Microphysics of the Tokamak Density Limit<u>s</u>: Recent Progress

Radiative Condensation → Strong Particle Flux and Scalings (especially ‘Power’)

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- Principal Collaborators:

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- Ackn Collaboration of:

  DIII-D, HL-2A, J-TEXT programs

Why Study Density Limits?

- Interested in max density - both line averaged and edge
- Constraint on operating space

  Lawson # $\sim n\,T\,\tau_E$

- Fusion power gain ~ n^2
- Emerging attractive feed back loop for burning plasma

  $P_{\mathrm{fusion}} \sim n^2$

  $n_{max} \sim P^{\alpha}$ ($0 < \alpha < 1$, but which P in BP?)

Setting the Stage: V_E' as Ubiquitous Edge Order Parameter

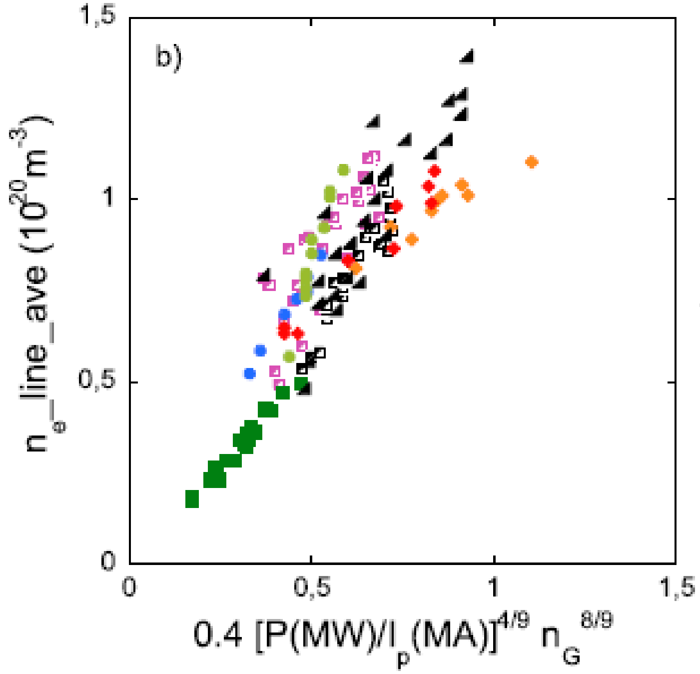
- Density limits as "back-transition" phenomena; V_E' physics crucial
- L-DL mechanism:
  - Shear layer degradation
  - Strong turbulence <u>spreading</u> → Blob emission
- α is key parameter, but not only

$\alpha \equiv$ adiabaticity

- Scalings of L-DL emerge from zonal flow physics
  - I_p scaling → neo dielectric
  - P scaling → Reynolds stress, radial force balance
- Novel hysteresis evident in L-DL dynamics
- Back Transition is in state of edge plasma.

Power Scaling and Physics of L-mode Density Limit (Singh, P.D. PPCF 2022)

- Power Scaling is an old story, keeps returning
- Zanca+ (2019) fits ➔ $\bar{n} \sim P^{1/4}$



Zanca +

- Giacomin+: Simulations recover power scaling
- Observe: $Q_i|_{\mathrm{bndry}}$ will drive shear layer → LH mech
- So: $P_{\mathrm{scaling}} \leftrightarrow$ shear layer physics: a natural connection
- $Q_i,\ Q_e$ at boundary as physical quantities

Expanded Kim-Diamond Model

- KD '03 – useful model of L→H dynamics (0D)
- See also Miki, P.D. et al '12, et. seq. (1D)
- Evolve $\varepsilon, V_{ZF}, n, T_i, V_E'$

←→

- Treats mean and zonal shearing
- Separates density and temperature contributions to P_i
- Heat and particle sources Q, S

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

Fluctuation Intensity

$$\frac{\partial v_z^2}{\partial t} = \frac{b_1 \mathcal{E} v_z^2}{1+b_2\mathcal{V}^2} - b_3 n v_z^2 + b_4\mathcal{E}^2$$

Zonal Intensity

$$\frac{\partial \mathcal{T}}{\partial t} = -c_1\frac{\mathcal{E}\mathcal{T}}{1+c_2\mathcal{V}^2} - c_3\mathcal{T} + Q$$

T_i

$Q \rightarrow$ power

$$\frac{\partial n}{\partial t} = -d_1\frac{\mathcal{E}n}{1+d_2\mathcal{V}^2} - d_3 n + S$$

