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

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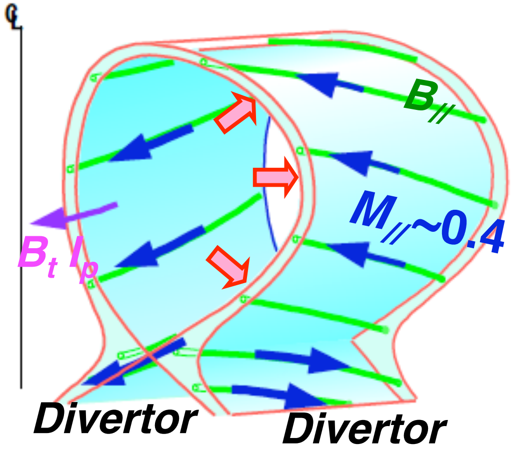
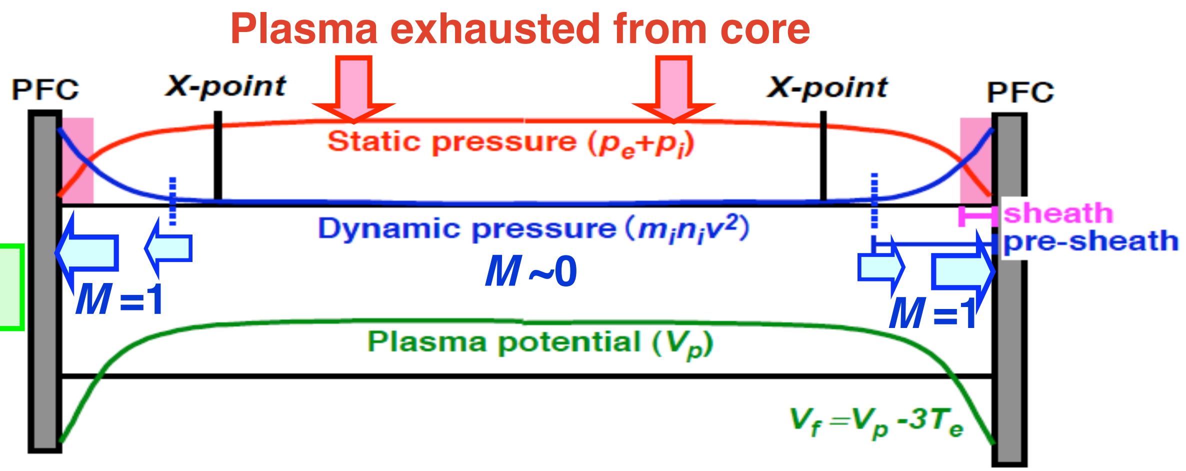
Parallel plasma flow in tokamak scrape-off layer

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.

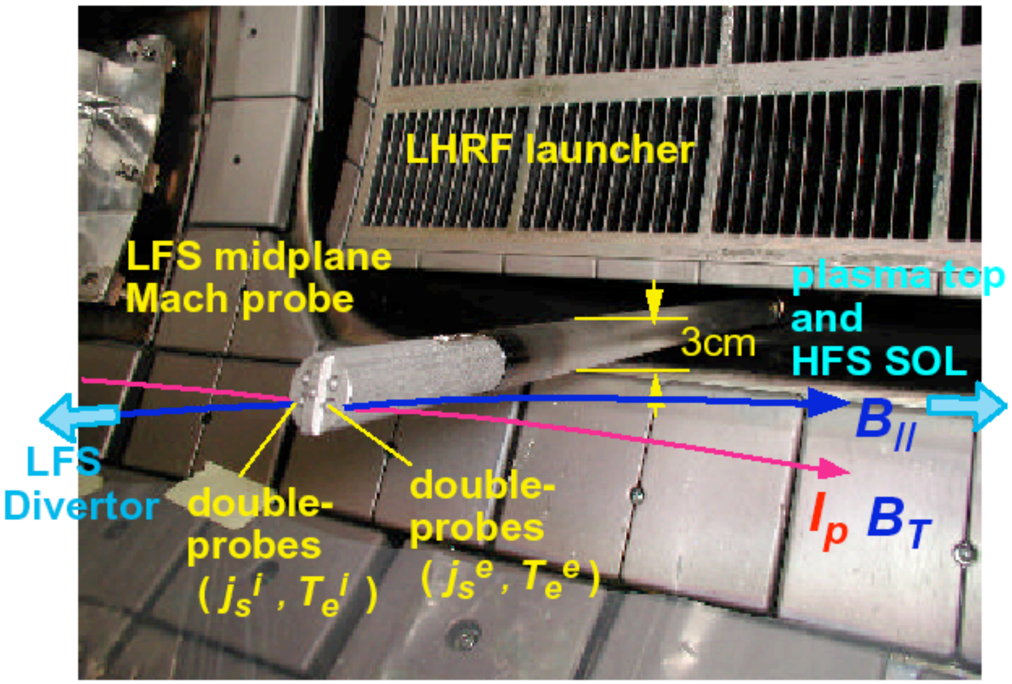
Multi physics processes (plasma drifts, diffusion, detachment, etc.) in tokamak divertor geometry.

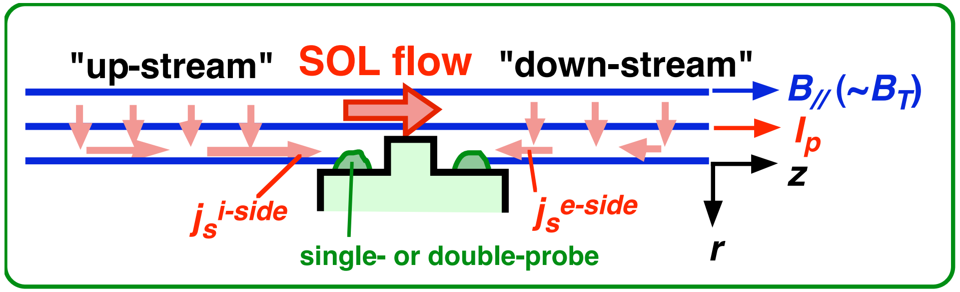
Plasma flow plays important role on *heat & particle transport in boundary plasmas:*

- Asymmetry in inner and outer divertors ⇒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:

$$M_{//} = M_c \ln[\, j_s^{i\text{-side}} / j_s^{e\text{-side}} \,] ,$$

where $M_c = 0.4$

I.H.Hutchinson, Phys. Rev. A37 (1988) 4358.

