Overview of Zonal Flow Physics

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Abstract. Zonal flows, by which we mean azimuthally symmetric band-like shear flows, are ubiquitous phenomena in nature and the laboratory. It is now widely recognized that zonal flows are a key constituent in virtually all cases and regimes of drift wave turbulence, indeed, so much so that this classic problem is now frequently referred to as "drift wave-zonal flow turbulence." In this theory overview, we present new viewpoints and unifying concepts which facilitate understanding of zonal flow physics, via theory, computation and their confrontation with the results of laboratory experiment. Special emphasis is placed on identifying avenues for further progress.

1. Introduction

This paper presents a critical assessment of the physics of zonal flows and their relevance to fusion plasmas. This assessment is based on a comprehensive review of zonal flow physics [1], recently completed and currently in press. In *this* paper, we focus on:

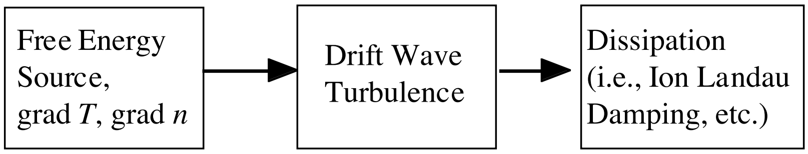
a.) presenting the current state of our understanding, i.e. describing and delineating *what we understand*, *what we think we understand but need more research on*, and *what we don't understand*,

b.) discussing the importance of zonal flow physics for magnetic fusion.

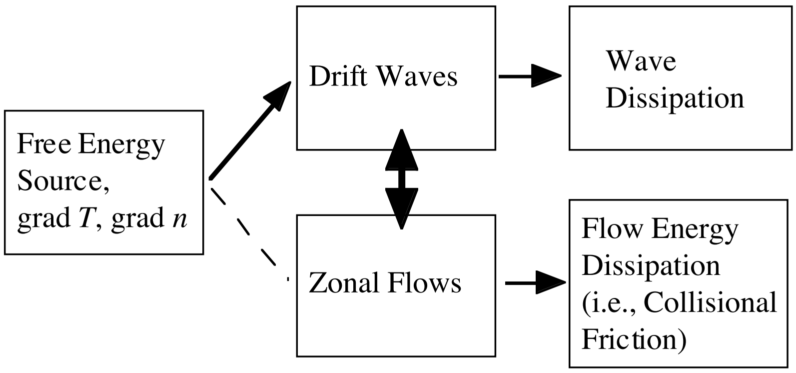
Due to length restrictions, this paper is necessarily quite terse. The interested reader is referred to the full-length manuscript of the review, and references therein, for a more detailed discussion.

2. Basic physics of zonal flows

Zonal flows are $n=0$, $m\cong 0$ electric field fluctuations with finite k_r. Thus, zonal flows cannot drive radial transport and so cannot tap the usual free energy sources ($\nabla n, \nabla T$, etc.). As a consequence, zonal flows must be 'pumped' by nonlinear interactions. Zonal flows co-exist with, and are excited by all types of microinstabilities (hereafter generically dubbed "drift waves") and regulate transport by shearing the underlying drift waves, thus quenching them by extracting energy from them. For this reason, zonal flows are a crucial player in the self-regulation mechanism for drift wave turbulence and transport, so much so that this type of turbulence is now commonly referred to as *drift wave - zonal flow turbulence*, as depicted in *FIG. (1)*.



Classic Paradigm of Drift Wave Turbulence



New Paradigm of Drift Wave-Zonal flow Turbulence

FIG.1 *New paradigm of drift wave turbulence with zonal flows*

As noted above, much of the interest in zonal flows is driven by the fact that they regulate turbulence via shearing. However, it is certainly true that all low-n modes in a spectrum of drift wave turbulence will shear and strain the larger-n, smaller-scale fluctuations. Indeed, non-local shearing-straining interactions are characteristic of 2D turbulence once large scale vortices are established. This, in turn, naturally motivates the questions: "What is so special about zonal flows (with n = 0)?" and "Why aren't other low-n modes given equal consideration as regulators of drift wave turbulence?" There are at least *three* answers to this very relevant and interesting question. These are discussed below.

