DOE FES Final Technical Report

Project Title: Fundamental Surface Science of PFCs for Improved Plasma Performance in NSTX-U

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Disclaimer:

Executive Summary

This research applies to improving the plasma performance in the National Spherical Torus Experiment-Upgrade (NSTX-U). NSTX-U will extend the high performance plasmas produced and controlled in NSTX by doubling the heating power and extending the pulse duration by a factor of five. Both of these will substantially raise the thermal stress on plasma facing components (PFCs). Liquid metal-based PFCs, in particular lithium, have been used to improve the plasma performance of many tokamaks, but the predictive understanding needed for confident application of liquid metals and coatings in NSTX-U and future machines is in its infancy. Our work is aimed at applying surface analysis techniques to relevant materials and coatings in a controlled laboratory environment to understand the fundamental surface science and measure key properties that will guide the operations and optimize plasma facing materials at the higher temperatures expected in NSTX-U. Current plans for NSTX-U are to begin operations with carbon PFCs and gradually transition to refractory metal PFCs and liquid metal PFCs toward the end of the first 5 years.

Accordingly, our research emphasizes the surface science of lithium on PFC substrates comprised of carbon, molybdenum, and stainless steel. Conditioning of these substrates with boron and the influence of impurities, such as water vapor, present in the tokamak environment will be investigated. These studies make quantitative measurements with low energy ion scattering (LEIS) and high-resolution X-ray photoelectron spectroscopy (HR-XPS) to characterize lithium and complex mixed-material deposits on metal single crystals, e.g. molybdenum, and practical alloys. We utilize ultrathin films of these deposits to be able to follow the surface chemistry and determine stoichiometry. The temperature dependence of surface properties and reactivity is a key parameter. Temperature programmed desorption (TPD) mass spectrometry is utilized to measure deuterium uptake and retention by these materials, and vibrational spectroscopy provides crucial information needed on surface species and chemical compounds. Additional measurements probe diffusion of oxygen into bulk lithium and explore lithium diffusion and wetting on molybdenum and stainless steel.

The outcomes of these studies contributes to an improved understanding of plasma surface interactions and specific information needed for NSTX-U operations and the future development of lithium-conditioned plasma-facing components in high-heat flux long-pulse scenarios.

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Technical Discussion

Introduction with major project goals

The NSTX-U upgrade will extend the high performance plasmas produced and controlled in NSTX by doubling the heating power and extending the pulse duration by a factor of five. Both of these will substantially raise the thermal stress on plasma facing components (PFCs). Liquid metal-based PFCs, in particular lithium, have been used to improve the plasma performance of many tokamaks, but the predictive understanding needed for confident application of liquid metals and coatings in NSTX-U and future machines is in its infancy. Our research is aimed at applying surface analysis techniques to relevant materials and coatings in a controlled laboratory environment with the aim of understanding the fundamental surface science and measuring the key properties that will guide the operations and optimize plasma facing materials at the higher temperatures expected in NSTX-U. Current plans for NSTX-U are to begin operations with carbon PFCs and gradually transition to high-Z PFCs and liquid metal PFCs toward the end of the first 5 years. Accordingly, our research emphasizes the surface science of lithium on PFC substrates comprised of carbon, molybdenum, and stainless steel. A major project goal is to investigate the conditioning of these substrates with boron as well as lithium and the influence of impurities in the tokamak environment (e.g. residual water vapor).

Overall our goals are to elucidate the surface chemistry that affects key issues in the use of coatings (B, Li, Sn) in future high power fusion devices (NSTX-U, FNSF) for present graphite tiles and future metal (Mo, TZM, W) plasma-facing components (PFCs). To accomplish these goals, we are using a surface science approach to investigate the fundamental surface chemistry at the plasma boundary interface using atomic-level diagnostics.

Methodology

To accomplish these objectives, our experimental program uses a surface science approach to obtain quantitative measurements under controlled conditions in order to provide a fundamental framework for understanding reaction mechanisms at the plasma materials interface. An array of surface sensitive probes will be used including low energy ion scattering (LEIS), Auger electron spectroscopy (AES), and high-resolution X-ray photoelectron spectroscopy (HR-XPS) to characterize lithium and complex mixed-material deposits on refractory metal single crystals (initially Mo) and practical alloys, e.g. TZM molybdenum alloy. To be able to follow the surface chemistry and determine stoichiometry, we will utilize ultrathin films of these deposits. The temperature dependence of surface properties and reactivity is a key parameter. Temperature programmed desorption (TPD) mass spectrometry will be utilized to measure deuterium uptake and retention, and vibrational spectroscopy will provide crucial information needed on surface species and chemical compounds.

