Theory and simulation modeling of the scrape-off layer heat flux width:

Lodestar work in support of the FY2010 US DOE Joint Research Target

J.R. Myra,[a] D.A. Russell,[a] D.A. D'Ippolito[a]

in collaboration with

R. Maingi,[b] J-W. Ahn,[b] R.J. Maqueda,[c] D.P. Lundberg,[c] D.P. Stotler,[c]

S.J. Zweben,[c] J. Boedo,[d] M. Umansky,[e] and the NSTX Team;

B. LaBombard,[f] J.L. Terry,[f] S. J. Zweben,[c] and the C-Mod Team.

a) Lodestar Research Corporation, b) Oak Ridge National Laboratory, c) Princeton Plasma Physics Laboratory, d) Univ. of California at San Diego, e) Lawrence Livermore National Laboratory, f) MIT Plasma Science and Fusion Center

September 2010

DOE/ER/54392-61 LRC-10-138

LODESTAR RESEARCH CORPORATION

2400 Central Avenue

Boulder, Colorado 80301

Introduction and executive summary – In support of experimental investigations of the size and scaling of the heat flux width for the FY2010 US DOE Joint Research Target (JRT), Lodestar has carried out simulation modeling to better understand the role of cross-field turbulent heat transport in the scrape-off layer (SOL). These studies were carried out using the Scrape-Off-Layer Turbulence (SOLT) code.[1] The next sub-section describes the physics basis of the SOLT code and how it was used in the present studies. The remaining sub-sections give results from simulations of NSTX and C-Mod discharges and our conclusions.

For NSTX we simulated the scaling of the near-SOL heat flux width, λ_q, with power, P, and plasma current, I_p, for several H-mode shots. The simulated λ_q as well as midplane SOL profiles of density and temperature were compared with gas-puff imaging (GPI), probe and midplane-mapped divertor infrared thermography (IRTV) data. It was concluded that the midplane turbulence simulated in SOLT explains some, but not all, of the experimentally observed λ_q scaling. We identified a new convective cell mechanism that determines the SOL width in our simulations of NSTX H-mode discharges. In related theoretical work, we found a transition from a diffuse to a convective SOL heat transport regime at critical values of power and connection length.

For C-Mod, an EDA H-mode shot was simulated. The SOLT code produced a heat flux SOL width of about $\lambda_q \sim 1$ mm, not far from the experimental result. Most of the edge turbulence was in a single mode with a poloidal wavelength of order 6 cm, which might be related to the quasi-coherent mode.

The SOLT code – SOLT is a fluid code that models turbulence in a two-dimensional region perpendicular to the magnetic field B at the outboard midplane of the torus. SOLT implements classical parallel physics using closure relations[2] for the midplane parallel current and parallel fluxes for collisional regimes ranging from sheath-connected to conduction limited. The SOLT code can describe arbitrarily strong nonlinear plasma dynamics ($\delta n/n \sim 1$), including blob formation, and the physics model supports interchange-type curvature-driven modes, sheath instabilities, and drift waves. SOLT also includes the self-consistent evolution of zonal (i.e., poloidally-averaged) flows and has been used to demonstrate the control of turbulence by sheared flows and the radial transport of zonal momentum by turbulent Reynolds' stress. For comparison with experimental gas puff imaging (GPI) data,[3] SOLT includes a synthetic GPI diagnostic which has recently been upgraded to simulate both He and D gas puffs.

SOLT has flexible sources for plasma density, temperature, and flows (n_e, T_e, v_y). In the present work, artificial sources for n_e and T_e are configured to maintain the experimentally observed profiles in the steep pedestal region inside the separatrix. These artificial sources are set to zero in the SOL, so that the SOL profiles themselves are determined self-consistently by the balance between perpendicular turbulent transport and parallel losses. Using the SOLT model, we are able to assess the role of electrostatic turbulence at the midplane in determining the cross-field transport fluxes and midplane profiles. Midplane turbulence gives rise to fluctuating $\mathbf{E} \times \mathbf{B}$ convection near the separatrix which can result in both diffusive and convective transport processes.

