SOL width decay lengths in NSTX

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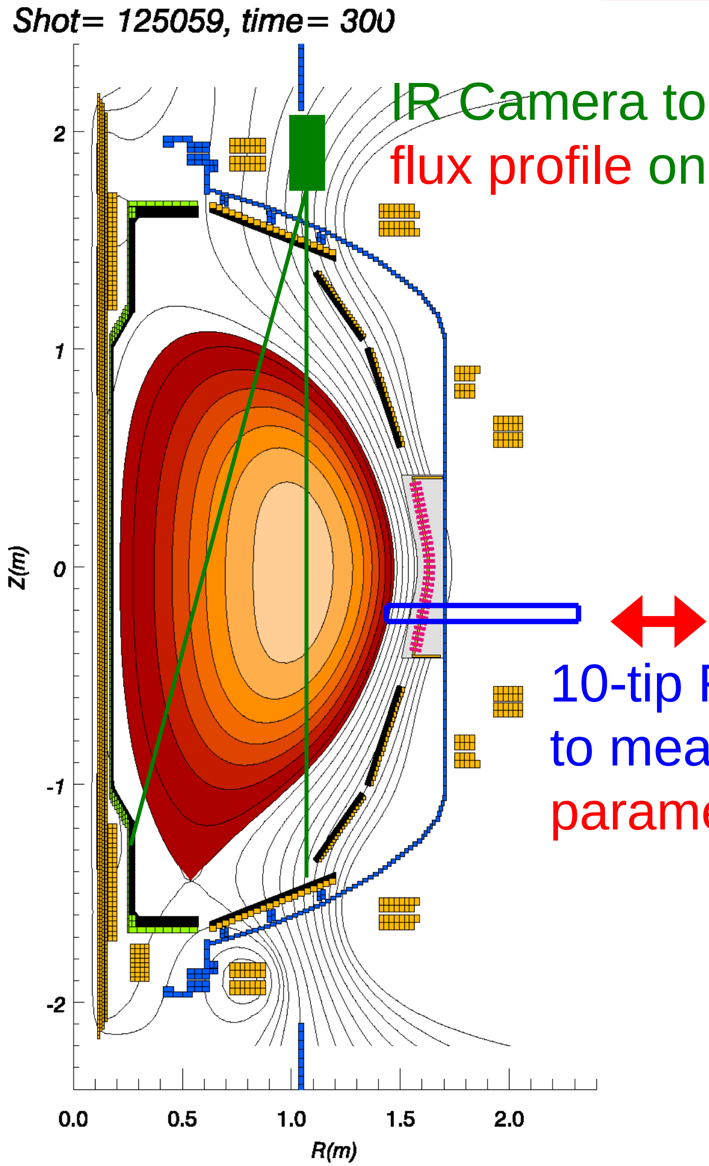
Analysis of SOL decay lengths in both near and far SOL regions

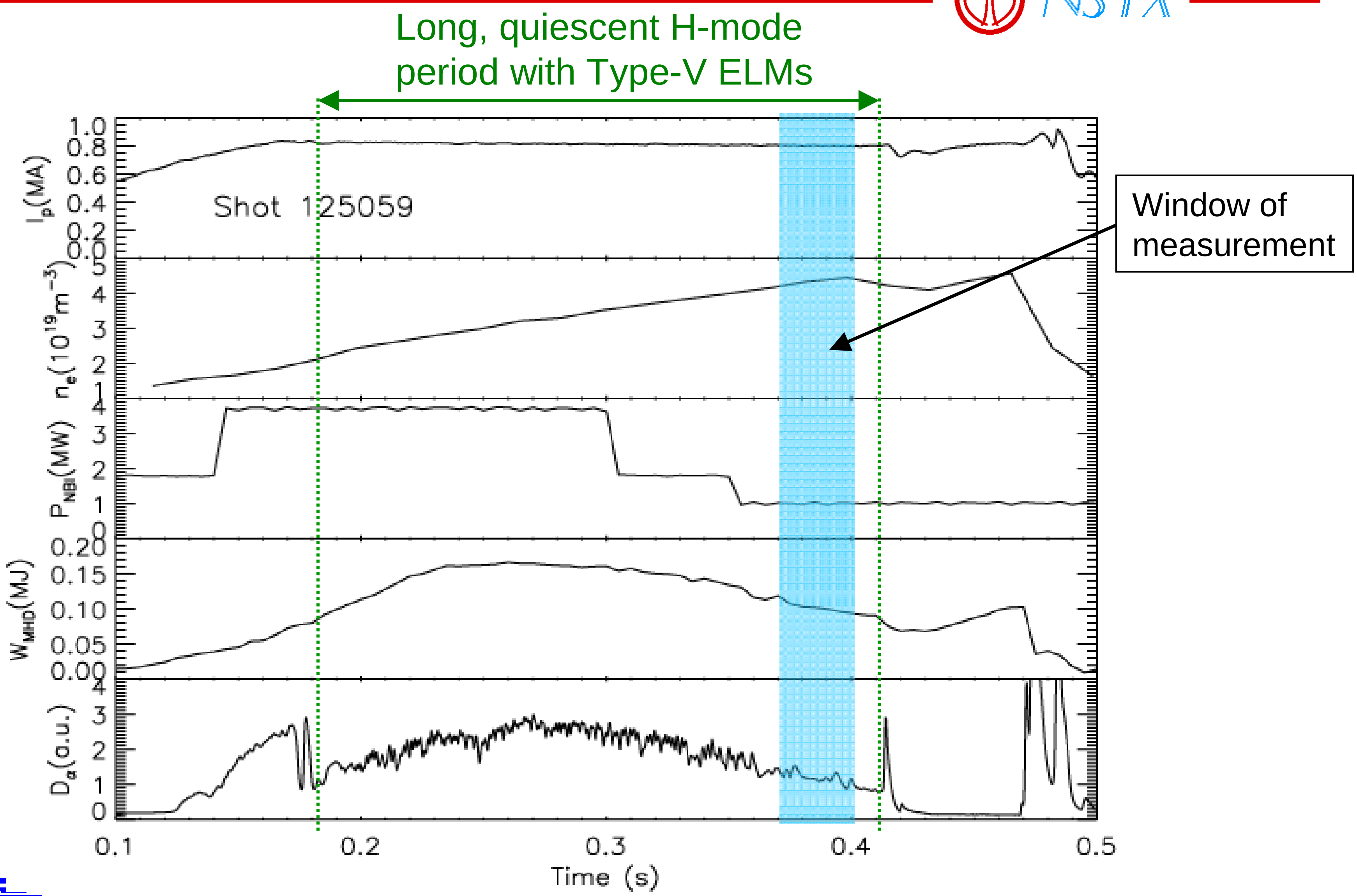
Poloidal cross-section of NSTX



IR Camera to measure heat flux profile on the lower tiles

10-tip Fast Reciprocating probe to measure upstream plasma parameter profiles (z = -18cm)

