Turbulence and zonal flow structures in the core and L-mode pedestal of tokamak plasmas

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Abstract. Zonal flows (ZF) play a crucial role in regulating ion temperature gradient (ITG) turbulence. In previous global gyrokinetic simulations using the ORB5 code with the adiabatic electron model, it was observed that long-lived ZF structures, leading to a corrugated transport and temperature gradient pattern, could develop in shaped tokamak plasmas much more than in circular shaped plasmas, resulting in reduced transport. These studies are extended to a hybrid electron model in which trapped electrons are kinetic while passing electrons are assumed to have a Boltzmann response for a case dominated by ITG modes. These confirm the results of the fully adiabatic electron model. Simulations done in “gradient-driven” mode, with a Krook-like relaxation towards a given profile, result in non-realistic corrugated heat source/sink profiles. However, after switching off completely the heat source/sink, it is shown that the ZF and transport corrugation remains. Thus the heat source corrugation is merely a consequence, not a cause, of the zonal structures and related radial transport pattern. Considering then core profiles with constant logarithmic gradients and pedestal profiles with linear gradients for L-mode plasmas, as in Ref.[2], we analyze how ITG transport and zonal structures react by independently varying the logarithmic gradients in the core and the linear gradients in the pedestal, using the adiabatic electron model. Results show the presence of large radial zones straddling the core-pedestal transition region. Avalanche-like events propagate over the radial zone at constant speed and repeat with a well defined frequency somewhat below the local geodesic acoustic mode (GAM) frequency. These avalanches are observed on the $E \times B$ ZFs, effective heat diffusivity and heat flux, thus a change of gradient in the core affects transport in the pedestal and vice versa. In spite of these non-local effects, attempt is made to characterize transport, and in particular its stiffness, quasi-locally. Global simulation results show that with increased input power the logarithmic gradient in the core is only slightly increased while the linear gradient in the pedestal is substantially enhanced.

1. Introduction
Thanks to the development of gyrokinetic theory and advanced numerical techniques adapted to high performance computing platforms, the fusion plasma research community has tools to study turbulent transport from first principles with an increasing level of detail and realism. In this paper, we focus on non-local transport effects mediated by zonal flows (ZF) in situations where the dominant primary micro-instability is the ion temperature gradient mode (ITG).
The role of ZFs in regulating ITG turbulence was established some time ago [4, 5]. Let us recall that the ZFs (in this paper we shall deal with $E \times B$ ZFs) are non-linearly generated by turbulence. The ZFs exist linearly in two branches, a zero frequency one, which was shown to be undamped in the collisionless limit [6] and a branch with finite frequency due to geodesic curvature, the geodesic acoustic mode (GAM) [7]. Nonlinearly, the ZFs exhibit another type of dynamics characterized by avalanches and bursts [8]. These avalanches result in intermittent, radially propagating bursts that carry a fraction of the turbulent heat, particle and momentum fluxes.

In global gyrokinetic flux-driven [9] and gradient-driven [1] simulations, it was shown that these avalanches are related to non-local, non-diffusive spatial behaviour, resulting in a corrugated self-organized flow structure with radially modulated temperature gradients and heat transport. It was furthermore shown that the geometry of the magnetic background configuration plays an essential role in this dynamics: plasma shaping, in particular elongation, increases both the steady residual ZF and the GAM damping, resulting in stronger, more persistent ZF structures. Since steady ZFs are more effective than oscillatory ZFs in suppressing turbulence [10]. ITG turbulent ion heat transport was shown to be reduced in ITER-shaped plasmas as compared to circular cross-section plasmas [1]. These simulations were performed assuming an adiabatic electron response. Here, we examine what happens to the shaping effect when a more realistic model for electrons is considered, namely for which trapped electrons are kinetic and only passing electrons are adiabatic. Since these results were obtained with “gradient-driven” simulations with a relaxation term to a prescribed equilibrium, the question remains as to whether the observed corrugations were not an artifact of the particular source term used. This question is also addressed in this paper.

