Physics 218c

Lecture 8a: Density Limit and Greenwald Scaling, SOL Width and Heatloads

(Monday) 8b: Sheaths and PWI (Tynan)

→ All good things must come to an end....

- Monday is last class
- Still missing 6+ write-ups... !

→ Loose Ends – Rotation and Momentum Transport

- For details on symmetry breaking, see P.D. review 2013
- For details on 'momentum pinch' see Hahm, et. al. '07
- For unifying Physical Picture, see Kosuga, P.D., Gurcan and refs. therin (especially Ozawa)

approach is entropy production —
due Q_i, ∇T_i, ITG etc.

vs.

entropy destruction — Zonal flow and intrinsic rotation drive

⇒ Engine Paradigm ...

— for phenomenology OV, see review by Ida, Rice

— for the physics of boundary effects on intrinsic rotation, see ??

⇒ major issue! Most works (theory) have no-slip B.C.

⇝ Many papers posted.

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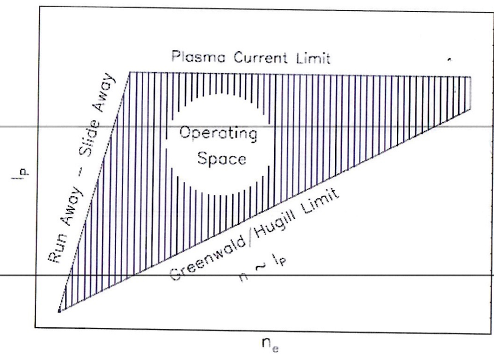
Density Limits: Some Basic Aspects

- Not a review!
- Greenwald density limit:

$$\bar{n} = \bar{n}_g \sim \frac{I_p}{\pi a^2}$$



Constrains tokamak Operating Space

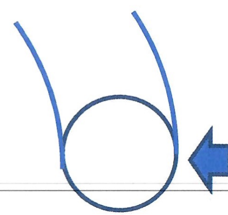
- Manifested on other devices
  - See especially RFP ($n \sim I_p$ scaling)

- Line averaged limit $\bar{n} \equiv$ line avg.
- (Too) simple dependence!? widely upheld
- Begs origin of I_p scaling?! → b

Stellarators?

- Most fueling via edge → edge transport critical to $\bar{n}$ limits

I_p at edge → B_θ.



N.B. Physics of I_p scaling usually loosely linked to q?!

→ Density Limits

- why?

→ high n is good

$$n\tau T)_{crit}$$

$$\beta = nT/B^2$$

→ fueling → gas + pinch

simple

i.e.

$$\Gamma = -D\nabla n + Vn$$

$$< 0$$

Thermoelectric TEP

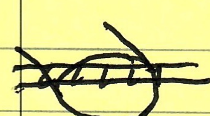
→ natural to puff lots of gas and seek maximize n

surprise!

→ there is a limit → Density Limit

$\bar{n}$ limit

line avg



→ now many limits condensed to

Greenwald Limit ('88)

$$\boxed{\bar{n} \sim I_p / \pi a^2}$$

fundamental constraint on tokamak operation

- not dimensionless parameter (!?)

- simplicity !

- other devices? stellarators — no current
  RFP
  $n \sim I_p$ (?)

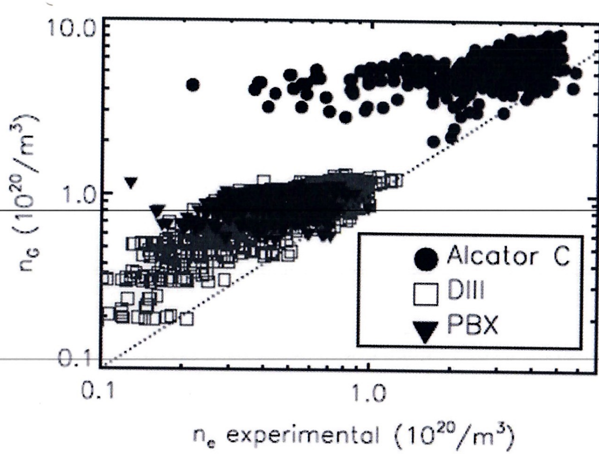
tokamak – stellarator comparisons have been illuminating

- heavily linked to edge physics, fueling interaction, cooling

SO

What does the edge look like?

