Width of turbulent SOL in tokamaks: from circular to diverted geometries

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Outline: discuss evidences for $\lambda$ set by turbulence

- 2D turbulence model vs experiments in circular geometry
  - blobs velocities & SOL with extrapolation to ITER current ramp

- Extension to divertor configurations:

  TOKAM-3X vs experiments
  - width reduction from circular to diverted
  - influence of divertor leg turbulence
Transport in circular geometry: Simulation vs Experiment

TOKAM-2D: interchange turbulence
- Density and vorticity conservation
- Flux driven, control parameters: $\rho_L/R$ & $q_{cyl}$
- Reduced model of blob dynamics & SOL width

Tore Supra: circular SOL well diagnosed
- Profile & fluctuation probes
- Wide SOL profiles: better probe resolution
- Fast camera: qualitative fluctuations properties

Density fluctuation snapshot

Average density profile

Tore Supra fast imaging (processed)
Confront turbulent model: dynamics of isolated blobs

- **TOKAM-2D vorticity equation:** \( \partial_t \omega + \mathbf{v}_\perp \cdot \nabla \omega = \mathbf{g} \partial_y \ln(p_e) + \sigma_{sh}(1 - e^{\Lambda - \Phi}) \)

- **Balance for isolated & ideal blob:** \( V_b = \frac{1}{2} \sigma_{sh} k_b^{-3} \left( \sqrt{1 + \left( \frac{k_b}{k_0} \right)^5} - 1 \right) \) (Krasheninnikov PLA 2001, Ghendrih IAEA 2004)

- **Working hypothesis** for data analyses:
  - local \( \tilde{n} \) maxima = blob signature
  - Average blobs built on set of time events

- **Average blobs characterized by:**
  \( \frac{\tilde{n}_b}{\bar{n}}, V_{E_\theta \times B}, k_\theta \), global parameters
average blob model applies to Tore-Supra data

- Large set (~10k) of average blobs from Ω plasmas, over large parameter intervals

**assumptions**

\[ T_i \approx 2T_e \]
\[ g = \frac{\rho_s}{R} \]
\[ \sigma = \frac{\rho_s}{Rq_{cyl}} \]

- \( B_T \in [3.1 - 4.1] \text{T} \)
- \( I_p \in [0.6 - 1.4] \text{MA} \)
- \( f_{GW} \in [0.2 - 0.7] \)
TOKAM-2D returns a non trivial regression scaling of $\lambda$

- Flux driven simulations, saturated turbulence
  
  - Scan of parameters: curvature $g$ & loss rate $\sigma_{sh}$

  \[ \lambda = 1.0 \ g^{0.3} \ \sigma_{sh}^{-0.75} \ \rho_S \]

- Similitude with:
  
  - isolated blob model
    \[ \lambda \propto g^{0.6} \ \sigma_{sh}^{-1.2} \ \rho_S \]
  
  - Simple interchange ordering
    \[ \lambda \propto g^{0.5} \ \sigma_{sh}^{-1} \ \rho_S \]
    Fundamanski NF 2011
  
  - model of intermittent transport
    \[ \lambda \propto \sigma_{sh}^{-0.62} \ \rho_S \]
    Ghendrih IAEA 2004

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Predictions of SOL density width agree with Tore Supra

About 100 profiles forming an ITER start-up database  

\[ T_i \approx 2 T_e \]

\[ g = \frac{\rho_s}{R} \]

\[ \sigma = \frac{\rho_s}{R q_{cyl}} \]
Assume SOL in sheath limited regime:

$$\lambda_q \approx \frac{1}{2} \lambda_n$$

Assume fixed separatrix temperature

$$T_e = 30\text{eV} \text{ (weak scaling sensitivity)}$$

Model applies to heat load decay length $\lambda_q$

*best $\lambda_q$ scaling law for Tore Supra database*

$$\lambda_q = 50R_{d_{cyl}}^{0.75} \left( \frac{P_L}{R} \right)^{0.55}, \left( T_e = 30\text{eV} \right)$$

$$\lambda_q = 3.1P_{\Omega,MW}^{-0.56\pm0.02}$$

$$\lambda_q = 2.1P_{\Omega,MW}^{-0.52\pm0.05}$$

*Gunn JNM 2013*
Predictions of $\lambda_q$ for ITER start-up circular phase

- Model predictions, given separatrix $T_e \approx 50\text{eV}$, agrees with multi-machines scaling