All the above-mentioned simulations were performed focusing on tokamak core parameters. For such parameters, it is generally found that turbulent transport is characterized by a threshold logarithmic gradient of temperature above which heat transport increases sharply. In other words, it is found (both in numerical simulations and in experiments) that a large increase in input power results in only a modest increase in logarithmic temperature gradient: this phenomenon has been named “profile stiffness”. This explains, partly at least, the degradation of energy confinement time with increasing input power observed in virtually all magnetic fusion devices. Recent experimental investigations [2] on the TCV tokamak have carefully examined this question with an unprecedented level of detail. In particular, it appears that experimental profiles of temperature and density can be parametrized by a “core” region (excluding the inside of the sawtooth inversion radius) with nearly constant logarithmic gradients and a “pedestal” region (even though these were L-mode plasmas) characterized by constant gradients. It was also found that increasing the input power results in profiles with almost no increase in the core logarithmic gradient whereas the pedestal linear gradients were substantially increased, hence the conclusion that core profiles are stiff while pedestal profiles are non-stiff. The question arises whether such profiles are compatible with the computed transport from global gyrokinetic simulations. As a first step in this direction, we address this question with a set of gradient-driven simulations in an ITG turbulent situation, using the adiabatic electron model. Spatially non-local effects will be evidenced: varying the core logarithmic gradient affects transport in the pedestal and vice-versa. The dynamics of ZFs, exhibiting avalanches that propagate through the pedestal and core regions, will be investigated, and provide a possible explanation for these nonlocal effects. The Krook-like source term used in gradient-driven simulations acts as an effective source / sink of power throughout the whole plasma. In order to obtain realistic power profiles, i.e. with a source localized in the core and a sink localized in the pedestal, specific combinations of core and pedestal gradient parameters are searched. For such profiles, it will be found that stiffness in the core is much higher than in the pedestal.

The remainder of the paper is structured as follows. In Section 2 the global gyrokinetic model
is introduced and parameters are described. In Section 3, the core turbulent heat transport using kinetic trapped electron model is computed for an ITER-shaped plasma and compared to a circular plasma of otherwise same profiles. In Section 4, the role of the source term in the ZF and transport self-organization is examined and it is shown that the source corrugation is merely a consequence, not a cause, of the observed ZF, ion heat transport and ion temperature gradient profile corrugation. In Section 5, global ITG simulations are performed with initial profiles characterized by constant logarithmic gradients in the core (\( \rho/a \leq 0.8 \)) and constant (linear) gradients in the pedestal (\( \sim 0.8 < \rho/a \leq 1.0 \)) and the question of core vs pedestal stiffness is examined. Discussion and conclusions are presented in the last section.

2. Global gyrokinetic model and parameters

The basis of our investigations is the gyrokinetic theory in which conservation properties are ensured, at the appropriate ordering level \([11]-[13]\). Numerical simulations are carried out with the global gyrokinetic code ORB5 \([14]\) based on a Lagrangian particle-in-cell (PIC) approach. The equations for the distribution function of each plasma species \( \sigma \) reads:

\[
\frac{\partial f_\sigma}{\partial t} + \mathbf{R} \cdot \frac{\partial f_\sigma}{\partial \mathbf{R}} + p_\parallel \frac{\partial f_\sigma}{\partial p_\parallel} = \sum_{\sigma'} C(f_\sigma, f_{\sigma'}) + S(f_\sigma),
\]

where \( p_\parallel = m_\sigma U + (e/c)J_0 A_\parallel \) is the canonical parallel momentum, \( J_0 \) is the gyroaverage operator, \( U \) is the parallel velocity, \( C \) is the Coulomb collision operator and \( S \) is a source term (see below). In this paper, collisions and electromagnetic effects will be neglected (\( C = 0, A_\parallel = 0 \)).

The system of equations is complemented by the Euler-Lagrange characteristics equations and the quasi-neutrality equation with linearized polarization density in the long wavelength approximation, \( k_\perp \rho_s < 1 \). Different approximations will be used for the perturbed electron density. The simplest model assumes purely electrostatic perturbations and an adiabatic electron response along the equilibrium field lines \( \delta n_e = (e n_{0e}/T_e)(\phi - \bar{\phi}) \) where \( \bar{\phi} \) is the flux surface-averaged perturbed potential. Defining toroidal magnetic coordinates \( (s, \theta, \varphi) \) and noting \( J \) the Jacobian we have \( \bar{\phi} = \int \phi J d\theta d\varphi/\int J d\theta d\varphi \). Trapped electron mode response can be taken into account in a ”hybrid” model, in which only passing electrons are assumed to respond adiabatically \( \delta n_e^{passing} = \alpha_p (e n_{0e}/T_e)(\phi - \bar{\phi}) \) where \( \alpha_p \) is the fraction of passing electrons, while the trapped electrons are assumed drift-kinetic. More details can be found in Refs.\([15, 16]\).