Results & discussion

In this project, we have addressed timely open questions regarding surface chemistry of the plasma-materials interface and the lithium surface science needed for long pulse PFCs. Specific surface science experiments of Li deposition and Li film growth on pure Mo and Ni single crystals, and Li and Sn deposition and film growth on polycrystalline samples of Mo, TZM molybdenum alloy, and W were carried out. In ultrahigh vacuum (UHV), clean surfaces are prepared with known composition and structure and fine control is exercised on gas phase species, ion energies, surface reactions, and ultimately compound formation. Ultrapure Li and Sn films can be deposited with submonolayer control onto metal substrates and these films can be subsequently analyzed by electron and ion spectroscopic techniques and TPD mass spectrometry. Our focus is on the reactions of deuterium (D) ions and atoms with these films, which are related to recycling properties of the surface, and the influence of temperature, impurity atoms and changes in film structure and reactivity, especially those that occur upon melting to form liquid surfaces.

We have conducted experiments of elementary rates of adsorption, scattering, and recombination for interactions of D_2, D atoms, and D^+ ions with these UHV-prepared Li films. Measurements were also made of D uptake and retention in mixed Li-C and Li-O deposits. We have conducted experiments probing reactions on these and related surfaces and characterizing the influence of substrate temperature and impurities, *e.g.*, melting, oxidation by water exposures, and deposition of carbon impurities.

H or D atoms are produced in our lab from H_2 or D_2 in pyrolytic sources using resistively heated Pt tubes or e-beam heated W tubes. The flux of these H (D) atom sources is ~1 x 10^{13} H (D) atoms/cm^{2}s. Our chambers are also equipped with a differentially pumped 5 kV ion source that can be used to produce low energy hydrogen ions at a flux higher than that of the atom sources at a range of ion energies. Using these ion sources, we made measurements to gain information on ion scattering probabilities and ion induced desorption of preadsorbed deuterium. We also conducted studies of synergistic effects associated with multiple species interacting with a given surface by use of an ECR plasma source capable of producing clean, high fluxes of H, N, and O atoms, ions, or atoms/ions (hybrid sources) over the energy range from neutral thermal atoms to above 1.5 eV and ion energies of 20 eV- 2 keV. This source is relatively intense compared to the differentially pumped ion sources and atom sources that we also use, but is still UHV-compatible.

Extensive thermal desorption studies were made of Li on polycrystalline Mo, TZM, and W substrates characterized by using AES, LEIS, XPS, and TPD measurements. Interpretation of these results specifically compares them to our measurements on Mo single crystal substrates to illuminate differences that are induced by grain boundaries and impurities. We have also carried out experiments exposing Li films on these polycrystalline substrates to low energy hydrogen ions using our differentially pumped ion source or ECR plasma source. Specifically, we obtained fundamental information on the sputtering of lithium and lithium compound films under deuterium and helium ion bombardment, hydrogen retention in lithium and lithium oxide films, and the post-exposure time dependence of deuterium retention in lithium and lithium compounds. Additional fundamental studies investigated secondary electron emission from lithium and lithium compounds.

We have also deposited clean films of Sn on refractory metal surfaces, and carried out a set of studies of Sn deposition and growth on polycrystalline Mo, TZM, and W substrates characterized by using AES, LEIS, XPS, and TPD measurements. These results can be compared with the few reports on Mo single crystals available in the literature to enable us to discuss differences that are induced by grain boundaries and impurities in these polycrystalline metal substrates.

In upgrades to the surface and materials characterization lab capabilities, we installed and used a newer, more powerful quadrupole mass spectrometer (QMS) system for TPD experiments, and this instrument is a resource that can be used in future research activities analyzing low energy ions, neutrals and radicals in UHV surface science applications. We also significantly upgraded our mass and velocity selected, differentially pumped ion source attached to our main ion scattering UHV chamber with a new decelerator lens system. With this lens, the extraction potential can be made greater allowing more beam current to be extracted from the ion source, and we have obtained useful ion beams at energies down to 5 eV, within a factor of four of the space charge limit.

In addition to the many collaborations with research staff at PPPL, we also worked closely with Prof. J.P. Allain (UIUC) and his students who were carrying out the initial studies of plasma facing component surface conditioning in the NSTX-U with the Materials Analysis Particle Probe (MAPP). We were especially involved, and in some cases instrumental, in assisting with data interpretation and peak deconvolution in XPS measurements using MAPP. We performed benchmark XPS, and high resolution (HR)-XPS measurements using a monochromatic X-ray source, in our laboratories using very high performance surface analytical instrumentation to enable much improved interpretation of the MAPP spectra, which are necessarily obtained in a lower performing system due to its space constraints and close proximity to NSTX-U and the attendant high magnetic fields. These experiments using MAPP were instrumental in helping to unravel wall conditioning effects on plasma facing components in NSTX-U, and especially to advance understanding of boronization on NSTX-U performance. We also collaborated with Prof. Predrag Krstic (Stony Brook U.) in connecting experiment with theory to yield new insights into this boronization chemistry. MAPP was also used to probe hydrogen retention in lithium on metallic walls via "in vacuo" analysis in LTX and this has important implications for high-Z plasma-facing components in NSTX-U.

In another activity, we collaborated on investigations of nano-tungsten materials with Prof. Jason Trelewicz of Stony Brook University. He and his group prepared novel samples for us to use in hydrogen retention experiments.