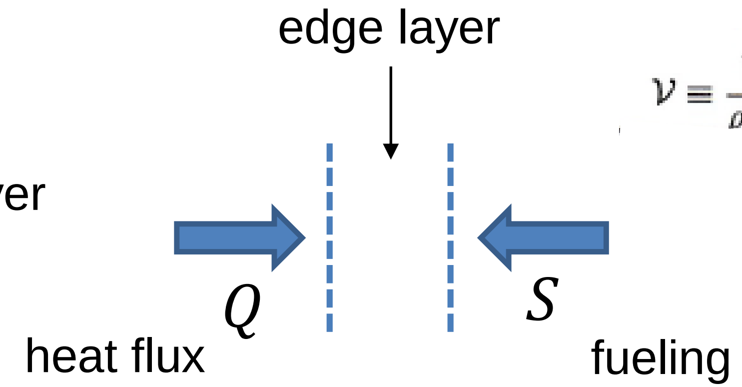
n

$S \rightarrow$ fueling

$$V_E' = -\rho_i v_{thi} L_n^{-1}(L_n^{-1} + L_T^{-1})$$

Shear (mean)

$$\mathcal{V} \equiv \frac{V_E' a}{\rho^* v_{thi}} = -\frac{n_0}{n}\mathcal{N}\left(\frac{n_0}{n}\mathcal{N} + \frac{T_0}{T}\mathcal{T}\right)$$



N.B. i) ZeroD → interpret as edge layer
ii) Does not determine profiles
iii) Coeffs for ITG

Power Scaling: LDL

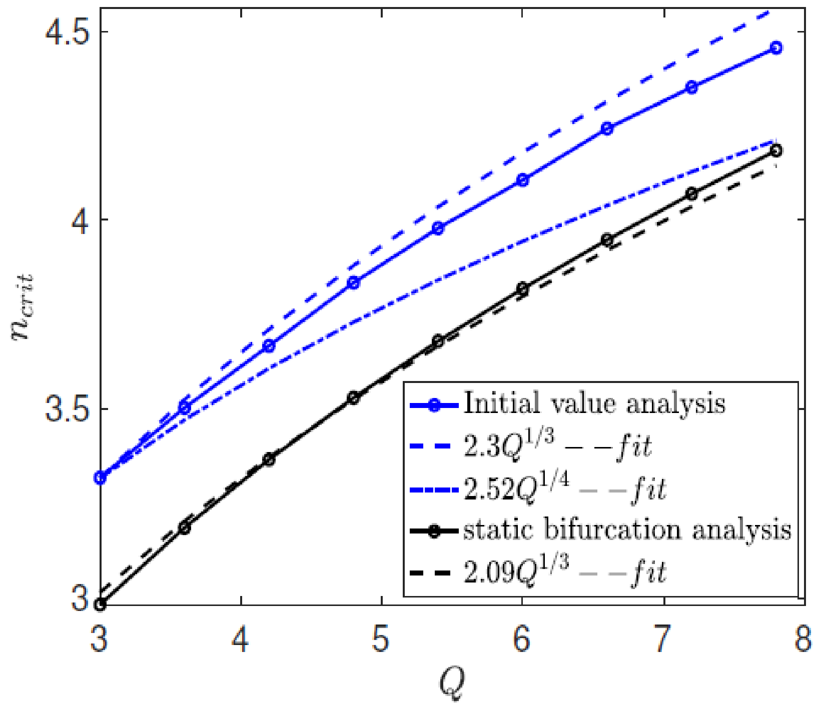
- $n_{\text{crit}} \sim Q^{1/3}$
- Distinct from Zanca, but close (model)
- In K-D, with neoclassical screening $n_{crit} \sim I_p \to I_P^2$
- Physics is $\gamma(Q)$ vs ZF damping
- Shear layer drive underpins power scaling

Physics: Q_i → Turbulence → Reynolds Stress → ZF shear

Increased ZF damping → Confinement degradation

NB: Unavoidable model dependence in scalings

- Novel hysteresis predicted
- Torque dependence !?



Reality intrudes:

Recent L-DL Experiments in DIII-D with NT

R. Hong, P.D., O. Sauter + → submitted to N.F. 2025

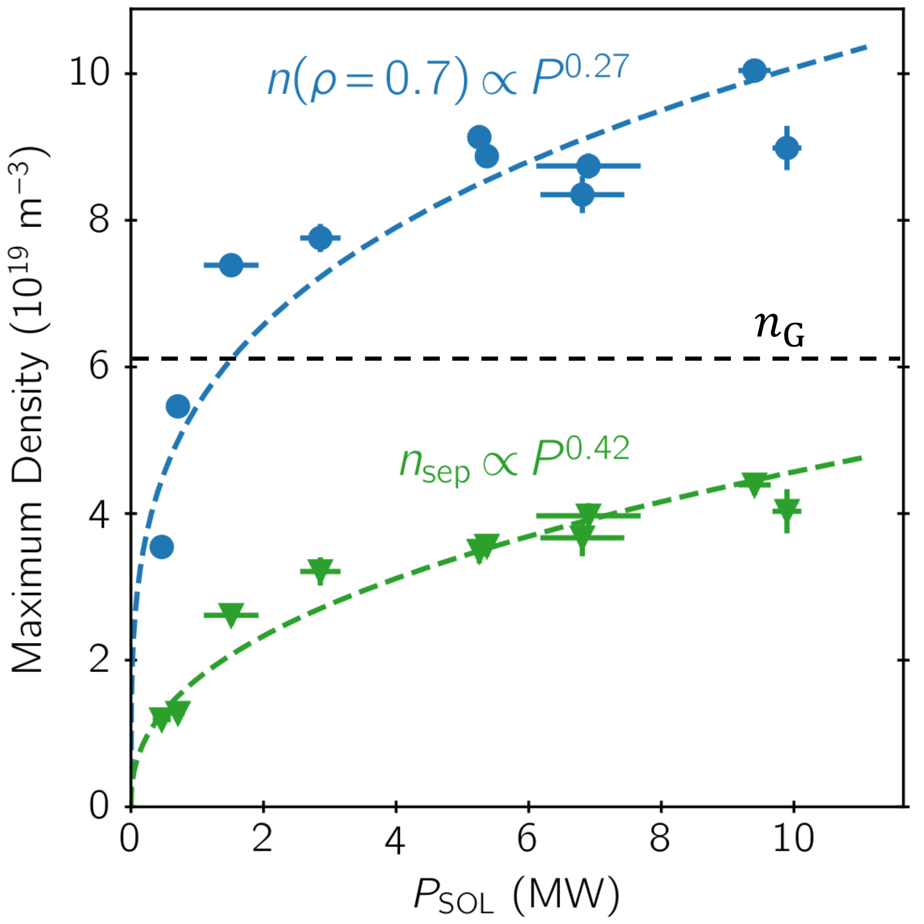
O. Sauter, R. Hong + → N.F. 2025

N.B. :
- NT suppresses L→H transition, even at high power
- Extends dynamic range of P for L-DL studies

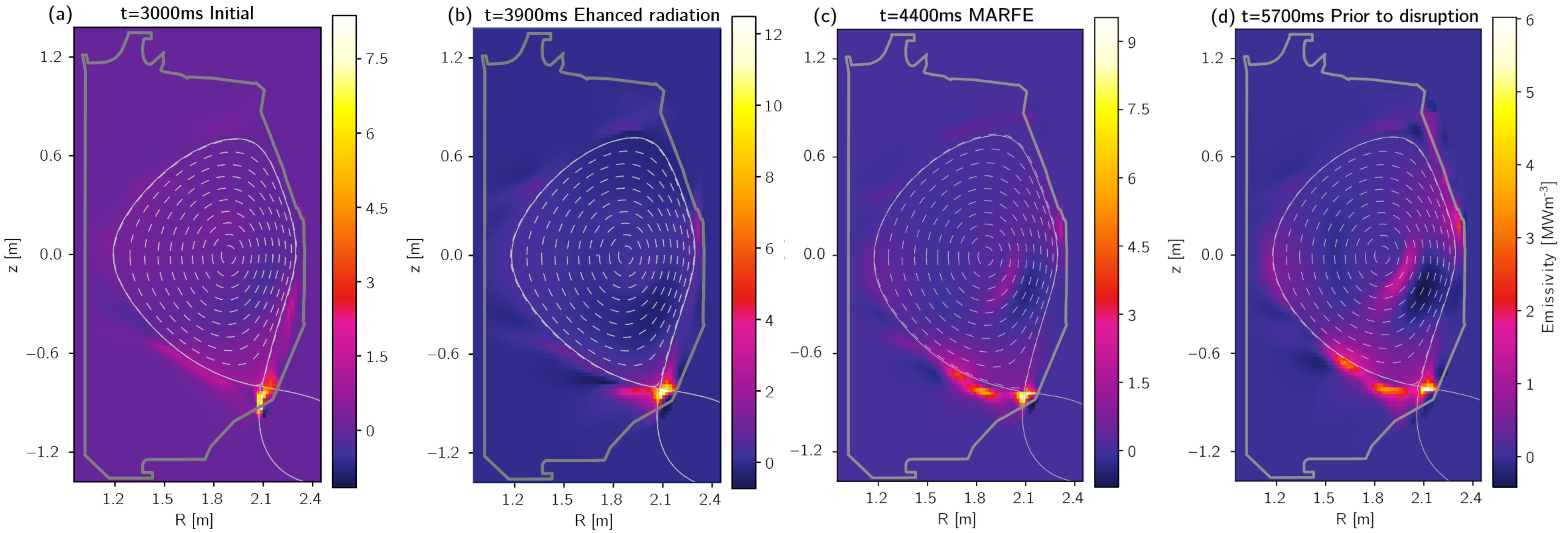
Punch Line: $\bar{n} \sim 1.8\, n_G$ for $P \sim 13\ MW$ usually 'soft' termination

