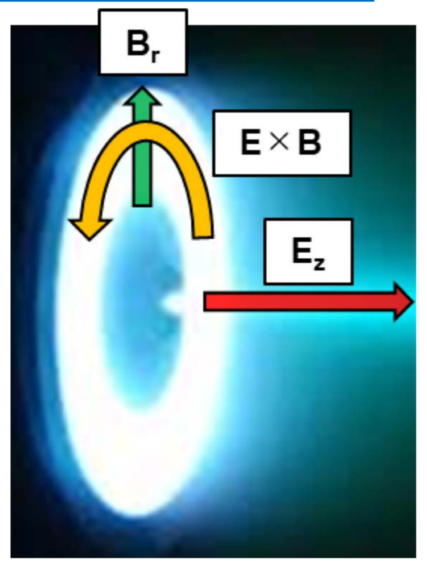
# Study of the electron anomalous transport in a Hall effect thruster using a 2D multi-fluid simulation

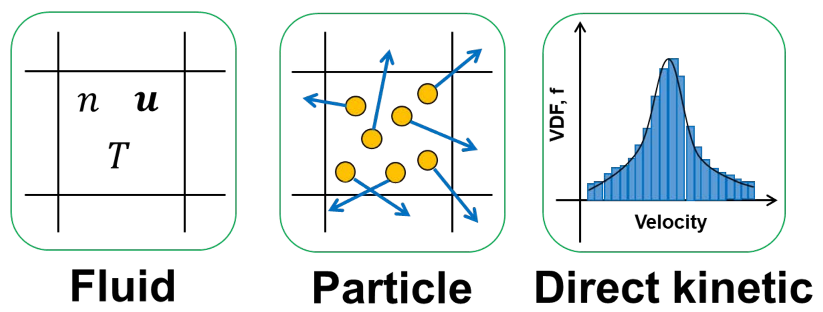
Yusuke Yamashita(1), Carlos Gonzalez(2), Kentaro Hara(2),(3), Shinatora Cho(4), Kazutaka Nishiyama(4)

(1) Department of Aeronautics and Astronautics, The University of Tokyo; (2) Aerospace Engineering, Texas A&M University;
(3) Aeronautics and Astronautics, Stanford University; (4) Japan Aerospace Exploration Agency (JAXA)

## Introduction




In Hall effect thrusters (HETs), electrons are confined by radial magnetic field, while ions are accelerated by axial electric field. The HET discharge plasma experiences anomalous transport in the axial direction, which still remains to be poorly understood. In this study, the transport is mainly investigated by developing numerical simulation tools.




Various numerical models are used to model the HET discharge,: fluid, particle, direct kinetic methods.[1] In this study, we introduce full-particle and multi-fluid model.

## 1D axial full-PIC model

We use a Particle-In-Cell (PIC) Monte Carlo collision (MCC) method.
Ion & electrons: macroparticles, neutral atoms : fluid

Tab.1 Simulation condition

| Item | Value |
|---|---|
| Time step | 2.5 ps |
| Grid size | $2\times10^{-5}$ m |
| Max $B_x$ | 160 G |
| $\nu_{ano} = \alpha_{ano}\omega_c$ | 1/16 (Inside)<br>1/160 (Outside) |
| Collision | Elastic, Excitation<br>Ionization |

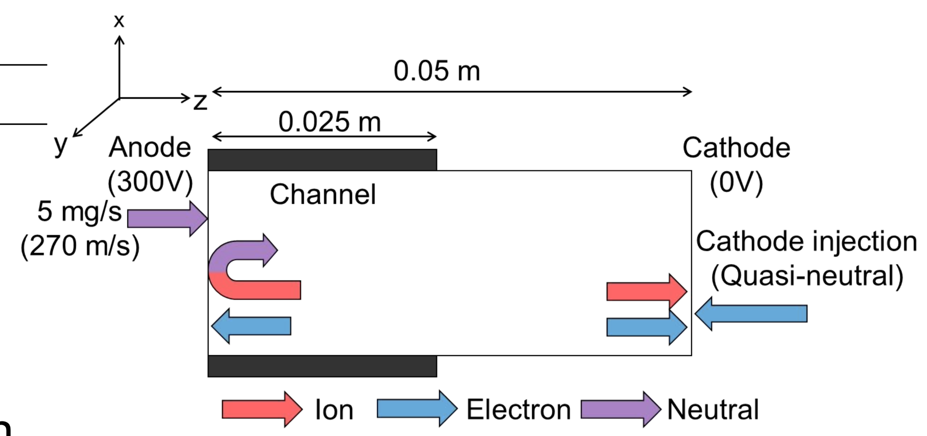



Fig.1 Boundary condition

## Time-averaged plasma parameters

In this model, anomalous momentum transfer frequency is considered as a scattering mechanism, e.g. ECDI [1] The two scattering cases considered are (i) scattering only in perpendicular direction and (ii) isotropic scattering.

