Modeling of low-recycling divertor with lithium coating in NSTX

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*Work supported by US DOE Grant No. DE-FG02-08ER54989 at UCSD
and Contracts Nos. DE-AC02-09CH11466 at PPPL and DE-AC52-07NA27344 at LLNL*

51st Annual Meeting of the APS Division of Plasma Physics
November 4th, 2009; Atlanta, Georgia

Outline

- Liquid Lithium Divertor concept
- UEDGE modeling of low recycling regimes
  - Parametric scan of divertor recycling
  - Plasma properties in low recycling regimes
- Thermal instability of lithium PFC due to evaporation
- Matching experimental data for NSTX with UEDGE
  - Edge plasma profiles
  - Impurity transport

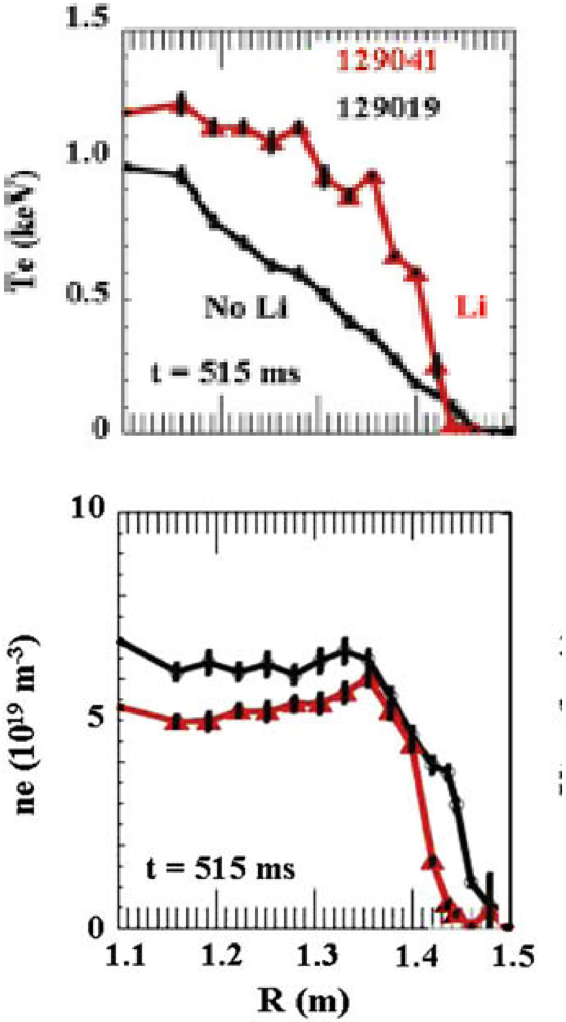
Low-recycling liquid lithium divertor concept

- The low-recycling regimes are expected to occur in the case when liquid lithium (or other liquid material, which can efficiently retain hydrogen) is used as the plasma facing material or as the recoverable coating on the divertor plates
- Improves the core plasma performance by reducing the plasma gradients, increasing the energy confinement time and the fusion power density
- Provides the capability for efficient handling the high peak plasma power loads both static and transient (ELMs)
- Allows the hydrogen density control via strong hydrogen retention in liquid layer while this layer is removed from the tokamak (or via fresh lithium coating in NSTX)

[1] S. Krasheninnikov and L. Zakharov, *Phys. Plasmas* **46** (2006) 604

[2] D. Mansfield et al., *J. Nucl. Matrials* **390-391** (2009) 764

Experiments with lithium divertor coatings in NSTX

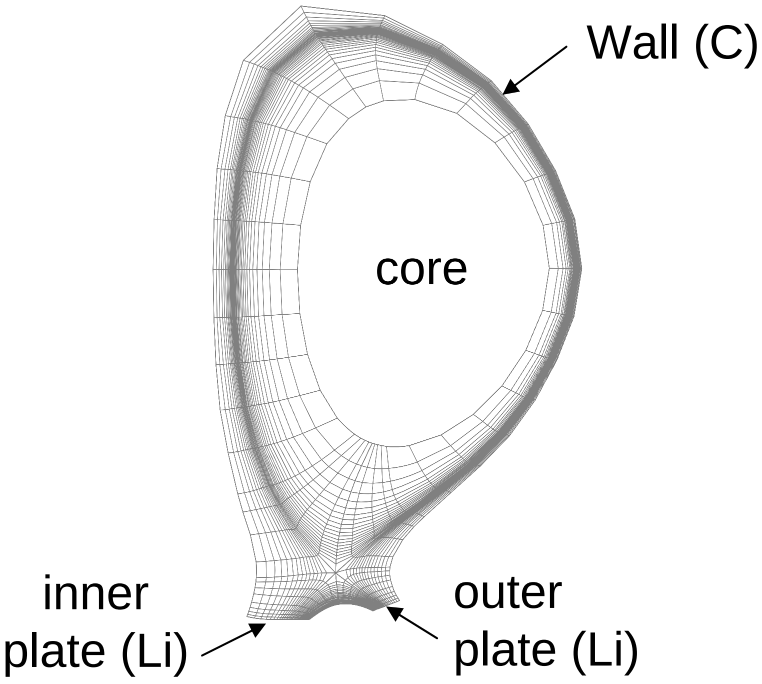


- Fresh Li coatings are pumping hydrogen since gas puff of 750 Amp is needed to maintain the plasma density
- Core/edge Te and Ti increased in discharges with Li (but density decreased?)
- Low concentration of Li in the core but increased carbon impurity level
- ELMs can be reduced or even suppressed
- However, edge density gradient is increased that is indicative of enhanced radial transport
- So far, thickest Li coverage is in the divertor

UEDGE simulation model

- Fluid 2D transport of all charged states of D, Li and C simultaneously
- Sources due to Li evaporation and sputtering at plates and walls
- Sources of C at walls that mimics sputtering and sublimation
- Atomic physics on Inter-species interaction (ADAS and ADPACK data)
- Lower single-null magnetic configuration

