REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
21 October 2016	Briefing Charts	30 September 2016 – 21 October 2016

4. TITLE AND SUBTITLE
Collisionless Electrostatic Shock Modeling and Simulation

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Daniel Crews

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
Q02Z

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RQRS
1 Ara Drive
Edwards AFB, CA 93524 - 7013

8. PERFORMING ORGANIZATION REPORT NO.

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RQR
5 Pollux Drive
Edwards AFB, CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RQ-ED-VG-2016-287

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited. The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.

13. SUPPLEMENTARY NOTES
For presentation at University of Washington; (21 October 2016) PA Case Number: #16490; Clearance Date:10/14/2016
Prepared in collaboration with ERC

14. ABSTRACT
Viewgraph/Briefing Charts

15. SUBJECT TERMS
N/A

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					D. Bilyeu
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	SAR	37	**19b. TELEPHONE NO** *(include area code)*
Unclassified	**Unclassified**	**Unclassified**			N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

Air Force Research Laboratory

Collisionless Electrostatic Shock Modeling and Simulation

Daniel W. Crews
In-Space Propulsion Branch (RQRS)
Aerospace Systems Directorate
Edwards AFB, CA
dcrews@uw.edu

Overview

- Motivation and Background
- What is a Collisionless Shock Wave?
- Features of the Collisionless Shock
- The Shock Simulation Model
- Simulation Results and Verification
- Future Work

Background

Who am I?

- Grew up in Olympia, WA, The City of Champions
- B.S. Aerospace Engineering 2016 | UW, Seattle
- Start Graduate Program at UW Autumn 2016
- Hobbies:
  - Studying classical guitar,
  - Observing the sky,
  - Appreciating existence and nature.

Investigation Motivation

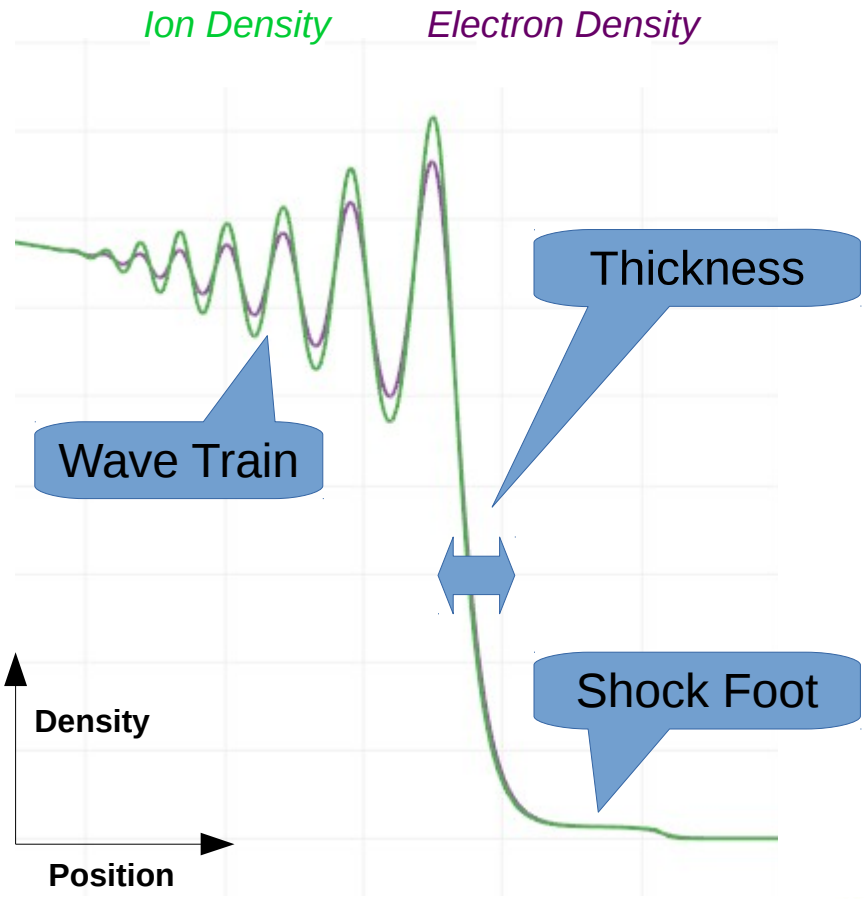
What's the Point?

- **The 1D Collisionless Ion-Acoustic Shock Wave:**
  - **Has a simple premise**
  - **Is rich in nonlinear effects difficult for theoretical prediction,**
    - **Wave Dispersion**
    - **Wave-Particle Interaction**
    - **Various Wave Dissipation Mechanisms**
  - **Shock structure is an active area of research. In particular,**
    - **Capacity to create ion beam of super-shock velocity.**
- **Validation of Simulation Frameworks**
  - **The shock is a model problem for simulation code validation.**

The Collisionless Shock Wave

Electrostatic Shock Features

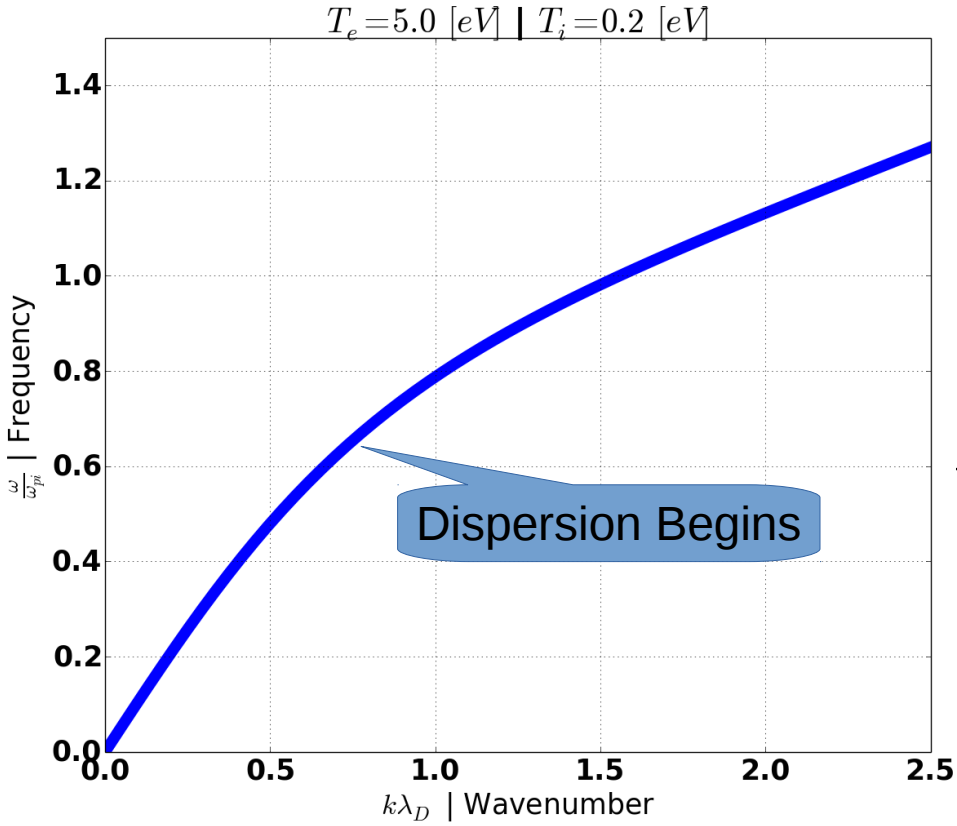
- Propagation occurs via collective electric interactions
- Shock front is dispersed across many Debye lengths
- Wave is accompanied by an electric field perturbation
- Two classes of shock:
  - Subcritical: M < M* ~ 1.8
    - Accompanied by undulating wave-train
  - Supercritical: M > M* ~ 1.8
    - Increase in dissipation
    - Reflects almost all ions



Details on Shock Structure

Shock Thickness

- Ion-acoustic dispersion relation predicts the electron contribution to acoustic speed to decay for wavelengths approaching the Debye length.
- Imagine shock formation: nonlinear steepening of an acoustic disturbance.



Wave steepening is balanced by dispersion;

short wavelength components recede from the wavefront.

$$t \approx k_D^{-1}$$

Linearized Ion-Acoustic Dispersion Relation

$$\left(\frac{\omega}{k}\right)^2 = \frac{1}{1+(k\lambda_D)^2}\frac{T_e}{m_i} + \gamma_i \frac{T_i}{m_i}$$

Details on Shock Structure

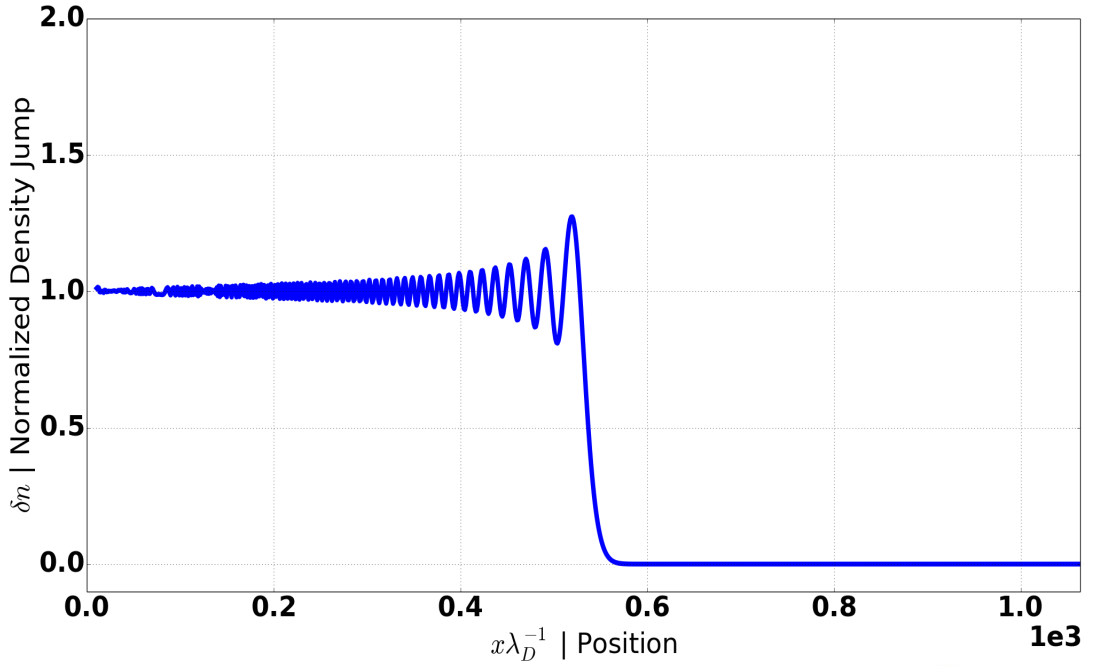
Wave Train Properties

- **Linearized Model of Dispersive Shock, the Integrated Airy Function:**
  - **Linearization of the fluid equations with piston-like boundary conditions gives a solution for the shock behavior.**
  - **Assumes cold upstream ions, therefore neglecting shock reflection.**

$$n(x,t) = n_0 + \frac{\delta n}{2}\int_{\beta}^{\infty} Ai(\alpha)d\alpha$$

$$\beta = \left(\frac{2}{3}\right)^{\frac{1}{3}}\left(\frac{\lambda_D}{x}\right)^{\frac{1}{3}}\frac{(x - C_s t)}{\lambda_D}$$

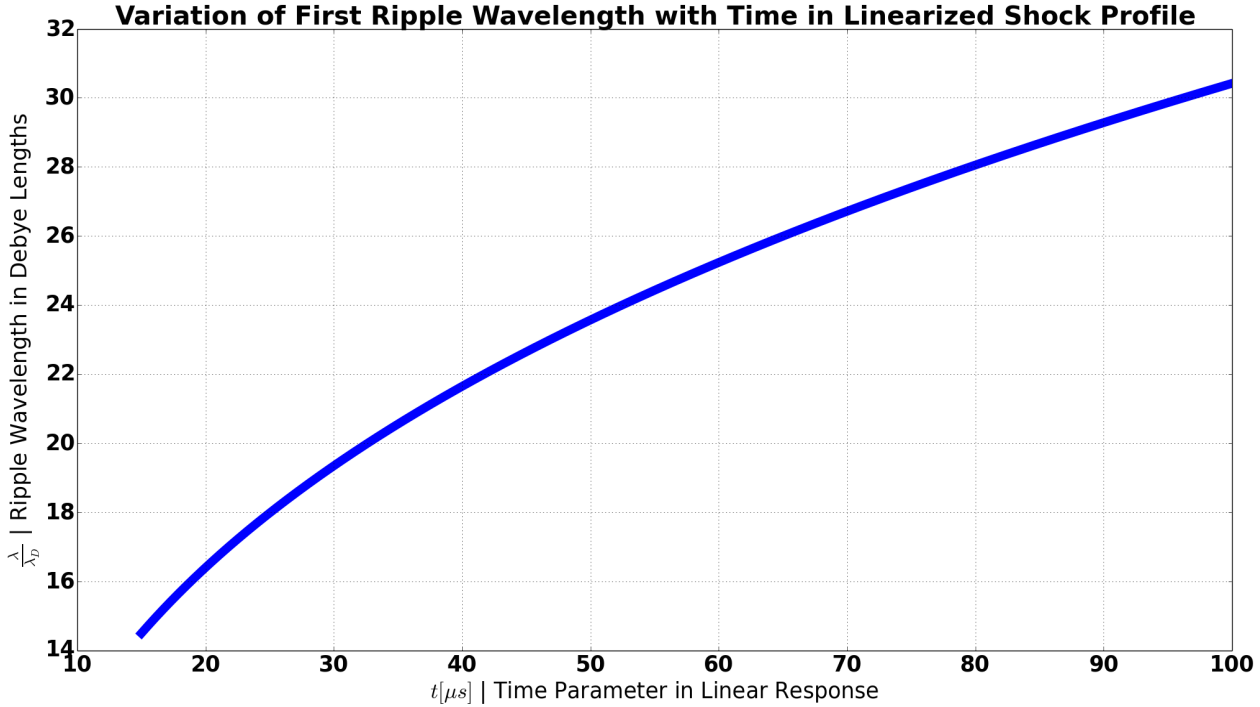
$$C_s = \left(\frac{T_e}{m_i}\right)^{\frac{1}{2}}$$



