

Turbulent Transport and the Scrape-off-Layer Width

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Introduction

- Study the effect of midplane turbulence on the SOL width
 - use reduced model: 2D, fluid, electrostatic
- Compare predicted trends (not absolute modeling) with NSTX data

hypothesis: turbulent ExB transport of particles and energy across the midplane separatrix determines the SOL width

Outline

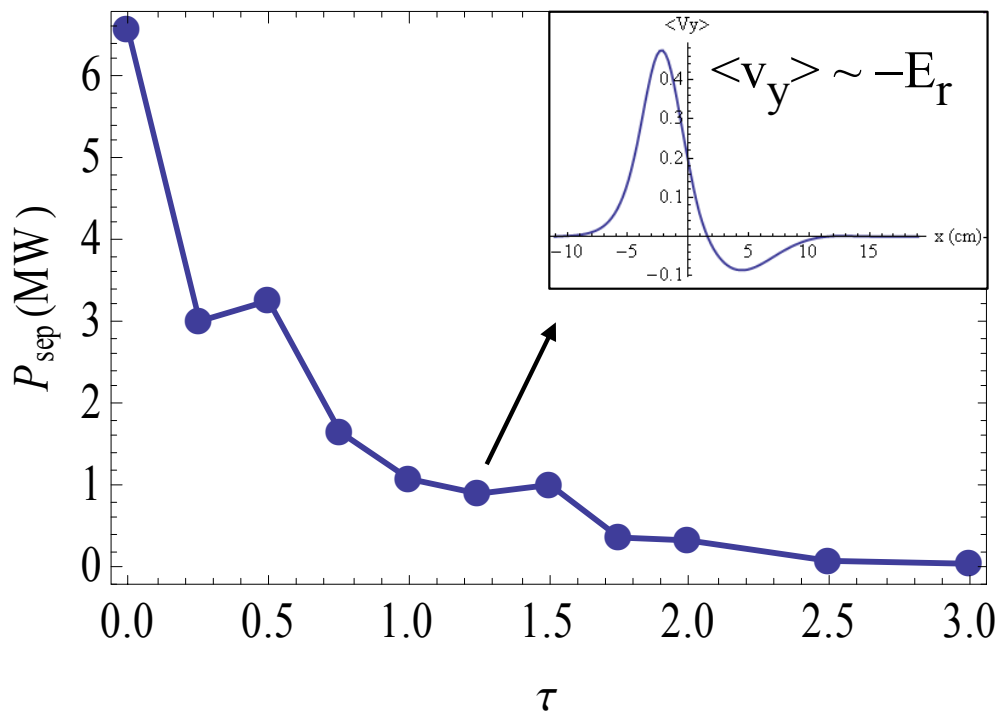
- the SOLT code
- low power ELM-free H-mode (NSTX)
- L_{\parallel} scaling: simulation and theory
- I_p scaling (NSTX)

The SOLT code: physics model

- Scrape-Off-Layer Turbulence (SOLT) code
 - 2D fluid turbulence code: model SOL in outer midplane
 - classical parallel + turbulent cross-field transport
 - evolves n_e , T_e , Φ with parallel closure relations
 - sheath connected, with flux limits, collisional
 - strongly nonlinear: $\delta n/n \sim 1 \Rightarrow$ blobs
 - model supports drift waves, curvature-driven modes, sheath instabilities
 - synthetic GPI diagnostic
 - flexible sources for n_e , T_e , v_y
- Present work:
 - curvature-driven interchange, sheath-connected
 - SOL simulation \Rightarrow edge region provides effective BC at separatrix
 - artificial sources maintain experimental n_e , T_e inside LCS
 - no sources from -1 cm to wall $\Rightarrow n_{\text{sep}}$, T_{sep} free

H-mode plasmas and SOL-width simulation

- previous SOLT simulations modeled L-mode
 - strong turbulence and blob emission
 - $\langle v_y \rangle$ driven by Reynolds's stress, blob emission and sheaths
 - GPI comparisons of far SOL convective transport
- H-mode simulations require a different approach
 - steeper gradients, but tamer turbulence \Rightarrow regulation mechanism



- impose mean $\langle v_y \rangle$ *in core*

$$v_y \sim \frac{1}{n} \frac{d}{dx} (nT_i) \sim -E_r$$
- control parameter $\tau = T_i / T_e$ regulates turbulence (E_r well depth)
- vary τ to match experimental P_{sep}
- SOL $\langle v_y \rangle$ still from RS and sheath physics
- SOLT P_{sep} scans hold core profiles fixed

\Rightarrow heat flux-driven BC for SOL simulation

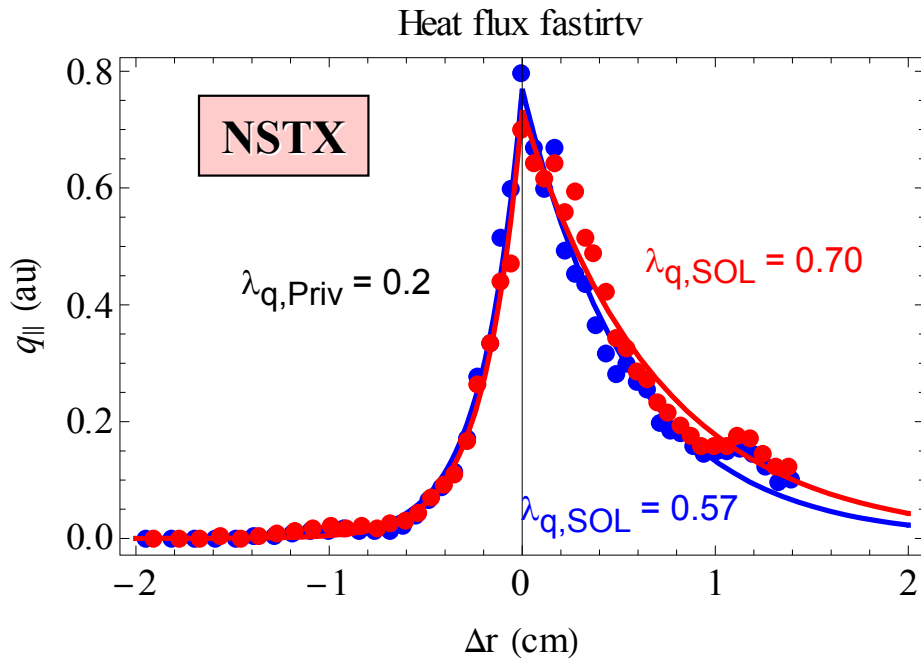
Summary of SOLT input and output

- input from experiment
 - power crossing separatrix P_{sep}
 - connection length in SOL $L_{\parallel}(\mathbf{r})$
 - plasma profiles inside LCS $n_e(\mathbf{r}), T_e(\mathbf{r}) \Rightarrow$ gradient drive, collisionality regime Λ (or v_{e*})
 - effective curvature R ; B_t, B_p
 - other input
 - dissipation parameters: viscosity, ZF damping
 - downstream / sheath conditions at divertor plate
 - output
 - $\langle q_{\parallel}(\mathbf{r}) \rangle$, and heat flux width λ_q
 - $V_x = \langle n v_x \rangle / \langle n \rangle$ (or $\langle n T v_x \rangle / \langle n T \rangle$)
 - $n_e(\mathbf{r}), T_e(\mathbf{r})$ SOL
 - 2D turbulence snapshots or movies
- } compare with experiment:
probes, GPI, divertor IRTV (midplane mapped)

