Weibel Instability in Anisotropically Inhomogeneous Plasma

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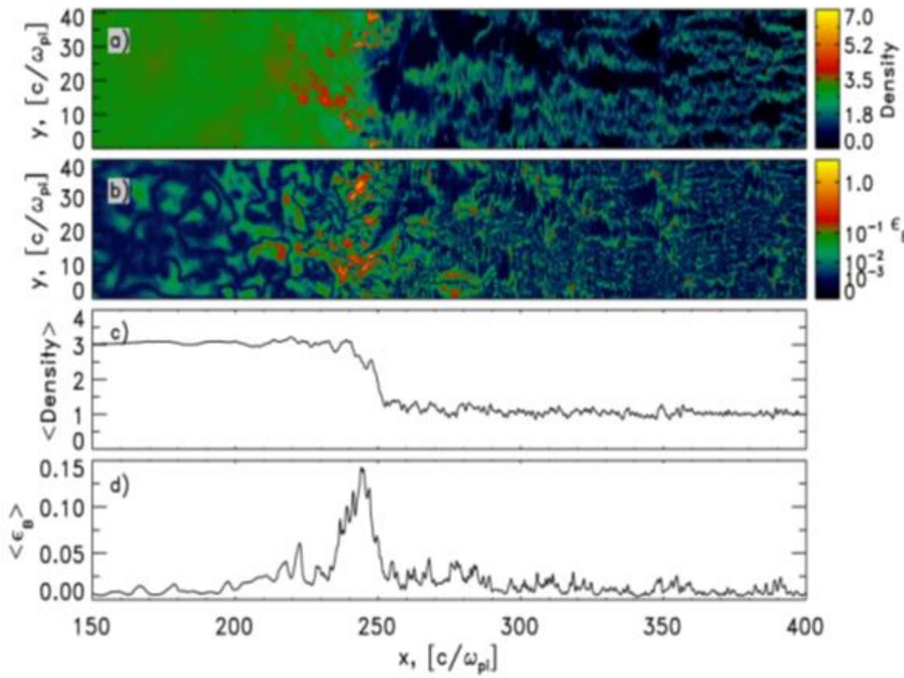
Motivation 1

Spitkovsky et al. 2008

For unmagnetized relativistick shocks, the Weibel instability is crucial role in the generation of magnetic fields, shock dissipation and particle acceleration.



GRB observations suggest that magnetic fields are strongly amplified in large emission regions.

However, PIC simulations showed that magnetic fields originated from the Weibel instability cannot occupy large regions because of the rapid decay.

a) **Density**
b) **Magnetic energy density**
   $\epsilon_B = B^2 / 4\pi\gamma_0 n_1 m_1 c^2$
c) **Transvrsely averaged density**
d) **transversely averaged ϵ_B**

Motivation 2

Early studies

Nonlinear evolution of the Weibel instability has been investigated for uniform plasmas or shocks in uniform plasmas.

