POWER SCALING OF THE DENSITY LIMIT AND PARTICLE TRANSPORT EVENTS

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Abstract

Developments in the theory of the transport physics of the density limit are summarized. The density limit follows enhanced particle transport events and edge cooling, resulting from the collapse of the edge shear layer -which is universally present. Shear layer collapse is a consequence of a drop in adiabaticity below unity. Current scaling, as in Greenwald limit, enters as a consequence of neoclassical dielectric effects on the zonal flow response. We show that increased edge ion heat flux can sustain edge shear layers against collapse. This establishes a power scaling of the density limit as $n_{edge} \sim Q_i^{1/3}$. A novel hysteresis phenomenon in n_{edge} vs Q_i is predicted. The power scaling theory is developed for collisionless ITG turbulence. Particle transport events which follow shear layer collapse are studied. These involve strong turbulence spreading and the emission of density blobs.

1. INTRODUCTION- OVERVIEW AND BASIC PHYSICS

Density limit (DL) physics is critical to magnetic fusion. This is because fusion power gain increases with density(n) as $\sim n^2$, thus pointing to high density as a regime for fusion reactors. DL physics is an ancient topic[1, 2], which remained unchanged over 20-30 years. However, in the past 5 years or so, it has undergone a revolution. This paper describes some of the key physics progress which enabled that revolution. The focus is primarily on the L-mode density limit(LDL), which is fundamental.

While DL physics has long been considered primarily an MHD topic, recent experiment and theory have identified the key role of transport physics, in general, the mechanism of shear layer collapse, in particular[3, 4, 5, 6, 7, 8]. A surge in edge fluctuations, transport and turbulence spreading has been observed to follow the weakening or collapse of the omnipresent edge shear layer[7]. The subsequent edge cooling, frequently, then triggers MARFEs, MHD, disruption etc.- the usual signature of density limit. Shear layer collapse is related to the transition from Boltzmann or drift-wave like dynamics, to non-adiabatic or hydrodynamic behavior. The transition necessarily forces a reduction on the efficiency of zonal flow generation, thus weakening the shear layer[4]. Note that this mechanism is very general, and not associated with the evolution of a specific mode. Note, too, that reduction in adiabaticity $\alpha = k_\parallel^2 v_{the}^2/\omega\nu_e(<1)$ is distinct from collisionality $\nu_\star$. In particular, turbulence can be collisional yet adiabatic. The onset of shear layer collapse for $\alpha \ll 1$ has been well documented[3], along with the concomitant changes in edge turbulence and transport. Of particular interest is the onset of particle transport events -i.e., bursts of turbulence spreading, and the emission of 'blobs'[7]. The onset of particle transport events is well correlated with a drop in α. A comprehensive theory of shear layer collapse has been developed and linked to DL phenomenology. A critical parameter has been identified. This theory is discussed further, in detail, in the paper.

The most significant recent development in DL physics is power scaling- or, more specifically, scaling of the maximal edge density n_{edge} with edge heat flux Q_i. The physics is simple - additional power further supports the edge shear layer against decay. Power scaling of the LDL was recently vividly demonstrated in negative triangularity discharges on the DIIID-D tokamak. These achieved $\overline{n} \sim 2n_G$, with $\sim$10MW auxiliary heating. The physics of NT discharges prevented an L$\rightarrow$H transition[9]. The upshot of power scaling is that the time-honored Greenwald

scaling[1] is now overtaken by events, and thus something of an antique. A key question, then, is the physics of LDL power scaling. Theory suggests that the power scaling results from a competition between: i) *fluctuation driven Reynolds stresses, computed in the presence of mean shear, and energized by drift-ITG turbulence*. ii) *collisional damping of edge zonal shear layer*. In particular, breakdown of adiabaticity is not relevant. The theory discussed below is for collisionless ITG turbulence. Collisionality enters only via zonal flow damping. This suggests the possibility of new regimes of high density at high power. Such regimes are especially interesting for burning plasmas. Also, a key bit of physics relevant to power scaling follows from its foundation in shear flow physics. In particular, we demonstrate a novel type of hysteresis in n_{edge} vs Q_i associated with power scaling.
The remainder of this paper is organized as follows. Section 2 details the model and physics of the LDL power scaling. Particle transport events following the shear layer collapse near the density limit are described in Section 3. Current issues are discussed in Section 4. Conclusions are drawn in Section 5.

