Particle-in-Cell Simulations of Synchrotron Maser Emission and Associated Particle Acceleration in Relativistic Shocks

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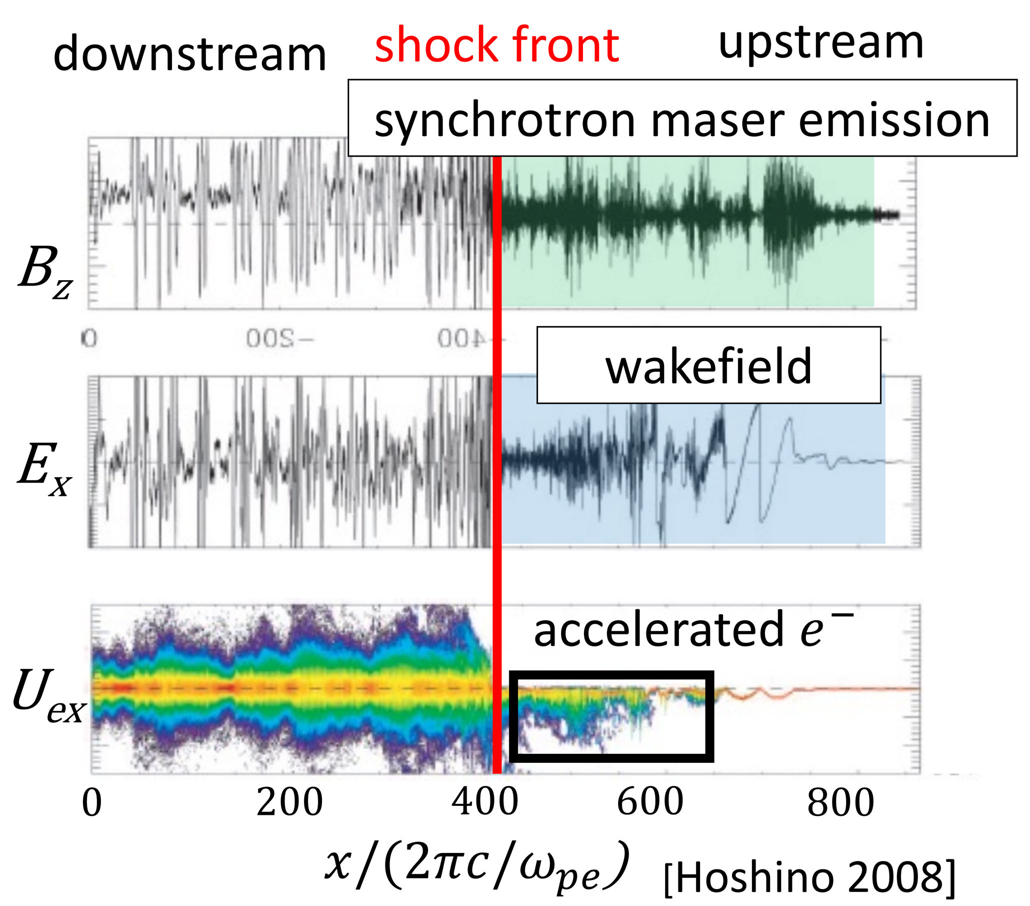
Abstract

We study synchrotron maser emission and associated particle acceleration at electron-ion relaivistic shocks by PIC simulations. Relativistic shocks emit intense electromagnetic waves from the shock front via the synchrotron maser instability. This synchrotron maser emission induces electrostatic plasma waves (i.e., wakefield) and transverse filamentary structures in the upstream region via the stimulated/induced Raman scattering and filamentation instability, respectively. Some lucky particles in the phase of the deceleration by the wakefield enter the filamentary structures. Then they are reflected by the wakefield and decoupled from the upstream bulk flow. These decoupled particles can feel the motional electric field and efficiently accelerated.

1. Introduction

- ✓ Relativistic shocks may generate ultra-high-energy cosmic rays (> 10^{18}eV)
  →the detailed acceleration mechanism is still unknown
- ✓ Relativistic shocks can emit coherent electromagnetic waves via the synchrotron maser instability [1]
- ✓ 1D PIC simulations show that the intense coherent emission induces the electrostatic waves (i.e., wakefield) via the stimulated/induced Raman scattering and that the efficient particle acceleration occurs in the upstream [2,3]
- ✓ Our high-resolution 2D PIC simulations [4] shows that the same acceleration indeed work even in realistic multidimensional systems.



