Boundary Physics Part I: Edging Towards The Density Limit

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1 Density Limits

High core density is good, which we know from both of our key figures of merit in the tokamak business: the Lawson criterion, $n\tau T$, and the plasma pressure term $\beta = nT/B^2$, which both rely on the density n.

1.1 Background

Today, the two main drivers for "improving" confinement in experiments are money (as a proxy for power) and/or good overall control - that is, it is more important to balance good confinement metrics with good power handling and good boundary control than to *just* achieve high parameters. In the past, however, the approach was more "survivalist", where the primary focus was to simply "max out" parameters. Without the money to get high power and without the understanding of how to get high confinement (until H-mode developed), the easiest way to get high confinement metrics was to increase the density.

The desire for high parameters led efforts to increase density in confinement experiments, since it was thought to provide the "easiest" path forward. In these early experiments, ohmic heating was limited, and beams were expensive and did not provide sufficient power. Today, this is less of a limitation because RF works well (particularly ECH), but without this equipment, initial experimental efforts focused on improving confinement by increasing the density. The density goes with the current, which is useful for ohmic heating, so this was an appealing path forward.

This approach appeared to be reasonable. Experiments in fueling successfully showed that if gas were loaded up and inserted into the edge, then the inward pinch would do the job to fuel the plasma, where the core would "soak up" the additional density injections via the pinch mechanism. The flux of particles goes as

$$\Gamma = -D\nabla n + vn, \tag{1}$$

where Γ is the particle flux, D is the diffusion coefficient, n is the density, and v is the pinch velocity, which is less than zero (and always opposite sign to the first term for up-gradient, inward-towards-the-center transport). This comes from thermoelectric and turbulent equipartition (TEP) effects, as previously discussed in this course.

Ideally, one could puff in gas at the edge indefinitely to "max out" their confinement metrics, but this was not the case. As it turns out, there was a Big Surprise: there is a limit on how much the density can be increased, which is referred to as the "density limit".

1.2 Greenwald limit

There are several density limits that have been reported in the context of tokamak physics, including the Murakami [1] and Hugill [2], which tended to be device-specific and overall were mostly garbage. However, the one density limit that has survived is the Greenwald limit [3].

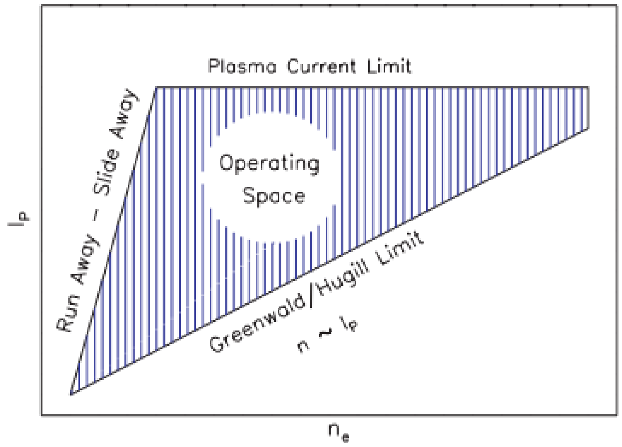


Figure 1: A schematic of the operating space for tokamaks or RFPs. Operation is bounded by a low-density limit characterized by run-away fast electrons and a high-density limit proportional to the plasma current. The limit on plasma current is due to MHD kink instabilities and applies to tokamaks. Figure and caption from [4].

The Greenwald limit $\bar{n}_g$ is a limit in the line-averaged density, where

$$\bar{n}_G = \frac{I_p}{\pi a^2}, \tag{2}$$

where the primary focus is on the scaling with the current, I_p (rather than the radial length a). This is a fundamental constraint on tokamak operation. The density limit prompts raised eyebrows when considering at the operational conditions proposed for the ITER device, where it has been postulated that the machine will operate at or near the Greenwald density limit. This is "make-or-break" constraint for ITER, and remains an ongoing area of investigation, lest everyone involved be convicted of fraud if ITER doesn't work.

The Greenwald limit is an engineering formula, since it has dimensions, rather than a physics constraint, which are dimensionless. This limit gives a limiting factor on the Lawson criterion, $n\tau T$, though the realization of the density limit predates its attachment to this figure of merit.

The density limit is not unique to tokamaks, and appears in many different kinds of large toroidal devices, like the stellarator and RFP. While stellarators don't have current, stellarators still have density limits, with notable work being performed by Carlos Hidalgo of TJ-II in Madrid. The RFP, which is a torus with the toroidal field generated by a dynamo process with Taylor relaxation, has a density limit that is also associated with the current, but the physics of the RMP is not well understood yet.

The Greenwald limit is a fundamental limit on the operating space, even in ohmic heating. In a plot of current versus density, a tokamak must operate above the Greenwald limit line, shown in Figure 1. From this plot, we can also see that we cannot operate at too low density, or else the plasma will "run away" in the "slide away" regime. There is also an upper limit on current, which

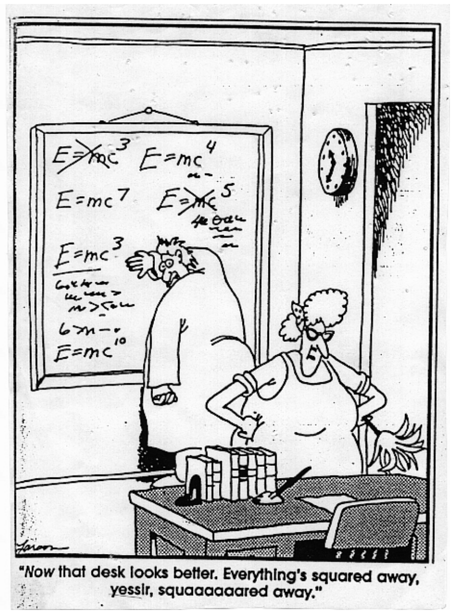


Figure 2: A scene reminiscent of efforts in confinement scaling.

can be achieved in today's machines. The operating space for a tokamak exists between these three limitations.