Previously, SOLT has been used to model blob generation and turbulence in L-mode plasmas on NSTX.[4] Detailed comparisons of simulation and experimental results for the distribution of blob sizes and speeds were made possible by using the simulated and experimental GPI diagnostic. For the FY2010 Joint Research Target (JRT) work, it was necessary to simulate H-mode discharges. The primary difference between H-mode and L-mode simulations in SOLT was the use of an imposed mean sheared flow inside the separatrix in the H-mode case. The radial profile of the poloidal flow was taken to be proportional to the ion diamagnetic drift, with a constant of proportionality τ. This imposes an E_r well inside the separatrix which regulates the turbulence. The value of τ was chosen such that the SOLT power flow across the separatrix, P_{sep}, matched the experimental value. In this way, we were able to achieve a heat-flux-driven boundary condition at the separatrix for our SOL simulation, which gives a first principles calculation of the turbulent transport in the SOL, i.e. without any ad-hoc sources or sinks of particles, momentum or energy.

Simulation power scans were performed, where the imposed flows were varied and the resulting simulated P_{sep} was determined from

$$P_{sep} = 2\pi R b_\theta \int dr\, q_{||}$$

where $b_\theta = B_p/B$ and the integral is taken across the entire SOL. The simulation for which P_{sep} most closely matched the experimental value was employed for comparison.

Results for NSTX simulations – Table 1 shows comparisons of the SOLT simulated heat flux width λ_q with NSTX midplane-mapped divertor infra-red thermography (IRTV) footprint data for a power (P) scan and a plasma current (I_p) scan. More details of how these comparisons were done are available elsewhere.[5,6] Shots 135009 and 135038 are low power ELM-free H-modes in lithium-walled shots.[7] Shots 128013 and 128797 are higher power shots in the pre-lithium phase of NSTX.[8]

shot	**I_p(MA)**	**P(MW)**	**$\lambda_{q,NSTX}$(cm)**	**$\lambda_{q,SOLT}$(cm)**
135009	0.8	0.8	0.36	0.30
135038	0.8	1.3	0.50	0.41
128013	0.8	5.8	1.73	0.76
128797	1.2	6.1	0.56	0.58

Table 1. Scaling of the SOL heat flux width for the power and current scans in NSTX. The last column is the midplane heat flux width from the SOLT simulations, and is to be compared with the experimental value in column 3. All widths are field-line-mapped to the outboard midplane.

From Table 1, we conclude that midplane turbulence simulated in SOLT explains some, but not all, of the experimentally observed λ_q scaling. Absolute agreement is within modeling uncertainties (factor of 2). Both simulation and experiment (shots 135009 and 135038) show a weak positive scaling of λ_q with power, but the scaling with I_p (shots 128013 and 128797) appears to be different, with the most significant discrepancy at the lowest I_p.

In SOLT, the parallel heat flux width is determined by the midplane turbulence. To check the role of this mechanism against experiment, we compared SOLT profiles of density, temperature and fluctuations directly against midplane NSTX data. This provides a more direct check on the role of midplane turbulence than comparison of the midplane-mapped heat flux width which is measured at the divertor plate, and is therefore potentially subject to broadening by other mechanisms.