Time trace of discharge parameters



The sheath-limited regime

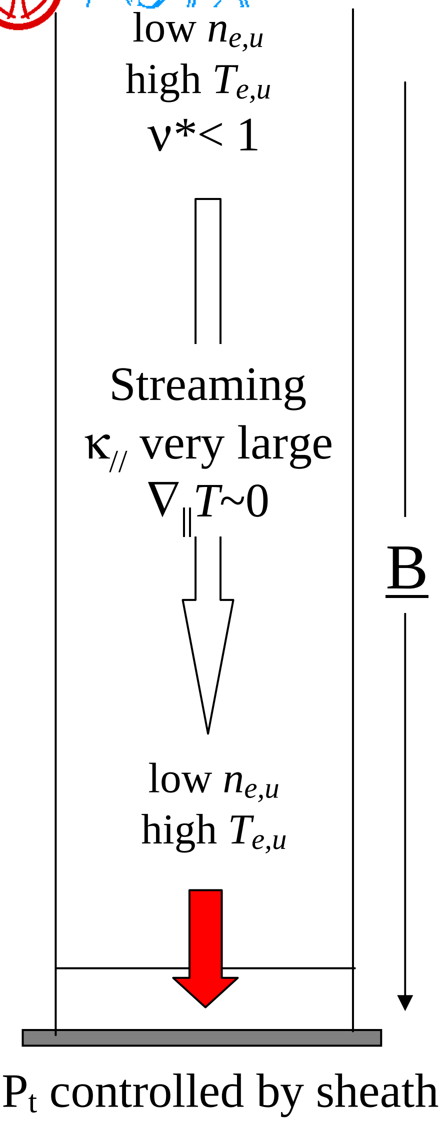
Consider low upstream density conditions -

- $n_{e,u}$ low $\Rightarrow$ upstream temperature $T_{e,u}$ high
- e^--e^- collisional mean free path, $\lambda_{ee} \propto T_e^2/n_e$ is long compared to distance along field lines to target, $L_{||}$

  $\Rightarrow$ low collisionality, $\nu^*(= L_{||}/\lambda_{ee}) < 1$
- Power carried along SOL by streaming

  $\Rightarrow$ heat conductivity $\kappa_{//}$ very large, small temperature gradients along SOL ($\nabla_{||}T$~0)
- Plasma pressure ($p \sim nk(T_e+T_i)+mnv^2$) constant along SOL ($\nabla_{||}p$~0)

  high $T_{e,u} \Rightarrow$ high target temperatures T_t
- Power to target, P_t, controlled by sheath



The conduction-limited regime

As upstream density rises -

- $n_{e,u}$ rises $\Rightarrow$ $T_{e,u}$ falls
- λ_{ee} shortens and $\nu^* >>1$
- Streaming replaced by e^- conduction

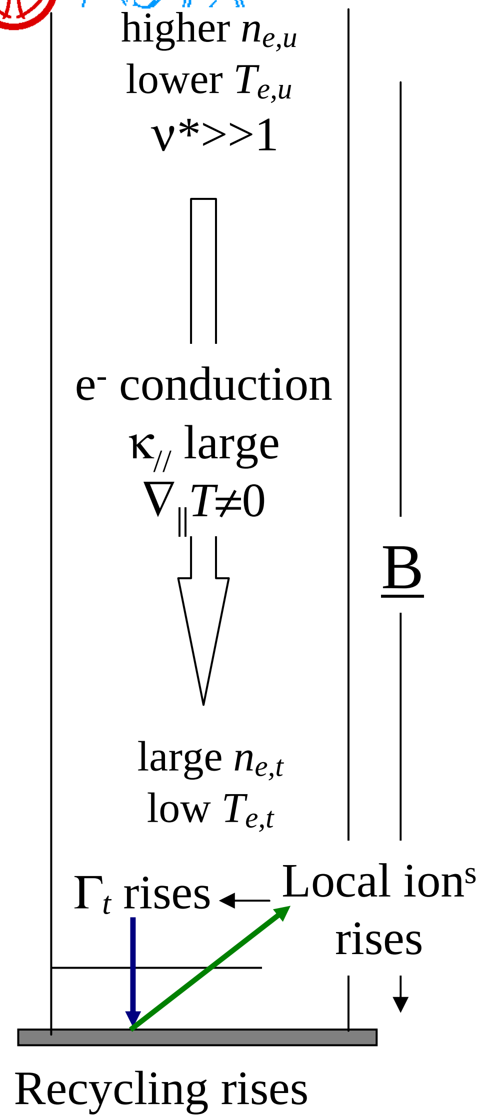
  $\Rightarrow$ heat conductivity $\kappa_{//}$ falls, temperature gradients develop along SOL ($\nabla_{||}T \neq 0$)

  $\Rightarrow$ T_t falls even more than $T_{e,u}$
- Plasma pressure still conserved $\nabla_{||}p \sim 0$

  $\Rightarrow$ n_t rises significantly, ionisation m.f.p. λ_{ion} falls
- Ion flux to target Γ_t rises

  $\Rightarrow$ recycling (release of neutrals by ion impact) increases
- λ_{ion} < scale length of SOL

