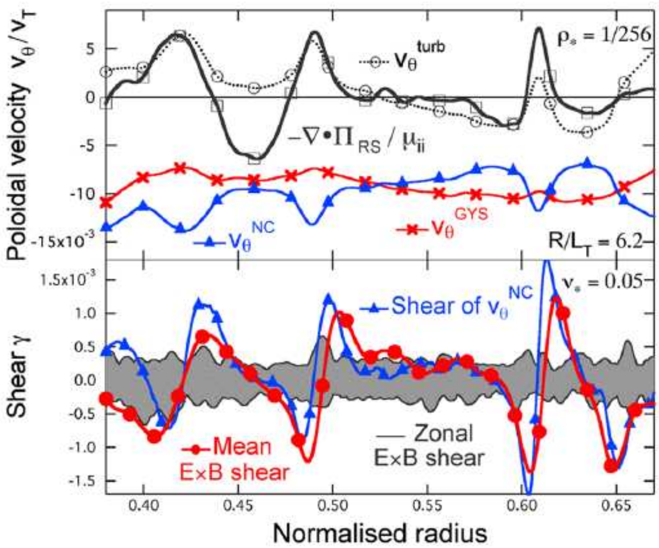

Fig.4: Comparison between the neoclassical poloidal velocity (blue) and the calculated one (red) (from [11]).

The last piece of the story, the toroidal velocity, is not the least intriguing. Indeed a major discovery during the recent years is that a tokamak plasma can spin-up in the toroidal direction in the absence of a core source of momentum. This feature is actually favourable since rotation is needed to stabilise various macroscopic MHD modes. In addition the source of momentum will be very weak in ITER plasmas. Since the geometry is axisymmetric, the plasma should satisfy a theorem of momentum conservation, at first sight contradictory with the observation. In fact there exist a number of processes leading to a transfer of momentum from one location of the plasma to the other. This is a very active field of research on both experimental and theoretical sides. A peculiarity of Tore Supra is that the geometry is in fact not axisymmetric because of the finite number of coils. This is actually true for all tokamaks, but the level of magnetic corrugation is quite high in Tore Supra, typically 7% in the edge, and smaller in the core. This corrugation, called ripple, is responsible for plasma braking which competes with other spin-up processes (in particular turbulent redistribution of momentum). The size of the plasma can be chosen in such a way that the ripple plays an increasing role. Theory predicts that for large ripple, the plasma should rotate in the direction opposite to the plasma current (counter-rotation). It turns out that this indeed the case, as shown in Fig.5 [12].

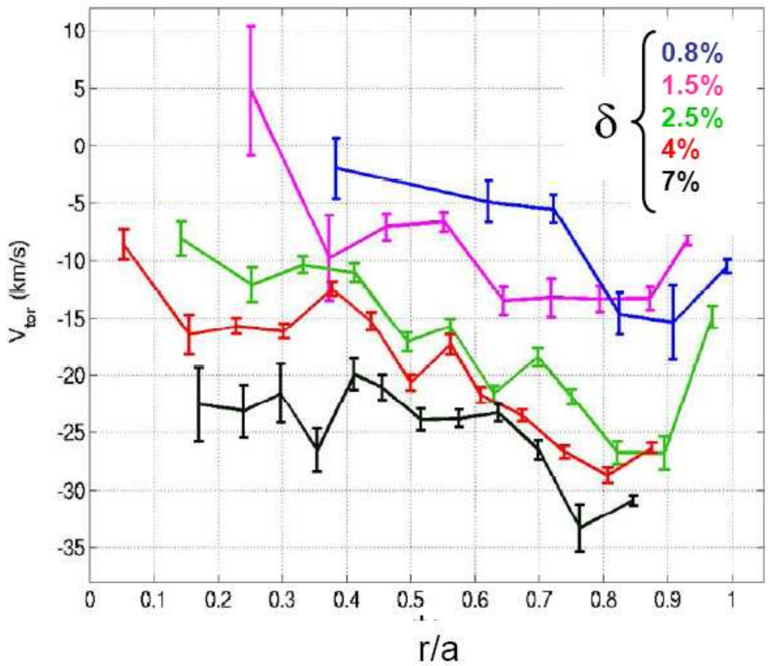

Fig.5: Measurements of the toroidal rotation by charge exchange spectroscopy in Tore Supra. The velocity changes sign when the ripple amplitude increases, moving from co- to counter-rotation (from [12]).