→ **The Weibel modes decay rapidly.**

In this study

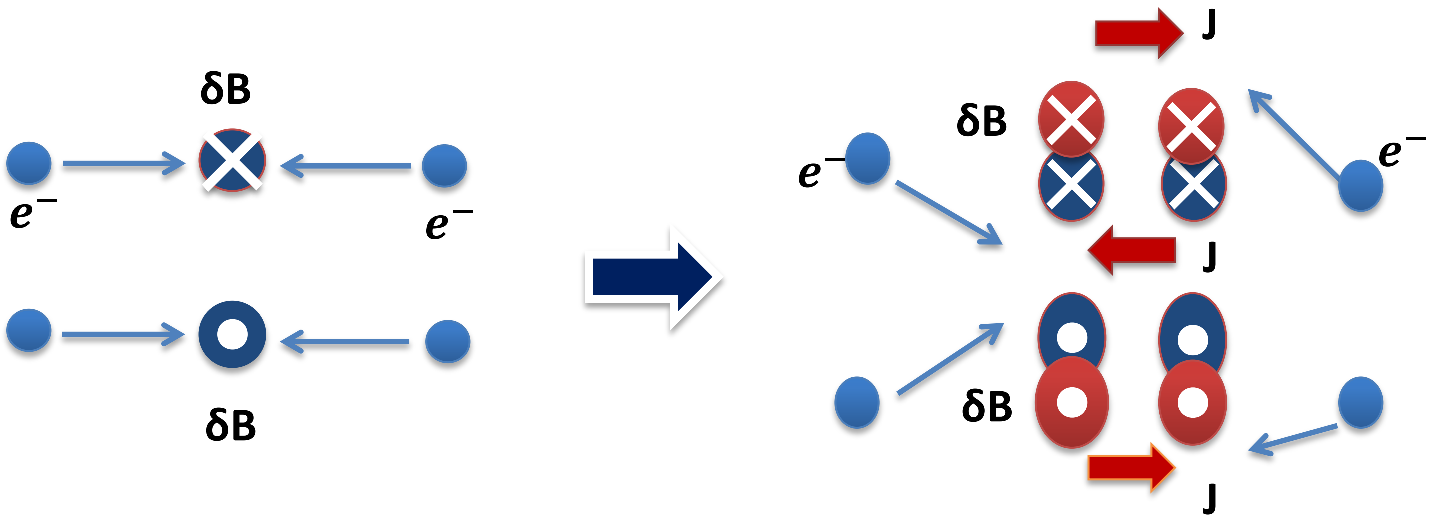
We investigate nonlinear evolution of the Weibel instability in an inhomogeneous plasma by using two-dimensional PIC simulations.

Especially, we consider anisotropic density distribution that is expected in the downstream region of relativistic shocks.

Weibel instability

The Weibel instability occurs in plasmas with anisotropic velocity distributions.

Ex.) $T_x > T_y$, counter streaming plasmas



Counter streaming plasma
+
Magnetic field perturbations,δB

The streaming plasmas are deflected by δB, so that currents are generated.
The currents amplify δB → unstable

The Weibel instability makes magnetic fields.

Simulation setup 1

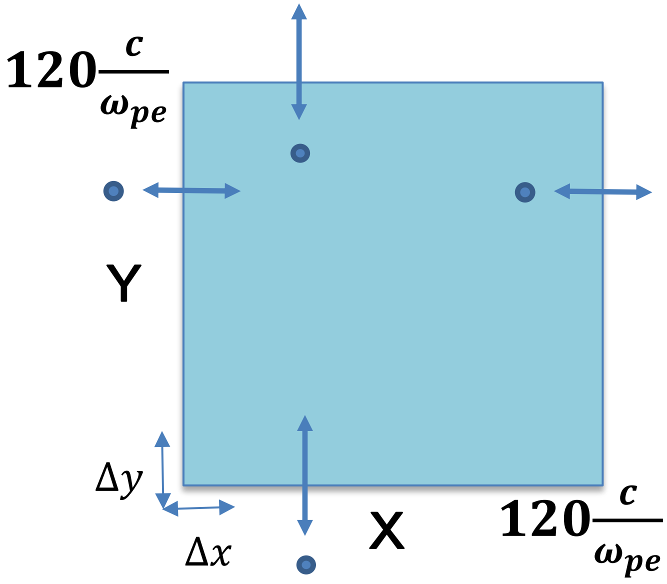
2D electromagnetic particle in cell code (pCANS)

- X-Y plane: periodic boundary condition in both directitons

- Box size: $L_x = L_y = 120\, {}^{c}/_{\omega_p}$

  ω_p: plasma frequency

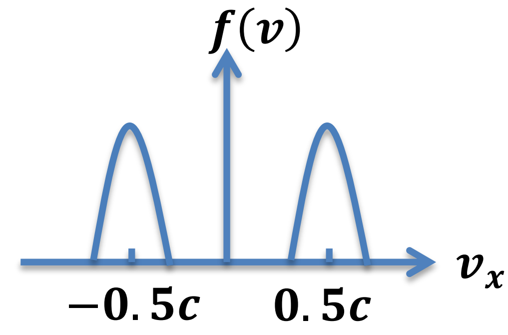
- Cell size: $\Delta x = \Delta y = 0.1\, {}^{c}/_{\omega_p}$