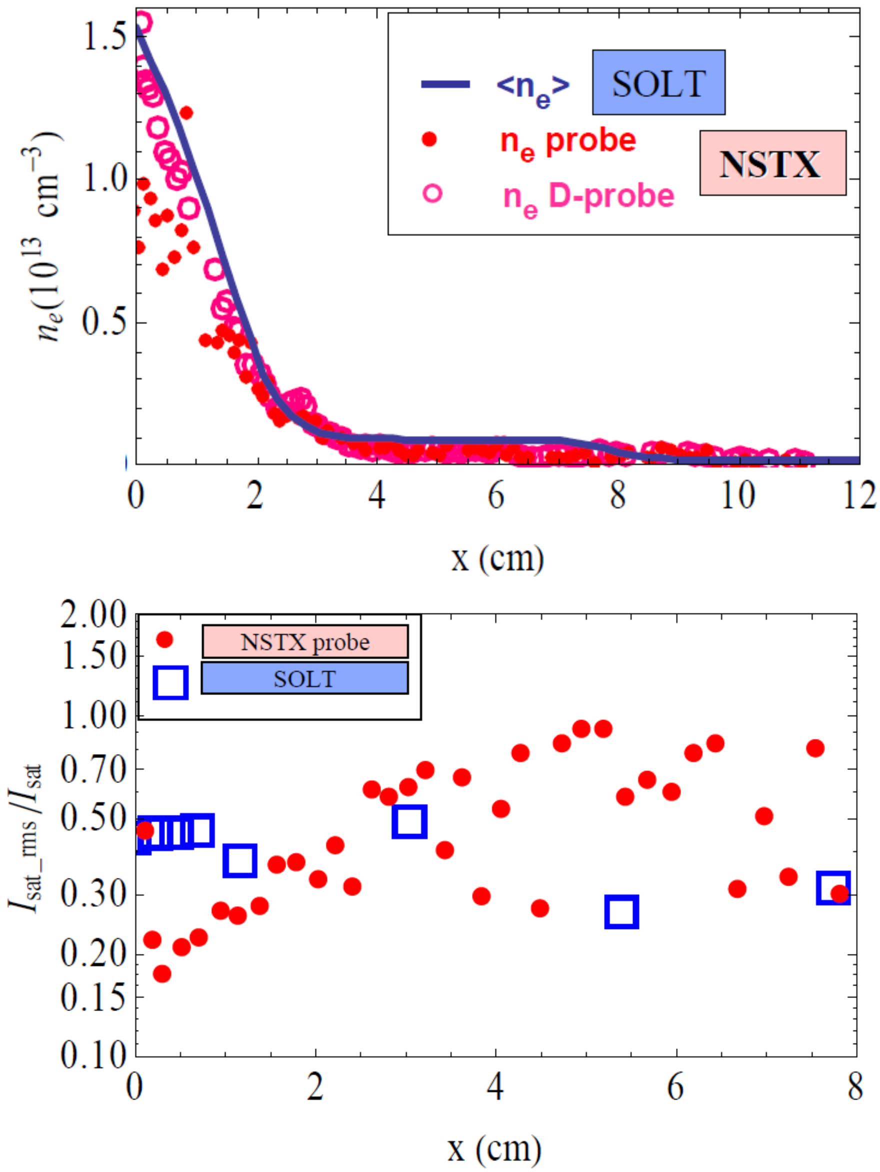

Fig. 1. (upper) Comparison of SOLT density profile with NSTX probe data; (lower) comparison of SOLT and NSTX probe I_{sat} fluctuation levels. [Fig. from Ref. 5]

For the low power shots, midplane reciprocating probe data was available for this comparison. Fig. 1 illustrates the comparison of SOLT and NSTX probe data for the average density profile and saturation current fluctuations, for shot 135009. The level of agreement is well within modeling uncertainties. Similar results were obtained for 135038. This validates the midplane turbulence calculations by SOLT, and together with the agreement in Table 1 for these shots (135009 and 135038) suggests that midplane turbulence is indeed responsible for the observed heat flux width seen at the divertor.

A somewhat different conclusion was reached for the I_p scan shots (128013 and 128797). Since probe data was not available for these high power shots, we compared SOLT fluctuation levels from synthetic GPI, with midplane NSTX GPI data. This comparison (not shown here, see Ref. 5) showed good agreement. Furthermore, the NSTX data, like the simulations, showed little difference in fluctuation levels with I_p. Consequently, it seems that the strong I_p scaling of the heat flux width seen in the NSTX data (Table 1) cannot be explained by midplane turbulence alone. Possible additional mechanisms include divertor leg instabilities,[9] ELM and MHD effects which could cause strike point motion,[10] and X-point loss of ions due to drift-orbit effects[11] which might be expected to be a particularly strong effect at low I_p. Caveats in our analysis include possible differences in downstream sheath conditions for the two shots and MHD activity not included in these electrostatic simulations.

An interesting spin-off from the modeling work was the identification of a new convective cell mechanism that appears to determine the SOL width in our simulations of NSTX H-mode discharges. This mechanism is the presence of intermittent separatrix-spanning convective cells. Figure 2 shows a snapshot of the turbulent density field in color shades, on top of which is superimposed some contours of electrostatic potential, giving the stream lines for the $\mathbf{E}\times\mathbf{B}$ flow. The potential shows an up-down flow pattern that is sheared from left to right. The flow pattern has embedded within it closed vortex structures (island convective cells) that can transport plasma radially. In the figure, finger-like structures (e.g. indicated by the arrow) have been ejected from the main plasma, but in the presence of the strong H-mode sheared flow, these structures cannot penetrate far radially into the SOL. Rather they are sheared downwards by the flow.