Conclusions

We successfully improved our capabilities for performing experiments on Li and Sn film deposition and growth studies on refractory metal substrates and measurements of the interactions of D_2, D atoms, and D^+ ions with UHV-prepared Li and Sn films on these substrates. We carried out investigations of the thermal stability of Li and Sn films on refractory metal substrates, including single crystal and polycrystalline Mo, and polycrystalline TZM and W, primarily thermal desorption studies using TPD measurements, but also including AES, LEIS, and XPS characterization. This later information was very helpful in studies of how oxidation of the refractory metal substrate and the Li and Sn films affected the thermal stability of Li and Sn films. Our main accomplishments included fundamental information on the sputtering of lithium and lithium compound films under deuterium and helium ion bombardment, hydrogen retention in lithium and lithium oxide films, and the post-exposure time dependence of deuterium retention in lithium and lithium compounds. Additional fundamental studies investigated secondary electron emission from lithium and lithium compounds.

We have made significant upgrades to the lab capabilities for future studies of fundamental PMI chemistry and physics by: (i) installation of a new QMS that has high sensitivity for TPD experiments and additional capabilities for the discrimination of radicals and analysis of low energy positive and negative ions in mechanistic studies of chemical and physical erosion and scattering; and (ii) implementation of a new low energy ion decelerator system in one of our ion sources enabling us to study incident ion energies down to a few eV, in the chemical erosion regime, and conducted experiments at several energies of elementary rates of adsorption, scattering, and recombination for interactions of D_2, D atoms, and D^+ ions with Li and Sn films on refractory metal substrates.

We collaborated extensively with J.P. Allain and his students, who carried out the first MAPP measurements on NSTX-U, including some data on boronization, and we were especially involved, and in some cases instrumental, in assisting with data interpretation and peak deconvolution in XPS measurements using MAPP. In addition, we performed benchmark XPS and HR-XPS measurements in our laboratories using high performance surface analytical instrumentation to enable much improved interpretation of the MAPP spectra.

Overall, our research applying surface analysis techniques to relevant materials and coatings in a controlled laboratory environment has advanced the understanding of fundamental surface science and measured key properties that will guide the operations and optimize plasma facing materials at the higher temperatures expected in NSTX-U.

<u>Project impact</u>

Specifically, the outcome of our fundamental studies is an improved understanding of plasma surface interactions and specific information needed for NSTX-U operations and the future development of lithium-conditioned plasma-facing components in high-heat flux long-pulse scenarios. More broadly, an improved understanding of plasma-materials interactions aids advances in fundamental understanding and the science and engineering of technologies in a wide range of applications involving plasma such as plasma-enhanced etching and deposition in microelectronics manufacturing, plasma-enhanced synthesis of nanomaterials, and promising applications for atmospheric plasmas in biomedical applications and for non-equilibrium plasmas in environmental remediation and energy applications.

At Princeton University, new information and innovations from the research outcomes were directly integrated into a course for undergraduates and graduate students in CBE 526 “Surface Science: Processes and Probes” taught at Princeton by B.E. Koel. There is also an impact on the development of human resources, in that opportunities for training, development and mentoring were provided for 6 graduate students and 3 postdoctoral research associates, along with many undergraduates participating in summer and senior thesis projects. All of these student researchers designed experiments, built instruments, performed experimental work, learned about on the job safety, and presented their research findings in oral and written communications.

This project improved research capabilities of the two laboratories for materials characterization and surface chemistry experiments that have been established at C-Site at PPPL under supervision of the PI (Koel): the Surface Science and Technology Laboratory (SSTL) located in room T-260 and the Surface Imaging and Microanalysis Laboratory (SIML) located in room C-123. In addition, these two labs have an impact on society beyond science and technology since they are available and utilized for public and educational tours at PPPL, and specific tours at PPPL for public and DOE administrators and other visitors.

NSTX-U Collaboration & Accomplishments

We collaborated extensively with many of the research staff at PPPL, as indicated in part by the list of coauthors on the grant products, including journal publications and conference papers and presentations. We specifically note a significant collaboration with J.P. Allain and his students, who carried out the first MAPP measurements on NSTX-U, including some data on boronization, and we were especially involved, and in some cases instrumental, in assisting with data interpretation and peak deconvolution in XPS measurements using MAPP.

Project Products

Journal publications

"Sputtering of lithium and lithium compound films under deuterium and helium ion bombardment", L. Buzi, Y. Yang, A.O. Nelson, R. Kaita, P.S. Krstić, B.E. Koel, *Nucl. Mater. and Energy,* **19**, 411−415 (2019). DOI:10.1016/j.nme.2019.02.037

"Post exposure time dependence of deuterium retention in lithium and lithium compounds", Y. Yang, L. Buzi, A.O. Nelson, R. Kaita, B.E. Koel, *Nucl. Mater. and Energy,* **19**, 161−165 (2019). DOI:10.1016/j.nme.2019.01.031

