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

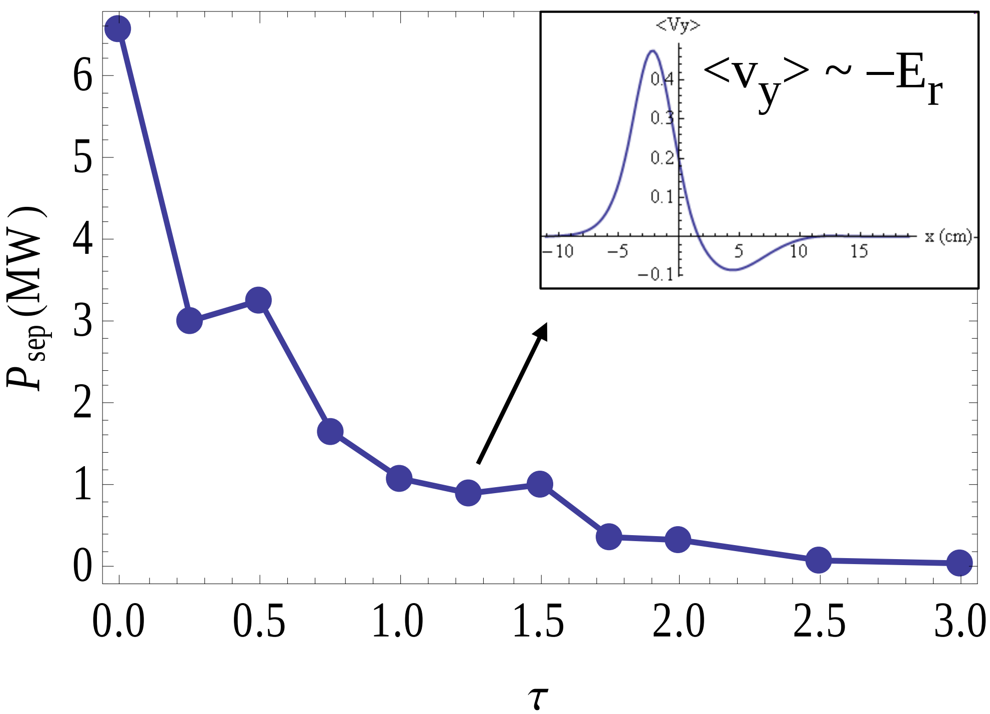
- the SOLT code
- low power ELM-free H-mode (NSTX)
- $L_{||}$ scaling: simulation and theory
- I_p scaling (NSTX)

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_{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 ⇒ 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}
- SOLT P_{sep} scans hold core profiles fixed

⇒ **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 $L_{||}(r)$
  - plasma profiles inside LCS $n_e(r)$, $T_e(r) \Rightarrow$ gradient drive, collisionality regime Λ (or ν_{e*})
  - effective curvature R; B_t, B_p
- other input
  - dissipation parameters: viscosity, ZF damping
  - downstream / sheath conditions at divertor plate
- output
  - $\langle q_{||}(r) \rangle$, and heat flux width λ_q
  - $V_x = \langle nv_x \rangle / \langle n \rangle$ (or $\langle nTv_x \rangle / \langle nT \rangle$)
  - $n_e(r)$, $T_e(r)$ SOL
  - 2D turbulence snapshots or movies

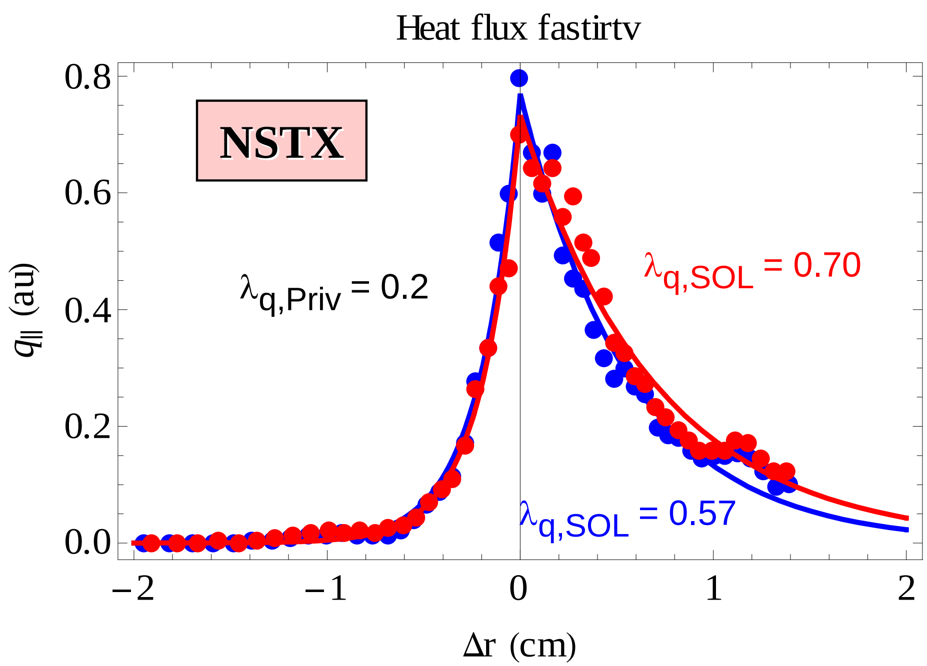
} compare with experiment:

probes, GPI, divertor IRTV (midplane mapped)

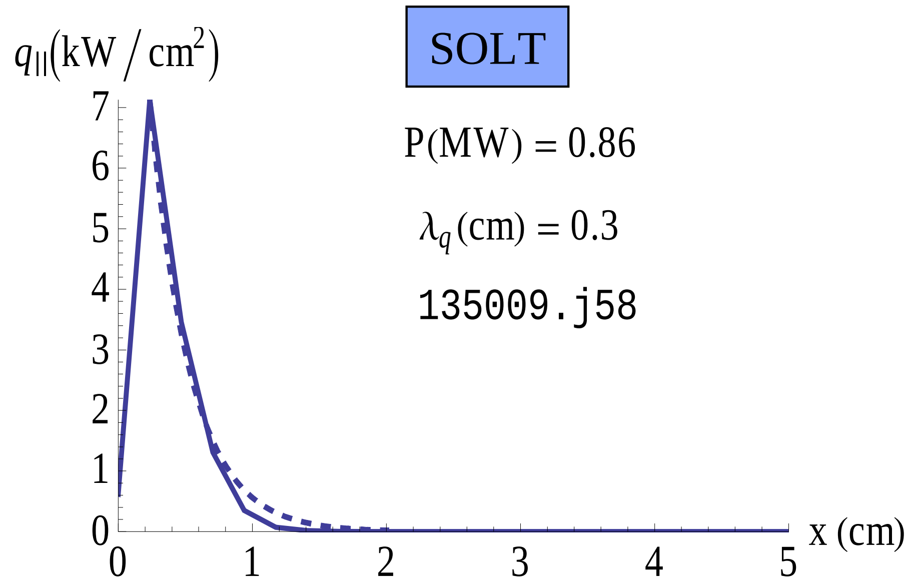
Low power ELM-free H-mode [J. W. Ahn - NSTX]

