Final Report

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"Edge Plasma Simulations in NSTX and CTF: Synergy of Lithium Coating, Non-Diffusive Anomalous Transport and Drifts"

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1. Introduction

This is the final report for the Research Grant DE-FG02-08ER54989 "Edge Plasma Simulations in NSTX and CTF: Synergy of Lithium Coating, Non-Diffusive Anomalous Transport and Drifts". The UCSD group including: A.Yu. Pigarov (PI), S.I. Krasheninnikov and R.D. Smirnov, was working on modeling of the impact of lithium coatings on edge plasma parameters in NSTX with the multi-species multi-fluid code UEDGE. The work was conducted in the following main areas: (i) improvements of UEDGE model for plasma-lithium interactions, (ii) understanding the physics of low-recycling divertor regime in NSTX caused by lithium pumping, (iii) study of synergistic effects with lithium coatings and non-diffusive ballooning-like cross-field transport, (iv) simulation of experimental multi-diagnostic data on edge plasma with lithium pumping in NSTX via self-consistent modeling of D-Li-C plasma with UEDGE, and (v) working-gas balance analysis. The accomplishments in these areas are given in the corresponding subsections in Section 2. Publications and presentations made under the Grant are listed in Section 3.

2. Accomplishments

2.1. Improvements in UEDGE code for lithium coating effect simulations

For modeling of plasma-lithium experiments in NSTX, the UEDGE model was improved (with the help of Dr. T.D. Rognlien, LLNL) by adding: (i) sources of impurities due to lithium evaporation at the divertor plates and chamber walls, which can be the functions of surface temperature, and (ii) sources due to sputtering of second plate material. We incorporated the radiation enhanced sublimation effects and updated the atomic physics for inter-species collisions.

In FY2011, we developed the capability for self-consistent time-dependent simulations with UEDGE code of the material surface temperature, on which lithium release rate strongly depends. In this case, for each material boundary cell of the modeling domain, we solve the 1-D equation for heat transfer based on heat power load including the plasma kinetic, ionization energy, and radiation.

2.2. Multi-parametric analysis of low-recycling divertor regimes in NSTX.

"Lithium pumping", the long-term retention of deuterium by recoverable lithium coatings, is the cause of transition from high to low recycling divertor operation regime. This has been confirmed by the experimental data obtained on NSTX as well as by the results of our modeling with UEDGE.

In Ref. [A1] and reports [P1-P3, T1,T5] we study the properties of low recycling divertor operation for NSTX. We perform a multi-parametric analysis by scanning the values of recycling coefficients and surface temperature on various material surfaces, by considering different gas-puff intensities and location, by varying the cross-field plasma transport coefficients (for diffusion and convection) in a wide range, and by changing the magnitude of flux-limiters as well as sputtering yields. Different magnetic configurations (low single-null and unbalanced double null) were also modeled.

The effect of “lithium pumping” due to lithium divertor plate coatings (treated as a reduced value of recycling coefficient R_{plate}) on divertor plasma parameters is summarized in the Fig.1 based on the results of UEDGE modeling of all charge states of D, Li and C ions. The figure shows the operational puff/pump window for a typical NSTX discharge. Here we emphasize the high sensitivity of divertor plasma parameters to the value of recycling coefficient. As seen, main trends in the edge-plasma parameter variation with recycling coefficient reduction are the decrease in the particle flux on divertor plates and the increase in the peak divertor temperature. At a given gas puff rate into the discharge, the reduction in recycling coefficient causes the transition from high to low recycling divertor regime. For example, for 500A gas puff rate, such transition occurs at rather high values of R_{plate}~0.99 (resulting in the elevated peak plasma temperature ~40eV).

