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Theoretical characterization of electron transport in partially magnetized plasmas

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## AFOSR FINAL REPORT

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# Theoretical characterization of electron transport in partially magnetized plasmas

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## Abstract:

In this AFOSR YIP project, we have developed a full fluid moment (FFM) model to investigate the effects of nonlinear inertia terms on the electron transport in partially magnetized plasmas. The FFM results are compared with drift-diffusion (DD) models, showing shear-induced electron transport. We also used several kinetic simulation codes to study the electron transport, guiding our development of the fluid models. The FFM code is extended to solve two-dimensional plasma flows and can be applied to a variety of plasma conditions and configurations. The impact of this AFOSR project is immense as the activity provided new computational tools in the low-temperature plasma (LTP) community.

## 1. Introduction

This AFOSR YIP project (start date: December 8, 2017, end date: December 31, 2021) focused on developing a new electron fluid model for partially magnetized plasmas (ions are non-magnetized while electrons are magnetized). The cross-field electron transport is poorly understood, and it is therefore important to develop a high-fidelity plasma model that captures the physics, e.g., plasma waves and instabilities. Recent experimental and theoretical studies show that the plasma turbulence may be the main contributor for non-classical (anomalous) electron transport across the magnetic field lines. Hence, the electron fluid model must account for the nonlinear inertial contributions to the electron momentum.

The YIP project started during the PI's 2<sup>nd</sup> year at Texas A&M University as an assistant professor. The PI moved from Texas A&M University to Stanford University in September 2019. Due to PI's transfer to a new university and COVID (starting March 2020), a one-year no-cost extension was requested and approved, which extended the project end date to December 31, 2021.

## 2. Accomplishments

### A. Research Objectives

The two main research objectives of this YIP project are

- (1) to develop a time-dependent momentum solver for electrons and
- (2) characterize the electron transport mechanisms, particularly the effects of inertia terms

The focus of this work is mainly in improving the electron momentum equation since the anomalous electron transport is often discussed and referred to in comparison to the drift-diffusion formulation. The time-dependent full momentum equation is given by,

$$\frac{\partial(\rho\mathbf{u})}{\partial t} + \nabla \cdot (\rho\mathbf{u}\mathbf{u}) = -\nabla p + qn(\mathbf{E} + \mathbf{u} \times \mathbf{B}) - \mathbf{F}_{drag},$$

where  $\rho = mn$  is the mass density ( $n$  being the number density and  $m$  being the mass),  $\mathbf{u}$  is the bulk velocity,  $p$  is the pressure (assuming isotropic pressure),  $q$  is the charge of the species,  $\mathbf{E}$  is the electric field,  $\mathbf{B}$  is the magnetic field, and  $\mathbf{F}_{drag}$  is the collisional drag due to the momentum exchange which is often written as  $\mathbf{F}_{drag} = -\rho\mathbf{u}\nu_m$  with  $\nu_m$  being the momentum exchange collision frequency. After neglecting the left hand side, the drift-diffusion (DD) flux can be obtained as

$$\rho\mathbf{u} = \rho\bar{\mu} \cdot \left( \mathbf{E} + \frac{1}{en} \nabla p \right),$$

where  $\bar{\mu}$  is the electron mobility tensor that includes the directionality parallel ( $\parallel$ ) and perpendicular ( $\perp$ ) to the magnetic field and along the ExB drift ( $\wedge$ ;  $\perp \mathbf{B}$  and  $\perp \mathbf{E}$ ).

Conservation of mass is given by  $\partial_t \rho + \nabla \cdot (\rho\mathbf{u}) = S$ , where  $S$  is the source and sink terms. For a non-neutral simulation where  $n_i \neq n_e$  ( $n_i$  is the ion density and  $n_e$  is the electron density), the Poisson's equation is solved to obtain the electric field. The way the problem is solved would vary with what models are used.

- Fluid moment (FM) model: solves for  $\rho$  and  $\rho\mathbf{u}$  in a coupled fashion.
- Drift-diffusion (DD) model: the drift-diffusion flux can be directly inserted into the conservation of mass. Thus, only one equation (for  $\rho$ ) is solved.

**Table 1:** Overview of electron fluids. Bold fonts are the names of the models.

	<i>Drift-diffusion flux (without inertia)</i>	<i>Fluid moment (with inertia)</i>
<i>Quasineutral (<math>n_i = n_e</math>)</i>	Baseline results [ <b>QDD</b> ]	N/A
<i>Nonneutral (<math>n_i \neq n_e</math>)</i>	1D (Task 1), 2D (Task 3) [ <b>NDD</b> ]	1D (Task 2), 2D (r-z: Task 4, r- $\theta$ : Task 5) [ <b>FM</b> ]

Table 1 shows an overview of developing a new fluid model (for the momentum equation). The strategy is that when developing a multifluid model, there will be two physical phenomena that would be updated in comparison to a quasineutral DD (**QDD**) model. (1) Quasineutral (QDD) vs Nonneutral DD (**NDD**): direct consequence would be the plasma sheath since the nonneutral model can account for the charge separation near the walls and electrodes. (2) Nonneutral full fluid moment (**FFM**): In addition to the nonneutral plasma effects, the inertia effects can contribute to the momentum exchange, e.g., shear.

