Alcator C-Mod

Cross-field Plasma Transport in the Scrape-off Layer

A key physics issue for SOL, divertor, and core plasma

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Presented at the
International Atomic Energy Agency
Technical Committee Meeting
on DIVERTOR CONCEPTS
September 11 — 14, 2001, Aix-en-Provence, France

Cross-field transport in SOL is a key physics issue...

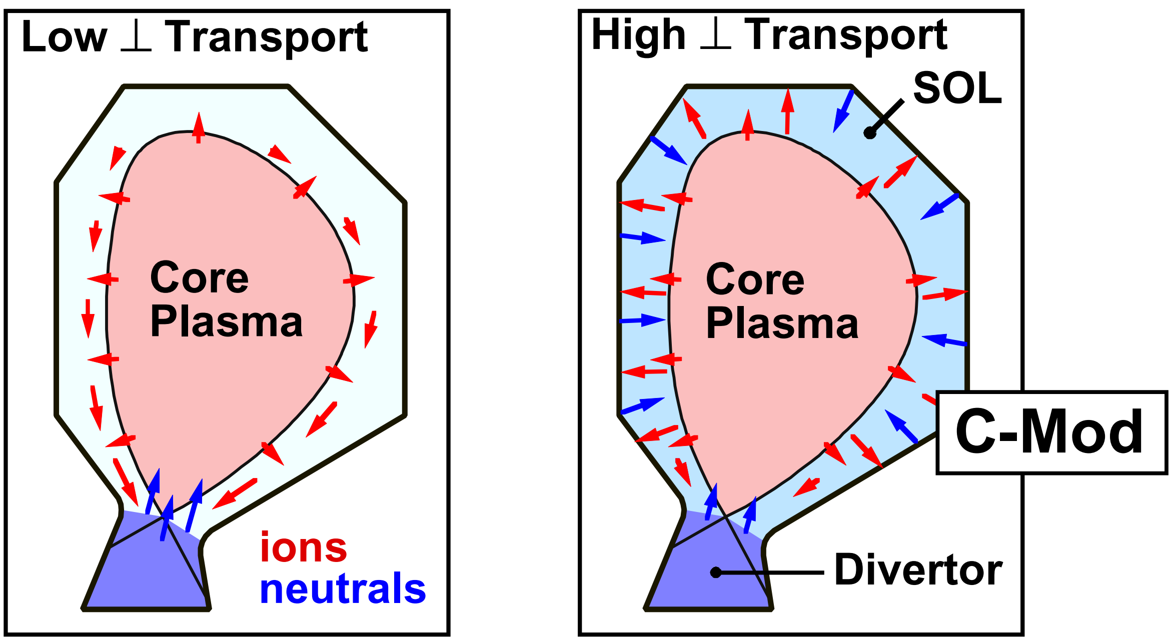
- impacts tokamak operation and divertor design

- $\Gamma_\perp$ determines level of plasma/wall interaction in main-chamber

  neutral pressures (<=> confinement)

  wall impurity sources

  => impacts divertor design



Q: What will be operating regime in a reactor?

Cross-field transport in SOL is a key physics issue...

- must be understood for predictive modelling

- Heat convection across separatrix and SOL increases with plasma density
  => may precipitate divertor detachment!

- Particle transport is characterized by 'bursty', large-transport 'events'
  => diffusive transport paradigm in SOL/divertor simulations is inadequate!

- can directly impact core plasma

- Near the density limit, cross-field convection dominates heat fluxes through entire SOL
  => empirical scaling of tokamak density limit may be set by the physics of SOL transport!

=> Need to develop scaleable empirical and physics-based understandings of underlying transport physics

None exist at present!

Outline of Talk

- **Main-Chamber Particle Balance**

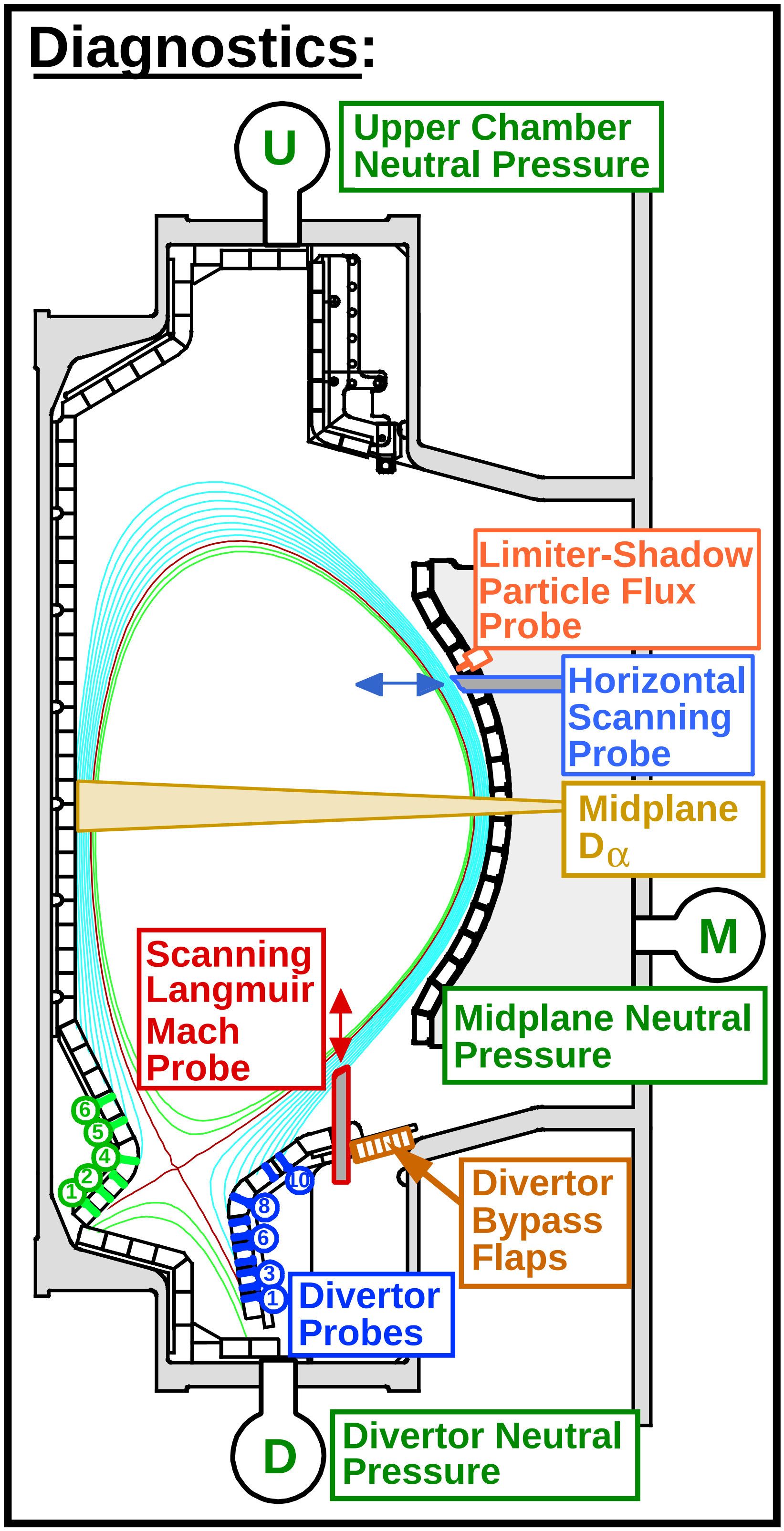
- **Critical Cross-Field Flux for Particle Control**

- **Effective Cross-Field Particle Diffusivites (D_{eff}) & Scalings**

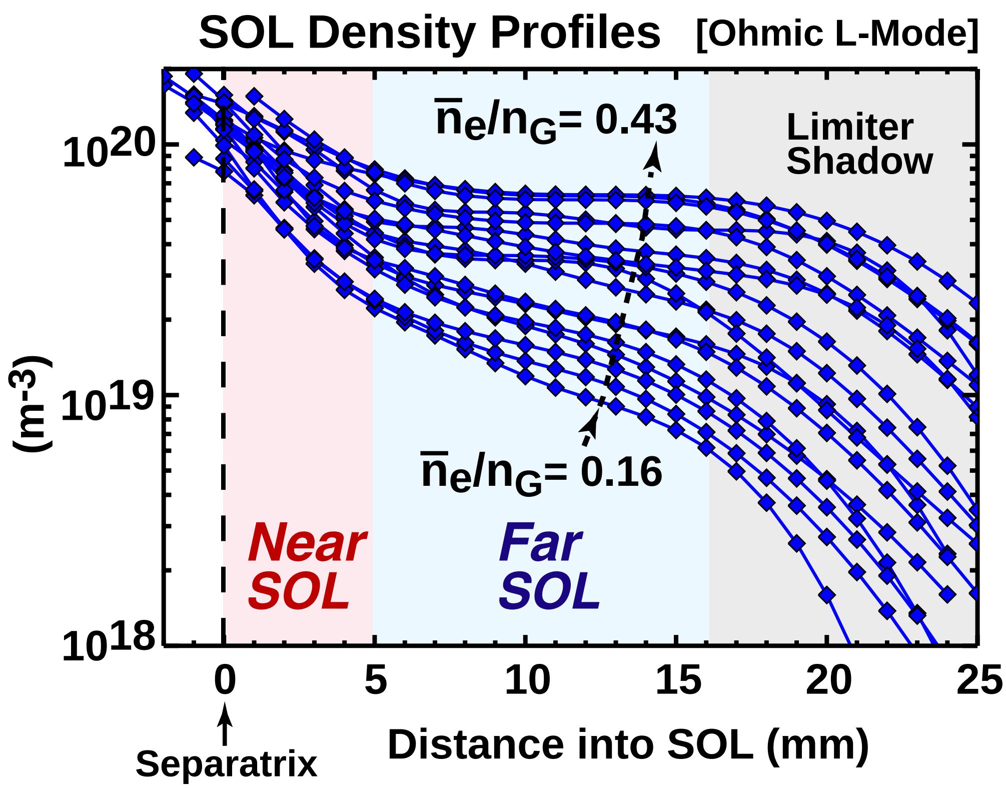
- **Cross-Field Heat Convection**

- **Character of SOL Fluctuations**

- **SOL Transport Physics and the Discharge Density Limit**



Scrape-off Layer Density Profiles Exhibit a "Two-Exponential" Decay†



Near SOL: steep decay, λ_n ~ 2 to 8 mm

Far SOL: shallow decay, λ_n ~ 8 to > 100 mm

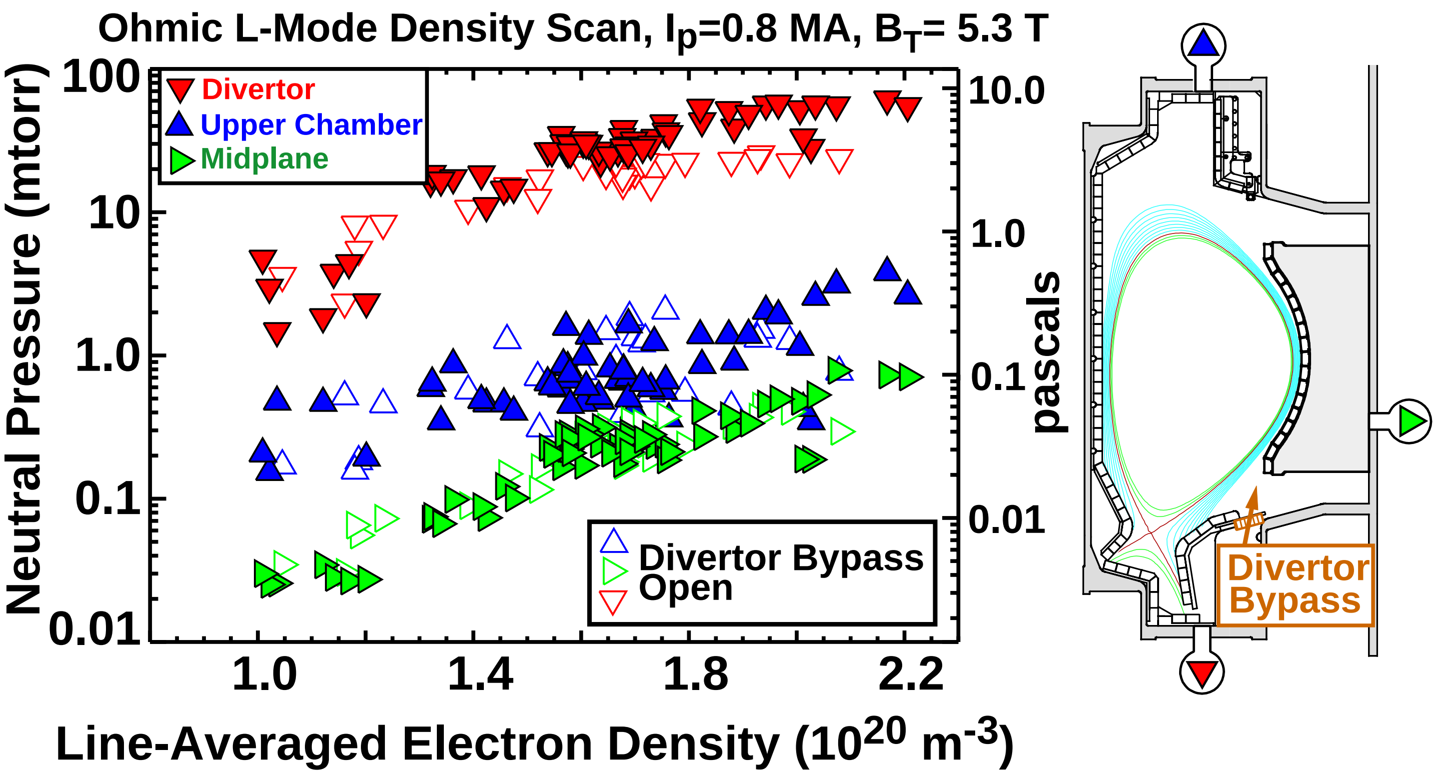
- At low $\bar{n}_e$, density at limiter edge is less than ~1/10 of separatrix density
- Density at limiter edge increases sharply with increasing $\bar{n}_e$

=> Always some level of main-chamber (limiter) recycling

Note: Similar *Far SOL* profiles are seen in H-mode discharges with the same midplane neutral pressure

† 'shoulders' on SOL profiles are prevalent in the literature: ASDEX, ASDEX-U, JT-60U, TEXT-U, ...

