UEDGE simulation of large parallel plasma flows in the SOL of NSTX

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Large parallel plasma flows have been observed in the SOL of some tokamaks (and recently studied on C-Mod).

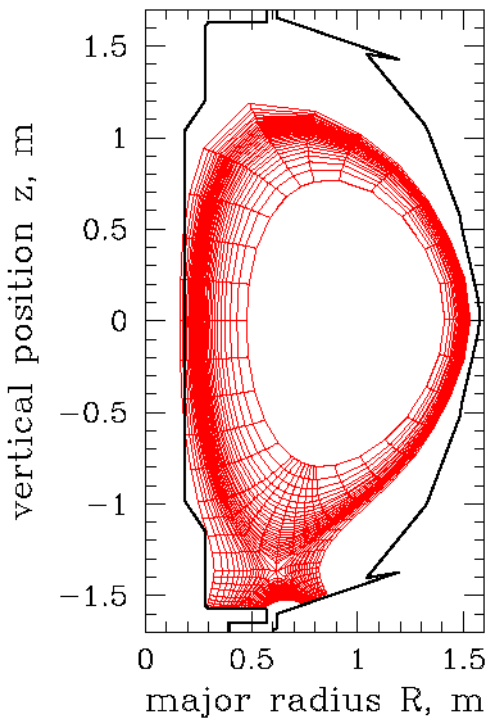
Why the detailed study is important?

1) The flows can be the byproduct of "natural" asymmetries in magnetic configuration and cross-field transport. So, the flows should be expected in ITER, as well.
2) The physics mechanisms of flow generation and acceleration/de-acceleration should be understood , e.g. for the flow control purposes.
3) These flows carry and re-deposit the material, tritium, and dust.

General physics picture for large parallel plasma flows in SN magnetic configuration of NSTX

1) In large aspect ratio tokamak, the SN magnetic configuration has strong inboard/outboard asymmetry,so that 80% of particles and energy is coupled to the outboard part of torus.
2) The ballooning-like cross-field transport (e.g. blobs) enhances the in/out asymmetry. Moreover, this transport pushes plasma/ momentum/ energy into the far SOL.
3) The far SOL is low-Te, low-Ne and allows for large plasma pressure gradients (both || and ⊥). Far SOL is typically coupled to the detached region in the divertor. The asymmetry generate the parallel plasma flow from outboard to inboard.
4) There is strong variation in magnetic field strength (from 0.3 to 2.2 T) along magnetic field lines that may accelerate the plasma flow to large velocity (M=0.5-08).
5) The plasma stream ends in the inner divertor. Plasma recycles (and even can recombine) there. The equivalent amount of particles leaks from the inner divertor through the separatrix, hence, closing the plasma flow loop.

Numerical mesh covers the space 0.6< ψn<1.08 for LSN magnetic configuration in NSTX



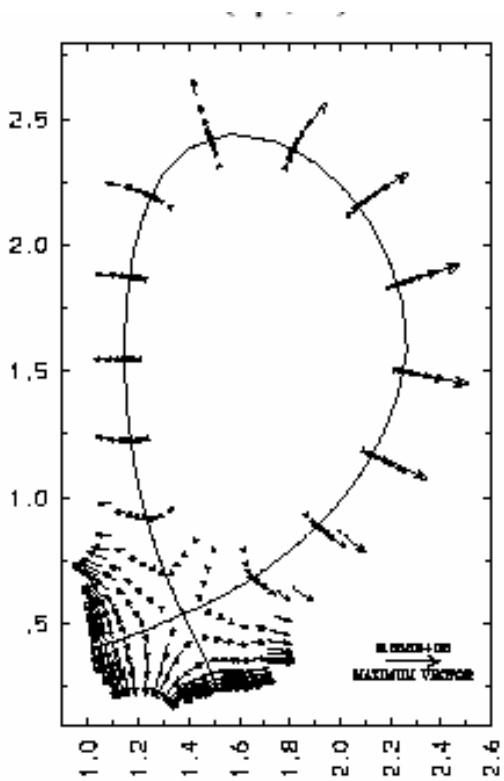
Shot #109033

In the Lower Single Null magnetic configuration, the surface area connected to the inboard SOL is much (~10X) smaller than the area connected to the outboard SOL.