Details on Shock Structure

Wave Train Properties

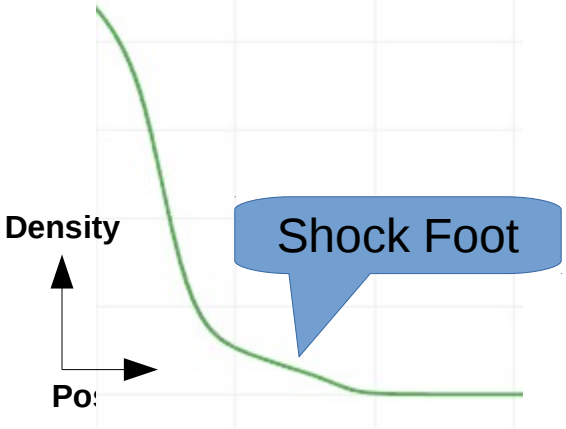
- **Linear Model Predicts:**
  - **The wave train spreads out in time; peak-to-peak wavelength increases.**
  - **No variation of non-dimensional wavelength with electron temperature.**
  - **The wave train increases in frequency towards the back of the train.**

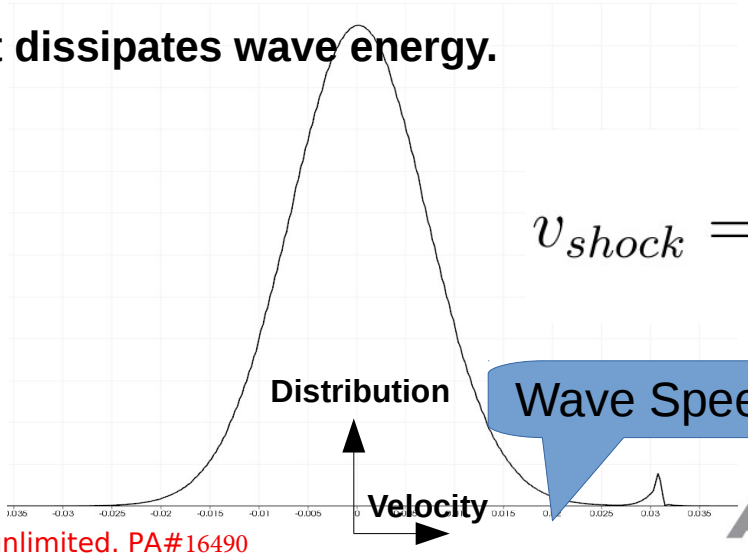


Details on Shock Physics

Sources of Collisionless Wave Dissipation

- **Landau Damping:**
  - A form of wave-particle resonance. Resonant particles sap wave energy.
  - Damping is proportional to slope of distribution function at wave velocity.
  - Higher electron temperature means greater shock speed, so less damping.
- **Ion Reflection / The Shock Foot:**
  - Higher shock strength brings a greater potential difference.
  - Ions unable to traverse difference are reflected downstream.
  - Formation of the shock foot dissipates wave energy.



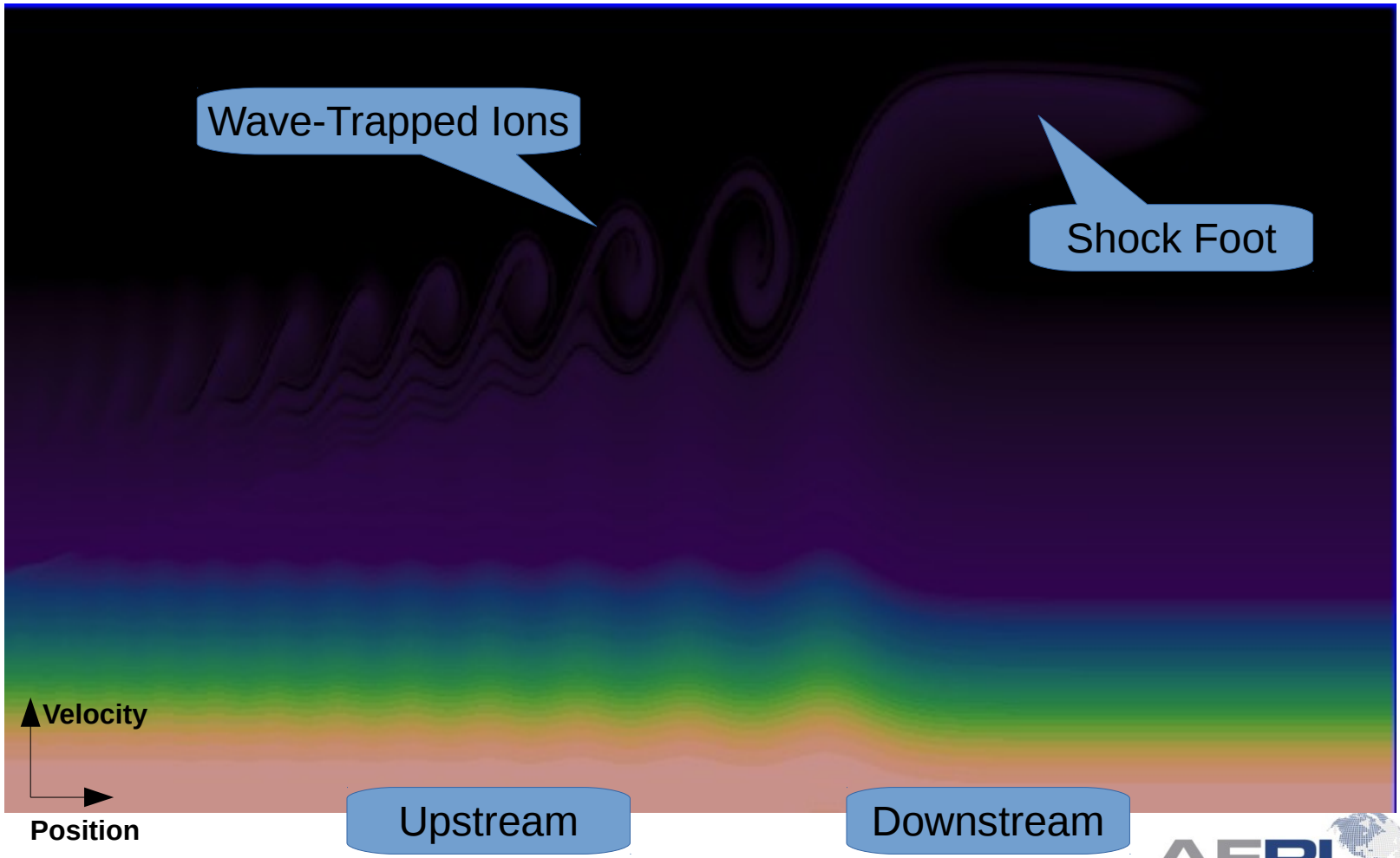


$$v_{shock} = M\sqrt{\gamma\frac{T_e}{m_i}}$$

Details on Shock Physics

Phase Space Indicators of Wave Dissipation

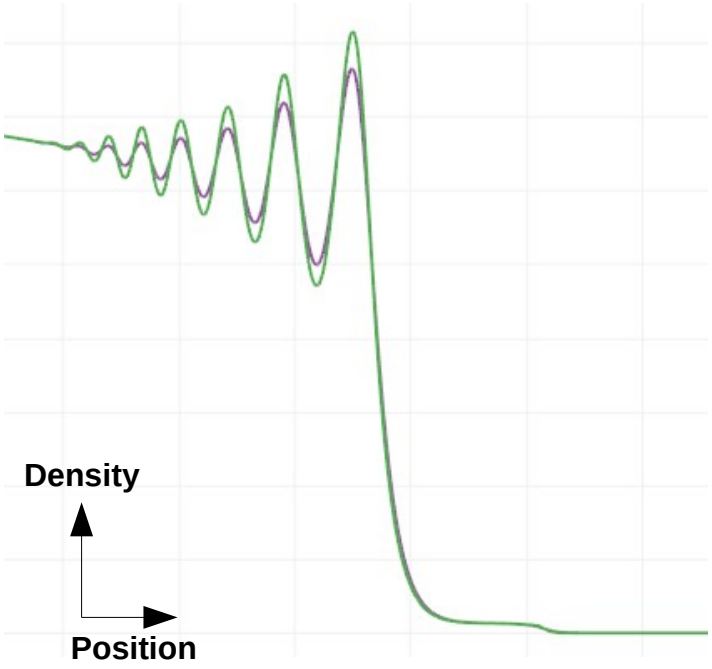
(Log View of Distribution)



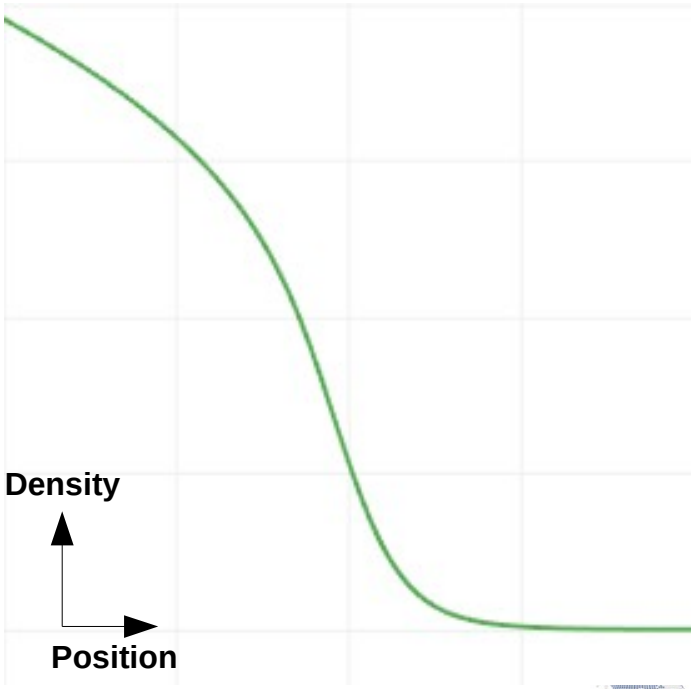
Dissipation Controls Wave Train

Under- and Over-damped Shocks

- **Under-damped**:
  - Dissipation is weak, ripples persist.
  - High $\frac{T_e}{T_i}$



- **Over-damped**:
  - Strong dissipation damps ripples.
  - Low $\frac{T_e}{T_i}$

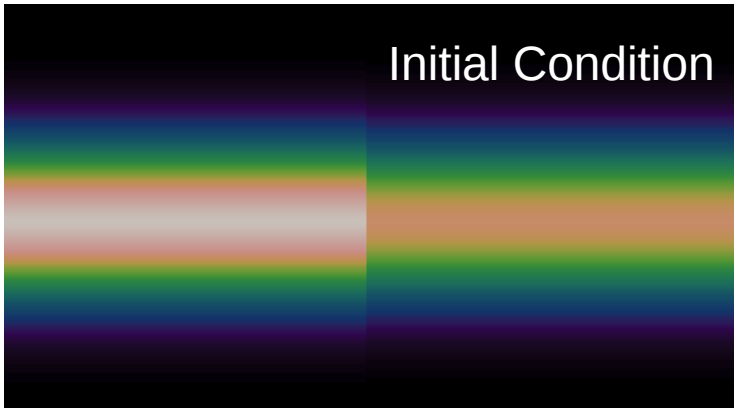


The Simulation Model

Initial Conditions: Ion-Acoustic Shock Tube

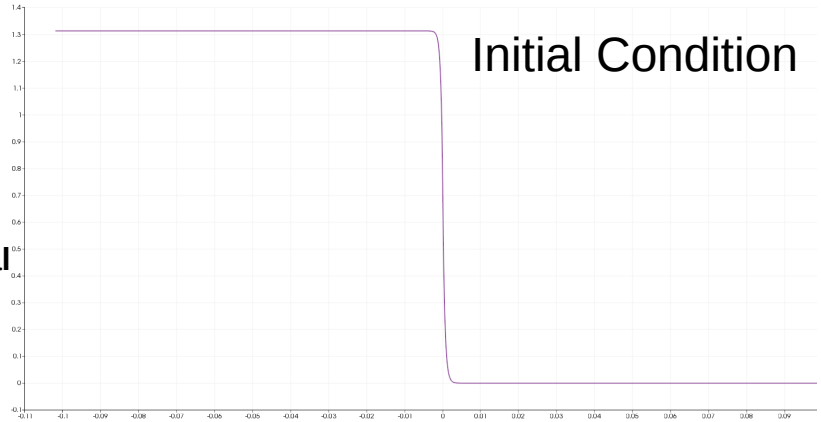
Shown: Velocity Distribution Function (VDF) $f(x, v)$
And Potential Profile $\phi(x)$

