Efficient modeling of Laser Wakefield Acceleration through the PIC code Smilei in CILEX project

Francesco Massimo

Arnaud Beck, Julien Derouillat, Mickael Grech, Frédéric Pérez, Imen Zemzemi, Arnd Specka

Outline

- **Motivations: CILEX**
- **Modeling Laser Wakefield Acceleration with Smilei**
  - **Envelope model, nonlinear wakefield benchmark**
  - **Field initialisation for relativistic species**
- **Case study: Laser Wakefield Acceleration with external injection**
  - **2D comparisons**
  - **1D comparisons**
- **Conclusions**

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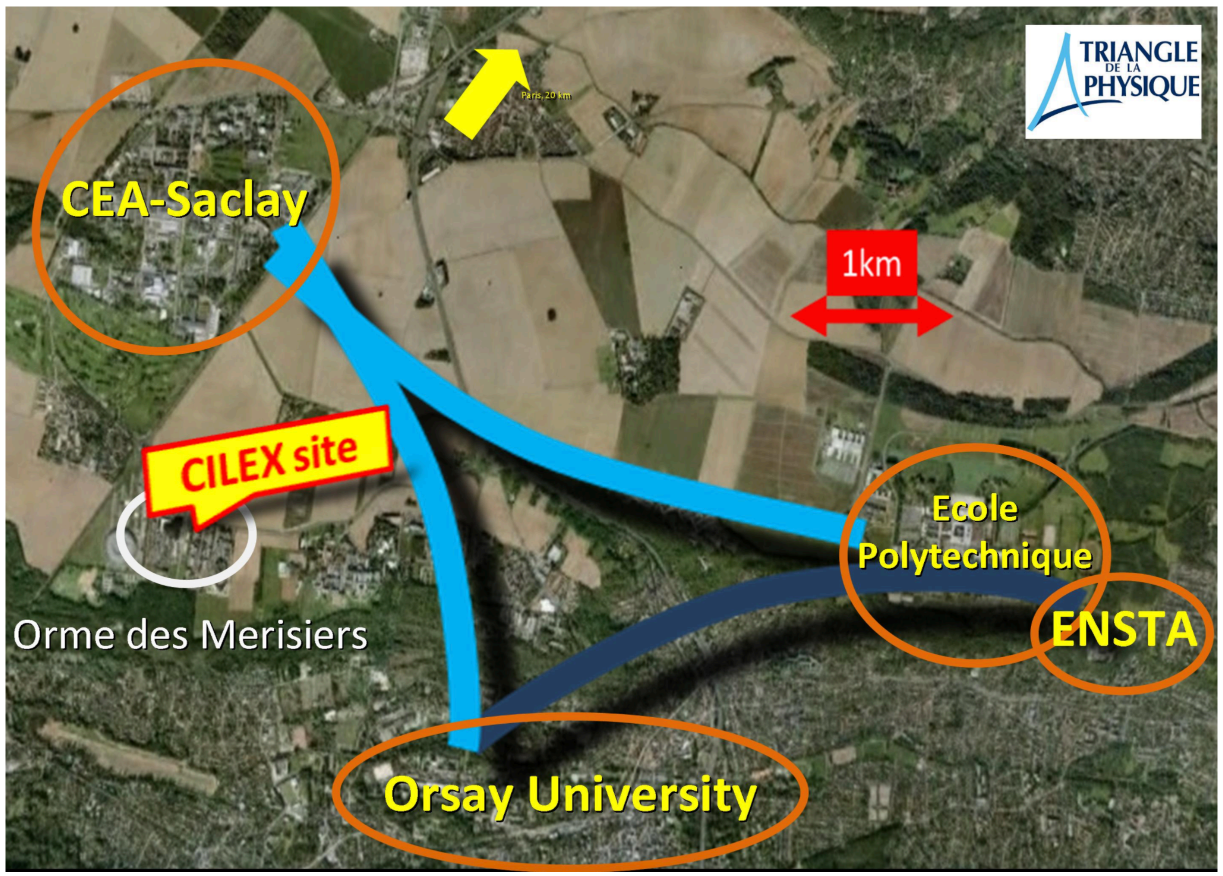
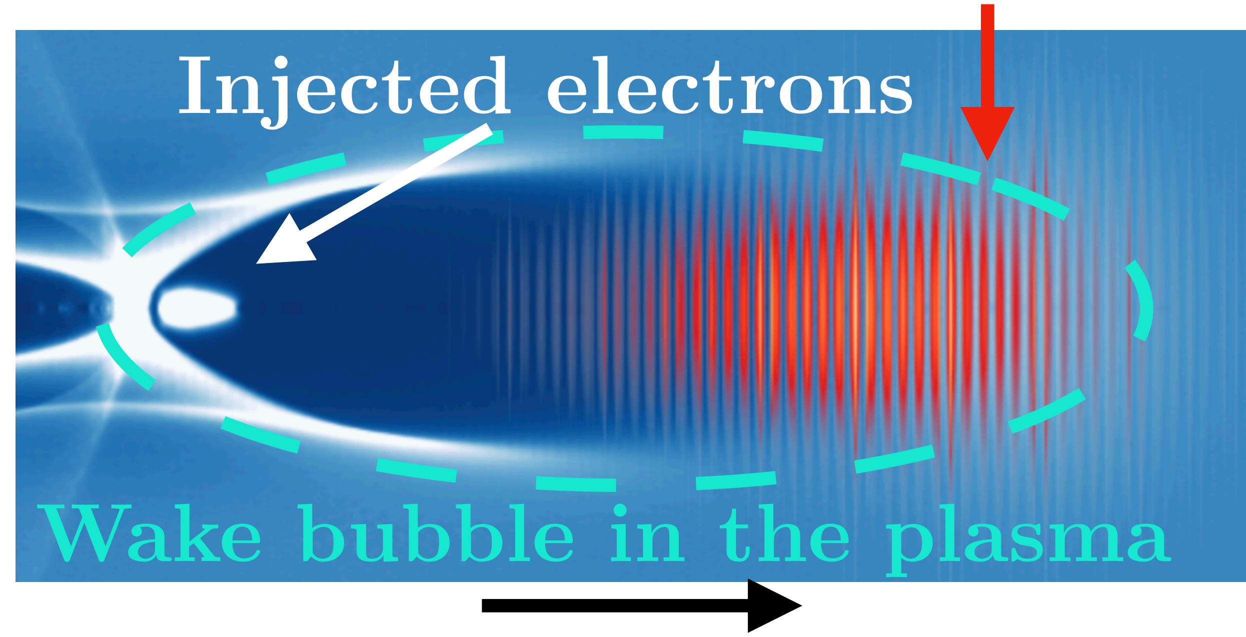
Centre Interdisciplinaire de la Lumière Extrême (CILEX)

