Direct Kinetic Simulation of Hall Thruster Discharge Plasma

Kentaro Hara[a], Iain D. Boyd [b] and Vladimir I. Kolobov[c]

(a) Department of Aerospace Engineering, University of Michigan (kenhara@umich.edu)
(b) Department of Aerospace Engineering, University of Michigan (iainboyd@umich.edu)
(c) CFD Research Corporation, Huntsville, Alabama (vik@cfdrc.com)

The discharge plasma in a Hall thruster is known to be in a non-equilibrium state due to complex phenomena such as wall reflection, ionization, and cross-field conductivity. Although particle simulations have been used to simulate non-equilibrium plasmas, the use of macro-particles causes two main problems: the difficulty of reducing statistical noise and the inability to resolve the high-energy electrons that contribute to inelastic collisions. In order to achieve a better resolution of the velocity distribution functions (VDFs) of each plasma species, a direct kinetic (DK) simulation that deterministically solves kinetic equations on a discretized phase space is being developed.

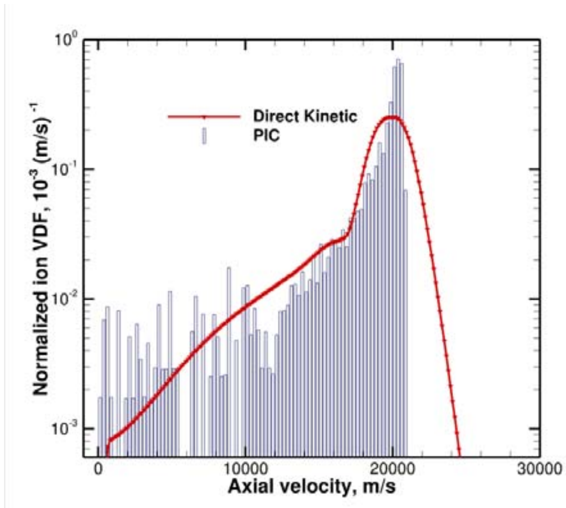


Figure 1 – Instantaneous ion VDF at the channel exit of a Hall thruster, SPT-100

A 1D hybrid simulation, in which a kinetic solver is used for heavy species and a fluid model is employed for electrons, is developed. The main goal of this study is to compare the hybrid particle-in-cell (PIC) simulation and the hybrid DK simulation for benchmarking purposes [1].

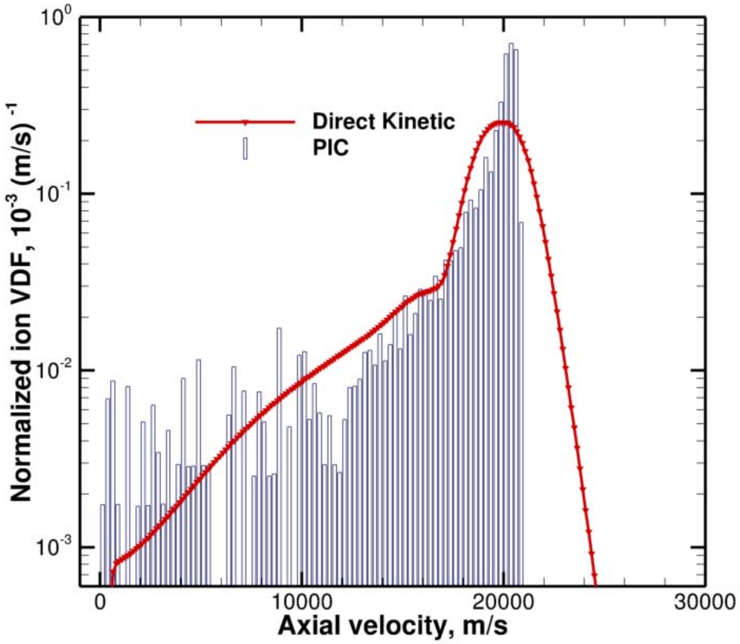
The most important observations are that (1) the kinetic effect of neutral atoms affects the plasma behavior including the breathing mode frequency and discharge current, (2) ionization is taken into account deterministically rather than probabilistically, and (3) a better resolution of plasma properties is achieved in the DK simulation. First, the VDF of neutral atoms can vary due to selective ionization in the diffusion, ionization, and acceleration regions [2]. A grid-based direct kinetic simulation does not need to account for the maximum number of macro-particles that affects the computational memory. Thus, ionization can be taken into account every time step. Finally, there is no statistical noise, which is inherent in hybrid-PIC simulation due to the use of macro-particles. Therefore, in the hybrid-DK simulation, better resolution of VDFs and in turn plasma properties is achieved. Future work includes applying the DK simulation to other plasma problems and extending the Hall thruster simulation to a multi-dimensional model.