Simulation setup 2

- **Unmagnetized $e^{\pm}$ plasmas**

  B$= 0, n_{e^+} = n_{e^-}$



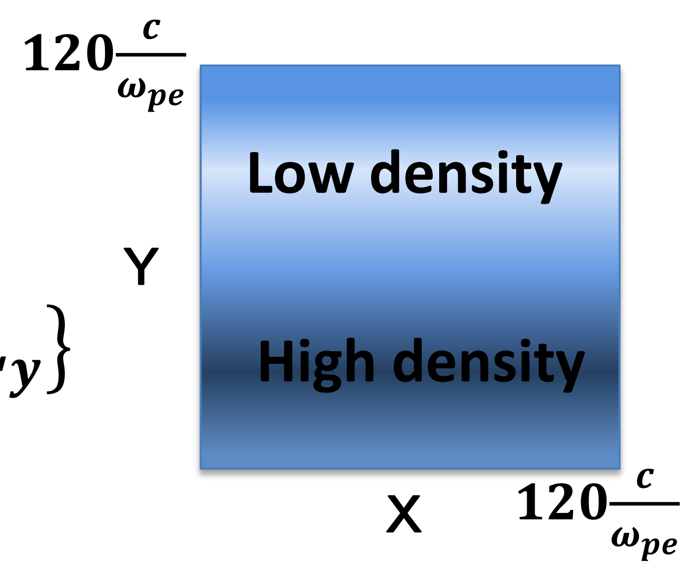
- **Two counter-streaming beams in the x direction**