  $\Rightarrow$ ionisation near target increases, further raising Γ_t



The detached regime

At still higher upstream density -

- T_t falls to ~5eV

  ⇒ local radiation losses dramatically increase

  ⇒ cools T_t still further, to ~1eV or less

- Ionisation front moves up to higher temperature region

  ⇒ ionisation near target falls

- Volume recombination begins close to target

  - further increasing the neutral density

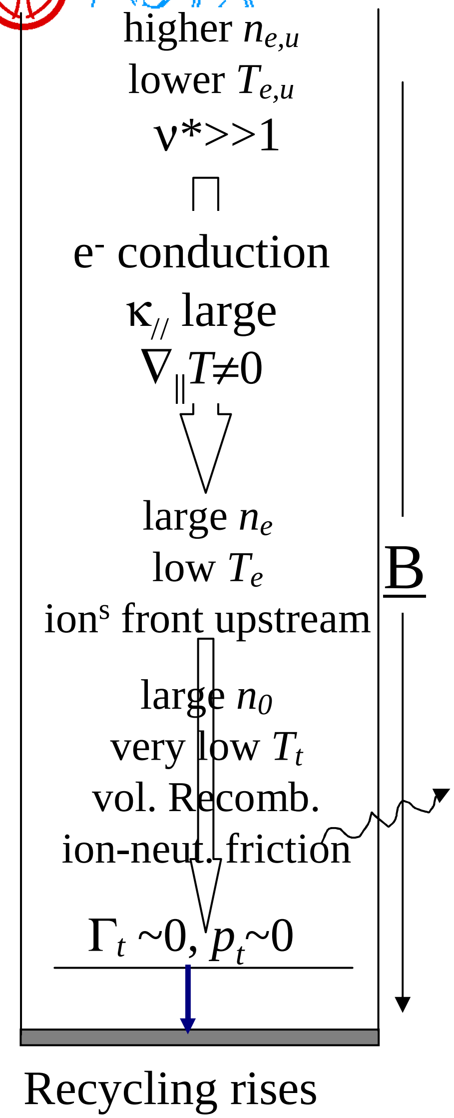
  - removing energy through neutral losses

- At high enough neutral densities

  - ion-neutral friction removes momentum from flowing ions

  ⇒ plasma pressure falls near target ($\nabla_{||}p \neq 0$), p_t~0

  ⇒ ion flux to target falls, Γ_t~0



The two-point model (2PM)

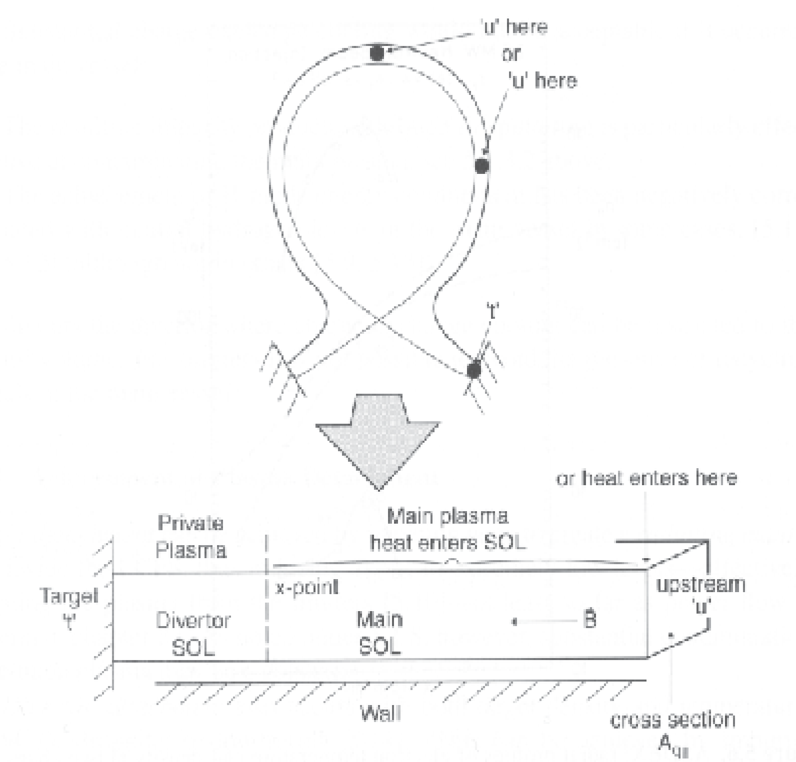


Figure from "The Plasma Boundary of Magnetic Fusion Devices", P.C.Stangeby, IoP Publishing (2000)

- 0D divertor model
- Simply relating upstream parameters ('u', $T_{e,u}$, $n_{e,u}$, etc) to the target ones ('t', $T_{e,t}$, $n_{e,t}$, etc)
- No attempt to model parallel variation of T_e, n_e