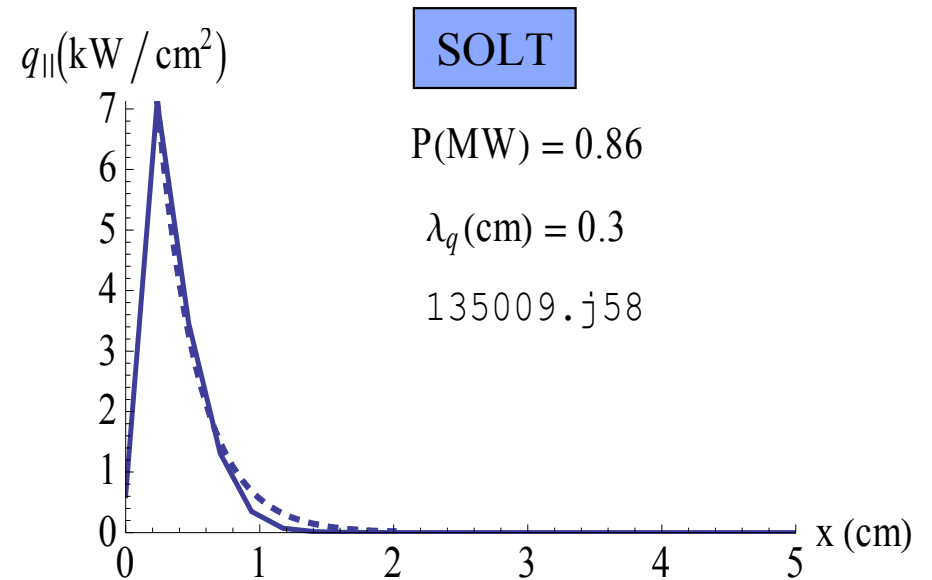
Low power ELM-free H-mode [J. W. Ahn - NSTX]

- power scan: shots 135009 at $P_{nb} = 0.8$ MW and 135038 $P_{nb} = 1.3$ MW

experimental heat flux



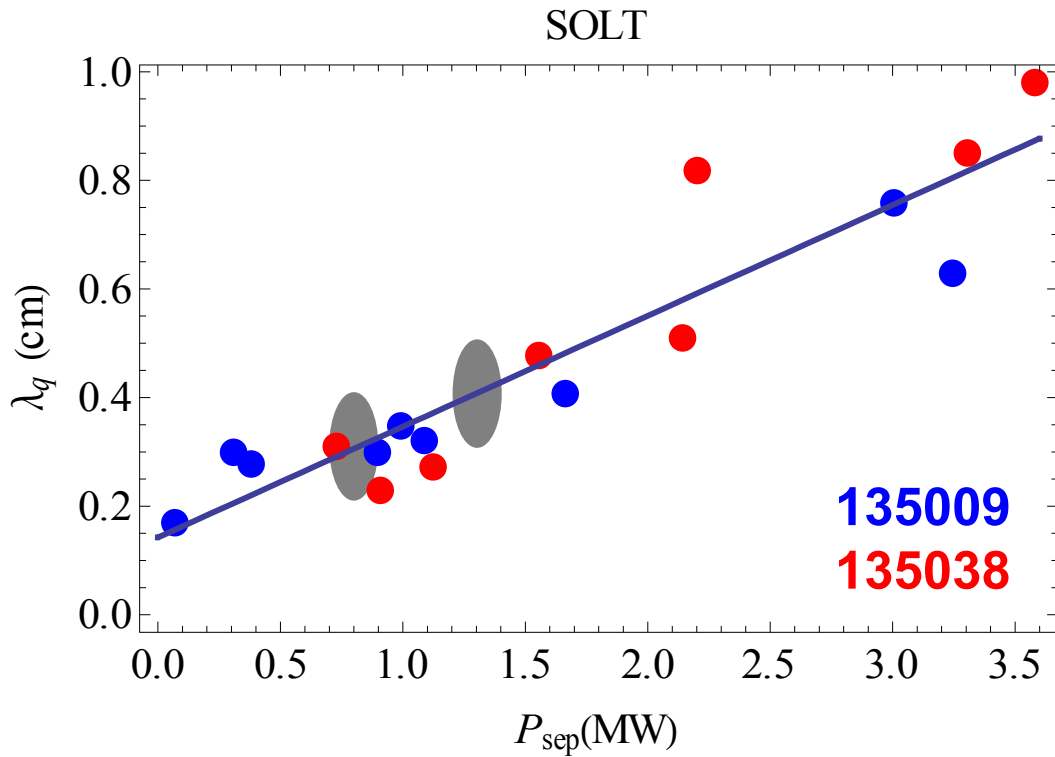
divertor data midplane mapped (dots)
exponential fits (solid)



SOLT (midplane) heat flux (thin solid line) and exponential fit (dashed).

$$P_{sep} = 2\pi R b_{\theta} \int dr q_{||}$$

SOLT simulations: power scans reproduce trend in data



- insignificant differences in the SOLT setup for the 2 shots
- solid line = linear fit to the combined results
- gray ellipses = experimental powers

subtract X-pt to plate broadening

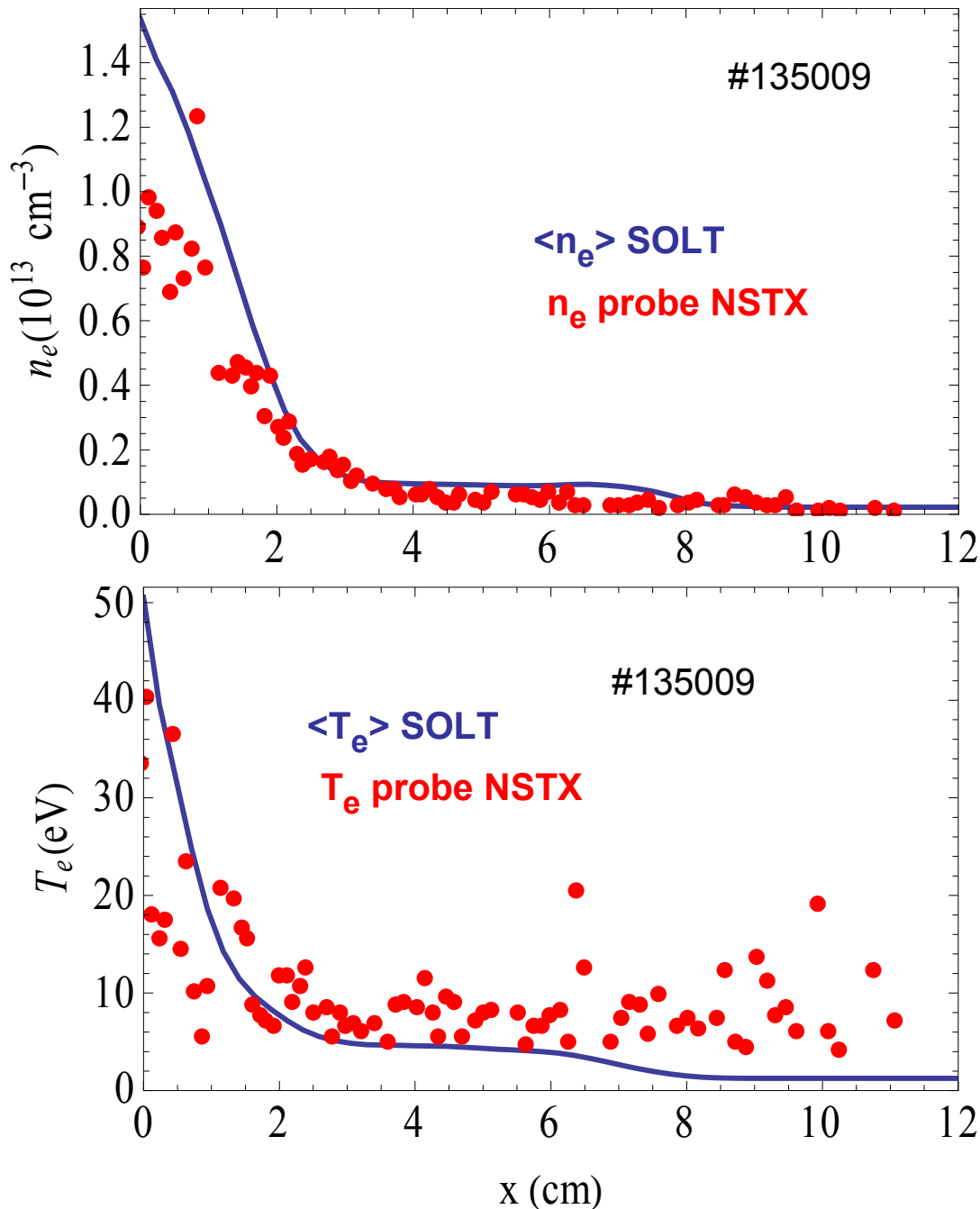
NSTX IRTV

SOLT

**SOL width:
simulation vs.
experiment**

shot	P(MW)	$\lambda_{q,SOL}$	$\lambda_{q,Priv}$	$\lambda_{q,SOL} - \lambda_{q,Priv}$	λ_q
135009	0.8	0.57	0.21	0.36	0.30
135038	1.3	0.70	0.20	0.50	0.41