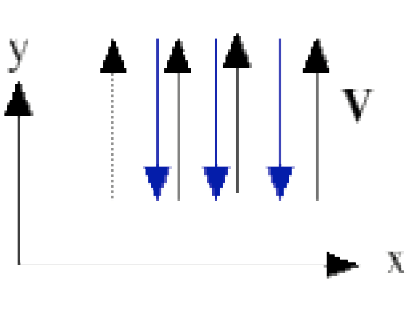
First, zonal flows may be said to be the '*modes of minimal inertia*'. This is because zonal flows, with $n = 0$ and $k_{\|} = 0$, are not screened by Boltzmann electrons, as are the usual drift-ITG modes. Hence, the potential vorticity of a zonal flow mode is simply $q_r^2 \rho_s^2 \hat{\phi}_q$, as opposed to $\left(1 + k_\perp^2 \rho_s^2\right)\hat{\phi}_k$, so that zonal flows have lower effective inertia than standard drift waves do. The comparatively low effective inertia of zonal flows means that large zonal flow velocities develop in response to drift wave drive, unless damping intervenes. In this regard, it is also worthwhile to point out that in the case of ETG turbulence, *both* zonal flows and ETG modes involve a Boltzmann ion response $\hat{n}_i / n_0 = -|e|\hat{\phi}/T$, since $k_\perp \rho_i >> 1$ for ETG. Hence, it is no surprise that zonal flow growth is slower for ETG turbulence than for its drift-ITG counterpart, since for ETG, zonal flows have an effective inertia *comparable* to other modes.

Second, zonal flows, with n = 0 and $k_{\|}$ = 0, are *modes of minimal Landau damping*. This means that the only linear dissipation acting on zonal flows for asymptotic times (i.e. $t \to \infty$) is due to collisions. In particular, no linear, time-asymptotic dissipation acts on zonal flows in a collisionless system.

Third, since zonal flows have n = 0, they are intrinsically incapable of driving radial $E \times B$ flow perturbations. Thus, they cannot tap expansion free energy stored in radial gradient. Thus, zonal flows do not cause transport or relaxation, and so constitute a *benign repository* for free energy. In contrast, other low n-modes necessarily involve a trade-off between shearing (a "plus" for confinement) and enhanced transport (a "minus").

Having established the physics of shearing, it is illuminating to present a short 'back-of-an-envelope' type demonstration of zonal flow instability. For other approaches, see the literature cited in [1]. Consider a packet of drift waves propagating in an ensemble of quasi-stationary, random zonal flow shear layers, as shown in *FIG. (2)*. Take the zonal flows as slowly varying with respect to the drift waves (i.e. $\Omega << \omega_k$), i.e. as quasi-stationary. Here, Ω is the rate of the change or frequency of the zonal flow and ω_k is the characteristic frequency of drift waves. The spatially complex shearing flow will result in an increase in $\langle k_r^2 \rangle$, the mean square radial wave vector (i.e. consider a random walk of k_r, as described above). In turn the drift wave frequency $\omega_{e*} \big/ \left(1 + k_\perp^2 \rho_s^2\right)$ must then decrease. Here, ρ_s is the ion gyroradius at the electron temperature. Since $\Omega << \omega_k$, the drift wave action density $N_k = E(k)/\omega_k$ is conserved, so that *drift wave energy must also decrease*. As the total energy of the system of waves and flows is also conserved (i.e. $E_{wave} + E_{flow} = const.$), *it thus follows that the zonal flow energy must*, in turn, *increase*. Hence, the *initial perturbation is reinforced*, suggestive of *instability*. Note that the simplicity and clarity of this argument support the assertion that zonal flow generation is a robust and ubiquitous phenomenon.

It is also important to clarify the distinction between zonal flows and the mean radial electric field. The latter is derived from a coarse-graining of the total electric field and varies smoothly in comparison to the zonal flow field. The zonal flow pattern is oscillatory and complex, exhibiting structure on scales of 10-20 ρ_i. The mean $\langle E_r \rangle$ evolves on transport time scales, while the zonal flows can evolve on turbulence time scales (i.e. on a few correlation times). The mean electric field shear coherently stretches vortices, so that $\langle \delta k_r^2 \rangle \sim k_\theta^2 \langle V_E' \rangle^2 t^2$. By way of contrast, the zonal flows diffusively scatter k_r, so $\langle \delta k_r^2 \rangle \sim D_k t$, where $D_k \sim k_\theta^2 \left\langle \tilde{V}_E'^2 \right\rangle \tau_c$. Here $\left\langle \tilde{V}_E'^2 \right\rangle$ is the mean square zonal shear and τ_c is the autocorrelation time of the zonal flow field. Finally, the mean electric field is driven by heating, fueling, momentum input, etc. (which determines the equilibrium profiles, which in turn regulate radial force balance), while zonal flows are driven *exclusively* by nonlinear wave interaction processes.



