*36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, O-4.040 (2009)*

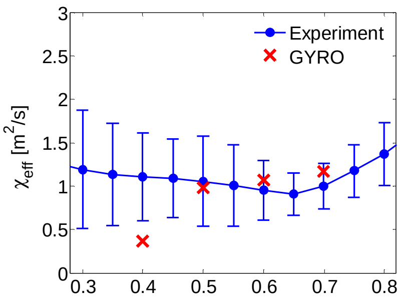
Turbulence in the TORE SUPRA Tokamak: Measurements and Validation of Nonlinear Simulations

A. Casati[1], T. Gerbaud[1,2], P. Hennequin[2], C. Bourdelle[1], J. Candy[3], F. Clairet[1], X. Garbet[1],
V. Grandgirard[1], Ö. D. Gürcan[2], S. Heuraux[4], G. T. Hoang[1], C. Honoré[2], F. Imbeaux[1],
R. Sabot[1], Y. Sarazin[1], L. Vermare[2] and R. E. Waltz[3]
[1]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.
[2]LPP, CNRS-Ecole Polytechnique, 91128 Palaiseau Cedex, France
[3]*General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA*
[4]*IJL, CNRS Nancy-Université, 54052 Nancy Cedex, France*

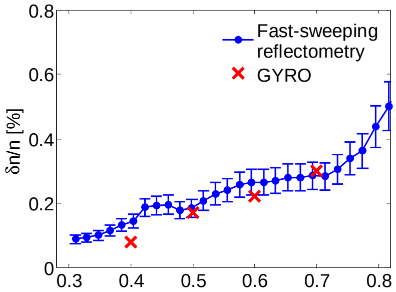
In this study [1], nonlinear gyrokinetic simulations are quantitatively compared to turbulence measurements on the TORE SUPRA tokamak. The relevance of this analysis relies on the fact that the high-order scalar observables are coherently verified also through the investigation of the lower-order spectral quantities. With respect to the previous works, the present study is qualified by the simultaneous validation of (1) the total heat transport coefficient, (2) rms values of the density fluctuations δn/n, (3) k_θ, and (4) k_r wave-number δn/n spectra.

Analysis of the fluctuation spectral power density in the wave-number space transverse to the magnetic field (k_θ, k_r), poloidal and radial wave-vectors respectively, allows us to characterize the turbulence structure, and gives insight into its dynamics in terms of flow of the turbulent energy E(k) at the scale 1/k. On most experiments, the density fluctuation wave-number spectrum $S(k_\perp)=|\delta n(k_\perp)/n|^2$ shows a decay $S(k_\perp)\approx k_\perp^\alpha$ with $\alpha=-3.5\pm0.5$. The TORE SUPRA tokamak is well suited to the study of local k spectra of density fluctuations in the medium-low range $k_\perp\rho_s<2$ (where ρ_s is the ion-sound Larmor radius): it is equipped with complementary microwave diagnostics, fast-sweeping [2] and Doppler [3] reflectometers. One standard TORE SUPRA L-mode ohmic discharge has been chosen as target, TS39596, having toroidal field B_T=2.4 T, plasma current I_p=0.8 MA, central line density $n_{e0}=4.5*10^{19}$ m^{-2}, central electron temperature T_{e0}=1.1 keV, no external momentum input, $\rho_*\approx 0.002$, $\beta\approx 0.25\%$ and $\nu_{ei}\approx 0.7c_s/a$. Nonlinear simulations have been performed with the gyrokinetic-Maxwell code GYRO [4] in the local (flux-tube) limit, using the experimental parameters. Electron-ion collisions, electromagnetic effects and Miller magnetic equilibrium are used; the experimental effective charge Z_{eff} is 1.6, nevertheless, the simulations assume Z_{eff}=1.0 and include gyrokinetic deuterium ions and drift-kinetic electrons with real mass ratio. Further details on these simulations are reported in Ref. [1].

The total effective heat diffusivity χ_{eff}, experimentally obtained from a power balance analysis performed with the CRONOS code [5], is defined as $\chi_{eff} = -(q_e + q_e)/[n(\nabla_r T_e + \nabla_r T_i)]$ where q_e and q_i are the electron and ion heat fluxes, respectively. The experimental uncertainty is estimated taking into account the time evolution of the profiles during 1 s. Making use of the relation $q_j = Q_j - 3/2\Gamma_j T_j$, where Q_j and Γ_j are the energy and particle flux for a species j predicted by GYRO, a good agreement between the numerical expectations and the experimental profile of χ_{eff} within the error bars is achieved (Fig. 1). The exception of r/a=0.4 is due to marginal turbulence found by the simulation on the experimental parameters. Nevertheless, the stiffness to $\nabla_r T_{e,i}$ (whose experimental uncertainty is about ±30%) inherent in the transport problem, suggests that a reliable validation of the turbulence model cannot be limited to this scalar quantity.



