Physics of Plasmas ARTICLE scitation.org/journal/php

Vlasov code simulation of contact discontinuities

Cite as: Phys. Plasmas **26**, 102107 (2019); doi: 10.1063/1.5100314
Submitted: 17 April 2019 · Accepted: 18 September 2019 ·
Published Online: 10 October 2019

View Online Export Citation CrossMark

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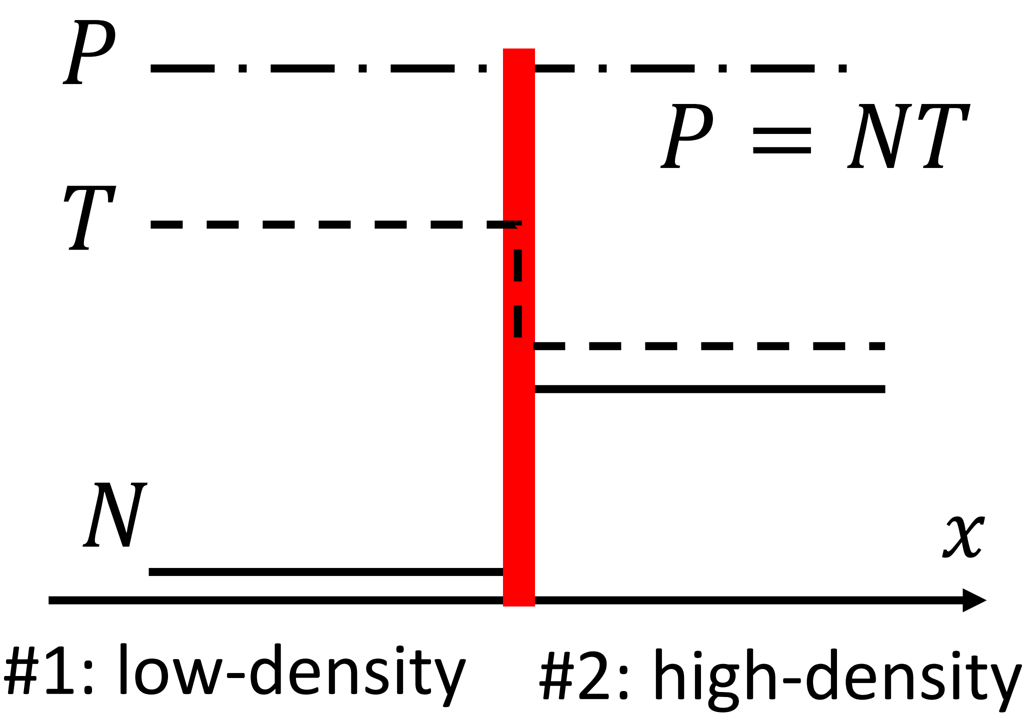
ABSTRACT

The stability of contact discontinuities formed by the relaxation of two Maxwellian plasmas with different number densities but the same plasma thermal pressure is studied by means of a one-dimensional electrostatic full Vlasov simulation. Our simulation runs with various combinations of ion-to-electron ratios of the high-density and low-density regions showed that transition layers of density and temperature without jump in the plasma thermal pressure are obtained when the electron temperatures in the high-density and low-density regions are almost equal to each other. However, the stable structure of the contact discontinuity with a sharp transition layer on the Debye scale is not maintained. It is suggested that non-Maxwellian velocity distributions are necessary for the stable structure of contact discontinuities.

Key Points

- The structure of transition layers of density and temperature formed by the relaxation of two Maxwellian plasmas with different number densities but the same plasma thermal pressure (i.e., the Tsai transition layer [Tsai et al. JGR 2009]) is not a stable contact discontinuity.
- The Tsai transition layers are not obtained by the Tsai condition [Tsai et al. JGR 2009], but are obtained by an almost equal electron temperature across the transition layer.

