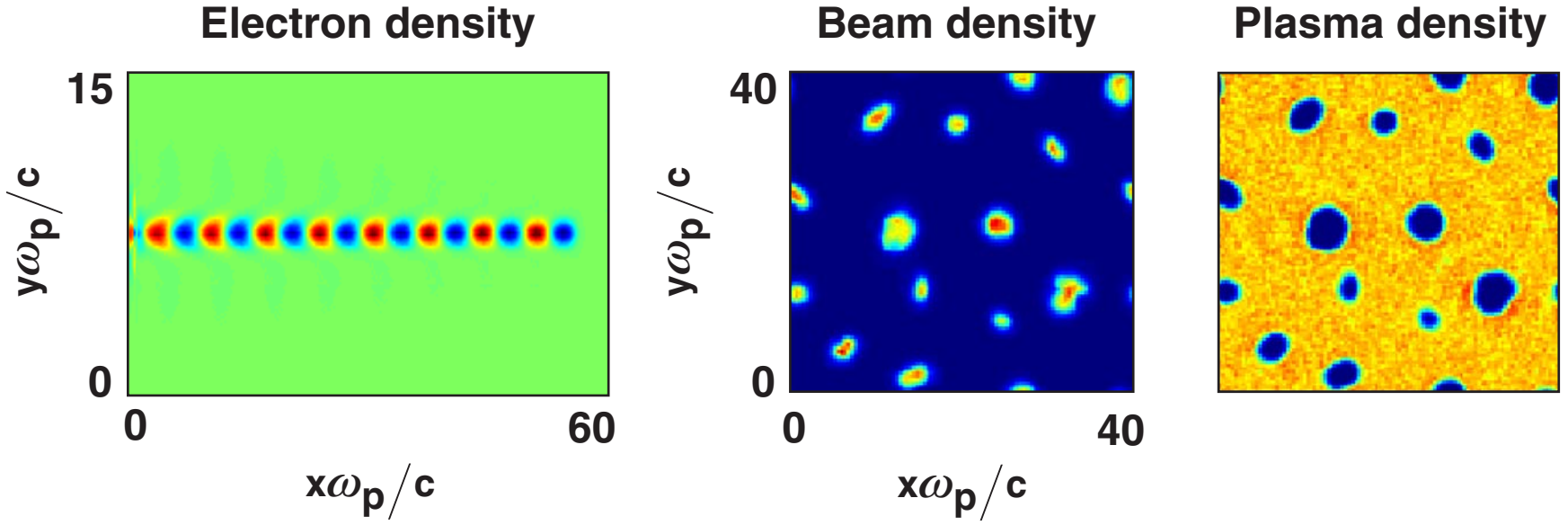
Simulation of Plasma Wakefields and Weibel Instability of Electron Beams in Plasma Using Codes LSP and OSIRIS



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Summary

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

UR LLE

- 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

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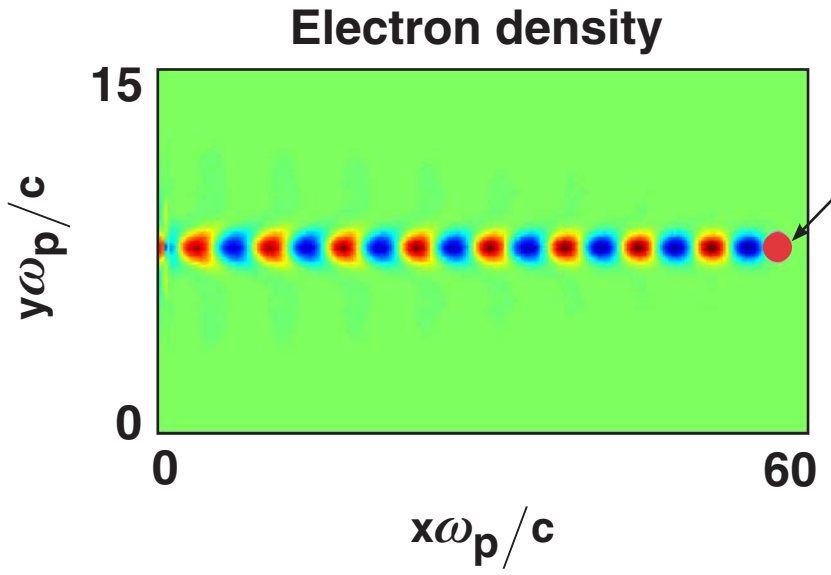
OSIRIS
(developed at UCLA)
Explicit
PIC

- **Courant condition for the electromagnetic fields**
  ($\Delta t < \Delta x/c$)
- **Numerical heating if**
  $\Delta x > 3\lambda_D$

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

- **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 $\Rightarrow \delta n/n_0 = 0.079$*

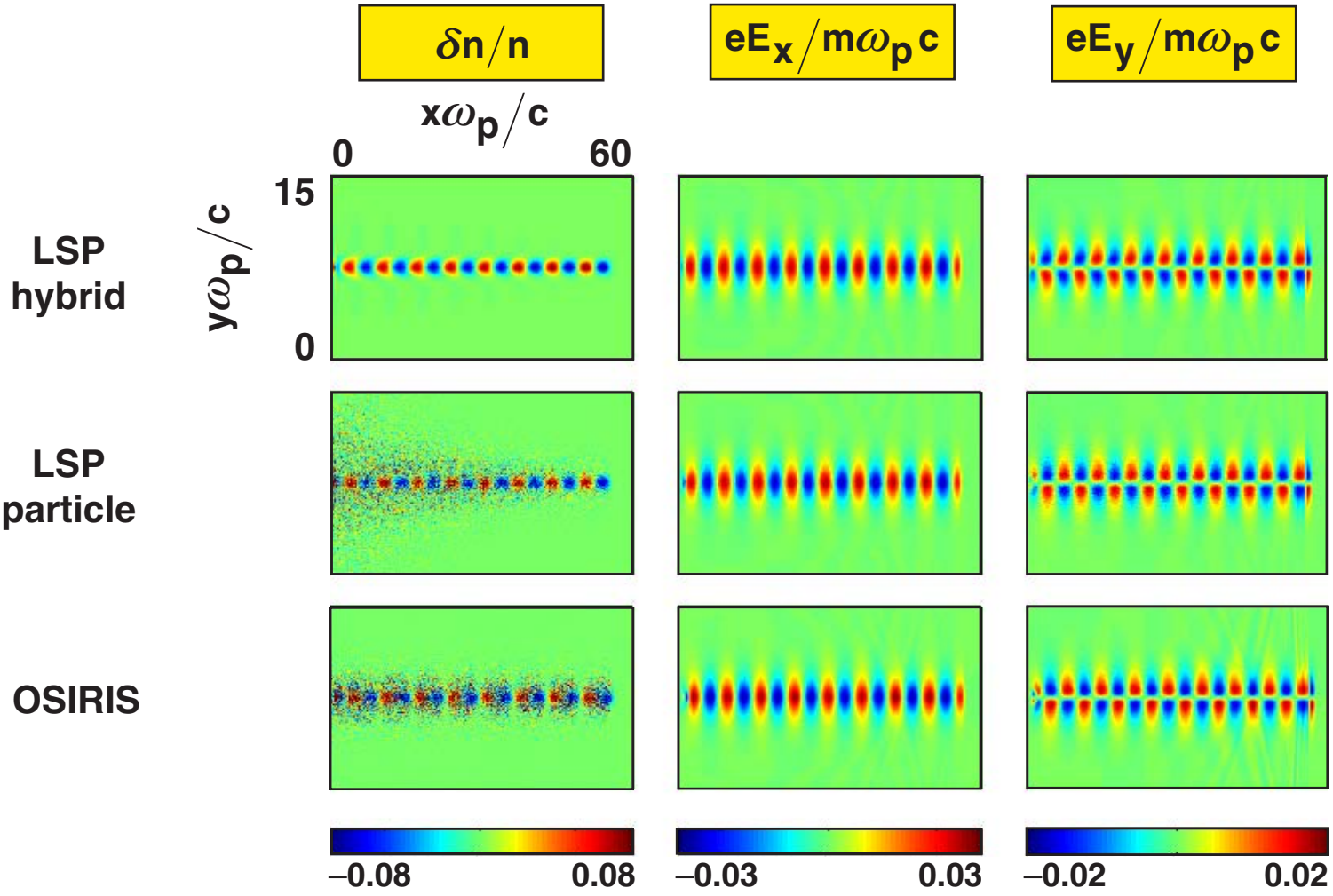
*See, for instance, E. Esarey *et al.*, IEEE Trans. Plasma Sci. 24, 252 (1996).