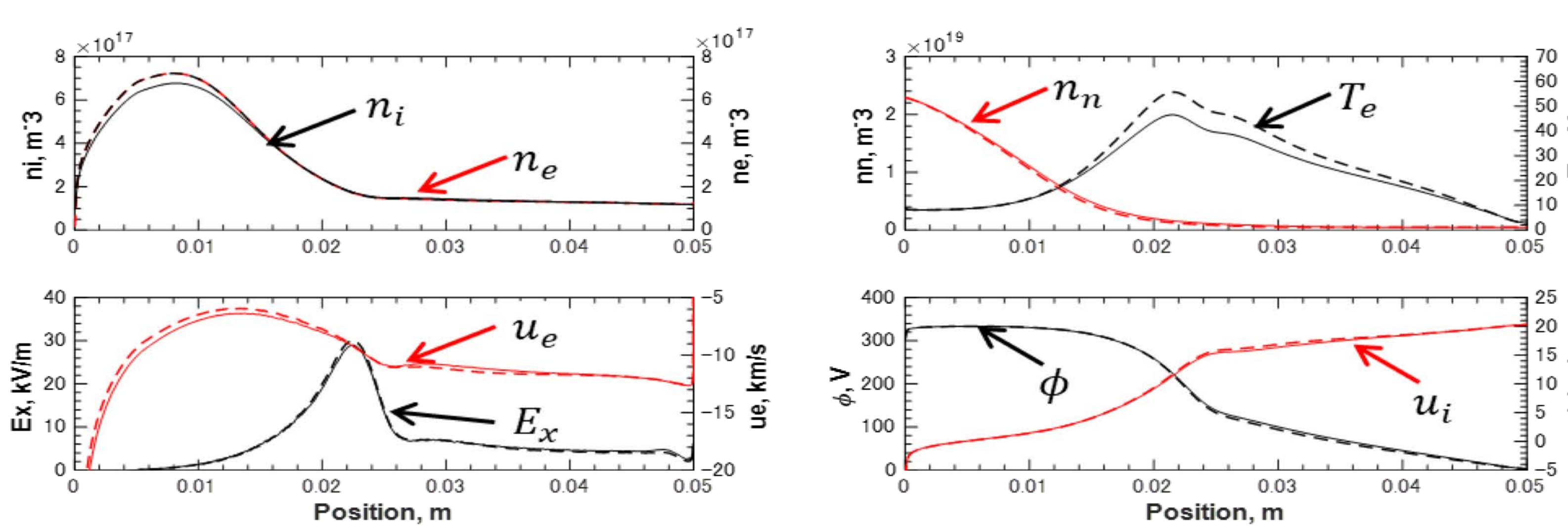



Fig.2 Time-averaged results. Solid : perpendicular, Dashed: isotropic

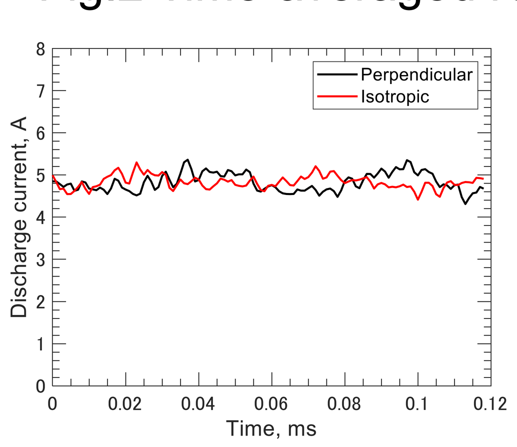



Fig.3 Discharge current

$n_i$ & $n_e$ are almost identical except for the anode sheath. Anode sheath is estimated as 29 V~3.2$T_e$. $E_x$ is largest near the channel exit.