- Trends well established



Greenwald '88

- Often (but not always!) linked to:
  - MARFE (radiative condensation instability) ←→ Impurity influx
  - MHD disruption

    radiation → condensation → cooling → $\Delta J \uparrow$ → Tearing → disruption
  - Divertor detachment ←
  - H→L Back-transition

N.B. HDL (H-mode Density Limit) $\equiv \bar{n}$ s/t back transition.

→ usually $\bar{n}_{HDL} \leq \bar{n}_G$.

→ Edge

Core ≡ closed field lines as discussed

SOL ≡ open field lines → connect to limiter, plate

– What is the Edge?

Core

✓ I ⇒ 'No Man's Land'

✓ II ⇒

? III ⇒

Pedestal

L, H

– pedestal, shear layer at edge in L, H

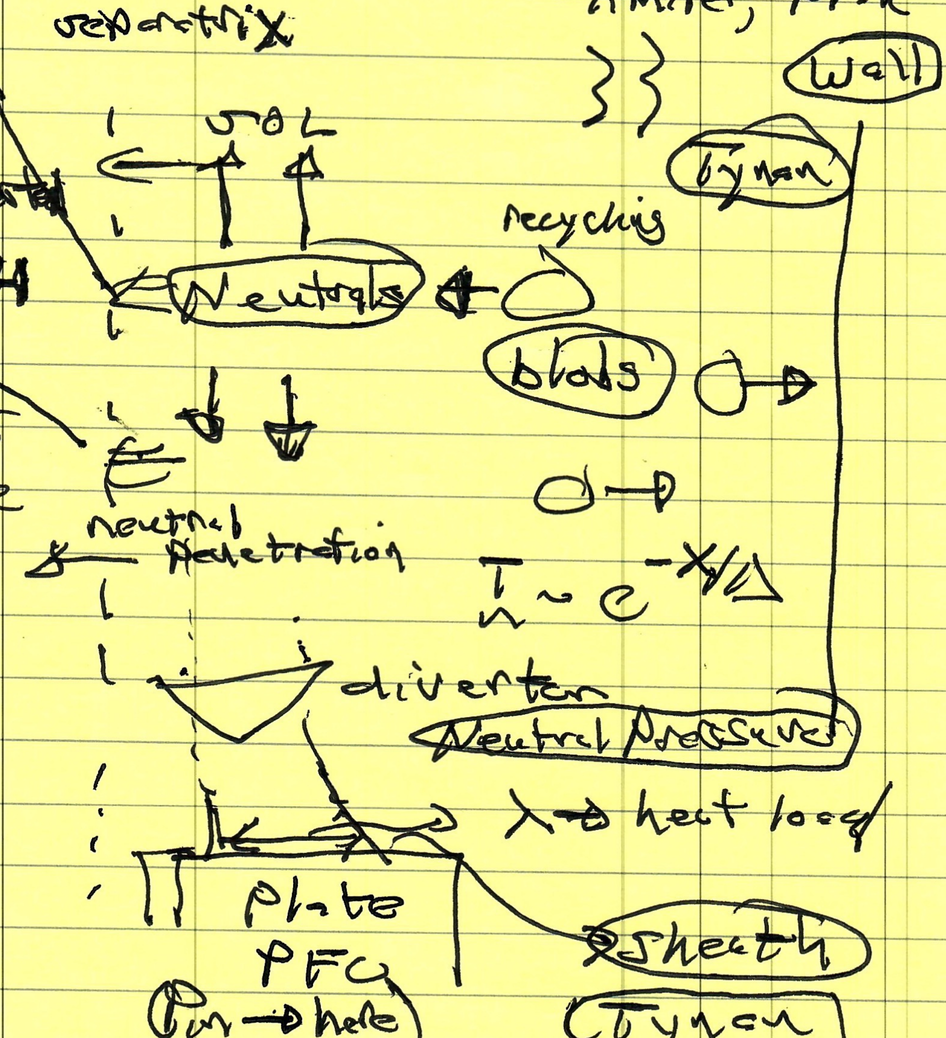
$\boxed{\text{Shear Layer}}$

– in L mode, edge turbulence is strong

$\frac{e\phi}{T}, \frac{\tilde{n}}{n} \gtrsim .1 \rightarrow 1$

D, χ

rising profile



Drop in H-mode

or

Langmuir probes often used to study edge.

→ "Which" Edge? transition L→H

n_e? → soft ⇓ P_{th}.