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

UR LLE

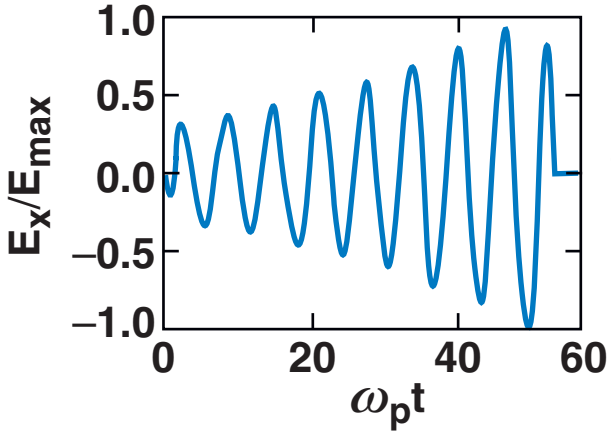
- One-component electron plasma

$$\Delta x = 0.25\,k_p^{-1},\ \Delta y = 0.063\,k_p^{-1}\ (\text{beam width } 0.5\,k_p^{-1}),\ \Delta t = 0.03\,\omega_p^{-1}.$$



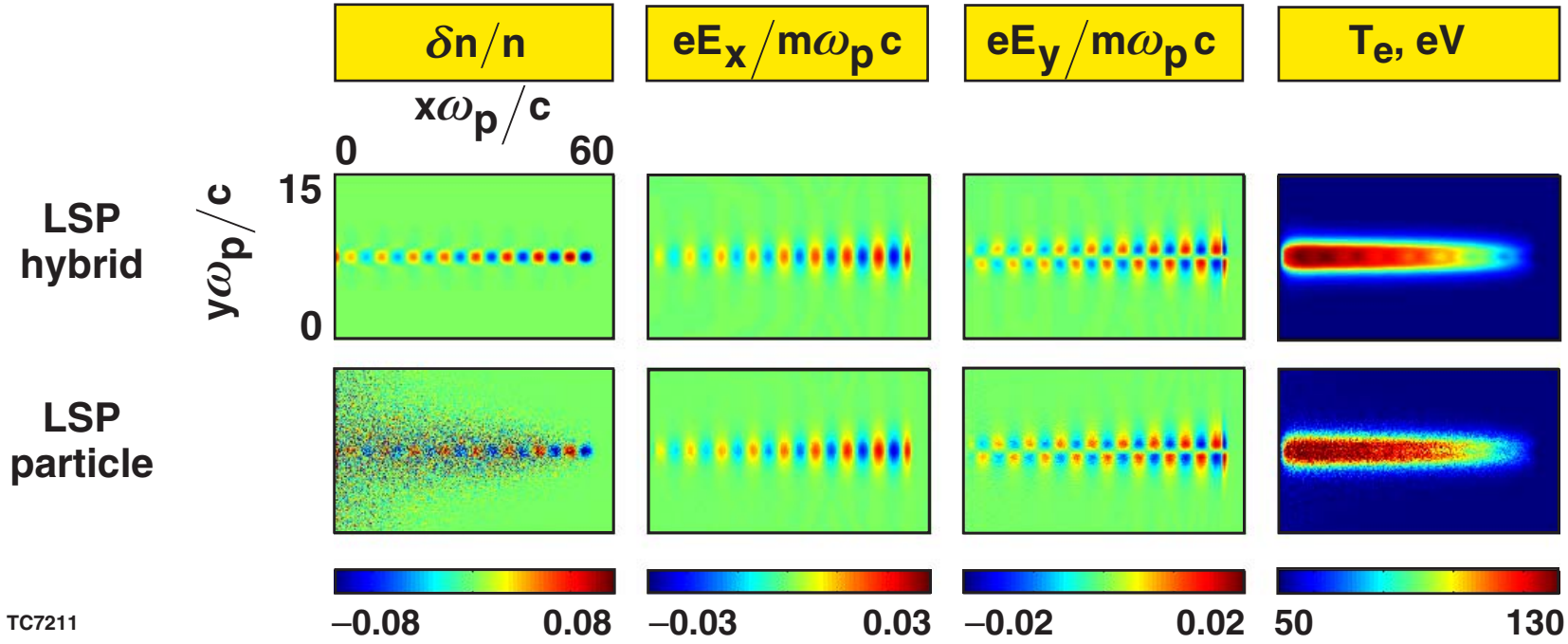
TC7207

The plasma wave collisional damping is simulated correctly in LSP (except for the Coulomb logarithm which should be corrected)



- Two-component plasma, $n_e = n_i = 10^{22}$ cm^{-3}, $Z_i = 2$.