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

experimental heat flux



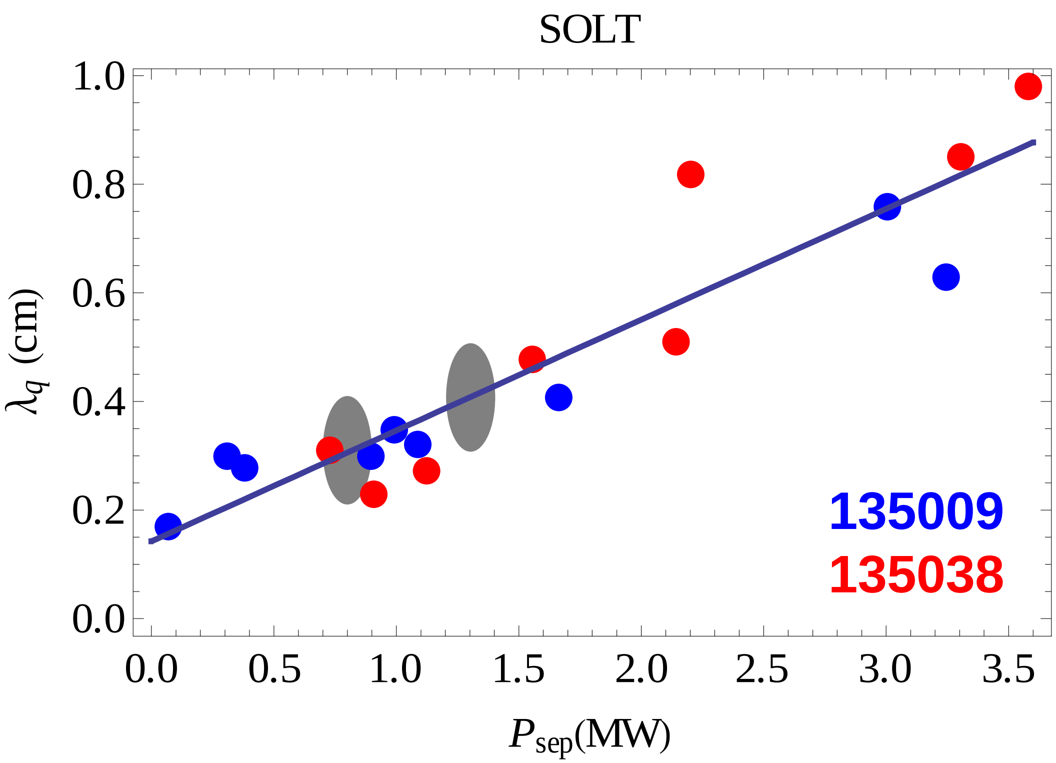
divertor data midplane mapped (dots) exponential fits (solid)



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

SOL width: simulation vs. experiment

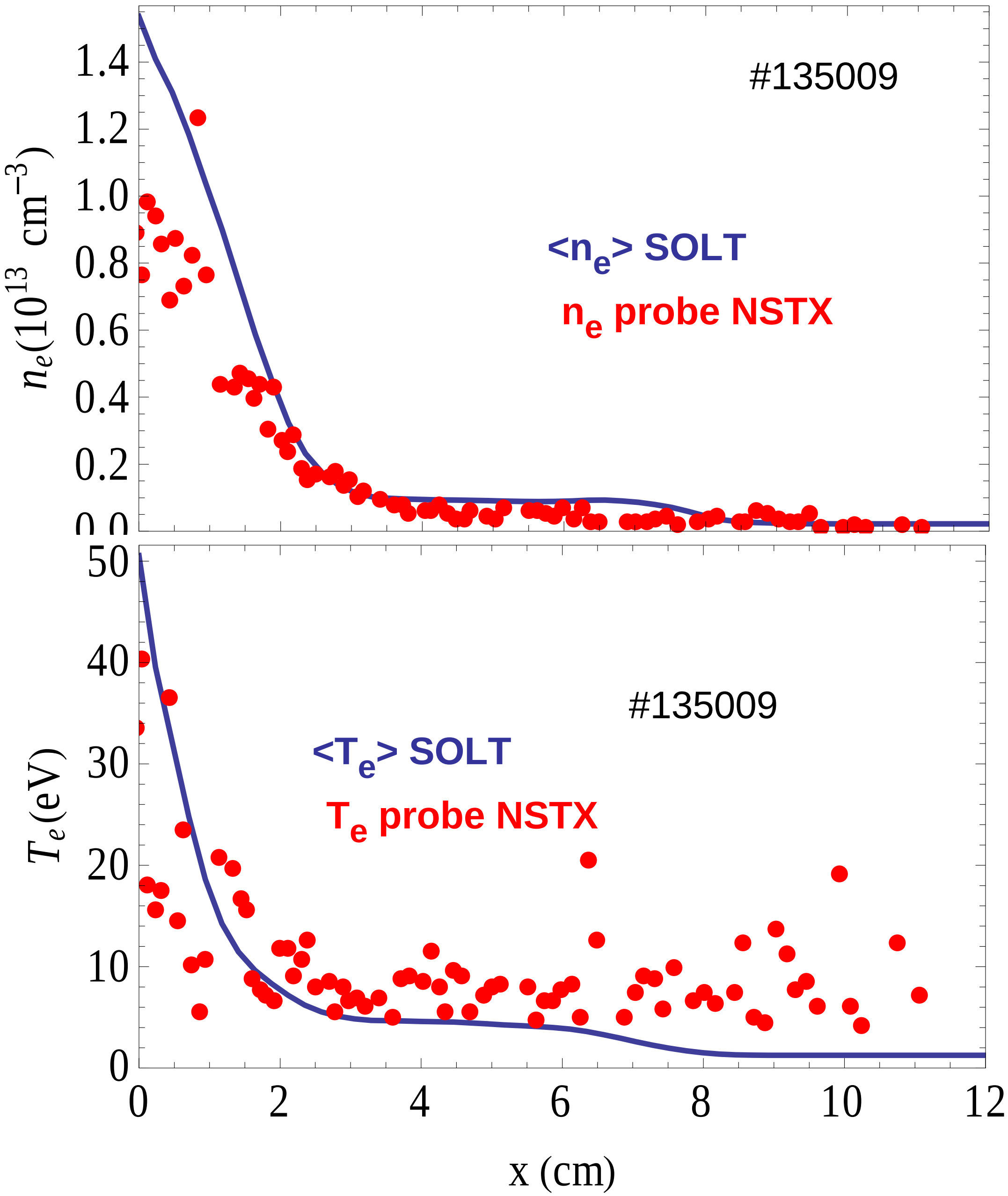
subtract X-pt to plate broadening

NSTX IRTV

SOLT

shot	P(MW)	$\lambda_{q,SOL}$(cm)	$\lambda_{q,Priv}$ (cm)	$\lambda_{q,SOL}$ - $\lambda_{q,Priv}$(cm)	λ_q (cm)
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