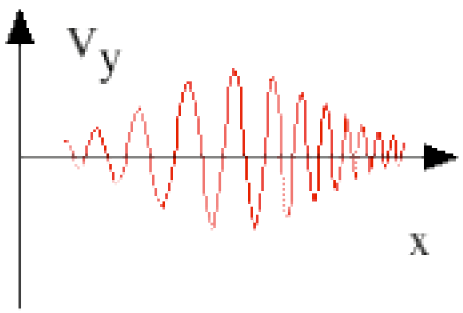


FIG.2 Zonal flows are illustrated

A key feature of zonal flows is their ability to co-exist with drift waves, and so form a self-regulating system. The drift wave zonal flow system can be described by a generalized predator-prey model for the evolution of W_d, the drift wave energy, and W_{ZF}, the zonal flow energy. Despite wide variability in the basic models and details of the system, the evolution equations have a universal structure of the form

$$\frac{\partial W_d}{\partial t} = \gamma[\nabla P_0, ...]W_d - \alpha W_d W_{ZF} - \beta W_d^2, \tag{1}$$

$$\frac{\partial W_{ZF}}{\partial t} = -\gamma_{damp}[\nu, \varepsilon_T, q]W_{ZF} + \alpha W_d W_{ZF} - \gamma_{NL}(W_{ZF})W_{ZF}. \tag{2}$$

Here, $\gamma[\nabla P_0, ...]$ is the drift wave growth rate, γ_{damp} is the linear zonal flow damping rate, $\gamma_{NL}(W_{ZF})$ is the nonlinear damping rate of zonal flows, in contrast to γ_{damp}, which is the linear damping rate due to electron-ion friction and α, β are coefficients. Note that drift waves and zonal flows can exchange energy. In the case where $\gamma_{NL} \to 0$, $W_d \sim \gamma_{damp} / \alpha$ so that the *drift wave amplitude is set by zonal flow damping*. Note that this damping is, in turn, set by the ion-ion collisionality and elements of the confinement geometry (i.e. via ε_T, q, etc.), so that zonal flow damping is thus identified as a 'control knob' for the level of drift wave turbulence. As a consequence, the drift wave thermal diffusivity is reduced from the standard gyroBohm prediction by a factor $R \sim \gamma_{damp}/\omega_{eff}$, so $\chi \sim R\chi_{gB}$. Additional transport reduction effects, such as those related to the transport cross-phase, may enter the R factor, as well. Note that the *R factor thus quantifies the net reduction in transport induced by zonal flows relative to the bare gyroBohm level.*

3. Importance of zonal flows for M.F.E.

One frequently hears the question or comment "zonal flows are interesting, but just why are they important for fusion?" There are at least five parts to the answer to this question, which are listed below.

First, as noted above, zonal flows regulate drift wave turbulence and transport, thus reducing transport coefficients in comparison to the gyroBohm reference value. This reduction, quantified by the R-factor, gives an intrinsic effective H-factor, even in the absence of a transport barrier. Given that $H_{eff} \sim R^{-0.6}$, it follows that zonal flow improvements can mitigate the cost of a reactor by a factor of $R^{-0.8}$ (i.e. \$cost ~ $R^{-0.8}$).

Second and in a similar vein, zonal flows can shift the effective boundary for the onset of significant turbulence and transport. This shift in onset, often referred to as the 'Dimits shift' [2], is a consequence of the fact that close to instability threshold in low collisionality regimes, most of the available free energy is coupled directly to zonal flows, with comparatively little left for cross-field transport. This Dimits shift regime may be thought of as a limiting case of the regime of cyclic bursts, produced by the competition between shearing (predator) and fluctuation growth (prey). As the inter-burst period is set by the zonal flow damping, it becomes arbitrarily large in the limit of weak collisional damping [3].

Third, and still continuing in the previous vein, the study of zonal flows has identified a new control knob on transport, which is the zonal flow damping rate. In the case of a tokamak, the damping in the low collisionality regime is set by the ion-ion collisionality, and the magnetic geometry, as it is due friction between trapped and untrapped particles [4,5]. The scaling of zonal flow damping in other configurations, such as stellerators and spherical tori, is of great interest and has not been addressed.