2. SCALINGS

2.1. Current scaling

To address the issue of Greenwald scaling $n_g \sim I_p/a^2$ within the shear layer collapse paradigm, we hypothesis that the key physics lies in screening of the zonal (shear) response by neoclassical dielectric $\epsilon_{neo} = 1 + 4\pi\rho c^2/B_\theta^2$[10]. This suggests poloidal ion gyroradius as the $\rho_{\theta i}$ as the effective zonal flow screening length. Thus, in light of basic aspects of zonal flow physics, this implies that the effective zonal flow inertia and screening length are lower for large I_p[11]. Thus, for larger current, the shear layer will be concomitantly stronger, and more resilient against collapse at high density, suggesting a higher DL. A new predator–prey model for turbulence-zonal flow evolution including the neoclassical zonal flow screening and incoherent and coherent mode couplings(modulational instability) is obtained. An important development from the analysis of the model is that the incoherent zonal noise polarization beats eliminate the threshold for zonal flow excitation. Rather, as linear growth increases, there is a continuous evolution from a state of weak zonal flow shear to a state of strong zonal flow shear. This can be seen in figure(1), where the blue and red curves show the zonal flow energy and turbulence energy phase curves, with zonal noise present. We take zonal flow 'collapse' to mean this continuous evolution from high shear to low shear - i.e, collapse is seen as a 'soft' transition. The shear layer collapses when the dimensionless ratio $\frac{\rho_s}{\sqrt{\rho_{sc}L_n}}$ falls below a critical value determined by *the zonal flow damping rate* γ_d*, turbulence nonlinear damping rate* η*, triad interaction time* Θ *and adiabaticity parameter* α. i.,e

$$\frac{\rho_s}{\sqrt{\rho_{sc}L_n}} \quad < \quad \left[\frac{\eta}{\Omega_i} \frac{\gamma_d}{2k_x^2\rho_s^2\Theta\Omega_i^2} \frac{\alpha}{q_\perp^2\rho_s^2} \frac{\left(1+q_\perp^2\rho_s^2\right)^3}{q_y^2\rho_s^2} \right]^{1/4}. \tag{1}$$

Here, ρ_s is ion sound radius, ρ_{sc} screening length, L_n is density scale length, Ω_i is ion gyro-frequency, k_x is zonal wave number, q is fluctuations wave number. *Crucially, note that smaller screening length* ρ_{sc} *-i.e., higher* B_θ *enlarges the regime of ZF persistence.* This prediction of a dimensionless key parameter $\frac{\rho_s}{\sqrt{\rho_{sc}L_n}}$ linked to density limit in tokamaks has been recently verified in tokamak disruption data base study[12]. This is shown in figure(2). This, in a sense, confirms the decisive role of shear layer collapse bifurcation in density limit physics.

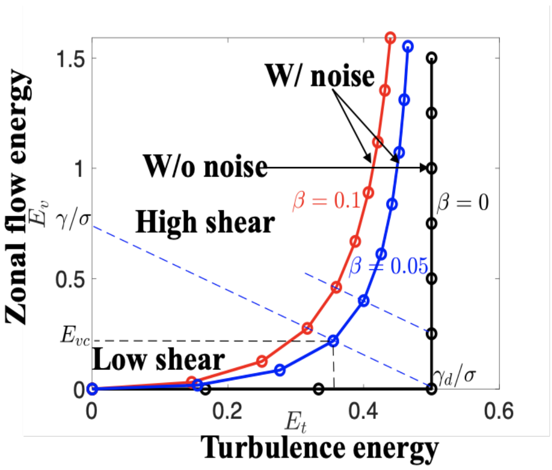

FIG. 1. Zonal flow energy E_v vs turbulence energy E_t in a linear growth rate γ scan with zonal noise strength β as a parameter.

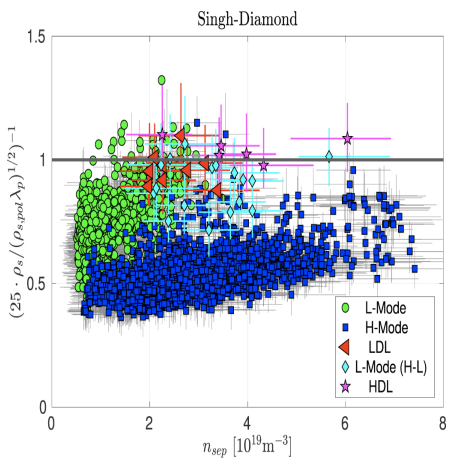

FIG. 2. Inverse of the key parameter against separatrix density from Manz et al[12].