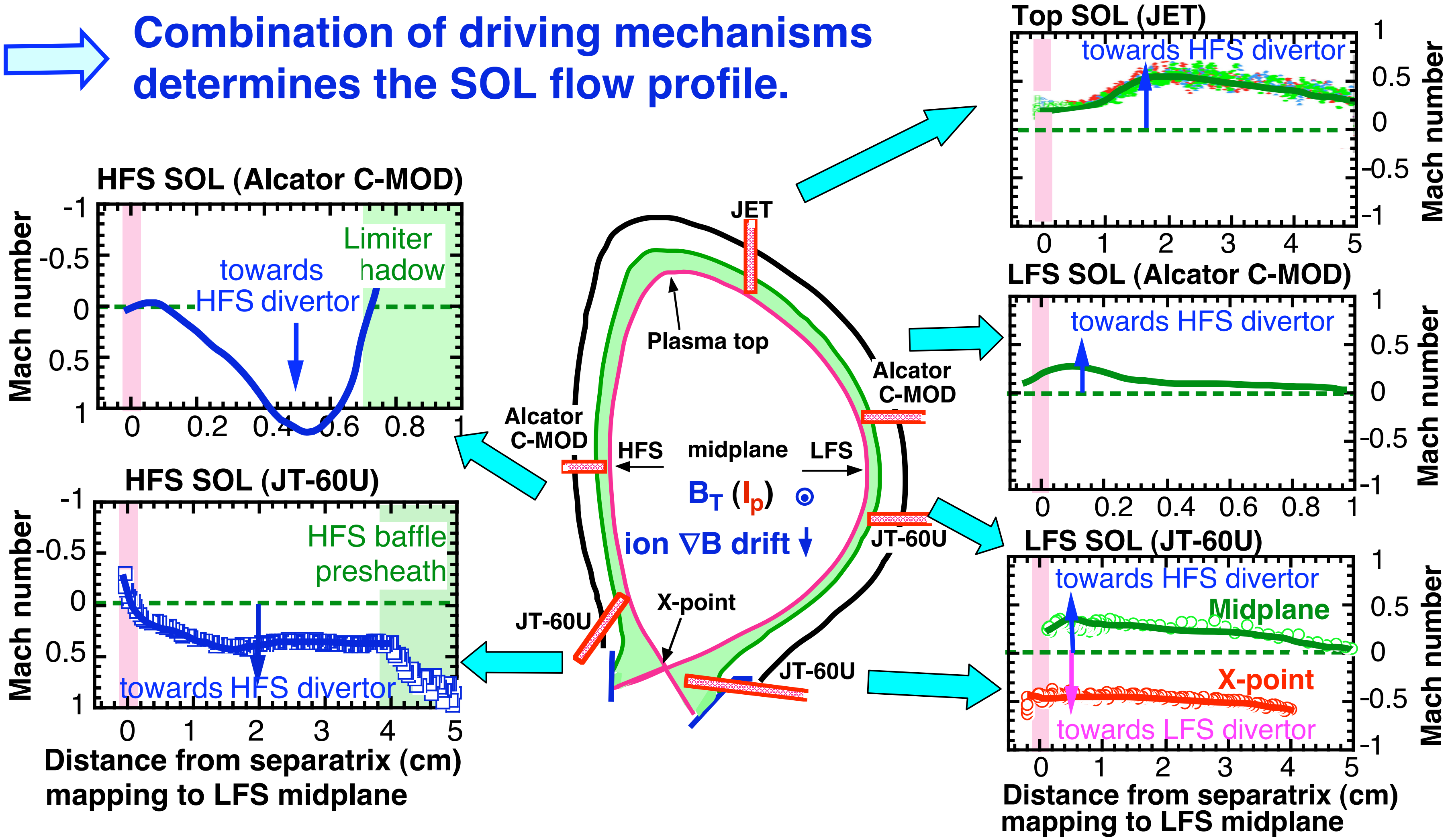
2. Scrape-off layer flow in tokamaks

SOL flow ($M_{//}$) profile changes at Low- and High-Field Sides

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

Far SOL **(*r* > λ_{ne}~cm)*:*** ***flow towards HFS divertor*** **increases at** ***Top&HFS*****.**

⇨ **Combination of driving mechanisms determines the SOL flow profile.**



Asakura et al. PPCF (2002) 2101, LaBombard, et al. NF 44 (2004) 1047, Erents et al. PPCF 46 (2004) 1757.

Key mechanisms to produce *parallel flow in tokamak SOL*:

(1) Asymmetrical diffusion, (2) Classical drifts, (3) Divertor detachment

Classical drifts

E_rxB, ∇pxB →

E_θxB →
($E_\theta = -\nabla_\theta T$)

Parallel flow

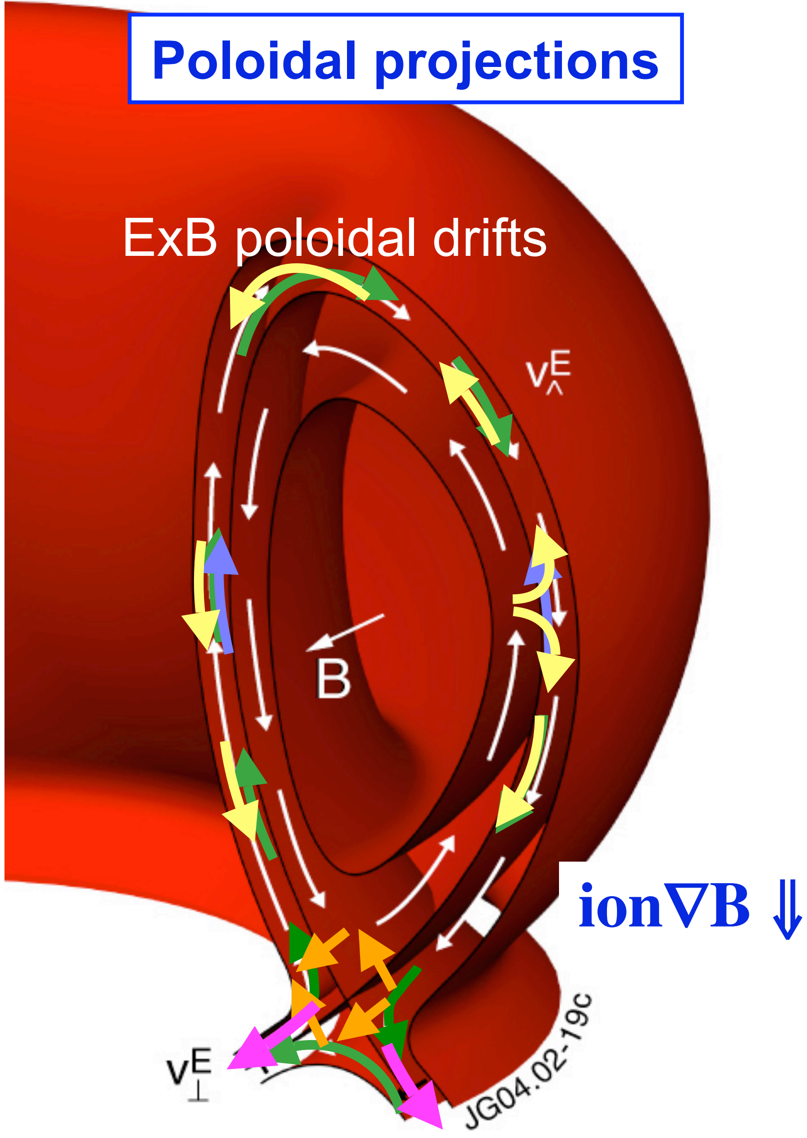
Pfirsch-Schlüter flow →

$V_{//}^{PS} = 2q_s V_\perp \cos\theta,\ V_\perp = (E_r - \nabla p_i) \times \boldsymbol{b}/B$

Asymmetrical diffusion →
(particle & momentum & energy)

Divertor sink →
Detachment, $\nabla_{//}$T, pre-sheath

Others: gas-puff, pumping, recycling



Fundamenski, et al JNM 337-330 (2005) 305, Pitts, et al. PPCF 45 (2005) B303

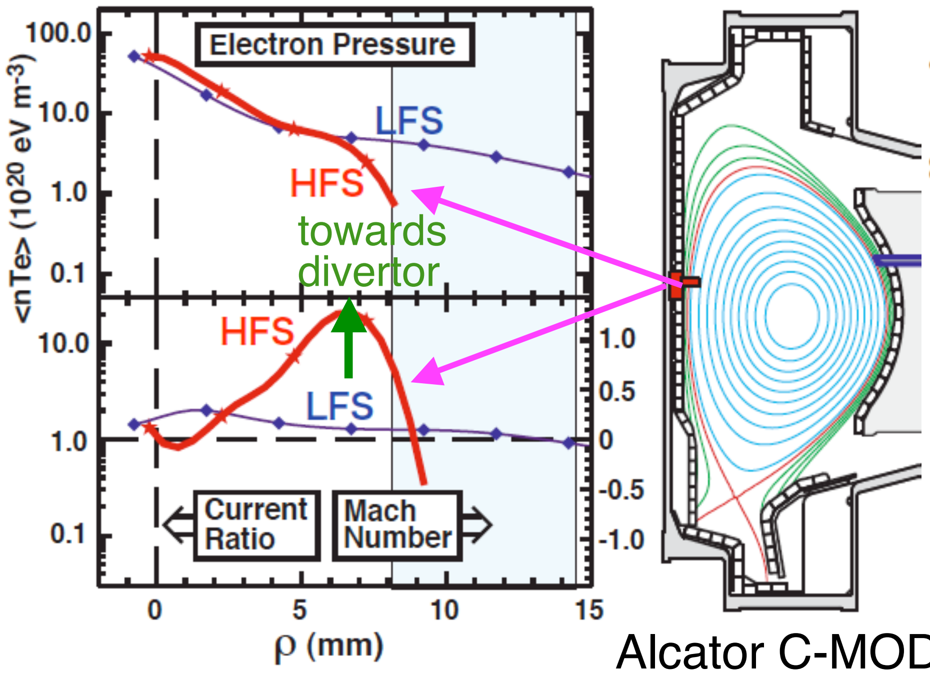
Key mechanism (1): *in-out asymmetry in diffusion*