  Drift velocity $v_d = \pm 0.5c$

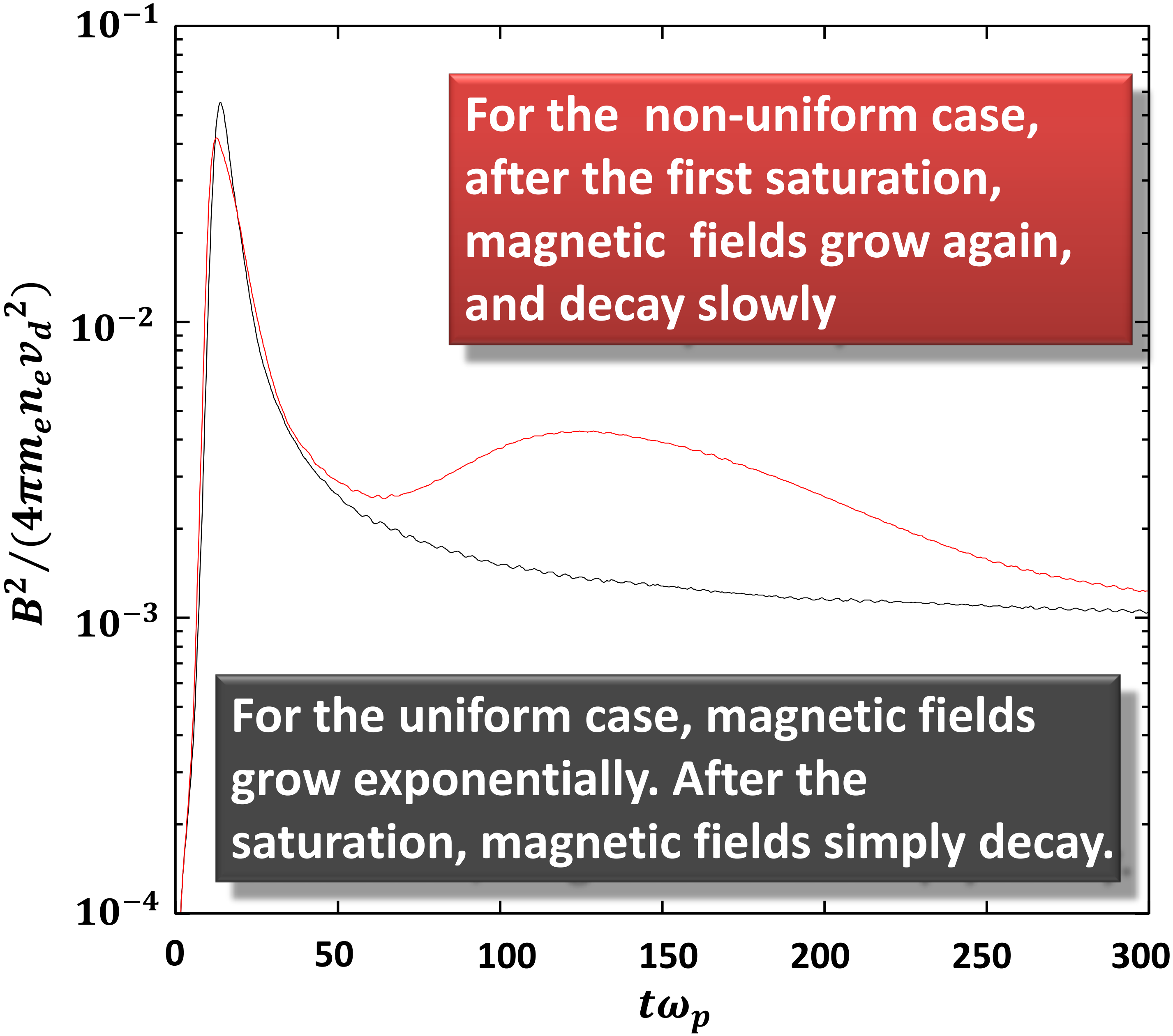
  Thermal velocity $v_{th} = 0.1c$

- **Spatial distribution of the $e^{\pm}$**

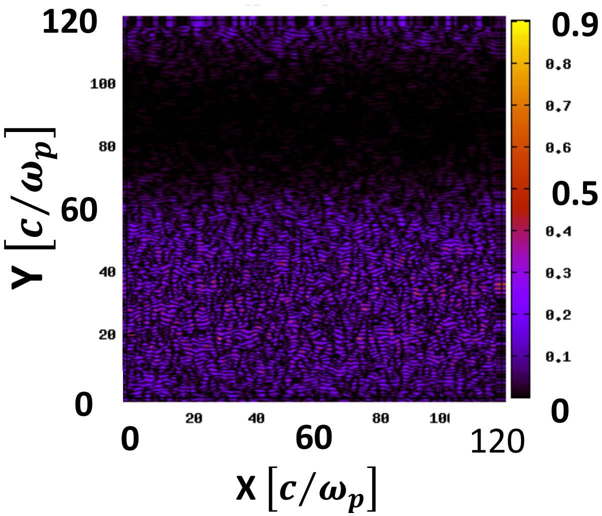
  $$n(x,y) = n_0\{1 + 0.5 \sin 2\pi y/L_y\}$$