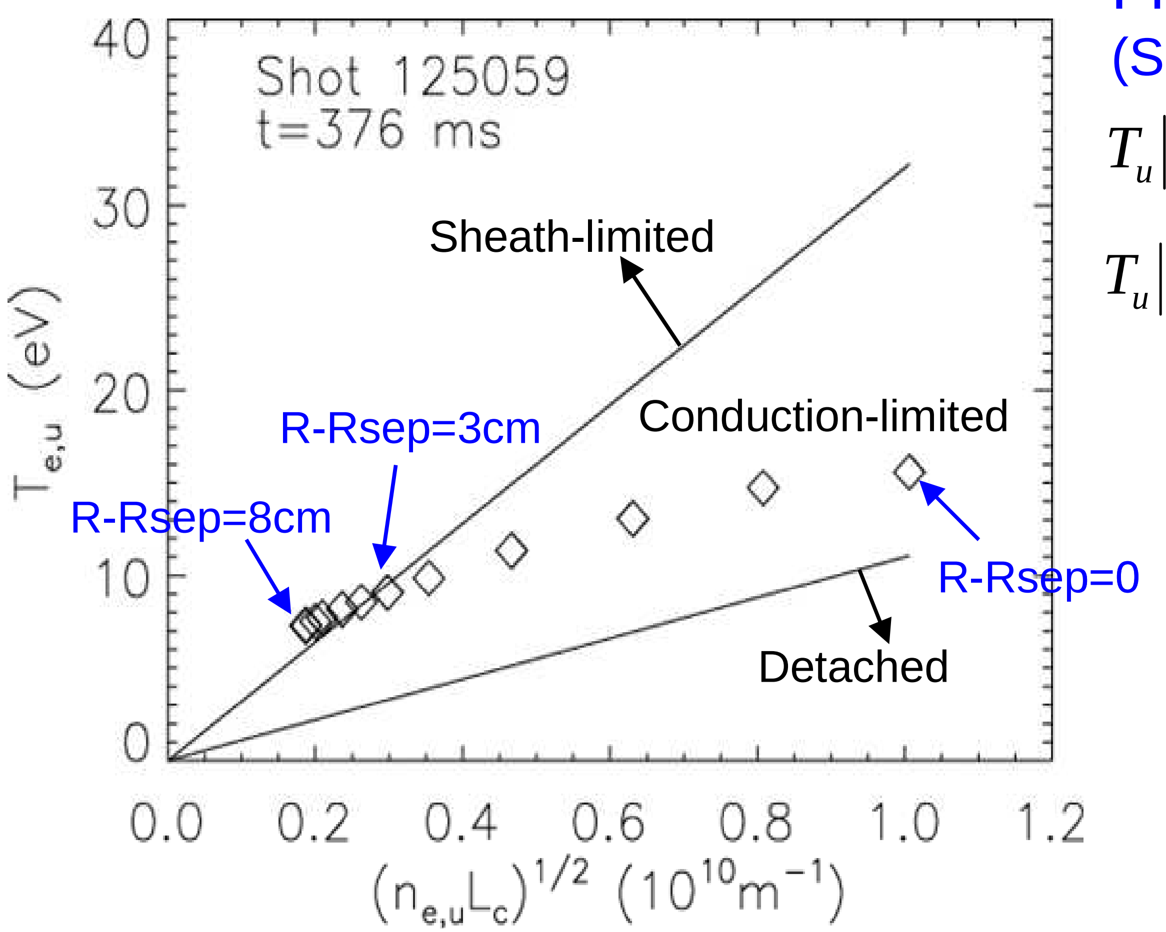
$$2n_t T_t = n_u T_u$$ Pressure balance

$$T_u^{7/2} = T_t^{7/2} + \frac{7}{2}\frac{q_\parallel L_c}{\kappa_{0e}}$$ Power balance

$$q_\parallel = \gamma n_t k T_t c_{st}$$ Power across the sheath

NSTX Near SOL in conduction-limited regime

SOL plasma regime judged from the upstream temperature and density, T_{eu} and n_{eu}, and the parallel connection length, L_c



From the 2PM analysis

(S.K.Erents, Nucl. Fusion 2000)

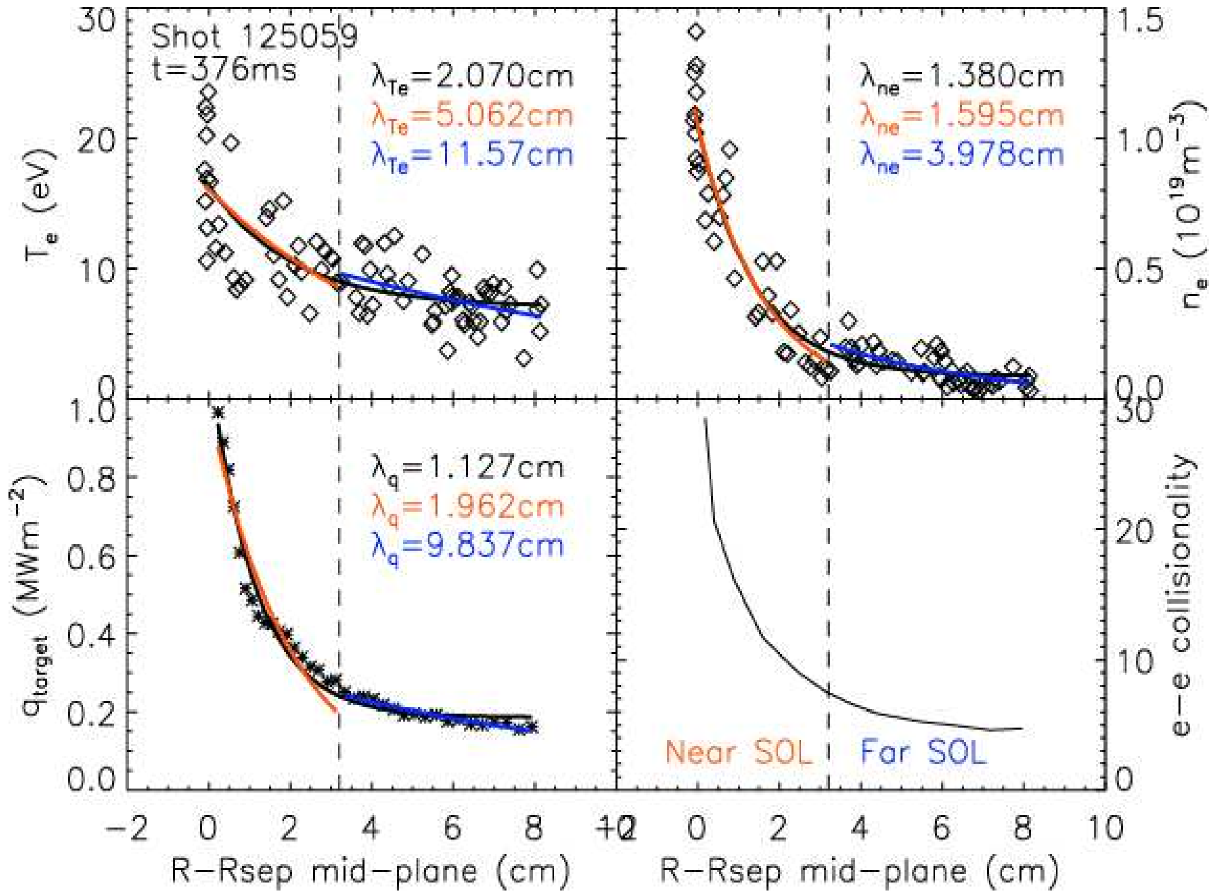
$$T_u\big|_{cond \Leftrightarrow sh} \approx 3.2\times10^{-9}\left(n_u L_c\right)^{1/2}$$

$$T_u\big|_{cond \Leftrightarrow \det} \approx 1.1\times10^{-9}\left(n_u L_c\right)^{1/2}$$

