Final Technical report

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“Modeling of far SOL plasma
transport in NSTX”

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I. Summary

The main goal of our research and collaboration with experimental team of National Spherical Tokamak Experiment (NSTX) at Princeton Plasma Physics Laboratory, Princeton, NJ, under the Department of Energy research grant No. DE-FG02-02ER54680 at UCSD during 2002-2005 financial years was a more comprehensive understanding and characterization of non-diffusive transport occurring in the tokamak edge plasma.

The results of our research were reported at the NSTX Boundary Physics Meeting, February 2005 [1]; Transport Task Force Conference, Napa CA, April 2005 [2]; 32nd European Conference on Controlled Fusion and Plasma Physics, Tarragona, Spain, July 2005 [3]; Plasma Edge Theory Conference, Juelich, Germany, October 2005 [4]; 45th Annual Meeting of DPP APS, Albuquerque, New Mexico, October 2003 [22]; 30th European Conference on Controlled Fusion and Plasma Physics, St. Petersburg, Russia, July 2003 [11]; 47th Annual Meeting of DPP APS, Denver, Colorado, October 2005 [5]. We also participated on the NSTX Results Review [6,20] and Research Forums [7,8,21] to share our ideas and to plan experiments on boundary plasma.

The results were published in the refereed journals (Refs. [4] and [12]) and in the proceedings of international conference (Refs. [3] , [11], [23], and [24]).

II. Major accomplishments

For better understanding and characterization of non-diffusive transport occurring in the NSTX tokamak edge plasma, we performed extensive simulations of NSTX edge plasmas with the multi-fluid two-dimensional UEDGE code [19] by using realistic model for impurity sputtering sources and hybrid (diffusive and convective [9]-[12]) model for anomalous cross-field transport. Our cross-field transport model incorporates the effects of non-diffusive intermittent transport by introducing anomalous convective velocities whose spatial profile is adjusted for each ion charge state to match available experimental data.

The research in 2002-2005 financial years was focused on the following areas: (i) development of capabilities for UEDGE simulation of NSTX spectroscopy data (i.e., the 3D real-geometry postprocessor UEDGE tools for comparison between UEDGE and experimental data), (ii) simulation of multi-diagnostic data from NSTX with UEDGE, (iii)

study of anomalous cross-field convective transport of impurity ions, (iv) analysis of divertor plasma opacity to resonance radiation, and (v) study the effects of ballooning-like anomalous cross-field transport and spherical-torus magnetic configuration on parallel plasma flows in the SOL. The progress in these areas is discussed in the Subsections.

A. UEDGE simulation of multi-diagnostic data from NSTX

In UEDGE modeling [12], we reproduce important features of plasma discharge conditions in NSTX. We use realistic non-orthogonal EFIT-based modeling domain that matches the

FIG. 1: The results of matching the radial profiles of plasma temperature using UEDGE code with constant $\chi_{\perp}$ (green solid ladder like line) and with profile $\chi_{\perp}(\psi_n)$ (red bold solid ladder line). In both cases $D_{\perp}$, V_{conv} are functions of ψ_n . Experimental Thomson Scattering data are shown by points.

temperature measured with Thompson Scattering system both at the outer and inner mid-planes; (ii) ion temperature and C+6 ion concentration at the mid-plane measured by CHERS; (iii) reciprocating probe data at outer mid-plane; (iv) gas pressure at the outer mid-plane location; (v) D-alpha emission measured in the outer divertor by CCD camera; and (vi) heat power load profile at the divertor plates.

geometry of the divertor plates. Since neutrals in NSTX penetrate far into the core plasma in the normalized poloidal magnetic flux space (ψ_n -space) than in DIII-D, the domain is extended into the core up to the closed magnetic flux surface $\psi_n^{\text{cp}}=0.65$. We include the intense gas puffing (30-50 l Torr/s) in particular locations. Our UEDGE solutions are consistent with the particle flux imbalance at the innermost boundary (ψ_n^{cp}) leading to the given increase rate in the central plasma density.