The source term \( S \) in Eq.\([1]\) has three purposes. First, it is used as a heat source, so that the temperature gradients are maintained above their marginal stability point over long times. Second, it is used in order to obtain a quasi-steady state, in which not only the fluxes and gradients, but also the entropy, keep a steady time-averaged value \([17]\). Third, it is used as a noise control scheme, in order to maintain the signal to noise ratio steady (again, in a time-averaged sense) over indefinitely long times \([18]\). The source term takes the form of a modified Krook operator, \( S = -\gamma_K \delta f + S_{corr} \), in which \( \delta f = f - f_0 \), \( f_0 \) is a time-independent prescribed function of phase space coordinates, \( \gamma_K \) is chosen small enough not to damp too much the physical eigenmodes (typically smaller than \( 1/10^3 \) of the most unstable linear growth rate) and \( S_{corr} \) is such that the zonal flow phase space structures are conserved \([18]\):

\[
\int dv S \left( \frac{\langle v_\parallel \rangle}{B} - \left[ \frac{\langle v_\parallel \rangle}{B} \right]_b \right) = 0
\]

where the overbar means flux surface-average, and the square bracket with subscript \( b \) means bounce-average. Moreover, \( S_{corr} \) is designed so as to conserve particle density and parallel momentum. There is the option, in addition, to conserve kinetic energy as well, in which case the source term acts merely as a noise control operator; if this option is not used, the source term
acts also as a heat source/sink that tend to restore the temperature profiles towards prescribed ones.

Two different profile definitions are used. First, as logarithmic gradient of the poloidal flux $\psi$:

\[
\frac{1}{T} \frac{dT}{d\psi} = -\frac{\kappa_T}{2} \left( \tanh(s_1/2\rho_s) - \tanh(s_2/2\rho_s) \right) \\
\times \left( 1 - 1/\cosh^2(s_1/0.05) - 1/\cosh^2(s_2/0.05) \right)
\]

with $s_1 = s - 0.025$, $s_2 = s - 0.975$, $s = \sqrt{\psi}$, $\tilde{\psi} = \psi/\psi_a$, $\psi_a$ is the poloidal flux at the plasma boundary. It produces profiles with $d \ln T / d\psi \approx \text{const} = -\kappa_T$ over most of the plasma radius ($s \in [0.2, 0.8]$) and going smoothly to zero outside this region. Second, as functions of $\rho_V = \sqrt{V(\psi)/V(\psi_a)}$, with different functional forms in the core and the pedestal:

\[
T(\rho_V) = \min \left( T_0, T_{\text{ped}} \exp \left( -\kappa_T(\rho_V - \rho_{V,\text{ped}}) \right) \right) \quad \rho \leq \rho_{V,\text{ped}} \\
T_1(1 - \mu_T(\rho_V - \rho_{V,\text{edge}})) \quad \rho_{V,\text{ped}} < \rho \leq \rho_{V,\text{edge}}
\]

where $T_0$, $T_1$, $\rho_{V,\text{ped}}$, $\rho_{V,\text{edge}}$, $\kappa_T$ and $\mu_T$ are given input parameters and $T_{\text{ped}} = T_1 + \mu_T(\rho_{V,\text{edge}} - \rho_{V,\text{ped}})$. Density profiles are defined in a similar way, with parameters $n_0$, $n_1$, $\kappa_n$ and $\mu_n$.

