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Simulations of NSTX with a Liquid Lithium Divertor Module

D. P. Stotler [a,*], R. Maingi [b], H. W. Kugel [a], A. Yu. Pigarov [c], T. D. Rognlien [d], V. A. Soukhanovskii [d]

[a] *Princeton Plasma Physics Laboratory, Princeton University, P. O. Box 451, Princeton, NJ 08543-0451, USA*

[b] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*

[c] *University of California at San Diego, San Diego, CA, USA*

[d] *Lawrence Livermore National Laboratory, Livermore, CA 94551, USA*

Abstract

The Liquid Lithium Divertor (LLD) module planned for installation in the NSTX lower divertor will provide a nearly toroidally continuous liquid lithium surface in contact with the plasma. The objective is to pump enough deuterium to allow full density control, thereby permitting quasi-steady, high performance H-modes with an increased non-inductively driven current fraction. This paper is the first step towards extending previous simulations of a pre-conceptual LLD design, using improved

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models and data. Transport coefficients in the 2-D edge plasma transport code UEDGE 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 a section of the divertor. The plasma heat flux to the lithium surface computed by UEDGE is input into a heat transport calculation to determine the temperature profile of the lithium with various substrates.

Key words: (PSI-17), NSTX, Edge plasma, (JNM) T0100 Theory and Modeling

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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 plasma facing or surface coating material to improve control of the core plasma density, reducing impurity influxes, increasing divertor heat flux handling capability, and improving core plasma performance. The lithium program has proceeded in stages, beginning with the injection of lithium pellets beginning in 2005. In 2006, an evaporative lithium system (LiThium EvaporatoR, or LiTER) was installed for the purpose of coating the graphite tiles that serve as the primary plasma facing material in NSTX [2]. During the 2008 campaign, two of these evaporators were used [3] The 2006 – 2007 experiments resulted in 50% reductions in L-mode density and 15%

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[*] Corresponding and presenting author
Email address: `dstotler@pppl.gov` (D. P. Stotler).

reductions in H-mode, along with improved energy confinement time and control of Edge Localized Modes (ELMs) [2,4]. Nonetheless, the core density still increases 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.

In this paper, we describe modeling aimed at predicting the scrape-off layer (SOL) plasma conditions under LLD operation and the resulting state of the lithium surface. In Sec. 2 we describe the LLD itself. Section 3 discusses the use of the 2-D edge plasma transport code UEDGE[5] to model an existing NSTX discharge. In Sec. 4, we present a scan of recycling coefficients performed with this UEDGE simulation as a baseline, 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. 5. Finally, the implications of these results are presented in Sec. 6.

2 Liquid Lithium Divertor

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 would serve as a target for the outer strike point or divertor. Multiple configurations for the LLD are being considered; a discussion of them is beyond the scope of this paper. For present purposes, we only need to know the radial location and width of the tray.

These need to be chosen so as to provide the desired degree of density reduction for both low and high triangularity discharges (Fig. 1). But, practical and programmatic considerations also enter. These considerations favor placing the tray on the outer divertor target plate, just outside the radius of 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.

3 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 included 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 (to mock up pumping by the LLD), we ignore more subtle 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 a low triangularity, single null single null discharge similar to that shown in Fig. 2(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 location for the LLD, so is the entire outer divertor leg of the computational mesh. Hence, we will simulate the pumping effect of the LLD as a uniform reduction in the recycling coefficient across the entire outer divertor target.

The computational mesh spans normalized flux values $\psi_{\rm n} = 0.85 - 1.07$. The electron density and temperature at the core boundary are obtained from the Thomson scattering data: 4.3×10^{19} m^{-3} and 130 eV, respectively. Since the ion temperature profile derived from charge-exchange recombination spectroscopy does not extend this far out in radius on this shot, 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 at the core boundary, separatrix and outer wall (D_c, D_s, and D_w, etc.). The values in between are computed via a linear interpolation on the radial mesh index, and all coefficients are constant along a flux surface. The ion thermal diffusivity is set equal to that for electrons, and the cross-field diffusivity of parallel momentum is set to 2/3 of χ_e. Our approach is thus intended to be more elaborate than in [7], but less so than that described in [6], in which a fully 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.

We adjust the D, χ_e, and v values to match the miplane Thomson scattering electron density and temperuature 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 incorporate external gas fueling into the core particle source and require that the magnitude of that source be consistent with the strength of the center stack gas puff (about 400 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} which should be consistent with robust UEDGE behavior.

0The simulated density profile obtained with the transport coefficients are $D_c = 0.04$ m^2/s, $D_s = D_w = 0.1$ m^2/s and $v_c \equiv 0$, $v_s = 25$ m/s, $v_w = 30$ 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 $\chi_{e,c} = 1.5$ m^2/s, $\chi_{e,s} = 25$ m^2/s, $\chi_{e,w} = 35$ m^2/s. The Thomson scattering profile shows a separatrix temperature of only 10 eV. This is much lower than the 30 – 40 eV range one obtains from power balance considerations and a simple 2-point model. 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 only 0.75 MW.

