Far SOL transport and main wall plasma interaction in DIII-D

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for the

DIII-D Team

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Outline

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Motivation

- Plasma interaction with the first wall is of critical importance to ITER and future power reactors.
- Far Scrape-off Layer (SOL) density profiles are often relatively flat and extend all the way to the outer wall.
- Fast edge diagnostics and turbulence simulation codes show the existence of intermittent coherent structures born near the LCFS and propagating radially towards the wall.
- If the intermittent structures reach the outer wall, they may cause erosion above the level expected from time-averaged SOL plasma parameters.
- Increased particle and heat cross-field fluxes during Edge Localized Modes (ELMs) may reach the outer wall and cause extra damage.

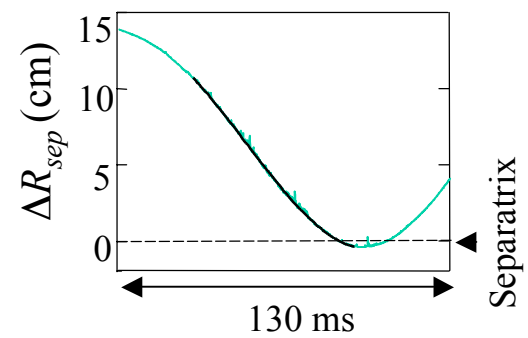
- Langmuir probes with their high spatial and temporal resolution provide an excellent diagnostic tool for far SOL plasma studies.
- A large database accumulated by the two plunging probe arrays on DIII-D contains plenty of far SOL and near-wall data yet to be analyzed.

Experimental setup

Mid-plane Reciprocating Probe Array

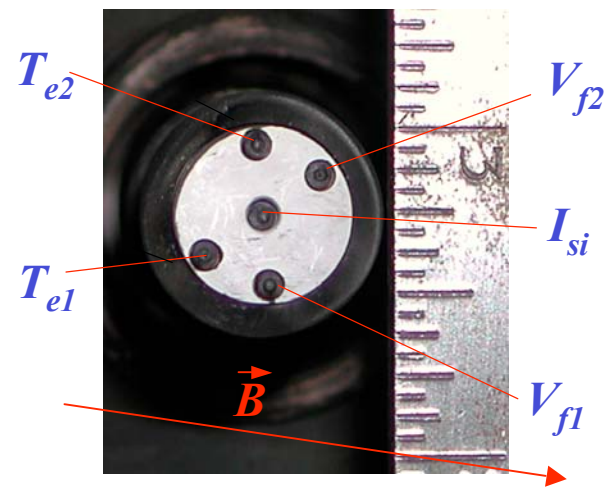
- The in-and-out plunge time is about 0.2 s
- The plunge length is about 15 cm
- On time scale < 1 ms probe can be considered stationary
- Spatial resolution: ~ 2 mm
- Temporal resolution: 1 μs (I_{sat} and V_f)
  10 μs (T_e)

Position trace of a probe plunge



- Measured parameters: I_{sat} T_e V_f
- Derived parameters: n_e V_p E_θ $\Gamma_\perp$ $Q_\perp$

Probe head layout

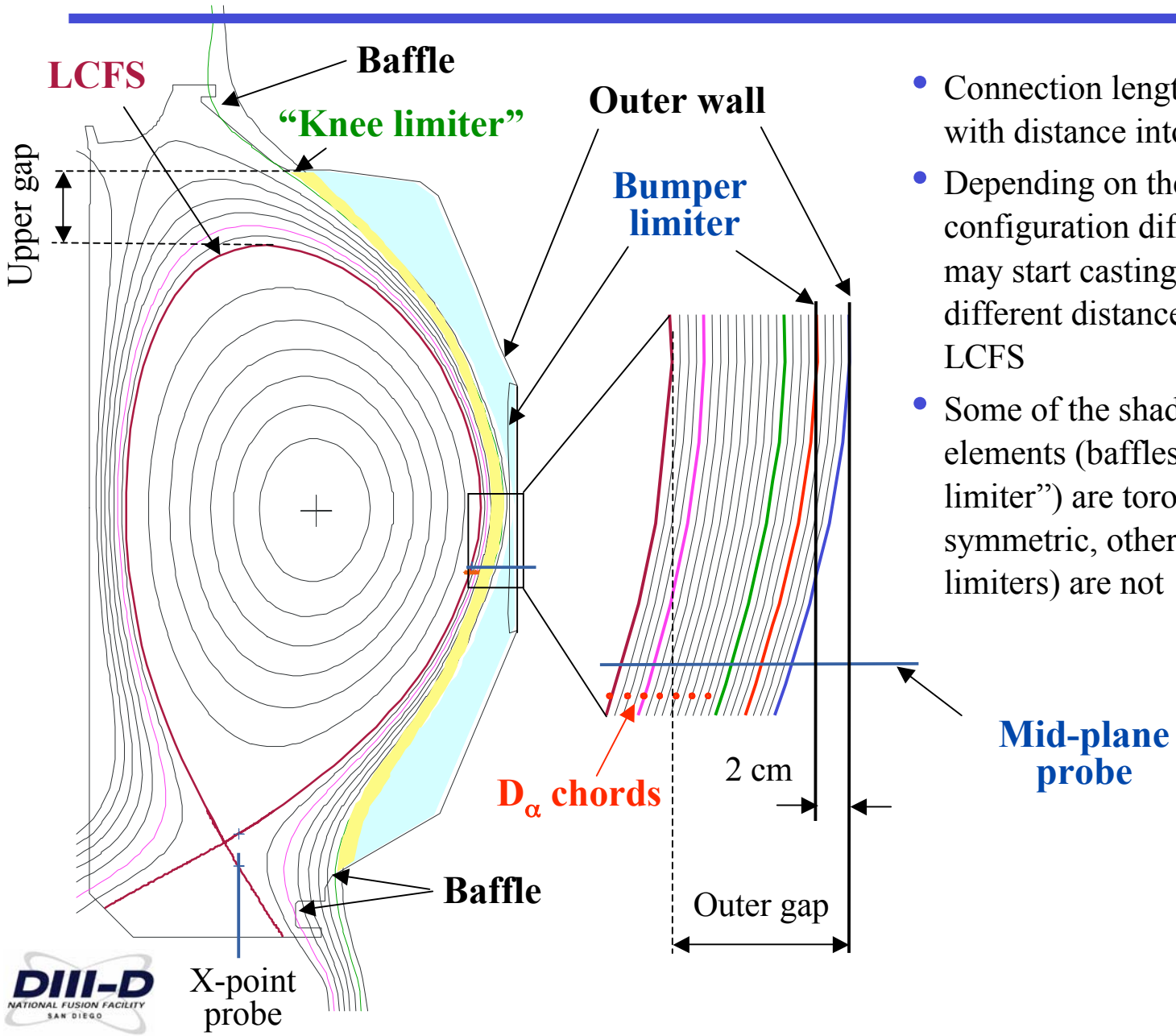


Turbulent particle flux: $\Gamma_r^{ES} = \frac{1}{B_\varphi} n_e \tilde{E}_\theta$

Turbulent heat flux: $Q_r^{ES} = \frac{3}{2B_\varphi} n_e k T_e \tilde{E}_\theta$

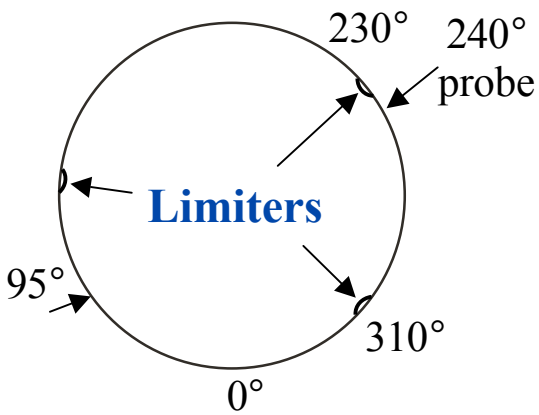
- Minimum resolved values: I_{sat} ~ 1 mA, $n_e \sim 10^{11}$ cm^{-3}, T_e ~ 3 eV