Cilex Apollon



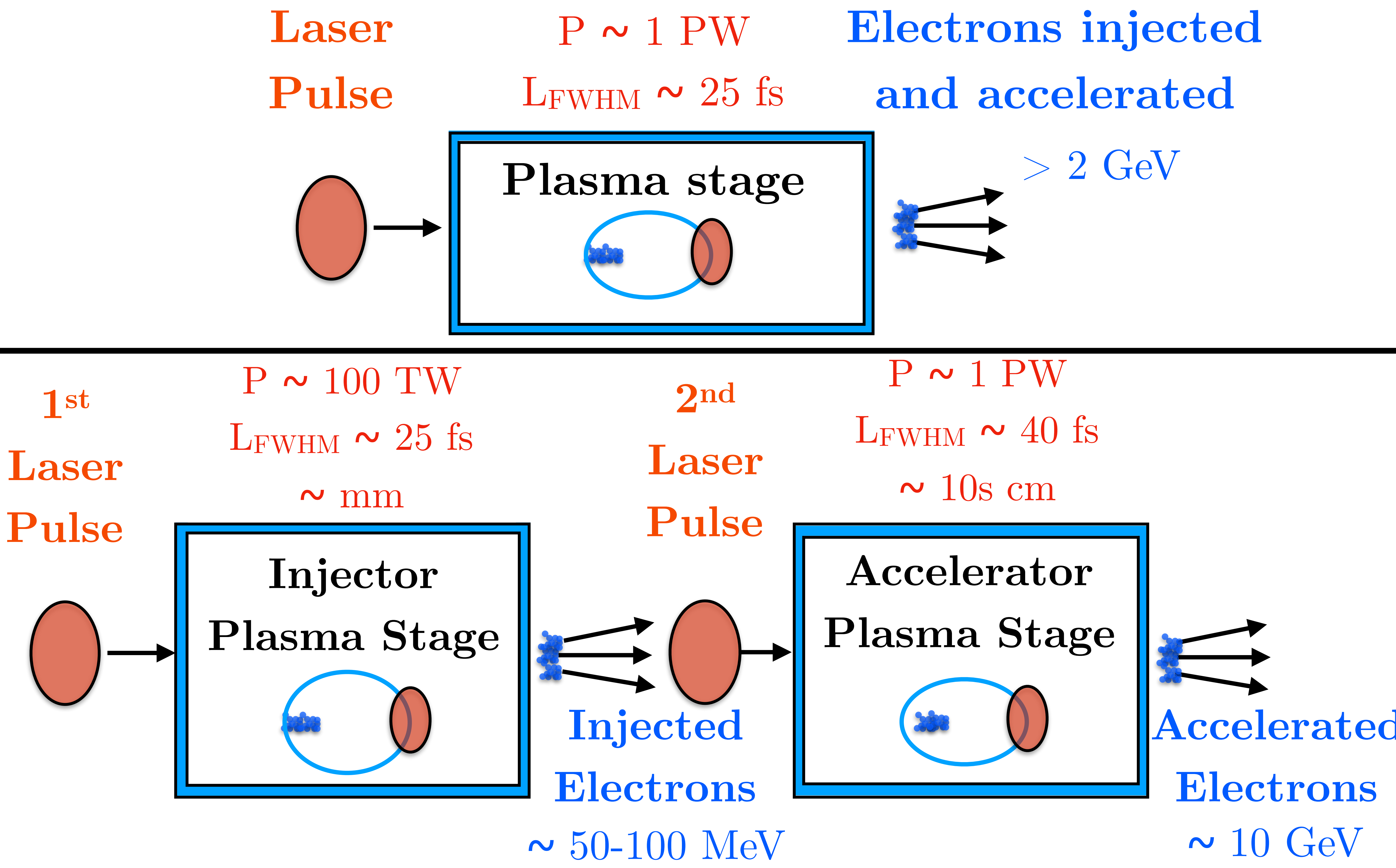
Laser Wakefield Acceleration (LWFA)

Laser Pulse



Propagation direction

Multistage Électron acceleration



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Code "Particle in Cell" (PIC) SMILEI

Smilei)

http://www.maisondelasimulation.fr/smilei/

- **Features**
  - Collaborative, open source
  - Python Interface for Input/Output
  - Advanced dynamic load balancing
  - Parallelization with hybrid MPI/OpenMP
  - Output OpenPMD, VTK
  - Geometries 1D, 2D, 3D
  - Ionization, Binary Collisions
  - QED Radiation reaction,
  - QED Photon emission

- **Next features to be released**
  - Vectorization
  - Interface with PICSAR library
  - Envelope model for the laser
  - Relativistic beam field initialisation
  - Azimuthal Fourier decomposition (X-R)