High Particle Density *Low Particle Density*



Velocity

Position



Potential

Position

Kinetic Model

Vlasov Equation $\frac{\partial f}{\partial t} + v \cdot \frac{\partial f}{\partial x} - \frac{e \nabla \phi}{m} \cdot \frac{\partial f}{\partial v} = 0$

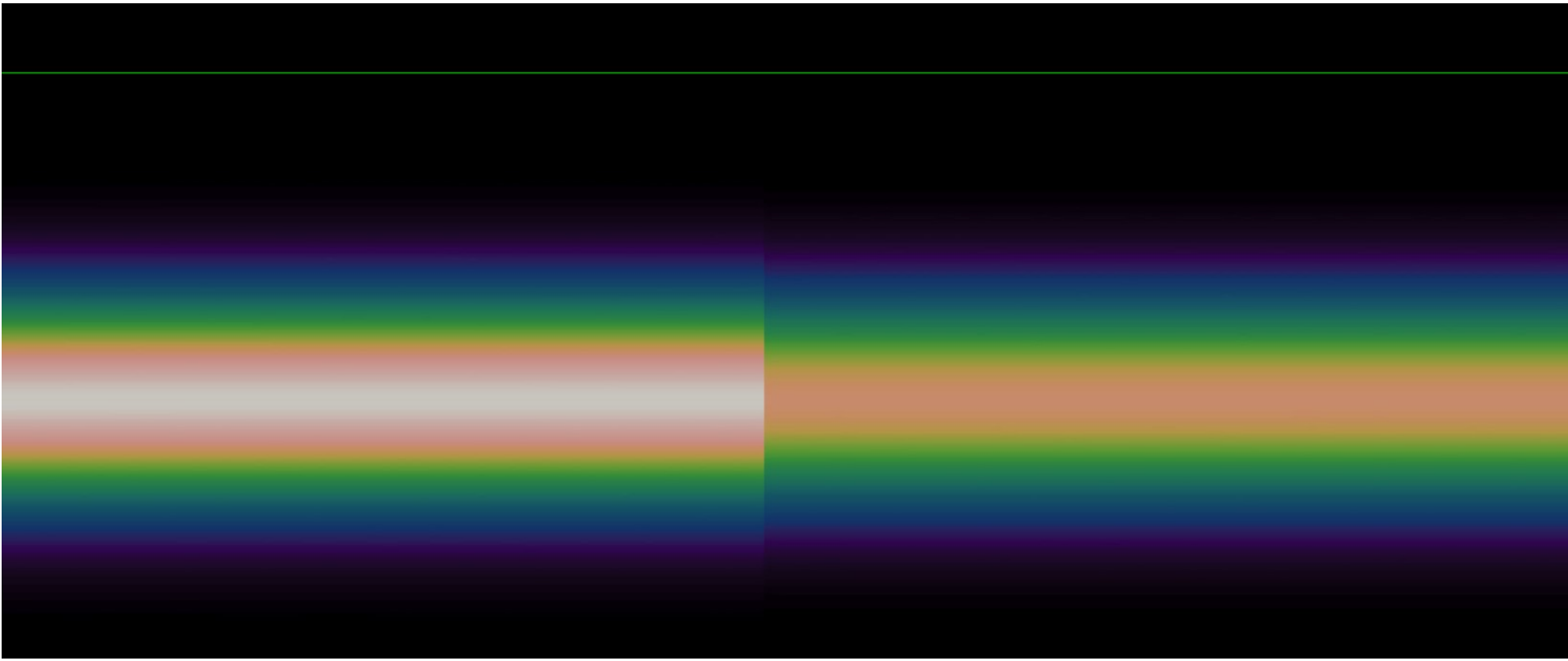
Poisson Equation $\epsilon_0 \nabla^2 \phi + \rho = 0$

Boltzmannian Electrons $n_e = n_{ref} \cdot \exp \frac{\phi}{T_e}$

Simulation Procedure:

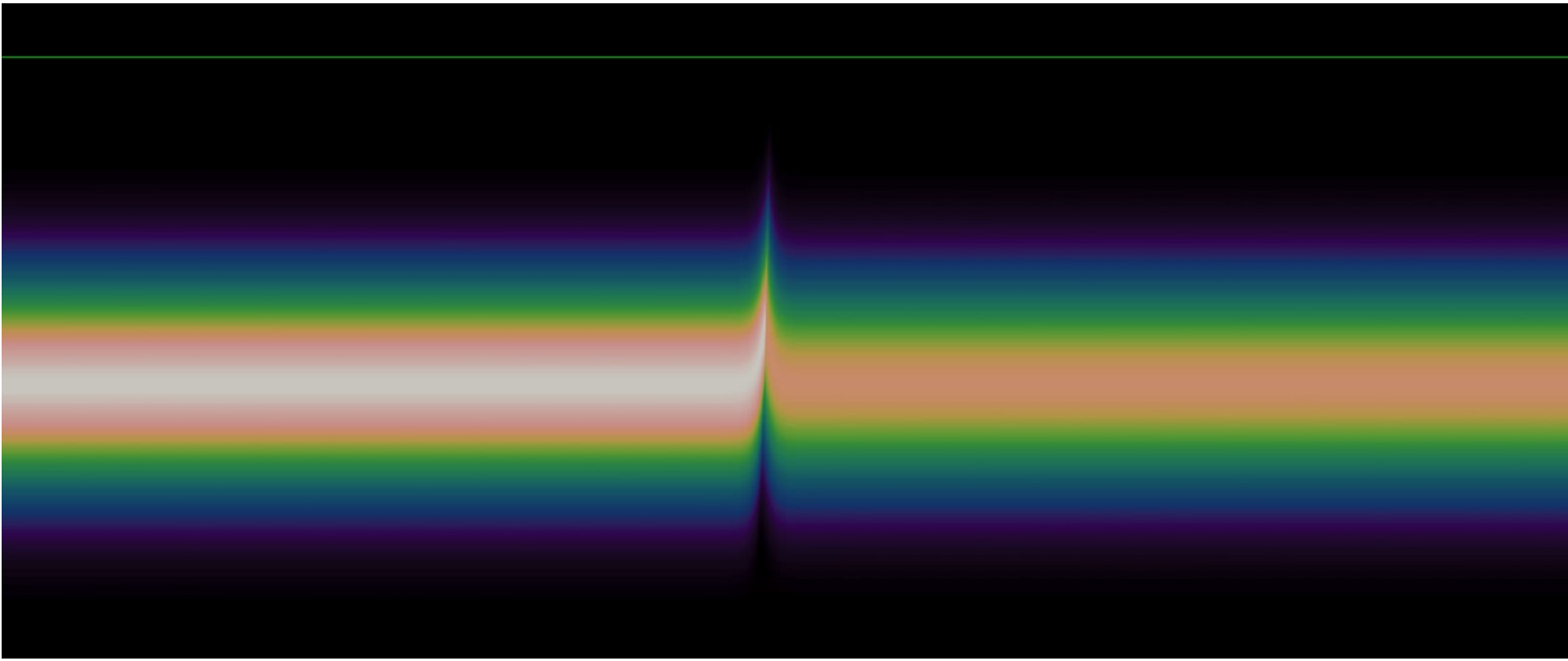
- **Solve Poisson's equation for potential.**
  - **VDF for ion density**
  - **Electron density from** $\exp \frac{\phi}{T_e}$
- **Update the distribution function via Vlasov equation.**
- **Repeat.**

Typical Simulation Result



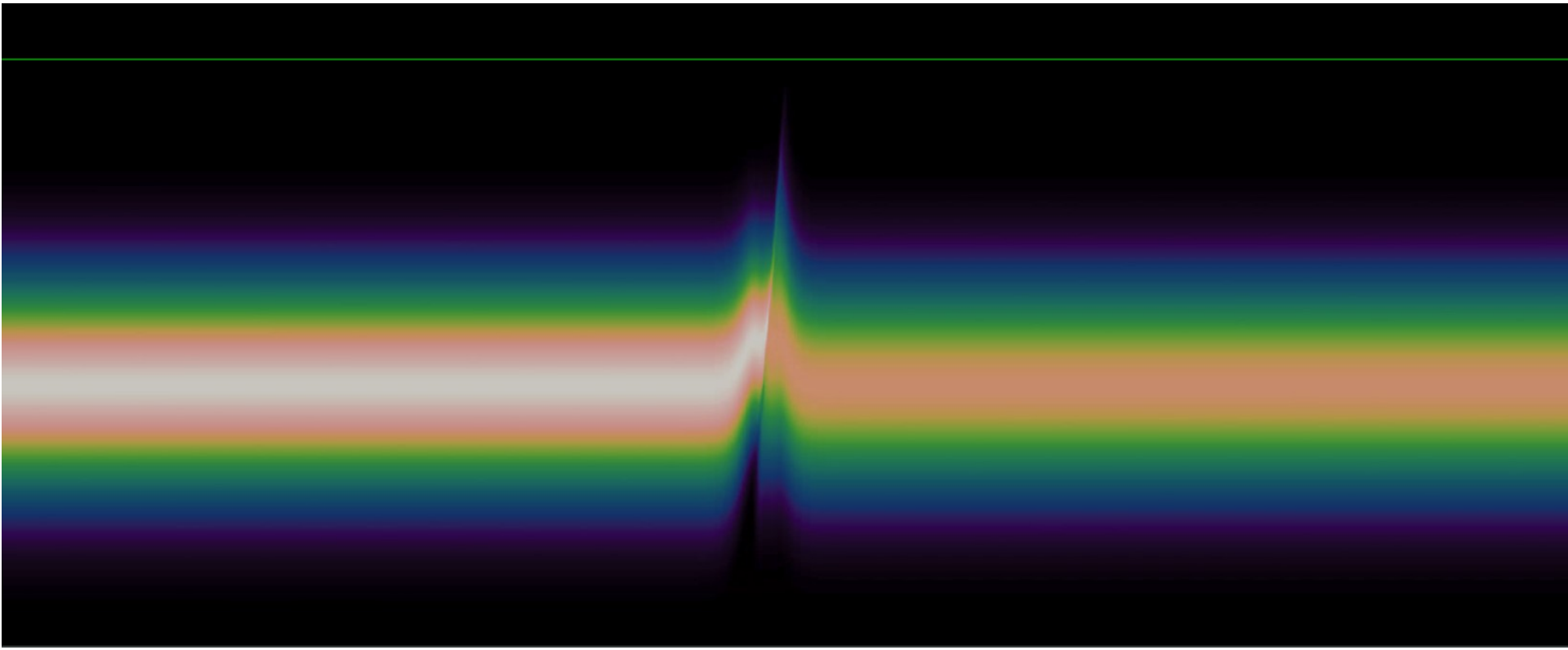
Lightly Damped Case
Electron Temperature: 5 eV | (Te/Ti = 25)
Density Difference: 30%

Typical Simulation Result



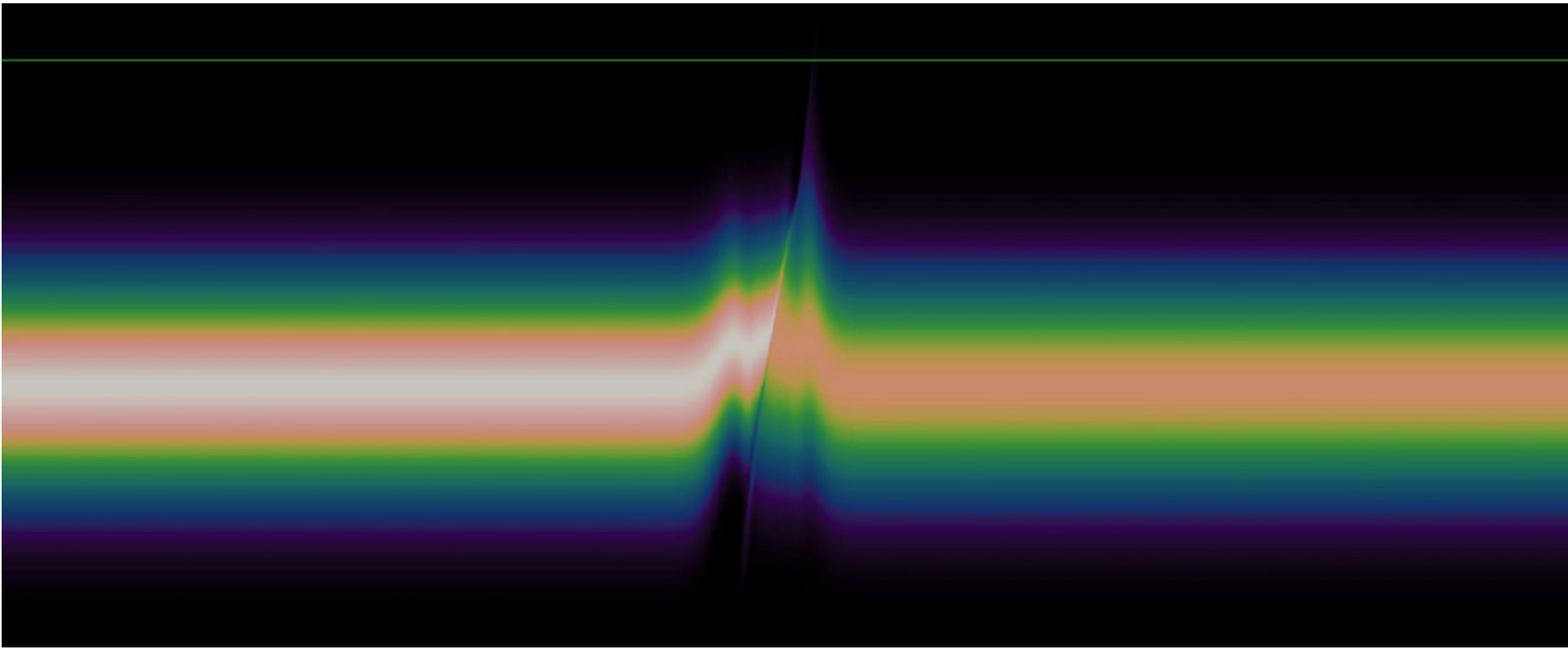
Lightly Damped Case
Electron Temperature: 5 eV | (Te/Ti = 25)
Density Difference: 30%

