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Simulations of NSTX with a Liquid Lithium Divertor Module

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Abstract

The UEDGE edge plasma transport code is used to model the effect of the reduced recycling provided by the Liquid Lithium Divertor (LLD) module that will be installed in NSTX. UEDGE's transport coefficients are calibrated against an existing NSTX shot using midplane and divertor diagnostic data. The LLD is then incorporated into the simulations as a reduction in the recycling coefficient over the outer divertor. Heat transfer calculations performed using the resulting heat flux profiles indicate that lithium evaporation will be negligible for pulse lengths < 2 s at low (∼ 2 MW) input power. At high input power (∼ 7 MW), the pulse length may have to be restricted.

Key words: (PSI-18) NSTX, Density control, Lithium, UEDGE, Cross-Field Transport, (JNM) D0500 Divertor Materials L0300 Liquid Metals T0100 Theory and Modeling
PACS: 52.55.Fa, 52.65.-y, 52.40.Hf, 61.25.Mv

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1 Introduction

The National Spherical Torus eXperiment (NSTX, $R = 0.85$ m, $a < 0.67$ m, $R/a > 1.27$) [1] has been investigating the use of lithium as a surface coating material to improve plasma performance and to provide better control of the core plasma density. The lithium program has proceeded in stages, beginning with lithium pellet injection in 2005. In 2006, an evaporative lithium system (LiThium EvaporatoR, or LiTER) was installed to coat the graphite tiles that serve as the primary plasma facing material in NSTX [2]. The 2006 – 2007 experiments resulted in 50% reductions in L-mode density and 15% reductions in H-mode [2]. During the 2008 campaign, two evaporators were used, resulting in improved energy confinement times ($\tau_E > 100$ ms), longer pulse lengths (1.8 s) [3], and reduced Edge Localized Mode activity [4]. Nonetheless, the core density still increased monotonically during a discharge. For this reason, NSTX is pursuing the next step in this progression, the Liquid Lithium Divertor (LLD), which will place a thicker, toroidally continuous liquid lithium surface in contact with the plasma.

The LLD is a joint collaboration between Sandia National Laboratory, University of California at San Diego, and the NSTX project. The basic concept is of a toroidally extended lithium containing tray that will serve as a target for the outer strike point or divertor. Ideally, the radial location and width of the tray would be chosen so as to obtain the greatest degree of density reduction for both low and high triangularity discharges (Fig. 1). However, practical and programmatic considerations also enter; these favor placing the tray on the outer divertor target plate just outside the co-axial helicity injection gap. Simple particle balance calculations suggest that in this location the core density will be reduced by about 50% for low triangularity (strike point directly on the LLD) and by about 25% with high triangularity. One of the objectives of the modeling effort associated with this paper is to put these estimates on a firmer footing.

We describe here modeling of the scrape-off layer (SOL) plasma conditions under LLD operation and the resulting temporal evolution of the temperature of the lithium surface. Section 2 discusses modeling of an existing NSTX discharge with the 2-D edge plasma transport code UEDGE [5]. With this as a baseline, we then (Sec. 3) vary the outer divertor recyling coefficient, representing the effect of the LLD on the SOL plasma. The thermal response of the LLD to these plasma conditions is estimated with a 1-D heat transfer calculation in Sec. 4. Finally, subsequent steps in this LLD modeling effort are described in Sec. 5.

2 Calibration of UEDGE Transport Model

The UEDGE-2D edge plasma transport code [5] solves fluid equations for ion density, electron and ion temperature, ion parallel flow velocity, and electrostatic potential. Transport along field lines is classical with flux limits incorporated to replicate important kinetic effects. Anomalous transport across field lines is used to simulate the effects of plasma turbulence, including the intermittent transport associated with "blobs" [6]. A Navier-Stokes fluid model describes the behavior of neutral deuterium. Because we are going to subsequently impose dramatic changes to the boundary conditions (the pumping provided by the LLD), we ignore subtler effects such as those associated with the multiple charge state carbon model and classical drifts.

We use an existing NSTX discharge to establish the input parameters to UEDGE. First, we derive a computational mesh from the equilibrium of a low triangularity, single null discharge similar to that shown in Fig. 1(a) (shot 128339 at 0.35 s; toroidal magnetic field = 0.5 T, plasma current = 1 MA). Not only is the strike point for this discharge located within the planned LLD location, so is the entire outer divertor target of the computational mesh. Hence, we will simulate the pumping effect of the LLD as a uniform reduction in recycling there.

