Reduced-model (SOLT) simulations of an EDA H-mode shot at C-Mod[†]

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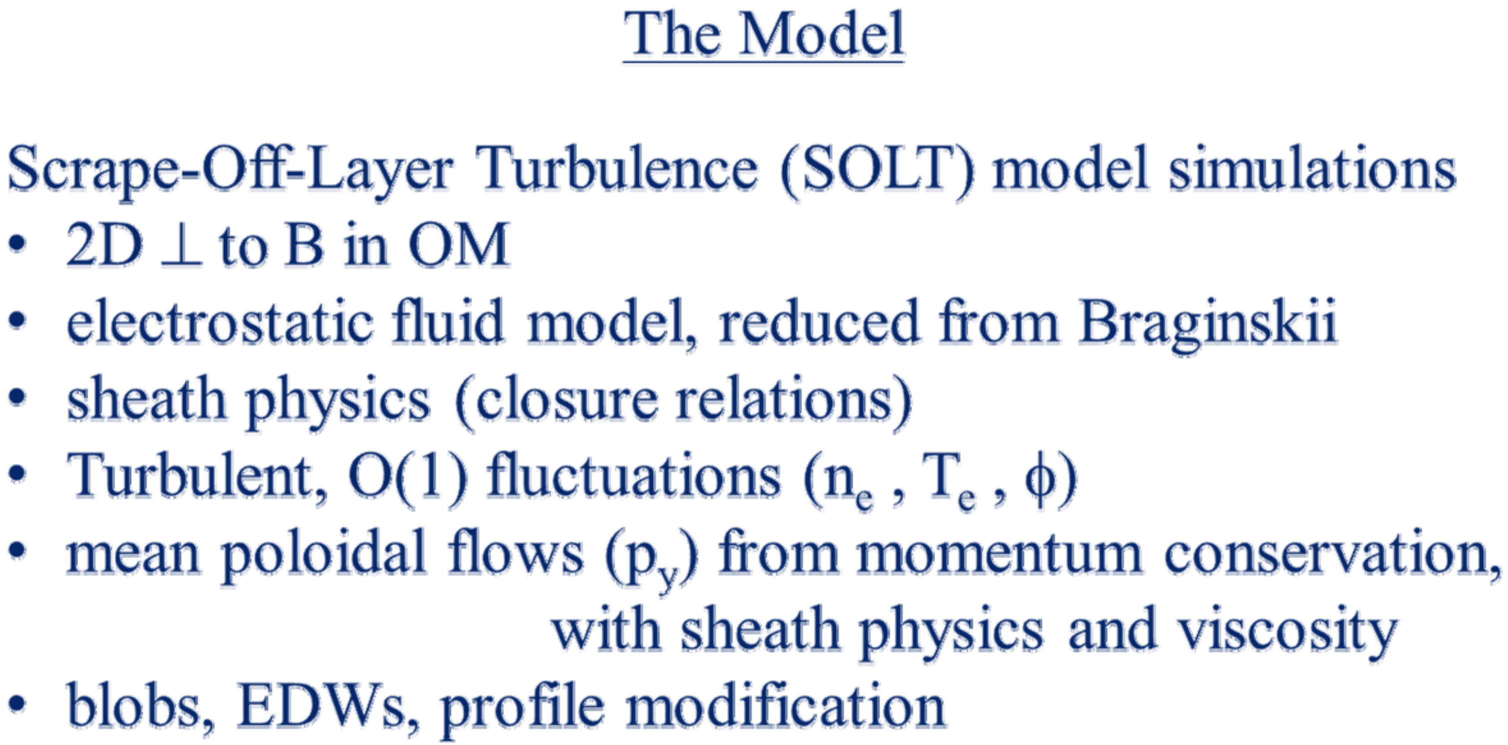
1) SOLT recovers the observed **heat-flux width scaling** of EDA H-modes at C-Mod

2) SOLT's quasi-coherent mode (QCM)



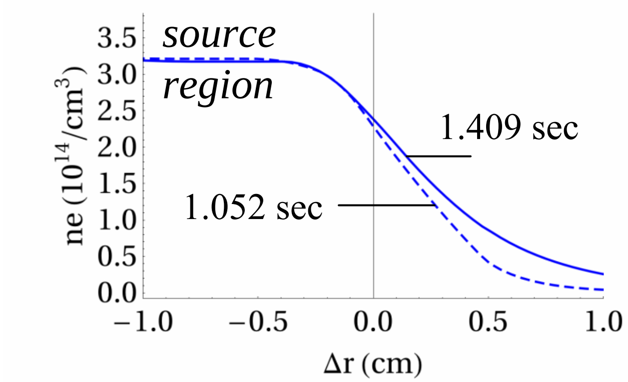
The Model

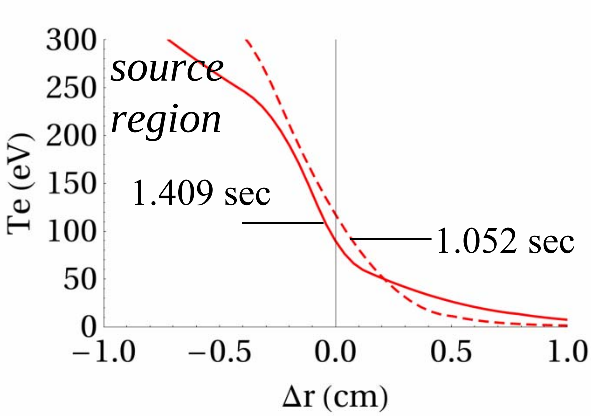
Scrape-Off-Layer Turbulence (SOLT) model simulations