"NSTX/NSTX-U theory, modeling and analysis results", S.M. Kaye, D.J. Battaglia, D. Baver, E. Belova, J.W. Berkery, V.N. Duarte, N. Ferraro, E. Fredrickson, N. Gorelenkov, W. Guttenfelder, G.Z. Hao, W. Heidbrink, O. Izacard, D. Kim, I. Krebs, R. La Haye, J. Lestz, D. Liu, L.A. Morton, J. Myra, D. Pfefferle, M. Podesta, Y. Ren, J Riquezes, S.A. Sabbagh, M. Schneller, F. Scotti, V. Soukhanovskii, S.J. Zweben, J.W. Ahn, J.P. Allain, R. Barchfeld, F. Bedoya, R.E. Bell, N. Bertelli, A. Bhattacharjee, M.D. Boyer, D. Brennan, G. Canal, J. Canik, N. Crocker, D. Darrow, L. Delgado-Aparicio, A. Diallo, C. Domier, F. Ebrahimi, T. Evans, R. Fonck, H. Frerichs, K. Gan, S. Gerhardt, T. Gray, T. Jarboe, S. Jardin, M.A. Jaworski, R. Kaita, B. Koel, E. Kolemen, D.M. Kriete, S. Kubota, B.P. LeBlanc, F. Levinton, N. Luhmann, R. Lunsford, R. Maingi, R. Maqueda, J.E. Menard, D. Mueller, C.E. Myers, M. Ono, J.-K. Park, R. Perkins, F. Poli, R. Raman, M. Reinke, T. Rhodes, C. Rowley, D. Russell, E. Schuster, O. Schmitz, Y. Sechrest, C.H. Skinner, D.R. Smith, T. Stotzfus-Dueck, B. Stratton, G. Taylor, K. Tritz, W. Wang, Z. Wang, I. Waters, B. Wirth, *Nucl. Fusion*, **59** (11), 112007 (2019). DOI:10.1088/1741-4326/ab023a

"Elemental and topographical imaging of microscopic variations in deposition on NSTX-U and DIII-D samples", C.H. Skinner, R. Bell, C.P. Chrobak , R. Kaita, B.E. Koel, W.R. Wampler, *Nucl. Mater. and Energy,* **18**, 35−40 (2018). DOI:10.1016/j.nme.2018.12.001

"Thermal stability of Li films on polycrystalline molybdenum substrates", O. Fasoranti and B.E. Koel, *J. Nucl. Mat.*, **509**, 532–541 (2018). DOI:10.1016/j.jnucmat.2018.05.081

"Hydrogen retention in lithium and lithium oxide films", L. Buzi, Y. Yang, F.J. Domínguez-Gutiérrez, A.O. Nelson, M. Hofman, P.S. Krstic, R. Kaita and B.E. Koel, *J. Nucl. Mat.* **502**, 161−168 (2018). DOI:10.1016/j.jnucmat.2018.02.010

"Unraveling the plasma-material interface with real time diagnosis of dynamic boron conditioning in extreme tokamak plasmas", F. J. Domínguez-Gutiérrez, F. Bedoya, P. S. Krstić, J. P. Allain, S. Irle, C. H. Skinner, R. Kaita and B. Koel*, Nucl. Fusion,* **57**, 086050 (2017). DOI:10.1088/1741-4326/aa7b17

"Overview of NSTX Upgrade initial results and modelling highlights", J. Menard, J.P. Allain, D. Battaglia, F. Bedoya, R. Bell, E. Belova, J. Berkery, M. Boyer, N. Crocker, A. Diallo, F.

Ebrahimi, N. Ferraro, E. Fredrickson, H. Frerichs, S. Gerhardt, N. Gorelenkov, W. Guttenfelder, W. Heidbrink, R. Kaita, S. Kaye, M. Kriete, S. Kubota, B. LeBlanc, D. Liu, R. Lunsford, D. Mueller, C. Myers, M. Ono, J.-K. Park, M. Podesta, R. Raman, M. Reinke, Y. Ren, S. Sabbagh, O. Schmitz, F. Scotti, Y. Sechrest, C. Skinner, D. Smith, V. Soukhanovskii, T. Stoltzfus-Dueck, H. Yuh, Z. Wang, I. Waters, J.-W. Ahn, R. Andre, R. Barchfeld, P. Beiersdorfer, N. Bertelli, A. Bhattacharjee, D. Boyle, D. Brennan, R. Buttery, A. Capece, G. Paganini Canal, J. Canik, C. Chang, D. Darrow, L. Delgado-Aparicio, C. Domier, S. Ethier, T. Evans, J. Ferron, M. Finkenthal, R. Fonck, K. Gan, D. Gates, I. Goumiri, T. Gray, J. Hosea, D. Humphreys, T. Jarboe, S. Jardin, M. Jaworski, B. Koel, E. Kolemen, S.-H. Ku, R. La Haye, F. Levinton, N. Luhmann, R. Maingi, R. Maqueda, G. McKee, E. Meier, J. Myra, R. Perkins, F. Poli, T. Rhodes, J. Riquezes, C. Rowley, D. Russell, E. Schuster, B. Stratton, D. Stutman, G. Taylor, K. Tritz, W. Wang, B. Wirth, S. Zweben*, Nucl. Fusion,* **57**(10), 102006 (2017). DOI:10.1088/1741-4326/aa600a