## B. Details of accomplishments

We have achieved most of the research plans during this AFOSR project, and the impact of the research products is high, as the developed codes and physical understanding are now utilized for a wide variety of low temperature plasma applications, including semiconductor manufacturing and high-power microwaves.

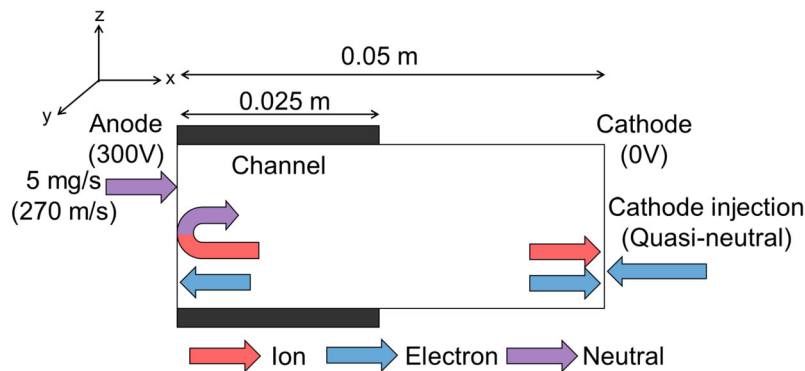
### i.) Development of QDD, NDD, and FFM models

To assess the utility of the FFM model, i.e., the effects of the inertia terms, FFM results are compared to the DD models. The quasineutral DD (QDD) model has been used in HPHall and Hall2De. The current conservation equation together with the DD flux yields a 2<sup>nd</sup>-order elliptic partial differential equation for potential, instead of solving the Poisson equation. On the other hand, the nonneutral DD (NDD) model is mostly used in the LTP community, as the nonneutrality is required to include the plasma sheath effects for RF plasma sources. However, it is known that the NDD formulation is numerical unstable. Thus, a numerical method called the Scharfetter-Gummel scheme is developed to limit the updates of the number density, making the NDD system numerically stable. The NDD formulation and development led to A. Mansour's MS thesis in Texas A&M University (2019).

The FFM is developed based on the numerical algorithms and schemes investigated in the computational fluid dynamics (CFD) community. For instance, from our studies, we have identified that the Steger-Warming scheme can generate numerical oscillations, particularly near the low Mach number region (i.e., where the bulk velocity is close to zero). Next, the boundary conditions must be treated with care. The conventional subsonic boundary conditions and extrapolation boundary conditions were found to be physically inconsistent, often resulting in numerical oscillations near the boundaries. To this end, we have developed a boundary condition treatment called the kinetic flux boundary condition. This technique assumes a velocity distribution function (VDF) obtained from the macroscopic properties, such as the number density, bulk velocity, and temperature. The fluxes going across an interface (e.g., wall) are calculated by taking the integral of the VDF.

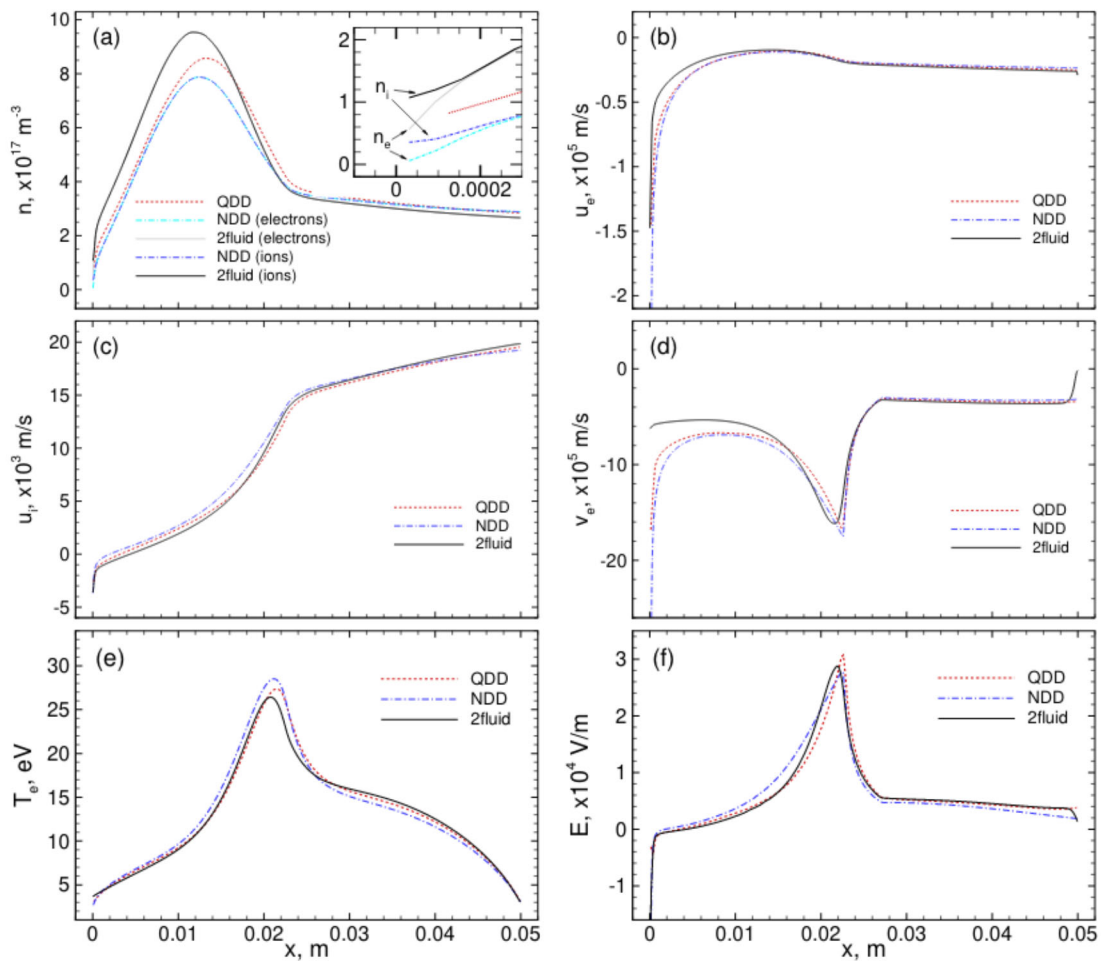
### ii.) Application of the fluid models to partially magnetized plasmas in 1D