2.2. Power scaling

The power scaling of the L-mode DL is of interest, both in regards to the basic physics of the DL and in the specific context of an improved confinement scenario of an internal transport barrier with an L-mode edge. A theory and model of the power dependence of the DL follows, within the shear layer collapse paradigm. Existing understanding and modeling results developed to address the L $\rightarrow$ H transition are useful to this end. The Kim–Diamond model, of the L $\rightarrow$ H transition, is extended to investigate the evolution of zonal shears (as present in L-mode) at high density, with auxiliary power. This model, dubbed hereafter as SD2, solves coupled evolution equations for normalized edge turbulence energy $\mathcal{E} = q_y^2\rho_s^2 I_q/q_y^2\rho_s^2\rho^{\star 2}$, normalized edge zonal flow energy $\mathcal{E}_z = v_z^2 = k_x^2\rho_s^2 I_k/k_x^2\rho_s^2\rho^{\star 2}$, normalized edge mean temperature gradient $\mathcal{T} = -a\nabla T/T_o$, and normalized edge mean density $\hat{n} = n/n_0$. Here, $\vec{q}$ refers to the wave vector for the "wavy" (or turbulent) mode and $\vec{k} = k_x\hat{x}$ refers to the wave vector of the zonal flow. The goal here is to demonstrate zonal shear collapse scalings, explore hysteresis, including noise effects (incoherent zonal mode emission) in a clear, physically motivated way. The equations are:

$$\frac{\partial \mathcal{E}}{\partial t} = \underbrace{\frac{a_1\gamma(\mathcal{N},\mathcal{T})\mathcal{E}}{(1+a_3\mathcal{V}^2)}}_{(1)} - \underbrace{a_2\mathcal{E}^2}_{(2)} - \underbrace{\frac{a_4\mathcal{E}_z\mathcal{E}}{(1+b_2\mathcal{V}^2)}}_{(3)} \quad (2)$$

$$\frac{\partial \mathcal{E}_z}{\partial t} = \underbrace{\frac{b_1\mathcal{E}\mathcal{E}_z}{(1+b_2\mathcal{V}^2)}}_{(1)} - \underbrace{b_3\hat{n}\mathcal{E}_z}_{(2)} + \underbrace{b_4\mathcal{E}^2}_{(3)} \quad (3)$$

$$\frac{\partial \mathcal{T}}{\partial t} = \underbrace{-c_1\frac{\mathcal{E}\mathcal{T}}{(1+c_2\mathcal{V}^2)}}_{(1)} - \underbrace{c_3\mathcal{T}}_{(2)} + \underbrace{Q}_{(3)} \quad (4)$$

$$\frac{\partial \hat{n}}{\partial t} = \underbrace{-d_1\frac{\mathcal{E}\hat{n}}{(1+d_2\mathcal{V}^2)}}_{(1)} - \underbrace{d_3\hat{n}}_{(2)} + \underbrace{S}_{(3)}, \quad (5)$$

Here, t is the time normalized by the gyro-Bohm diffusion time i.e., $t \equiv tD_{GB}/a^2$, where $D_{GB} = c_i\rho_i\rho^\star$ is the gyro-Bohm diffusivity and a is the minor radius. Finally, the normalized mean flow shear $\mathcal{V} \equiv V_E' a/\rho^\star c_i$ is related to the temperature gradient $\mathcal{T}$, the density gradient $\mathcal{N}$ and the local density n through the diamagnetic part of radial force balance

$$\mathcal{V} \equiv \frac{V_E' a}{\rho^\star v_{thi}} = -\frac{1}{\hat{n}}\mathcal{N}\left(\frac{1}{\hat{n}}\mathcal{N} + \frac{1}{\hat{T}}\mathcal{T}\right). \quad (6)$$

Here, couplings to mean poloidal and toroidal flows are ignored for simplicity. $\hat{T} = T/T_0$ is normalized local temperature. Meaning of different terms are discussed in the table(1). Note that this model is an outgrowth of, and yet different from, the KD03 model, in the sense that it considers the effect of zonal noise, and also includes the effect of mean $E \times B$ induced suppression of turbulence growth, and modulational zonal growth and transport cross-phase reduction. Density gradient $\mathcal{N}$ and local temperature $\hat{T}$ are not evolved. Notice the neoclassical polarization dependence of the modulational growth parameter ($b_1 \sim \varepsilon^{-1} \sim I_p^2$), the zonal noise parameter ($b_4 \sim \varepsilon^{-2} \sim I_p^4$), and the density dependence of γ, zonal flow damping rate b_3, and the mean $E \times B$ flow shear $\mathcal{V}$. These features make this model suitable for the study of the scalings of zonal collapse. The model yield power and current scalings of the density limit for shear layer collapse. Sensitivity of the scalings to the type of turbulence can be studied by adopting different expressions for γ. Here, we assume that the turbulence is dominated by the toroidal ion temperature gradient (ITG) driven modes.