Boundary conditions are the unicity condition for $\phi$ at the magnetic axis ($s = 0$) and $\phi = 0$ at the plasma boundary ($s = 1$), which sets (unrealistically) turbulent field fluctuations to zero there. On the other hand, we do not impose $\delta f = 0$ at the boundary, but instead put back the particles that eventually leave the plasma in a way that conserves particle energy, magnetic moment and toroidal canonical momentum. These somewhat artificial boundary conditions are a weak point of our current approach, especially when considering turbulent transport in the pedestal. More realistic boundary conditions will be considered in future works.

The equilibrium magnetic configuration is taken from a numerical solution of the axisymmetric ideal MHD equilibrium Grad-Shafranov equation obtained with the CHEASE code [19]. Two cases will be considered: an ITER-shaped configuration (details in Ref.[1]) and the overbar denotes flux-surface average. We define the gyro-Bohm unit $P_{\text{GB}} = \rho_s^2 c_s a_0 / a$, with $a$ the minor radius on the equatorial plane, $\rho_s$ the ion sound Larmor radius and $c_s$ the ion sound speed with the electron temperature taken at a reference magnetic surface and the magnetic field on axis. The finite size parameter is defined as $\rho^* = \rho_{s0}/a$ and an effective size parameter [20] as $\rho^{*\text{eff}} = \rho_{s0}/w$, with $w$ the radial width of the linearly unstable region. The gyro-Bohm power unit is $P_{\text{GB}} = n_0 m_i \rho_{s0}^2 c_s^3 a_0^3$.

3. ITG transport in shaped plasmas with the hybrid electron model

We consider an ITER-shaped ideal MHD equilibrium [1] with initial profiles defined by Eq.[3], $T_e = T_i$, with varying $\kappa_T$, $\kappa_n$, keeping $\eta_i = \kappa_T / \kappa_n$ constant at 3.15, and three different system sizes $1/\rho^* = 90, 180, 360$. We use the hybrid electron model. Even though trapped electron response is taken into account, for these parameters the dominant micro-instabilities are ITGs. In Ref.[1] a similar study, except for the use of the adiabatic electron model, showed that plasma shaping was favourable for confinement: ion heat transport was much reduced as compared to a circular cross-section plasma with otherwise similar parameters. The nonlinear critical temperature gradient was found higher and stiffness lower.

The present study with the hybrid electron model largely confirms the previous findings. As expected, for a given value of $R/L_T$ the ITG-driven transport is higher when the non-adiabatic
Figure 1. Left: ion (solid lines) and electron (dashed lines) heat diffusivity for an ideal MHD ITER-shaped equilibrium (squares) and a circular configuration (circles) computed with the ORB5 code using the hybrid electron model. The numbers indicate the values of $1/\rho_*$. Right: ion heat diffusivity versus effective normalized size $\rho_{*\text{eff}}$ for the hybrid electron model (filled symbols), circular (circles) and ITER-shaped (squares), $R/L_T = 5$. The open circles are for the circular, Cyclone case, $R/L_T = 6.9$, with adiabatic electrons, data from Ref.[20] computed with ORB5 and GENE codes. The dashed lines are linear data fits.

Figure 2. Contours of ZF shearing rate vs radius and time for a circular (left) and an ITER-shaped ideal MHD equilibrium (right), with the hybrid electron model and $1/\rho_* = 360$.

trapped electron response is taken into account. Other than that, a systematic comparison with a circular plasma leads to the same qualitative conclusions. Figure 1 (left) shows the effective ion (solid lines) and electron (dashed) heat diffusivity of as a function of $R/L_T$, for ITER-shaped (squares) and circular (circles) plasmas and two values of $1/\rho_* = 90, 180$. For all cases, even though this is basically an ITG situation, there is a finite electron heat transport of about 30%-50% of the ion heat transport. The decrease in both ion and electron heat transport with plasma shaping is evident.

Finite size (finite $\rho_*$) effects, computed at a value of $R/L_T = 5$, are shown in Fig. 1(b).
Figure 3. Time-averaged radial profiles of effective ion heat diffusivity $\chi_{\text{eff}}[\chi_{GB0}]$, ZF shearing rate $\omega_{E\times B}[c_{s0}/a]$, ZF velocity $v_{E\times B}[c_{s0}]$, logarithmic temperature gradient $R/L_T$, and heat source/sink [a.u.] (a). The thin vertical lines are drawn to underline the correspondence between local maxima of $\chi_{\text{eff}}$, minima of $R/L_T$, maxima of $v_{E\times B}$ and zeros of $\omega_{E\times B}$. ITER MHD configuration, $1/p_e^* = 720$, adiabatic electrons, with modified Krook as heat source and noise control. Time-averaged radial profiles of $R/L_T$ (b) and $\omega_{E\times B}$ (c), with heat source on (black) and off (red). Gyro-Bohm units are defined at mid radius, $p_V = 0.5$.