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

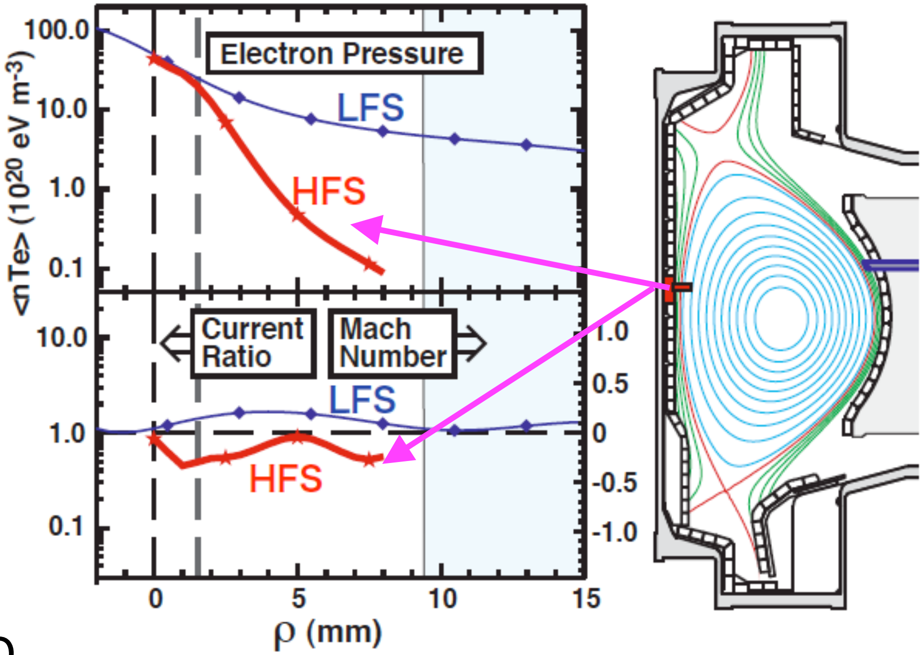
⇨ **HFS SOL plasma (in single null) is transported from the LFS SOL**

Lower Single Null Divertor



Alcator C-MOD

Double Null Divertor



LaBombard et al. NF 44 (2004) 1047

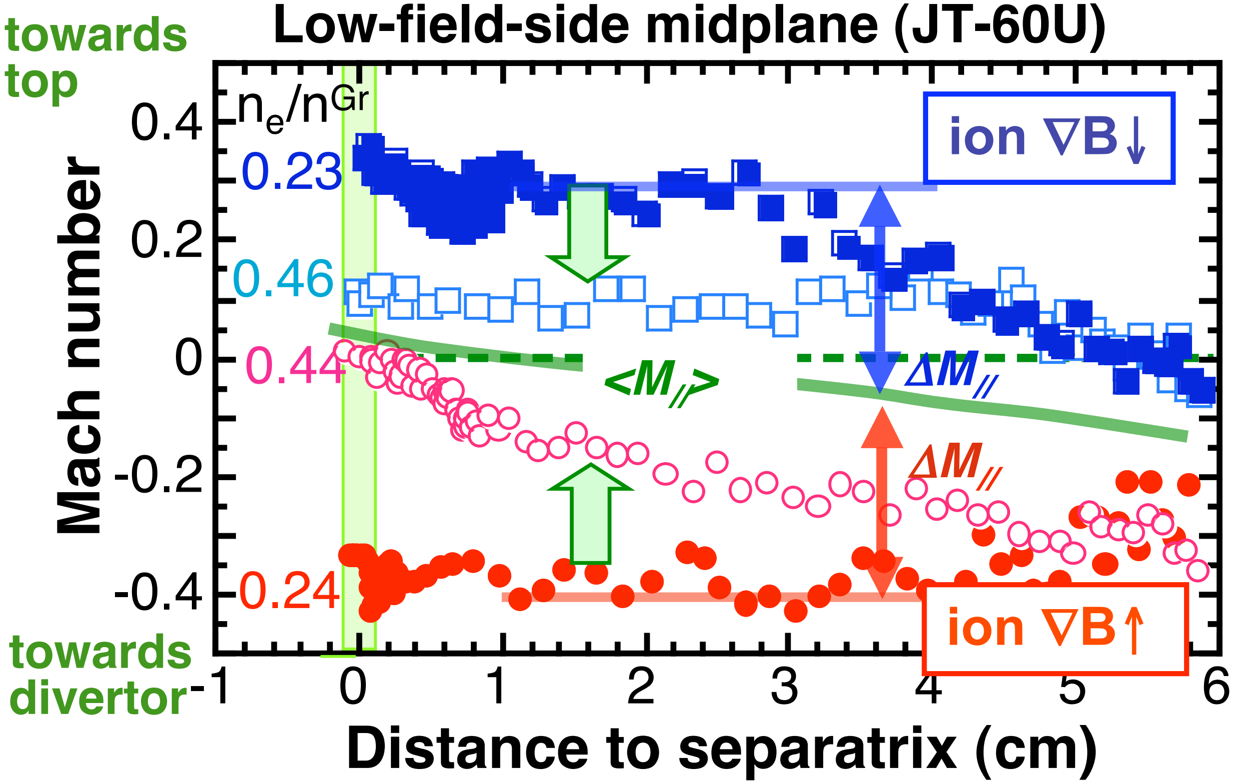
Key mechanism (2) : *Classical drifts in tokamak*

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

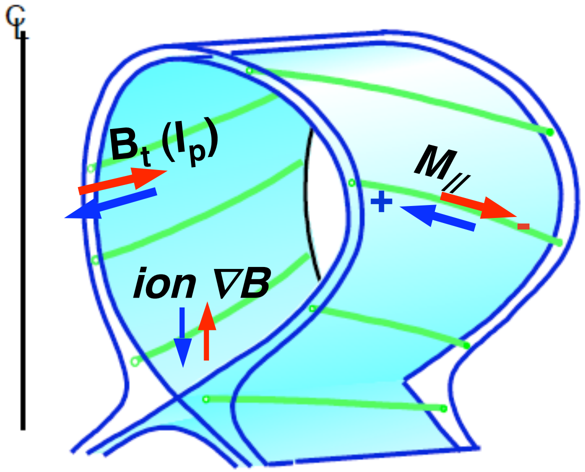
$\langle M_{//}\rangle$ ~0 (LFS midplane), ~0.2 (plasma top in JET)

Parallel flow is produced *against ion ∇B direction.*

$M_{//}$ (drift effect) decreases with n_e.



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

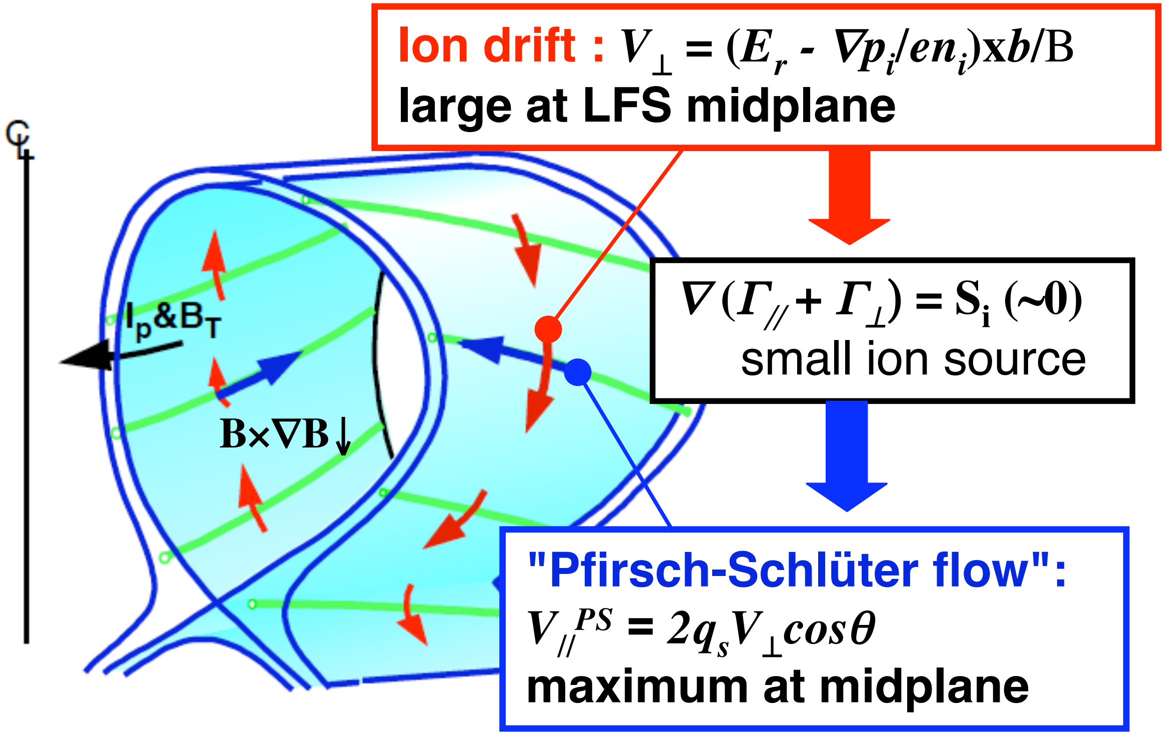


Similar results were found in C-MOD, TCV, and limiter tokamak (ToreSupra)

JT-60U:Asakura et al. PRL 84 (2000) 3093, LaBombard et al. NF 44 (2004) 1047, Erents et al. PPCF 46 (2004) 1757, TCV: Pitts et al. TCV.J.N.M. 363-365 (2007) 507, TS: Gunn et al, J.N.M. 363-365 (2007)484.