"Compatibility of lithium plasma-facing surfaces with high edge temperatures in the Lithium Tokamak Experiment (LTX)", R. Majeski, R. E. Bell, D. P. Boyle, R. Kaita, T. Kozub, B. P. LeBlanc, M. Lucia, R. Maingi, E. Merino, Y. Raitses, J. C. Schmitt, J. P. Allain, F. Bedoya, J. Bialek, T. M. Biewer, J. M. Canik, L. Buzi, B. E. Koel, M. I. Patino, A. M. Capece, C. Hansen, T. Jarboe, S. Kubota, W. A. Peebles, K. Tritz, *Phys. of Plasmas,* **24**, 056110 (2017). DOI:10.1063/1.4977916

"Advances in boronization on NSTX-Upgrade", C. H Skinner, F. Bedoya, F. Scotti, J.P. Allain, W. Blanchard, D. Cai, M. Jaworski, B.E. Koel, *Nucl. Mater. and Energy,* **12**, 744-748 (2017). DOI:10.1016/j.nme.2016.11.024

"Initial studies of plasma facing component surface conditioning in the National Spherical Tokamak Experiment Upgrade with the Materials Analysis Particle Probe", F. Bedoya, J.P. Allain, R. Kaita, C.H. Skinner, B.E. Koel and F. Scotti, *Nucl. Mater. and Energy,* **12**, 1248-1252 (2017). DOI:10.1016/j.nme.2017.03.035

"Hydrogen retention in lithium on metallic walls from "in vacuo" analysis in LTX and implications for high-Z plasma-facing components in NSTX-U", R. Kaita, M. Lucia, J.P. Allain, F. Bedoya, R. Bell, D. Boyle, A. Capece, M. Jaworski, B.E. Koel, R. Majeski, J. Roszell, J. Schmitt, F. Scotti, C.H. Skinner, V. Soukhanovskii, *Fusion Engin. Design,* **117** 135–139 (2017). DOI:10.1016/j.fusengdes.2016.06.056

"Unraveling wall conditioning effects on plasma facing components in NSTX-U with the Materials Analysis Particle Probe (MAPP)", F. Bedoya, J. P. Allain, R. Kaita, C. H. Skinner, L. Buzi and B. E. Koel, *Rev. Sci. Instrum.* **87**, 11D403-1-3 (2016). DOI:10.1063/1.4955276

"Secondary Electron Emission from Lithium and Lithium Compounds", A.M. Capece, M.I. Patino, Y. Raitses, and B. E. Koel, *Appl. Phys. Lett.,* **109**, 011605-1-5 (2016). DOI:10.1063/1.4955461

"Effect of Temperature on the Desorption of Lithium from Molybdenum (110) Surfaces: Implications for Fusion Reactor First Wall Materials", M. Chen, J. Roszell, E.V. Scoullos, C. Riplinger, B.E. Koel, and E.A. Carter, *J. Phys. Chem. B,* **120(26)**, 6110–6119 (2016). DOI:10.1021/acs.jpcb.6b02092

Invited seminars at Universities and Laboratories

"Fundamental surface science of PFCs for improved plasma performance in NSTX-U"
General Atomics, San Diego, CA, DIII-D Boundary/PMI Center, 3/21/17

Invited conference papers and presentations

Hydrogen Retention in Lithium and Lithium Compounds
L. Buzi, Y. Yang, O. A. Nelson, **B. E. Koel**
45th IEEE International Conference on Plasma Science (ICOPS 2018), Session 5D: 4.7 Plasma Material Interactions I, Denver, CO, 6/26/18

Invited Tutorial: Chemistry at the edge: Surface science probes of plasma-materials interactions
B. E. Koel
23rd International Conference on Plasma Surface Interactions in Controlled Fusion Devices (PSI-23), Princeton, NJ, 6/17/18

Conference papers and presentations

"Deuterium Retention in Lithium and Lithium Compounds"
Y. Yang and B.E. Koel
78th Physical Electronics Conference, University of New Hampshire, Durham, NH, June 2018

"Time Dependence of Deuterium Retention in Lithium and Lithium Compounds on Plasma Facing Components"
Y. Yang, L. Buzi, A.O. Nelson, R. Kaita and B.E. Koel
International Conference on Plasma-Surface Interactions in Controlled Fusion Devices (PSI-23), Princeton University, Princeton, NJ, June 2018

"Deuterium sputtering and retention in lithium-coated plasma-facing components"
A.O. Nelson, L. Buzi, Y. Yang, R. Kaita, B.E. Koel
International Conference on Plasma-Surface Interactions in Controlled Fusion Devices (PSI-23), Princeton University, Princeton, NJ, June 2018

"Investigation of Deuterium Retention in Thick Lithium Oxide Films on High-Z Plasma-Facing Components"

A. Maan, R. Kaita, D. Elliott, D.P. Boyle, R. Majeski, D. Donovan, L. Buzi, B.E. Koel, T.M. Biewer
International Conference on Plasma-Surface Interactions in Controlled Fusion Devices (PSI-23), Princeton University, Princeton, NJ, June 2018