High Neutral Pressures Surround Core Plasma, Independent of Divertor Bypass



- **Divertor Pressure drops by factor of 2 when bypass is opened at high density**
- **Yet, robust relationship between Midplane pressure and line-averaged density is seen†**
- **Neutral pressures in Upper Chamber can be higher than at Midplane!**

=> implies large neutral fluxes (Γ_W) attack core plasma directly from main-chamber "wall" surfaces

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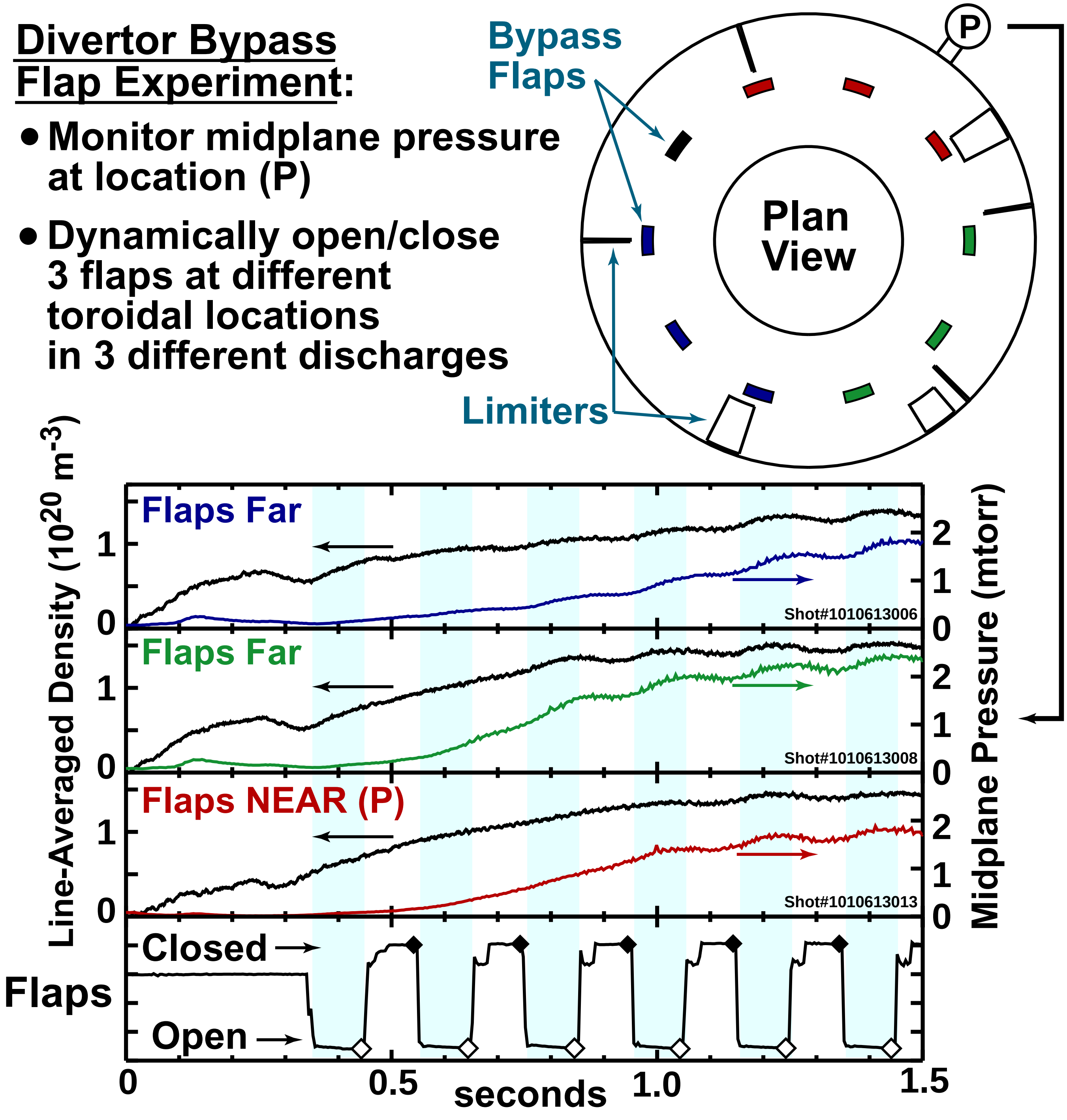
† as noted on ASDEX-U ...

Local Midplane Pressure is Insensitive to Neutral Leakage Through Local Divertor Bypass

Divertor Bypass Flap Experiment:

- Monitor midplane pressure at location (P)
- Dynamically open/close 3 flaps at different toroidal locations in 3 different discharges



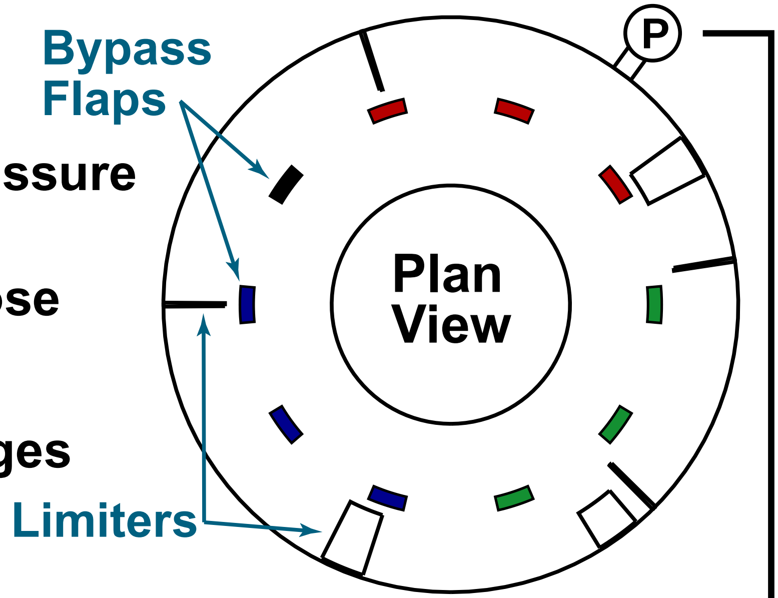
Local midplane pressure and line-averaged density perturbations are of similar magnitude, independent of toroidal location of active bypass flaps

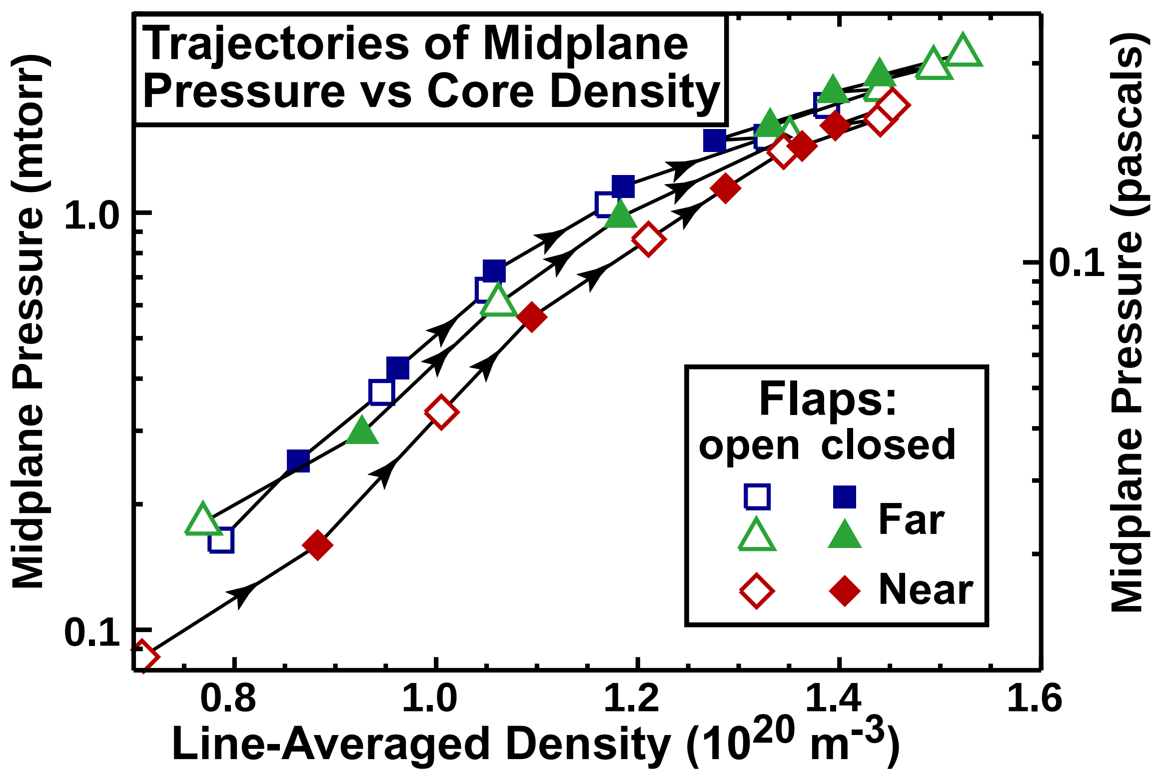
=> Most of neutral leakage from divertor does not directly contribute to midplane pressure

Local Midplane Pressure Tracks Core Density, Independent of Local Divertor Bypass State

Divertor Bypass Flap Experiment:

- Monitor midplane pressure at location (P)
- Dynamically open/close 3 flaps at different toroidal locations in 3 different discharges



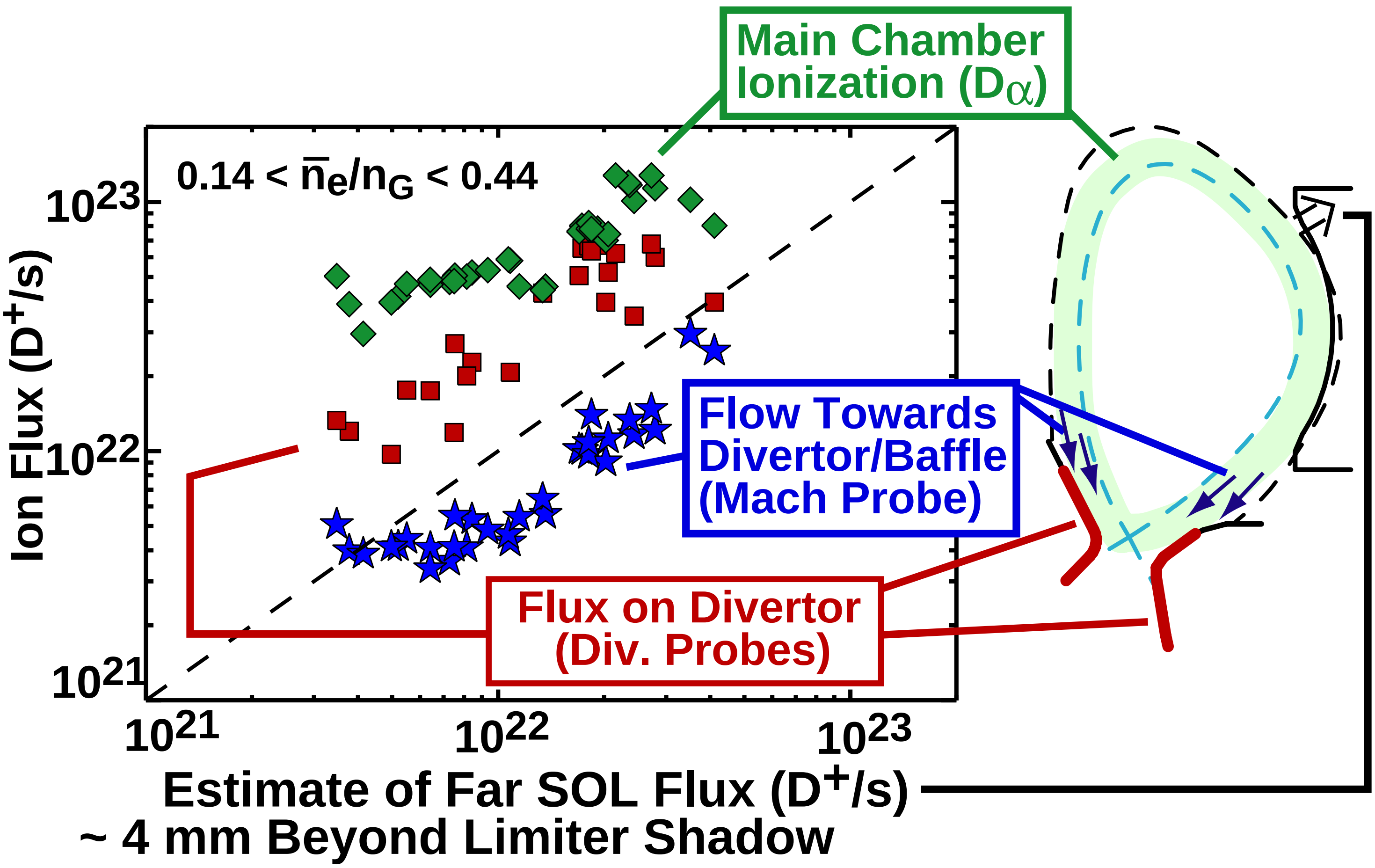


Local midplane pressure tracks line-averaged density, independent of toroidal location of active bypass flaps