Scans of Q and edge density fueling source S were performed for 'L-mode' conditions (i.e. Q below criticality for the L $\rightarrow$ H transition). Results are given in figure(3), which shows the evolution of zonal flow energy (shear layer strength) versus time during Q (power) and S (fueling) variation. Note that zonal energy rises as Q is increased, flat-tops at constant Q and then decays as S increases. The edge density increases with S (for fixed Q). The values of S and n_{edge} for which v_z^2 vanishes clearly increase with Q, indicative of power scaling of shear layer collapse and thus of the L-mode DL. Oscillations in zonal energy during the Q-ramp are of the usual sort found in predator–prey systems. The critical densities obtained from the numerical initial value experiment and the static bifurcation analysis (for increasing power) are plotted in figure(3). Both initial value analysis and a static bifurcation analysis yield a critical density which scales with the power and current as as $n_{crit} \sim I_p^2 Q^{1/3}$. Thus, *shear layer physics leads naturally to power scaling of density limit.* However, the absolute value of the n_{crit} obtained from the initial value analysis is larger that than the n_{crit} obtained from the static bifurcation analysis. This is due to dynamical delay in bifurcation caused by "critical slowing down" effect at the static bifurcation point. This has consequences for the microscopics discussed in the following paragraph. The power scaling $Q^{1/3}$ obtained here based on shear layer collapse paradigm is somewhat milder than the power scalings, $Q^{4/9}$-based on radiative power balance model[13], $Q^{0.48}$-based on the resistive ballooning modes analysis[14] and $Q^{0.7}$-based on unstable X-point radiators[15]. A recent study comparing regression analysis of DL disruptions with different DL power scaling models claims that our model is closest to the experimental scaling of $Q^{0.38\pm0.08}$[12].

Terms→ Equations ↓	(1)	(2)	(3)
Turbulence energy $\mathcal{E}$-eqn	Linear growth γ with reduction factor $\frac{1}{1+a_3\mathcal{V}^2}$ due to mean ExB shear. $a_1 \equiv a_1 a/c_i\rho^{\star 2}$	Non-linear damping from triple correlation.[16, 5] $a_1 \equiv a_1 a/c_i\rho^{\star 2}$	Local damping due to scattering of turbulence in k_x-space by mean square zonal flow shear with inhibition $\frac{1}{1+b_2\mathcal{V}^2}$ in forward transfer by mean ExB shear[17]. $a_4 = b_1 \sim I_p^2$
Zonal flow energy $\mathcal{E}_z$-eqn	Positive Reynolds power due to negative turbulent viscosity induced by symmetry breaking by eddy tilting by a seed ExB shear. Inhibition of modulational growth by mean shear captured by factor $\frac{1}{1+b_2\mathcal{V}^2}$. This also reflects as reduction in local damping of turbulence due to forward scattering in k_x-space. $b_1 = 2(k_x^2\rho_s^2/\varepsilon\rho^{\star 2})\left(\sum_q \Theta_{k,-q,q}c_s/a\right)$, Θ is triad interaction time, $\varepsilon \sim I_p^2$ is neoclassical polarization $b_1 \sim I_p^2$	Collisional damping of zonal flow $\sim n$.	Zonal noise due to incoherent mode coupling .[16, 5]$b_4 = (4/\varepsilon^2\rho^{\star 2})\sum_q q_x^2\rho_s^2 q_y^2\rho_s^2\Theta(c_s/a)$ $b_4 \sim I_p^4$
Temperature gradient $\mathcal{T}$-eqn	local damping by turbulent heat diffusion with factor $\frac{1}{1+c_2\mathcal{V}^2}$ due to transport cross-phase reduction by mean ExB shear[18]. $c_1 = (a/L)^2(\chi_T/D_{GB})$	Neoclassical heat transport. $c_3 = (a/L)^2(\chi_{nc}/D_{GB})$	Input heat source. (Control parameter) $Q = a^2\nabla S_T/T_0 c_i\rho^{\star 2}$, S_T is the actual heat source function
Density $\hat{n}$-eqn	local damping by turbulent particle diffusion with factor $\frac{1}{1+d_2\mathcal{V}^2}$ due to transport cross-phase reduction by mean ExB shear. $d_1 = (a/L)^2(D_T/D_{GB})$	Neoclassical particle transport. $d_3 = (a/L)^2(D_{nc}/D_{GB})$	Particle source.(Control parameter) $S = aS_n/n_0 c_i\rho^{\star 2}$, S_n is the dimensional particle source function

TABLE 1. Physics of different terms in model equations(2), (3), (4) and (5).