2D diffusive/convective model for cross-field transport suggests the in/out asymmetry

Cross-field plasma flux:

$$\Gamma_\perp(\psi,\theta) = -D_\perp(\psi,\theta)\, \partial n/\partial r \;+\; n\, V_\perp conv\,(\psi,\theta)$$

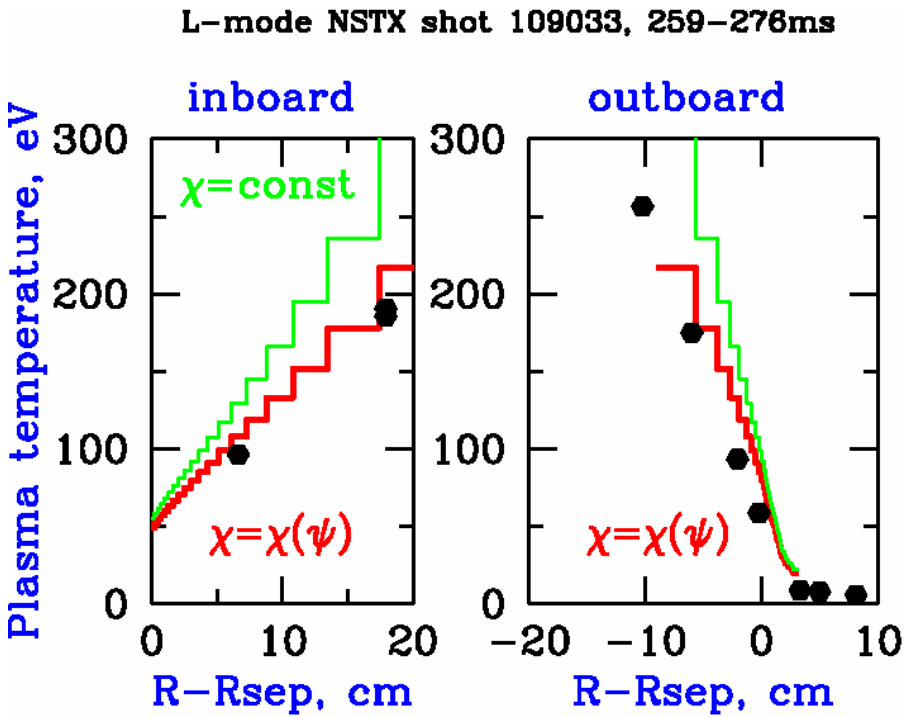


The edge physics code adjusts $\mathbf{D_\perp(\psi,\theta)}$, $\boldsymbol{\chi_\perp(\psi,\theta)}$, $\mathbf{V_\perp conv\,(\psi,\theta)}$ profiles to match a set of experimental data.

Poloidal profiles of $\mathbf{D_\perp(\psi,\theta)}$, $\boldsymbol{\chi_\perp(\psi,\theta)}$, $\mathbf{V_\perp conv\,(\psi,\theta)}$ are asymmetric. They mimic the ballooning type of cross-field transport

Vconv varies poloidally by (3-4)X and is peaked at outer mid-plane.

To match experimental data, anomalous transport coefficients $D_\perp$, $\chi_\perp$, and $Vconv_\perp$ should vary also radially in the ψ_N-space