References

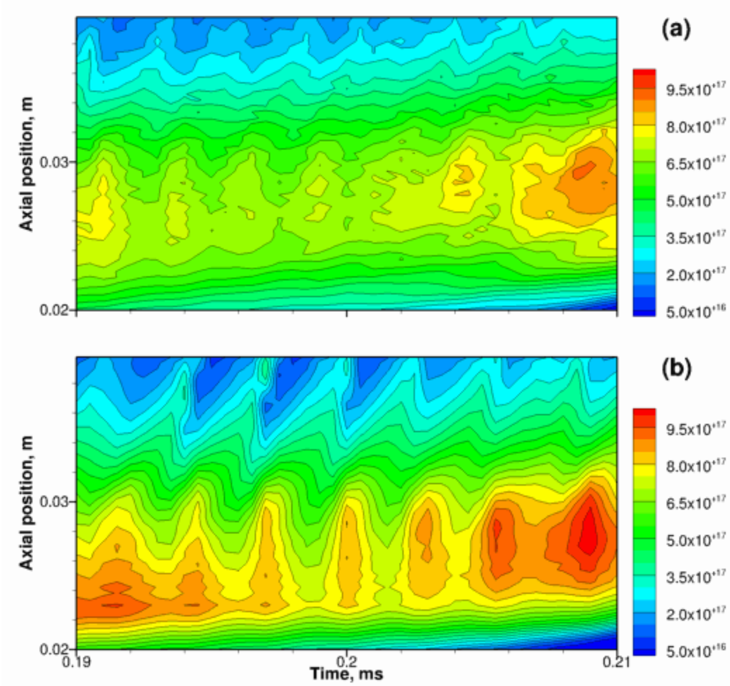
[1] K. Hara, I. D. Boyd, and V. I. Kolobov, Physics of Plasmas, **19**, 113508 (2012).
[2] W. Huang, A. D. Gallimore, and R. R. Hofer, Journal of Propulsion and Power, **27**, 553 (2011).

DIRECT KINETIC SIMULATION OF HALL THRUSTER DISCHARGE PLASMA

- **Direct kinetic simulation, which solves kinetic equations to obtain velocity distribution functions (VDFs), is employed to model the heavy species of the discharge plasma in a Hall thruster. A fluid model is used for electrons.**
- **In comparison to a particle simulation, statistical noise due to the use of macro-particles is greatly reduced and plasma oscillations are well resolved.**



- **Instantaneous ion VDF at channel exit of a Hall thruster**



- **Plasma density: t ~20 μs**

Application of Wall Probe for Plasma Research and Gas Analysis

V. I. Demidov[(a)], M. E. Koepke[(a)], A. A. Kudryavtsev[(b)],
P. M. Pramatarov[(c)] and M. Stefanova[(c)]
(a) West Virginia University, Morgantown, WV 26506
(b) St. Petersburg State University, St. Petersburg, Russia
(c) Institute of Solid State Physics, BAS, Sofia, Bulgaria

In plasmas having a nonlocal electron energy distribution function (EEDF), the electron energy relaxation length, λ_ε, is greater than the width of the plasma, which, in turn is greater than the mean-free path of the electrons, λ_e. (See Fig. 1.) In this case a wall probe may be useful for measuring the EEDF in the entire volume of the plasma. The wall probe does not require a holder and therefore reduces the disturbance of the plasma compared to an ordinary Langmuir probe. The size of the plasma can also be dramatically reduced by using the wall probe since there is no need to insert a Langmuir probe into the plasma. This allows making measurements of the EEDF in the plasma for pressures up to one atmosphere.

Application of wall probes may lead to the development of novel approaches for gas analysis. This approach is based on measuring the fine structure associated with atomic and molecular plasma processes reflected in the high-energy portion of the EEDF in a plasma having nonlocal properties.

A short (without positive column) dc discharge with a cold cathode and conducting walls was used in this work, as shown in Fig. 2. An example of the measured EEDF in the discharge (as shown by the second derivative of the sensor current with respect to the sensor voltage) is in Fig. 3. It has been demonstrated that similar devices enable measurements for gas pressures close to 1 atm (in contrast to the low-pressure devices discussed in Ref. 1) and therefore are able to provide gas analysis up 1 atm.