The total power flowing in from the core boundary 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 the25 core boundary is 440 A and a 142 A current of D atoms is flowing through this boundary in the other direction, 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 calibration data for shot 128339 will be available only after the end of the present NSTX run campaign, we utilize D_α data 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. While the outer divertor heat flux profile associated with unity recycling may be a better match to the data, 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.

4 Scan of Recycling Coefficients

The LLD is introduced into the simulations as a reduction in the ion recycling coefficient and neutral gas albedo along the entire outer divertor target plate. We equate the two parameters since lithium absorbs deuterium ions and atoms with roughly the same probability. We do not know a priori what suitable recycling coefficients for the LLD will be. That will depend on the purity of the lithium surface [11] and other factors beyond the scope of this calculation. Instead, we perform a scan over recycling coefficient / albedo and examine the response of the plasma characteristics.

We transform the core boundary condition from specified density and temperature to specified particle flux and power using the values obtained in the baseline calculation described in Sec. 3. These are held fixed during the scan as are all of the transport coefficients. The latter is a necessary approximation since we lack predictive capability for this situation. We anticipate that the core transport [12,13], will be altered as recycling is reduced, but we have no basis for predicting the impact on the SOL transport.

The absolute minimum value of recycling obtainable with a clean lithium target set by the particle reflection coefficient is expected to be in the $0.1 - 0.3$ range. But, the actual values obtained in the experiment will likely be higher due to variations in coating thickness and surface contamination [11]. For this reason, we argue that the practical lower limit of $\mathcal{R}_{od} = \mathcal{A}_{od} = 0.65$ set by the ability of UEDGE to obtain a converged solution provides us with an adequate range of recycling coefficients for this application. Since our baseline simulation has $\mathcal{R}_{od} = \mathcal{A}_{od} = 0.98$, we add to the scan an additional data point at $\mathcal{R}_{od} = \mathcal{A}_{od} = 1$.

In Fig. 4(a), we show the variation of the core and maximum divertor electron density with recycling coefficient. The former is of interest in planning the LLD experiments and will be compared with the 0-D particle balance calculations used in establishing the LLD radius and width. The latter, together with the divertor electron temperature in Fig. 4(b), will impact the transport of lithium evaporated or sputtered from the LLD surface.

The total neutral atom 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 factor of 60. In contrast, the liqiuid lithium tray experiments on CDX-U yielded D_α emission rates about a factor of three lower than obtained with a bare, stainless steel tray [12]. This difference underscores the practical difficulty in preparing and maintaining a lithium surface that approaches the theoretical minimum recycling level.

5 Thermal Response Calculation

The divertor heat flux profiles resulting from these simulations are input to a 1-D heat transport calculation to estimate the time evolution of the lithium at the surface of the LLD. These results will factor into the planned operation of the LLD since the temperature of the lithium must be kept below 450 °C to avoid excessive evaporation.

Rajesh is working on this. Will get a plot showing time evolution of lithium temperature for, say, $\mathcal{R} = 0.98$, 0.8 and 0.65 for various substrates. He will then scale the heat fluxes to higher input powers to determine maximum pulse lengths for each.

6 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 Sec. 3 and Sec. 4 will be used to place on a firmer footing the 0-D 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. 5 will be feed into surface models to compute the reflection, sputtering, and evaporation of lithium. A self-consistent erosion and redeposition simulation can then be performed, yieldiing the net flow of lithium away from the surface. This flux can be input back to UEDGE to get the distribution of lithium in the core and SOL.

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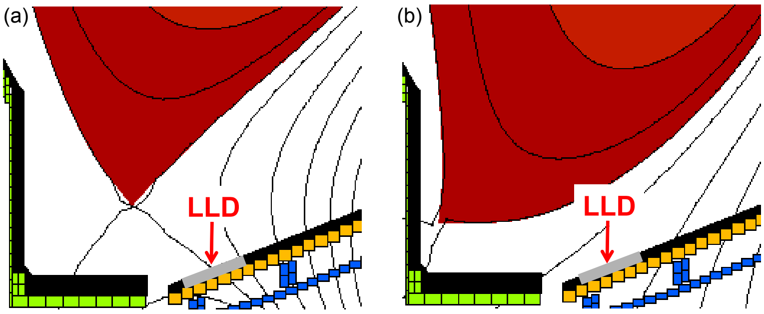

Figure 1. The LLD will be located on the outer divertor target. The outer strike point of low triangularity 90.45) discharges (a) will hit it directly. In high triangularity (0.7) configurations, the LLD will be pumping farther out in the SOL.