With UEDGE, we match the following experimental data: (i) profiles of plasma density and

Our calculations showed that anomalous transport coefficients (i.e. particle and heat diffusivities, $D_{\perp}$ and $\chi_{\perp}$, and convective velocity, $V_{\perp\text{conv}}$) must not be constants but they should vary radially (as well as poloidally, in a ballooning like manner) in the ψ_n -space.

Diffusive transport is dominant in the core plasma, whereas the convective transport is dominant in the far SOL. As an example, the results of matching the mid-plane plasma temperature profiles with UEDGE for a typical L-mode discharge are shown of Fig. 1. Major experimental L-mode data are matched well when $\chi_{\perp}$ is strongly decreasing function of ψ_n (from $\chi_{\perp}=15\text{-}20\text{ m}^2/\text{s}$ at $\psi_n=0.65$ down to $\chi_{\perp}=5\text{-}6\text{ m}^2/\text{s}$ at $\psi_n>1$) and when convective velocity $V_{\perp\text{conv}}$ is strongly increasing function of ψ_n (from $V_{\perp\text{conv}}<1\text{ m/s}$ at $\psi_n=0.65$ up to $V_{\perp\text{conv}}=40\text{ m/s}$ at $\psi_n=1$ and further to $V_{\perp\text{conv}}=150\text{-}200\text{ m/s}$ at the wall). It is important to note that variation of $D_{\perp}$, $\chi_{\perp}$, $V_{\perp\text{conv}}$ in the ψ_n -space results in strong asymmetry of transport coefficients in the real space that allows us to match the measured in/out profile asymmetries.

The UEDGE simulations for L-mode NSTX shots indicate that anomalous convective transport (that stands for non-diffusive intermittent transport) dominates in the far scrape-off layer. It substantially increases the plasma flux the outer chamber wall and the particle recycling in the main chamber. The central plasma region ($\psi_n<\psi_n^{\text{cp}}$) is fueled predominantly by neutrals originating from chamber walls. We also find that chamber wall sputtering is an important source of impurities. These results are similar to the results of our UEDGE analysis performed for DIII-D and C-Mod.

B. Study of anomalous cross-field convective transport of impurity ions

We also analyzed recent experimental profile data from NSTX on C^{+6} impurity ion concentration, heat power load on divertor plates, and plasma density and electron temperature at the mid-plane as well as on the ion temperature measured by CHERS. In order to match available experimental data of L-mode shots with the multi-species UEDGE code, we use the sophisticated impurity cross-field transport model, in which different impurity charge states have different magnitudes and signs in their convective velocities.

FIG.2 : The inner divertor temperature T_{ed} , the ratio q_{in}/q_{out} of peak heat fluxes to the inner (q_{in}) and outer (q_{out}) divertor plates, and Z_{eff} due to C^{+6} ions are shown as a function of impurity model parameter $\eta_{ccc} = [V_{conv}(C^{+1}) + V_{conv}(C^{+2}) + V_{conv}(C^{+3})] / [V_{conv}(D^{+})]$ (see Ref. [12], for the details). Experimental NSTX data are scattered between two broken horizontal lines.

There results of matching are shown on Fig.2 (see Ref. [12], [14], for the details). We found that observed level of C^{+6} impurity concentration in the core plasma is consistent with the hypothesis [13] that due to specific properties of intermittent non-diffusive cross-field plasma transport the lowest carbon ion charge states are rapidly convected in the radial direction from walls toward the core plasma, whereas the highest charge states are convected radially in the opposite direction. Similar conclusions about the importance of inward intermittent cross-field

convection in the low charge state impurity transport for the core plasma contamination by impurities were made by us for the DIII-D and Alcator C-Mod edge plasmas based on matching of extensive experimental data with UEDGE code [11], [12].