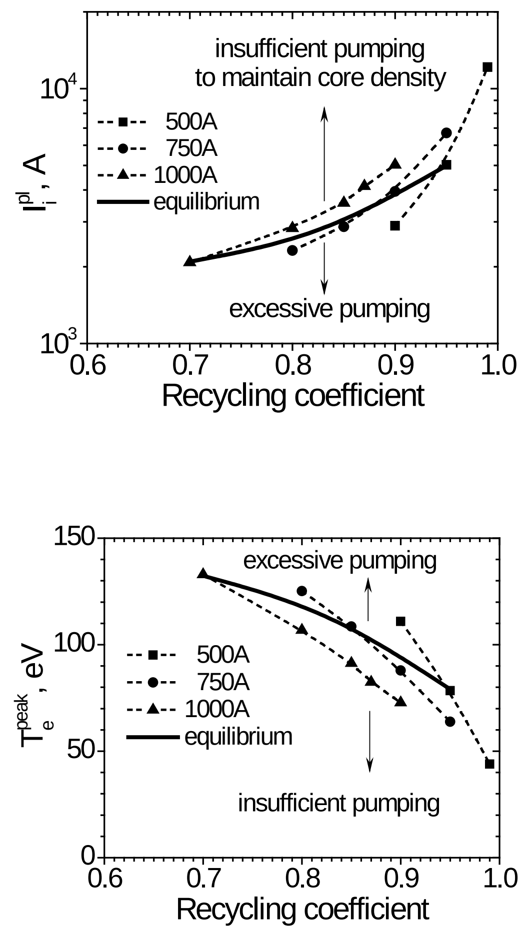

Fig. 1: The plasma ion flux (top panel) and peak electron temperature (bottom) at the outer divertor plate displayed as functions of the recycling coefficient for the three different gas puffing rates. The solid curves represent the solutions corresponding to the particle equilibrium with the core plasma.

Studying the plasma properties in the low recycling regimes of the NSTX divertor operation caused by "lithium pumping", we made several important conclusions:

(i) plasma-sheath-limited conditions are applied to both inner and outer divertors (this is because the connection length between the midplane and divertor plates along the magnetic field line in NSTX is roughly equal to the mean free path of thermal electrons);

(ii) hence, the plasma temperature is rather flat along magnetic field lines in the SOL and divertors (see Fig.2), and the plasma ion and electron temperatures are high ~100 eV in the near SOL for a given set of transport coefficients;

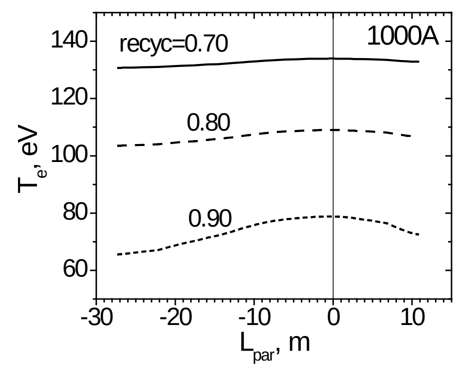

Fig.2: The electron temperature profiles along a magnetic field line at the separatrix for the three different values of the divertor recycling coefficient and the gas puffing rate of 1000A. The connection length L_{par} is calculated from the outer midplane position.

(iii) plasma parallel transport transits into the free streaming regime, the flow velocity is large attaining the unity Mach number in the vicinity of divertor plates;

(iv) plasma density decreases along magnetic field lines while plasma accelerates toward the plate, since parallel plasma flux is roughly constant in the magnetic flux tube;

(v) power loads on the divertor plates around the strike points are dominated by the electron heat conduction; the peak power load on the outer plate slightly decreases with reducing the recycling, mainly because of larger heat flux transported to the inner plate;

(vi) impurity particles originated from divertor plates (due to sputtering and sublimation) are well retained in the divertor volume, so that the impurity flux into the core is small.

In Ref. [A3], initial parametric analysis based on UEDGE modeling was also done for Liquid Lithium Divertor module.