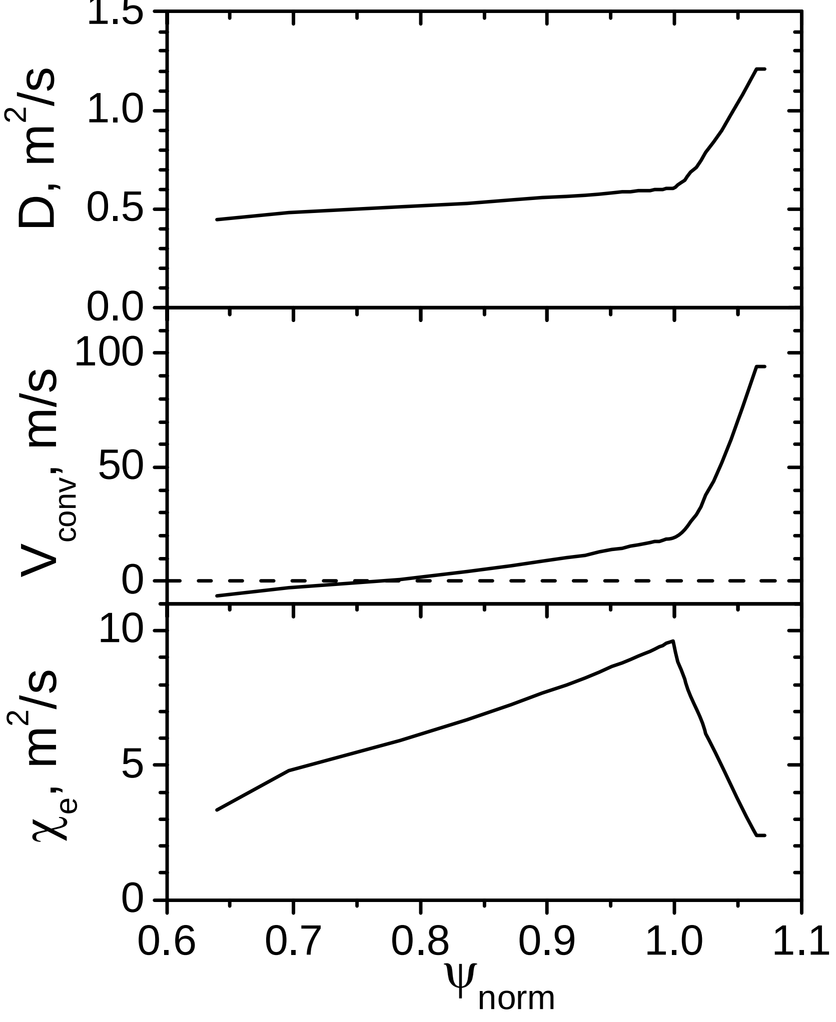
UEDGE mesh for NSTX single-null configuration



Model parameters

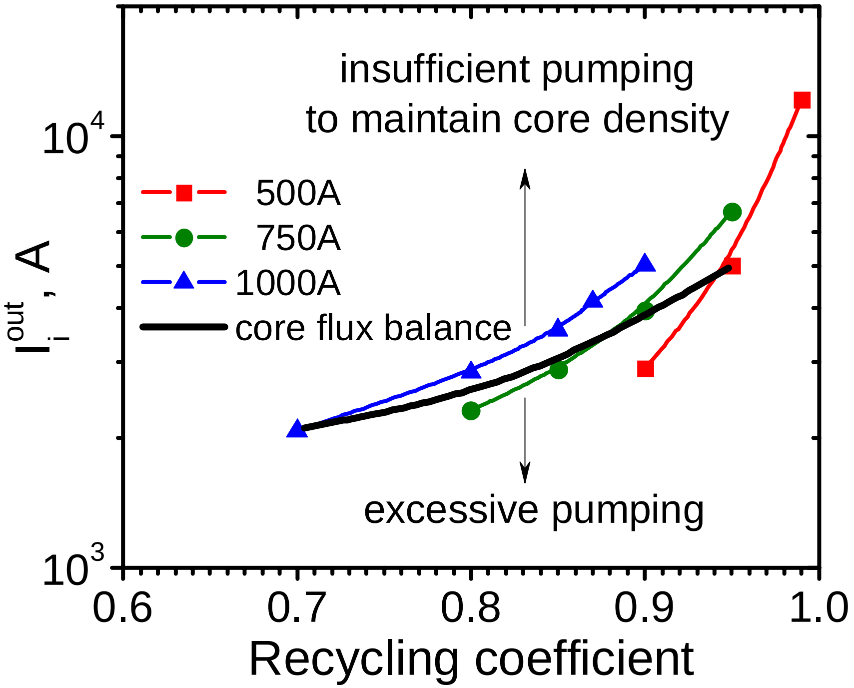
- Gas puffing 500-1000 A
- Core interface density ~$5^x10^{19}m^{-3}$
- Separatrix Te~70-100eV; Core Te~500eV
- Recycling coefficient at divertor plates varied from 0.70 to 0.99
- Plate surface temperature has asymmetric Gaussian profile with the peak temperature 600-900K

Outer midplane transport coefficients



Effect of Li pumping

Ion current
to the outer divertor plate



Only one value of the recycling coefficient corresponds to the core particle flux equilibrium for a given gas puffing rate

To maintain equilibrium in the core larger gas puffing rate is required in the low-recycling regimes

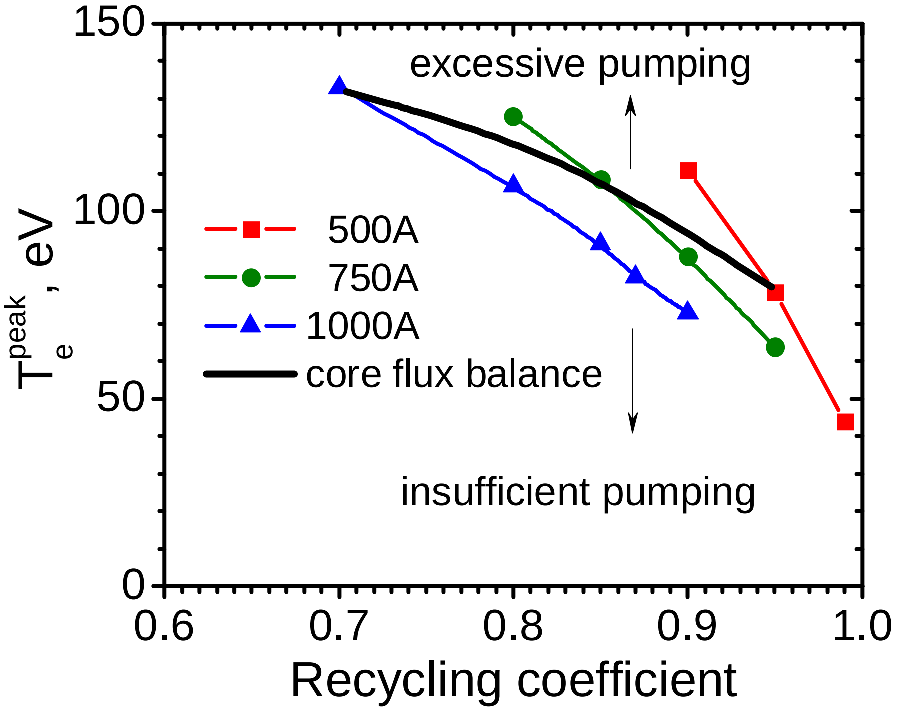
Li pumping substantially decreases the ion flux to plate