C. Study of divertor plasma opacity to resonance radiation.

Our recent calculations with UEDGE of NSTX divertor plasma have showed that for some reasons e.g. due to magnetic topology specific to spherical tori, the neutral atom density is

FIG.3 : The calculated radial profiles of plasma and neutral atom densities near the diveror plates. The inner divertor region corresponds to the radii between 30 and 50 cm.

at very high level ($>10^{20} \text{ m}^{-3}$) in the inner divertor, as shown on Fig. 3. The mean free path for resonance Ly- α line absorption is about 1 millimeter, whereas the characteristic sizes of high neutral density region are 20 cm in radial direction and 5 cm in vertical direction. Under these conditions, the Ly- α line radiation is highly trapped. We estimate the radiation escape factor [17]-[18] to be very small $\text{REF}=10^{-4}$ in this region. The obtained results motivate us to incorporate new physics into the UEDGE code. We notice that transport of resonance radiation may be important for interpretation of experimental data [7].

D. Study the effects of ballooning-like anomalous cross-field transport and spherical-torus magnetic configuration on parallel plasma flows in the SOL.

Recent experiments on several tokamaks showed two important features of plasma transport in the scrape-off layer (SOL) during standard single-null tokamak operation, namely: (i) strong anomalous cross-field plasma convection (due to intermittency), and (ii) existence of large-Mach-number parallel plasma flows in the SOL. It is expected that anomalous convective cross-field transport is ballooning like with strong asymmetry in transport values at the high field side (HFS) and at the low field side (LFS) of the torus (i.e., the highest transport is at the LFS). Such transport pushes plasma, momentum, and energy into the far SOL at the LFS causing the plasma pressure build-up in this region vs.

divertor pressure and, as a result, the plasma flows along the magnetic field line (mfl) on the divertor plates.

To confirm the existence and investigate the driving mechanisms of large parallel plasma flows in NSTX tokamak, we perform multi-ion multi-fluid 2D simulations of edge plasma and neutral gas transport with the UEDGE code. We employ the multi-ion diffusive-and-convective model for anomalous cross-field plasma transport which introduces the asymmetric (e.g. ballooning-like) 2D profiles for transport coefficients. The UEDGE calculations were performed for typical L-mode shot 109033 (at 350ms into the discharge, low single null (SN), 3MW NBI, 400 A gas puff at the HFS location) in the NSTX tokamak. The best fit to available experimental data for this shot (see [3-5]) provide

Fig. 4: Radial profiles of parallel plasma velocity, Mach number, and plasma density at the inner mid-plane. The profiles are calculated by UEDGE code for NSTX shot 109033

Fig. 5: Radial profiles of parallel plasma flux density, total toroidal field, and plasma temperature at the inner mid-plane.

the UEDGE solutions in which anomalous cross-field convection dominates in the outer far SOL and a strong HFS/LFS asymmetries are prescribed to all transport coefficients. In these solutions, such transport causes large cross-field plasma fluxes at the LFS in the far SOL that result in HFS/LFS asymmetry of plasma parameters. Since plasma in

divertor regions connected to the far SOL is weak, it does not build up a high pressure due to recycling processes (as plasma near separatrix does) and does not cause stagnation of plasma flow. Therefore, plasma ejected into the far SOL on the LFS flows almost freely into the divertors with Mach about unity. Some results of these calculations are given in Fig.4 and Fig.5.

We demonstrated that magnetic configuration has strong impact on parallel plasma flows in the SOL. In spherical torus SN configuration, the poloidal (along the mfl) profile of parallel velocity $V_{||}$ (and of Mach number) has distinct maximum in value $|V_{||}|$. This maximum is attained exactly at the HFS mid-plane. Moreover the position of maximum

coincides with position of maximal magnetic field strength B_{total} . From the top of LSN to the inner mid-plane the B_{total} increases by factor of 4 and $V_{\parallel}$ also increases by the same factor. Such behavior of $V_{\parallel}$ can be explained by the nozzle-like effect caused by magnetic configuration. Due to low aspect ratio of the NSTX tokamak, there is strong (~ 10) HFS/LFS asymmetry in B_{total} . The cross-section area of an effective magnetic flux tube ($\propto 1/B_{\text{total}}$) is maximal at the outer mid-plane of SOL where particles flow from core due to ballooning-like transport. On the inner mid-plane the flux tube area shrinks leading to plasma acceleration in order to conserve the particle throughput. The plasma velocity decreases after passing the HFS mid-plane, since B_{total} decreasing.