The lower transport for the ITER-shaped plasma is evident at all scales. The results of the Cyclone case (circular, adiabatic electrons, $R/L_T = 6.9$) are also reported on the same graph with open symbols (data from Ref. [20]). For the three cases shown (circular adiabatic electrons, circular hybrid electrons, ITER-shaped hybrid electrons) the strength of the finite $p_e^*$ effect is of comparable magnitude. Linear fits through the data (dashed lines) seem to indicate complete turbulence suppression for $p_{e^*}^{\text{eff}} \approx 0.025$ [although it is probably a coincidence that this threshold value is the same for all three cases].

The reduced transport with plasma shaping was attributed to plasma self-organization mediated by ZFs, with more steady ZF in the shaped case as compared to the circular case [1]. The same qualitative behaviour is found with the hybrid electron model: Fig. 2 shows contours of the $E \times B$ ZF shearing rate versus radius and time. In both cases avalanches and GAMS are excited, however there is a definitely higher fluctuating component (avalanches) in the circular plasma (left) than in in the ITER-shaped plasma (right).

4. On the effect of sources in gradient-driven simulations

In the previous section, as well as in Ref. [1], simulations have been carried out in “gradient-driven” mode, i.e. with a Krook-like source term that tends to restore the system towards specified initial profiles. These simulations showed a self-organization of the plasma characterized by ZF structures, radially modulated gradients and transport with a corrugated pattern. The temperatures and corresponding gradients can deviate from their original profiles but this results in a heat source/sink that depends on the system evolution. An example is shown in a global ITG simulation of ITER with adiabatic electrons, Fig. 3 (a): the time-averaged power heat source shows radial modulations which are clearly correlated to the self-organized corrugations.
of ZFs and transport. Hence, it may be suspected that the self-organization is an artefact of the particular “gradient-driven” source model used. We note that the heat source is positive to the left of local maxima of $\chi$ (which are also local minima of $R/L_T$), and negative (i.e. a sink) to the right of these radial positions. This can be explained as follows: corrugations of heat transport lead to local flattening of the temperature profile. On the left side of these flatter regions, the temperature will be lower than prescribed and the Krook term will tend to restore it back, hence a positive heat source. On the right side of these flatter regions, the temperature will be higher than prescribed and the Krook term will tend to restore it back, hence a negative heat source (i.e. a sink).

We have continued the simulation of Fig.3 (a), still with a modified Krook operator but enforcing kinetic energy conservation, effectively switching off the heat source/sink and keeping it as a noise control tool. Our results indicate that, after heat source switch-off, the radial corrugations of the ZFs stay on practically unchanged while the gradient corrugations are even enhanced, Fig.3(b)(c). The effective heat diffusivity corrugation is maintained with a slow gradual decrease over time of the radial averaged $\chi$ (Fig.4).

To eliminate the possibility that self-organization would nevertheless result from the Krook-like source term, we have continued the simulation further, switching off the Krook term completely. Again, the ZF, heat transport and gradient corrugation subsists. However, the absence of noise control is felt, with a signal to noise ratio decreasing over time, preventing us from obtaining physically sound results beyond $t = 2 \times 10^6[\Omega_i^{-1}]$.

This shows without ambiguity that the simulated self-organized structures relating heat transport, Zonal Flows and temperature gradients are not a result of the particular “gradient-driven” source term used. Rather, the observed radial modulation of the heat source is merely a consequence of the temperature profile corrugation, which itself results from the turbulent transport modulation by ZFs. If the heat source corrugation has any effect, it is eventually to reduce the temperature gradient corrugation.

