Particle control and SOL plasma flow (from recent experiments in JT-60U)

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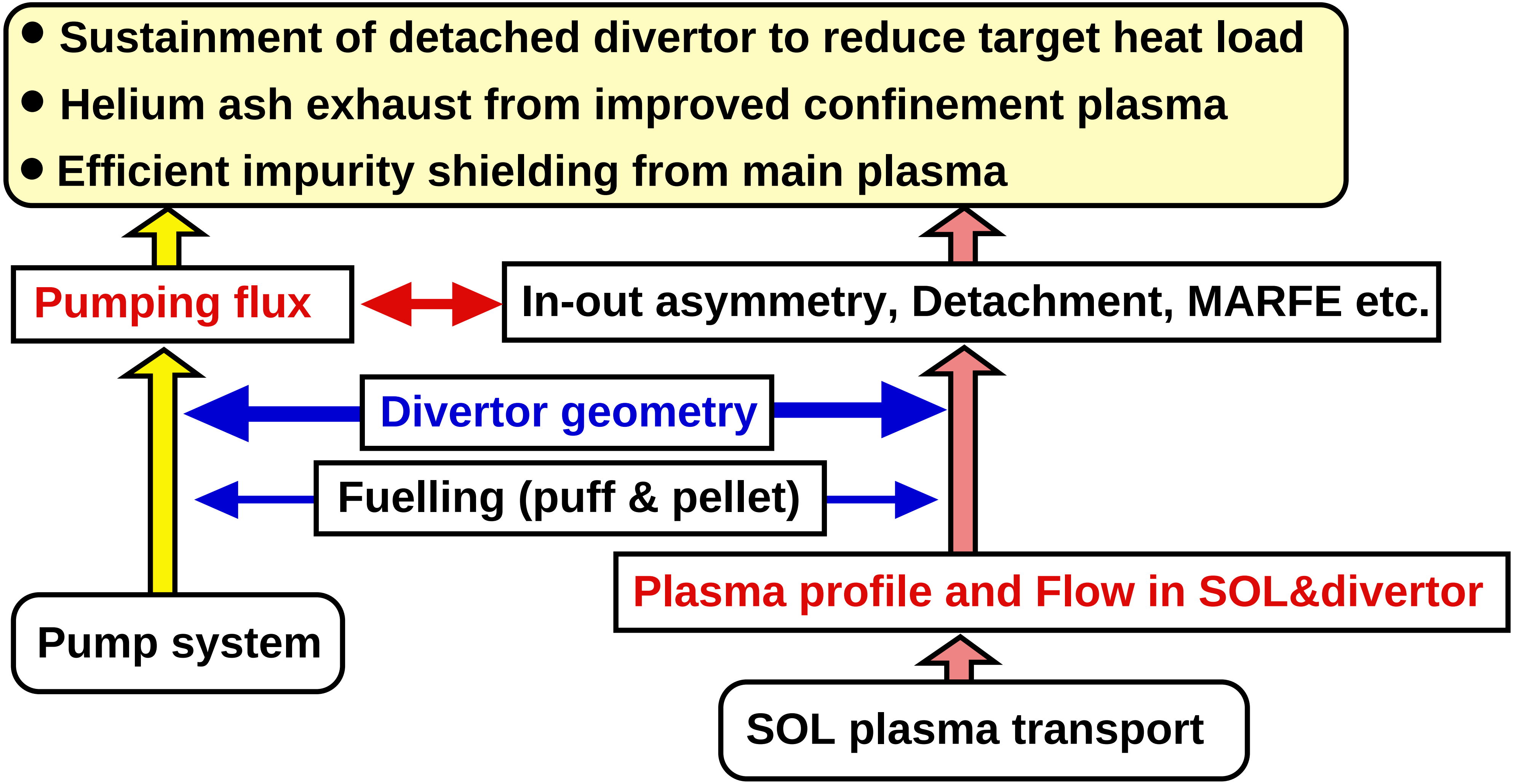
1. Introduction Particle control in SOL and divertor

Compact design of the divertor is required, with satisfying

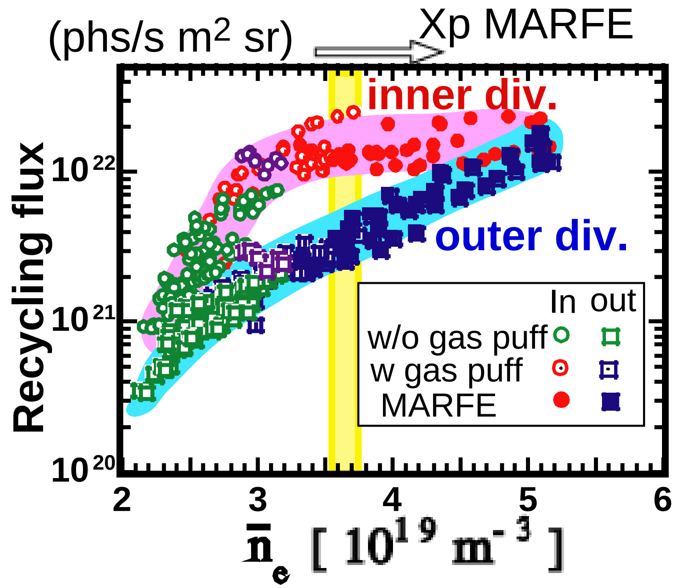
Divertor performance:

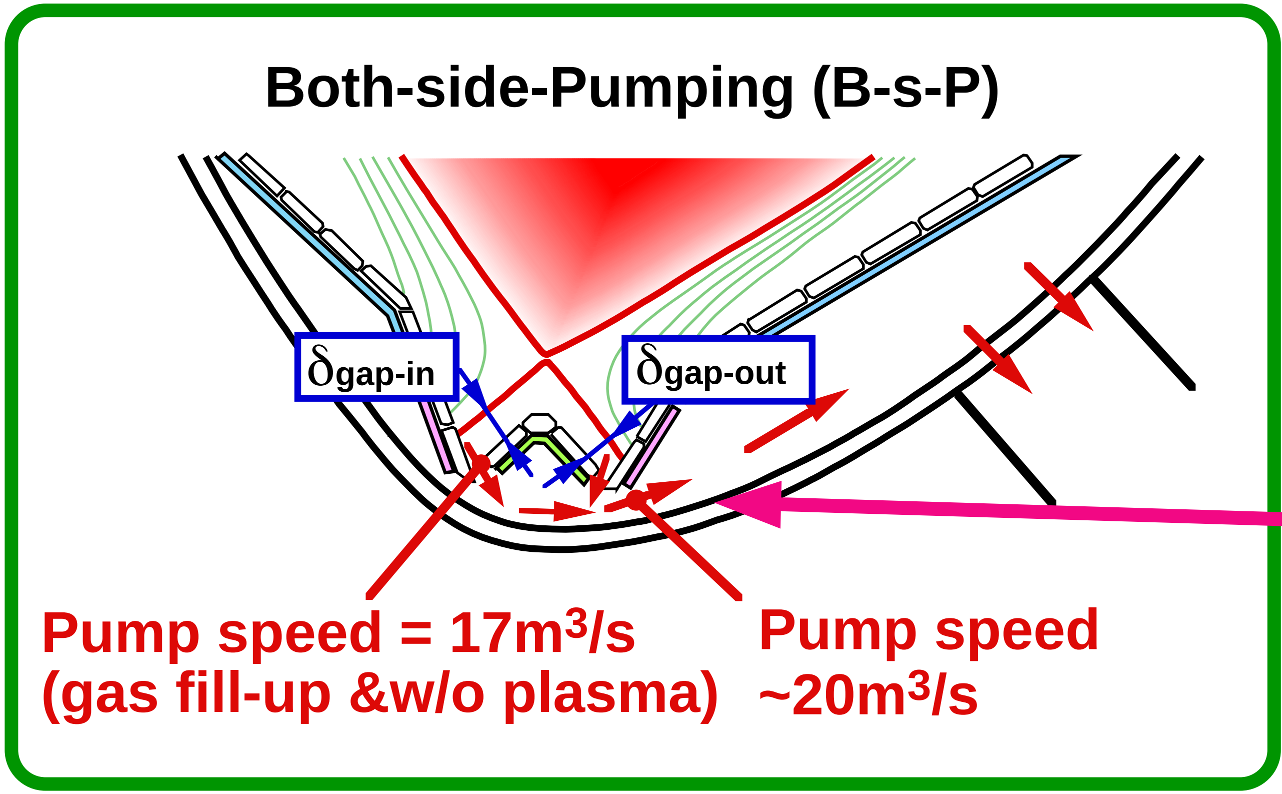


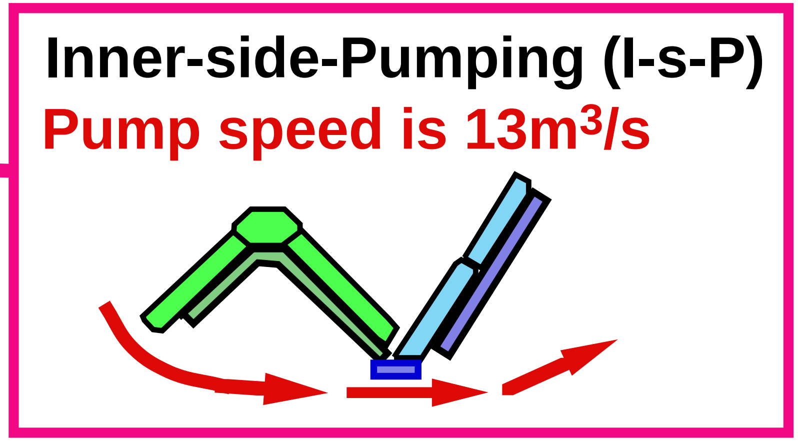
- **Divertor pumping and SOL flow studies will contribute to optimize the divertor design.**

2. Pumping in the W-shaped divertor

- Pumping from private flux region (with dome) has advantages for detachment control, He exhaust, reduction of carbon generation.
- Leak of neutrals was anticipated for B-s-P geometry due to in-out asymmetries of recycling and separation btw. pumping-slot and strike-point (δgap-in, δgap-out).

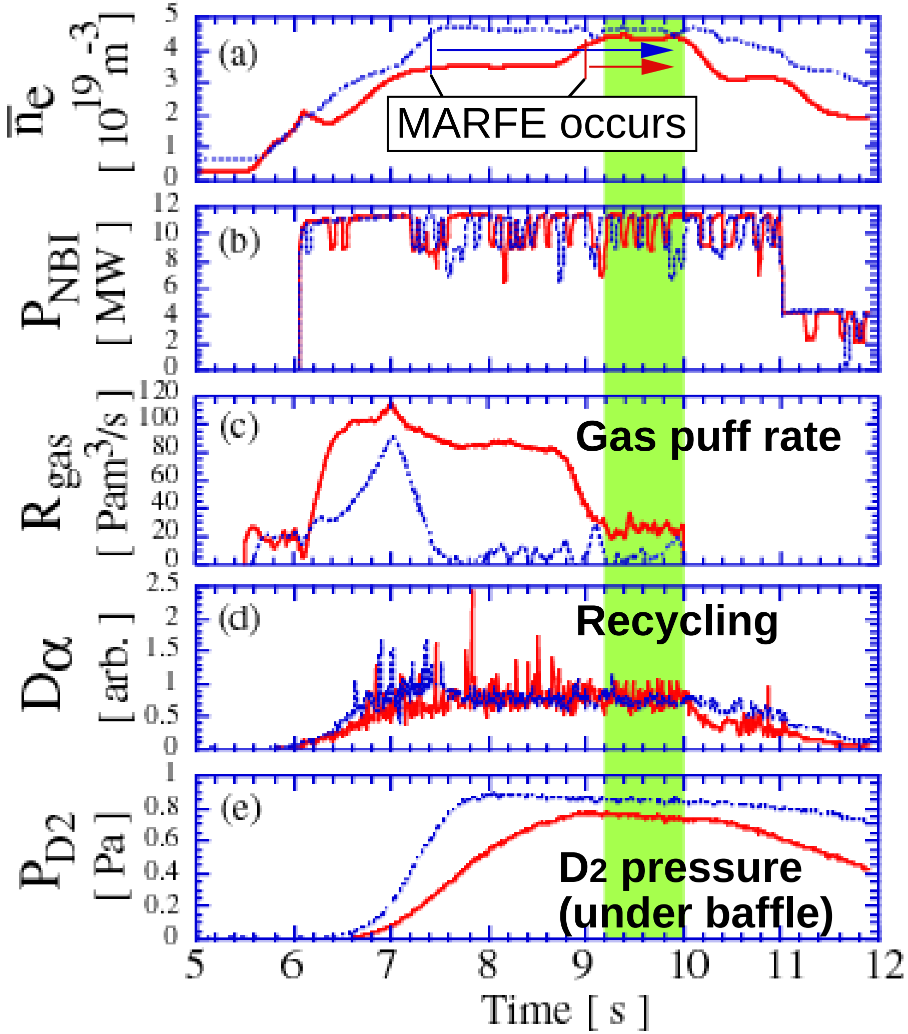






Pumping flux is deduced from gas puff rates for pump ON and OFF

ELMy H-mode plasma:
w pump, w/o pump



I_p =1.5MA, B_T =3.5T, q_{95} =3.94, P_{NB} =11MW

Inner private flux pumping case:

($\delta_{gap,in}$ = 3.5cm)

w pump

$$\Phi_{NB} + \Phi_{GP}^{W\text{-}P} = \Phi_{absorb} + \Phi_{pump}$$

w/o pump

$$\Phi_{NB} + \Phi_{GP}^{W/O\text{-}P} = \Phi_{absorb}$$

$$\Phi_{pump} = \Phi_{GP}^{W\text{-}P} - \Phi_{GP}^{W/O\text{-}P}$$

Φ_{NB} = 1×10^{21} /s

$\Phi_{GP}^{W\text{-}P}$ = 13×10^{21} /s

$\Phi_{GP}^{W/O\text{-}P}$ = 5×10^{21} /s

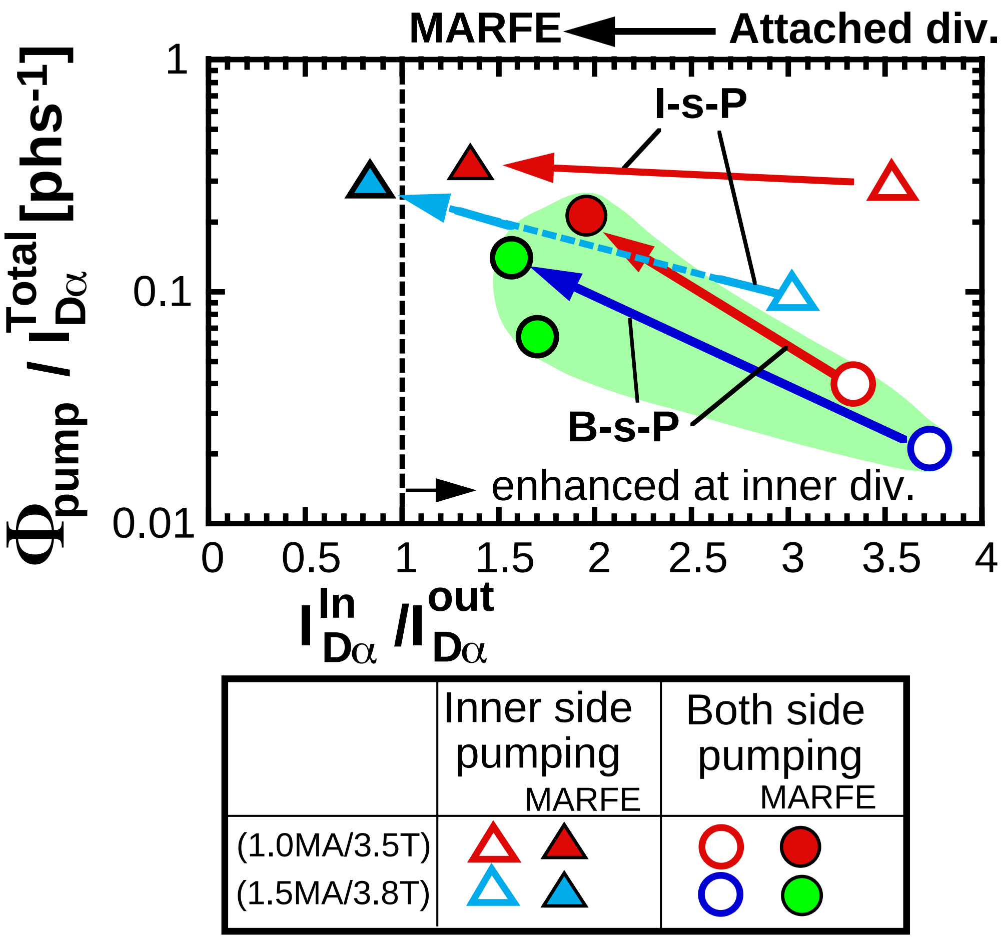
- Φ_{pump} = 8×10^{21} /s : P_{D2}=0.75 Pa (under baffle)
  → **Pumping speed ~ 40 m^3/s**

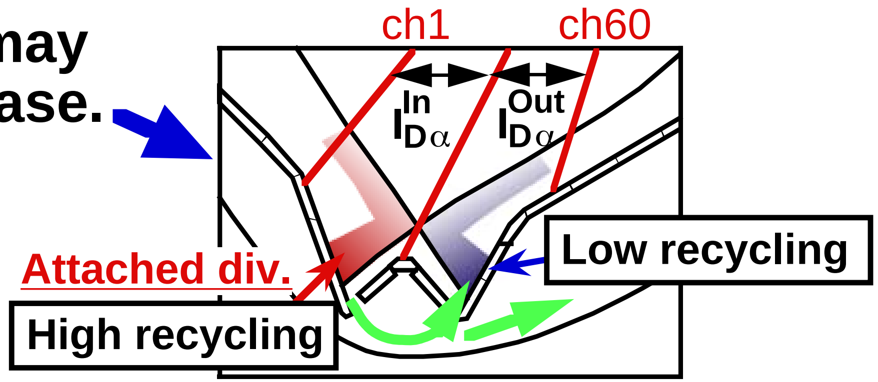
Pumping ratio: $\Phi_{pump} / \Phi_{recycle}$ is estimated to be 3%.

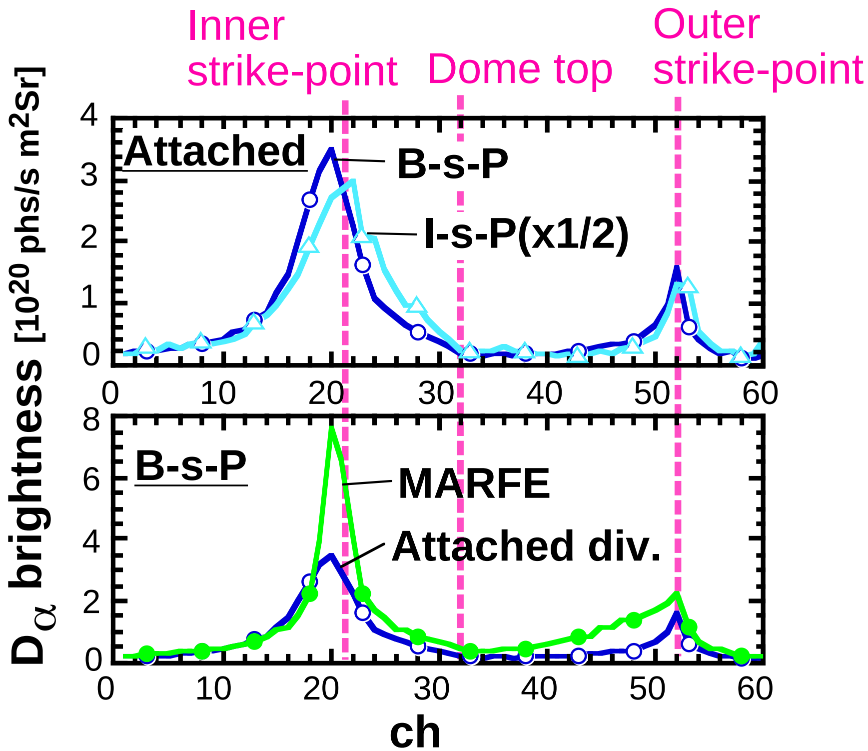
- Φ_{absorb} = 6×10^{21} /s :
  → **comparable to pumping flux**

Pumping ratio for B-s-P was smaller than that for I-s-P (1/6-1/4 at low n_e) .
In the detached divertor, pumping ratio (B-s-P) was greatly increased.

- **Neutral leak from Inner to Outer divertor may be dominant for large in-out asymmetry case.**





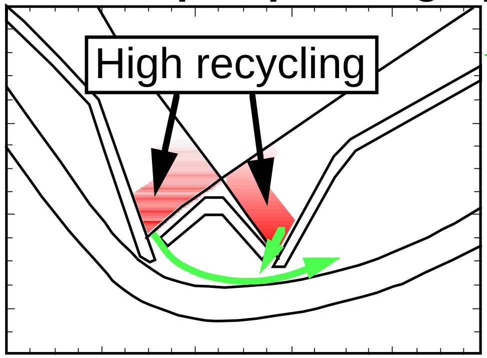


Ref. H. Takenaga, et al. appears in Nucl. Fusion 2001

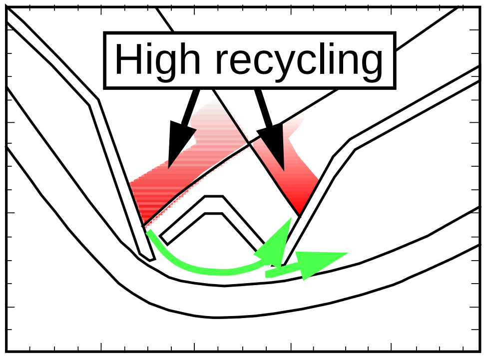
Pumping ratio is improved for closure gap operation

- **Pumping ratio for small-gap (~0.5cm) was increased 2-3 times.**
  Small δ_{gap} was allowable since Dome tiles were replaced from Graphite (I-s-P) to CFC (B-s-P).
- **Large ratio (4.8%) was obtained in detached divertor compared to I-s-P (3% for δ_{gap} = 3.5cm).**

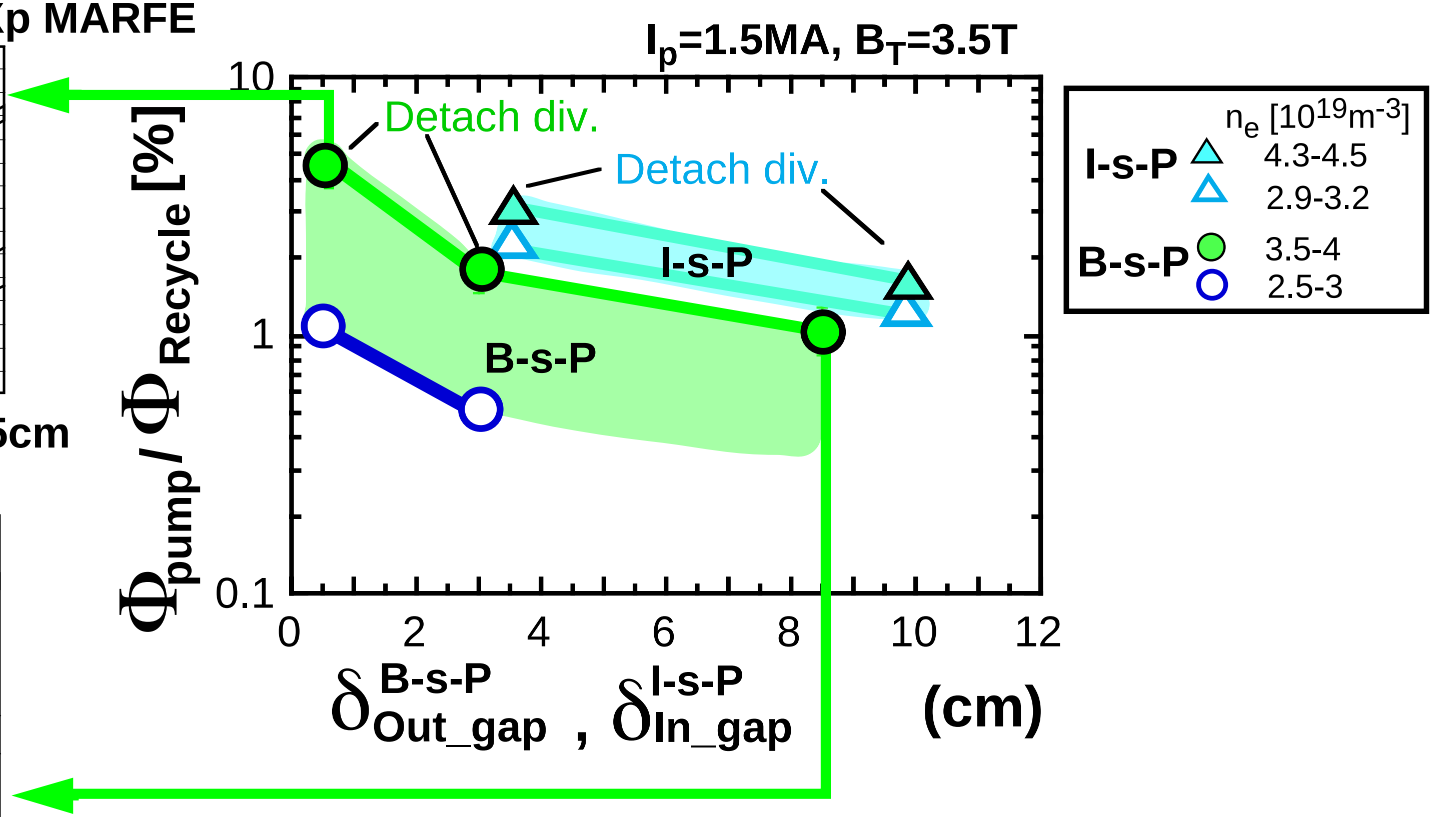
Both-side pump.during Xp MARFE



$\delta^{I\text{-}s\text{-}P}_{In\_gap}$ = 1cm / $\delta^{B\text{-}s\text{-}P}_{Out\_gap}$ = 0.5cm