One of the challenges for the model comparisons is the choice of the test case. While in the CFD, LTP, and other fundamental plasma physics communities have proposed a numerical test case to benchmark and verify the codes, a well-established test case was not proposed nor available to investigate partially magnetized plasmas. Therefore, we have proposed a test case based on a Hall effect thruster discharge plasma, shown in Figure 1. The magnetic field is imposed in the direction out of the plane to set up a cross-field plasma discharge.



**Figure 1: Computational domain and setup of a 1D axial Hall effect thruster plasma discharge**

The results of the benchmarking between QDD, NDD, and FFM are shown in Figure 2. While the overall plasma profiles are qualitatively similar, there are a few noticeable differences. First, QDD does not resolve the sheath, while the NDD and FFM models are able to capture the plasma sheath near the anode (Fig 2a). The electron axial velocity (Fig 2b) and ion axial velocity (Fig 2c) are similar in the plume ( $x > 2.5$  cm), but differences can be seen in the discharge channel ( $x < 2.5$  cm). The most noticeable difference is in the electron azimuthal velocity (Fig 2d), where the QDD and NDD results overestimate the azimuthal velocities near the anode sheath. This is due to the DD formulation that the azimuthal velocity is a product of the Hall parameter and the axial velocity, whereas the FFM results can capture the inertia term that accelerates the electrons toward the anode sheath. Thus, the electron bulk velocity estimation is significantly improved near the anode sheath. The electron azimuthal shear affects the electron transport, and in turn show some effects in the electric field calculation (Fig 2f), resulting in some changes in the electron temperature (Fig 2e).



**Figure 2:** Hall thruster simulation with QDD, NDD, and FFM solvers. [Sahu, Mansour, and Hara PoP 20]

One of the key innovations of this study is that we have proposed the “shear-driven” electron transport. It is to be noted that this test case is designed to obtain steady-state plasma profile for a clear benchmarking between different models. The shear-driven transport effects may have a

much larger impact when plasma oscillations are present, generating some fluid-type plasma turbulence.

### iii.) Investigation of kinetic instabilities in partially magnetized plasmas

While kinetic modeling has not been what we planned to perform in this AFOSR project in the original proposal, characterization of the electron transport cannot be done without any kinetic models, particularly if kinetic instabilities are present. To this end, we have participated in two international kinetic benchmarking activity, called the LANDMARK project, initially led by Dr. Jean-Pierre Boeuf.