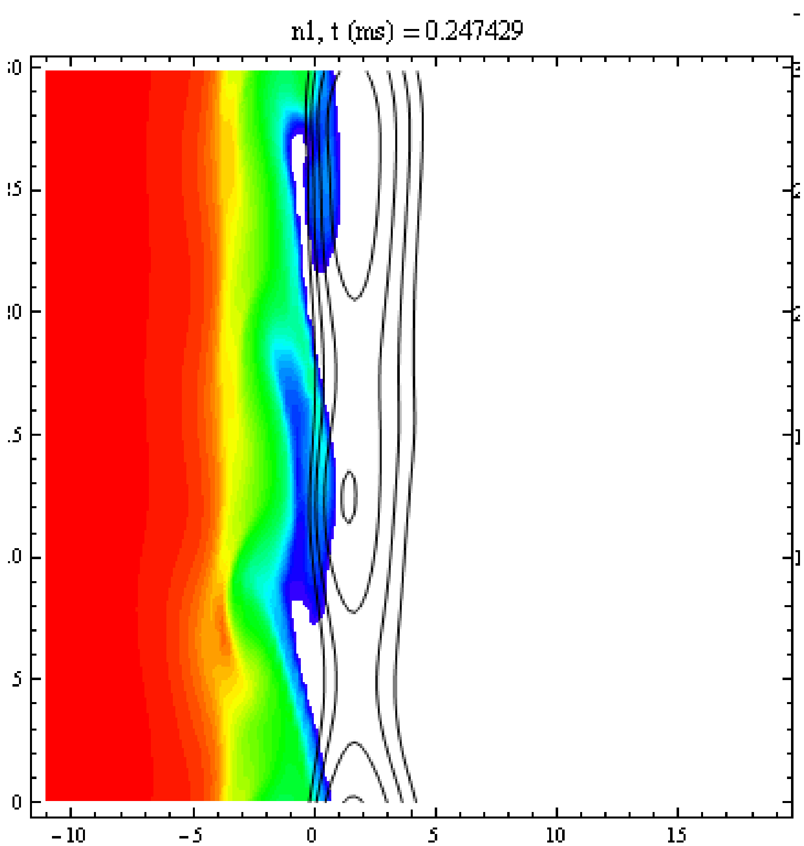
- NSTX shot #135009
- midplane probe data [Ahn]

- SOLT overestimates near-SOL n_e (omits 3D effect of parallel sonic expansion)

- far SOL T_e discrepancy – far SOL $L_{||}$ 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 ⇒ SOL width



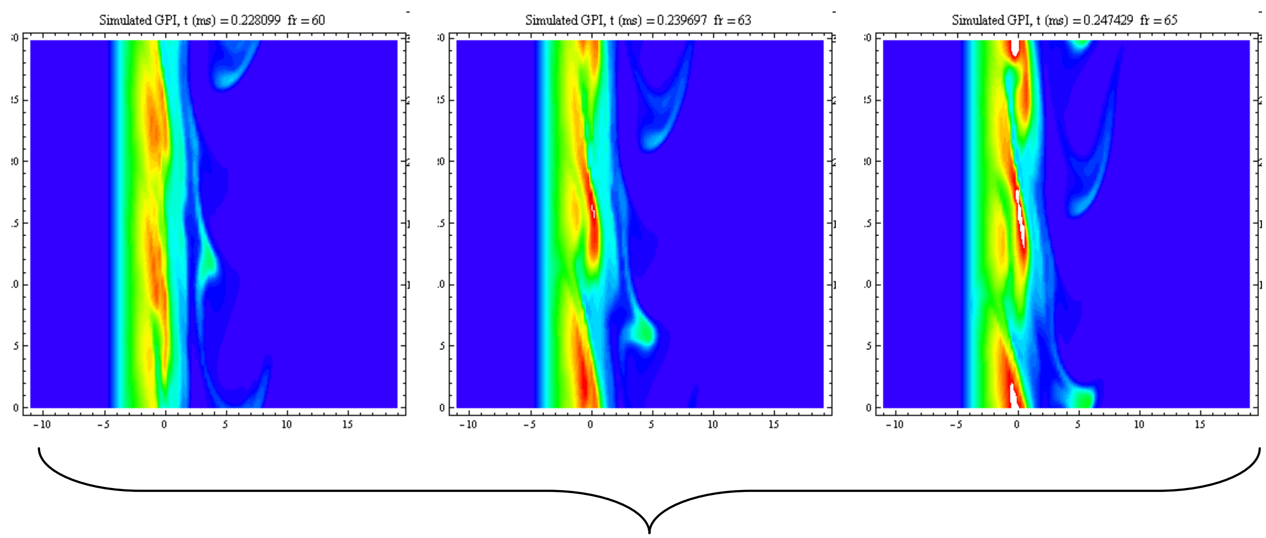
turbulent snapshot

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

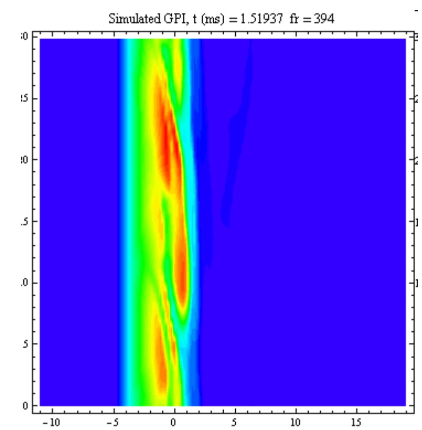
Simulated GPI – NSTX 135009

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)



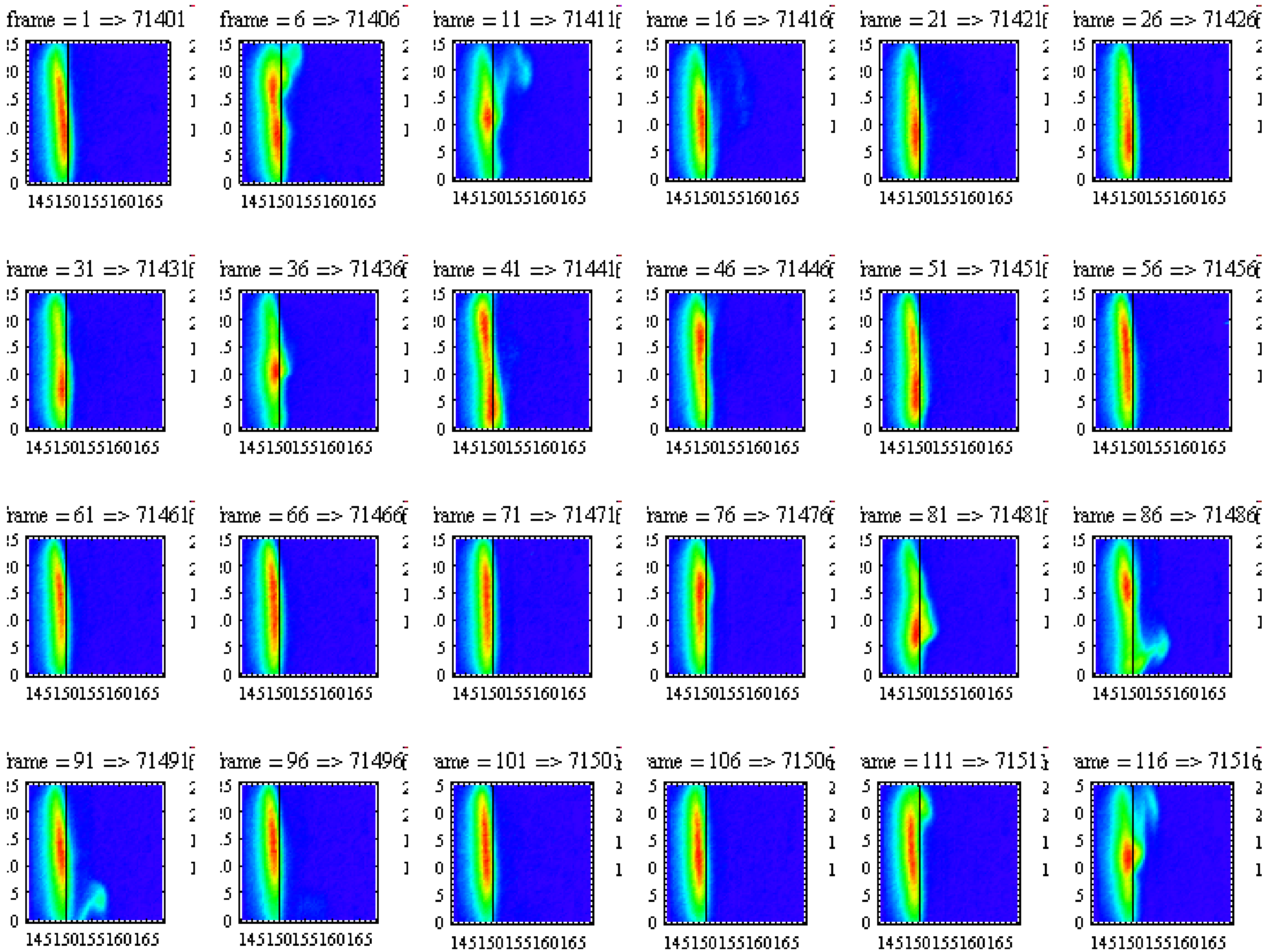
quasi-steady state
(late)

