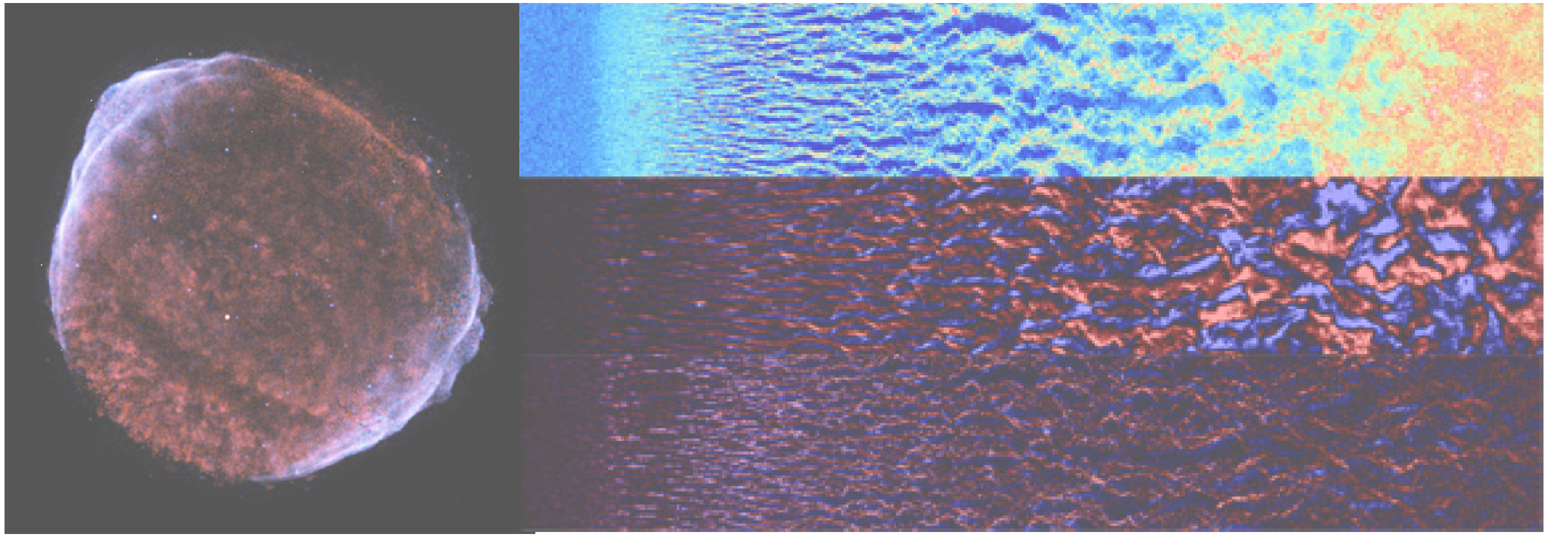
Non-Relativistic Collisionless Shocks in Unmagnetized and Weakly Magnetized Electron-Ion Plasmas



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Simulation of Collisionless Shocks

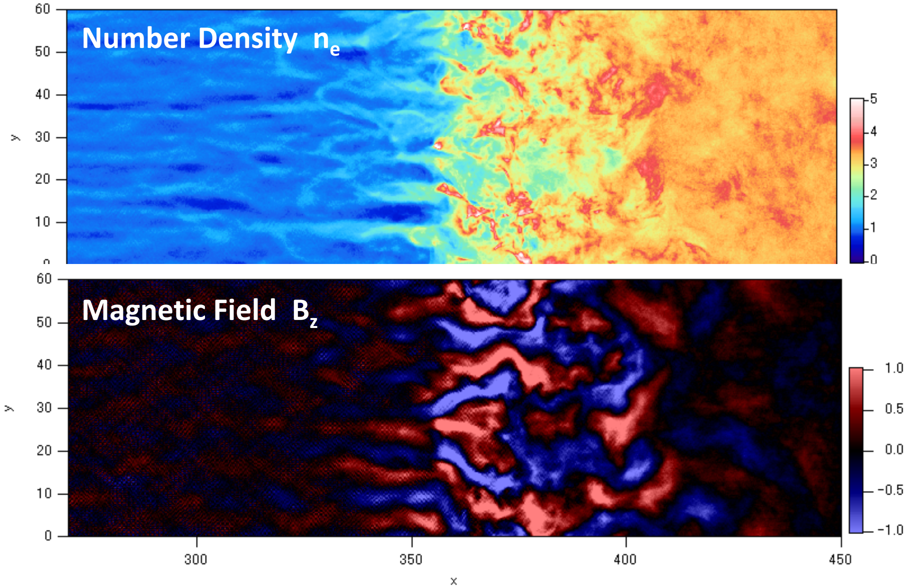
In Electron-Ion Plasma
without Background Magnetic Field

Relativistic Collisionless Shocks in Unmagnetized Plasmas

“Weibel-mediated” Shocks

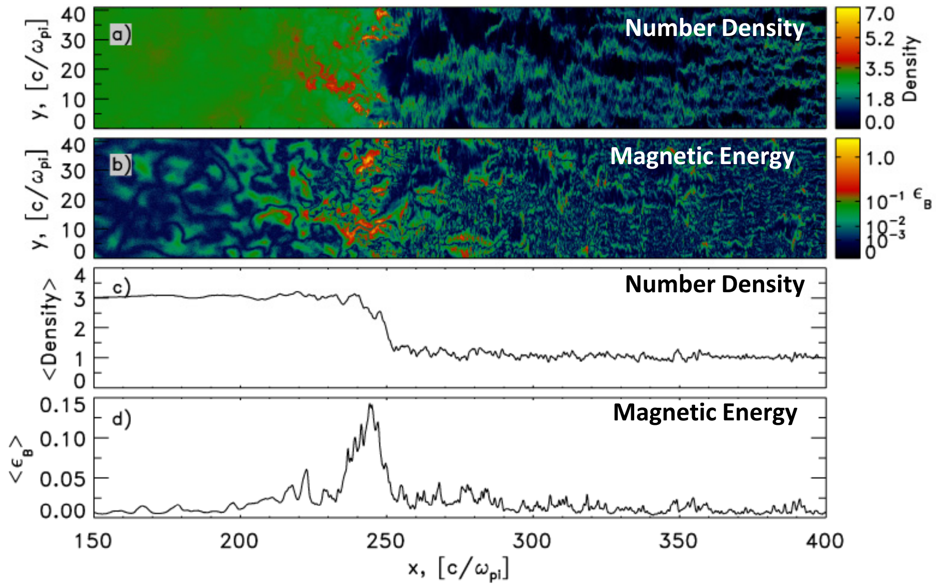
in Electron-Positron Plasma (Γ=2.2)

(Kato 2007)



in Electron-Ion Plasma (Γ=15)

(Spitkovsky 2008)



The **Weibel instability** generates **strong magnetic fields** and provides an effective **dissipation mechanism** for the shock formation

Motivation

The shocks in supernova remnants are **non-relativistic**

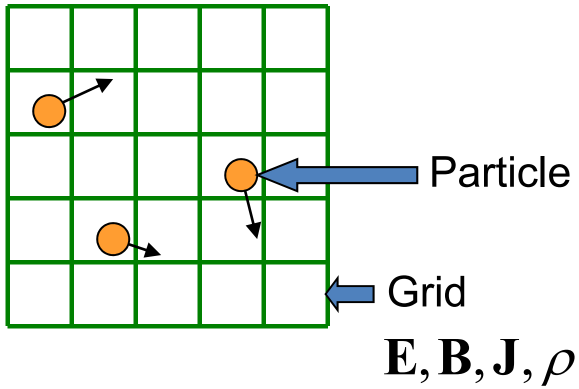
Typically, **V ~ 3000 km/s ~ 0.01c**

The "Weibel-mediated" collisionless shocks
exist in **non-relativistic** regime?

Particle-in-Cell (PIC) Simulation

Particle in Cell Method

- **Particles:** calculating individual trajectory
- **Electromagnetic field**: solving Maxwell's equations on grid



Steps of calculation

$$(\mathbf{E},\mathbf{B}) \rightarrow (\mathbf{x},\mathbf{p}) \rightarrow (\mathbf{J},\rho) \rightarrow (\mathbf{E},\mathbf{B}) \rightarrow \ldots$$

Basic Equations

Field — Maxwell's equations

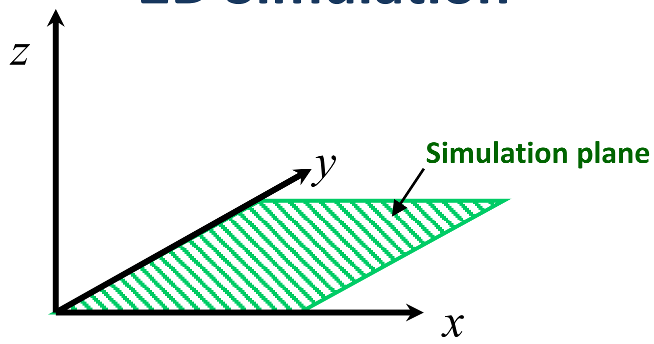
- $$\frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \frac{4\pi}{c}\mathbf{J}$$
- $$\nabla \cdot \mathbf{E} = 4\pi\rho$$
- $$\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$
- $$\nabla \cdot \mathbf{B} = 0$$

Particle — Equation of motion

- $$\frac{d\mathbf{p}}{dt} = q\left(\mathbf{E} + \frac{\mathbf{p}\times\mathbf{B}}{\gamma mc}\right)$$

Simulation Settings

2D Simulation



- The simulation plane = the x-y plane
- The z axis is perpendicular to it

Units

Time	$\tau_0 = 1/\omega_{pe}$
Length	$\lambda_e = c/\omega_{pe}$ (skin depth)
EM Fields	$E_* = B_* = c\sqrt{4\pi n_{e0} m_e}$

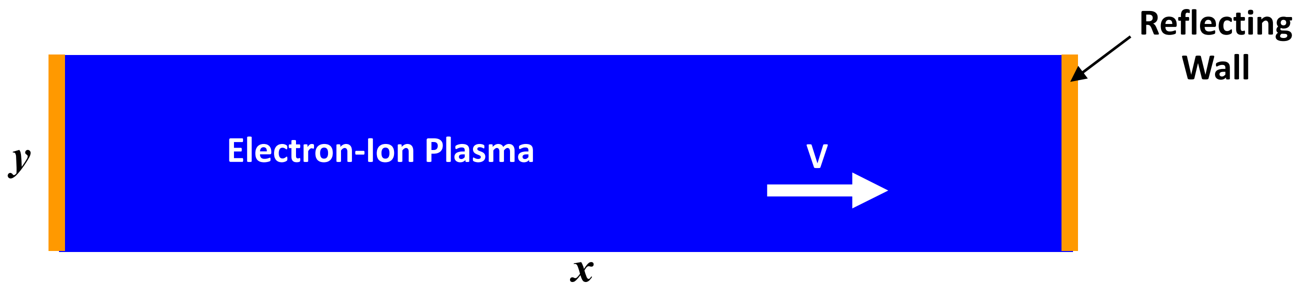
Settings

Composition	Electron, Ion
Physical Size	2240×280
Grid Size	4096×256
Particle Number	5×10^7 particles / species (27 particles / cell)
B.C.	Periodic
Magnetic Field	None

Mass Ratio	20
Bulk Velocity	0.45c

How to Drive a Shock Wave

"Injection Method"



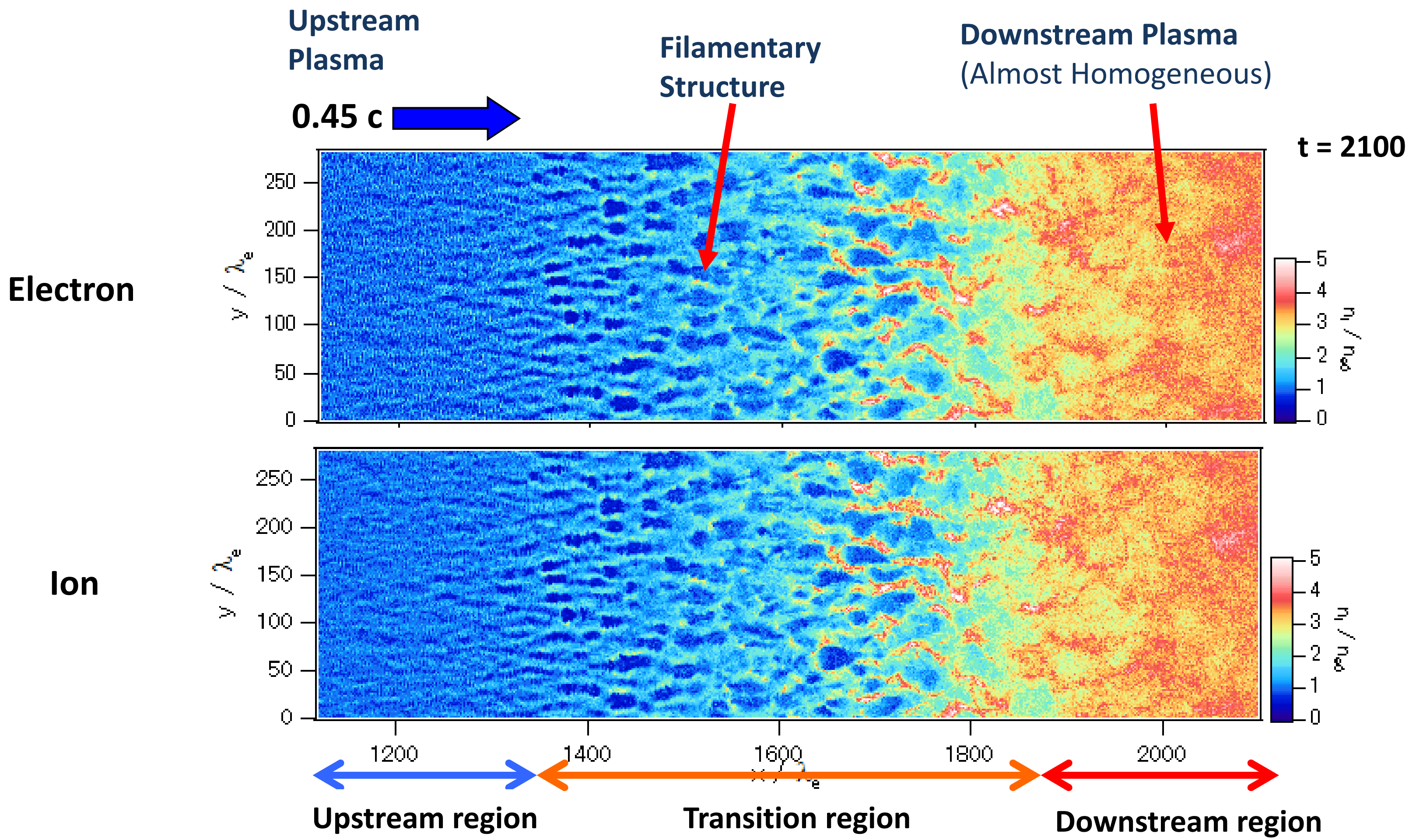
1. Initially, particles are loaded in the area between two reflecting walls with bulk velocity of V to the right.
2. Particles that strike **the right wall** are **reflected**.
3. The reflected particles interact with the incoming particles to **cause some plasma instabilities**.
4. Then, a **shock wave** is formed and propagates to the left.

Note: the simulation frame corresponds to the downstream rest frame.

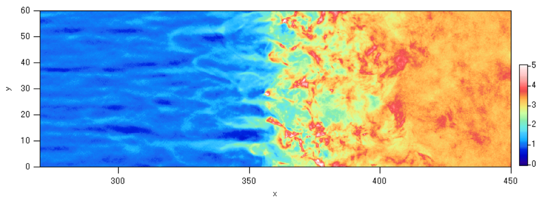
Number Density

V=0.45c

Kato & Takabe, ApJ, 2008, 681, L93

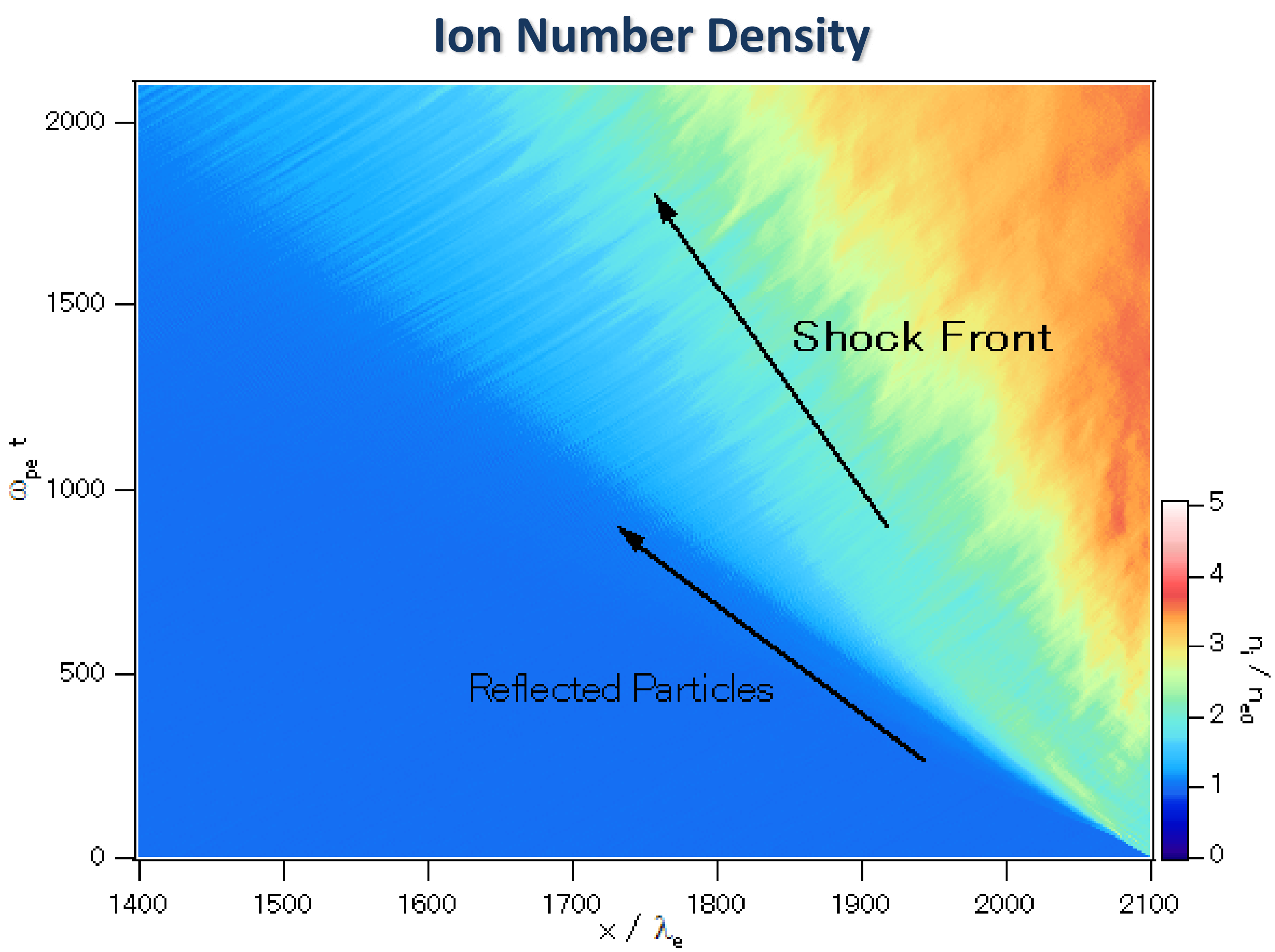


Relativistic Electron-Positron Case



- A collisionless shock is formed
- Structure is **similar** to that in the **relativistic cases**
- There are a lot of **filaments** in the transition region