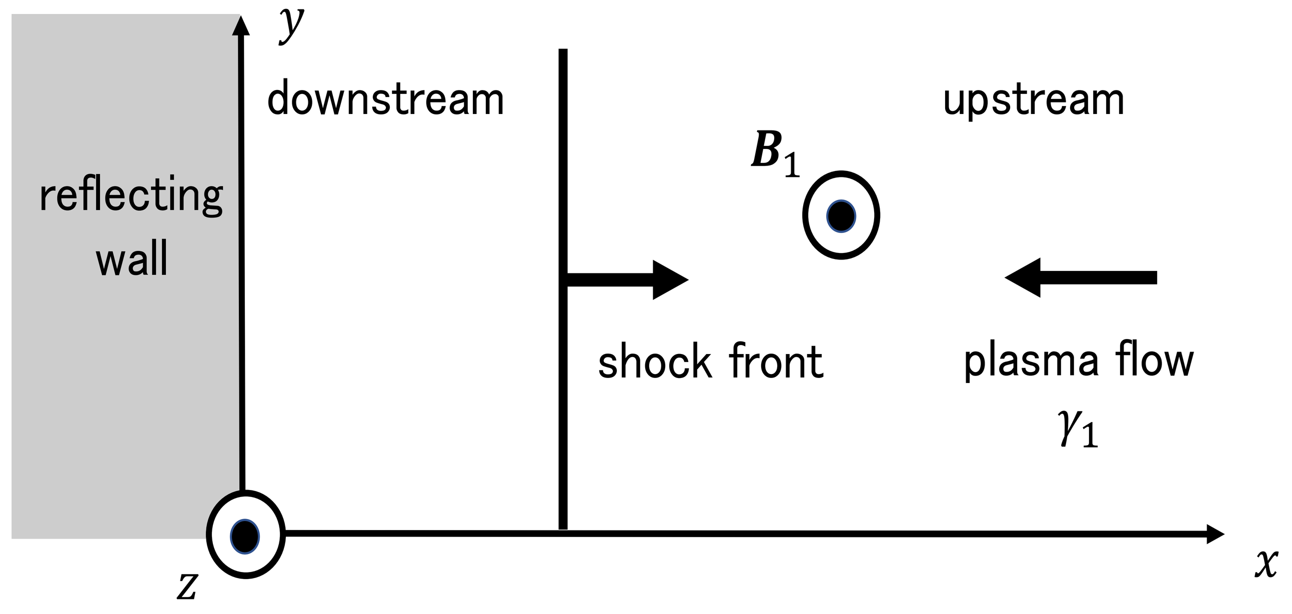
[Hoshino 2008]