~ Density Limit	L-mode	H-mode
very strong turbulence	strong turbulence	weak turbulence
collapse of shear layer	Shear Layer ⇓ (Reynolds stress, Neoclassical)	Strong Shear ⇓ $(\nabla P/n)$ + ...
D_r ↑	High Transport	ELMs → MHD events (Turbulence)
density outflow	Pinch	D, χ_i, χ_ϕ ⇓ χ_e up. Pinch (?) (don't take too far)

~ Order Parameter

$$0 \longleftarrow V_E' / \Delta\omega_k \longrightarrow \text{high}$$

→ How determine E_r?

− Core → $\nabla \cdot J = 0$, with mainly
(closed) $\partial_r J_{pol} \cong 0$
⟺ Radial force balance

− SOL → $\nabla \cdot J = 0$ with $\partial_r J_r + \nabla_\parallel J_\parallel = 0$
(open) ⇓
sheath b.c.

→ What about the edge?

– Stupidity ⇔ Core – SOL Boundary

Core : SOL

What people think

→ →

sep

ROK | DPRK

Universe A | Universe B

Key: transition layer.

How big – ρ_s?

(λ-mode)

38th Parallel

What it's really like!

USA ↔ MX

TJ

∇P

Core: $\langle E_r \rangle$ → radial force balance

Edge: $\langle E_r \rangle \to \langle \phi \rangle \to$ Sheath

$$\langle \phi \rangle \simeq \frac{T}{|e|} \sim T \sim e^{-x/\lambda}\, T_{sep}$$ [redacted]

so $V_E' \simeq \frac{1}{\lambda^2} \frac{T_{sep}}{|e|}$

SOL width

- In SOL

$\nabla \cdot \Gamma = 0 \Rightarrow \nabla_\perp \Gamma_\perp + \nabla_\parallel \Gamma_\parallel = 0$
Q

$\nabla_\parallel \Gamma_\parallel \downarrow$ Parallel losses

In core

$\underline{\nabla} \cdot \underline{\Gamma} = 0$

$\rightarrow \Gamma = \underline{\text{const.}}$ (fixed flux)

For Density Limit, first ask:

→ What of L-mode? → base state

- lots of Info → Langmuir probes (since Zeta → Robinson + Rusbridge)
- intensities, direct measurement of fluxes → $\langle \tilde{V}_r \tilde{n} \rangle$, $\langle \tilde{V}_{r,E} \tilde{V}_{\theta,E} \rangle$ especially
  T harder!
- interestingly, frequently see:

$\tilde{n}/n \sim \dfrac{|e|\tilde{\phi}}{T}$ (but $\alpha < 1$?)

— Candidates → see Zoo

[CDW, DTEM [ITG RBM [DM (CRGDT) continues

($\alpha > 1$, $\kappa < 1$ continuous)

"~ Drift Waves", extended to hydrodynamic electron regime

does it matter?

Non adiabatic behavior is not surprising → "MHD-like" candidates

— What does matter? — Shear Layer

— L-mode tokamak edges support a stellarator

Shear layer — universal

— Observed first TEXT — mid 80's.

Exhibited effects on eddys, etc. linked to turbulence control. →

Ritz 1990.

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Evidence for Confinement Improvement by Velocity-Shear Suppression of Edge Turbulence

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The electrostatic fluctuations are decorrelated in the region of a naturally occurring $\mathbf{E}_r \times \mathbf{B}$ velocity shear close to the outermost closed flux surface of regular Ohmic TEXT discharges. The concomitant local steepening of the density profile and suppression of the fluctuations are consistent with theoretical predictions. The high-confinement mode (H mode) found in other tokamaks shows in exaggerated form similar characteristics and could thus be related to the same mechanism leading to a locally improved confinement.

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Quantitative comparisons on the TEXT tokamak demonstrate that electrostatic fluctuations are a major cause of the anomalous particle and energy transport[1] in Ohmic discharges as suggested previously by other experiments.[2,3] In addition, a radial electric field E_r has been shown to modify the global confinement[4] as well as the edge turbulence and electrostatic-fluctuation-induced transport.[2,5] Most recently a series of experiments has been conducted on the Constant Current Tokamak (CCT) using a highly biased emissive electrode.[6] The biasing triggered a transition to a regime with the characteristics of the high-confinement mode (H-mode regime first reported on ASDEX[7]), which is one of the most successful paths to improve the plasma confinement in tokamaks. Associated with the transition on CCT was a measured increase in E_r, and thus in the rotation velocity $\mathbf{v}_E \equiv \mathbf{v}_{\mathbf{E}_r \times \mathbf{B}}$. Such changes in E_r have also been observed on DIII-D, a large tokamak, at the transition to the H mode.[8] Since the physics of H modes is not well understood, this is a motivation for further experimental studies.