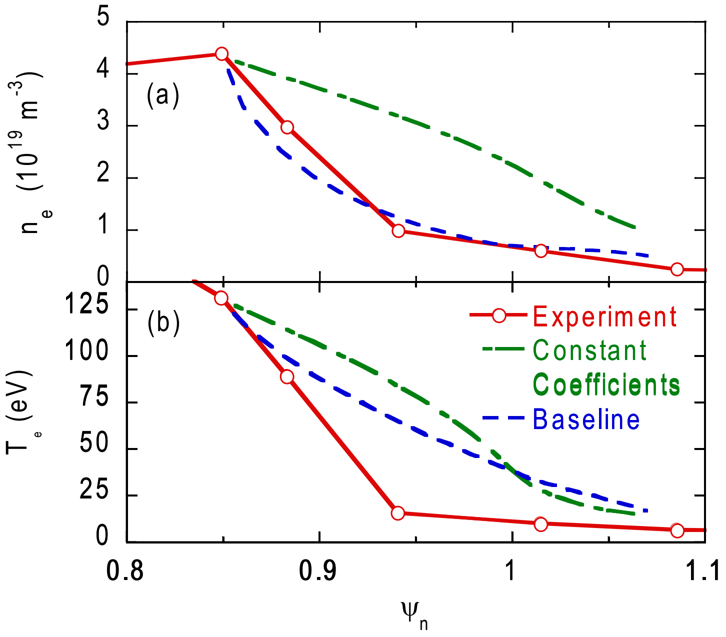

Figure 2. The experimental midplane electron density (a) and temperature (b) profiles obtained from Thomson scattering are compared with a UEDGE simulation having constant $D = 0.5$ and $\chi_e = 1$ m^2/s, and with our baseline simulation utilizing the radially varying transport coefficients described in the text.

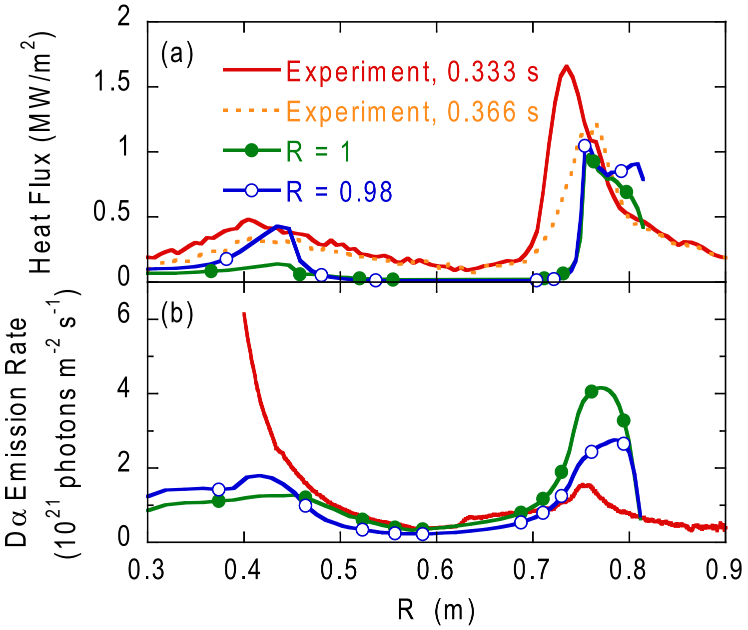

Figure 3. (a) The experimentally measured heat flux derived from an infrared camera is compared with our baseline UEDGE simulation having a recycling coefficient of 0.98 and a variant with unit recycling. (b) The same two simulations are compared with the D_α emission seen by a divertor camera. These data were taken from the similar shot 125065.

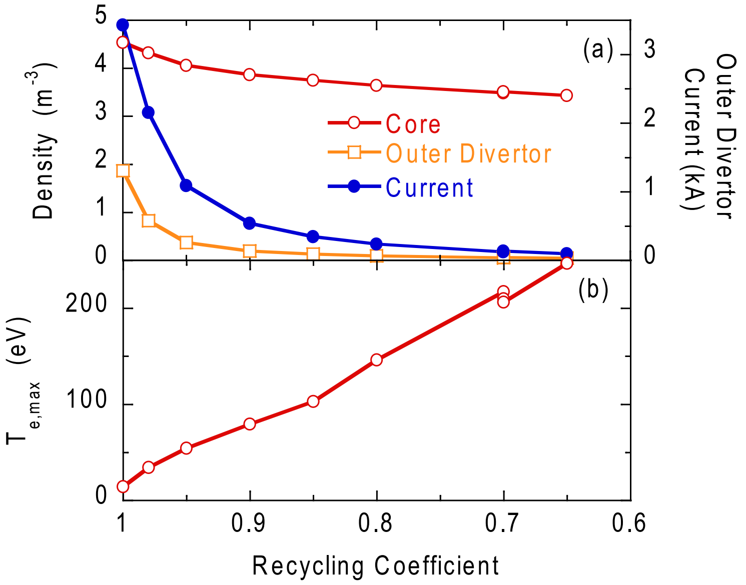

Figure 4. (a) Shows the variation of the core electron density, peak electron density on the outer divertor and total neutral current coming off of the outer divertor as a function of recycling coefficient. (b) The peak electron temperature on the outer divertor is shown separately.