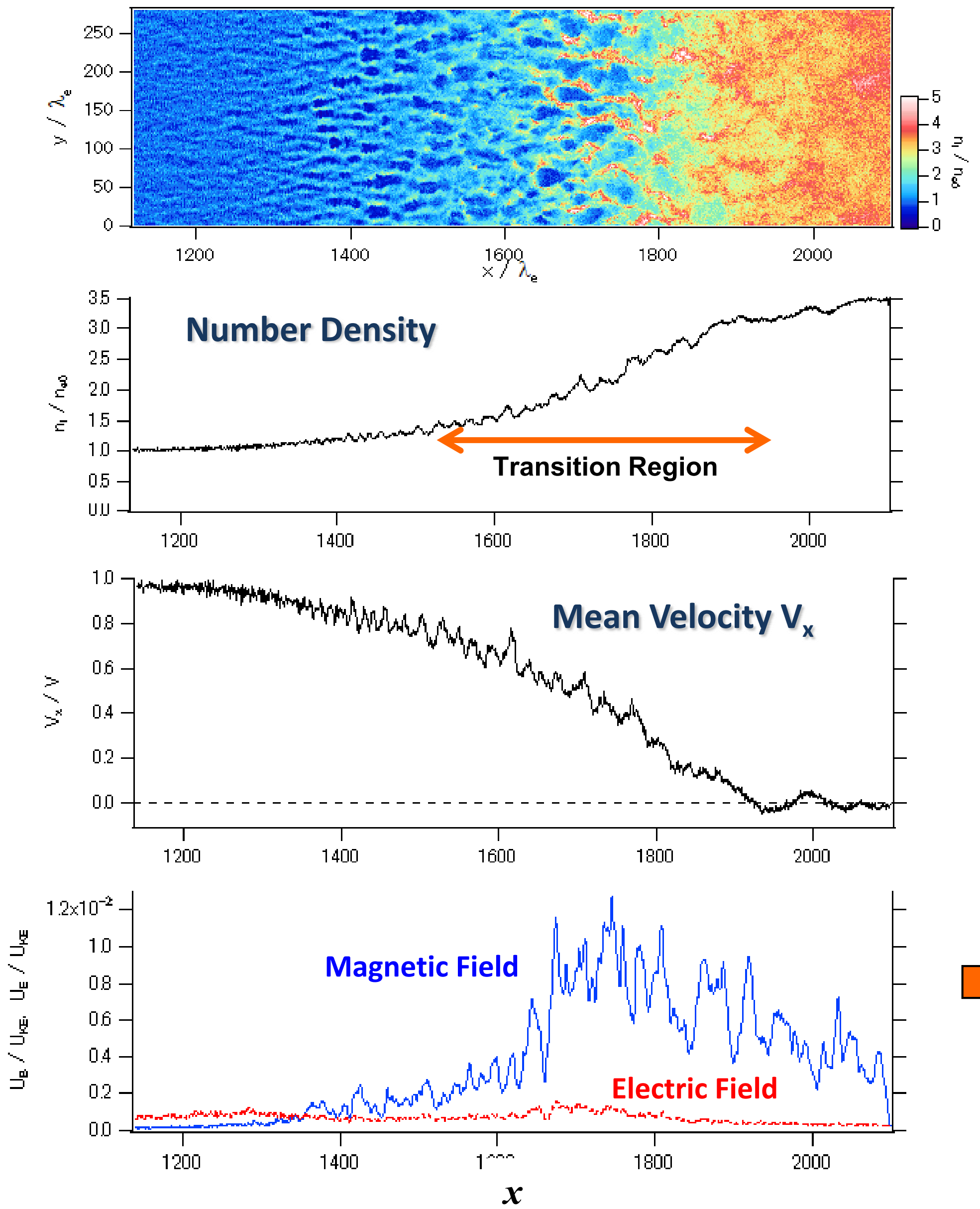
Propagation of the Shock



The shock propagates into the upstream region at **an almost constant speed**.

Shock speed $V_{\mathrm{sh,d}} = -0.18c, \quad V_{\mathrm{sh,u}} = -0.63c$

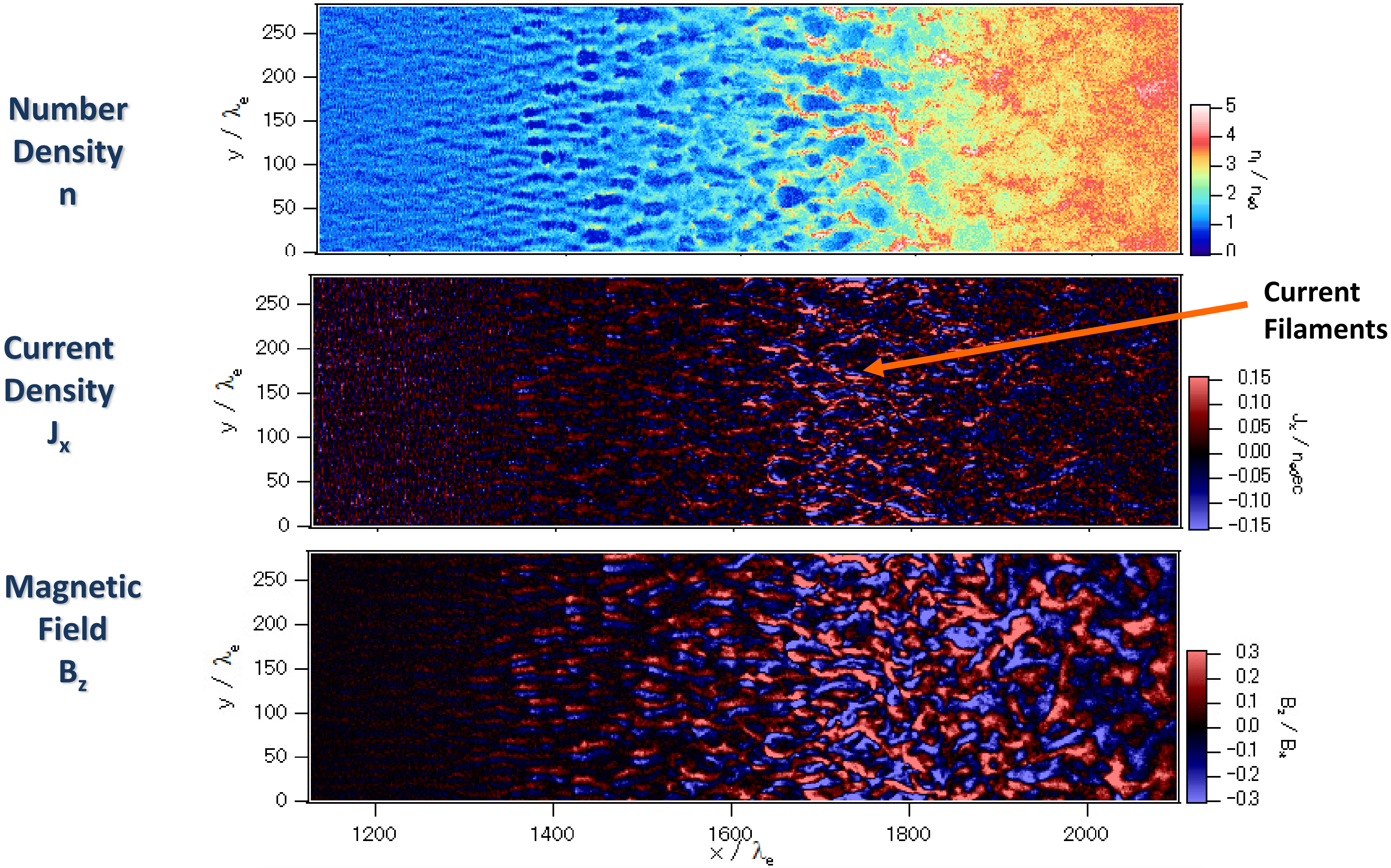
Profiles



- The transition region extends x = 1400 – 1900.
- The compression ratio is about 3.5.
- The mean velocity is rapidly decelerated within the transition region.
- There is **strong magnetic field** in the transition region.
  (**~1%** of the upstream bulk kinetic energy density)

Strong magnetic field provides an effective dissipation mechanism for the upstream plasma

Generation of Magnetic Field



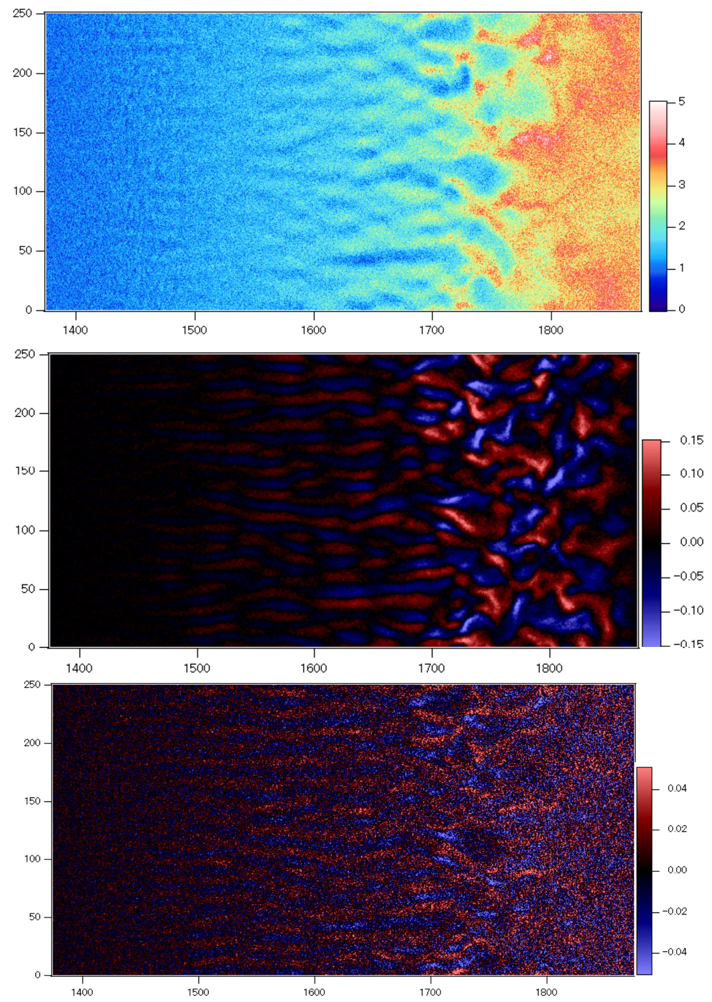
Current filaments generate **strong magnetic fields** within the transition region → **Weibel instability**

Case of V=0.1c

Number Density
n

Current Density
J_x

Magnetic Field
B_z



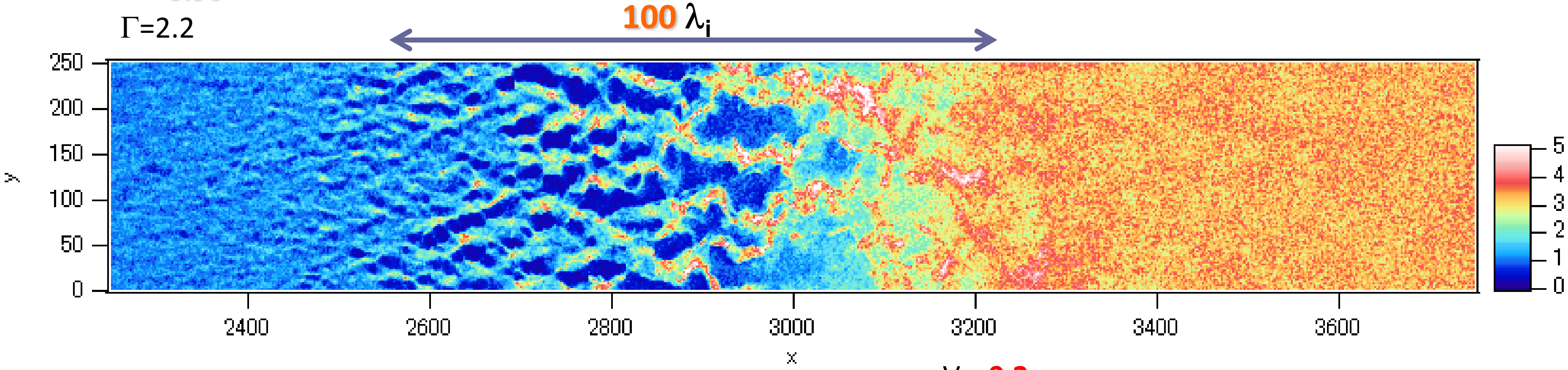
The Weibel-mediated shock forms even for **V = 0.1c**

Shock Structure

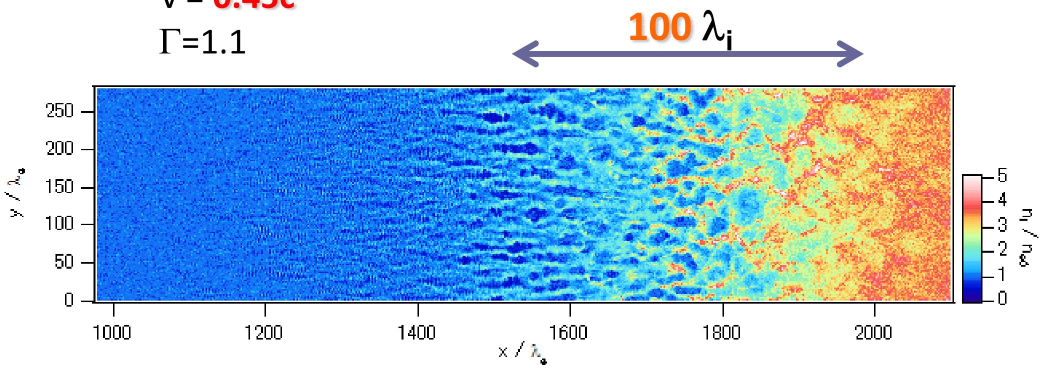
$m_p/m_e = 20$

Ion Number Density

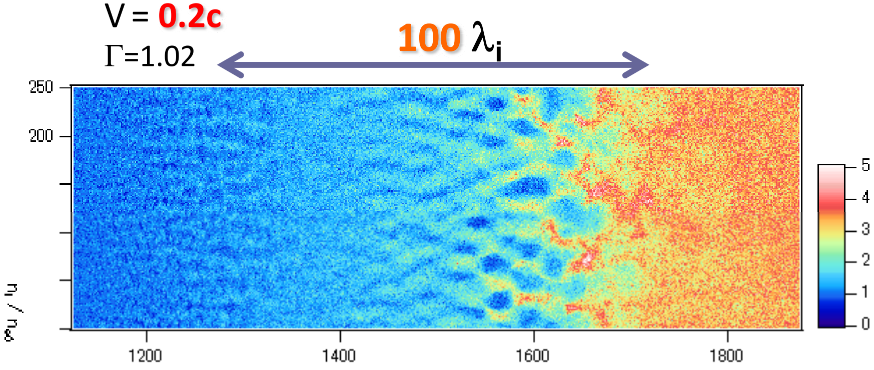
V = **0.9c**
Γ=2.2



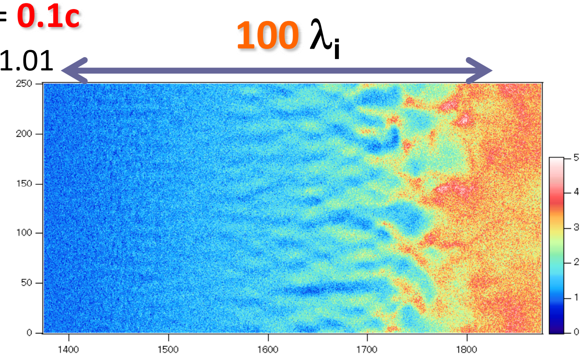
V = **0.45c**
Γ=1.1



V = **0.2c**
Γ=1.02



V = **0.1c**
Γ=1.01

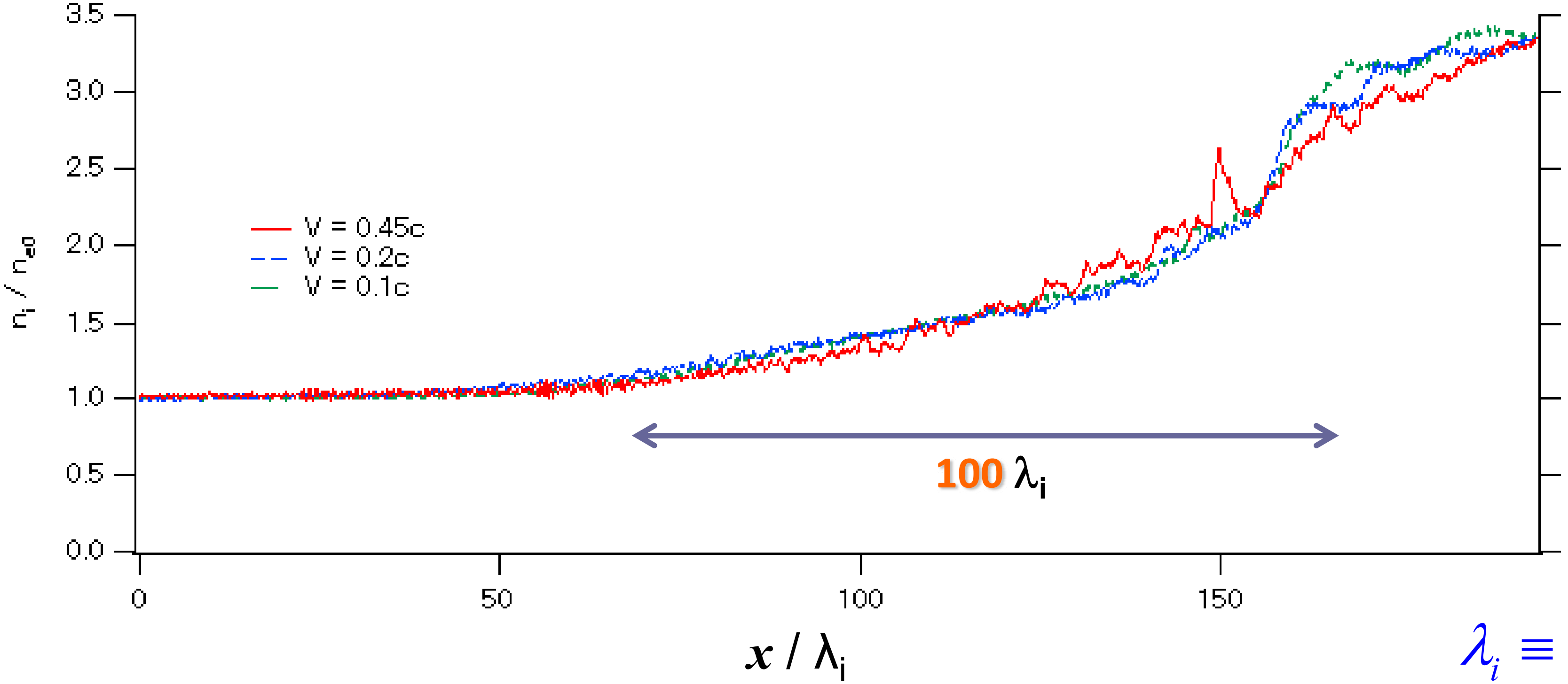


The width of the transition region is approximately **100 ion inertia length λ_i**