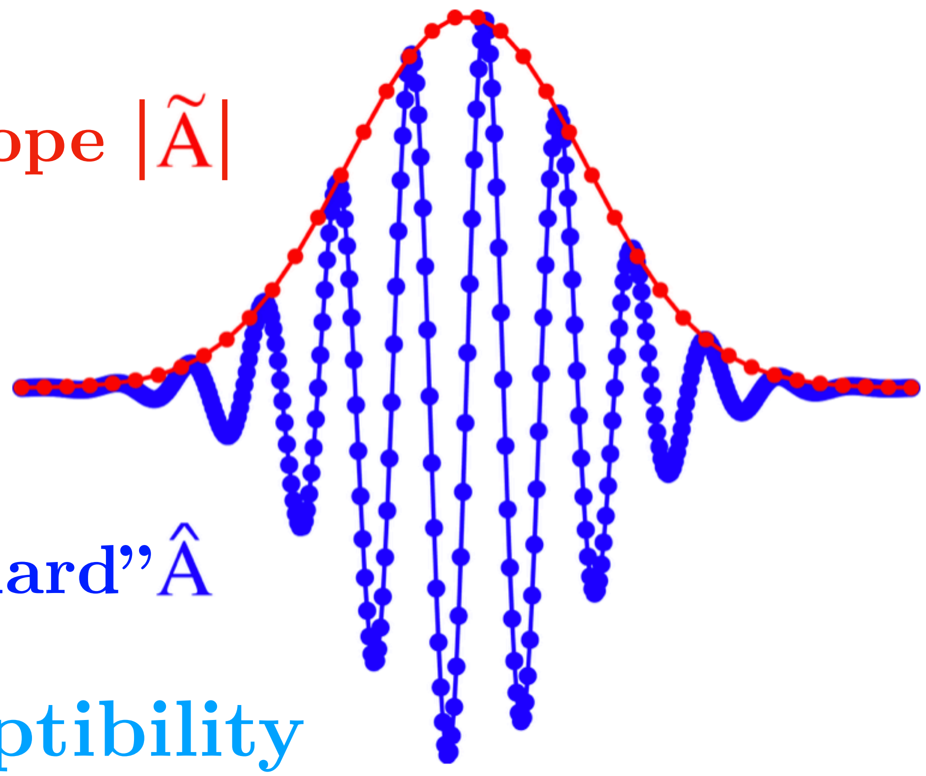
J. Derouillat, et al., Comput. Phys. Commun. 222, 351-373 (2018)

Modèle d'Enveloppe Complexe pour le Laser

Hypothesis:

$$\hat{A}(\mathbf{x},t) = Re\left[\tilde{A}(\mathbf{x},t)e^{ik_0(x-ct)}\right]$$

Complex envelope of $\hat{A}$



Envelope Equation:

$$\nabla^2\tilde{A} + 2i\left(\partial_x\tilde{A} + \partial_t\tilde{A}\right) - \partial_t^2\tilde{A} = \chi\tilde{A}$$

$$\chi(\mathbf{x}) = \sum_s \frac{q_s^2}{m_s}\sum_p \frac{w_p}{\bar{\gamma}_p} S(\mathbf{x}-\bar{\mathbf{x}}_p)$$

Plasma susceptibility

Motion Equations for the macroparticles:

$$\frac{d\bar{\mathbf{x}}_p}{dt} = \frac{\bar{\mathbf{u}}_p}{\bar{\gamma}_p}$$

$$\bar{\gamma}_p = \sqrt{1 + \bar{\mathbf{u}}_p^2 + \frac{|\tilde{A}(\bar{\mathbf{x}}_p)|^2}{2}}$$