Intermittently, the extra plasma gets carried across the LCS by the convective cells. The resulting cross-field motion competes with parallel flow to establish the SOL width.

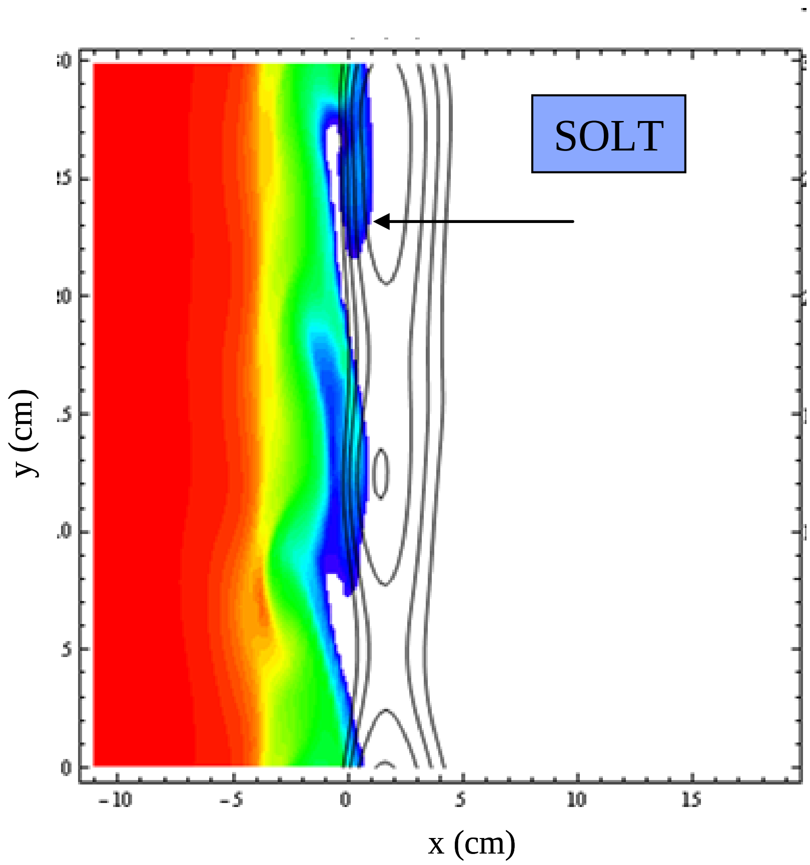

Fig. 2. Turbulent fields of density (log palette, truncated to white for $n/n_{ped} < 0.3$), and potential (contours). The arrow points to a downward-sheared finger structure

Other, ongoing theoretical scaling studies, were stimulated by the JRT work. One important example is that for certain parameters, the SOLT results were found to transition from a diffusive dominated near-SOL structure to one that is convection dominated, and much broader.[6] In the latter case, some of the intermittent separatrix-spanning convective cells start to form structures which break free as blobs. Qualitatively similar trapping and release of blobs is evident in the NSTX GPI data.

Results for C-Mod simulations – The SOLT code was employed[12] to simulate an EDA H-mode shot[13] that was part of the JRT campaign, using a similar procedure to that employed for NTSX. Results of a SOLT code power (τ) scan for Alcator C-Mod are shown in Fig. 3. For this time slice, the experimental power is 1.79 MW and the observed midplane-mapped heat flux e-folding width is $\lambda_{q,exp}$ = 1.3 mm. Comparing with the e-folding widths in Fig. 3, we find that absolute agreement is well within factor-of-two modeling uncertainties. The measured integral heat flux width (Loarte width)[14] mapped to the outboard midplane for this same case is $\lambda_{q,int}$ = 3.7 mm due to the presence of a tail in the heat flux extending into the far SOL, while the SOLT $\lambda_{q,int}$ = 1.13 because the tail is not present. This point will require further study. Nevertheless, it is satisfying that the same SOLT code physics model provides rough agreement in the near-SOL λ_q for both NSTX and C-Mod cases, where outboard-midplane B is different by more than an order of magnitude. The scaling of λ_q with power in C-Mod using another time slice is presently under study.