- 2D $\perp$ to B in OM
- electrostatic fluid model, reduced from Braginskii
- sheath physics (closure relations)
- Turbulent, O(1) fluctuations (n_e , T_e , ϕ)
- mean poloidal flows (p_y) from momentum conservation, with sheath physics and viscosity
- blobs, EDWs, profile modification

Input to SOLT from Experiment

- C-Mod profiles (n_e , T_e) for EDA H-mode shot #1100303018 at two time slices :





- SOLT profiles are damped to these for $\Delta r < 0$, otherwise they evolve by (self-consistent) SOLT dynamics.

- We add an adjustable mean flow (ZF): $\langle v_y \rangle_y \equiv \bar{v}_y(\Delta r, t)$ based on ion pressure balance.

- ➢ In the SOL ($\Delta r > 0$), the flow evolves by momentum conservation and sheath physics.
- ➢ On the core-side ($\Delta r < 0$), the flow is damped to a reference, $\bar{V}_{y0}$, derived from the C-Mod profiles.

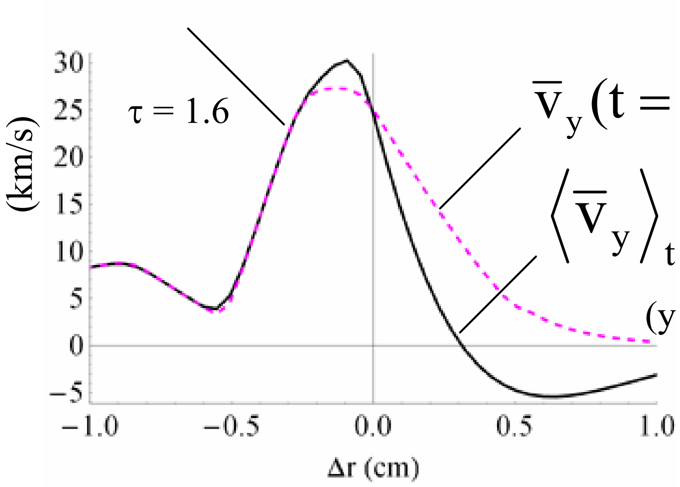
Reference Flow :

$$e Z n_i E_r - \partial_r (n_i T_i) = 0$$

$$\Rightarrow E \times B \text{ drift :}$$

$$\bar{v}_{y0} = \boxed{-\tau} \cdot \partial_r (n_e T_e)/n_e, \tau \sim T_i/T_e$$

τ controls the turbulence



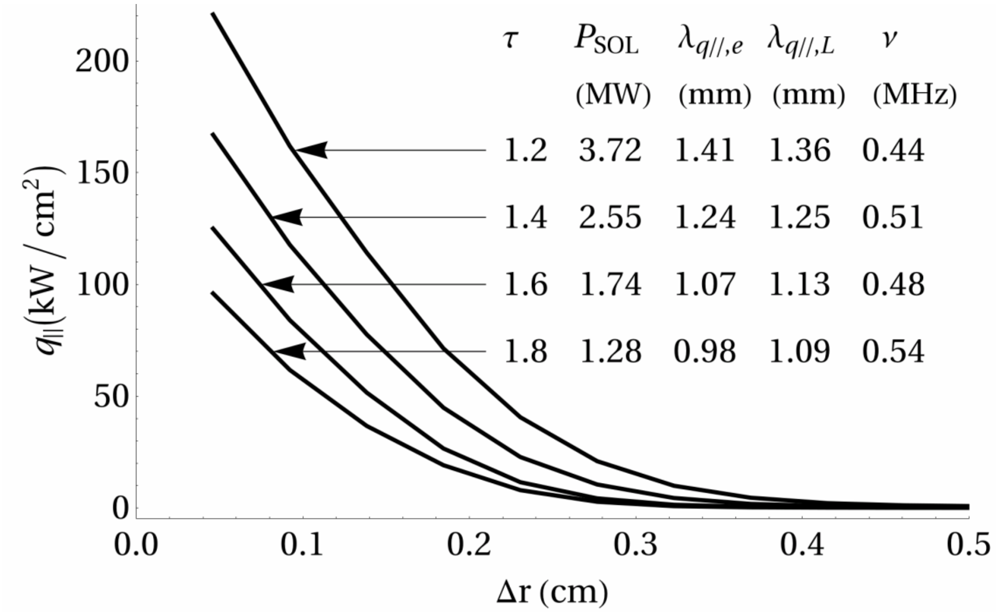
$\bar{v}_y(t=0)$ SOLT initial condition

$\langle \bar{v}_y \rangle_t$ SOLT equilibrium

(y : poloidal dimension)

τ-Scan Results from SOLT

Change τ, the amplitude of $\overline{V}_{y0}$, in SOLT to scan P_{SOL} and $q_{//}$ ($v_{//}n_eT_e$).