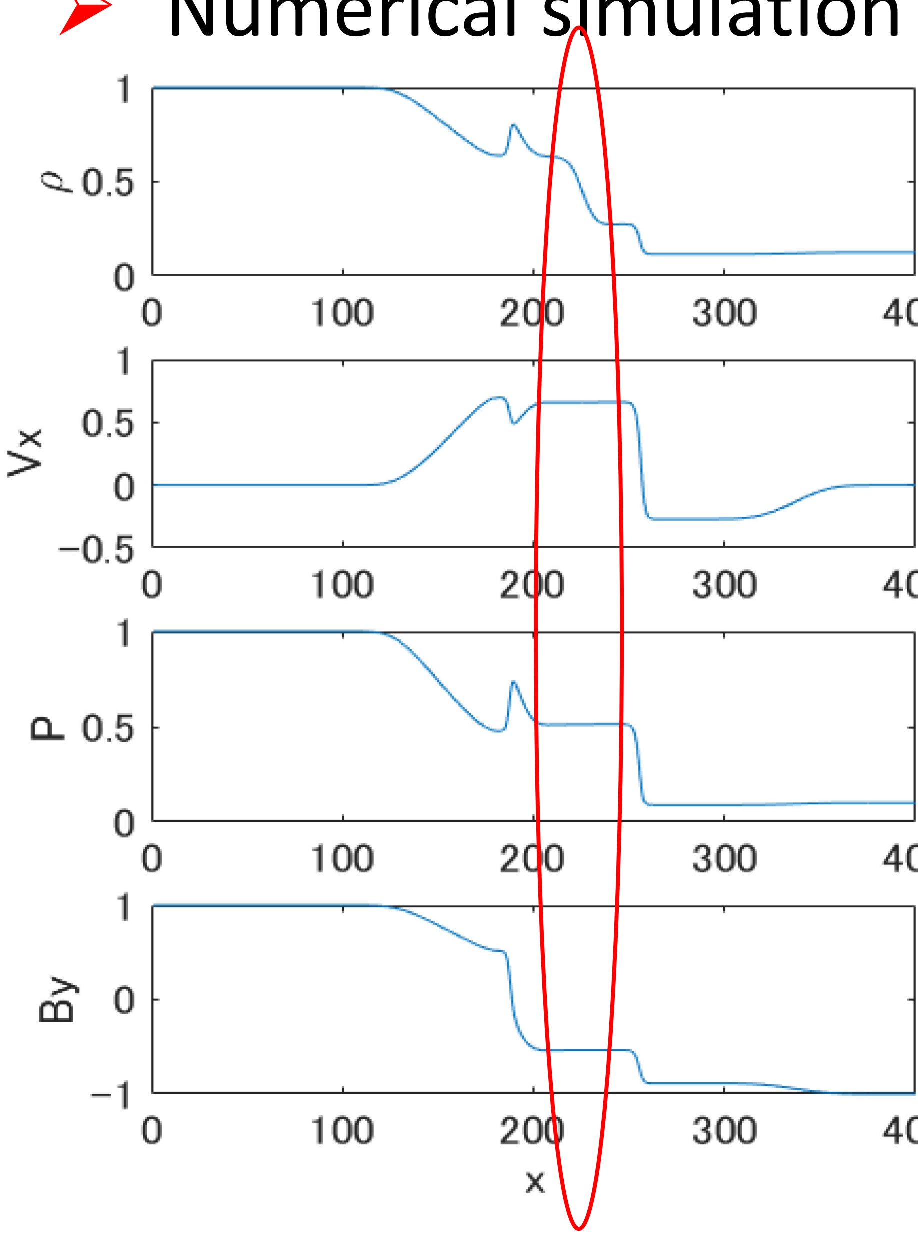
MHD Contact Discontinuities



- $N_1 < N_2 \quad (N_e \approx N_i)$
- $T_1 > T_2$
- $P_1 = P_2$ Pressure
- $U_{n1} = U_{n2}$ Normal velocity
- $U_{t1} = U_{t2}$ Tangential velocity
- $B_{n1} = B_{n2}$ Normal B-field
- $B_{t1} = B_{t2}$ Tangential B-field