1)



2)

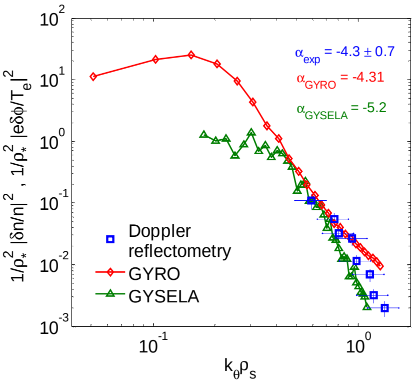
Fig 1: Radial profile of the experimental effective heat diffusivity and comparison with the GYRO predictions.

Fig 2: Radial profile of the experimental rms δn/n and comparison with the GYRO predictions.

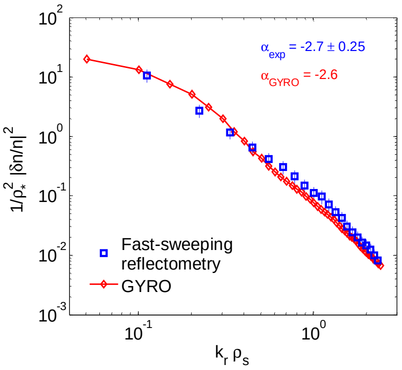
The radial profile of the rms δn/n measured by the fastsweeping system is shown in Fig. 2. Consistently with the diagnostic, this quantity is calculated from the density fluctuations predicted by GYRO at the outboard midplane as $\left.\frac{\delta n}{n}\right|_{rms} = \left(\int_{1cm^{-1}}^{10cm^{-1}} dk_r \int_{0}^{10cm^{-1}} dk_\theta \left|\delta n/n(k_r,k_\theta)\right|^2\right)^{1/2}$. Fig. 2 reports a quantitative agreement with the experimental radial profile within the error bars, matching also the slight increase of δn/n towards external radii found by the diagnostic.

The density fluctuations k_θ spectrum at r/a=0.7 from Doppler reflectometry is presented in Fig. 3. The present analysis focuses only on the region $k_\theta \rho_s \le 1$, where a power law decay with spectral index $\alpha_\theta = -4.3 \pm 0.7$ is found. To reproduce the Doppler measurements, the relation $S(k_\theta) = \int_0^{1cm^{-1}} dk_r \left|\delta n/n(k_r,k_\theta)\right|^2$ is used on the δn simulated by

GYRO at the outboard midplane. The simulation gives a spectral index of $\alpha_\theta = -4.3$ for $0.4 < k_\theta \rho_s < 1$, in remarkable agreement with the reflectometry data within experimental uncertainty. A similar agreement has also been recovered with global electrostatic simulations performed with the semi-Lagrangian gyrokinetic code GYSELA [6], where the equilibrium profile is self-consistently evolved. The main additional difference with respect to GYRO simulations is the adiabatic assumption for the electron response, such that density and electrostatic potential fluctuations are equal. This approximation can be though justified in this case due to the high levels of collisionality. Local TORE SUPRA parameters have been matched in the global simulation at r/a=0.7, but the normalized gyroradius was increased up to $\rho_* = 0.008$ because of limited numerical resources. However, that such a mismatch should not impact the results provided the turbulence exhibits a gyro-Bohm scaling, as expected at these low ρ_* values.



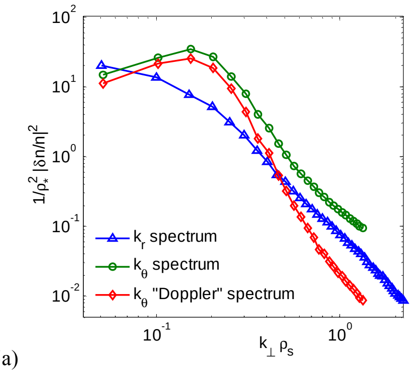
3)



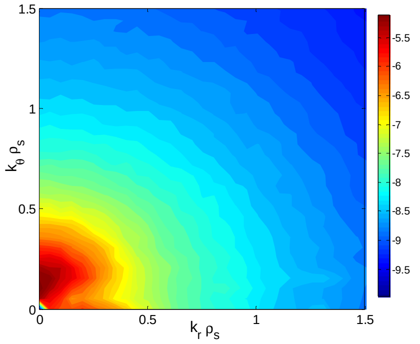
4)

Fig 3: Experimental density fluctuation k_θ spectrum at r/a=0.7, and comparison with the GYRO and GYSELA predictions.