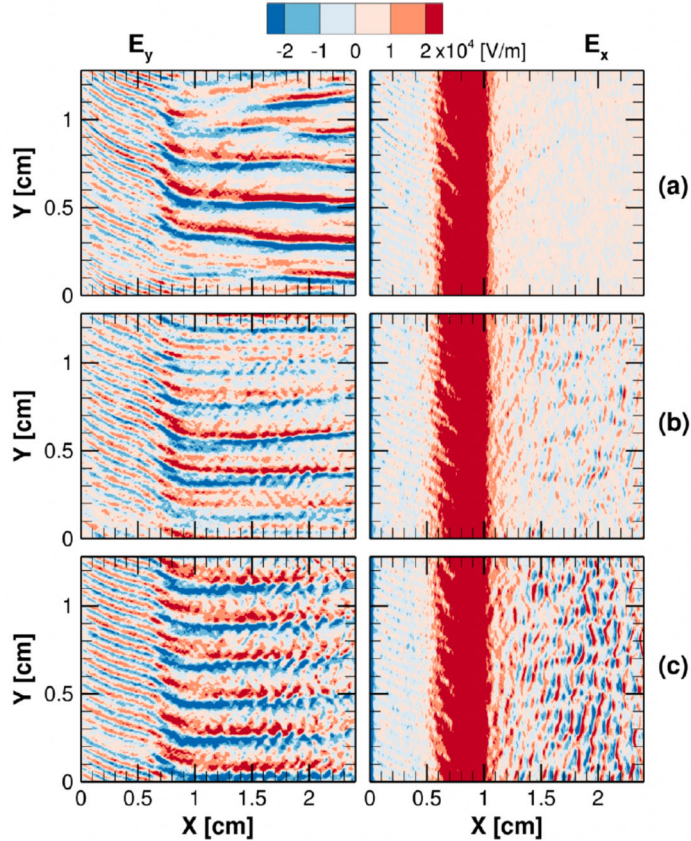
The first activity focused on the investigation of the electron cyclotron drift instability (ECDI) in a two-dimensional z-theta plasma configuration [Charoy et al. PSST 2019]. We have developed our in-house PIC simulation, now called the XPIC. The ions are accelerated in z direction via an anode-cathode configuration, while the magnetic field is applied in r direction generating an ExB drift in theta direction. The ExB drift generates a plasma wave in the azimuthal direction, leading to collisionless cross-field electron transport.

The second activity focused on investigation of the coupling between ECDI and the modified two-stream instability (MTSI) in a similar but slightly different geometry, i.e., two-dimensional r-theta configuration. The plasma now sees walls in the radial direction, leading to a plasma diffusion in the radial direction (parallel to the magnetic fields). This sets up a finite  $k_z$  component of the plasma waves, which leads to the generation of MTSI. In the azimuthal direction, the ECDI is still present. Thus, the ECDI and MTSI couples together in the nonlinear saturation phase. This study resulted in a paper [Villafana et al. PSST 2021]. While participating in the PIC simulation benchmarking, A. Denig, a PhD student in the PI's group, has also contributed to the development of a theoretical framework of the kinetic instabilities.

Using XPIC that is developed and benchmarked against various PIC codes, we have further extended this study of the kinetic instabilities in partially magnetized plasmas. Taking the same plasma configuration and geometry that was used in the LANDMARK benchmarking, we have added doubly charged ions to study the coupling between ECDI and ion-ion two-stream instability (IITSI), which was experimentally observed by S. Tsikata [Tsikata et al. PoP 2014]. The results obtained from the XPIC simulations have revealed the multidimensional plasma wave formation due to the axial wave initiated by IITSI and the azimuthal wave driven by ECDI. It was observed that the cross-field electron transport is indeed affected by the multidimensional plasma waves. [Hara and Tsikata, PRE 2020]. Figure 3 shows the electric field structures due to the coupling of ECDI and IITSI.

Recently, we have also included triply charged ions into the XPIC simulations, showing that the cross-field electron transport is reduced due to the plasma wave damping in the presence of triply, doubly, and singly charged ions. The physical hypothesis is that the amplitude of the plasma waves affects the cross-field electron transport [Kumar, Tsikata, and Hara, JAP 2021].

The comparison between the fluid (e.g., FFM) and kinetic (e.g., PIC/MCC) models is necessary to advance our understanding of the electron transport in low-temperature magnetized plasmas. We are also involved in another ExB benchmarking activity currently, in which the magnetron discharge will be simulated to understand the multiscale nature of the instabilities, oscillations, and turbulence in partially magnetized plasmas.



**Figure 3:** Instantaneous azimuthal and axial electric fields due to the cross-field plasma instabilities in the presence of singly and doubly charged ion streams. (a) singly charged ions only, illustrating the ECDI in the azimuthal direction, (b) 10% doubly charged ions (moderate-amplitude IITSI), and (c) 20% doubly charged ions (large-amplitude IITSI). The axially modulated electric field develops as the fraction of doubly charged ions increases. The color bar is saturated, particularly for  $E_x$ , to allow for visualization of the plasma waves in the downstream region. [Hara and Tsikata, PRE 2020]

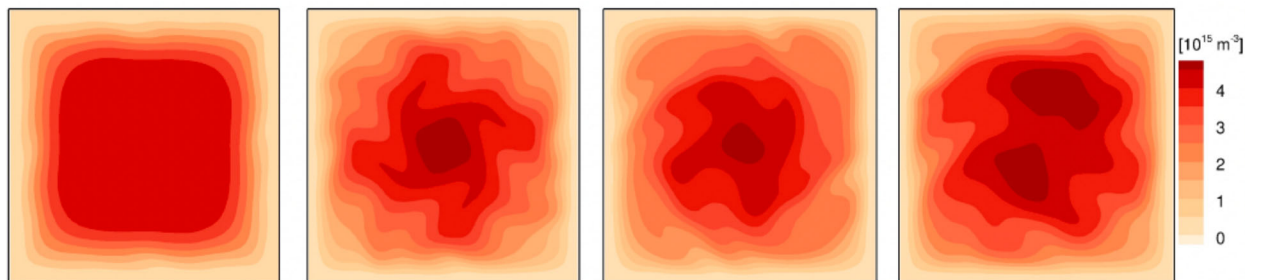
#### iv.) Application of the FFM to 2D partially magnetized plasmas