$\delta^{I\text{-}s\text{-}P}_{In\_gap}$ = 4cm / $\delta^{B\text{-}s\text{-}P}_{Out\_gap}$ = 8cm



UEDGE/DEGAS2 to evaluate pumping&leak fluxes

SOL& Divertor plasma (Background plasma)

↓

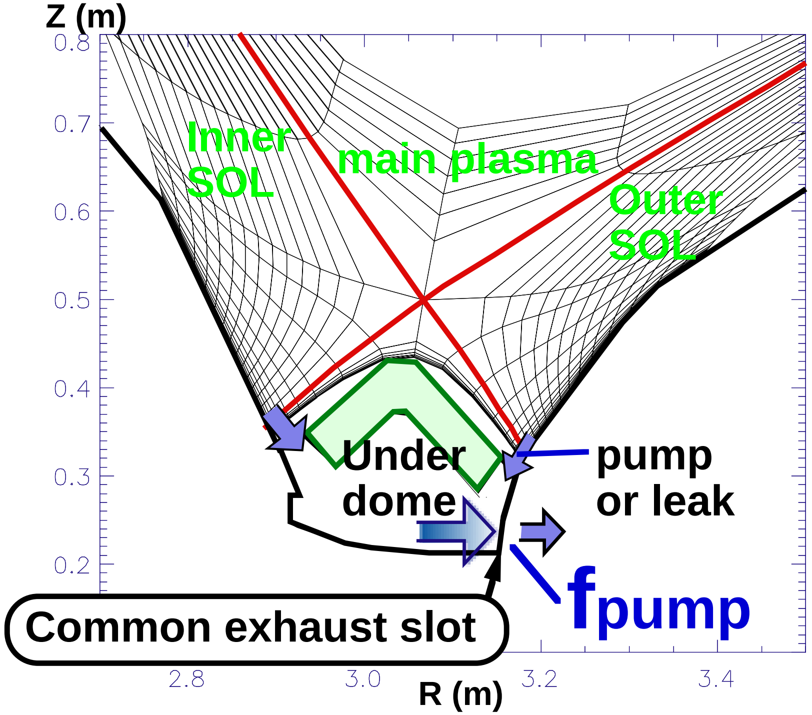
Neutral transport

UEDGE	**2-D fluid code** **fluid neutral model** **sputtered impurity**

DEGAS2	**3-D Monte-Carlo code**

- **Iterative calculation between UEDGE-DEGAS2 was not used. Background plasma was fixed.**

- **Pumping flux was calculated for various pumping ratio at common exhaust slot: f_{pump} = 0 - 0.5.**



Code-run was supported by Drs G. D. Porter, T.D. Rognlien and M.E. Rensink (LLNL).

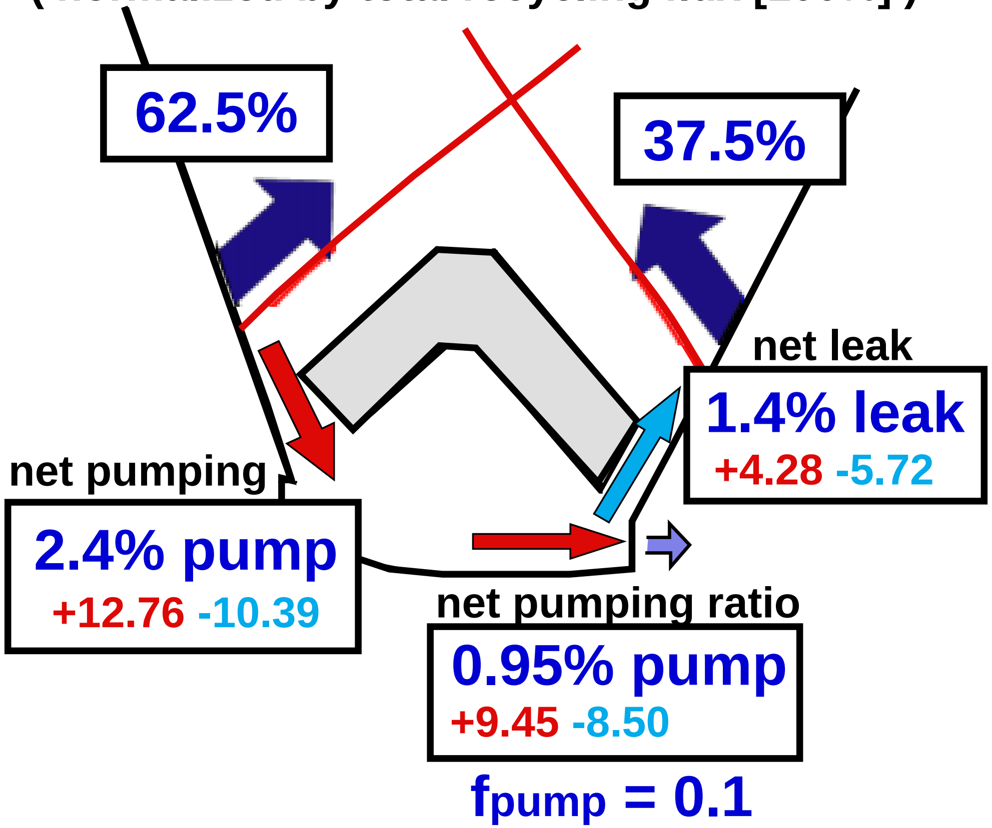
Closure-operation: net leak at outer pumping-slot can be minimized.

→ Net pumping ratio is increased by 60% (1% → 1.6% of $\Phi_{recycle}$).

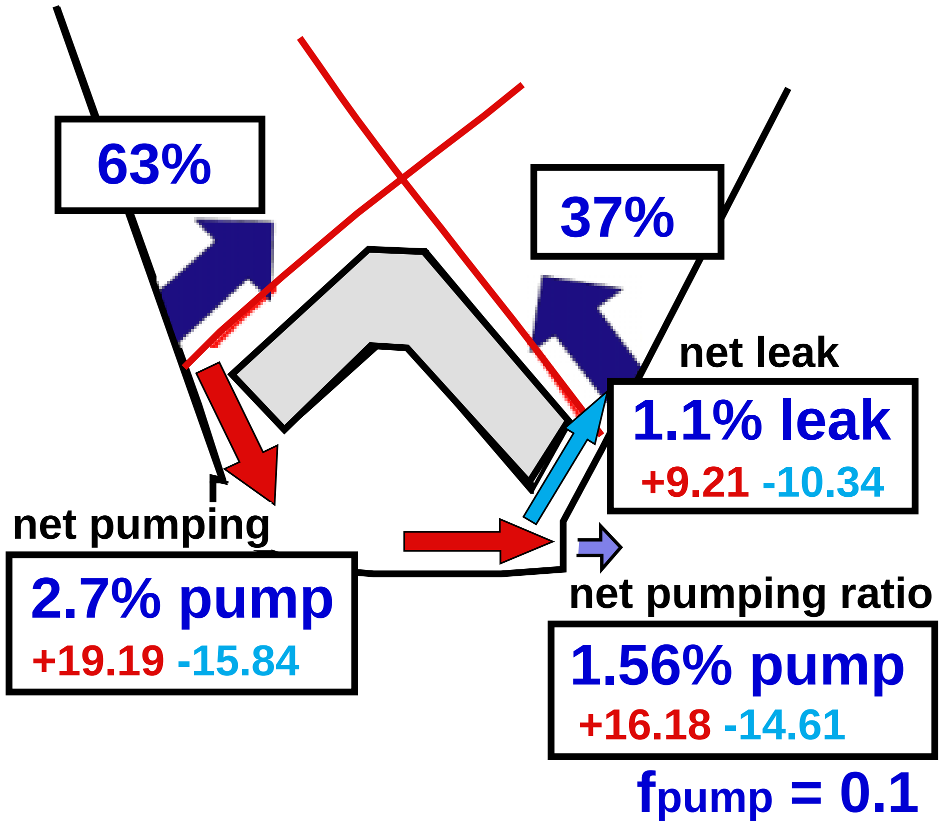
Net leak at outer pumping-slot is not suppressed for f_{pump} up to 0.5 in the attached divertor (due to in-out asymmetry of recycling).

Pumping ratio ($\delta_{g\text{-}In}$, $\delta_{g\text{-}Out}$ = 3cm)

(normalized by total recycling flux [100%])



Pumping ratio ($\delta_{g\text{-}In}$= 1, $\delta_{g\text{-}Out}$= 0.5cm)



SOLDOR/ NEUT2D for divertor design of JT-60SC

SOL& Divertor plasma

SOLDOR Complex divertor mesh (non-orthogonal mesh, Finite Volume Method)

2-D fluid code (Newton-Raphson method)

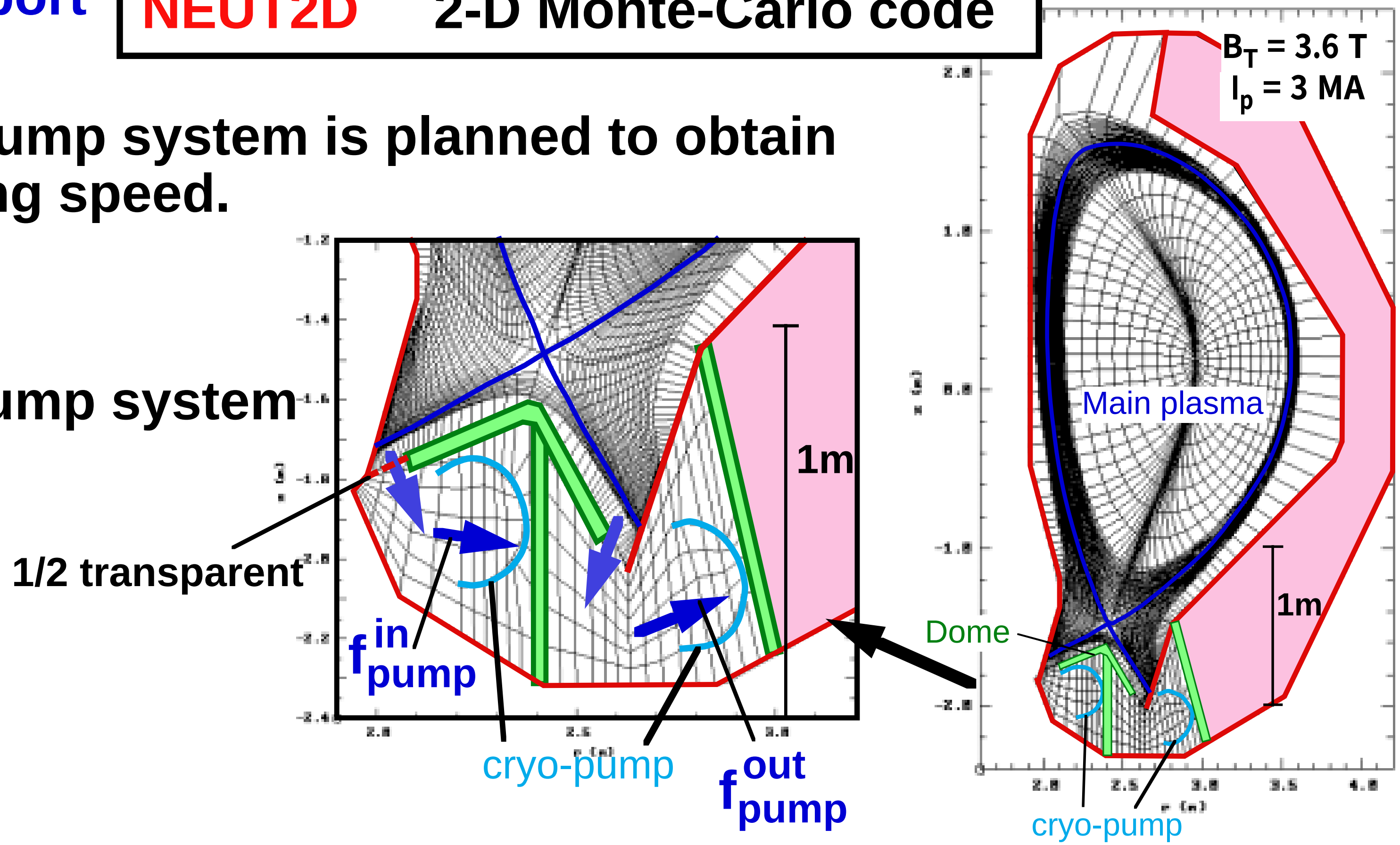
Sputtered impurity will be introduced with Monte-Carlo calc. (IMPMC)

Neutral transport

NEUT2D 2-D Monte-Carlo code

- Separate 2 pump system is planned to obtain large pumping speed.