However……

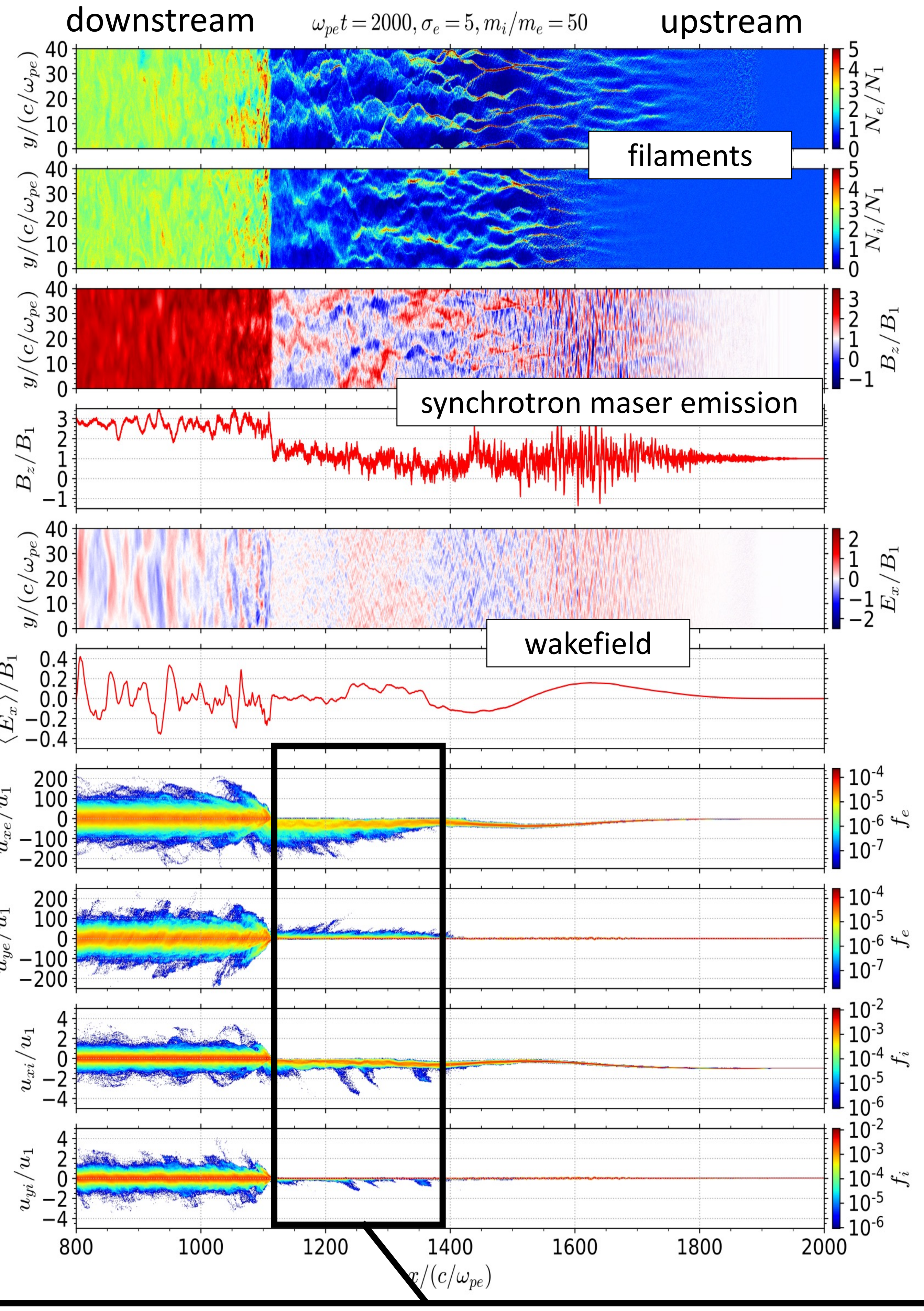
How do particles are accelerated?
How much is the maximum energy?

