

**Final report for DE-SC0016473 “Fluctuations and Self-Organization in Plasma Boundary Layers”**

(Co PI’s: Scott Baalrud and Robert Merlino) \$655,000, 7/1/2016 – 6/30/2020 (2-year no-cost extended).

**Publications**

(I) R. Hood, B. Scheiner, S. D. Baalrud, M. M. Hopkins, E. V. Barnat, B. T. Yee, R. L. Merlino, and F. Skiff, Ion flow and sheath structure near positively biased electrodes, Phys. Plasmas 23, 113503 (2016). <https://doi.org/10.1063/1.4967870>

(II) S. Mattingly and F. Skiff, Velocity space degrees of freedom of plasma fluctuations, Physics of Plasmas 24, 090703 (2017). <https://doi.org/10.1063/1.4996012>

(III) F. Chu, S. W. Mattingly, J. Berumen, R. Hood, and F. Skiff, On determining the fraction of metastable ions produced by direct ionization, J. Instrum. 12, C11005 (2017). DOI 10.1088/1748-0221/12/11/C11005

(IV) S. Mattingly, and F. Skiff, A technique for plasma velocity-space cross-correlation, Phys. Plasmas 25, 055707 (2018). <https://doi.org/10.1063/1.5016352>

(V) S. Mattingly and F. Skiff, FPGA based demodulation of laser induced fluorescence in plasmas, Rev. Sci. Instrum. 89, 043508 (2018). <https://doi.org/10.1063/1.4995971>

(VI) J. Berumen and F. Skiff, Analysis and comparison of ion-acoustic wave reflection using laser-induced fluorescence and Langmuir probes, Phys. Plasmas 25, 122102 (2018). <https://doi.org/10.1063/1.5058805>

(VII) F. Chu, and F. Skiff, A Lagrangian model for laser-induced fluorescence and its application to measurements of plasma ion temperature and electrostatic waves, Physics of Plasmas 25, 013506 (2018). <https://doi.org/10.1063/1.5020088>

(VIII) F. Chu, R. Hood and F. Skiff, Measurement of wave-particle interaction and metastable lifetime using laser-induced fluorescence, Phys. Plasmas 26, 042111 (2019). <https://doi.org/10.1063/1.5089178>

(IX) F. Chu and F. Skiff, Determining Metastable Ion Lifetime and History through Wave-Particle Interaction, PRL 122, 075001 (2019). <https://doi.org/10.1103/PhysRevLett.122.075001>

(X) R. Hood, S. D. Baalrud, R. Merlino, and F. Skiff, “Laser-induced fluorescence measurements of ion fluctuations in electron and ion presheaths, Phys. Plasmas 27, 053509 (2020)  
<https://doi.org/10.1063/1.5142014>.

### Broader impacts publications

(I) <https://www.youtube.com/watch?v=XZ3NBdwAMFo>

(II) Elgendy, H., Maia, Skiff, F., Denehy G., Qian, F., Comparison of light propagation in dental tissues and nano-filled resin-based composite, Clinical Oral Investigations (2019) 23:423–433  
<https://doi.org/10.1007/s00784-018-2451-9>

(III) E H Ismail, D V Dawson, C Vidal, F N Skiff, K Brogden, R R Maia, “The Effect of Varying Dentin Chroma and Enamel Thickness on the Color of A2 Double-layered Resin Composite”, Oper. Dent. Dec 15, (2022). <https://doi.org/10.2341/21-138-L>