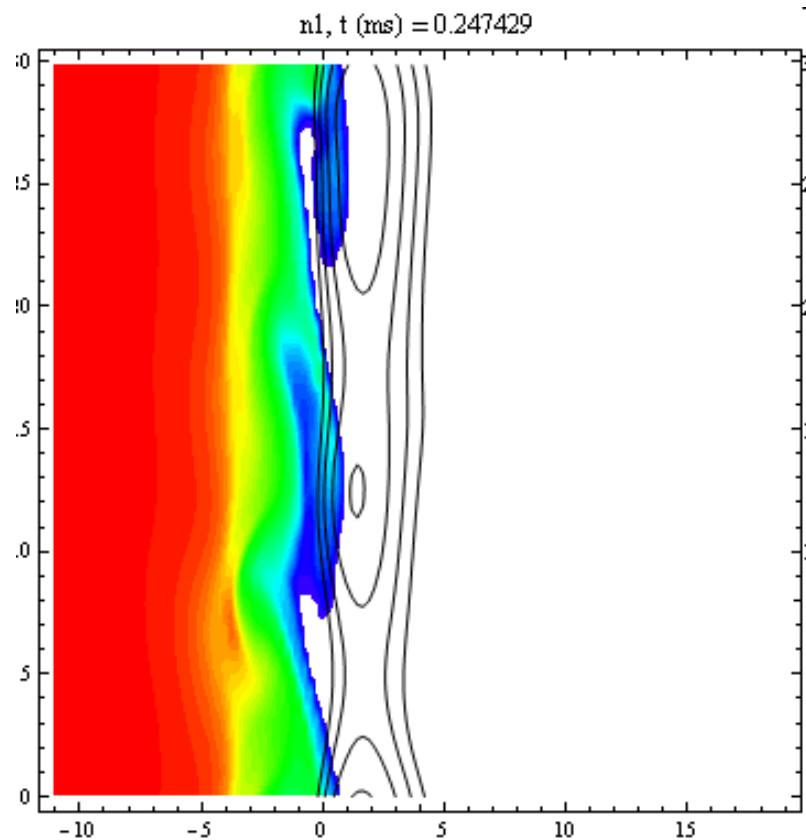
Midplane profiles: simulation vs. experiment



- NSTX shot #135009
- midplane probe data [Ahn]
- SOLT overestimates near-SOL n_e (omits 3D effect of parallel sonic expansion)
- far SOL T_e discrepancy – far SOL L_{\parallel} used in simulation may not be accurate (no LRDFIT there)

SOL width not set by ejected blobs, but by separatrix-spanning convection

- sheared flow is too strong to let blobs detach
- growing fingers are sheared down by zonal flows, but intermittently get carried across separatrix by convective cells
- resulting cross-field motion competes with parallel flow \Rightarrow SOL width



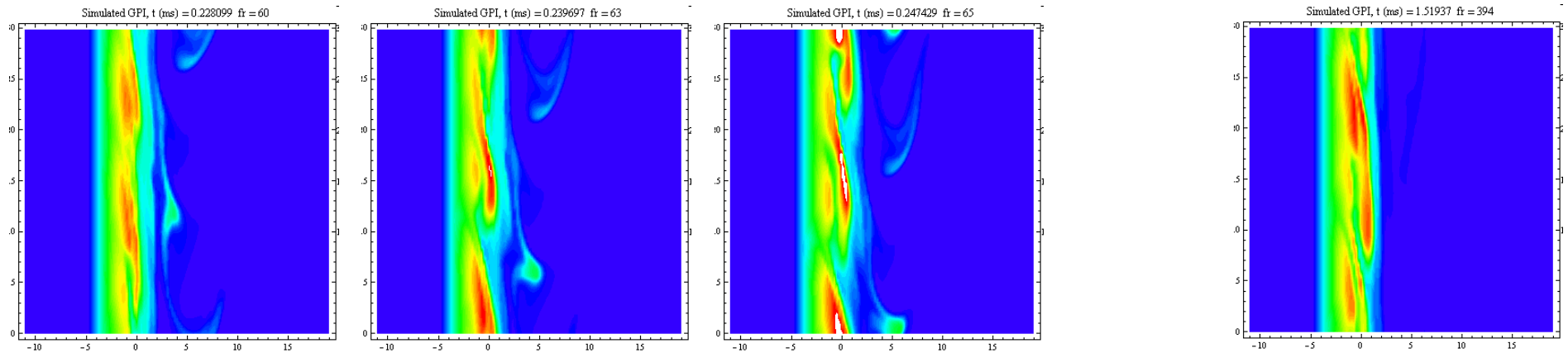
turbulent snapshot

- density $n(x,y)$
 - color palette (white for $n < 0.6$ to illustrate the plasma edge)
- potential $\Phi(x,y)$
 - contours at $\{.7, .8, .9, 1.0\}$ to illustrate separatrix-spanning convective cell

Simulated GPI – NSTX 135009

Lundberg-Stotler fits for $D_0(x)$ puff profile

- In SOLT (for this shot) blob ejection only occurs due to transients – here at the start of the simulation



transient blob ejection
(early in simulation)

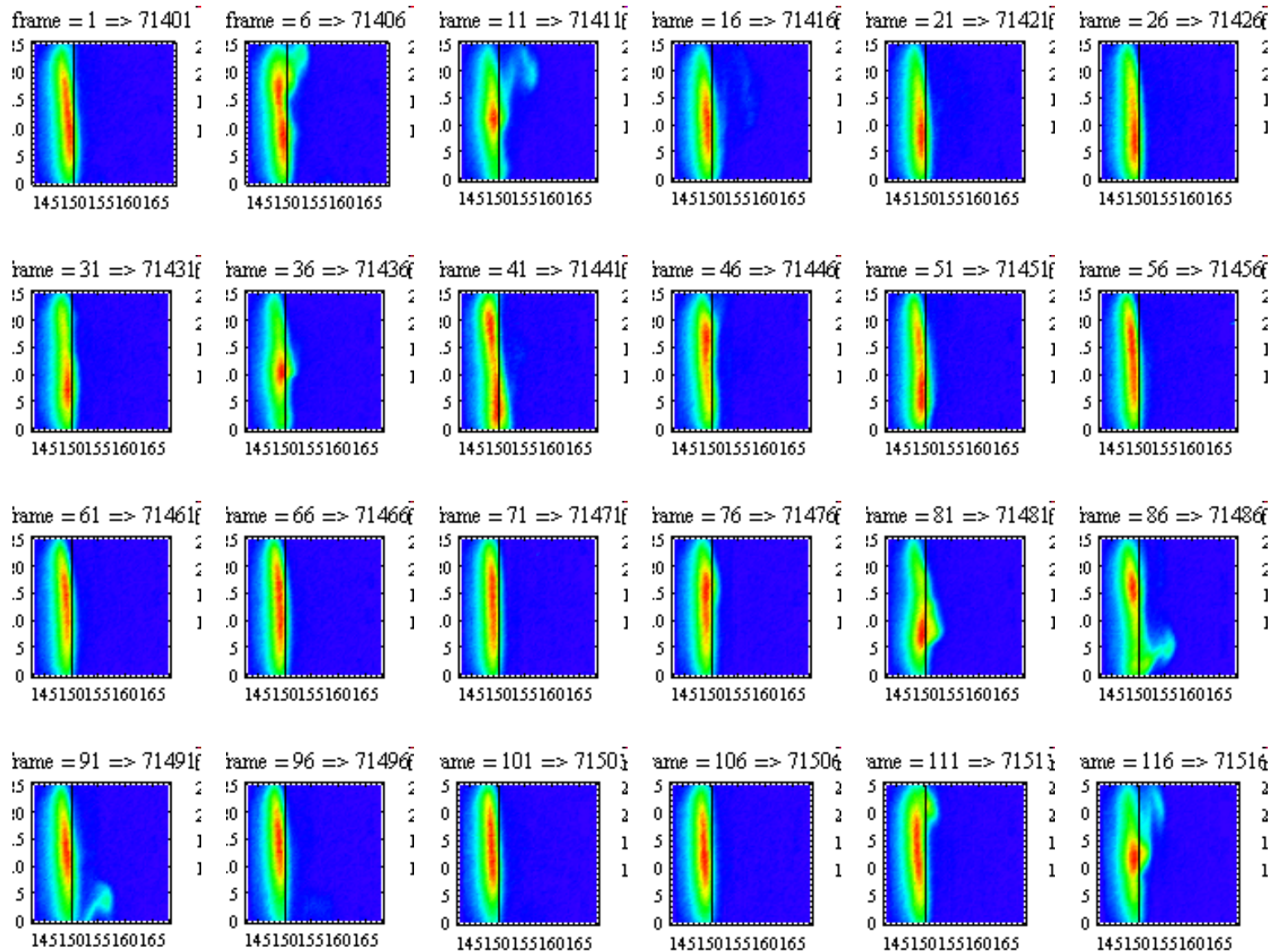
quasi-steady state
(late)