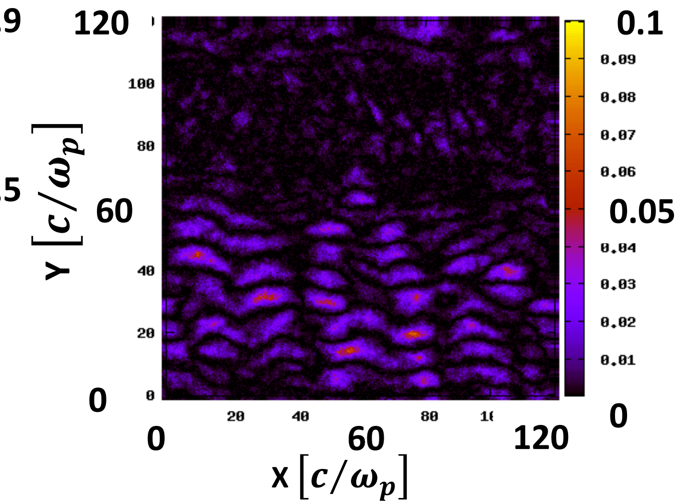
Time evolution of magnetic fields 1



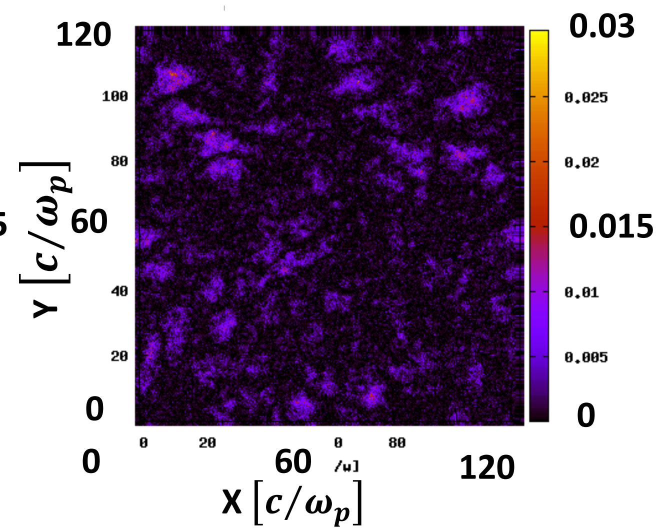
Time evolution of the magnetic field 2



a) At the 1th saturation
$t = 13/\omega_p$



b) At the 2nd saturation
$t = 120/\omega_p$



c) After the 2nd saturation
$t = 300/\omega_p$

- ✓ a) Magnetic fields are strongly amplified in the high density region

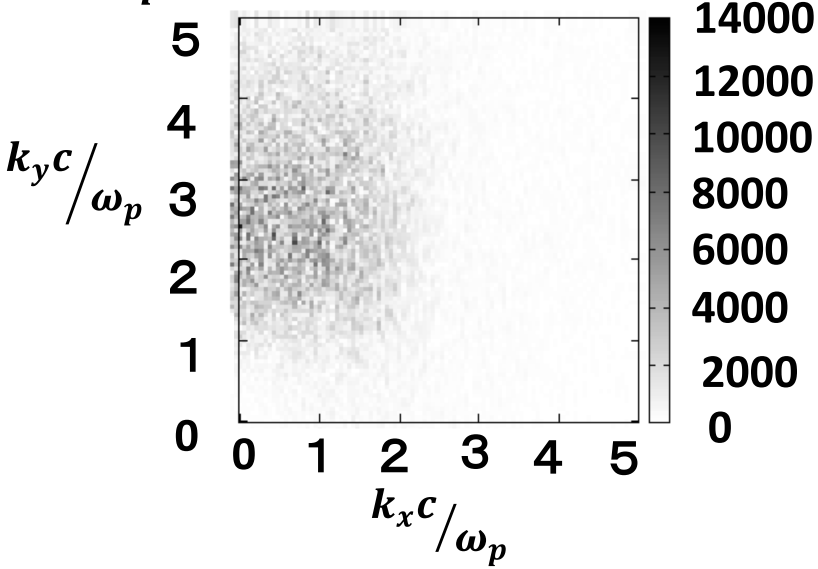
  The growth rate of Weibel instability $\gamma \propto \omega_{pe} \propto n_e$^1/2
- ✓ The typical length scale