=> Midplane neutral pressure is set primarily by recycling on main-chamber surfaces rather than divertor leakage†

†see Lipschultz et al., this conference

Main Chamber Ionization and Ion Fluxes to Main Chamber Limiters are Large Compared to Flows Towards Div./Baffle



- **Recycling in Main Chamber SOL is primarily balance by fluxes onto main-chamber walls†**
- **Poloidal flows to divertor/baffle are weak**

Main-Chamber Recycling Regime (MCR) persists over wide parameter range

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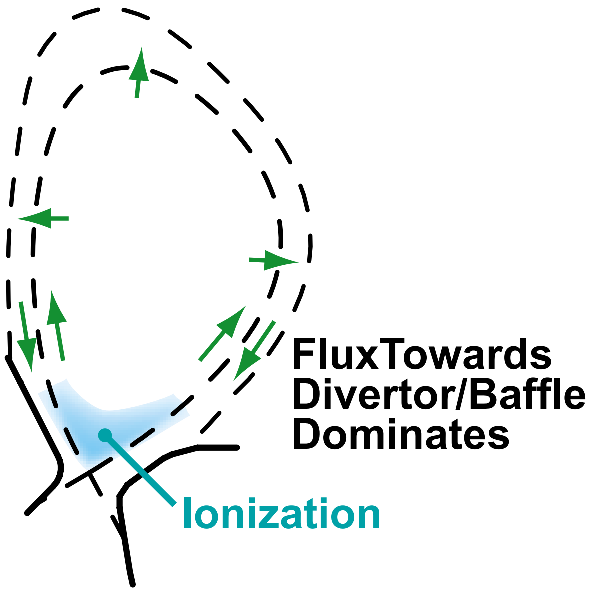
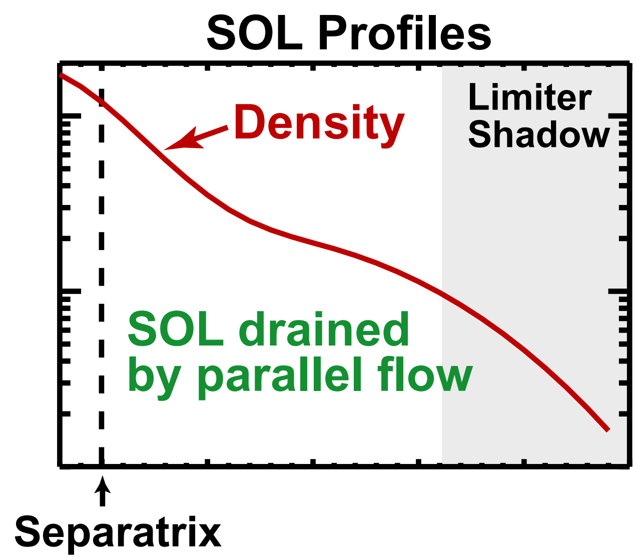
†M.V. Umansky, et al. Phys. Plasmas 5, 3373 (1998).

A New View of Particle Transport Processes in SOL

Old Paradigm:

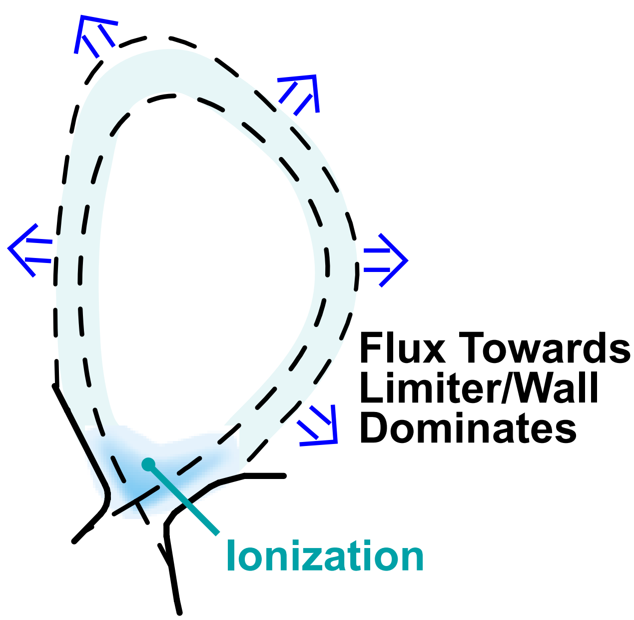
- **SOL density decays "exponentially" because...**
  plasma drains along field lines towards divertor/baffle

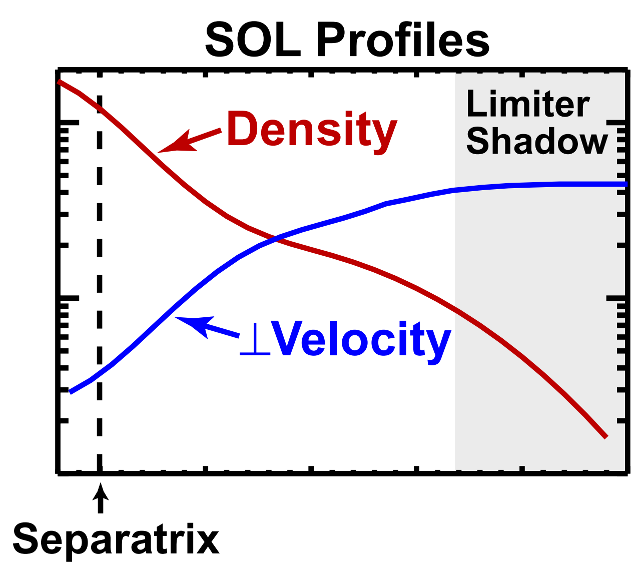




New Paradigm:

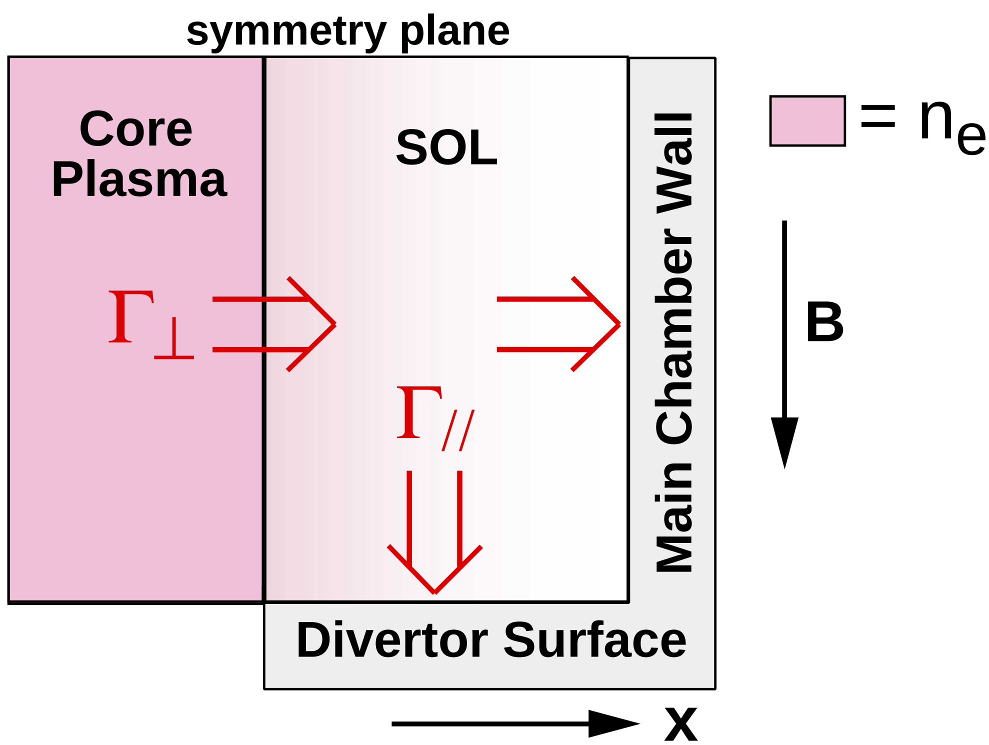
- **SOL density decays "exponentially" because...**
  cross-field transport velocity increases across SOL, maintaining cross-field flux towards wall





Q: What level of cross-field transport leads to loss of particle control in the main chamber?

Consider simplified SOL:



- **Plasma Continuity**

$$\nabla \cdot \underline{\Gamma} = n_0 n_e k_{ion}$$

- **Flux Surface Average** $\langle \ldots \rangle$

$$\frac{\partial}{\partial x}\langle \Gamma_\perp \rangle \approx n_e [\langle n_0 \rangle k_{ion} - \frac{C_s}{2L}]$$

Note #1: If a critical flux-surface averaged neutral density is exceeded, $\langle \Gamma_\perp \rangle$ must increase across SOL†

$$\langle n_0 \rangle_{crit} \sim \frac{C_s}{2 k_{ion} L}$$

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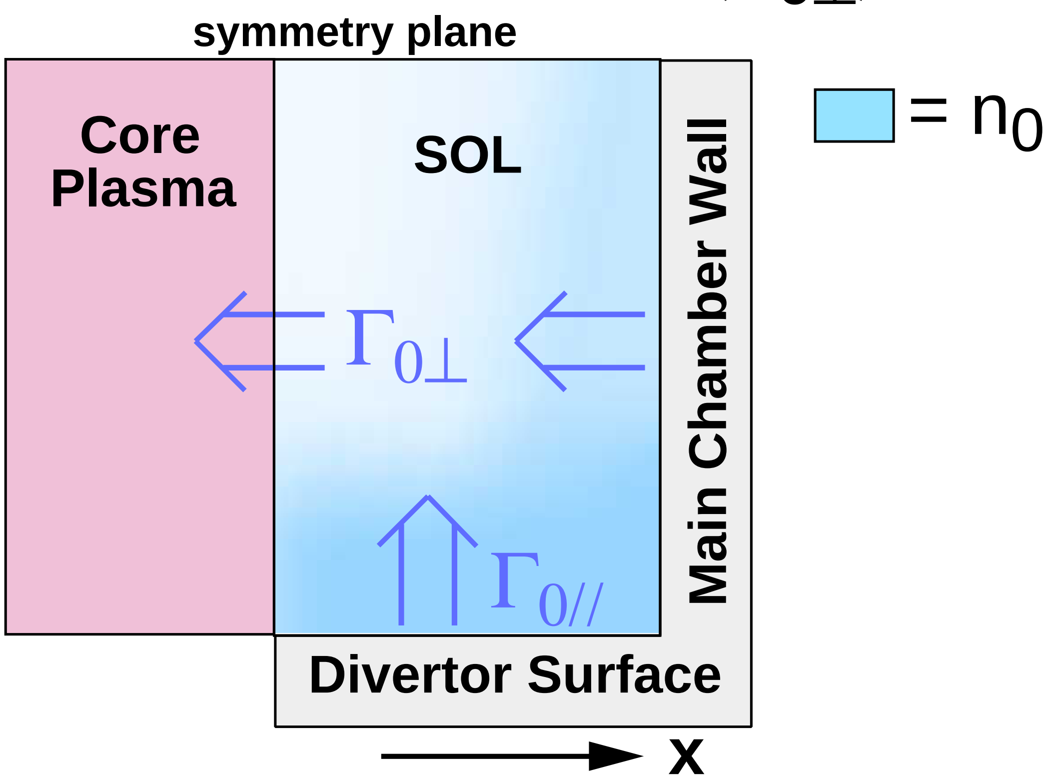
†a well known over-ionization condition (e.g., Stangeby et al.)

Q: What level of cross-field transport leads to loss of particle control in the main chamber?

Note #2: Mass balance requires: $\langle \Gamma_{0\perp} \rangle = -\langle \Gamma_{\perp} \rangle$



Note #3: Neutral Flux requires minimum Neutral Density:

$$\langle n_0 \rangle \geq \sim -\langle \Gamma_{0\perp} \rangle / v_{th0\perp} \quad \text{(}v_{th0\perp} \sim \text{ set by CX)}$$

A: If $\langle \Gamma_{\perp} \rangle$ exceeds ~ $\dfrac{C_s\, v_{th0\perp}}{2\, k_{ion}\, L}$ at x=x0 then $\langle \Gamma_{\perp} \rangle$ increases with x for x > x0†

=> Result is insensitive to separatrix-wall distance and divertor geometry!