Classical drifts in tokamak:

Upward parallel flow is driven for ion ∇B↓ by in-out asymmetry of drifts



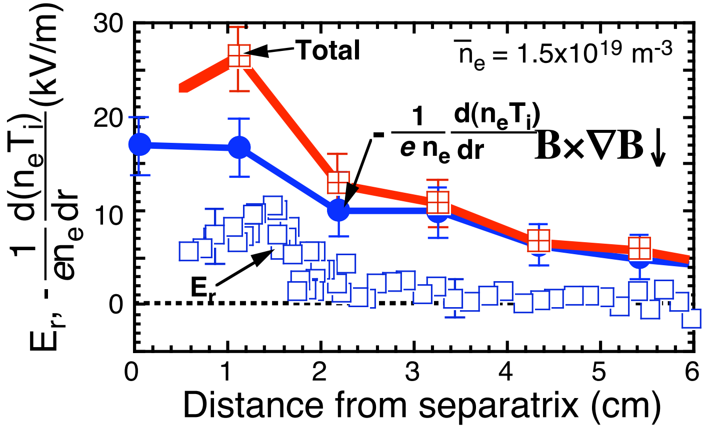
Ion drift : $V_\perp = (E_r - \nabla p_i/en_i) \mathrm{x} b/\mathrm{B}$
large at LFS midplane

$\nabla(\Gamma_{//} + \Gamma_\perp) = \mathrm{S_i}\ (\sim 0)$
small ion source

"Pfirsch-Schlüter flow":
$V_{//}^{PS} = 2q_s V_\perp \cos\theta$
maximum at midplane

$V_{//}^{\mathrm{PS}}$ **was evaluation from** $E_r \sim \nabla(V_f + \alpha T_e)$, ∇T_i **profiles**

LFS midplane (JT-60U)



Asakura et al. PRL 84 (2000) 3093
TCV: Pitts, et al. J.N.M. 363-365(2007)507

- **"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 ExB part):
better resolution of T_i profile will provide accurate evaluation of $V_{//}^{PS}$.

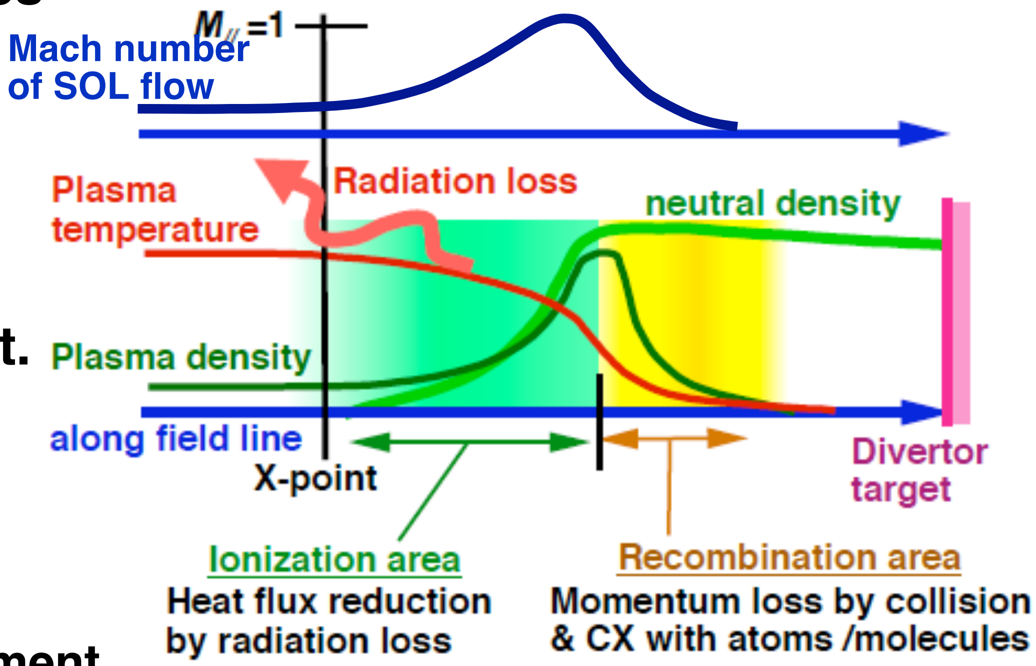
Classical drifts review: Chankin and Stangeby, PPCF 36 (1994) 1485 & 38 (1996) 839, NF 36 (1996) 839.

Key mechanism (3) : Influence of divertor detachment

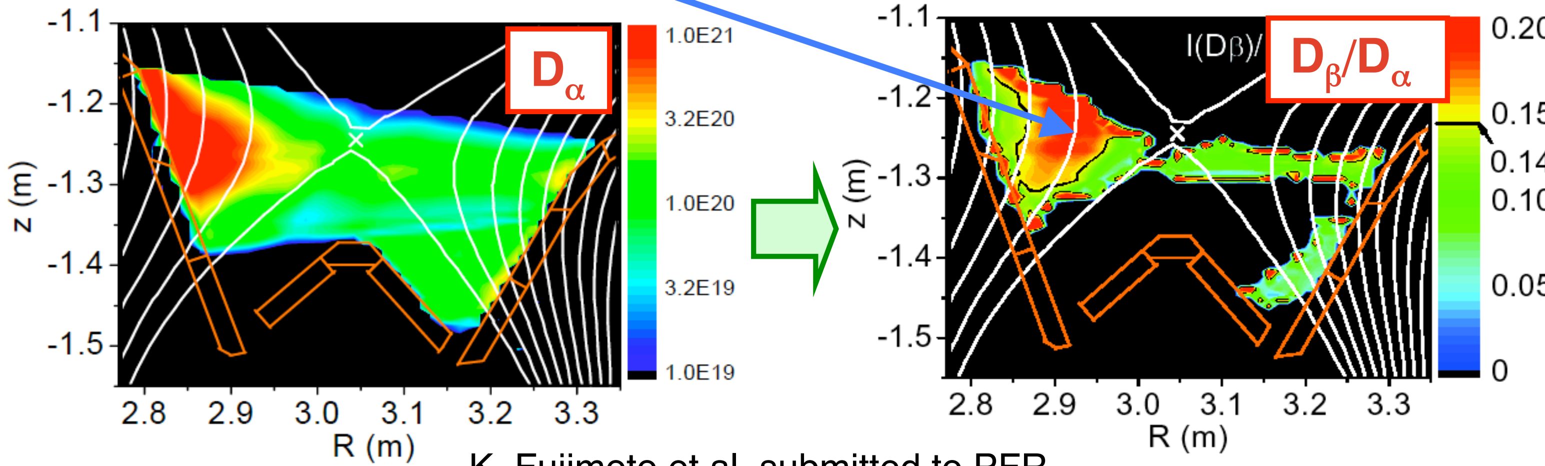
Recombination process becomes dominant in dense and cold divertor (< a few eV).

Plasma flow becomes Sonic level at the recombination front.

Parallel flow at the upstream SOL is increased.



2D divertor spectroscopy measurement (D_α- D_θ) determined recombination region



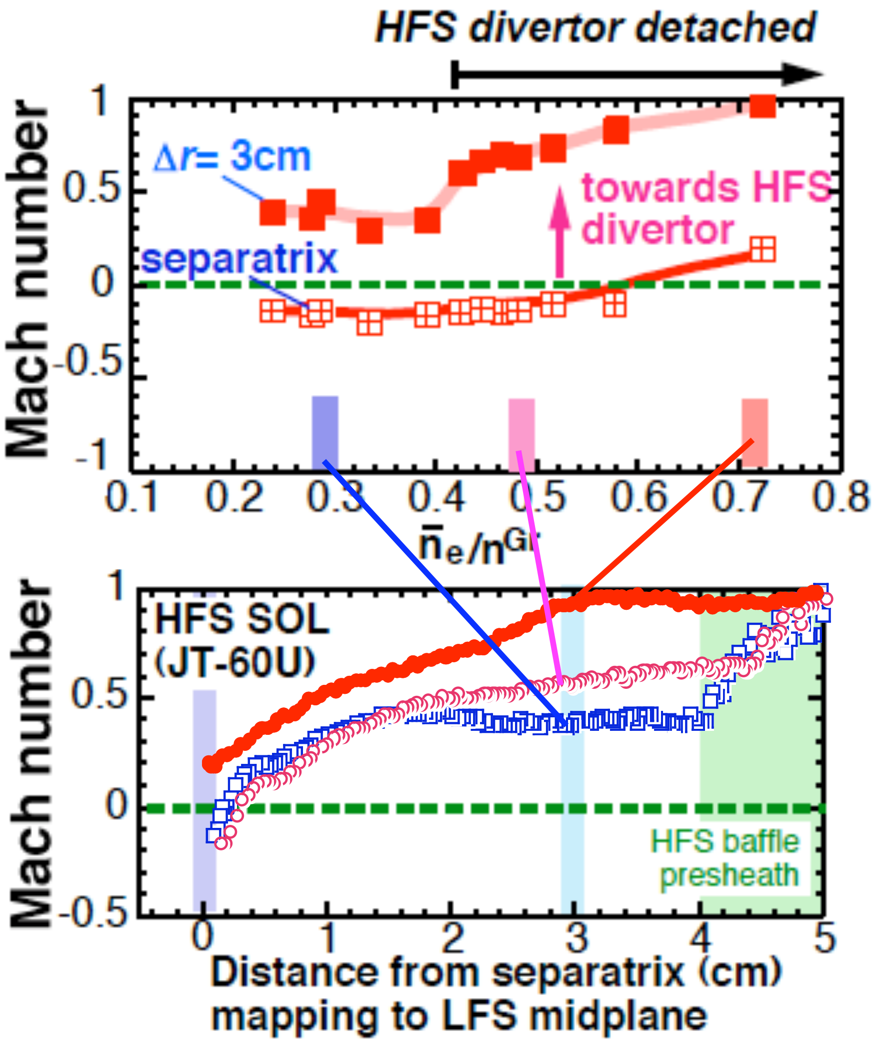
I_p=0.8MA,
B_t=3T,
n_e~1.2x$10^{19}$$m^{-3}$
n_e/n^{GW}~0.47