Power Scalings

- Distinct power scalings of sep. and core density, over wide range
- No unique "Density Limit"
- $n_{sep} < n_G$ but steadily increasing with power
- Most cases don't terminate in disruption
- Radical departure from conventional wisdom



Evolution of Radiation and MARFE

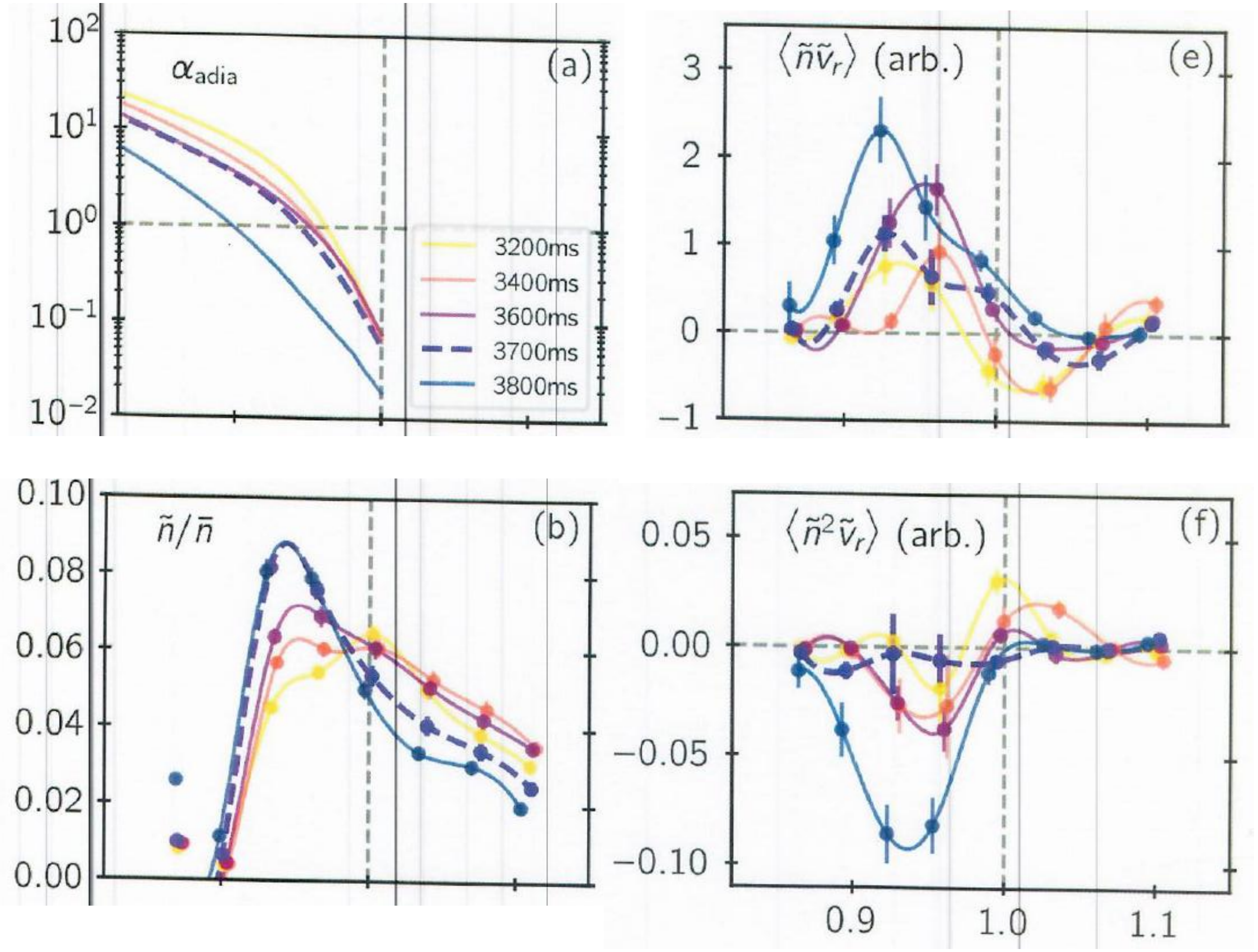


- Edge density limit linked to radiation
- Disruption follows strong MARFE

α, Transport and Spreading

- With strong radiation:
  - α drops
  - $\tilde{n}/n$ increases
  - $\langle \tilde{v}_r \tilde{n} \rangle$ increases
  - spreading flux $\langle \tilde{v}_r \tilde{n}^2 \rangle$ increases, spreading inward