- 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

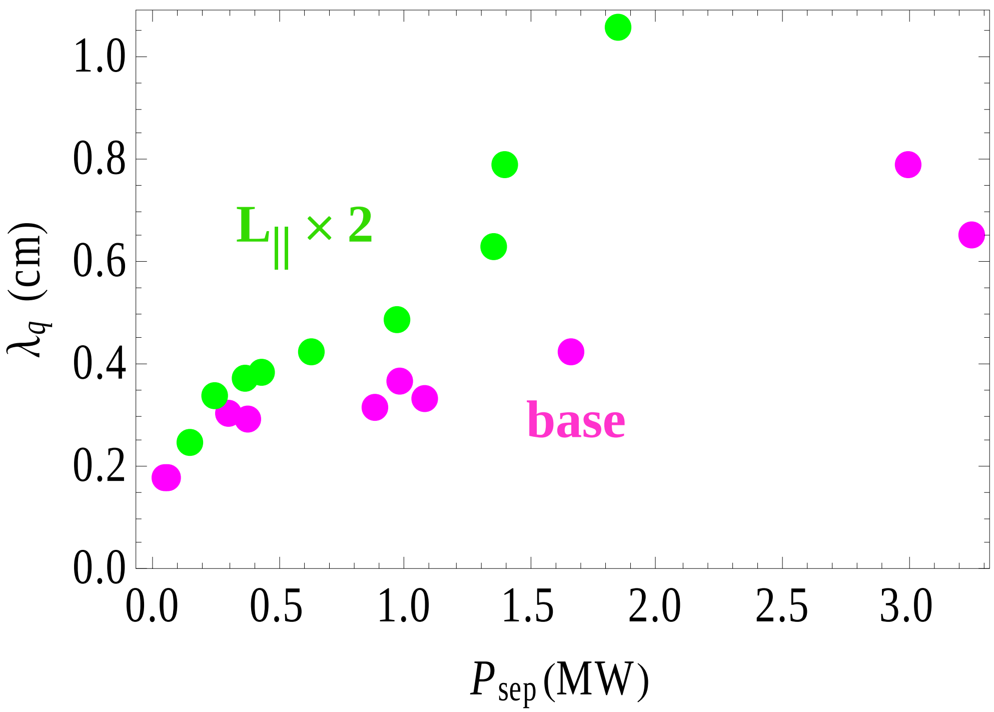
R. Maqueda
#135009

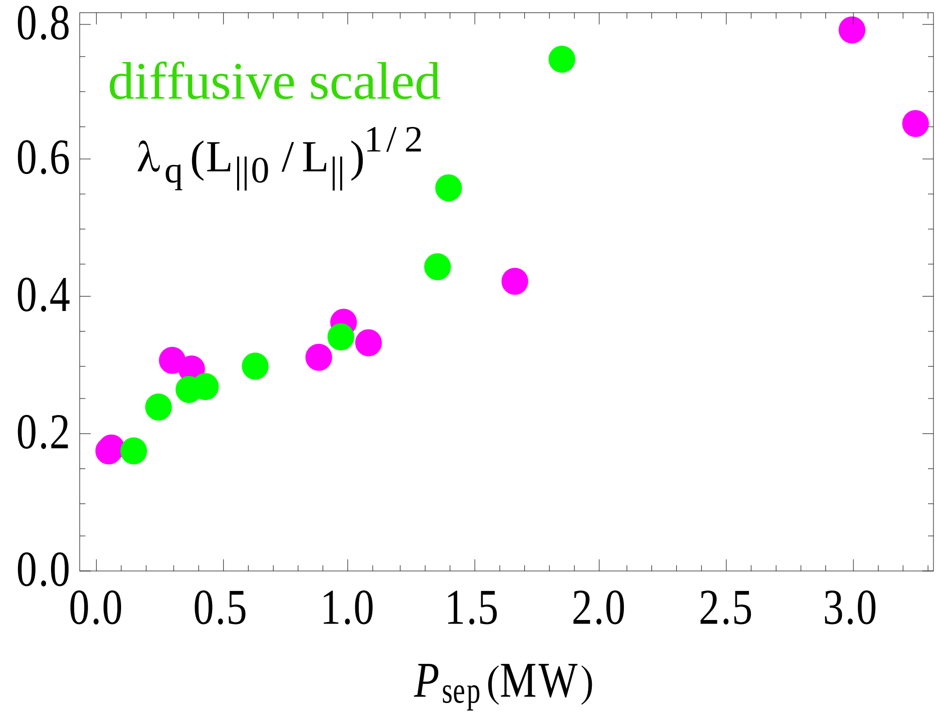


frames shown every 35 μs for a total duration of 0.84 ms (higher time res. available)

Connection length scaling: simulation and theory

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





Transition from diffusive to convective scaling at high power

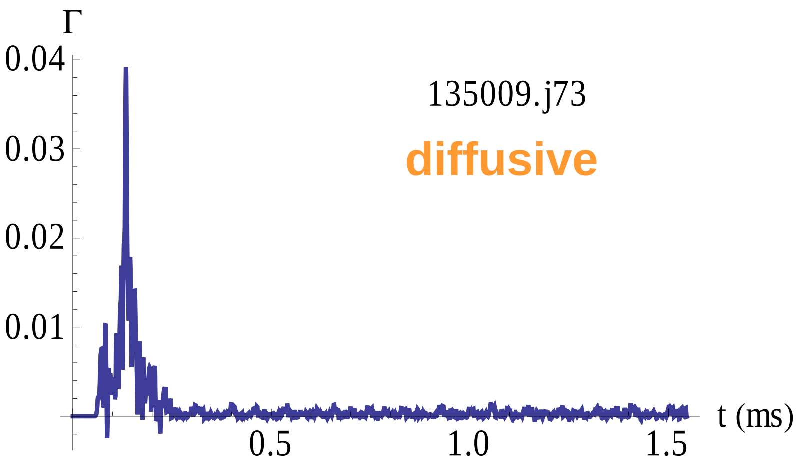
$\lambda_{diff} \sim \sqrt{D\tau_{||}} \sim L_{||}^{1/2}$ $\lambda_{conv} \sim V\tau_{||} \sim L_{||}$ assuming parallel convective limit $\tau_{||} \sim L_{||}/v_{||}$