Ponderomotive Force

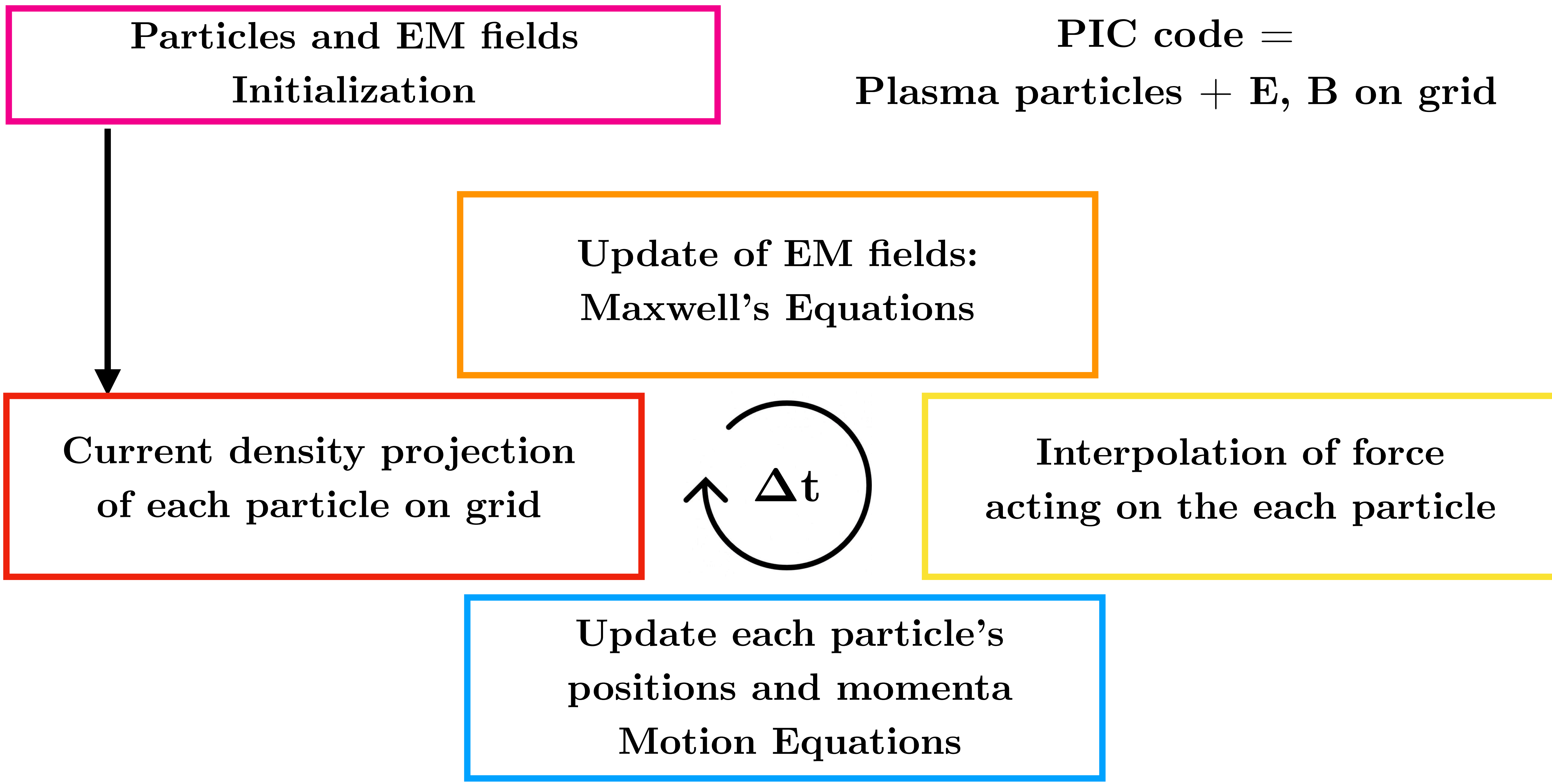
$$\frac{d\bar{\mathbf{u}}_p}{dt} = r_s\left(\bar{\mathbf{E}}_p + \frac{\bar{\mathbf{u}}_p}{\bar{\gamma}_p}\times\bar{\mathbf{B}}_p\right) - r_s^2\frac{1}{4\bar{\gamma}_p}\nabla\left(|\tilde{A}_p|^2\right)$$

$$r_s = q_s/m_s$$

Lorentz Force

B. Quesnel and P. Mora, Physics Review E 58, 3719 (1998)
S. Sinigardi et al., ALaDyn v2017.1 zenodo (2017)
D. Terzani et al., submitted (2018)

Standard Particle in Cell (PIC) loop



C.K. Birdsall, A.B. Langdon, Plasma Physics Via Computer Simulation (1985)

PIC loop with Envelope ("Ponderomotive" PIC)

"Ponderomotive" PIC Code = Plasma Particles + $\bar{E}$, $\bar{B}$, $\tilde{A}$ on grid

