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Studies of Plasma Sheath Physics using Continuum Kinetic Simulations of Plasmas

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14. ABSTRACT
We propose to study plasma-material interactions by developing continuum kinetic models and high-order numerical methods to directly solve the Vlasov-Maxwell equations. We plan to develop an understanding of secondary electron emissions, sheath stability, wall erosion, and energy deposition at the wall for applications involving plasma-material interactions with a focus on Hall thrusters. The continuum kinetic treatment will be applied to each of the ion and electron species with the ability to utilize our existing fluid models to pursue hybrid fluid-kinetic algorithms if necessary. As a part of this proposal, we will develop and include surface physics to capture the plasma-wall interaction while maintaining energy conservation in our continuum kinetic solvers. We will also develop and include the appropriate physics for ion-ion, ion-electron, and electron-electron collisions, as well as atomic physics in the form of ionization, recombination, charge exchange, and radiation losses as relevant to the regimes of interest. We will compare our simulation results to available experimental measurements from Princeton Plasma Physics Laboratory's Hall Thruster Experiment. Another important outcome of this proposal will be the development of appropriate boundary conditions at plasma-material interfaces with accurate surface physics in different regimes. The insight obtained about boundary conditions using an energy conserving kinetic algorithm can then be appliedto hydrodynamic codes to more accurately capture energy deposition and wall effects. This proposal has two primary overarching objectives: Objective 1: Develop high-order accurate and computationally efficient continuum kinetic plasma solvers that treat ions and electrons as separate kinetic species for a range of collisionality while also including appropriate boundary conditions for surface physics and any relevant atomic physics. Objective 2: Apply the multi-dimensional, multi-species continuum kinetic solver to applications relevant to the air force such as plasma-surface interactions and sheath stability for Hall thruster electrodes.

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1 Objectives

This work was performed by Virginia Tech in collaboration with Princeton University as a subcontractor.

The aim of this project was to develop a continuum-kinetic model to study plasma sheaths and plasma-material interactions for applications of relevance to the U.S. Air Force. Key successes of this project include the development of a continuum-kinetic multi-dimensional framework with electron emission boundary conditions. Studies of plasma-material interaction are now possible in this model with the effects of material emission. Initial studies provide noise-free decrease in sheath potential with electron emission. Specific air force-relevant applications of this capability constitute future work.

There were two primary objectives we proposed as a part of this effort that were discretized into a number of tasks.

Objective 1 : Develop high-order accurate and computationally efficient continuum kinetic plasma solvers that treat ions and electrons as separate kinetic species for a range of collisionality while also including appropriate boundary conditions for surface physics and any relevant atomic physics.

Objective 2 : Apply the multi-dimensional, multi-species continuum kinetic solver to study plasma-surface interactions and sheath stability for applications relevant to the air force

2 Accomplishments

This project has successfully met the milestones that were proposed. The success of our project is measured through the following:

- For objective 1 outlined above we have developed a 6-dimensional, computationally-efficient, continuum-kinetic plasma solver with collisions for ion and electron kinetic species in the Gkeyll code https://gkeyll.readthedocs.io/. We incorporated boundary conditions to model classical sheaths and electron emission. In addition to producing several peer-reviewed publications, this framework is now open-source and available to the community.

- For objective 2 outlined above, we published several papers on sheaths and plasma-surface interactions in Physics of Plasmas, Journal of Computational Physics, and Radiation Effects and Defects in Solids.
- This work directly contributed to a highly downloaded Virginia Tech PhD dissertation of Dr. Petr Cagas who was supported by AFOSR for the entire duration of his PhD

The continuum-kinetic multi-dimensional algorithm development and details of the solver are highlighted in peer-reviewed journal publications listed below as [1, 2, 8]. Applications of this framework to study plasma sheath physics are presented in the peer-reviewed journal publications listed below as [3, 5, 7, 9, 10]. Specific algorithmic details along with the physics implications of electron emission on sheath profile are published in the Journal of Computational Physics paper [3]. Lastly, in the process of benchmarking the code early in the project, a Weibel instability test case produced three papers in Physics of Plasmas, The Astrophysical Journal, and Plasma Sources Science and Technology owing to new discoveries [4, 6, 1].