On the other hand, ZFs are essential: in simulations where ZFs are artificially suppressed, the self-organized structures disappear altogether. Due to the self-organization, the local heat diffusivity is not simply a function of the local driving gradient: in Fig.3 we note that $\chi_{\text{eff}}$ has local minima where $R/L_T$ has local maxima, and reciprocally. The appearance of these “mini transport barriers” is, again, a consequence of the nonlinear interaction of ZFs with turbulence.
Figure 5. Left column (a)-(c): scan in $\kappa_T$ at constant $\mu_T = 12$. Right column (d)-(f): scan in $\mu_T$ at constant $\kappa_T = 3.1$. Radial profiles of $R/L_T$ (a)(d), effective heat diffusivity $\chi$ (b)(e) and power through the magnetic surfaces (c)(f), in gyro-Bohm units defined at $\rho_V = 1$. 
Figure 6. Power through magnetic surfaces $P_{\text{GB0}}$ (a), heat diffusivity $\chi \chi_{\text{GB0}}$ (b), temperature $T/T(1)$ (c) and $-\frac{1}{T(1)}dT/d\rho_V$ (d) radial profiles, for $(\kappa_T, \mu_T)$ combinations that give power profiles as flat as possible, i.e. with a corresponding heat source localized well into the core and a heat sink localized in the pedestal near the edge. Gyro-Bohm units are defined at $\rho_V = 1$.

5. Core and pedestal ITG turbulent transport

We now turn to the question of edge and pedestal transport stiffness. Careful investigations conducted on the TCV tokamak in series of experiments have led to the conclusion that, even in L-mode plasmas, a “pedestal” region can be defined, typically covering the outer 20% of the plasma radius, in which temperature and density profiles gradients are constant, whereas in the core region (but outside the sawtooth inversion radius) logarithmic gradients are constant. Moreover, power scan studies have revealed that the core logarithmic gradients remain approximately constant whereas pedestal linear gradients strongly depend on the input power. The present study examines whether these findings can be reproduced, at least qualitatively, with global gyrokinetic simulations. For the sake of simplicity, however, the adiabatic electron model will be used and an ITG situation is examined, whereas the experiments were mostly in the TEM regime, so a quantitave match cannot be expected.

We consider an ideal MHD equilibrium reconstructed from TCV shot #43516 and specify initial profiles as in Eq.(4), with $\rho_{V, \text{ped}} = 0.8$, $\rho_{V, \text{edge}} = 1.0$, $T_0 = 10$, $T_1 = 1$, $n_0 = 5$, $n_1 = 1$, $\kappa_T = 3.1$, $\mu_T = 12$, $\kappa_T = 3.3$, $\mu_T = 15$, $\kappa_T = 3.5$, $\mu_T = 18$. 
Figure 7. Top: contours of the effective ion heat diffusivity vs radius and time, for $\kappa_T = 3.1$, $\mu_T = 12$. Middle: contours of the $E \times B$ ZF shearing rate, for $\kappa_T = 3.1$, $\mu_T = 12$. Bottom: frequency spectrogram of the $E \times B$ ZF shearing rate vs radius, for $\kappa_T = 3.1$, $\mu_T = 12$ (left) and for $\kappa_T = 3.1$, $\mu_T = 10$ (right).

We set $T_e = T_i$ and vary both $\kappa_T$ and $\mu_T$. The reference surface for ORB5 profile normalization and definition of gyro-Bohm units is taken at $\rho_V = 1$ which, for TCV parameters, leads to $1/\rho_s = 245$ [Note that with a reference surface at mid-radius, the $1/\rho_s$ parameter is around 100.]. Simulations are performed with $256 \times 10^6$ particles, a 3D grid $N_s \times N_{\theta_s} \times N_\phi = 256 \times 512 \times 256$, and a field-aligned Fourier filter with $\Delta m = 5$, which is found appropriate to include all physically-relevant modes with sufficient signal/noise ratio. Note that the field-aligned Fourier filter keeps only modes $m \in [nq(s) - \Delta m \ nq(s) + \Delta m]$ such that unphysical high $k_\parallel$ modes, which anyway do not satisfy gyrokinetic ordering, are eliminated [16]. The modified Krook operator, with enforced conservations of density, parallel momentum and ZF residual phase space structure, Eq. (2), is used as a noise control and heat source.
Simulations are run for a long enough time so that the system has reached a quasi-steady state, in the sense that a time-independent power balance is satisfied: we verify that the power heat source integrated over the volume inside any given magnetic surface is equal to the power heat flow through that surface. Typically, we run the simulations for \( t = 3.2 \times 10^5 \Omega_1^{-1} \), with \( c_{s0} \) evaluated at the plasma temperature at the plasma boundary. With a reference temperature \( T_0 \), this is \( t \approx 3200 [c_{s0}/a] \). In the following, time-averaged quantities are defined over the interval \( 1.2 \times 10^5 \leq t \leq 3.2 \times 10^5 \Omega_1^{-1} \).