2.3. Study synergistic effects with lithium coatings and non-diffusive ballooning-like cross-field transport.

The role of the cross-field plasma transport in low-recycling regimes is studied in [A1,A2] and it is demonstrated here in Fig.3, where the radial profiles of the electron density and radial ion flux are shown for three different sets of radial transport coefficients corresponding to the low, medium and high convective transport. The medium transport case is consistent with NSTX experimental data. As an expected trend, the density profile becomes flatter in the core and the density gradient becomes larger in the SOL due to improved particle confinement, as the radial plasma transport decreases (low transport case), whereas the density gradient increases in the core and the profile becomes flatter in the SOL (high transport case).

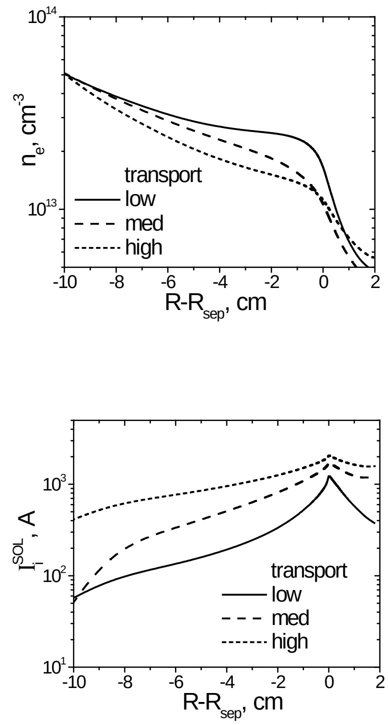

Fig.3: Radial profiles of the plasma density (top panel) and of the cross-file ion flux through the edge and SOL magnetic surfaces (left) for different profiles of cross-field transport coefficients corresponding to the high, medium, and low radial plasma transport (see [A1]).

The Fig.3 (bottom) also highlights the importance of particle recycling on the wall. When the cross-field plasma transport is strong (high, medium), there is significant flux of neutrals from the wall, which penetrate deeply into the plasma maintaining the steep plasma density gradients in the core edge. In this case, the integral flux from the wall is ~1kA, i.e. comparable to the gas puffing rate. In contrast, the reduction of the plasma transport (low case) substantially decreases the wall recycling, much below the gas puffing rate. While the integral radial ion flux in the core and far-SOL regions decreases significantly, the reduction of the flux into SOL through the separatrix is far less substantial. The increase of the electron density at the separatrix by a factor of ~2 is also relatively small compared to the about 5 fold decrease of the transport coefficients in the low vs. medium transport cases. We explain such behavior by the plasma recycling in the divertor, which continues to supply the recycled neutrals to the SOL that are subsequently ionized in the near-separatrix plasma region. It is important to note that in the cases when the wall recycling is substantially reduced (either due to slow radial transport or due to short connection length in the high-triangularity unbalanced double-null configuration of NSTX), the transition from high to low recycling regimes may occur at higher recycling coefficients and the requirement for sufficient gas puffing to maintain the core flux balance is much stronger.

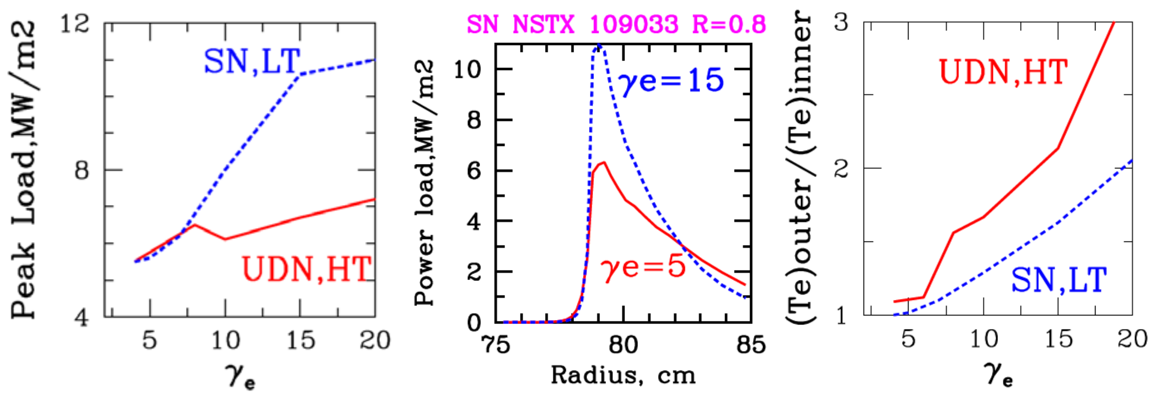

Fig.4a: Variation of the peak power load to outer divertor plate with the sheath electron power transmission factor γ_e