Shadow-casting elements of DIII-D vessel

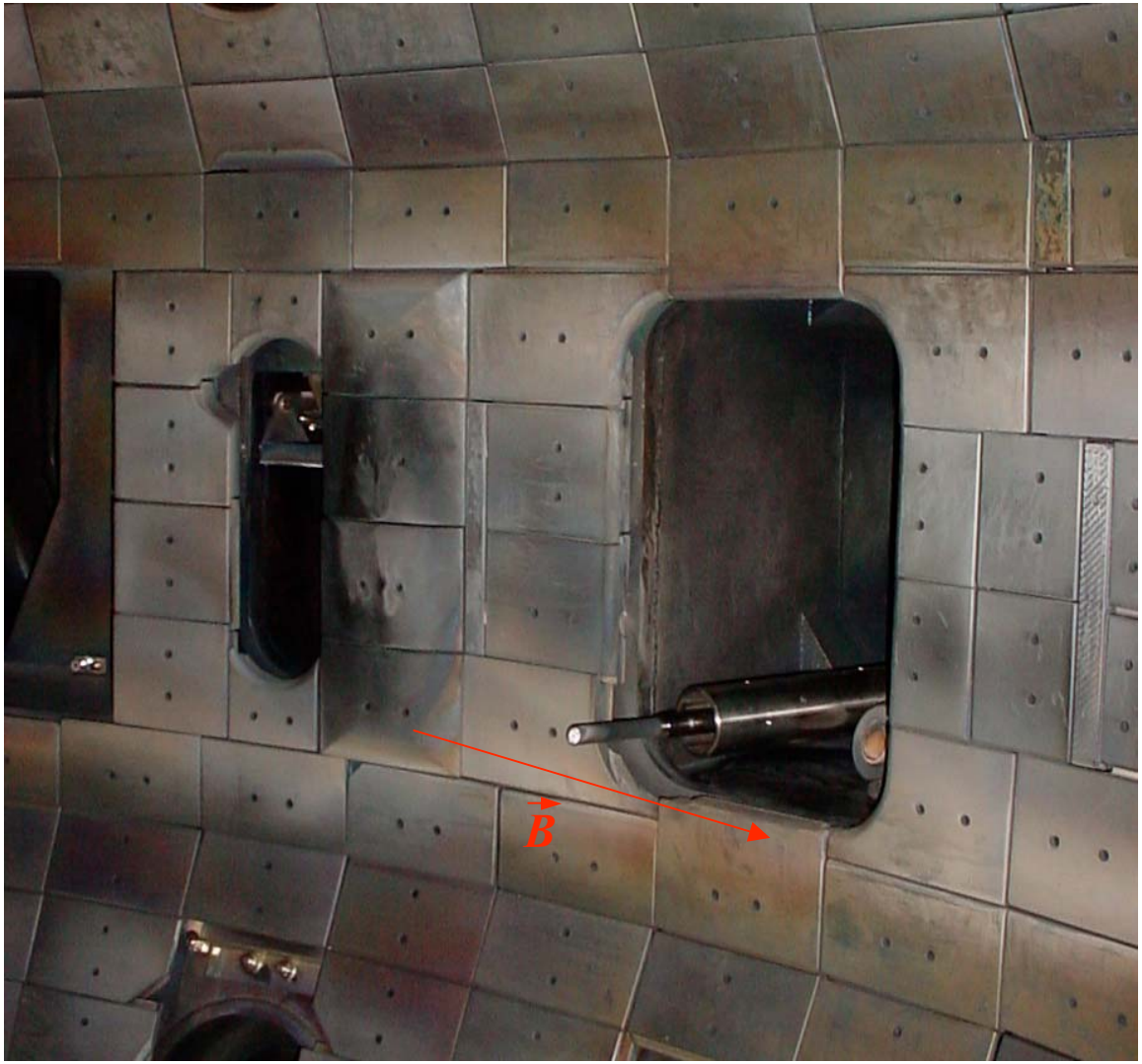


- Connection length decreases with distance into the SOL
- Depending on the magnetic configuration different elements may start casting shadow at different distances from the LCFS
- Some of the shadow casting elements (baffles, "knee limiter") are toroidally symmetric, others (bumper limiters) are not

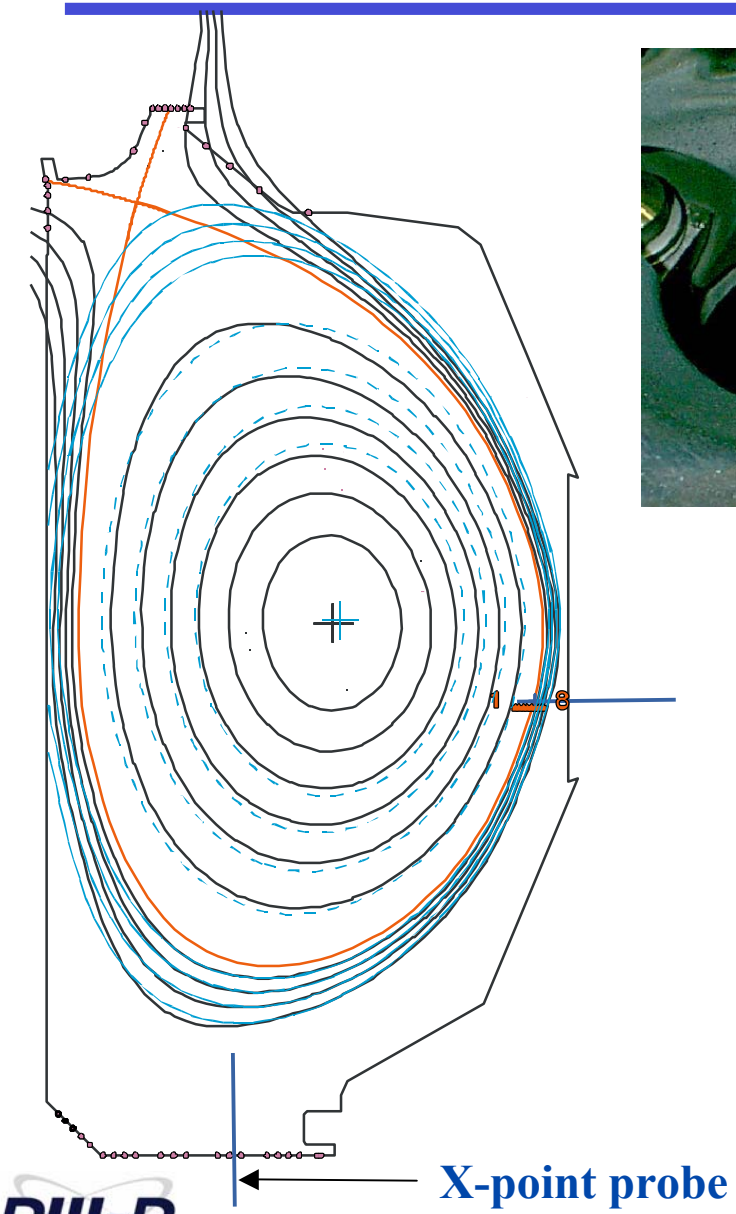
Bumper limiters - most protruding elements of the outer wall

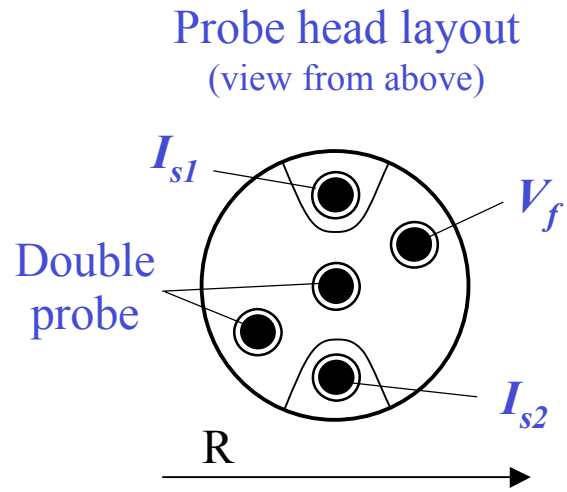


- There are 3 toroidally displaced limiters
- Limiters have radial extent of about 2 cm
- 230° limiter is close to the mid-plane probe



X-point probe array

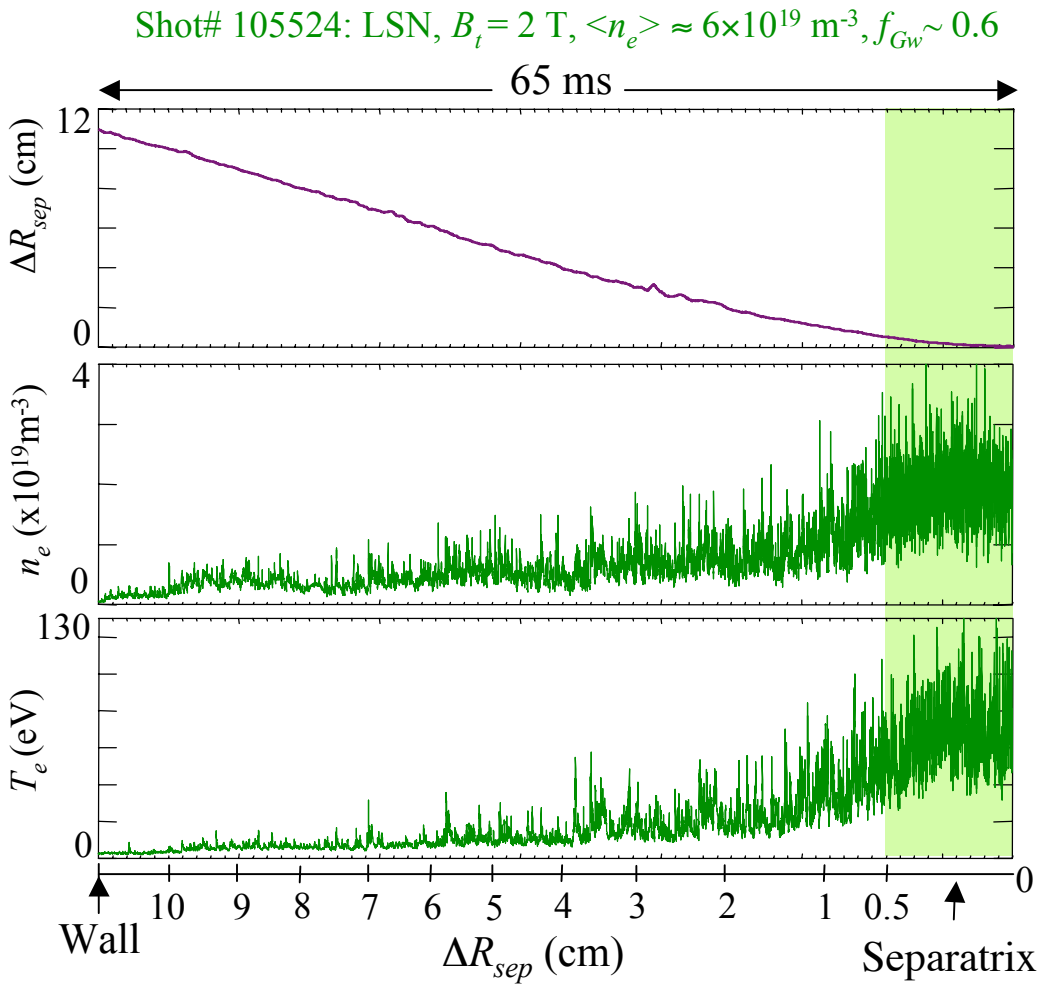




- The in-and-out plunge time is 0.3 s
- The plunge length is about 25 cm
- Spatial resolution: ~ 1 mm
- Temporal resolution: 1 μs (I_s and V_f)
- n_e and T_e profiles derived from double probe data
- Mach number of ion flow derived from two saturation currents

Far SOL density and temperature profiles in Lower Single Null (LSN) Simple As Possible Plasmas (SAPP) L-mode