Fig 4: Experimental density fluctuation k_r spectrum at r/a=0.7, and comparison with the GYRO predictions.



5a)



5b)

Fig 5a: δn spectra from the GYRO simulation at r/a=0.7, and the impact of reconstructing the Doppler reflectometry instrumental response on the k_θ spectrum.

Fig 5b: Contour plot of the GYRO $\log_{10}\left|\delta n / n(k_r, k_\theta)\right|^2$.

GYSELA k_θ fluctuation spectrum is also shown in Fig. 3, giving a spectral exponent $\alpha_\theta = -5.1$ for $0.4 < k_\theta \rho_s < 1$. In this global simulation, the spectral power density at low k_θ is flatter, likely due to the presence of large scale sheared flows in the frequency range of geodesic acoustic modes. In the range $k_\theta \rho_s > 0.4$, the nonlinear cascades leads to spectra similar to the measured and the local GYRO ones. This evidence suggests that, in tokamak plasmas, the turbulence wave-number spectrum exhibits a rather general character, likely governed by the dominant nonlinearities in the system, namely, the ExB convection terms.

The local k_r density fluctuation spectrum from fast-sweeping reflectometry at the same radial position r/a=0.7 is shown in Fig. 4. The measurements still exhibit power law decay with a spectral exponent $\alpha_\theta = -2.7 \pm 0.25$ for scales corresponding to $0.4 < k_\theta \rho_s < 2.0$. This spectral quantity is reconstructed through the relation $S(k_r) = \int_0^{10cm^{-1}} dk_\theta \left|\delta n / n(k_r, k_\theta)\right|^2$, which has been applied to the GYRO δn predictions at the outboard midplane. A very good agreement with the fast-sweeping reflectometry data is achieved, both in the magnitude and the slope of the relative fluctuation level, covering also the larger spatial scales up to $k_r \approx 1$ cm^{-1}.

At the same radial location r/a=0.7, the two reflectometers provide then different (above the experimental uncertainties) fluctuation spectral exponents in the perpendicular plane, i.e., $\alpha_\theta = -4.3 \pm 0.7$ while $\alpha_r = -2.7 \pm 0.25$ for $k_\perp \rho_s > 0.4$ (Figs. 3 and 4). Such a discrepancy could suggest a highly anisotropic turbulence, favouring the formation of radially elongated structures. On the contrary, the GYRO results motivate a revised interpretation of this experimental evidence: the two dissimilar exponents may be simply ascribed to intrinsic instrumental effects. While for the fast-sweeping k_r spectrum the contributions of medium-low k_θ wave numbers are retained, the Doppler reflectometry k_θ spectrum selects only very low radial wave numbers. The k_θ fluctuation spectral exponents predicted by GYRO clearly exhibit a difference when integrating over the Doppler range $0 < k_r < 1$ cm^{-1}, giving $\alpha_\theta = -4.3$ in agreement with the measurements, rather than $\alpha_\theta \approx -2.9$ when accounting for all the radial wave numbers [Fig. 5(a)]. A strong anisotropy carried by the peak in the k_θ axis significantly affects the $k_\perp \rho_s < 0.4$ ranges, while the asymmetry appears weaker, but still present, at smaller spatial scales. The iso-level contours of $\left|\delta n / n(k_r, k_\theta)\right|^2$ in the perpendicular plane computed by GYRO [Fig. 5(b)] confirm the expected picture, identifying linearly driven turbulence anisotropy around the $k_\perp \rho_s \approx 0.2$ scales, which are not accessible by our Doppler reflectometry.

References

[1] A. Casati et al., Phys. Rev. Lett. **102**, 165005 (2009)
[2] F. Clairet et al., Plasma Phys. Control. Fusion **43**, 4 (2001)
[3] P. Hennequin, C. Honoré, A. Truc et al., Nucl. Fusion **46**, S771 (2006)
[4] J. Candy and R. E. Waltz, Phys. Rev. Lett. **91**, 045001 (2003)
[5] V. Basiuk et al., Nucl. Fus. **43**, 822 (2003)
[6] V. Grandgirard et al., Plasma Phys. Control. Fusion **49**, B173 (2007)