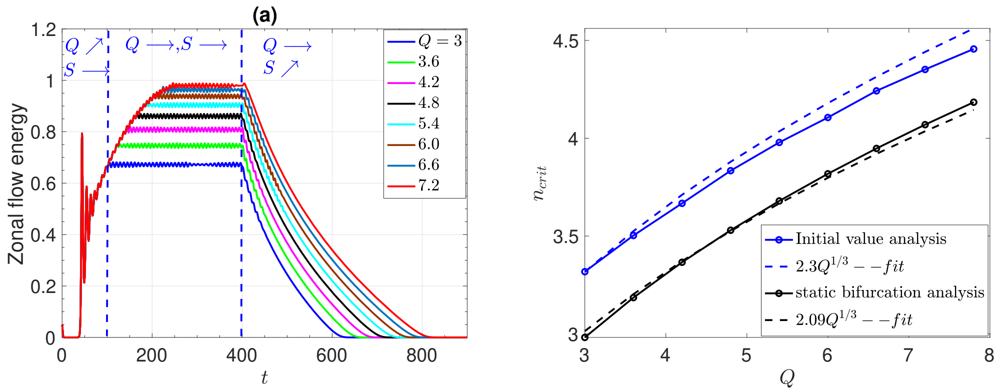

FIG. 3. (a): Zonal flow energy damping with particle source S ramp up at different powers Q. The zonal flow damping time increases with the input power. Clearly, the critical density for the zonal flow collapse increases with the input power. Diagonal arrow means ramp up and right arrow means steady.

2.3. Hysteresis:

Above analysis showed that shear layer bifurcation physics is the key to emergence of power scaling of the density limit. Hysteresis is a dynamical manifestation of bifurcation phenomenon when the control parameter is varied across a bifurcation point. For example, L-H hysteresis appears when input power is ramped back and forth across the L-H power threshold (i.e., the bifurcation point). The system jumps from one stable state(L-mode) to another stable state (H-mode) in a Hopf bifurcation. So hysteresis is symptomatic of a transport bifurcation process. One wonders whether the transport bifurcation leading to zonal shear collapse is hysteretic? Investigations of cyclic Q ramp evolution clearly manifest hysteresis in all fields. These results are evident in figure(4), which shows both time evolution and a hysteresis loop in zonal flow energy versus Q. It should be clear that there is only one stable fixed point at any Q. So, the hysteresis observed here is not due to static bistability, but due to dynamic delay caused by critical slowing down at the bifurcation point. *Nevertheless, this result is likely of significant interest, as it links scaling to microscopics, and sets forth a clear, testable prediction of dynamics.*

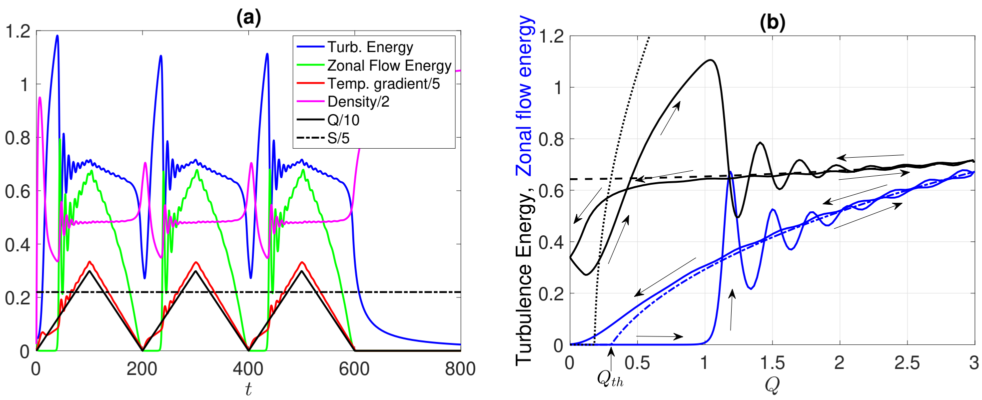

FIG. 4. (a): Evolution of turbulence energy, zonal flow energy, temperature gradient and density under the action of a cyclic ramp of input power Q. (b): Zonal collapse hysteresis in a cyclic power ramp. Hysteresis plots made within the time interval $t = [200, 400]$. The black dotted curve is static bifurcation curve for turbulence energy without zonal flow, the black dashed curve is that with zonal flow. The blue dashed dotted curve is the static bifurcation curve for zonal flow energy. The arrows indicate the causal flow of the system.