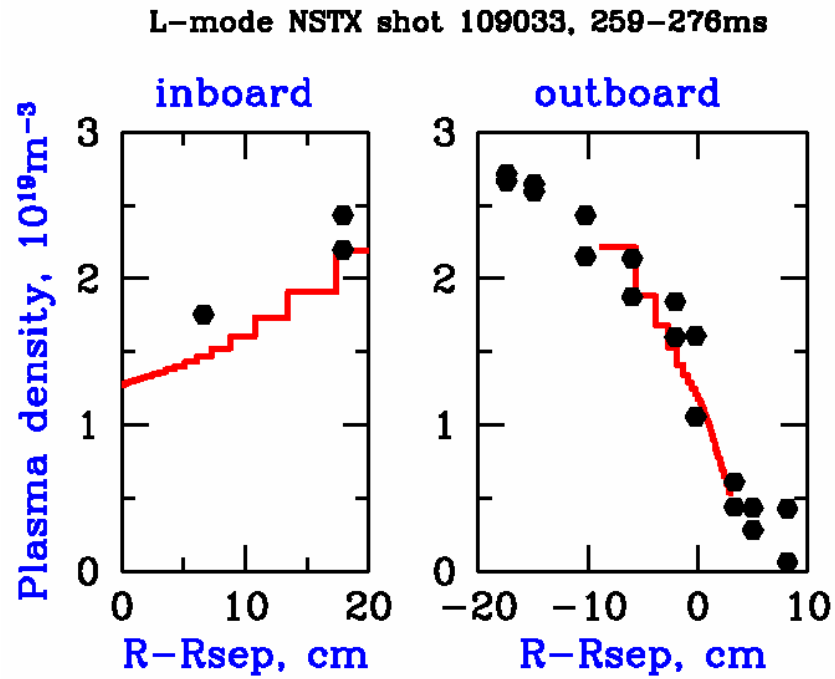


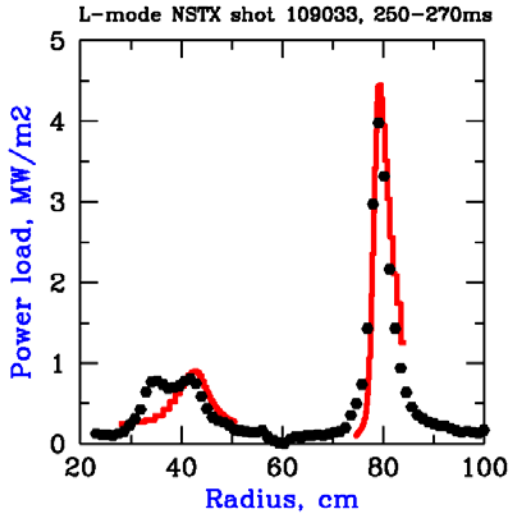
$D_\perp$ is a weakly increasing with ψ . It is typically around 0.6m^2/s at ψ=1.

$\chi_\perp$ is strongly decreasing function by factor 2-3. In L-mode, typically χ=15-20 m^2/s at ψ=0.7.

Vconv strongly increases with ψ (in L-mode, from zero at ψ=0.7 to 40m/s at ψ=1 and further to 200m/s at the wall.

Important features of NSTX edge plasma are well reproduced with UEDGE



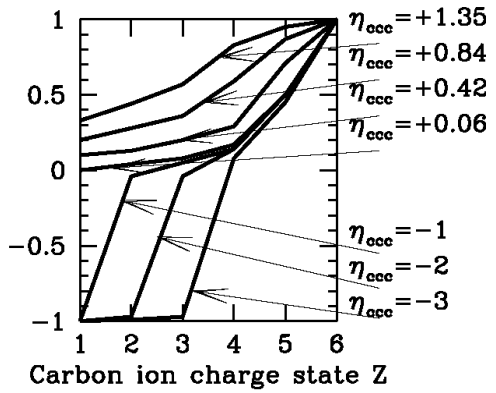


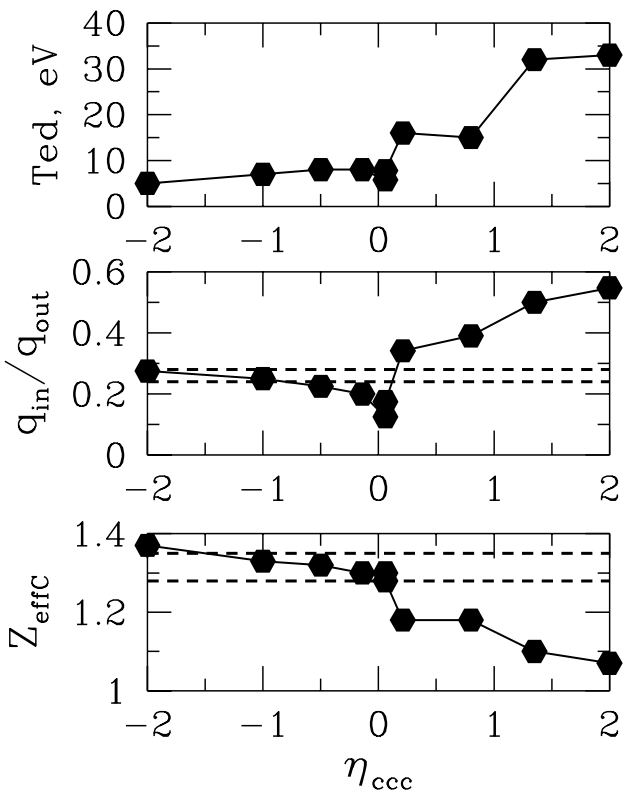
1) Intense gas puff provides deep core plasma fueling at the rate higher than NBI fueling rate consistent with observed core density increase

2) Strong in/out asymmetry in radial plasma profiles and in plasma heat flows

3) Far-SOL shoulders and large mid-plane pressure indicative of main chamber recycling

In NSTX, the direction of impurity ion anomalous convection has strong impact on edge plasma





Velocity of impurity ion with charge state z:

$$V_{conv}(\psi,\theta, z) = V^{[D+]}_{conv}(\psi,\theta)\, A(z)$$

$-1<A<1$ is the amplitude factor, $A(6)=1$

Continuous parameter: $\eta_{CCC}=A(1)+A(2)+A(3)$

The weaker the carbon atom penetration into SOL, the stronger should be the inward impurity ion convection