To verify an important role of magnetic configuration on parallel plasma flows, we compare two different UEDGE solutions for NSTX (see Ref. [4]). The first solution is the usual tokamak solution just discussed. It is based on original mesh generated using EFIT reconstruction of magnetic equilibrium and real toroidal field ($B_t = B_o/R$). In the second solution, we also apply original mesh but substitute the constant field $B_t = B_o$ that roughly corresponds to the cylindrical case. We show that, because of symmetry, large parallel flows are washed out in the cylindrical case in comparison to the tokamak case.

We compare our findings for parallel plasma flows in NSTX with that for C-Mod and DIII-D (Ref. [4]). The higher the magnetic field variation, the higher is the plasma flow velocity, but this dependence is not linear. The HFS/LFS variation of magnetic field in C-Mod is by factor 3 smaller than that in NSTX and we show that magnetic configuration of spherical torus has the strongest impact on plasma flows.

E. Development capabilities for UEDGE simulation of NSTX spectroscopy data

As has been mentioned above, important part of our research is multi-diagnostic data analysis for a tokamak discharge. As a rule, several diagnostics are involved in the UEDGE analysis, in particular: Thomson Scattering System (TSS), pressure gauges, Charge Exchange Recombination Spectroscopy (CHERS), and CCD arrays. Recently, in collaboration with S. Paul (PPPL) we developed a capability for UEDGE to simulate data from bolometer arrays and CHERS installed on NSTX [5]. A 3D ray-tracing code, which calculates precisely the view-cone-averaged bolometer signals based on the profiles of

plasma, neutral gas, and impurities calculated with UEDGE, was developed by I.V. Dobrovolskaia, the graduate student in our group at UCSD.

References

- [1] A. Yu. Pigarov, “UEDGE simulation of large parallel plasma flows in the SOL of NSTX”, presented at the NSTX Boundary Physics Meeting, February 2005; available at http://nstx.pppl.gov/DragNDrop/ET_Meetings/Boundary_Physics/03-02-05%20Flows/PigarovNSTXflows_vg.pdf
- [2] A. Yu. Pigarov, “Results of numerical experiment on large parallel plasma flows in the tokamak SOL”, Joint US-EU Transport Task Force Meeting, Napa, April 2005; available at <http://www.mfescience.org/TTF2005/>
- [3] S. I. Krasheninnikov, A. Yu. Pigarov, G.Q. Yu, “Anomalous radial convection and flows in tokamak scrape-off layer plasma”, Proceedings of the 32nd European Conference on Controlled Fusion and Plasma Physics (Tarragona, Portugal, 27 June-1 July, 2005), ECA vol.28G, paper P-4.020
- [4] A. Yu. Pigarov, S.I. Krasheninnikov, B. LaBombard, “Multi-fluid modeling of large parallel plasma flows in the tokamak scrape-off layer”, Contributions to Plasma Physics 46, 604-610 (2006).
- [5] A.Yu. Pigarov, S.I. Krasheninnikov, J. Boedo, R. Bell, S. Paul, A. Roquemore, et al., “Simulation of convective cross-field transport, toroidal plasma flows, and dust dynamics in NSTX with UEDGE and DUSTT codes”, Bul. Americ. Phys. Soc. **50**, 323 (2005), RP1-20
- [6] A. Yu. Pigarov, “Results of multi-fluid transport simulation in the edge and SOL of NSTX”, http://nstx.pppl.gov/DragNDrop/Results_Review_04/Pigarov_RR04.pdf
- [7] A.Yu. Pigarov, “Multi-fluid plasma transport simulations in the edge and SOL of NSTX”, http://nstx.pppl.gov/DragNDrop/Research_Forum_04/Thur_PM_Boundary/Pigarov_RF04.pdf