We are grateful to have had the opportunity to work with AFOSR and to have received funding support from AFOSR so we could further fundamental plasma physics research of relevance to the U.S. Air Force. This AFOSR project has had an impact on the fundamental physics capabilities and advances on a number of non-AFOSR projects as well. Development of this high-dimensional kinetic capability has impacted and enabled other projects that have been supported by the Department of Energy Office of Science, Department of Energy ARPA-E, and the National Science Foundation. Results were disseminated through peer-reviewed publications and conference posters/presentations including an invited talk at the APS DPP conference. Section 4 includes all the publications and conference presentations that were produced from this project.

3 Impacts

The multi-dimensional continuum-kinetic solver is unique in its capabilities and the electron emission boundary conditions coupled with this open-source solver produces access for the community to a novel set of tools that can be used to study a variety of applications of relevance to AFOSR, DOE, NSF, and other governmental and academic entities. The applications include plasma-material interactions relevant to thrusters and other devices, instabilities relevant to laboratory and space plasmas, novel numerical techniques for efficient and accurate computation of fluid and kinetic equations, and others. As a result of this project, there is broad applicability of this research across fields including computational mathematics, fluid dynamics, and plasma physics. A graduate student was supported on this project for the entirety of their PhD and a postdoctoral researcher was supported at Princeton University towards workforce development of future academic or laboratory researchers. As the project is open-source with online documentation and code access provided publicly, the Gkeyll code has been used for educational purposes including for projects offered in the graduate computational plasma dynamics course at Virginia Tech. Additionally, this code has been used to support high school outreach efforts at Virginia Tech through the Center for the Enhancement of Engineering Diversity.

The impact to society is both through scientific contributions across a broad range of applications as well as through education and workforce development. The plasma physics applications of this effort towards defense, energy, and space are of substantial benefit to society. Furthermore, improving public knowledge of plasma physics has an educational impact to society and also promotes future workforce much needed in DOD and DOE national laboratories.

4 List of publications and presentations acknowledging AFOSR support

Published journal articles

1. Wang, L, Hakim, A, Juno J, Srinivasan B. Electron cyclotron drift instability and anomalous transport: two-fluid moment theory and modeling. Plasma Sources Science and Technology. 2022 (Accepted)

2. Hakim A, Francisquez M, Juno J, Hammett GW. Conservative discontinuous Galerkin schemes for nonlinear Dougherty-Fokker-Planck collision operators. Journal of Plasma Physics. 2020 Aug;86(4). https://doi.org/10.1017/S0022377820000586

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PhD Dissertation

1. Cagas, Petr. ”Continuum Kinetic Simulations of Plasma Sheaths and Instabilities.” PhD dissertation, Virginia Tech, 2018. https://vtechworks.lib.vt.edu/handle/10919/84979

Conference publications and abstracts

1. Srinivasan, B., Cagas, P., Hakim, A. “Solving the Continuum Kinetic Equations for Plasmas using the Discontinuous Galerkin Method” In SIAM Computational Science and Engineering Abstracts, 2019

2. Cagas, P., Juno, J., Hakim, A., Srinivasan, B. “High-order Discontinuous Galerkin Discretization for Multi-physics Simulations of Plasmas” In SIAM Computational Science and Engineering Abstracts, 2019

3. Cagas, P., Hakim, A., Srinivasan, B. “Studies of plasma sheaths with self-consistent emitting walls using continuum kinetic simulations” In APS DPP Meeting Abstracts, 2018

4. Cagas, Petr, Ammar Hakim, and Bhuvana Srinivasan. “Hall thruster relevant continuum kinetic sheaths simulations with self-consistent secondary electron emission.” In 53rd AIAA/SAE/ASEE Joint Propulsion Conference, p. 4810. 2018.

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7. Cagas, P., Srinivasan, B. “Studies of plasma sheath physics using continuum kinetic simulations.” In AFOSR Student Research Day, 2017.

8. Srinivasan, B., Hakim, A., Cagas, P., Song, Y. “Solving Fluid and Continuum Kinetic Equations in Plasma Physics Using the Discontinuous Galerkin Method.” In SIAM Computational Science and Engineering, MS195 Computational Plasma Physics, 2017

9. Cagas, Petr, Bhuvana Srinivasan, and Ammar Hakim. “Continuum kinetic simulations of magnetized sheaths in Hall thrusters with secondary electron emissions” In 52nd AIAA/SAE/ASEE Joint Propulsion Conference, p. 4631. 2017.

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11. Cagas, Petr. Virginia tech HPC Day, Student Research Lightning Talks, 2017

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