=> Main-chamber particle contol depends critically on the level of ⊥ particle transport

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† **'critical flux' is comparable to level of $\langle \Gamma_{\perp} \rangle$ observed in C-Mod**

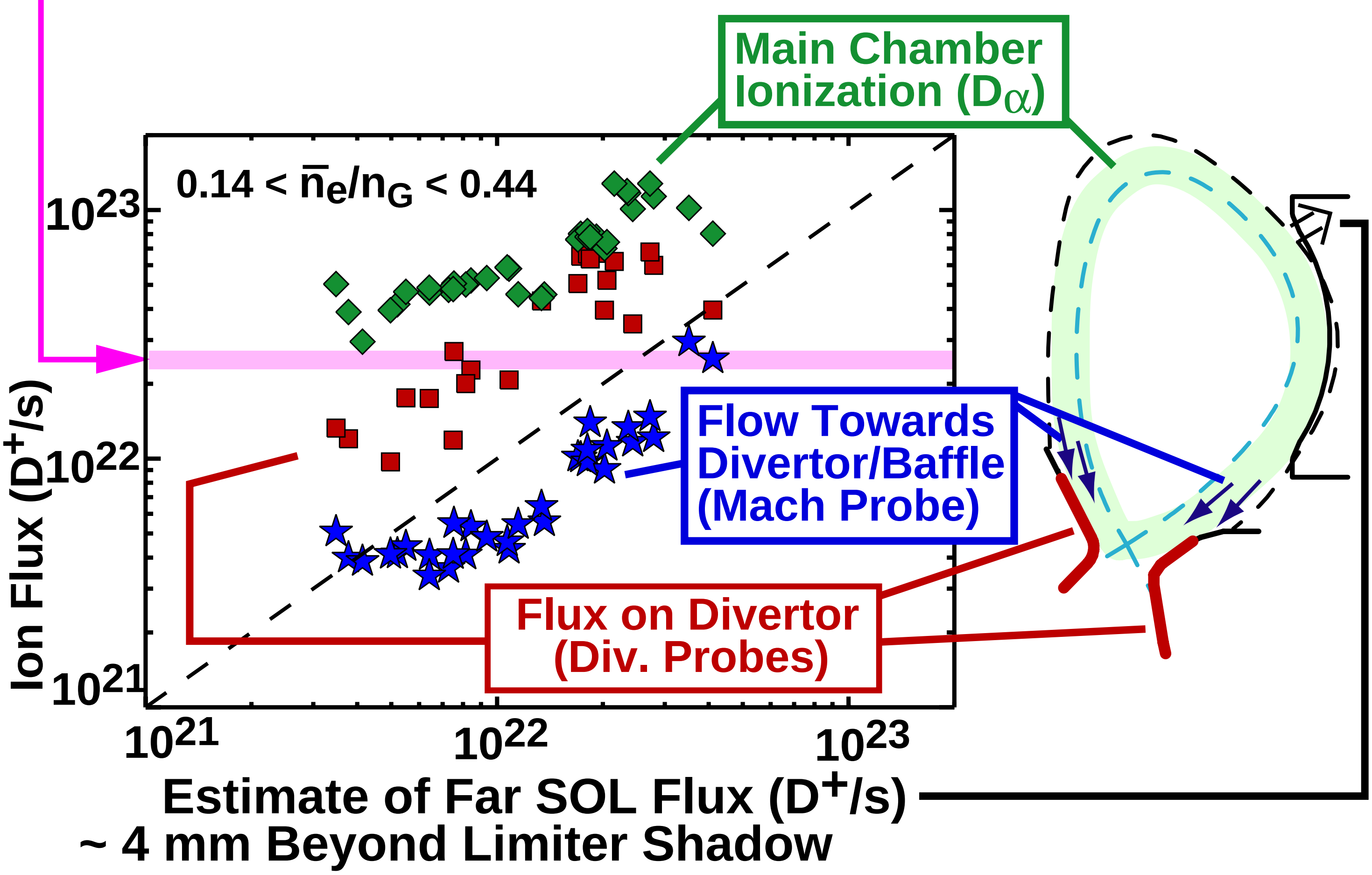
Main Chamber Ionization (D_α) in C-Mod Exceeds Upper Bound Estimate of $\langle\Gamma_\perp\rangle_{crit}$

Estimate with $T_0 \approx T_i \approx T_e$, free-streaming neutrals

$$\langle\Gamma_\perp\rangle_{crit} \approx 2\text{x}10^{20} \frac{T\,(\text{eV})}{q\,R\,(\text{m})} (\text{m}^{-2}\ \text{s}^{-1})$$

Typical Number (with T~50 eV):

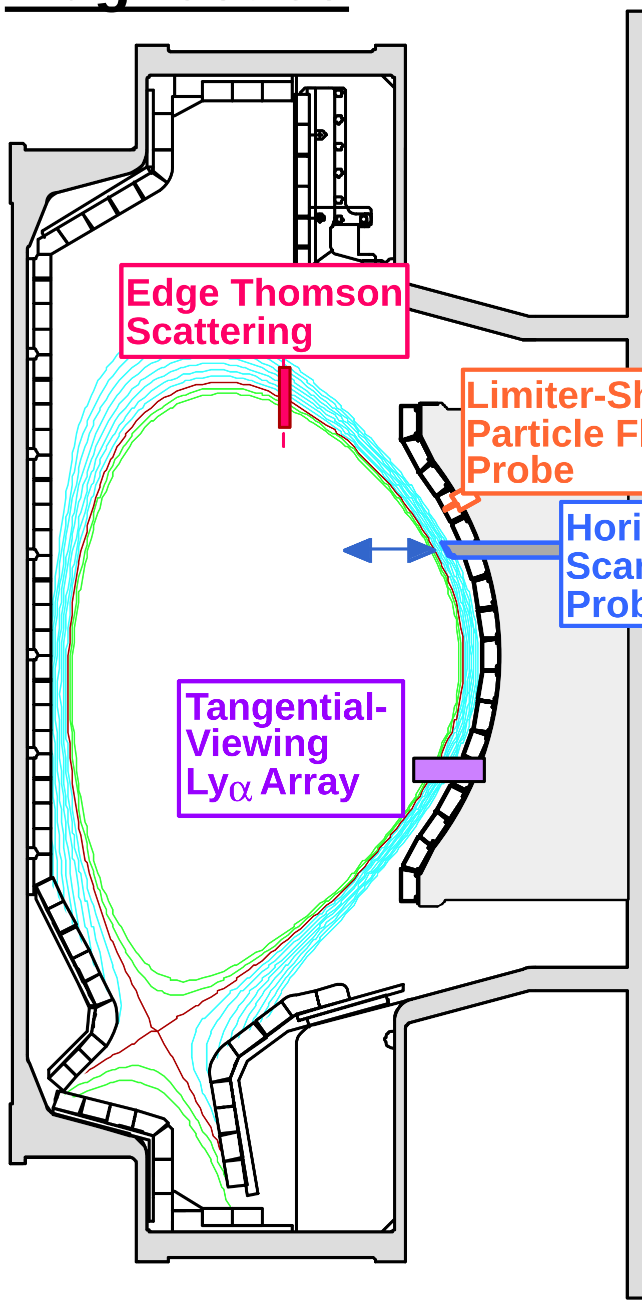
$$\langle\Gamma_\perp\rangle_{crit} A_{sep} \sim 2.6\text{x}10^{22}\ (\text{s}^{-1})$$



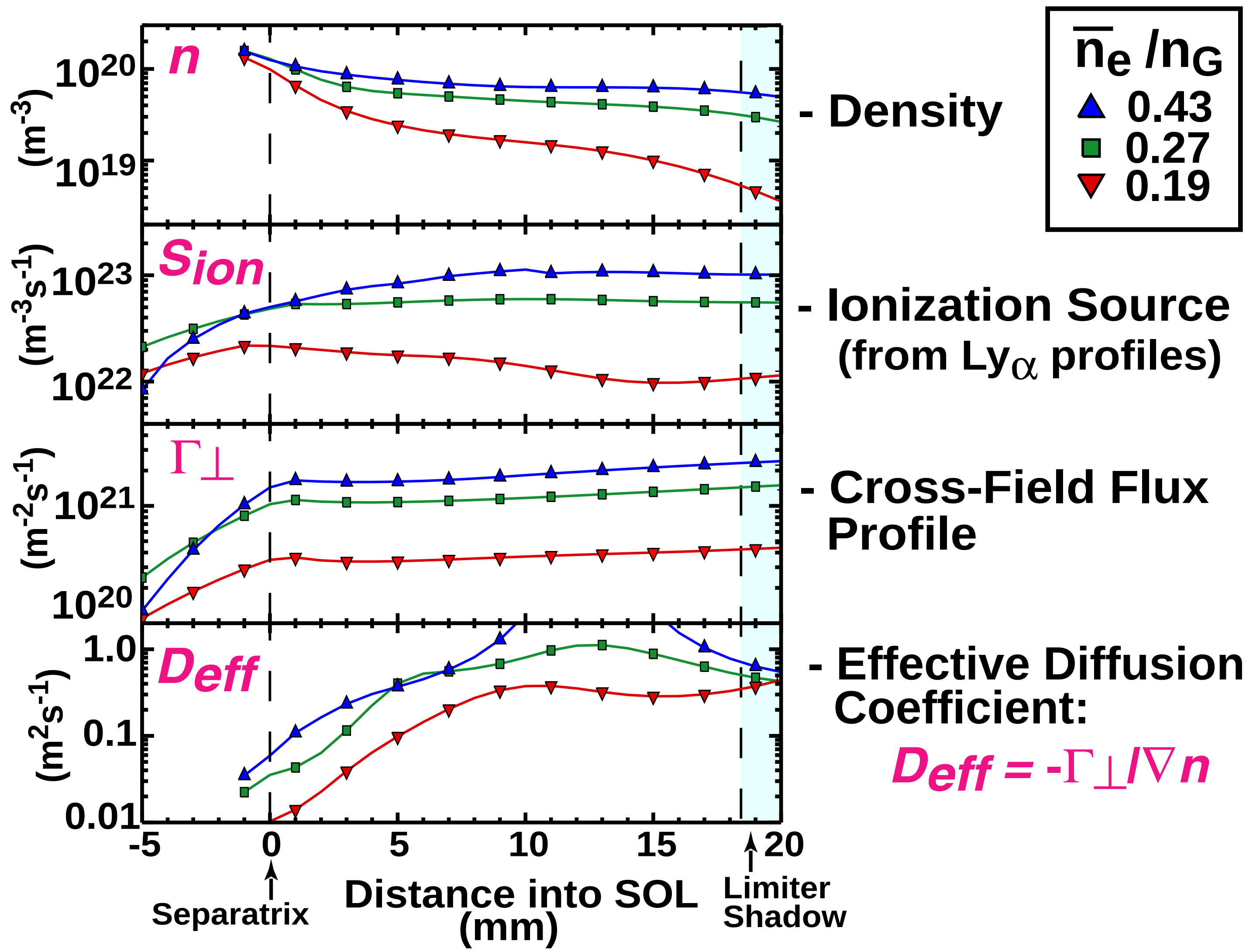
Outline of Talk

- Main-Chamber Particle Balance
- Critical Cross-Field Flux for Particle Control
- **Effective Cross-Field Particle Diffusitives (*D*eff) & Scalings**
- **Cross-Field Heat Convection**
- Character of SOL Fluctuations
- SOL Transport Physics and the Discharge Density Limit

Diagnostics:



In MCR Regime, Cross-Field Diffusion Coefficient Profiles (D_{eff}) can be Inferred Directly from Profile Measurements†



- Persistent trend of D_{eff} increasing by ~ 10 or more with distance from separatrix††
  - *=> variation in D_{eff} reflects variation in ∇n*
- D_{eff} increases with discharge density
  - *=> $\Gamma_\perp$ gets larger, ∇n gets smaller*

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†Method benchmarked against UEDGE modeling

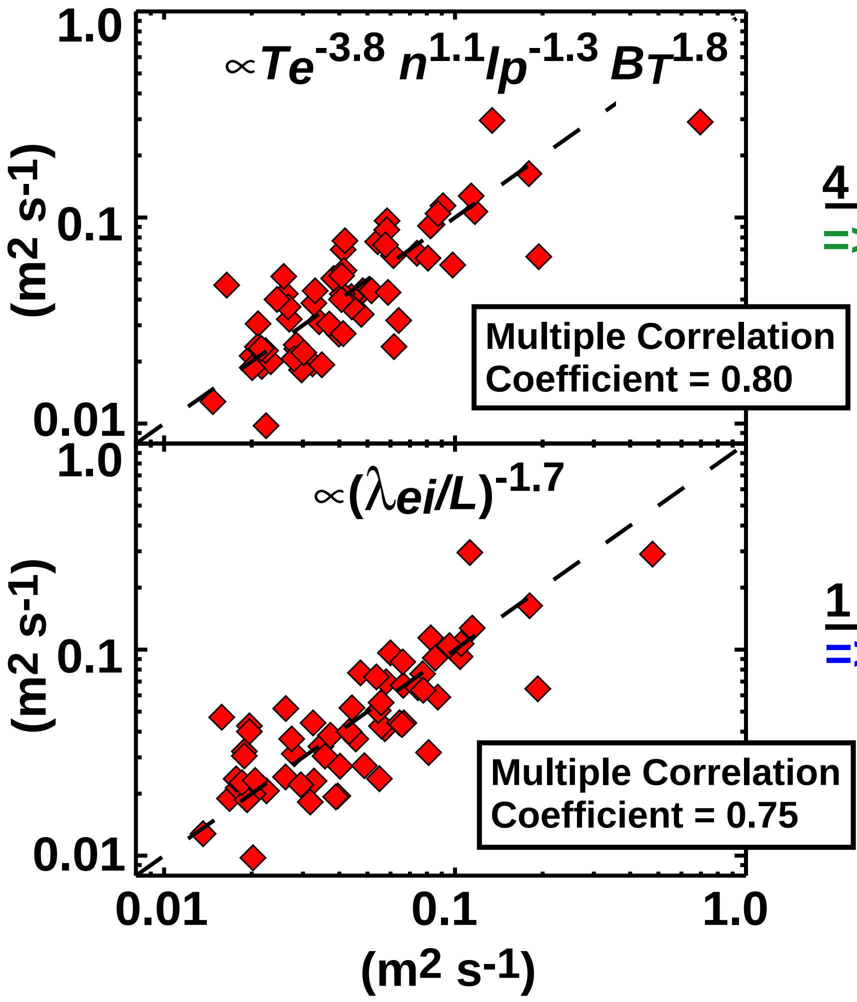
††D_{eff} (χ_{eff}) increasing seen before: ASDEX, JT-60, JET, ...