- [8] S.I. Krasheninnikov, A. Yu. Pigarov, "Study of dust dynamics in the NSTX", http://nstx.pppl.gov/DragNDrop/Research_Forum_04/Thur_PM_Boundary/Krash_Dust-NSTX_Forum04.pdf
- [9] A. Yu. Pigarov, S. I. Krasheninnikov, T. D. Rognlien, M. J. Schaffer, and W. P. West, *Physics of Plasmas* **9** (2002) 1287
- [10] A.Yu. Pigarov et al., *J. Nuclear Materials* **313-316** (2003) 1076
- [11] A. Yu. Pigarov, S. I. Krasheninnikov, B. LaBombard, B. Lipschultz, W. P. West, R. Maingi, V. Soukhanovsky, and T. D. Rognlien, "Analysis of non-diffusive transport and SOL recycling with multi-fluid plasma code UEDGE", *30th EPS Conference on Contr. Fusion and Plasma Phys., St. Petersburg, 7-11 July 2003 ECA Vol. 27A, P-3.170*
- [12] A. Yu. Pigarov, S. I. Krasheninnikov, T. D. Rognlien, W. P. West, B. LaBombard, B. Lipschultz, R. Maingi, and V. Soukhanovsky, "Multi-fluid code simulation including anomalous non-diffusive transport of plasma and impurities in the tokamak SOL", *Contributions to Plasma Physics*, **44** (2004) 228.
- [13] S. I. Krasheninnikov, A. Yu. Pigarov, et al., "Blobby Cross-Field Plasma Transport In Tokamak Edge", 19th International Conference on Plasma Phys. and Controlled Fusion Research, Lyon, France, 14-19 October 2002, paper IAEA-CN-94/TH/4-1.
- [14] A. Yu. Pigarov, E. M. Hollmann, S. I. Krasheninnikov, T. D. Rognlien, and W.P. West, "Multi-ion fluid simulation of tokamak edge plasmas including non-diffusive anomalous cross-field transport", *J. Nuclear Materials* **337-339** (2005) 371.
- [17] A. Yu. Pigarov, J.L. Terry, B. Lipschultz, *Plasma Physics Controlled Fusion* **40** (1998) 2055
- [18] A. Yu Pigarov, B. Frolov, S. Krasheninnikov, "Simulation of plasma afterglow phase in an inertial fusion energy chamber", *Phys. Plasmas* **11**, 5130 (2004)
- [19] T. D. Rognlien, J. L. Milovich, M. E. Rensink, G. D. Porter, *J. Nuclear Materials* **196** (1992) 205
- [20] http://nstx.pppl.gov/DragNDrop/Results_Review_2002/Research_Forum/Boundary/
- [21] http://nstx.pppl.gov/DragNDrop/Research_Forum_03/Boundary/
- [22] A.Yu. Pigarov et al., "Multi-Fluid edge plasma simulations including anomalous non-diffusive transport", *Bul. Americ. Phys. Soc.* **48**, 230 (2003), LP1-92.
- [23] Kaye S.M., Bell M.G., Bell R.E., Bernabei S., Bialek J., Biewer T., Blanchard W., Boedo J., Bush C., Carter M.D., Choe W., Crocker N., Darrow D.S., Davis W., Delgado-Aparicio L., Diem S., Ferron J., Field A., Foley J., Fredrickson E.D., Gates D.A., Gibney