Fig.4b: Profiles of plasma power load to outer divertor plate in the SN+LT case

Fig. 4c: Variation of the ratio of peak electron temperatures at the outer and inner divertor plates with factor $\gamma_{e.}$

Special attention was paid in [A2,T5] to simulation the possible effect of secondary electron emission (SEE) on plasma profiles in the low-recycling divertor operation, since the sheath potential collapses in the case when SEE yield is Y_{see}>0.85. According to our calculations [T3, T5], the condition Y_{see}>0.85 for lithium (averaged over velocity distribution function at the sheath) occurs at rather low T_e~12 eV, whereas the peak T_e at plate is much higher in the low recycling regime. The SEE strongly affects the electron energy plasma-sheath transmission coefficient γe and we scanned the γe values in our analysis. As seen in Fig. 4, the SEE can: (i) substantially increase the peak heat flux on plate, (ii) reduce the half-width of power load profile, and (iii) increase the inboard/outboard asymmetry of divertor plasma. Magnetic configuration has an impact on SEE effects, as one see in Fig4, comparing the curves corresponding to single-null low-triangularity (SN+LT) and unbalanced double-null high-triangularity (UDN+HT) magnetic configurations.

The thermally unstable heating of PFCs can occur when a positive feedback loop exists between the plasma heat flux and the surface temperature. In [A4], we calculate characteristics and compared three possible mechanisms of such feedback: (1) thermionic electron emission, (2) recycling of desorbed gases, (3) vaporization and ionization of surface material. Instability analysis showed that the third mechanism can lead to overheating of beryllium and lithium PFCs at lower plate temperatures, prior to the "classical" thermionic electron emission mechanism. The surface temperatures and the plasma parameters, at which the vaporization/ionization mechanism triggers the local overheating is shown in Fig 5. The increase in the surface heat load due to secondary electron emission was also considered. It was shown that the combined effects of energy and impact angle distributions of the plasma electrons can increase the averaged secondary electron emission yield to values higher than unity and hence can lower the average electron energy, at which such yields are achieved.

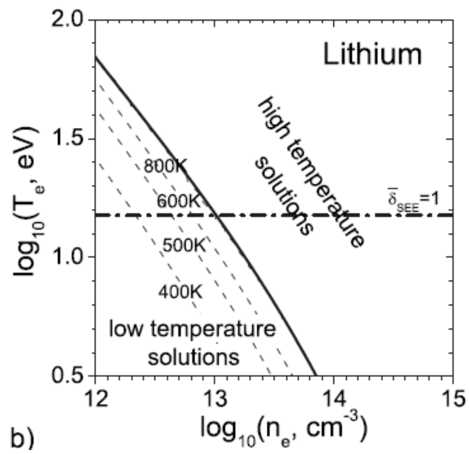

Fig. 5: Dashed curves display the low equilibrium temperatures of Li PFC as functions of plasma parameters. Solid curve represents parameters at which bifurcation via vapor recycling occurs

We also used the UEDGE code to model self-consistently a positive loop, in which the heat load increases with an increase in evaporating lithium for typical NSTX discharge. Some results are shown in Fig. 6. As seen, with increase in the plate temperature from 700K to 850K, simultaneously increasing the impurity ion and plasma heat fluxes as well as the ionization energy released by ions on plate. Since an increasing heat flux increases the plate temperature, the divertor plasma can evolve into the detached (>850K) or MARFE

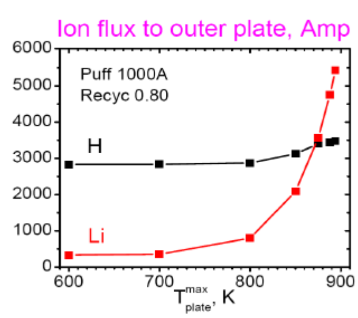

Fig.6a: Stationary fluxes vs. peak plate temperature.