3. PARTICLE TRANSPORT EVENTS AT THE DENSITY LIMIT

With the collapse of the edge shear layer, there is a marked change in the state of the edge plasma. The upshot is that while Reynolds power and zonal flow production drop[4] after the collapse, the power coupled to turbulence spreading increases. This suggests that the energy stored in the edge shear layer is ultimately transferred to turbulence spreading across the separatrix and ultimately into the SOL. The results of Langmuir probe studies of turbulence during a density scan on the J-TEXT tokamak[7], demonstrate this -see figure(4). At the same time,

density fluctuation skewness increases, indicating an increased rate in the formation of “blobs” and other structures. This tells us that with the collapse of the shear layer approaching the DL, the edge density profile essentially fractures into an ensemble of eddies, blobs, etc. Interestingly, the most robust indicator of this evolution is an increase in the density spreading flux $\langle \tilde{v}_r \tilde{n}\tilde{n} \rangle$. So, at the DL, the shear layer collapsed and the edge density fractalizes into a ‘soup’ of spreading, patchy turbulence. This has implications for plasma-boundary interaction.
Given the obvious importance of the edge shear layer for DL, it is natural to explore the effects of externally driven shear on DL[19]. Studies of edge electrode bias experiments on the J-TEXT tokamak indicate that positive bias can increase the line averaged density by $\sim 15\%$, and nearly double the edge density. Hysteresis is observed in the evolution of the adiabaticity parameter with the edge ExB shear. Moreover, the density turbulence spreading flux $\langle \tilde{v}_r \tilde{n}\tilde{n} \rangle$ once again emerges as the quantity which responds most dramatically to the changes on the edge shear layer.

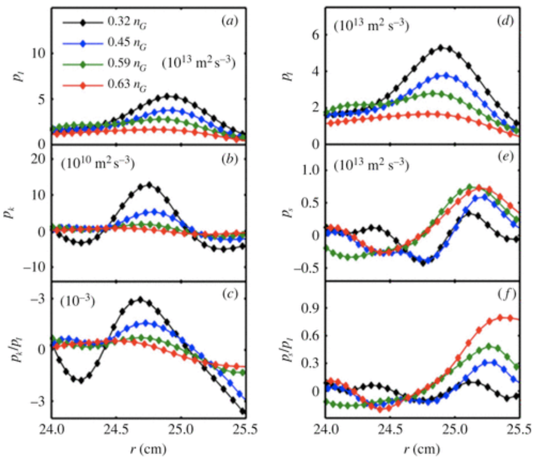

FIG. 5. In a standard collisionless drift wave (CDW) model, the turbulence production power (a) from ∇n is $P_I = -c_s^2 \langle \tilde{v}_r \tilde{n} \rangle \frac{1}{\langle n \rangle} \frac{d\langle n \rangle}{dr}$, and the Reynolds power (b), the power coupling to the zonal flow is $P_{Re} = P_k = \langle \tilde{v}_r \tilde{v}_\theta \rangle \langle v_E \rangle'$. Obviously, both P_I and P_k/P_I drop (c) as n_e/n_G rises. Meanwhile, the turbulence spreading ratio P_s/P_I enhances as n_e/n_G rises (d–f).

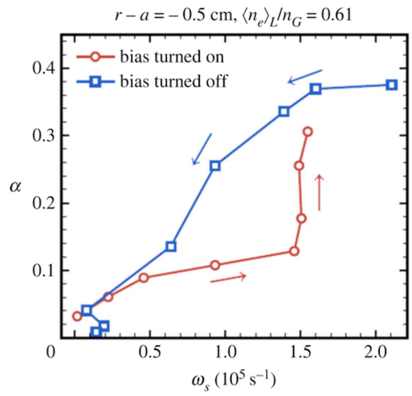

FIG. 6. α vs ω_s exhibits a hysteresis loop during the electrode bias switch on or off. N.B. the counter-clockwise direction of the trajectory indicates that ω_s shear ‘leads’ α.