Existence of Contact Discontinuities

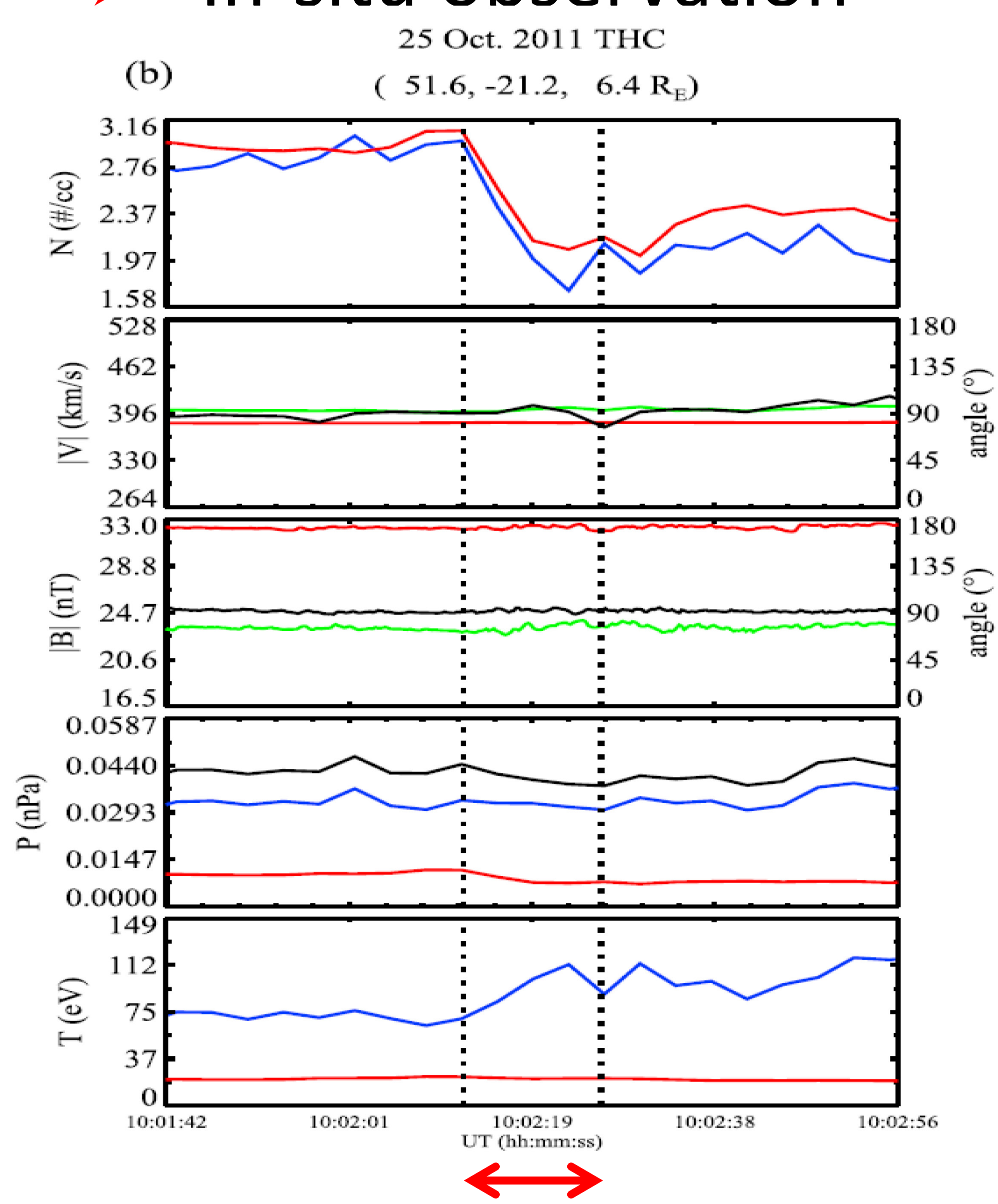
- Numerical simulation



Constant pressure, velocity, B-field

Brio & Wu MHD shock tube [JCP 1988]