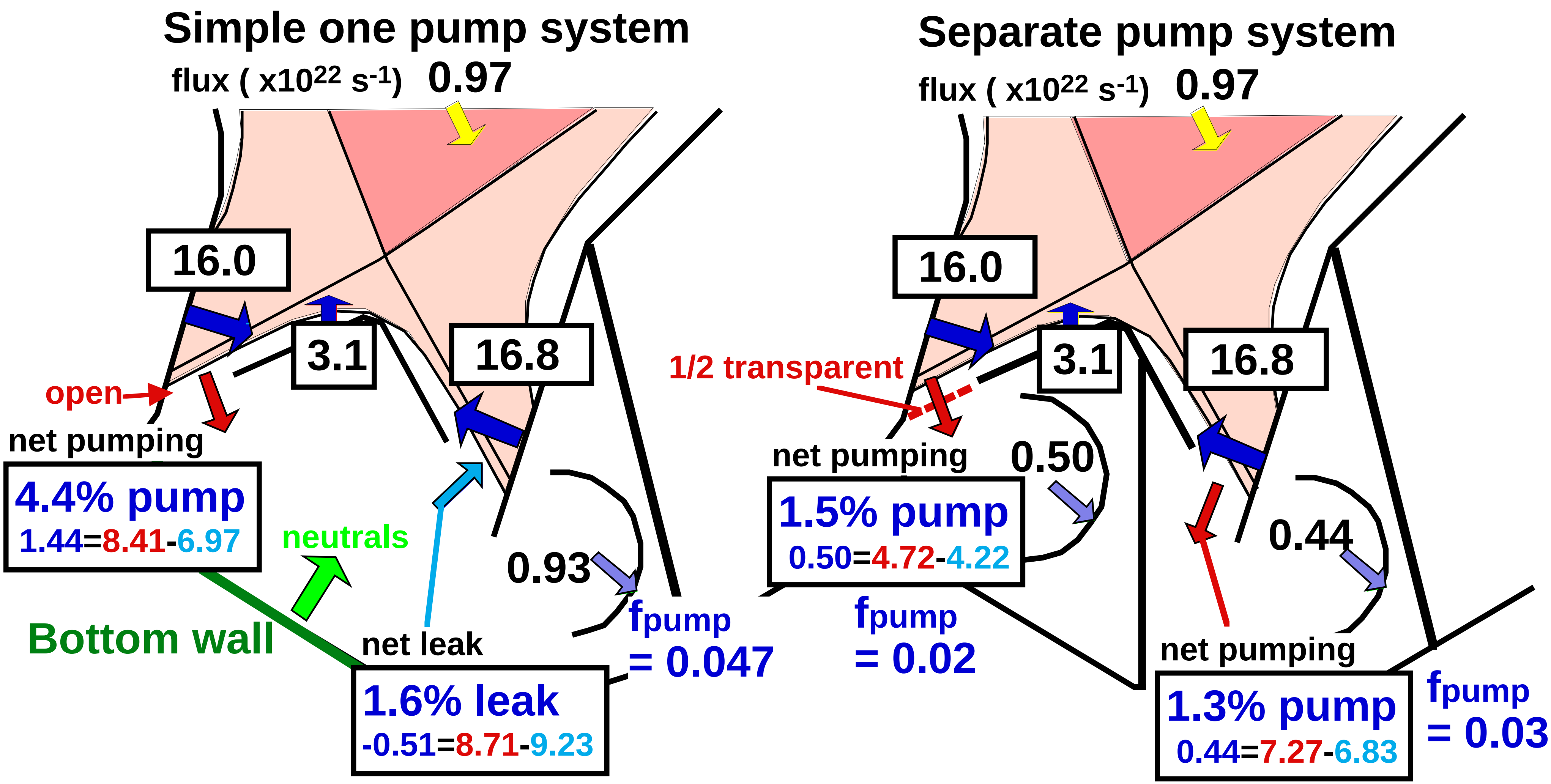
1 common pump system is tested.



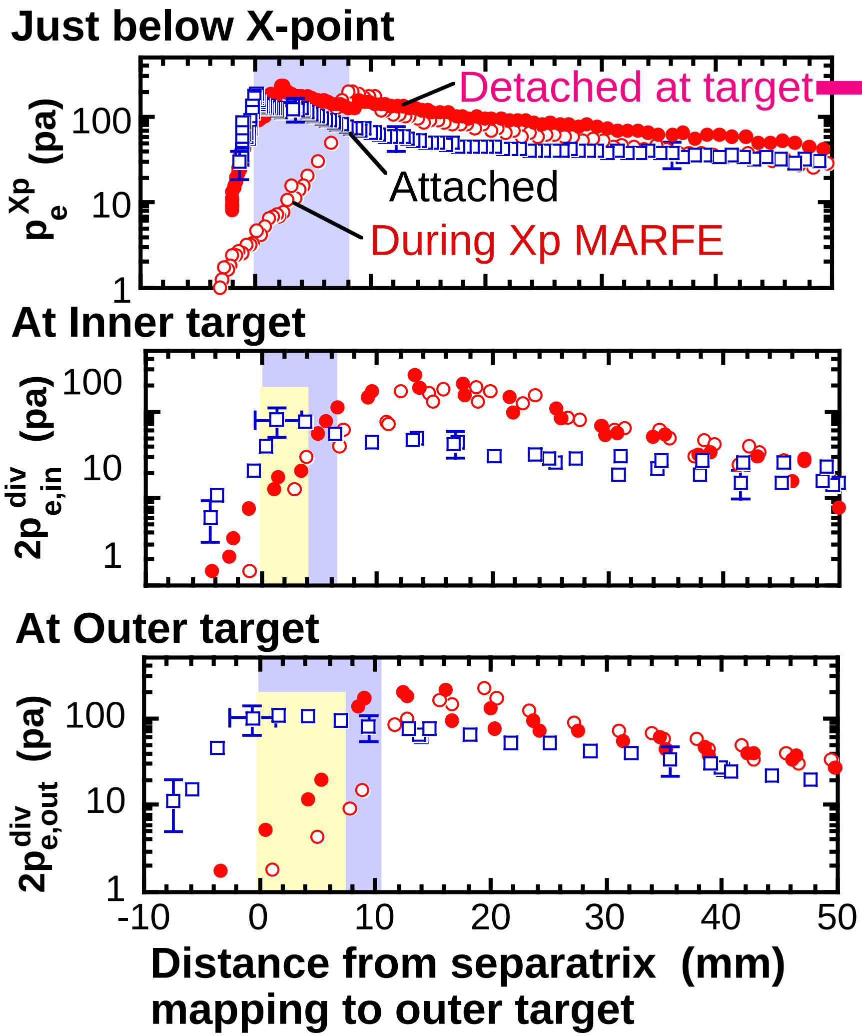
Net neutral leak is seen for one pumping in detached divertor.

- **Bottom wall angle may affect neutral leak at the outer divertor.**

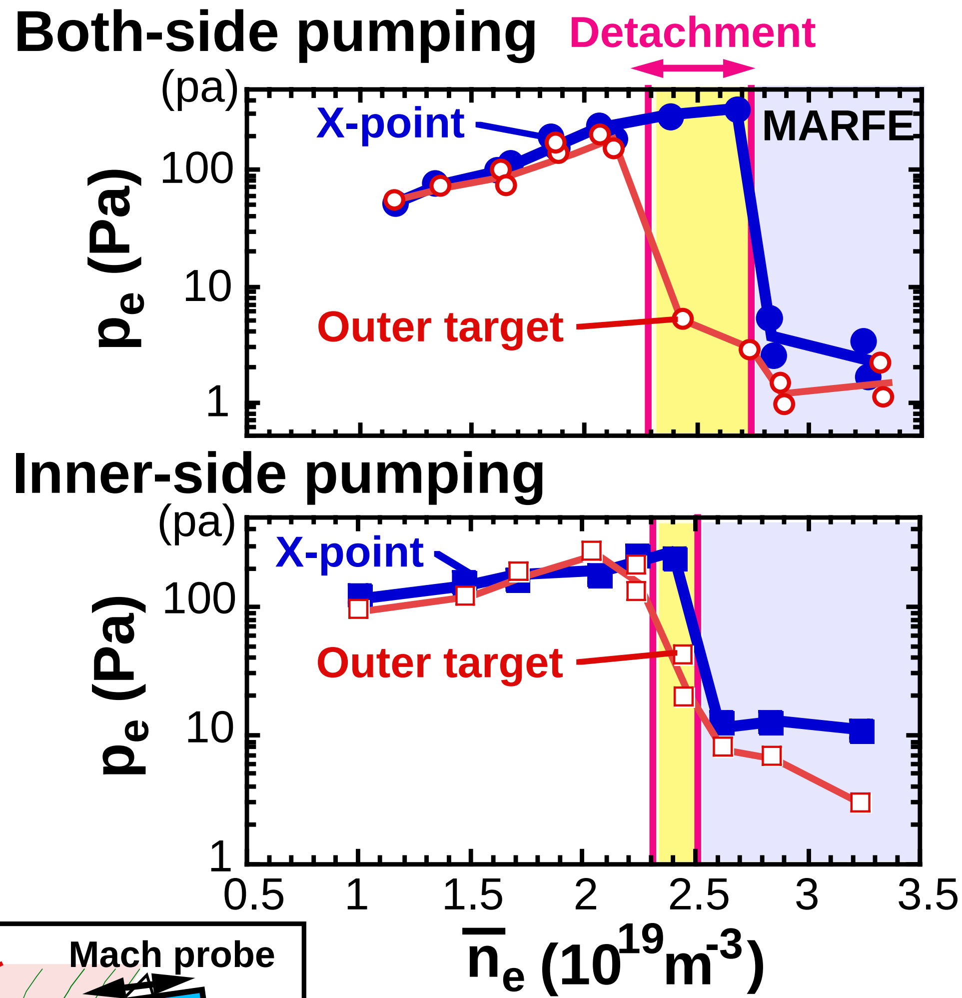
Optimizations of wall & target angles, pump location will be required.

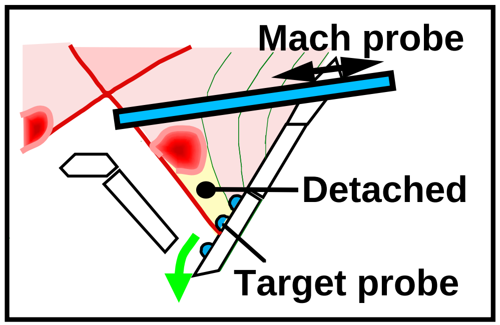


Partially detached divertor (w/o x-point MARFE) was sustained for closure B-s-P: Plasma density range was extended higher than I-s-P.