### Contributed papers

|      |                                                                                                                                                                                                                                                                                                                                                                                         |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2019 | 34th International Conference on Phenomena in Ionized Gasses, <i>An electron plasma wave transmission diagnostic</i> , Sapporo, Japan Presenters/Authors: Skiff, Frederick N Student Presenters/Authors: Hood, Ryan, Beving, Lucas                                                                                                                                                      |
| 2018 | 60th Annual Meeting of the APS Division of Plasma Physics, <i>An electron plasma wave absorption diagnostic</i> , American Physical Society, Portland, Oregon Presenters/Authors: Skiff, Frederick N, Hood, Ryan, Beving, Lucas                                                                                                                                                         |
| 2018 | 60th Annual Meeting of the APS Division of Plasma Physics, <i>High frequency electric-field-driven instability in the electron presheath</i> , American Physical Society, Portland, Oregon Presenters/Authors: Skiff, Frederick N, Baalrud, Scott Student Presenters/Authors: Beving, Lucas, Hood, Ryan                                                                                 |
| 2018 | 60th Annual Meeting of the APS Division of Plasma Physics, <i>Using Gyrokinetic Simulations to Explore the Acceleration of Auroral Electrons by Alfvén Waves</i> , American Physical Society, Portland, Oregon Presenters/Authors: Skiff, Frederick N, Howes, Gregory G, Schroeder, James W.R., Klein, Kristopher G, Kletzing, Craig A Student Presenters/Authors: Verniero, Jennifer L |
| 2019 | International Conference on Laser Spectroscopy, <i>Plasma Spectroscopy on Metastable Ions</i> , Dodd Waals Center, New Zealand, Queenstown, New Zealand Presenters/Authors: Skiff, Frederick N, Chu, Feng                                                                                                                                                                               |
| 2019 | European conference on plasma diagnostics, <i>A wave absorption diagnostic for electron plasma waves</i> , European Physical Society, Lisbon, Portugal Presenters/Authors: Skiff, Frederick N Student Presenters/Authors: Hood, Ryan, Beving, Lucas                                                                                                                                     |
| 2018 | 8th International Workshop on Plasma Spectroscopy, <i>Understanding LIF on Metastable States</i> , University of Oxford, Oxford, England Peer-Reviewed/Refereed Presenters/Authors: Skiff, Fred Student Presenters/Authors: Chu, Feng                                                                                                                                                   |
| 2017 | Division of Plasma Physics, <i>New Frontier Science Campaign on DIII-D launched in</i>                                                                                                                                                                                                                                                                                                  |