Typical Simulation Result



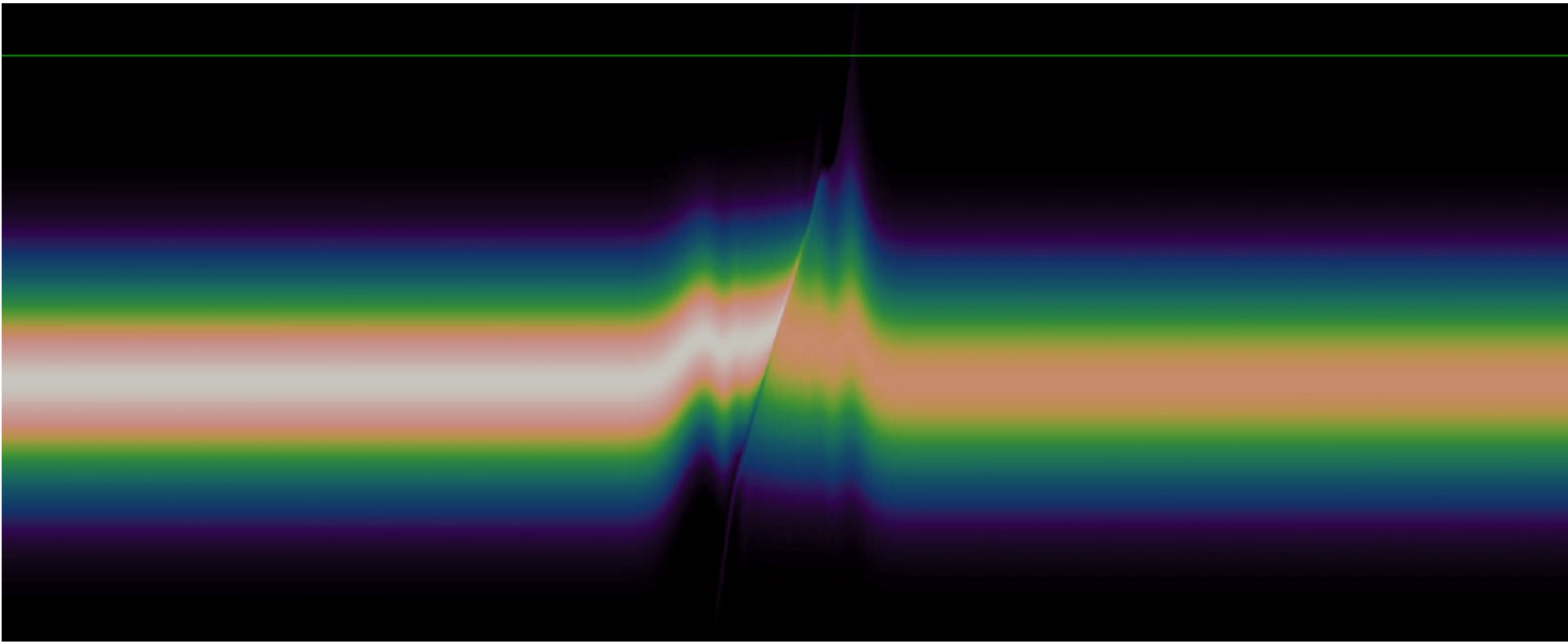
Lightly Damped Case
Electron Temperature: 5 eV | (Te/Ti = 25)
Density Difference: 30%

Typical Simulation Result



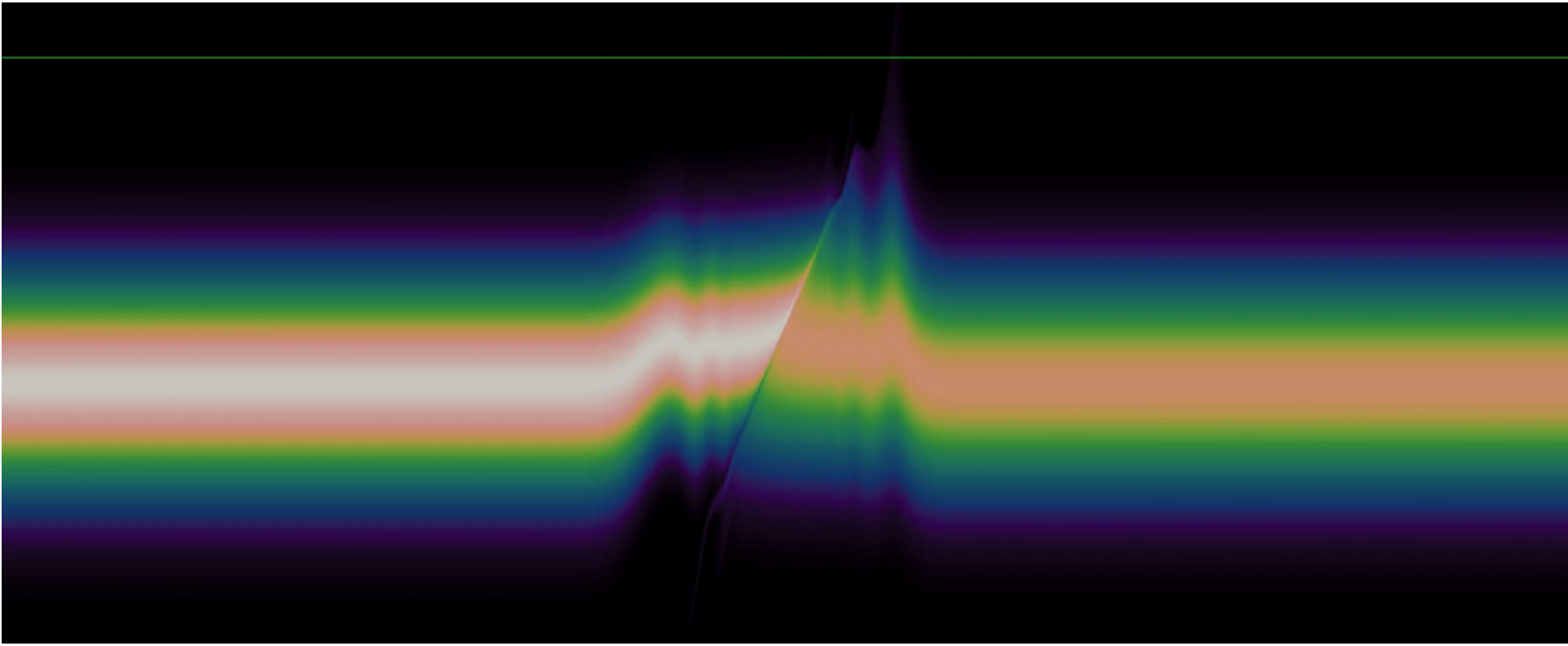
Lightly Damped Case
Electron Temperature: 5 eV | (Te/Ti = 25)
Density Difference: 30%

Typical Simulation Result



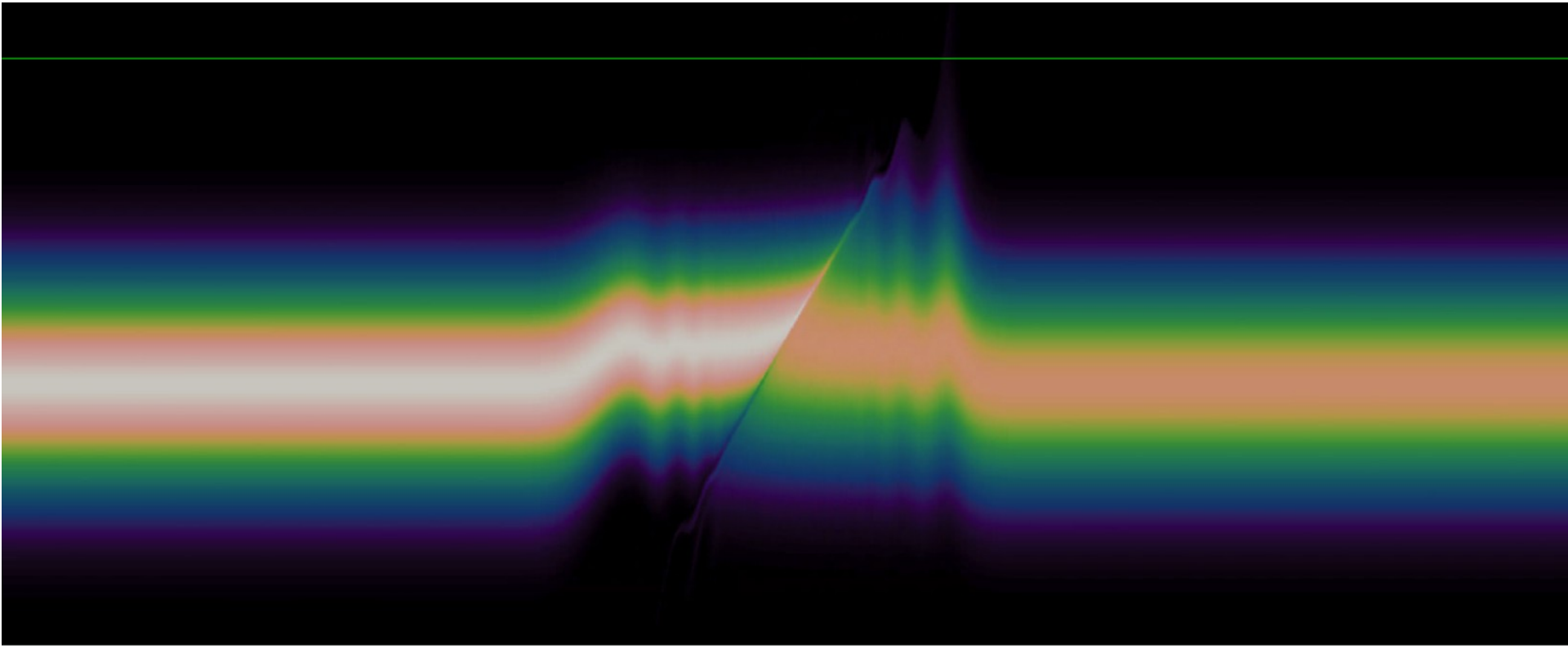
Lightly Damped Case
Electron Temperature: 5 eV | (Te/Ti = 25)
Density Difference: 30%

Typical Simulation Result



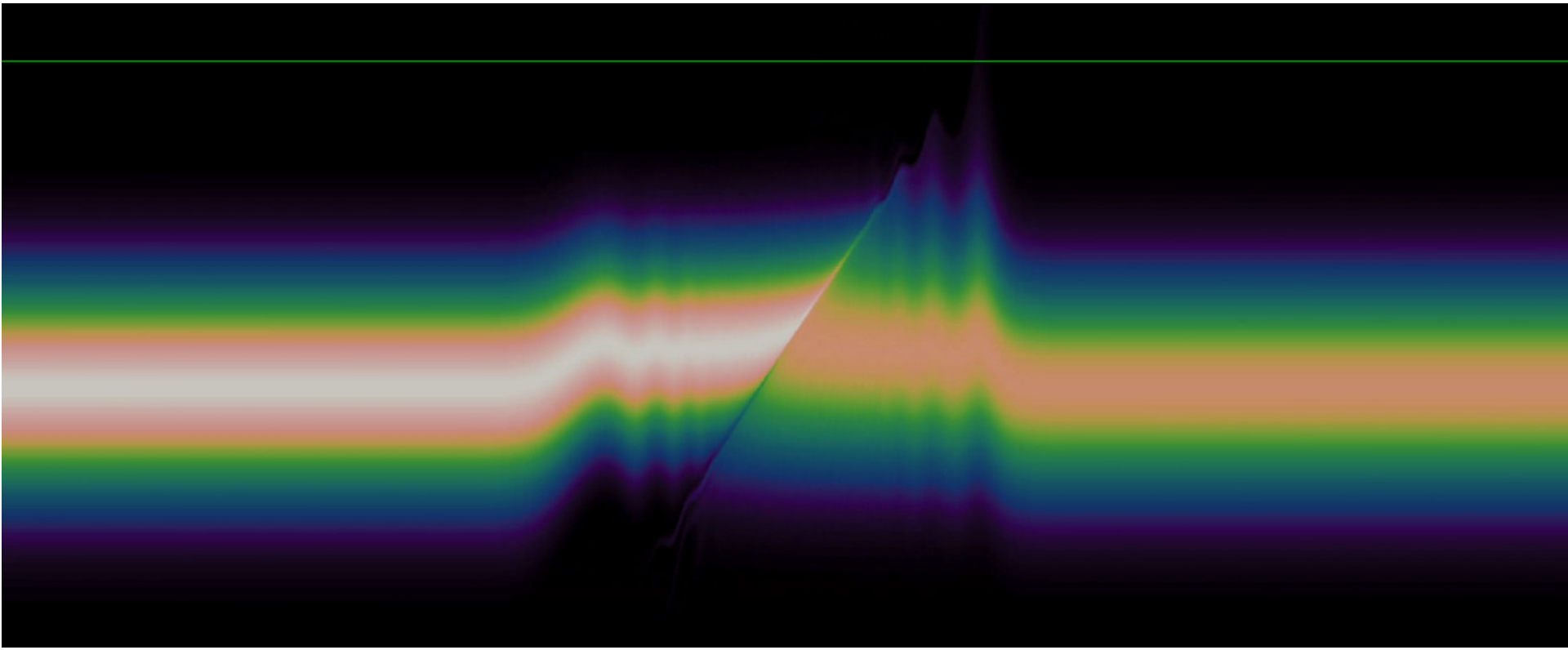
Lightly Damped Case
Electron Temperature: 5 eV | (Te/Ti = 25)
Density Difference: 30%