This computational mesh spans normalized flux values $\psi_{\rm n} = \psi/\psi_{\rm sep} = 0.85 - 1.07$. The electron density and temperature at the core boundary are obtained from the Thomson scattering diagnostic: 4.3×10^{19} m^{-3} and 130 eV, respectively. Ion temperature data from charge-exchange spectroscopy do not extend this far in radius; instead we note that $T_i \sim T_e - 15$ eV at slightly smaller radii and set the ion temperature boundary condition to 115 eV.

We specify on input to UEDGE the particle diffusivity D, electron thermal diffusivity χ_e, and anomalous radial convective velocity v with values given at the core boundary, separatrix and outer wall (D_c, D_s, and D_w, etc.). The values in between are computed via linear interpolation on the radial mesh index; all coefficients are constant on a flux surface. The ion thermal diffusivity $\chi_i = \chi_e$, and the cross-field diffusivity of parallel momentum is set to $2/3\chi_e$. Our approach is thus intended to be more elaborate than that in [7], but less so than that described in [6], in which a 2-D characterization of transport was developed specifically to investigate the connection between poloidal asymmetries in the radial transport coefficients and high speed SOL flows.

Second, we adjust the D, χ_e, and v values to match the miplane Thomson scattering n_e and T_e profiles, as well as the power flowing in from the core. The latter is estimated to be in the range of 1.7 – 1.8 MW (1 MW NBI, $\simeq 1$ MW OH, $\sim 15\%$ beam ion loss, and < 0.1 MW of core radiation). For particle balance, we lump all external fueling into the core particle source and require its magnitude to be consistent with the sum of center stack gas puff (about 400 A) and NBI fueling (18 A).

Since we have no experimental data with which to constrain transport within the private flux region (PFR) and since the plasma parameters elsewhere are relatively insensitive to it, we treat the PFR diffusivity as a free parameter that can be adjusted as needed to yield PFR densities $> 10^{17}$ m^{-3} to maintain UEDGE convergence.

The simulated density profile obtained with transport coefficients $D_c = 0.04$, $D_s = D_w = 0.1$ m^2/s, $v_c \equiv 0$, $v_s = 25$, $v_w = 30$ m/s is shown in Fig. 2. Note the very different shape and separatrix density obtained with a nominal, constant $D = 0.5$ m^2/s and $v = 0$. The thermal diffusivities are $\chi_{e,c} = 1.5$, $\chi_{e,s} = 25$, and $\chi_{e,w} = 35$ m^2/s. The Thomson scattering profile shows a separatrix temperature of only 10 eV. However, this is likely the result of a slight inaccuracy in separatrix location since power balance considerations and a simple 2-point model indicate separatrix temperatures in the 30 – 40 eV range. Hence, our baseline profiles sit well above the experimental ones in the SOL. The profile obtained with a constant $\chi_e = 1$ m^2/s differs only slightly in the outer SOL, but corresponds to an input power of just 0.75 MW.

The total power flowing in from the core boundary in our baseline simulation is $P_e = 0.98$ MW and $P_i = 0.82$ MW, for a total of 1.8 MW, consistent with experimental power balance. The D^+ current flowing into the problem from the core boundary is 440 A, and a 142 A current of D atoms is flowing through this boundary in the other direction; again this is compatible with the experimental particle balance.

We also verify that the simulation reasonably reproduces the available data along the outer divertor target where the LLD will be situated. The heat flux is determined experimentally by analysis of infrared emission from the graphite divertor tiles [8]. Profiles from two time slices around the time of interest (0.35 s) are plotted in Fig. 3(a) as a function of major radius along the divertor floor. We also compare with the D_α emission seen by divertor camera [9]. Since D_α calibration data for shot 128339 will be available only after the end of the present NSTX run campaign, we instead utilize D_α data from shot 125065 at 0.4 s, which has the same magnetic configuration, core density and input power as 128339 at 0.35 s.