For R~0.8, ion flux is ~2KA, comparable to ion flux on wall

If ~20% of D+ is pumped by Li coating, the gas puff rate should be >800A

Divertor temperature in low-recycling

Peak electron temperature
at the outer divertor plate



Electron temperature at the plate is peaked near separatrix

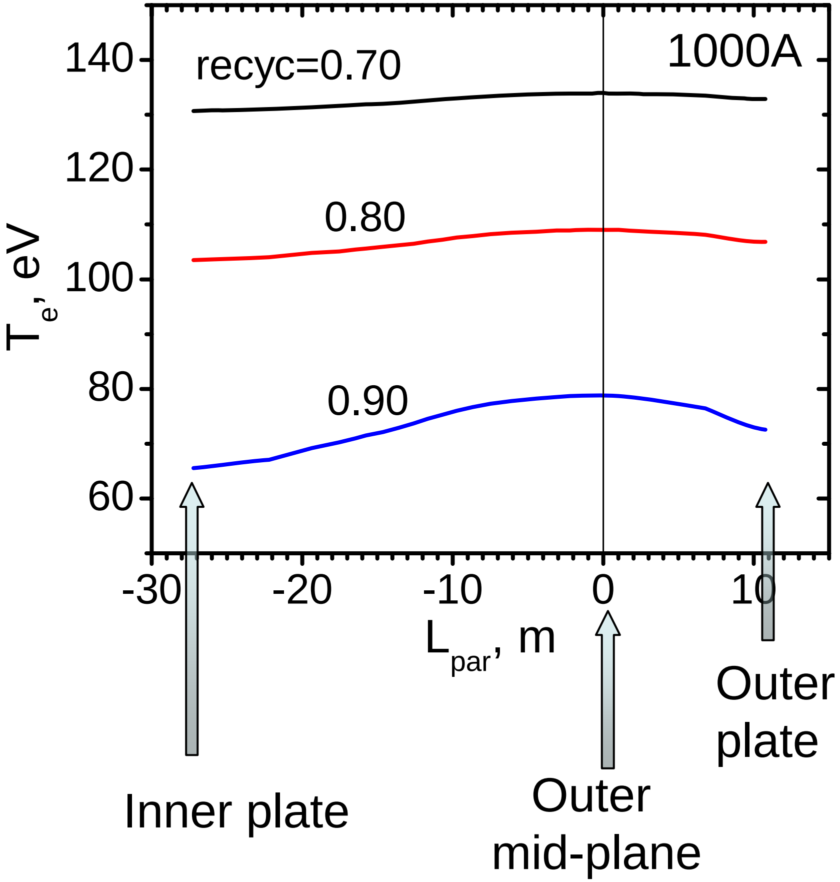
The higher the Li pumping (smaller R), the higher is the peak Te at plate

For R<0.95, Te>50 eV !

Small Te (<20eV) can mean small Li pumping

Low-recycling results in flux limited heat transport regimes

Parallel profiles of electron temperature along separatrix



Because of low upstream density and high Te, the electron mean free path is large

mfp(m)=2×10^{10} $[T(eV)]^2$/ne(cm^{-3})

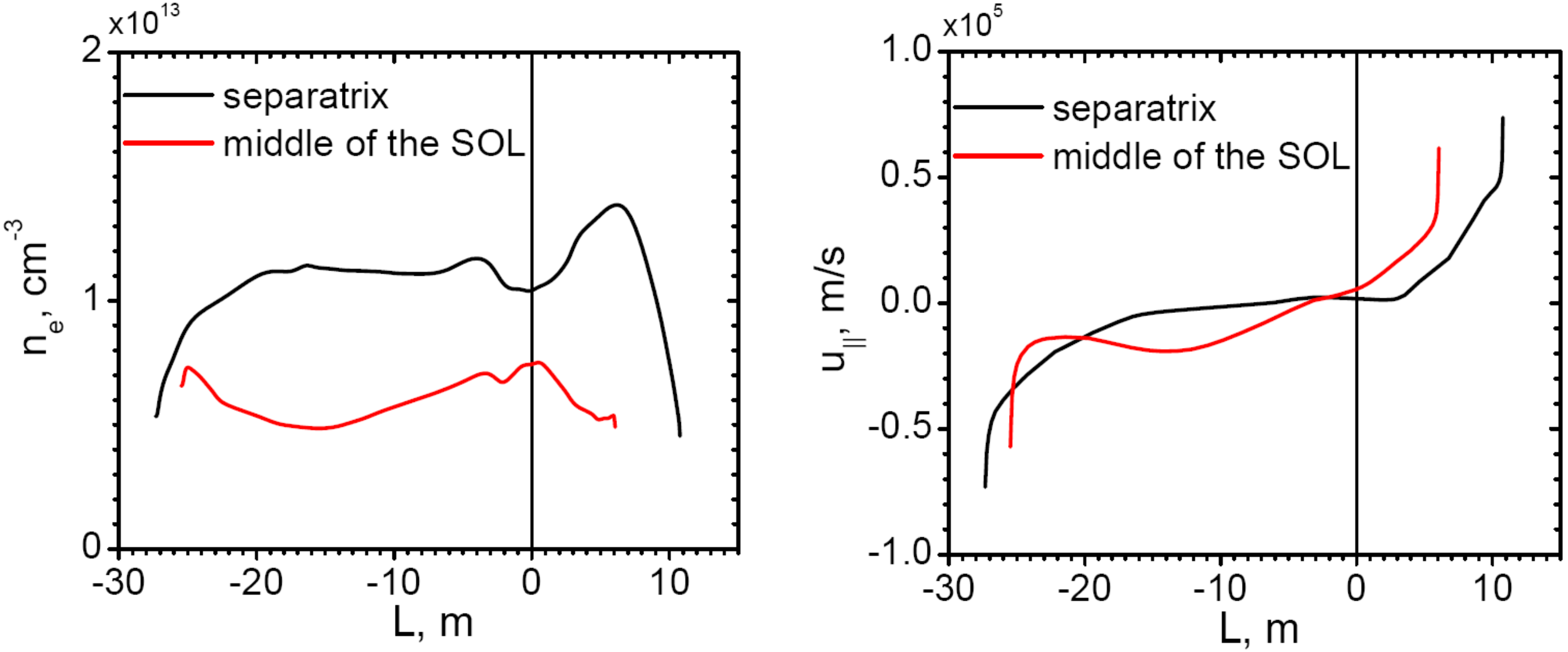
For Te~100eV ne~10^{13} cm^{-3}
mfp~20m

mfp exceeds the connection length to the outer divertor plate and mid-plane (10m)