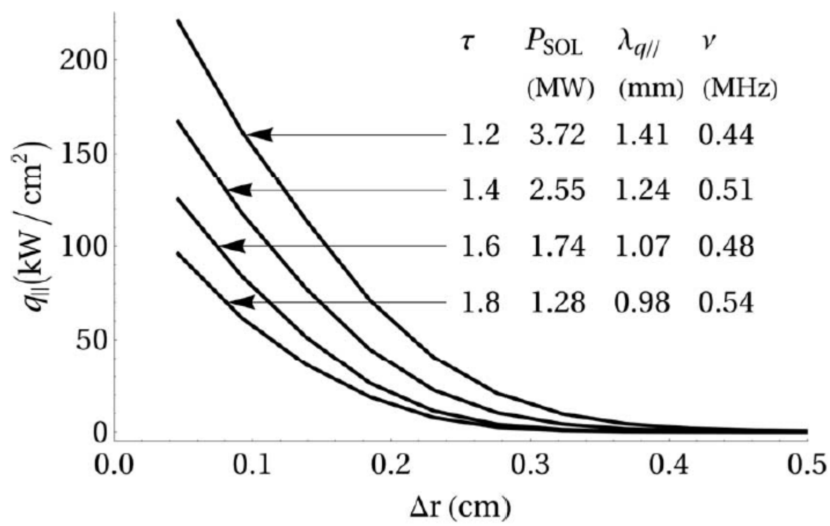

Fig. 3. Heat flux width variation in a SOLT power (τ) scan for a C-Mod EDA H-mode. The dominant mode frequency ν is also tabulated.

An intriguing result from the SOLT simulations of the C-Mod EDA is the appearance of a mode that has at least some qualitative similarities to the quasi-coherent (QC) mode that is observed experimentally in the EDA regime.[15,16] The frequency spectrum of density fluctuations from SOLT is shown in Fig. 4. A "quasi-coherent" feature at 480 kHz is evident for this case. (See the legend in Fig. 3 for the variation of the frequency during a SOLT power scan.) This feature results from density fluctuations at a wavelength of about 6 cm which originate in the strong gradient region just inside the separatrix, and are convected and Doppler shifted by the **E**×**B** flows. The QC mode frequency in the lab frame is affected by the radial electric field and toroidal rotation. Although SOLT does not provide a first principles model of these effects, it is encouraging that simulated frequencies are in the range of several hundred kHz, which is characteristic of QC mode frequencies seen experimentally. In SOLT, the "QC" mode is responsible for cross-field transport fluxes, and is a key player in setting the SOL width. Finally, the inset in Fig. 4 shows the same spectrum on a log-log scale. The broad features (low-frequency plateau and algebraic high-frequency decaying tail) are typical of both simulation and experimental data for intermittent edge turbulence.