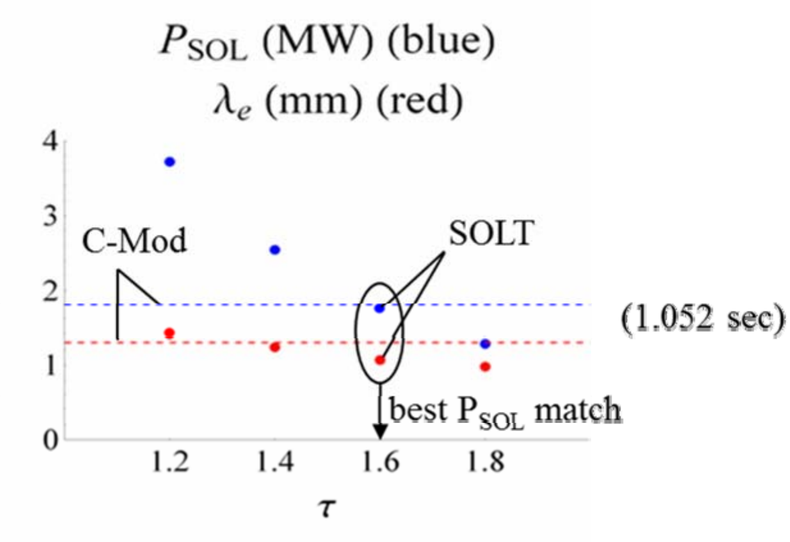


τ	P_{SOL} (MW)	$\lambda_{q//,e}$ (mm)	$\lambda_{q//,L}$ (mm)	ν (MHz)
1.2	3.72	1.41	1.36	0.44
1.4	2.55	1.24	1.25	0.51
1.6	1.74	1.07	1.13	0.48
1.8	1.28	0.98	1.09	0.54

$\lambda_{q//,e}$: exponential fit; $\lambda_{q//,L}$: Loarte length

ν: location of the peak in the density fluctuation spectrum at Δr = 0.46 mm.

τ-Scan Results from SOLT (cont.)



For the best P_{SOL} match at each time-slice :

t (s)	$P_{C\text{-}Mod}$	P_{SOLT}	$T_{C\text{-}Mod}$	T_{SOLT}	$\lambda_{e\ C\text{-}Mod}$	$\lambda_{e\ SOLT}$
1.052	1.79	1.74	117	63	1.31	1.07
1.409	1.39	1.32	86	48	2.27	1.57

SOL width (λ_e) decreases with increasing power (and T_{sep})
in both experiment and simulation.

Parallel Heat Flux is Limited by Collisions in the near-SOL

parallel heat flux regimes

- flux-limited:

$q_{FL} = C_{FL} n_e v_e T_e$

- sheath-limited:

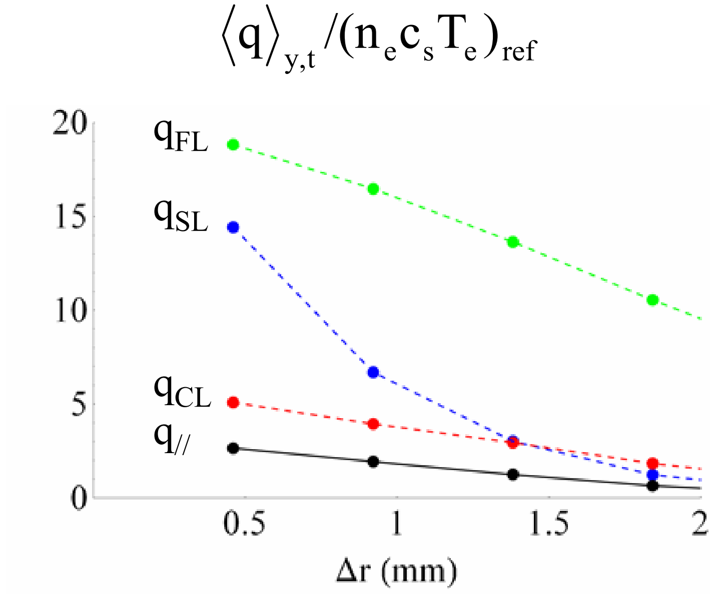
$q_{SL} = s_E n_e c_s T_e \exp[e(\Phi_B - \Phi)/T_e]$

- collision-limited:

$q_{CL} = 3.2 n_e c_s T_e / \Lambda$

- $1/q_{//} = 1/q_{FL} + 1/q_{SL} + 1/q_{CL}$

The bottleneck sets the regime.