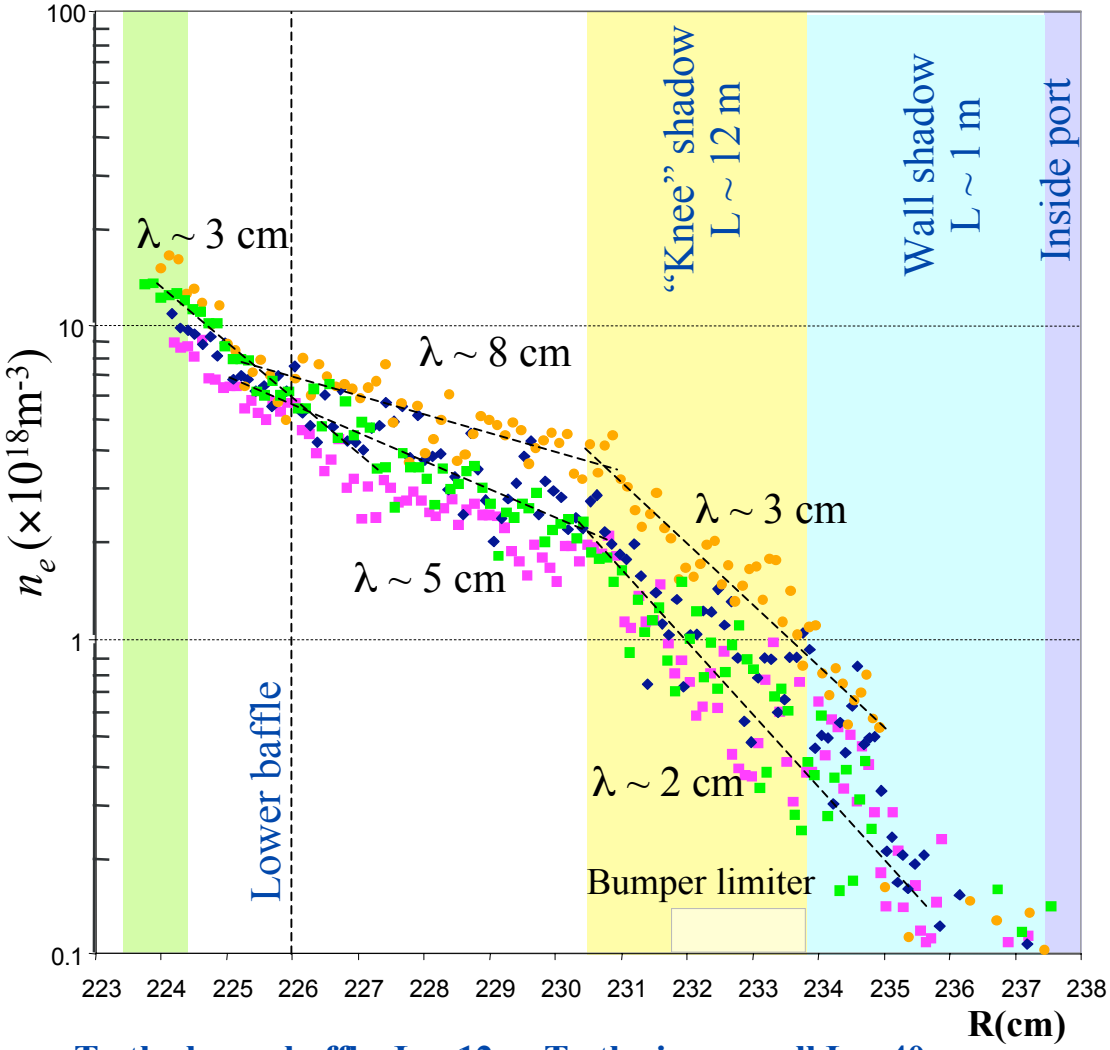
Generation of profiles from the probe data

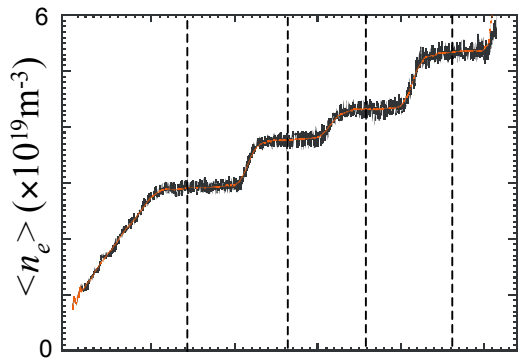


- In 1 ms the probe moves by about 1.5 mm, which is twice smaller that the radial extent of the tips
- Therefore, on the time scale of below 1 ms the probe may be roughly considered stationary
- Profiles are generated by time-averaging of the probe data over 1 ms

Note: density and temperature feature intermittent spikes

SOL density profiles in SAPP L-mode show 3 distinct regions





SAPP L-mode

B = 2 T, I_p = 1 MA

- **Shot 107405**
  $<n_e> \approx 2.8\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.27$
- **Shot 107405**
  $<n_e> \approx 3.7\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.35$
- **Shot 107404**
  $<n_e> \approx 4.3\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.4$
- **Shot 107404**
  $<n_e> \approx 5.3\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.5$

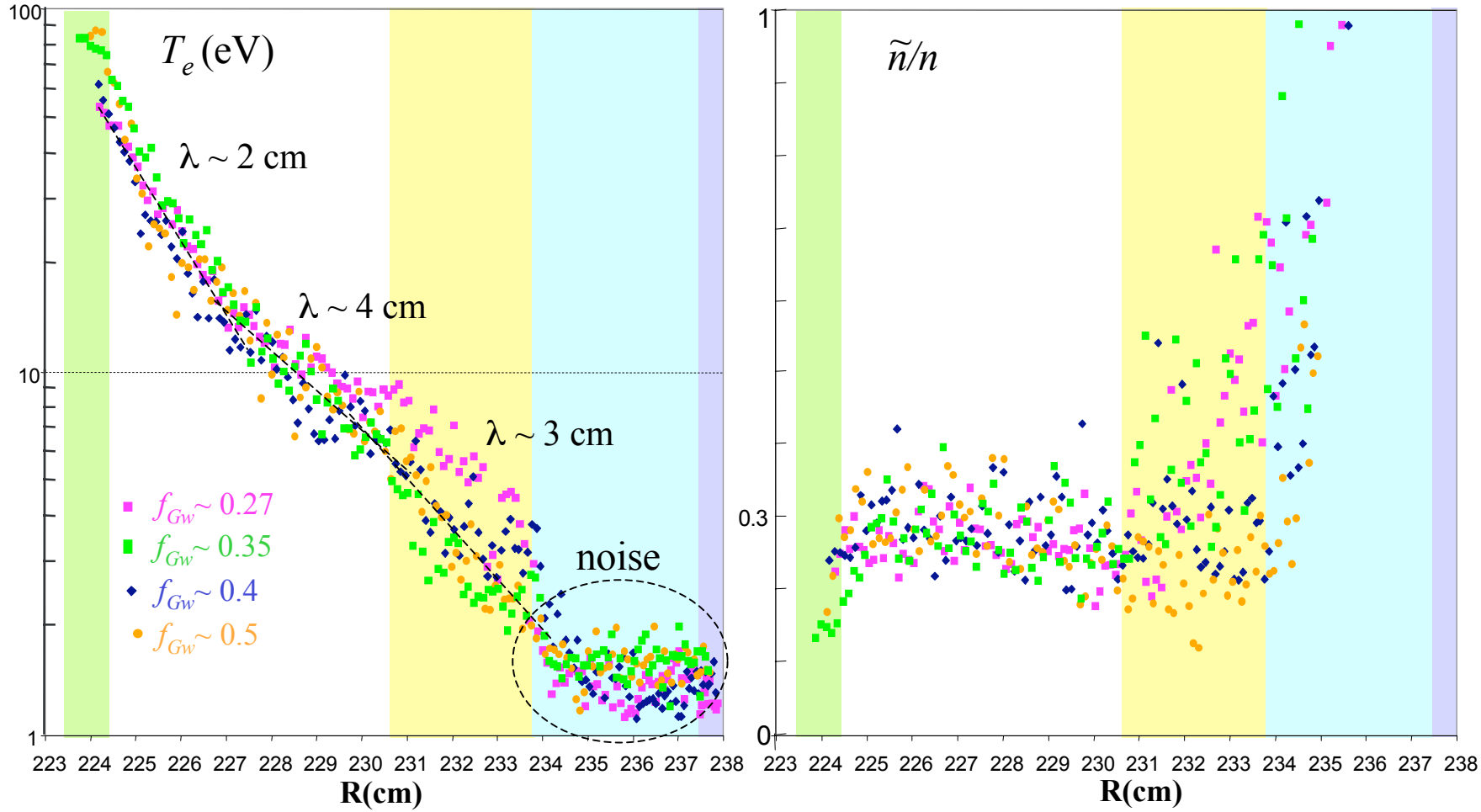
$$f_{GW} = \langle n_e \rangle / n_{GW} = \frac{\langle n_e \rangle \left(10^{20}\,\mathrm{m}^{-3}\right)}{I_p(\mathrm{MA}) * \pi (a(\mathrm{m}))^2}$$

To the lower baffle L ~ 12 m To the inner wall L ~ 40 m

Profiles show clear break when entering the "knee limiter" shadow

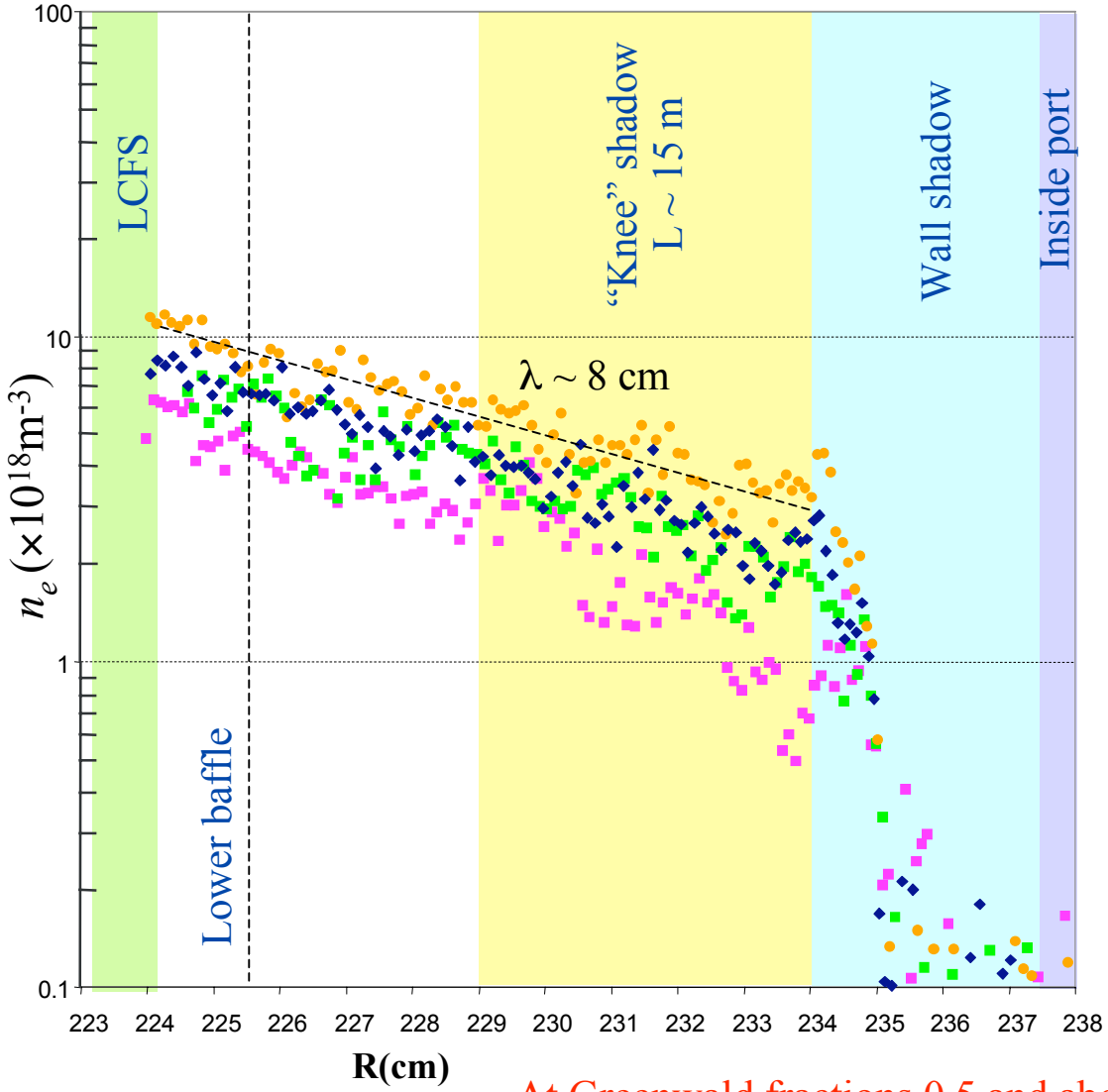
Bumper limiter has no effect on the profiles

