DOE-USD-SC0014226: Final Scientific/Technical Report

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DOE project abstract:

The common states of matter on Earth are solids, liquids and gases. Putting energy into gases can result in the 4th state of matter known as plasma, which consists of electrically charged particles (electrons and ions, both positive and negative) and neutral atoms and molecules. While uncommon on the Earth, plasma makes up more than 99% of the visible matter in the universe. Where plasma comes in contact with material boundaries, a thin region near the plasma boundary usually forms to isolate the plasma from the boundary. This thin region is called the plasma sheath. Experiments performed under aimed at improving our understanding of plasma sheaths and associated phenomena as fundamental to understanding all bounded plasmas. Plasma studied in this work are similar to those used in plasma applications such as the etching of semiconducting materials to make computer chips, in plasma space propulsion satellite engines, and used in experimental plasma fusion devices. The majority of experimental studies were carried out at the University of Wisconsin-Madison in close collaboration with Dr. Severn at the University of San Diego (USD), where most of diagnostic development for laser-induced fluorescence (LIF) measurements were carried out. USD is primarily an undergraduate institution. The award made possible outreach activities that promoted engagement of undergraduate students with diverse backgrounds in science, technology, engineering and mathematics (STEM) disciplines.

Experiments addressed important questions associated with sheaths and the Bohm Criterion in multiple ion species plasma, many for the first time. In previous work, this collaborative group discovered anomalous sheath edge velocities while testing the Bohm Criterion in two ion species plasma. This effect has now been theoretically explained via the introduction of ion-ion streaming instabilities that led to something now called instability enhanced collisional friction (IEF). As a result, many different aspects of sheath formation must be reevaluated in light of the new theory, and much of our work involved experimental tests of the theory that were performed for the first time. Moreover, there had been no tests of the Bohm Criterion in magnetized plasmas that involved measurements of ion flow. The experiments performed under this award were the first. We found that currently accepted model of the magnetized plasma boundary was not valid. In what follows, a brief overview of salient results will be given.

As we have said, plasma sheaths are non-neutral regions that form at plasma boundaries to balance electron and ion losses. They are the most ubiquitous feature of bounded plasma. Although Langmuir introduced the terms sheath and plasma almost 100 years ago, benchmark experiments of sheath formation and associated presheaths in unmagnetized and magnetized plasma have only recently been performed. We describe our work under two headings referred to above, I) Consequences of instability enhanced collisional friction, and II) Fundamental phenomenology of magnetic presheaths and sheaths. These are described below.

I) Sheaths are a very important property of all plasmas. They are important because sheath properties are critical in plasma processing responsible for ultra large scale integrated circuit (IC) fabrication that provides, for example, the IC's that power computers and cell phones. Sheaths were first discussed in Langmuir's pioneering work in the 1920's, however the first detailed experiments to benchmark theory wasn't performed until eight decades later. These experiments studied single ion species plasma. It was verified that in order for the sheath to form, presheaths that were later suggested by Bohm were formed to accelerate ions to super-sonic speed at the sheath edge as predicted.

In previous funding cycles, we carried out the first ever experimental studies in two ion species plasma. Ion flow at the sheath edge was not found to occur as predicted. We discovered instability-enhanced collisional friction (IEF), which is inherent in all multiple ion species plasma, and which later was found to agree with a new kinetic theory of the process. In the work supported between FY15-FY18, we performed the first experiments ever studying sheath formation in 3 ion species plasma, (see figure 1) and the first three publications in this new area of research have come out. The individual Bohm speed (super-sonic speed) is still widely used as the default assumption in the literature for modeling ion flow to the plasma boundary in multiple ion species plasma in a wide variety of bounded

plasma systems ranging from processing plasma to the scrape off layer in tokamaks. The chief result of this work is that in a 3 ion species plasma, this is generally not true. The most impactful publication in this area of our work was, "Experimental studies of ion flow near the sheath edge in multiple ion species plasma including Argon, Xenon, and Neon," Greg Severn, Chi-Shung Yip, Noah Hershkowitz, Scott Baalrud, Plasma Sources Sci. Technol. 26 055021 May (2017).