  at the 1st saturation ~ $1\, c/\omega_p$

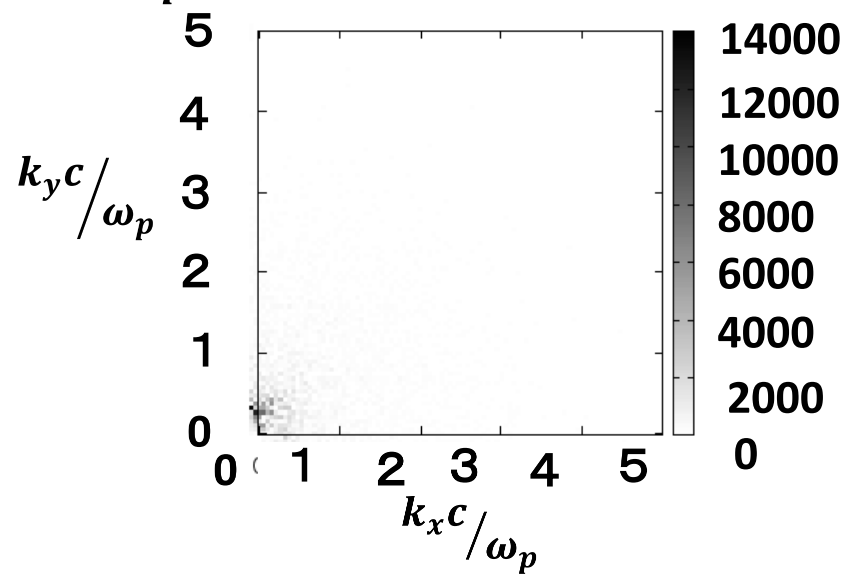
  at the 2nd saturation ~ 20 c/ω_p

Time evolution of the magnetic field 3

ω_pt=13 (at the 1st saturation)



ω_pt=120 (at the 2nd saturation)



At the 1st saturation, magnetic field fluctuations are excited in

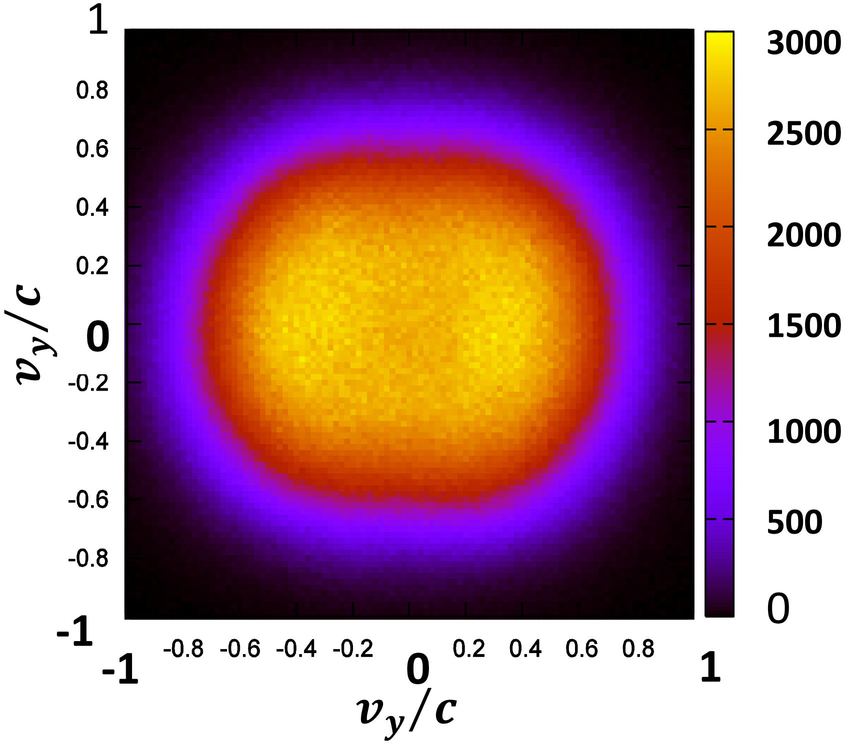
$$k_x \leq 1\,\omega_p/c \;, k_y \leq 1\omega_p/c$$

At the 2nd saturation, magnetic field fluctuations are excited in

$$k_x \sim 0, k_y \sim 0.3\,\omega_p/c$$

Magnetic fields with a larger length scale are excited by the 2nd growth.