Fourth, the study of zonal flows has advanced our understanding of secondary mesoscale fluctuations and their effect on tokamak phenomena. These structures include zonal fields (i.e. the magnetic counterparts of zonal flows), which can seed neoclassical tearing modes, and avalanches, which trigger an intermittent heat flux and which necessarily compete against zonal flows. Thus, zonal flow physics enters considerations pertaining to the beta limit and peak heat loads. Zonal flow physics has also been linked to resistive wall mode dynamics.

Fifth, the study of zonal flow physics has led to a paradigm shift, so that self-generated shear layers are now viewed as an equal constituent, along with drift waves, in drift wave turbulence. This has sparked the development of the 'predator-prey' paradigm of drift wave-zonal flow turbulence, discussed here and in the references.

4. Zonal flow physics - a critical assessment

In this section, we present a critical assessment of our understanding of zonal flow physics. This assessment divides the issues into three groups:

a.) what we understand,

b.) what we think we understand, but need more work on,

c.) what we do not understand,

which we discuss sequentially below.

4.1 What we understand about zonal flows

It is clear that several aspects of zonal flows physics are now well understood. These are:

1.) Zonal flows are universal phenomena in microturbulence.

2.) In low collisionality regimes, zonal flows damp by scale-independent friction between trapped and circulating ions.

3.) Zonal flows are pumped by modulational instability of the drift wave gas. The detailed manifestation of the modulational instability dynamics varies considerably with parameters.

4.) Drift wave zonal flow turbulence is a self-regulating system, of the predator-prey type. Hence, both stationary and bursty or cyclic states are possible.

Assertions 1-4 are discussed immediately below.

The universality of zonal flows is indisputable. Zonal flow generation and the concomitant shear suppression of turbulence and transport has been observed in numerical simulations of ITG, CTEM, ETC, resistive ballooning, resistive interchange and collisional drift wave turbulence. This list encompasses virtually all of the "usual suspects" for the cause of anomalous transport.

Zonal flows damp (linearly) in low collisionality regimes by (collisional) friction between circulating ions and trapped ion bananas. For standard tokamak geometry, in the banana regime, $\gamma_{damp} \cong -\nu_{ii}/\varepsilon_T$, so the damping is proportional to ion-ion collisionality. Note that the Rosenbluth-Hinton 'residual' flow is damped *only* by collisions. Hence, even in "nearly collisionless regimes," the zonal flow damping is *strictly* collisional.

It is now quite clear that flows grow by *modulational instability*. In all cases, a modulational stability analysis seeks to explore the stability of a drift wave state to a 'test' zonal flow shear. The basic drift wave state can be one of a single coherent mode, or one of drift wave turbulence. The stability analysis can be linear, or, with additional strong simplifying assumptions, nonlinear. Thus, modulational stability of drift waves has been predicted by single wave parametric modulational calculations [6,7], spectral wave-kinetic calculations [8,9,10,11,12], reductive perturbation theory analyses [13,14], and by studies of coherent [15,16] and turbulent [17] trapping. The wide variety of approaches (i.e. see Chapter 3 of Ref. [1]) to the modulational problem can be instructively classified in the 2D space of Kubo number and drift wave ray Chirikov parameter, as shown in *FIG. (3)*. Modulational instability of developed drift wave *turbulence* has been verified by a *numerical experiment* using gyrokinetic particle simulation codes [18]. Thus, it seems incontrovertible that modulational instability of drift waves is the route to zonal flow formation.