1.2.1 Current

One important observation about the density limit formula is that it is pathetically simple. In general, confinement scaling formulas are complicated, often with myriad coefficients with non-integer powers that fell out of someone's carefully crafted Excel™ spreadsheet (see Figure 2). For the Greenwald scaling, we have a linear relationship between the two parameters of interest. So where does the current come from in this relationship?

The relationship between the density limit and current is likely a result of a dependence on B_θ, which indicates an association with both q and ρ_θ. The link to ρ_θ also suggests a loose affiliation with the zonal flow screening length, which will be discussed later on.

We have seen from experiment Figure 3 that the Greenwald scaling works, and works *very well*, but what are the physics behind this relationship?

The density limit is often limited to disruptions, large-scale MHD events that can be catastrophic for the confined plasma. Disruptions usually happen as a result of tearing modes, which are driven by current gradients near low-order rational surfaces (like $q = 2$, which would be near the outside of the plasma). Current gradients are often due to cooling, which results from radiation. This brings a strong association to the MARFE (**M**ulti-**F**aceted, **A**xisymmetric **R**adiation **F**rom the **E**dge, or Earl **Mar**mar and Steve Wol**fe**, two pioneers in the study of the MARFE [5]). It also makes for delightful jargon: "The plasma MARFEd on me" or "The plasma MARFEd and then it disrupted".

MARFEs are a case of radiative condensation. The theory of radiative condensation comes from astrophysics from George Field, and brought into fusion by Drake. The mechanism is that you

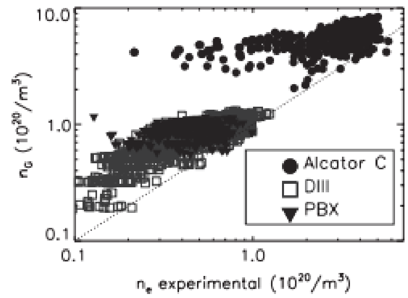
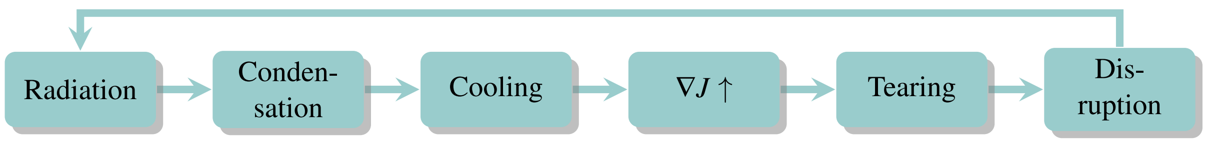


Figure 3: Measured densities are plotted against the Greenwald limit. From [4].

raise the density, meaning you radiate more, so to balance the pressure as the temperature goes down, the density goes up, leading to an instability:



This MARFE process will cause an instability and collapse the profile.

The density limit also plays an important role in divertor detachment. Divertor detachment has a strong dependence on high plasma density, and there can be significant MARFE activity in the transition to the detached divertor regime [6].

1.2.2 The end of the world?

While the density limit is related to the MARFE process, there are plenty of times that the density is limited and nothing terrible happens. You can't raise the density once this point is reached, but sometimes, there is no disruption or MARFEing, and no mess needs to be cleaned up. A MARFE is simply one termination scenario, and one that is not guaranteed.

1.3 H-mode Density Limit (HDL)

What about the H-mode? Nobody quite understands it yet, but there is an interesting phenomenology for the density limit in the H-mode, which is essential to understand because of its relevance to ITER and ignition in reactor conditions. This is the HDL, which is not just the good cholesterol, but also an **H**-mode **d**ensity **l**imit. The difference between this and the Greenwald density limit is that the HDL is specific to H-mode, and plays an important role in the L-H transition. In general, $\bar{n}_{HDL} \leq \bar{n}_G$. At the HDL, as density is increased, there is a back-transition to L-mode. Increasing the density further means you proceed to the Greenwald density, where the density can no longer be raised. In H-mode, to get to the Greenwald density, you must always pass through the HDL. This has not yet been explained definitively, though some think they have figured it out. 

2 The Edge Plasma

The plasma is fueled by particles entering at the edge, meaning the density limit is inextricably tied to the physics of the edge plasma and boundary. Although the plasma *can* be fueled by beams or other means, like plasmoids or other pellet-related procedures, ITER is most likely too large and too dense for these methods to work, and will likely be reliant on puffing at the edge. solidifying the study of edge plasma as a "hot topic" in the fusion world today.

2.1 Roadmap

Boundary physics, or "edge" physics, covers the regions from the outer section of the core plasma to the walls of the machine, encompassing the transition from the region of closed magnetic field lines (in the core) to open magnetic field lines (in the "scrape-off layer", or "SOL"). This entire region is shown in Figure 4. The divide between these two regions is called the "separatrix", which is an area of great interest that will be explored later. The magnetic field lines in the SOL connect to a limiter or the wall of the machine. There is considerable interest in the areas where these field lines intersect the wall, since the plasma is now acting on a material surface. The study of this region is called "PWI" or "PMI", for "plasma wall interactions" or "plasma material interactions", respectively. The intersection of the field lines with the wall is also important for the management of exhaust coming from the core: all power expelled from the core plasma is directed by these open field lines to some first-wall surface, which is usually a little plate (also called a "target") positioned away from the core plasma that is specially designed to handle extreme heat loads.