We further extended the 1D FFM model to 2D, focusing on the plasma dynamics perpendicular to the magnetic field lines. First, we implemented the simulation in a z-theta (Task 5) like geometry. However, it was found that the FFM results struggle to find a steady state result. The boundary condition and the physical system are quite challenging in such a condition. Thus, we reserve this study for future work.

On the other hand, we also simultaneously developed the code to simulate a Penning type geometry where the plasma is bounded by physical walls (e.g., anode/cathode) and the magnetic field is applied in the perpendicular direction. Under such configurations, it is known that azimuthal rotating spokes form. Figure 4 shows the transient of the rotating spoke formation and the long-time evolution.

The numerical results opened new questions about the rotating spoke instability theory, which we also have worked on. However, one of the most important achievements of this investigation

is that we developed a robust 2D FFM model with similar numerical algorithms chosen in the 1D FFM. The 2D FFM model will play an important role in a wider range of low-temperature plasmas, e.g., semiconductor manufacturing and high-power microwaves.

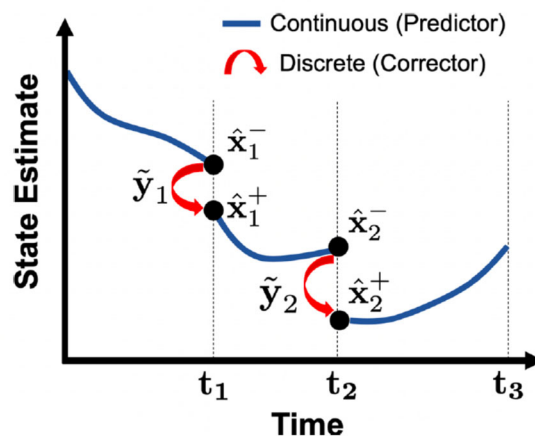


**Figure 4:** Electron number density for the partially magnetized configuration with self-consistent energy equation ( $B= 100$  G, into the page) at different time (from 0 to 15  $\mu$ s). [Mansour and Hara, AIAA 2021-3412]

It is also to be noted that we have not pursued the r-z configuration (Task 4) as the curved magnetic fields and boundary conditions are found to be trickier than the activities we pursued. Thus, we reserve the r-z FFM code for future investigations.

#### v.) Data-driven modeling of plasma oscillations

While the data-driven modeling was not proposed in the initial project proposal, C. Greve, a PhD student who was awarded NDSEG fellowship, worked on the data-driven modeling of plasma dynamics in partially-magnetized plasmas. This led to a collaboration between the PI’s group and the AFRL Edwards Air Force Base [Greve et al. JAP 2019]. Furthermore, we have developed an extended Kalman filter (EKF) for partially magnetized plasmas. Here, the idea is that we can take a reduced-order plasma model (e.g., global model) and augment the estimated plasma properties from the experimental data. Figure 4 shows a schematic of the EKF. This resulted in two publications [Greve, Majji, and Hara PoP 2021] [Greve and Hara JPD 2022].



**Figure 4:** A visual representation of the continuous-discrete extended Kalman filter (EKF) process over two measurement data points. The model continuously propagates forward until such a time that measurement data arrive and a discontinuous correction is applied to the system. [Greve, Majji, and Hara PoP 2021]

## vi.) Other achievements

After obtaining this AFOSR YIP project, the PI has received several awards, including

- May 2021, Office of Naval Research Young Investigator Program (YIP) Award
- September 2019, Kuriki Award for Young Professionals, Electric Rocket Propulsion Society
- June 2018, Department of Energy Early Career Research Program Award

## C. Dissemination of the results

The results obtained from this present AFOSR project were disseminated through various peer-reviewed journal and conference presentations.