Magnitude of D_{eff} in Near SOL is Correlated with Collisionality in Near SOL

64 Ohmic L-Mode Datapoints:

$0.8 < \bar{n}_e < 2.5\times10^{20}\ m^{-3}$
$0.6 < I_p < 1.0$ MA
$4 < B_T < 6$ tesla
$0.14 < \bar{n}_e/n_G < 0.47$

Regression Analysis of D_{eff}, 2 mm into SOL



<u>4 Parameter Regression</u>:
=> Suggests (B_T/I_p), q, or L dependence

<u>1 Parameter Regression</u>:
=> Statistics point to (λ_{ei}/L) as most relevant parameter

=> D_{eff} correlates with local collisionality:

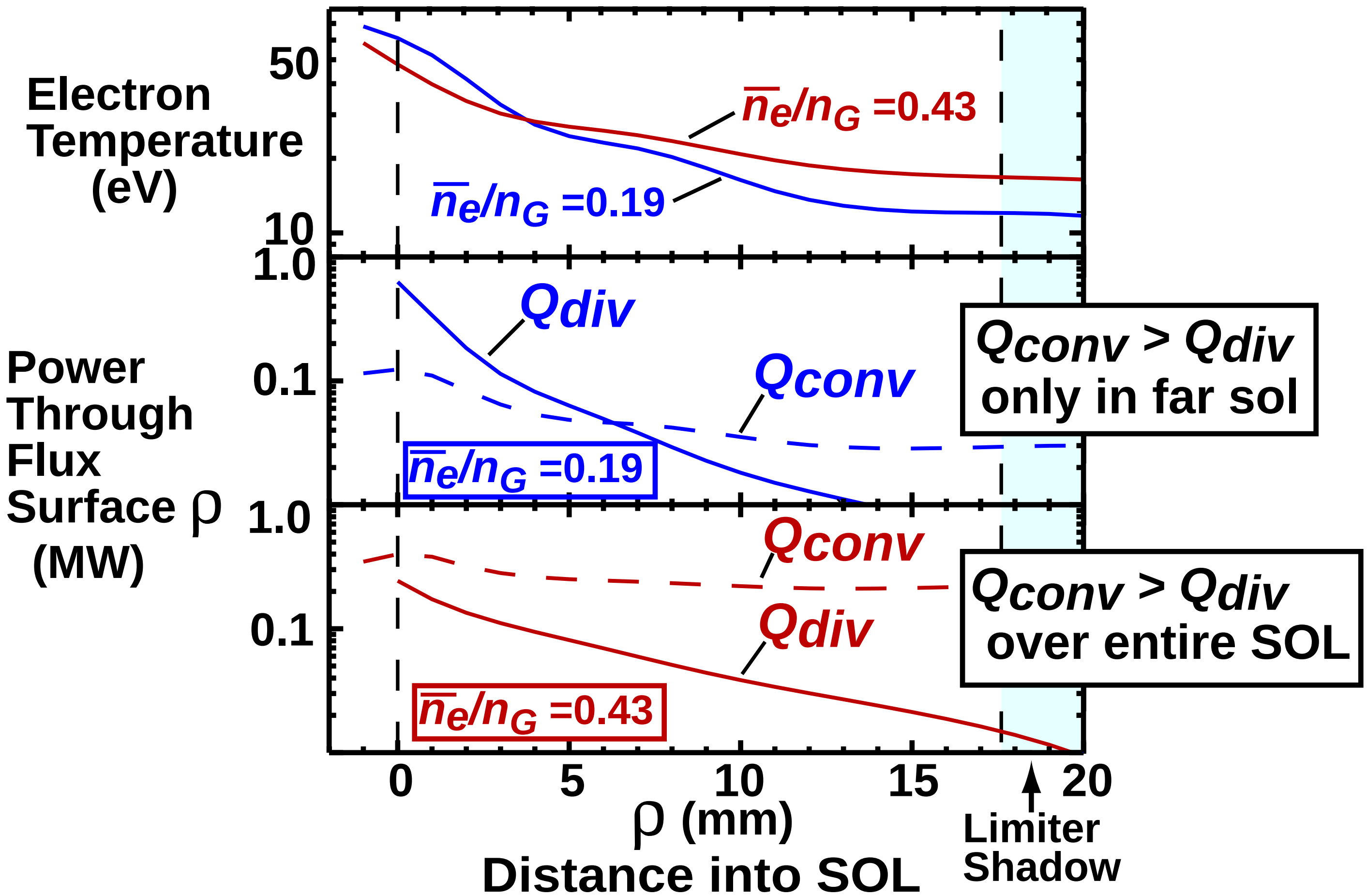
$$D_{eff} \sim (\lambda_{ei}/L)^{-1.7}$$

Trend: $n_e/n_G \uparrow$ => $\lambda_{ei}/L \downarrow$ => $D_{eff} \uparrow$ near sep.

Cross-Field Heat Convection to Limiter/Wall Competes with Parallel Conduction Losses to Divertor at Moderate $\bar{n}_e/n_G$

Finite T_e on open field lines
=> power conducted to divertor: $Q_{div} \propto \int_{\rho}^{\infty} T^{7/2}/L \, \delta\rho'$

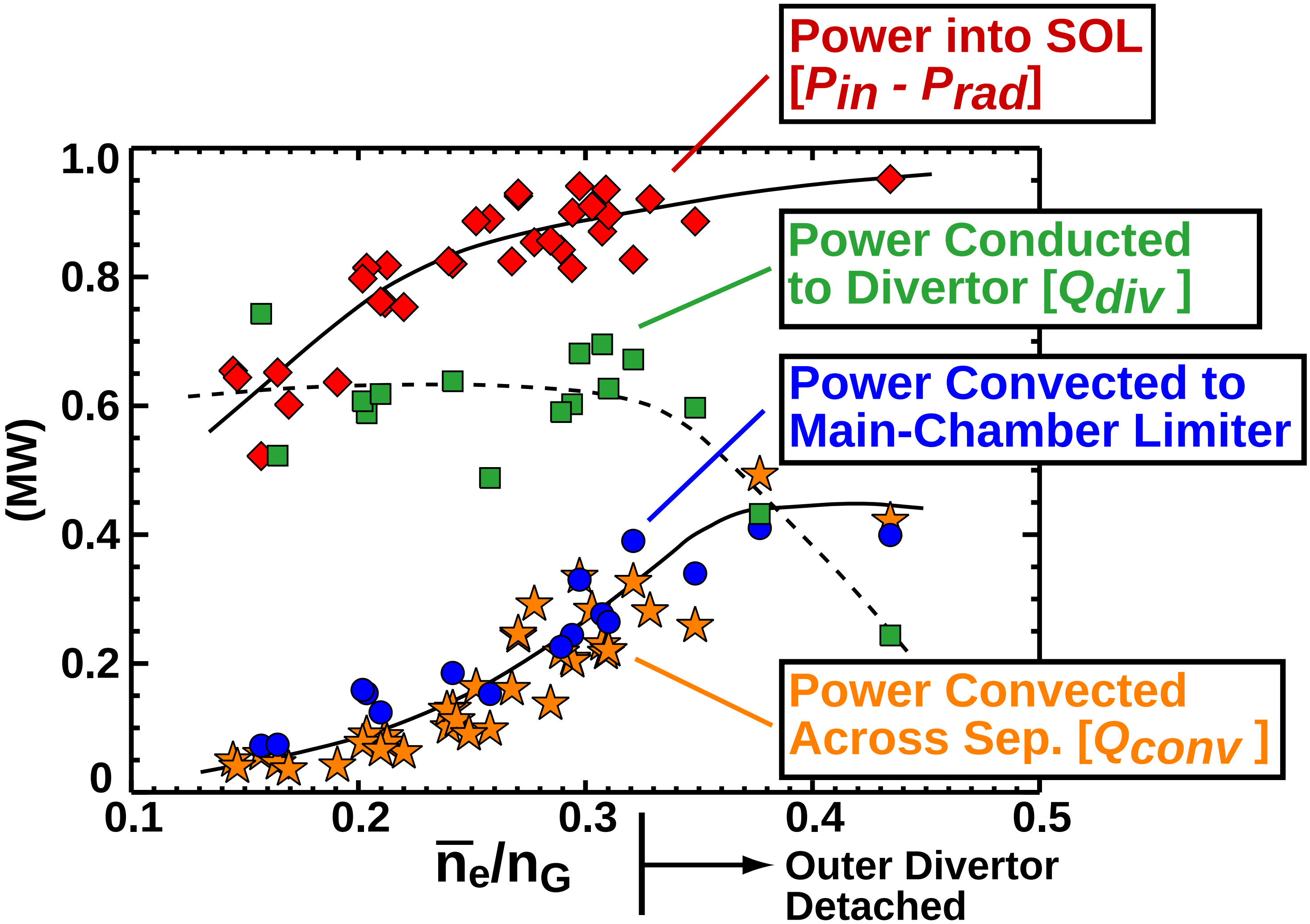
Cross-field particle fluxes ($\Gamma\perp$)
=> power convected: $Q_{conv} \sim 5\, T_e\, \Gamma\perp\, A_{sep}$



- At low density, heat losses in *Near SOL* are dominated by parallel conduction to Divertor

- At moderate density, cross-field heat convection to Limiter/Wall exceeds conduction losses to Divertor/Baffle over *entire SOL*

Cross-Field Convection Increases with $\bar{n}_e/n_G$, Affecting SOL Power Balance



- At low density, parallel conduction to Divertor dominates SOL power balance

- At moderate density, cross-field heat convection to Limiter/Wall becomes important

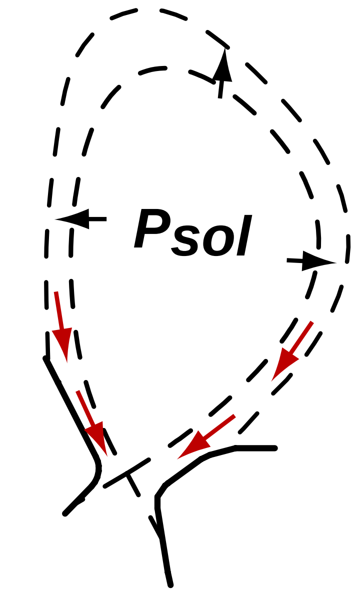
=> Cross-field convection losses to main-chamber wall may precipitate divertor detachment

A New View of Heat Transport Processes in SOL

(in absence of a "radiating mantle")

Old Paradigm:

- Parallel e^- conduction to divertor dominates heat losses in Near SOL region



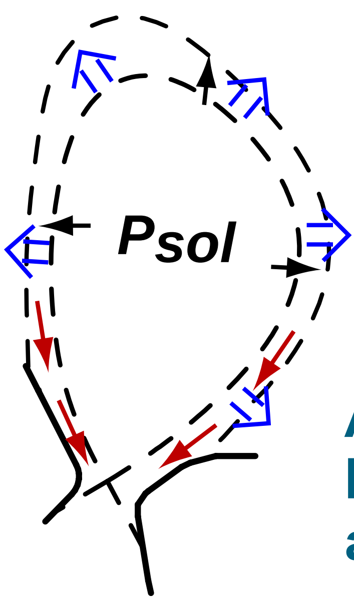
T_e at separatrix (T_{sep}) is a weak function of λ_{T_e} and SOL power (P_{sol}):

$$T_{sep} \propto (P_{sol} / \lambda_{T_e})^{2/7}$$

Modified Paradigm:

- Parallel e^- conduction and cross-field heat convection contribute to heat losses in Near SOL region

(CX is typically a minor player)



At low collisionality, parallel conduction regulates T_{sep}:

$$T_{sep} \propto (P_{sol} / \lambda_{T_e})^{2/7}$$

At high collisionality, heat convection becomes large, T_{sep} is reduced and is no longer "regulated" by this law!