Temperature and relative density fluctuation profiles



- Temperature decay length is shorter than that for density in near and middle SOL
- In the shadow region temperature and density decay lengths are close
- Relative fluctuation levels stay flat and do not change with average density
- Absolute fluctuation levels increase with density

At lower I_p profiles do not show a break



SAPP L-mode

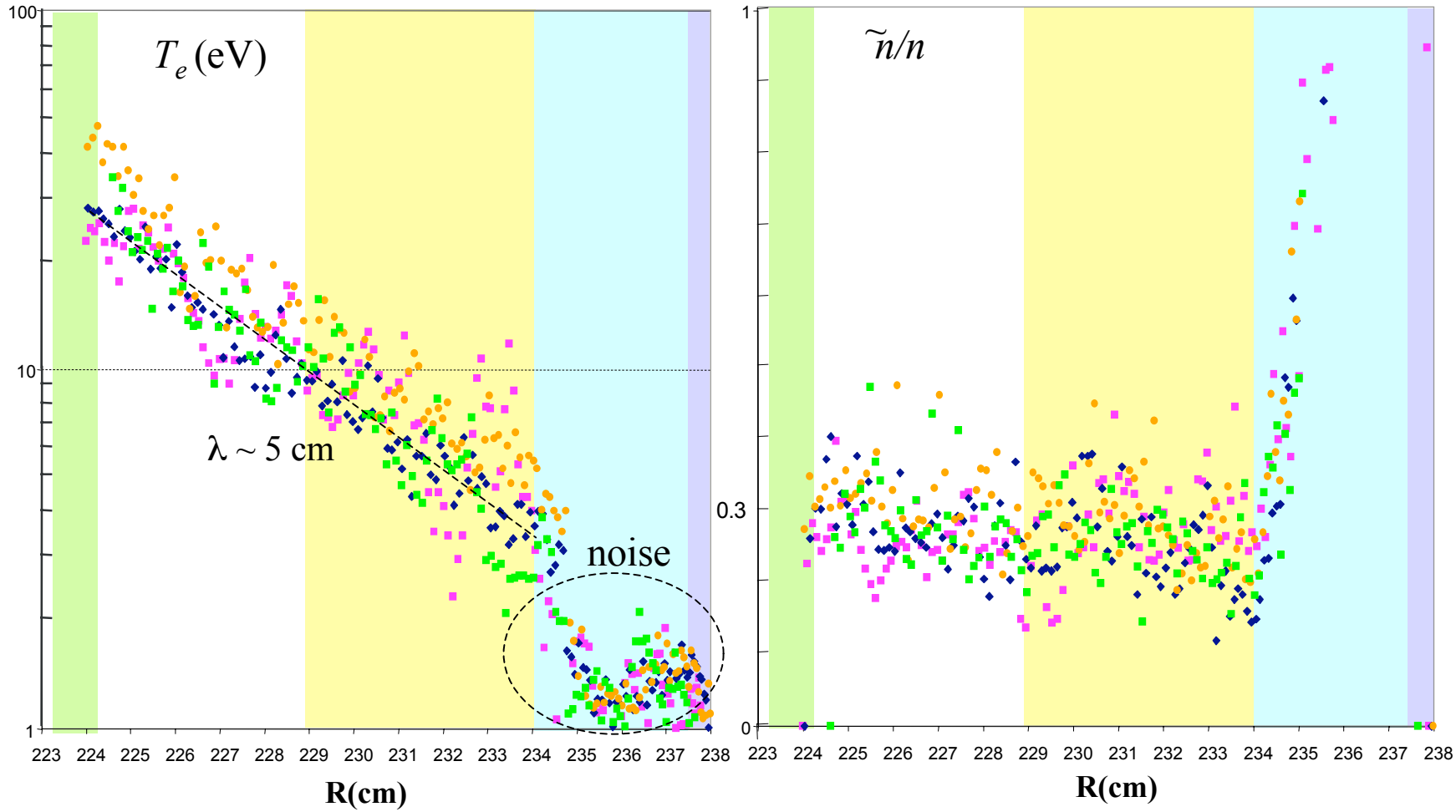
B = 2 T, I_p = 0.8 MA

- **Shot 107408**
  $\langle n_e \rangle \approx 2.8\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.36$
- **Shot 107408**
  $\langle n_e \rangle \approx 3.7\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.48$
- **Shot 107409**
  $\langle n_e \rangle \approx 4.3\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.56$
- **Shot 107410**
  $\langle n_e \rangle \approx 4.5\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.58$

At Greenwald fractions 0.5 and above

the "knee" shadow does not affect profiles

Temperature and relative density fluctuation profiles



- Temperature profile does not seem to be affected by the shadows in this case
- Temperature decay length is longer than at higher I_p
- Relative fluctuation levels stay flat and at about the same level

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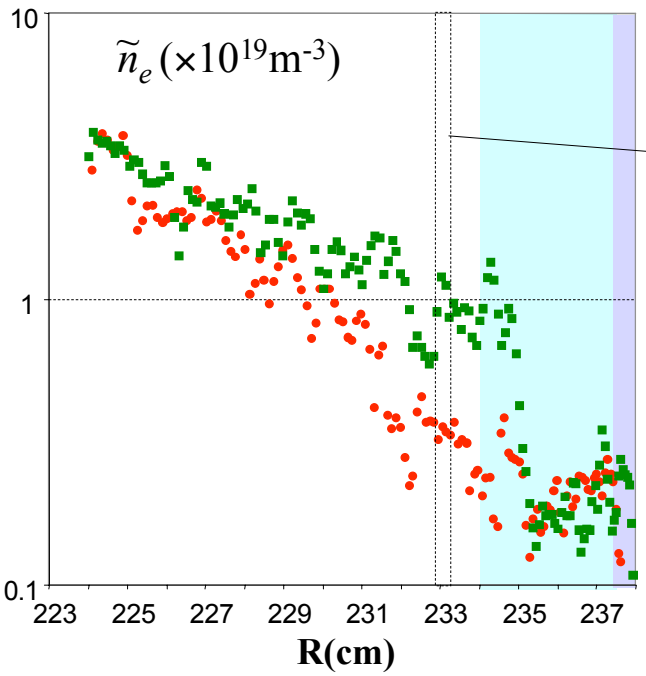
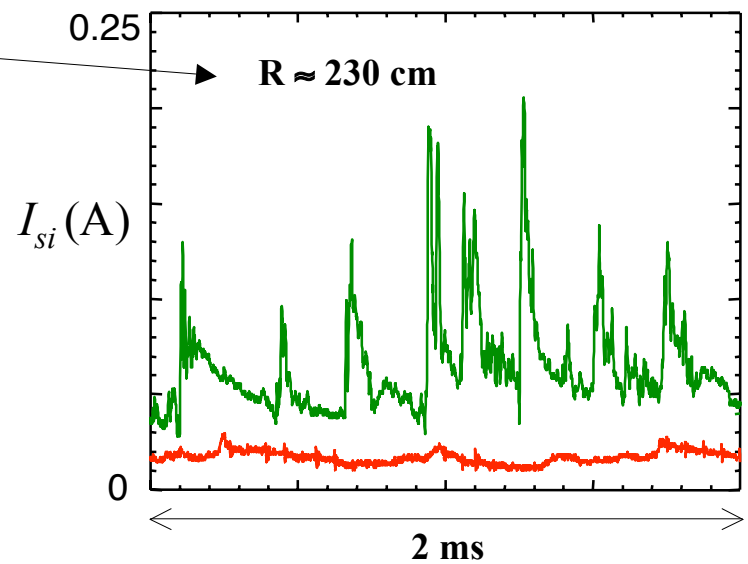
So, what is different between those two groups of shots?