1.052 sec
SOLT

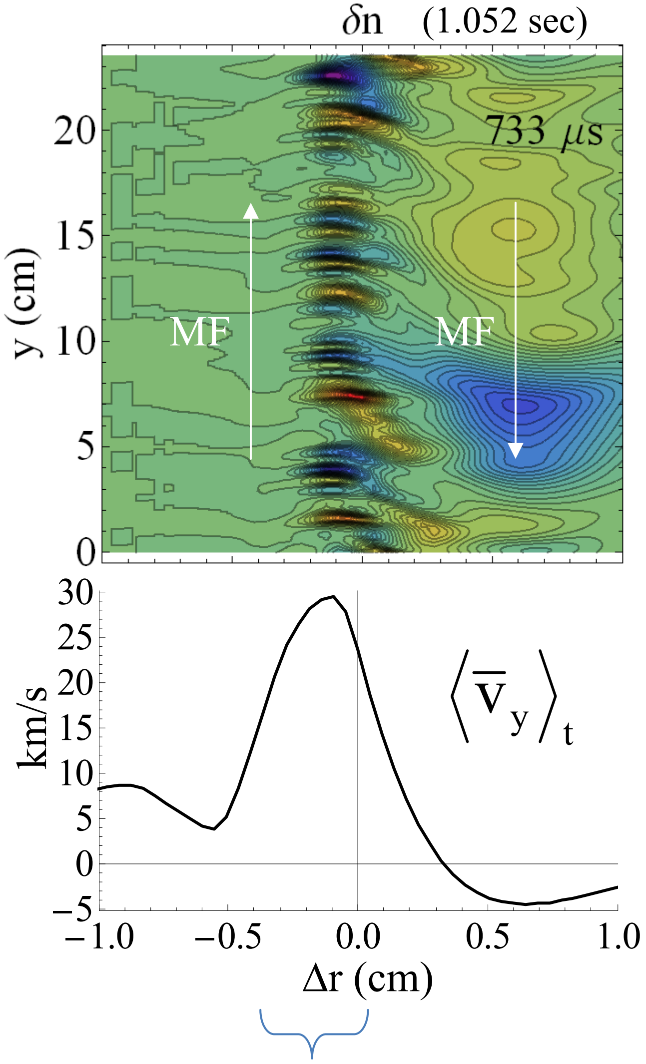
$$\nabla \cdot q = 0$$
$$\Downarrow$$
$$\lambda_e \sim L_{//} q_\perp / q_{//}$$

$$\boxed{q_{CL} \sim T_e^{7/2} \Rightarrow \text{smaller SOL widths } (\lambda_e) \text{ at higher } T_e}$$

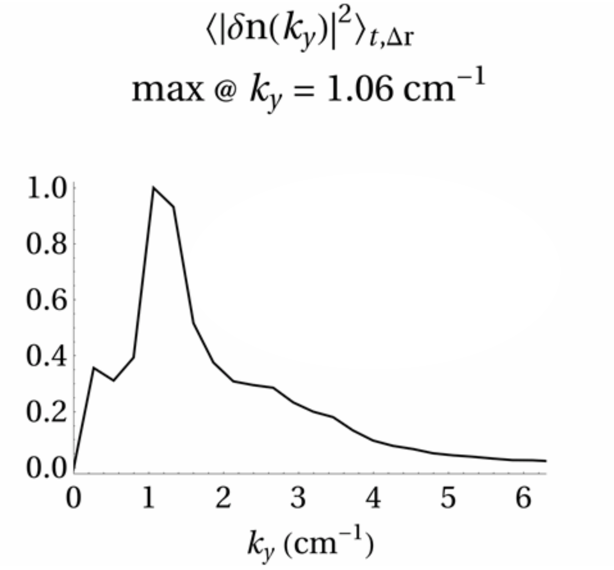
fin de 1)

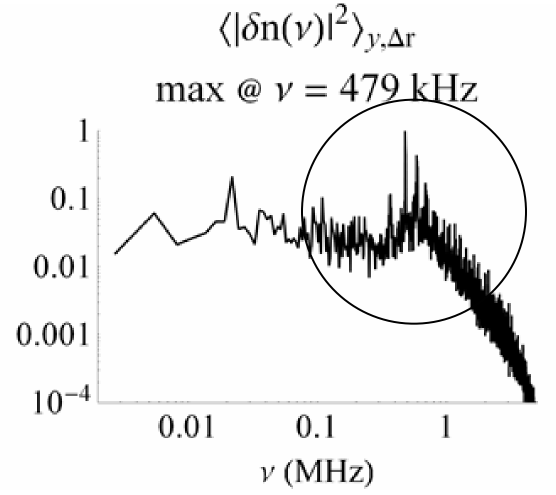
SOLT's QCM

The saturated turbulent state consists of a string of blobs, radially-localized about a maximum of the mean flow (MF) just inside the SEP, intermittently spilling plasma into the SOL where the flow reverses.