"Sputtering of Li-C-O compounds under deuterium ion bombardment of plasma-facing component materials"
L. Buzi, Y. Yang, A.O. Nelson, R. Kaita, P.S. Krstić and B.E. Koel
International Conference on Plasma-Surface Interactions in Controlled Fusion Devices (PSI-23), Princeton University, Princeton, NJ, June 2018

"Elemental and topographical imaging of microscopic variations in deposition on NSTX-U and DIII-D samples"
C.H. Skinner, R. Bell, C.P. Chrobak, R. Kaita, B.E. Koel, W.R. Wampler
International Conference on Plasma-Surface Interactions in Controlled Fusion Devices (PSI-23), Princeton University, Princeton, NJ, June 2018

"Low Energy Deuterium Ion Interaction with Sn Films for Fusion Applications"
O. Fasoranti and B. E. Koel
2017 MRS Fall Meeting, Symposium: ES08: Advanced Nuclear Materials—Design, Development and Deployment, Boston, MA, November 2017

"Deuterium uptake by Sn films on a W substrate"
O. Fasoranti and B. Koel
70th Annual Gaseous Electronics Conference, Session WF2: Plasma-Surface Interactions, Pittsburgh, PA, November 2017

"Surface Properties of Tungsten for Plasma Interactions"
H. Khurram and B. Koel
PEI Summer of Learning Symposium, Princeton, NJ, October, 2017

"Hydrogen retention in Li and Li-C-O films" BP11 73
L. Buzi, A.O. Nelson, Y. Yang, R. Kaita, B.E. Koel
59th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP17), Milwaukee, WI, October 2017

"Deuterium sputtering of Li and Li-O films" BP11 74
A. Nelson, L. Buzi, R. Kaita, B. Koel
59th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP17), Milwaukee, WI, October 2017

"Elemental and topographical imaging of microscopic variations in deposition on NSTX-U and DIII-D samples" JO4 11
C.H. Skinner, R. Kaita, B.E. Koel, C.P. Chrobak, W.R. Wampler
59th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP17), Milwaukee, WI, October 2017

"XPS investigation of depth profiling induced chemistry" JP11 18
Q. Pratt, C. Skinner, B. Koel, Z. Chen
59th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP17), Milwaukee, WI, October 2017

"The LTX-β Research Program" UP11 102
R. Majeski, R.E. Bell, D.P. Boyle, P.E. Hughes, R. Kaita, T. Kozub, E. Merino, X. Zhang, T.M. Biewer, J.M. Canik, D.B. Elliott, M.L. Reinke, J. Bialek, C. Hansen, T. Jarboe, S. Kubota, T. Rhodes, M.A. Dorf, T. Rognlien, F. Scotti, V.A. Soukhanovskii, B.E. Koel, D. Donovan, A. Maan
59th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP17), Milwaukee, WI, October 2017

"Investigation of lithium PFC surface characteristics and low recycling at LTX/LTX-β" UP11 108
A. Maan, R. Kaita, D. Elliott, D. Boyle, R. Majeski, D. Donovan, L. Buzi, B.E. Koel, T.M Biewer
59th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP17), Milwaukee, WI, October 2017

"XPS study of depth profiling induced chemistry in NSTX-U tile samples"
Q. Pratt, C. Skinner, B. Koel, Z. Chen
DOE Science Undergraduate Laboratory Internship (SULI) Program Poster Presentations, PPPL, Princeton, NJ, August 2017

"Deuterium retention in thin lithium films as a function of surface temperature, oxygen impurities, and post-exposure time"
B.E. Koel, L. Buzi, Y. Yang and M. Hofman
23rd International Symposium on Plasma Chemistry, Montreal, Canada, July 2017

"The Effect of Temperature and Oxygen Concentration on the Stability of Li and Sn Films on Polycrystalline Tungsten"
O. Fasoranti, B. E. Koel
MRS 2016 Fall Meeting, Boston, MA, November 2016

"Advances in boronization on NSTX-Upgrade" GO6 8
C.H. Skinner, W. Blanchard, D. Cai, M. Jaworski, F. Bedoya, J.P. Allain, F. Scotti, B.E. Koel,
58th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP16), San Jose, CA, November 2016

"In-vacuo studies of Boronization and Lithiumization in NSTX-U and relationship to plasma performance" GO6 9
C. Bedoya, J. P. Allain, R. Kaita, C. Skinner, S. Filippo, B. Koel,

58th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP16), San Jose, CA, November 2016

"Impurity contamination effects on the interaction of Li and Sn Films on W(poly)" GO6 15
O. Fasoranti, B. Koel
58th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP16), San Jose, CA, November 2016

"Temperature Dependence of Lithium Reactions with Air" JP10 54
R. Sherrod, C.H. Skinner, B. Koel,
58th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP16), San Jose, CA, November 2016

"Analysis of surface chemistry of boronized TZM samples in NSTX-U between plasma exposures" NP10 41
H. Schamis, F. Bedoya, J. P. Allain, R. Kaita, B. Koel
58th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP16), San Jose, CA, November 2016