The simulated profiles are affected by the amount of pumping (or absorption) of deuterium ions ("recycling" $\mathcal{R}$) and atoms ("albedo" $\mathcal{A}$) by graphite surfaces at various locations around the vacuum vessel. In both, cases a value of unity implies that the surface does no pumping / absorption. Following [10], we assume a nominal amount of pumping with recycling coefficients and albedos that are equal at the outer wall $\mathcal{R}_w = \mathcal{A}_w = 0.95$, nearly unity at the inner divertor $\mathcal{R}_{id} = 0.99$, $\mathcal{A}_{id} = 1$, and slightly lower on the outer divertor $\mathcal{R}_{od} = \mathcal{A}_{od} = 0.98$. The resulting divertor profiles are compared with the experimental data and a corresponding simulation with unit recycling in Fig. 3. The two simulated heat flux profiles are similar, but some amount of pumping is essential to bring the D_α emission rate within a factor of two of the observations. Note that neither simulation agrees with the D_α emission in the inner divertor. Improving agreement there requires an approach along the lines described in Ref. [10] and probably physics not included there. Henceforth, we will only be varying $\mathcal{R}_{od}$ and $\mathcal{A}_{od}$; for brevity we will refer to them as the "recycling coefficient" $\mathcal{R} = \mathcal{R}_{od} = \mathcal{A}_{od}$.

3 Scan of Recycling Coefficient

The absolute minimum value of recycling obtainable with a clean lithium target is set by the particle reflection coefficient and is expected to be in the $0.1 - 0.3$ range. However, the actual values obtained in the experiment will likely be higher due to variations in coating thickness and surface contamination [11]. Since we cannot predict these factors, we perform a scan over the recycling coefficient.

We first transform UEDGE's core boundary condition from specified density and temperature to specified particle flux and power using the values obtained in the baseline calculation from Sec. 2. These are held fixed during the scan as are all of the transport coefficients. The lower limit of the scan, $\mathcal{R} = 0.65$, is set by the ability of UEDGE to obtain a converged solution.

In Fig. 4(a), we show the variation of the core and maximum outer divertor n_e with $\mathcal{R}$. The former is of interest in planning the LLD experiments and will be compared with the simple particle balance calculations used in establishing the LLD radius and width. The peak divertor n_e and T_e [Fig. 4(b)] will impact the transport of lithium evaporated or sputtered from the LLD surface.

The total recycled gas current flowing away from the outer divertor target [Fig. 4(a)] drops roughly a factor of 40 over this range of recycling coefficients; the peak D_α emission rate decreases by a similar factor (60). In contrast, the liqiuid lithium tray experiments on CDX-U yielded D_α emission rates only about a factor of three lower than that obtained with a bare, stainless steel tray [12]. This disparity underscores the practical difficulty in preparing and maintaining a lithium surface capable of approaching the theoretical minimum recycling level.

4 Thermal Response Calculation

We now use the outer divertor (LLD) heat flux profiles from the simulations of Sec. 3 in a thermal conduction calculation to estimate the temperature rise of the lithium. The surface temperature rise ΔT due to a constant heat flux F, assuming a semi-infinite solid with conductive cooling is $\Delta T = (2F/K)\sqrt{\kappa t/\pi}$ [13], where K is the thermal conductivity and κ is related to K, the mass density ρ and specific heat C_p by $\kappa = K/\rho C_p$. Thus, ΔT increases linearly with heat flux and the square root of the exposure time t.

The LLD design consists of a copper (Cu) base with a thin stainless steel (SS) barrier. A film of molybdenum (Mo) flame-sprayed on top of this serves as the substrate for the liquid lithium (Li). The Mo and SS layers are sufficiently thin that their thermal properties are unimportant here. The effective thermal properties of the LLD will then fall between those of Cu (for a thin Li coating) and that of Li (thick coating). Since we do not *a priori* know the Li thickness, we consider both extremes. The resulting temperature rise over time for the two materials using the $\mathcal{R} = 0.65$ simulation is shown in Fig. 5(a). In addition to this case, we also consider one with an input power of 7.2 MW, corresponding to the maximum heating power available to NSTX. We assume that the divertor heat flux profile scales linearly with input power [8] so that we only need to multiply the heat flux profile from Sec. 3 by four.