The above experiments suggest that one possible mechanism for improved confinement is a change in the edge electric field, and concomitant change in the $\mathbf{E} \times \mathbf{B}$ rotation velocity v_E and the fluctuation levels. Theoretical work[9–14] shows that, if changes in radial electric field result in an angular-velocity shear, then turbulence can be reduced leading to a decreased outward transport. In this paper we examine the theoretical predictions of turbulence suppression by sheared plasma rotation. Based on results from TEXT we demonstrate a clear correlation between velocity shear, reduction of the turbulence, and local improvement of the confinement.

A velocity shear due to a peaking plasma potential close to the outermost closed flux surface has been characterized on TEXT[15] and other devices.[16,17] The mean velocity of the fluctuations perpendicular to $\mathbf{B}$ measured with a two-point correlation technique in the laboratory frame of reference,

$$v_{ph} = \sum_{k>0,\omega} [\omega/k_\theta(\omega)] S(k,\omega) \Big/ \sum_{k>0,\omega} S(k,\omega) ,$$

is dominated by $v_E = E_r/B$ effects,[18] as shown in Fig. 1(a), where v_{de} is the diamagnetic drift velocity. (The contribution to v_E from ∇p is thus small and only slowly varying with radius.) The density and floating potential fluctuations, $\tilde{n}$ and $\tilde{\varphi}$, are reduced in a region shifted to larger r/a from the shear region by roughly half the radial shear width, as shown in Fig. 1(b). The mean density is slightly steepened in the region of maximal shear, as

phase velocity

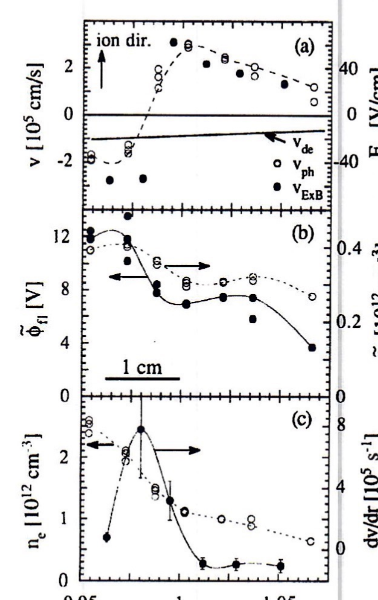

FIG. 1. Radial profiles for a discharge with $B_\phi = 2$ T, plasma current of 200 kA, and chord-averaged density of $n_{chord} = 2\times10^{13}$ cm^{-3}. (a) Phase velocity of the fluctuations v_{ph} (closed circles), $v_{\mathbf{E}_r\times\mathbf{B}}$ plasma rotation (open circles), and drift velocity v_{de}. (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 $r/a \simeq 0.02$.

13.

shown in Fig. 1(c). The steepening is not pronounced, but consistently found on reproducible discharges.

The (one-point) correlation time τ_c^{lab} of the fluctuations measured in the laboratory frame of reference is obtained from the e-folding time τ of the autocorrelation function $R(\tau,\mathbf{r}) \equiv \langle x(t,\mathbf{r}) x(t+\tau,\mathbf{r})\rangle$. The fluctuation quantity $x(t,\mathbf{r})$ is the ion saturation current (proportional to density) and the angular brackets represent averaging over a temporal interval large compared to τ and ensemble averaging over several realizations. From Fig. 2 we find $\tau_c^{\text{lab}} = 10 \pm 1.5$ μs behind the velocity shear ($r/a \simeq 1$), 2 ± 0.4 μs at the location of maximal shear, and 5 ± 1 μs on the bulk plasma side of the shear layer ($r/a \simeq 0.95$).

Similarly we compute the normalized cross-correlation function between two points $\mathbf{r}$ and $\mathbf{r}+\delta\mathbf{r}$,

$$\gamma(\tau,\mathbf{r},\delta\mathbf{r}) \equiv C(\tau,\mathbf{r},\delta\mathbf{r})/[R(\tau=0,\mathbf{r})R(\tau=0,\mathbf{r}+\delta\mathbf{r})]^{1/2},$$

where the cross-correlation function is

$$C(\tau,\mathbf{r},\delta\mathbf{r}) \equiv \langle x(t,\mathbf{r}) y(t+\tau,\mathbf{r}+\delta\mathbf{r})\rangle .$$