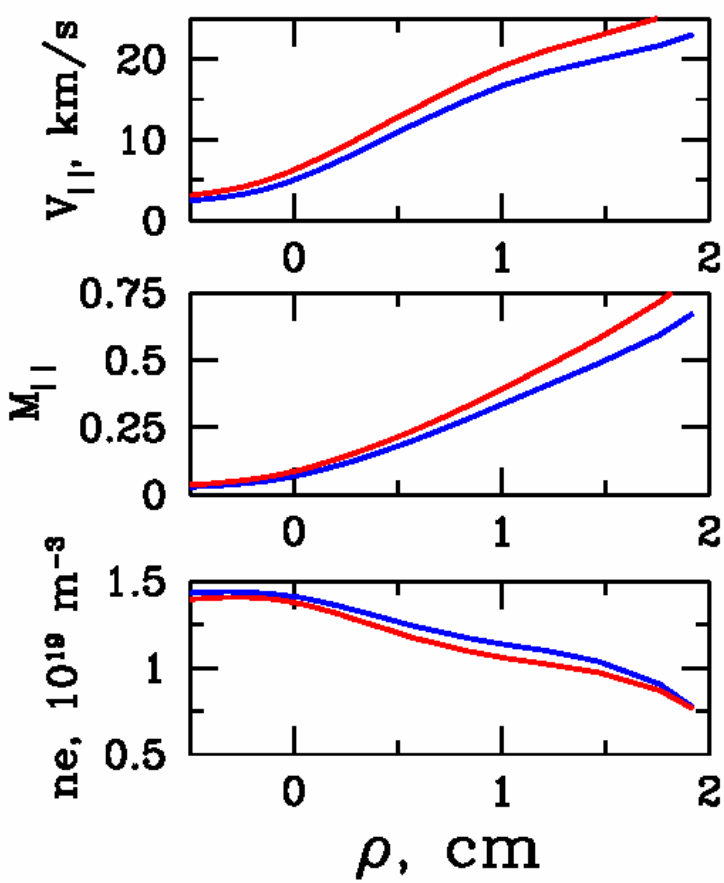
The more ion charge states are directed inward, the closer is the divertor to detachment.

Major parameters are matched at

$$-2<\eta_{ccc}<-0.5$$

ie low charge states are convected inward

The plasma flow up to M=0.8 is predicted by UEDGE at the inner mid-plane



Here magnetic flux surfaces are mapped to the outboard mid-plane. The inner SOL is 2-2.5X broader.

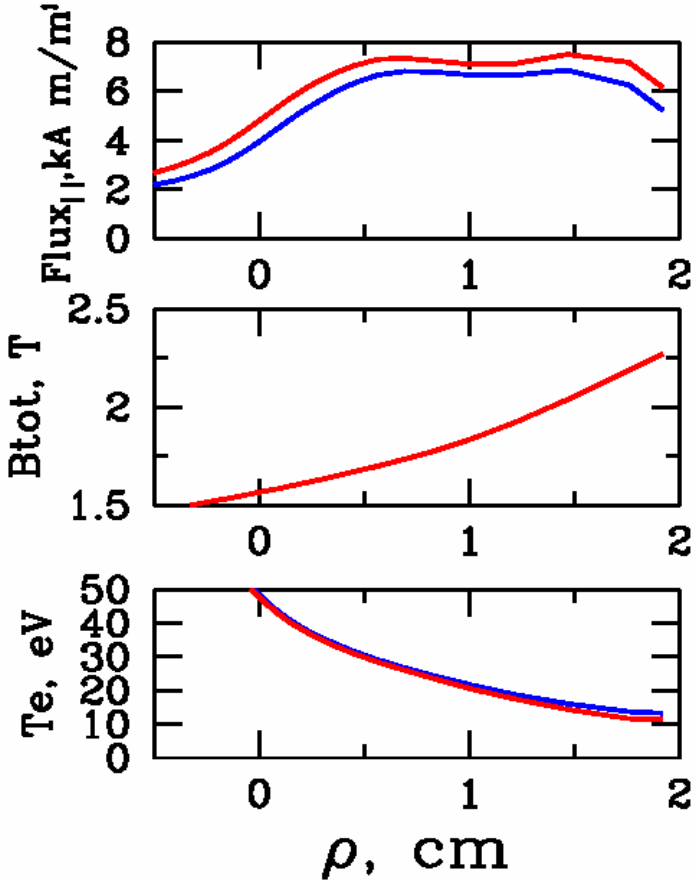
At the inner mid-plane, plasma in the entire SOL is moving toward the inner divertor plate.

Parallel plasma velocity V|| is 10-25 km/s.

V|| and M||=V||/sqrt[(te+ti)/mD] are increasing toward the chamber wall. In the far SOL, M|| increases mostly because of increase in V||.

V|| attained at inner mid-plane doesn't depend on boundary conditions at the divertor plates.