- Experimental GPI data [Maqueda] shows intermittent but very sparse, blob ejection: Is it also driven by transients from the core?

GPI camera data shows sparse intermittent blob ejection

NSTX

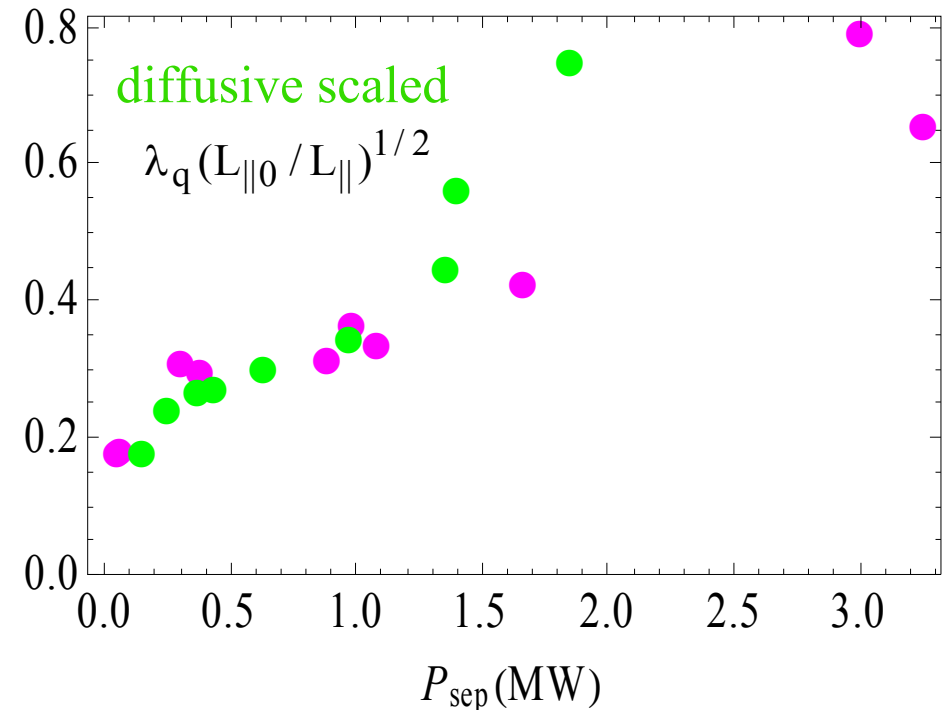
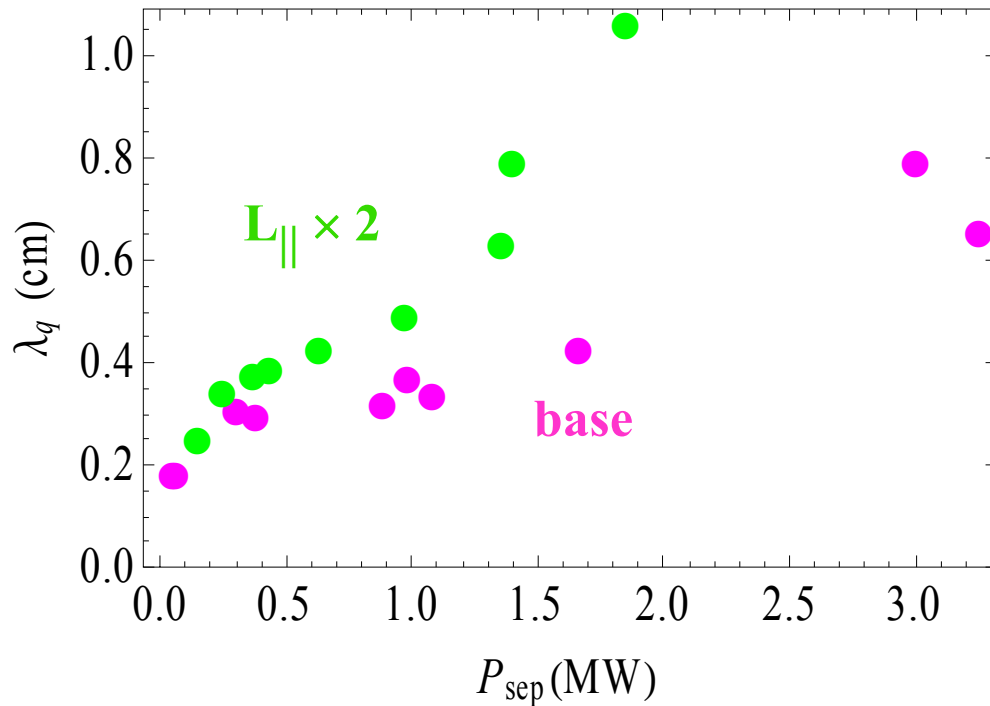
R. Maqueda
#135009



frames shown every 35 μ s for a total duration of 0.84 ms (higher time res. available)

Connection length scaling: simulation and theory

- use previous shot 135009 as a base case
- artificially double $L_{\parallel}(r)$ holding everything else fixed