At the outer edge of the core, profiles of plasma parameters are typified by rather steep gradients in both L- and H-mode, driven primarily by heat and momentum flux.

2.2 Scrape-Off Layer (SOL)

In the scrape-off layer, some particles travel through the separatrix, but the temperature and density decay exponentially, where $T, n \sim e^{-x/\Delta}$. These particles travel through the SOL and towards the wall. Here, a fluctuation of particles described as $\tilde{n}/n$ will go up, since n is decaying exponentially. This results in large chunks of particles, called "blobs", shown in Figure 4 as the dark purple globules, that float like icebergs through the separatrix and into the wall [7, 8][1]. These blobs are associated with vortices, and account for the majority of particle transport through the scrape-off layer.

While the majority of the incoming heat and particle flux to the SOL gets directed to the divertor and into the target, these blobs can break off of particle flows and float off to hit the wall. This is not good, since although these blobs will not carry intense heat flux to the material surfaces, the interaction of the blob with the wall can cause in recycling within the main chamber. Recycling is when the plasma interacts with a surface, and the plasma is essentially reflected back as neutral particles. Recycling in the main chamber can be problematic, since the neutrals produced by the recycling process cannot be directed by the field lines and can penetrate the core plasma.

[1] The author acknowledges her shameless self promotion, but remains very proud of her bad Photoshop skills.

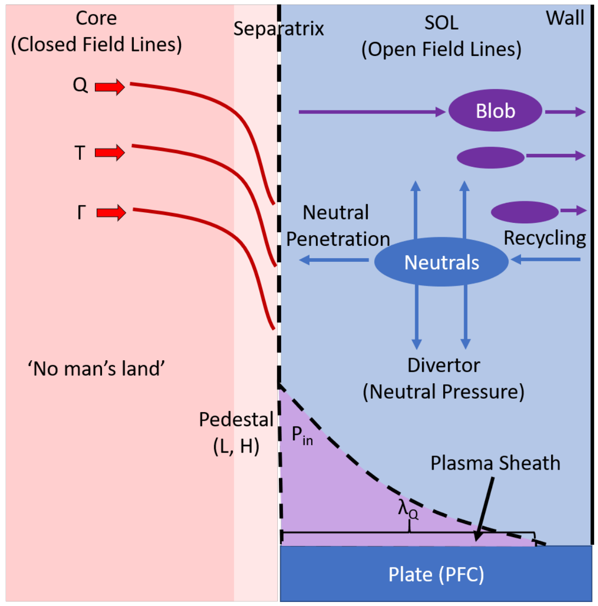


Figure 4: Cartoon of the edge plasma. Areas highlighted in pink are in the core, and areas in blue are in the SOL. Components in purple are components in the SOL that come from the core (plasma blobs in dark purple, and exhaust, spread over the width λ_Q, in light purple). The structure of heat flux, temperature, and particle flux profiles in the core are shown in dark red, and the pedestal region is highlighted on these profiles in light pink. The separatrix is denoted in the thick, dashed black line.

However, neutrals are important for proper functionality of the divertor, where they are an essential ingredient in the dissipative losses that lead to divertor detachment.

It is important that the plasma is fueled by heat and momentum from the core (or, particles from the core in beam-fueled discharges, but this is usually not the case), while the particles are driven from the edge. In L-mode the edge turbulence is very strong. Typically, parameters will be in the range of

$$\frac{e\phi}{T}, \frac{\tilde{n}}{n} \geq .1 \to 1$$

inside the separatrix, and not in the vicinity of a blob. These numbers go down in H-mode because of shear suppression.

Universally, there is a rising profile in intensity of the fluctuations and in the transport coefficients D and χ.

2.3 Diagnostics

Langmuir probes are used to study the edge, which are electrodes inserted into the plasma to measure electron density, electron temperature and electric potential, allowing for direct measurements of $\frac{e\phi}{T}$ and $\frac{\tilde{n}}{n}$. Special probes can be used to measure flows, and in some cases, temperature fluctuations at the edge. This means that the edge can be fairly well-resolved in terms of diagnostics, and we have a reasonably good idea of the processes occuring at the edge.

Similar levels of diagnostic capability do not exist for the core plasma. Langmuir probes cannot be used in the core plasma, so there is considerably more insight into turbulence physics at the edge than in the core because of these measurements. It is possible, to measure core turbulence using a technique like Beam Emission Spectroscopy, or BES, which measures density fluctuations, but it is difficult to measure potential fluctuations in the core. The only diagnostic that really does it is a heavy ion beam probe, which uses ions - immediately raising concerns about how to get the diagnostic ions across the magnetic field in a magnetic confinement device. This limits this technique to small devices with weak fields that the process could actually work on, and it is not particularly useful due to these technological constraints.

2.4 Separatrix

The "separatrix" refers to the last closed flux surface - the magnetic surface that separates the core and SOL plasmas and the barrier between open and closed field lines. However, there are multiple visions of this division that complicate the discussion and physics of this transition region.

2.4.1 Which edge?

The edge suffers from multiple personality disorder, with three different "personalities" of the edge: the L-mode (with no distinction between L-mode and ohmic L-mode), H-mode, and in the vicinity of the density limit. The psychiatric evaluation is summarized in Table 1.

L-mode is characterized by strong turbulence, and the H-mode is characterized by weaker turbulence, at least at larger scales and longer wavelengths.