Parallel flow at the inner mid-plane can carry significant particle flux



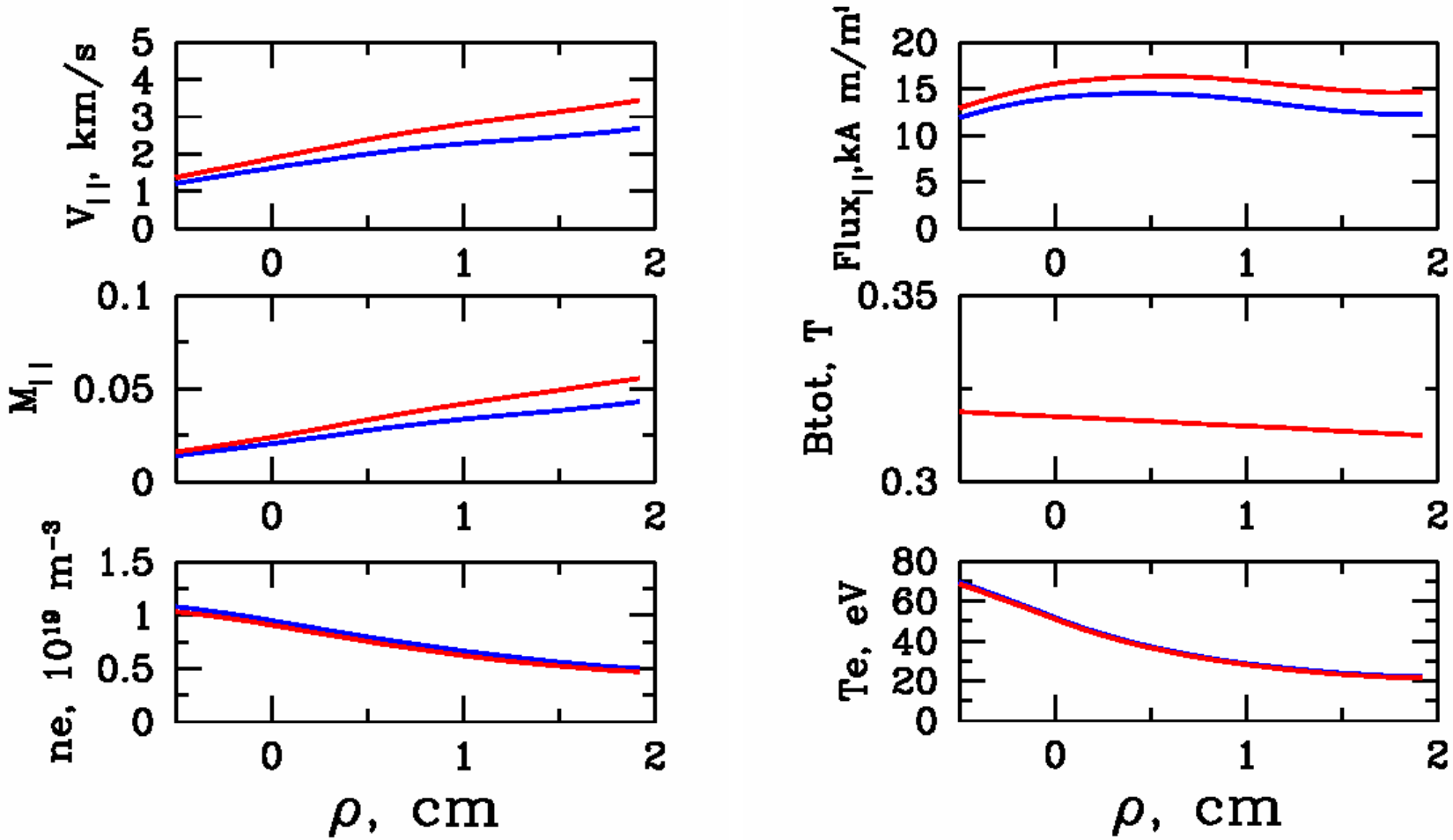
The averaged flux density is Flux||~ 7 kA/m tends to be constant over the SOL width.

The integral flux corresponds to few hundred Amperes flowing toward the inner divertor.