Transition from diffusive to convective scaling at high power

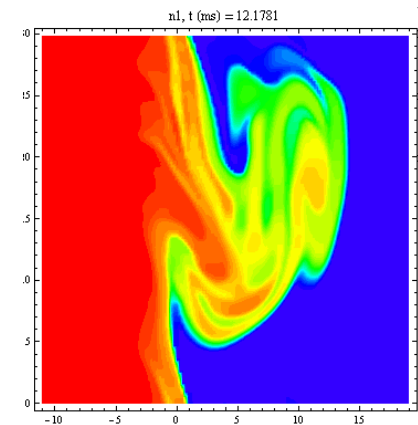
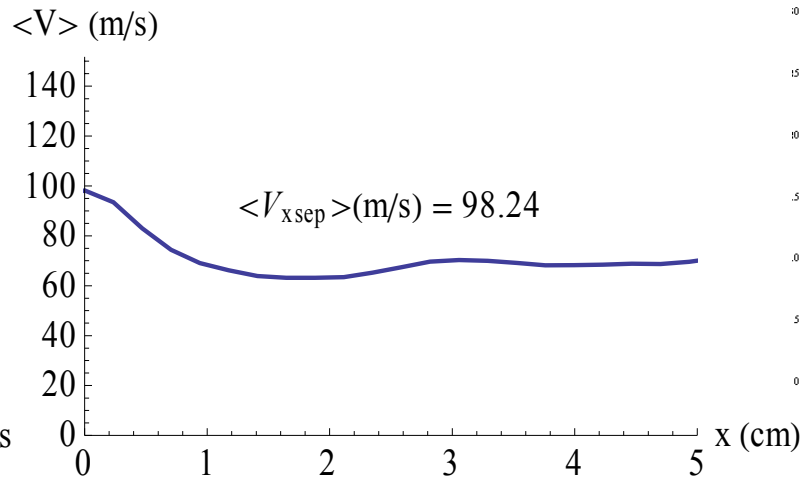
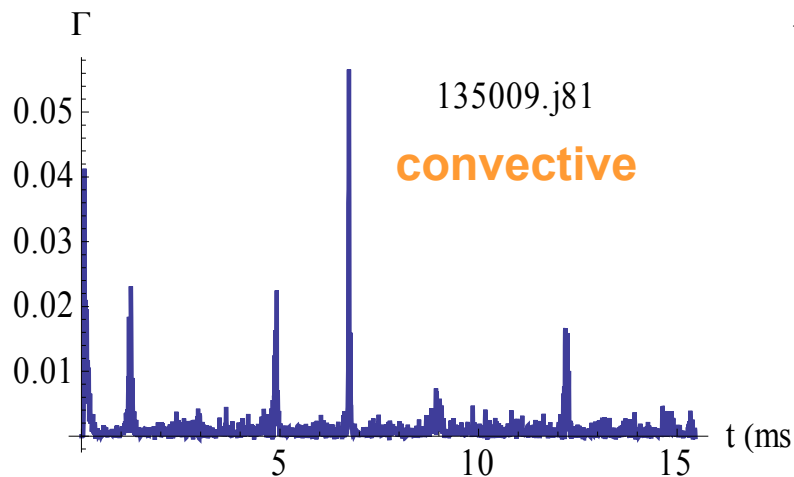
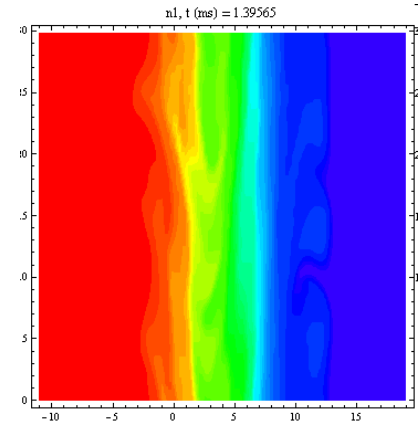
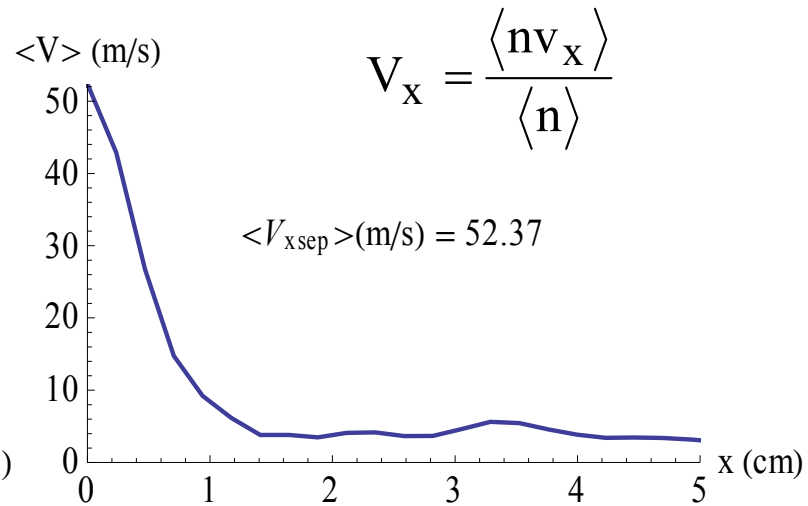
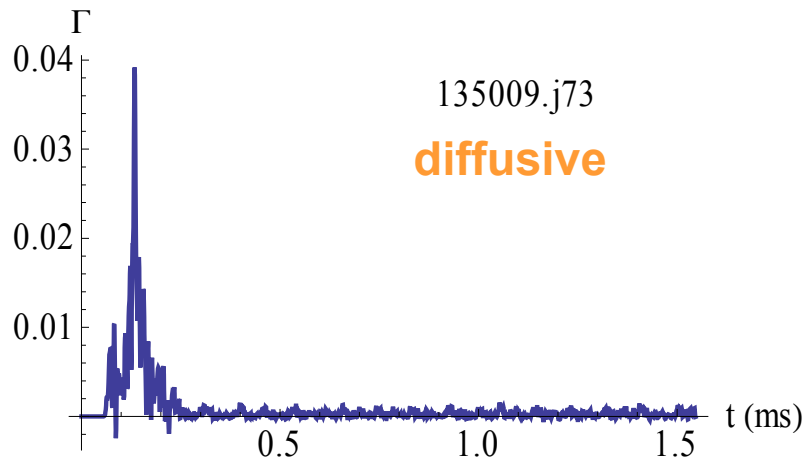
$$\lambda_{\text{diff}} \sim \sqrt{D\tau_{\parallel}} \sim L_{\parallel}^{1/2}$$

$$\lambda_{\text{conv}} \sim V\tau_{\parallel} \sim L_{\parallel}$$

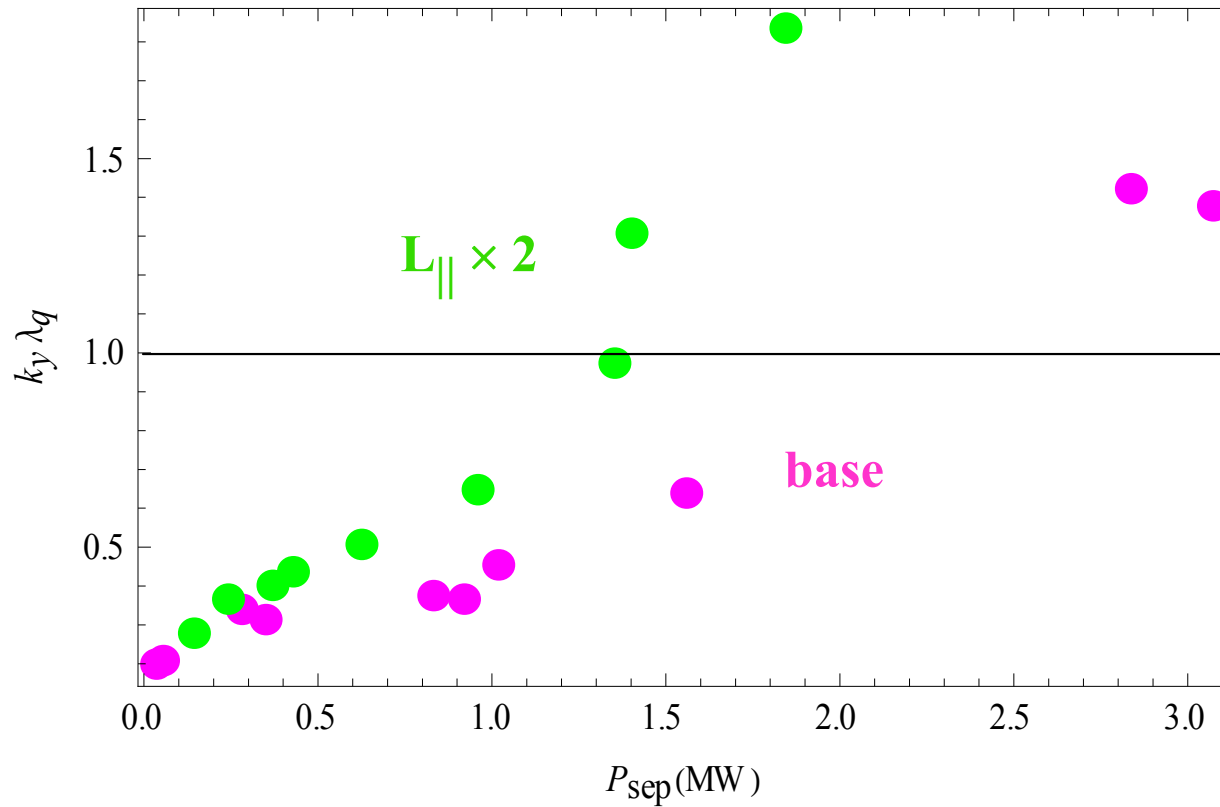
assuming parallel convective limit $\tau_{\parallel} \sim L_{\parallel}/v_{\parallel}$