"Overview of the Lithium Tokamak eXperiment-Beta" NP10 59
R. Kaita, D.P. Boyle, T. Kozub, M. Lucia, R. Majeski, E. Merino, F. Scotti, B.E. Koel, S. Kubota, T. Rhodes, T. Biewer, M. Reinke, D. Donovan
58th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP16), San Jose, CA, November 2016

"The temperature and ion energy dependence of deuterium retention in lithium films" UO4 9
L. Buzi, B.E. Koel, C.H. Skinner
58th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP16), San Jose, CA, November 2016

"Deuterium uptake in boronized ATJ graphite walls of NSTX-U" YP10 99
J. Dominguez, F. Bedoya, P. Krstic, J.P. Allain, S. Irle, C. Skinner, R. Kaita, B. Koel
58th Annual Meeting of The American Physical Society Division of Plasma Physics (DPP16), San Jose, CA, November 2016

"High resolution imaging of W deposits on DIII-D graphite samples"
C. H. Skinner, W. R. Wampler, B. E. Koel
DIII-D National Campaign Ideas Forum, Princeton Plasma Physics Laboratory, Princeton, NJ, October 2016

"Recent progress in fundamental surface science for improved plasma performance in NSTX-U"
B. E. Koel, L. Buzi, O. Fasoranti, and X. Yang
NSTX-U Results Review, Princeton Plasma Physics Laboratory, Princeton, NJ, September, 2016

"PPPL Institutional Overview"

C. Skinner, J.P. Allain, F. Bedoya, M. Jaworski, R. Kaita, B. Koel, E. Kolemen, R. Majeski, R. Maingi, J. Menard
Fusion Materials/Plasma Materials Interactions PI Meeting, Oak Ridge National Laboratory, July 2016

"Fundamental surface science of PFCs for improved plasma performance in NSTX-U"
B.E. Koel,
NSTX-U Diagnostic Research Plan Meeting, PPPL, May 2016

"Unraveling wall conditioning effects of plasma facing components in NSTX-U with the Materials Analysis Particle Probe (MAPP)"
F. Bedoya, J.P. Allain, R. Kaita, C. Skinner , L. Buzi and B.E. Koel
21st Topical Conference on High Temperature Plasma Diagnostics (HTPD 2016), Madison, WI, June 2016

"Advances in boronization on NSTX-Upgrade"
C.H. Skinner, J.P. Allain, F. Bedoya, W. Blanchard, D. Cai, B.E. Koel, F. Scotti
22nd International Conference on Plasma Surface Interactions in Controlled Fusion Devices (22nd PSI), Rome, Italy, May 2016

"Secondary electron emission from several materials relevant to magnetic fusion devices"
Y. Raitses, M. Patino, A. Capece, B.E. Koel, and P. Dourbal
22nd International Conference on Plasma Surface Interactions in Controlled Fusion Devices (22nd PSI), Rome, Italy, May 2016

"In vacuo measurements of surface characteristics for lithium plasma facing components exposed to tokamak plasma discharges"
M. Lucia, J.P. Allain, F. Bedoya, M.A. Jaworski, R. Kaita, B.E. Koel, R. Majeski
22nd International Conference on Plasma Surface Interactions in Controlled Fusion Devices (22nd PSI), Rome, Italy, May 2016

"Initial studies of PFC conditioning in the National Spherical Tokamak Experiment Upgrade with the Materials Analysis Particle Probe"
F. Bedoya, J.P. Allain, R. Kaita, C. H. Skinner, M. Lucia, M. Jaworski, F. Scotti and B. E. Koel
22nd International Conference on Plasma Surface Interactions in Controlled Fusion Devices (22nd PSI), Rome, Italy, May 2016

"Sensitivity of WallDYN material migration modeling to uncertainties in mixed-material surface binding energies"
J.H. Nichols, M.A. Jaworski, K. Schmid, L. Buzi, B. Koel
22nd International Conference on Plasma Surface Interactions in Controlled Fusion Devices (22nd PSI), Rome, Italy, May 2016

"Effects of Temperature on the stability of Li and Sn on PFC Substrates"
O. Fasoranti and B. E. Koel

Princeton E-ffiliates Partnership 4th Annual Meeting, Princeton University, Princeton, NJ, November 2015

"Thermal Stability of Sn and Li on Polycrystalline Molybdenum"
O. Fasoranti and B. E. Koel
75th Annual Meeting of the Physical Electronics Conference, New Brunswick, NJ, June 2015

"Multi-scale, integrated divertor plasma-material simulation"
P. Krstić, D. Stotler, I. Kaganovich, and B. E. Koel,
FES Community Planning PMI Workshop, Princeton, NJ, May, 2015

"Coordinated experimental-modeling approach to low-risk PFCs for FNSF/DEMO"
C.H. Skinner, P. Krstic, J.P. Allain, R. Kaita, B.E. Koel, D.N. Ruzic,
FES Community Planning PMI Workshop, Princeton, NJ, May, 2015

"NSTX-U Collaboration Research Plans for Princeton University Surface Science"
B. E. Koel, J. Roszell, C. Skinner, T. Thiem
NSTX-U Physics Meeting, PPPL, Princeton, NJ, March 2015