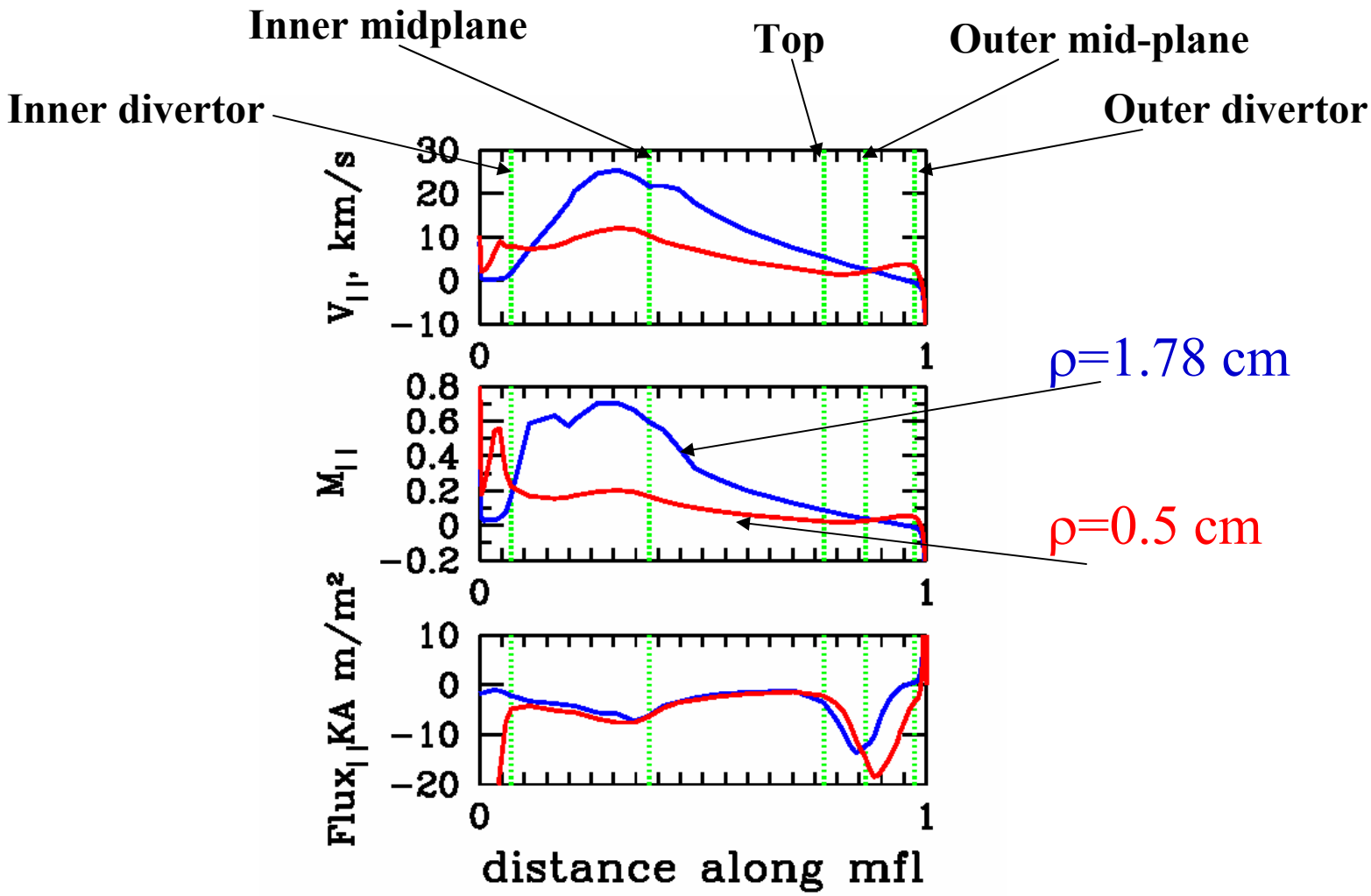
The high M|| flow is near the wall. The higher the Btot, the higher the M||.

Here magnetic flux surfaces are mapped to the outboard mid-plane. The inner SOL is ~(2-2.5)X broader.

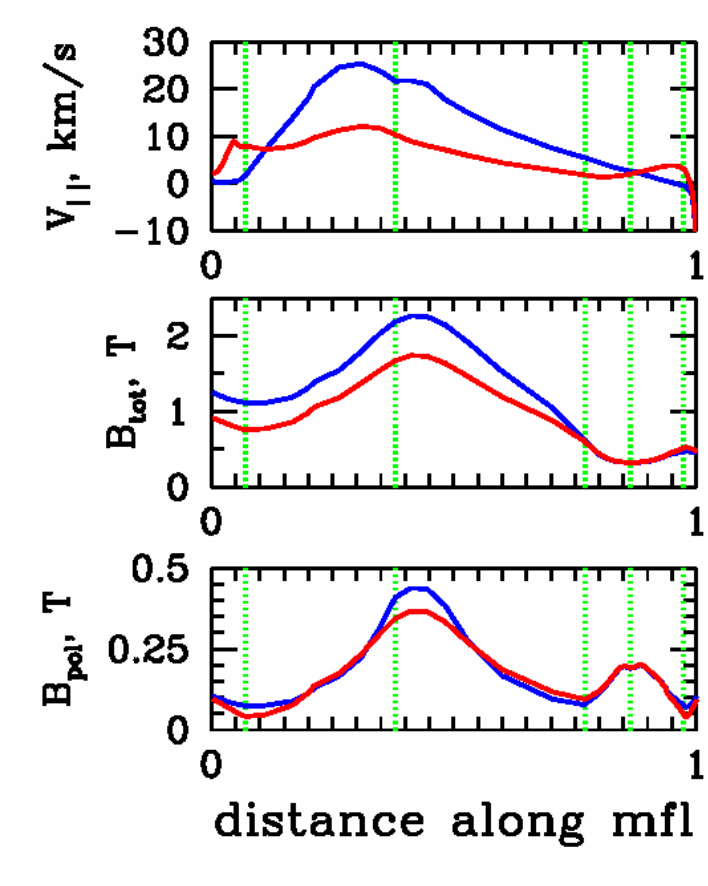
At the outboard mid-plane, the parallel flow is directed to inboard but is relatively quiescent <V||>~2.5km/s, <M||>~0.03