The discharge current is stationary, which is similar to the quasi-neutral model. [2]

## Anisotropy of $T_e$ & EVDF

Due to E × B drift and magnetic field, EVDF is not an isotropic Maxwellian. In this case, $T_{e,i,j}$ (i and j are the index for directions) could be different.

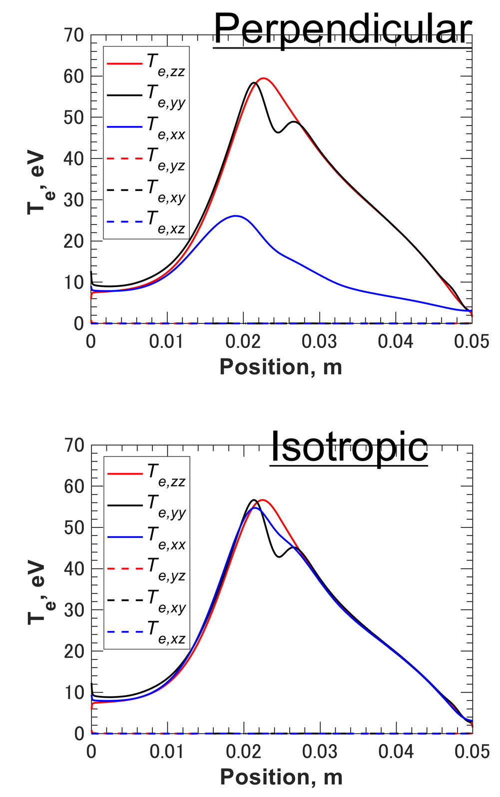



Fig.4 $T_{e,i,j}$

In both cases, non-diagonal terms ($i \neq j$) can be neglected. Difference between $T_{zz}$ and $T_{yy}$ is due to E × B drift. $T_{xx}$ is deviates from $T_{zz}$ in the perpendicular scattering model. $T_{xx}$ (radial direction) depends on scattering model, but does not change the plasma drastically (see Fig. 2)

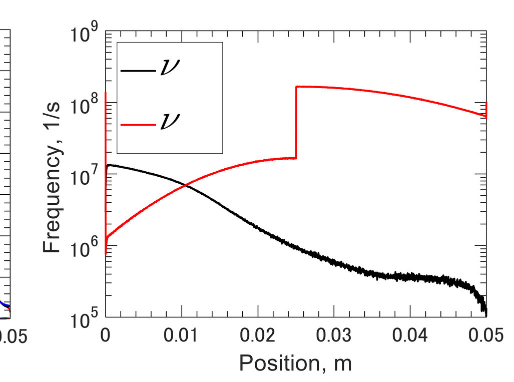



Fig. 5: $\nu_{ano}$ (input) & $\nu_n$

It is found from Fig.5 that the anisotropy occurs where the ExB drift is large and the electrons are not heated in the x direction enough.

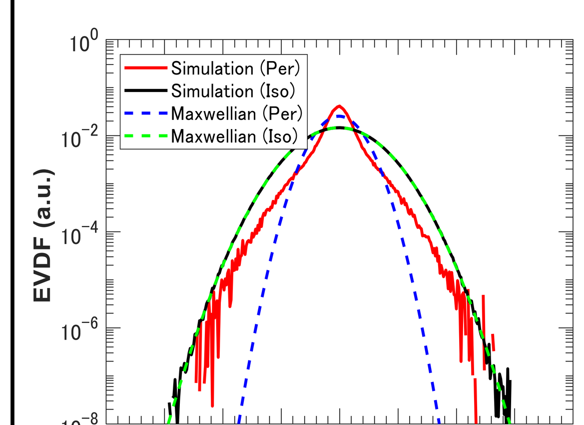



Fig.6 Y-EVDF @ channel exit

EVDF in the ExB direction (y) is strongly anisotropy.[3] If the real anomalous transport phenomena produces perpendicular scattering (e.g. ECDI vs MTSI), the pressure model may need to account for anisotropic non-Maxwellian.

$$f(v) = \sqrt{\frac{m_e}{2\pi k T_e}} \exp\left\{-\frac{m_e(v-u_{peak})^2}{2kT_e}\right\}$$

$$u_{peak} = \int v f(v)dv,\ T_e = m(v-u_{peak})^2 f(v)dv$$

## Cross-field transport

Non-Maxwellian electron distribution exists near the anode. The high energy tail of EVDFs near the anode is similar to that of the EVDF in the channel exit. The high energy tail in the channel will contribute to the electron transport?