$$\lambda_i \equiv c/\omega_{pi}$$

Number Density Profiles

n_i / n_{e0} for **V** = **0.45c**, **0.2c**, **0.1c**



$\lambda_i \equiv c / \omega_{pi}$

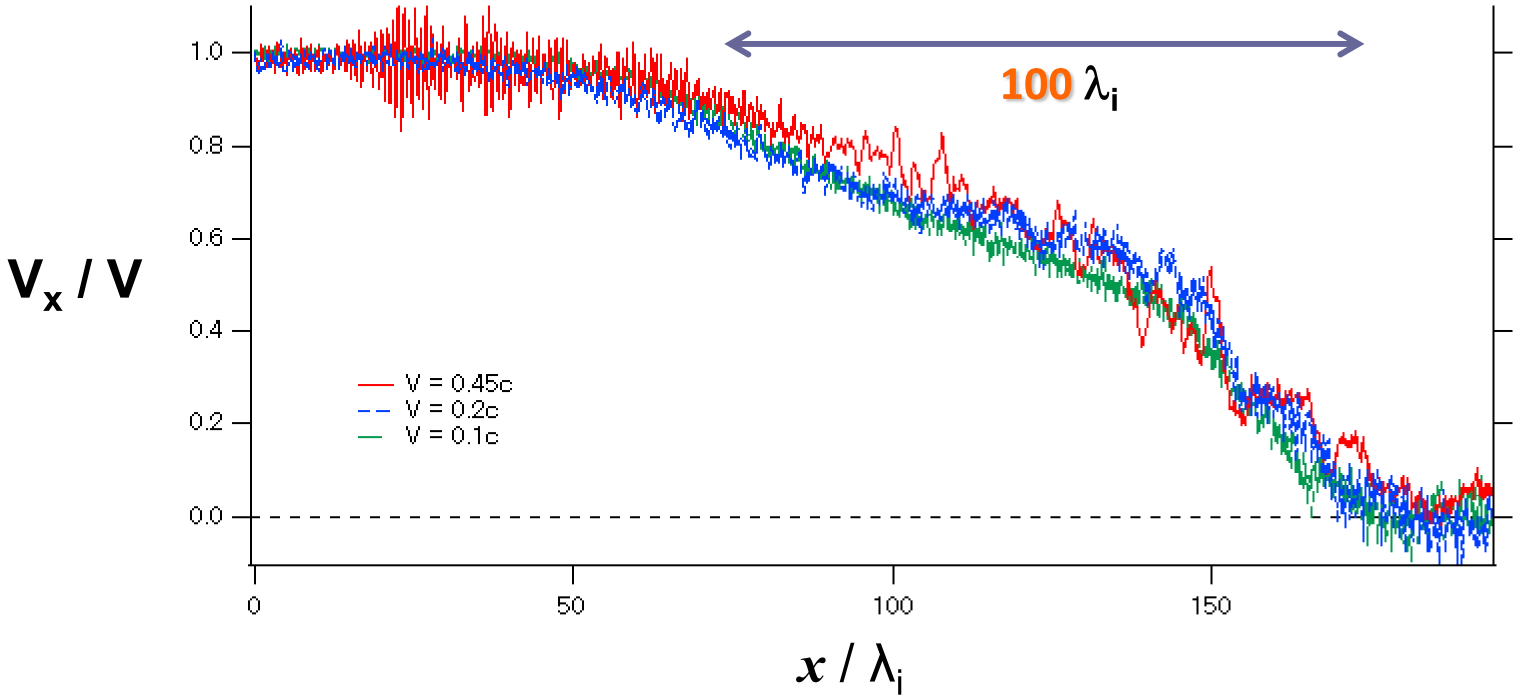
- **Normalized by the upstream number density**
- The spatial scale is normalized by the ion inertia length

The profiles are **almost identical independently of velocity**

In particular, W ~ **100** λ_i , n_2 / n_1 ~ **3.4** in all cases

Normalized Velocity Profiles

for **V = 0.45c, 0.2c, 0.1c**

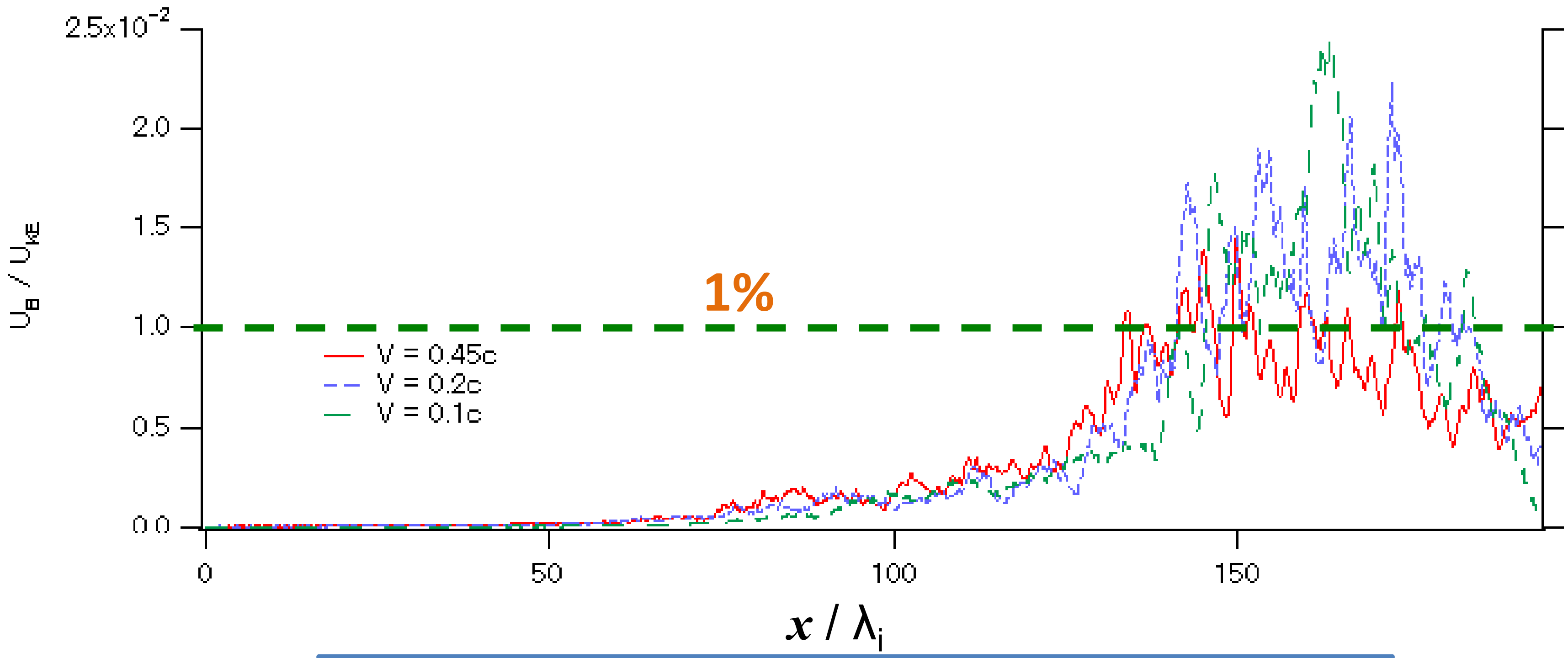


- **Normalized by the upstream velocity**
- The spatial scale is normalized by the ion inertia length

Almost identical profiles

Profiles of Magnetic Energy Density

U_B / U_{KE} for **V = 0.45c, 0.2c, 0.1c**



- **Normalized by the upstream bulk kinetic energy density**
- The spatial scale is normalized by the ion inertia length

Typically, the energy density of generated magnetic fields reach **~1%** of the upstream bulk kinetic energy in all cases.

Simulation of Collisionless Shocks

In Electron-Ion Plasma
with Background Magnetic Field

Field Strength around SNRs

There exist **weak magnetic fields** in ISM

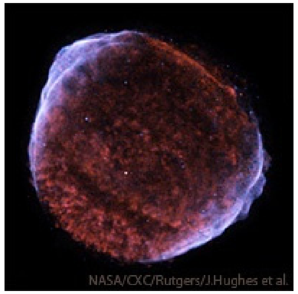
- Magnetic Field: $B_0 \sim 3\mu G$
- Number Density: $n \sim 0.1$ cm^{-3}

The magnetization parameter:

$$\sigma \equiv \frac{U_B}{U_{\mathrm{KE}}} = \frac{B_0^2/8\pi}{\frac{n}{2}\left(m_{\mathrm{p}} + m_{\mathrm{e}}\right)V^2}$$

$$\sigma \approx 4.3\times10^{-4}\left(\frac{B}{3\mu G}\right)^2\left(\frac{n}{0.1\mathrm{cm}^{-3}}\right)^{-1}\left(\frac{V}{1000\mathrm{km/s}}\right)^{-2}$$

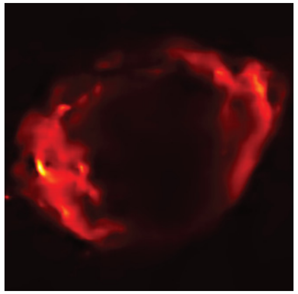
SN1006 (1003 years old)



$V_s \sim 3000$ km/s

⇒ $\sigma \sim 5 \times 10^{-5}$

G1.9+0.3 (~140 years old?)

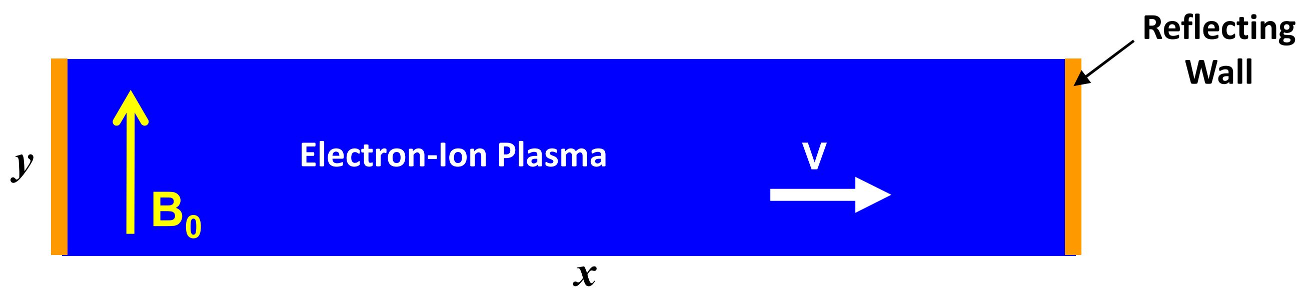


$V_s \sim 14{,}000$ km/s

⇒ $\sigma \sim 2 \times 10^{-6}$

Typically, $10^{-6} < \sigma < 10^{-3}$, in young SNRs

Initial Condition for Shocks in Magnetized Plasmas



A background magnetic field is set in the **y-direction**

"Perpendicular Shock"

Simulation Parameters

- **Perpendicular Shock** (θ=90˚)
- σ = **10^{-4}** **(Low-sigma)**
- M_A^* = **100** **(High Mach Number)**

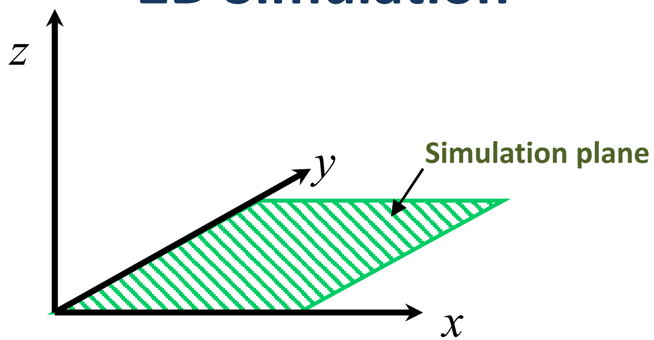
$M_A^* = V / v_A$

- 2D PIC simulation
- V = **0.25c**
- m_i/m_e = **30**
- (L_x, L_y) = **($3200\lambda_e$, $200\lambda_e$)**

λ_e: electron skin depth

Simulation Settings

2D Simulation



- The simulation plane = the x-y plane
- The z axis is perpendicular to it

Units

Time	$\tau_0 = 1/\omega_{pe}$
Length	$\lambda_e = c/\omega_{pe}$ (skin depth)
EM Fields	$E_* = B_* = c\sqrt{4\pi n_{e0} m_e}$

Settings

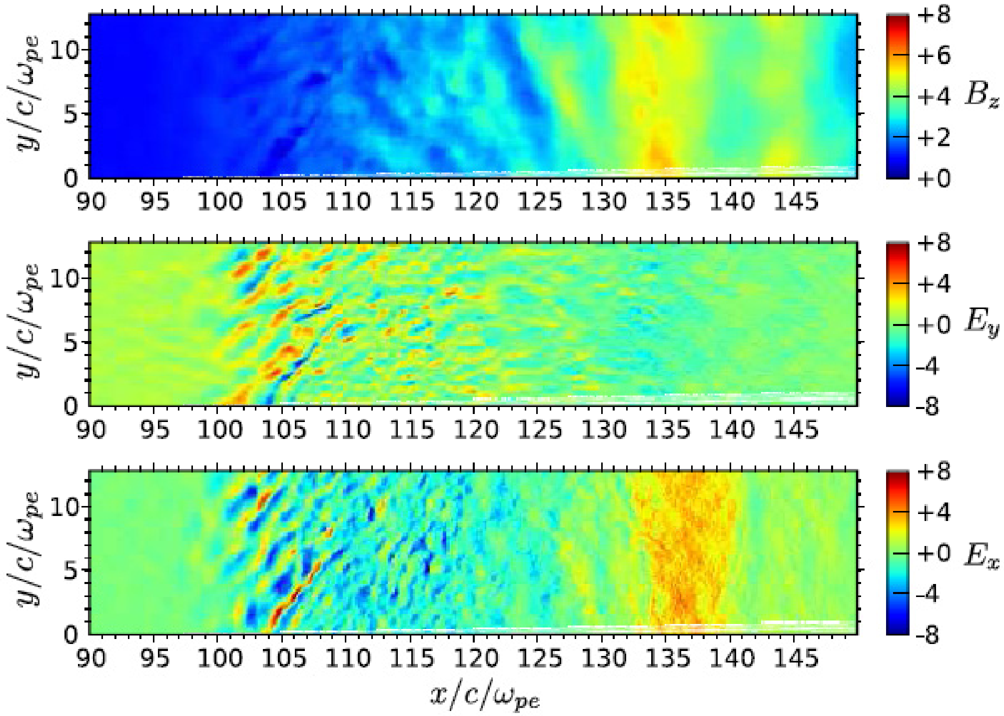
Composition	Electron, Ion
Physical Size	3200 × 200
Grid Size	16384 × 1024
Particle Number	6×10^8 particles / species (40 particles / cell)
B.C.	Periodic
Magnetic Field	Perp. (in y) $\sigma=10^{-4}$

Mass Ratio	30
Bulk Velocity	0.25c

2D Perpendicular Shock Simulation

Amano & Hoshino, ApJ, 2009, 690, 244

Nonrelativistic perpendicular 2D PIC simulation



- **Perpendicular Shock** (θ=90˚; **out of plane**)
- **σ ~ 10^{-2}**
- **M_A = 14**

- 2D PIC simulation
- V = **0.2c**
- m_i/m_e = **25**
- (L_x, L_y) = (**204**λ_e, **12.8**λ_e)