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|      | 2017, American Physical Society, Milwaukee, Wisconsin, United States<br>Presenters/Authors: Koepke, Mark, Buttery, Richard, Carter, Troy, Egedal, Jan, Fox, William, Ji, Hantao, Sarff, John, Skiff, Fred, Spong, Don, Forest, Cary, Howes, Gregory G                                                                                                           |
| 2017 | 59th Annual Meeting of the APS Division of Plasma Physics, <i>Direct measurement of the concentration of metastable ions produced from neutral gas particles using laser-induced fluorescence</i> , APS, Milwaukee, Wisconsin, United States Presenters/Authors: Skiff, Fred Student Presenters/Authors: Chu, Feng, Berumen, Jorge, Mattingly, Sean, Hood, Ryan |
| 2017 | 59th Annual Meeting of the APS Division of Plasma Physics, <i>Exploring the Alfvén-wave acceleration of auroral electrons in the laboratory</i> , APS, Milwaukee, Wisconsin, United States Presenters/Authors: Schroeder, James, Howes, Gregory G, Skiff, Fred, Kletzing, Craig A, Carter, Troy A, Vincena, Steven, Dorfman, Seth                               |
| 2017 | 59th Annual Meeting of the APS Division of Plasma Physics, <i>Ion-Acoustic Wave-Particle Energy Flow Rates</i> , APS, Milwaukee, Wisconsin, United States Presenters/Authors: Skiff, Fred Student Presenters/Authors: Berumen, Jorge, Chu, Feng, Hood, Ryan, Mattingly, Sean                                                                                    |
| 2017 | 59th Annual Meeting of the APS Division of Plasma Physics, <i>Using field-particle correlations to study auroral electron acceleration in the LAPD</i> , APS, Milwaukee, Wisconsin, United States Presenters/Authors: Schroeder, James, Howes, Gregory G, Skiff, Fred, Kletzing, Craig A, Carter, Troy A, Vincena, Steven, Dorfman, Seth                        |
| 2017 | 59th Annual Meeting of the APS Division of Plasma Physics, <i>Velocity-space cross-correlation matrix measurements and potential applications to space plasmas</i> , APS, Milwaukee, Wisconsin, United States Presenters/Authors: Skiff, Fred Student Presenters/Authors: Mattingly, Sean                                                                       |
| 2017 | 18TH Laser Aided Plasma Diagnostics, <i>A Lagrangian Model for LIF and its Application to Measurements of Plasma Ion Temperature and Electrostatic Waves</i> , Prague, Czech Republic Presenters/Authors: Skiff, Fred Student Presenters/Authors: Chu, Feng                                                                                                     |
| 2017 | 18TH Laser Aided Plasma Diagnostics, <i>Velocity-space Cross-correlation for Electrostatic Mode Identification</i> , Prague, Czech Republic Presenters/Authors: Skiff, Fred Student Presenters/Authors: Mattingly, Sean                                                                                                                                         |
| 2017 | XXXIII ICPIG, <i>High-resolution laser-induced fluorescence in the pre-sheath of a positively biased probe</i> , Estoril/Lisbon, Portugal Presenters/Authors: Skiff, Fred, Merlino, Robert, Baalrud, Scott Student Presenters/Authors: Hood, Ryan                                                                                                               |
| 2017 | 44th European Physical Society Conference on Plasma Physics, <i>Parametric coupling to kinetic degrees of freedom</i> , EPS, Belfast, United Kingdom Presenters/Authors: Skiff, Fred                                                                                                                                                                            |
| 2016 | 58th Annual Meeting of the APS Division of Plasma Physics, <i>A Vlasov equation to describe the Alfvén wave CVK spectrum</i> , APS, San Jose, California, United States Presenters/Authors: Skiff, Fred                                                                                                                                                         |
| 2016 | 58th Annual Meeting of the APS Division of Plasma Physics, <i>Ion-Acoustic Wave Scattering description using Case-Van Kampen modes</i> , APS, San Jose, California, United States Presenters/Authors: Skiff, Fred Student Presenters/Authors: Berumen, Jorge                                                                                                    |
| 2016 | 58th Annual Meeting of the APS Division of Plasma Physics, <i>Ion flow and sheath structure near positively biased electrodes</i> , APS, San Jose, California, United States Presenters/Authors: Skiff, Fred, Baalrud, Scott, Hopkins, Matthew, Barnat, Ed, Yee, Benjamin, Merlino, Robert Student Presenters/Authors: Hood, Ryan, Scheiner, Brett              |
| 2016 | 58th Annual Meeting of the APS Division of Plasma Physics, <i>Modeling Laser-induced</i>                                                                                                                                                                                                                                                                        |

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|      | <i>Fluorescence Measurements of Plasma Ion Temperature and Mean-field Waves using a Lagrangian Approach</i> , APS, San Jose, California, United States Presenters/Authors: Skiff, Fred Student Presenters/Authors: Chu, Feng                                                                                                                           |
| 2016 | 58th Annual Meeting of the APS Division of Plasma Physics, <i>Phase Space Velocity Correlation and Degrees of Freedom</i> , APS, San Jose, California, United States Presenters/Authors: Skiff, Fred Student Presenters/Authors: Mattingly, Sean                                                                                                       |
| 2016 | 58th Annual Meeting of the APS Division of Plasma Physics, <i>Progress Towards a Laboratory Test of Alfvénic Electron Acceleration</i> , APS, San Jose, California, United States Presenters/Authors: Skiff, Fred, Howes, Greg G., Kletzing, Craig A, Carter, Troy A, Vincena, Steven, Dorfman, Seth Student Presenters/Authors: Schroeder, James W.R. |
| 2016 | 69TH ANNUAL GASEOUS ELECTRONICS CONFERENCE, <i>Effect of an electrostatic wave on optical pumping</i> , APS, Bochum, Germany Presenters/Authors: Skiff, Fred Student Presenters/Authors: Chu, Feng                                                                                                                                                     |
| 2016 | 43rd European Physical Society, Division of Plasma Physics, <i>A kinetic model for plasma wave scattering</i> , EPS, Leuven, Belgium Presenters/Authors: Skiff, Fred Student Presenters/Authors: Berumen, Jorge                                                                                                                                        |
| 2016 | Fifth International Workshop on the Theory and Applications of the Vlasov equation, <i>A Vlasov model for wave scattering</i> , Copanello, Italy Presenters/Authors: Skiff, Fred Student Presenters/Authors: Berumen, Jorge                                                                                                                            |
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#### Invited Lectures