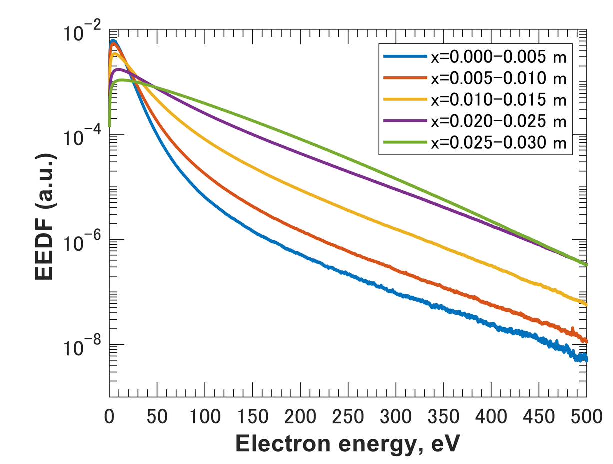



Fig.7 EEDF

From the EVDF in 2D, non-Maxwellian electrons can be seen due to the truncation of positive velocity particles due to the anode sheath. The electrons have a velocity of -1.5 × $10^7$ m/s. The Larmor radius $r_L$ Is 0.005 m @ 160 G. and $r_L$ is 20 % of channel length. Hence, **non-Maxwellian EVDFs can contribute to cross-field transport with a Larmor radius effect.**

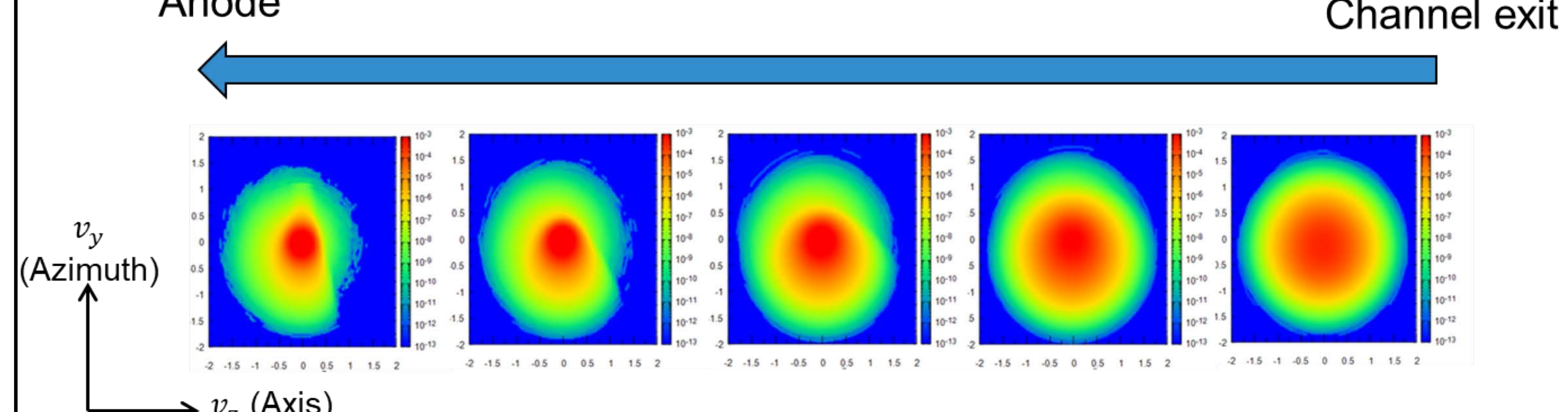



Fig.8 2D-EVDF (Axial-Azimuthal)

## 2D multi-fluid model

To model electron dynamic and non-neutral effects of the HET plasma, we have developed a multi-fluid model, which solves the conservation equations for mass, momentum and energy density for each plasma species. The coupling between the species is given by the Poisson equation for the electric potential.