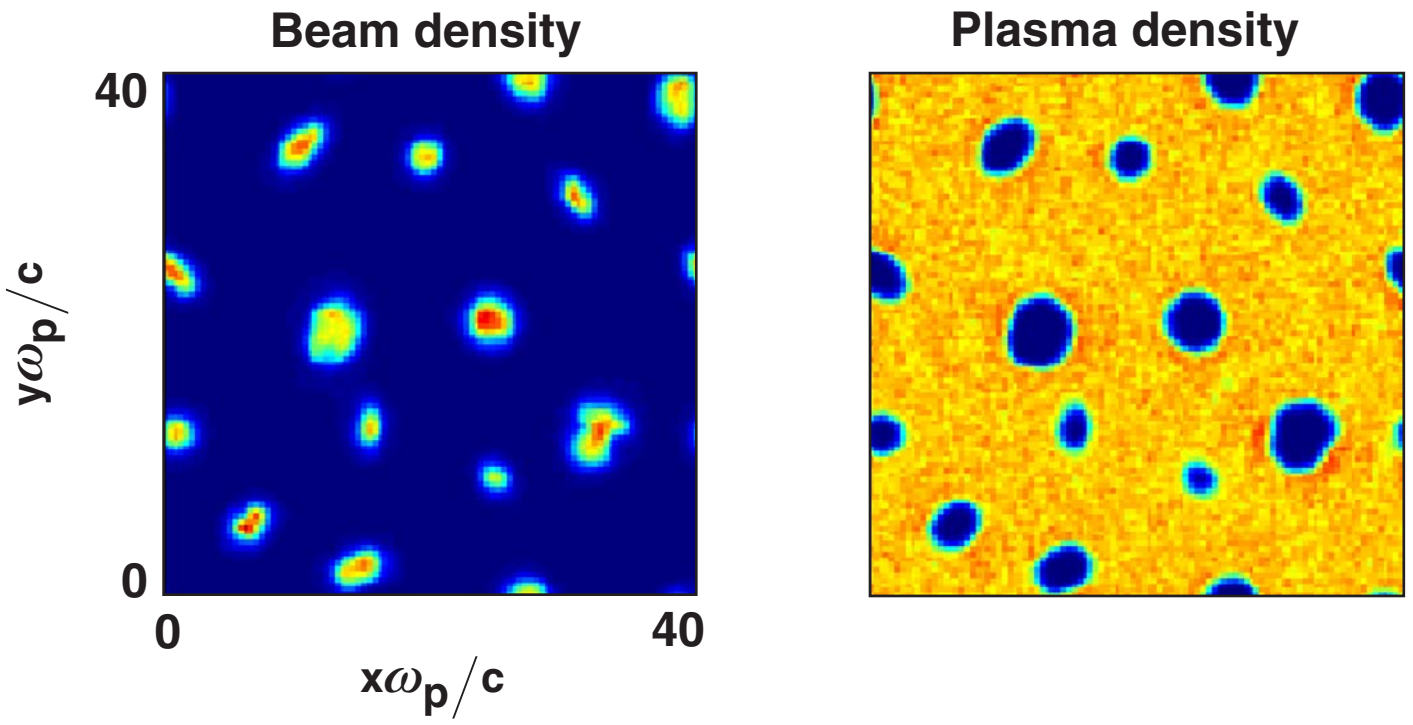
$$\nu_{ei}/\omega_{pe} = 5.16 \times 10^{-11} Z_i n_e^{1/2} T_e^{-3/2} \ln \Lambda$$



TC7211

We have performed 2-D simulations of Weibel instability of an electron beam as a FI-relevant benchmarking problem

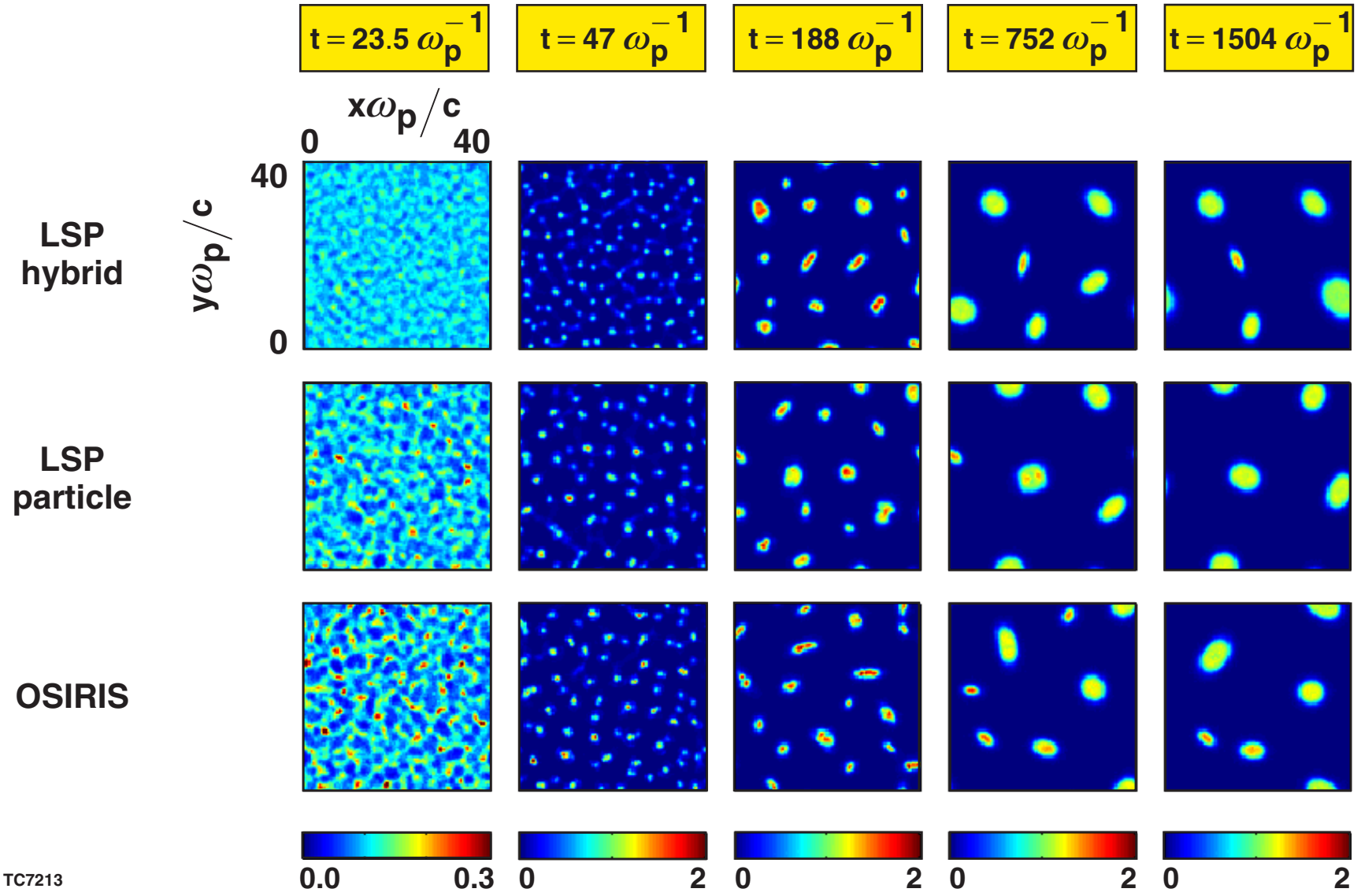
UR LLE



- Simulation parameters
  - $n_p = 10^{22}$ cm^{-3}, $n_b = 0.1\ n_p$, $\gamma\beta_b = 2.8$, $T_e = 5$ keV
  - $\Delta x = \Delta y = 0.4\ c/\omega_p$
  - $\Delta t_{min} = \Delta x/2c$