Fig.5 (left column) shows time-averaged radial profiles obtained with constant pedestal gradient, \( \mu_T = 12 \), and varying the core logarithmic gradient \( \kappa_T \) from 2.7 to 3.9. Increasing \( \kappa_T \) by a factor 1.26, from 3.1 to 3.9, leads to a heat diffusivity increasing by a factor of about 2, Fig.5(b) and a heat power increasing by a factor of about 3, Fig.5(c). This is the well-known stiffness in the core. We note, however, that the heat diffusivity increases in the pedestal region \( (\rho_V > 0.8) \) as well, even though the local gradients do not change there. This is a spatially non-local effect: turbulence in the core affects the pedestal region. The case \( \kappa_T = 2.7 \) is more puzzling, since it leads to comparable core heat diffusivity as for \( \kappa_T = 3.1 \), whereas diffusivity is lower in the pedestal even though the gradients are unchanged there. This is another manifestation of a spatially non-local effect: turbulence in the pedestal spreads to the core region, lowering the turbulence level in the pedestal and increasing it in the core.

The right column of Fig.5 shows the same quantities as in the left column, however for a fixed value of the core logarithmic gradient \( \kappa_T = 3.1 \) and varying the pedestal gradient \( \mu_T \) from 7 to 15. Again, spatially non-local effects are found: transport in the core \( (\rho_V < 0.8) \) is affected by the change in gradients in the pedestal \( (\rho_V > 0.8) \), even though the core gradients do not change. The behaviour of input power is remarkably non-monotonic with \( \mu_T \): for \( \mu_T = 12 \), we find that the power profile is mostly flat for \( \rho_V \in [0.6, 0.9] \), which corresponds thus to a (positive) heat source localized well inside \( (\rho_V < 0.6) \) and a heat sink localized in the outer pedestal region \( (\rho_V > 0.9) \). For \( \mu_T \) values both lower and higher than that, the total input power is larger and the heat source/sink profile is much less realistic. The case \( \kappa_T = 3.1, \mu_T = 12 \) thus appears close to what one would obtain in flux-driven simulations, though this needs to be confirmed in future works.

A double scan in \( (\kappa_T, \mu_T) \) parameters was then carried out, aiming at obtaining parameter combinations that result in power profiles as flat as possible, i.e. over the widest possible radial interval. The aim is to find a power profile consistent with heat sources well localized in the core and heat sinks close to the edge, as one would expect similar results in truly flux-driven simulations (which are left for future studies). Such cases are shown in Fig.6. Interestingly, the heat diffusivity does not exhibit apparent non-local effects, in the sense that, at every location, \( \chi \) increases where the temperature gradient increases, and the transport might be interpreted quasi-locally. Concerning stiffness, increasing the power by a factor of about 3 corresponds to an increase in \( \kappa_T \) by only 11% (from 3.1 to 3.5), and an increase in \( \mu_T \) by 50% (from 12 to 18). Thus the empirical conclusion that “core profiles are stiff and pedestal profiles are non-stiff” appears justified. We note, in passing, the striking similarity of temperature profiles (Fig.6, top right) with those measured experimentally (Fig.3(b) of Ref.[2]), characterized by a clear deviation from constant logarithmic profiles in the pedestal (dotted lines). On the bottom right we show the temperature gradient profiles, \(-dT/d\rho_V\), with initial profiles as dotted lines and time-averaged quasi-steady profiles as solid lines. For all cases the different radial dependencies in the core and the pedestal are clear. Interestingly, increasing the power leads to an almost uniform increase of the gradients at all radii: if stiffness would be measured by the variation of power vs linear gradients (instead of logarithmic), there would be no substantial difference between core and pedestal stiffness.