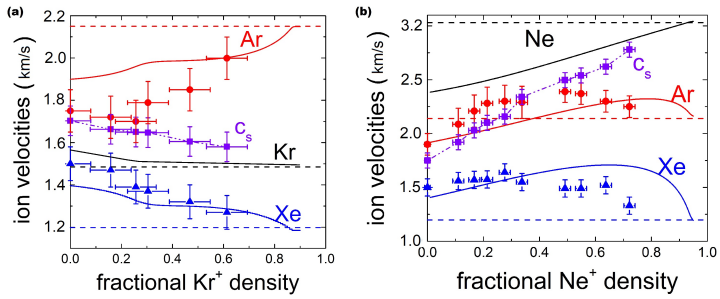

Figure 1: velocities at the sheath edge for argon (red) and xenon (blue). The theory calculations assumed $T_e/T_i = 1.95/0.026 = 75$, and assumed Ar, Xe ion densities remained equal and fixed. Theory curves are solid lines, given for all three ions, krypton in black in figure (a) on the left, and neon in black in figure (b) on the right. The individual sounds speeds are indicated by dashed lines. For all data points in this figure $T_e = 1.95 \pm 0.08eV$.

II) Many bounded plasmas of importance employ magnetic fields for plasma confinement, and understanding sheath formation at plasma boundaries in which magnetic fields are present is only now becoming the subject of benchmark experiments. These plasma systems are important because they are essential components for next generation energy production technology such as tokamak magnetic fusion reactors. They are also of critical importance in plasma based ion thrusters, in current use in satellite positioning control, a necessary component of the world's GPS, TV, and communication systems. In this and previous funding cycles, we carried out the first ever studies of presheath measurements with laser-induced fluorescence (LIF) in the neighborhood of a grounded stainless steel limiter plate oriented obliquely to the ambient magnetic field, (see figure 2) published in the work referenced below. The experiments were performed in two argon helicon experiments (MARIA at the University of Wisconsin-Madison and HELIX at West Virginia University), using LIF. A 3D ion fluid model that accounted for ionization and charge-exchange collisions was found to accurately describe the measured ion flows in regions where the ion flux tubes intersect the boundary. This work was original in many respects and advanced scientific knowledge of magnetic presheaths, however, the result of chief importance was this: the generally accepted magnetic presheath model, first published in the early 80's, was shown to be invalid. The most impactful publication in this area of our work was, "Models, assumptions, and experimental tests of flows near boundaries in magnetized plasmas, " M. Umair Siddiqui, D. S. Thompson, C. D. Jackson, J. F. Kim, N. Hershkowitz, and E. E. Scime, Phys. Plasmas **23** 057101 (2016).

At USD, two undergraduates, Quinn Pratt and Eugene Wackerbarth participated in the research and have learned to perform LIF measurements and to reduce the data to moments of the velocity distribution function. Both wrote matlab scripts to control NI-DAQ hardware and to perform data analysis. Quinn was accepted into the Summer Undergraduate Laboratory Internship (SULI) program at PPPL (summer 2017), and later was admitted as a graduate student in Physics at UCLA. Eugene Wackerbarth has recently begun to work for Leidos. Dr. Severn trained and mentored these students, as well as graduate students and research staff in the lab of his collaborator, Dr. Noah Hershkowitz.

Major activities and results:

Sheath formation in multiple-ion species plasma LIF measurements has been carried out in plasmas consisting of Ar+, Xe+ and Ne+, and Ar+, Xe+, and Kr+ plasma. Estimation of relative ion concentrations are being improved through the adoption of G-H. Kims loss-production balance model [NK Kim et al., J. Phys. D: Appl. Phys. 48 (2015) 225201]. As with the case with added Kr+ ions, the escape velocity of Ar+ and Xe+ ions started near the system sound speed without any Ne+ ions and did not approach their individual Bohm speed until 80% Ne+ ions were added to the system. G-H. Kims loss-production balance model as well as an improved model using Baalrud et al.s instability enhanced collisional friction theory had been applied to both the previous Ar-Kr-Xe LIF data and new Ne-Ar-Xe LIF data. Again qualitative agreement was achieved. This work resulted in multiple publications and conference papers and an APS-GEC invited talk (GEC-2016 Bochum, Germany).