4. CURRENT ISSUES

DL physics is an active and multi faceted research topic. Current research topics in transport physics of the DL include:

1. H-mode density limit (HDL): The HDL is typically a 2-step process -first, a back transition from H-to-L mode, then second, a progression to the Greenwald limit[20]. The back transition trigger mechanism is of greatest interest. Candidates include ballooning modes at the separatrix, as suggested by the observed correlation of the HDL with α_{MHD} at the boundary[21]. An alternative is the invasion of the pedestal by turbulence spreading, triggered by the onset of SOL instability at high density[22]. The key physics here is broadening of the SOL layer, leading to weaker ExB shear in the SOL.The possible role of electromagnetic pedestal turbulence and it’s impact on mean radial electric field shear merits consideration too.

2. Core fueling: Virtually all DL models are concerned with edge phenomenology, motivated by the simple fact that fueling is usually via the edge layer. Yet future plasmas may likely be fueled through the core by pellet injection, etc. Very little in the way of consideration of density limits in this regime is available. An obvious issue is the interplay of power deposition and fueling, which determines the critical η_i parameter.

3. Collisionless regimes: Most of the theoretical work on DL physics employs fluid models, which are frequently dubious in collisionless regimes. Of particular note here is the emphasis on adiabaticity, specifically $\alpha < 1$ regimes, and the onset of resistive ballooning turbulence. These are not likely relevant to a collisionless edge. Limitations on high density in collisionless regimes have not been considered. This is obviously a gap in our thinking which should be promptly rectified.

4. Theoretical matters: Two theoretical matters stand out. First, models should predict profiles, not only local edge densities, etc. To this end we plan to develop a 1D model of power scaling , similar to the 1D model of

the L→H transition[23]. The aim is to predict the density profile scale length. This is a much more challenging deliverable for theory then simple scaling is. Second, the question of triple point 'phase-coexistence' of L-mode, H mode and a strongly turbulent DL regime remains unresolved and is of fundamental interest.

5. CONCLUSIONS

This paper presented a comprehensive survey of recent developments on the transport physics of the density limit. Density limits are of great interest for burning plasmas, since fusion power increases $\sim n^2$. The principal results of this paper are:

1. the theory of shear layer collapse scenario of edge density limit is developed in detail. The poloidal field dependence of the neoclassical dielectric is identified as the origin of current scaling. A critical parameter is identified, which has been shown to be consistent with the analysis of a large data set. The shear layer collapse scenario is summarized in figure(7).