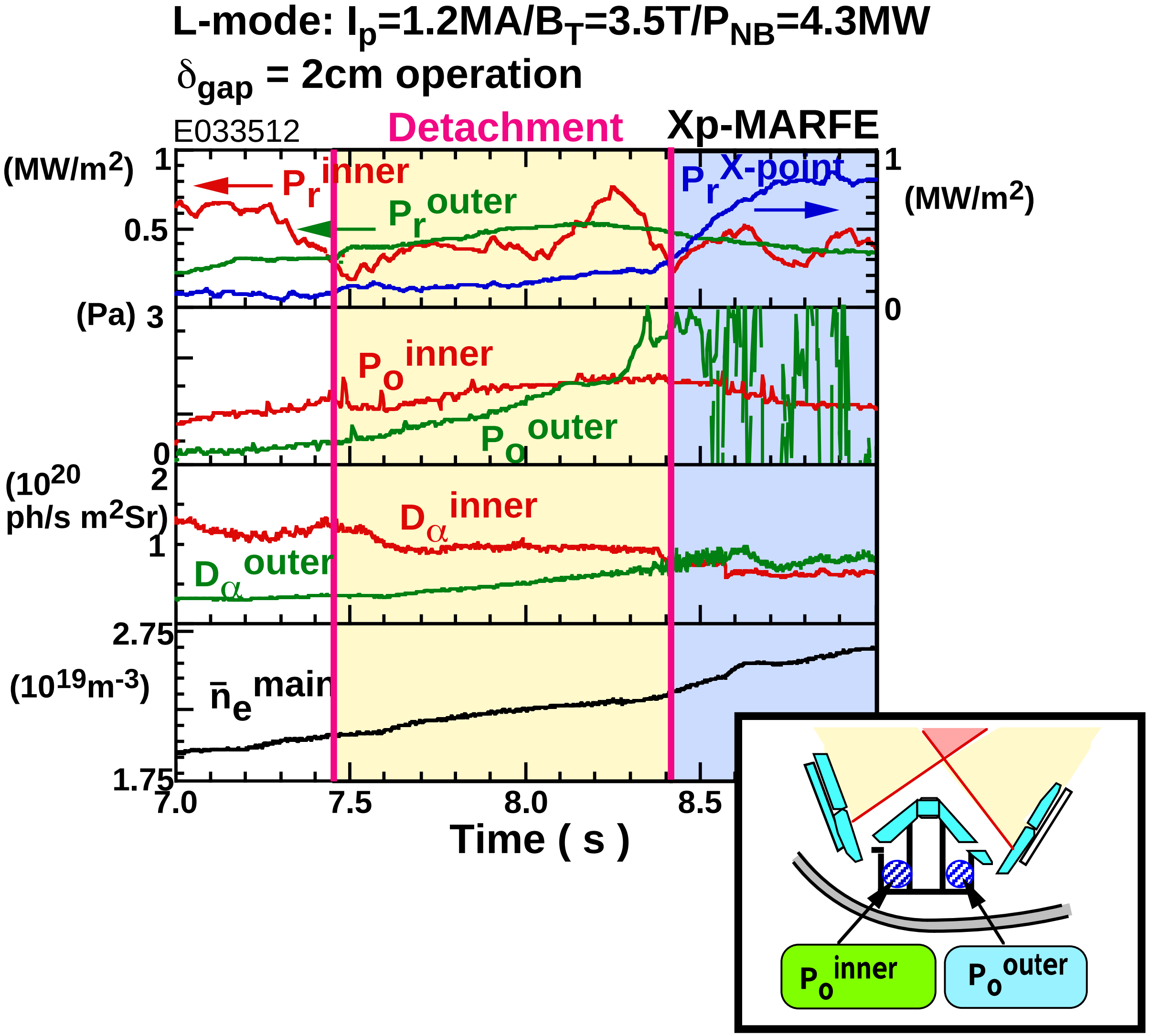
$\delta_{gap\text{-}in}$ = 3cm, $\delta_{gap\text{-}out}$ = 1cm

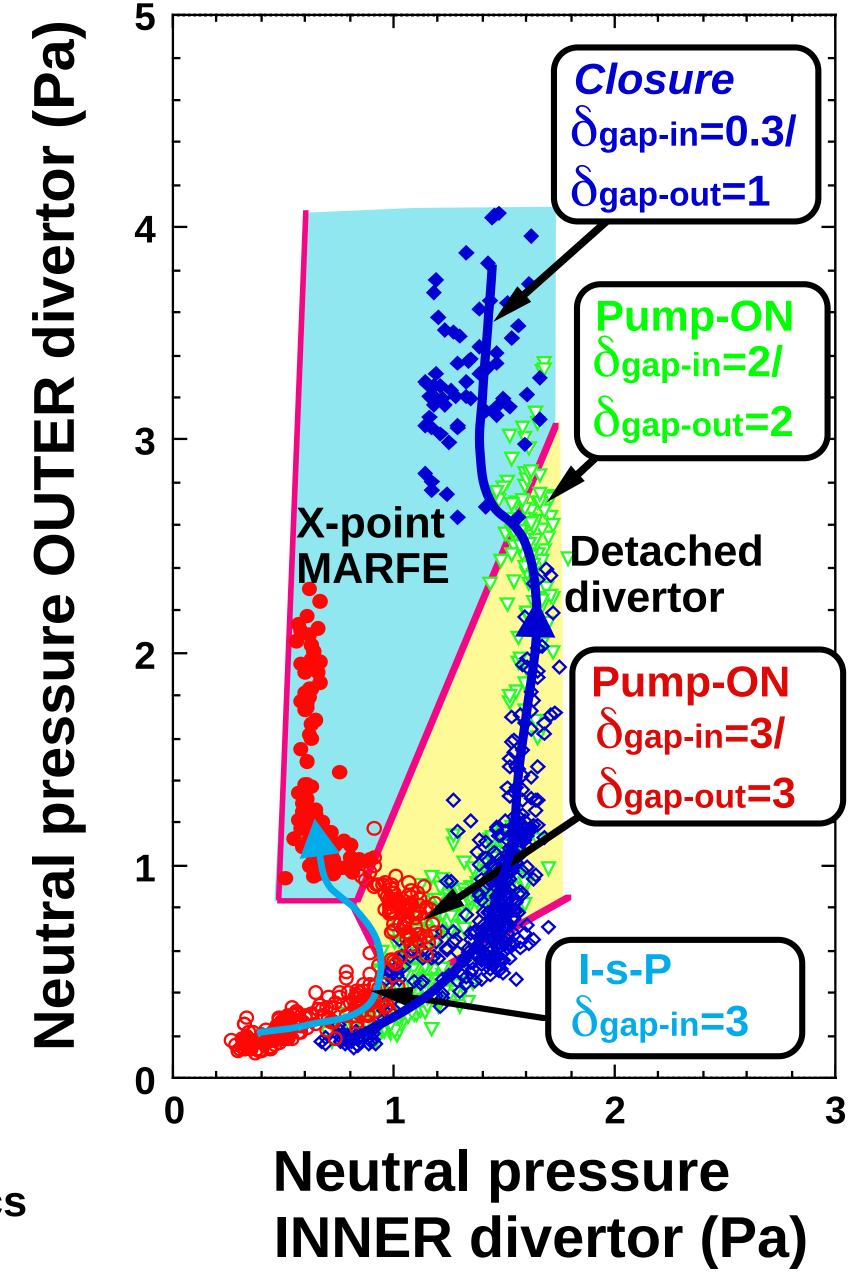




Ref. N. Asakura et.al. ,
J. Nucl. Mater. 290-293(2001) 825

Divertor pressure for closure B-s-P was higher than I-s-P: suggests that pumping at inner and outer divertors is achieved in detached divertor.





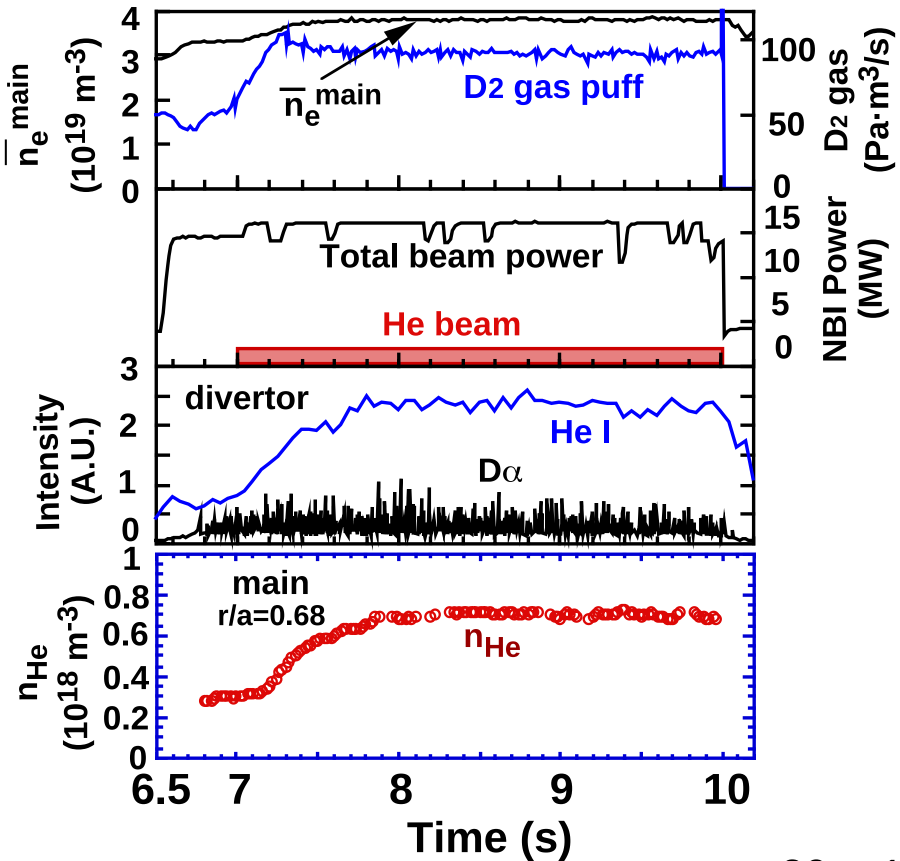
Ref. H. Tamai et.al. ,
Proc. 26th EPS Conf. on Contr. Fusion and Plasma Physics (EPS, Mulhouse), 23J (1999) 409

He exhaust efficiency was improved in the closure operation of B-s-P

(δ_{gap-in} =1.4 cm, $\delta_{gap-out}$ = 0.8 cm)

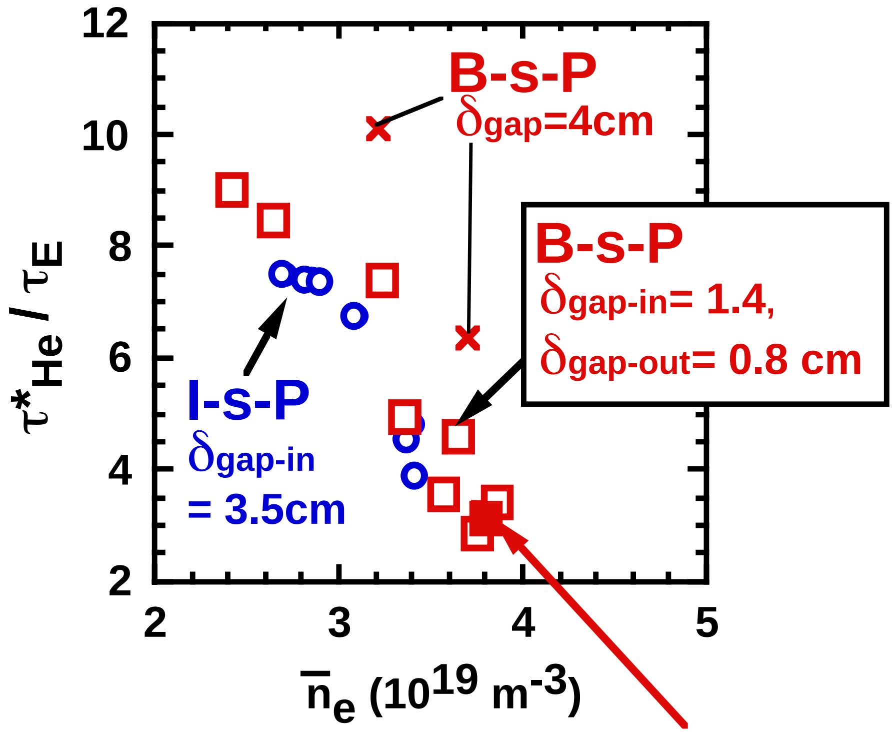
He beam injected into ELMy H-mode plasma
(τ_E = 0.13s, $H^{ITER-89P}$~1.2)