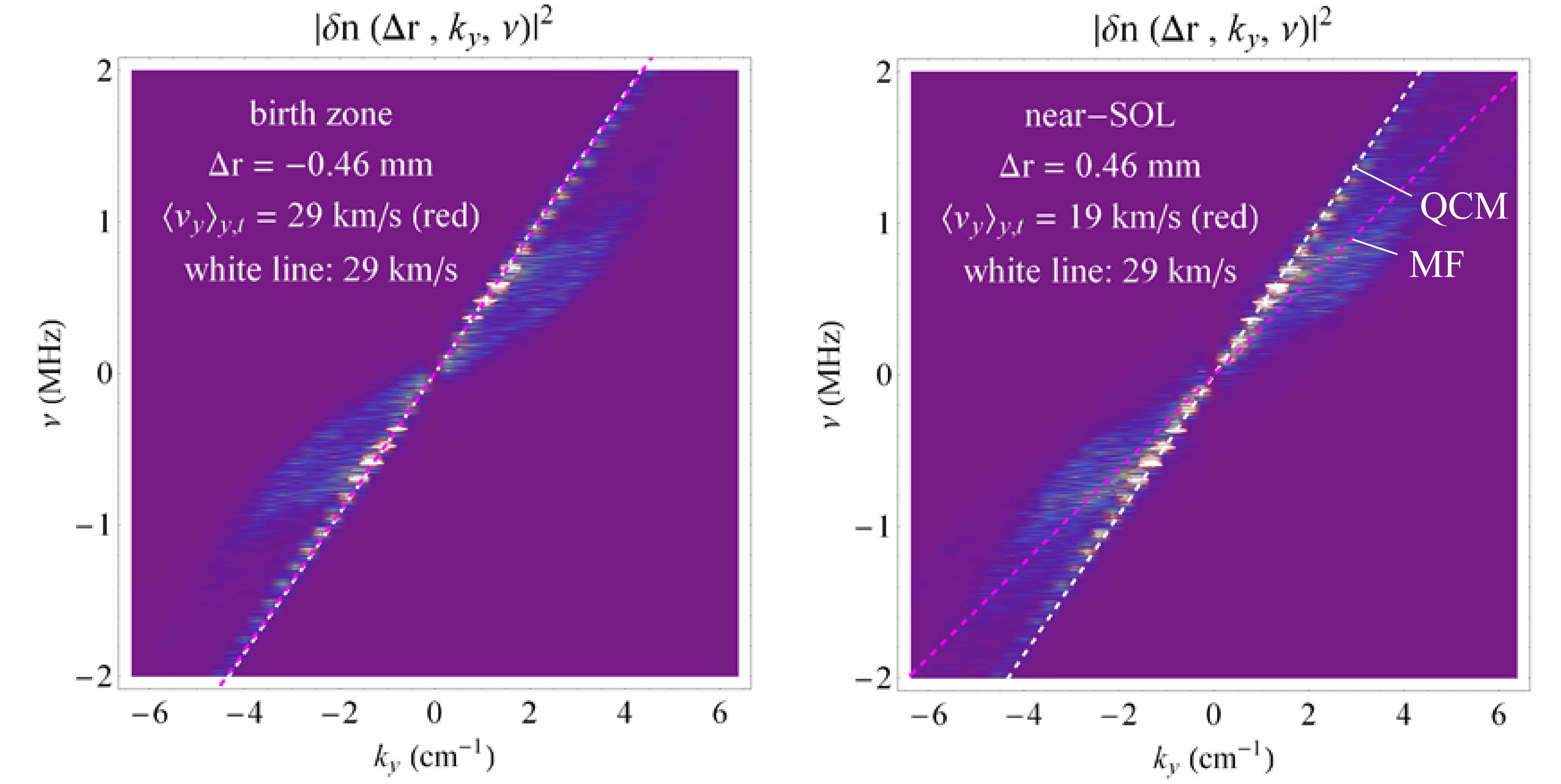


birth zone



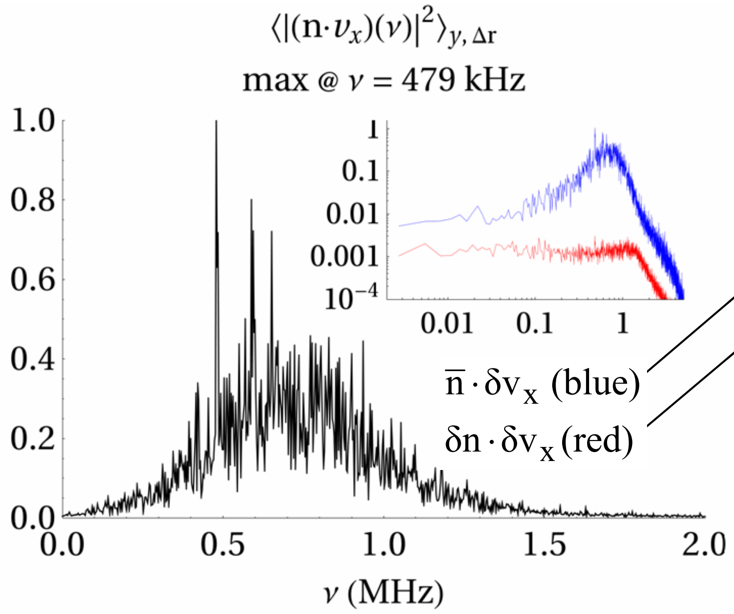


QCM dispersion is established in the birth zone.



The local Doppler frequency corresponds to the QCM dispersion line (bright beads) only in the birth zone, where the time-averaged MF is maximized (flow shear = 0).