ITER start-up ITPA database
Horacek PPCF 2016

Model predictions

<table>
<thead>
<tr>
<th>$I_P$ (MA)</th>
<th>ITPA (mm)</th>
<th>TOKAM2D (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>69 ± 18</td>
<td>62</td>
</tr>
<tr>
<td>5</td>
<td>54 ± 14</td>
<td>44</td>
</tr>
<tr>
<td>7.5</td>
<td>44 ± 11</td>
<td>29</td>
</tr>
</tbody>
</table>
Summary:
predictive model for SOL width $\lambda$ in circular geometry

- Extensive data from Tore Supra: SOL width, blob dynamics
- 2D interchange model, flux driven, isothermal, predicts:
  - blob velocity
  - SOL width
- 2 generic control parameters: curvature $g$ & loss rate $\sigma_{sh}$

Open issue: how to translate to diverted geometries?

Include poloidal asymmetries & physics specific to divertor
TOKAM-3X solves 3D turbulence in diverted geometry

- Interchange turbulence dominates SOL transport in circular & diverted geometry
- Similar ballooning feature of radial particle flux (in magnetic coordinate)
- Clear impact of X-point/flux expansion on turbulence mitigation
Flux driven isothermal simulations

- circular & LSN diverted geometry (COMPASS like)
- similar control parameters (\( \rho_s/R, q_{95} \))

<table>
<thead>
<tr>
<th>TK-3X:</th>
<th>Div.</th>
<th>Circ.</th>
<th>TK-2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_N (\rho_L) )</td>
<td>11</td>
<td>73</td>
<td>60</td>
</tr>
</tbody>
</table>

ongoing work: role of magnetic shear @ X-point
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$\lambda$ reduction similar to experimental evidences

TCV L-mode data from outer target infra red & Langmuir probes

$\lambda_\|_q$ about 6 times smaller than TOKAM-2D predictions

BUT, follows TOKAM-2D model sensitivity:

- TOKAM-2D predictions:
  \[ \lambda \propto R^{0.45} q_{95}^{0.75} B^{-0.55} T_{sep}^{0.27} \]

- JET + AUG experimental scaling:
  \[ \lambda \propto R^{0.26} q_{95}^{0.73} B^{-0.4} P_{SEP}^{0.13} \]

Scarabosio JNM 2013

heat flux decay length

TCV LSN

TCV x6

Tore Supra circular

TCV 51333
Unexpected impact of divertor geometry on $\lambda_q$ in TCV

- TCV L-mode data
- Scan of outer divertor leg length (X3)
- x2 increase of $\lambda_q$, not $S$
- Agreement infra red & Lang. probes
- NOT reproduced by transport codes (SOLEDGE-2D EREINE)

Gallo PPCF 2017
Isothermal turbulent simulations in realistic geometries

Quantitative variation of $\lambda_N$ matched (+ no change in $S$)

Due to turbulence spreading from main SOL to divertor leg

$\lambda_q(L_{div})$ reproduced by TOKAM-3X: interchange turb
Conclusions & prospects

- A generic 2D interchange model describes SOL transport in circular geometry
- **TOKAM-3X simulations:** turbulence sets $\lambda$ in both circular & diverted geometries
- As in experiments (L-mode):
  - $\lambda$ much smaller in diverted than circular $\rightarrow$ probable role of X-point magnetic shear
  - $\lambda$ increases with divertor leg length $\rightarrow$ Asymmetric turbulence along divertor leg
- Alternative divertor concepts should favor interchange turbulence to increase $\lambda$:
  - vertical leg
  - minimize magnetic shear
- $\rightarrow$ Reduced turbulence model needed in 2D transport codes (SOLPS, SOLEDGE, etc)
Build average blobs on TOKAM-2D, compare to

\[ V_b = \frac{1}{2} \sigma_{sh} k_b^{-3} \left( \sqrt{1 + \left( \frac{k_b}{k_0} \right)^5} - 1 \right) \]
expectations from TOKAM-2D model about multi-machine scaling of divertor $\lambda_q$ in (H-mode)

- Assumes given mitigation factor $\lambda^H_q = f_H f_{\text{div}} \lambda^{2D}_q$
  $f_{\text{div}} \approx 1/6$ & $f_H \approx 1/2$

- Compare to most-recent multi-machine scaling (Eich NF 2013)

Scaling H-mode [Eich NF 2013]

TOKAM-2D predictions