I_P=1.4 MA, B_T=3.5 T **with He pump**



He beam: 60 keV, 1.4 MW (1.5 x 10^{20} s^{-1})
equivalent to 85 MW α heating

- **τ^*_{He}/τ_E was reduced from 3.9 (I-s-P) to 2.8 (B-s-P with small δ_{gap}).**



τ^*_{He}/τ_E = 2.8 and τ^*_{He}=0.36 s
(τ^*_{He}/τ_E = 5 for ITER-FEAT)

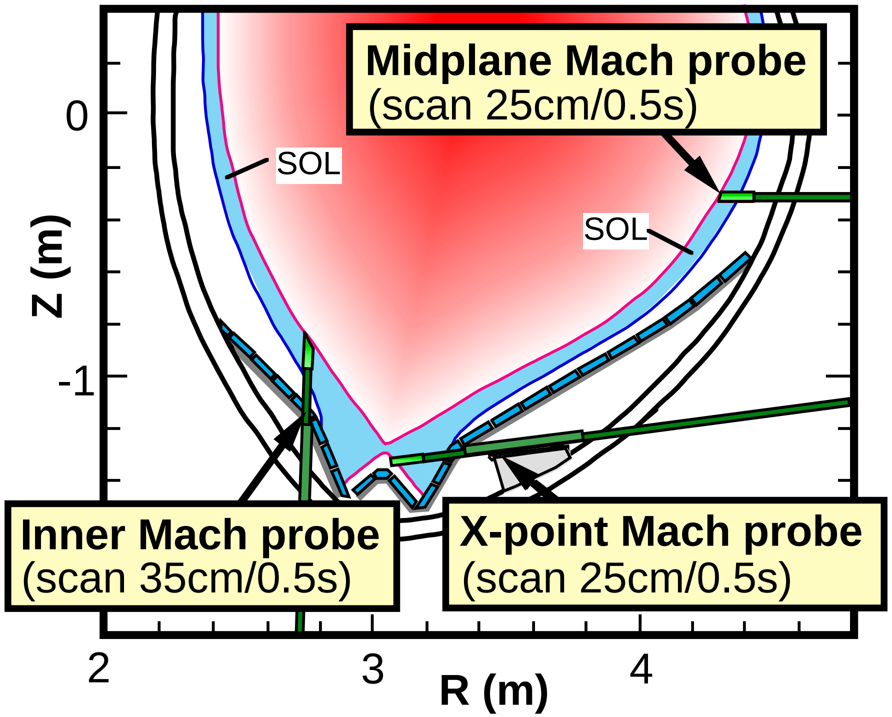
Ref. A. Sakasai et.al. , J. Nucl. Mater. 290-293 (2001) 957

3. SOL plasma flow study

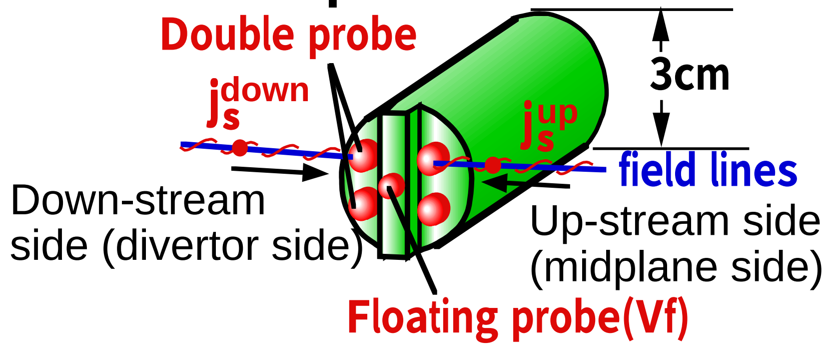
- **SOL flow is an important factor to determine the divertor condition: in-out asymmetry of particle flux, impurity shielding.**

SOL plasma profile and flow pattern were measured at 3 locations (Inner, X-point and outer midplane) with reciprocating Mach probes.

High-field-side SOL plasma was measured (2001.4-), for the first time, in the divertor tokamak.



Mach probe electrodes



- ***j_s*-ratio ($j_s^{down\text{-}stream}$ $/j_s^{up\text{-}stream}$)** shows SOL flow direction along the field lines.
- Mach number is calculated using Hutchinson's formula:

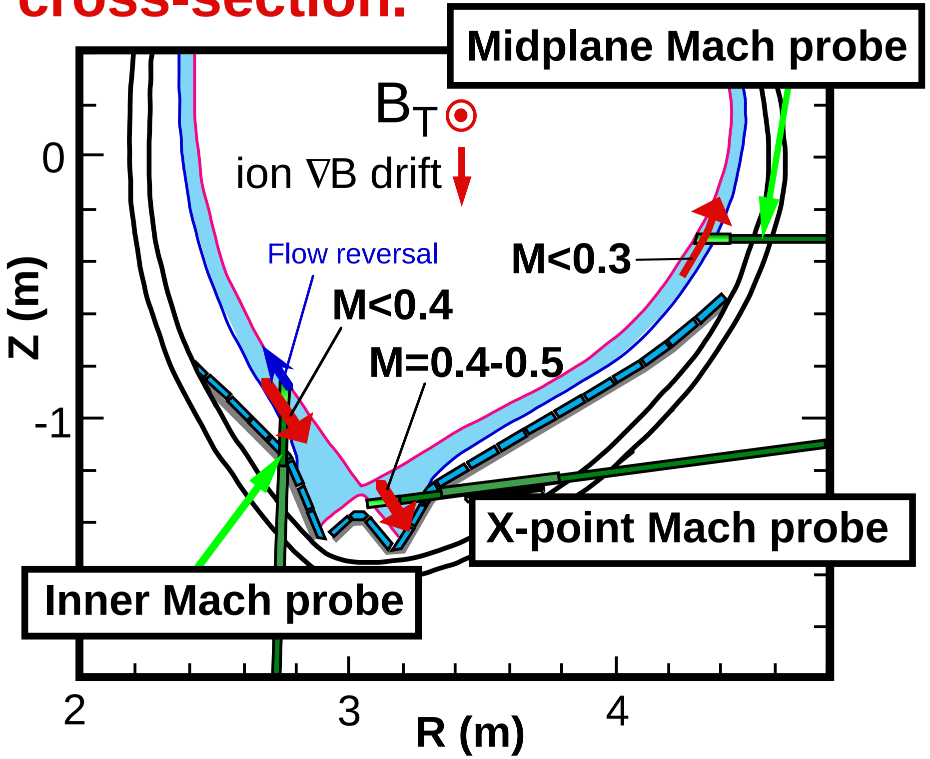
$M = 0.35 \ln[\, j_s^{down} \; / j_s^{up} \,]$

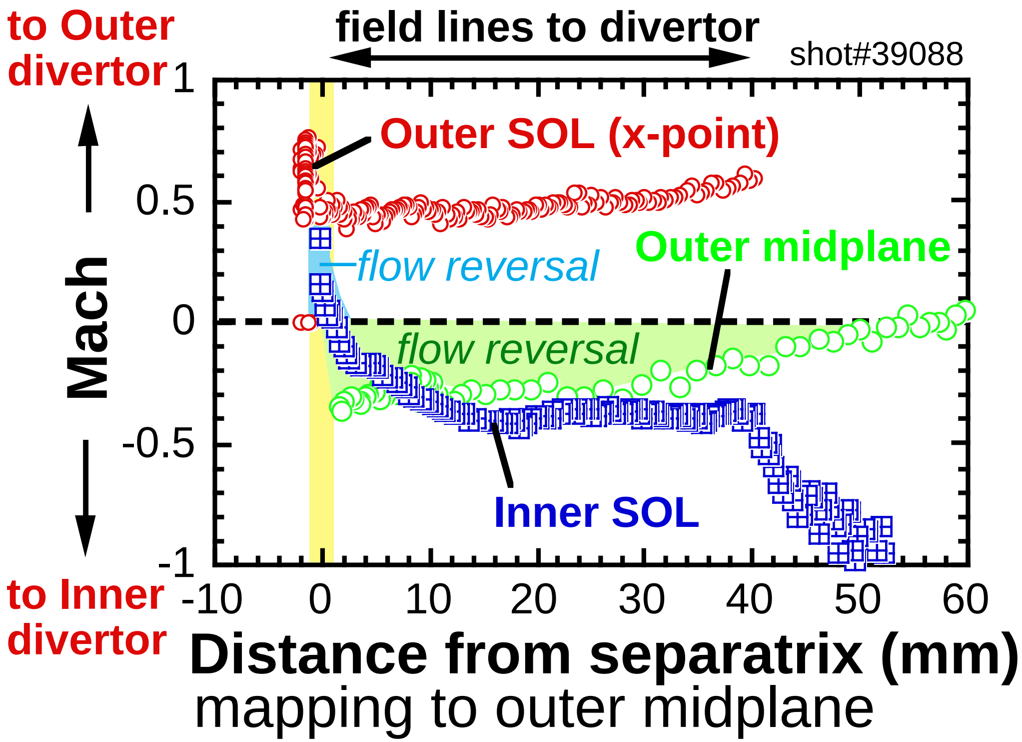
Ref. I.H. Hutchinson, Phys. Rev. A37 (1988) 4358.

Mach probe measurement suggests
parallel SOL flow (1) stagnating between x-point and outer midplane,
and (2) from outer midplane to the inner divertor.

- **"Flow reversal" occurs: narrow near High-field-side separatrix,**
  and wide (5cm) at Low-field side midplane.

SOL flow projected on the poloidal cross-section.