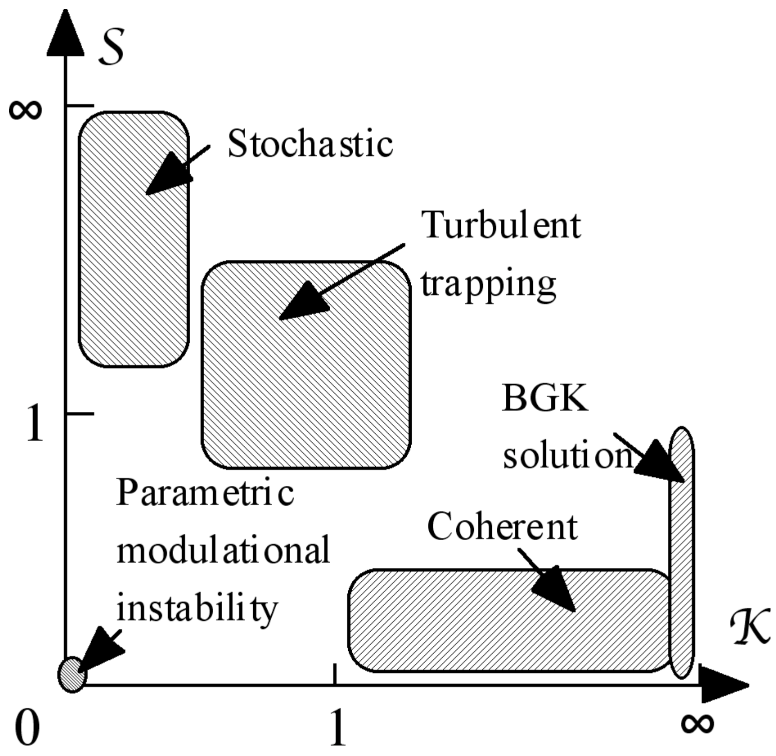


FIG.3 Parameter domains for various theoretical approaches

4.2 What we think we understand about zonal flows, but need more research on

As mentioned above, zonal flow dynamics are naturally self-regulating. This follows from the fact that zonal flow generation extracts energy from drift waves, which may in turn be dissipated by zonal flow damping mechanisms. While return of energy from the zonal flow repository to the drift waves gas is possible, it does not readily occur, especially in plasmas with magnetic shear. Note that fixed points, limit cycles, and fixed points with long relaxation times (i.e. which are the time asymptotic states of slow modes) are possible.

Several other basic aspects of zonal flow physics are understood, but remain topics of current research in the hope of obtaining deeper or more precise quantitative understanding. These are:

1.) **Zonal flows really do exist.**

2.) **Several viable mechanisms for zonal flow saturation in regimes of low collisionality have been identified and explored.**

3.) **Zonal flows can modify the onset criterion for turbulence and turbulent transport.**

4.) **Magnetic field structures with $m = n = 0$ and finite k_r, called zonal fields, can be generated by drift wave turbulence.**

5.) **The interaction of zonal and mean flows at the L$\rightarrow$H transition can lead to pre-transition dithering and modify hysteresis.**

6.) **A variant of the zonal flow, referred to as the GAM or geodesic acoustic mode, is likely important in regulating edge turbulence.**

7.) **Zonal flow 'control knobs' have been identified.**

Assertions 1-7 are discussed immediately below.

While there have been several experimental results which are suggestive of the existence and effects of zonal flows, a definitive experiment has only recently been performed, using a dual beam HIBP system on the CHS device. Poloidally and toroidally extended, but radially localized, electric field structures have been identified. Moreover the existence of radial structure and correlations has been demonstrated by exploiting the unique capabilities of the dual-beam system [19,20]. For details, the reader is referred to paper EX8-5Rb in this conference.

At least three types of collisionless saturation mechanisms for zonal flows have been identified, any one of which can define an effective $\gamma_{NL}(W_{ZF})$, which in turn yields a finite value of W_d as $\gamma_{damp} \rightarrow 0$. These mechanisms include higher order scattering of drift wave rays in zonal flows [21], ray trapping in zonal flows [22,23], and Kelvin-Helmholtz (i.e. 'tertiary') instability of the zonal flows [24]. The higher order wave kinetics is very similar to nonlinear Landau damping, familiar from weak turbulence theory. Here the drift wave ray corresponds to the "particle" and the zonal flow corresponds to the "wave." Third order perturbation theory yields a nonlinear saturation effect, proportional to the mean square zonal flow shear. The reliability of the theory near drift wave marginality needs further investigation, though. Continuing in this vein, the trapping calculation may be viewed as a study of BGK solutions (of the wave kinetic equation), which trap drift wave rays. The condition of saturation ties the ray 'bounce' frequency to the drift wave growth rate. Further study of this interesting mechanism is necessary in order to assess its viability in systems of practical interest. A third type of saturation mechanism is Kelvin-Helmholtz type instability of the zonal flows, driven by their shear. Such an instability would generate a turbulent viscosity, thus damping zonal flows and coupling some of their energy back to the drift wave spectrum. While such "tertiary" instability is a natural candidate for zonal flow saturation, its stability in a sheared magnetic field, its dependence on zonal flow profile, and its behavior in a background of drift waves are all quite subtle, and much more research is required to quantitatively assess its viability as a zonal flow saturation mechanism [25].

As noted before, in low collisionality plasmas, the extent of the Dimits shift regime defines an effective shift in the critical gradient for the onset of significant transport. This shift occurs in the region "near" marginal stability, thus begging the question of " just *how* near is near?" This is effectively the same question as the one pertaining to the mechanism of collisionless saturation. Thus, the physics of higher order wave kinetic processes, ray trapping and tertiary instability, all can define an effective shift. The quantitative impact of this on confinement is presently under study, as is the parameter dependence of the extent of the Dimits shift regime.

