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 ⊥ to B in OM
- electrostatic fluid model, reduced from Braginskii
- sheath physics (closure relations)
- Turbulent, O(1) fluctuations ($n_e$, $T_e$, $\phi$)
- mean poloidal flows ($p_y$) from momentum conservation, with sheath physics and viscosity
- blobs, EDWs, profile modification
• C-Mod profiles \((n_e, T_e)\) for EDA H-mode shot #1100303018 at two time slices:

\[
\begin{align*}
\text{1.052 sec} & \quad \Delta r (\text{cm}) \\
\text{3.0} & \quad n_e (10^{14} \text{ cm}^{-3}) \\
\text{1.409 sec} & \quad T_e (\text{eV})
\end{align*}
\]

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

• We add an adjustable mean flow \((ZF)\):

\[
\left\langle \bar{v}_y \right\rangle_y = \bar{v}_y (\Delta r, t)
\]

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:

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

\[\Rightarrow E \times B \text{ drift:}
\]

\[
\bar{v}_{y0} = -\tau \partial_r (n_e T_e)/n_e, \tau \sim T_i/T_e
\]

\(\tau\) controls the turbulence

\[
\begin{align*}
\bar{V}_y (t = 0) & \quad \text{SOLT initial condition} \\
\left\langle \bar{V}_y \right\rangle_t & \quad \text{SOLT equilibrium} \\
(y : \text{poloidal dimension})
\end{align*}
\]
Change $\tau$, the amplitude of $\bar{V}_{y0}$, in SOLT to scan $P_{\text{SOL}}$ and $q_{//} (v_{//} n_c T_e)$. 

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

$v$: location of the peak in the density fluctuation spectrum at $\Delta r = 0.46 \text{ mm}$. 

$\tau$ | $P_{\text{SOL}}$ (MW) | $\lambda_{q_{//,e}}$ (mm) | $\lambda_{q_{//,L}}$ (mm) | $v$ (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
SOL width ($\lambda_e$) 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:**
  \[ q_{CL} = 3.2 n_e c_s T_e / \lambda \]

- \[ 1/q_{\parallel} = 1/q_{FL} + 1/q_{SL} + 1/q_{CL} \]

\[ \nabla \cdot q = 0 \]

\[ \lambda_e \sim L_{\parallel} q_{\perp} / q_{\parallel} \]

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

*The bottleneck sets the regime.*

Lodestar/Russell/TTF/2011

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
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).
44% of the net 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

\begin{itemize}
\item drift-interchange mode
\item blob birth zone
\item straddles (±) MF regions
\item blob emission
\item sheath mode
\item blob graveyard
\end{itemize}
Beyond Linear Analysis: The Vorticity Cascade Barrier

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

\( \alpha_{\text{dw}} \): Drift Wave Adiabaticity Parameter
- \( \sim k_y^2 / v_{ei} \)
- \( f (B \text{ field topology}) \)

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 \((\delta n, \delta \phi)\) near the inflection point in the \( \alpha_{\text{dw}} \) profile.

\[ \langle |\delta n(k_y)|^2 \rangle_{t, \Delta r} \]
max @ \( k_y = 1.06 \text{ cm}^{-1} \)

Why is the peak at \( k_y \sim 1 \text{ cm}^{-1} \)?
Summary

Part 1
Scaling of the SOL width for parallel heat flow

• Matching $P_{\text{SOL}}$ with SOLT simulations, by adjusting the mean flow ($\tau$)
  \[ \Rightarrow q_{//} - \text{width scaling with } T_e \]

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

  ➢ 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, $k_y \sim 1 \text{ cm}^{-1}$
  ➢ 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 \( \Rightarrow \langle |\delta n(k_y)|^2 \rangle \) peaks at $k_y > 0$
The phase relation between $\delta \phi$ and $\delta n$ changes abruptly at the entrance to the DW region.

**Cross-Phase**

$$
\sin(\Theta) = \langle \delta n(\Delta r, k_y, t) \cdot \delta \varphi(\Delta r, -k_y, t) \rangle_t / \langle(top) \rangle
$$

The phase relation between $\delta \phi$ and $\delta n$.

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

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