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- Main-Chamber Particle Balance
- Critical Cross-Field Flux for Particle Control
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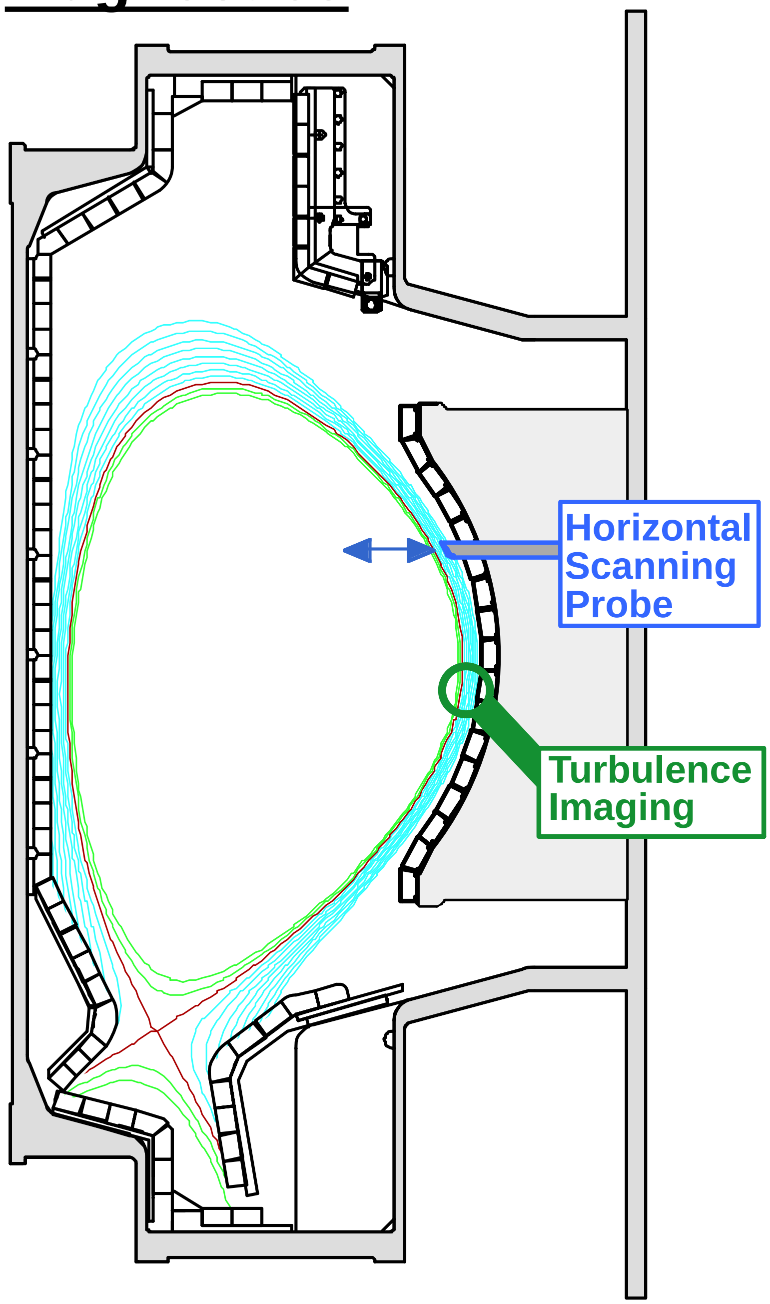
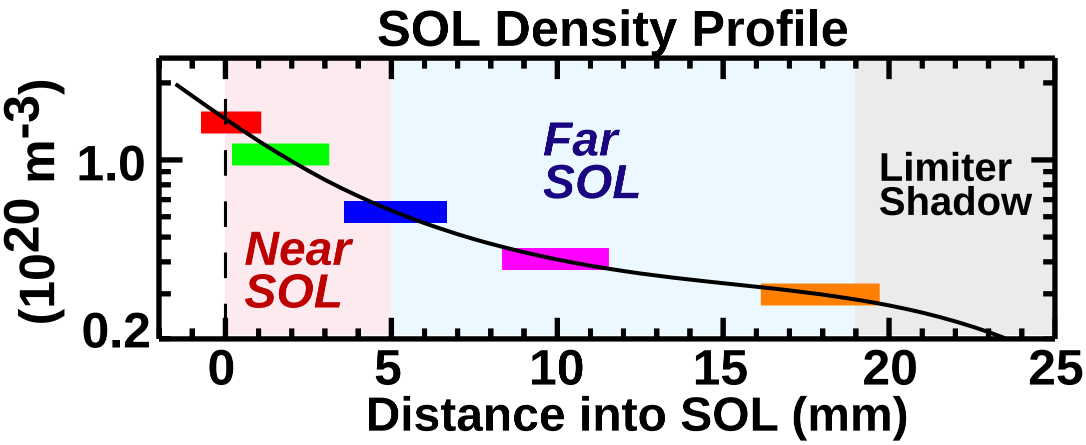
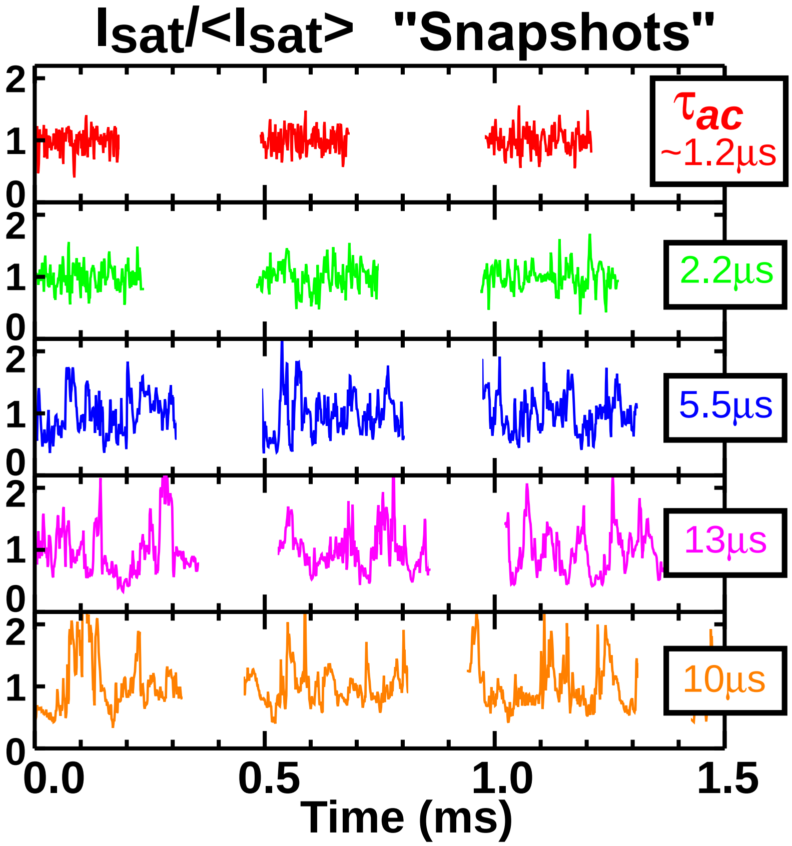
- Cross-Field Heat Convection
- **Character of SOL Fluctuations**
- SOL Transport Physics and the Discharge Density Limit

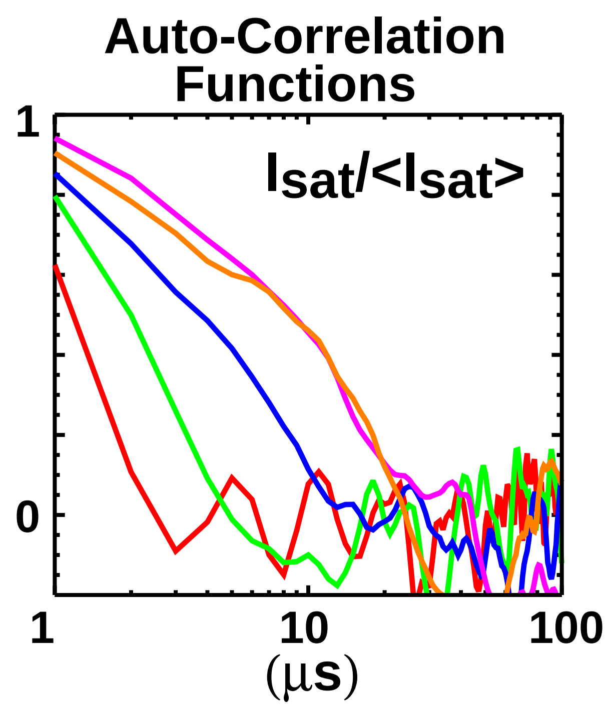
Diagnostics:



Fluctuations Exhibit Different Character in *Near* and *Far* SOL Regions







Near SOL **(steep n profile):**

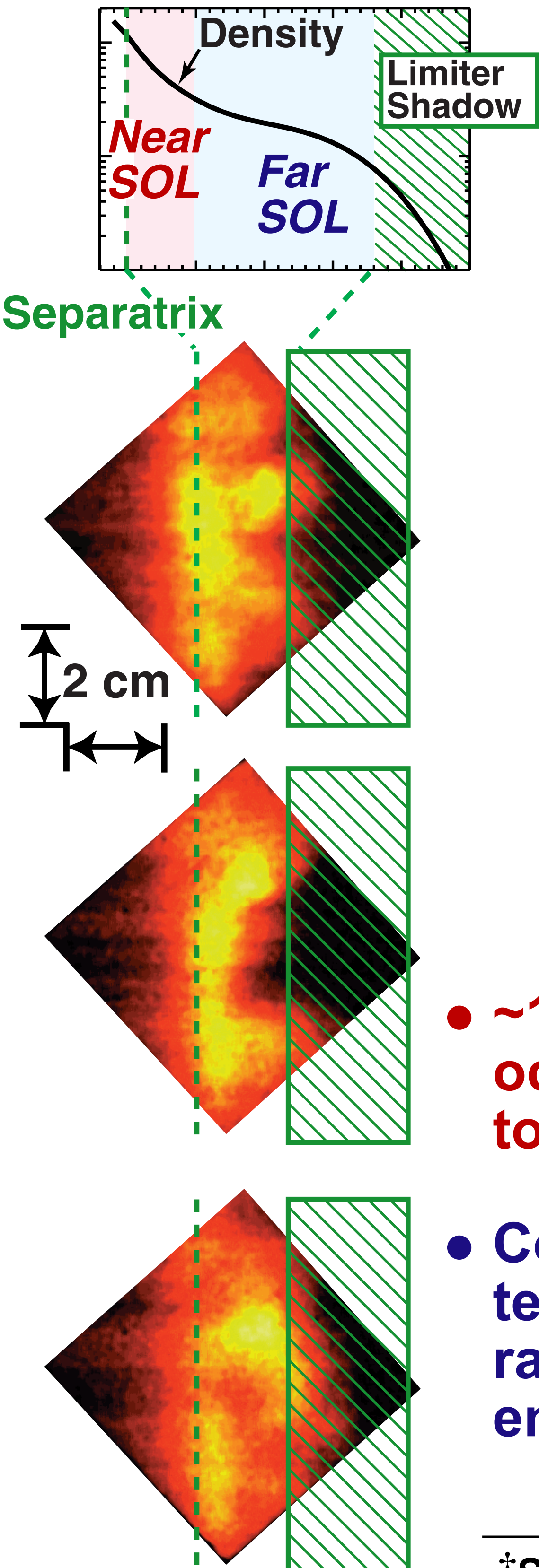
-> moderate amplitude, "random" fluctuations

Far SOL **(flatter n profile):**

-> large amplitude, intermittent I_{sat} "bursts"

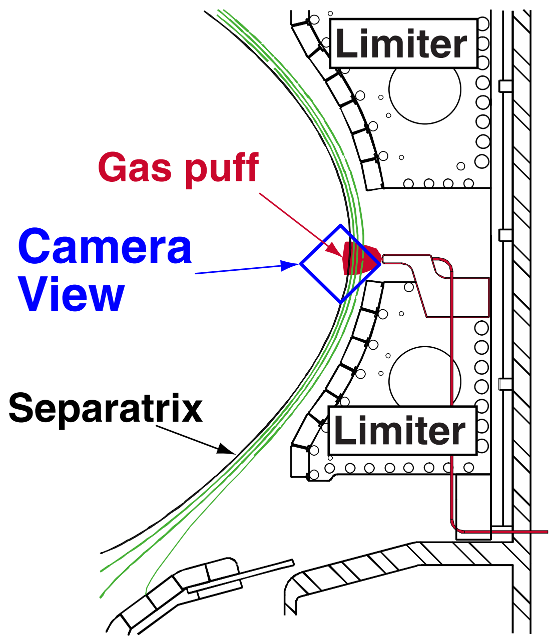
=> Consistent with D_{eff} ↑ with distance into SOL

2-D Turbulence Imaging: Intermittent, ~1 cm Scale "Blobs" of Emission Extend into Far SOL



Turbulence Imaging:†

Camera looks along field lines at a D_2 gas puff



2 s exposure times
17 ms between exposures

- ~1 cm scale blobs intermittently occupy Far SOL zone, and extend to Limiter Shadow
- Consistent with large density and temperature (?) perturbations rapidly transporting particles and energy to Limiter/Walls

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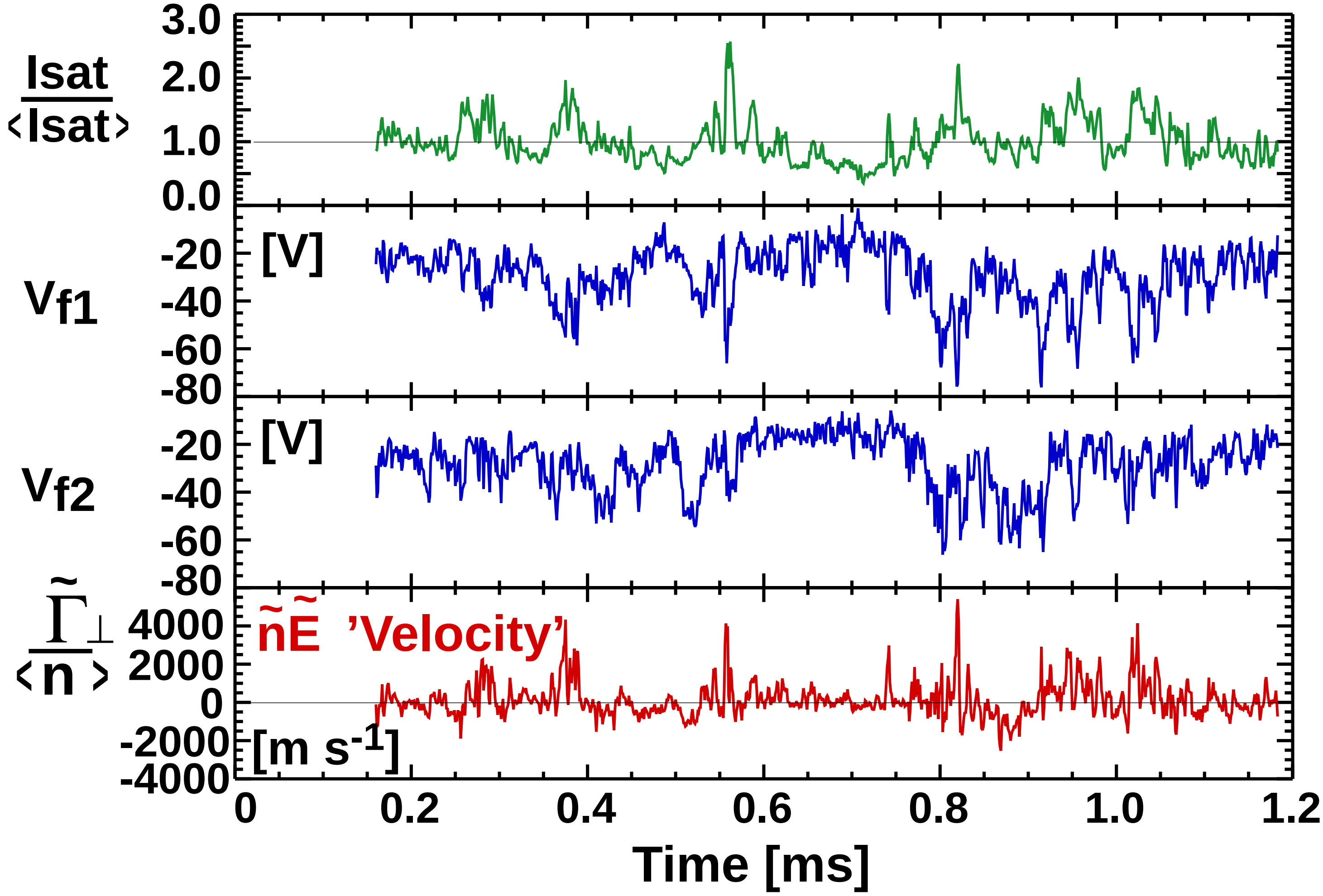
†S. Zweben, J.L. Terry, R. Maqueda