III Particle and impurity transport

Until recently, attention was focused on electron and ion transport. Details can be found in [1]. Momentum (section II) and particle transport were only addressed recently. One striking feature is the ability of main species (electrons, deuterium and tritium), and "impurities" to pinch towards the centre of the discharge. Indeed the ionization sources are usually localised in the edge of the plasma. Therefore, a purely diffusive model (Fick's law) would predict flat density profiles. This is not usually the case, and profiles are peaked in most cases. This is actually an advantage for the main ion species since the fusion power increases as the square of the density. However, the accumulation of impurities in the core is deleterious since it leads to dilution, and also line radiation that cools down the plasma. These impurities come from the plasma/wall interaction, the injection of radiating gases such as Neon or Argon, and also from fusion reactions themselves (Helium ashes). The particle flux Γ is usually written for each species as $\Gamma = -D\nabla n + Vn$, where n is the density and V is called the "pinch" velocity. One important question is to determine whether the diffusion coefficient D and the pinch velocity are due to collisions (the neoclassical theory already mentioned) or turbulence. A powerful method to determine D and V consists in injecting a small amount of impurity in the plasma edge (gas puff for light impurities, or laser blow-off for heavy species). If the concentration is low enough, the impurity behaves as a passive scalar. Spectroscopy measurements provide information on the dynamics, from which the transport coefficients D and V can be calculated.

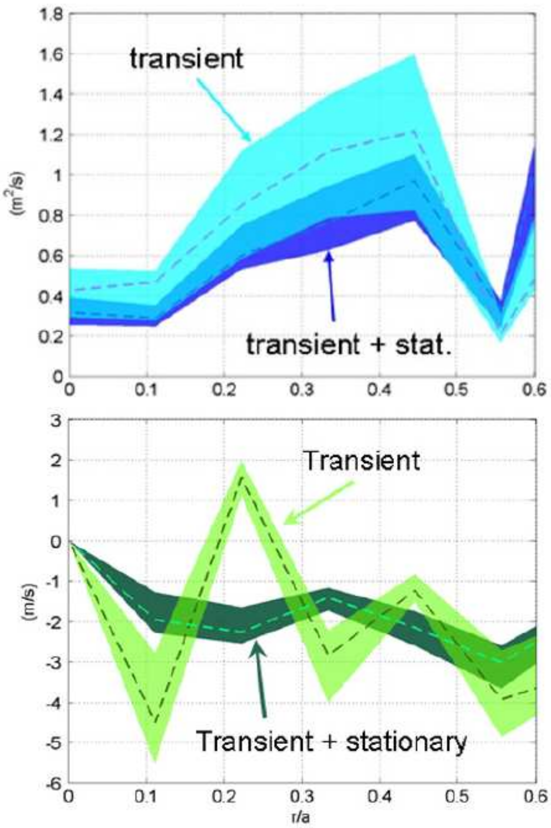

Fig.6: Diffusion and pinch velocity determined from Nitrogen supersonic injection in Tore Supra. The combination between the measured steady-state profile and the transient leads to a strong reduction of error bars (from [13]).

Usually the uncertainties on these two quantities are quite large. However, progress has been made by using a supersonic gas injection and by combining information coming from transient and steady-state regimes. An example is shown in Fig.6 for Nitrogen injection

[13]. Comparison with simulations shows that both D and V are controlled by turbulence, and are well above the neoclassical values, except close to the centre of the discharge (magnetic axis) or in transport barriers (see next section).

An important issue for fusion plasmas is to reach situations where the turbulent transport is low, i.e. with an improved confinement. Transport barriers, which are regions where turbulence is reduced or quenched, are now routinely produced and maintained in tokamaks. Flow shear and/or magnetic shear play a central role in the formation and sustainment of these transport barriers. The onset and self-sustainement of transport barriers are now well documented, though not entirely understood. In particular, it turns out that transport barriers tend to appear when the minimum of the safety factor (winding number of the helical field lines) are close to low order rational numbers. This puzzling behaviour remains unexplained to date.