### Accepted journal article

- C. M. Greve and K. Hara, "Estimation of Plasma Properties Using an Extended Kalman Filter with Plasma Global Models", *Journal of Physics D: Applied Physics* **55**, 255201 (2022)
- C. M. Greve, M. Majji, and K. Hara, "Real-time state estimation of low-frequency plasma oscillations in Hall effect thrusters", *Physics of Plasmas* **28**, 093509 (2021)
- S. Tsikata, K. Hara, and S. Mazouffre, "Characterization of hollow cathode plasma turbulence using coherent Thomson scattering", *Journal of Applied Physics* **130**, 243304 (2021)
- P. Kumar, S. Tsikata, and K. Hara, "Effects of multiply charged ions on microturbulence-driven electron transport in partially magnetized plasmas", *Journal of Applied Physics* **130**, 173307 (2021)
- R. Sahu, A. R. Mansour, and K. Hara, "Full fluid moment model for low-temperature magnetized plasmas", *Physics of Plasmas* **27** 113505 (2020)
- K. Hara and S. Tsikata, "Cross-field electron diffusion due to the coupling of drift-driven microinstabilities", *Physical Review E* **102**, 023202 (2020)
- K. Hara, "An overview of discharge plasma modeling for Hall effect thrusters", *Plasma Sources Science and Technology* **28**, 044001 (2019)
- K. Hara and C. Treece, "Ion kinetics and nonlinear saturation of current-carrying instabilities", *Plasma Sources Science and Technology* **28**, 055013 (2019)
- T. Charoy, J-P. Boeuf, A. Bourdon, P. Chabert, D. Eremin, L. Garrigues, K. Hara, I. Kaganovich, A. Powis, A. Smolyakov, D. Sydorenko, A. Tavant, and W. Villafana, "2D axial-azimuthal Particle-In-Cell benchmark for ExB discharges", *Plasma Sources Science and Technology* **28**, 105010 (2019)
- I. M. DesJardin, K. Hara, and S. Tsikata, "Self-organized standing waves generated by AC-driven electron cyclotron drift instabilities", *Applied Physical Letters* **115**, 234103 (2019)

### Conference paper

- A. R. Mansour and K. Hara, "Two-Dimensional Full-Fluid Simulations for Low Temperature Rotating Spokes", 49th IEEE ICOPS 2022.
- C. M. Greve and K. Hara, "Real-Time State Estimation of Plasma Parameters in Hall Effect Thruster Models", 2022 AIAA SciTech Forum, AIAA 2022-1563, San Diego, CA, January 2022

- S. T. Sewell, P. Kumar and K. Hara, "Cross-field electron transport due to coupling of drift-driven microinstabilities in the presence of singly, doubly, and triply charged ion streams", 2022 AIAA SciTech Forum, AIAA 2022-2192, San Diego, CA, January 2022
- D. Kuldinow, A. R. Mansour, and K. Hara, "Development of 10-moment Fluid Model for Plasma Simulations", 2022 AIAA SciTech Forum, AIAA 2022-1564, San Diego, CA, January 2022
- C. M. Greve and K. Hara, "Real-time Estimation of Plasma Dynamics Using an Extended Kalman Filter", in 2021 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, Aug 9-11, 2021, AIAA 2021-3425 (virtual).
- A. R. Mansour and K. Hara, "Development of 2D Full-Fluid Moment Model for Partially-Magnetized Low-Temperature Plasmas", AIAA-2021-3412, 2021 AIAA Propulsion and Energy Forum, August 2021 (virtual)
- A. C. Denig, K. Hara and S. Tsikata, "Three-Dimensional Coupling of Electron Cyclotron Drift Instability and Ion-Ion Two Stream Instability", AIAA 2021-3397, 2021 AIAA Propulsion and Energy Forum, August 2021 (virtual).
- K. Hara and S. Tsikata, "Cross-field anomalous electron transport due to multidimensional plasma instabilities", 47th IEEE International Conference on Plasma Science (ICOPS-2020), December 2020 (virtual)
- A. R. Mansour, C. Osgood, R. Sahu, and K. Hara, "Development of a one-dimensional full-fluid moment model for Hall effect thrusters", AIAA 2020-3623, 2020 AIAA Propulsion and Energy Forum, August 2020 (virtual).
- C. M. Greve, A. Thomas, M. Majji, and K. Hara, "Real-time Estimation of Electron Dynamics in Hall Effect Thrusters using an Extended Kalman Filter", AIAA 2020-3621, 2020 AIAA Propulsion and Energy Forum, August 2020 (virtual).
- S. Tsikata and K. Hara, "Plasma instabilities in cross-field configuration: an analysis of the relevance of different modes for electron transport", IEPC-2019-758, the 36th International Electric Propulsion Conference, Vienna, Austria, September 2019.
- K. Hara, Y. Yamashita, S. Tsikata, B. Vincent, and S. Cho "New insights into electron transport due to azimuthal drift in a Hall effect thruster", IEPC-2019-691, the 36th International Electric Propulsion Conference, Vienna, Austria, September 2019.
- Y. Yamashita, C. Gonzalez, K. Hara, S. Cho, and K. Nishiyama, "Study of the electron anomalous transport in a Hall effect thruster using a 2D multi-fluid simulation", IEPC-2019-716, the 36th International Electric Propulsion Conference, Vienna, Austria, September 2019 (poster).
- R. Sahu, C. Gonzalez, and K. Hara, "Development of 1D Magnetostatic Two-Fluid Plasma Simulation of a Hall Effect Thruster", IEPC-2019-726, the 36th International Electric Propulsion Conference, Vienna, Austria, September 2019.
- K. Hara, "High-energy ion generation due to the plasma wave driven by current-carrying instabilities", AIAA-2019-4249, AIAA Propulsion and Energy Forum and Exposition, Indianapolis, IN, August 2019.