Zonal flow physics in finite beta plasmas exhibits two important new features. First, magnetic stresses grow and compete against $E \times B$ velocity-induced stresses, i.e. $\left\langle \tilde{V}_{E,x} \tilde{V}_{E,y} \right\rangle \rightarrow \left\langle \tilde{V}_{E,x} \tilde{V}_{E,y} \right\rangle - \left\langle \tilde{B}_x \tilde{B}_y \right\rangle$, thus reducing or quenching the amplification of velocity shear. This will, in turn, result in a net *increase* in the turbulence level. A second effect is the amplification of secondary magnetic fields with a structure similar to that of zonal flows [26]. These fields, called *zonal fields*, can react back on the turbulence via a process of random or corrugated magnetic shearing. The process of zonal field amplification may be thought of as one where the turbulence produces a current layer via a "negative turbulent resistivity," generated by drift Alfven wave spectra with slopes of a certain sign. The generation process proceeds via transport of magnetic potential, just as the zonal flow generation process proceeds via vorticity transport. It should be noted that *while this process amplifies field, it does not amplify magnetic flux*, and so is not, strictly speaking, a "dynamo" in the conventional sense of the word [27] (i.e. as in the alpha-effect). Rather it is a process which *redistributes* flux, causing local field intensification. In practice, zonal field magnetic shearing is usually weak, for most tokamak parameter regimes. As with zonal flows, some possibility of tertiary instability of zonal fields exists as well. In this case, the most likely instability mechanism would be something akin to a current and electron temperature gradient driven microtearing instability. One other interesting offshoot of zonal field research is the realization that zonal fields may seed neoclassical tearing modes [28].

Zonal flows differ from the mean $\underline{E} \times \underline{B}$ flow, in that the latter can persist in the absence of turbulence, while the former is exclusively turbulence driven. Mean flows can thus suppress zonal flows, as well as drift waves by quenching the turbulence which drives the zonal flows. As a consequence, there are interesting possibilities for energy exchange between the zonal flows and the mean flow. A simple model has been used to explore this possibility, and has predicted that zonal flow coupling will produce pre-transition dithering, modify the expected transition threshold and alter the back-transition hysteresis [29]. Further work is needed, especially on the implications of zonal flows for the dynamics of pedestal build-up.

Two practical points concern the relation between zonal flows and GAMs, and the possibility of using aspects of zonal flow physics as to construct a 'control knob' for the turbulent transport. First, at lower temperatures characteristic of the edge ν_{ii} increases and c_s/R decreases, so the characteristic frequencies of zonal flows and GAMs begin to overlap [30]. As a consequence, geodesic-acoustic coupling becomes an important element in and limitation on zonal flow generation processes [31]. Second, an understanding of the zonal flow drive and damping has suggested several routes to improving confinement via externally driven flow shear amplification [32] or by tuning the configuration design to lower the zonal flow damping.

4.3 What we do not yet understand about zonal flow physics

There are several aspects of zonal flow physics where significant future study is required. These are:

1.) **A convincing experimental link between zonal flow excitation and enhancement of confinement remains to be demonstrated.**

2.) **The rule governing how the system *selects* among the various collision saturation mechanisms must be derived.**

3.) **Quantitative *predictability with understanding* remains elusive. In particular, quantitative rules for *actually calculating* the *R*-factor, the extent of the Dimits shift regime, the threshold for shear suppression and the onset of bifurcative transitions must all be developed.**

4.) **Our understanding of the interaction and competition between various secondary structures, such as zonal flows and avalanches or streamers, is rudimentary and must be improved.**

5.) **The factors limiting the *efficiency* of the control of zonal flows must be determined.**

Clearly, many interesting challenges and discoveries await researchers working on the subject of zonal flows!

5. Conclusion

In conclusion, the study of zonal flow physics had led to a paradigm shift in our most basic concept of "drift wave turbulence and transport." We now think of "drift wave - zonal flow turbulence" as a self-regulating system, with shearing and shear-induced modulational instability providing the key feedback elements. This natural self-regulation can be important for magnetic fusion, both by defining a reduction in transport relative to gyroBohm (i.e. the *R*-factor, discussed above) and by its effect on transport barrier formation. We can look forward with confidence to future discoveries of the role of secondary flows and fields in different areas of fusion physics, such as TAE instabilities, neoclassical tearing modes and resistive well modes, just to name a few possibilities.

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