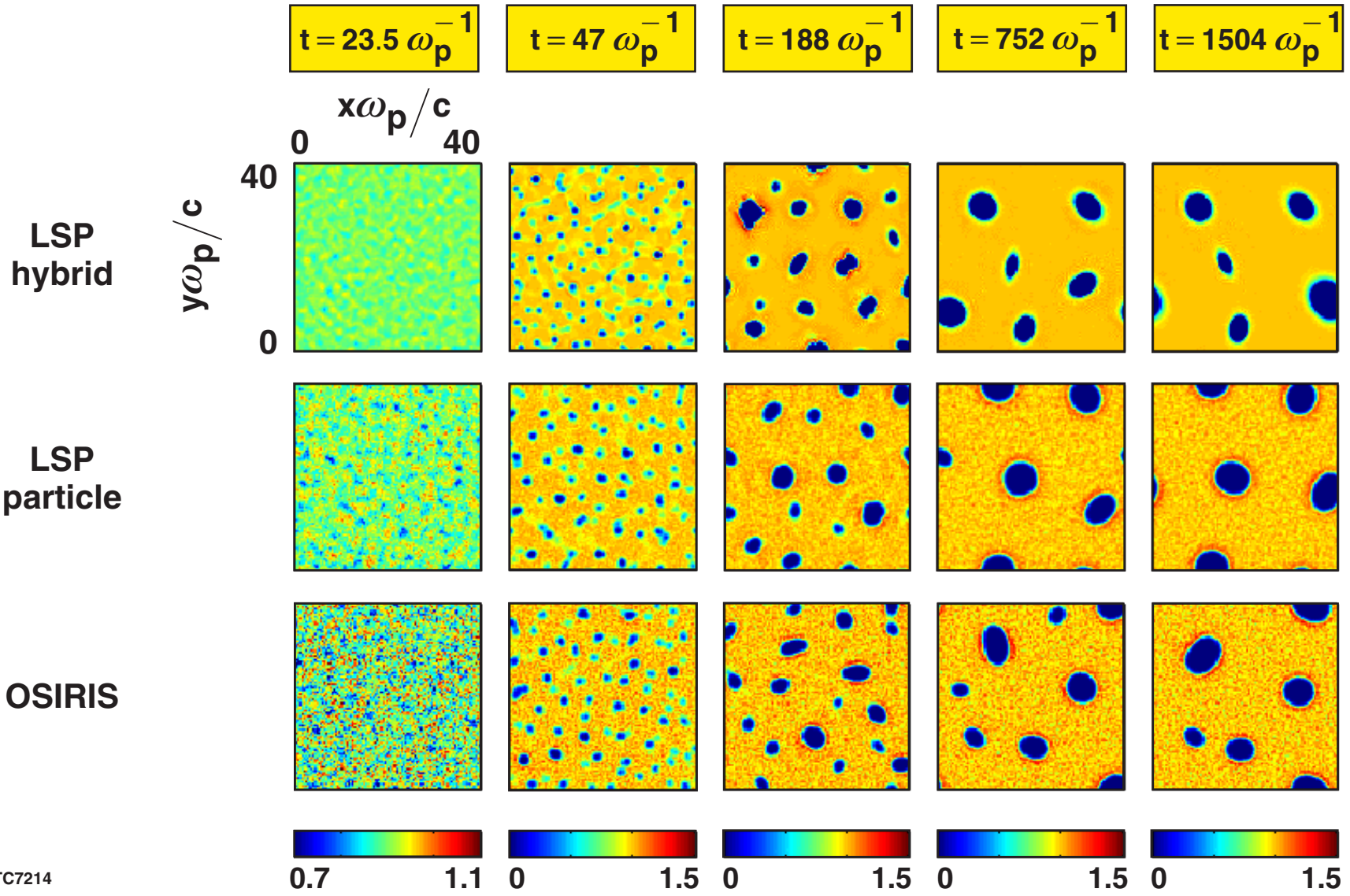
TC7212

LSP and OSIRIS simulations with immobile ions show similar electron-beam density profiles



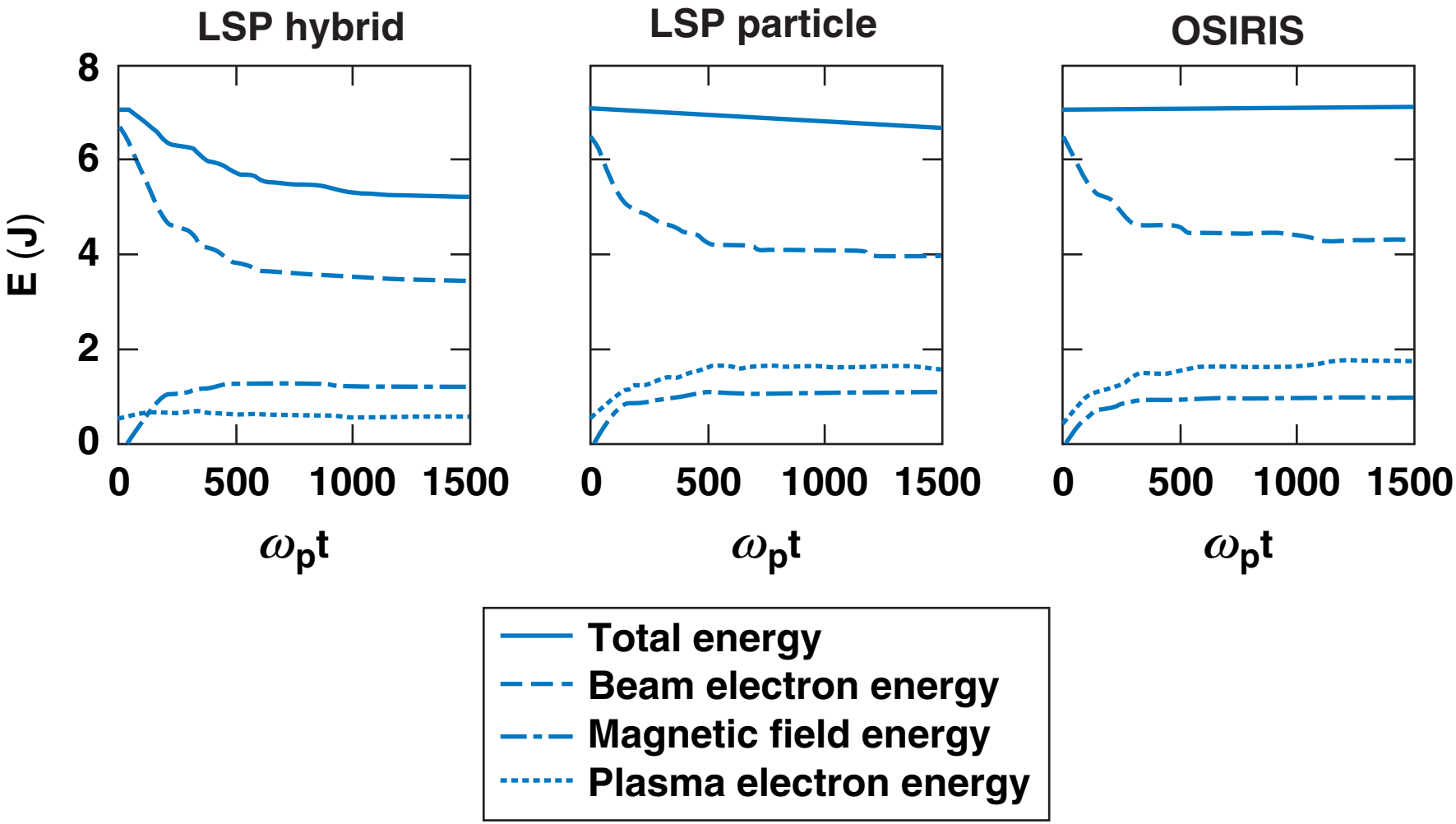
TC7213

LSP and OSIRIS simulations with immobile ions show similar plasma-density profiles