- In-situ observation

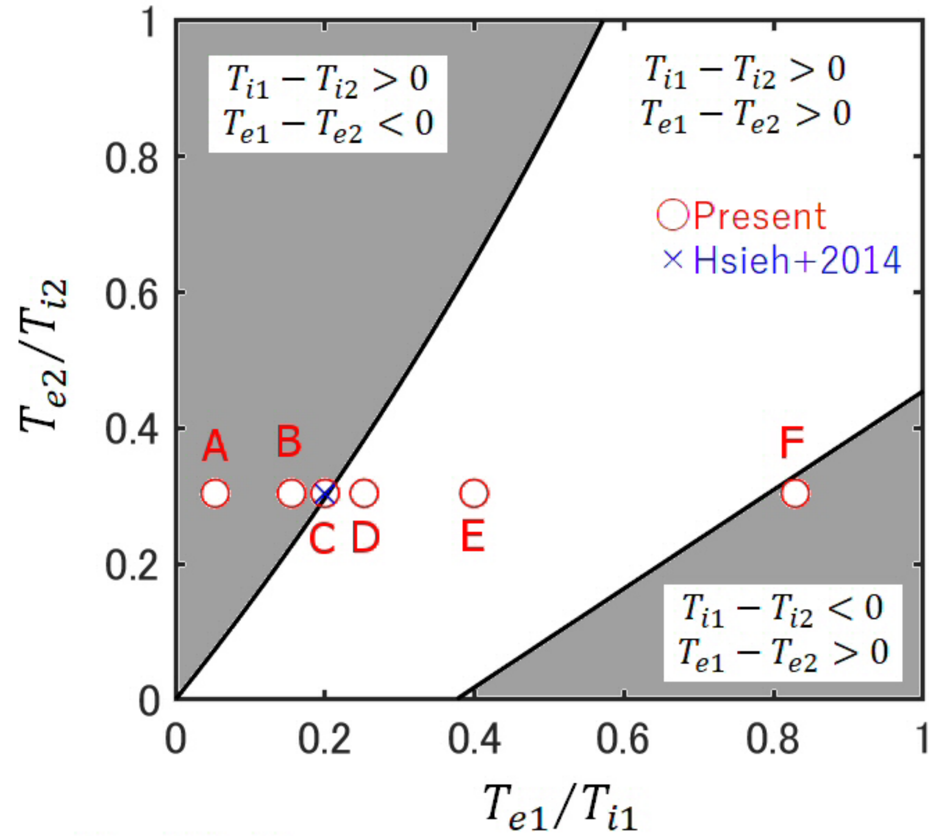


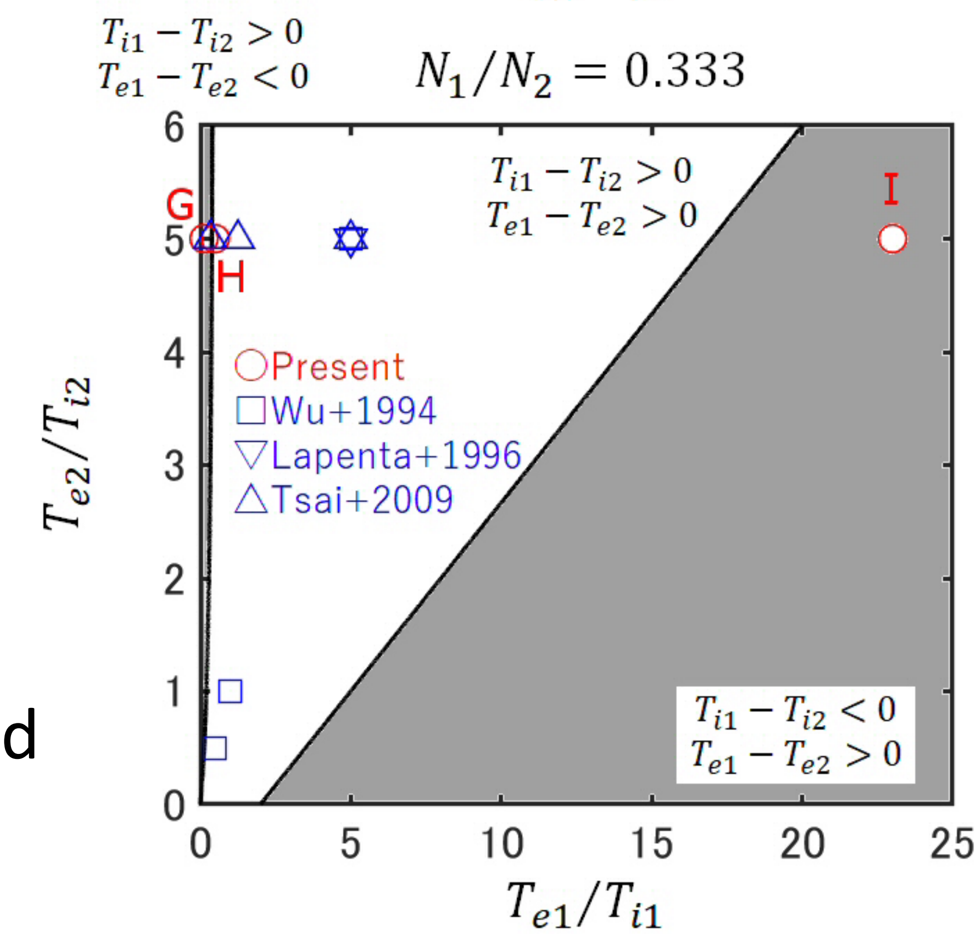
$\delta \approx 4 - 12 r_i \sim 10 \lambda_{Di}$

THEMIS obs.[Hsieh et al. GRL 2014]

Vlasov Simulation Parameters

Run	T_{e1}/T_{i1}	T_{e2}/T_{i2}	N_1/N_2	Tsai condition[5]	T_{e1}/T_{e2}	$\Delta\phi$
A	0.0536	0.304	0.727	Negative	0.3	1.8
B	0.1569	0.304	0.727	Negative	0.8	1.0
C	0.2000	0.304	0.727	Negative	0.983	0.7
D	0.2554	0.304	0.727	Positive	1.2	0.3
E	0.4050	0.304	0.727	Positive	1.7	−0.6
F	0.8443	0.304	0.727	Negative	2.7	−2.6
G	0.1250	5	0.333	Negative	0.4	3.2
H	0.5000	5	0.333	Positive	1.2	1.9
I	17.947	5	0.333	Negative	3.41	−1.7