λ_e: electron skin depth

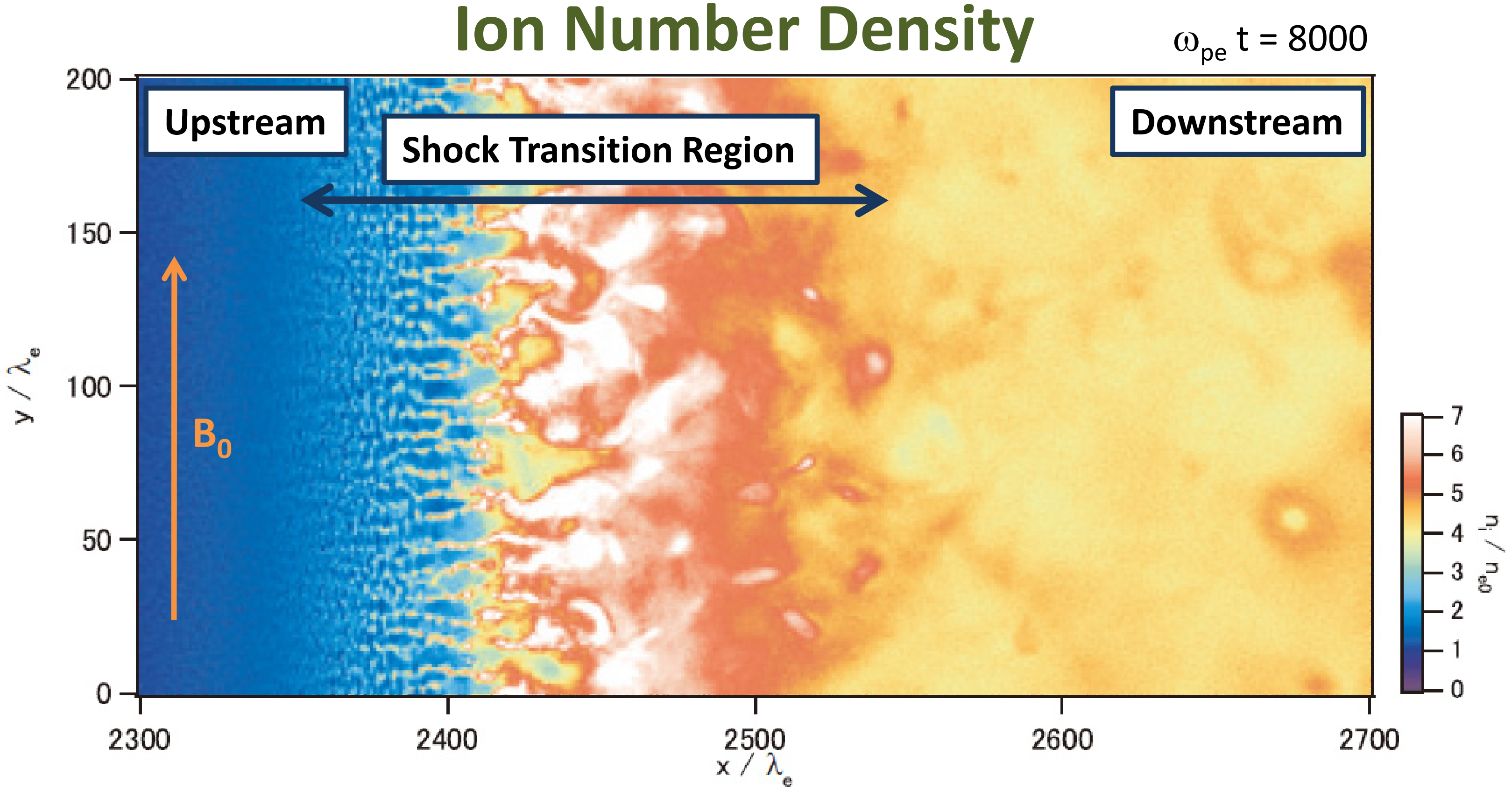
Electron acceleration is observed

⟺ Our simulation: **on-plane** magnetic field, **low-sigma** (**σ=10^{-4}**), and high Mach number (**M_A^*=100**)

Results

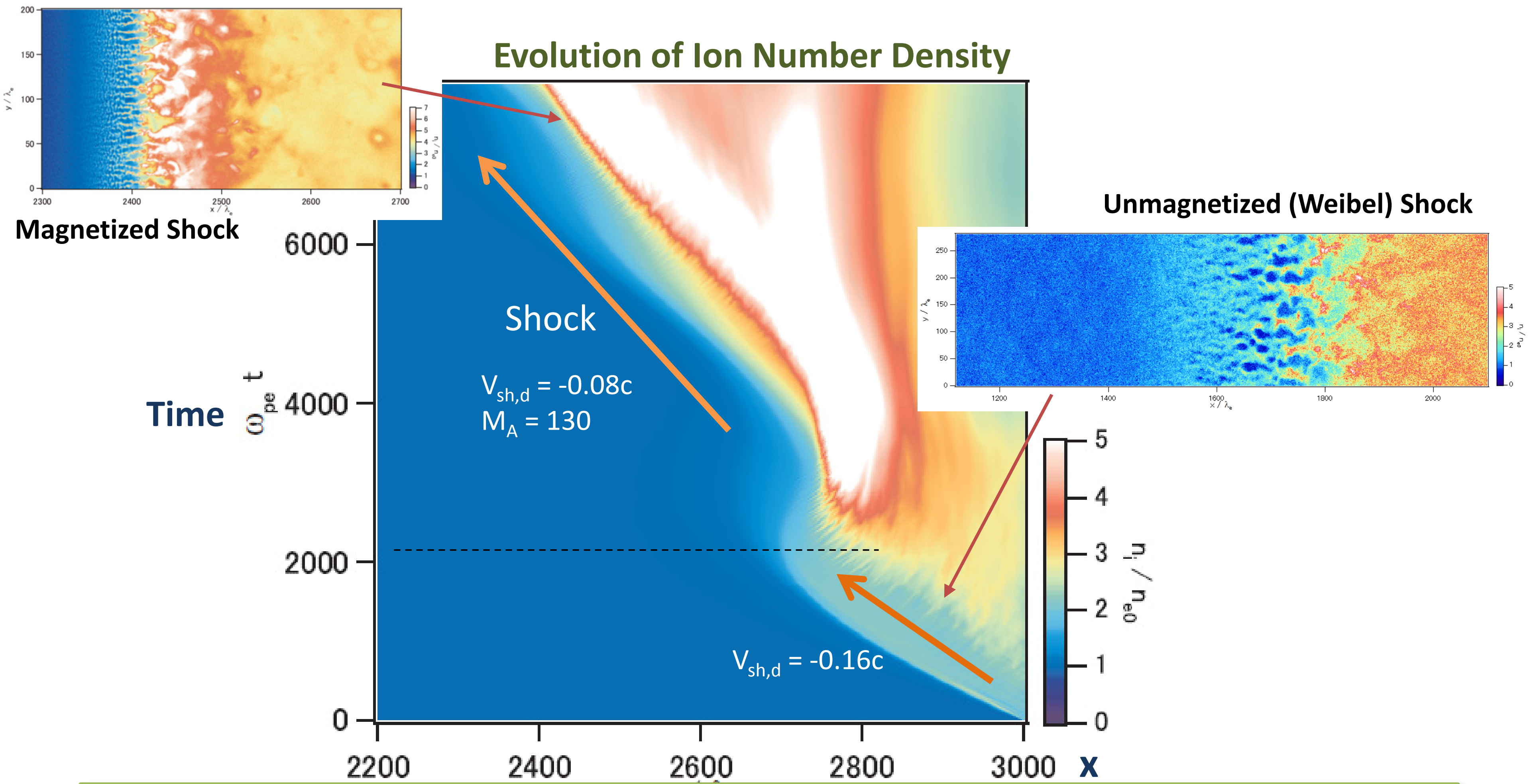
V=0.25c, $\sigma=10^{-4}$, $\theta=90^{\circ}$

Ion Number Density



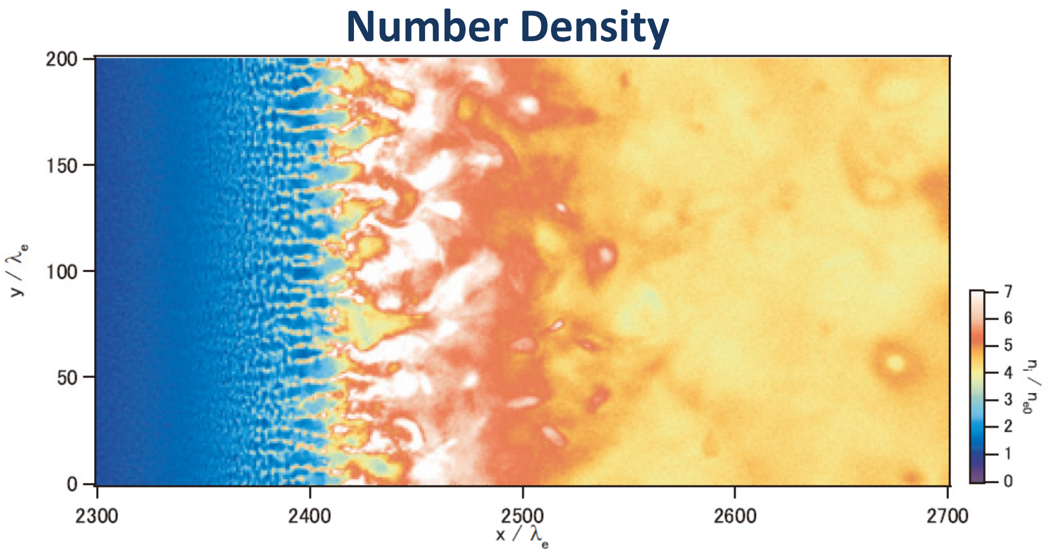
- Collisionless shock is formed
- **Filamentary structures** in the leading edge of the transition region
- **Highly inhomogeneous** structure in the transition region
- Downstream region is almost **homogeneous**

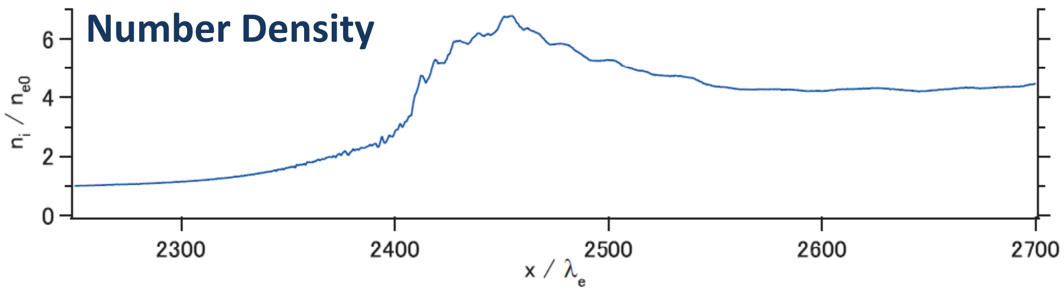
Propagation of Shock

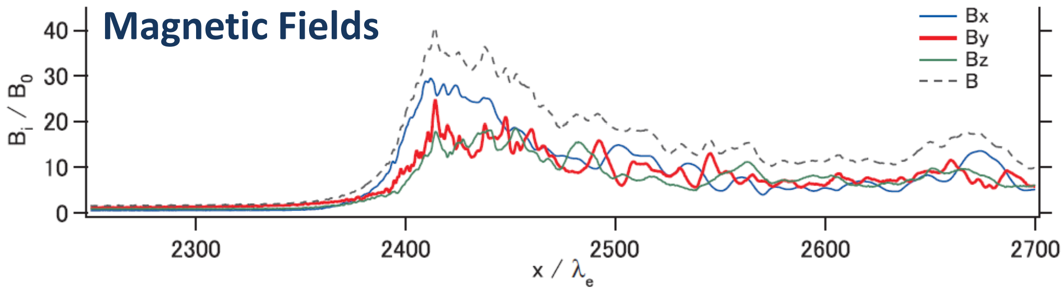


- First, a **unmagnetized (Weibel-mediated) shock** is formed. Then, a **magnetized shock** is formed
- Both shocks propagate at almost **constant speeds**
- **No shock reformation** is observed

Profiles





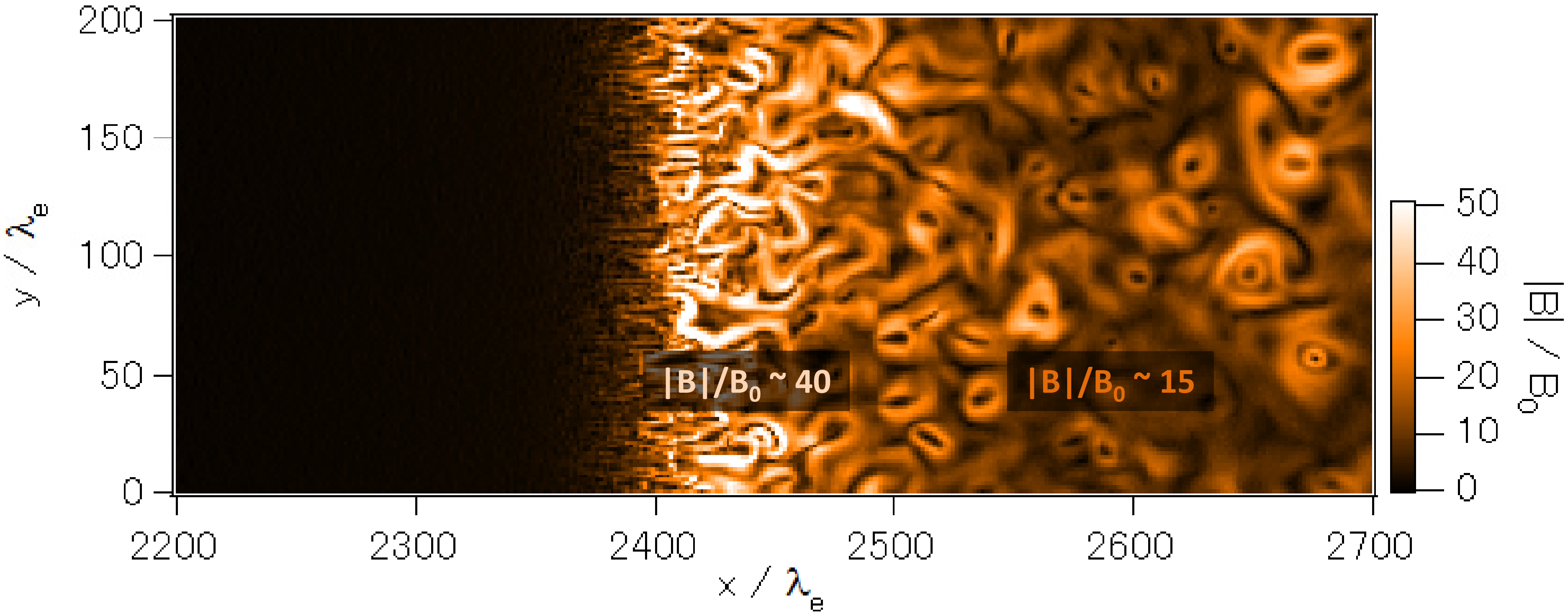


- Density jump is **~4**
- **B_x,B_z** components are **generated** as well as the **compression** of the upstream field **B_y**
- In the transition region, **B_x is dominant**
- In the downstream region, mean magnetic field strength is **~15 times** the upstream strength

Magnetic field generation in the transition region

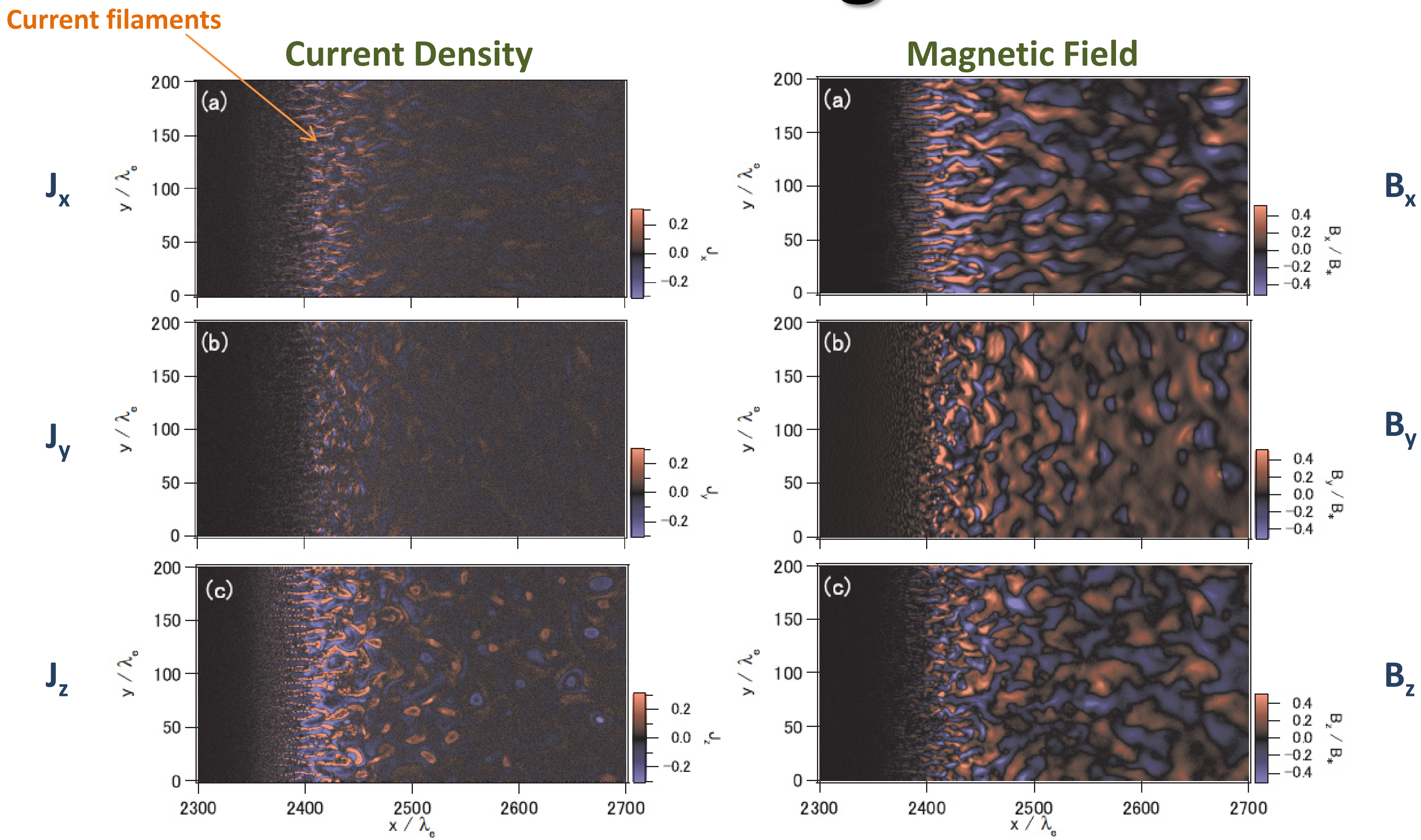
Magnetic Field Generation

Magnetic field strength normalized to the upstream B_0



Highly tangled strong magnetic field is generated, in the **shock transition region** (**$|B|/B_0$~40**) and in the **downstream region** (**$|B|/B_0$~15**)