The Li is anticipated to be maintained in a molten state with *in situ* heaters at a starting temperature ($t = 0$) between 200 and 250 °C. We take the upper limit for the Li surface temperature to be 430 °C [7,14], corresponding to a maximum $\Delta T \simeq 200$ °C. We use the curves from Fig. 5(a) and analogous ones computed with the UEDGE solutions at the other $\mathcal{R}$ values to determine the pulse length at which this temperature rise is met, Fig. 5(b). The Cu case with 1.8 MW input power is not plotted since allowable pulse lengths are all > 5 s. The < 2 s discharges presently utilized by NSTX would not be a problem for the 1.8 MW Li case either. At the 7.2 MW power level, however, operation would be restricted to shorter pulse lengths, especially if the thermal properties of the LLD are closer to those of Li than those of Cu. Note that these are conservative estimates since the strike point is not swept and convection in the lithium is ignored.

5 Discussion

These calculations represent the initial stage of a collaborative effort to predict the performance of the LLD and to begin delineating its operational space. The UEDGE simulations described in Secs. 2 and 3 will be used to place on a firmer footing the simple particle balance calculations that were utilized in the LLD planning to date. The UEDGE divertor plasma parameters from the recycling scan, together with the thermal response calculations of Sec. 4 will be fed into surface models to compute the reflection, sputtering, and evaporation of lithium. A self-consistent erosion and redeposition simulation can then be performed, yielding the net flow of lithium away from the surface. This flux can be input back into UEDGE to get the distribution of lithium in the core and SOL.

Acknowledgments

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Figure Captions

(1) The outer strike point of low triangularity (0.45) discharges (a) hits the LLD directly; with high triangularity (0.7), pumping will be farther out in the SOL.
(2) Comparison of experimental midplane n_e (a) and T_e (b) profiles with a constant coefficient ($D = 0.5$ and $\chi_e = 1$ m^2/s) UEDGE simulation and with our baseline simulation having radially varying transport coefficients.
(3) (a) Comparison of the outer divertor experimental heat flux with the baseline UEDGE simulation ($\mathcal{R} = 0.98$) and a variant with unit recycling. (b) Comparison of the same two simulations with divertor D_α emission from the similar shot 125065.
(4) (a) Variation of core and peak outer divertor n_e, and total outer divertor recycled gas current with recycling coefficient. (b) The peak outer divertor T_e and heat flux from the scan over $\mathcal{R}$.
(5) (a) LLD temperature rise computed with the $\mathcal{R} = 0.65$ heat flux profile. (b) Pulse length required to reach $\Delta T = 200$ °C for a range of $\mathcal{R}$ values.