- Greenwald fraction is higher for the second group (lower plasma current) shots
- Connection lengths to the upper and lower baffles are about 25% longer for the second group
- **More interestingly:**

Shot 107404 $\langle n_e \rangle \approx 5.3\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.5$, $I_p = 1$ MA

Shot 107410 $\langle n_e \rangle \approx 4.5\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.58$, $I_p = 0.8$ MA





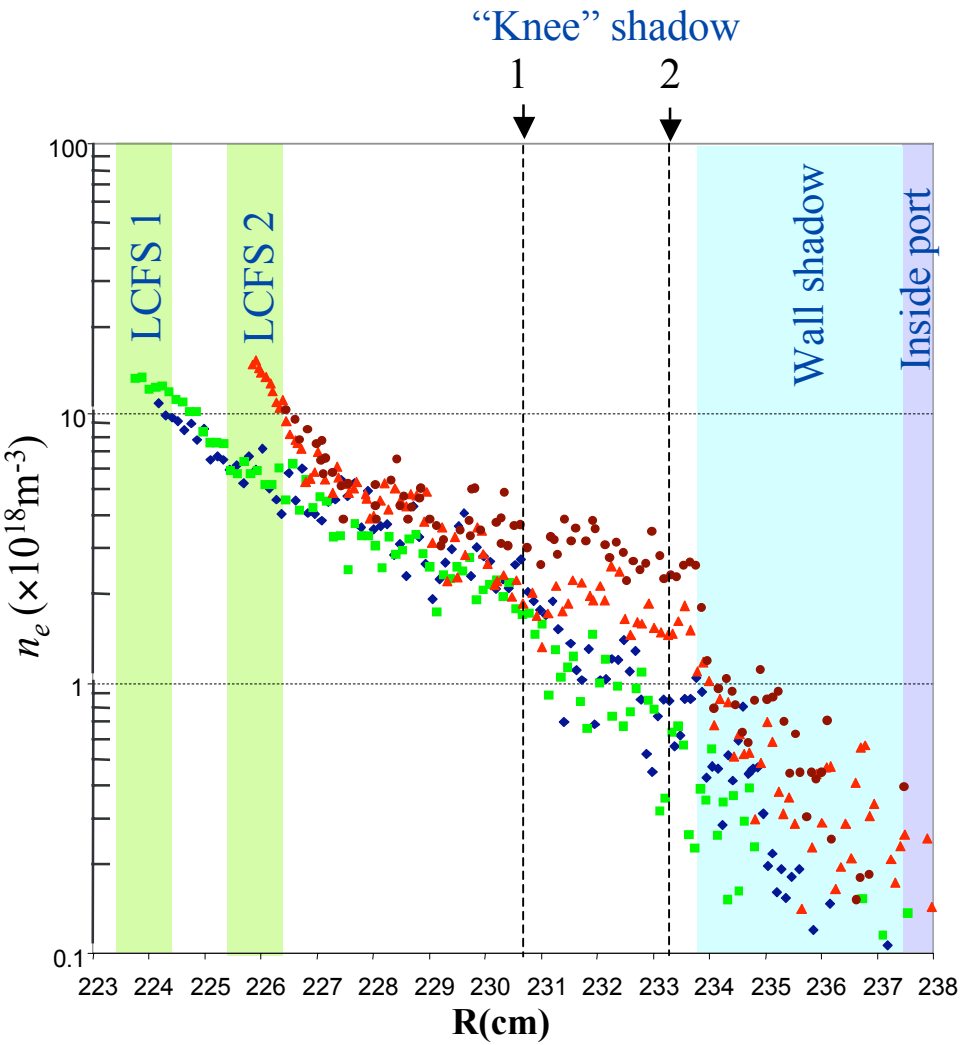
In the second group of shots absolute fluctuation levels are higher in far SOL

In the second group of shots far SOL fluctuations exhibit large bursts

We will come back to this later

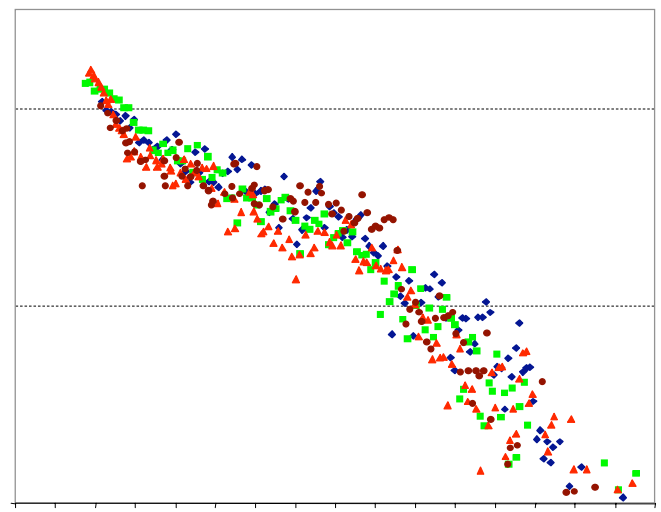
Effect of the outer and upper gap scans on the far SOL profiles

Far SOL density decreases with increased outer gap



Gap 1: ■ $\langle n_e \rangle \approx 3.7\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.35$
◆ $\langle n_e \rangle \approx 4.3\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.4$

Gap 2: ▲ $\langle n_e \rangle \approx 3.5\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.37$
● $\langle n_e \rangle \approx 4.2\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.42$



Same data aligned with respect to LCFS

Looks like the outer gap does affect the far SOL density!

Caution: the "knee" shadow has moved as well, so it may be a combined effect

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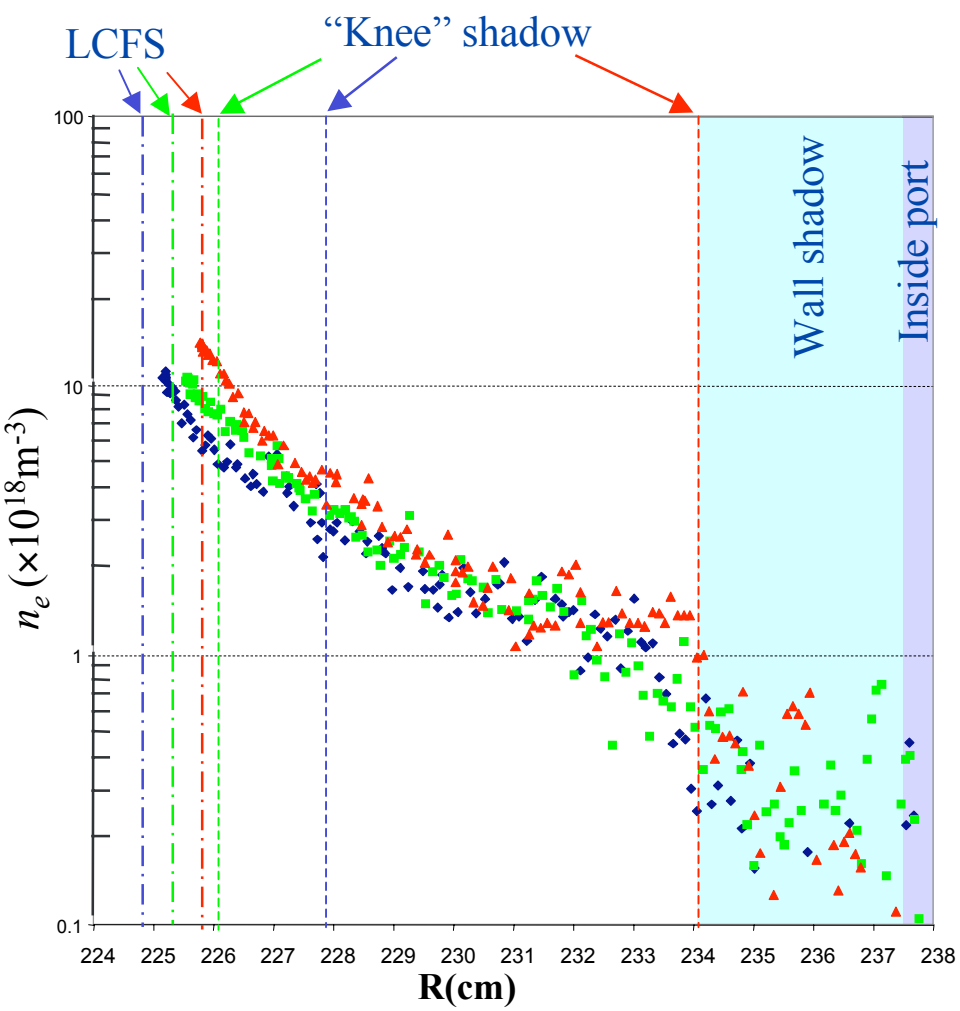
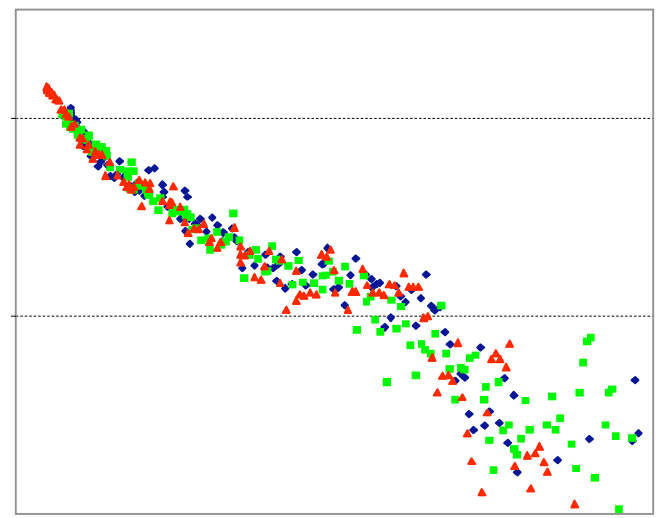
Upper gap scan does not affect SOL profiles

All 3 shots: $\langle n_e \rangle \approx 2.7\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.3$



Upper gap:
- **23.5 cm**
- **9 cm**
- **2 cm**



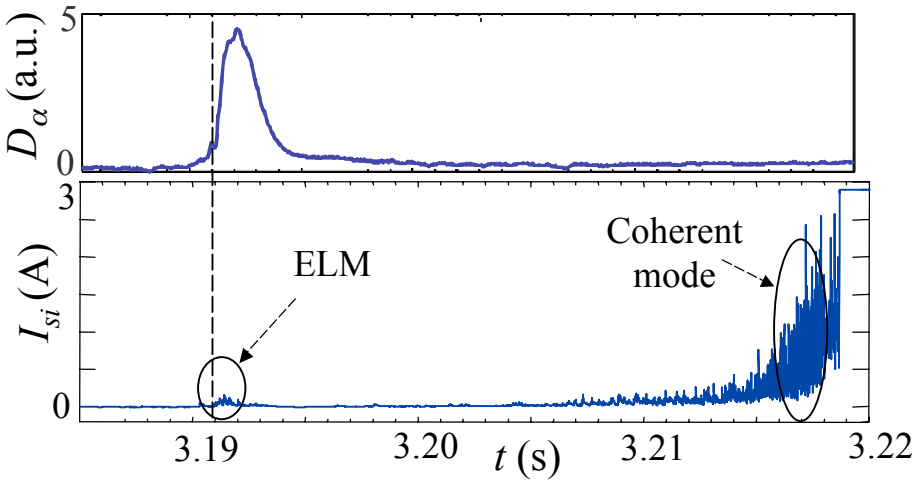
Same data aligned with respect to LCFS

"Knee limiter" shadow does not seem to matter much in this case!