Near SOL (R-Rsep ≤ 3cm)
conduction-limited regime

Far SOL (R-Rsep ≥ 3cm)
sheath-limited regime

NSTX SOL parameter profiles



- T_e, n_e, and v^*_{ee} : probe measurement
- q_{target} : IR meausrement
- All profiles mapped to the mid-plane

—— Offset exponential fitting to the whole profile

—— Simple exponential fitting to the near SOL profile

—— Simple exponential fitting to the far SOL profile

Conventional λ_{Te}/λ_q ratio in conduction-limited regime

Assume || electron conduction dominates the SOL transport

$$q_{\parallel} \approx q_{\parallel}^{e} = -\kappa_0 T_e^{5/2} \frac{dT_e}{ds_{\parallel}}$$

Electron heat conduction equation

$$T_e \sim \left(\frac{7}{2} \frac{q_{\parallel} L_c}{\kappa_0} \right)^{2/7}$$

If there exists significant $\nabla_{\parallel} T_e$

Assume simple exponential profiles

$$T_e = T_{e0} \exp\left(-\frac{R - R_{sep}}{\lambda_{Te}} \right)$$

$$q_{target} = q_0 \exp\left(-\frac{R - R_{sep}}{\lambda_q} \right)$$

$$\lambda_{Te} = \frac{7}{2} \lambda_q$$

The observed λ_{Te}/λ_q ratio for the whole profile is not 7/2

NSTX

Observation

Profiles follow approximately offset exponential function

Use $a = a_1 + a_0 \exp\left(-\frac{R - R_{sep}}{\lambda_a}\right)$

to fit T_e and q_{target} profiles

$\lambda_{Te}/\lambda_q \sim 1.8$

↔

Conventional prediction

$\lambda_{Te}/\lambda_q = 7/2$

is expected for conduction-limited regime from 2PM

λ_{Te}/λ_q ratio for the near SOL is closer to 7/2

NSTX

Observation

The near SOL ($0 \leq R-R_{sep} \leq 3$cm) is expected to be dominated by conduction, thus in the conduction-limited regime

Use simple exponential

$$a = a_0 \exp\left(-\frac{R - R_{sep}}{\lambda_a}\right)$$

to fit T_e and q_{target} profiles

$\lambda_{Te}/\lambda_q \sim 2.6$

↔

Conventional prediction

$\lambda_{Te}/\lambda_q = 7/2$ is expected for conduction-limited regime from 2PM

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Offset exponential function put in the conduction equation

Assume || electron conduction dominates the SOL transport

$$q_{||} \approx q_{||}^{e} = -\kappa_0 T_e^{5/2} \frac{dT_e}{ds_{||}}$$

Electron heat conduction equation

$$T_e \sim \left(\frac{7}{2} \frac{q_{||} L_c}{\kappa_0} \right)^{2/7}$$

If there exists significant $\nabla_{||} T_e$

Assume offset exponential profiles

$$T_e = T_{e1} + T_{e0} \exp\left(-\frac{R - R_{sep}}{\lambda_{Te}} \right)$$

$$q_{target} = q_1 + q_0 \exp\left(-\frac{R - R_{sep}}{\lambda_q} \right)$$

$$\lambda_{Te} = \frac{7}{2} \lambda_q \left(\frac{T_e - T_{e1}}{T_e - C q_1 T_e^{-5/2}} \right)$$

where, $C = \frac{7}{2} \frac{L_c}{\kappa_0}$

Additional λ_{Te}/λ_q ratio factor well matches experiment

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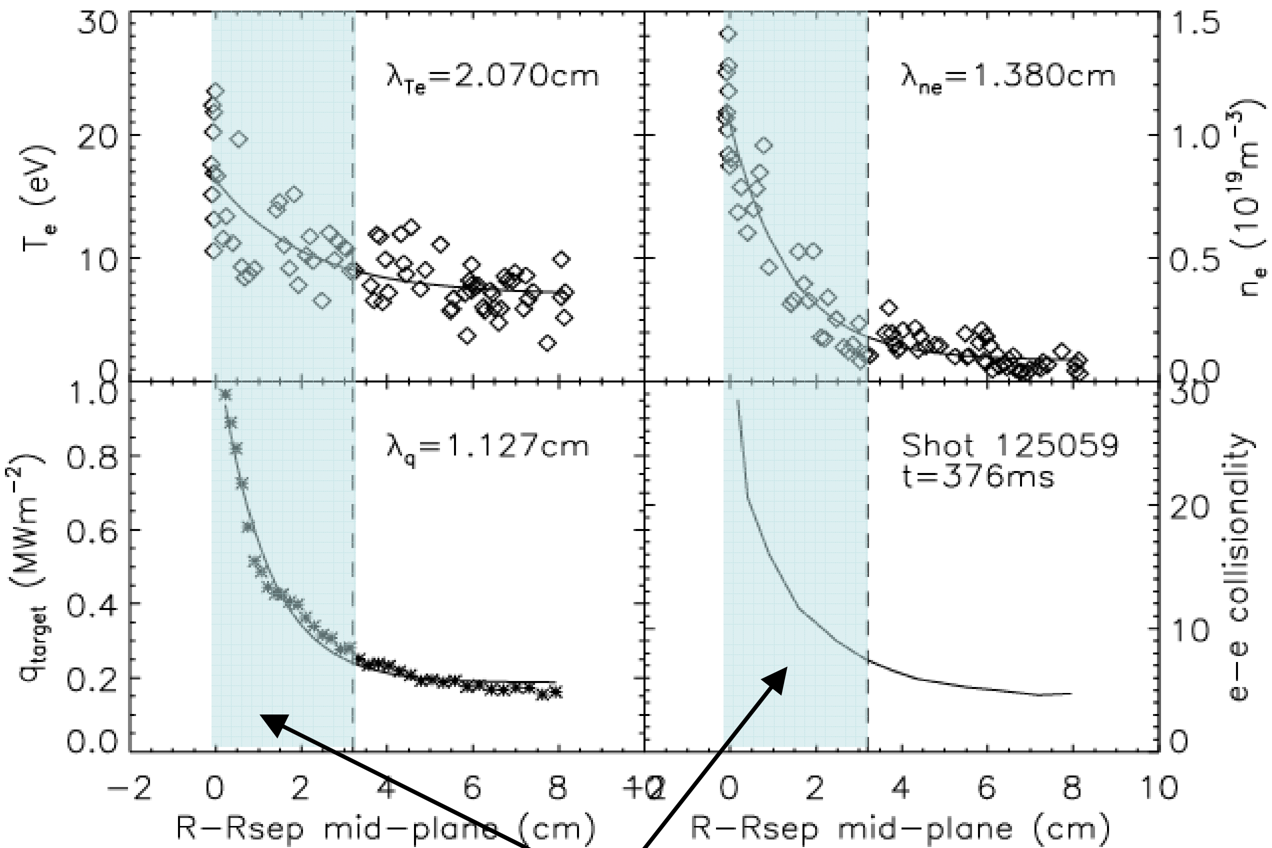
Profiles fitted to the offset exponential function