Te significantly increases and its profile along the magnetic field line is rather flat in the low-recycling regimes

Parallel plasma transport

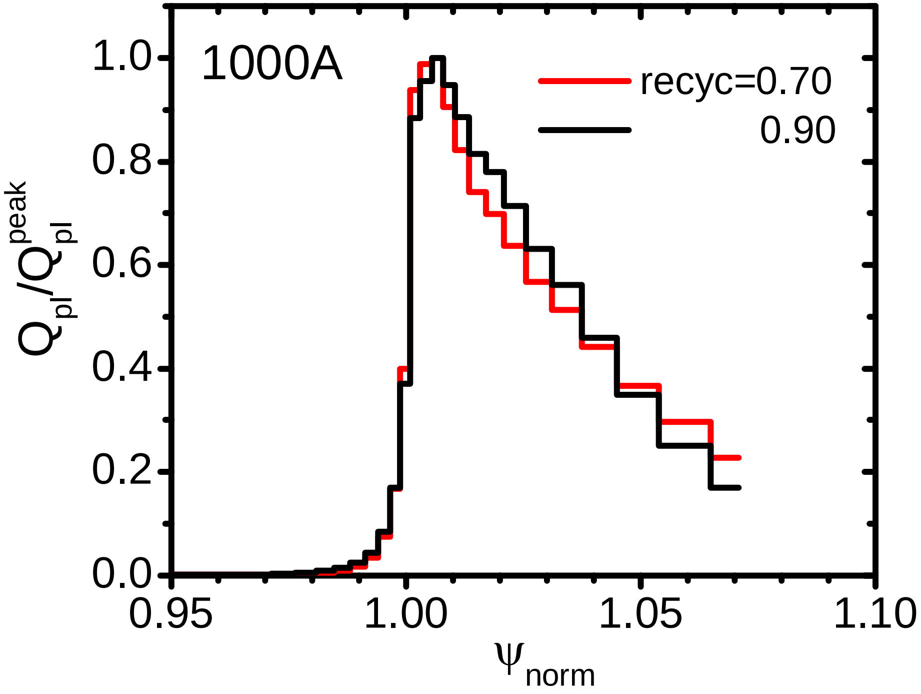
In the low-recycling regimes the plasma density decreases towards the plate and the parallel plasma velocity increases as the change of the parallel particle flux is not very large



L is the distance along a flux line, L=0 corresponds to the outer midplane

Heat flux to plate in low recycling regime

Radial profiles of the heat load to the outer divertor plate



Input plasma power 3MW

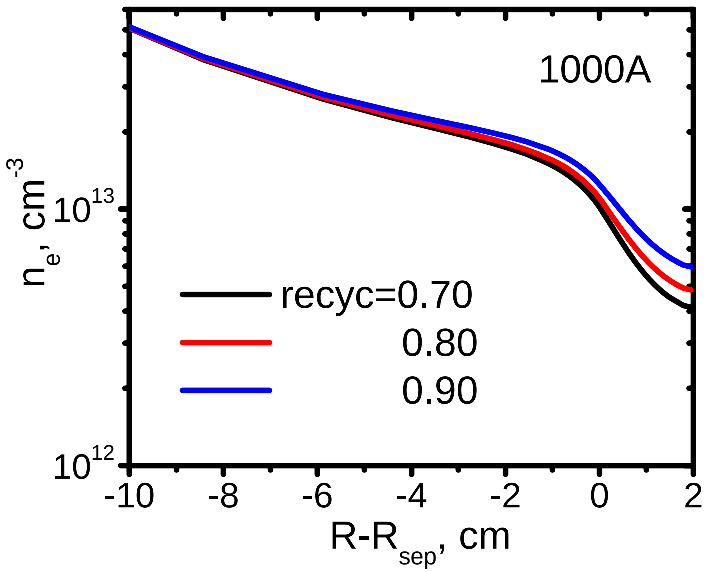
Heat flux in the SOL is carried predominantly by the electrons

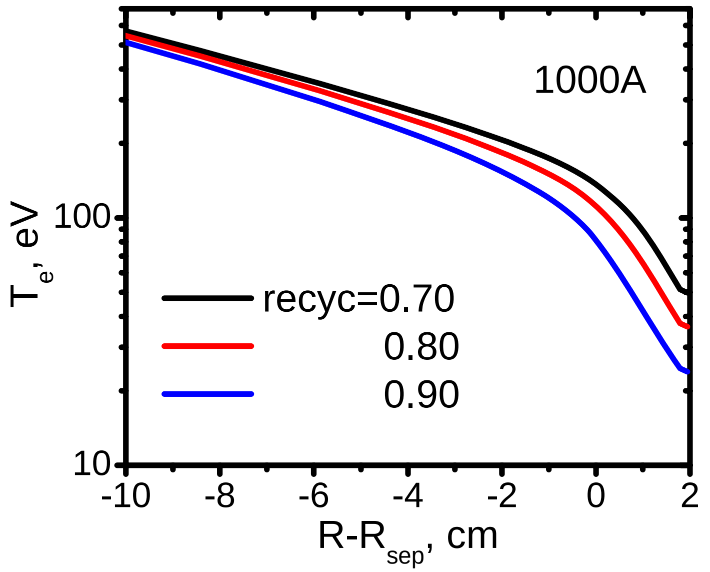
Flux-limited parallel electron heat conduction dominates

The profile narrows in the low-recycling regimes due to faster parallel transport

In the low-recycling regime, the peak heat flux to outer plate can be high enough to melt Li around the strike point

Radial plasma profiles at the midplane





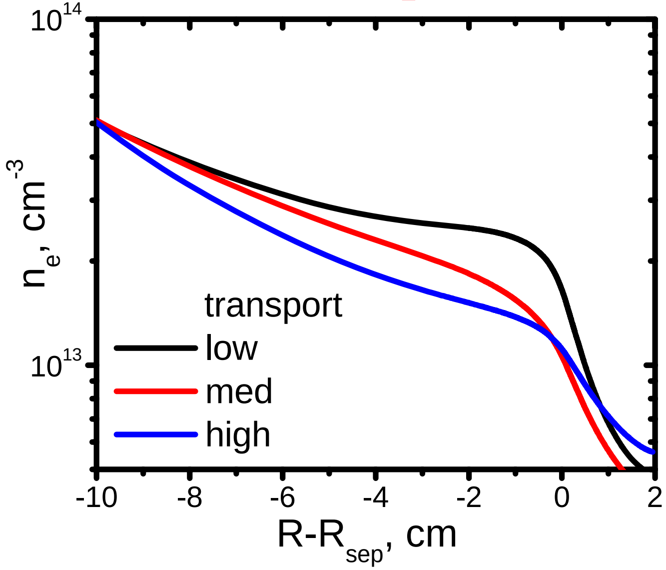
SOL plasma transport transits to a free-streaming regime in the low-recycling cases