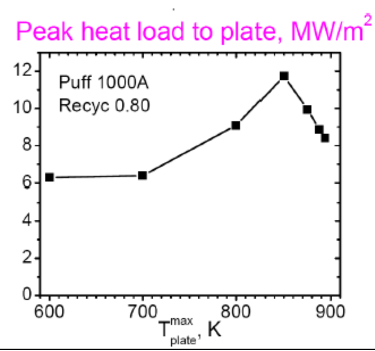

Fig. 6b: Peak heat flux vs. peak plate temperature.

states on different time scales depending on conditions of heat transport inside PFC. Stabilization by upstream plasma radiation can be a topic of the further study.

We note that the considered mechanisms of thermal instabilities can be potentially a serious threat for usage of liquid PFC in the future high-power-loading machines, like NHTX and CTF, due to strong heat contraction, “hot spot” creation, excessive evaporation of lithium, and PFC infrastructure damage.

This work was reported on topical meetings [T1],[T3], the paper [A4] was published on this topic, and new experiments on NSTX were proposed [T4].

2.4. Simulation of experimental multi-diagnostic data on edge plasma with lithium pumping in NSTX using UEDGE.

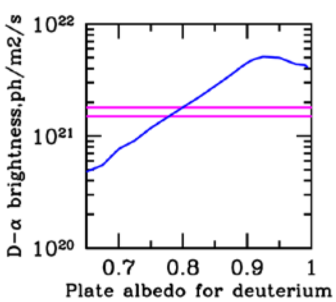

Fig.7: D-α brightness vs. the outer plate recycling.

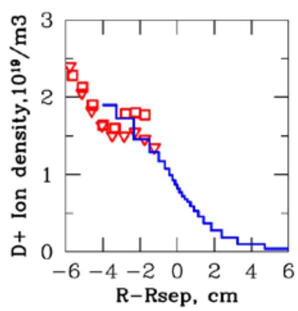

Fig.8: Radial profile of deuterium ion density.

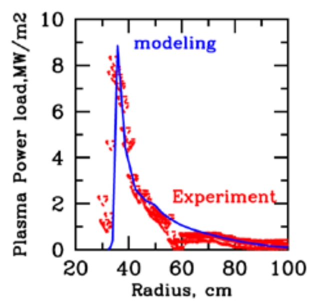

Fig.9: Profile of power load on outer plate.

Nearly 200 runs of UEDGE code were done for two NSTX shots, 129061 and 129014, in order to obtain agreement between calculated and experimental data from the following diagnostics: (i) D-α brightness measurements in the divertor and midplane regions which provide information on deuterium recycling source; (ii) Langmuir probe measurements at the divertor floor and gas pressure measurements from divertor and mid-plane gauges which provide the particle fluxes; (iii) Li atom line brightness measurements in the recycling regions, (iv) midplane profiles of electron density and temperature from Thompson laser system, (v) profiles of ion temperature and density of fully-stripped ions of deuterium, lithium and carbon from CHERS, and (vi) profile of plasma heat flux on divertor floor deduced from IR TV camera. The core plasma particle balance should also satisfy the imbalance condition for hydrogen: $\Gamma_{nbi}+\Gamma_n-\Gamma_{ion}=G_d$, where Γ_{nbi} is the NBI particle injection rate, Γ_n is the flux of neutrals into the core, Γ_{ion} is the flux of ions from the core. $G_d=(dI/dt)_{100}$ is the core-plasma deuterium inventory increase which was evaluated using CHERS data averaged over 100ms around the reference time slice of the discharge. Examples of diagnostic data matching for 129061 are shown in Figs. 7-9. High sensitivity of divertor plasma parameters to the recycling coefficient R_{plate} (pumping is 1-R_{plate}) at the outer divertor plate which is covered with lithium allows us to conclude about lithium pumping efficiency. As seen on Fig.7, experimental data are well matched with R_{plate}=0.8 for fixed gas puff rate J_{puf}=700Amp.