Particles and EM fields Initialization

Update of EM fields: Maxwell's Equations

Current density projection of each particle on grid

Δt

Interpolation of force acting on the each particle

Update particles Positions

Update laser envelope: Envelope Equation

Update particles momenta

Projection of susceptibility on grid

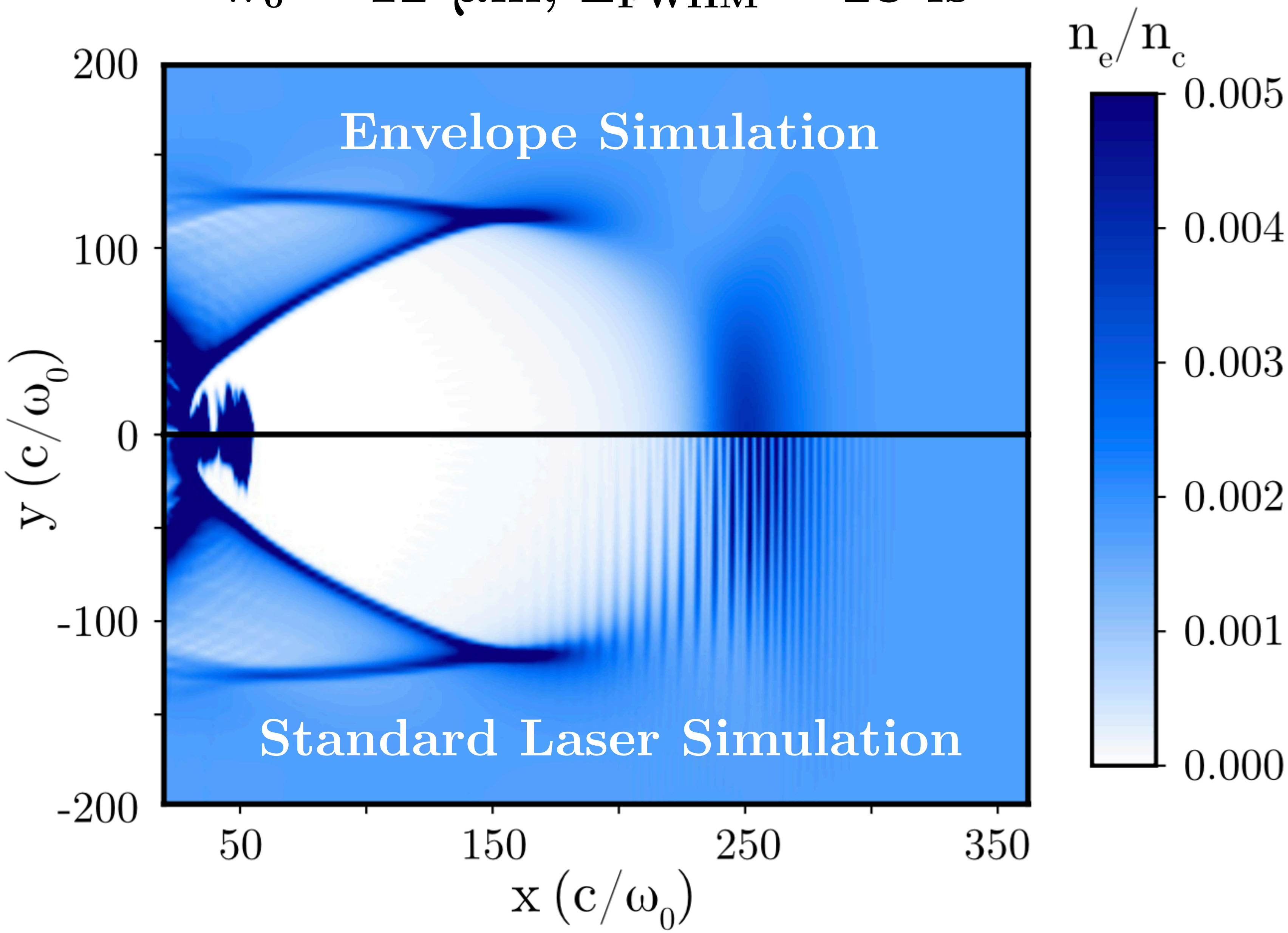
S. Sinigardi et al., ALaDyn v2017.1 zenodo (2017)