K. Fujimoto et al. submitted to PFR

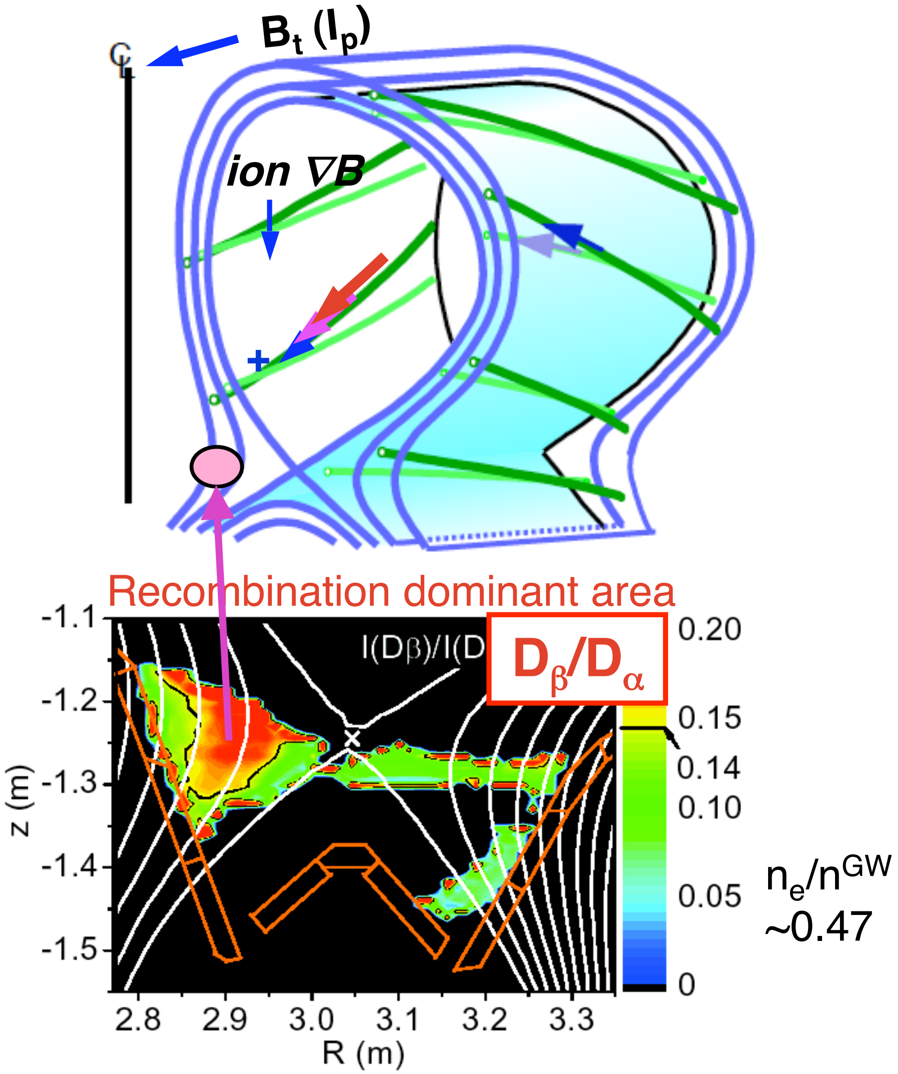
Divertor detachment affects *Subsonic-Sonic flow at HFS*

$M_{//}$ 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

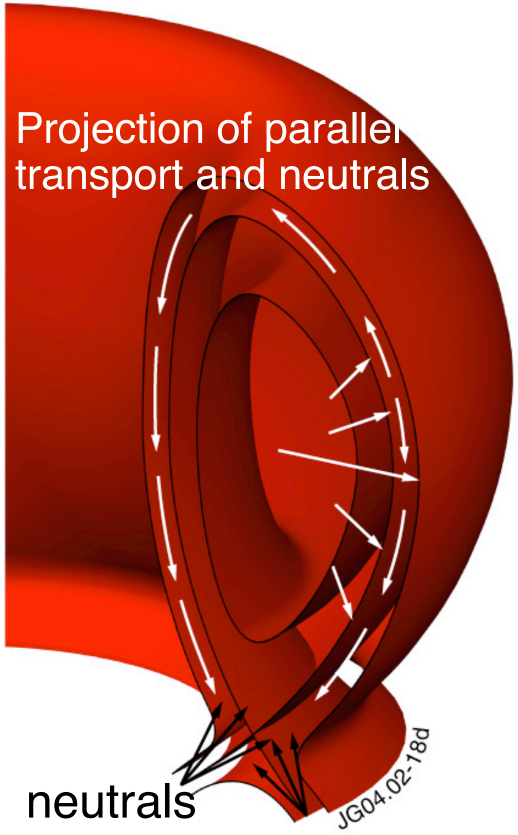


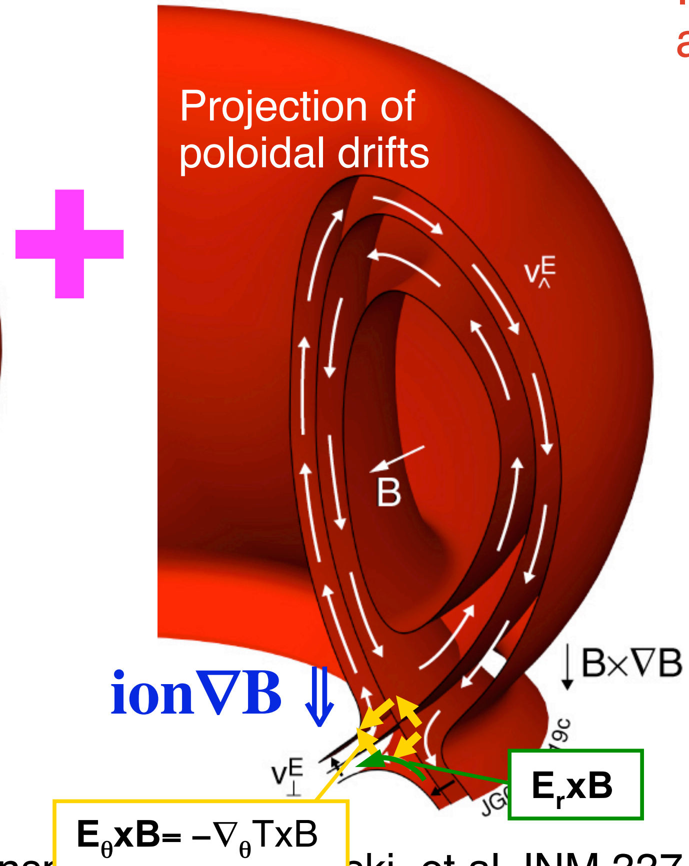
3. Divertor particle flux and in-out asymmetry

Drifts plays an important role near divertor null (X-point)