At the diffusive – convective transition:

- strongly bursty fluxes
- convective velocity $V_x(x)$ flattens
- blob ejection events
- further into convective regime
 - burst frequency f_p increases



Diffusive - convective transition occurs when $k_y \lambda_q > 1$



$$V_x \sim \begin{cases} D \nabla \ln n \sim \frac{\gamma}{k_y^2 L_n} & \text{diffusive} \\ v_b f_p \sim \frac{\gamma}{k_y} f_p & \text{convective} \end{cases}$$

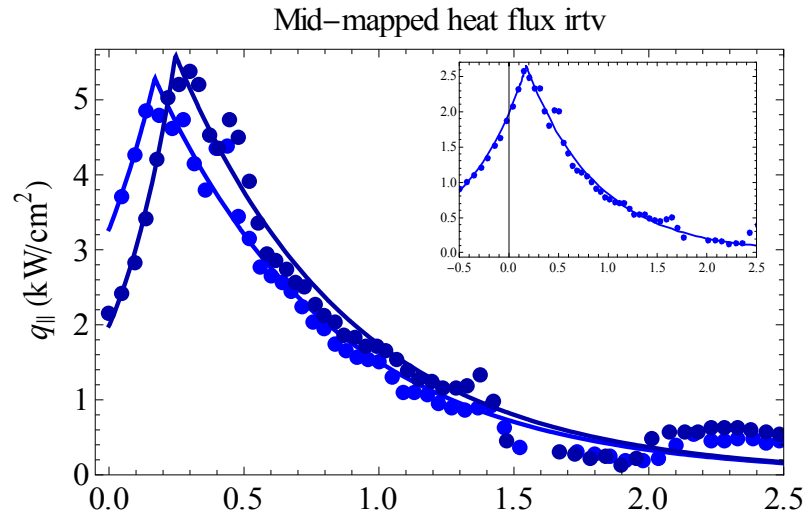
diffusion : convection

$$\frac{1}{k_y L_n} : f_p$$

Current scaling of the power width [R. Maingi - NSTX]

$$P_{nb} = 6 \text{ MW}$$

NSTX IRTV data

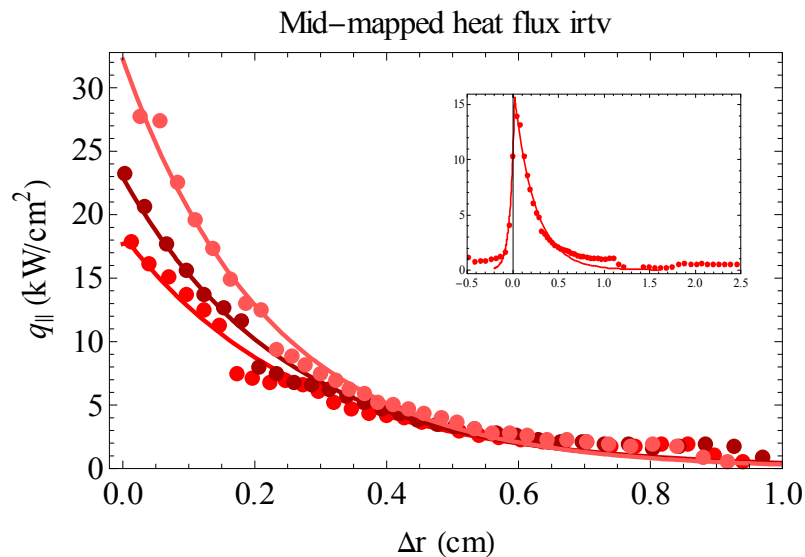


128013 = 0.8 MA

$$\lambda_{q,int} = 1.4 - 2.2 \text{ cm}$$

$$\lambda_{q,exp} = 0.64 - 0.66 \text{ cm}$$

$$\lambda_{q,int} \equiv \frac{P_{sep}}{2\pi R b_{\theta} q_{||peak}}$$

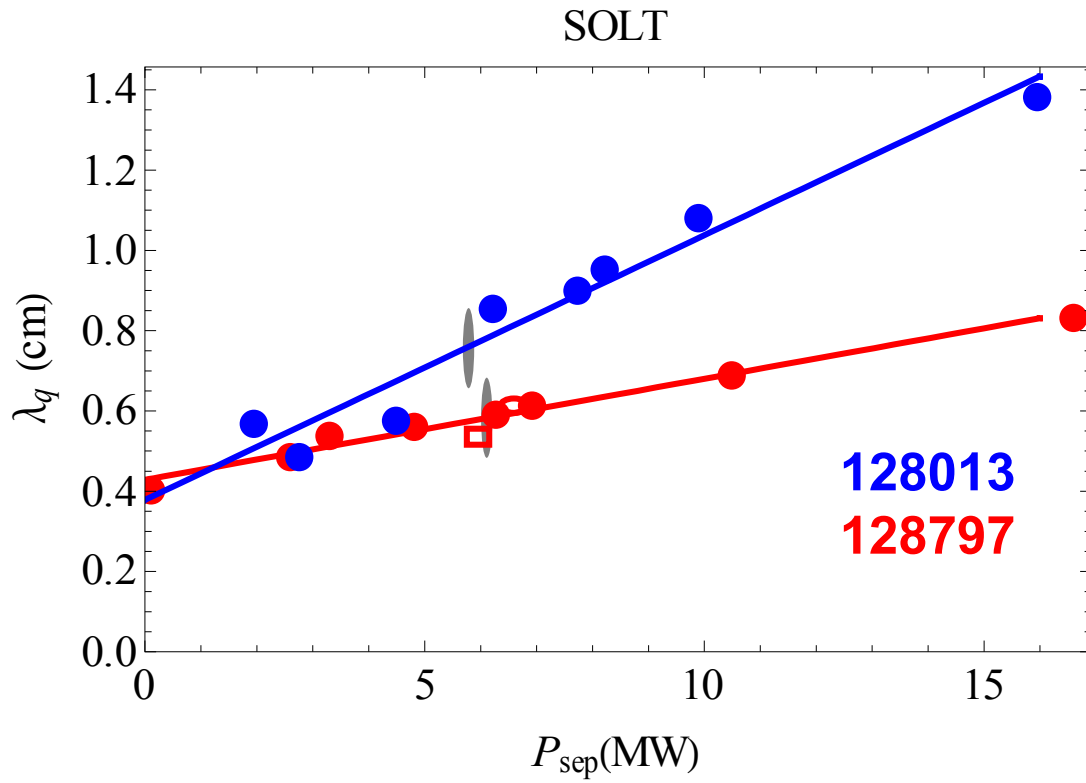


128797 = 1.2 MA

$$\lambda_{q,int} = 0.48 - 0.63 \text{ cm}$$

$$\lambda_{q,exp} = 0.21 - 0.27 \text{ cm}$$

SOLT and NSTX exhibit different scalings with I_p



- $L_{||}(r)$ and pedestal n_e , T_e profiles different for the 2 shots
- small differences in P , B_t , B_p