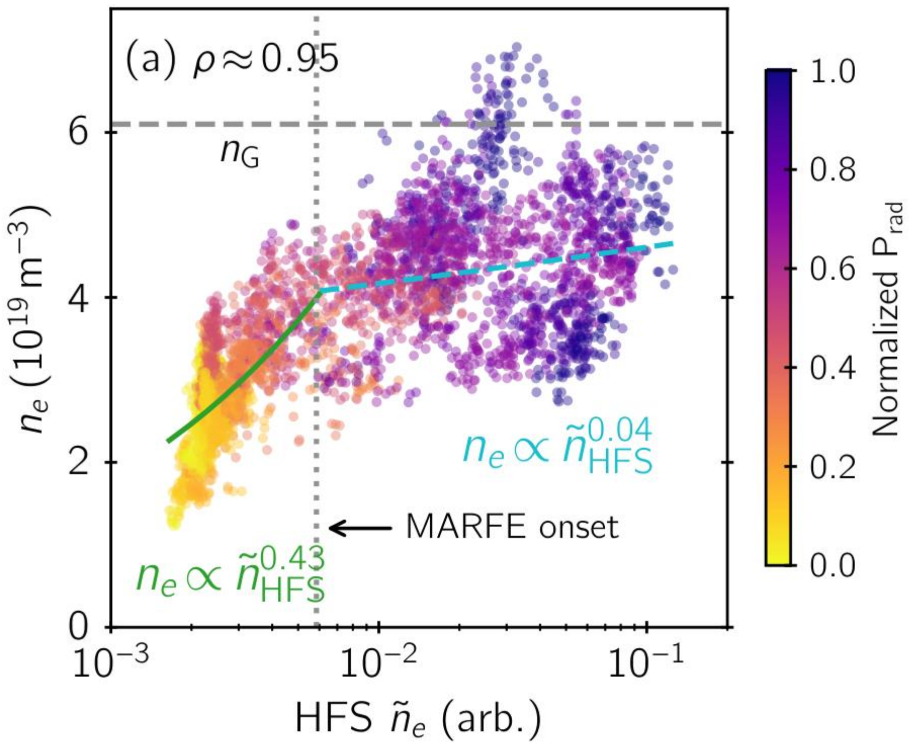
N.B.: From BES, velocimetry



- Suggests DL as Radiation ←→ Condensation ←→ Turbulent Transport Synergy

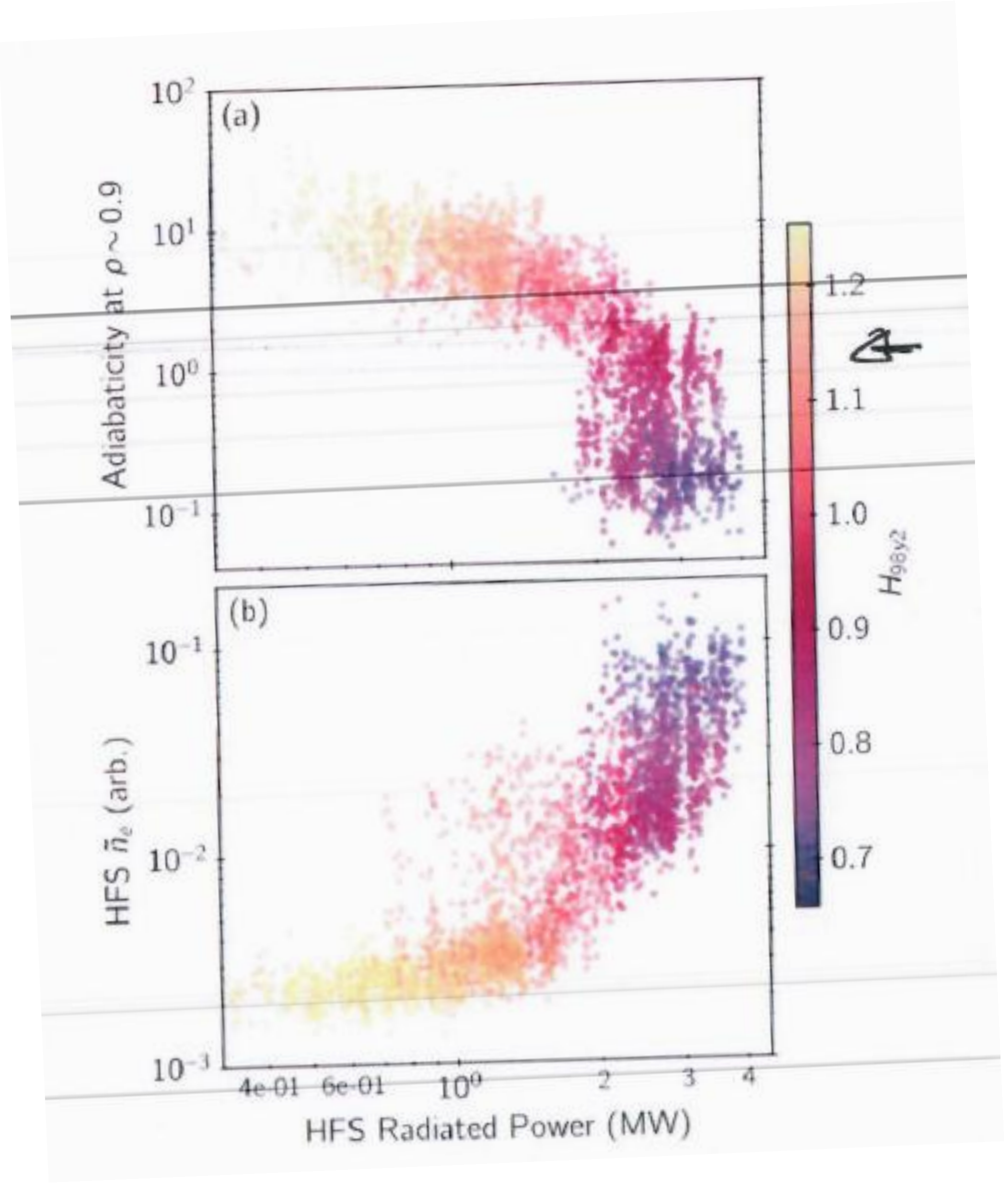
Fluctuations and Density

- Edge density rises with $\tilde{n}_{HFS}$ pre-MARFE