In the region of the steep gradient in the plasma profile at the edge, there is a strong gradient in the velocity shear layer, even in L-mode. In H-mode, this velocity shear layer becomes the transport barrier, which was discussed previously in the course. To form a shear layer, there must be both a Reynolds stress and a gradient in the Reynolds stress. A non-trivial derivative in the Reynolds stress exists where there is a non-trivial variation in the intensity of the turbulence, which occurs in the edge region, and means that a shear layer will form. This is a nearly universal phenomenon in tokamaks and stellarators, attributed to this Reynolds stress and neoclassical transport. In H-mode, there is a very strong shear layer, which is linked to the pressure gradient by radial force balance.

There is high transport in L-mode, but with all the turbulence, there is often a pinch. In H-mode, particle diffusion, momentum flux, and χ_i, χ_ϕ often go down. The pinch is not clear; it is not understood what happens with the particles in H-mode. The electron transport, χ_e, tends to stay up in H-mode, probably because it is working through shorter wavelength processes that are not so sensitive to the shear. The edge obviously becomes more quiescent in H-mode than in L-mode, which

Table 1: Characteristics of the three distinct regimes at the edge of the plasma.

	At the Density Limit	L-mode	H-mode
Turbulence	Very strong	Strong	Weak
Shear	Collapse of shear layer	Shear layer (Reynolds stress, neoclassical)	Strong shear $\rightarrow$ $(\nabla P/n)$ + ...
Transport	$D_n \uparrow$	High transport	ELMS $\leftrightarrow$ MHD events (turbulence)
Particles	Density outflow	Pinch	$D, \chi_i, \chi_\phi \downarrow$, $\chi_e \uparrow$, Pinch $\rightarrow$?
Order parameter $\frac{\acute{v}_E}{\Delta\omega_k}$	0	Less than 1	High

is good confinement from the steepened gradient. There are periodic bursts of particles, the ELMS, that behave like sawteeth cycles, but there are cases where they are small and quasi-continuous. There is no difference between ELMS and turbulence in practice, but these phenomenon each have a different origin; the small and quasi-continuous ELMs are a kind of weak turbulence.

The third "face" to the edge's multiple personalities is in the vicinity of the density limit at very high densities in L-mode. In this scenario, the turbulence is not just strong, but **very** strong, and it seems that the shear layer collapses. The particle diffusion goes up, and there is a density outflow, even if you do not MARFE or disrupt. There is a natural kind of order parameter, which should not be taken *too* seriously (but some idea gives better than no idea at all), which is the ratio of the shearing rate to the decorrelation rate:

$$0 \leftarrow \frac{\acute{v}_E}{\Delta\omega_k} \rightarrow \text{High}$$

In L-mode, this is less than one, and in H-mode, this is very high. Towards the density limit, the shear layer nearly collapses, and this term approaches zero, since the $\acute{v}_E$ will become small and the $\Delta\omega_k$ will become large as the turbulence gets stronger. Using the shearing parameter as an order parameter is a way of unifying the phenomenology, which might be debatable, but it's better than nothing.

Given that there is strong shear at the edge, how do you determine the radial electric field? In the core, there are closed field lines, where $\vec{\nabla} \cdot \vec{J} = 0$, with mainly

$$\partial_r J_{pol} \cong 0, \tag{3}$$

which allows for a radial force balance.

Figure 5: On the left, the 38th Parallel [9]. On the right, the San Ysidro port of entry [10].

In the scrape-off layer, the magnetic field lines are open, and connect to the plate. This means there is current flow along these field lines, and $\vec{\nabla} \cdot \vec{J} = 0$ becomes

$$\nabla_{\perp} J_{\perp} + \nabla_{||} J_{||} = 0, \tag{4}$$

where the $\nabla_{||} J_{||}$ term has a sheath boundary condition at the terminal end of the field line on the target. A plasma sheath is a region close to the plasma-material interface where the electric field changes. This will be discussed further in the next lecture (stay tuned).

2.4.2 Border patrol

In general, people think of and treat the core and the SOL as two different worlds, separated distinctly by the separatrix. This model of the edge plasma is like the 38th parallel on the Korean peninsula, where two distinct universes exist along the same border, as in the left-hand picture shown in Figure 5. This model is usually taken for simplicity and convenience, and the transition between the two "zones" is rarely (if ever) acknowledged or discussed.

The reality of the situation that the boundary is porous, much more akin to the US-Mexico border, where much goes in and much goes out (at least in L-mode), as in the right-hand picture in Figure 5. While going "too far" from the boundary definitely shows distinct core-like or SOL-like characteristics of the plasma, there is a transition layer between these two zones with distinct dynamics that are different than deeper into the core or SOL. The natural candidate for the transition layer might be one correlation length of the turbulence or a poloidal gyroradius, ρ_{θ}. However, this view is controversial, since some believe that the width of the SOL in H-mode is one gyroradius (see Figure 6). This would mean there would be no transition, and the change between the two regions would be instantaneous.

In the SOL, the electric field is determined by the sheath, where $\langle E_r \rangle \rightarrow \langle \phi \rangle \rightarrow$ Sheath. This makes

Figure 6: Somewhere in PPPL.

sense because the electric field is determined by the temperature:

$$\langle \phi \rangle \simeq \frac{T}{|e|} \sim (T \sim e^{-x/\lambda} T_{sep}), \tag{5}$$

where T_{sep} is the temperature at the separatrix. From this relationship, we can see that the shear is strongly dependent on the scrape-off layer width, since this would mean that

$$\acute{v}_E \simeq \frac{1}{\lambda^2} \frac{T_{sep}}{|e|}. \tag{6}$$

This indicates that there needs to be a transition layer in the electric field evolution, but it is not well understood.