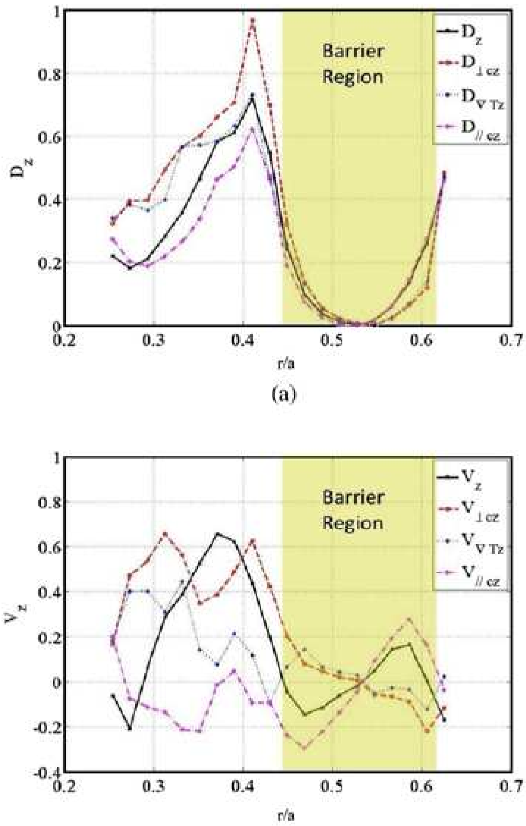

Fig.7 : Computed diffusion and pinch velocities in a presence of a transport barrier due to a reversed magnetic shear. Within the barrier, turbulence is quenched and turbulent transport coefficients are close to zero, as they should. In the plasma core, the impurity pinch velocity is positive, i.e. corresponds to a decontamination of the profile (from [14]).

One important issue, among others, is the behaviour of impurities. It is quite crucial to maintain their concentration at the lowest possible level in the core, since line radiation may cool down the plasma. It has been found numerically that turbulent transport tends to decontaminate the plasma core in presence of a transport barrier [14]. This effect must compete with a strong neoclassical inward pinch within the barrier, so that the final answer is not clear yet. Also another recent finding is that geometry plays an important role in the dynamics of zonal flows [15]. Hence shaping offers another way to control the confinement.

Conclusion

In summary, it is certainly fair to say that tremendous progress has been done in the understanding of turbulent transport in tokamaks, thanks to recent developments of advanced diagnostics and numerical tools. Virtually all transport channels are now investigated, i.e. particle, momentum and heat transport. The direct comparison between simulations and measurements has also done progress, though a more systematic study should be done. Nevertheless, it is also certainly a fact that the confidence in the prediction of confinement is not firm enough to design a future reactor with accuracy. One reason is that the time required by gyrokinetic simulations is enormous so that these simulations cannot be routinely done. Hence one must rely on reduced transport models, whose precision must be improved. Regarding the latter issue, a breakthrough has certainly been done with the emergence of a new generation of models based on quasi-linear theory, linear stability analysis and improved mixing-length rules. Another reason is that some fundamental issues still resist to the understanding. One may quote for instance the spontaneous spin-up of the plasma, of the onset of transport barriers (at the edge or in the core). Also it is now well established that mesoscale structures (e.g. avalanches or zonal flows) play a prominent role in the turbulence dynamics. Hence locality and scale separation assumptions might be invalid. A large part of the work will be dedicated to these questions in the coming years, to prepare as best as possible the operation of ITER, planned to operate in 2018.

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Hoang, F. Imbeaux, R. Sabot, A. Smolyakov, Y. Sarazin, J.L. Segui, E. Trier, L. Vermare, D. Villegas.

References

[1] X. Garbet, C. R. Physique **7**, 573 (2006). See also other papers in this special issue on turbulent transport in fusion plasmas.

[2] A. Casati et al., Phys. Rev. Lett. **102**, 165005 (2009).

[3] X Garbet, Y Idomura, L Villard, T H Watanabe, "Gyrokinetic simulations of turbulent transport", to appear in Nucl. Fusion.

[4] P. Hennequin, et al., Plasma Phys. Control. Fusion **46**, B121-B133 (2004).

[5] Ö. D. Gürcan et al., Phys. Rev. Lett. **102**, 255002 (2009).

[6] A. Casati et al., Nucl. Fusion **49**, 085012 (2009).

[7] A. Casati et al., Nucl. Fusion **49**, 085012 (2009).

[8] C. Bourdelle et al., Physics Plasmas **14**, 112501(2007).

[9] E. Trier et al., Nucl. Fusion **48**, 092001 (2008).

[10] X. Garbet et al., Phys. Plasmas **16**, 062503 (2009).

[11] G. Dif-Pradalier et al., Phys. Rev. Lett. **103**, 065002 (2009).

[12] C. Fenzi et al., submitted to Plasma Physics and Controlled Fusion .

[13] R. Guirlet et al., Nucl. Fusion **49**, 055007 (2009).

[14] S. Futatani et al., Phys. Rev. Lett. **104**, 015003 (2010).

[15] P. Angelino et al., Phys. Rev. Lett. **102**, 195002 (2009) .