Observation

λ_{Te}/λ_q=1.84

Prediction

$$\left(\frac{T_e - T_{e1}}{T_e - Cq_1T_e^{-5/2}}\right) = 0.63$$

λ_{Te}/λ_q=2.21

Additional factor, $\left(\frac{T_e - T_{e1}}{T_e - Cq_1T_e^{-5/2}}\right)$, tested in the near SOL

Conventional λ_{Te}/λ_q ratio in sheath-limited regime

Electron energy balance equation

$$L_c \frac{d}{dr}\left[n\chi_\perp \frac{d(kT_e)}{dr} + \frac{5}{2} kT_e D_\perp \frac{dn}{dr} \right] = \frac{1}{2} n c_s \gamma_s^e kT_e$$

Power flow into the SOL

Power reaching target through the sheath

Assume simple exponential profiles

$$T_e = T_{e0} \exp\left(-\frac{R - R_{sep}}{\lambda_{Te}} \right) \qquad q_{target} = q_0 \exp\left(-\frac{R - R_{sep}}{\lambda_q} \right)$$

$$\frac{1}{\lambda_q} = \frac{1}{\lambda_n} + \frac{3}{2\lambda_{Te}}$$

λ_{Te}/λ_q ratio for the far SOL is far from prediction

NSTX

Observation

The far SOL ($R-R_{sep} \geq$ 3cm) is expected to be in the sheath-limited regime from the conventional categorization