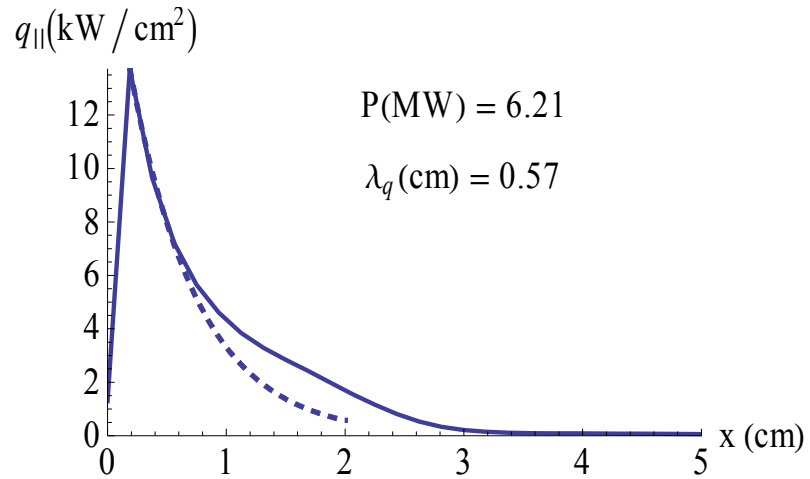
NSTX IRTV
SOLT

**SOL width:
simulation vs.
experiment**

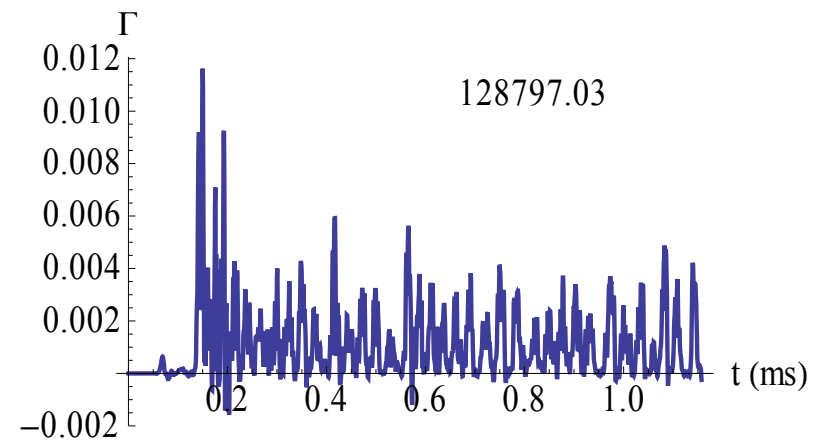
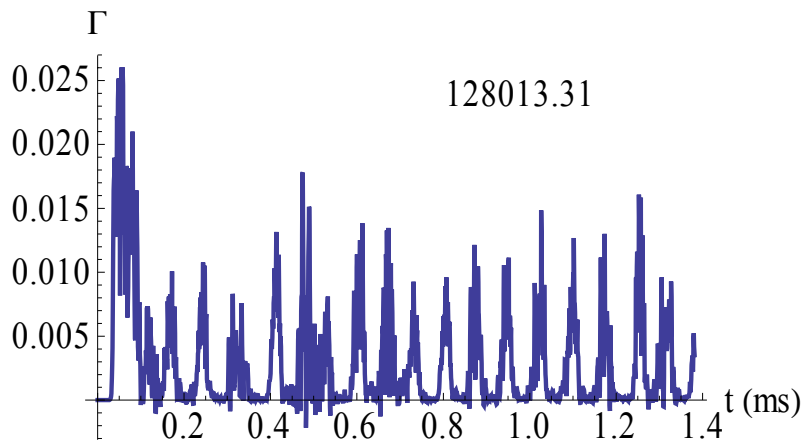
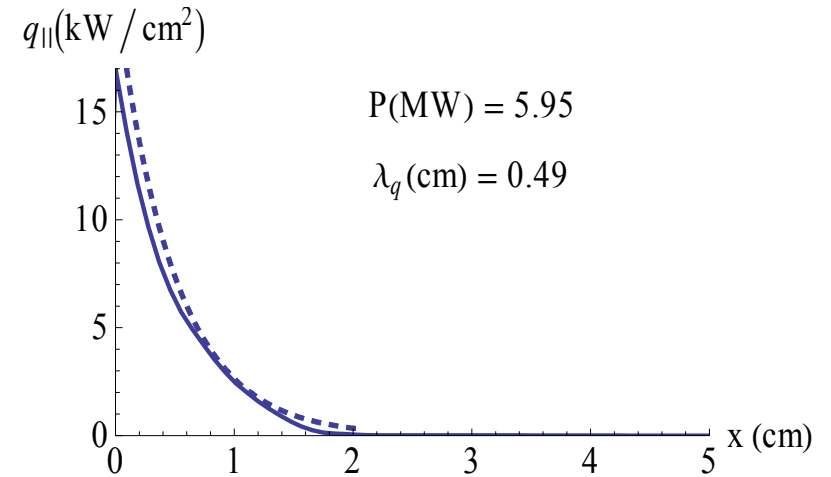
shot	I_p (MA)	P (MW)	$\lambda_{q,exp}$	$\lambda_{q,int}$	$\lambda_{q,int}$
128013	0.8	5.8	0.65	1.73	0.76
128797	1.2	6.1	0.24	0.56	0.58
ratio			2.7	3.1	1.3