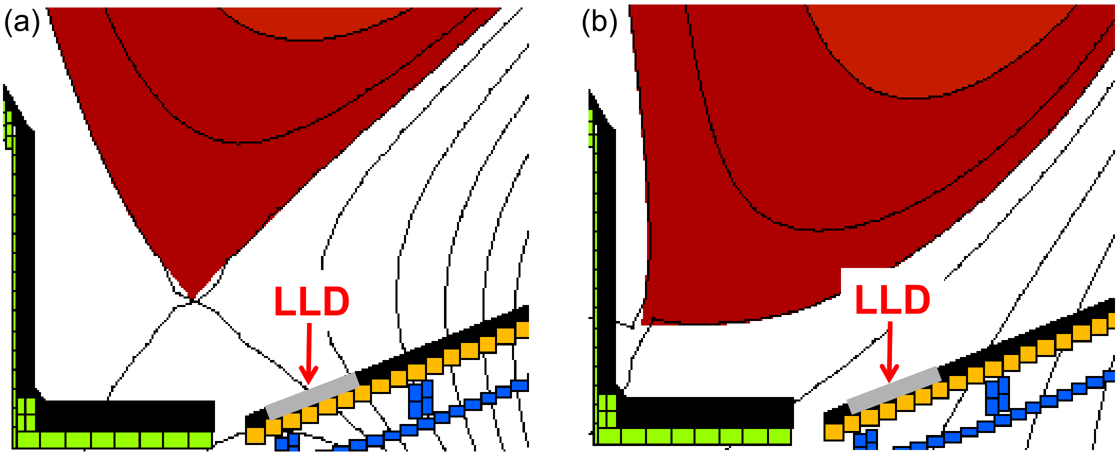
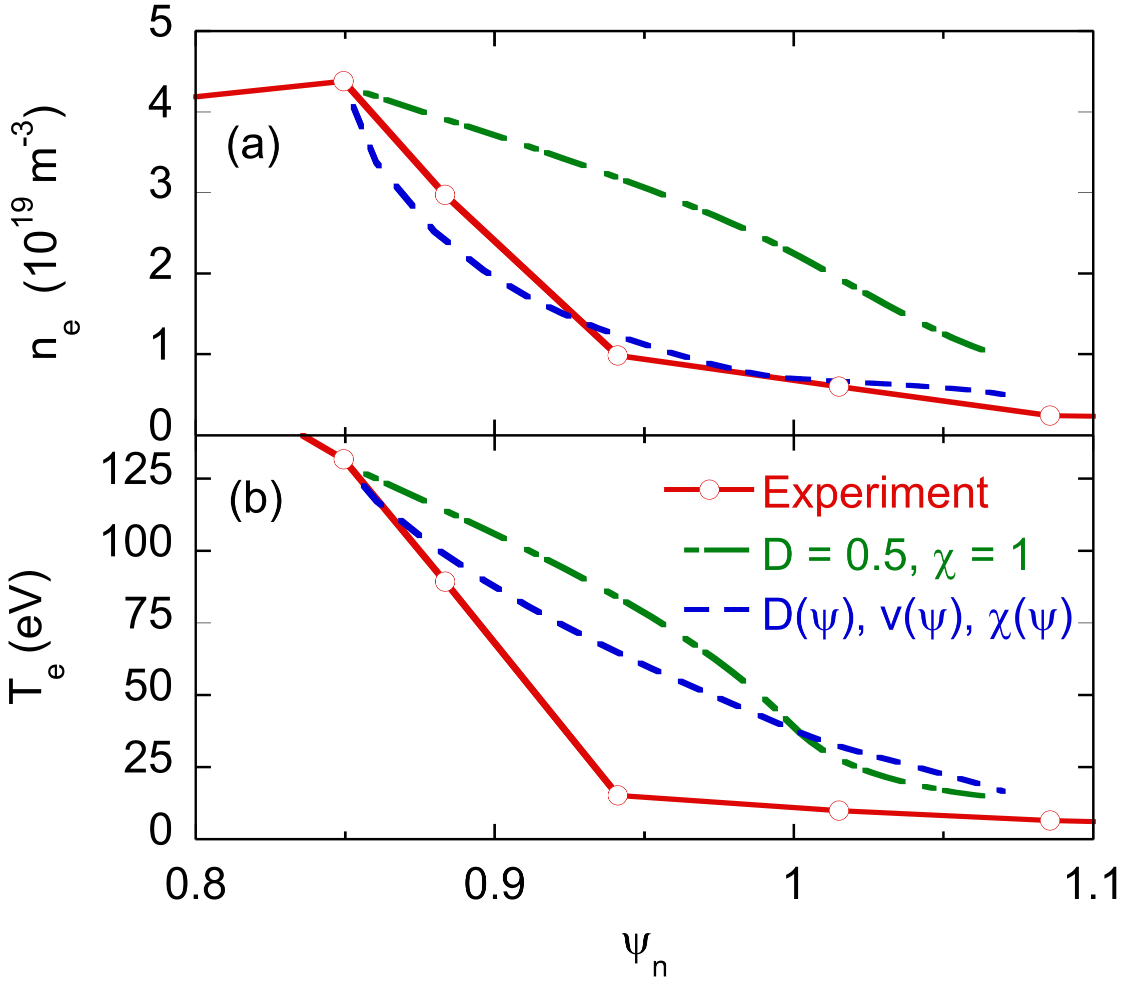