- Post MARFE edge density ~ “clamps”, manifesting a ‘limit’, as $\tilde{n}_{HFS}$ increases.
- Broad range edge n_e, some exceeding n_G.
- Larger fluctuations and density saturation follow radiation onset.



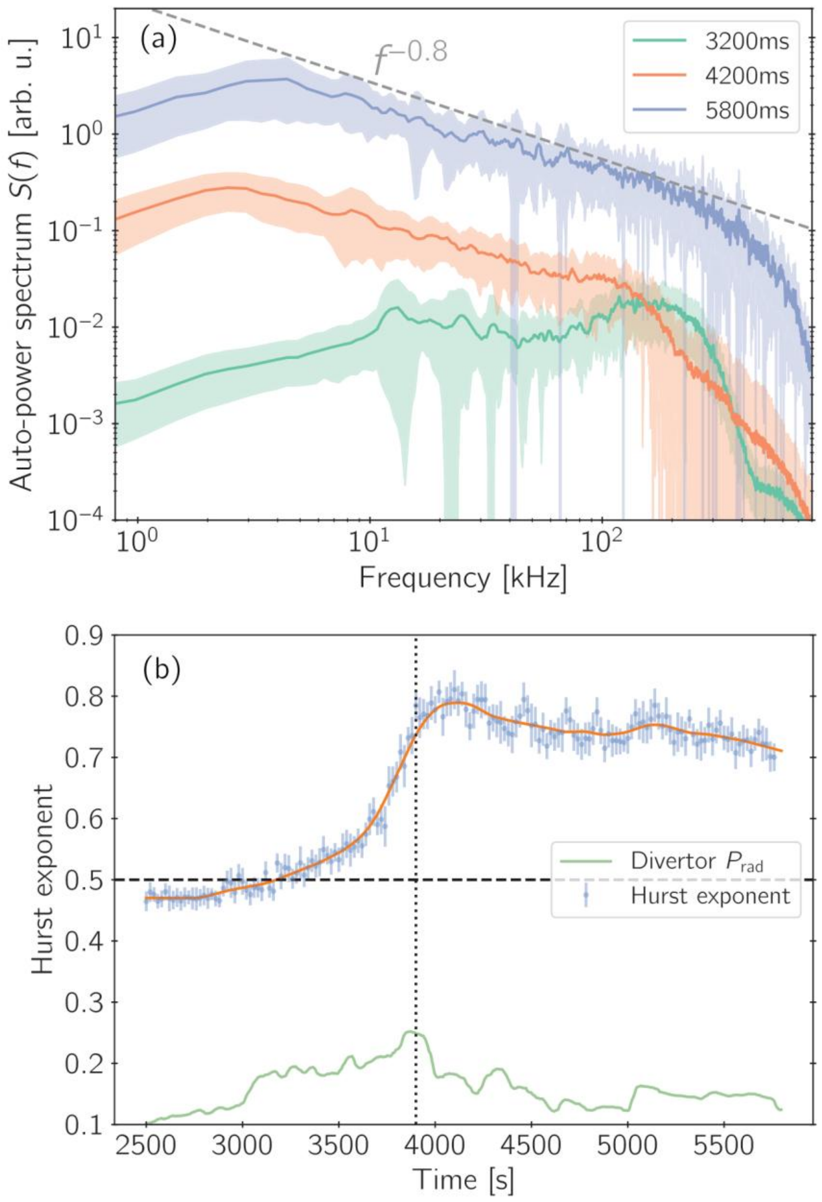
α and turbulence level versus radiated power