Particle Flux from the QCM

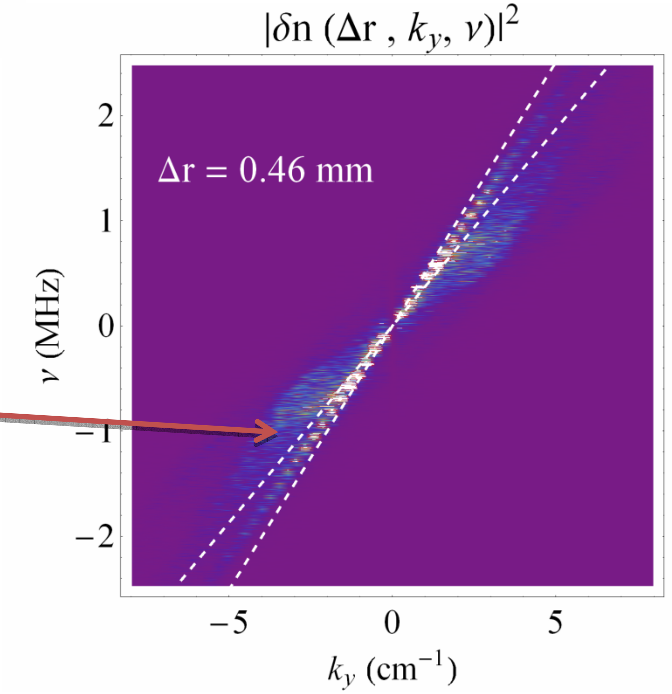


$\bar{n}\cdot\delta v_x$ (blue)

$\delta n\cdot\delta v_x$ (red)

no net flux, *circulating*

yes : net particle flux



44% of the <u>net</u> particle flux,

$$\langle\Gamma\rangle_{y,t} = \sum_{k_y,\nu} \delta n(k_y,\nu)\cdot\delta v_x(k_y,\nu)^*,$$

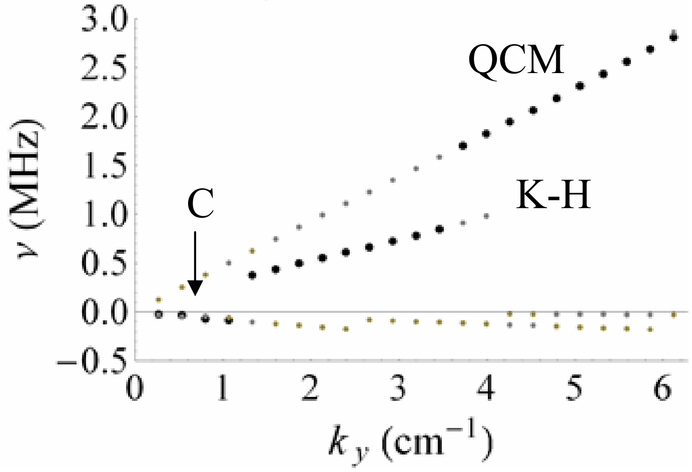
comes from inside the wedge

that includes the QCM.

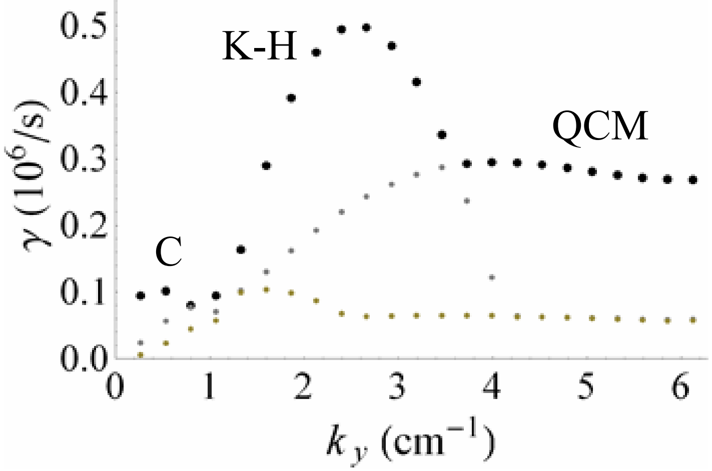
Linear Analysis of Time-Averaged Profiles

suggestive of underlying transport dynamics

frequency

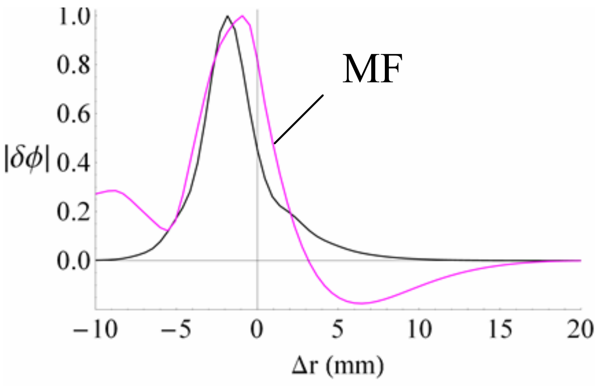


growth rate



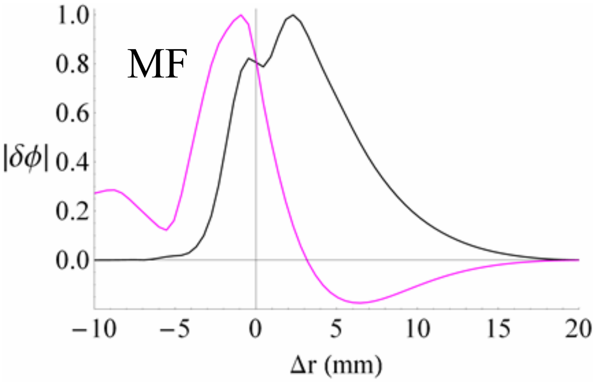
radial eigenfunctions, |δϕ(Δr)| :

