Investegation of Laser wakefield acceleration through numerical modeling

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Abstract: Laser Wakefield Accelerators (LWFA) introduce a novel mechanism [1] for generating high-energy electron beams. Laser plasma interaction in an under-dense gas generates plasma waves with accelerating fields orders of magnitude greater than the ones supported by radiofrequency cavities in conventional accelerators. Further research is required to generate higher charge electron bunches with low energy spread, and low emittance suited for a variety of applications, including radiation therapy [2], free electron lasers [3], and future compact colliders.

While the 1D fluid model provides a general description of the Laser Wakefield excitation, numerical modeling is a powerful method to analyze and design the optimum laser and plasma parameters for LWFA experiments. A brief overview of fluid and kinetic LWFA description models and numerical simulations with SMILEI for future LWFA experiments by the ITFIP team (LPGP) is presented.

Multiple Descriptions for LWFA modeling

Fluid Model

Coupling of fluid density and momentum equations with Maxwell's equations.

Excitation of Plasma fields by a propagating laser field [4].

$$\frac{dn}{dt} + \vec{\nabla}.(n\vec{v}) = 0$$

$$\frac{d\vec{p}}{dt} + \vec{v}(\vec{\nabla}\cdot\vec{p}) = -e\cdot n(\vec{E} + \vec{v}\times\vec{B})$$

$$\vec{E} = -\vec{\nabla}\phi \qquad \vec{\nabla}\times\vec{B} = \mu_0\vec{j} + \mu_0\epsilon_0\frac{\partial\vec{E}}{\partial t}$$

Nonlinear plasma wave excitation

$$\frac{d^2\phi}{d\xi^2} = \frac{{k_p}^2}{2}\left[\frac{(1+a^2)}{(1+\phi)^2} - 1\right]$$

The laser field is represented by the normalized vector potential $a = \frac{[e]A_\perp}{m_0c^2}$

Kinetic Modeling

Non-linear and multi-dimensional effects are significant in LWFA.

Kinetic modeling is required to simulate the physical phenomena and design future LWFA experiments.

Particle in Cell (PIC) codes provide a kinetic modeling of laser-plasma interaction.

Solve numerically the Vlasov-Maxwell system of equations. [5]

Accuracy, Flexibility, and Self-Consistency.

Efficient parallelization

Smilei PIC Code

A collaborative, open-source, multi-purpose, PIC code.

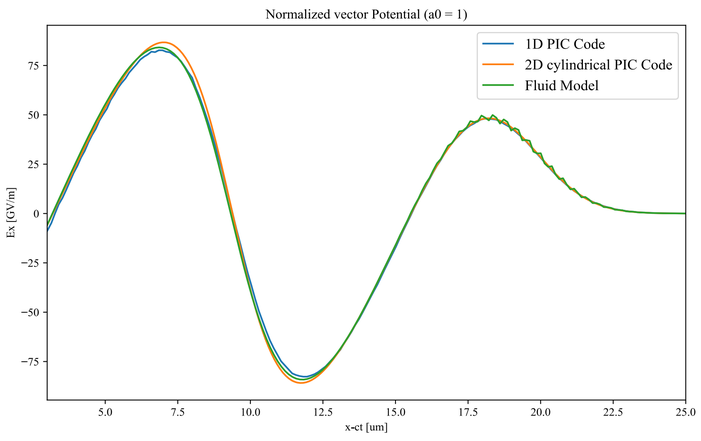
https://smileipic.github.io/Smilei/index.html.

An incorporated envelope model for Laser-plasma interaction [6] to reduce the computation time

Simulation results are compared to the ones of the 1D fluid model.

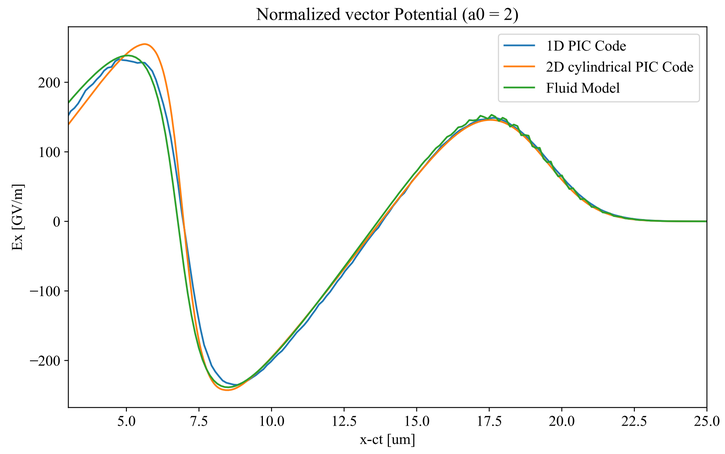
1D Fluid Model vs Smilei PIC simulations

Linear Regime



1D PIC simulation results agree with the 1D cold fluid model.
Multi-dimensional effects deform the plasma waves in 2D cylindrical PIC simulation

Non-linear regime



Triangular plasma waveforms are spotted in the relativistic regime $(a_0 > 1)$.
Considerable change in the longitudinal electric field is observed.