$$\frac{\partial n_s}{\partial t} + \nabla\cdot(n_s u_s) = \dot{n}^{ion}$$

$$\frac{\partial n_s \vec{u_s}}{\partial t} + \nabla\cdot\left(n_s \vec{u_s}\vec{u_s} + \frac{p_s}{m_s}\right) = \frac{q_s n_s}{m_s}(\vec{E} + \vec{u_s}\times\vec{B})$$

$$\frac{\partial \epsilon_s}{\partial t} + \nabla\cdot\{(\epsilon_s + p_s)\cdot\vec{u_s}\} = q n_s \vec{E}\cdot\vec{u_s}$$

$$\epsilon_0 \nabla^2\phi = \sum_s q_s n_s, \quad \vec{E} = -\nabla\phi$$

A cell-center finite volume formulation is employed in a Cartesian mesh and the advective fluxes at the cell-interface are obtained using the HLLC approximate Riemann solver [4].

We have tested our numerical code with the Kelvin-Helmholtz instability, which is a standard fluid dynamic test case. We also performed a grid convergence study to stablish the uncertainty of the numerical solution.

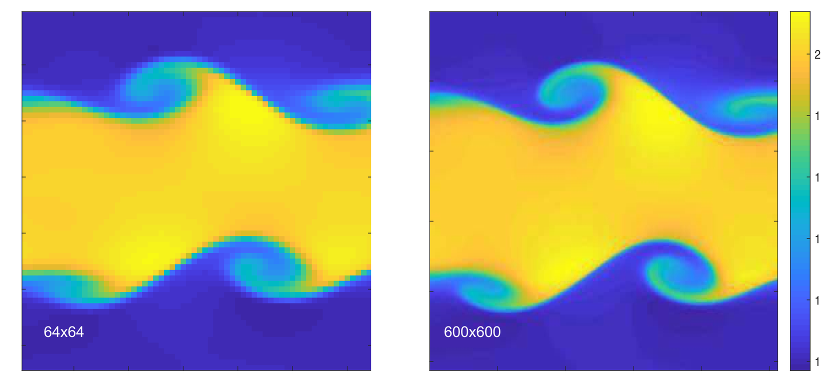



Fig.9 Kelvin-Helmholtz instability with different grid size

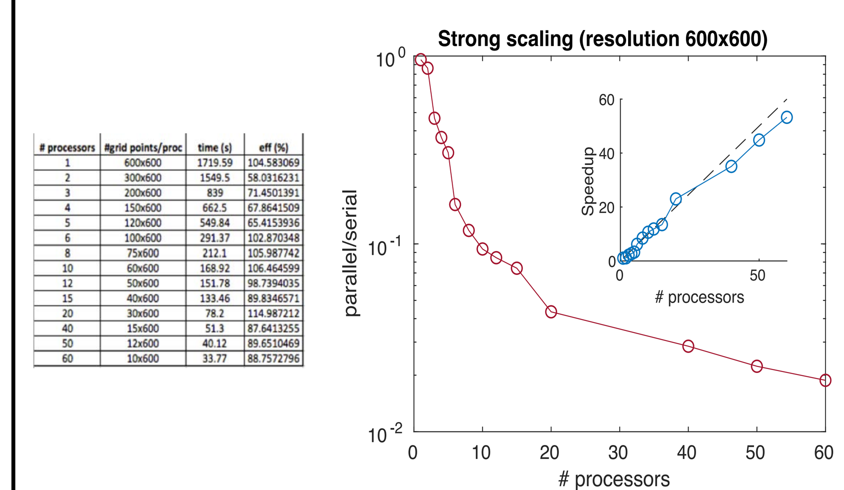



Fig.10 Scaling for 2D MPI code

The code is parallelized using Message Passing Interface (MPI). The strong scaling shows a good trend in terms of computational time vs the number of processors, which allow us to run in parallel computers and decrease the computational time that is needed in order to be able to resolve the small scales related to the electrons.

## Conclusions

### 1D-axial full-PIC

★ Anisotropy of $T_e$, is observed. Difference of $T_{yy}$ is derived from E × B drift. Difference of $T_{zz}$ is derived from anomalous scattering model.

★ Non-Maxwellian electrons contribute to the cross-field transport with Larmor radius effect.

### 2D full-fluid

★ We have advanced in the development and parallelization of the 2D multi-fluid model for HET plasma. We are now focus on the physical studies of the HET using multi-fluid simulations.

★ We are currently developing a coupled full-fluid model to simulate the HET plasma in z-theta coordinates.

## Reference

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