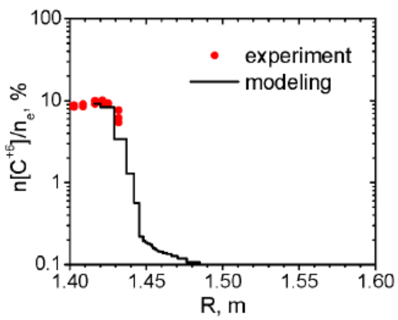

Fig.10 : Radial profile of [C+6]/ne

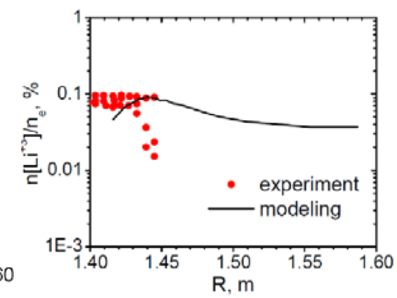

Fig.11: Radial profile of [Li+3]/ne

Important aspect of lithium coating usage in tokamaks is the contamination of core plasma by impurities. Experiments on NSTX showed that core concentration of $[Li^{+3}]$ ion is at 0.1% level whereas the concentration of $[C^{+6}]$ is at very high level ~10%. The results of impurity profiles modeling with UEDGE are given in Figs 10 and 11. We showed that lithium and carbon impurities sputtered and/or evaporated from divertor plates are very well retained in the divertor volume and that the core contamination by Li is relatively small $[Li^{+3}]$/ne~0.1%. At the same time, the concentrations of $[C^{+6}]$/ne~10% in the core can be modeled under assumption of strong inward pinch velocity (radially and poloidally dependent). In this case, the radial transport asymmetry results in the convective cell (influx on inboard and outflux on outboard) for C^{+6} ions that substantially increases the lifetime and concentration of this ion in the core.

We compared the results of experimental data matching with UEDGE (Fig. 12) for two NSTX discharges, 129061 and 129014, which have similar magnetic configuration. The shot 129061 was with and shot 129014 was without "lithiumisation" of divertor plates. The modeling showed the low sensitivity of separatrix density to the transport coefficient variation. UEDGE predicted that in the shot with lithiumisation the values of cross-field particle transport coefficients should be increased by factor 2.5 with respect to the shot without lithiumisation. We concluded that fresh lithium coating enhances the edge plasma transport.

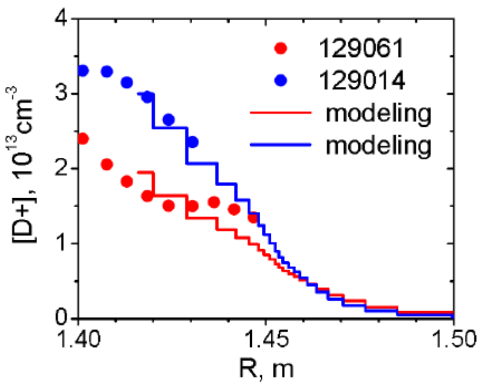

Fig. 12: Deuterium density profile w and w/o lithiumisation

The results of experimental data simulation with UEDGE were reported in [T1] and [P3] and the paper [A2] was prepared.

2.5. Gas Balance Study

Working-gas balance analysis in tokamaks was the OFES DoE milestone and the featured experiments were carried out on NSTX in 2009. On the request of NSTX team, we took part in the analysis of experimental data.