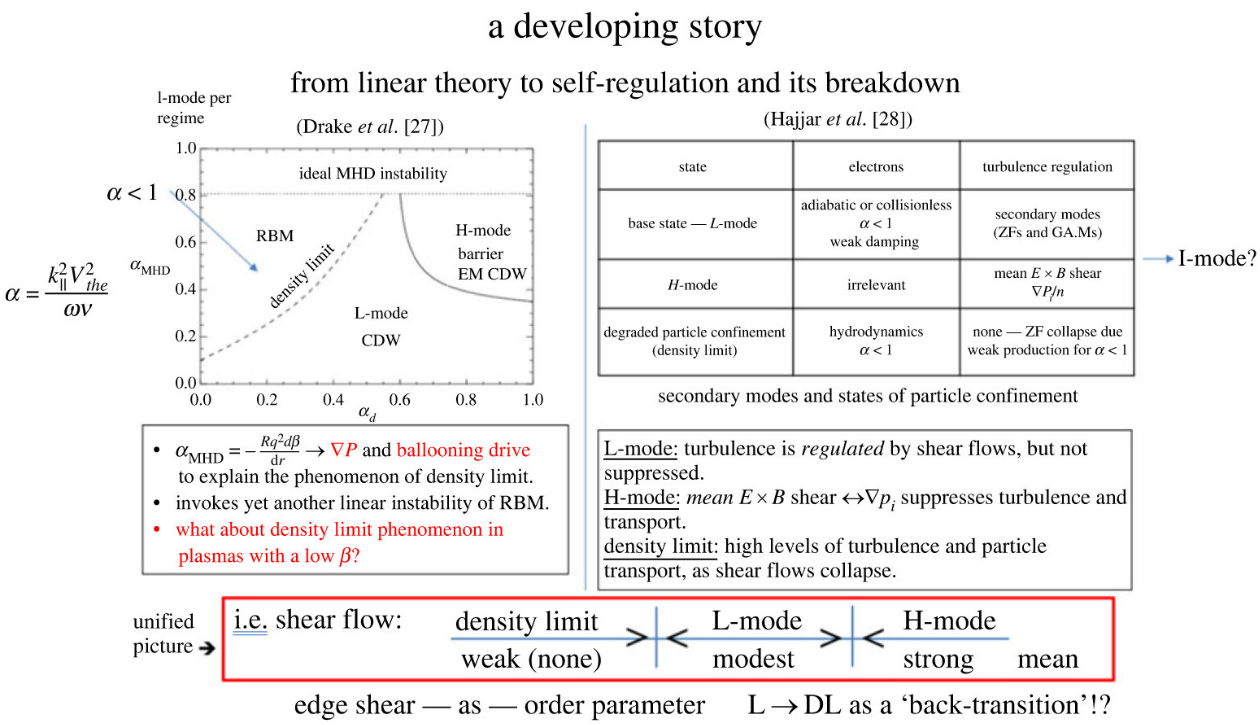

FIG. 7. Evolution of the perspective on the DL. The lower bar in red summarizes the role of shear flow.

2. the edge density (in L-mode) n_{edge} is shown to scale with edge heat flux Q_i as $n_{edge} \sim Q_i^{1/3}$. The physics is the power dependence of the the Reynolds stress which support edge shear layers. This dynamics underpins observed macroscopic power scaling. The result is of particular significance, as it suggests the interesting feedback loop of the form: increased fusion power → increased density → increased fusion power etc in a burning plasma. More generally, power dependence represents a significant departure from from the familiar Greenwald scaling. The theory of power scaling is developed for collisionless ITG turbulence.

3. A novel type of n_{edge} vs Q_i hysteresis is identified and offered as a corollary of power scaling. It constitutes a non-trivial fundamental prediction related to the basic physics. The hysteresis mechanism is due to critical slowing down and not to bistability, as for L→H, H→L transitions.

4. Shear layer collapse is shown to trigger enhance particle transport events. These consist of strong turbulence spreading and emission of density blobs. The observance of particle transport events relates strong intermittent turbulence to shear layer collapse and the onset of the density limit.

5. Current issues are discussed. These include the H-mode density limit and various aspects of the theory. The need for 1D models of profile evolution is discussed.

Overall, the transport physics of the density limit is a dynamic and developing topic which will only grow in importance in coming years.

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REFERENCES

[1] Martin Greenwald. *Plasma Physics and Controlled Fusion*, 44(8):R27–R53, 2002.

[2] M. Greenwald et al. *Nuclear Fusion*, 28(12):2199–2207, 1988.

[3] R. Hong et al. *Nuclear Fusion*, 58(1):016041, 2017.

[4] R. J. Hajjar, P. H. Diamond, and M. A. Malkov. *Physics of Plasmas*, 25(6):062306, 2018.

[5] Rameswar Singh and P.H. Diamond. *Nuclear Fusion*, 61(7):076009, 2021.

[6] Rameswar Singh and P H Diamond. *Plasma Physics and Controlled Fusion*, 64(8):084004, 2022.

[7] T. Long et al. *Nuclear Fusion*, 61(12):126066, 2021.

[8] P H Diamond et al. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 381(2242):20210227, 2023.

[9] A.O. Nelson et al. *Nuclear Fusion*, 62(9):096020, 2022.

[10] F. L. Hinton and J. A. Robertson. *The Physics of Fluids*, 27(5):1243–1247, 1984.

[11] M. N. Rosenbluth and F. L. Hinton. *Phys. Rev. Lett.*, 80(4):724–727, Jan 1998.

[12] P. Manz et al. *Nuclear Fusion*, 63(7):076026, 2023.

[13] P. Zanca, F. Sattin, and D.F. Escande. *Nuclear Fusion*, 59(12):126011, 2019.

[14] M Giacomin et al. *Phys. Rev. Lett.*, 128:185003, 2022.

[15] U. Stroth et al. *Nuclear Fusion*, 62(7):076008, 2022.

[16] Rameswar Singh and P H Diamond. *Plasma Physics and Controlled Fusion*, 63(3):035015, 2021.

[17] P. H. Diamond, S.-I. Itoh, K. Itoh, and T. S. Hahm. *Plasma. Phys. Cont*, 47(5):R35–R161, 2005.

[18] Eun-jin Kim and P. H. Diamond. *Phys. Rev. Lett.*, 91:075001, 2003.

[19] Rui Ke et al. *Nuclear Fusion*, 62(7):076014, 2022.

[20] M Bernert et al. *Plasma Physics and Controlled Fusion*, 57(1):014038, 2014.

[21] T. Eich et al. *Nuclear Fusion*, 58(3):034001, 2018.

[22] A.O. Brown and R.J. Goldston. *Nuclear Materials and Energy*, 27:101002, 2021.

[23] K. Miki et al. *Nuclear Fusion*, 53(7):073044, 2013.