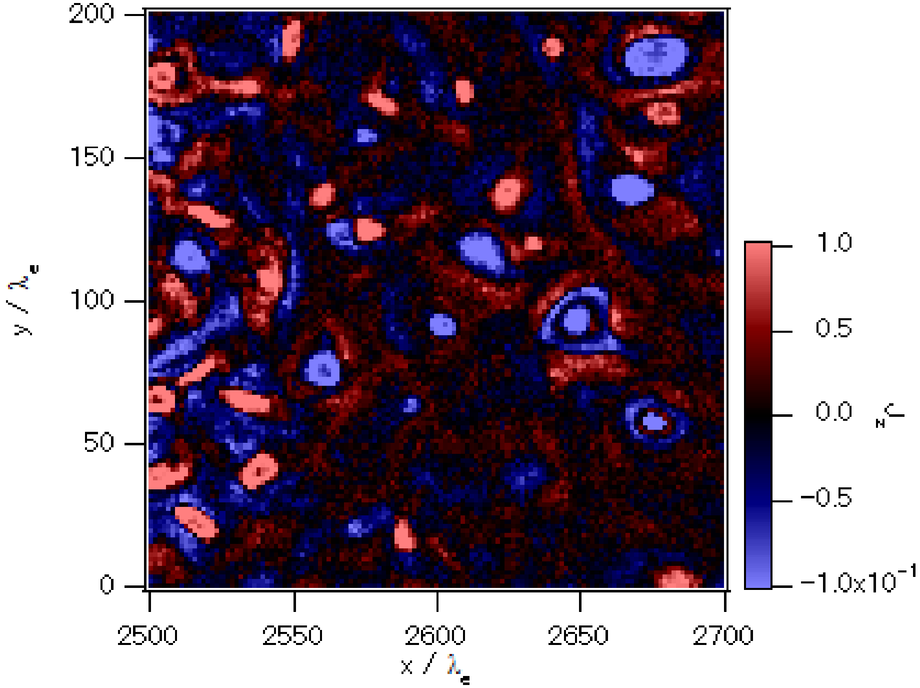
Currents and Magnetic Field



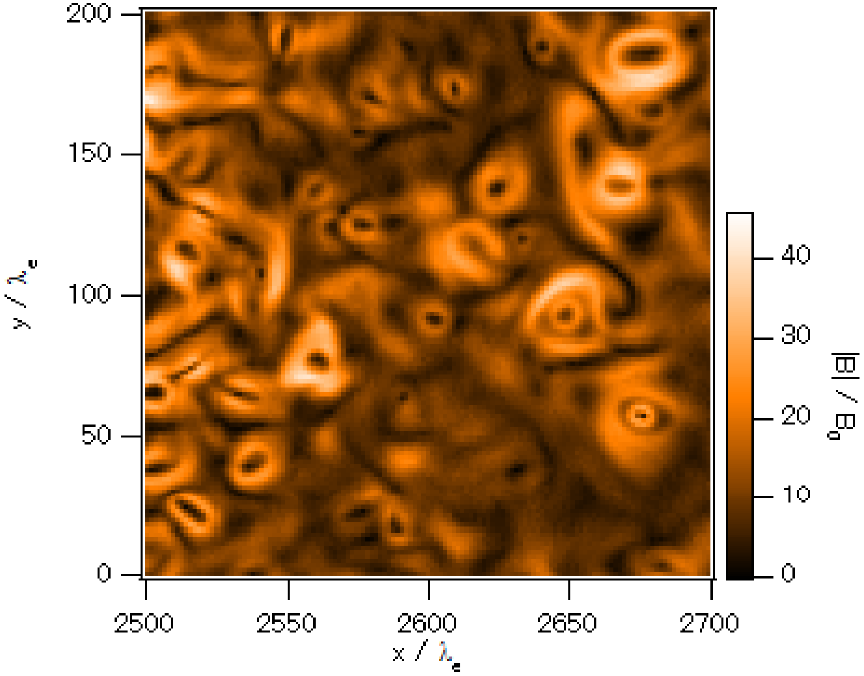
- In the transition region, there are **current filaments** generated by **Weibel instability**
- The current filaments **generate magnetic field**, while the **background field** is also **compressed**

Downstream Magnetic Fields

Current Density J_z



Magnetic Field $|B|/B_0$



- Downstream magnetic fields are generated by a lot of **current filaments in z-direction, J_z**
- Some of the filaments have **coaxial** structure

Electrostatic Mode

Two-stream instability (electron vs. ion beam)

Buneman instability

- **Condition** $2V_{sh} > V_{\mathrm{th,e}}$
- **Wave length**

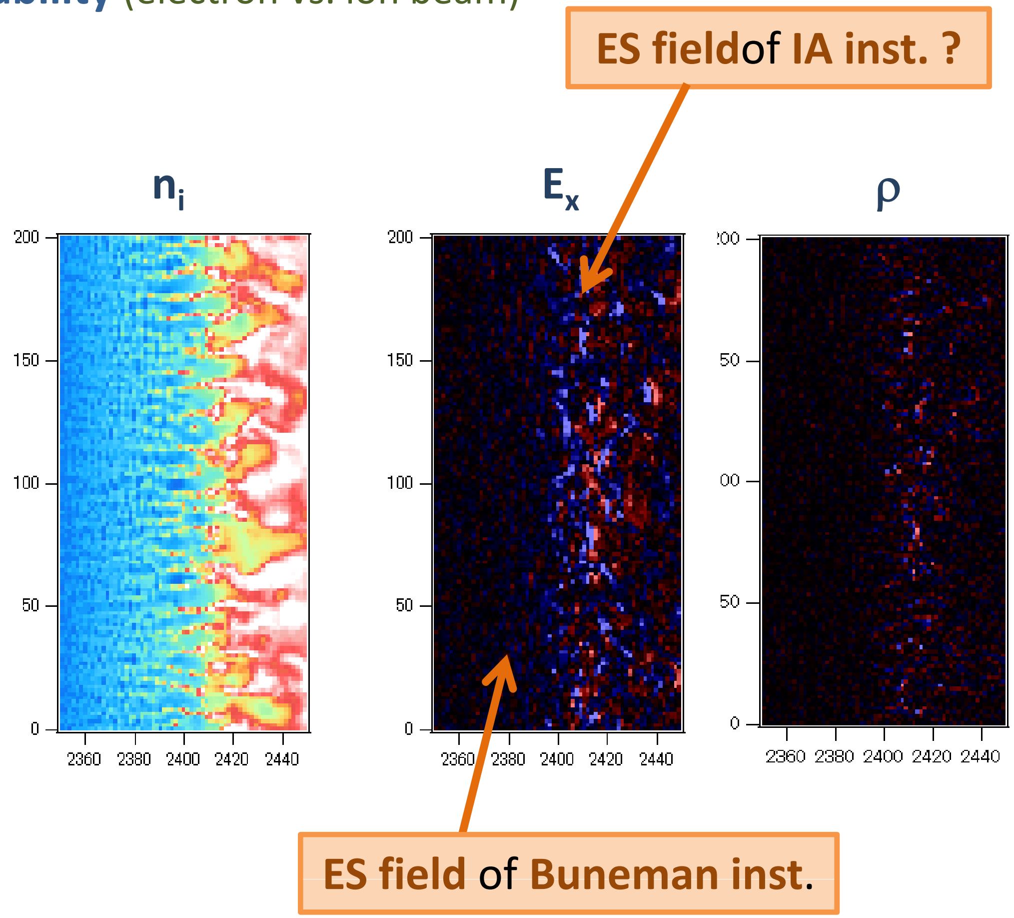
$$\lambda \approx 2\pi \frac{2V_{\mathrm{sh}}}{\omega_{\mathrm{pe}}} \approx 4\lambda_e$$

Ion acoustic (IA) instability

- **Condition** $T_e / T_i \gg 1$

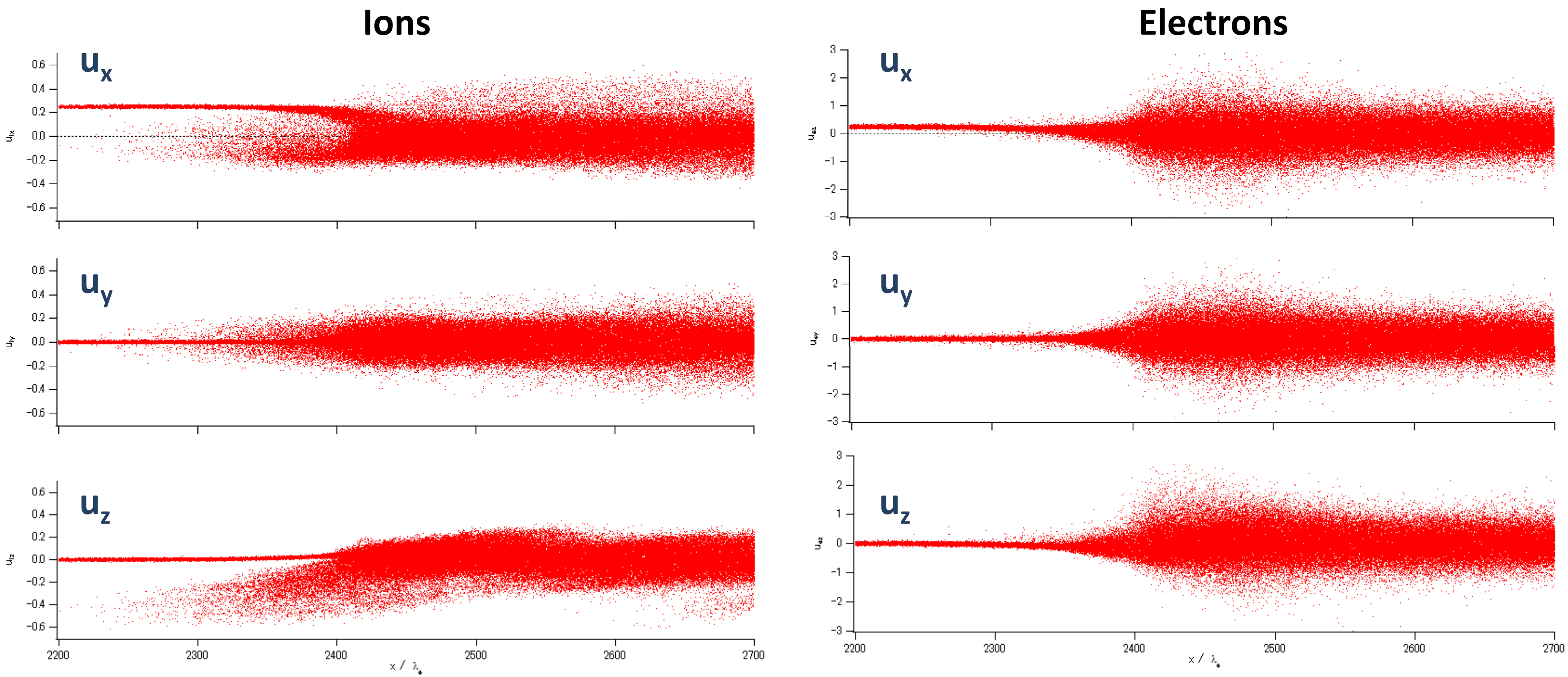
$2V_{sh} / V_{\mathrm{th,e}} > 0.3 - 1$

- **Wave length** $\lambda \approx 4\lambda_e$



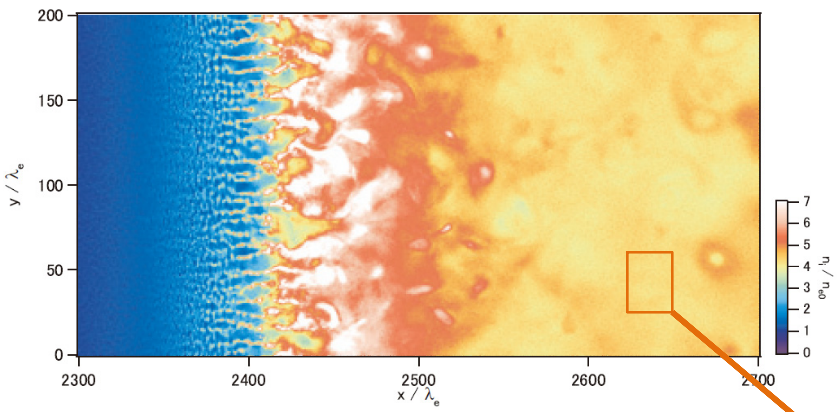
Buneman instability (and IA?) grows in the shock foot region

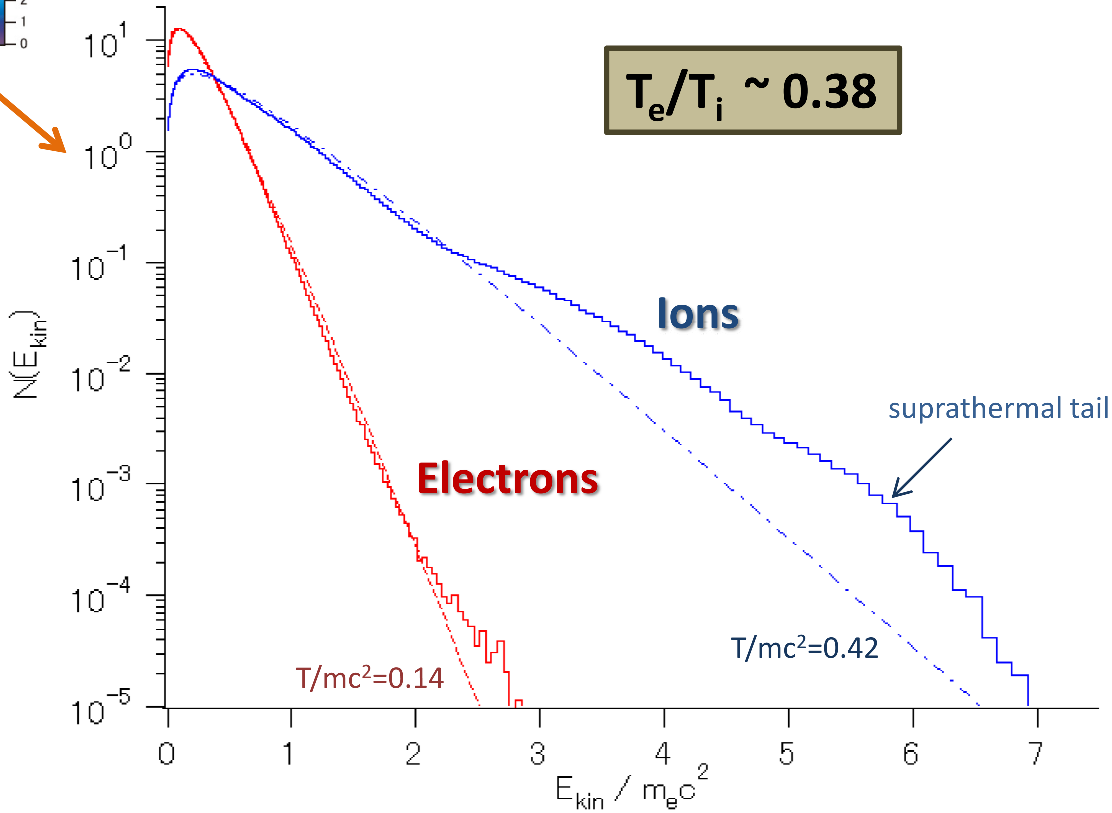
Phase Space Plots



- Both electrons and ions are **isotropically thermalized** in the downstream region
- Thermalization would be due to mainly **magnetic field** and partly **Buneman instability** (for electrons)

Downstream Energy Distribution





- Both electrons and ions are almost **Maxwell distribution**
- Electron temp. is **lower** than ion temp.
- There are some **suprathermal ions**
- **No** prominent **acceleration** for electrons

Jump Condition

From the simulation, we obtain

$$n_2/n_1 \sim 4.1,\ \ V_1/V_2 \sim 3.9,\ \ ((T_e+T_i)\ /\ m_i)^{1/2} \sim 0.14c$$

On the other hand, the (MHD) Rankine-Hugoniot relation gives

$$n_2/n_1 \sim 4,\ \ V_1/V_2 \sim 4,\ \ ((T_e+T_i)\ /\ m_i)^{1/2} \sim 0.15c$$

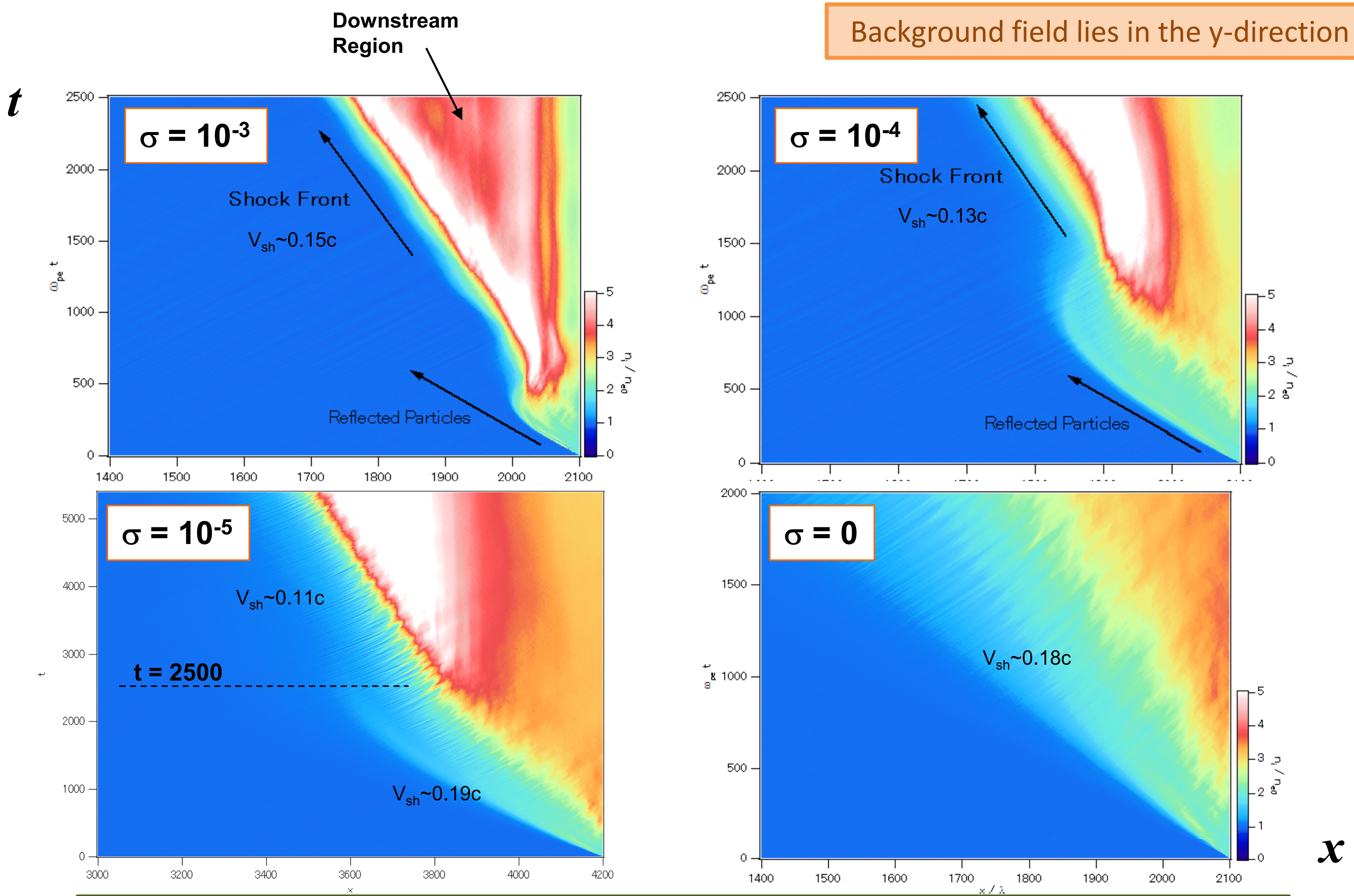
(e.g., Tidman & Krall 1971)