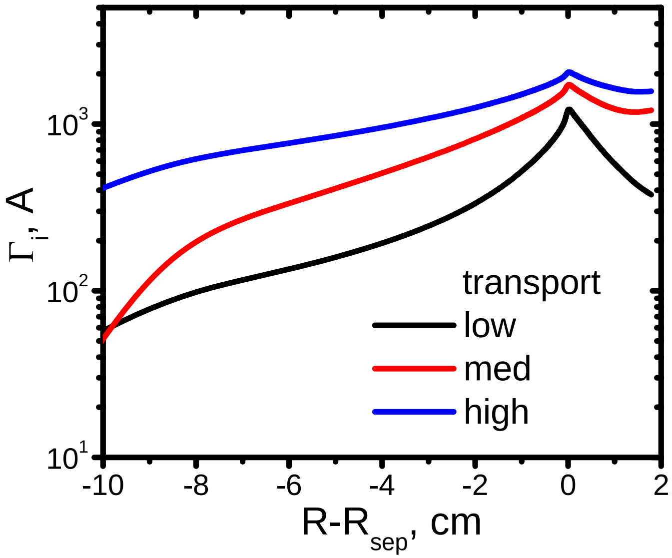
The radial plasma density gradient increases and the density at the separatrix is reduced slightly reflecting the increased pumping action of the divertor

The strong parallel plasma transport in the SOL also reduces radial plasma flux to the wall

The radial profiles of the electron temperature become flatter due to the raised overall electron temperature and heat conduction coefficients

Effect of radial transport on plasma profiles at the midplane





Edge density gradient corresponds to large ion flux into SOL

Decrease of radial transport causes flattening the density profile in the core and sharper gradient in the SOL. Te and Ti increase (not shown).

Decrease of transport coefficient roughly by factor 5 increases the n_sep by factor 2 (compare red and black curves). Ion flux decreases by factor 1.5.

It suggests that lower radial plasma transport in the SOL may help establishing the low-recycling operational regimes

Low recycling is main chamber + gas puff recycling regime

For single-null, small triangularity
Recycling coefficient = 0.70

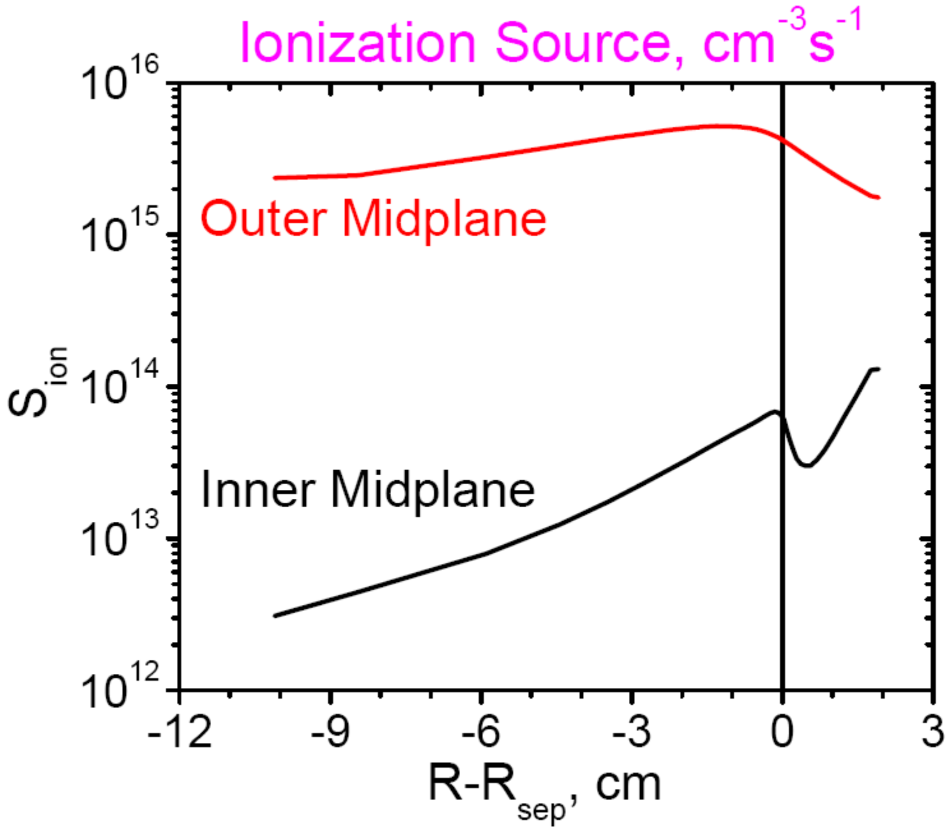
Gas puff rate = 1000 A

Ion flux into SOL = 1920 A

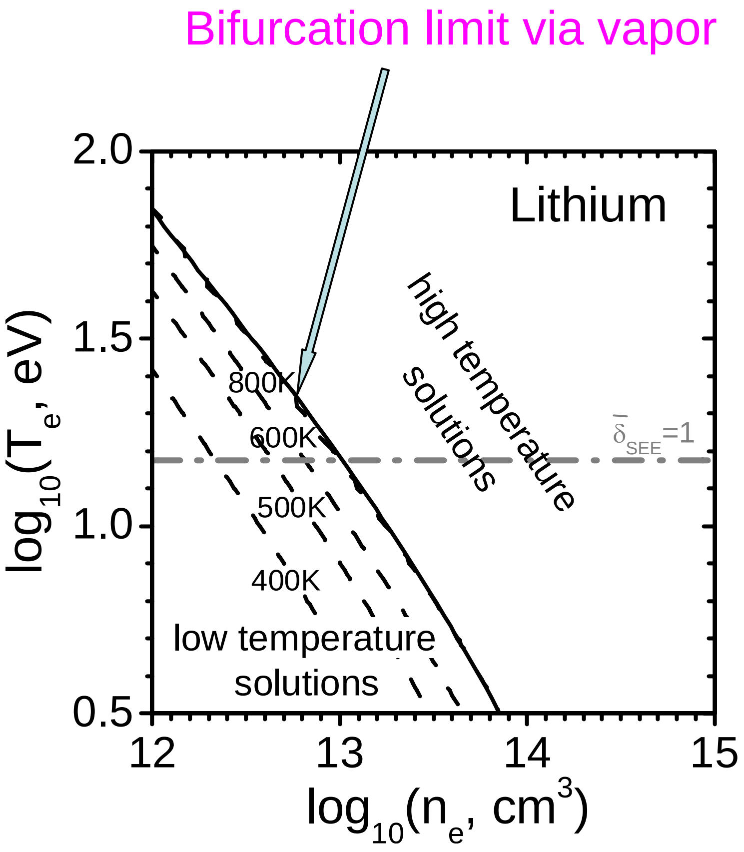
Ion flux to wall=neutrals from wall ~1210 A