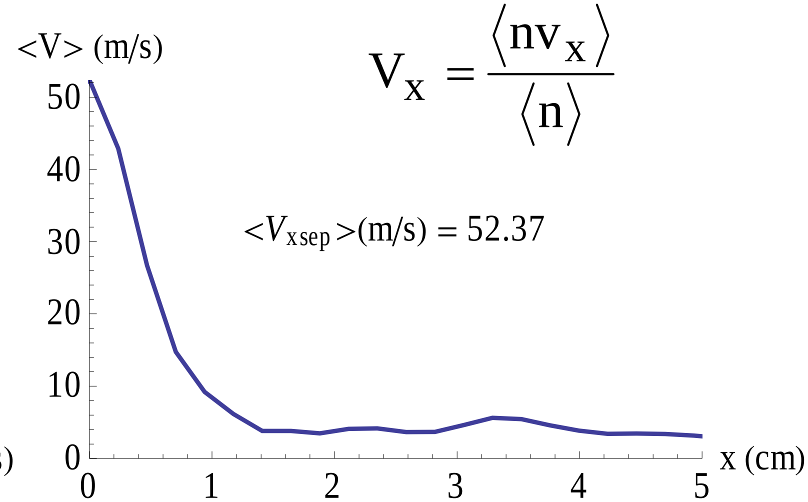
At the diffusive – convective transition:

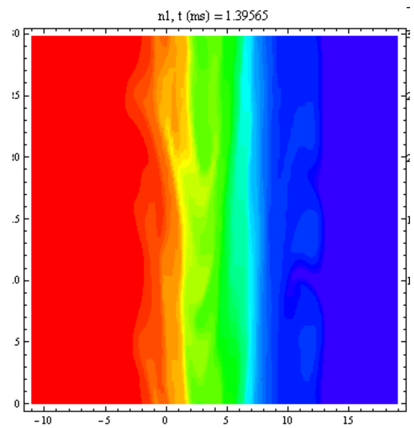
- strongly bursty fluxes
- convective velocity $V_x(x)$ flattens
- blob ejection events

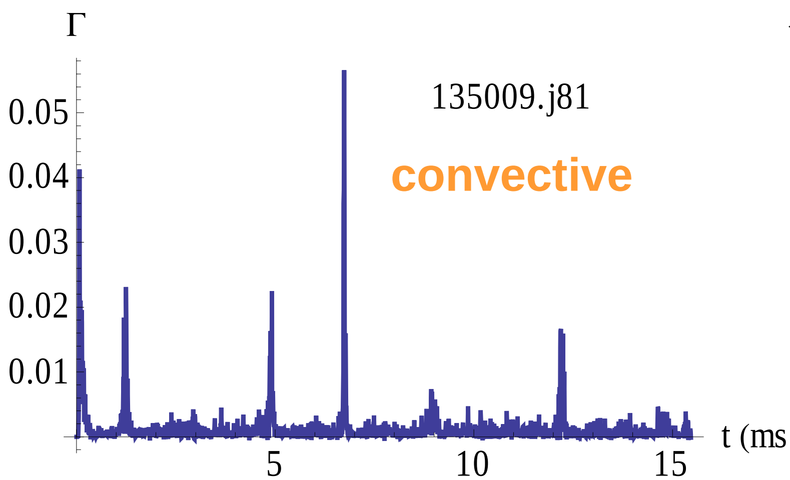
- further into convective regime
  - burst frequency f_p increases

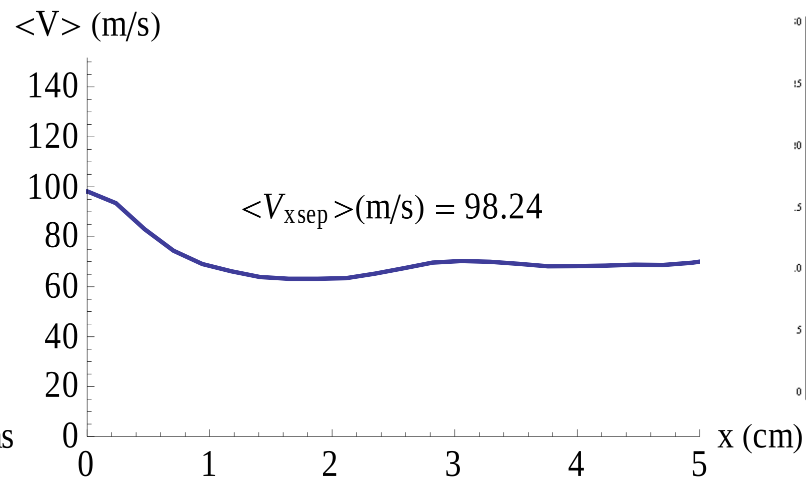
$$V_x = \frac{\langle n v_x \rangle}{\langle n \rangle}$$