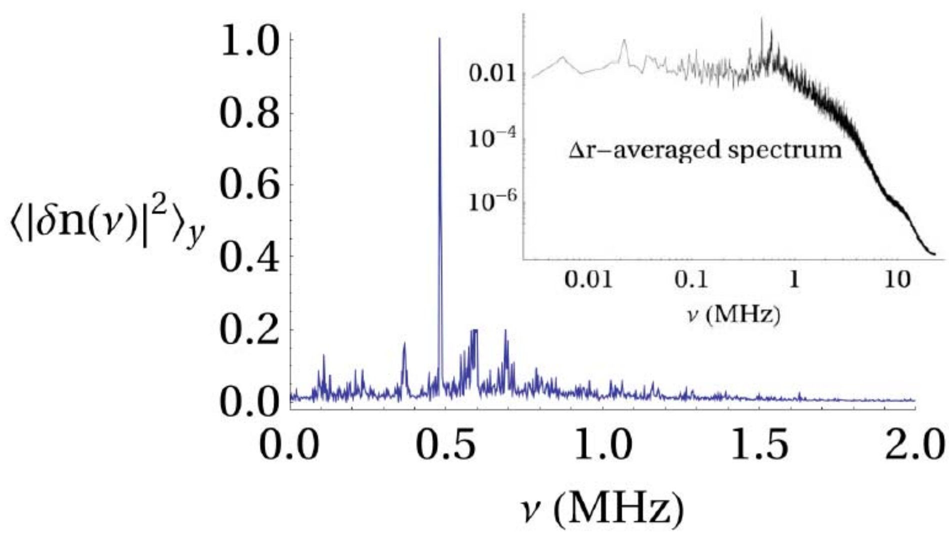

Fig. 4. Density fluctuation spectrum for the SOLT EDA simulation at τ = 1.6

Conclusion – Modeling of JRT-relevant discharges in NSTX and C-Mod using the SOLT turbulence code have made some important qualitative and quantitative connections of theory with heat flux experimental data. Simulated and experimentally measured heat flux widths were found to agree for all cases investigated within factor-of-two modeling uncertainties. Modeled and NSTX experimental scaling trends were similar, however scaling with plasma current was stronger in the experiment than in the simulations, suggesting the importance of additional broadening mechanisms beyond midplane region turbulence. Physics mechanisms which set the SOL width were elucidated, such as the role of intermittent separatrix-spanning convective cells, and quasi-coherent modes. The experimental JRT data both validates some aspects of the modeling and raises additional challenges for theory.

Acknowledgments – This work was supported by the US DOE under grants DE-FG02-02ER54678 and DE-FG02-97ER54392, and by PPPL under subcontract S009625-F; however, such support does not constitute an endorsement of the views expressed herein.

References

1 D. A. Russell, J. R. Myra and D. A. D'Ippolito, Phys. Plasmas **16**, 122304 (2009); and refs. therein.
2 S. I. Krasheninnikov, D. A. D'Ippolito, and J. R. Myra, J. Plasma Physics **74**, 679 (2008).
3 S.J. Zweben, R.J. Maqueda, D.P. Stotler et al, Nucl. Fus. **44**, 134 (2004).
4 D. A. Russell, J. R. Myra, D. A. D'Ippolito, T. L. Munsat, Y. Sechrest, R. J. Maqueda, D. P. Stotler, S. J. Zweben and the NSTX Team, Lodestar Report # LRC-10-135, www.lodestar.com/LRCreports/, submitted to Phys. Plasmas.
5 J.R. Myra, D.A. Russell, D.A. D'Ippolito, J-W. Ahn, R. Maingi, R.J. Maqueda, D.P. Lundberg, D.P. Stotler, S.J. Zweben, J. Boedo , M. Umansky and the NSTX team, Lodestar Report # LRC-10-136, www.lodestar.com/LRCreports/, submitted to Phys. Plasmas.
6 J.R. Myra, D.A. Russell, D.A. D'Ippolito, J.-W. Ahn, R. Maingi, R.J. Maqueda, D.P. Lundberg, D.P. Stotler, S.J. Zweben, J. Boedo , M. Umansky and the NSTX team, Lodestar Report #LRC-09-132, www.lodestar.com/LRCreports, to be published in J. Nucl. Mater.
7 J. W. Ahn (private communication, 2010); and manuscript in preparation.
8 T. K. Gray, R. Maingi, J. E. Surany, V. A. Soukhanovskii, J-W. Ahn and A. G. McLean, presented at the 2010 PSI meeting; and to be published in J. Nucl. Mater.; R. Maingi, C.E. Bush, R. Kaita, H.W. Kugel, A.L. Roquemore, S.F. Paul, V.A. Soukhanovskii, and NSTX Team , J. Nucl. Mater **363-365**, 196 (2007).

9 D.D. Ryutov and R.H. Cohen, Contrib. Plasma Phys. **48**, 48 (2008).
10 E. R. Solano et al., J. Nucl. Mater. **337–339** 747 (2005).
11 S. Ku, H. Baek, and C. S. Chang, Phys. Plasmas **11**, 5626 (2004).
12 D.A. Russell et al., in progress (2010).
13 B. LaBombard, J.L. Terry, J.W.Hughes, et al., to be published in J. Nucl. Mater.; B. LaBombard, et al., *Boundary Layer Heat Transport Experiments in Alcator C-Mod in Support of the FY2010 US DoE Joint Research Target*, PSFC/RR-10-14
14 A. Loarte, et al., J. Nucl. Mater. **266-269**, 587 (1999).
15 M. Greenwald et al., Phys. Plasmas **6**, 1943 (1999).
16 J.L. Terry et al., Nucl. Fusion **45**, 1321 (2005).