QCM



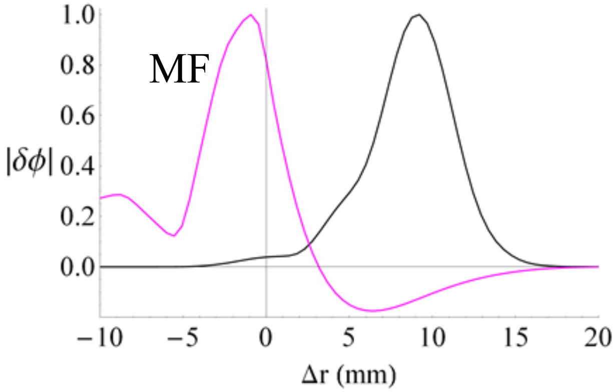
- drift-interchange mode
- blob birth zone

K-H



- straddles (±) MF regions
- blob emission

C



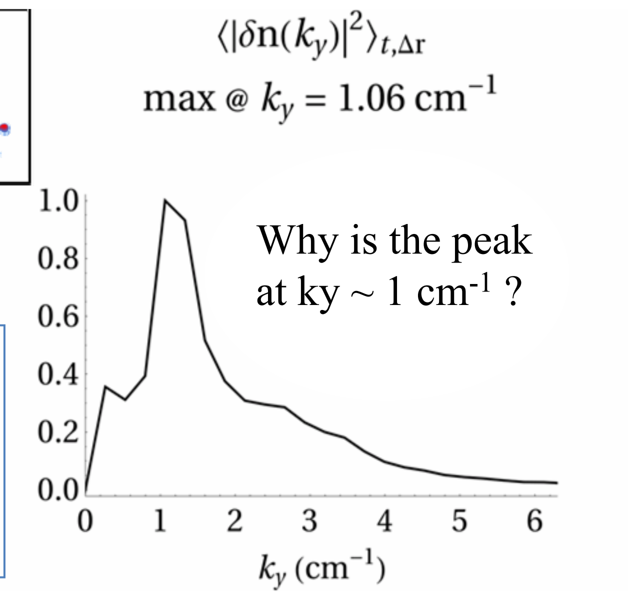
- sheath mode
- blob graveyard

Beyond Linear Analysis: The Vorticity Cascade Barrier

$$\frac{d}{dt}\nabla^2\tilde{\Phi} = \left\{ \alpha_{dw}(\Delta r)\,\frac{\bar{T}^{3/2}}{\bar{n}}\left(\Phi - T\ln n\right) + \ldots \right\}$$

α_{dw} : Drift Wave Adiabaticity Parameter

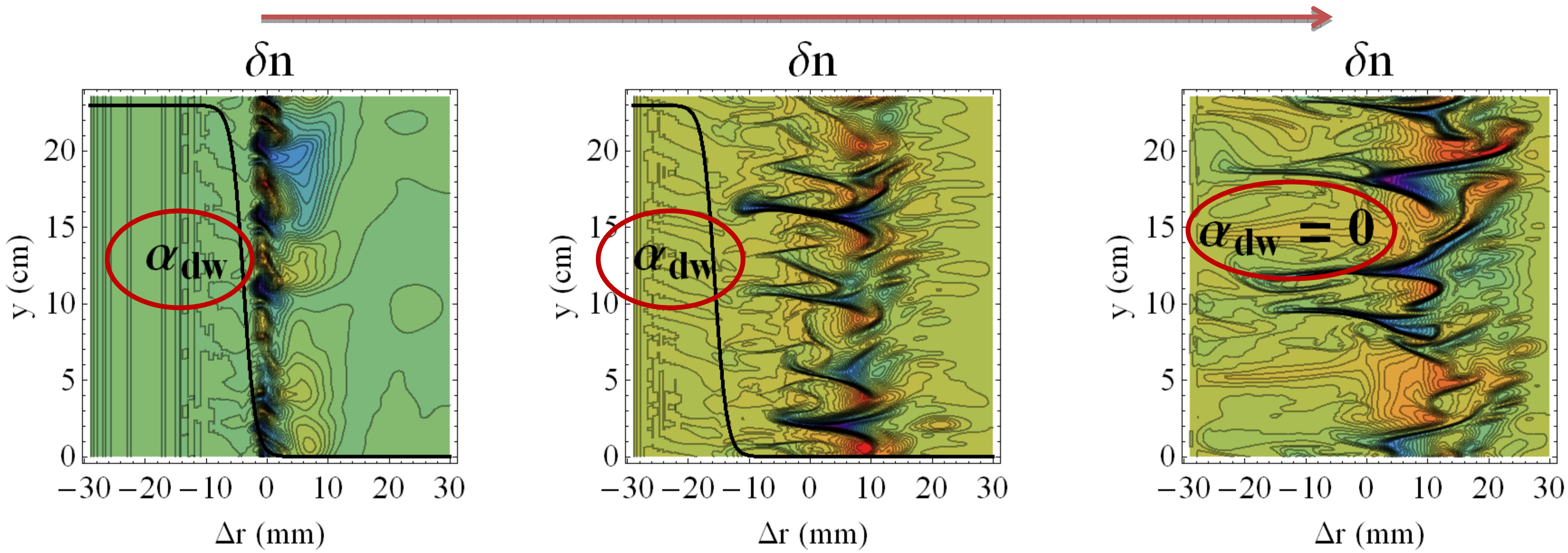
- $\sim k_{//}^2 / \nu_{ei}$
- f (B field topology)