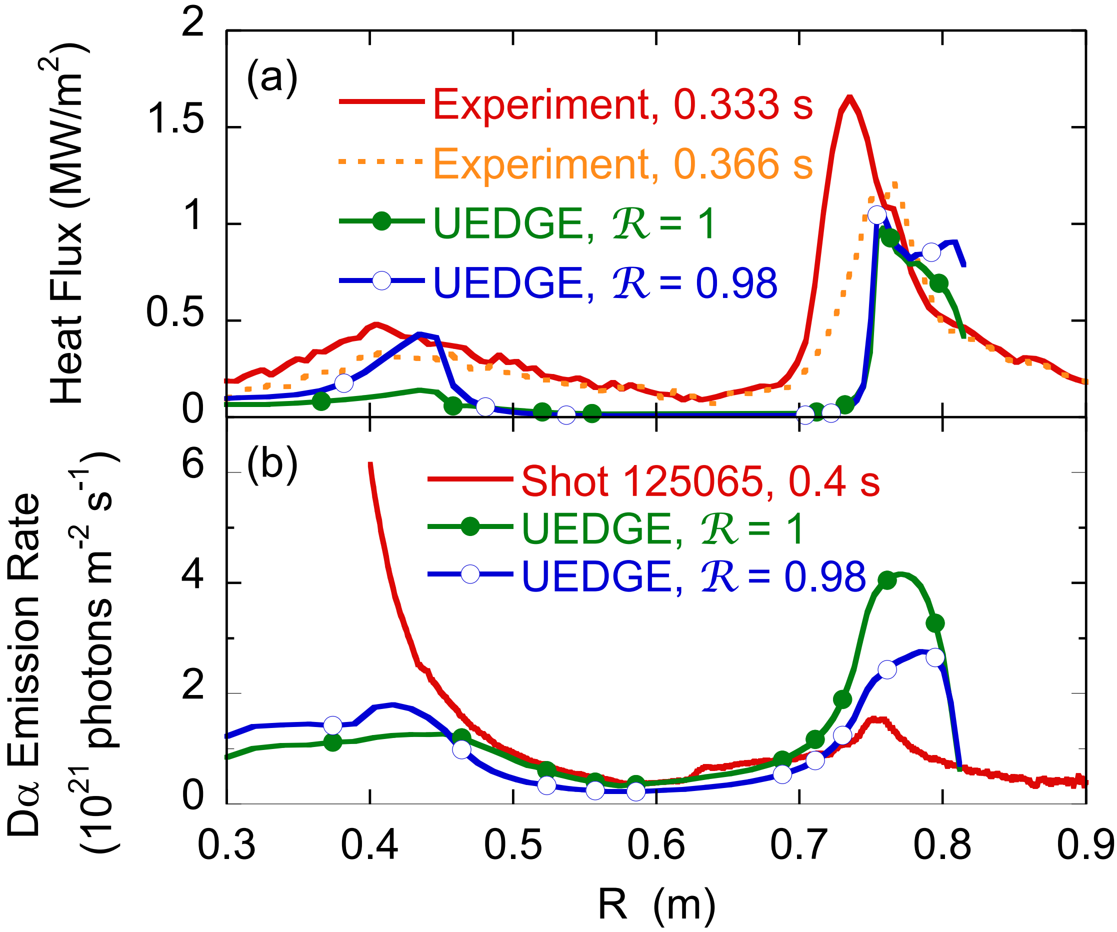