Ion flux to divertor plates
1200+2080 =3280A

Divertor plasma is still opaque to neutrals from the divertor plates, but SOL is transparent



Liquid Li PFC overheating



R. Smirnov et al., submitted to PoP 2009

Thermally unstable heating can occur when a positive feed-back exists between the plasma heat flux to PFC and the PFC’s surface temperature Tpfc.

We found new mechanism of liquid surface overheating via positive loop caused by evaporating flux.

Bifurcation is near Tpfc=800K for Li. For Be bifurcation is at 1500K (near melting point).

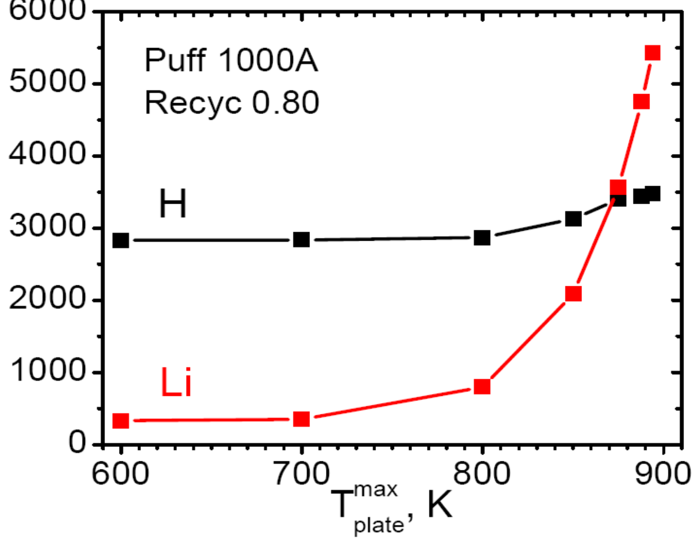
This mechanism drives overheating at much lower Tpfc than the well-known mechanism via thermionic emission.

Secondary electron emission may enhance PFC heating and can shift bifurcation limit towards lower Tpfc

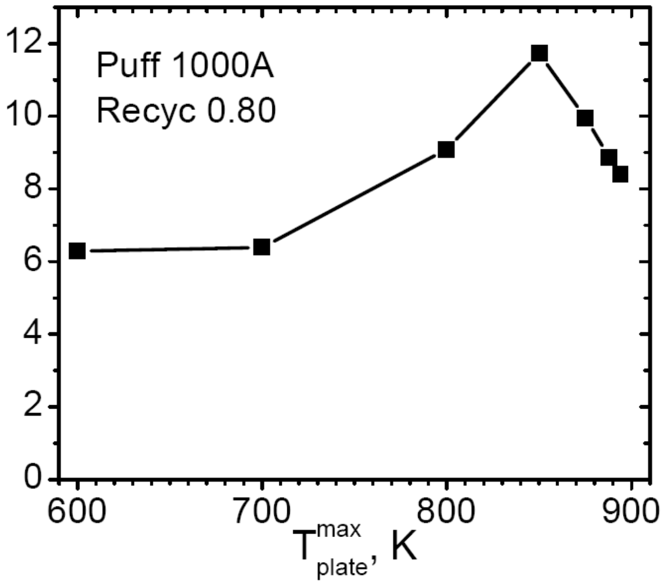
May be related to Li BLOOMs observed in disruptions on T-11

Vapor instability modeled with UEDGE

Ion flux to outer plate, Amp



Peak heat load to plate, MW/m^2



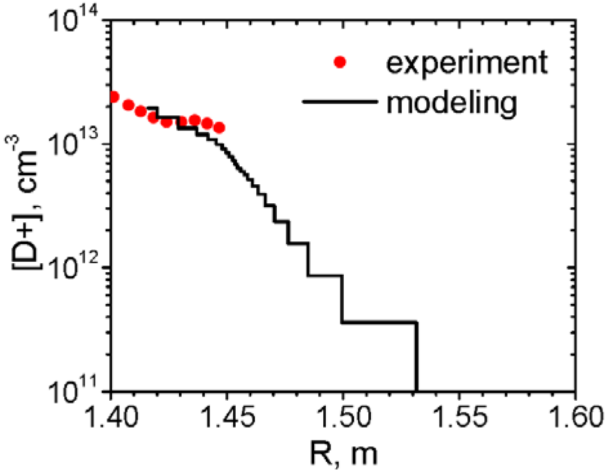
Until impurity radiation heat losses dominate, increase of Tpfc enhances the evaporation and the heat flux to PFC due to increased flux of the recycled vapor ions, that increases Tpfc further.

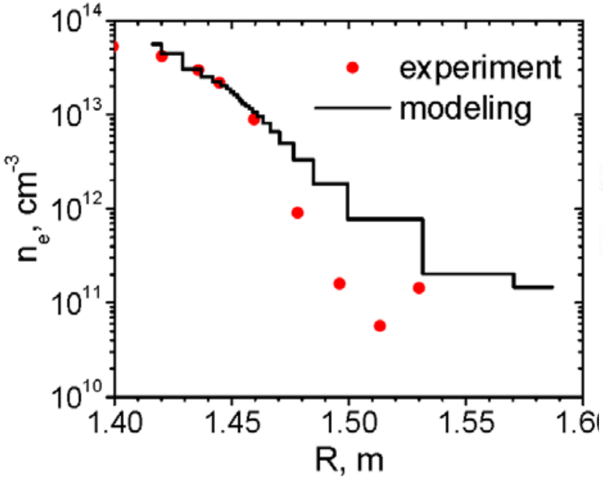
Possibly, the instability can be stabilized by impurity radiation upstream reducing the heat flux.