For this study, we developed new code, the Wall Gas Balance (WGB) code [T2]. This is multi-region multi-species 0-D transport code, which calculates the temporal evolution of average plasma and gas parameters in different regions (core plasma, edge plasma, NBI volume, gas puff valves, port with pressure gauge, etc) as well as the particle inventories in the chamber wall and divertor plate using the simplified "wall" models. We apply WGB to model the dynamics of deuterium deposition into the graphite tiles with and without lithium coatings using the discharge

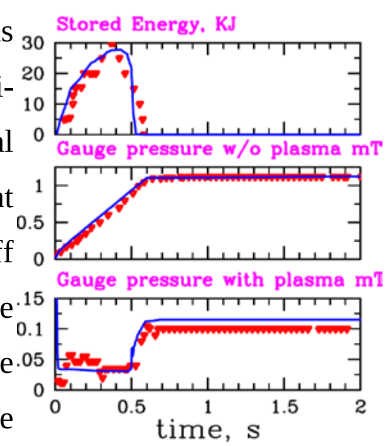

Fig.13: Results of WGB modeling for OH shot w and w/o recoverable Li coating

experimental waveforms as well as the deuterium out-gassing after the discharge in NSTX. In particular, WGB modeling confirmed that as high as 95% of the gas introduced into the discharge is deposited into the material surfaces. Initial modeling results were presented on APS DPP [P4] and ITPA meetings.

3. Publications/Presentations

As a result of our research performed in 2009-2011, four papers A1-A4 (and 3 of them were published in referred journals) and nine presentations on international conferences (P1-P4) and on topical meetings (T1-T5) were made.

3.1. Papers:

[A1] R.D. Smirnov, A.Yu. Pigarov, S.I. Krasheninnikov, T.D. Rognlien, V.A. Soukhanovskii, M. Rensink, R. Maingi, C.H. Skinner, D. P. Stotler , R. Bell, H. Kugel, “Multi-fluid modeling of low-recycling divertor regimes”, Contributions to Plasma Physics **50** (2010).

[A2] A.Yu. Pigarov, V.A. Soukhanovskii, C.H. Skinner, R.E. Bell, R. Maingi, T.D. Rognlien, D.P. Stotler, “Edge plasma modeling for lithium-coating experiments in NSTX”, paper, to be submitted.

[A3] D.P. Stotler, R. Maingi, L.E. Zakharov, H.W. Kugel, A.Yu. Pigarov, T.D. Rognlien, V.A. Soukhanovskii, “Simulations of NSTX with a Liquid Lithium Divertor Module”, Contributions to Plasma Physics **50** (2010).

[A4] R.D. Smirnov, S.I. Krasheninnikov, A.Yu. Pigarov, “On temperature bifurcation of beryllium and lithium plasma facing components”, Physics of Plasmas **16** (2009) 122501.

3.2. Presentations at International Conferences:

[P1] A.Yu. Pigarov, R.D. Smirnov, S.I. Krasheninnikov, V.A. Soukhanovskii, T.D. Rognlien, M. Rensink, R. Maingi, D. Stotler, C.H. Skinner, R. Bell, H. Kugel, "Modeling of Lithium Coating Impact on NSTX Divertor Plasma", Oral presentation at the Joint EU-US Transport Task Force Workshop (April 2009), San Diego CA. Available at the TTF website: http://physics-file.ucsd.edu/ttf2009/working/ab_storage/ab_1453/Pigarov-AYu.pdf

[P2] R.D. Smirnov, A.Yu. Pigarov, S.I. Krasheninnikov, C.H. Skinner, D. Stotler, R. Bell, H. Kugel, V.A. Soukhanovskii, T.D. Rognlien, M. Rensink, R. Maingi, "Modeling of low-recycling divertor regimes", poster P2-07 at the 12th International Workshop on Plasma Edge Theory in Fusion Devices (September 2009), Rostov Velikij, Russia;

ibid. D.P. Stotler, R. Maingi, L.E. Zakharov, H.W. Kugel, A.Yu. Pigarov, T.D. Rognlien, V.A. Soukhanovskii, "Simulations of NSTX with a Liquid Lithium Divertor Module", poster P2-08. Available at http://www.pet12.ru/PosterSes.html