$\langle|\delta n(k_y)|^2\rangle_{t,\Delta r}$

max @ $k_y = 1.06\ \mathrm{cm}^{-1}$

Why is the peak at ky ~ 1 cm^{-1} ?

Moving the DW region further into the core allows vorticity cascade to smaller k_y.



- ➢ This is consistent with the sharp change in the sign of the cross-phase (δn,δϕ) near the inflection point in the α_{dw} profile.

Summary

Part 1
Scaling of the SOL width for parallel heat flow

•Matching P_{SOL} with SOLT simulations, by adjusting the mean flow (τ)

$\Rightarrow$ $q_{//}$ - width scaling with T_e :

•<u>$q_{//}$ is limited by collisions in the near-SOL</u>: $q_{//, CL} \sim T_e^{7/2}$

- consistent with T_e – dependence observed for this shot
- differs from a similar study of NSTX scaling in the sheath-limited regime
- (note: sheath-limited heat flux dominates in the far-SOL)

Part 2
Quasi-Coherent Mode

•A string of quasi-stationary blobs, moving with the mean flow in the edge

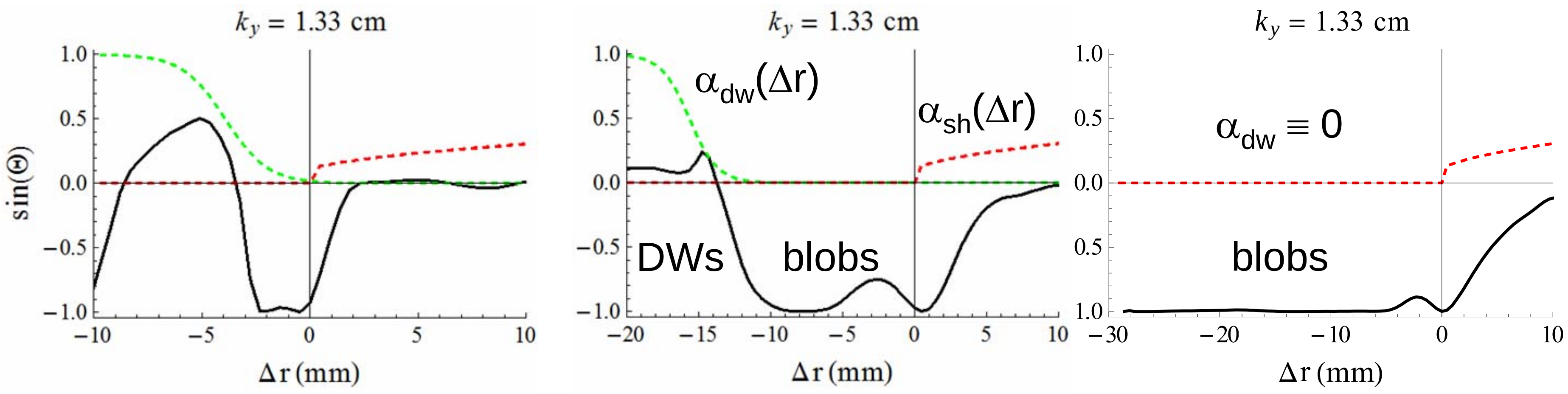
- centered in the birth zone, where the mean flow shear rate = 0
- energy spectrum consistent with experiment, $k_y \sim 1\ \mathrm{cm}^{-1}$
- accounts for 44% of the net particle flux, consistent with sustaining the EDA H-mode
- linear unstable modes (drift-interchange, K-H) drive transport in the saturated state
- drift-wave transition region is a barrier to vorticity cascade $\Rightarrow \left\langle \left|\boldsymbol{\delta n(k_y)}\right|^2 \right\rangle$ peaks at $k_y > 0$

extra
slide

The phase relation between $\delta\phi$ and δn changes abruptly at the entrance to the DW region.

Cross-Phase

$$\sin(\Theta) = \left\langle \delta n(\Delta r, k_y, t)\cdot \delta\varphi(\Delta r, \text{-}k_y, t)\right\rangle_t / \left|(\mathit{top})\right|$$



$\sin(\Theta) < 0$: conducive to the blob/hole generation and propagation paradigm

$\sin(\Theta) > 0$: suppresses blob formation