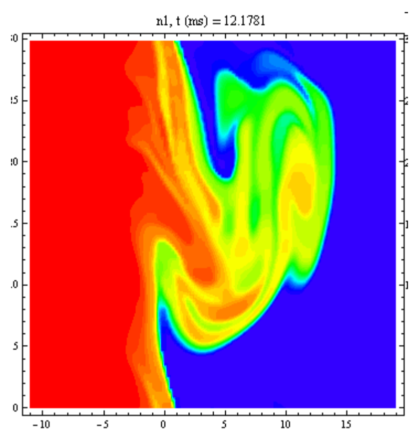




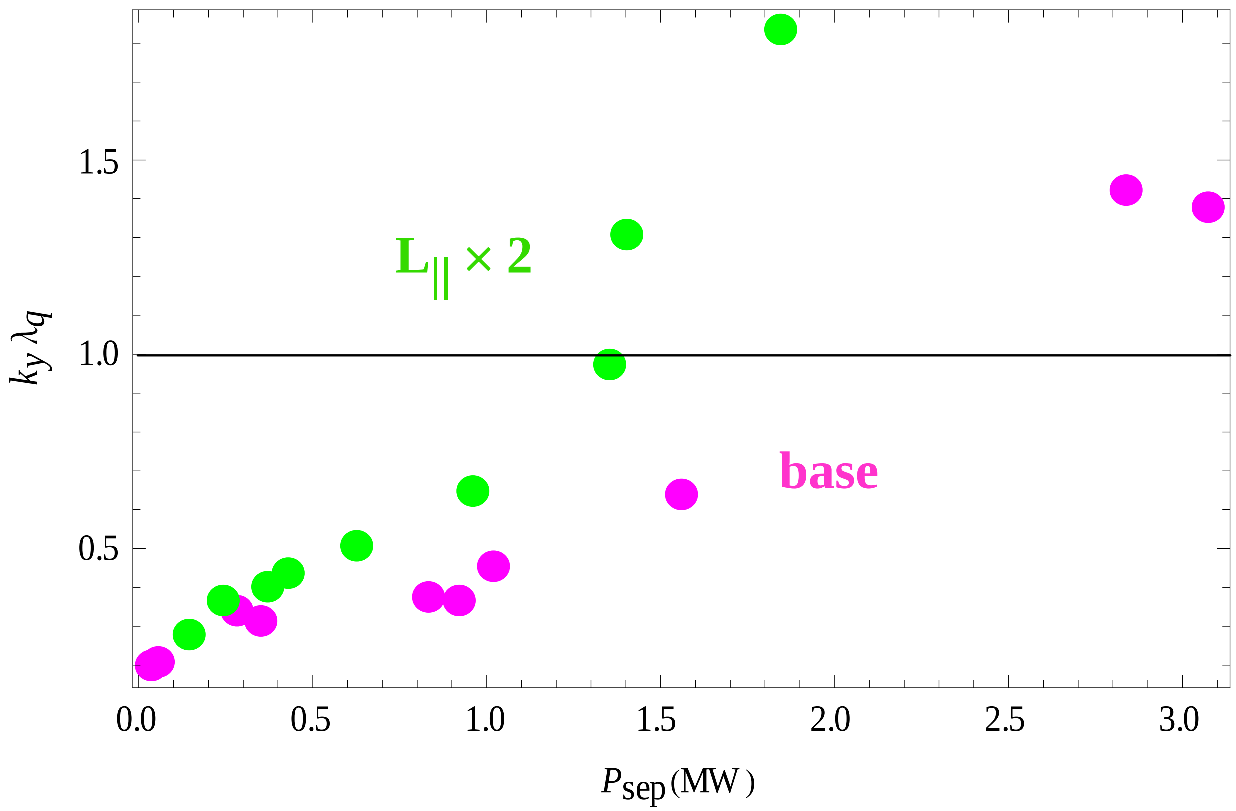








Diffusive - convective transition occurs when $k_y \lambda_q > 1$



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

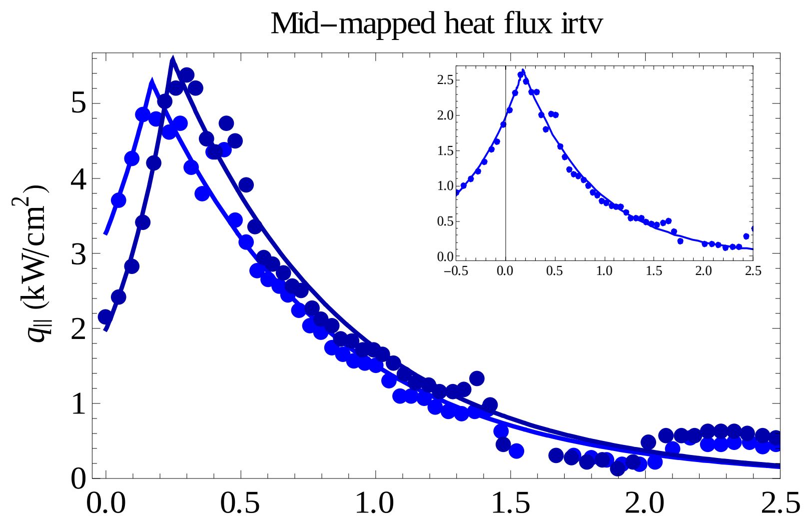
diffusion : convection

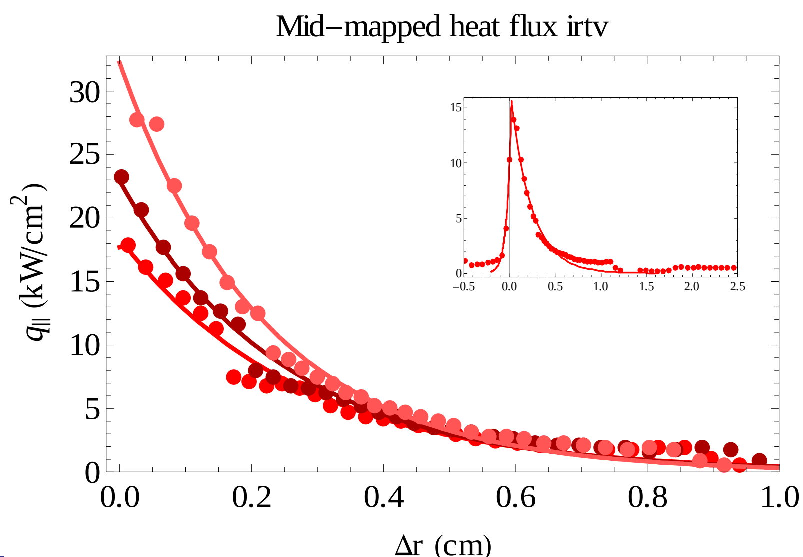
$$\frac{1}{k_y L_n} : f_p$$

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

P_{nb} = 6 MW

NSTX IRTV data





128013 = 0.8 MA

$\lambda_{q,int}$ = 1.4 – 2.2 cm

$\lambda_{q,exp}$ = 0.64 – 0.66 cm

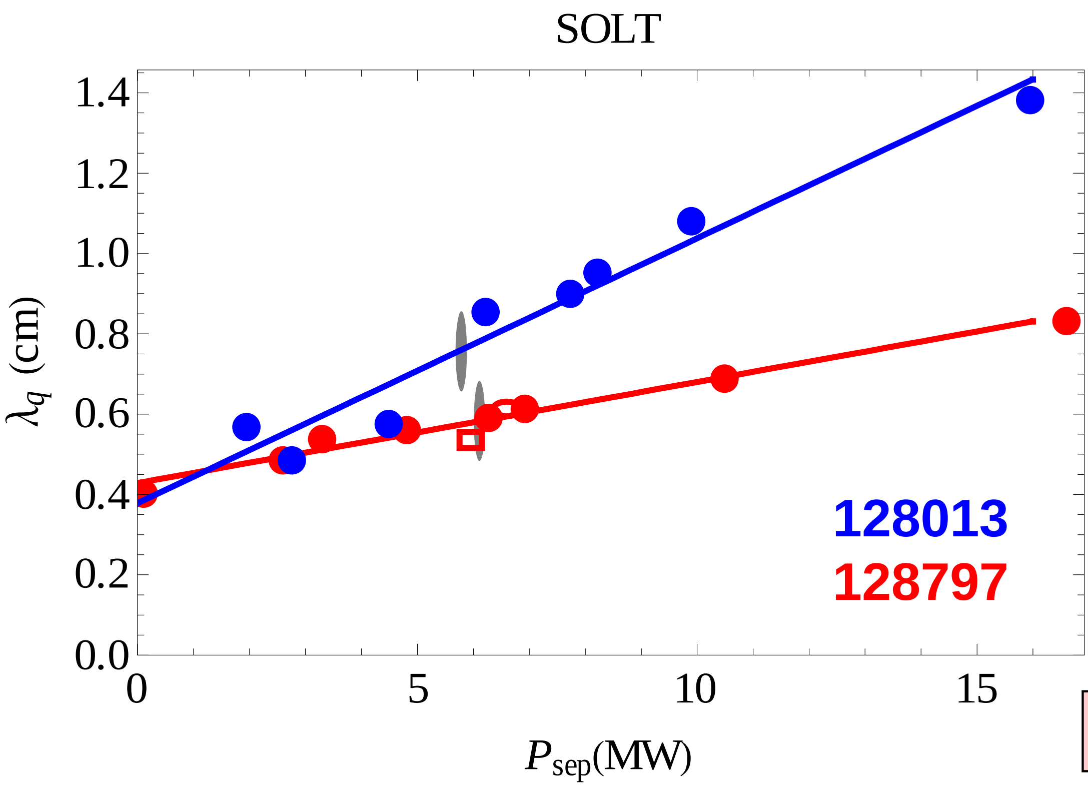
$$\lambda_{q,int} \equiv \frac{P_{sep}}{2\pi R b_\theta q_{||peak}}$$

128797 = 1.2 MA

$\lambda_{q,int}$ = 0.48 – 0.63 cm

$\lambda_{q,exp}$ = 0.21 – 0.27 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