R-H relation holds very well

Although **$|B|/B_0 \sim 15$** in the downstream, the **plasma beta** is **~25** and **the magnetic field is negligible** for the jump condition

σ –dependence

Background field lies in the y-direction



Shock structure changes at about ¼ the ion gyro-motion at least $\sigma > 10^{-5}$

Summary

2D PIC simulation of **nonrelativistic** collisionless shocks in **unmagnetized** and **weakly magnetized** electron-ion plasmas

Unmagnetized (Weibel) shock

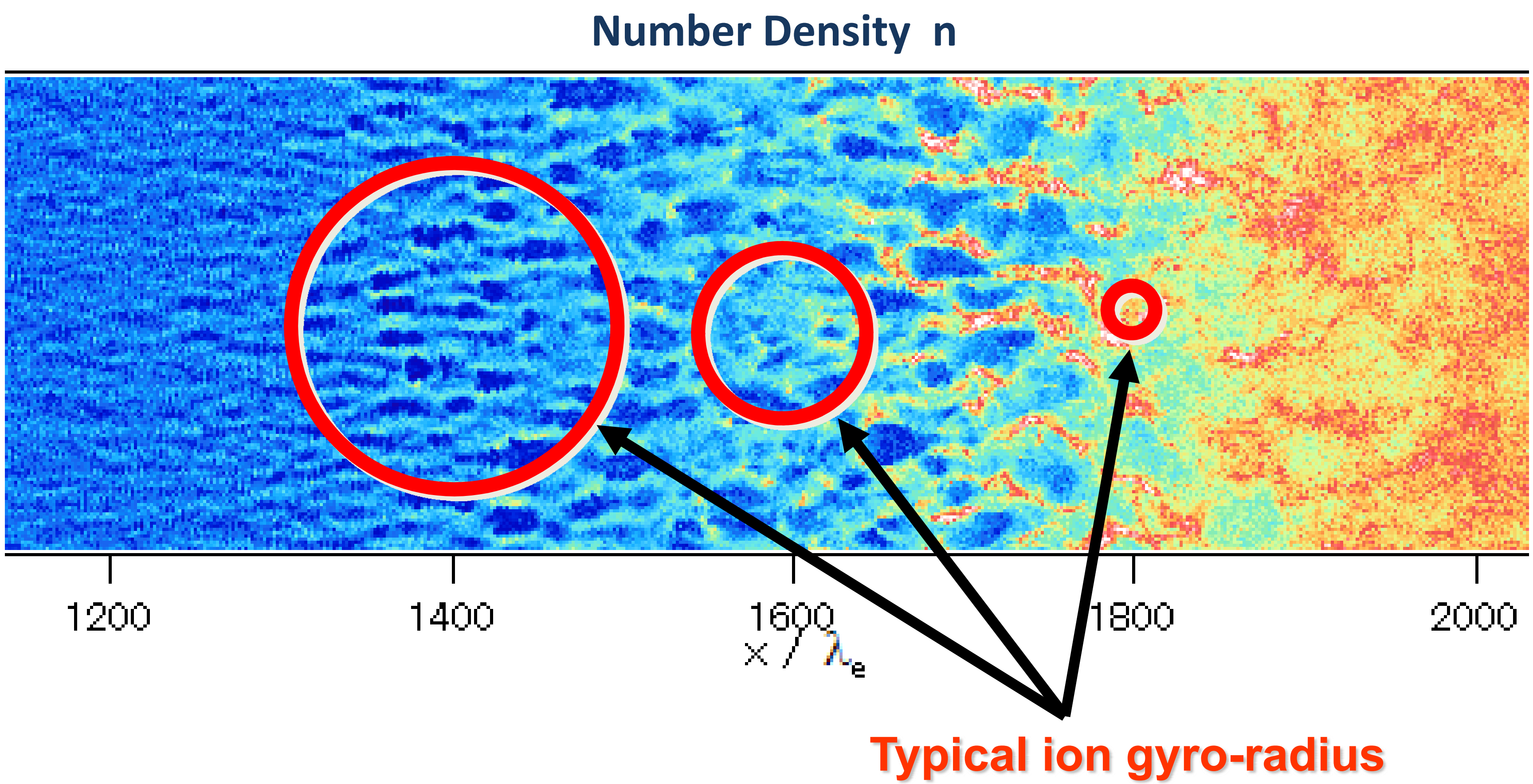
- The **Weibel-mediated shocks exist** in the **non-relativistic** regime
- The structure is **similar** to those in the **relativistic** cases
- The shock exist at least **V > 0.1c**
- **Profiles of number density, normalized velocity, normalized magnetic field** are almost **independent of V**

Weakly magnetized shock ($\sigma=10^{-4}$)

- First, **Weibel-mediated shock**, then **magnetized shock** are formed
- In the **transition region**, **current filaments** and **strong magnetic fields ($|B|/B_0$ ~ 40)** are generated by the **Weibel instability**
- In the downstream region, **highly tangled magnetic fields ($|B|/B_0$ ~ 15) remain**
- **No shock reformation**
- Electrons and ions are **thermalized** and well fitted by **Maxwellian** distributions in the downstream. Temp ratio is **T_e/T_i~0.4**
- **No** prominent **particle acceleration** is observed

Thank you for your time and your attention

Saturation of Magnetic Field



Magnetic field saturates when **filament radius=ion gyro-radius**

➡ **Isotropization of particles** ➡ **Dissipation**

Filament Radius at Saturation

R_f : radius of current filament

Magnetic field generated by the current filament

$$B \approx 2\pi R_f qnV / c$$

Gyro-radius

$$R_g \approx \frac{\gamma m_i c V}{eB} \approx \frac{\gamma m_i c^2}{2\pi n q^2 R_f}$$

Condition for saturation: $R_f \sim R_g$ **(corresponding to the ion Alfven current)**

$$\Rightarrow \quad R_f \approx \sqrt{2\gamma}\,\frac{c}{\omega_{pi}}$$

~ ion inertial length (including relativistic effect)

Independent of **V**

Energy density of magnetic field

$$U_B = \frac{B^2}{8\pi} \approx \frac{1}{4}\gamma m_i V^2 \quad \Rightarrow \quad \frac{U_B}{U_{KE}} \approx \frac{1}{4}\frac{\gamma V^2}{\gamma - 1}$$

sub-equipartition

Model for Current Filament

Coalescence of two current filaments

$$J \sim \eta e n V, \quad B \sim 2\pi \eta e n R \frac{V}{c}$$

V: Flow velocity
R: Filament radius
l: Distance between two filaments

$$\Rightarrow \quad \frac{d^2 l}{dt^2} = \frac{\eta}{2} \omega_{pi}^2 \left(\frac{V}{c} \right)^2 R$$

E.O.M for two filaments

Order estimate

Time scale of coalescence: $\tau \sim (\alpha / \eta)^{1/2} \, \omega_{pi}^{-1} \left(\frac{V}{c} \right)^{-1}$ $\quad (l = \alpha R)$

Independent of **R, l**

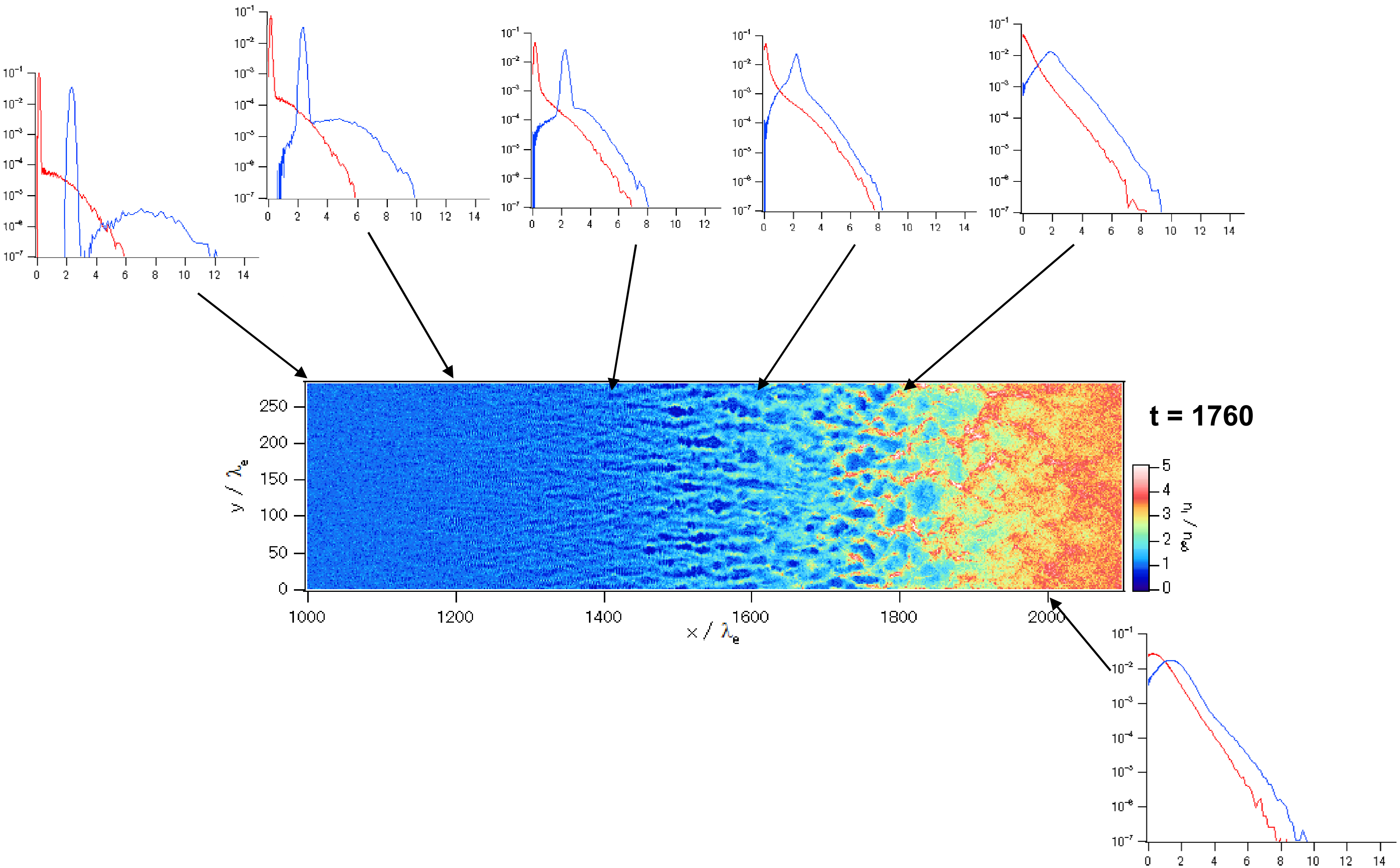
Time scale for which filament radius becomes twice:

$$\Delta W \sim V\tau \sim (\alpha / \eta)^{1/2} \lambda_i$$

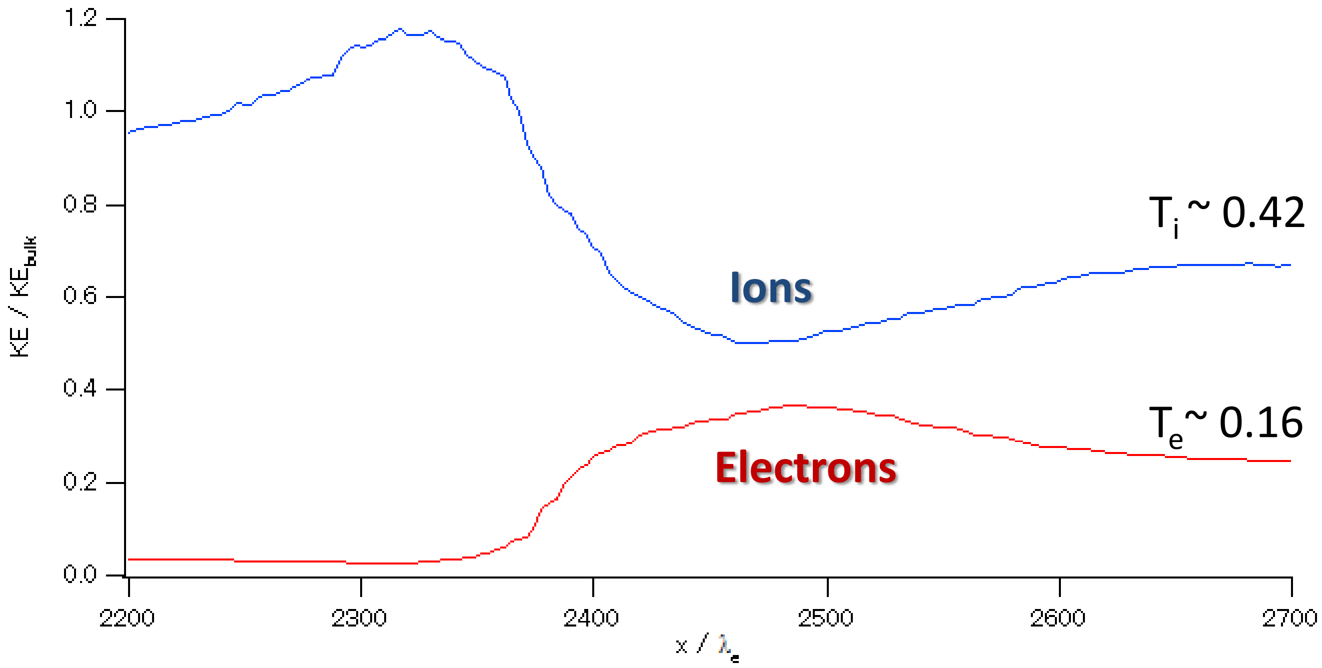
Independent of **V**

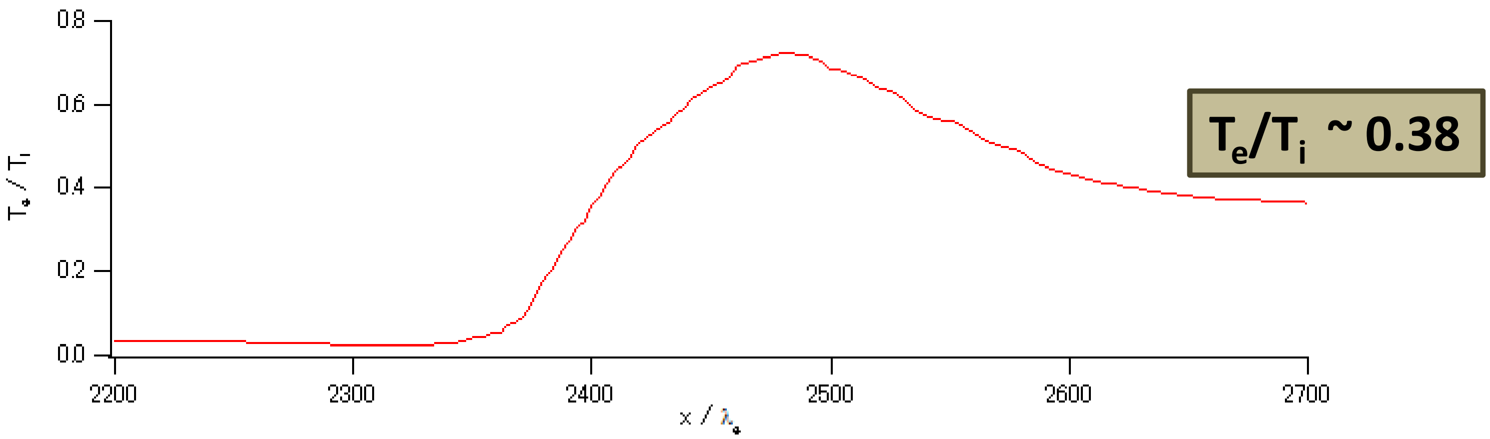
$\Rightarrow$ If **R_0~c/ω_{pe}, R_1~c/ω_{pi}**, then **W** is **independent of V**