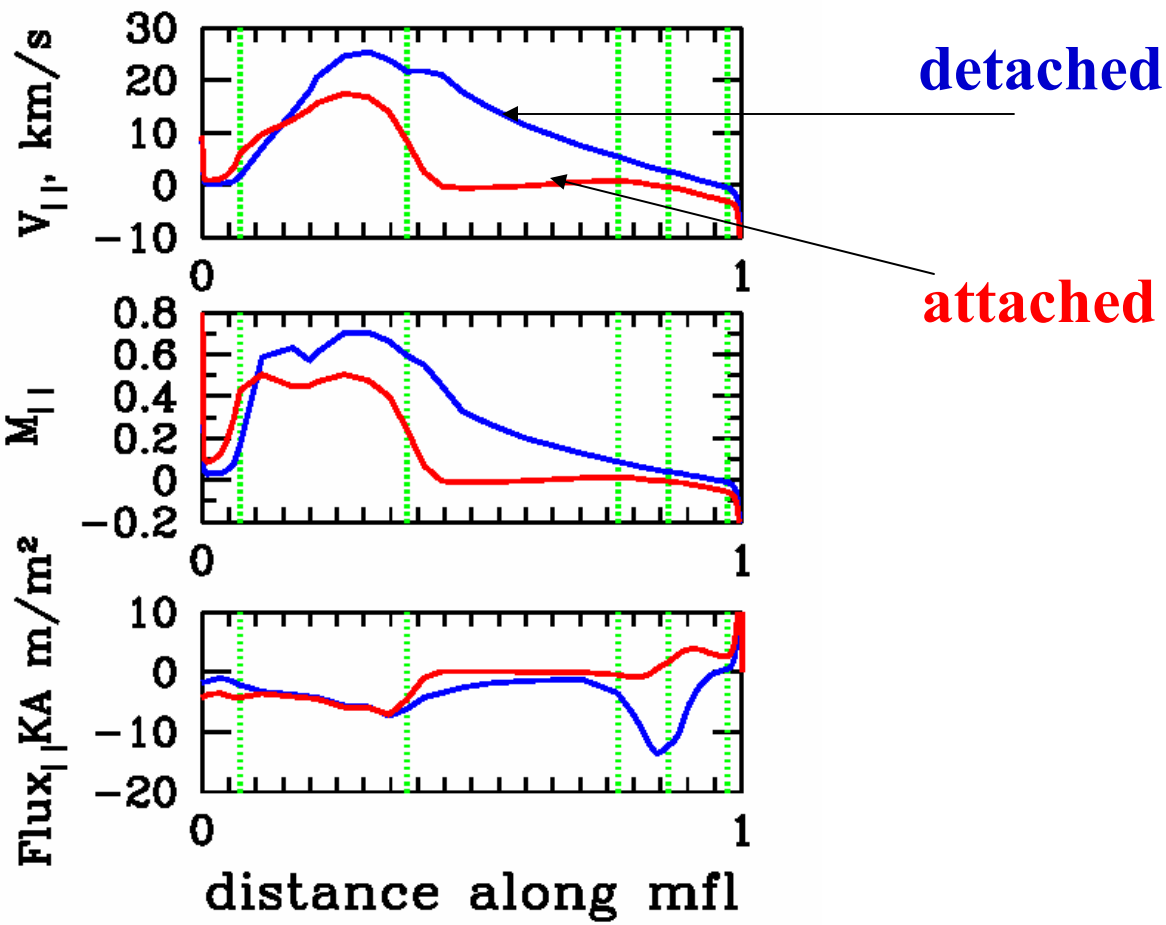
Parallel plasma velocity increases all the way from the outer to the inner mid-plane. The maximum of M|| is around the inner mid-plane



Poloidal distribution of V|| follows the distribution of Btot along the mfl. Plasma can accelerate as well as de-accelerate depending on gradB