TC7214

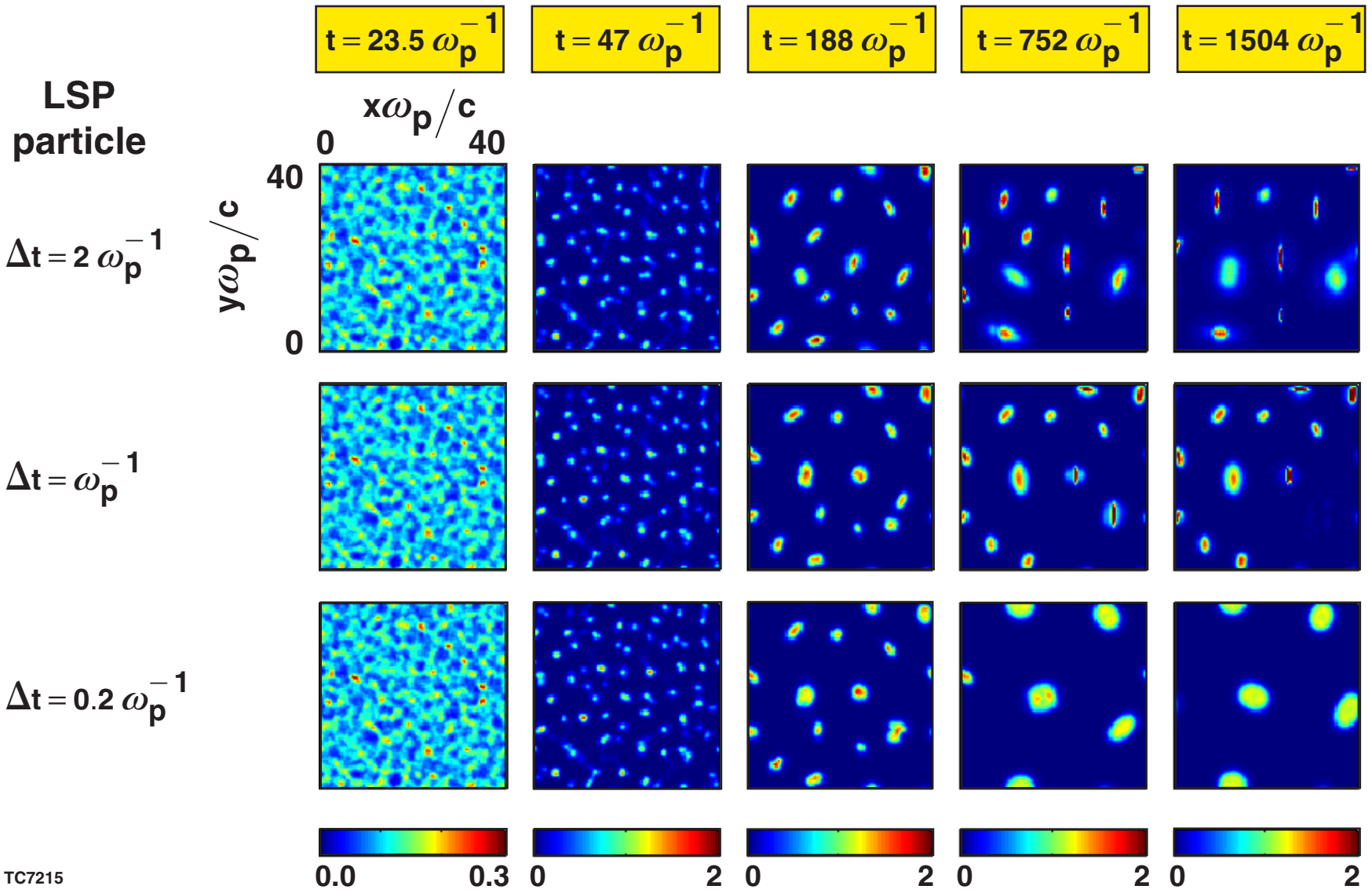
LSP hybrid simulations show poor energy conservation