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| 2017 | BRINGING SPACE DOWN TO EARTH, Exploring waves through their effects on particle velocity distributions for ions and electrons, UCLA Basic Plasma Science Facility, Los Angeles, California, United States Presenters/Authors: Skiff, Fred |
| 2017 | Collisionless Boltzmann (Vlasov) equation and modeling of self-gravitating systems and plasmas, <i>On putting experimental data into the Vlasov-Poisson equations</i> , CIRM, Luminy, France Presenters/Authors: Skiff, Fred              |

#### Keynote/Plenary lectures

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| 2019 | 3 <sup>rd</sup> Asia-Pacific Conference on Plasma Physics (AAPPS-DPP), Hefei China Observing Plasma Kinetic Degrees of Freedom Using Advanced Diagnostics, Presenters/Authors: Skiff, Fred          |
| 2016 | The 18th Israeli Conference on Plasma Science and its Applications, <i>Experiments on the kinetic degrees of freedom of electrons and ions</i> , Beer Shiva, Israel Presenters/Authors: Skiff, Fred |

#### Intellectual Merit

The ambitious goal of measuring structure and fluctuations in a plasma sheath using laser-induced fluorescence (LIF) was broken into steps and resulted in four highly successful PhD thesis projects.

Firstly, it was demonstrated that LIF provides a way to make measurements of wave reflection at the plasma sheath. All previous attempted measurements of ion acoustic wave reflection were hampered by the limitations of using probes and were not able to determine a wave reflection coefficient. Figure 1 illustrates the complexity of measuring wave reflection from a plasma boundary and why previous measurements of wave reflection were flawed. Not only is there the possibility of generating the intended reflected wave at the boundary, but perturbed electrons produced near the antenna can quickly induce a scattered wave from the sheath or directly interfere with a probe signal. Likewise, a wave incident on a sheath can induce perturbations in fast electrons (which are not part of the wave response) which can also be observed on a probe. Only by carefully avoiding these effects can a reflection coefficient be obtained – this was the thesis topic for J. Berumen.

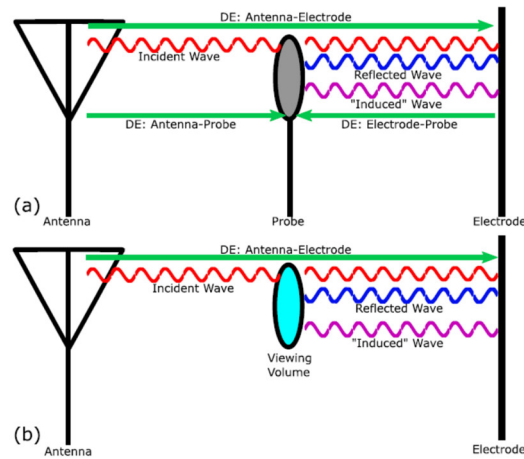


Figure 1 Schematic showing sources of true and false signals in reflection.

LIF mitigates the fast electron problem but does not eliminate the possibility of fast-electron induced wave emission from the edge. The addition of an external magnetic field does not fundamentally alter the measurement technique. Figure 2 shows sample velocity and space resolved LIF measurements from which a reflection coefficient can be obtained.