3 Edge Particle Transport

3.1 Shear layer

Recall that in the scrape-off layer, the magnetic field lines are open, and connect to the plate. The flow along these field lines, with $\nabla \cdot \Gamma,\ Q = 0$, becomes

$$\nabla_{\perp} J_{\perp} + \nabla_{||} J_{||} = 0. \tag{7}$$

Parallel flow in the SOL means there will be parallel losses. In contrast, the core has closed closed field lines, where $\nabla \cdot \Gamma, = 0$, with Γ=constant, since there is fixed flux in the core.

For the density limit, we must consider what is happening in L-mode, specifically focusing on the base state at the edge. This is fairly well-defined, since there is a long history of probe experiments on the edge plasma starting in the 1950s. This includes work on Zeta, from Robinson and Russbridge, which was an ancient reversed-field pinch in Culham from 1958. It is easy to stick probes into plasma and get direct measurements of fluxes (usually the particle flux, $\tilde{v}_r\tilde{n}$ or the Reynolds stress, $\tilde{v}_r\tilde{v}_\theta$; note the critical role of the cross phase in these relationships). Temperature and heat flux measurements are harder to measure than the particles and stresses in the edge, and all quantities are difficult (if not impossible) to measure in the core.

Edge turbulence frequently deviates from the Boltzmann relation, so

$$\frac{\tilde{n}}{n} \not\sim \frac{e\phi}{T}. \tag{8}$$

This is because the edge region is cooler, so it becomes non-adiabatic, since $\alpha \leq 1$.

Turbulence in the edge manifests as a multitude of players, all of whom are rather similar. These candidates include collisional drift waves (CDW), dissipative trapped electron modes (DTEM), ITGs, resistive ballooning modes (RBMs), resistivity gradients ($\nabla\eta$), which are all "kinda-sorta" drift waves that have been extended to the hydrodynamic electron regime. Ultimately, non-adiabatic behavior is not surprising, and there are many "MHD-like" candidates for what causes it. In other words, $k_{||}^2 v_{th,e}^2/\omega\nu < 1$. This is the point, and what needs to be considered, rather than splitting hairs on which mode is causing what.

With this in mind, the important thing to consider is the shear layer. Shear layers are a universal feature of the edge, observed in both tokamaks and stellarators since the early 1990s [11]. This has been observed in both L-mode and H-mode, first observed in TEXT in the mid-1980s. This showed there were effects of the shearing on eddies, linked to turbulence control [12].

Evidence of the shear layer can be seen in probe measurements from these experiments. The phase velocity of the fluctuations is shown in Figure 7(a), where there is a transition at the edge. This transition is also observed in the potential, shown in Figure 7(b). The density monotonically decreases, while the steep part of the velocity gradient peaks at the location of the shear layer, shown on the left and right axes (respectively) of Figure 7(c). The two-point correlation for poloidally and radially separated probes is shown in Figure 8, which shows a dip that corresponds to the location of the shear layer.

The L-H transition seems to build on the base state of the L-mode shear layer, which has been studied by Hildalgo. The bottom line for the shear layer is that it comes from the turbulent Reynolds stress because there is a boundary. There is a peak in fluctuation intensity, which naturally gives a Reynolds stress from a phase correlation of $k_r k_\theta$. Then, the gradient of the Reynolds stress at the edge becomes very large, and the flow will form a shear layer.

3.2 Shear layer collapse

This shear layer regulates the turbulence, even in L-mode. This makes the shear layer critical to the density limit: what happens if this shear layer weakens or goes away? This is the shear

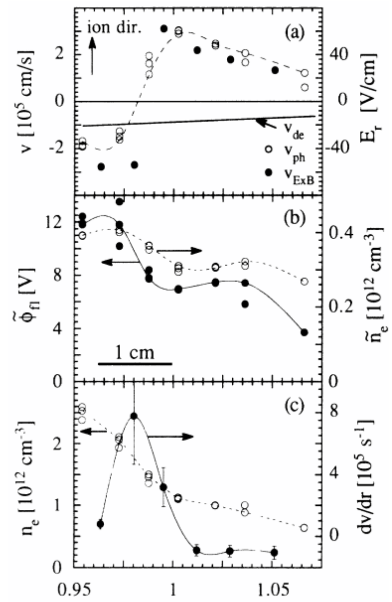


Figure 7: Radial profiles for a discharge with B =2 T, plasma current of 200 kA, and chord-averaged density of $n_{chord} = 2x10^{13}cm^{-3}$. (a) Phase velocity of the fluctuations v_{E_rxB} (closed circles), v_{E_rxB} plasma rotation (open circles), and drift velocity v_d, . (b) Density and floating potential fluctuations. (c) Density and velocity shear. The statistical error for individual shots is of order the symbol size and shot-to-shot reproducibility is given by the individual symbols. The systematic error in the plasma position is 0.5 cm or r/a=0.02. Figure and caption from [12].

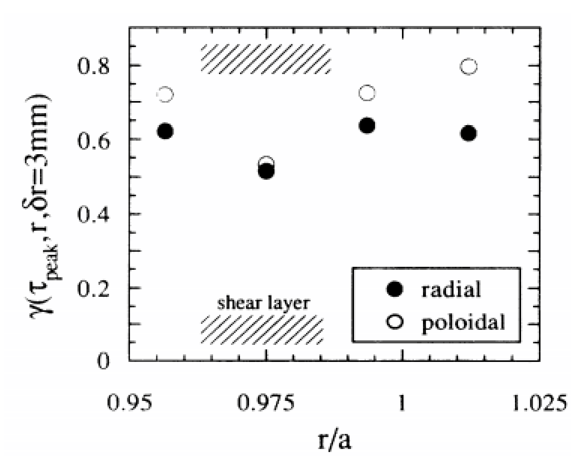


Figure 8: Peak values of the normalized two-point correlation function for poloidally and radially separated probes with fixed separations of $\delta r = 3$ mm.