An invited talk and an oral presentation on these issues have been delivered at the EPS Satellite Conference on Plasma Diagnostics in Espoo, Finland (July 6, 2013). An invited paper has been submitted to *Plasma Physics and Controlled Fusion.*

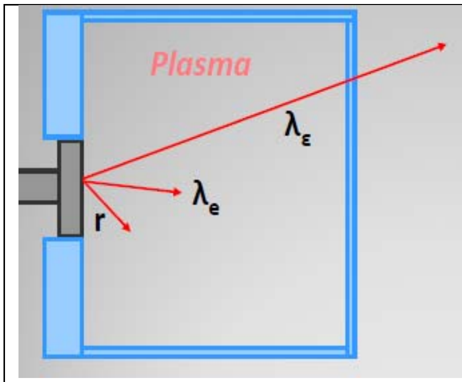


Figure 1 – A wall probe with can measure the nonlocal EEDF in the entire plasma volume.

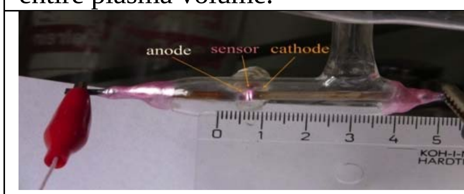


Figure 2 – Proof of principle device.

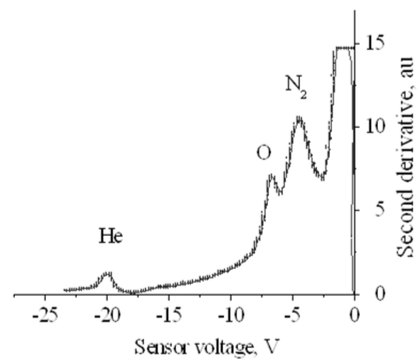


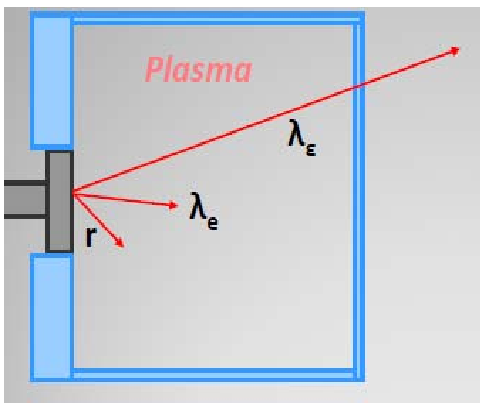
Figure 3 - Measured EEDF in the device shown in Fig. 2 (Air/He mixture).

References

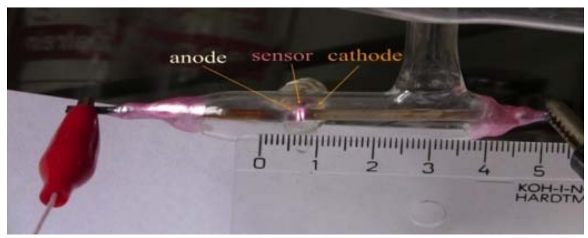
[1] V. I. Demidov et al., Contrib. Plasma Physics. **50**, 808 (2010).

APPLICATION OF WALL PROBES FOR EEDFs AND GAS ANALYSIS

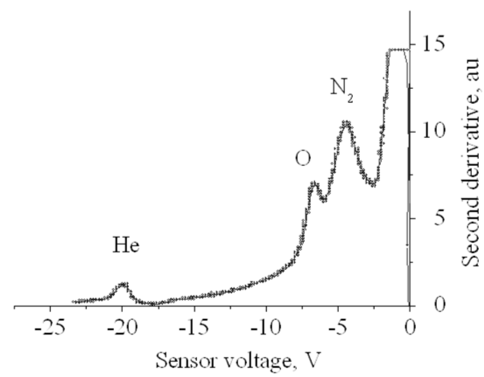
- A wall probe may be useful for measuring the nonlocal electron energy distribution (EEDF) function in the entire plasma when the electron energy relaxation length, λ_ε, is greater than the plasma width, which in turn is greater than the mean-free path of electrons, λ_e.
- Application of wall probes may lead to the development of novel approaches for gas analysis which are based on measurements of EEDF fine structure.
- Demonstrations have been made of high pressure operation of wall probes to measure EEDFs and gas composition.



- A wall probe can measure nonlocal EEDFs



- Proof of principle device



- Measured EEDF in Air/He mixture

HIGHLIGHT

West Virginia University

Center for Predictive Control of Plasma Kinetics: Multi-Phase and Bounded Systems

PSC Department of Energy Plasma Science Center

DOE Plasma Science Center
Control of Plasma Kinetics