Rise in fluctuations tracks drop in $\alpha < 1$ as HFS P_{rad} increases



Core Fluctuations

- Recall ~ independent core density limit
  - as n rises, $S(f) \sim f^{-0.8}$
  - P_{rad} Hurst exponent → 0.7
  - Core DL ←→ Avalanching ?!
- Also:
  - PDF($\tilde{n}$) tails fatten
  - Kurtosis rises



What have we learned?

- No single “DENSITY LIMIT”, but rather an edge and core n saturation, with different mechanisms
- Power dependence unambiguous
- Soft limit → most plasmas don’t disrupt
- Suggests evolution:

Radiative condensation MARFE → edge cooling → $\alpha < 1$ hydro-regime → enhanced transport with shear layer collapse → DL via particle outflow

$\boxed{\text{i.e. Radiative cooling releases strong particle transport → ‘density clamp’}}$

A Bit More Theory

- A Work in Progress

What is Needed?

- $\boxed{\text{Model of radiative condensation/MARFE in } \underline{\text{turbulent}} \text{ medium}}$
- Radiative condensation: Thermal (cooling) instability s/t $\omega < k_{\parallel} c_s$ so $\delta P = 0$

$$\gamma = \frac{2}{5n}\left(\frac{2L}{T} - \frac{\partial L}{\partial T}\right) - \chi_{\perp} k_{\perp}^2 - \chi_{\parallel} k_{\parallel}^2$$

- c.f. G. Field .. 1965 → Drake 1987 (linear theory in cylinder)

↓

infinity of papers on ISM c.f. Balbus, 1995 for tutorial

- R.C. plus turbulence intensively studied in ISM cf Max Gronke+ MNRAS 2021

Strategy

- Incorporate radiative cooling into reduced model
- Defining competition for power scaling will be Heat Flux vs Turbulence + Cooling
  - α sets branching ratio
  - Coupling: cooling $\uparrow$ → $\alpha \downarrow$ → transport $\uparrow$

    Ratio [R.C. / Transport] of interest
- Minimal Model:
  - Fluctuation energy
  - Zonal energy
  - T_e → high n, $T_e \sim T_i$; $D \sim \chi_e$ for electrostatics

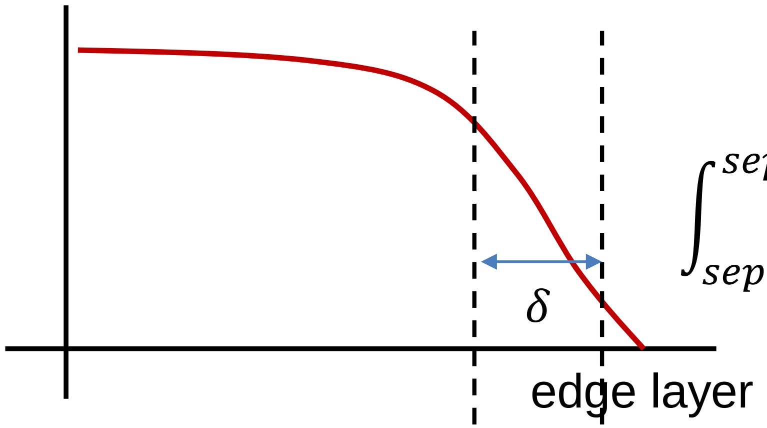
Proto-Model

- Temperature Equation – Mean field, $k_{\parallel} = 0$

$$n\frac{\partial T}{\partial t} = \nabla_r\, n\chi(\varepsilon)\nabla_r T - L$$

radiative loss ($L > 0$)
$L = L(n, T) \approx n^2\Lambda$

turbulent transport
$\chi(\varepsilon)$ - fluctuation dependent



$$\int_{sep-\delta}^{sep}$$

- So

$$\frac{\partial E}{\partial t} = n\chi(\varepsilon)\nabla_r T\,\Big|_{sep} - n\chi(\varepsilon)\nabla_r T\,\Big|_{sep-\delta} - \int_{sep-\delta}^{sep} L$$