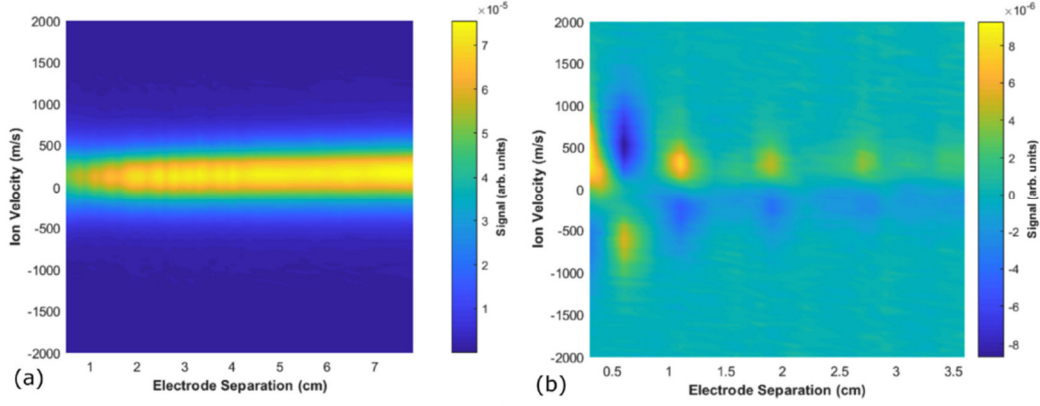


Figure 2 Color maps of LIF F0 and F1 data for ion wave reflection ( $B=0$ ).

Measurements were made, for the first time, of the of the cross-correlation matrix:

$C = \langle f(x, v, t) f(x', v', t-T) \rangle_t$ . This, fundamental two-point correlation in phase space had never been measured in a plasma. Each of the two instances of  $f$  in the formula were measured using different lasers and metastable levels. The symmetry property  $C(v, v', T) = C(v', v, -T)$  was shown to be true over a bandwidth sufficient to identify low frequency modes and systematic effects breaking the symmetry were identified. Because counting photons will entail undercounting if the rate is too high, the total flux was divided among 32 channels and the correlation function was averaged using an FPGA to accumulate the signals. This also reduced the dead-time in data acquisition. A typical output is shown in Figure 3 (and the diagonal of the Hermitian matrix of velocity-velocity cross-power spectra (which shows the previously-never-measured Kruskal-Oberman energy density for the incoherent plasma fluctuations) is shown in Figure 4. This remarkable experiment was the thesis work of Sean Mattingly.

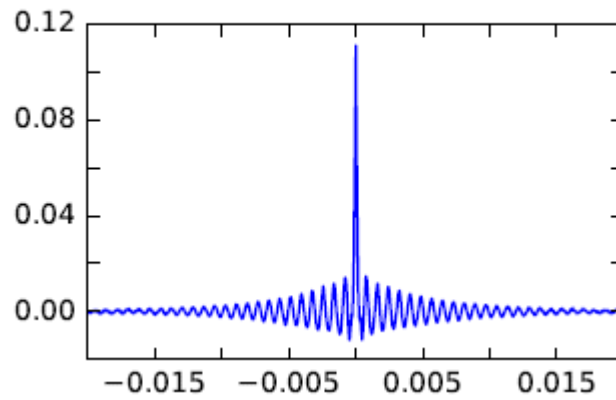


Figure 4 Typical time cross-correlation  $C(x,v,x',v',\tau)$  vs  $\tau$ .

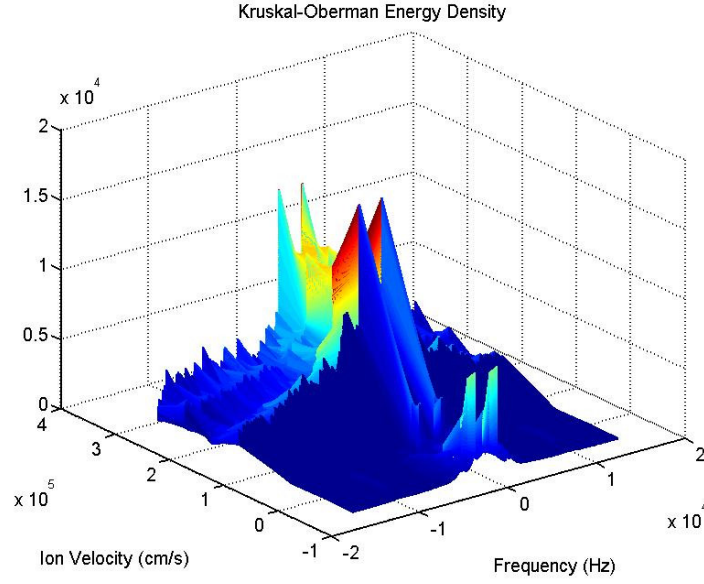


Figure 6 Diagonal term in the 1-D velocity-space cross correlation at one spatial location in the velocity parallel to the magnetic field of a uniform magnetized plasma.