TC7206

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

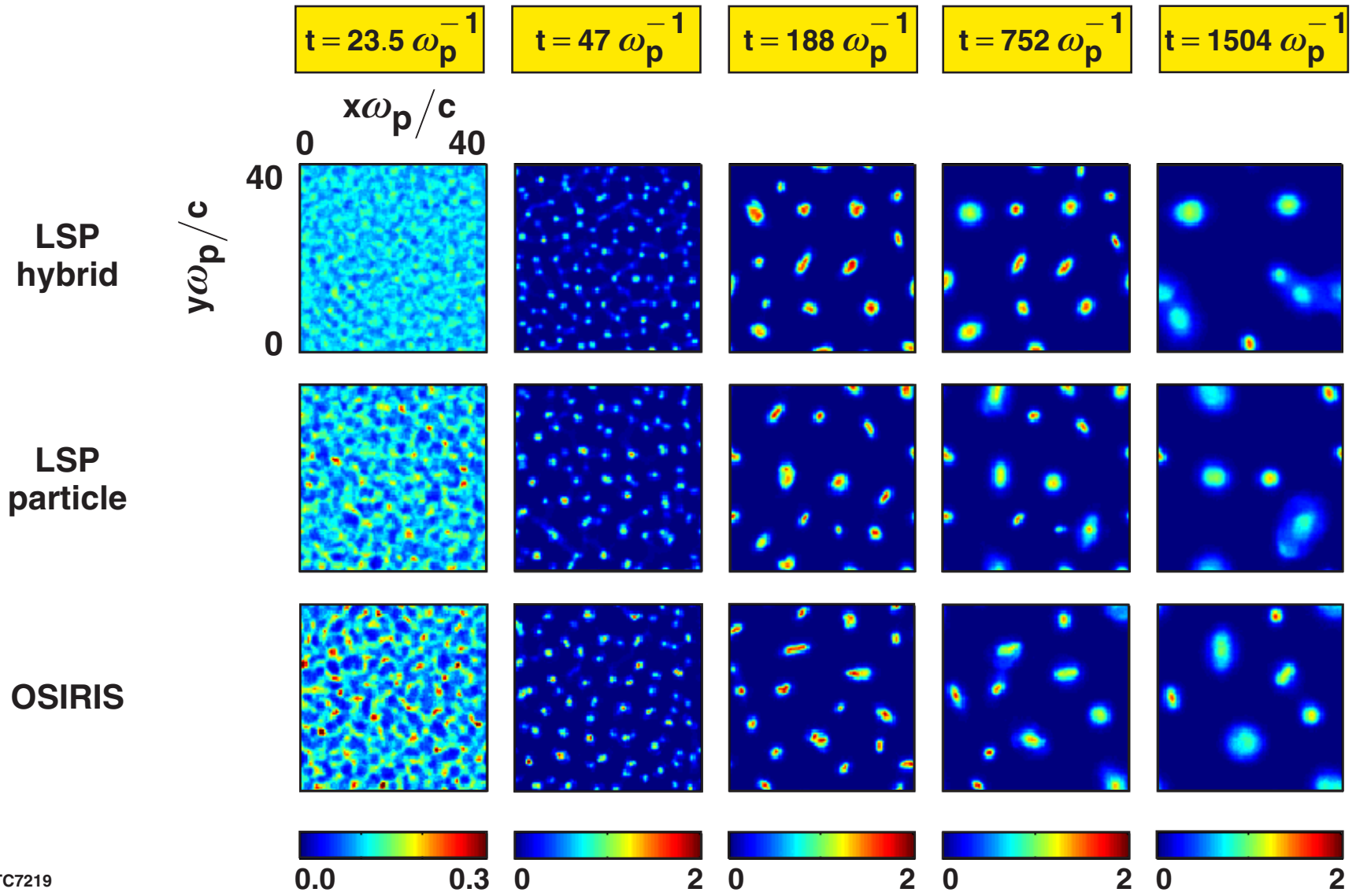
UR LLE



TC7215

LSP and OSIRIS simulations with mobile ions (H^+) show qualitatively similar beam-density profiles