Energy Distribution

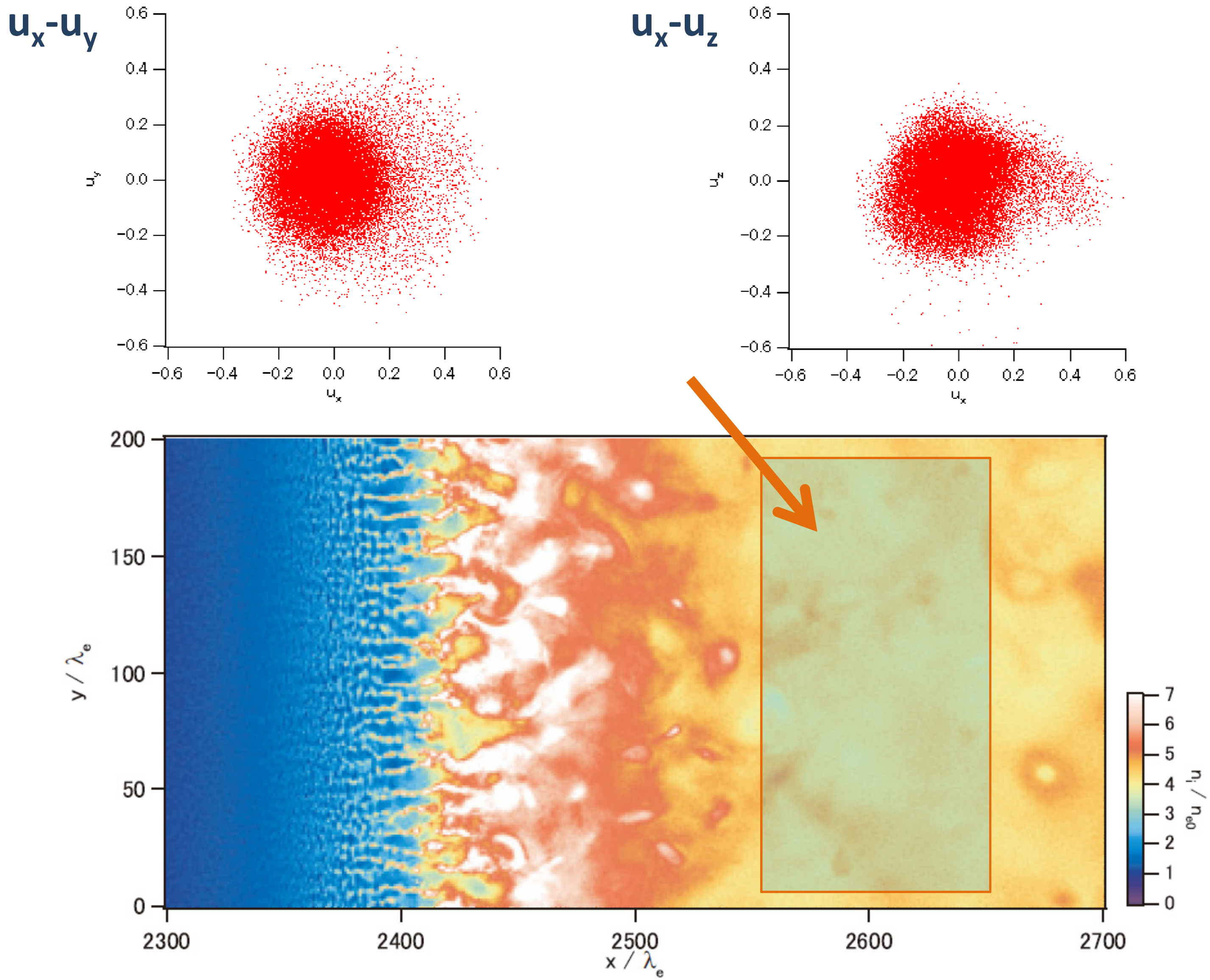


Averaged Particle Kinetic Energy



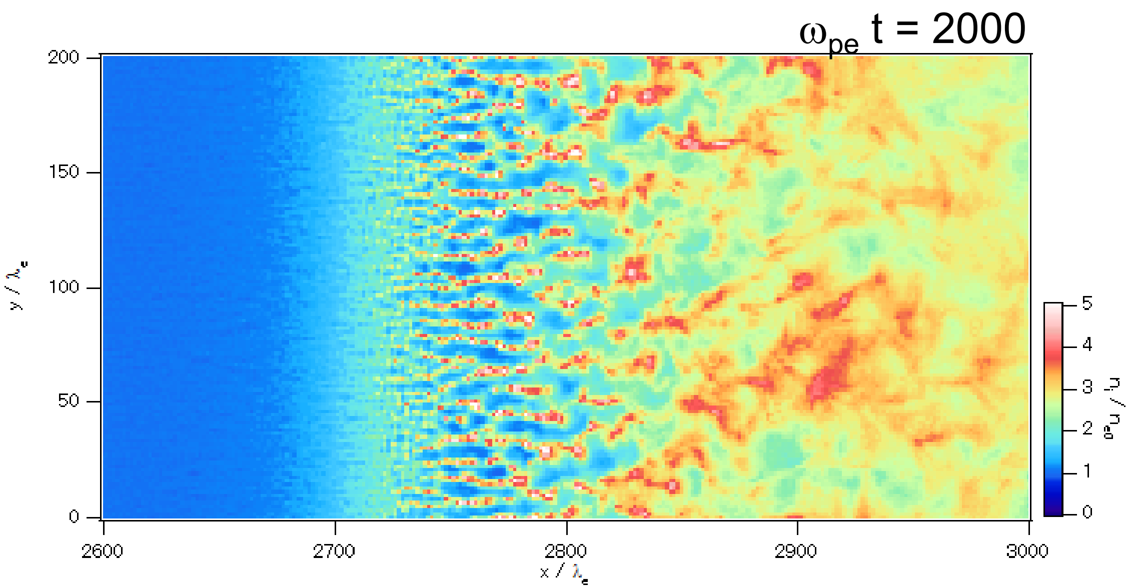


Ion Velocity Distribution

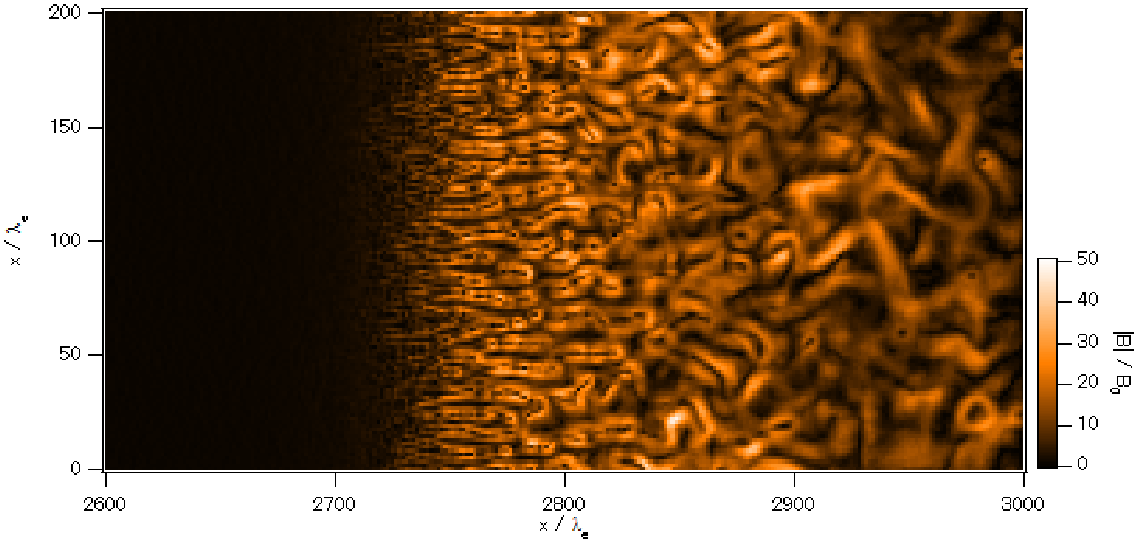


Early Evolution

Ion number density



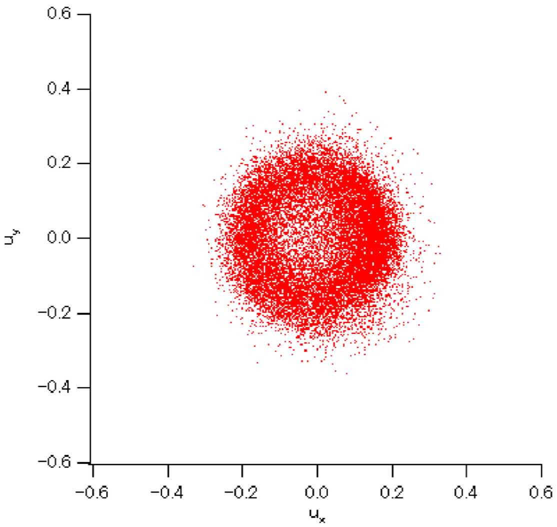
Magnetic field strength
$|B|/B_0 \sim 30$



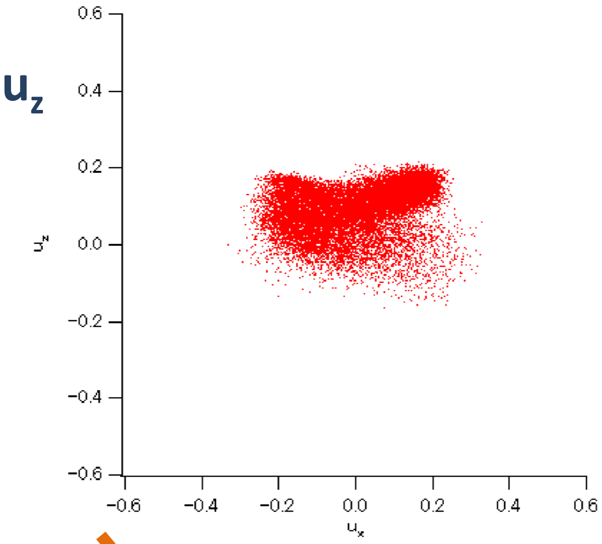
Early Evolution

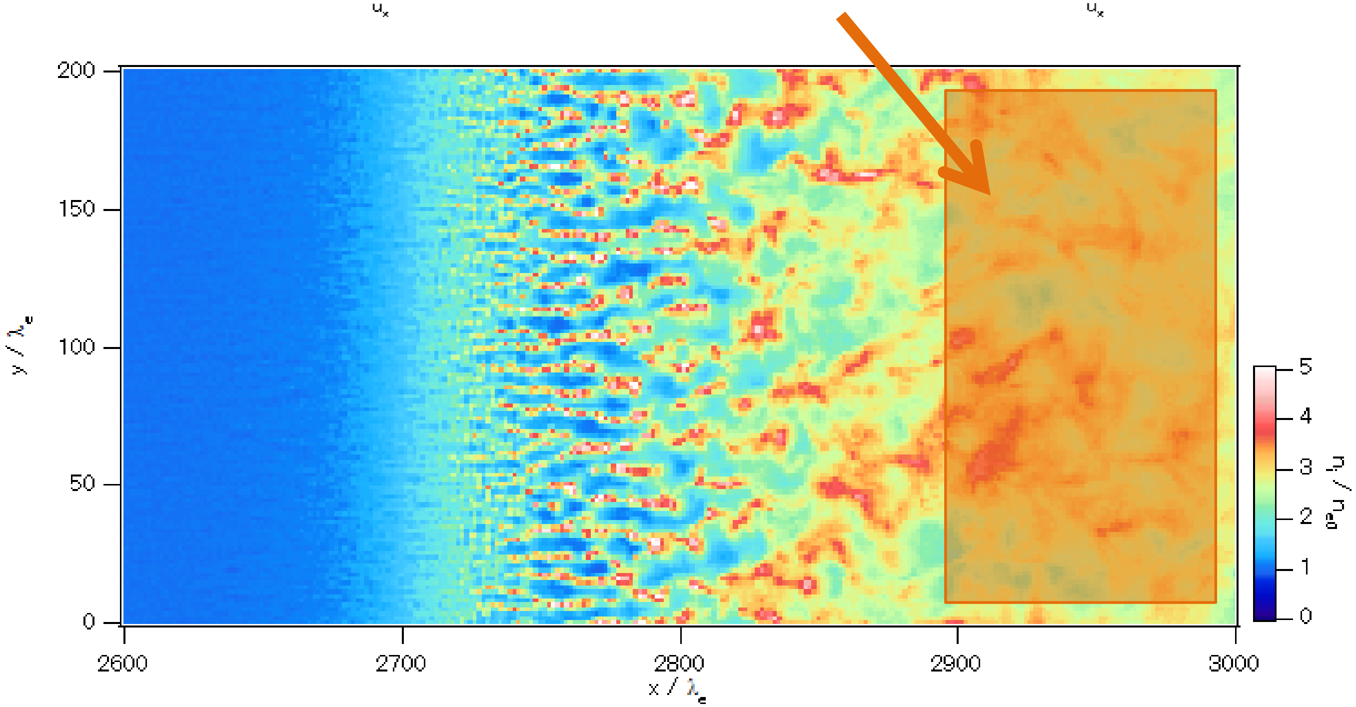
u_x-u_y

almost isotropic in x-y plane, but not thermalized



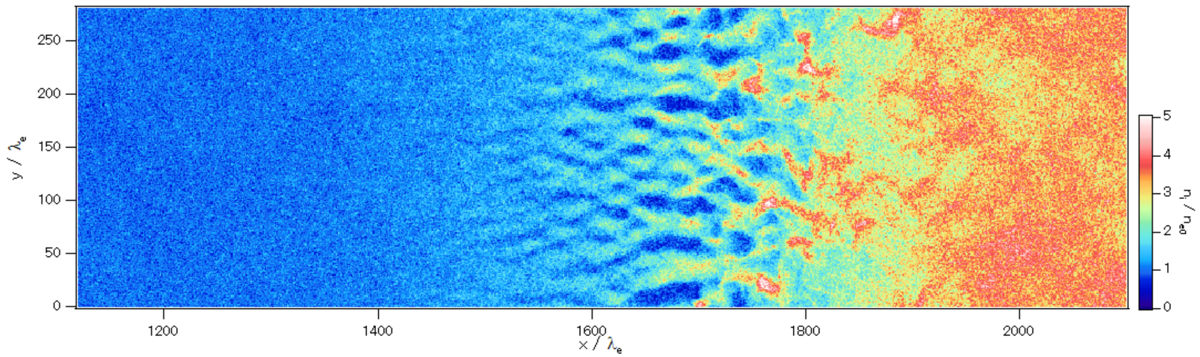
u_x-u_z



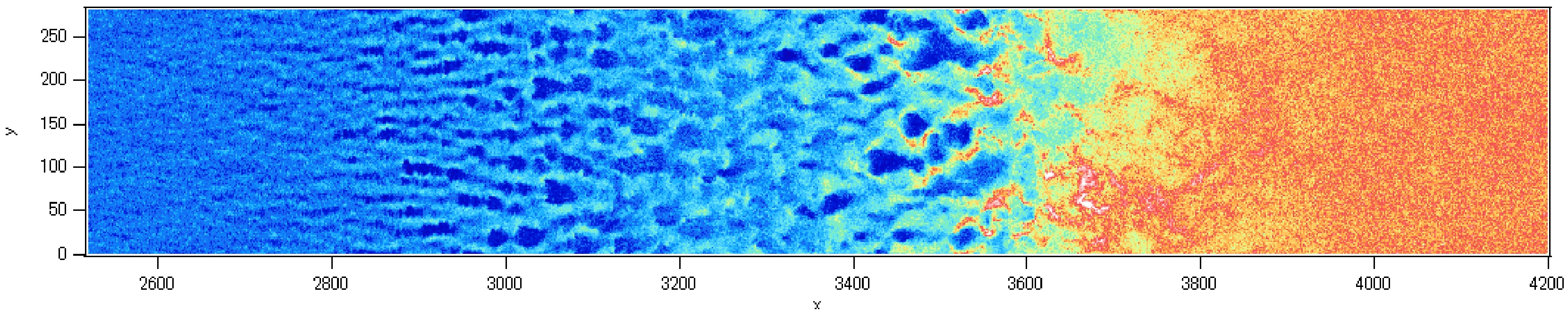


Parallel Background Field

σ = 10^{-4}

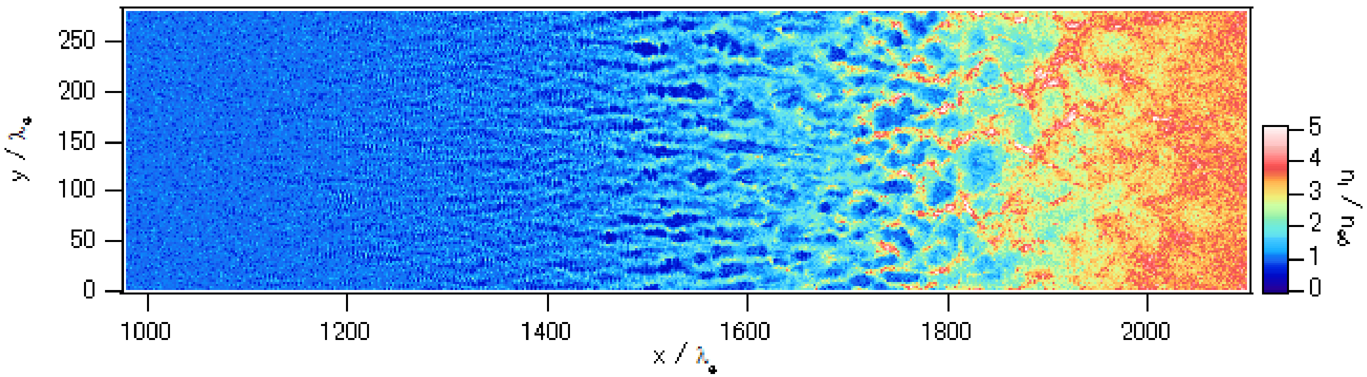


σ = 10^{-5}



σ = 0

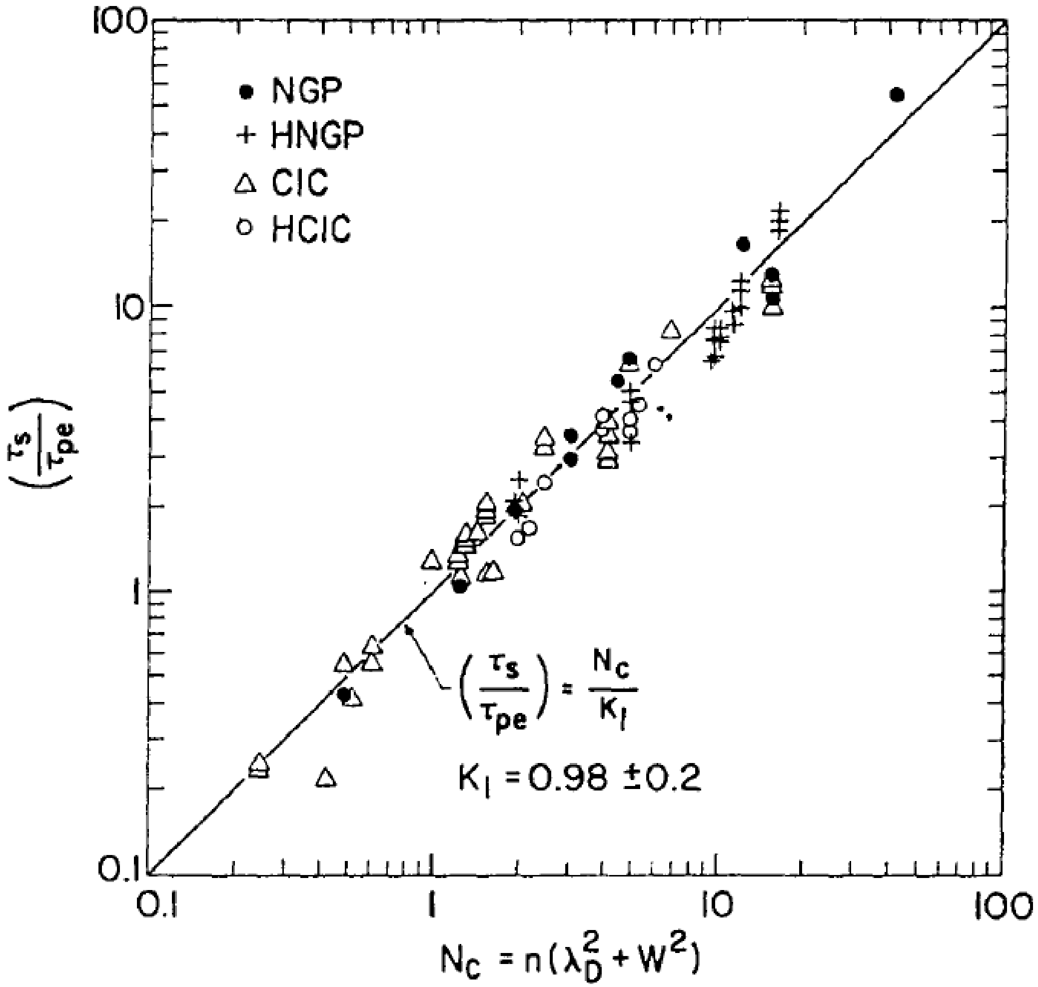
(Weibel Shock)