The origin of the 2nd growth



Velocity distribution
in high density region
$(20\,\omega_p/c \leq y \leq 40\,\omega_p/c)$
at $t\omega_p$=100

Anisotropic velocity distribution

$<(\Delta V_x)^2> \; > \; <(\Delta V_y)^2>$

Temperature anisotropy

$$A = T_{x,z}/T_y - 1 \approx 0.2$$

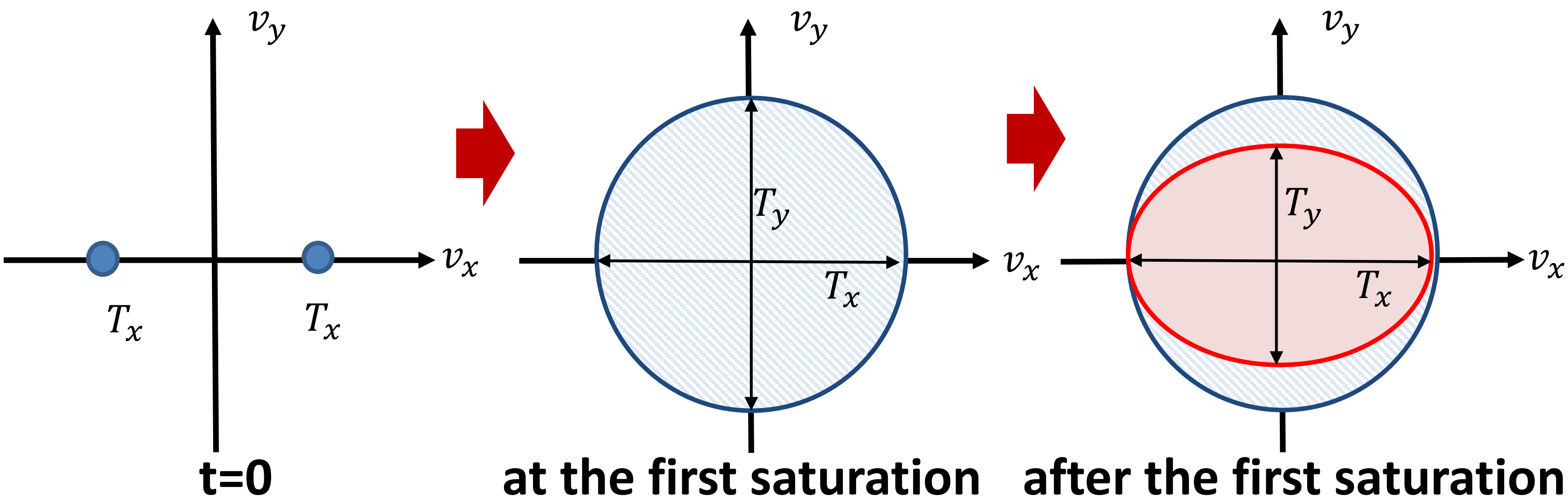
The maximum growth rate
of the Weibel instability

$$\gamma_{max} \approx 1.6 \times 10^{-2}\omega_p$$

at $k_y \approx 0.26\ \omega_p/c$

→consistent with our simulation

Temperature anisotropy produced by anisotropic density structures



After the 1st saturation, the velocity distribuiton becomes large, and particles with large v_y start to escape from the high density region. Then, the temperature in the Y direction becomes smaller than that in the X direction.

Consequently, magnetic fields are generated by the Weibel instability again.

Summary

- Magnetic fields produced by the Weibel instability cannot occupy large regions for shocks in uniform plasma.

- We investigated nonlinear evolution of the Weibel instability in a non-uniform plasma.

  For anisotropic density structure, we observed the 2nd growth of magnetic fields after the 1st saturation.

  The 2nd growth of magnetic fields is also due to the Weibel instability.

  The temperature anisotropy is produced by the anisotropic density structure after the 1st saturation.

- Such a situation can be expected in the downstream region of relativistic shocks.

The 2nd Weibel instability could be important for radiation from GRB, particle accelerations and generation of magnetic fields.

Discrete Fourier Transform

$$\tilde{f}(k_x, k_y) = \iint_{-\infty}^{\infty} dxdy\, e^{-k_x}\, e^{-k_y}\;\, f(x, y)$$