Typical Simulation Result



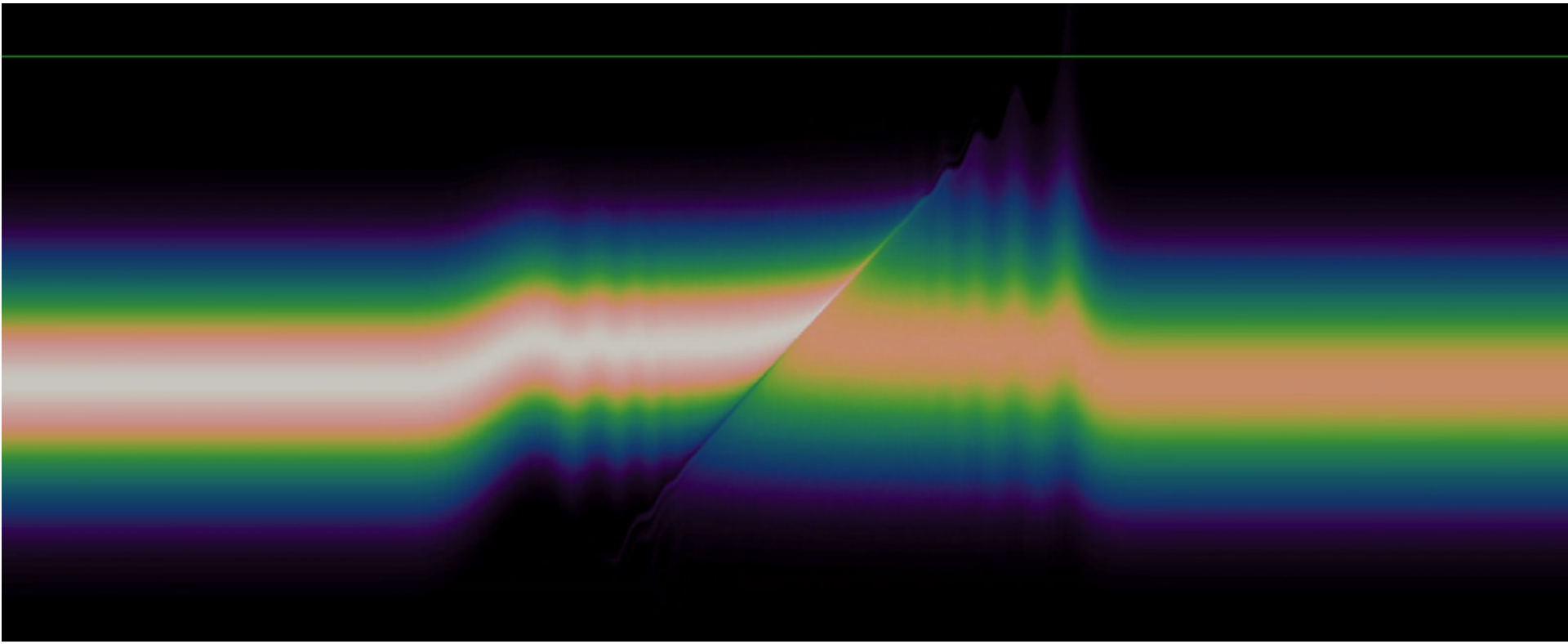
Lightly Damped Case
Electron Temperature: 5 eV | (Te/Ti = 25)
Density Difference: 30%

Typical Simulation Result



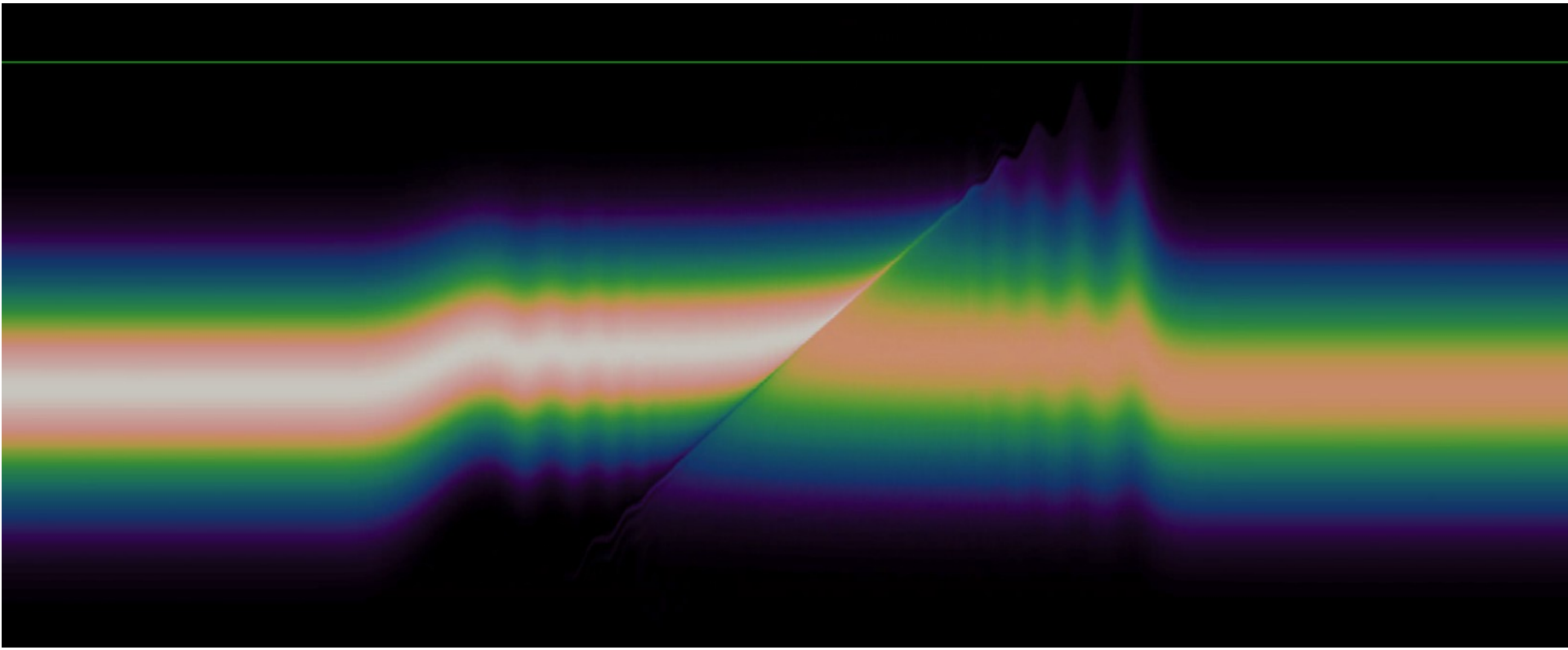
Lightly Damped Case
Electron Temperature: 5 eV | (Te/Ti = 25)
Density Difference: 30%

Typical Simulation Result



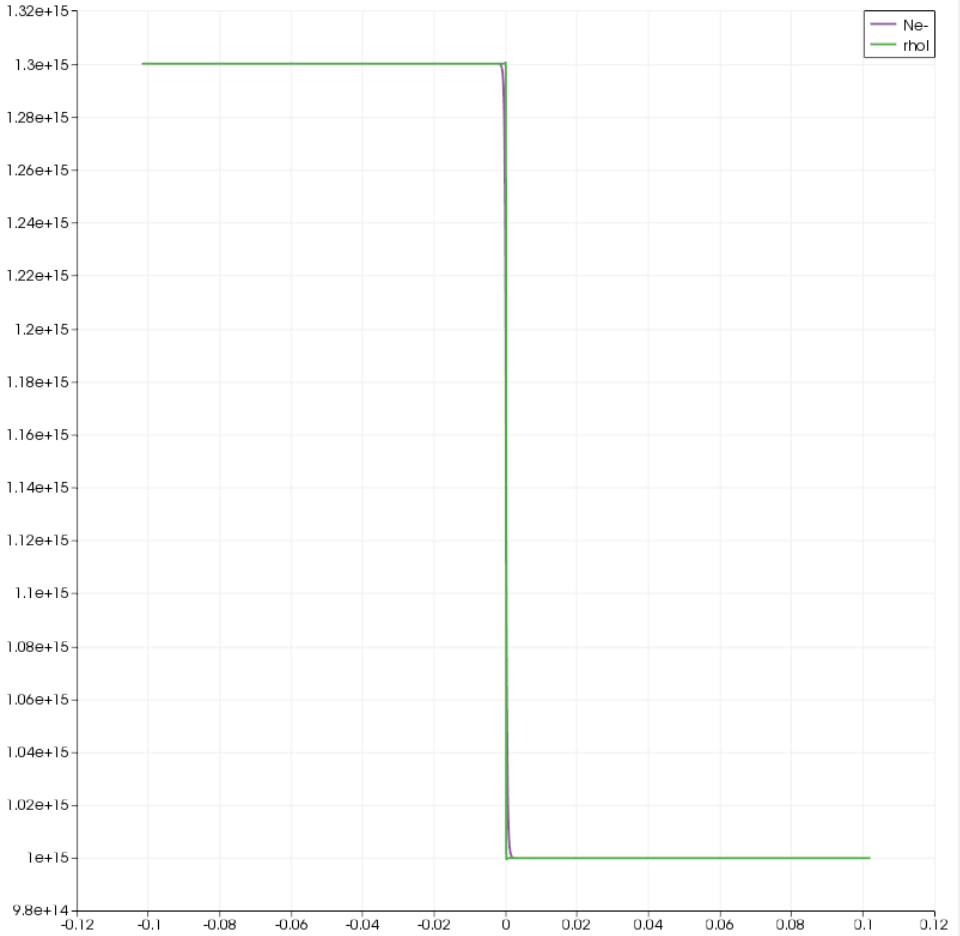
Lightly Damped Case
Electron Temperature: 5 eV | (Te/Ti = 25)
Density Difference: 30%

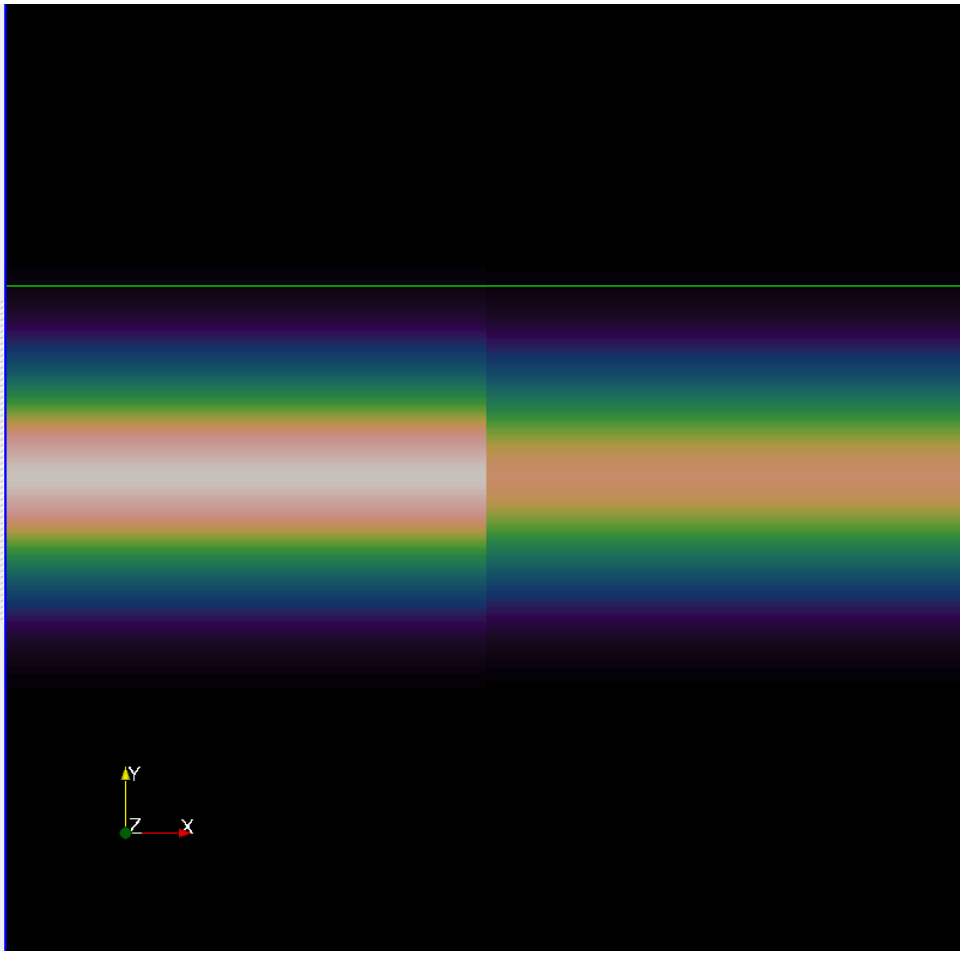
Typical Simulation Result



Lightly Damped Case
Electron Temperature: 5 eV | (Te/Ti = 25)
Density Difference: 30%