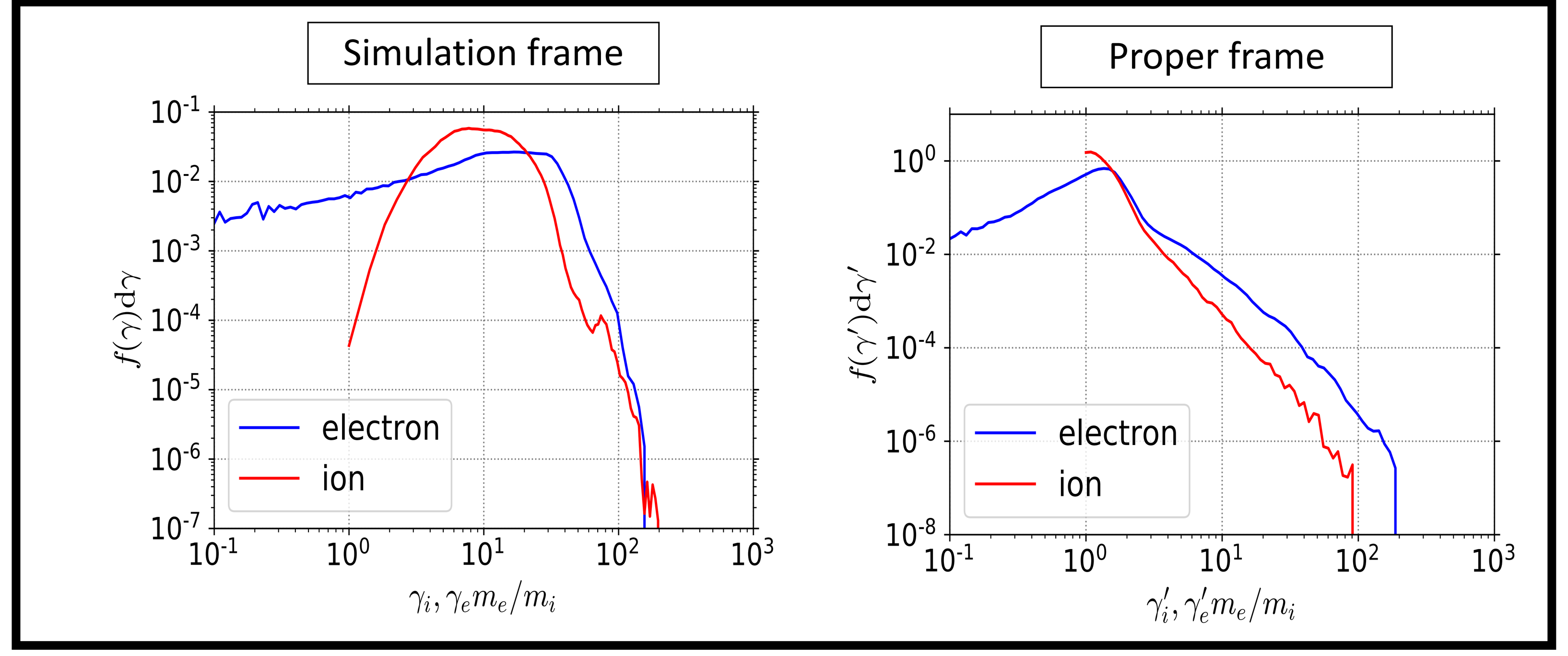
2. Simulation Setting

- ✓ Time step:
  $\omega_{pe}\Delta t = 0.025$
- ✓ Grid size:
  $\frac{\Delta x}{c/\omega_{pe}} = 0.025$
- ✓ Particle number/cell:
  $N_1 \Delta x^2 = 64$
- ✓ Upstream Lorentz factor:
  $\gamma_1 = 40$
- ✓ Mass ratio:
  $\frac{m_i}{m_e} = 50$
- ✓ Magnetization parameter:
  $\sigma_i = \frac{B_1^2}{4\pi\gamma_1 N_1 m_i c^2} = 5, \sigma_e = \frac{m_e}{m_i}\sigma_i = 0.1$



3. Results

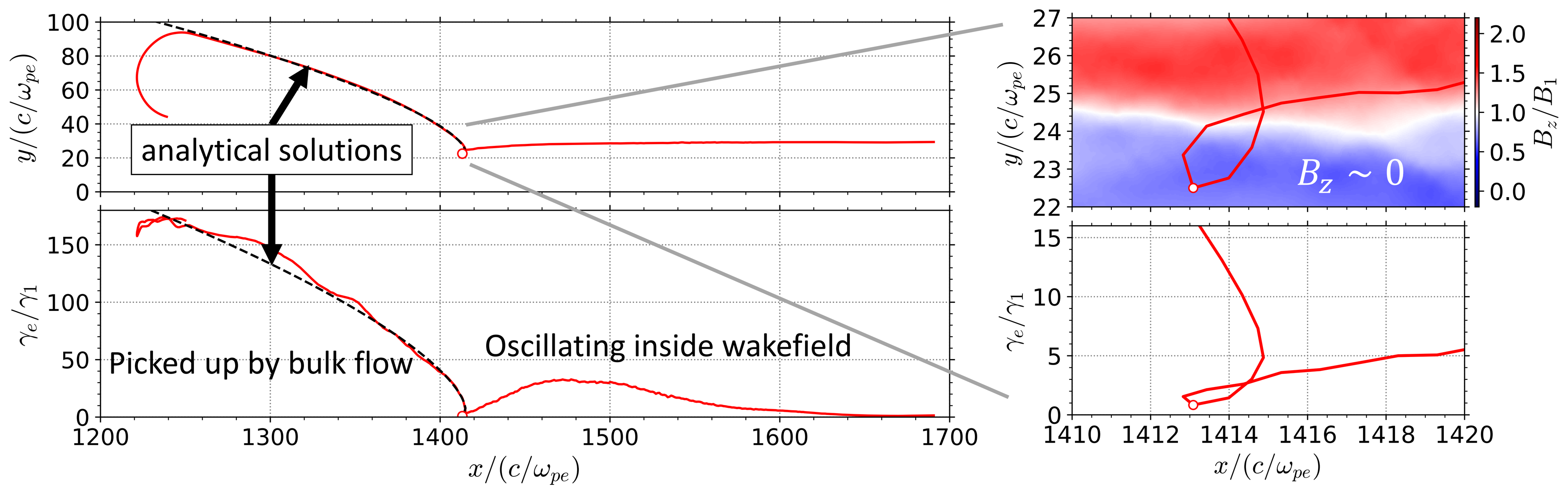




- ✓ Synchrotron maser emission induces the wakefield.
- ✓ The filamentation instability induced by the synchrotron maser emission [5] generates the transverse filamentary structures.
- ✓ The nonthermal ions and electrons are generated in the upstream.