#### Conference presentations

- A. R. Mansour and K. Hara, "Two-Dimensional Full-Fluid Moment Model for Low-Temperature Magnetized Plasmas", the 74th Annual Meeting of Gaseous Electronics Conference, October 2021 (virtual)
- P. Kumar, S. Tsikata, and K. Hara, "Cross-field electron transport due to coupling of drift-driven microinstabilities in the presence of singly, doubly, and triply charged ion streams", 74th Annual Meeting of Gaseous Electronics Conference, October 2021 (virtual)

- C. M. Greve, K. Hara and M. Majji, "Application of State Estimation Methods to Low-Temperature Plasma Dynamics", 60th Conference on Decision and Control, December 2021 (virtual)
- C. M. Greve and K. Hara, "Real-time Estimation of Plasma Parameters using an Iterated Extended Kalman Filter", 74th Gaseous Electronics Conference, October 2021 (virtual)
- A. R. Mansour and K. Hara, "Two-Dimensional Full-Fluid Moment Model for Hall-Effect Thrusters", 48<sup>th</sup> IEEE International Conference on Plasma Science, September 2021 (virtual)
- C. M. Greve and K. Hara, "Real-Time Estimation of Discharge Current Oscillations Using an Iterated Extended Kalman Filter", 48th IEEE International Conference on Plasma Science, September 2021 (virtual).
- C. M. Greve, A. Thomas, M. Majji, and K. Hara, "Data-Driven Global Model for Low Temperature Plasma Dynamics", 73rd Gaseous Electronics Conference, Oct 5-9, 2020 (virtual).
- A. R. Mansour, C. L. Osgood, R. Sahu, and K. Hara, "A Full-Fluid Model for Low-Temperature Magnetized Plasmas", the 73rd Annual Gaseous Electronics Conference, October 2020 (virtual).
- K. Hara and S. Tsikata, "Enhanced cross-field electron transport due to multidimensional plasma turbulence", 73rd Annual Gaseous Electronics Virtual Conference, Oct 5-9, 2020 (virtual).
- C. M. Greve and K. Hara, "A Data-Driven Approach to Model Calibration for Nonlinear Plasma Behavior", MW1.00026, the 72nd Annual Meeting of Gaseous Electronics Conference, College Station, TX, October 2019. (poster)
- R. Sahu, A. R. Mansour, and K. Hara, "Development of a Two Fluid Model for Low-Temperature Magnetized Plasmas", UF3.00001, the 72nd Annual Meeting of Gaseous Electronics Conference, College Station, TX, October 2019.
- K. Hara and S. Tsikata, "Plasma instabilities and cross-field electron transport in low-temperature magnetized plasmas", the 72nd Annual Meeting of Gaseous Electronics Conference, College Station, TX, October 2019.
- K. Hara, "Vlasov-Poisson simulation of current-carrying ion acoustic instability: nonlinear saturation and ion kinetics", 2019 IEEE Pulsed Power and Plasma Science Conference, Paper # 1249, Orlando, FL, June 2019.
- K. Hara, "Overview and challenges of partially magnetized plasma modeling", 2019 IEEE Pulsed Power and Plasma Science Conference, Paper # 1251, Orlando, FL, June 2019.

PI Hara has been invited to give a talk on several occasions to present the work of this AFOSR project.

- K. Hara, "Dynamics of Low Temperature Magnetized Plasmas: Self-Organization and Anomalous Electron Transport," Michigan Institute of Plasma Science and Engineering, December 2021.
- K. Hara, "Cross-field electron diffusion due to the coupling of drift-driven microinstabilities," International Online Plasma Seminar, April 2021.
- K. Hara, "Computational models of ionized gases for aerospace applications", CTO Seminar Series, Lam Research Corporation, Virtual, September 2020
- K. Hara, "Computational models of ionized gases for aerospace applications", ET Guest Lecture Series, Applied Materials, Santa Clara, CA, February 2020
- K. Hara, "Computational plasma dynamics for space propulsion and low temperature plasmas", NASA Ames Research Center, Mountain View, CA, November 2019.

- K. Hara, "Verification, validation, and benchmarking of plasma models", Workshop on Modeling and Validation, 72nd Annual Meeting of Gaseous Electronics Conference, College Station, TX, October 2019.
- K. Hara, "Computational Methods for Kinetic Models of Gases and Plasmas", SIAM CSE Meeting, Spokane, WA, February 2019. (Invited)
- K. Hara, "Quasineutral plasma modeling of low-frequency oscillations in cross-field discharge plasmas: breathing mode and rotating spokes", 71st Gaseous Electronics Conference, Portland, OR, November 2018. (Invited)

### 3. Impacts

The FFM model is a new model compared to the state-of-the-art models in the LTP community. In this plasma regimes, one of the main applications is the semiconductor etching and deposition using capacitively or inductively coupled plasmas. The FFM model developed through this AFOSR project has led to collaborations with industrial partners. We believe that the research outcome and insights gained from this AFOSR project have immense impact to the future directions of plasma research and development.