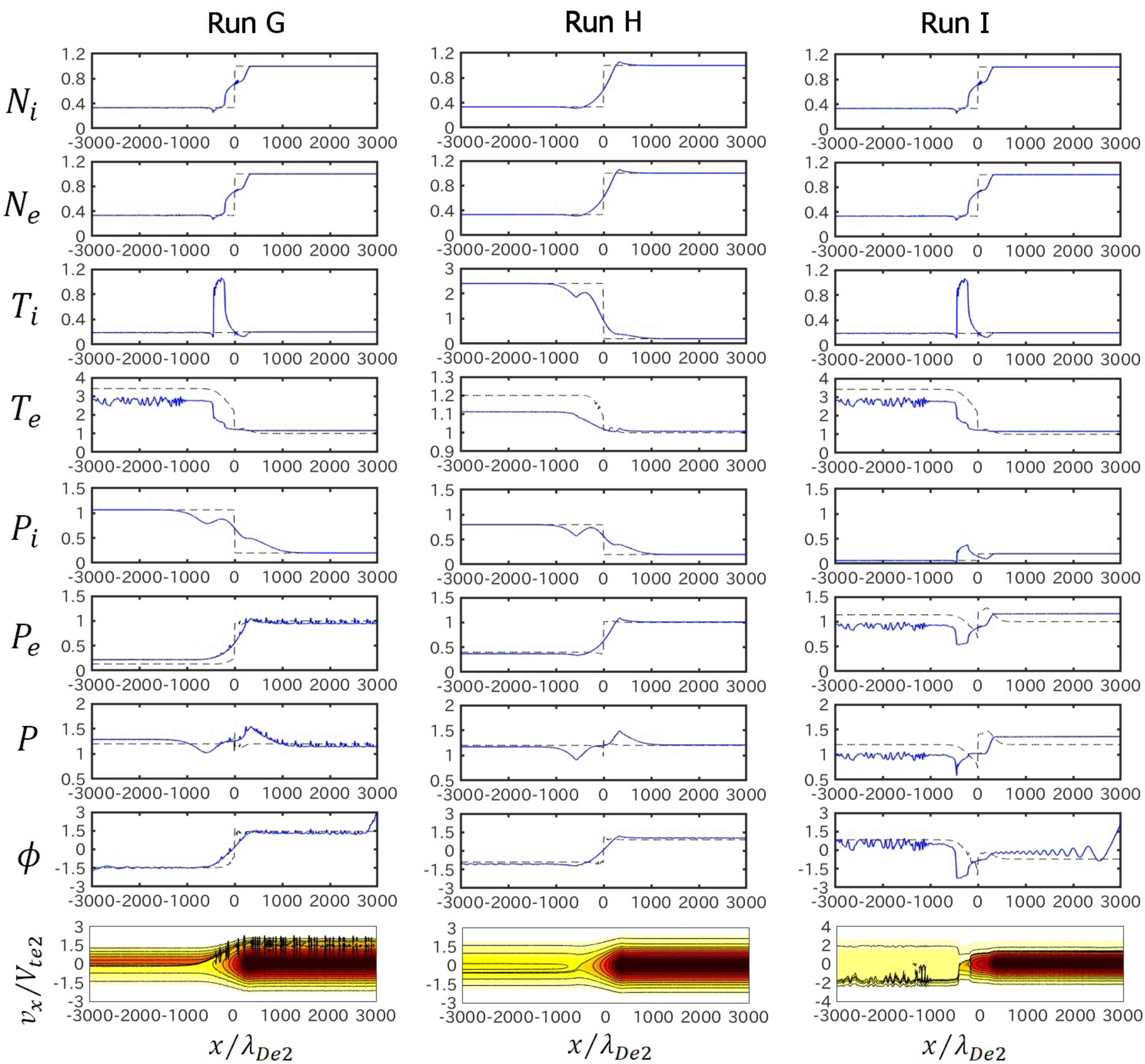




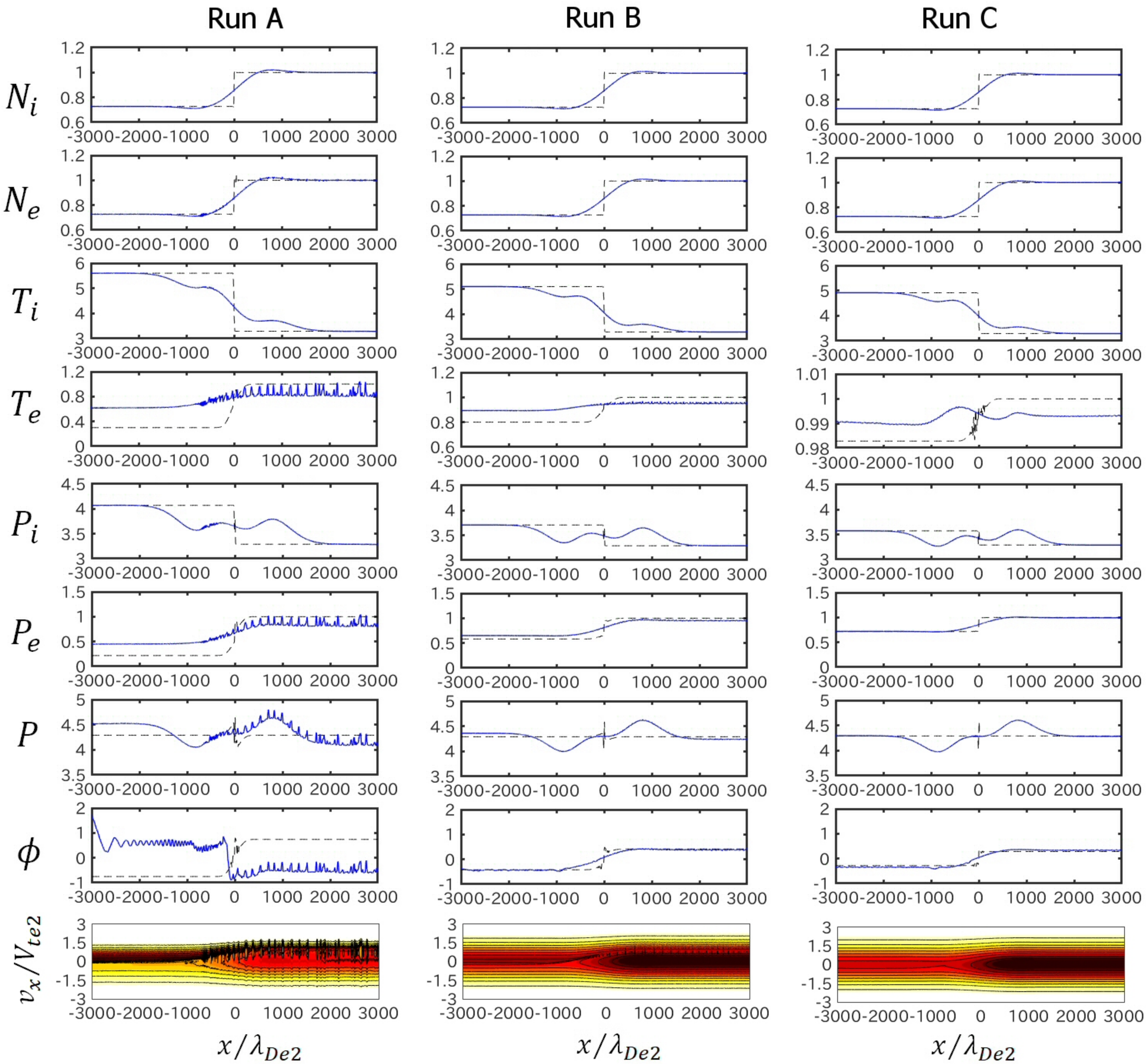
- By using 1D Vlasov simulation, we examine the relaxation of two Maxwellian plasma with
$$N_1(T_{i1} + T_{e1}) = N_2(T_{i2} + T_{e2})$$
- The Tsai condition [JGR 2009]:
$$(T_{i1} - T_{i2})(T_{e1} - T_{e2}) < 0$$
- Runs A, B, C, D, F, G, and I satisfy the Tsai condition.
- The CD observed by THEMIS [Hsieh et al. GRL 2014] satisfied the Tsai condition.