T., Harvey R., Hatcher R.E., Heidbrink W., Hill K., Hosea J.C., Jarboe T.R., Johnson D.W., Kaita R., Kessel C., Kubota S., Kugel H.W., Lawson J., LeBlanc B.P., Lee K.C., Levinton F., Maingi R., Manickam J., Maqueda R., Marsala R., Mastrovito D., Mau T.K., Medley S.S., Menard J., Meyer H., Mikkelsen D.R., Mueller D., Munsat T., Nelson B.A., Neumeyer C., Nishino N., Ono M., Park H., Park W., Paul S., Peebles T., Peng M., Phillips C., Pigarov A.Yu., Pinsker R., Ram A., Ramakrishnan S., Raman R., Rasmussen D., Redi M., Rensink M., Rewoldt G., Robinson J., Roney P., Roquemore A.L., Ruskov E., Ryan P., Sabbagh S.A., Schneider H., Skinner C.H., Smith D.R., Sontag A., Soukhanovskii V., Stevenson T., Stotler D., Stratton B., Stutman D., Swain D., Synakowski E., Takase Y., Taylor G., Tritz K., von Halle A., Wade M., White R., Wilgen J., Williams M., Wilson J.R., Zhu W., Zweben S.J., Akers R., Beiersdorfer P., Betti R., Bigelow T., Bitter M., Bonoli P., Bourdelle C., Chang C.S., Chrzanowski J., Domier C., Dudek L., Efthimion P.C., Finkenthal M., Fredd E., Fu G.Y., Glasser A., Goldston R.J., Greenough N.L., Grisham L.R., Gorelenkov N., Guazzotto L., Hawryluk R.J., Hogan J., Houlberg W., Humphreys D., Jaeger F., Kalish M., Krasheninnikov S., Lao L.L., Lawrence J., Leuer J., Liu D., Luhmann N.C., Mazzucato E., Oliaro G., Pacella D., Parsells R., Schaffer M., Semenov I., Shaing K.C., Shapiro M.A., Shinohara K., Sichta P., Tang X., Vero R., Walker D., and Wampler W., "Progress towards high performance plasmas in the national spherical torus", *Nuclear Fusion* **45**, S168-180 (2005).

[24] Ono M., Bell M.G., Bell R.E., Bernabei S., Bialek J.M., Bigelow T., Bitter M., Biewer T.M., Blanchard W., Boedo J., Bush C., Chrzanowski J., Darrow D.S., Dudek L., Feder R., Ferron J.R., Foley J., Fredrickson E.D., Gates D.A., Gettelfinger C., Gibney T., Harvey R., Hatcher R., Heidbrink W., Jarboe T.R., Johnson D.W., Kalish M., Kaita R., Kaye S.M., Kessel C., Kubota S., Kugel H.W., Labik G., LeBlanc H.P., Lee K.C., Levinton F.M., Lowrance J., Maingi R., Manickam J., Maqueda R., Marsala R., Mastrovito D., Mazzucato E., Medley S.S., Menard J., Mueller D., Munsat T., Nelson B.A., Neumeyer C., Nishino N., Park H.K., Paul S.F., Peebles T., Perry E., Peng Y.-K.M., Phillips C.K., Pinsker R., Ramakrishnan S., Raman R., Roney P., Roquemore A.L., Ryan P.M., Sabbagh S.A., Schneidert H., Skinner C.H., Smith D.R., Sontag D.A., Soukhanovskii V., Stevenson I., Stotler D., Stratton B.C., Stutman D., Swain D.W., Synakowski E., Takase Y., Taylor G., Tritz K.L., Von Halle A., Wilgen J., Williams M., Wilson J.R., Zatz I., Zhu W., Zweben S.J., Akers R., Beiersdorfer P., Bonoli P.T., Bourdelle C., Carter M.D., Chang C.S., Choe W., Davis W., Diem S.J., Domier C., Ellis

R., Efthimion P.C., Field A., Finkenthal M., Fredd B., Fu G.Y., Glasser A., Goldston R.J., Grisham L.R., Gorelenkov N., Guazzotto L., Hawryluk R.J., Heitzenroeder P., Hill K.W., Houlberg W., Hosea J.C., Humphreys D., Jun C., Kim J.H., Krasheninnikov S., Lao LL., Lee S.G., Lawson J., Luhmann N.C., Mau T.K., Menon M.M., Mitarai O., Nagata M., Oliaro G., Pacella D., Parsells R., Pigarov A., Porter G.D., Ram A.K., Rasmussen D., Redi M., Rewoldt G., Ruskov E., Schmidt J., Semenov I., Shaing K., Shinohara K., Schaffer M., Sichta P., Tang X., Timberlake J., Wade M., Wampler W.R., Wang Z., Woolley R., Wurden G.A., and Xu X, "Status and Plans for the National Spherical Torus Experimental Research Facility", Transactions of the Institute of Electrical Engineers of Japan, Vol. 125 A, 868-880 (2005).