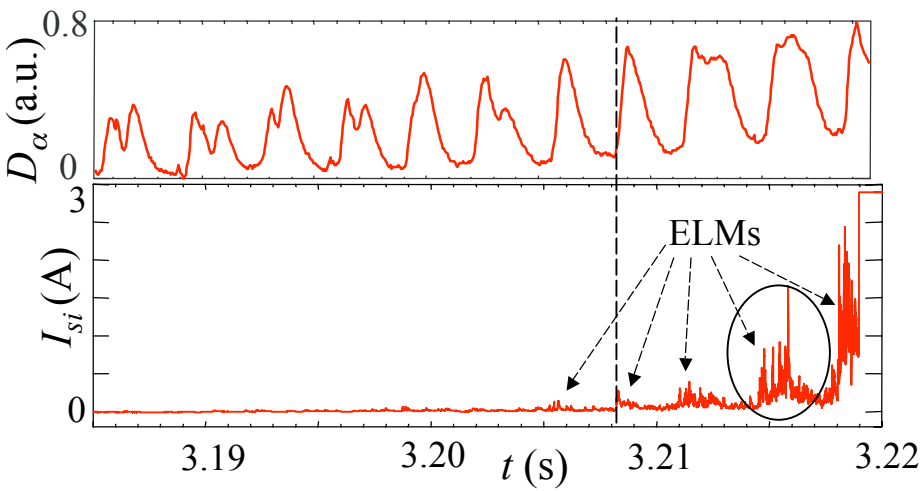
Comparison of L and H modes in LSN

High-density H-modes with small ELMs

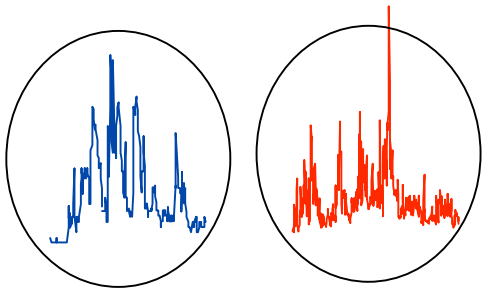
Shot# 107805: LSN, B_t = 1.6 T, P_{NBI} = 1.7 MW, f_{Gw} ~ 1



Shot# 107806: LSN, B_t = 1.6 T, P_{NBI} = 0.75 MW, f_{Gw} ≈ 0.85

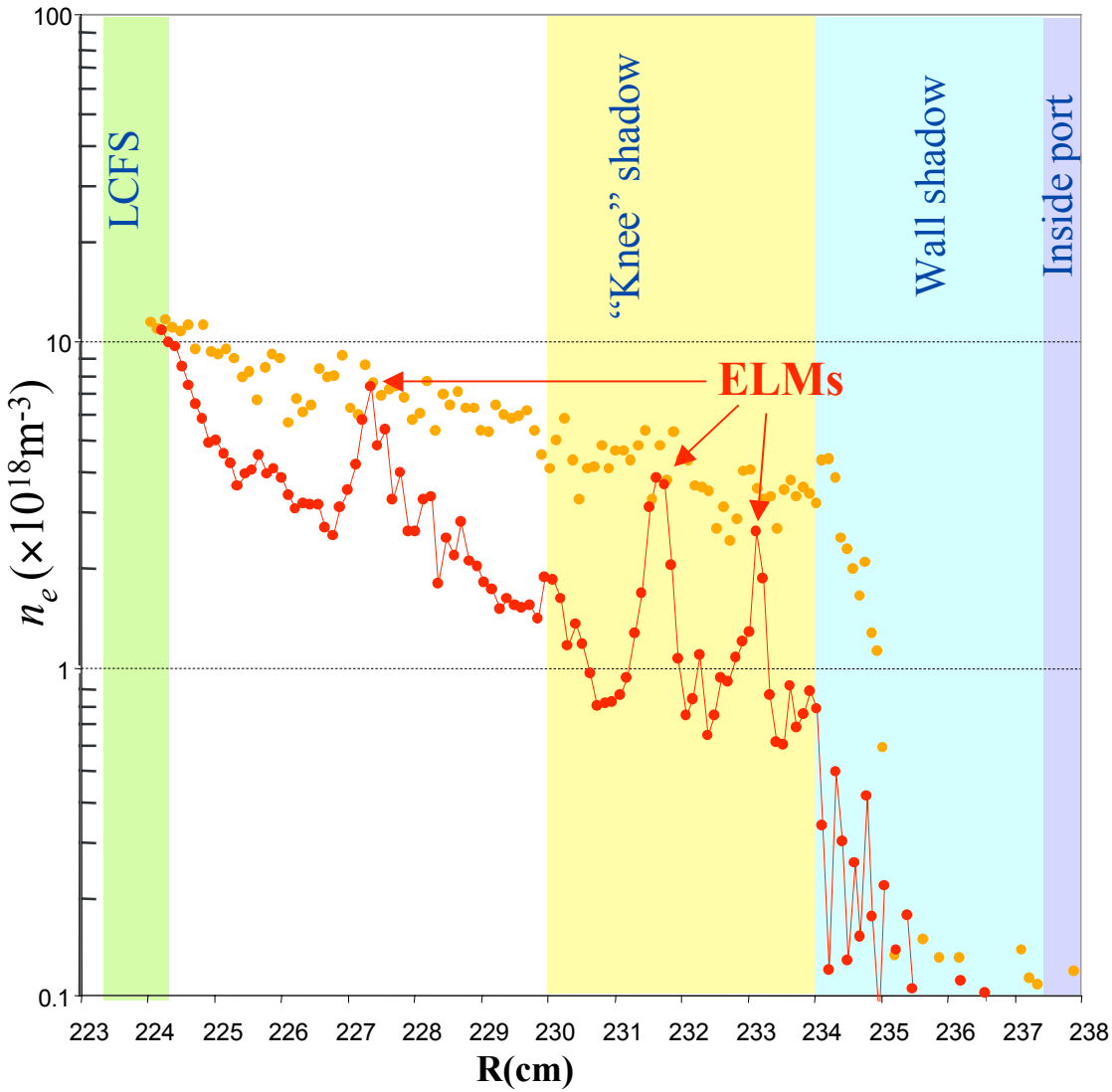


- Two consecutive high-density H-mode discharges
- First discharge had higher heating power and comparatively long (~30 ms) ELM-free periods
- Second discharge had smaller (about 6 times) but very frequent ELMs
- ELM duration from D_α is 2-3 ms



- **To the probe ELMs appear as series of spikes rather than a discrete event as on D_α**

In H-mode between ELMs SOL density is lower than in L-mode



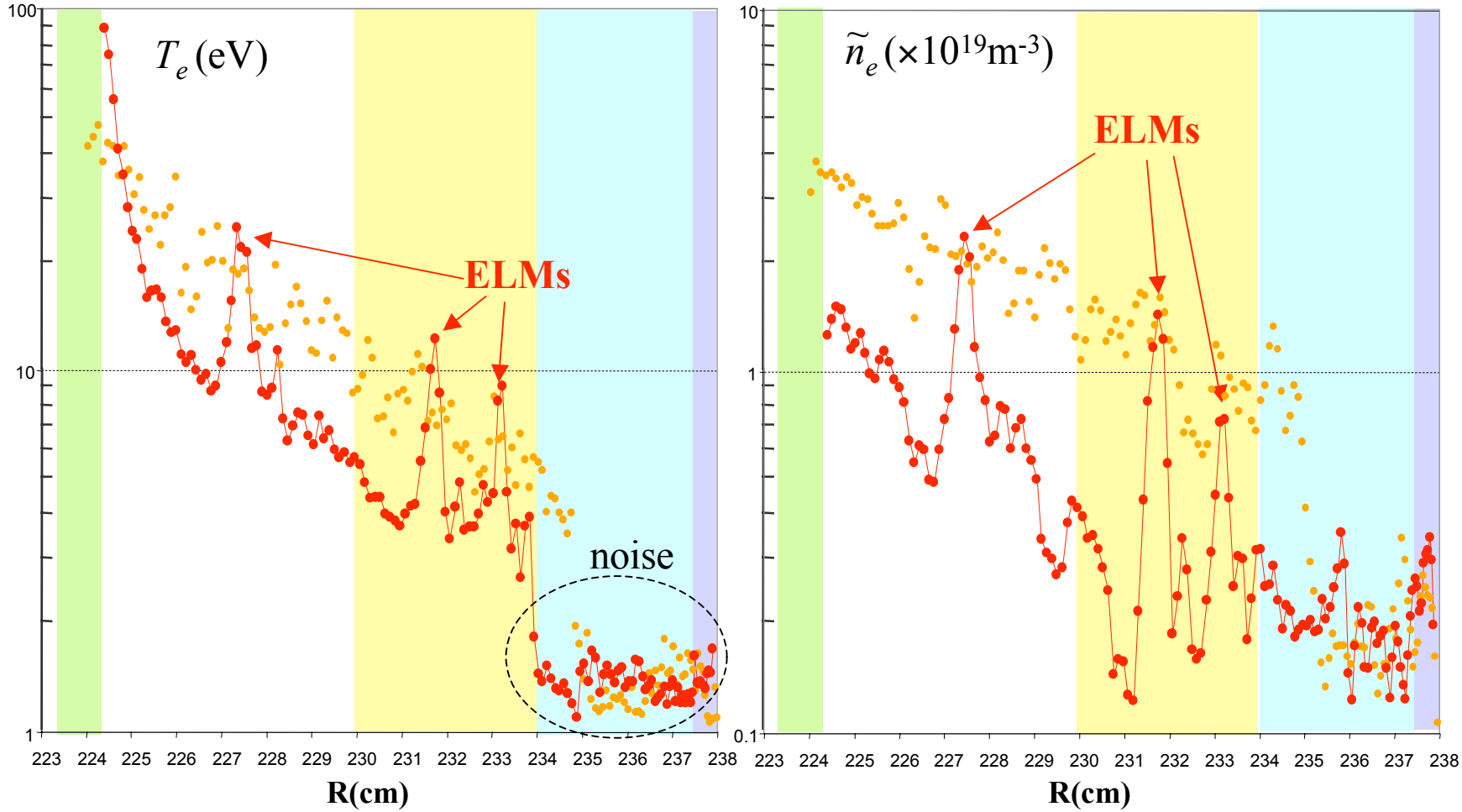
LSN configuration

- **L-mode**
  Shot 107410
  $\langle n_e \rangle \approx 4.5\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.58$