Previous studies	Code	CD	Tsai condition
Wu et al. [GRL 1994]	Hybrid PIC	Stable	Not satisfied
Lapenta & Brackbill [GRL 1998]	Hybrid PIC	Stable	Not satisfied
	Full PIC	Not stable	
Tsai et al. [JGR 2009]	Vlasov	Stable on electron scale	Satisfied

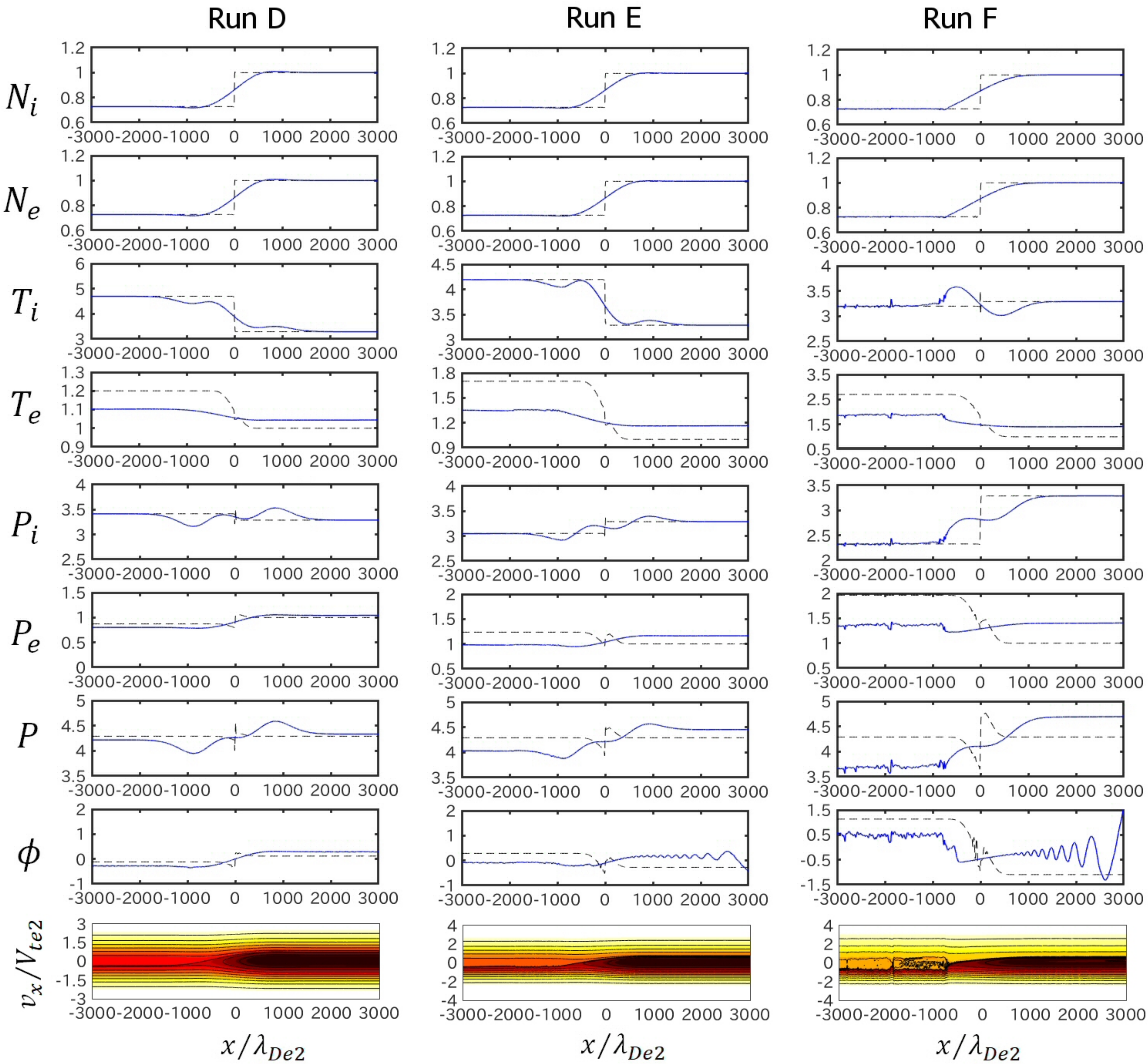
Vlasov Simulation Results



- The structure of transition layers of density and temperature with different number densities but the same plasma thermal pressure is obtained in Runs Runs B, C, D, G, and H.
- This structure is known as the “Tsai transition layer.”