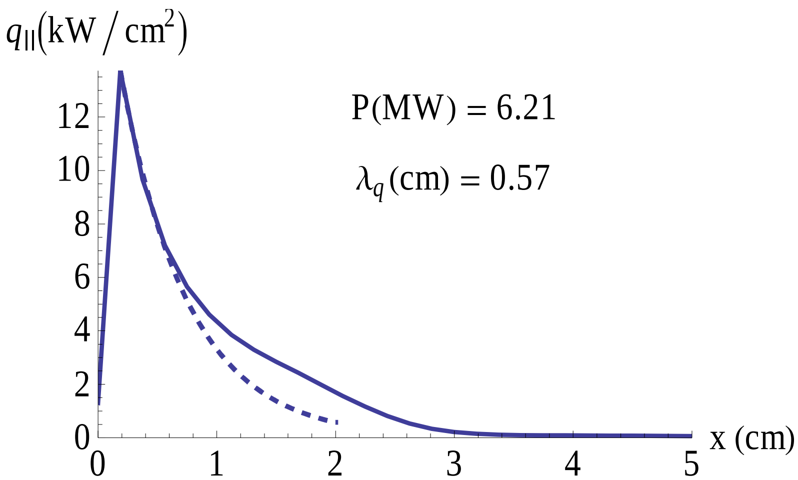
SOL width: simulation vs. experiment

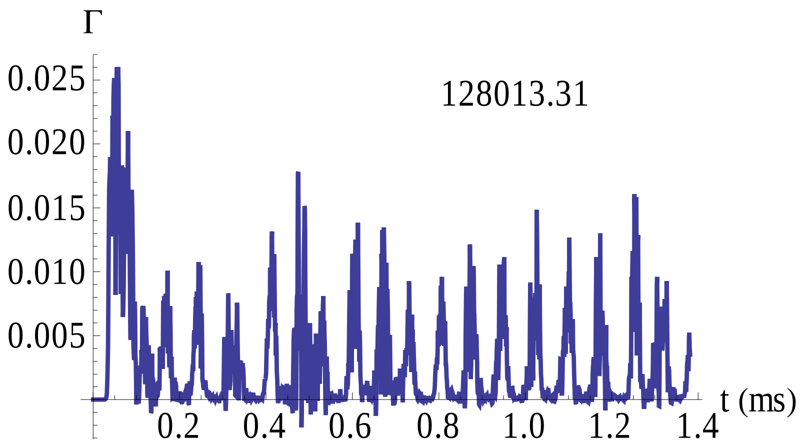
NSTX IRTV (shot, I_p, P, $\lambda_{q,exp}$, $\lambda_{q,int}$) — SOLT ($\lambda_{q,int}$)

shot	I_p(MA)	P(MW)	$\lambda_{q,exp}$ (cm)	$\lambda_{q,int}$ (cm)	$\lambda_{q,int}$ (cm)
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**

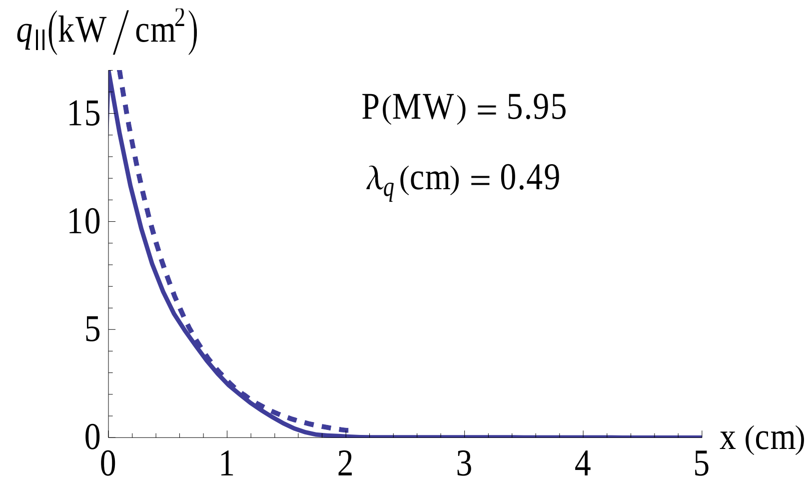
SOLT suggests start of diffusive-convective transition at low I_p