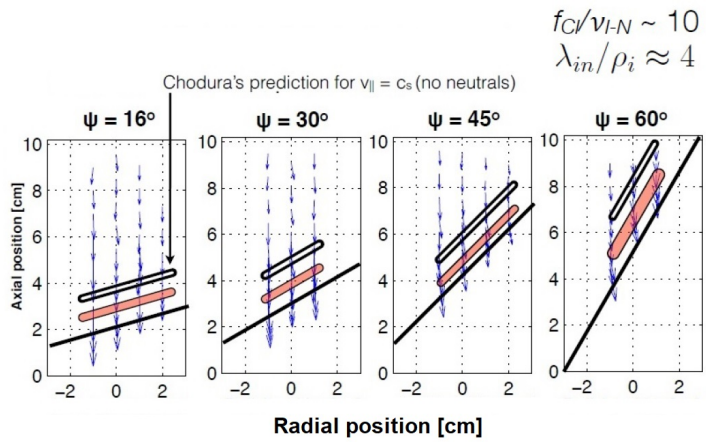

Figure 2: Here 2D argon ion flow field plots taken upstream of the grounded limiter plate in the MARIA helicon source for four different angles ψ, relative to the axial magnetic field. The black lines show the locations of the grounded plate, the red ovals show the locations where $v_{\parallel} = c_s$ was measured, and the black ovals show where Choduras prediction for this location should be in the system

Virtual Cathodes Ion transfer in virtual cathodes had been investigated using the LIF technique. Ion velocity-locking phenomena within the virtual cathode and its adjacent presheath were identified. Reflected ions were detected when the electrode was biased 1Te/e above the bulk plasma potential. Ion velocity-locking where ions gained less than 10% of the potential energy traveling through the potential profile was observed to be strongly associated with the detection of reflected ions. The BCH two-stream instability enhanced collisional friction theory was invoked to explain the observation of ion velocity-locking and provided good qualitative agreement with the experimental results. This work resulted in one publication and multiple conference papers.

Magnetic presheaths Many bounded plasmas of importance employ magnetic fields for plasma confinement, and understanding sheath formation at plasma boundaries in which magnetic fields are present is only now becoming the subject of benchmark experiments. These plasma systems are important because they are essential components for next generation energy production technology such as tokamak magnetic fusion reactors. They are also of critical importance in plasma based ion thrusters, in current use in satellite positioning control, a necessary component of the world's GPS, TV, and communication systems. In this and previous funding cycles, we carried out the first ever studies of presheath measurements with laser-induced fluorescence (LIF) in the neighborhood of a grounded stainless steel limiter plate oriented obliquely to the ambient magnetic field, published in the work referenced above. The experiments (see, e.g., Siddiqui et al., "'Models, assumptions, and experimental tests of flows near boundaries in magnetized plasmas," Phys. Plasmas 23 057101 (2016)) were performed in two argon helicon experiments (MARIA at the University of Wisconsin-Madison and HELIX at West Virginia University), using LIF. A 3D ion fluid model that accounted for ionization and charge-exchange collisions was found to accurately describe the measured ion flows in regions where the ion flux tubes intersect the boundary. This work was original in many respects and advanced scientific knowledge of magnetic presheaths, however, the result of chief importance was this: the generally accepted magnetic presheath model, first published in the early 80's, was shown to be invalid.

Comparison of Langmuir probe and emissive probes We have demonstrated that the plasma potential measured by cylindrical Langmuir probes are measurably different from that of emissive probe measurements in the neighborhood of a negatively biased sheath, in a weakly collisional, weakly ionized, low temperature argon plasma. Specifically, we so far demonstrated 4 things:

1. the cylindrical probe measurement of the plasma potential is more positive than that measured by the emissive probe beginning multiple sheath thicknesses from the biased electrode,
2. and becomes increasing positive through the presheath and dramatically so in the sheath. throughout the body of the plasma, including a portion of the presheath, the plasma potential measured by the emissive probe is offset positively with respect to that of the cylindrical Langmuir probe, by a fraction of an electron temperature ((identical profile, but displaced).

3. results similar to 4.1) and 4.2) have been found to be true of 2 sided planar Langmuir probes and Langmuir probes with one side coated so that current is collected from the side facing away from the biased electrode and facing the bulk plasma.
4. results with coated Langmuir Probe measurements with one side coated so that current is collected from the wake formed around the probe by ion flow through the presheath, in the usual process of sheath formation, actually follows emissive probe measurements to some extent, more nearly than any of the other Langmuir probe configurations.