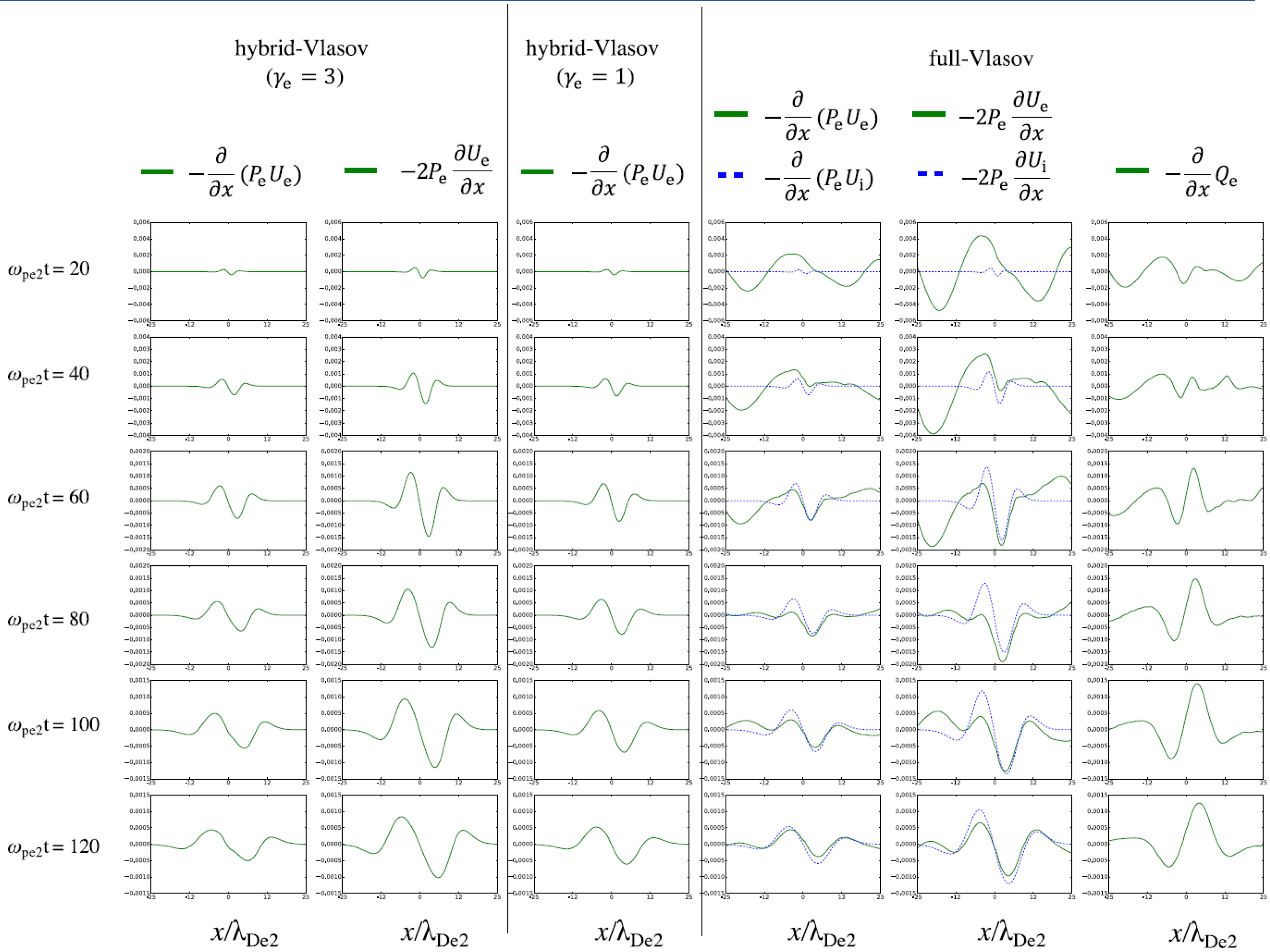


- Tsai et al. [JGR 2009] suggested that the Tsai transition layer was obtained by the Tsai condition.
- The present study has shown that the Tsai transition layer is obtained by $T_{e1} \approx T_{e2}$.
- The obtained transition layers in all the runs relax through free streaming of ions, which is consistent with Lapenta & Brackbill [GRL 1996].



- The Tsai transition layer formed by the relaxation of two Maxwellian plasmas does not develop into steady contact discontinuity.
- The potential gap at the transition layer is approximated as $\Delta\phi \approx T_{e2} - T_{e1}N_1/N_2$.
- Non-Maxwellian velocity distributions are necessary for an electrostatic (Vlasov-Poisson) equilibrium.

Hybrid- versus Full-Vlasov Simulations



Pressure equation including heat flux.

$$\frac{\partial P_e}{\partial t} = -\frac{\partial}{\partial x}(P_e U_e) - (\gamma_e - 1) P_e \frac{\partial U_e}{\partial x} - \frac{\partial Q_e}{\partial x}$$

$\gamma_e = 3$ or 1 in hybrid-Vlasov
$\gamma_e = 3$ in full-Vlasov

- Ion profiles in hybrid- and full-Vlasov simulations are quite similar to each other.
- Electron profiles approach to ion profiles.
- The heat flux term cancels the compressional term in full-Vlasov simulation.