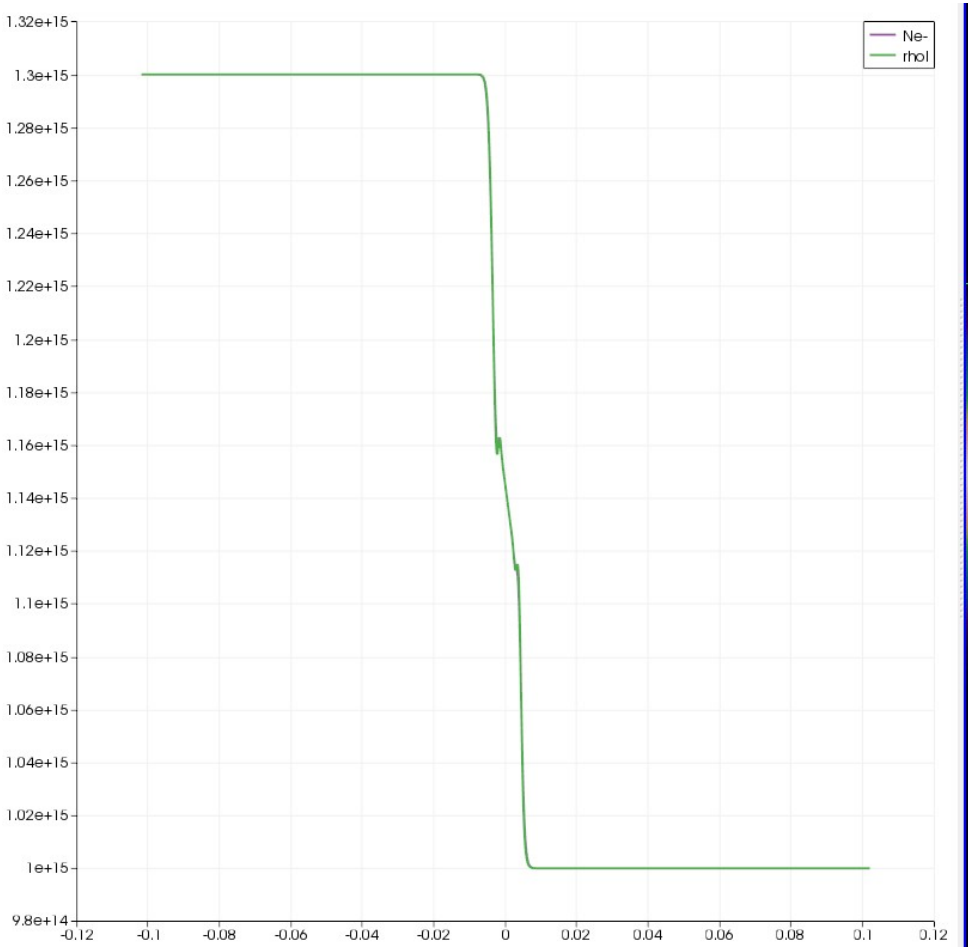
Typical Simulation Result

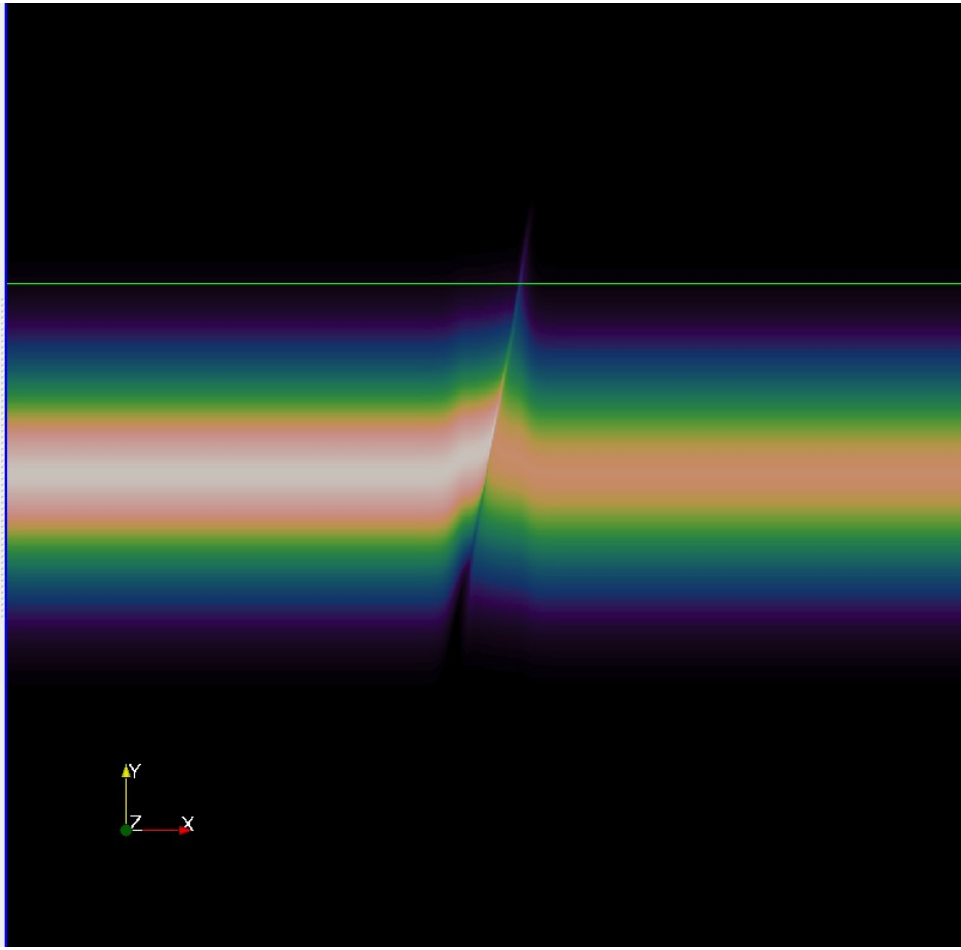




Heavily Damped Case
Electron Temperature: 1.5 [eV] | (Te/Ti =7.5)
Density Difference: 30%

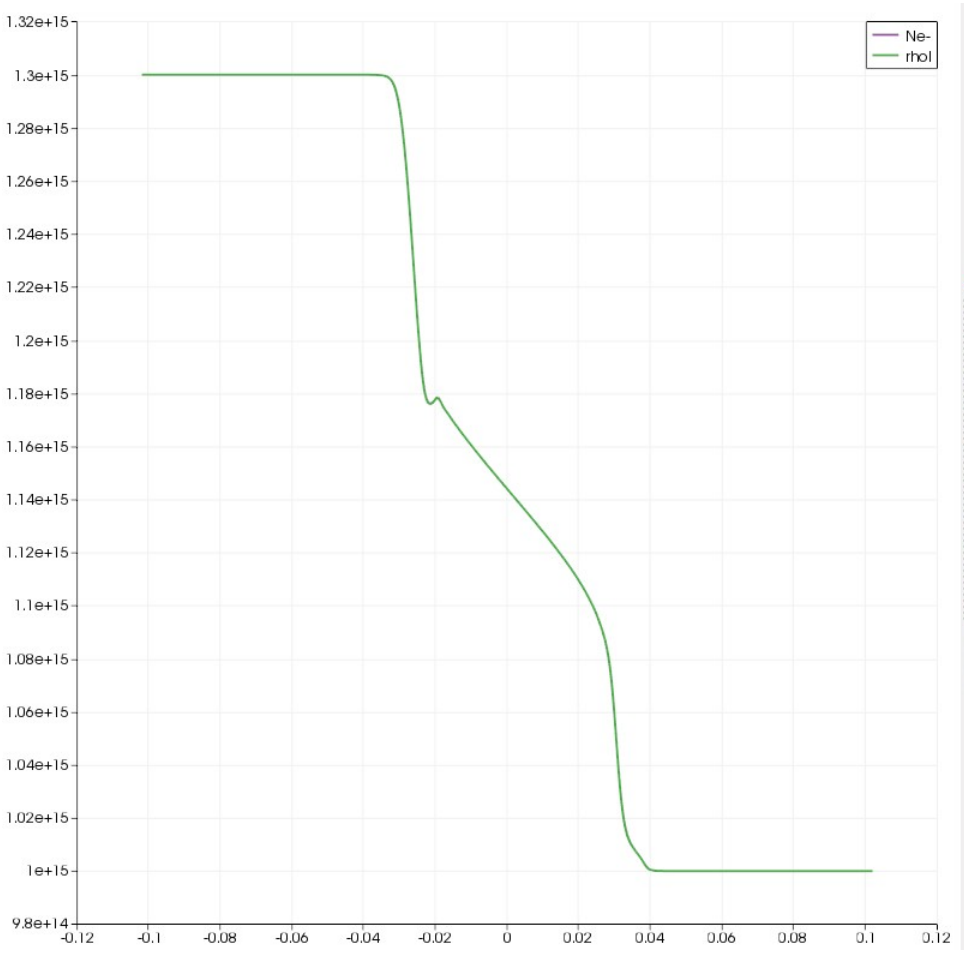
Typical Simulation Result

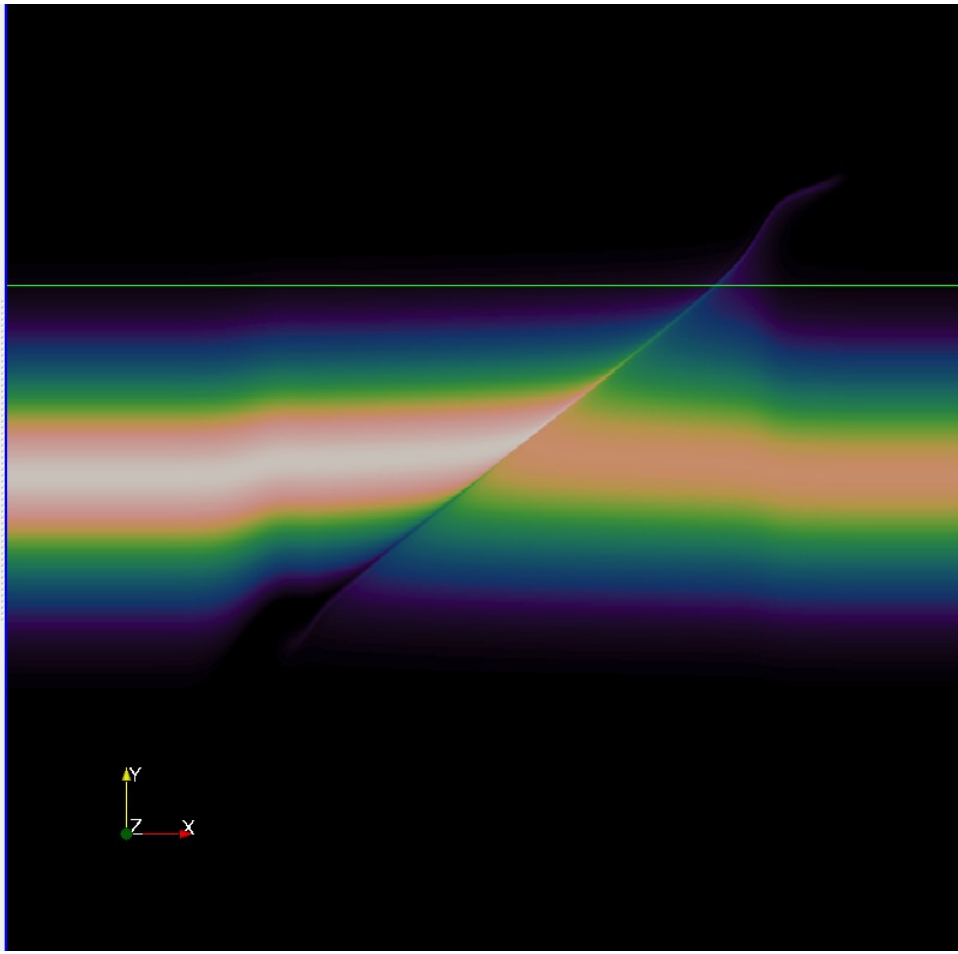




Heavily Damped Case
Electron Temperature: 1.5 [eV] | (Te/Ti =7.5)
Density Difference: 30%