By varying the Langmuir-probe separation $\delta\mathbf{r}$ we obtain the correlation lengths in the radial, poloidal, and toroidal directions from the separations for which the peak values of $\gamma(\tau,\mathbf{r},\delta\mathbf{r})$ decrease to $1/e$ of the values at $\delta\mathbf{r}=0$. The resulting correlation lengths on the bulk plasma side of the velocity shear ($r/a = 0.95$) are $\sigma_r \simeq 0.5$ cm, $\sigma_\theta \simeq 1$ cm, and $\sigma_\phi \simeq 100$–200 cm.[19] To study the dependence of the correlation length on the velocity shear we measured the fluctuations simultaneously with an array of four probes separated poloidally and toroidally by a fixed distance of $\delta r = 3$ mm. As shown in Fig. 3 the peak values of the normalized cross-correlation function decrease in the shear layer with respect to the values on either side for both radially and poloidally separated probes. (The decrease is not large since the probe spacing is within a correlation length.) Furthermore, the τ dependences of $\gamma(\tau,\mathbf{r},\delta\mathbf{r})$ in the poloidal and radial directions are similar in the shear layer.

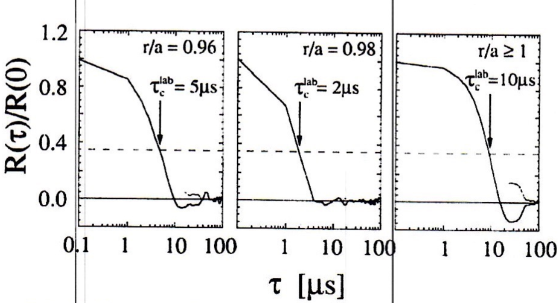

FIG. 2. Normalized one-point correlation function for two positions on either side of the shear layer and in the velocity shear. Dotted curve is the absolute value. Arrow indicates e-folding time τ_c^{lab}.

The turbulence is thus isotropic perpendicular to the magnetic-field direction, in contrast to the turbulence on either side of the shear layer where the decorrelation is faster in the radial direction than in the poloidal direction, consistent with the correlation-length measurements.

Relating the experimental observations to theoretical models, we can form three groups of questions: (i) What causes the peaking plasma potential leading to the strongly nonuniform electric field? (ii) Can the free energy in the velocity shear drive instabilities? (iii) Can the velocity shear suppress turbulence and thus improve the confinement? The first two questions are only briefly addressed for completeness.

On TEXT the width of the plasma potential peak which is connected with the velocity shear is typically 2 cm and thus approximately of the width of a poloidal ion Larmor radius (banana orbit width) for the hot-ion tail with $\nu^*(v) \leq 1$. The positive peak of the plasma potential causing the nonuniform radial electric field is thus possibly due to a differential orbit loss mechanism at the outermost closed flux surface.[11,20,21] Mechanisms causing a nonambipolar transport may also generate such effects.

For the strong velocity shear measured here, the Kelvin-Helmholtz (KH) instabilities[22] must be examined. The radial extent over which significant fluctuation levels are observed experimentally is much larger than the velocity-shear region. Further the fluctuation level is reduced and not enhanced in the velocity-shear region. Based on these experimental results, the KH instability is not expected to dominate the edge turbulence. A theoretical study also comes to the conclusion that the edge plasma of TEXT is KH stable because of the stabilizing role of the magnetic shear.[9]

Before the velocity shear is sufficient to destabilize KH instabilities it is already capable of reducing the ambient turbulence level due to the fissuring of fluid elements subject to a velocity shear:[12] A *nonuniform* radial electric field ($E_r' = \partial E_r/\partial r \neq 0$) causes in a slab a velocity dif-

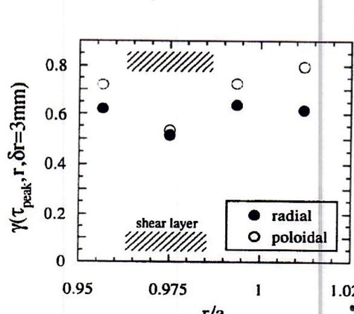

FIG. 3. Peak values of the normalized two-point correlation function for poloidally and radially separated probes with fixed separations of $\delta r = 3$ mm.

- L→H transition builds on base state of OH shear layer (Hidalgo)

- Shear Layer accountable from turbulent Reynolds stresses.

Now back to Density Limit ...

- Edge particle transport crucial to density limit

↓

- Greenwald small pellet relaxation

⇒ Edge sheds excess density without disruption

⟺ Density limit linked to intrinsic physics of L-mode edge transport.