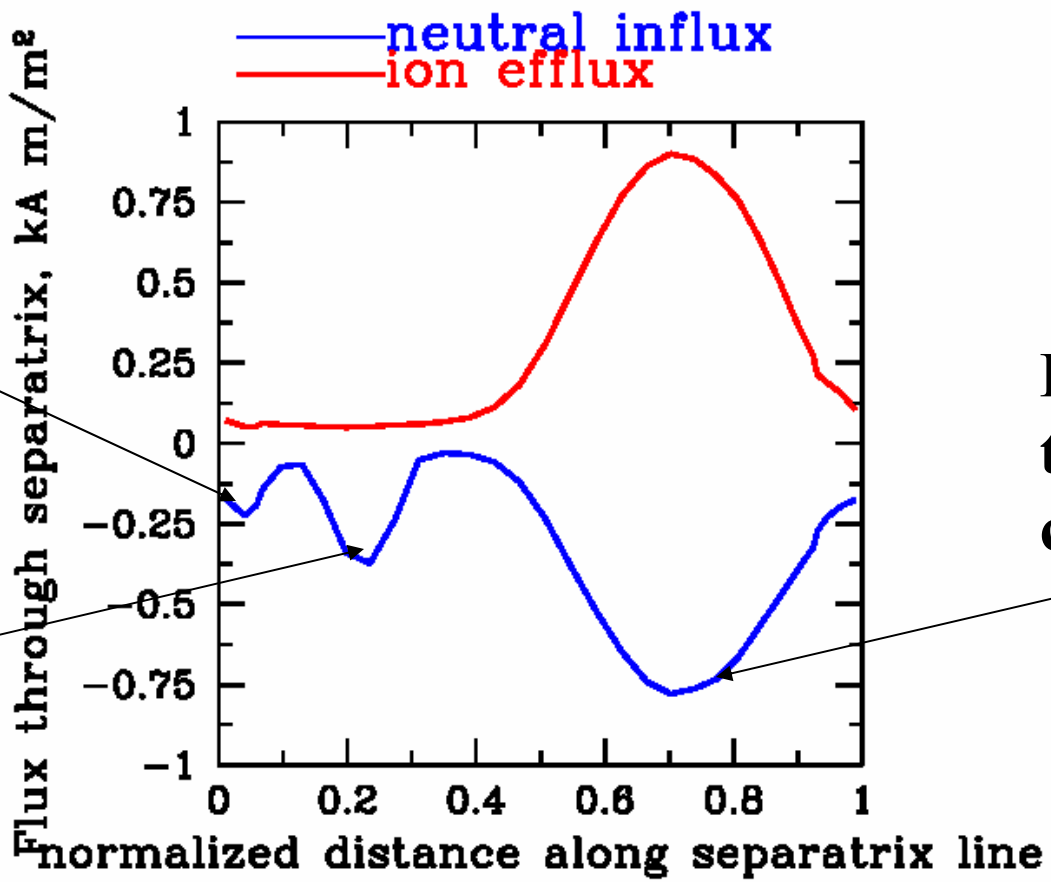


Most pronounced || flows predicted for detached inner divertor



Plasma flow ends in the inner divertor. The equivalent amount of particles leaks from the inner divertor into the core through the separatrix.

Leakage from inner divertor



Recycling at the outboard chamber wall

Gas puff and associated recycling

Additional results of numerical experiment on parallel SOL flows.

1) The inversion of inboard/outboard asymmetry in the plasma cross-field transport by changing the poloidal profile of anomalous cross-field convective velocity heavily toward the inner SOL results in the reduction of flows and in an attached inner divertor plasmas.

2) The multi-species simulation shows that parallel flows of low charge states (C^{+1} and C^{+2}) of intrinsic carbon impurities can be supersonic in the region between the outer and inner mid-planes.

3) We perform calculation with and without drifts. We found that drifts do not affect directly the parallel plasma flows. However, even for large values of drift reduction factors (~10), drifts cause the strong detachment of both inner and outer divertors.

4) Large parallel flows predicted by UEDGE also for **C-Mod and DIII-D**.

Conclusions

1) Recent UEDGE simulation confirms that large parallel plasma flows exist in the SOL of NSTX.
2) The calculations show that these plasma flows can be driven by a combination of inboard/outboard asymmetries in the magnetic configuration and in the cross-field transport.
3) In a high aspect ratio tokamak, the strong poloidal variation of the magnetic field strength can provide a powerful mechanism for acceleration and de-acceleration of parallel plasma flows in the SOL.
4) The largest simulated flows occur in the case when inner divertor in the lower single null magnetic configuration is detached. In this case the parallel flow (totalized of about few hundred amperes) originated in the outer divertor accelerates from the flow velocities ~3 km/s at the outer mid-plane up to ~30 km/s (i.e. to the Mach number 0.5-0.7) at the inner mid-plane near the chamber wall and then de-accelerates toward the inner divertor plate.

Conclusion (Cont.)

5) The ion flux carried by parallel flow into the inner divertor is equal to the flux of neutrals penetrating from the inner divertor into the core plasma through the separatrix.
6) The inversion of inboard/outboard asymmetry in the plasma cross-field transport by changing the poloidal profile of anomalous cross-field convective velocity heavily toward the inner SOL results in the reduction of flows and in an attached inner divertor plasmas.
7) The multi-species simulation shows that parallel flows of low charge states (C^{+1} and C^{+2}) of intrinsic carbon impurities can be supersonic in the region between the outer and inner mid-planes.