In spite of the apparent locality of transport in Fig.6 we know from the study in Fig.5 that spatially non-local effects are in fact present. Considering the case \( \kappa_T = 3.1, \mu_T = 12 \) as a
typical example, we show in Fig.7 that non-local effects show up as avalanches which propagate over a large fraction of the plasma radius that straddles the pedestal and core regions. Most of them propagate inwards and some outwards — though the heat flux associated with avalanches is always outward. Their velocity of propagation is constant, despite the fact that the background temperature varies by a factor of up to 8 over the radial range where they propagate, and their frequency, while close to the local GAM frequency at the edge, is much below the local GAM frequency in the core. Moreover, avalanches are not reflected, and the observed pattern is not that of a global linear eigenmode, even though there is a high radial coherence and a rather well defined frequency constant over radius, \( \omega = 0.63[c_{s0}/a] \), see Fig.7 bottom left. In physical units and for TCV parameters this is a frequency of \( f = 28.2 \text{kHz} \), which corresponds very well to the experimentally measured frequency, see Fig.3(a) of Ref.[21]. In our parameter scans, we found that avalanches do not always repeat with a well-defined frequency. It seems that there is a minimal value of \( \mu_T \) necessary for this to happen. In the \( \mu_T \) scan of Fig.5 (right column), we find that long-range propagating avalanches are always present, but they have a well-defined frequency for \( \mu_T = 12,15 \) and not for \( \mu_T = 7,10 \). We show in Fig.7 bottom right the spectrogram for \( \mu_T = 10 \): no radial coherent mode is present in this case.

6. Conclusions
We have evidenced several spatially non-local turbulent transport effects, for all of which the ZF nonlinear interaction with turbulence appears to play a major role. These are responsible for establishing radial structures modulating the turbulence. First, we have confirmed that these structures are also present, at least in an ITG-dominated situation, when considering a hybrid electron model in which trapped electrons are kinetic and only passing electrons are assumed adiabatic. Moreover, geometrical effects are also present: plasma shaping was shown to lead to more steady ZFs and lower ion and electron heat transport (Figs.1 and 2).

We have then verified that the self-organized structures observed in our gradient-driven simulations were not an artifact of the implied sources and sinks, which also exhibit corrugations. The corrugated structures persist even when heat sources/sinks are removed (Fig.3). The fundamental phenomenon at the basis of radial structure formation, in which avalanches can be present, (self-organization) is the ZF interaction with turbulence. These structures lead to a radial modulation of heat transport, which then leads to the corrugation of temperature profiles: local minima of \( \chi \) coincide with local maxima of temperature gradient, forming a series of “mini transport barriers”.

Finally, our studies of profiles with constant logarithmic gradients in the core and constant linear gradients in the pedestal have evidenced that (1) this type of profile appears compatible with global turbulent simulations: sets of parameters were found leading to realistic power deposition profiles (Fig.6). (2) Changing the gradients in the core is affecting turbulence in the pedestal, and vice-versa (Fig.5). These spatially non-local phenomena appear to be related to avalanches mediated by ZFs (Fig.7). (3) In spite of these obvious non-local effects, it seems that transport could be interpreted locally (Fig.6).

Although these results so far do not contradict experimental findings, more work is necessary before claiming that gyrokinetic theory and global numerical simulations are validated. Some more realistic boundary conditions, in particular, should be implemented: currently our model assumes \( \phi = 0 \) at the edge of the computational domain, leading to an unrealistic vanishing of perturbations there. Flux-driven simulations, with specified input power profile and sinks should be carried out to investigate more realistic profile evolutions. These confinement timescale simulations [22] are very demanding. Also, the study of core and pedestal gradients should be pursued with a more complete physical model and include cases dominated by trapped electron mode (TEM) turbulence. In this context, studies of the core and edge stiffness in the TEM regime including fully kinetic electrons, examining the effect of plasma triangularity, have
recently being carried out [23], with results indicating a weaker stiffness near the edge than in the core, similarly to what was found in the present work that dealt with ITG turbulence.

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