Project publication, and conference presentations:

21. *Exploiting Zeeman Effect Symmetries to Measure Ion Velocities in Magnetized Plasmas,* Green, Jonathan; Schmitz, Oliver; Severn, Greg; Winters, Victoria, Meas. Sci. Technol, **30** 055202 (2019).

20. *Experimental studies of ion flow near the sheath edge in multiple ion species plasma including Argon, Xenon, and Neon* by Severn, Greg; Yip, Chi-Shung; Hershkowitz, Noah; Baalrud, Scott D, Plasma Sources Sci. Technol. 26 055021 May (2017).

19. *Ion velocity-locking in the neighborhood of virtual cathodes via instability enhanced collisional friction* Chi-Shung Yip, Noah Hershkowitz, and Greg Severn, Plasma Sources Sci. Technol. **26** 015008, (2017).

18. *Laser-induced fluorescence measurements of argon and xenon ion velocities near the sheath boundary in 3 ion species plasmas* Chi-Shung Yip, Noah Hershkowitz, Greg Severn and Scott D. Baalrud Phys. Plasmas 23, 050703 (2016).

17. *Development of Spectroscopic Diagnostics for Assessing the Role Neutral Fueling Plays in the Production of High Density Helicon Plasmas,* Jonathan Green, Patrick J Leonard (Univ of Wisconsin, Madison), Nicholas I Arnold, Stuart David Loch (Auburn Univ), Gregory D Severn, and Oliver Schmitz (Univ of Wisconsin, Madison) , 60th Annual Meeting of the APS Division of Plasma, Physics, APS-DPP, November 5 9, 2018; Portland, Oregon

16. *Is Bohm's criterion satisfied near a negatively biased grid in a single ion species Krypton Plasma?* Eugene Wackerbarth (Dept. Physics & Biophysics, University of San Diego), Noah Hershkowitz (Dept. Engineering Physics, University of Wisconsin, Madison), and Greg Severn (Dept. Physics & Biophysics, University of San Diego), 60th Annual Meeting of the APS Division of Plasma Physics, APS-DPP, November 5 9, 2018; Portland, Oregon

15. *Emissive probe measurements in sheath, presheath, and virtual cathode,* Peixuan Li , Noah Hershkowitz , Sirous Nourgostar , Lutfi Oksuz , Gregory D Severn, 60th Annual Meeting of the APS Division of Plasma Physics, APS-DPP, November 5 9, 2018; Portland, Oregon

14. *Experimental studies of sheath formation in multiple ion species plasma, electronegative and electropositive* Greg Severn (Dept. Physics & Biophysics, University of San Diego), Noah Hershkowitz (Dept. Engineering Physics, University of Wisconsin, Madison), 71st Annual Gaseous Electronics Conference, November 5 9, 2018; Portland, Oregon

13. *Spectroscopic Plasma Diagnostics and Plasma Fueling Experiments for Improved Axial Density Uniformity in Helicon Plasmas Considered for Plasma Wakefield Accelerators*, J. Green, P.J. Leonard, O. Schmitz (Univ of Wisconsin, Madison), I. Arnold, S. Loch (Auburn University, Auburn, AL), G. Severn (University of San Diego, San Diego, CA) A. Caldwell (Max Planck Institute for Physics, Munich, Germany), E. Gschwendtner (CERN, Geneva, Switzerland), O. Grulke (Max Planck Institute for Plasma Physics, Greifswald, Germany), 18th Advanced Accelerator Concepts Workshop, Breckenridge, CO, Aug 12 - 17 2018

12. *Acting like an experimentalist: Transforming post-lab reports into in-lab notebooks*, Chad Kishimoto and Greg Severn, 2018 Conference on Laboratory Instruction Beyond the First Year, BFY III: 3D Physics: Integrating Experiment, Theory, and Computation, Loyola University, Baltimore MD, July 25-27 2018

11. *Progress Towards Spectroscopic Diagnostics of Plasma Parameters and Neutral Dynamics in Helicon Plasmas,* Jonathan Green, Oliver Schmitz (Univ of Wisconsin, Madison), Greg Severn (University of San Diego), Lars van Ruremonde (Eindhoven University of Technology), Victoria Winters (University of Wisconsin, Madison), 59th Annual Meeting of the APS Division of Plasma Physics, APS-DPP, October 23 27, 2017; Milwaukee, Wisconsin

