KINETIC SIMULATIONS OF PARTIALLY MAGNETIZED PLASMA IN A HALL THRUSTER

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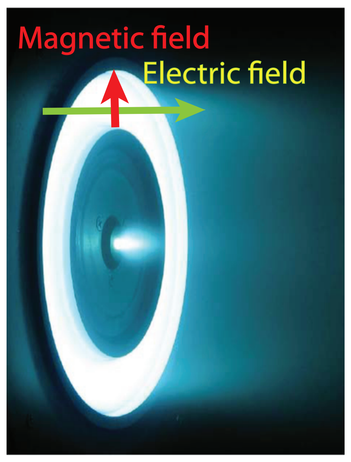
Introduction



Partially magnetized plasma in Hall thrusters

- Ions are relatively non-magnetized while electrons are magnetized.
- The discharge plasma exhibits wide bandwidth of oscillatory modes (10 kHz - 1 GHz).
- Non-equilibrium state is due to the interaction of ionization and acceleration.

High-fidelity numerical simulation

- Fluid approach has been widely used but neglect the non-equilibrium behavior.
- Particle simulations, such as Particle-in-cell (PIC) and Monte Carlo methods, capture the non-equilibrium phenomena yet contain statistical noise inherently.
- A high-fidelity kinetic simulation method that can achieve a better resolution of plasma properties is required.

In this study, a hybrid method is used to model the discharge plasma in a Hall thruster and we compare two kinetic simulation methods to model ions: (a) PIC method and (b) direct kinetic (DK) simulation. An identical fluid model is used for electrons.[1] DK method solves the plasma kinetic equation deterministically in the discretized phase space (velocity and physical space):

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} + \frac{q}{m}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f}{\partial \mathbf{v}} = S$$

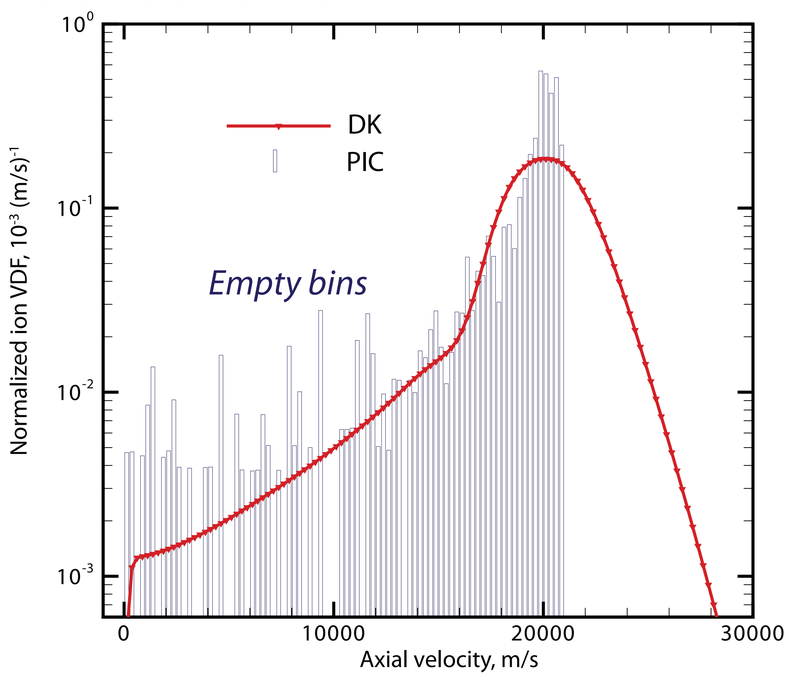
Discussion

The main differences of the two kinetic simulations are:

1. Ionization is treated each time step in DK simulation whereas PIC takes it into account probabilistically. For example, PIC skips ionization at one out of four time steps in our calculation.

2. Resolution of velocity distribution functions is improved in DK simulation (Figure). Hence, plasma properties are also well resolved spatially and temporally. Empty bins in the VDFs are observed in PIC simulation due to the use of macro-particles.

Instantaneous velocity distribution functions at the channel exit.



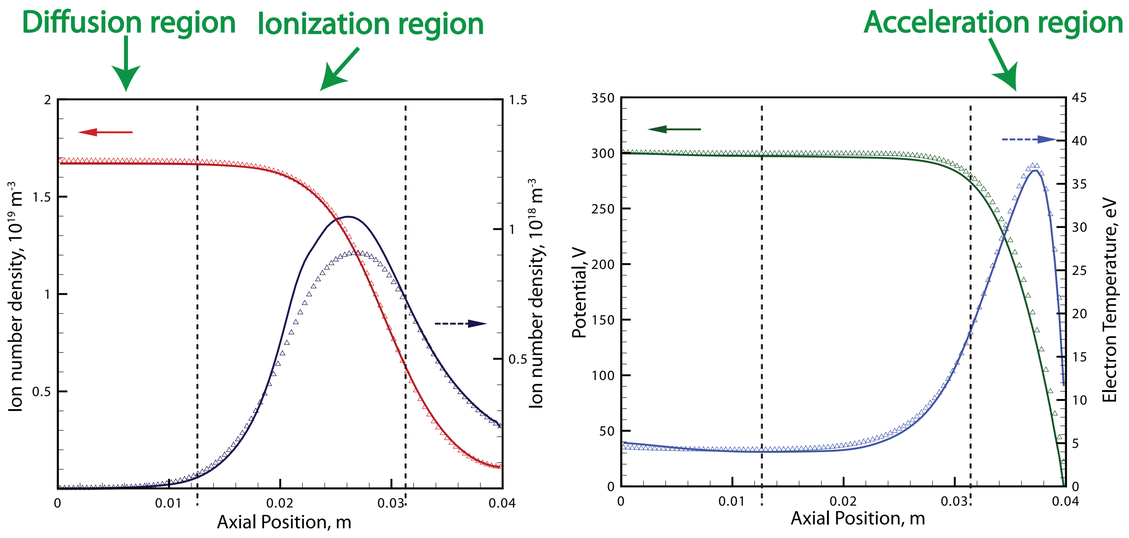
Impact

A direct kinetic simulation method provides temporally and spatially detailed results for non-equilibrium plasmas.
(1) Small scale effects, such as turbulence and high-frequency oscillations, can be examined and (2) a more accurate modeling can be performed for low density regions, such as near-wall sheath and plume.

