Simulation of Plasma Wakefields and Weibel Instability of Electron Beams in Plasma Using Codes LSP and OSIRIS

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47th Annual Meeting of the American Physical Society  
Division of Plasma Physics  
Denver, CO  
24–28 October 2005
Summary

We benchmarked two PIC codes—LSP and OSIRIS—simulating two physical problems

- Excitation of plasma wakefields by electron beams
  - Both codes correctly simulate the plasma wakefield excitation provided a sufficient spatial and temporal resolution.
  - LSP correctly simulates the collisional plasma wave damping.

- Weibel instability of electron beams in plasma
  - Both codes simulate qualitatively similar the Weibel instability. The most agreement is found for the OSIRIS and LSP particle mode.
  - The degree of plasma heating is different in particle and LSP hybrid simulations.
  - The total energy is not conserved in LSP hybrid simulations.
Codes LSP and OSIRIS

OSIRIS
(developed at UCLA)
Explicit PIC

LSP
(product of MRC, Albuquerque)
Explicit or implicit Particle (PIC) or fluid (hybrid PIC)

• Courant condition for the electromagnetic fields
  \( \Delta t < \Delta x/c \)

• Numerical heating if
  \( \Delta x > 3\lambda_D \)

• Courant condition is unnecessary in the implicit mode; nonresolved temporary modes are damped, remaining limitation
  \( \Delta t < \Delta x/\nu_{te} \)

• Implicit PIC
  – numerical heating or cooling if \( \Delta x > \lambda_D \)

• Implicit hybrid PIC
  – no numerical heating or cooling
We simulate a linear plasma wakefield excited by a Gaussian electron beam in a plasma (2-D case)

- Electron beam with a maximum density $n_b = 0.1 \, n_p$, width $w = 0.5 \, k_p^{-1} (k_p = \omega_p / c)$, and velocity close to $c$
- Plasma temperature $T_p = 51$ eV
- Theory $\Rightarrow \delta n / n_0 = 0.079^*$

LSP and OSIRIS correctly simulate the plasma wakefield provided a sufficient spatial and temporal resolution

- One-component electron plasma
  \[ \Delta x = 0.25 k_p^{-1}, \, \Delta y = 0.063 k_p^{-1} \, (\text{beam width } 0.5 k_p^{-1}), \, \Delta t = 0.03 \omega_p^{-1}. \]
The plasma wave collisional damping is simulated correctly in LSP (except for the Coulomb logarithm which should be corrected).

- Two-component plasma, \( n_e = n_i = 10^{22} \text{ cm}^{-3}, \ Z_i = 2 \).
  \[
  \nu_{ei}/\omega_{pe} = 5.16 \times 10^{-11} Z_i n_e^{1/2} T_e^{-3/2} \ln \Lambda
  \]

- \( \delta n/n \) 
- \( eE_x/m\omega_p c \) 
- \( eE_y/m\omega_p c \) 
- \( T_e, \text{ eV} \)
We have performed 2-D simulations of Weibel instability of an electron beam as a FI-relevant benchmarking problem.

- Simulation parameters
  - \( n_p = 10^{22} \text{ cm}^{-3} \), \( n_b = 0.1 \, n_p \), \( \gamma \beta_b = 2.8 \), \( T_e = 5 \text{ keV} \)
  - \( \Delta x = \Delta y = 0.4 \, c/\omega_p \)
  - \( \Delta t_{\text{min}} = \Delta x/2c \)
LSP and OSIRIS simulations with immobile ions show similar electron-beam density profiles.
LSP and OSIRIS simulations with immobile ions show similar plasma-density profiles.

\[
\begin{align*}
t &= 23.5 \omega_p^{-1} \\
t &= 47 \omega_p^{-1} \\
t &= 188 \omega_p^{-1} \\
t &= 752 \omega_p^{-1} \\
t &= 1504 \omega_p^{-1}
\end{align*}
\]
LSP hybrid simulations show poor energy conservation.
Implicit simulations with large time steps show more filaments and distortions at the late stage of Weibel instability: $\Delta t < \Delta x/v_e$ is not satisfied.

\begin{align*}
LSP & \text{ particle} \\
\Delta t = 2 \omega_p^{-1} & \quad \Delta t = \omega_p^{-1} & \quad \Delta t = 0.2 \omega_p^{-1}
\end{align*}
LSP and OSIRIS simulations with mobile ions ($\text{H}^+$) show qualitatively similar beam-density profiles.
LSP hybrid simulations with mobile ions predict stronger plasma density compressions at the late stage of the instability.
LSP hybrid simulations with mobile ions predict stronger ion-density compressions at the late stage of the instability.

$t = 23.5 \omega_p^{-1}$
$t = 47 \omega_p^{-1}$
$t = 188 \omega_p^{-1}$
$t = 752 \omega_p^{-1}$
$t = 1504 \omega_p^{-1}$

LSP hybrid

$LSP$

$LSP$

particle

OSIRIS

$x \omega_p / c$

$y \omega_p / c$

0 40

0 40

0 40

0 40

$0.9$ 1.1

$0.9$ 1.1

$0.5$ 2.0

$0$ 4.0

$0$ 4.0
The energy is not conserved in LSP hybrid simulations.
We benchmarked two PIC codes—LSP and OSIRIS—simulating two physical problems

• Excitation of plasma wakefields by electron beams
  – Both codes correctly simulate the plasma wakefield excitation provided a sufficient spatial and temporal resolution.
  – LSP correctly simulates the collisional plasma wave damping.

• Weibel instability of electron beams in plasma
  – Both codes simulate qualitatively similar the Weibel instability. The most agreement is found for the OSIRIS and LSP particle mode.
  – LSP hybrid simulations with mobile ions show stronger density compressions at the late stage of Weibel instability than particle simulations.
  – The degree of plasma heating is different in particle and LSP hybrid simulations.
  – The total energy is not conserved in LSP hybrid simulations.
  – LSP implicit simulations with a time step exceeding the Courant limit show more filaments at the late stage of Weibel instability than simulations with a small time step.
Even better spatial and temporal resolution is necessary in the LSP fluid mode to overcome numerical damping if the particle momenta are well averaged on the grid.

- Larger values of the averaging parameter have a stabilizing effect on grid noise and are recommended in documentation.

LSP hybrid fluid electron streaming factor = 0.15

LSP hybrid fluid electron streaming factor = 0.01
LSP hybrid simulations show poor energy conservation

LSP hybrid
Fluid electron streaming factor = 0.01

LSP hybrid
LSP hybrid
LSP particle
OSIRIS

\( \omega_p t \)
\( \omega_p t \)
\( \omega_p t \)
\( \omega_p t \)

Total energy
Beam electron energy
Magnetic field energy
Plasma electron energy