Scrape-off layer plasma flow and drifts in the tokamak divertor magnetic geometries

Nobuyuki Asakura

Japan Atomic Energy Agency, Naka

Acknowledgements:
R.A.Pitts (CRPP), W.Fundamenski, K.Erents (UKAEA), B.LaBombard, B.Lipschultz (MIT), A. Loarte (EFDA), X.Bonnin (Univ. Paris), K. Fujimoto, K. Shimizu and the JT-60 team (JAEA)

Ceratopia Toki, Gifu, October 15-19, 2007
1. Introduction:
   Plasma flow in the tokamak and measurement

2. Scrape-off layer flow in tokamaks

3. Divertor particle flux and in-out asymmetry

4. Approach of SOL and divertor modelling

5. Conclusions
Parallel plasma flow in tokamak scrape-off layer

Parallel plasma flow is produced towards Plasma Facing Component

1-D momentum transport along SOL field lines

3-D plasma flow in tokamak

SOL flow measurements at various poloidal locations in tokamaks exhibit 2-3D flow pattern.

Multi physics processes (plasma drifts, diffusion, detachment, etc.) in tokamak divertor geometry.

Plasma flow plays important role on heat & particle transport in boundary plasmas:

• Asymmetry in inner and outer divertors \(\Rightarrow\) detachment, pumping flux
• Impurity shielding and exhaust, and long-range transport
• Edge plasma formation and plasma energy confinement
SOL flow measurement using Mach probes

Low-field-side midplane Mach probe in JT-60U

Mach number of parallel flow is calculated from $j_s$ at i-side and e-side using Hutchinson's formula:

$$M_\parallel = M_c \ln \left( \frac{j_s^e}{j_s^i} \right),$$

where $M_c = 0.4$

2. **Scrape-off layer flow in tokamaks**
SOL flow ($M_{\parallel}$) profile changes at Low- and High-Field Sides

**Near separatrix:** flow towards HFS divertor is large at LHS SOL.

**Far SOL ($r > \lambda_{ne} \sim \text{cm}$):** flow towards HFS divertor increases at Top & HFS.

Combination of driving mechanisms determines the SOL flow profile.

Key mechanisms to produce parallel flow in tokamak SOL:
(1) Asymmetrical diffusion, (2) Classical drifts, (3) Divertor detachment

Classical drifts

\[ E_r \times B, \nabla \rho \times B \]
\[ E_\theta \times B \]
\[ (E_\theta = -\nabla _\theta T) \]

Parallel flow

Pfirsch-Schlüter flow
\[ V_{//}^{PS} = 2q_s V_\perp \cos \theta, \quad V_\perp = (E_r - \nabla p_i) x b/B \]

Asymmetrical diffusion
(particle & momentum & energy)

Divertor sink

Detachment, \( \nabla _// T \), pre-sheath

Others: gas-puff, pumping, recycling

Key mechanism (1): *in-out asymmetry in diffusion*

**Single null divertor:** comparable plasma pressure, but fast SOL flow towards HFS divertor

**Double null divertor:** showed low $p_e$ and *flow stagnation* at HFS SOL

→ HFS SOL plasma (in single null) is transported from the LFS SOL
Key mechanism (2): **Classical drifts in tokamak**

Forward/ Reversal $B_t$: $\Delta M// \text{ direction above/below average base-level}$

$\langle M// \rangle \sim 0$ (LFS midplane), $\sim 0.2$ (plasma top in JET)

Parallel flow is produced against ion $\nabla B$ direction.

$M// \text{(drift effect)}$ decreases with $n_e$.

Low-field-side midplane (JT-60U)

Similar results were found in C-MOD, TCV, and limiter tokamak (ToreSupra)

**Classical drifts in tokamak:**

*Upward parallel flow is driven for ion $\nabla B \downarrow$ by in-out asymmetry of drifts*

**Ion drift:**

$$V_\perp = (E_r - \nabla p_i/en_i)x/b/B$$

large at LFS midplane

**"Pfirsch-Schlüter flow":**

$$V_{//}^{PS} = 2q_s V_\perp \cos \theta$$

maximum at midplane

- *"Pfirsch-Schlüter flow" is zero at plasma top & bottom.*
- $V_\perp$ and $V_{//}^{PS}$ are large at low density.

_Evaluation of $M_{//}$ is smaller than measurement (using only $E \times B$ part):_

better resolution of $T_i$ profile will provide accurate evaluation of $V_{//}^{PS}$.

Recombination process becomes dominant in dense and cold divertor (< a few eV).

Plasma flow becomes Sonic level at the recombination front.

Parallel flow at the upstream SOL is increased.

2D divertor spectroscopy measurement ($D_\alpha - D_\theta$) determined recombination region.
Divertor detachment affects **Subsonic-Sonic flow at HFS**

*\( M_// \) in far SOL at HFS* is enhanced when the divertor detachment occurs. 