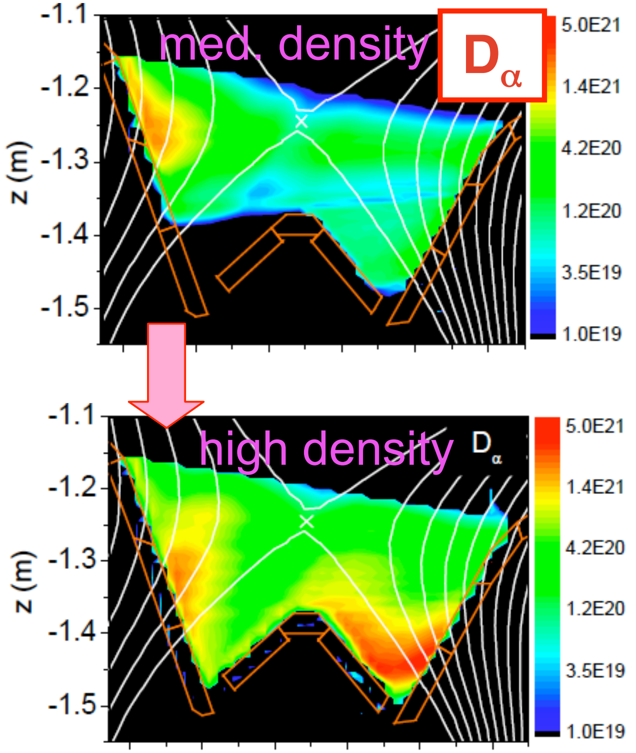
- **Heat and particle fluxes along B are separated in HFS/ LFS divertors**
- **Change of in-out asymmetries in heat and particle fluxes was NOT explained by parallel model (simulations)**

depending on *B_t direction* ⇒ Drifts (cross-field) transport in divertor





In-out asymmetry was reversed at high n_e (MARFE appears)



Effects of drifts on heat transport: Fundamenski, et al JNM 337-330 (2005) 305

SOL ion fluxes towards HFS&LFS divertors are evaluated

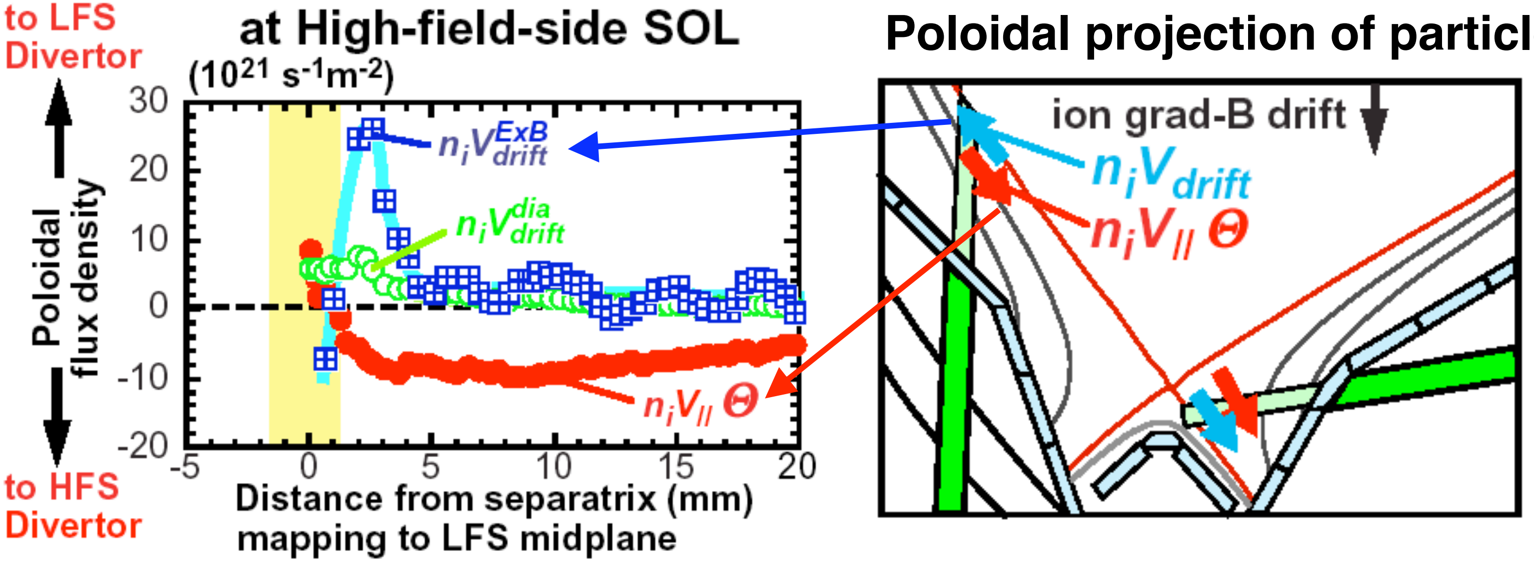
Poloidal components **of convection flux (**$n_i v_{//}\Theta$**) and drift flux (**$n_i v_{dr}^{ExB}\Phi$**) are evaluated at the *HFS* and *LFS SOLs* (Mach probe locations):**

Drift flux is large near the separatrix.

Net ion flux towards divertor: $\Gamma_p^{HFS/LFS} = 2\pi\int n_i[v_{//}\Theta \pm v_{dr}^{ExB}\Phi]Rdr$

(HFS: - / LFS: + for *ion ∇B drift towards divertor*).

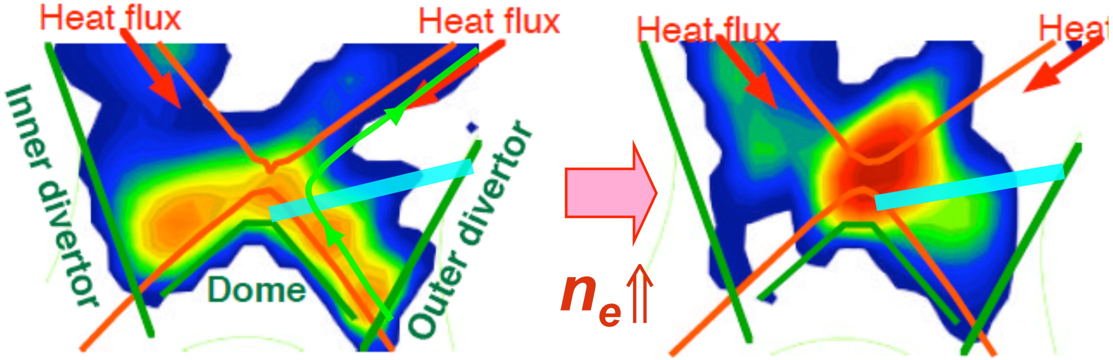
$n_iV_{//}\sim M_{//}j_s/e$, $\Theta = B_p/B_{//}$, $\Phi = B_p/B_{\perp}\sim 1$, $n_i = n_e$.



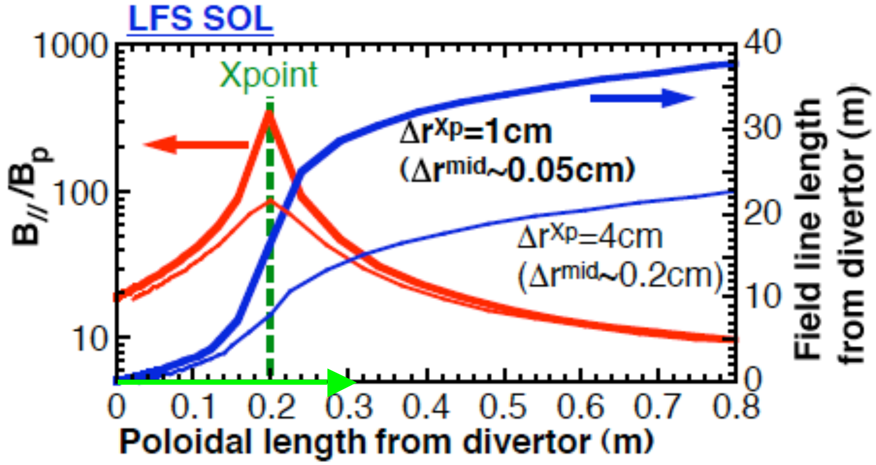
Asakura et al., JNM 313-316 (2003) 820.