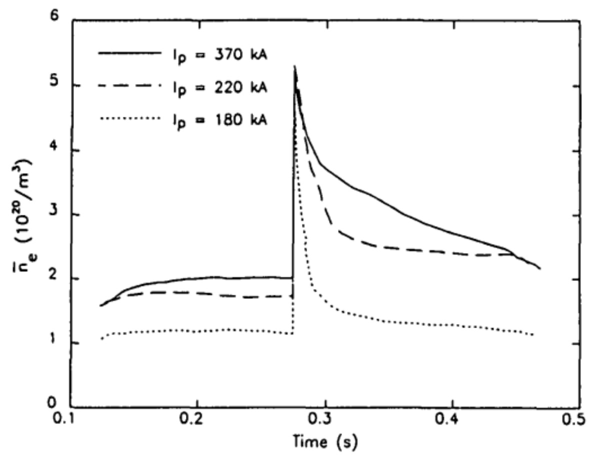


Figure 9: Density decay after injection of a single pellet for discharges with different plasma currents (Alcator C). Figure and caption from [4].

layer collapse scenario, which is often overlooked in considerations of the density limit. There is a myopic focus on the MARFE and MHD-related catastrophes that occur at the density limit, but these are a secondary outcome, and the collapse of the shear layer is often not considered. However,

The "clue" that the density tracked the current in its evolution came from analysis of experimental data. In tokamak discharges, it was observed that when the current was ramped down, the plasma density also decreased, which led to the investigation of the relationship between density and current that eventually led to the conclusions of the density limit.

Another important contributor to the discovery of the density limit was pellet injection in Alcator-C during perturbative transport experiments. This showed that the density limit is linked to the intrinsic physics of L-mode density transport. In these experiments, the density decayed without disruption after shallow pellet injection, shown in Figure 9. The MARFE and disruption likely comes from trying to push in too much gas and cooling the edge too much, which triggers the MHD instability, but that did not happen here. Instead, it was observed that the plasma "kicks out" particles, and sheds the excess density without disruption. In these experiments, the amount and rate of relaxation is linked to the current, and the asymptotic density $\bar{n}$ scales with the current, I_p, meaning the value where the density "leveled out" after the relaxation scaled with the current. This indicated the the density limit is enforced by transport-induced relaxation. The relaxation rate was not studied in these experiments.

Later experiments on C-Mod studied the relaxation of the particle confinement after a perturbation, which provided more evidence for the role of edge transport in the density limit. These studies looked at post-pellet decay time vs. $\bar{J}/\bar{n}$, which is essentially the Greenwald parameter, rewritten in a convenient and measurable way. This is shown in Figure 10. Note that at small values of the parameter $\bar{J}/\bar{n}$, the plasma will relax very quickly, while at larger values, the plasma will relax much more slowly. The limit for where this relaxation increases is around $\bar{J}/\bar{n}$=1, consistent with Greenwald scaling.

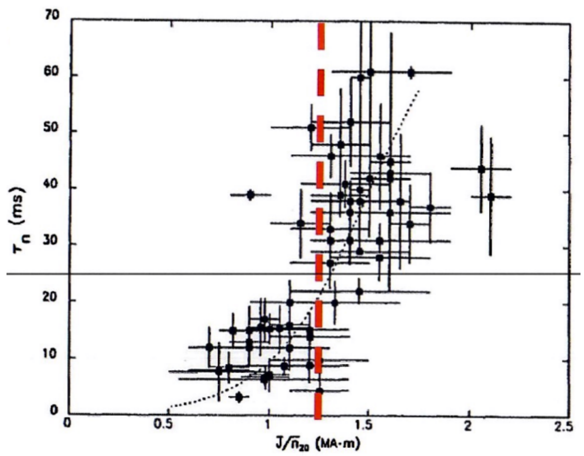


Figure 10: Post-pellet density decay time vs. $\bar{J}/\bar{n}$. From C-Mod.

The association between particle transport and the density limit was also studied in DIII-D in the 1990s. These experiments showed that if you didn't mess with the edge, you could beat the density limit, indicating a strong relationship between the edge plasma transport and the density limit. In these experiments, large pellets were injected directly into DIII-D, in contrast to the Greenwald experiments, which surveyed shallow pellets injected as perturbations to the edge plasma. This allowed DIII-D to go over the Greenwald limit, shown on the density plot in **??**. Once the density limit was reached, the density stayed high; particle transport was reduced, which led to impurity accumulation. This is one region why the H-mode with grassy ELMs or the Quiescent H-mode with the EHO and the turbulent pedestal state is of interest, because you like to have some turbulence to kick out the impurities. These experiments showed that it was easy to beat the Greenwald limit - you could peak the profile and essentially just sit there. While there were problems with impurity accumulation, there was no catastrophe.

Later, people started to look at fluctuation studies, which are still ongoing. Continuing to puff away on the gas means that the fluctuations go up. With these larger fluctuations, there is larger transport, larger particle flux, and changes in the autocorrelation times. As the density increases, there is higher perpendicular transport, which starts to expand and increases the fluctuation activity. This means that as the average plasma density is increased as a result of edge fueling and approaches the density limit, turbulence levels and perpendicular particle transport increase.