Typical Simulation Result



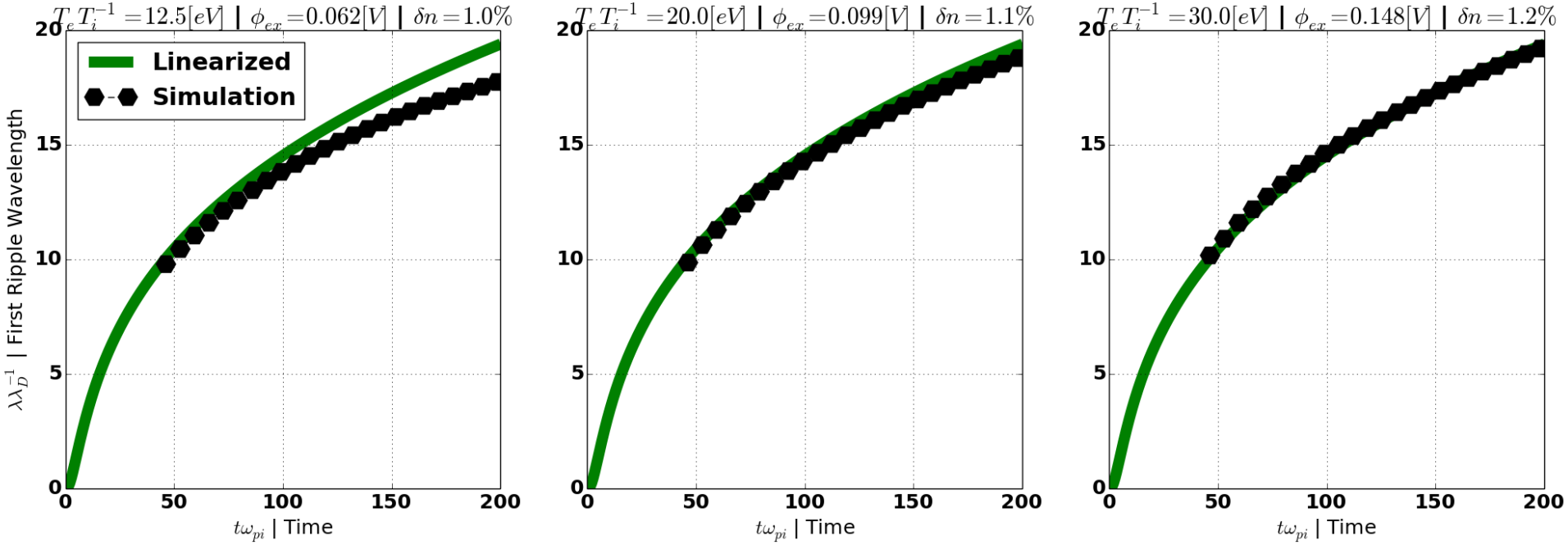


Heavily Damped Case
Electron Temperature: 1.5 [eV] | (Te/Ti =7.5)
Density Difference: 30%

Model Verification

Comparison with Linearized Solution

- **Evolution of the First Ripple Wavelength:**
  - **Simulated weak shocks (1% jump) for different temperature ratios.**
  - **Greater ion reflection at lower electron temperature alters the first ripple.**
  - **Agreement improves with hot electrons, as ion reflection decreases.**

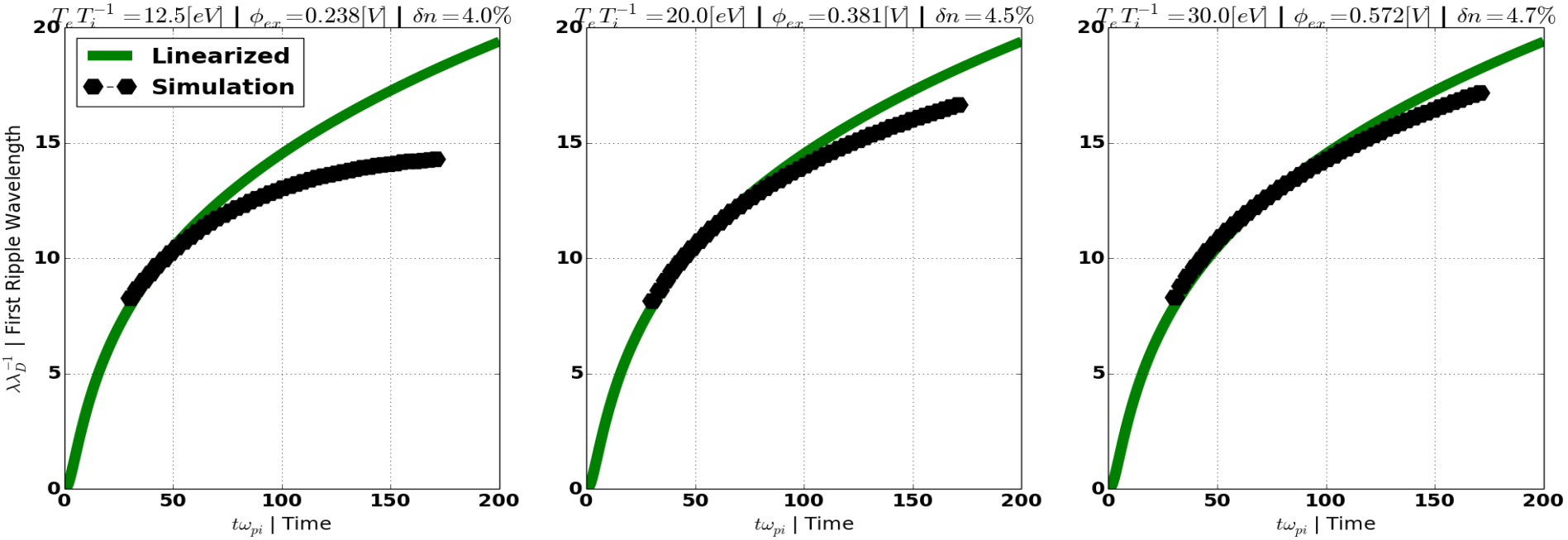


Model Verification

Comparison with Linearized Solution

– **Evolution of the First Ripple Wavelength:**

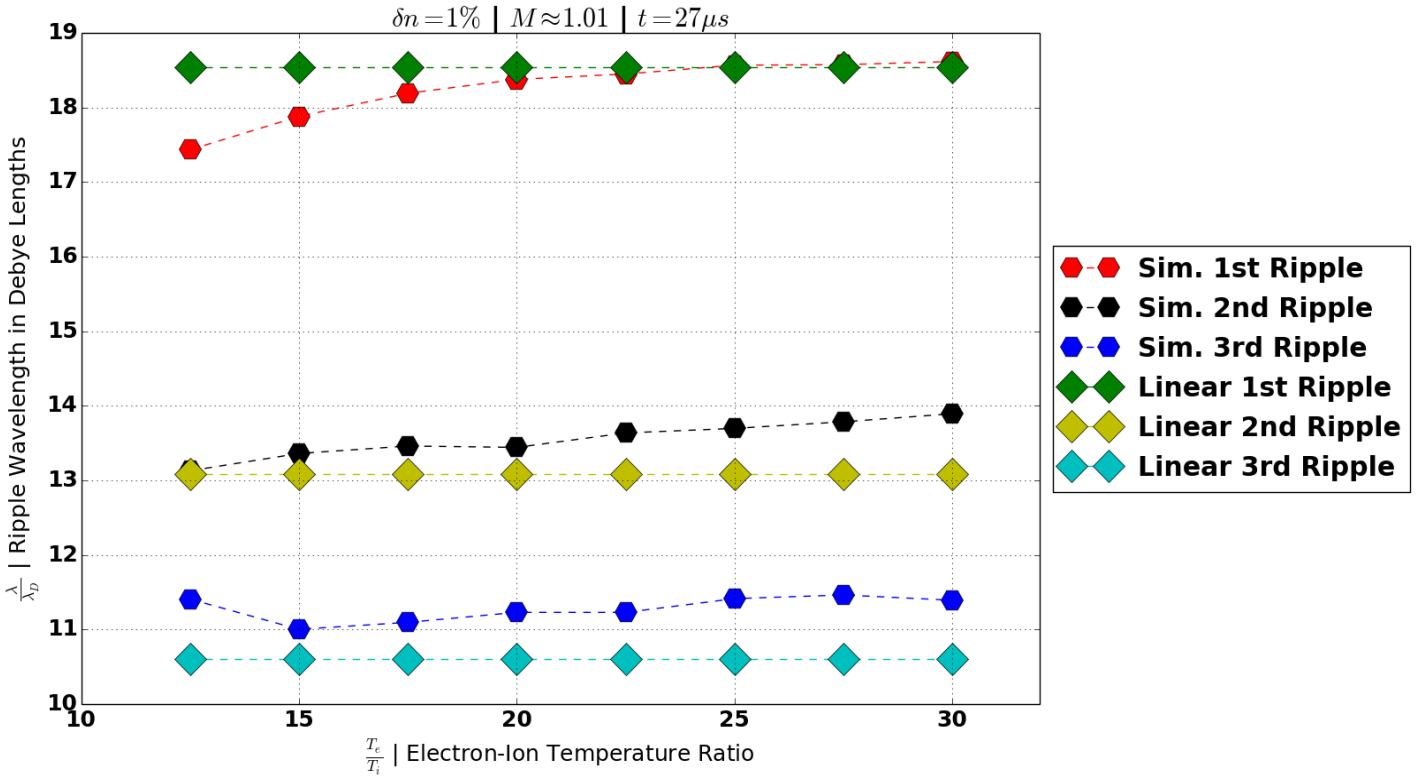
- **Stronger shocks (4%) show poorer agreement at lower electron temperature.**
- **Stronger shocks reflect more ions, causing stronger dissipation.**
- **Agreement with linearized model improves with electron temperature.**



Model Verification

Comparison with Linearized Solution

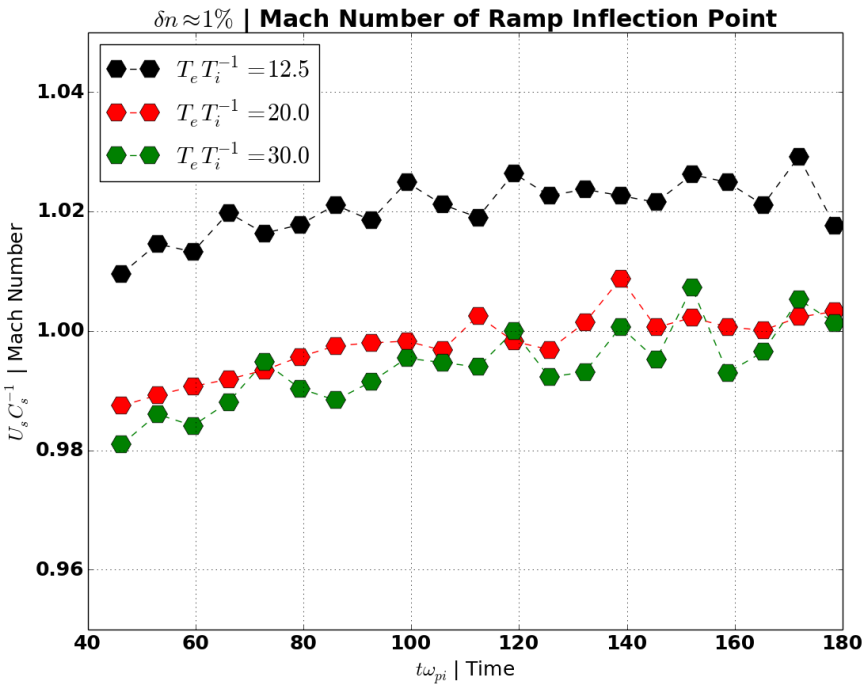
- **Trailing Ripple Wavelengths:**
  - **Subsequent wave train ripples diverge from the model.**
  - **Simulated ripples do not approach zero wavelength like the linearized model.**

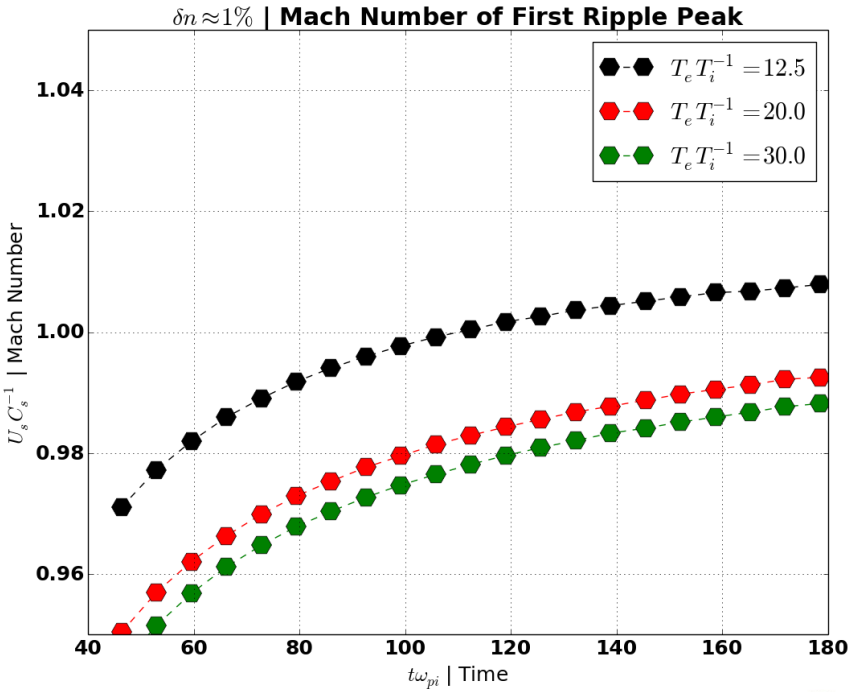


Results on Shock Structure

Other Weak Shock Results

- **Shock Mach Number**:
  - For the same density jump (1% here),
    - Shock speed increases with electron temperature, Mach number decreases.
  - The first wave train oscillation peak travels less quickly than the shock ramp.