10. *Measurement of sheath potential by three emissive-probe methods in DC filament plasmas near a biased grid,* In-Je Kang, In-Sun Park, Min-Keun Bae, Kyu-Sun Chung (Dept. Electrical Engineering, Hanyang University, Seoul, Republic of Korea), Noah Hershkowitz (Dept. Engineering Physics, University of Wisconsin, Madison), Eugene Wackerbarth, Greg Severn (Dept. Physics & Biophysics, University of San Diego), 59th Annual Meeting of the APS Division of Plasma Physics, October 23 27, 2017; Milwaukee, Wisconsin

9. *Is Bohm's Criterion satisfied in a weakly ionized Kr discharge, in the vicinity of a biased grid that permits counter streaming ion flow?* Eugene Wackerbarth, Greg Severn (Dept. Physics & Biophysics, University of San Diego), In-Je Kang, In-Sun Park, Min-Keun Bae, Kyu-Sun Chung (Dept. Electrical Engineering, Hanyang University, Seoul, Republic of Korea), Noah Hershkowitz (Dept. Engineering Physics, University of Wisconsin, Madison), 59th Annual Meeting of the APS Division of Plasma Physics, October 2327, 2017; Milwaukee, Wisconsin

8. *Are the things you read in theory papers that have not been experimentally validated true?*, Greg Severn, University of San Diego, and Noah Hershkowitz, University of Wisconsin-Madison, 20th Anniversary NSF/DOE Plasma Partnership Workshop, NSF , Arlington VA, 9-11 January 2017

7. *Ion transport and entrapment in electrostatic virtual cathodes*, Chi-Shung Yip, Noah Hershkowitz, University of Wisconsin Madison, and Greg Severn, University of San Diego, 58th Annual Meeting of the APS Division of Plasma Physics, October 31November 4 2016; San Jose, California

6. *Ion loss in weakly collisional three ion species plasmas*, Chi-Shung Yip, Noah Hershkowitz, University of Wisconsin Madison, and Greg Severn, University of San Diego, 58th Annual Meeting of the APS Division of Plasma Physics, October 31November 4 2016; San Jose, California

5. *Upgrades to the MARIA Helicon Experiment at UW-Madison*, Jonathan Green, Noah Hershkowitz, Victoria Winters, and Oliver Schmitz, University of Wisconsin Madison, and Greg Severn, University of San Diego, 58th Annual Meeting of the APS Division of Plasma Physics, October 31November 4 2016; San Jose, California

4. *"MEASUREMENT OF AXIAL ION FLOW PROFILES IN A LINEAR HELICON PLASMA WITHOUT EXPLICIT DE-CONVOLUTION OF THE MEASURED LINE SHAPES"* J. Green, O. Schmitz, V. Winters, University of Wisconsin - Madison, Department of Engineering Physics, Madison, WI, USA, G. Severn, University of San Diego, Department of Physics and Biophysics, San Diego, CA, USA, 19th International Conference on Atomic Processes in Plasmas, (APiP) Paris, April 2016

3. *BP12.00058 : The MARIA Helicon Plasma Experiment at UW Madison: Upgrade, Initial Scientific Goals Mission and First Results*, Victoria Winters, Jonathan Green, Noah Hershkowitz, and Oliver Schmitz, University of Wisconsin Madison, Greg Severn, University of San Diego, 57th Annual Meeting of the APS Division of Plasma Physics, November 1620, 2015; Savannah, Georgia

2. *GT1.00037 : Is the Bohm Criterion satisfied in magnetized plasmas, and how does ion-neutral collisionality matter?* Greg Severn, Dept. of Physics, University of San Diego, Jonathan Green, Victoria Winters, Chi-Shung Yip, Noah Hershkowitz, Oliver Schmitz, Dept. of Engineering Physics, University of Wisconsin-Madison) 68th Annual Gaseous Electronics Conference/9th International Conference on Reactive Plasmas/33rd Symposium on Plasma Processing, October 1216, 2015; Honolulu, Hawaii

1. *NR3.00006 : Virtual Cathodes near small electrodes biased near the plasma potential and its effects on Langmuir probes,* Chi-Shung Yip, Noah Hershkowitz, Dept. of Engineering Physics, University of Wisconsin-Madison, Greg Severn, Dept. of Physics, University of San Diego, 68th Annual Gaseous Electronics Conference/9th International Conference on Reactive Plasmas/33rd Symposium on Plasma Processing, October 1216, 2015; Honolulu, Hawaii