Proto-Model, cont'd

- But: $-n\,\chi(\varepsilon)\nabla_r T|_{sep-\delta} \;= Q$ → heat flux from core

So for edge layer:

transport loss at sep. $\nabla_r T < 0$

$$\frac{\partial E}{\partial t} = Q_{core} - (\delta)L \;+\; n\,\chi(\varepsilon)\nabla_r T\,\Big|_{sep}$$

radiative losses

and can simplify to:

$$\frac{\partial T}{\partial t} = -\frac{\chi(\varepsilon)T}{\Delta^2} + q - \frac{L(n,T)}{n}$$

becomes a simple mean field temperature equation

Key Ratio

- Physics of Power Scaling of Great Interest

- From T eqn, radiation and transport compete for q, so

$$\frac{L/n}{\chi(\varepsilon)T/\Delta^2} \sim \boxed{\frac{\gamma_{RC}}{\chi(\varepsilon)/\Delta^2} \sim D_{a,R}\,(Q, n, \ldots)}$$

Radiative Damkohler #
(after Gronke)

$D_a \sim \tau_{turb}/\tau_{react}$ → Damkohler # from combustion

$D_a \gg 1$ → reaction time short → flame sheets

$D_a \ll 1$ → mixing time short → pre-mixed flame

Key Ratio, cont'd

- Now have radiative Damkohler number

- $D_{a,R} \sim \tau_{transp} / \tau_{rad}$

- $D_{a,R} \ll 1$ → strong turbulent transport thru layer. P scaling by transport physics

  $D_{a,R} \gg 1$ → radiation dominated. P scaling by radiation

- Expect : $D_{a,R}$ first

  – rises to $\gg 1$ as R.C. grows

  – drops to $\lesssim 1$ as edge plasma cools

∴ time history of considerable interest → drop in $D_{a,R}$ should correspond to 'density clamp'.

Minimal Model → ala' Singh + P.D.

$$\frac{\partial T}{\partial t} = -\frac{\chi \varepsilon T}{\Delta^2} + q - \frac{L(n,T)}{n}$$ → temp

$$\frac{\partial \varepsilon}{\partial t} = a_1\, \gamma(n,T)\varepsilon - a_4\, V_Z^2 \varepsilon f(\alpha) - a_2 \varepsilon^2$$ → fluctuation energy

$$\frac{\partial V_Z^2}{\partial t} = a_4\, V_Z^2\, \varepsilon\, f(\alpha) - b_3 n V_Z^2$$ → zonal flow

→ $f(\alpha) \equiv$ adiabaticity "switch" - T evolves

$\alpha \sim k_\parallel^2\, v_{th}^2 / \omega\nu \sim T^2$ accounts for Z.F. decay, production drops

$f(\alpha) \sim 1, \alpha > 1$

$f(\alpha) \ll 1, \alpha \ll 1$

Next Steps

- Exercise Model
- 1D version → cooling fronts !?

  ➔ cooling + transport fronts ?!

- Profile structure, magnetic geometry?

N.B. $\chi_{\parallel} k_{\parallel}^{2} \sim (D_T \chi_{\parallel})^{1/2}\, k_{\theta}/L_s$ ➔ higher m modes damped by conduction + turbulence

- Can radiative condensation couple to turbulence dynamics directly? How?

Speculations

- Soft limit defined by $\gamma_{rad}(n)$ sufficient to induce $\alpha < 1$?!

  ➔ n_{crit} for strong transport ➔ soft DL ?!

- Burning Plasma ?

  $\bar{n} \sim P^{\alpha}$, but $P = P_{thermal}$

  ∴ density limit likely linked to alpha channelling efficiency

- Control edge Rad. Condens. using stochastic layer?

Partial Conclusion

- "Causality" counter-intuitive

  Radiation/MARFE → cooling → strong transport

  $$\alpha > 1 \rightarrow \alpha < 1$$

  Opposite conventional wisdom!

- Non-disruptive termination

- Two channels for power scaling, strongly coupled. $D_{a,R}$ is useful → experimental analysis

$$D_{a,R} \sim \gamma_{rad} / \frac{\chi(\varepsilon)}{\Delta^2}$$

- Model extended to encompass radiative condensation

From then to now of DL

- Greenwald (1988) scaling → Wrong → Power Scaling, Multiple Limits

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

- Sudo (1990) Scaling (stellarator) → mainstream, albeit incomplete → G + S unification

  $\bar{n} \sim P^{1/2}$

- DL as MHD + Disruption phenomenon → frequently, even usually, not

  Rebut, Gates, White (revision needed!)

- DL as a ‘Back-Transition’ → from heresy to convention
- Radiation triggers MHD → Rad. triggers transport...
- Better Density ‘Saturation’ than ‘Limit’ !

Thank You !