A systematic study and simulation of systematic effects in LIF was undertaken to improve the quality of data comparisons with theory. A Lagrangian model was validated which permitted a measurement of the metastable lifetime and the relative numbers of metastable ions coming directly from an ionized neutral relative to those coming from other ionic states. This results in a significant improvement in the ease of interpreting LIF performed on metastable states in a gas discharge. Precision quantitative comparisons with theory require understanding the relative importance of the two populations of metastable ions. This Lagrangian model and its validation was the subject of the thesis of F. Chu.

Finally, a comparison with the theories of Baalrud on fluctuations in the sheath require making high-frequency incoherent fluctuation measurements near a sheath using LIF. Many photon pairs must be detected within the fluctuation correlation time. This very difficult measurement was accomplished (Thesis of Ryan Hood). A typical LIF power spectrum is shown in Figure 7. Preliminary to the fluctuation measurement, it was necessary to map out the plasma conditions, including 2-D flows and distribution functions in the vicinity of the electrode before making the fluctuation measurements.

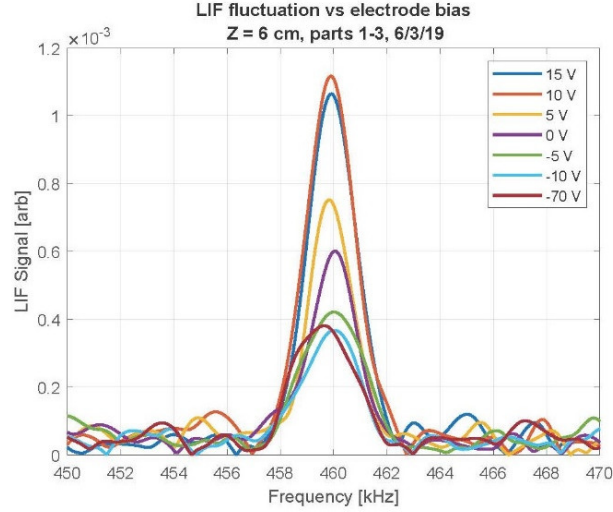


Figure 7 LIF power spectrum for incoherent plasma fluctuations in a pre-sheath.

### Broader Impacts

One of the primary broader impacts of the work accomplished under prior funding was the complete training of four PhD students. All of the breakthrough work accomplished was part of the thesis work of the students. When they published their thesis work, their were papers selected as editor picks or “Scilights” by the journal editors. All four have had multiple job offers and have gone on to do the work that they wanted. One student is from underrepresented groups in physics.

In terms of the specific research results, the validation of a Lagrangian model for LIF on metastable states is of importance for a number of research areas, especially plasma propulsion. Advancing the understanding of ion and electron sheaths is of importance to almost every plasma application.

Another broader impact; students from my lab participated in building a Planeterella for use as a demonstration of radiation belt plasma physics. They have subsequently driven across the country several times to APS-DPP meetings in order to participate in the Plasma Expo. (for hundreds of school children) and for the general public. Undergraduate students were also involved in constructing a new plasma physics experiment for the Intermediate Laboratory course and made improvements to a custom diode pumped NdYLF used for LIF at 1057 nm.

The existence of the plasma laser spectroscopy lab led to a brief collaboration with the UI College of Dentistry on radiative transfer in tooth reconstructions. The PI helped two PhD students design, construct and analyze measurements from apparatus evaluating laser light scattering from human teeth.



The PI participated in a performance of experimental music where a poetic description of chaos in the dynamical degrees of freedom of a cymbal was given.