In addition to the industrial collaborations, the FFM models are used to study low-temperature magnetized plasmas, which motivated the development of kinetic models to understand the kinetic effects in these plasma conditions. The investigation of the partially magnetized plasmas has led to the DOE Early Career Award in which the kinetic effects of self-organization in low-temperature magnetized plasmas are studied. The AFOSR and DOE projects complement each other. In addition, through the discussions via this AFOSR project (e.g., through the PEEP review meeting), the PI started discussions with the ONR Directed Energy Weapons program, which led to the PI receiving ONR YIP award. While the topic is different from the AFOSR project, the outcome of this AFOSR project immensely helped broadening the applications of the PI's research.

The present AFOSR project had significant impact for training the next generation scientists and engineers. The students directly supported by the AFOSR grant include Rupali Sahu and Adnan Mansour. There have also been visiting students and postdocs including Yusuke Yamashita, and Carlos Gonzalez. The AFOSR project helped the international presence of the PI's research, collaborating with researchers in France, Italy, Canada, and Germany.

PI's group has now several national fellowship students, receiving NDSEG, NASA NSTGRO, Japanese JASSO fellowship, and DOE NNSA SSGF. All of these are outcome of the student's achievements and research opportunities within PI's group at Stanford University.

PI has established good teaching records both at Texas A&M University and Stanford University, teaching introductory classes for undergraduate students and several graduate courses, including spacecraft electric propulsion, advanced plasma physics and engineering, compressible flow, and rarefied gas dynamics.

### 4. Changes

The AFOSR YIP project was awarded to Texas A&M University when PI was there from September 2016 to August 2019. The project started in December 2017 and was selected

when Dr. Jason Marshall was the program manager of the PEEP program. After PI moved to Stanford University, the AFOSR project was kept at Texas A&M University and was sub-awarded to Stanford University so that PI continues the work. Hence, the biggest change of this AFOSR YIP project is the change in location of the research. The main graduate student researcher for this project, Adnan Mansour was a PhD student at Texas A&M University and moved to Stanford University with the PI. The move affected the research productivity for less than a year (cf. June 2019 – December 2019).

Despite some delays and major changes in the work location, we have accomplished a significant portion (~80%) of the proposed tasks. The main part that we did not achieve is Task 2 (2D NDD) and Task 4 (2D r-z FFM). We observed the advantages and limitations of the QDD, NDD, and FFM from a thorough 1D comparison [Sahu, Mansour, and Hara, PoP 2020]. The conclusion was that the NDD is limited to be used in magnetized plasmas, due to the numerical signals that arise around the boundary condition where the electric field sets up in the direction of the wall. However, such a strong electric field near the sheath can produce a large transverse bulk velocity, due to ExB drift (or diamagnetic drift in the case of pressure gradient). Thus, we decided to not pursue the development of a 2D NDD during our AFOSR project. In addition, Task 4 was decided to be postponed due to the complexity of the curved magnetic field etc. Instead, we have focused on the rotating spoke application, which we believe was successful in the end.

For Task 5 (2D z-theta FFM), we indeed have implemented the z-theta version of the code. However, the numerical oscillations in the systems were found to be large and the simulations do not reach a steady state. We believe that this is due to the coupling of the 2D nature of the FFM formulation and the physical instabilities, leading to an oscillatory simulation. This is one of the future investigations that we plan to work on.

## 5. Collaborations

AFRL Edwards AFB: PI's group has worked closely with Dr. Justin Koo, Dr. Rob Martin (currently in Army), Dr. David Bilyeu, and Dr. Dan Eckhardt in the In-Space Propulsion Group at Edwards AFB. Ms. Christine Greve, a doctoral student in my group, is awarded NDSEG and spent one summer as a summer intern at Edwards.

CNRS, France: PI has been established a good collaboration with Dr. Sedina Tsikata, CRNS France, who is a world-leading expert in Thomson scattering. We have started a collaboration using their experimental data for validating the numerical models that we are developing.

JAXA, University of Tokyo: Dr. Yusuke Yamashita, who was a doctoral student in University of Tokyo when visiting my research group from May to July 2019, contributed to the AFOSR project indirectly. Although Dr. Yamashita's research was not the main focus of the AFOSR project, his research on explicit 1D full-PIC simulation was essential to the progress of NDD and FM models. In particular, the assessment of boundary condition and the numerical setup were helpful setting up the two fluid models.

Landmark project: Initially led by Dr. Jean-Pierre Boeuf (University of Toulouse), PI Hara was involved in an important international collaboration, called the Low-temperature magnetized plasma benchmarking (LANDMARK) project. We have compared the 2D PIC code to study electron cyclotron drift instability and anomalous electron transport across magnetic fields.