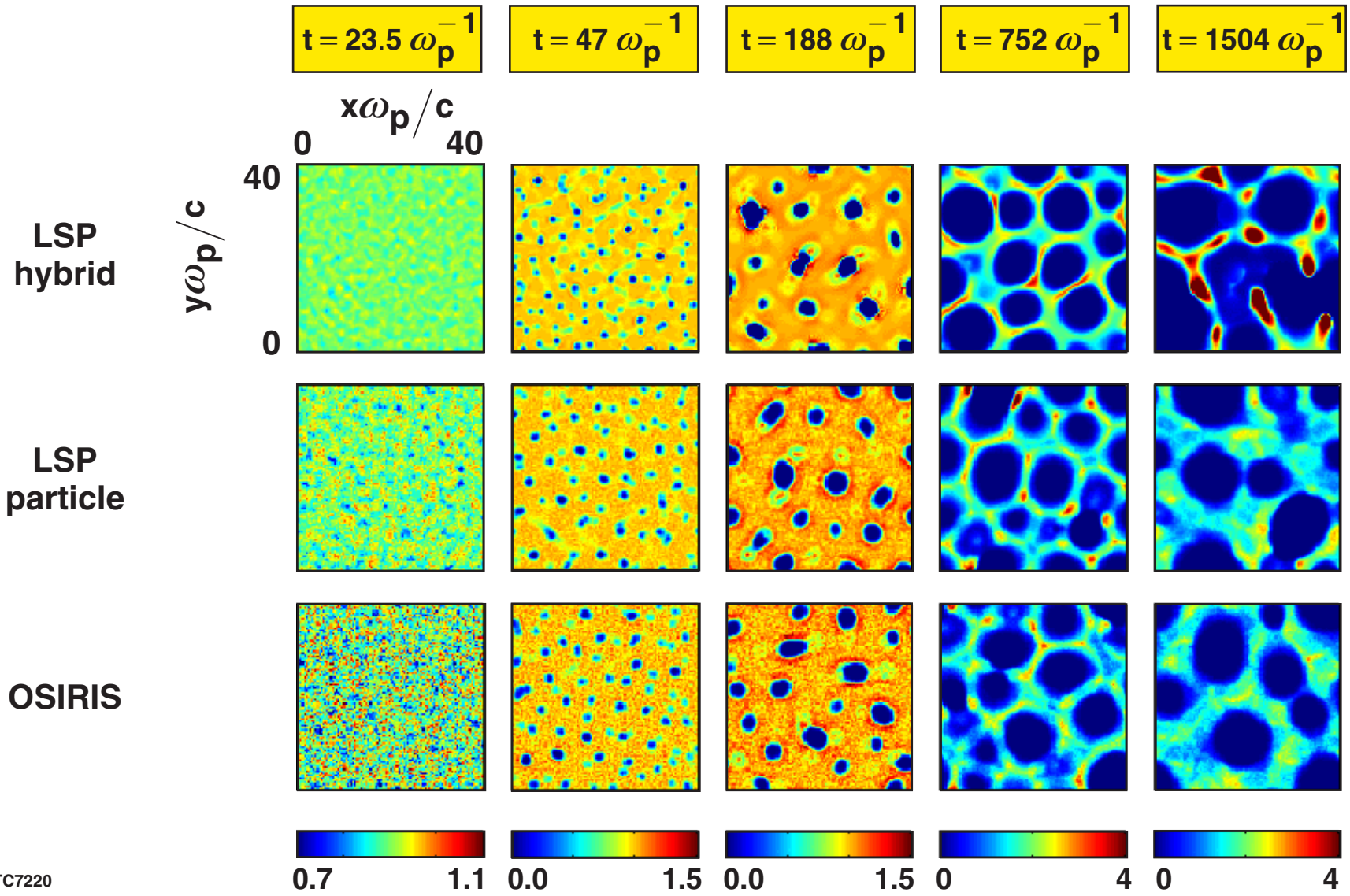
UR LLE



TC7219

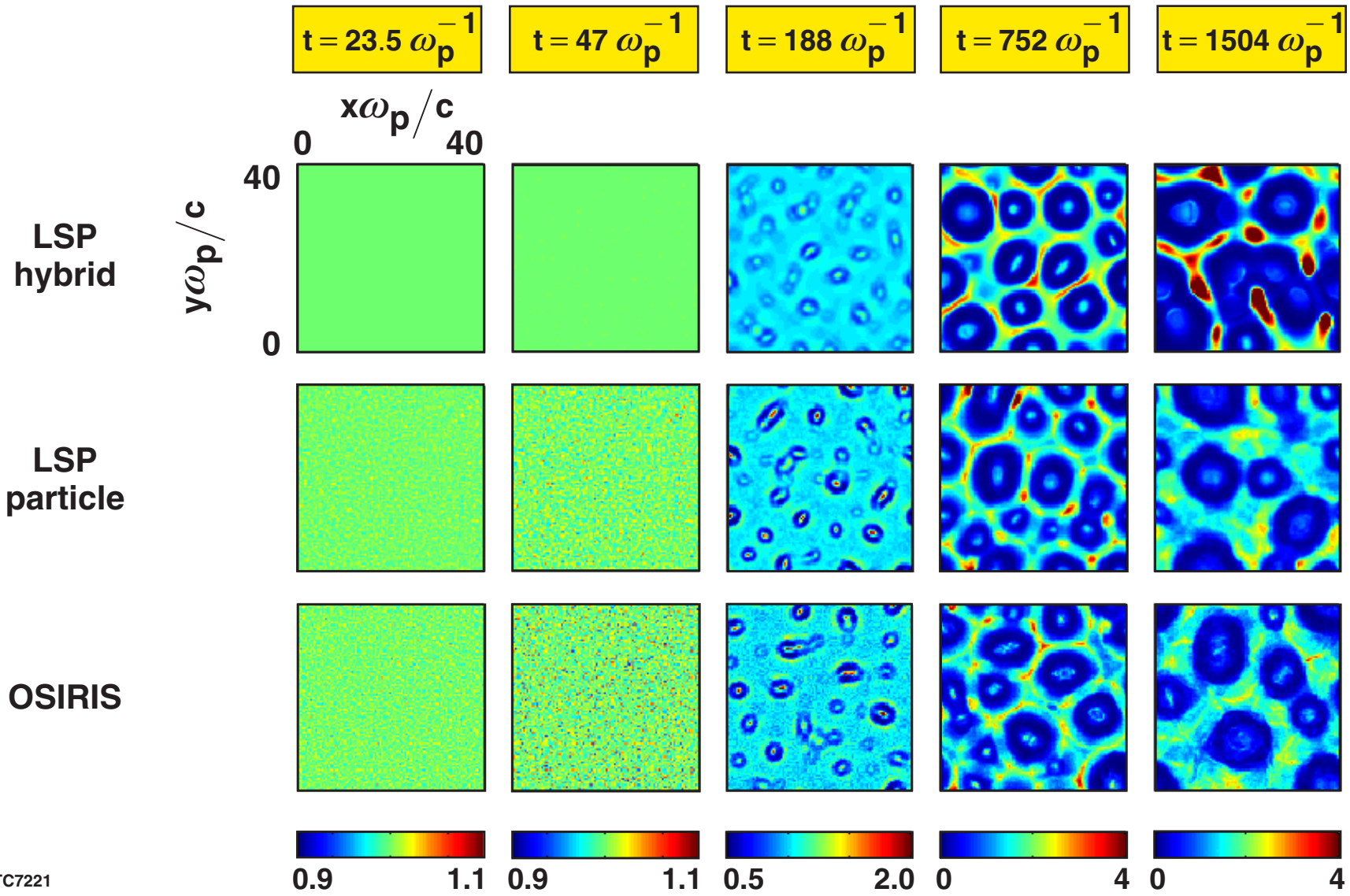
LSP hybrid simulations with mobile ions predict stronger plasma density compressions at the late stage of the instability

UR LLE



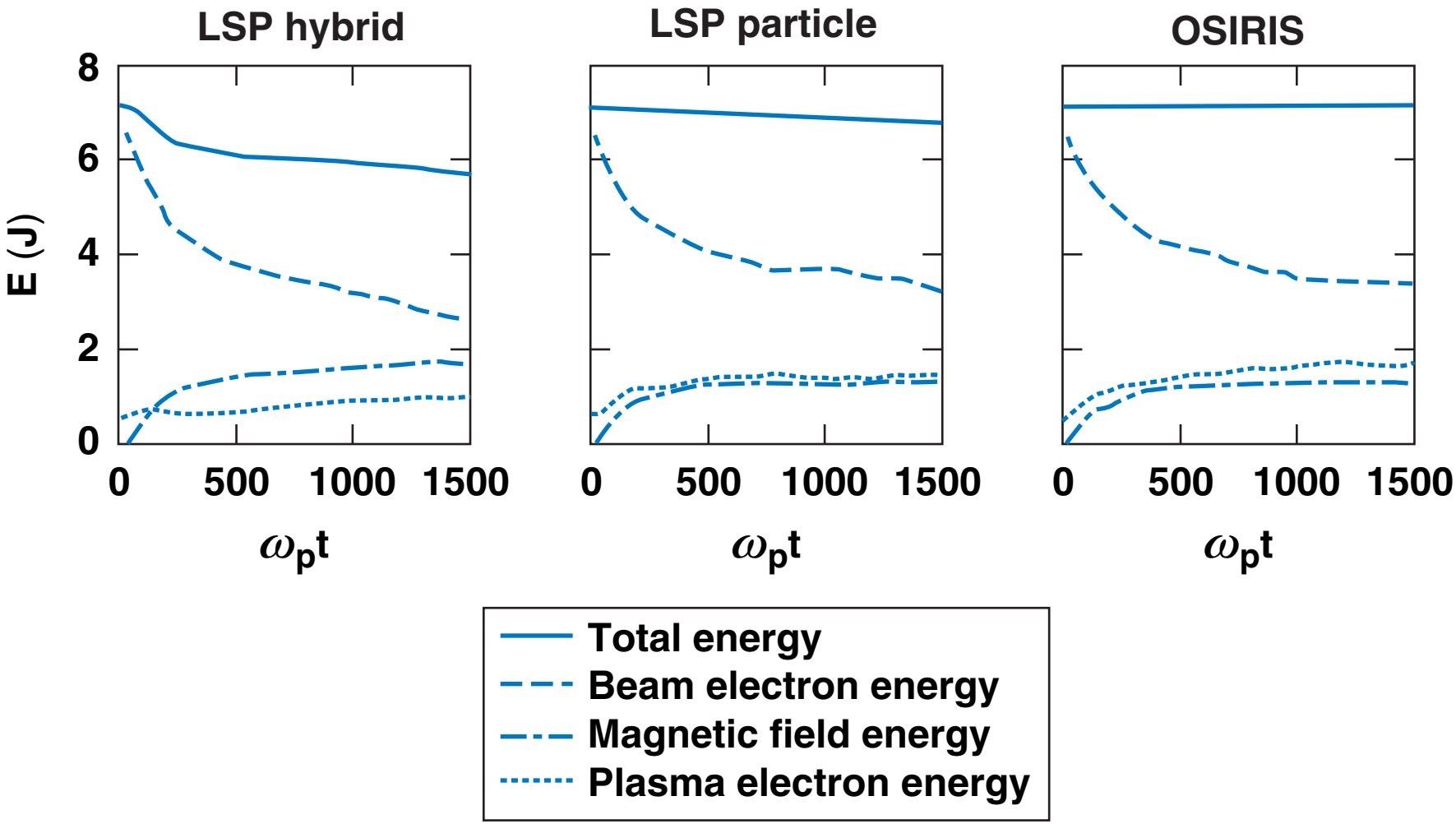
TC7220

LSP hybrid simulations with mobile ions predict stronger ion-density compressions at the late stage of the instability