Time-History of Fluctuation-Driven Flux Shows Large-Amplitude, Bursty Behavior

Data from Midplane Probe,
7 mm outside LCFS

Particle flux estimate neglects $\tilde{T}_e$



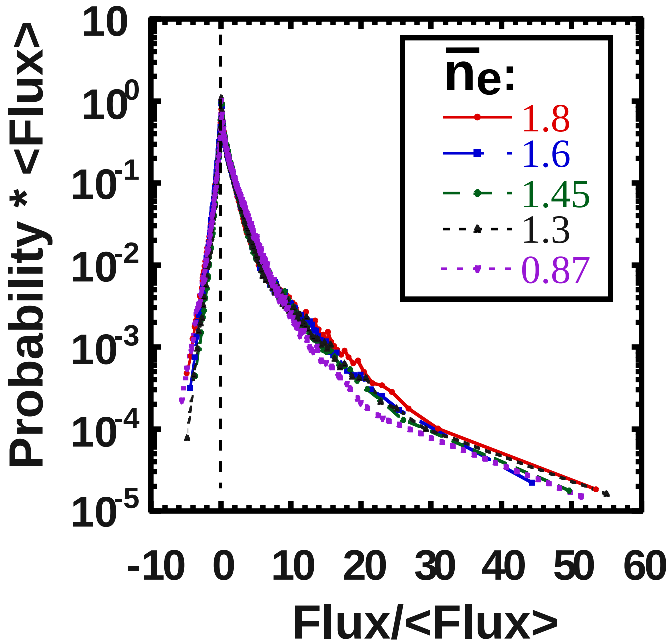
Time-averaged transport velocity: $\frac{\langle \Gamma_\perp \rangle}{\langle n \rangle} \sim 120\ \mathrm{m\ s^{-1}}$

'Bursts' in transport velocity exceed 2000 m s^{-1}

What is influence of $\tilde{T}_e$ on these estimates?

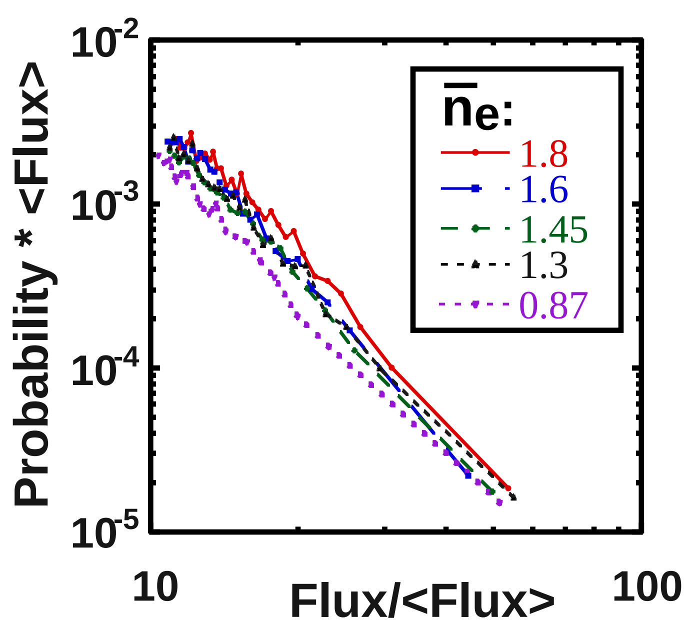
PDF of Fluctuation-Driven Particle Flux Exhibits Power-Law Tail, Independent of $\bar{n}_e$†

$\Gamma_\perp$ **Inferred from Midplane Probe, ~7 mm outside LCFS**



Similar P($\Gamma_\perp$) for all densities
=> change in <$\Gamma_\perp$> not associated with change in P($\Gamma_\perp$)

Always has SOC-Like behavior: ††



Positive $\Gamma_\perp$ 'events' with $\Gamma_\perp$ greater than 4.6 <$\Gamma_\perp$> account for 50% of total particle transport.

These events happen ~5% of time.

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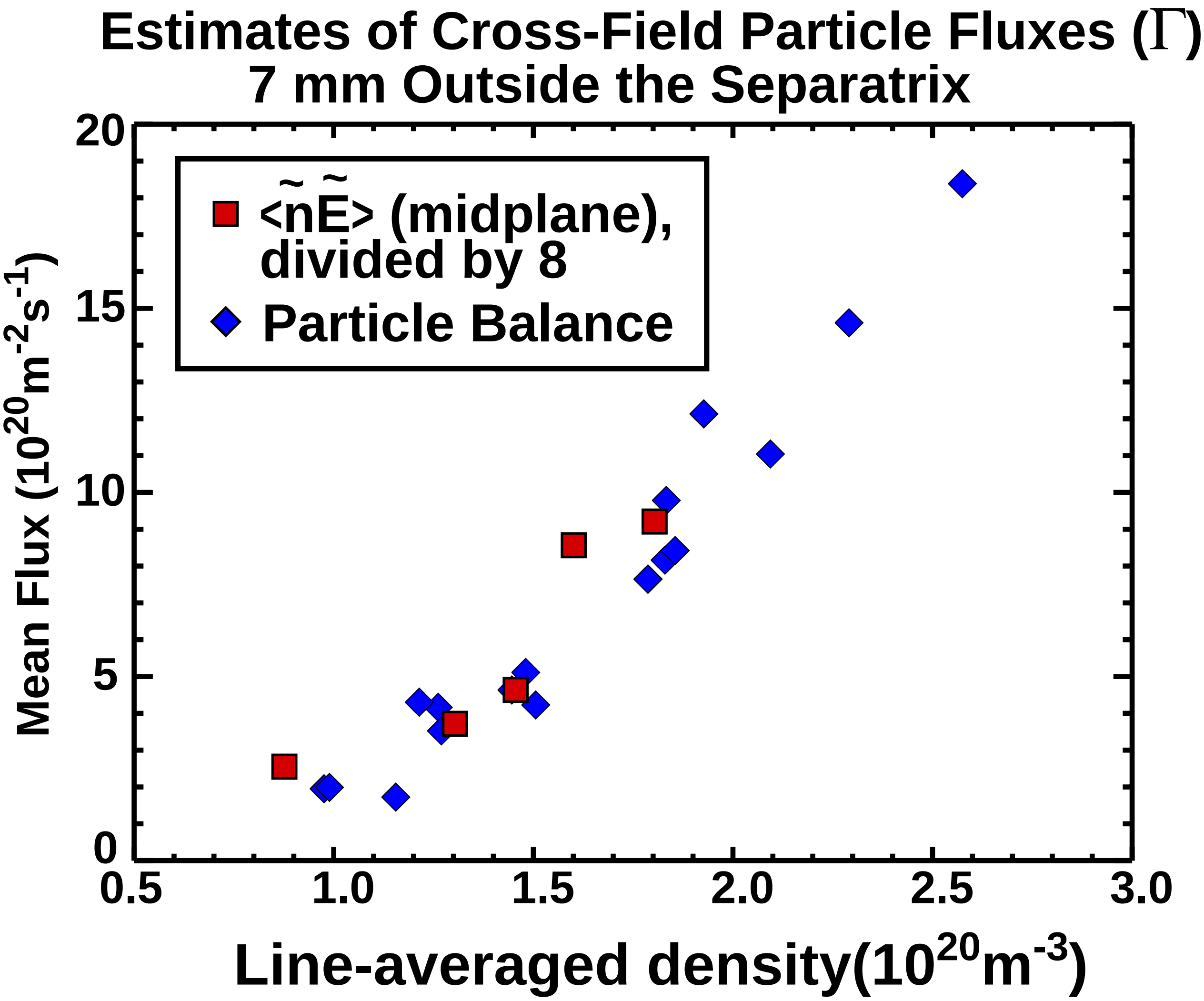
†Analysis by B. A. Carreras, V. E. Lynch.

††Bursty, SOC-like behavior of SOL plasma is universally seen in SOL plasmas including non-tokamak devices.

$\langle\tilde{n}\tilde{E}\rangle$ -Derived Cross-Field Flux Shows Similar Trend with $\bar{n}_e$ as Particle Balance-Derived Flux



$\langle\tilde{n}\tilde{E}\rangle$ - inferred Γ does not account for possible $\tilde{T}_e$

- Γ from both methods show similar trend, nonlinearly increasing with $\bar{n}_e$ †
- Magnitude of Γ inferred from Midplane Probe $\langle\tilde{n}\tilde{E}\rangle$ is a factor of ~8 times larger than that derived from particle balance

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† $\langle\tilde{n}\tilde{E}\rangle$ increasing with density seen before: ASDEX

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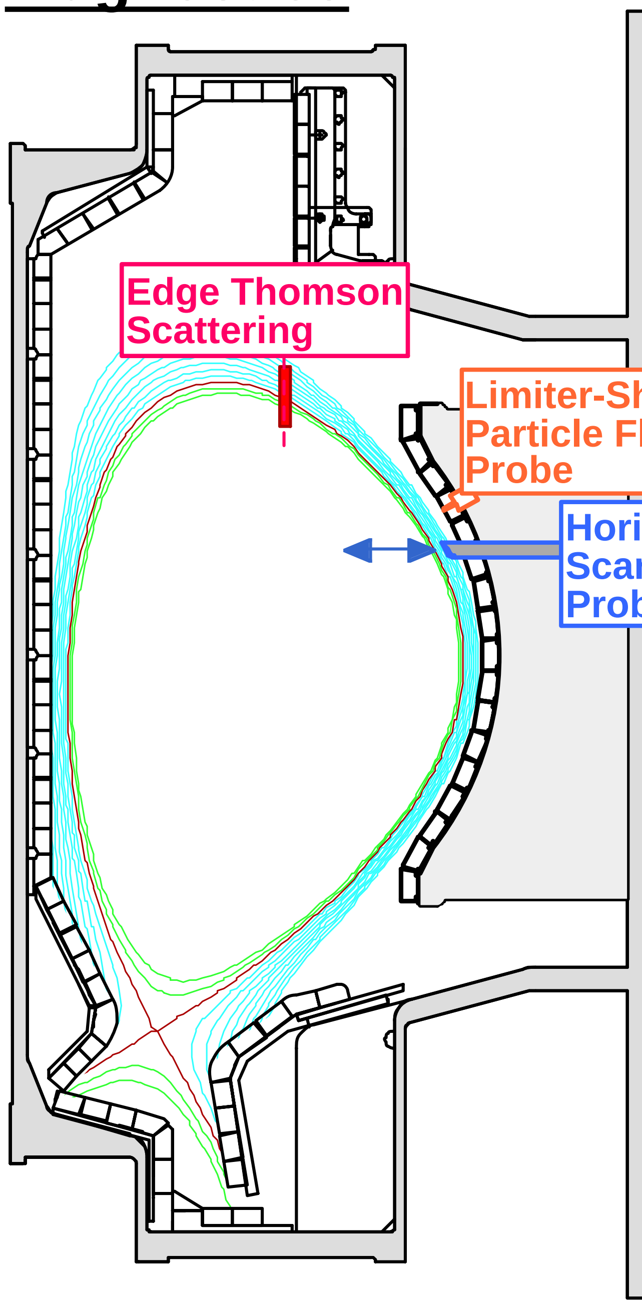
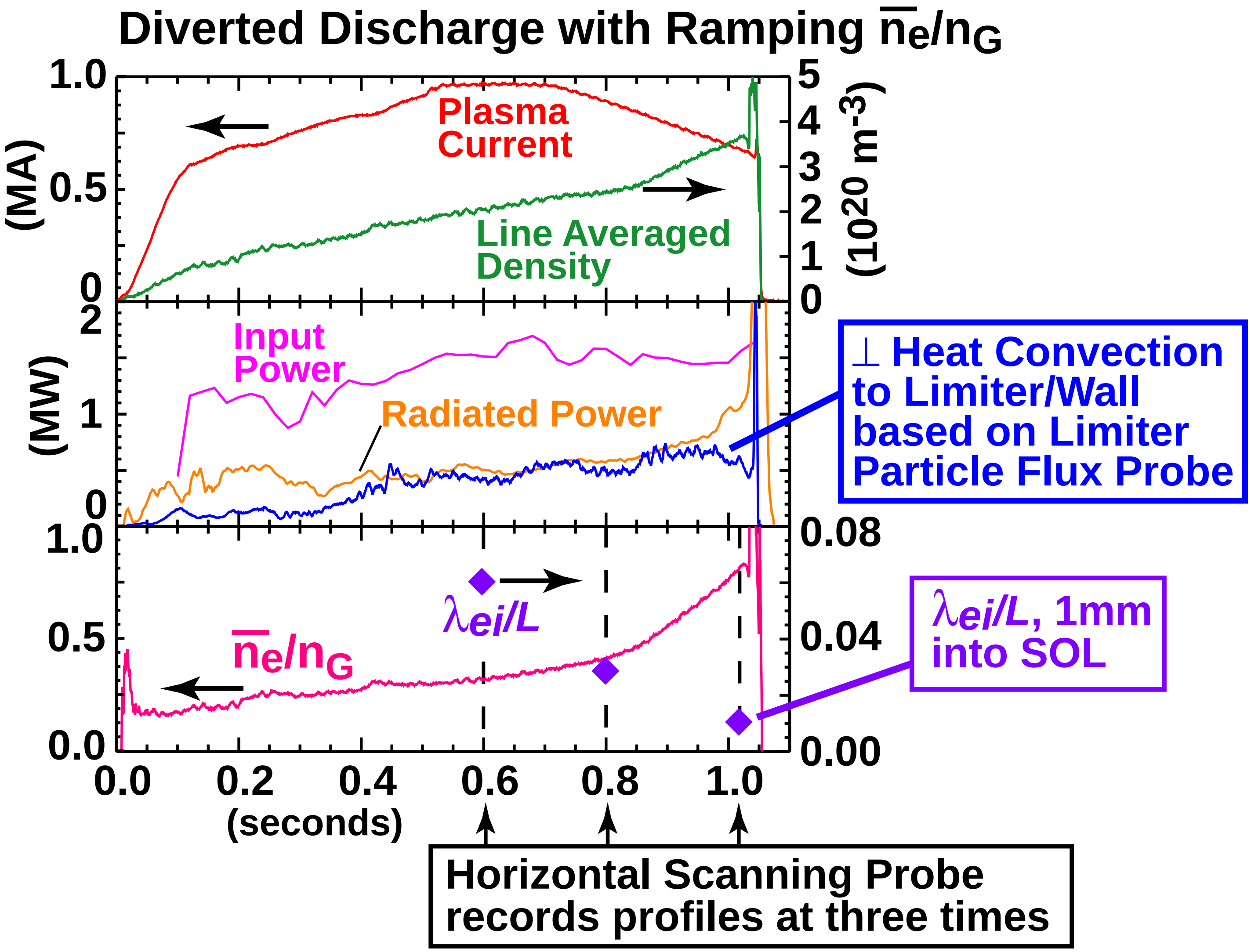
- **SOL Transport Physics and the Discharge Density Limit**