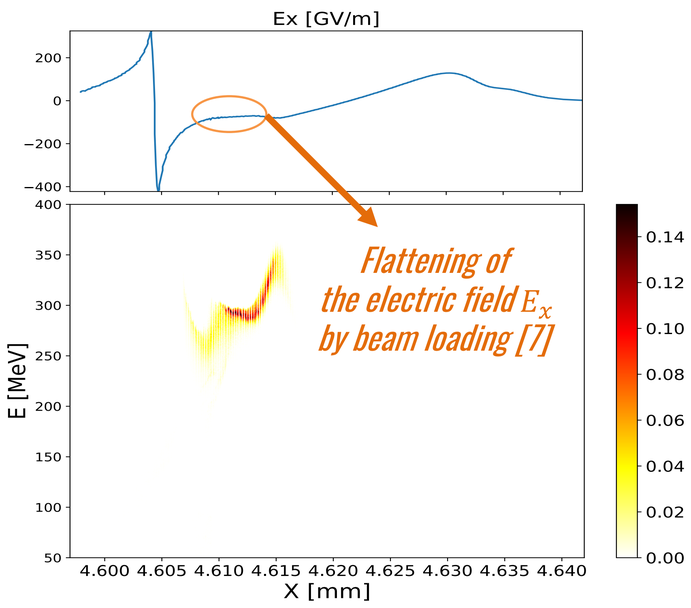
The Multi-dimensional effects in Laser Wakefield Excitation aren't treated by the The 1D fluid model.

PIC simulations show significant Multi-dimensional non-linear effects, mainly at high laser fields $(a_0 > 1)$

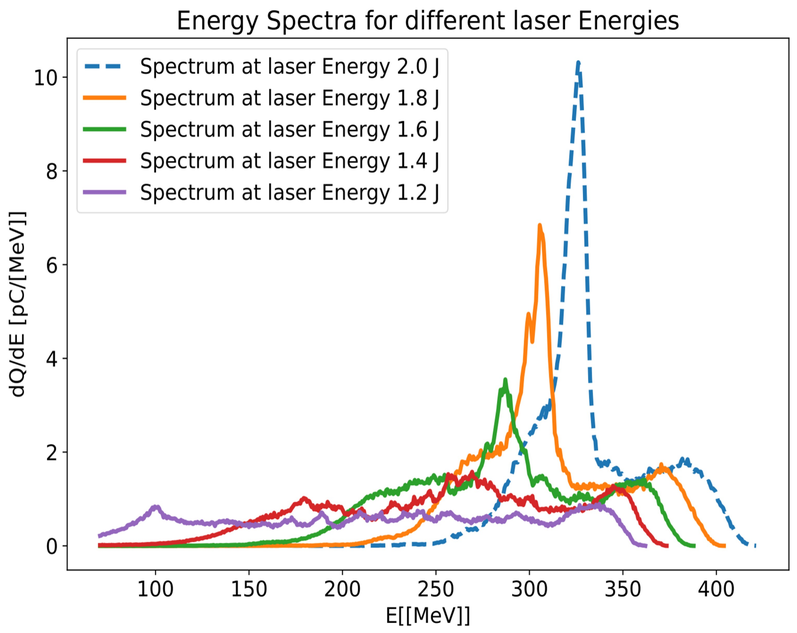
Necessity of Advanced numerical modeling to study the LWFA non-linear and multi-dimensional phenomena for future experiments.

PIC Simulations of high performance LWFA using Ionization Injection

Electron position-energy spectrum after acceleration



Dependence on laser energy



Conclusion

Elementary study of the LWFA using the 1D cold fluid model is valid only for $(a_0 < 1)$

PIC simulations are needed to describe the non-linear regime

PIC simulations with SMILEI to model future LWFA experiments by the ITFIP team (LPGP)

Reduction of the electron beam's energy spread

Boost in electron bunch charge

Possible studies of other parameter's effect on the electron's bunch quality (e.g. focal plane position).

References

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