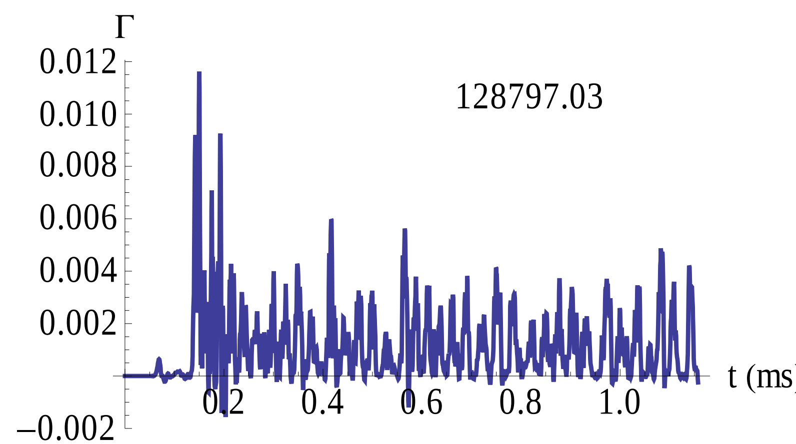
128013 = 0.8 MA





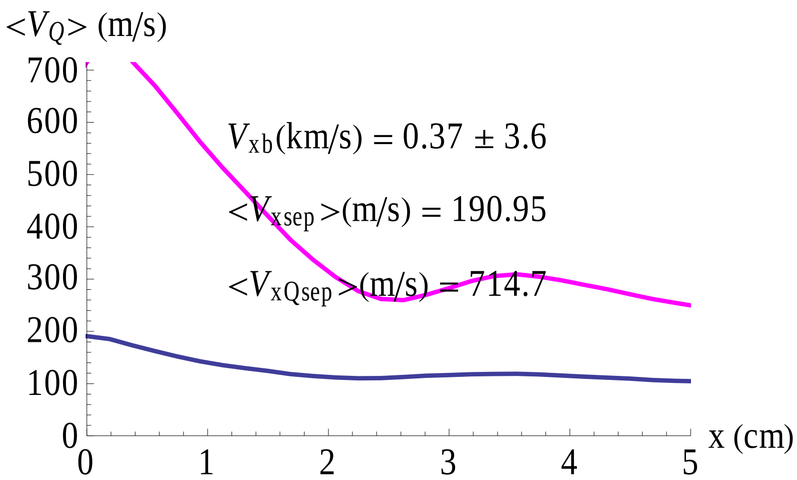
128797 = 1.2 MA

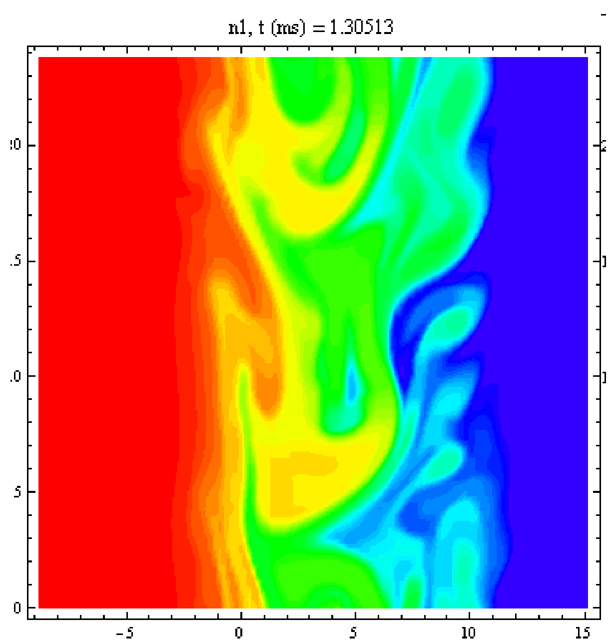




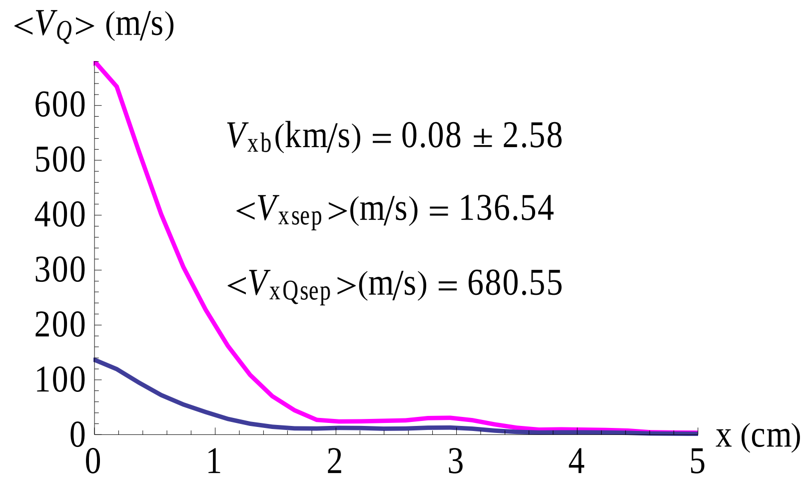
… also evident in convective velocity profile and turbulent snapshots

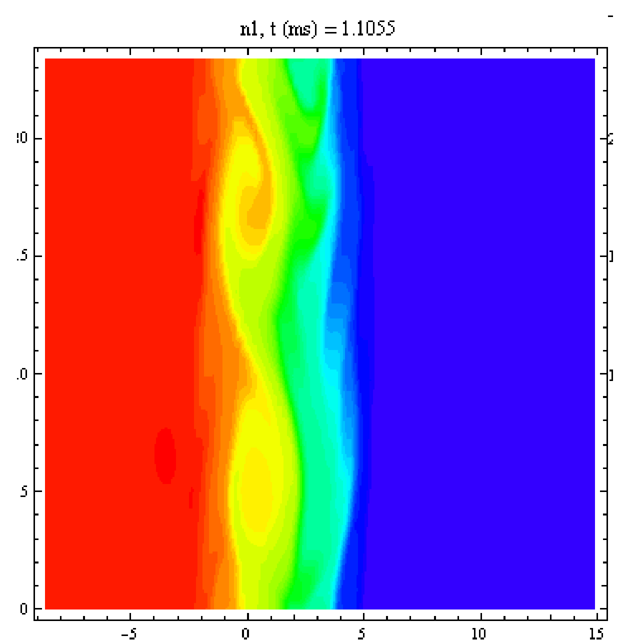
128013 = 0.8 MA



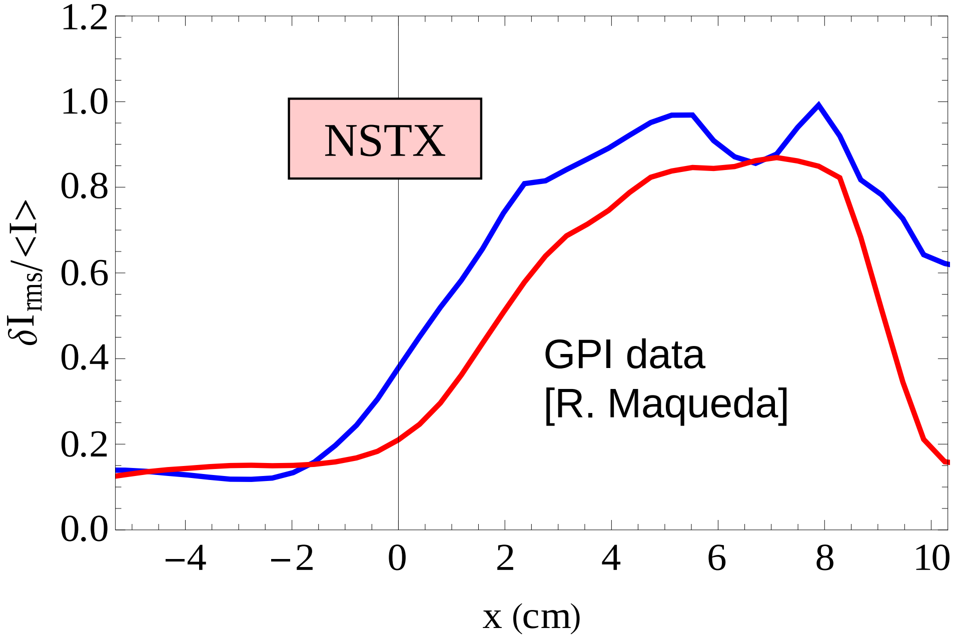


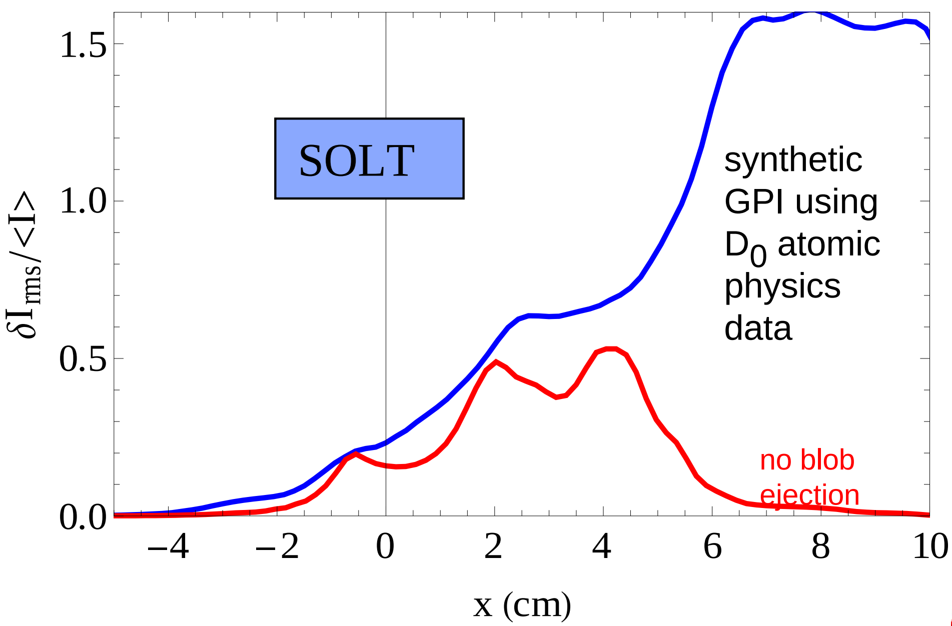
128797 = 1.2 MA





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 δI/<I> 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}, $L_{||}/R$, and Λ (or ν_{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 $q_{||}$ 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}, $L_{||}$)
- 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)