Diagnostics:



Collisionality at the Separatrix and ⊥ Heat Convection to Limiter/Wall Increases as Discharge Density Limit is Approached



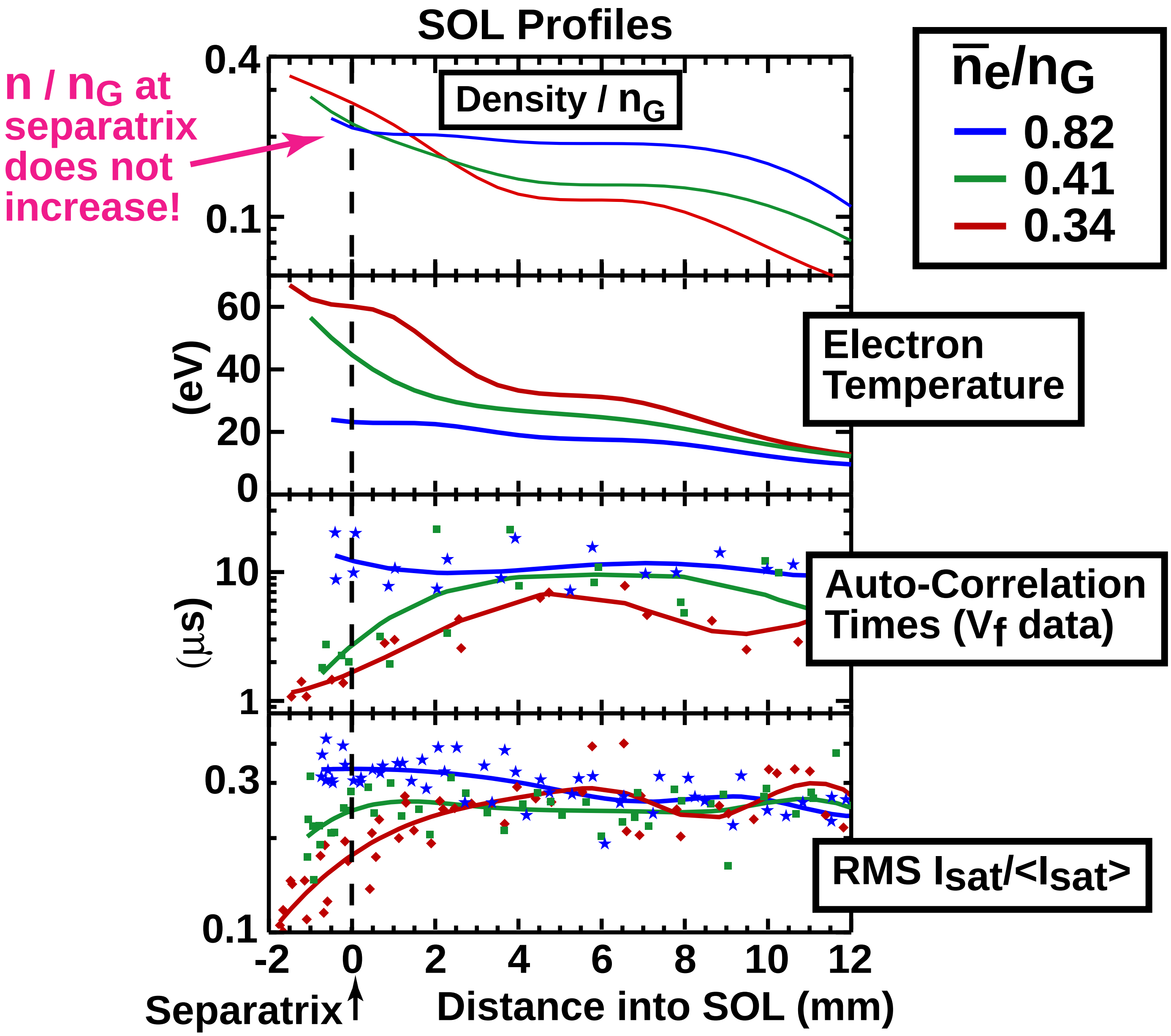
As density limit is approached:

- λ_{ei}/L near separatrix drops dramatically
- Radiation and ⊥ Convection to Limiter/Wall are comparable and mostly account for input power

Near density limit:

- Radiation + <u>⊥ Convection to Walls</u> ~ Input Power

Near Density Limit: Large Amplitude, Long-Correlation Time Fluctuations Envelop Entire SOL and Cross Separatrix

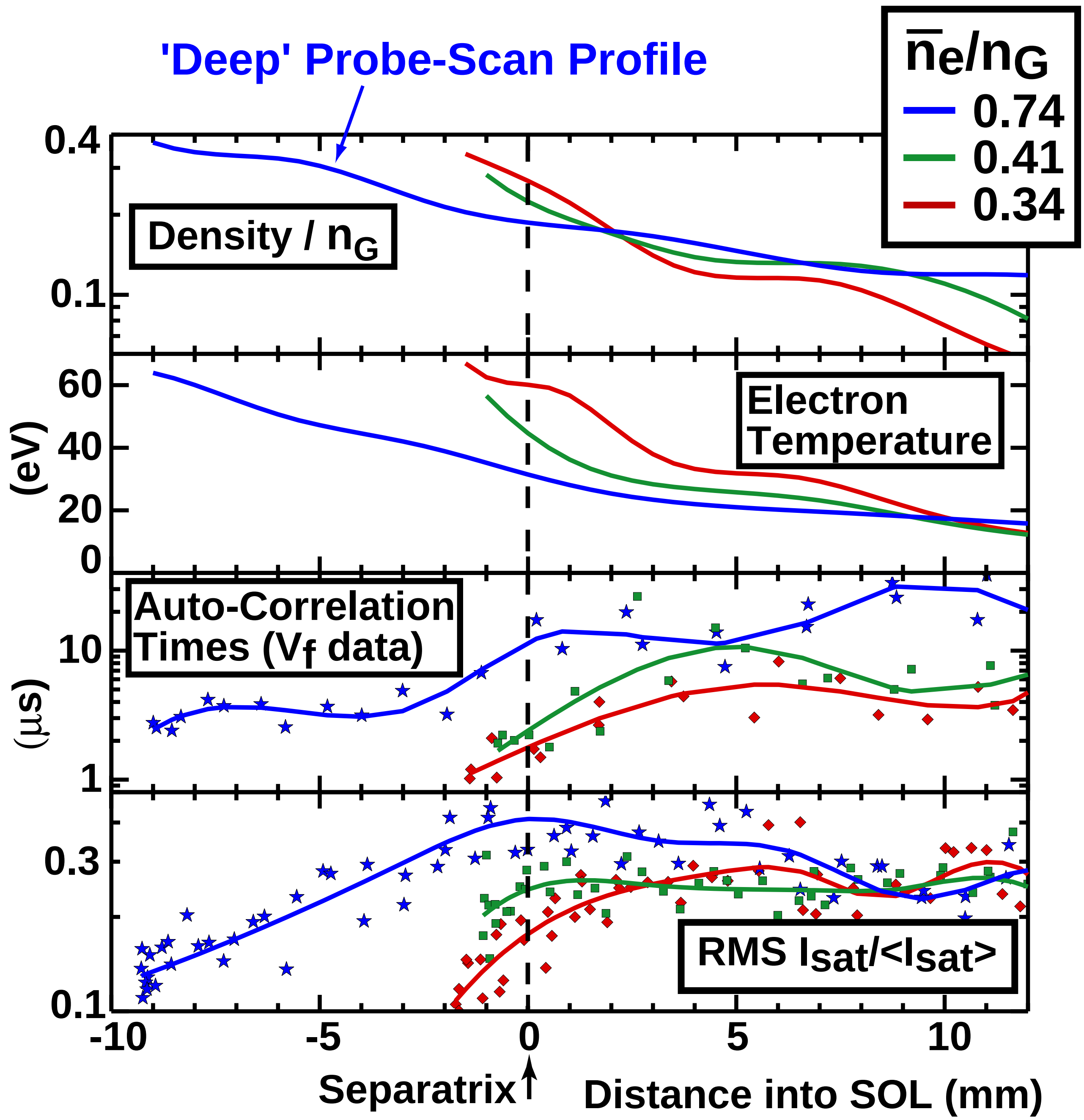


Near density limit:

- **SOL n & T_e profiles become flat, T_{sep} low ~ 25 eV!**
- **Fluctuations characteristic of "*Far SOL*" now occur everywhere, <u>even across the separatrix</u>**

=> Consistent with large ⊥ Convection Losses

Near Density Limit: 'SOL' Effectively Moves onto Closed Flux Surfaces

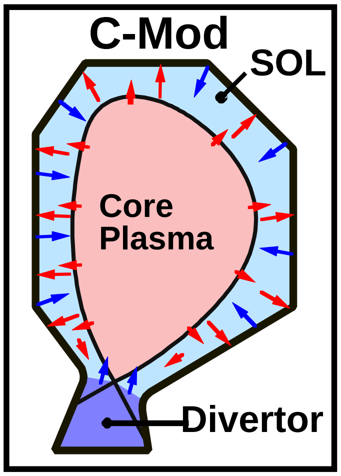


Near density limit:

- **Edge n & T_e profiles are apparently *not impacted by magnetic topology!* (open vs closed field lines)**

=> Consistent with ⊥ transport dominating particle and energy losses in edge plasma

Summary



- **SOL density profiles exhibit a "two-exponential" decay: *Near* and *Far SOL***
- **Yet, Main-chamber plasma exhausts primarily onto Limiter/Wall surfaces!**

- Why? -

=> New Particle Transport Paradigm:

- **Density "decays exponentially" because ... cross-field transport (D_{eff}) increases rapidly with distance into SOL**

  ... not because parallel flows "drain" SOL plasma

- **$\perp$ Particle (D_{eff}) and heat convection near separatrix *increases with collisionality*:**

$$D_{eff} \sim (\lambda_{ei}/L)^{-1.7}$$

=> Heat Transport Paradigm Modified:

- **At moderate collisionality ($\overline{n}_e/n_G \sim 0.5$), cross-field heat convection exceeds conduction losses**

  T_{sep} no longer regulated by "conduction law":

$$T_{sep} \propto (P_{sol}/\lambda_{Te})^{2/7}$$

Summary (page 2)

- Fluctuation behavior supports picture of particle & energy transport increasing with distance into SOL

Near SOL: (steep density profile) low amplitude "random" fluctuations

Far SOL: (flat density profile) large amplitude intermittent "bursts" in I_{sat} and ~ 1 cm "blobs" in D_{α}, extending into Limiter Shadow

=> Large cross-field velocites, > 100 m s^{-1}

- $\langle \tilde{n}\tilde{E} \rangle$ -derived cross-field flux (Γ) supports results inferred from particle balance:

  Γ similarly increases with $\bar{n}_e$

  Γ is factor of ~8 times larger than particle balance => supporting MCR conclusion

- Far SOL turbulence has some SOC-like characteristics (~generic to edge plasmas)

  PDF(Γ) has power-law tail (independent of $\bar{n}_e$)

Summary (page 3)

=> **New Insight on Density Limit Physics:**

- As density limit is approached, λ_{ei}/L near separatrix drops and transport across the SOL increases dramatically

  $\perp$ Heat Convection to Limiter/Wall becomes large fraction of input power

  "Bursty" fluctuations (large transport) occur over entire SOL and begins to attack plasma on closed flux surfaces

~ at limit:

Radiation + Convection to Wall ~ Input Power

Rapid increase of $\perp$ Heat Convection as edge plasma cools may play role in thermal instability leading to disruption

★ Need to develop scaleable empirical and physics-based understandings of underlying transport physics