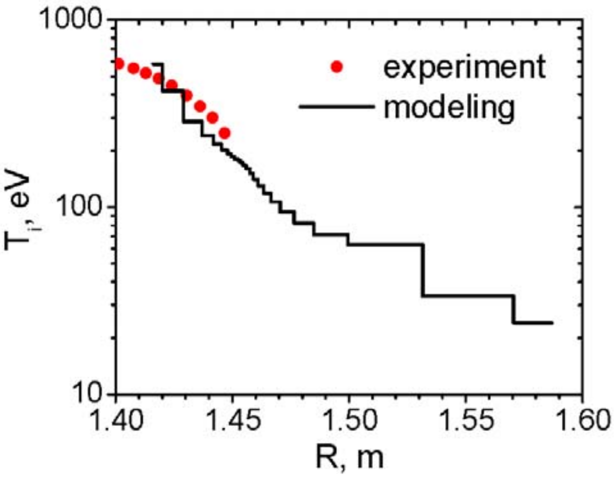
Self-consistent UEDGE modeling of plasma/vapor transport and Tpfc is in progress.

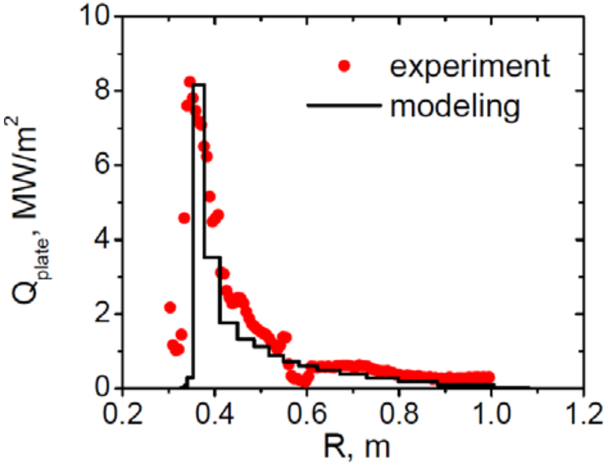
Instability may be a potential threat to NHTX and LLD