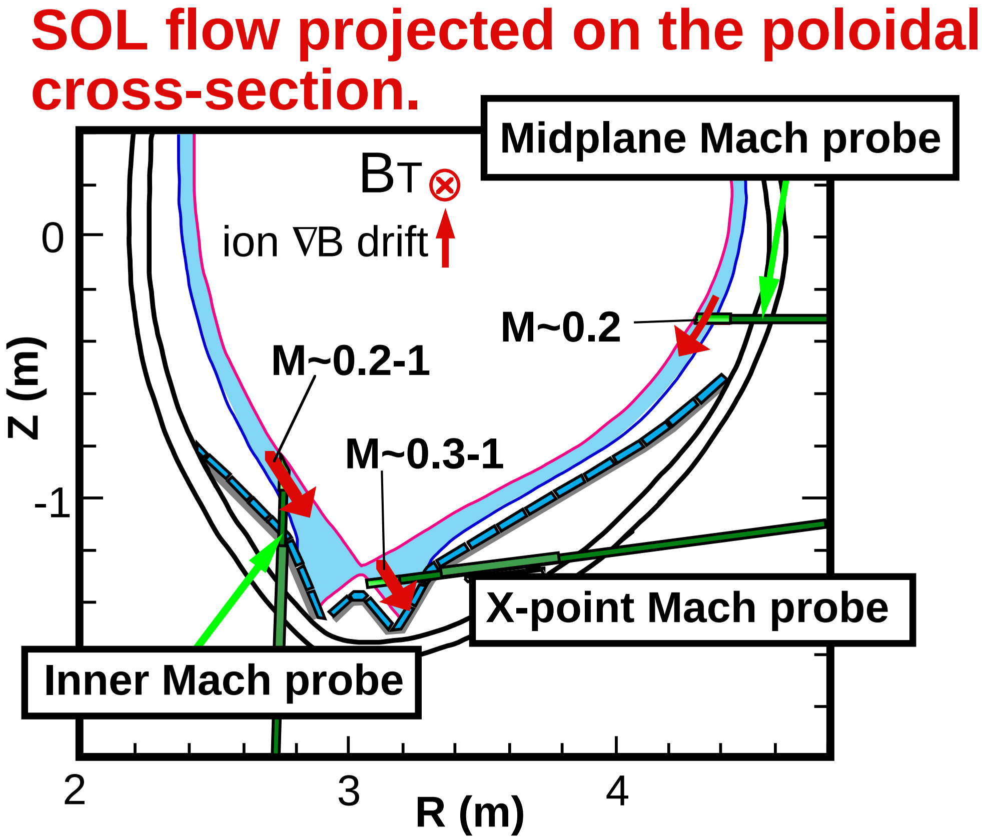


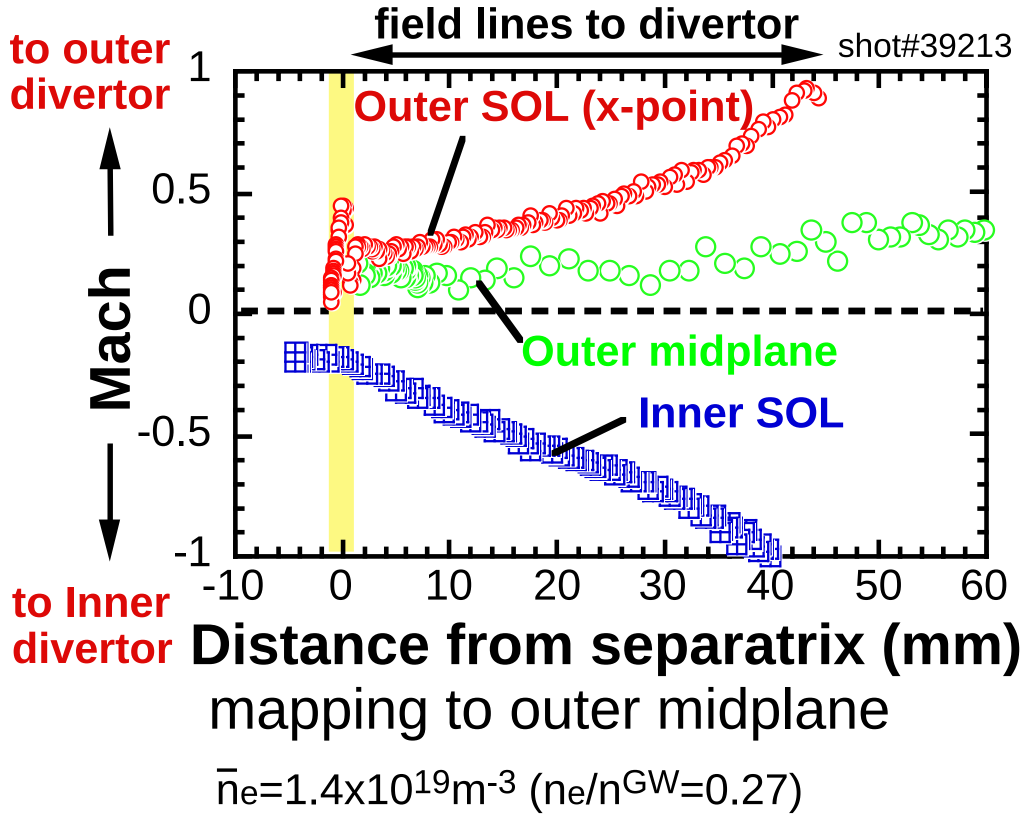
L-mode: I_p=1.6MA, B_T=3.3T, P_{NB}=4.3MW
$\bar{n}_e=1.5\times10^{19}m^{-3}$ (n_e/n^{GW}=0.29)

Flow reversal in the SOL of the main plasma was observed in Alcator C-MOD, ASDEX-U and JET.

Reversal of ion grad-B drift direction produces SOL flow towards divertor.

- **Large flow velocity was observed at outer flux surfaces above inner baffle (High-field side) and near x-point (Low-field sides).**





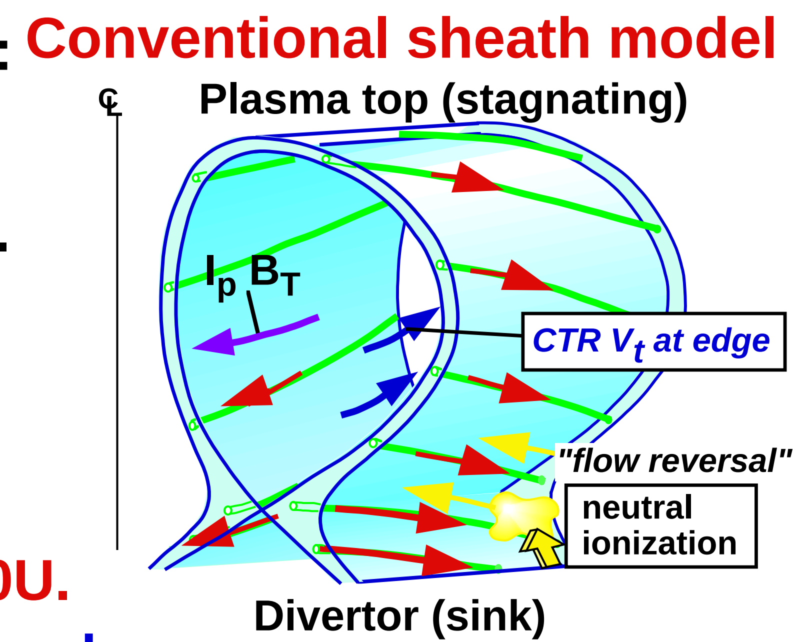
Mechanisms to produce parallel SOL flow

- **Sheath model (plasma flow along field lines): Flow is driven towards divertor (sink).**

+ Local ionization is enhanced in SOL/divertor.

Recycling near divertor ➡ *"Flow reversal"*

⟷ Exp. shows flow towards divertor.



- **Momentum diffusion from the edge plasma**

⟷ Exp. shows CTR rotation at edge in JT-60U.

***"Flow reversal"* near separatrix can not explained.**

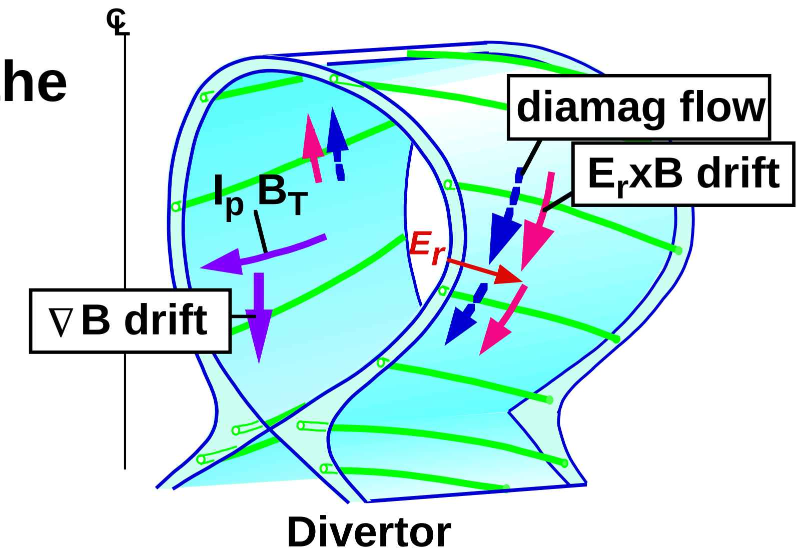
- **In torus, ion drifts perp. to field lines affect the SOL flow (the direction changes by B_T).**

(1) grad-B drift

(2) E_r x B drift

(3) diamagnetic flow

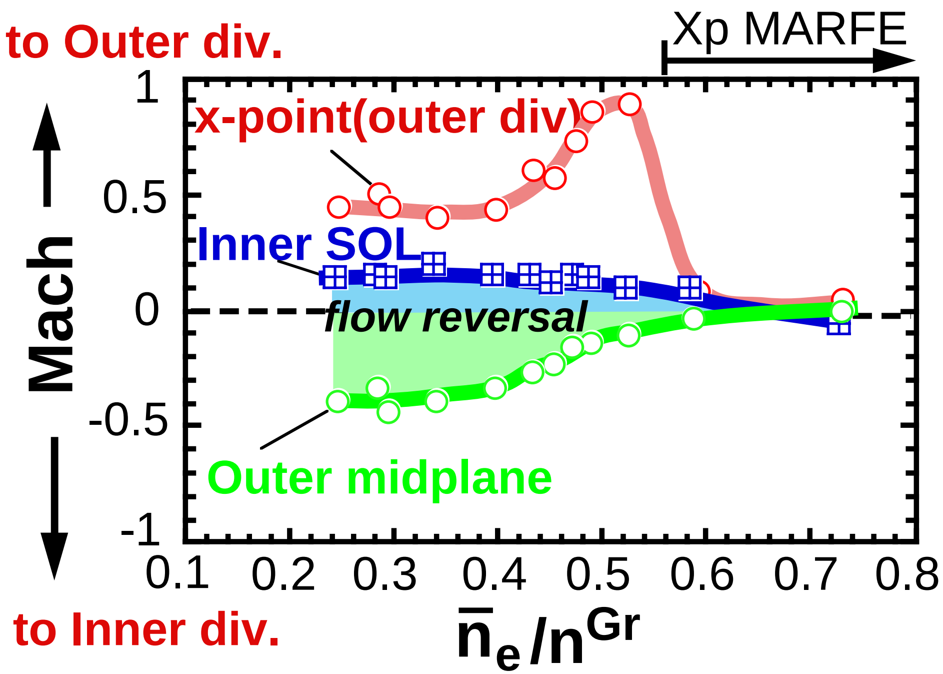
Those drift velocities are in-out asymmetry since $B = B_0/R$



A candidate mechanism:

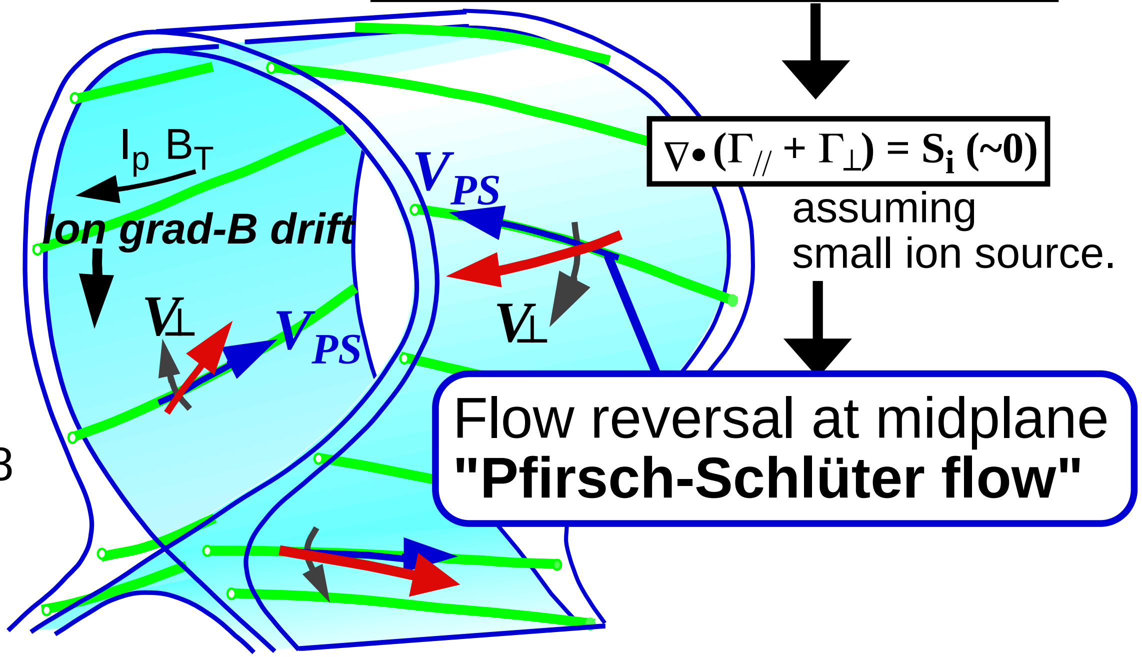
"Flow reversal" for ion grad-B towards divertor can be explained as "Pfirsch-Schlüter flow" caused by ion drift in torus.