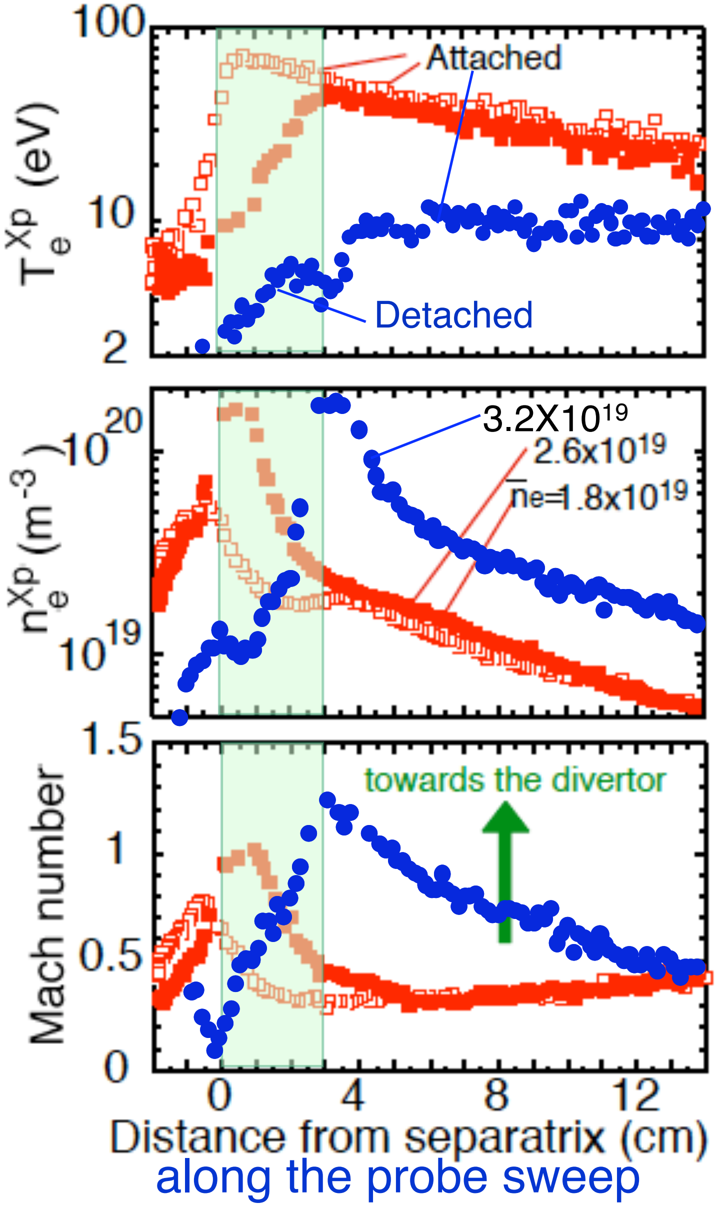
Radiation peak (MARFE) stays near the X-point (LFS), and detachment occurs at the down-stream of the MARFE.

2D divertor bolometer measurement determined radiation peak location



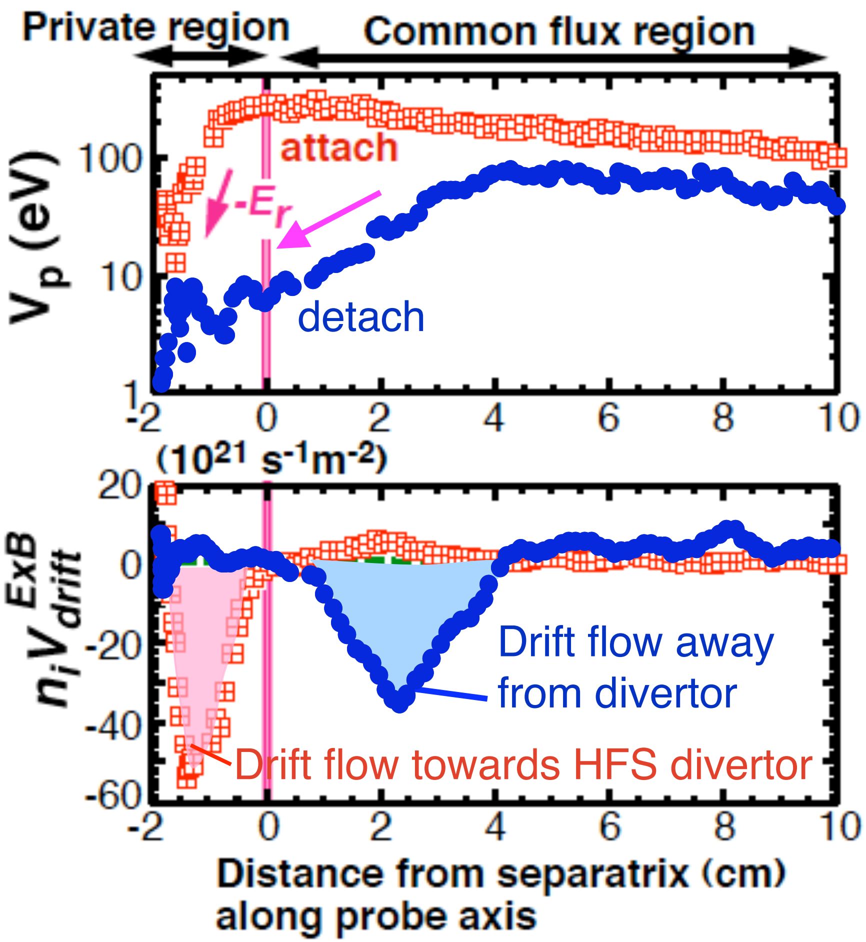
Field line length increased close to X-point, comparable to one toroidal turn (~19m).



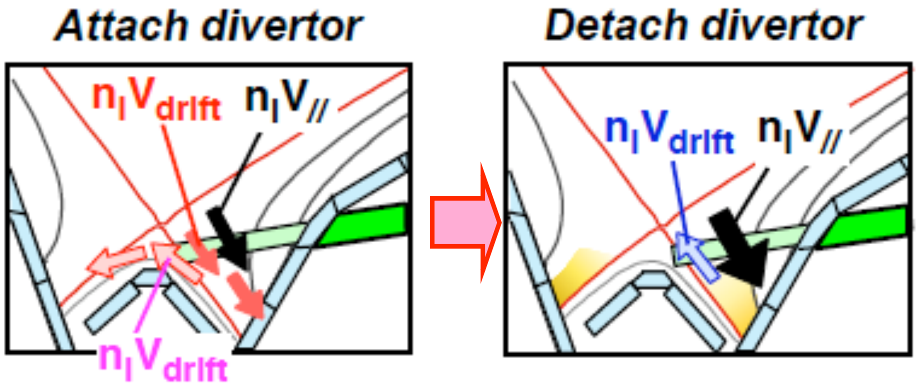


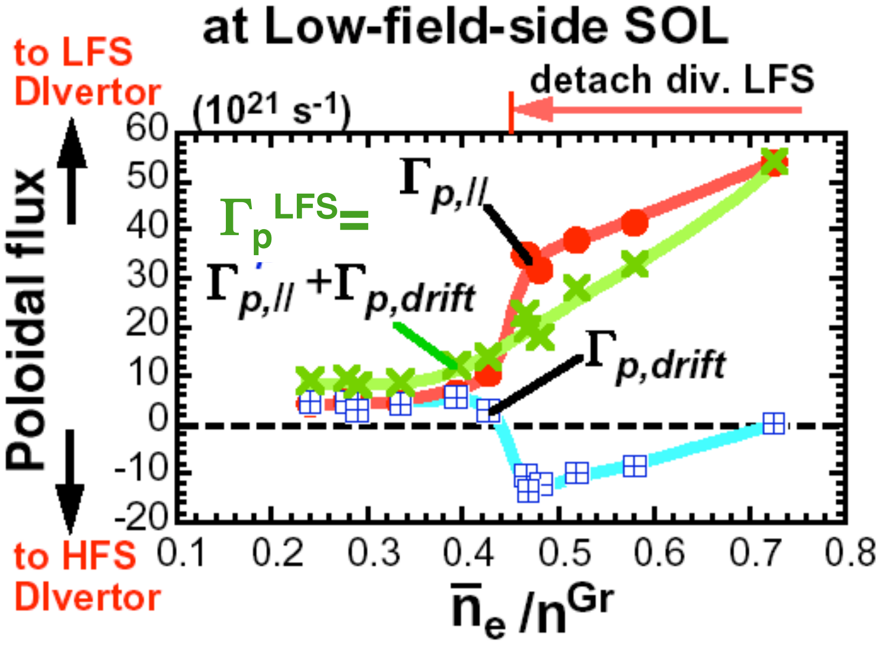
In private flux region under attached divertor condition, *large drift flow from LFS to HFS divertor* is produced.

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



Attached div. in DIII-D: .A. Boedo, et.al. Physics Plasma 7 (2000) 3093.