[P3] R.D. Smirnov, A.Yu. Pigarov, S.I. Krasheninnikov, C.H. Skinner, D. Stotler, R. Bell, H. Kugel, V.A. Soukhanovskii, T.D. Rognlien, M. Rensink, R. Maingi, "Modeling of low-recycling divertor with lithium coating in NSTX", NSTX session, Contributed poster PP8-41 at the 51st Annual Meeting of the APS Division of Plasma Physics (November 2009), Atlanta GA; *ibid.* PP8-37 V.A. Soukhanovskii, T.D. H. Kugel, R. Kaita, R. Bell, D.A. Gates, J.E. Menard, D. Mueller, B. LeBlanc, S. Paul, A. Roquemore, D.P. Stotler, R. Maingi, R. Raman, A. Pigarov, R. Smirnov, "Modifications in divertor and scrape-off layer conditions with lithium coatings in NSTX".

Slides are available at NSTX website: http://nstx.pppl.gov/DragNDrop/Scientific_Conferences/APS/APS-DPP_09/Contributed%20Posters/PP8.41-SmirnovRD-Low_recycling_modeling.pdf

[P4] A.Yu. Pigarov, S.I. Krasheninnikov, J. Cary, A. Hakim, S. Kruger, A. Pletzer, R. Cohen, T. Rognlien, T. Epperly, C.H. Skinner, "Self-consistent edge-wall simulations with WALLPSI", poster presentation at the 51st Annual Meeting of the APS Division of Plasma Physics (November 2009), Atlanta GA.

3.3. Topical Meetings.

[T1] A.Yu. Pigarov, R.D. Smirnov, S.I. Krasheninnikov, V.A. Soukhanovskii, T.D. Rognlien, D. Stotler, C.H. Skinner, R. Bell, H. Kugel, R. Maingi, "Modeling of Lithium Coating Experiments on NSTX with UEDGE", NSTX Research/Theory Results Review (16 September 2009), Princeton NJ. Slides are available at NSTX website: http://nstx.pppl.gov/DragNDrop/NSTX_Meetings/Results_Reviews/2009/Lithium/PigarovNSTXreview09.pdf.

[T2] A. Yu. Pigarov, "Wall Gas Balance (WGB) code summary", Plasma Facing Component Steering Committee: Special Topic "Plasma-Material Modeling", e-Meeting (26 October 2009). Slides available at: https://engineering.purdue.edu/PFC/PFC_Mini-Calls_files/Pigarov_WallPSI_WGB_sums.pdf .

[T3] R.D. Smirnov, A.Yu. Pigarov, S.I. Krasheninnikov, "On temperature bifurcation of beryllium and lithium plasma facing components", oral presentation at the Unipolar Arcs Workshop (January 2010). Argonne IL. Slides available at ANL website: https://twindico.hep.anl.gov/indico/sessionDisplay.py?sessionId=15&slotId=0&confId=69#2010-01-29.

[T4] S.I. Krasheninnikov, A.Yu. Pigarov, "Experiments on the physics of hot spots", FY2010 NSTX Research Forum (1-3 December 2009), Princeton NJ.

Slides available at NSTX website: http://nstx.pppl.gov/DragNDrop/NSTX_Meetings/Research_Forum/FY2010/Lithium%20Research/Krash_Thermal%20instability.pdf

[T5] A.Yu. Pigarov, V. Soukhanovskii, C.H. Skinner, R. Maingi, S. Gerhardt, "Study of secondary electron emission and thermoelectric current effects with Lithium" FY2010 NSTX Research Forum (1-3 December 2009), Princeton NJ.

Slides available at NSTX website:

http://nstx.pppl.gov/DragNDrop/NSTX_Meetings/Research_Forum/FY2010/Boundary%20Physics/PigarovNstxForum10.ppt