Parallel flow near main plasma separatrix is driven to the plasma top:
***"flow reversal"* is decreased at high density.**



$$V_\perp = \left(E_r - \frac{\nabla p_i}{e n_i}\right) \times \frac{B}{B^2}$$

large at outer midplane

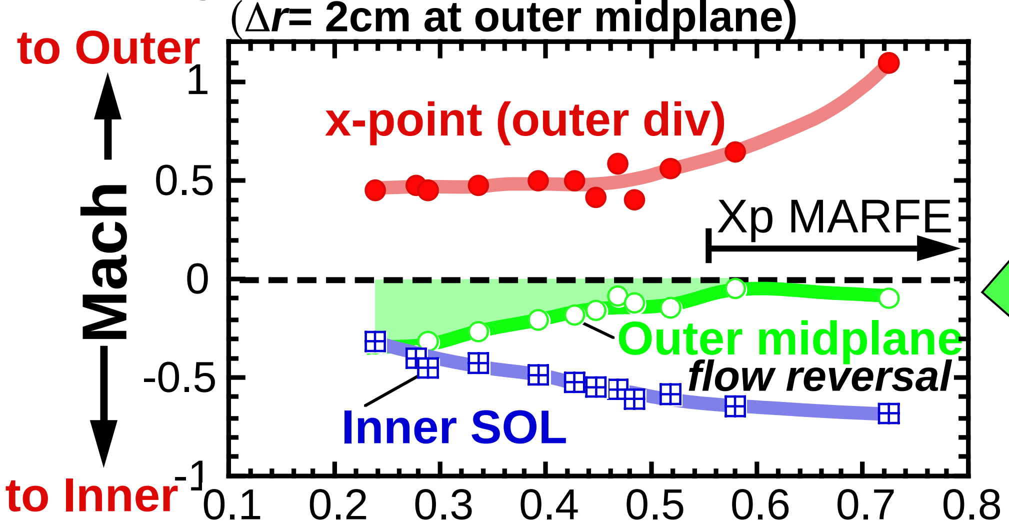


Consistent with *Pfirsch-Schlüter flow* model: $\frac{V_{PS}}{C_s} = \frac{2r}{R B_\theta C_s}\left[E_r + T_i\left(\lambda_{n_e}^{-1} + \lambda_{T_i}^{-1}\right)\right]$

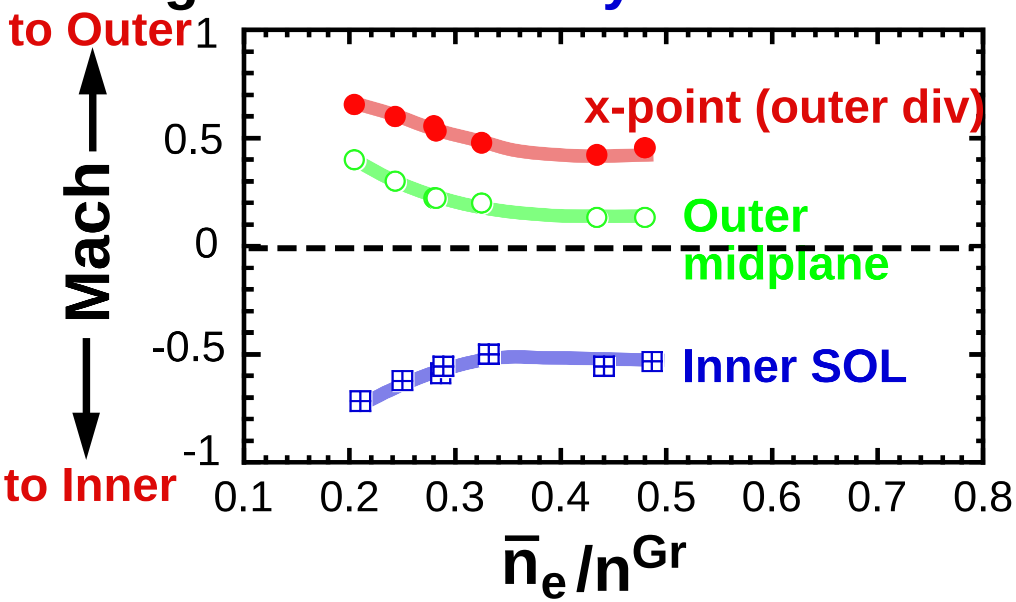
Ref. N. Asakura et.al. , Phys. Rev. Lett. 84 (2000) 3093

Flow velocity to divertor is increased/ decreased for ion ∇B drift towards / away from divertor (at the outer flux surfaces).

Ion grad-B drift towards divertor

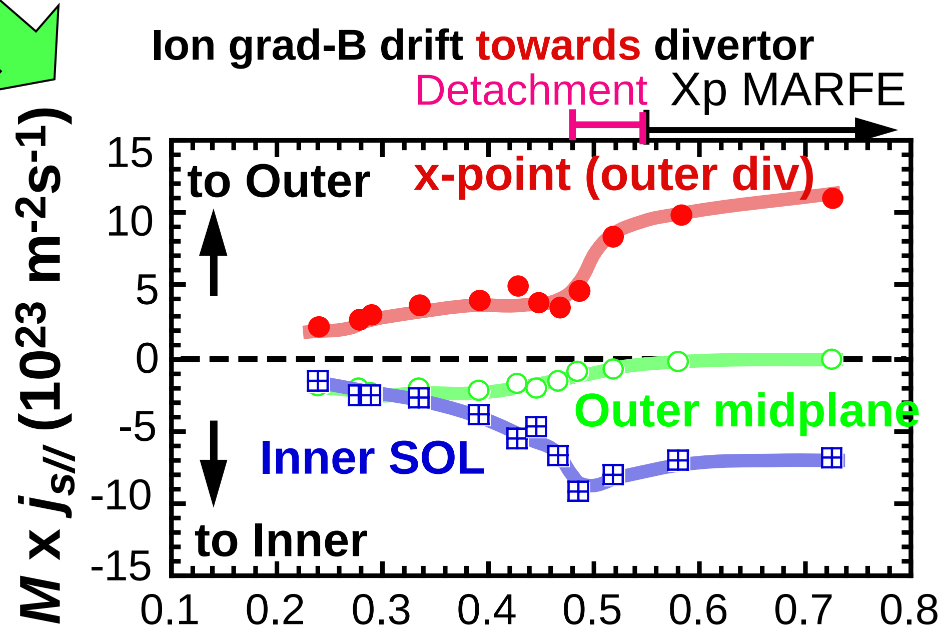


Ion grad-B drift away from divertor



- **In-out asymmetry in flux density ($M \times 1/2C_s n_e$) is observed:**

Convection flow in common flux region affects in-out asymmetry.

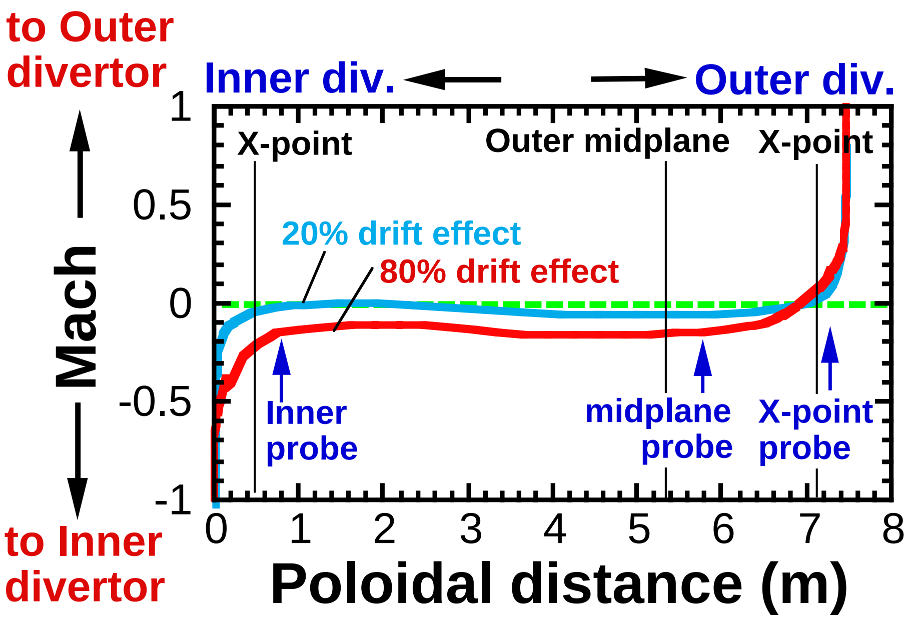


Introduction of *ion drifts* into SOL/divertor simulation (UEDGE) produces parallel SOL flow to the Inner divertor (preliminary results).

Mach numbers (at inner SOL and Xp) are smaller than measurements

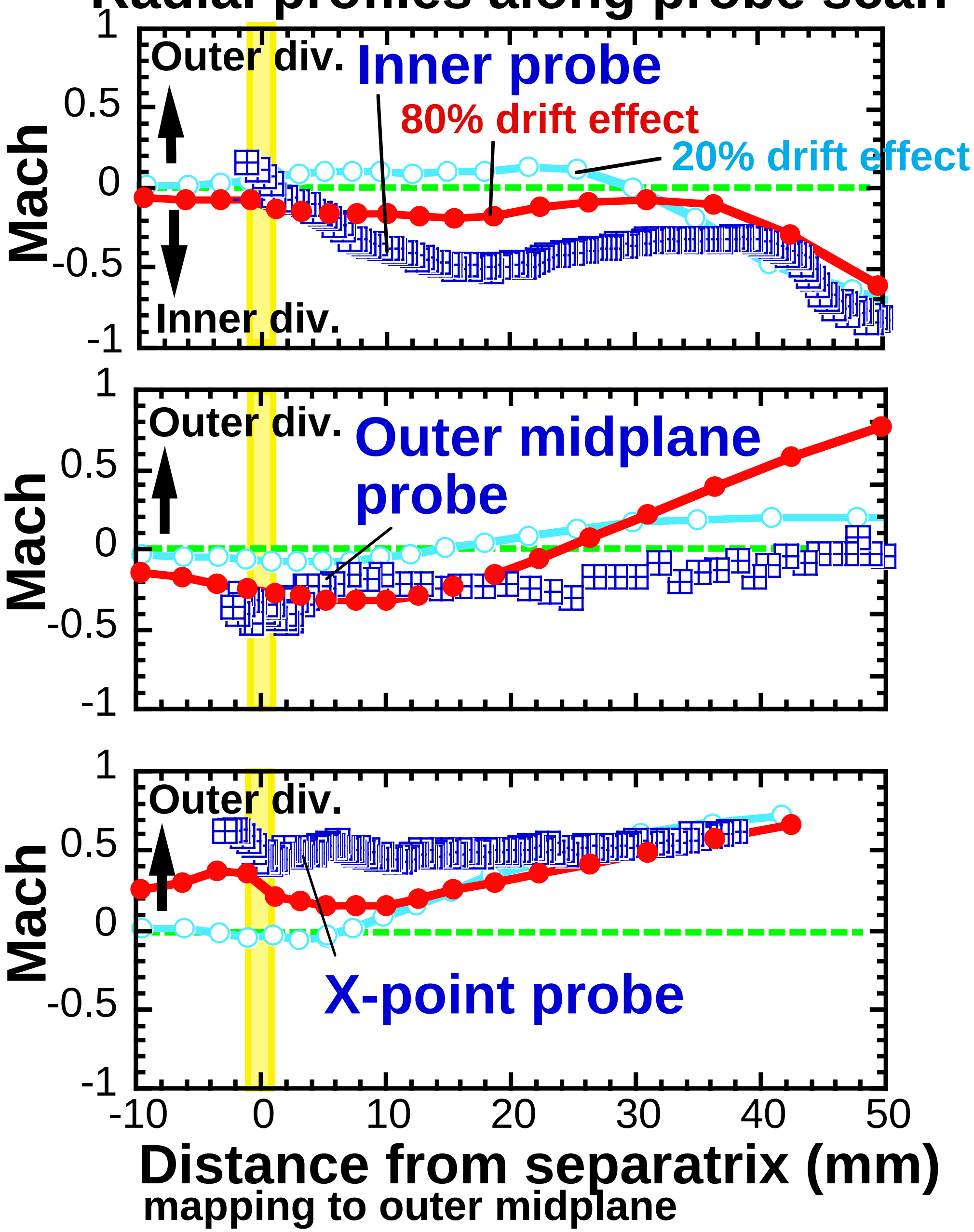
(using Hutchinson's formula).

- There are other factors such as impurity level, diffusion coefficient, electric field etc. (under investigation)



(Δr = 1cm outer separatrix)

Radial profiles along probe scan



4. Summary

Pumping in the divertor:

Maximum pumping ratio and improved performance were observed in the detached divertor, provided that closure operation was available.

Optimization of pump location, wall & target angles, pump duct will be required to obtain efficient pumping for a compact divertor.

SOL plasma flow study

SOL flow measurements and introduction of drifts into simulation show that parallel SOL flow is produced from Low- to High-field side (for ion grad-B drift towards divertor) .

SOL flow affects in-out asymmetries in plasma&recycling fluxes in the divertor (will also affects impurity transport).

- **Quantitative understanding of the SOL flow and neutral/molecule transport in sub-divertor will contribute to a compact divertor design.**