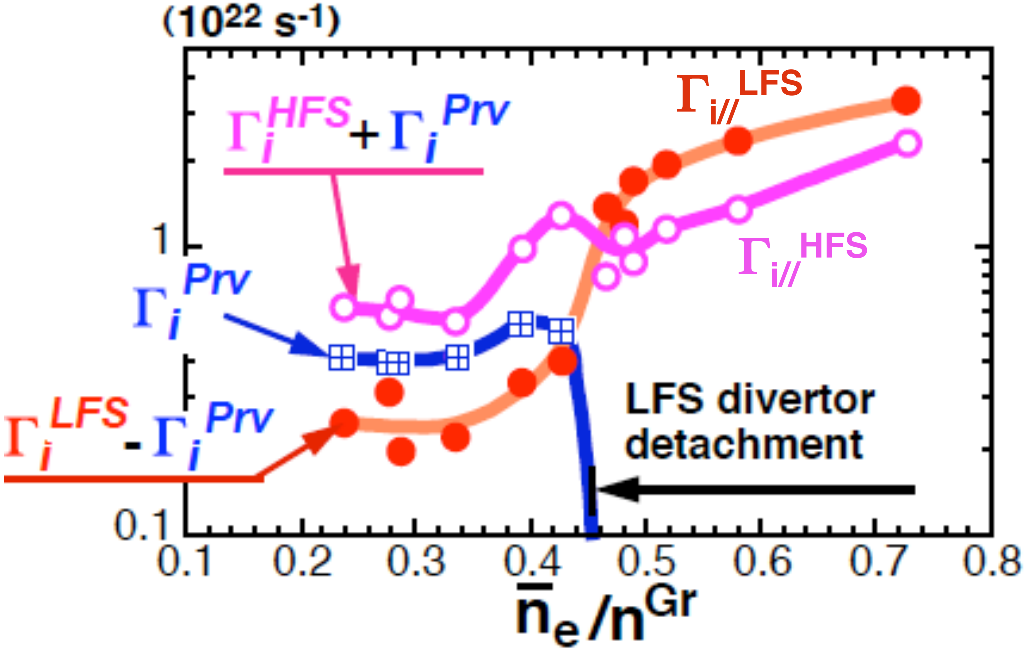
Drift flow in the private region and divertor detachment play an important role on producing in-out asymmetry in divertor.

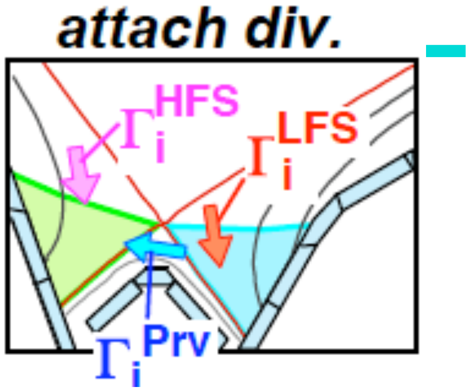
LFS divertor is attached:

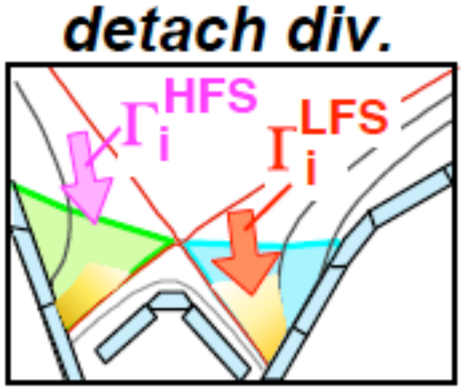
Γ_p^{prv} (drift flux in prv.) is added to Γ^{HFS} (HFS SOL flux), for *ion ∇B drift towards the divertor*

LFS divertor is detached:

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







Boedo et al., PP 7 (2000) 1075,
Asakura et al., JNM 313-316 (2003) 820.

4. Approach of SOL and divertor modelling

Approach of SOL & divertor modelling with drifts & diffusion

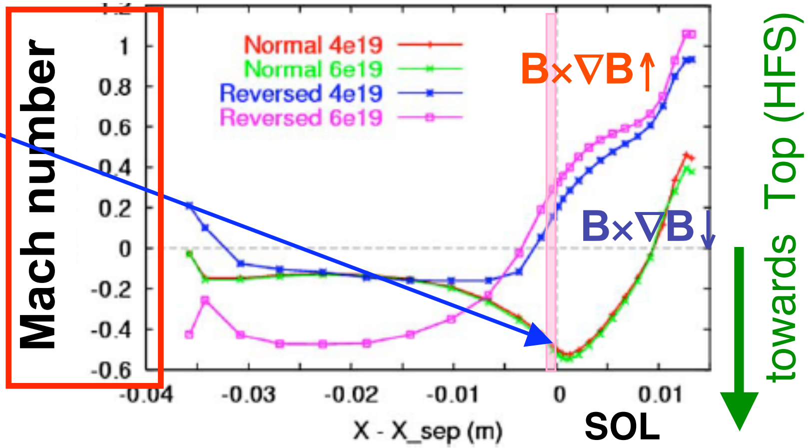
2-D fluid codes (SOLPS, UEDGE, EDGE2D) include classical drift effects, qualitatively reproduce normal/reversed B_t effects, but small $M_{//}$ (~0.1)

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

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

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

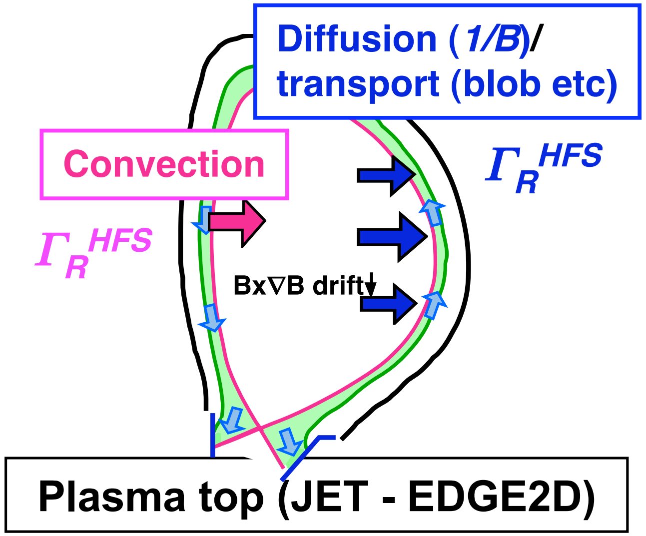
LFS midplane (C-MOD - B2SOLPS)



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

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

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



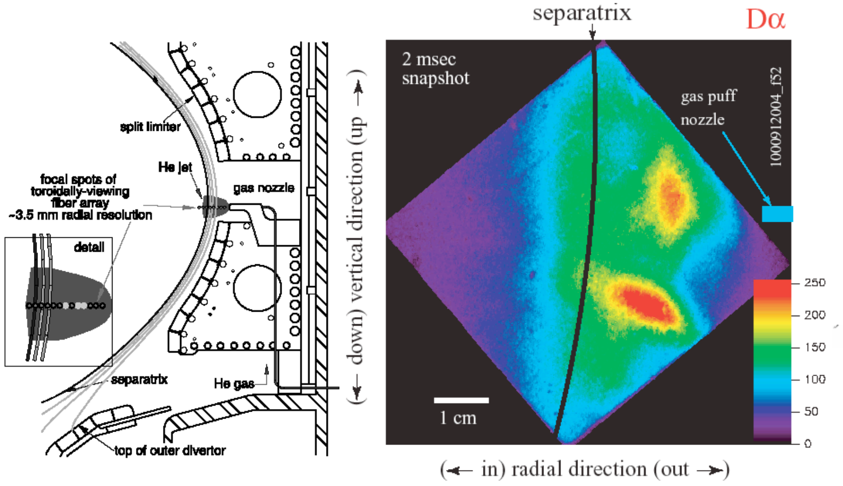
Kirnev, et al JNM 337-339 (2005) 271, Coster et al. IAEA 2004, Pigarov et al. 10th PET 2005

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.*

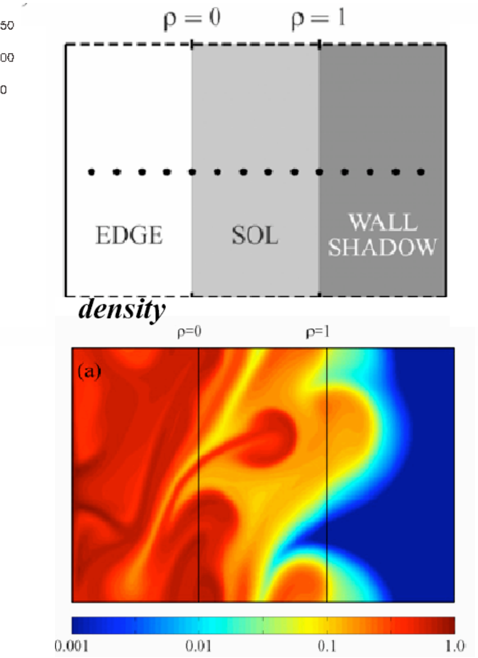
Alcator C-MOD

J.Terry, et al., J. Nucl. Mater. 290-293, 757 (2001).



- **Non-linear simulation of the turbulence transport can evaluate contribution of outflux to the fast SOL flow: $\langle M_{//} \rangle \sim 0.1\text{-}0.2$ 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.

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