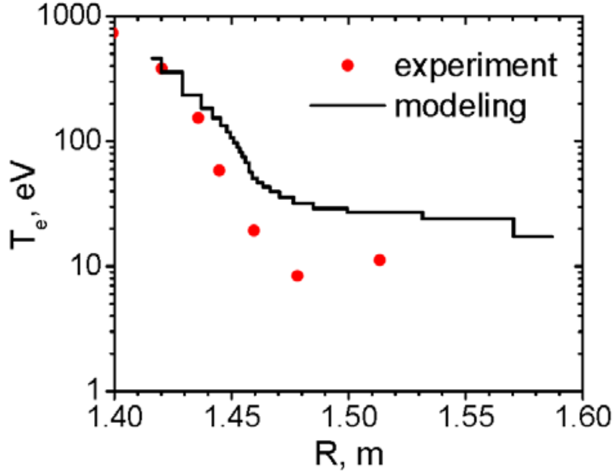
Fitting NSTX data with UEDGE











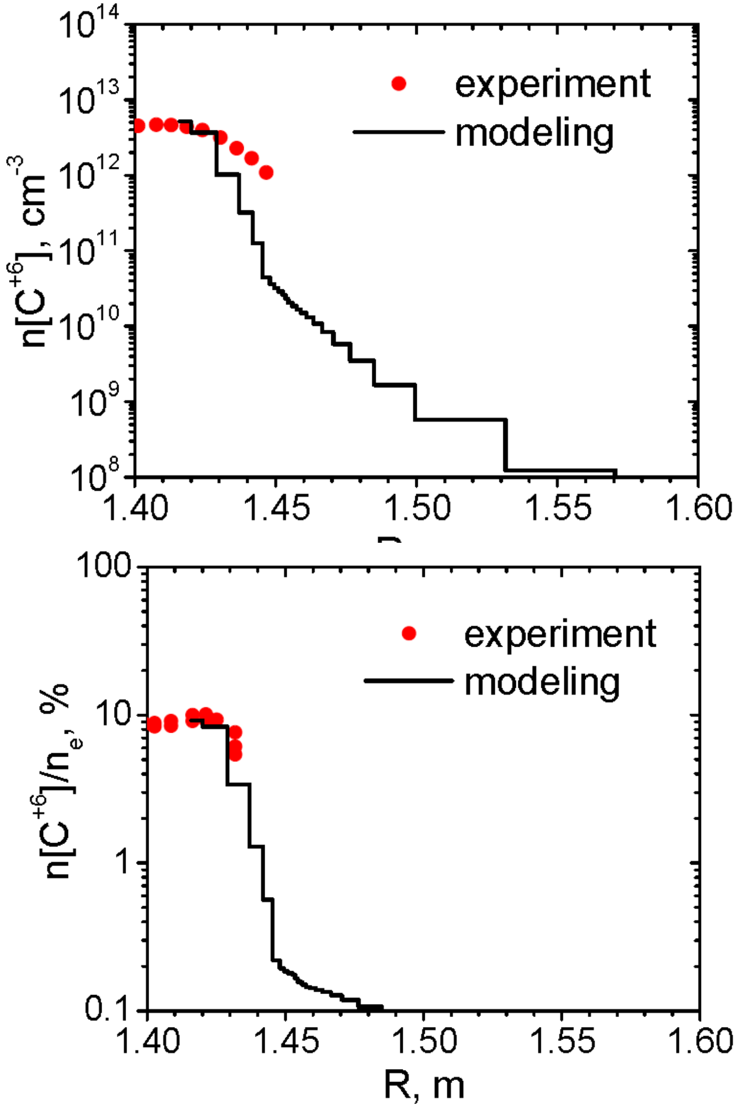
Shot 129061

UDN With Li

Low recycling conditions with recycling coefficient 0.85

R in the figures is the major radius

Density "ears" via carbon impurities are successfully modeled



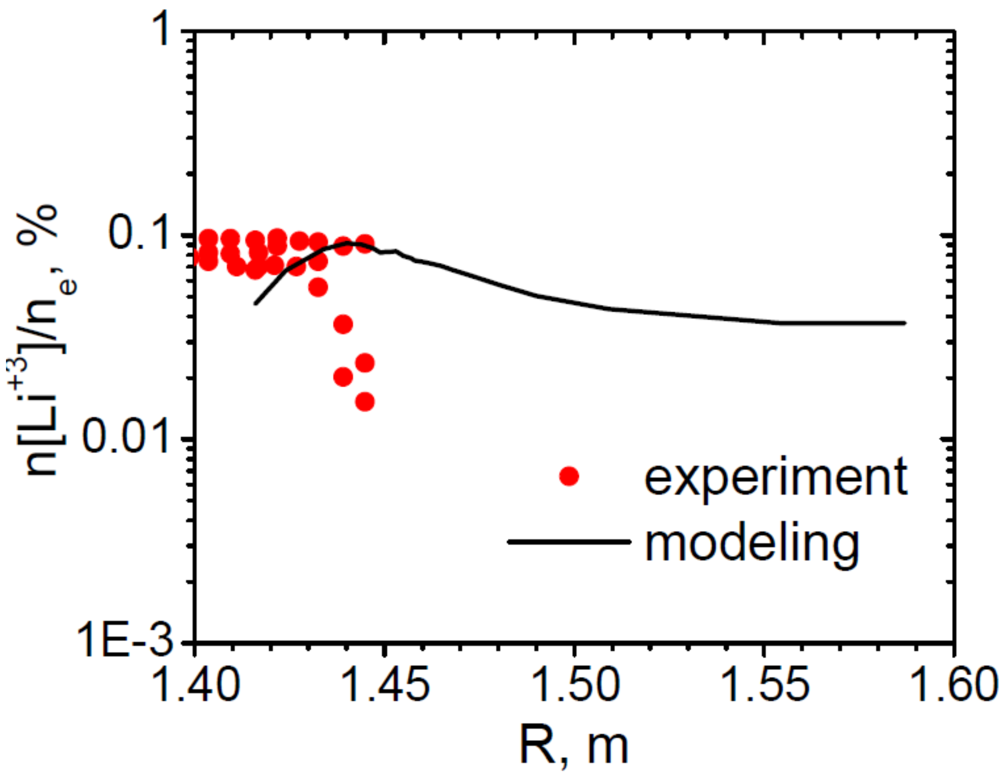
We assume a combination of inward pinch velocity (radially and poloidally dependent) and reduced diffusivity in the ear region in core.

Creates a convective cell (influx at inboard, outflux at outboard)

Concentration of C ions is at 10% level

C originates from upper plates and wall

UEDGE shows relatively low concentrations of Li in core



[Li+3]/ne~0.1% is modeled

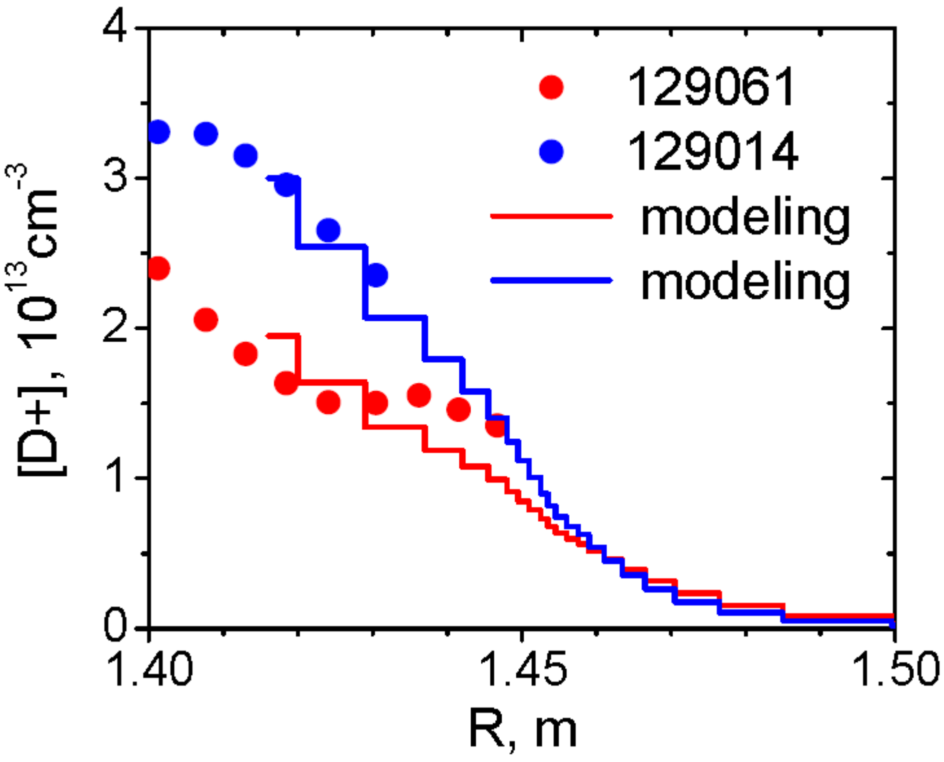
Lithium impurities originated from divertor plate via evaporation/ sputtering

Li is very well retained in the divertor volume (upper plates and wall are sinks).

However, with inward pinch assumption
[Li+3] can be ~1%.

Li coating tends to enhance the edge transport

WITH LITHIUM Igas=750A R=0.85



W/O LITHIUM Igas=250A R=0.97

Compare similar discharges in NSTX: 129061 with Li and 129014 without Li.

Although there is no data points at separatrix (i.e. if extrapolation is valid), experimental data shows different [D+] gradients with and w/o Li.

UEDGE shows that with Li all transport coefficient should be increased by factor of 2.5 with respect to without Li discharge

Low sensitivity of separatrix density to transport coefficient variation

Conclusions

Modeling with UEDGE of the plasma and impurity transport in low-recycling regimes for NSTX divertor coated with Li shows that

- to maintain core plasma equilibrium larger hydrogen gas puffing rate is required to offset increased divertor pumping action
- the low-recycling divertor regime is characterized by convection limited parallel heat transport in the SOL, flattening of the parallel profiles and the significant increase of Te
- free-streaming regime of parallel plasma transport is established in the low-recycling cases that increases radial plasma density gradients in the SOL and narrows heat load profile at the plate
- the plasma fueling can be dominated by gas-puff and main-chamber recycling

- increased evaporation of lithium surfaces heated above ~800K can reverse the divertor regimes from low- to high-recycling

- until the radiation heat losses start to dominate, heat load to the lithium divertor rises as the recycled Li ion flux increases for plate temperatures up to ~850K that can lead to the thermal instability

- Li impurity concentration in the core is relatively small, Li is well retained in the divertor

- peaked radial profiles of carbon impurity density in the core edge (“ears”) can be modeled with the in/out asymmetric inward pinch and reduced diffusivity of impurities at the edge

- with Li, the edge plasma transport tends to increase

Acknowledgements

Work supported by US DOE Grant No. DE-FG02-08ER54989 at UCSD and Contracts Nos. DE-AC02-09CH11466 at PPPL and DE-AC52-07NA27344 at LLNL