Convergence of the ponderomotive guiding center approximation in the LWFA

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Motivation

- Simulations are a very useful tool to understand and optimise experiments.
- Numerical simulations need to solve the smallest relevant physical structure.
- For LWFA (Laser Wakefield Acceleration), this represents the laser wavelength $\lambda \lesssim 1\,\mu m$.
- Full PIC simulations are computationally expensive. Total propagation distance $L > 1\,mm$.

Ponderomotive Guiding Center (PGC) algorithm

- We explored a model to reduce the simulation size, the PGC, and implemented in OSIRIS [1].
- We model the laser envelope. The particles are pushed through the self-consistent plasma fields and the laser ponderomotive force [2].

Objective

- Produce high-quality electron beams that will be used as an external injector for PWFA (for example in EuPRAXIA). Beam parameters: energy ~150 MeV, charge ~100pC, energy spread ~5%.
- Thus, we investigate the plasma density down-ramp injection mechanism in our simulations [3].

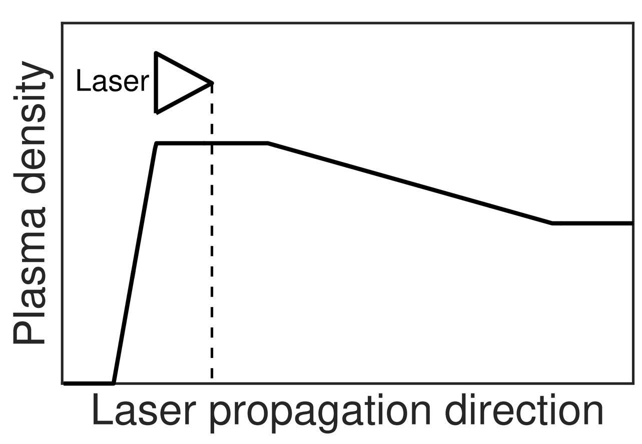
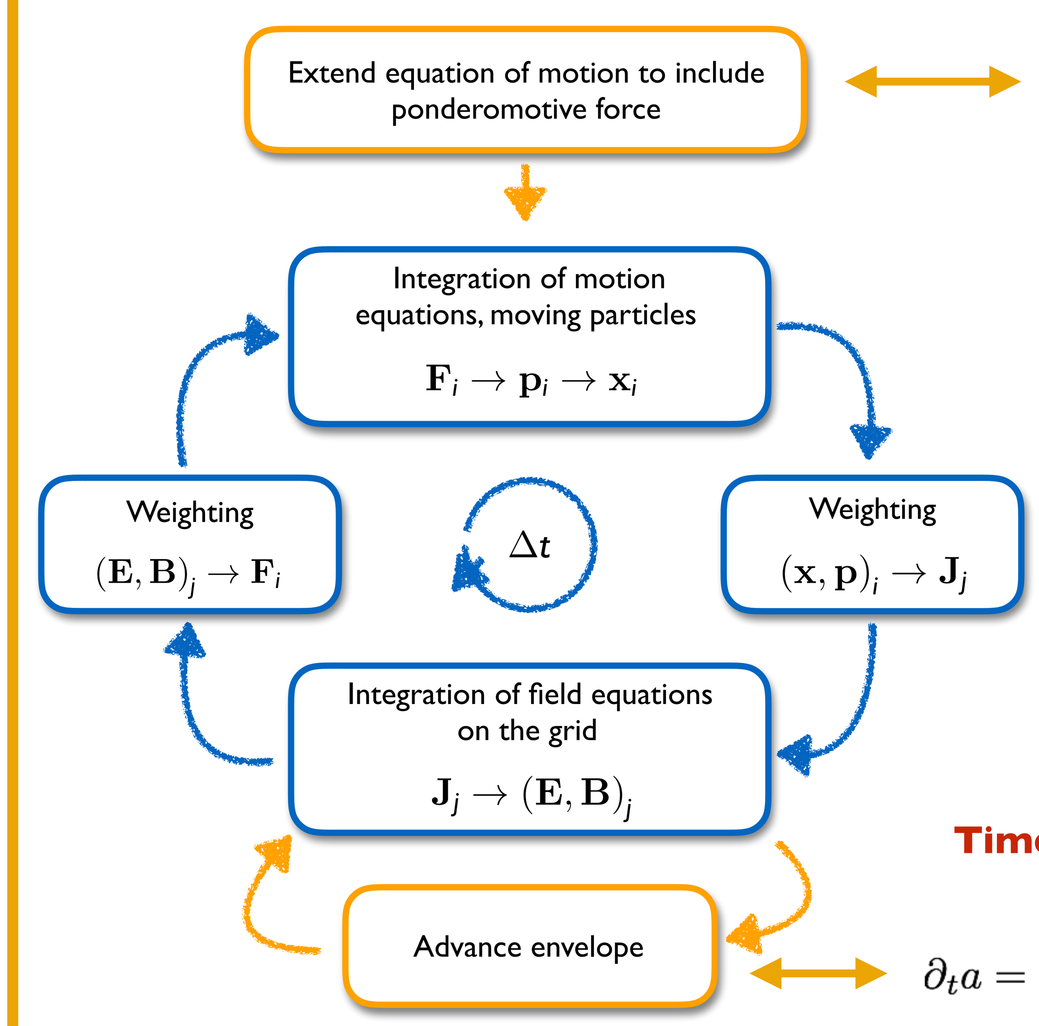