SOLT suggests start of diffusive-convective transition at low I_p

128013 = 0.8 MA

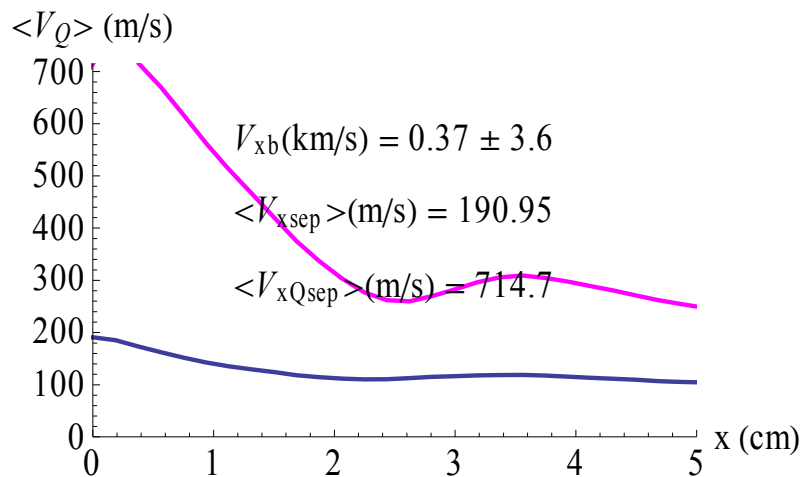


128797 = 1.2 MA

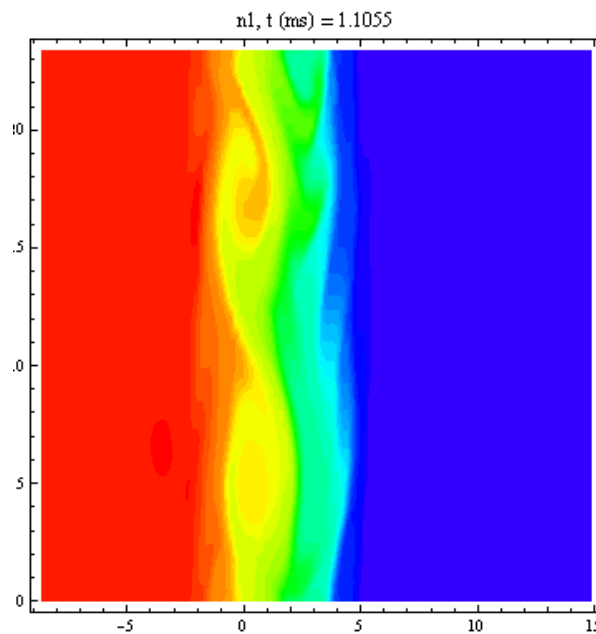
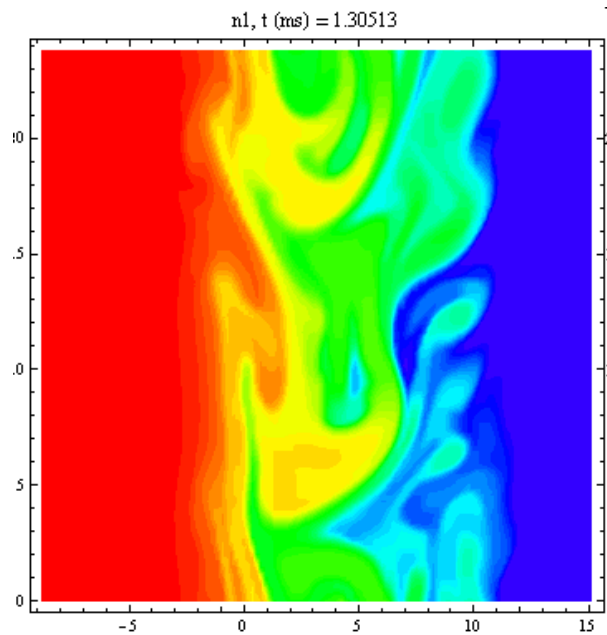
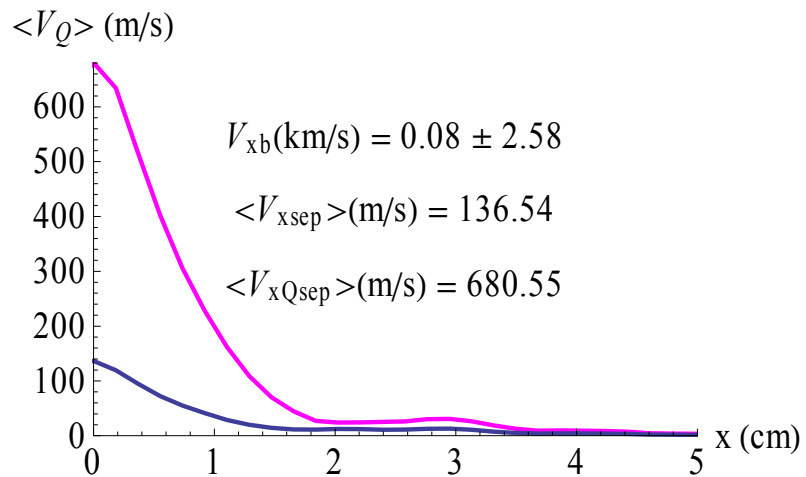


... also evident in convective velocity profile and turbulent snapshots

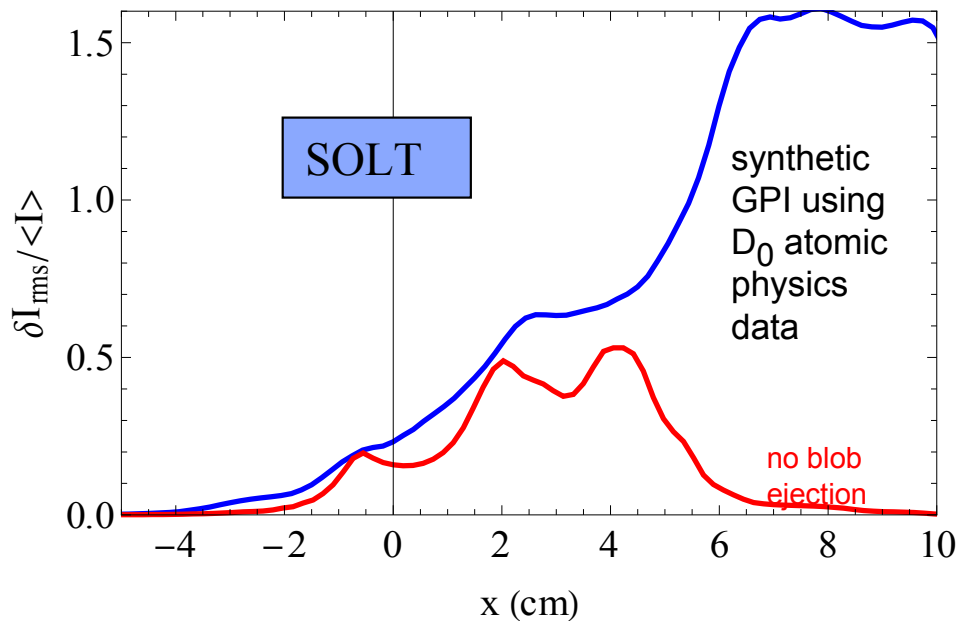
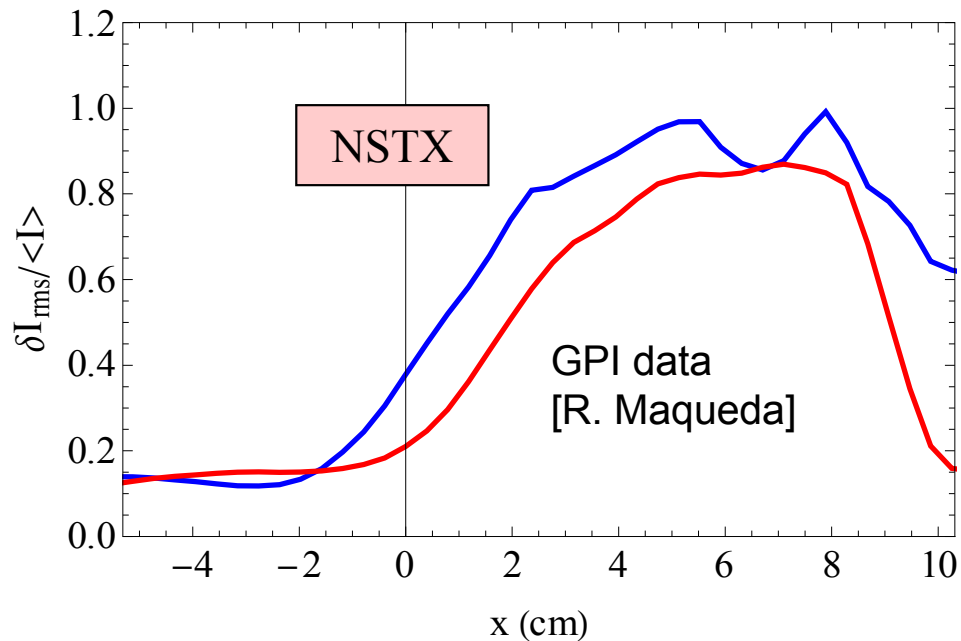
128013 = 0.8 MA



128797 = 1.2 MA



NSTX GPI data vs. SOLT simulation



- 128013 (& 128014) $I_p = 0.8$ MA
- 128808 (for 128797) $I_p = 1.2$ MA
- midplane turbulence levels as characterized by $\delta I / \langle I \rangle$ are similar for the 2 shots in both NSTX and SOLT
 - skewness $S(x)$ also similar
- suggests that λ_q differences are not due to midplane turbulence
- caveats
 - hot ions
 - downstream / sheath conditions
 - MHD activity

Summary

- SOLT 2D fluid simulations calculate midplane SOL profiles and SOL widths in an electrostatic model
 - important inputs are P_{sep} , L_{\parallel}/R , and Λ (or v_{e*})
 - intermittent separatrix-spanning convective cells dominate the near-SOL width
 - blob ejection in H-mode simulations is typically triggered by transients
- Comparison with experiment for n_e , T_e and q_{\parallel} data in low-power ELM-free H-mode suggests that midplane turbulence is the main contributor to the λ_q width in this scenario
- A transition from diffusive to convective near SOL width is predicted theoretically for critical parameters (P_{sep} , L_{\parallel})
- The experimentally (NSTX) observed strong I_p scaling of λ_q is NOT seen in SOLT simulations suggesting the importance of other mechanisms (e.g. MHD, X-pt motion, divertor leg instabilities)