4. Discussion

Trajectory of nonthermal electron



- ✓ The incoming nonthermal electrons are reflected by the wakefield and gains the energy during propagating the +y direction
  →accelerated by the motional electric field $E_y = -\beta_1 B_1$
- ✓ Considering only $B_z = B_1$ and $E_y = -\beta_1 B_1$, we have solved the relativistic equations of motion and derived the analytical solution

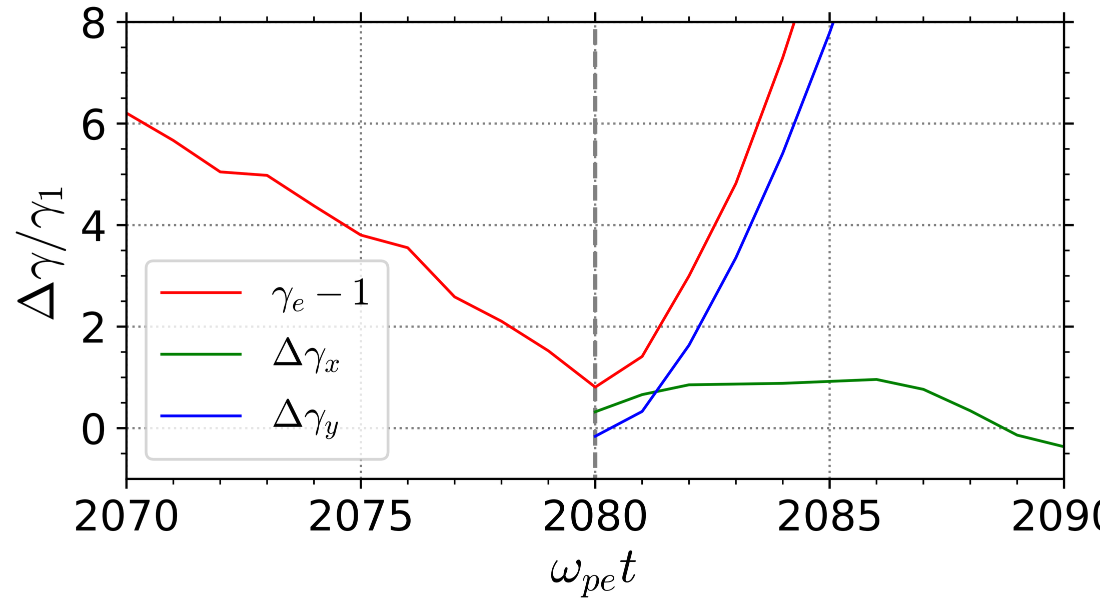
$$\gamma_s \sim \gamma_1^2 \gamma_{0s} \left[(1 + \beta_1 \beta_{0s}) - \beta_1 (\beta_1 + \beta_{0s}) \cos\left(\frac{\omega_{cs} t}{\gamma_1^2 \gamma_{0s} (1 + \beta_1 \beta_{0s})} \right) \right]$$

($s = i, e$, γ_{0s}: Lorentz factor when picked up by the upstream bulk flow)

- ✓ This analytical solution is consistent with our simulation (also consistent with nonthermal ions)
- ✓ The nonthermal electron enter the filaments where the magnetic field vanished and then they are picked up by the bulk flow
  →The filaments seems to trigger this particle acceleration

- ✓ $\Delta\gamma_x$ and $\Delta\gamma_y$: work done by E_x and E_y
- ✓ The nonthermal electron are pre-accelerated by E_x and then further accelerated by E_y
- ✓ Inside filaments: $B_z \sim 0$
  →$qE_{wake} > q\beta_y B_z$
  →trapped and accelerated by the wakefield
- ✓ Our simulation results indicates $\gamma_{0e} \sim \gamma_1$ and $\gamma_{0i} \sim 1 + m_e\gamma_1/m_i$
- ✓ From the analytical solution, the maximum Lorentz factor can be estimated as

$$\gamma_{max,e} \sim \gamma_1^3$$
$$\gamma_{max,i} \sim \left(1 + \frac{m_e}{m_i}\gamma_1\right)\gamma_1^2$$



5. Summary

In this work, we investigated the particle acceleration associated with the synchrotron maser emission in relativistic ion-electron shocks by 2D PIC simulations. We found that particles are pre-accelerated by the wakefield within the filaments and then further accelerated by the motional electric field. The maximum Lorentz factors of the electron and ion can be estimated as

$$\gamma_{max,e} \sim \gamma_1^3 , \gamma_{max,i} \sim \left(1 + \frac{m_e}{m_i}\gamma_1\right)\gamma_1^2$$

References

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