Figure 1.



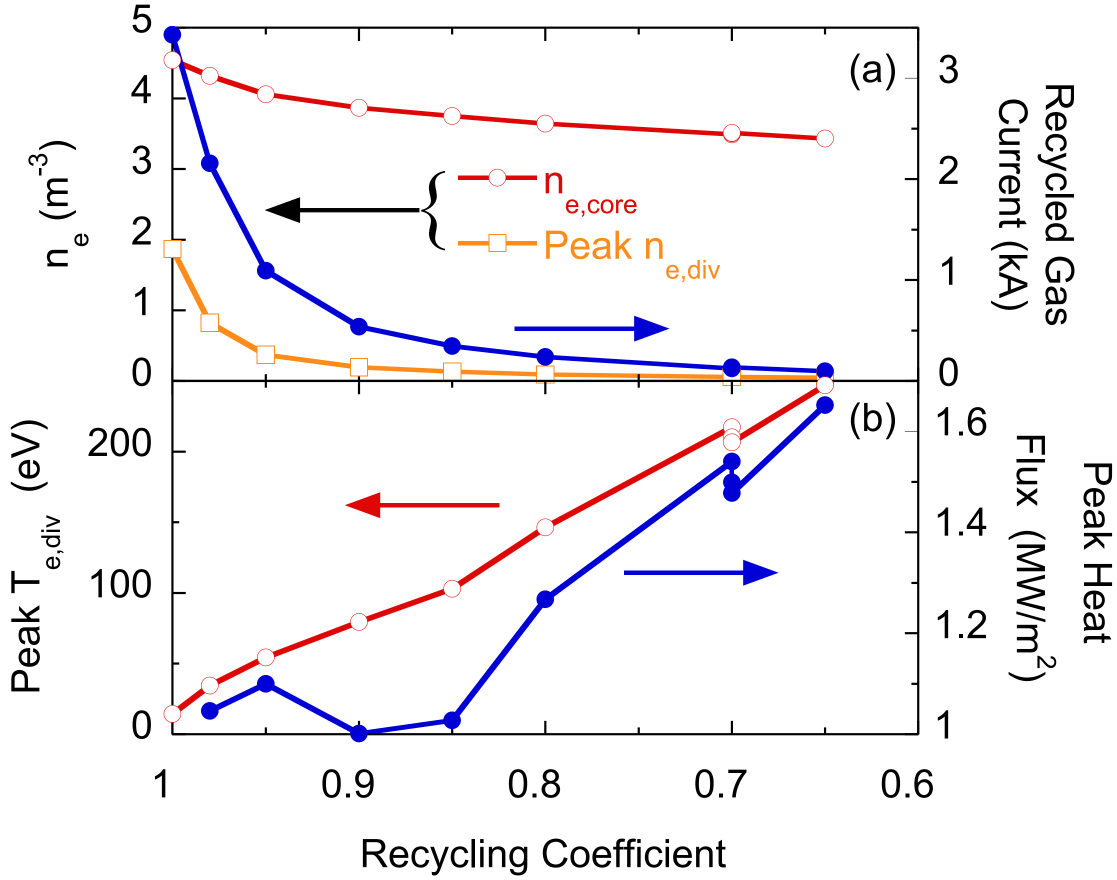
(a)
(b)
n_e (10^{19} m^{-3})
T_e (eV)
ψ_n
Experiment
D = 0.5, χ = 1
D(ψ), v(ψ), χ(ψ)
0
1
2
3
4
5
0
25
50
75
100
125
0.8
0.9
1
1.1

Figure 2.



(a)
Experiment, 0.333 s
Experiment, 0.366 s
UEDGE, $\mathcal{R}$ = 1
UEDGE, $\mathcal{R}$ = 0.98
Heat Flux (MW/m^2)
2
1.5
1
0.5
0
(b)
Shot 125065, 0.4 s
UEDGE, $\mathcal{R}$ = 1
UEDGE, $\mathcal{R}$ = 0.98
Dα Emission Rate
(10^{21} photons m^{-2} s^{-1})
6
4
2
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
R (m)

Figure 3.



(a)
(b)
n_e (m^-3)
Recycled Gas Current (kA)
n_e,core
Peak n_e,div
Peak T_e,div (eV)
Peak Heat Flux (MW/m^2)
Recycling Coefficient

Figure 4.

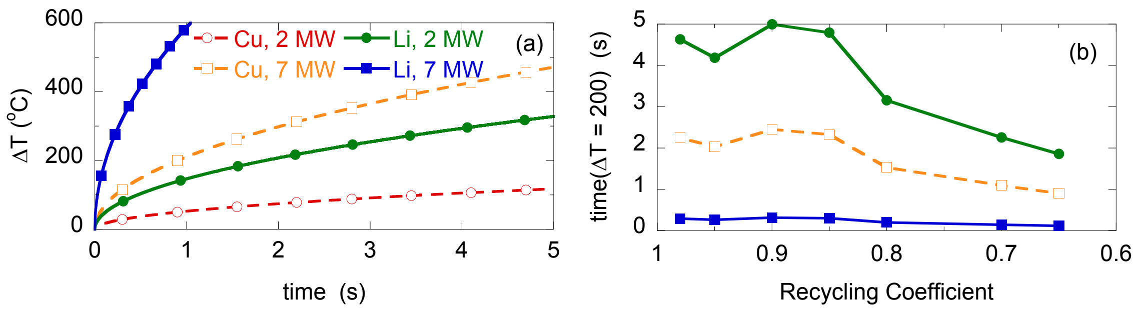

600
400
200
0
ΔT (°C)
Cu, 2 MW
Li, 2 MW
Cu, 7 MW
Li, 7 MW
(a)
0
1
2
3
4
5
time (s)
5
4
3
2
1
0
time(ΔT = 200) (s)
(b)
1
0.9
0.8
0.7
0.6
Recycling Coefficient

Figure 5.

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