- **H-mode**
  Shot 107411
  $\langle n_e \rangle \approx 6.5\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.65$

During ELMs SOL density increases to L-mode level

Temperature and fluctuation levels, H versus L mode



- T_e between ELMs is lower than in L-mode through most of the SOL
- Fluctuation levels of both n_e and T_e are lower between ELMs than they are in L-mode
- During ELMs n_e, T_e and fluctuation levels increase to or above L-mode levels

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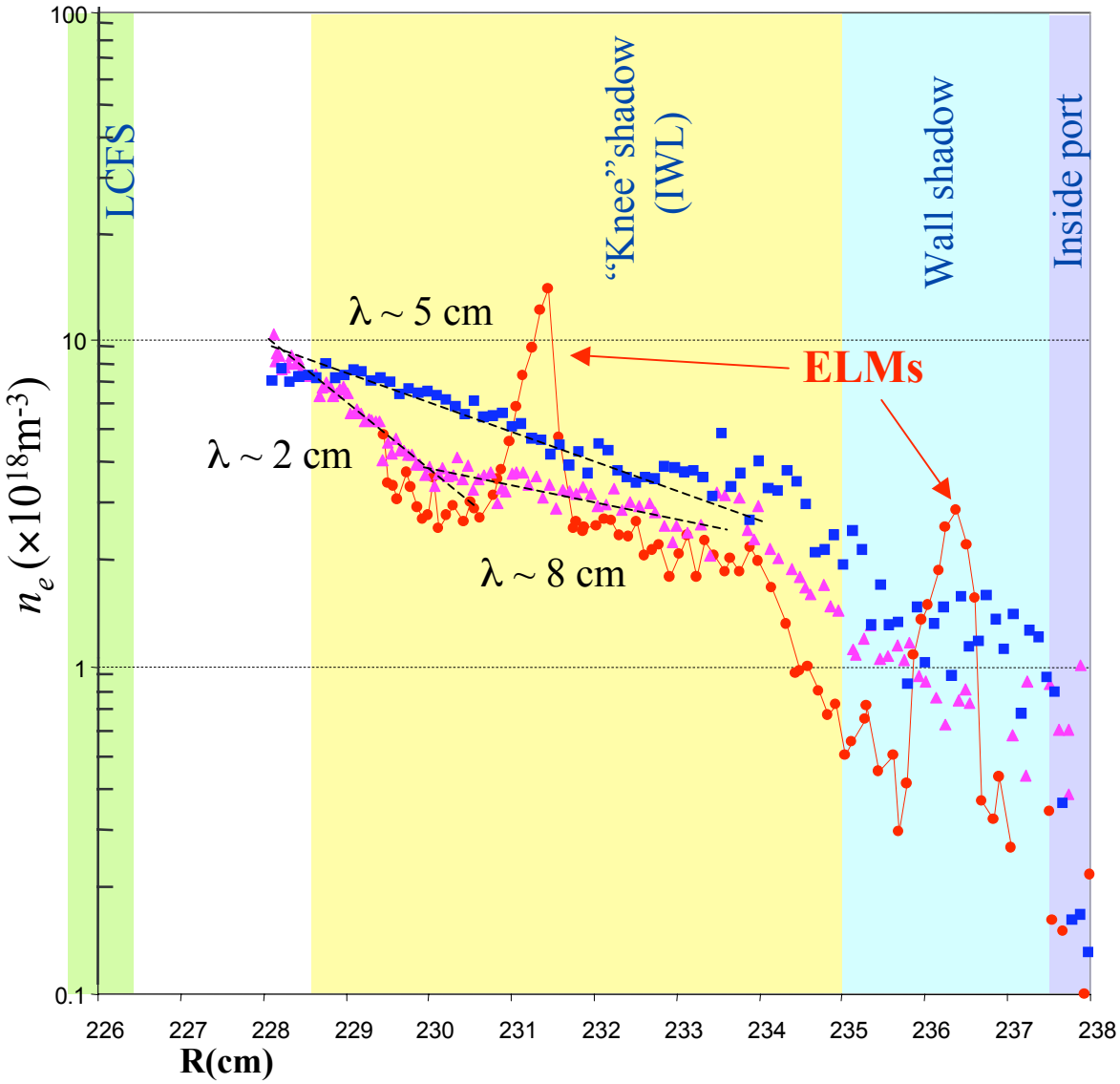
Far SOL profiles in Upper Single Null (USN) and Inner Wall Limited (IWL) configurations

Outer SOL density profiles are relatively flat in USN and IWL



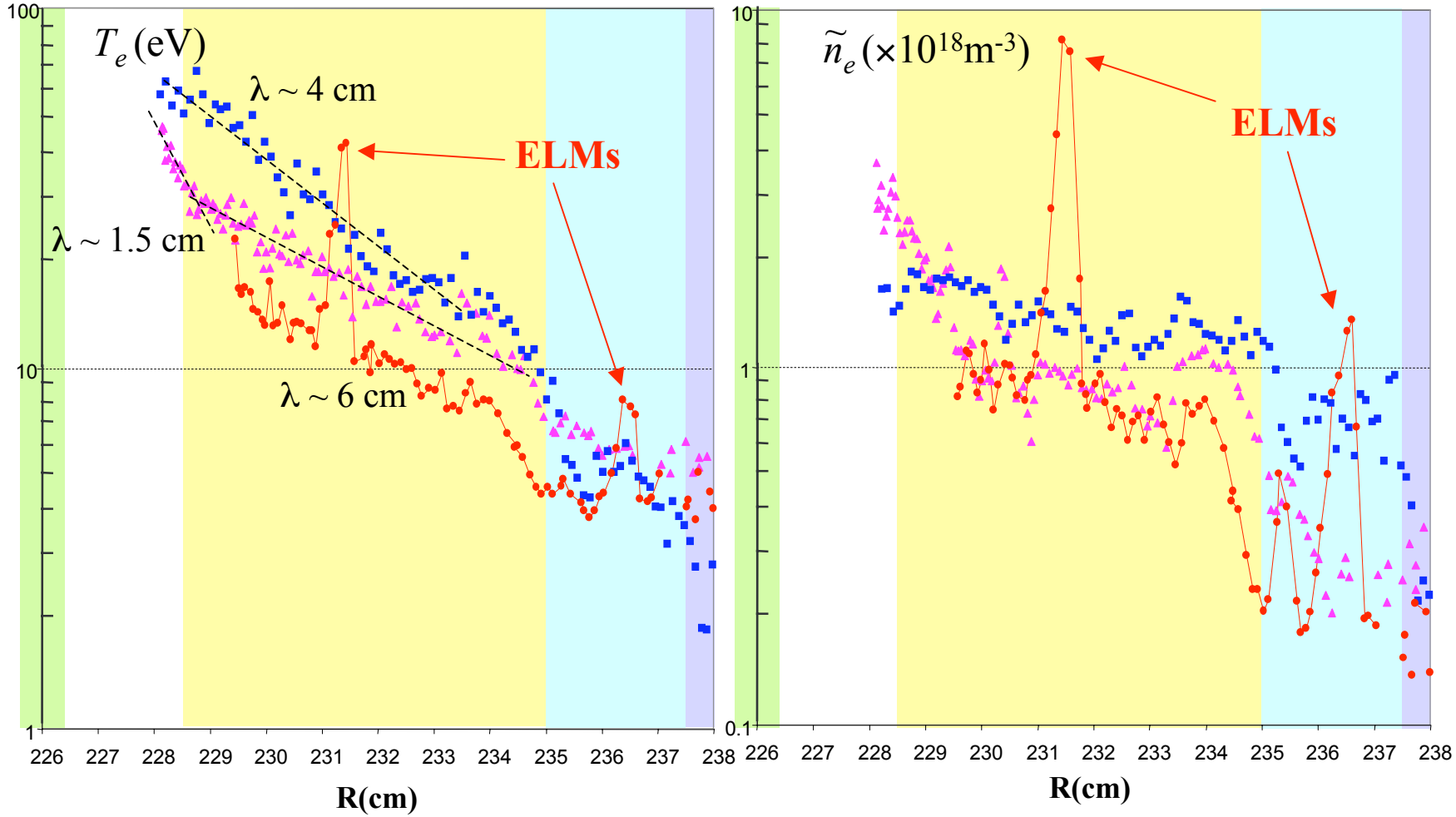
Shot 114850
USN configuration L-mode
▲ **B = 2 T, I_p = 1 MA**
P_{NBI} ~ 4 MW, P_{ECH} ~ 2 MW
$\langle n_e \rangle \approx 1.9\times10^{19}$ m^{-3}, f_{Gw} ~ 0.2

Shot 107577
■ **IWL configuration L-mode**
B = 2 T, I_p = 1 MA
P_{NBI} ~ 6.5 MW
$\langle n_e \rangle \approx 2.5\times10^{19}$ m^{-3}, f_{Gw} ~ 0.32

Shot 114851
● **USN configuration H-mode**
B = 2 T, I_p = 1 MA
P_{NBI} ~ 4 MW
$\langle n_e \rangle \approx 4.1\times10^{19}$ m^{-3}, f_{Gw} ~ 0.46

Far SOL density is higher than in LSN discharges with comparable average density

Temperature and density fluctuation profiles



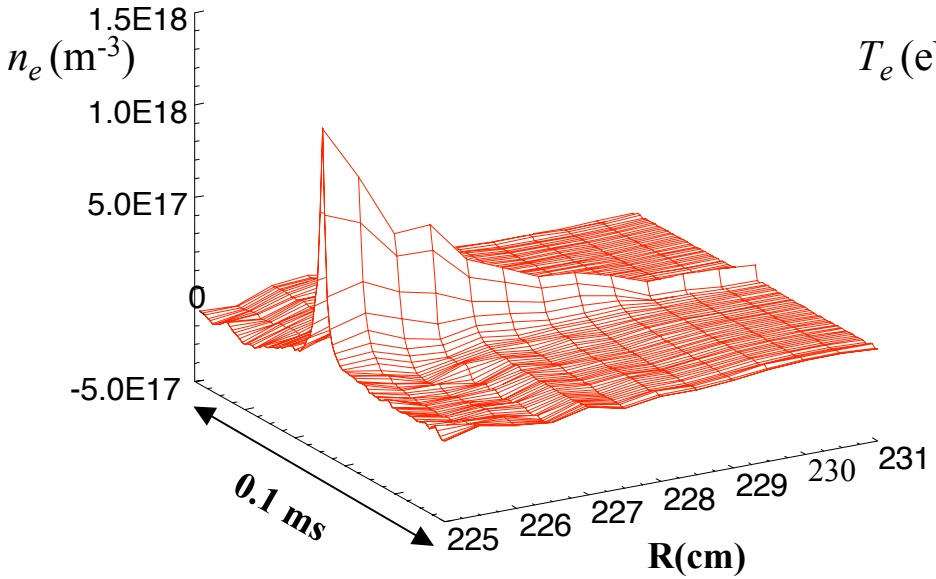
- Far SOL temperature is higher than in LSN discharges (but this may be explained by higher heating power)
- RMS fluctuation levels are rather flat, so relative levels increase towards the wall
- During ELMs T_e and fluctuation levels are higher than in L-mode