[1] Boeuf, J. P. and Garrigues, L., Phys. Plasmas, Vol. 84, pp. 3541-3554 (1998).
[2] Hara, K., Boyd, I. D., and Kolobov, V. I., AIAA Paper 2012-4314, (2012).

Time-Averaged results

Hybrid-DK and hybrid-PIC simulations show similar results.
- Three distinct regions are shown: diffusion, ionization, and acceleration
- There are slightly more ions generated from the hybrid-DK simulation.
  Ionization is more accurately modeled in DK simulation than PIC simulation.

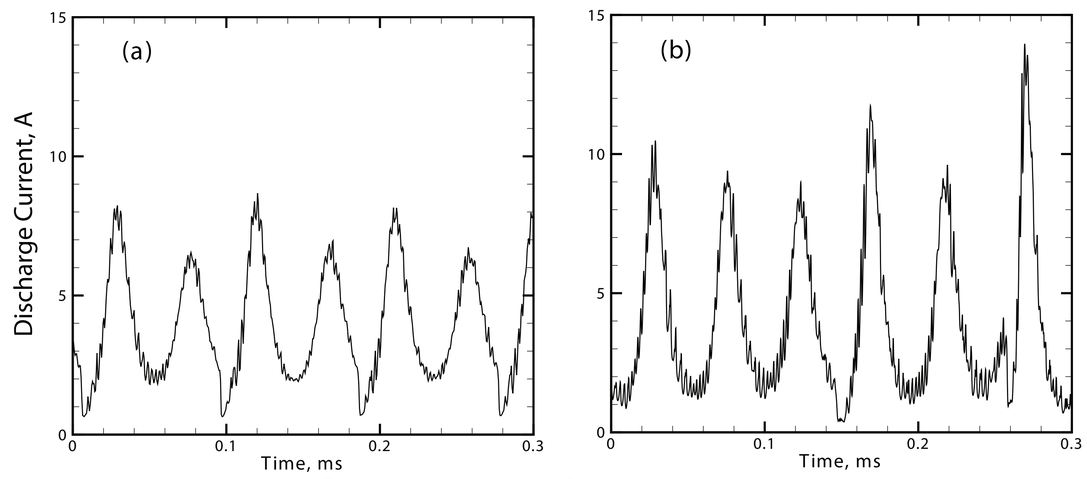


(Solid): Hybrid-DK method, (Symbol): Hybrid-PIC method

Time-resolved results

The time-resolved results obtained from **(a) hybrid-PIC** and **(b) hybrid-DK** simulations are shown.[2]

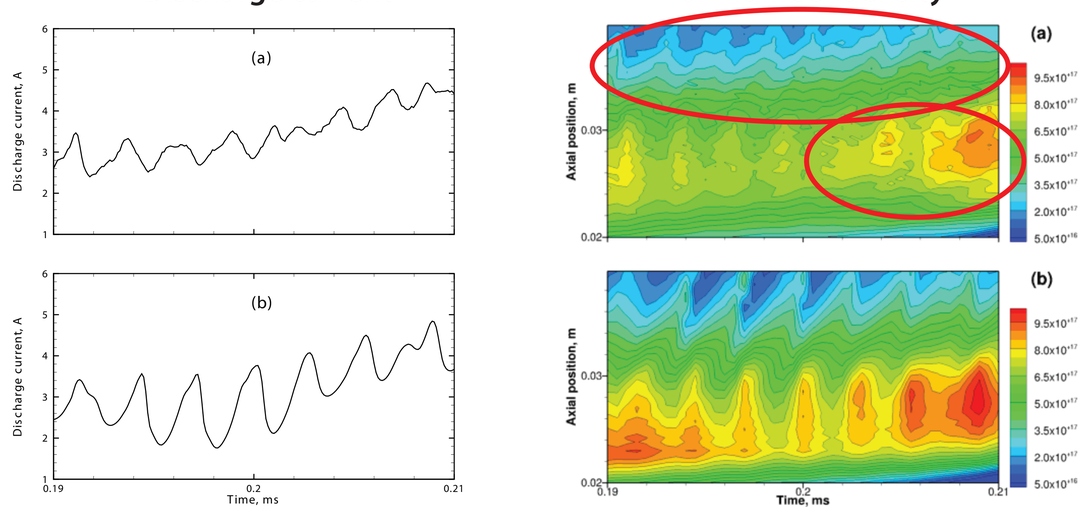
The discharge oscillations are similar in terms of the shape and the mean value. Low frequency oscillations are often called "Breathing mode" in the Hall thruster community. The breathing mode frequency agrees with theories and experiment. Note that the difference in the peak discharge current is mainly due to the difference in ion number density that was shown in the time-averaged results.



Breathing mode frequency: 20 kHz

High frequency oscillations are often referred to as "transient oscillation mode." The DK simulation exhibits a smoother discharge current and plasma density than the PIC results, which contain **statistical noise**.

Discharge current **Ion number density**



Transient mode frequency: 300 kHz

Small spatial scale and small time scale can be resolved using a direct kinetic simulation method!

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