TC7221

The energy is not conserved in LSP hybrid simulations



TC7208

Summary/Conclusions

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

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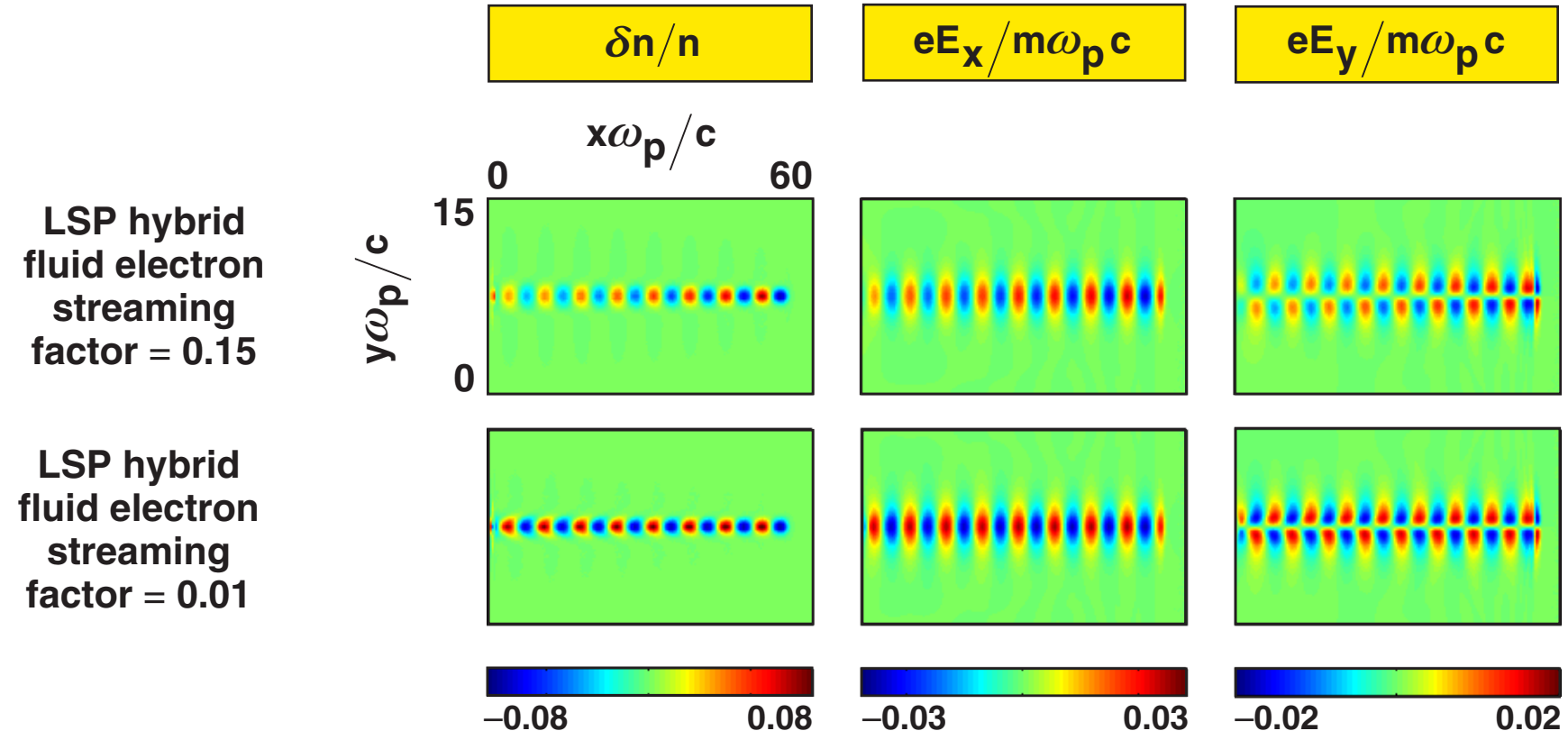
  - LSP correctly simulates the collisional plasma wave damping.
- Weibel instability of electron beams in plasma
  - Both codes simulate qualitatively similar the Weibel instability. The most agreement is found for the OSIRIS and LSP particle mode.
  - LSP hybrid simulations with mobile ions show stronger 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

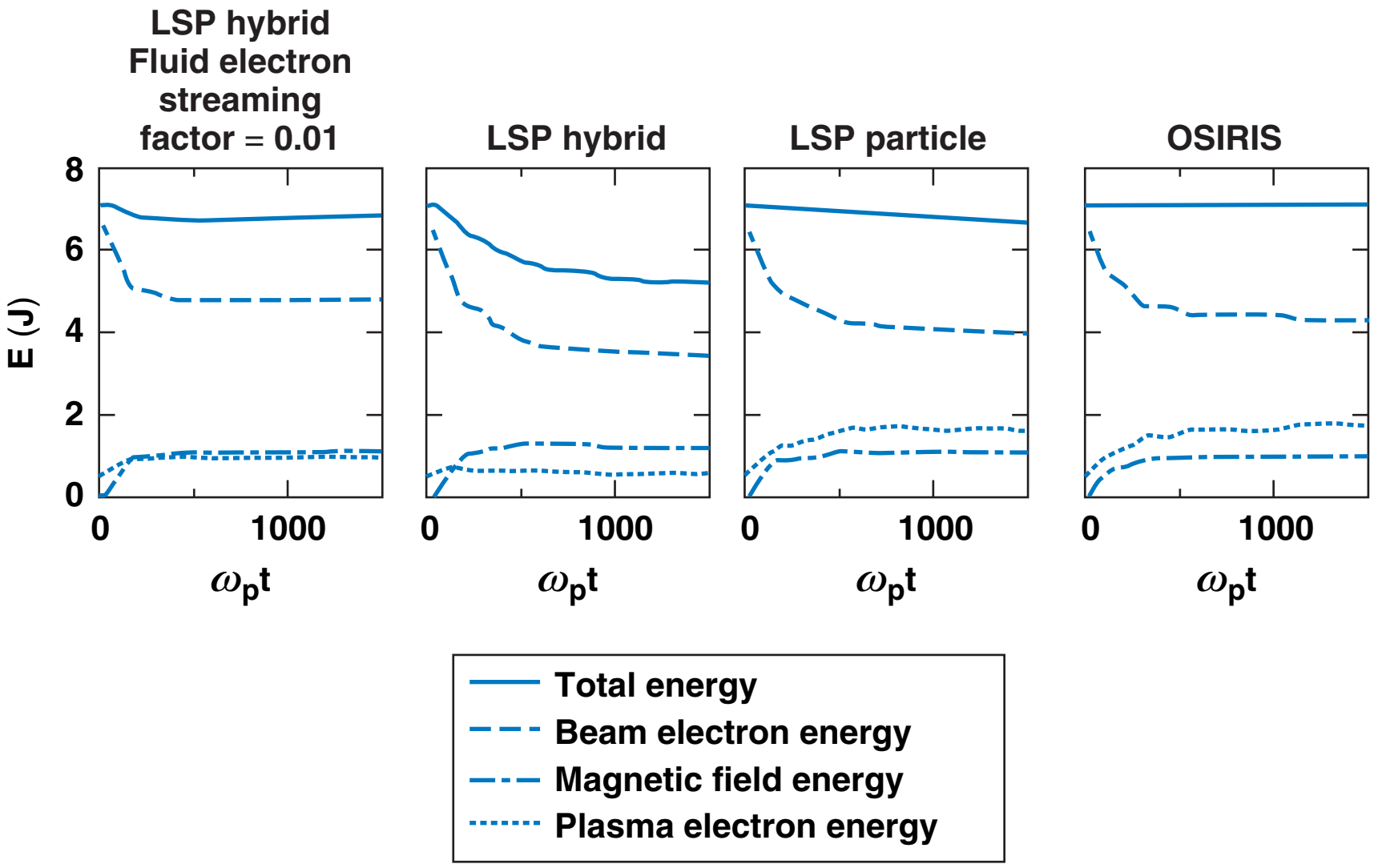
UR LLE

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



TC7209

LSP hybrid simulations show poor energy conservation



TC7210