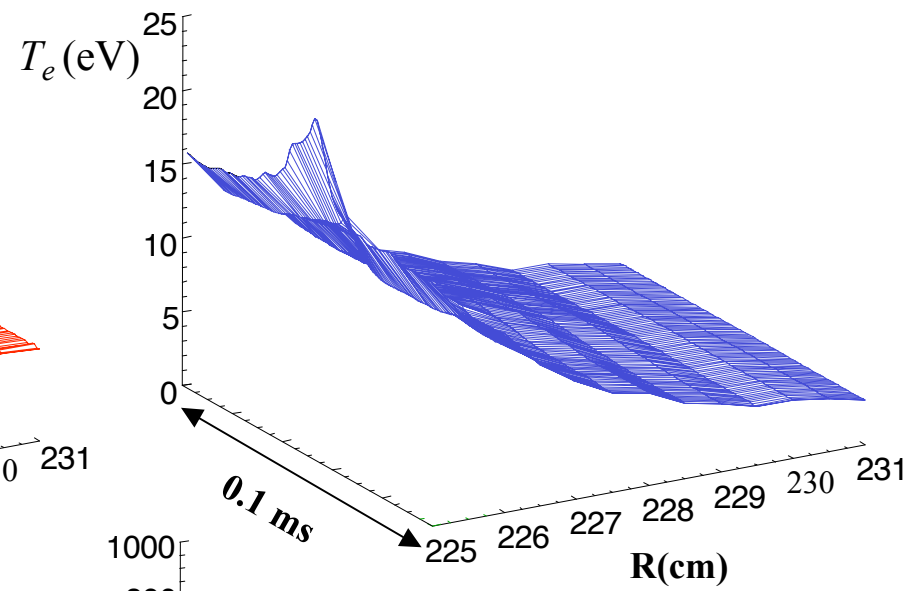
Intermittent convection
and its possible effect on the outer wall

Intermittent cross-field convection in the SOL of DIII-D

- Plasma density, electron temperature and time-resolved particle and heat fluxes in the SOL are intermittent in space and time.
- Probe, Beam Emission Spectroscopy (BES) and mid-plane tangential D_α data show the existence of intermittent coherent structures born near the LCFS and propagating radially towards the wall.
- Intermittent structures have been shown to account for up to 70% of the net cross-field particle and energy transport.
- Intermittent events have qualitatively similar character in L-mode and H-mode both between and during ELMs.
- Amplitudes of the intermittent events during ELMs are comparable to those in high density L-mode.
- In ELM-free H-mode intermittent events are much smaller.
- Previous analysis have shown that the intermittent structures drain particles and heat, slow down and shrink in size as they propagate to the wall.
- **Do the intermittent structures get to the wall and can they cause sputtering?**

In low density L-mode intermittent events slow down and decay before they reach the wall



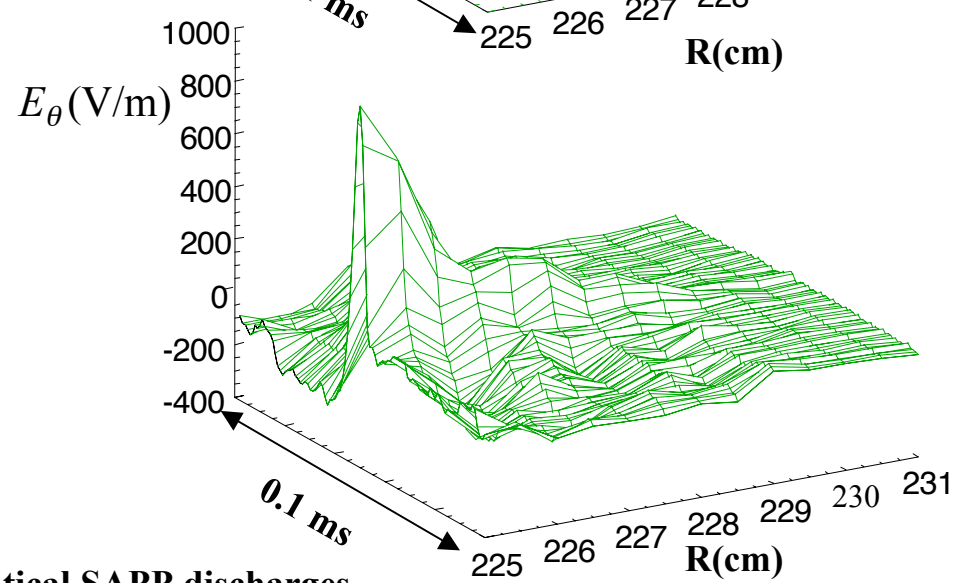


Shots 116243 - 116263

B = 2 T, I_p = 1 MA

$\langle n_e \rangle \approx 2.7\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.28$

LCFS	223 cm
"Knee" shadow	228.5 cm
Limiter	231.5 cm
Wall shadow	233.5 cm

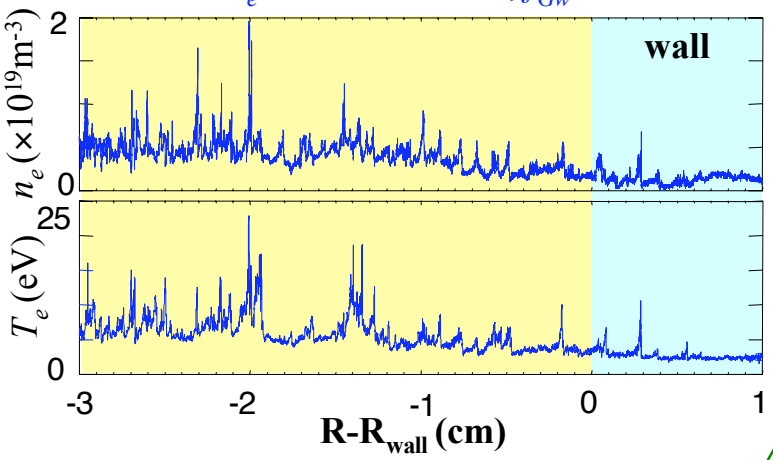


Data taken over a series of 22 identical SAPP discharges with mid-plane probe moved between shots in 5 mm steps

Do intermittent events ever get to the wall? Yes, they do!

Shot 105524 L-mode

$\langle n_e \rangle \approx 6.5\times10^{19}$ m^{-3}, $f_{Gw} \sim 0.6$

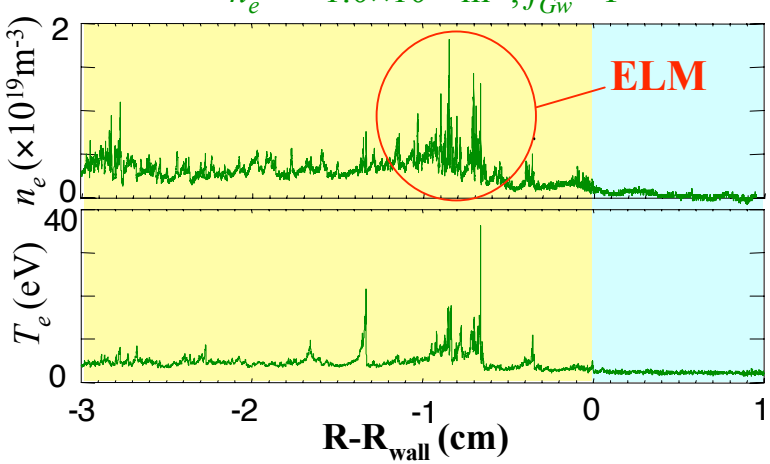


In high density L-mode and in H-mode during ELMs intermittent events do get to the wall

But between ELMs even in high density H-mode signals at the wall are very low

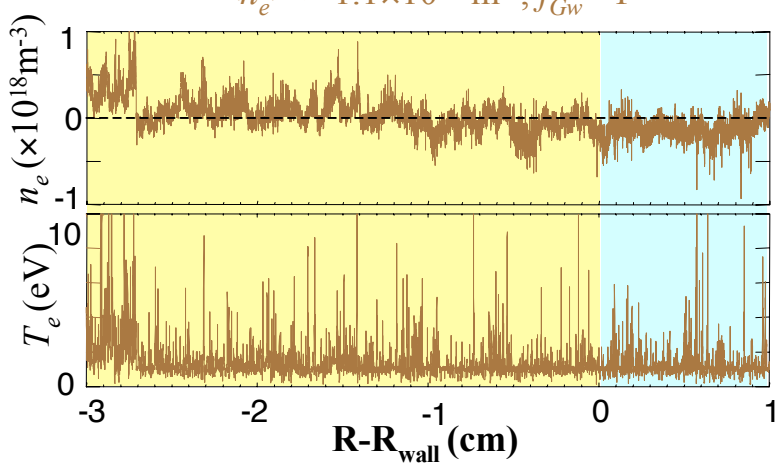
Shot 105522 H-mode

$\langle n_e \rangle \approx 1.0\times10^{20}$ m^{-3}, $f_{Gw} \sim 1$



Shot 107805 H-mode

$\langle n_e \rangle \approx 1.1\times10^{20}$ m^{-3}, $f_{Gw} \sim 1$



Further experiments are needed to quantify the sputtering effect

Summary

- SOL density in L-mode is measurable all the way out to the wall
- Increasing outer wall gap decreases plasma-wall contact
- Fluctuation-induced cross-field transport increases with density and flattens far SOL profiles, thus increasing plasma-wall contact
- Particle and heat pulses of ELMs reach remote structures such as outer wall and divertor baffles
- Between ELMs plasma-wall contact is weaker than in comparable L-mode conditions
- Intermittent events in low density L-mode quickly thermalize with the background plasma, slow down and decay as they propagate towards the wall
- In high density L-mode and during ELMs in H-mode intermittent events do get to the wall and may cause sputtering