"Surface Science Collaboration"
B. E. Koel, C. Skinner, J. Roszell
NSTX-U Research Forum, PPPL, Princeton, NJ, February 2015

"Optimal Mo tile surface"
C. Skinner, B. E. Koel, J. Roszell
NSTX-U Research Forum, PPPL, Princeton, NJ, February 2015

"Effect of B conditioning"
C. Skinner, B. E. Koel, J. Roszell, J.P. Allain, F. Bedoya
NSTX-U Research Forum, PPPL, Princeton, NJ, February 2015

Participants & Collaborating Organizations

<u>A. The following individuals from Princeton University worked on this project.</u>

1. Koel, Bruce; PI, CBE, Princeton University
2. Buzi, Luxherta; Postdoctoral Research Associate in CBE, Princeton University
3. Chen, Zhu; graduate student in CBE, Princeton University
4. Fasoranti, Oluseyi; (minority, black) graduate student in Chem., Princeton University
5. Hofman, Michelle; (female) graduate student in Chem., Princeton University
6. Kraya, Laura; Postdoctoral Research Associate in CBE, Princeton University
7. Scoullos, Emanuel; graduate student in CBE, Princeton University
8. Thiem, Thomas; graduate student in CBE, Princeton University
9. Yang, Xiaofang; Associate Research Scholar in CBE, Princeton University
10. Yang, Yuxin; graduate student in CBE, Princeton University

Details on individuals from Princeton University are given below.

1. Name: Bruce E. Koel
2. Total Number of Months: 0
3. Project Role: PI
4. Researcher Identifier: 01
5. Contribution to Project: Directed and managed this project.
6. State, U.S. territory, and/or country of residence: New Jersey, USA
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: No
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay:

1. Name: Luxherta Buzi
2. Total Number of Months: 15
3. Project Role: Postdoctoral position
4. Researcher Identifier: 02
5. Contribution to Project: Participated in UHV surface science studies. Supervised laboratory experiments, student training, lab safety. Repaired and improved equipment.
6. State, U.S. territory, and/or country of residence: New Jersey, USA
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: No
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay:

1. Name: Chen Zhu
2. Total Number of Months: 7
3. Project Role: Graduate student
4. Researcher Identifier: 04

5. Contribution to Project: Designed and built equipment. Repaired equipment. Participated in UHV surface science studies. Trained students for UHV surface science studies.
6. State, U.S. territory, and/or country of residence: New Jersey, USA
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: No
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay:

1. Name: Oluseyi Fasoranti
2. Total Number of Months: 15
3. Project Role: Graduate student
4. Researcher Identifier: 04
5. Contribution to Project: Participated in UHV surface science studies. Designed and built equipment. Repaired equipment.
6. State, U.S. territory, and/or country of residence: New Jersey, USA
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: No
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay:

1. Name: Michelle Hofman
2. Total Number of Months: 3
3. Project Role: Graduate student
4. Researcher Identifier: 05
5. Contribution to Project: Participated in UHV surface science studies. Designed and built equipment. Repaired equipment.
6. State, U.S. territory, and/or country of residence: New Jersey, USA
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: No
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay:

1. Name: Laura Kraya
2. Total Number of Months: 6
3. Project Role: Postdoctoral position
4. Researcher Identifier: 06
5. Contribution to Project: Participated in UHV surface science studies. Supervised laboratory experiments, student training, lab safety. Repaired equipment.
6. State, U.S. territory, and/or country of residence: New Jersey, USA
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: No
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay:

1. Name: Emanuel Scoullos
2. Total Number of Months: 5
3. Project Role: Graduate student
4. Researcher Identifier: 07
5. Contribution to Project: Participated in UHV surface science studies.
6. State, U.S. territory, and/or country of residence: New Jersey, USA
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: No
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay:

1. Name: Thomas Thiem
2. Total Number of Months: 5
3. Project Role: Graduate student
4. Researcher Identifier: 08
5. Contribution to Project: Participated in UHV surface science studies.
6. State, U.S. territory, and/or country of residence: New Jersey, USA
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: No
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay:

1. Name: Xiaofang Yang
2. Total Number of Months: 5
3. Project Role: Postdoctoral position
4. Researcher Identifier: 09
5. Contribution to Project: Participated in UHV surface science studies. Supervised laboratory experiments, student training, lab safety. Repaired and improved equipment.
6. State, U.S. territory, and/or country of residence: New Jersey, USA
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: No
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay:

1. Name: Yuxin Yang
2. Total Number of Months: 13
3. Project Role: Graduate student
4. Researcher Identifier: 10
5. Contribution to Project: Participated in UHV surface science studies. Designed and built equipment. Repaired equipment.
6. State, U.S. territory, and/or country of residence: New Jersey, USA
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: No
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay:

B. Other Collaborators

1. Allain, Jean P.; University of Illinois at Urbana-Champaign
   Collaborations using the MAPP probe on NSTX-U.

2. Krstic, Predrag S.; Stony Brook University
   Collaborations involving modeling of materials containing D, Li, C, O, and Mo.

3. Trelewicz, Jason R.; Stony Brook University
   Collaborations on investigations of nano-tungsten materials.