**Static pressure** is reduced → **upstream \( M_// \) increases to Sonic level**

---

Asakura et al. PPCF 44 (2002) 2101

---

**Graph and Diagram Details:**

- **Graph 1:**
  - Title: HFS divertor detached
  - Y-axis: Mach number
  - X-axis: Distance from separatrix (cm) mapping to LFS midplane
  - Data points showing Mach number variation with distance.
  - Annotations: \( \Delta r = 3 \text{cm} \)
  - Red arrow indicating direction towards HFS divertor

- **Graph 2:**
  - Title: HFS SOL (JT-60U)
  - Y-axis: Mach number
  - X-axis: Mach number
  - Data points showing Mach number variation with distance.
  - Annotation: HFS baffle presheath

- **Diagram:**
  - Magnetic field lines (\( B_\perp \))
  - Ion trajectories
  - Recombination dominant area
  - Color scale: \( n_e/n_{GW} \sim 0.47 \)

---

**Mathematical Expression:**

\[
\frac{D_\beta}{D_\alpha} \approx 0.47
\]
3. Divertor particle flux and in-out asymmetry
Drifts play an important role near divertor null (X-point)

- Heat and particle fluxes along B are separated in HFS/ LFS divertors
- Change of in-out asymmetries in heat and particle fluxes was NOT explained by parallel model (simulations) depending on $B_t$ direction ⇒ Drifts (cross-field) transport in divertor

SOL ion fluxes towards HFS&LFS divertors are evaluated

Poloidal components of convection flux \((n_i v_{\parallel} \Theta)\) and drift flux \((n_i v_{\text{dr}}^{\text{ExB} \Phi})\) are evaluated at the HFS and LFS SOLs (Mach probe locations): Drift flux is large near the separatrix.

Net ion flux towards divertor: 
\[
\Gamma_p^{\text{HFS/LFS}} = 2\pi \int n_i [v_{\parallel} \Theta \pm v_{\text{dr}}^{\text{ExB} \Phi}] R \, dr
\]
(HFS: - / LFS: + for ion \(\nabla B\) drift towards divertor).

\[
n_i V_{\parallel} \sim M_{\parallel} j_s / e, \quad \Theta = B_p / B_{\parallel}, \quad \Phi = B_p / B_{\perp} \sim 1, \quad n_i = n_e.
\]

Radiation peak (MARFE) stays near the X-point (LFS), and detachment occurs at the down-stream of the MARFE.

Field line length increased close to X-point, comparable to one toroidal turn (~19m).
In private flux region under attached divertor condition, large drift flow from LFS to HFS divertor is produced.

In common flux region, when LFS divertor is detached, large drift flow away from LFS divertor appears.

Drift flow in the private region and divertor detachment play an important role on producing in-out asymmetry in divertor.

LFS divertor is attached:
\[ \Gamma_i^{prv} (\text{drift flux in prv.}) \] is added to \( \Gamma_i^{HFS} \) (HFS SOL flux), for ion \( \nabla B \) drift towards the divertor.

LFS divertor is detached:
In-out asymmetry is determined by parallel flows towards HFS & LFS divertors, \( \Gamma_{i//}^{HFS} < \Gamma_{i//}^{LFS} \).

4. Approach of SOL and divertor modelling
Approach of SOL & divertor modelling with drifts & diffusion

2-D fluid codes (SOLPS, UEDGE, EDGE2D) include classical drift effects, qualitatively reproduce normal/reversed $B_t$ effects, but small $M_{//}$ (~0.1)

(1) **SOLPS for C-MOD** (Bonnini, et al) showed $M_{//} \sim 0.5$ near separatrix.

Modelling of potential and current near separatrix may affect $M_{//}$?

[Boninni et al, JNM 337-330 (2005) 301]

(2) Poloidal asymmetry models for $D_\perp, \chi_\perp$

1) Radial convection: **EDGE2D(JET)**
   - HFS$\Rightarrow$LFS for Norm-B (LFS$\Rightarrow$HFS for Rev-B.)

2) LFS-enhanced diffusion ($D_\perp \sim 1/B$), in some cases, $\Gamma_R^{HFS}$ enter confined plasma: **EDGE2D(JET), SOLPS(JET), UEDGE(C-MOD)**
   - Large $\Gamma_R^{LFS}/\Gamma_R^{HFS} (\sim 50)$ explains fast $M_{//} \sim 0.5$

Influence of intermittent/Blob radial transport on parallel flow are implicated in 2D fluid simulations -- active area of study

Experiment results (C-MOD, DIII-D, TCV, JT-60U, ASDEX-U, JET, NSTX, etc): 2D fast imaging by blobs/ statistic analysis of fluctuations (skewness-flatness of P.D.F.) show intermittent out-flux at LFS SOL such as ExB turbulence.

Alcator C-MOD

- Non-linear simulation of the turbulence transport can evaluate contribution of outflux to the fast SOL flow: $\langle M \rangle \sim 0.1-0.2$ for JET

ESEL for TCV LFS SOL: Garcia et al. PPCF 48 (2006) L1
Conclusions

Understanding of Flow pattern in SOL-Divertor has been progressed with development of diagnostics to measure 2D profiles (Mach probes, etc.):

**Flow pattern** is produced by *combination of main driving mechanisms*:
1. Asymmetry in diffusion/ transport,
2. Classical drifts ($B_t$ direction),
3. Divertor detachment, and other effects (recycling, intense-puff&pump)

Those play an important role on formation of SOL & divertor plasmas:
- Subsonic-Sonic SOL/divertor flow,
- in-out asymmetry in divertor plasma,
- Detachment and divertor MARFE etc.,

*Also influence on impurity transport* (deposition, shielding from core) and *energy confinement at edge* (L-H transition, transport barrier).

All processes are important under reactor condition. Understanding of both // and ⊥ transport in tokamak magnetic geometry is urgent issue.

$\Rightarrow$ **Quantitative determination of the SOL flow pattern** BOTH from experiments ($M_\parallel$) and simulation (appropriate modelling in real magnetic configuration) are crucial for diveror design and operation.