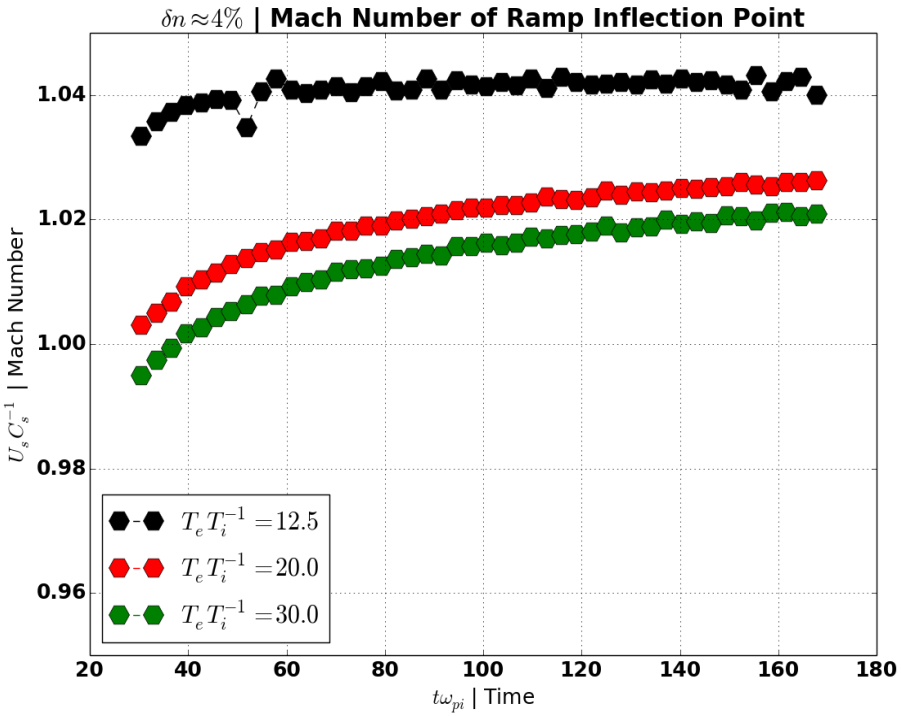


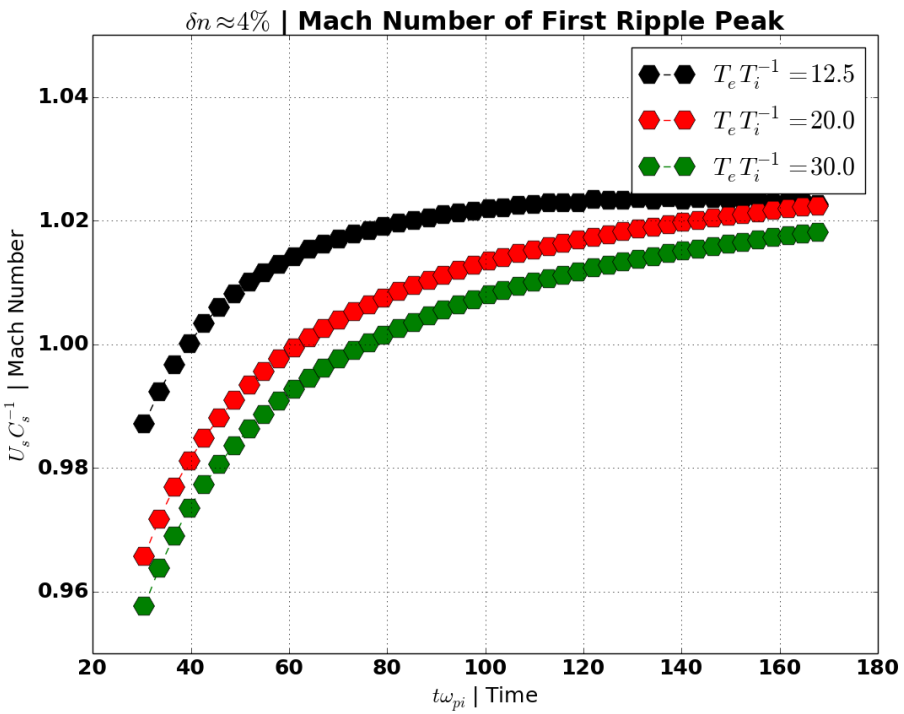
Results on Shock Structure

Other Weak Shock Results

– **Shock Mach Number**:

- **The same trends are apparent for slightly stronger shocks (4% jump here).**
- **Ion reflection appears to damp the shock acceleration.**





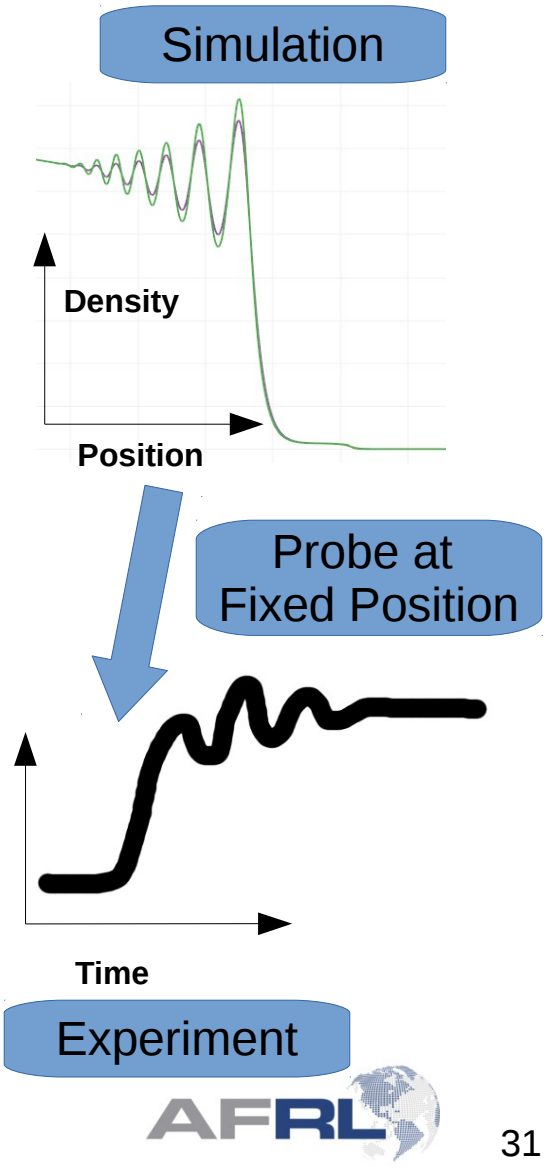
Model Validation

Gathering Experiment Data

- **Double Plasma Device**:
  - Can produce low Mach number collisionless shocks.
- **Diagnostics**:
  - Langmuir probes; density and electron temperature.
    - Shock speed, and density at fixed position.
  - Ion temperature is necessary for proper validation.

Validation Comparisons

- **The Wave Train**:
  - Simulation suggests ripples should occur for:
    - Moderate Mach numbers (~1.2 – ~1.6)
    - High electron-ion temperature ratio (>10)
- **Wave Train Wavelength**
- **Shock-Front Mach Number**
- **Reflected Ion Beam Velocity**



Towards Validation and Extension

Towards Validation of Collisionless Model

- **Verification:**
  - Simulated weak shocks agree with the linearized cold-ion solution.
- **Validation:**
  - Results should be compared to experimental shock data.
  - Inconsistencies in published 1969 double-plasma device data hampered validation.

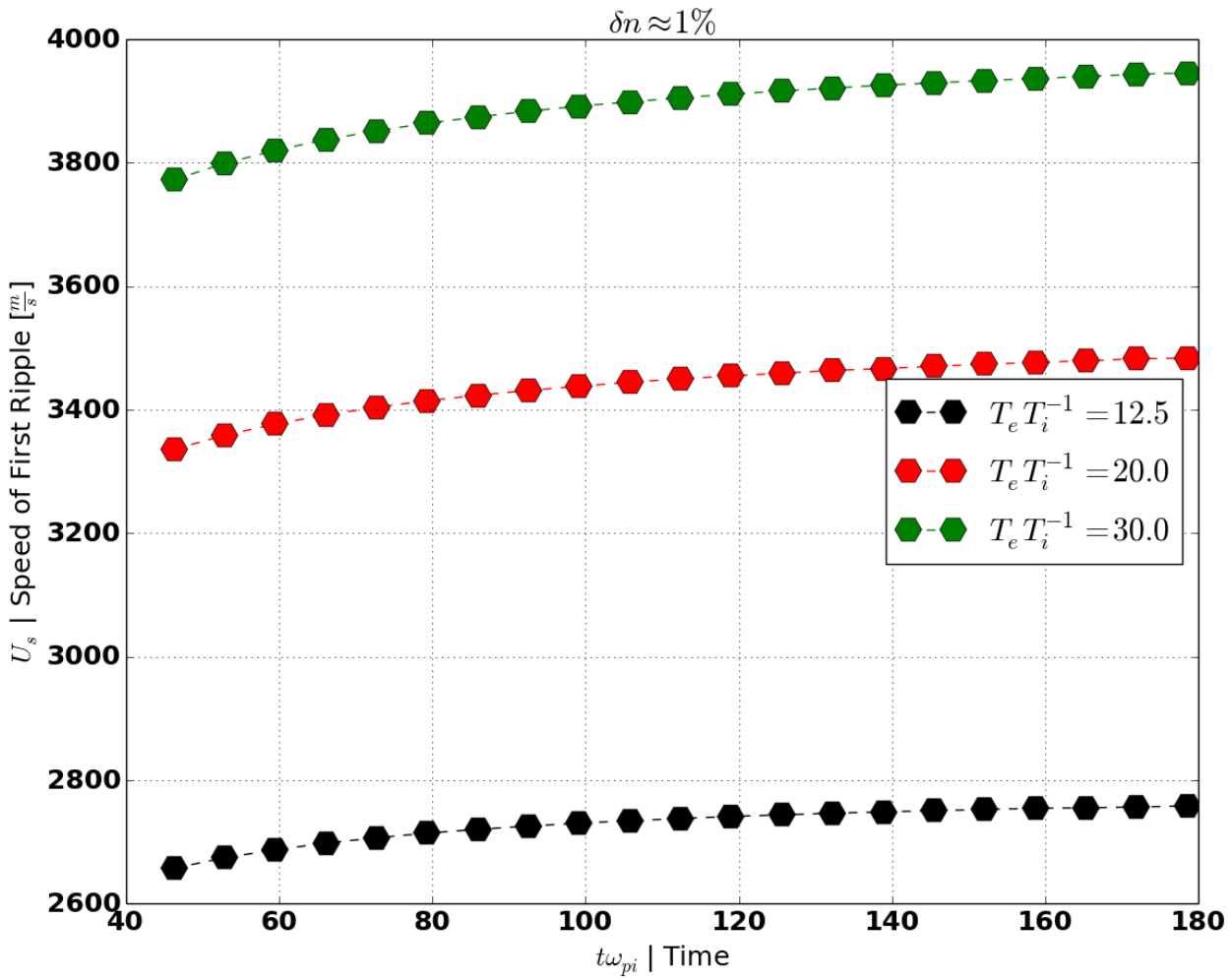
Future Work: Extension to Moderately Collisional Problem

- **Collision Operators:**
  - Presence of a few mean collisions in shock transition invalidates Vlasov equation.
  - The collisional ion-acoustic shock requires the full Boltzmann equation with appropriate choice of collision operator.
  - Moderately collisional shocks should be hybrid dispersive-dissipative shocks.
- **Validation of Collision Algorithms:**
  - Tuning parameters in a shock experiment can yield moderately collisional data.

Back Up Slides

Results on Shock Structure

Example of Shock Speed at 1%



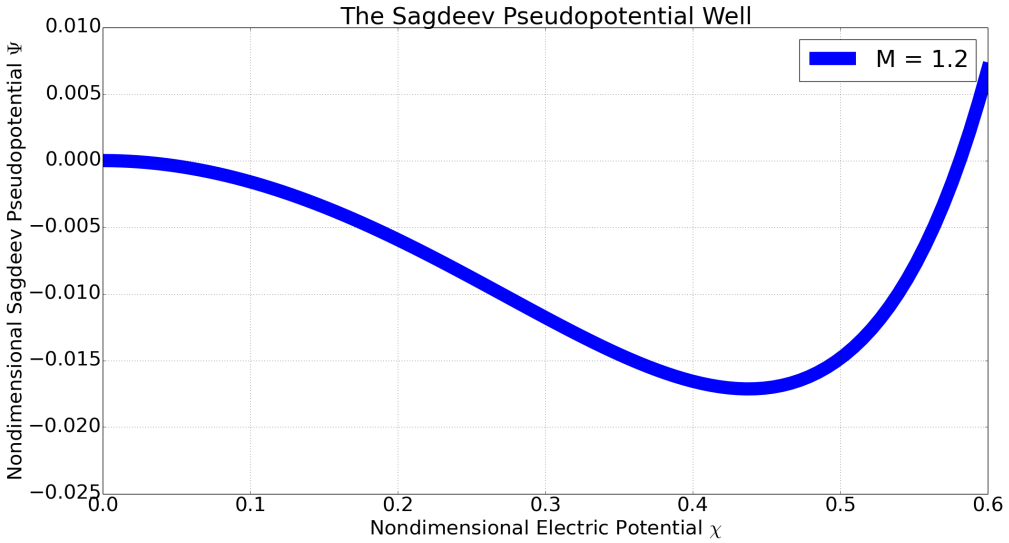
Details on Shock Structure

Wave Train Properties

- **Sagdeev Pseudopotential**:
  - **An analogy to motion in a potential well, describes oscillations in wave train.**
  - **Dissipation within the well leads potential to settle at the minimum.**

$$\frac{d^2\chi}{d\xi^2} = -\frac{dV(\chi)}{d\chi}$$

$$V(\chi) = 1 - e^{\chi} + M^2\left(1 - \left(1 - \frac{2\chi}{M^2}\right)^{\frac{1}{2}}\right)$$



Electric Field Details