Figure 1: Plasma density down-ramp injection scheme

Osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium ⇒ UCLA + IST
- Scalability to ~ 1.6 M cores
- Xeon Phi support

PGC algorithm



Ponderomotive force

$$F_p = -\frac{1}{4}\frac{q^2}{\langle m \rangle}\nabla |a|^2$$

OSIRIS full PIC

Time-averaged laser envelope equation

$$\partial_t a = \frac{1}{2i\omega}\left[\left(1 + \frac{1}{i\omega}\partial_\xi\right)(\chi a) + \nabla_\perp^2 a\right]$$

Figure 2: Schematic of the PGC algorithm implemented in OSIRIS

PGC vs. PIC comparison

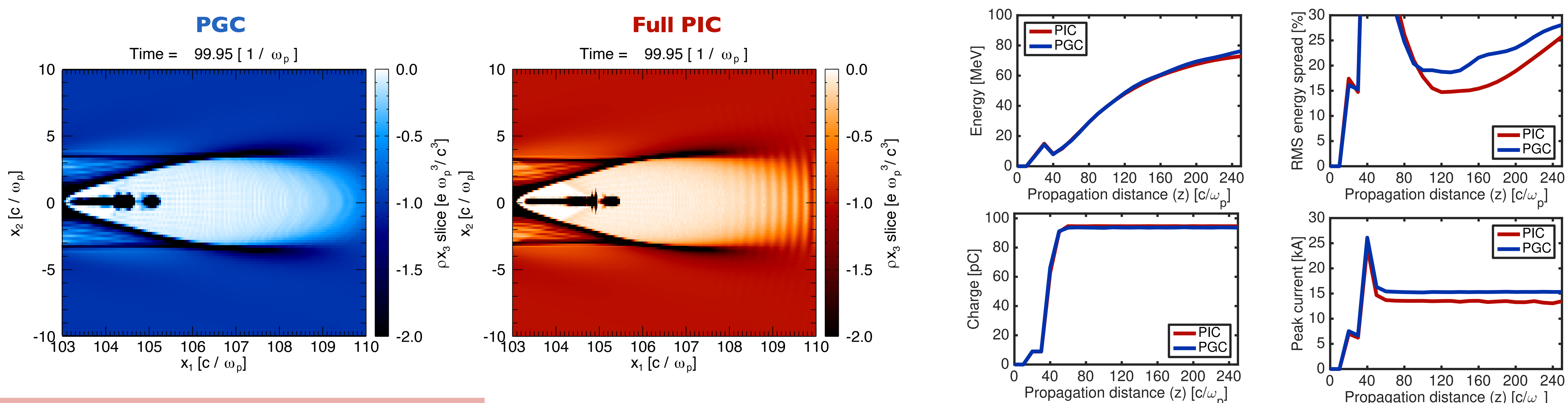
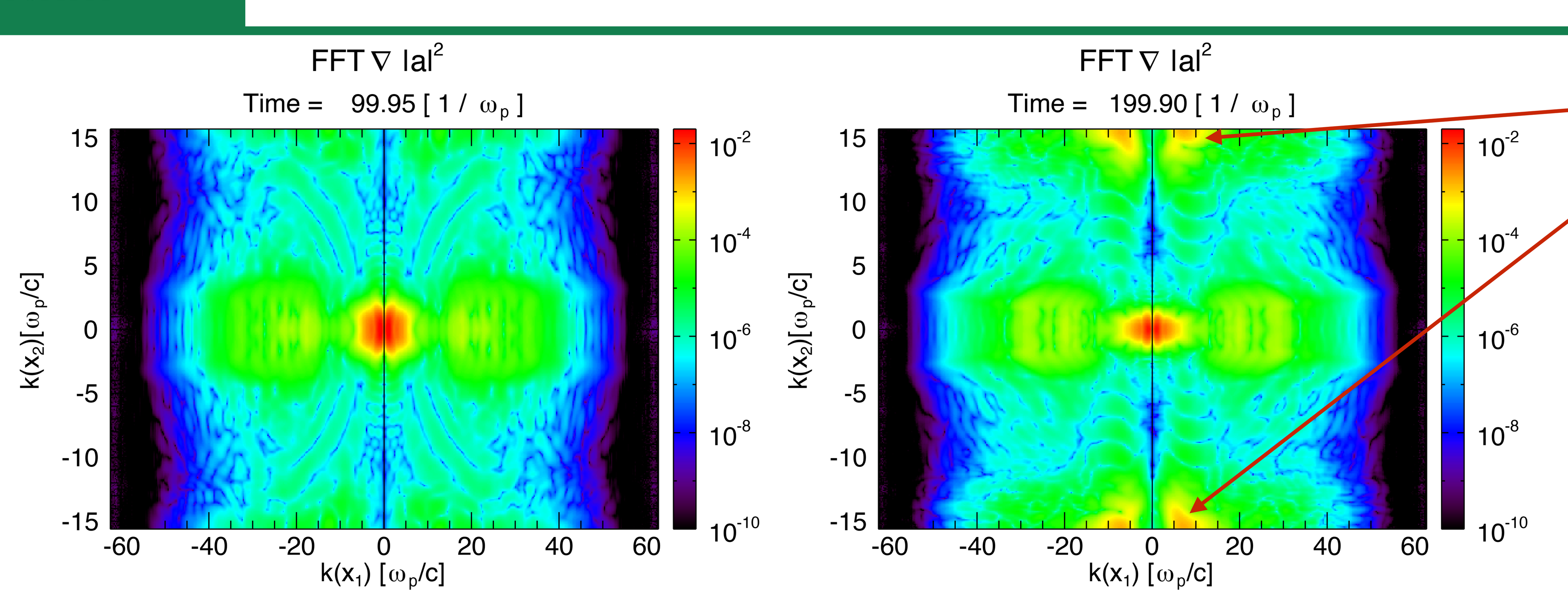


Figure 3: a) Plasma density; **b)** Beam parameters

Stability of the algorithm

- Assumes that the laser central frequency is constant. This is violated near the pump depletion.
- The algorithm is subjected to unphysical growth due to Raman side-scattering. The growth rate increases with $k_\perp$.
- However, simulation results show that the algorithm is breaking earlier than expected.



Unphysical modes

We found that these modes appear because of a missing term in the envelope equation

$$\partial_t a = \frac{1}{2i\omega}\left[\left(1 + \frac{1}{i\omega}\partial_\xi\right)(\chi a) + \nabla_\perp^2 a\right]$$

Figure 4: Fourier transform of the ponderomotive force for two different times.

Conclusions

- The PGC algorithm allows us to reduce the resolution is simulations of LWFA, thus saving computational time.
- The laser is modelled by a time-averaged envelope equation. The particles motion equation has an additional term, the laser ponderomotive.
- While the algorithm is valid, there is a very good agreement in the self-injected beam parameters compared with the full PIC code.
- We recently noted unphysical modes that break down the approximation earlier than expected .
- This was due a previously ignored term that is going to be added to the envelope equation, allowing for a longer simulation time.
- In OSIRIS, the algorithm is constantly being evolved, expanding it to other dimensions and adding new features (such as smoothing).

References & Acknowledgements

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[3] X. Xu, et al., High quality electron bunch generation using a longitudinal density-tailored plasma-based accelerator in the three-dimensional blowout regime. *arXiv:1610.00788*, (2016).

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