Use simple exponential

$$a = a_0 \exp\left(-\frac{R-R_{sep}}{\lambda_a}\right)$$

to fit T_e and q_{target} profiles

λ_q = 10cm

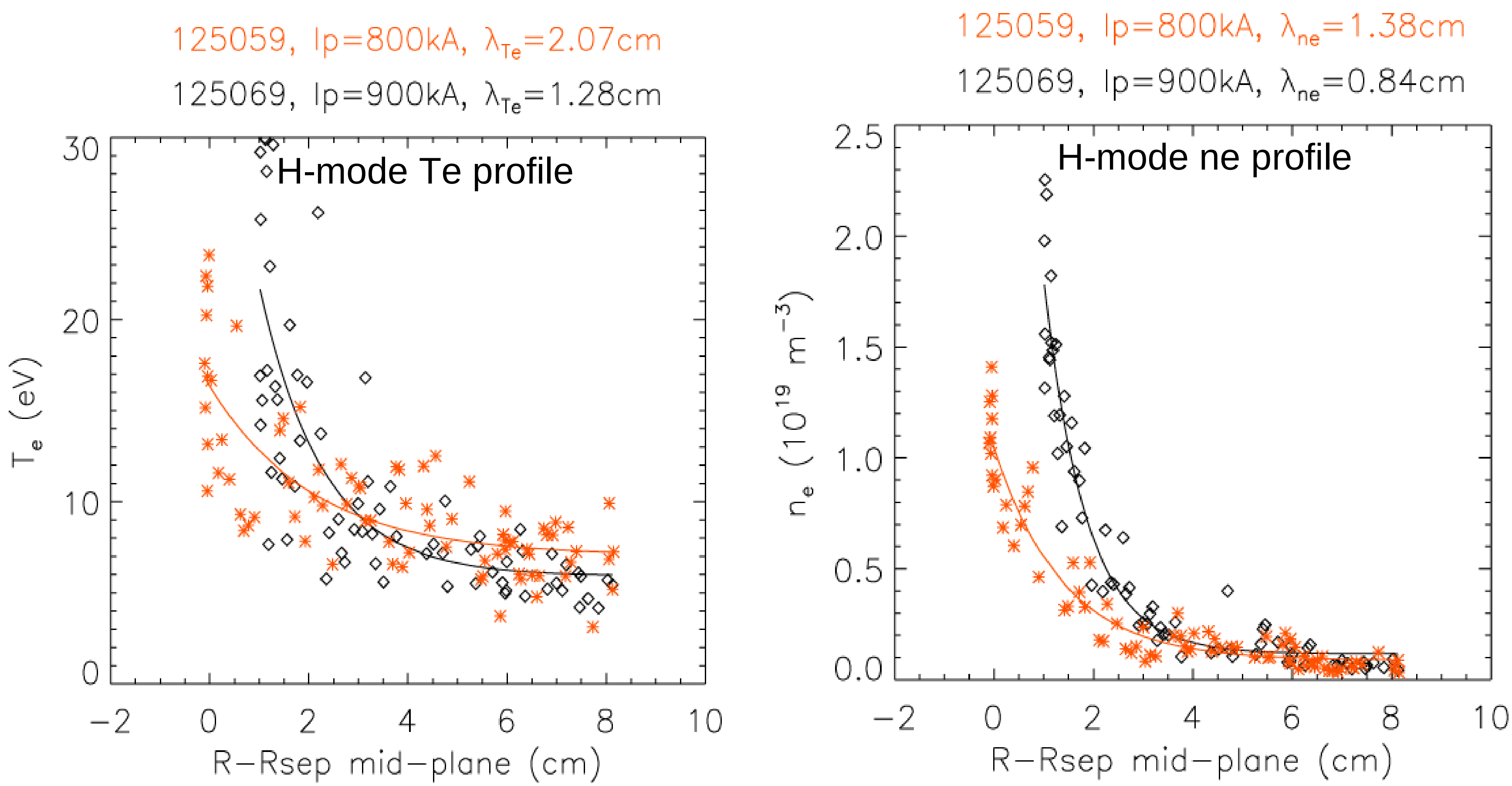
↔

Conventional prediction

λ_q = 2.6cm is expected for sheath-limited regime from 2PM

SOL decay length dependence on plasma conditions

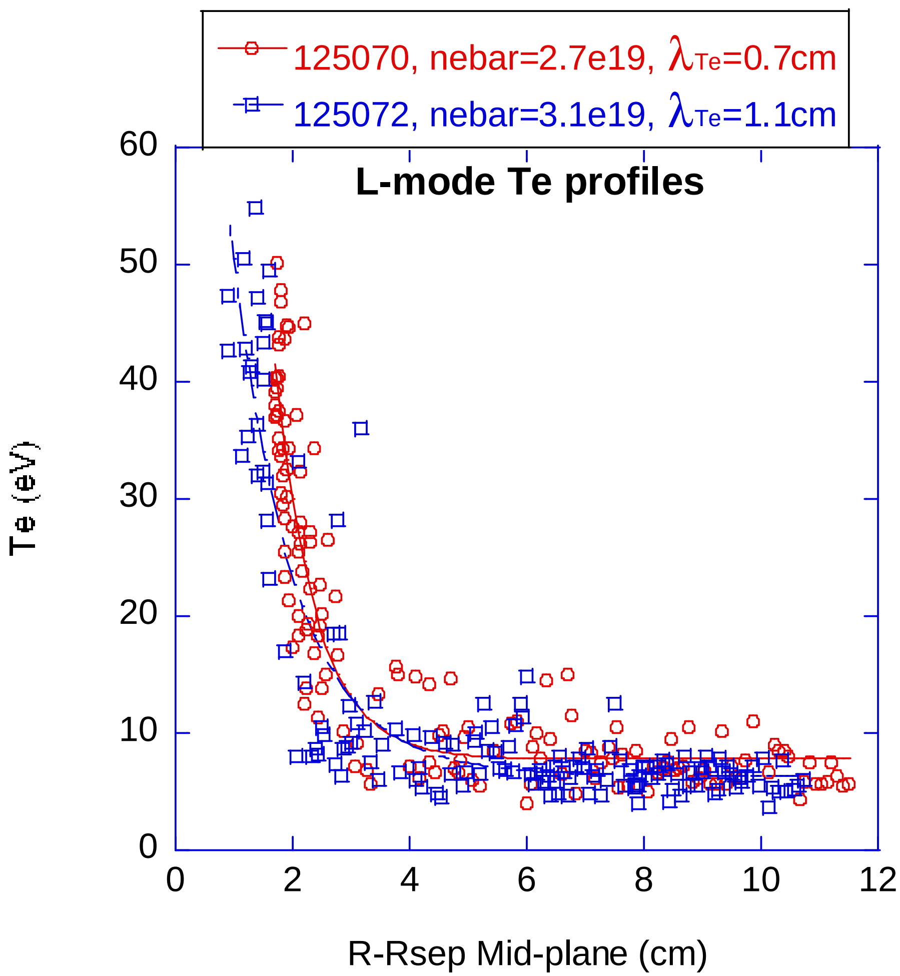
SOL width decreases with increasing I_p

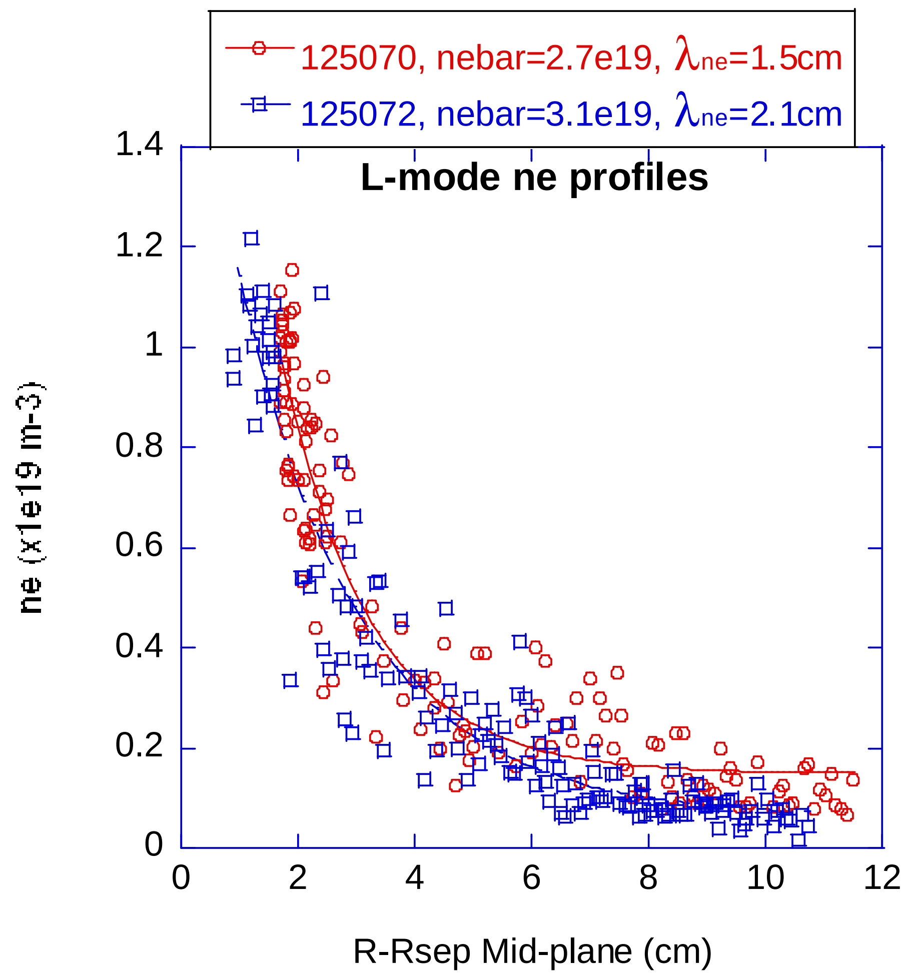


nebar = 4.0 (x10^{19} m^{-3})
P_{NBI} = 1MW

Conventional SOL width scaling laws do not address I_p dependence

SOL width increases with increasing density



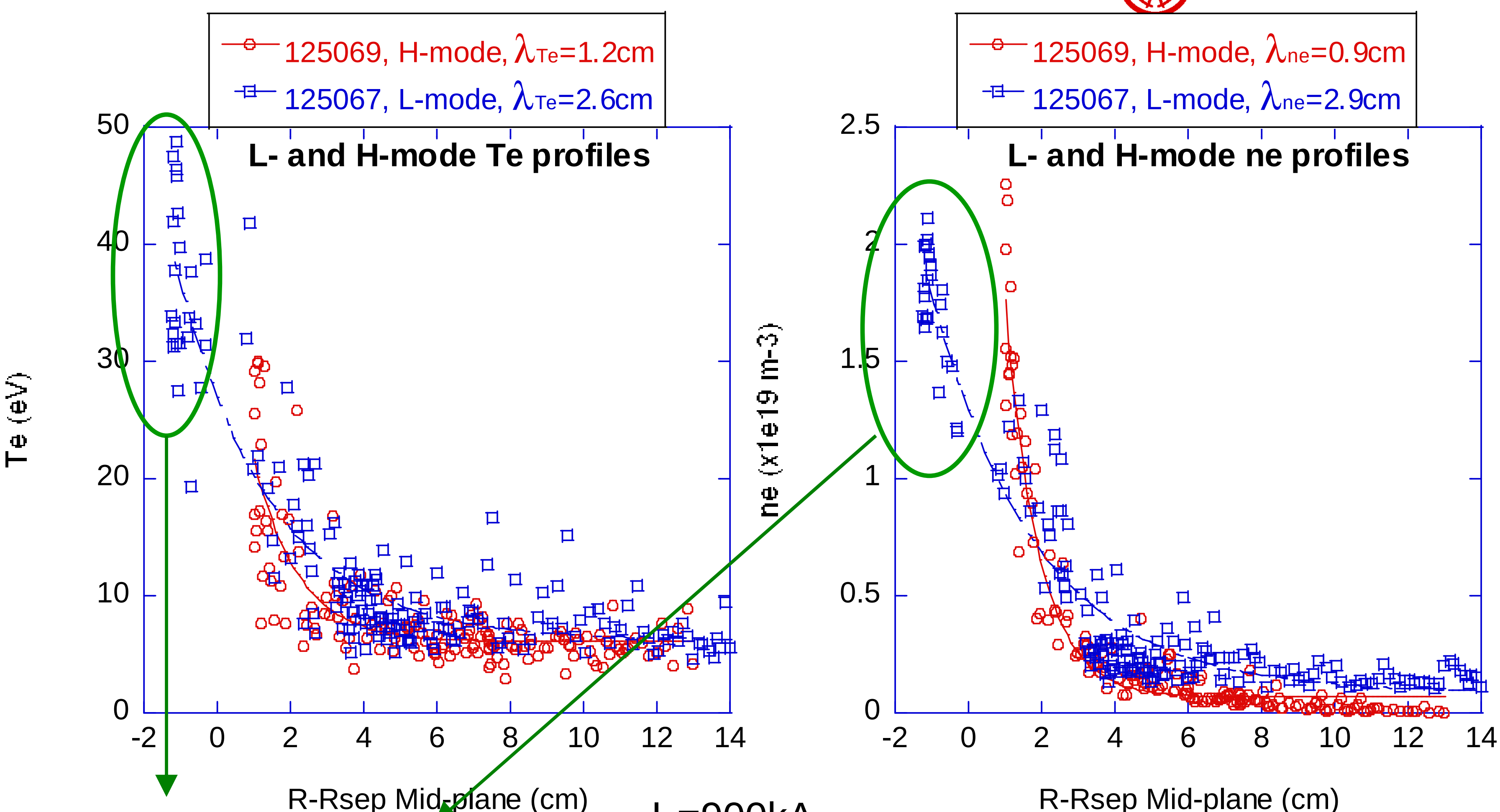


I_p=700kA

P_{NBI}=1MW

This result is consistent with conventional scaling laws

H-mode has narrower SOL width than L-mode



Probe was plunged past the separatrix!!

I_p=900kA
P_{NBI}=1MW
nebar=4.0 ($\times 10^{19}$ m^{-3})

Summary

NSTX

1. NSTX near SOL is in the conduction-limited regime and the transport is dominated by parallel electron conduction
2. NSTX far SOL is in the sheath-limited regime and does not follow classical transport processes
3. NSTX SOL plasma profiles have offset values in the far SOL and offset exponential function can be used to re-evaluate the relation between T_e and heat flux decay lengths (λ_{Te} and λ_q) in the near SOL
   the additional ratio factor better reproduces the experimental results
4. Dependences of near SOL width on plasma parameters have been confirmed ($I_p \uparrow$ $\lambda_{Te,ne,q} \downarrow$, $n_e \uparrow$ $\lambda_{Te,ne,q} \uparrow$)
   H-mode SOL width is narrower than in L-mode

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