It is also interesting to note that the profile variation across the separatrix from core to SOL is smooth, not discontinuous, indicating the inadequacy of the "38th parallel" plasma model. While there is a difference in behavior in the core and SOL regions, there isn't a discontinuity that would indicate that the core and SOL are entirely separate.

An increase in $D_\perp$ relative to $\chi_{||}$ (which occurs at high n, since $\chi_{||} \sim 1/n$) could be a good explanation of detachment. This would mean that all the losses are by perpendicular transport.

It was observed that increasing the density will decrease the plasma temperature, meaning there will be cooling at the edge, shown in Figure 12. This leads to increased $\mathbf{E}\times\mathbf{B}$ transport, but also leads to increased radiation and the MARFE, which will induce a feedback loop where the plasma temperature decreases further because of the radiation, causing more radiation, and so on.

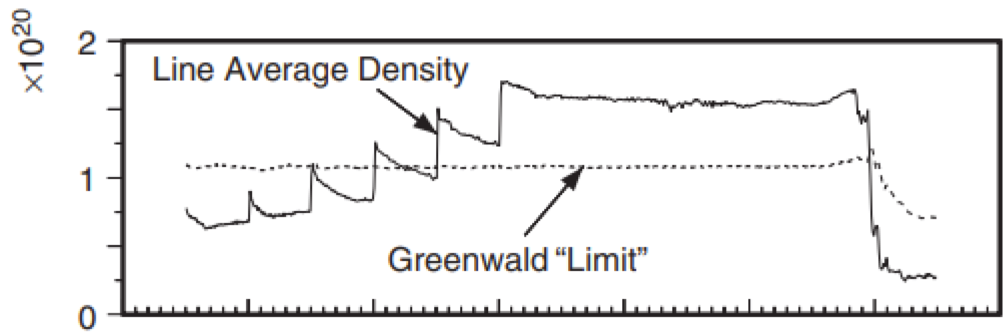


Figure 11: Discharges with good confinement are achieved at densities above the empirical limit by pellet fuelling in DIII-D. Because the density limit is due to edge physics, plasmas with peaked density profiles can reach higher average densities than those with flat profiles. In these discharges, confinement is enhanced over L-mode in part due to the improved core confinement associated with peaked profiles. The concomitant accumulation of impurities leads to a strong increase in radiation and discharge termination. Figure and caption from [4].

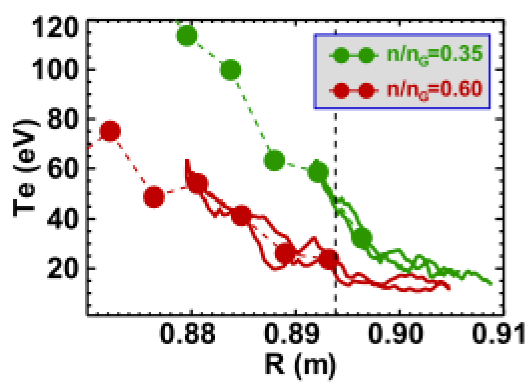


Figure 12: Edge temperature profiles show the progressive edge cooling as the normalized density is increased toward n_G. Figure from [13].

The density limit appears to be related to the intrinsic physics of the L-mode edge transport. There is strong turbulence, and things increase towards the edge, and there are shear layers. We know that the shear layer strongly regulates the transport. To understand why the edge goes wild as we increase the density towards the density limit, recall the predator prey model: if the $\mathbf{E}\times\mathbf{B}$ shear v'_E is regulating the transport, look what happens to the shear layer.

3.2.1 Experimental evidence

The shear layer collapse is a study of recent history. There have been many experiments on the shear layer collapse, but the shear layer was first investigated (although not in the context of the density limit) in stellarators from Hidalgo and Pedrosa in 2006-2007. These studies looked at long-range correlations (LRC), which are studies of the statistical correlations between the data of fluctuations from two probes that are separated by some toroidal separation distance (hopefully at the same radius). A zonal flow (or, a shear flow that is only a function of radius) might leave a footprint on the measured fluctuations, which would show as a correlation on the two probes. There is a decrease in the maximum correlation value of the LRC (i.e. zonal flow shear strength) as the line averaged density is increased. At high density, the LRC dropped rapidly with increasing density. Probe measurements of the electric field also indicated that the reduction in the LRC from the increasing density was also accompanied by a reduction in edge mean radial electric field, which was also related to zonal flows. This indicated that the confinemnt was being degraded, and it was related to a shear flow, because if the shear flow collapses, the LRC between the different set of probes would also decline.

Density is strongly associated with collisionality. If the collisionaltity increases, one might expect the flow generation to decrease. A stellarator experiment showed that as the collisionality is increased and the adiabaticity parameter is lowered, the shear flow went away. The ratio of the power in the zonal flows to the total power only went down as the collisionality increased. Other experiments showed that as the density is increased, there is weakened shear flow production from the Reynolds stress that results in the density limit. The density limit is not a result of the damping, but rather a result of a drop in the production of the flow.

Another key quantity is the electron adiabaticity parameter,

$$\alpha = \frac{k_{||}^2 v_{th}^2}{|\omega|\nu_e}, \tag{9}$$

which emerges as an interesting local parameter in density scans [14]. It was observed that particle flux increases and Reynolds power $P_{Re} = -\langle V_\theta\rangle\partial_r\langle\tilde{V}_r\tilde{V}_\theta\rangle$ drops, meaning zonal flow production decreases, as the α parameter drops below unity, shown in Figure 13. Initially, it was thought that this could be attributed to a new and exciting instability attributed to the resistive ballooning mode, but in these scenarios, the plasma β remained low. Despite n being very high, the temperature was very low, and since $\beta \sim nT$, the resistive ballooning mode was not possible. There was also no observable difference in the basic character of the turbulence. The turbulence got stronger, but the spectral structure did not change.