Almost the **same structure** as that of **unmagnetized Weibel shocks**

Numerical Collision Effect (2D)

Hockney, 1971, J. Comput. Phys., **8**, 19



Experimental Formula

$$\frac{\tau_{\mathrm{coll}}}{\tau_{\mathrm{pe}}} \approx N_C$$

$$N_C = n\left[\lambda_D^2 + R^2\right]$$

Effective size of particle

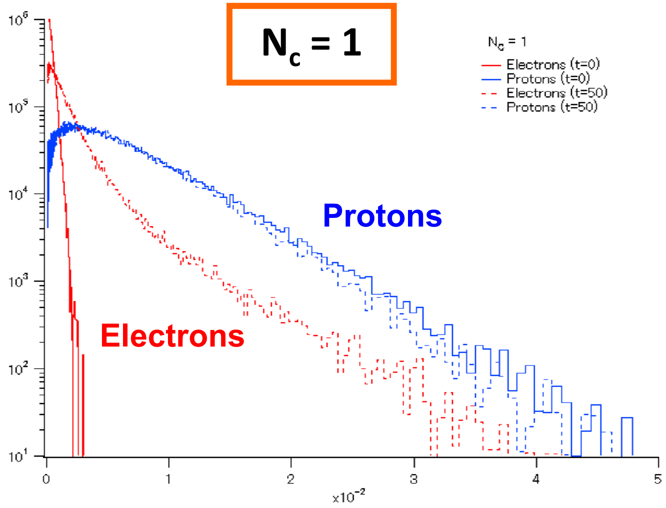
N_c must be large enough for long-term simulations

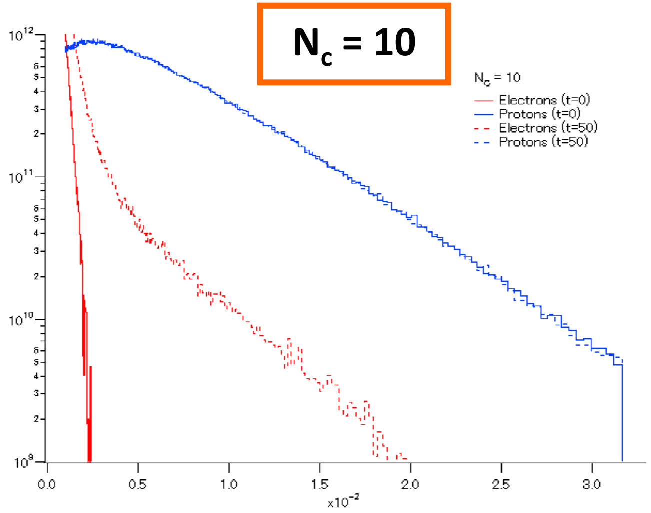
PIC Simulation of Two-Temp e-p Plasma

$m_p / m_e = 20$

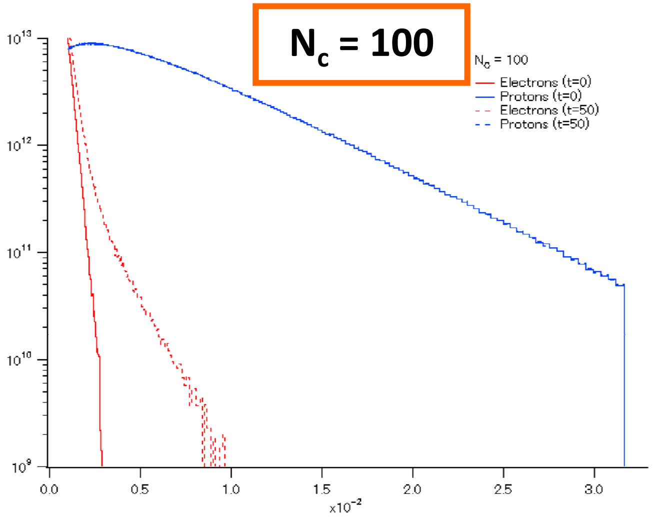
$(R = \Delta x = 15\, \lambda_D)$

Solid: **t = 0**, Dotted: **t = 50**





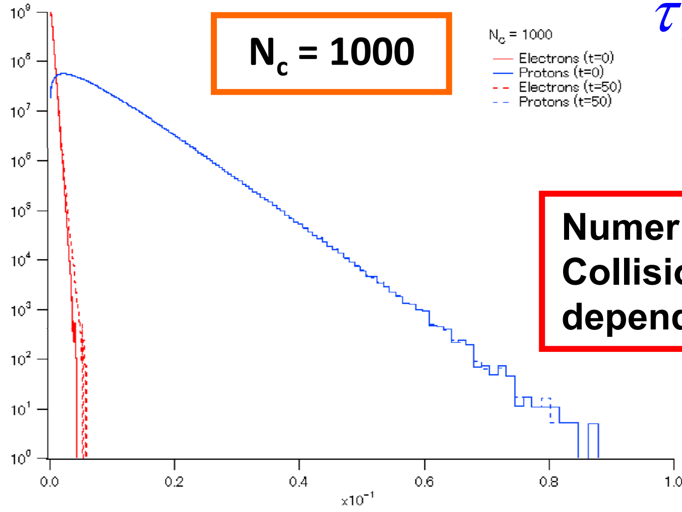
N(E)



$E / m_e c^2$

Numerical Collision Timescale

$$\tau_{ep} \approx 120 N_c$$

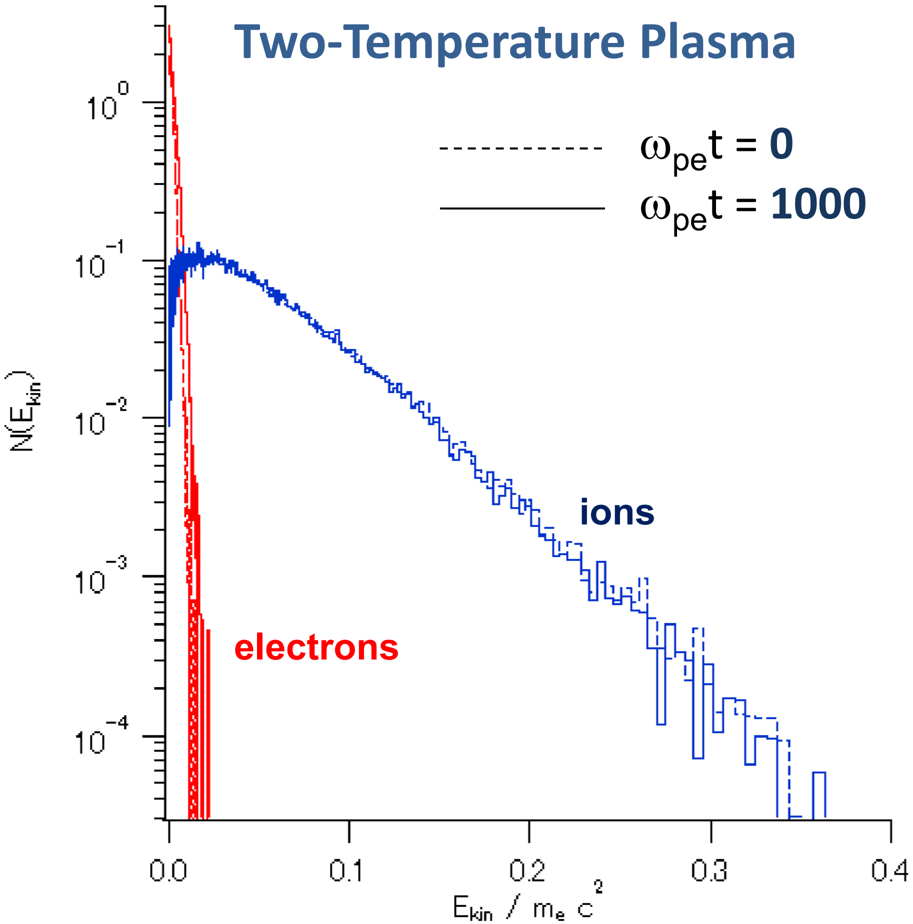


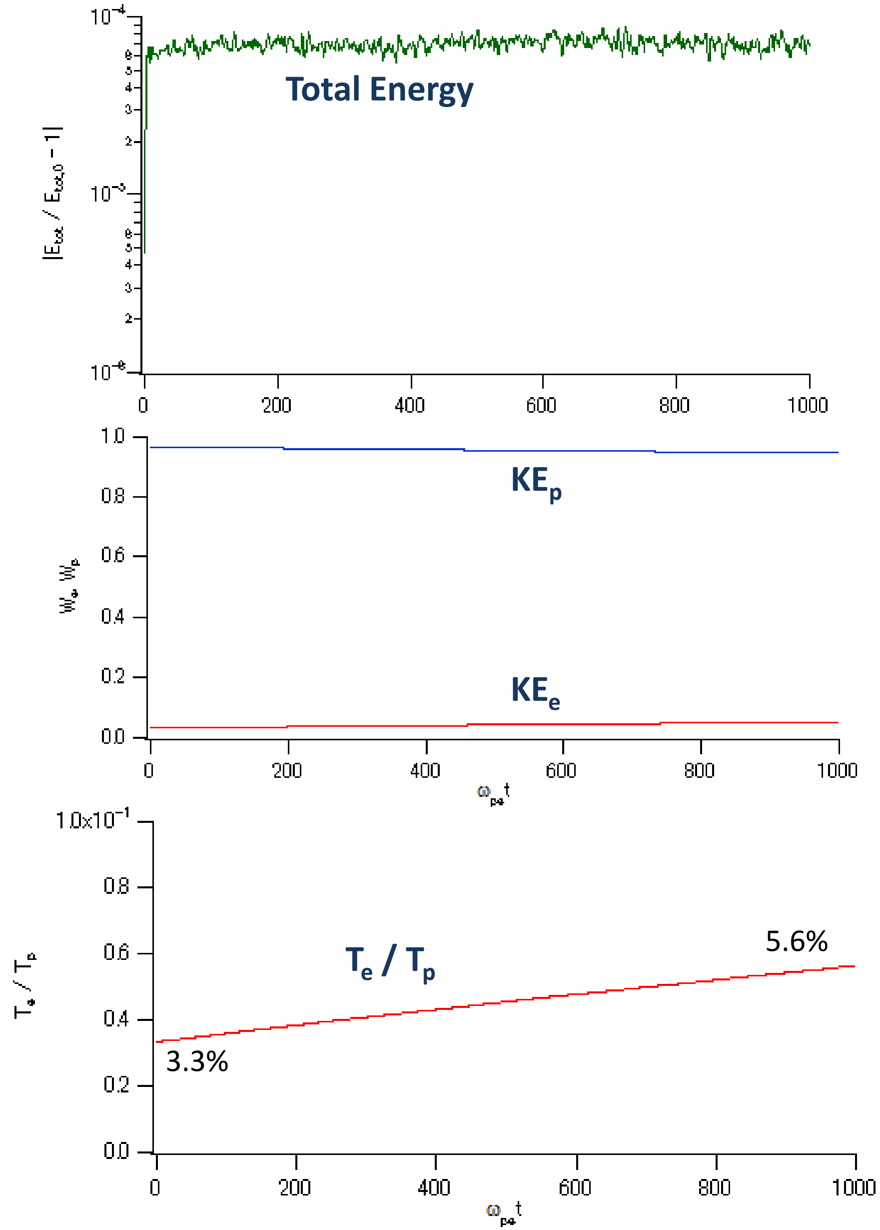
Numerical Collision occurs depending on N_c

Numerical Collision Effect

N_{PPC} = **40**, PQS

m_i/m_e=**30**, $v_{the}=v_{thi}$=**0.2c**





Simulation Parameters

In the simulations

$m_i / m_e = 20$

$V = 135{,}000$ km/s

However,
in real situations

$m_i / m_e = 1836$

$V \sim 3{,}000$ km/s

Scaling Law

What happens when m_i ,V, and B are changed **with fixed σ** ?

$$\sigma \approx \frac{B^2/8\pi}{\frac{1}{2}n_i m_i V^2} = \text{const.} \quad \Rightarrow \quad n_i \propto \frac{1}{m_i}\frac{B^2}{V^2}$$

Time scales

Ion gyro time

$$T_c \propto \frac{m_i}{B}$$

Same dependence

Growing timescale of the Weibel instability

$$T_W \propto \frac{1}{\omega_{pi} V} \propto \frac{m_i^{1/2}}{n_i^{1/2} V} \propto \frac{m_i}{B}$$

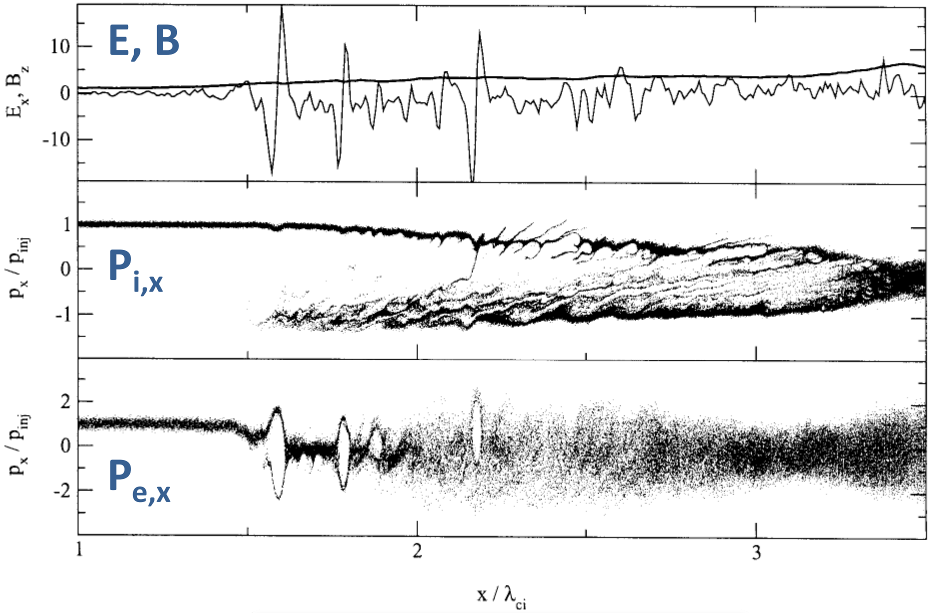
Ratio of the two time scales does not change
→ Structure would not change significantly , too.

σ is the fundamental parameter to determine the shock structure?

Plasma Beta

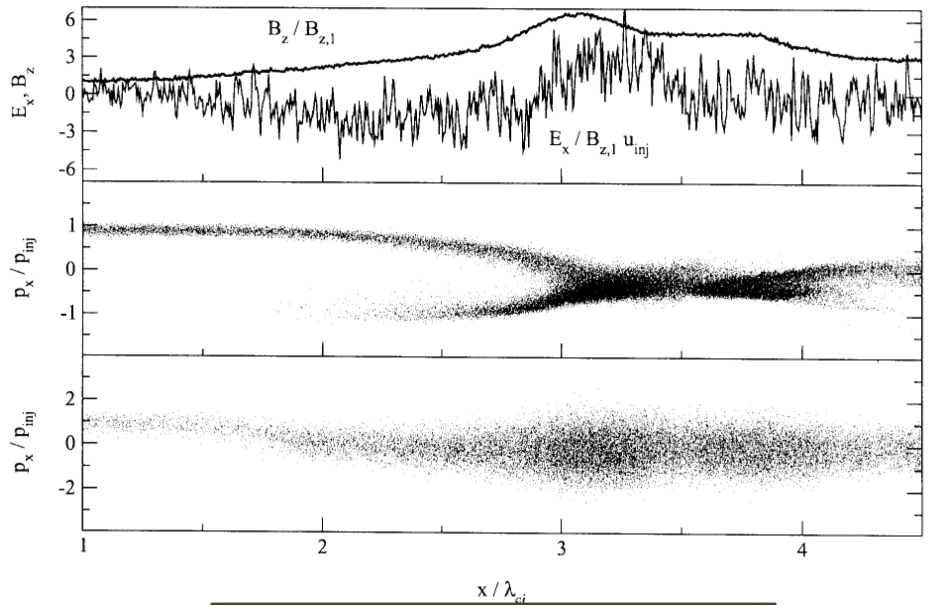
1D PIC Simulation (Schmitz et al., 2002)

β=0.15



- Shock reformation
- Buneman instability
- Electron holes
- Surfing acceleration

β=1



- **No** Shock reformation
- **No** Buneman instability
- **No** electron holes
- **No** Surfing acceleration

The shock structures are **completely different**