Overall, what do these experiments tell us?

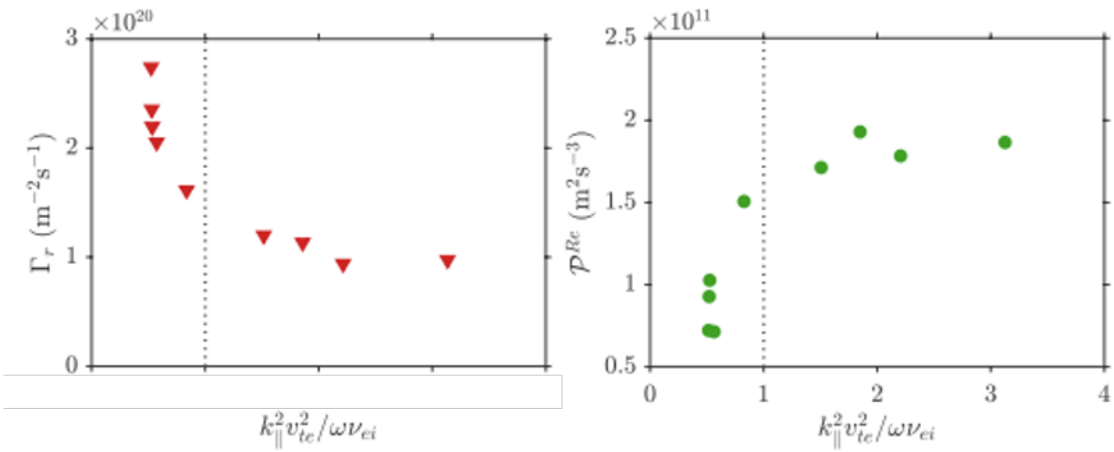


Figure 13: The volume averaged particle flux (upper) and Reynolds power (bottom) plotted as a function of the adiabatic parameter. Figure and caption from [14].

The shear layer collapses, leading to a rise in turbulence and particle transport (D), as the density approaches the Greenwald density, $\bar{n}/\bar{n}_G \to 1$. This appears to have an effect on production, and is related to adiabaticity: zonal flows and zonal flow production collapse as the electron adiabaticity parameter drops from α>1 to α<1 (or through zonal flow damping). The degradation of particle confinement in L-mode is due to the breakdown of self-regulation by zonal flow. It is also important to note that these effects are not due to the plasma β, so this behavior cannot be explained by resistive ballooning modes.

We can see that the density limit is reminiscent of a back transition, or a second-order phase transition. Recall our discussions of transport bifurcations: in the L-H transition, there is strong turbulence in the L-mode and a shear layer that forms the transport barrier in H-mode. A similar, 'inverse' process occurs as the density limit is reached. At the density limit, the shear layer collapses, meaning the plasma goes from a state with a shear layer and some turbulence to a regime of much stronger turbulence.

3.3 What the HDL?

There are not many concrete explanations as to why the HDL is what it is. One idea is that the HDL is related to an instability in the SOL, associated with the heat flux width λ. It was discovered in C-Mod that the heat flux width scaled with $1/B_\theta$ (LaBombard, [15]). This is bad news, since we want good current for confinement, and raising the current raises B_θ, meaning "better" confinement will result in a thinner channel for the heat flux.

This bad news was not well-received (see Figure 6). Further investigation led to the development of a heuristic drift-based model of the SOL width, which scales as

$$\lambda \sim v_D \tau_{||} \sim \frac{\cancel{v_{th,i}}\rho_i}{\cancel{R}} \frac{\cancel{R}q}{\cancel{v_{th,i}}} \sim \rho_i \frac{B_T}{B_\theta} \frac{r}{R} \sim \rho_\theta \varepsilon. \tag{10}$$

where v_D is the drift velocity, $\tau_{||}$ is the parallel transit time, and $v_{th,i}$ is the ion thermal velocity [16].  This formula is annoyingly simple, but works *very* well. Like LaBombard's scaling, this estimation of the heat flux width is also bad news: ρ_θ tells us that a high current is bad, and a dependence on the size of the machine through the parameter ε tells us that bigger is not better. For ITER, this is doubly bad news, since ITER is very large and will operate with a high current.

How do we deal with this? One way is to make the scrape-off layer turbulent, which would result from raising the density. Note that $\tau_{||}$ is related to parallel conduction, $\chi_{||}/(Rq)^2$. Since $\chi_{||}$ scales as $1/n$, raising the density will increase λ. Increasing λ will make the $\mathbf{E}\times\mathbf{B}$ shear weaker, which allows the scrape-off layer to become turbulent and widening the width of the SOL. The problem with this is that when you create turbulence in the SOL, the turbulence will spread from the SOL into the edge. Think of a cup of water: if you stir it in one localized region, the turbulence will spread and all the water in the cup will be affected - and this cannot be avoided. This is a problem because when the turbulence spreads to the edge in H-mode, the transport is increased and the H-mode is lost. This mechanism is the argument for Rob Goldston's  explanation for the HDL, that this limit is the onset of SOL turbulence at high n. To measure this properly would require a measurement of turbulence spreading at the HDL, measuring turbulence from the edge to the SOL in H-mode at high density. Parties interested in novel physics and/or probe sacrifice are encouraged to participate.

3.4 Final Thoughts

The Greenwald density limit is an intrinsic property of the edge turbulence that seems to be related to the collapse of the shear layer. If you fuel from the edge, it is not easy to get around hitting the Greenwald limit. It is important to remember that high density is the future of fusion.

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