D. Terzani et al., submitted (2018)

Validation test:
Nonlinear LWFA, Electron density

$a_0 = 5$, $n_0 = 3 \cdot 10^{18}$ cm^{-3},
$w_0 = 12$ μm, $L_{FWHM} = 28$ fs

8 ppc, $\Delta y = \Delta z = 3\ c/\omega_0$



Propagation direction

Standard Laser simulation

$\Delta x = 0.125\ c/\omega_0$

$\Delta t = 0.124\ c/\omega_0$

Envelope simulation

$\Delta x = 0.75\ c/\omega_0$

$\Delta t = 0.675\ c/\omega_0$

$$\frac{T_{\text{Standard Laser}}}{T_{\text{Envelope}}} = 20!$$

@1 mm

$T_{\text{Envelope}} = 16$ kh-cpu

Initialisation des Champs Électromagnétiques

Immobiles Species: Poisson's Equation

$$\nabla^2\Phi = -\rho$$

Relativistic Species: "Relativistic" Poisson's Equation

$$\left(\frac{1}{\gamma_0^2}\partial_x^2 + \nabla_\perp^2\right)\Phi = -\rho$$

$$\mathbf{E} = \left(-\frac{1}{\gamma_0^2}\partial_x\Phi, -\partial_y\Phi, -\partial_z\Phi\right)$$

$$\mathbf{B} = \frac{\beta_0}{c}\hat{\mathbf{x}} \times \mathbf{E}$$

Hypothesis:
Negligible energy spread

If non-negligible energy spread:
Repeat for each energy "slice"

http://www.maisondelasimulation.fr/smilei/relativistic_fields_initialization.html

J.-L. Vay, Physics of Plasmas 15, 056701 (2008)

P. Londrillo, C. Gatti and M. Ferrario, Nucl. Instr. and Meth. A 740, 236-241 (2014)

F. Massimo, A. Marocchino and A. R. Rossi, Nucl. Instr. and Meth. A 829, 378-382 (2016)

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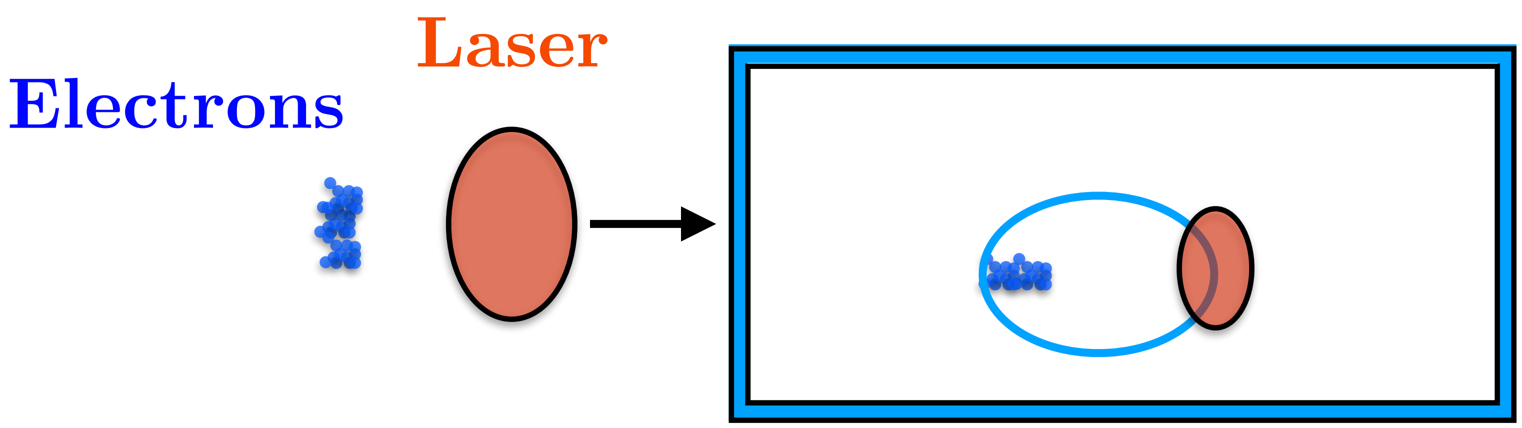
LWFA with external injection of relativistic electron beam

Plasma stage

$n_0 = 1.5 \cdot 10^{17}$ cm^{-3} (parabolic)



Electron beam:

$Q = 30$ pC

$E_0 = 150$ MeV

$\sigma_E/E = 0.05\%$,

$\sigma_x = 2$ μm

$\sigma_{yz} = 1.3$ μm

$\varepsilon_{yz} = 1$ mm-mrad

Laser Pulse:

$a_0 = 1.4$

$w_0 = 45$ μm

$L_{FWHM} = 110$ fs

8 ppc, $\Delta y = \Delta z = \lambda_0$

Standard Laser simulation

$\Delta x = \lambda_0/32$

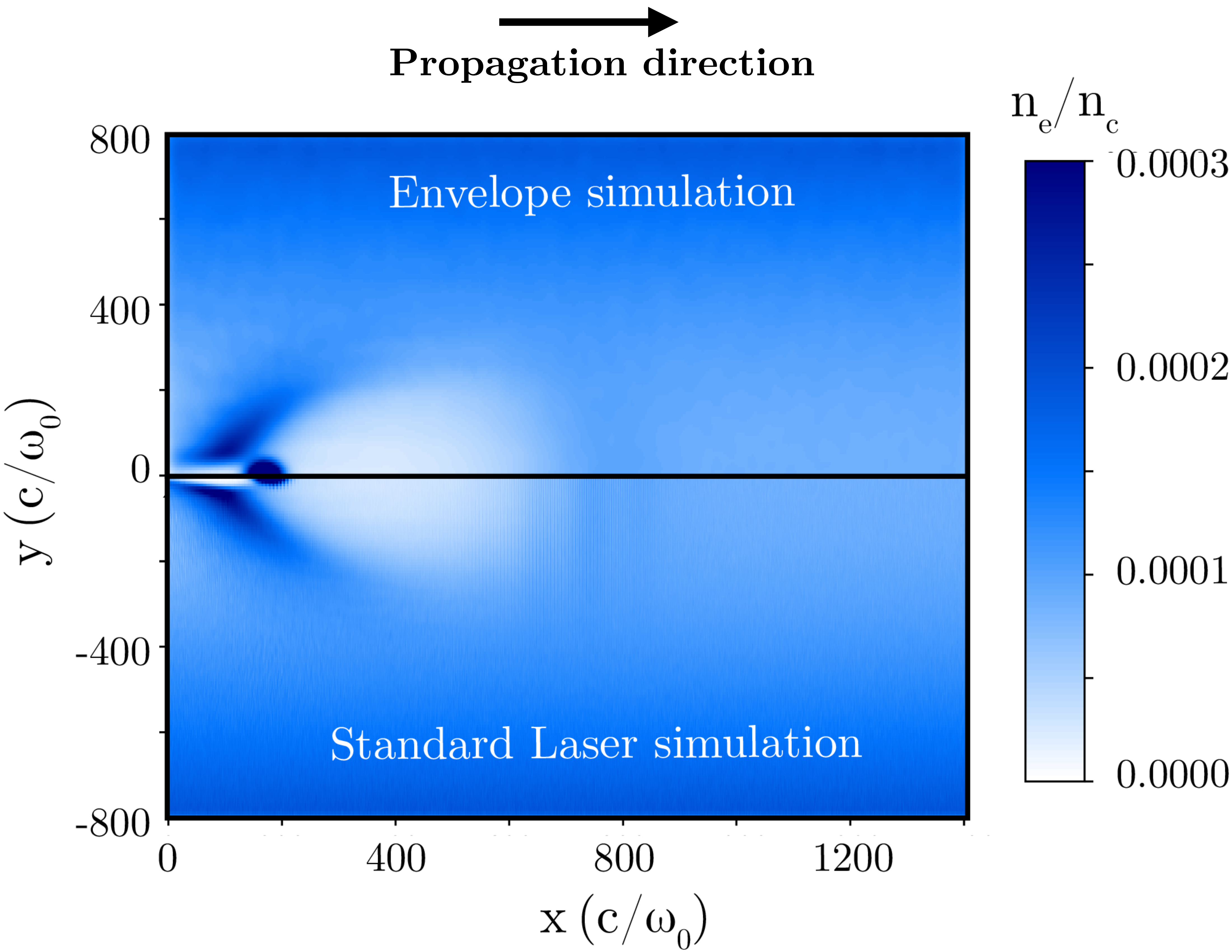
$\Delta t = 0.95\ \Delta x$

Envelope simulation

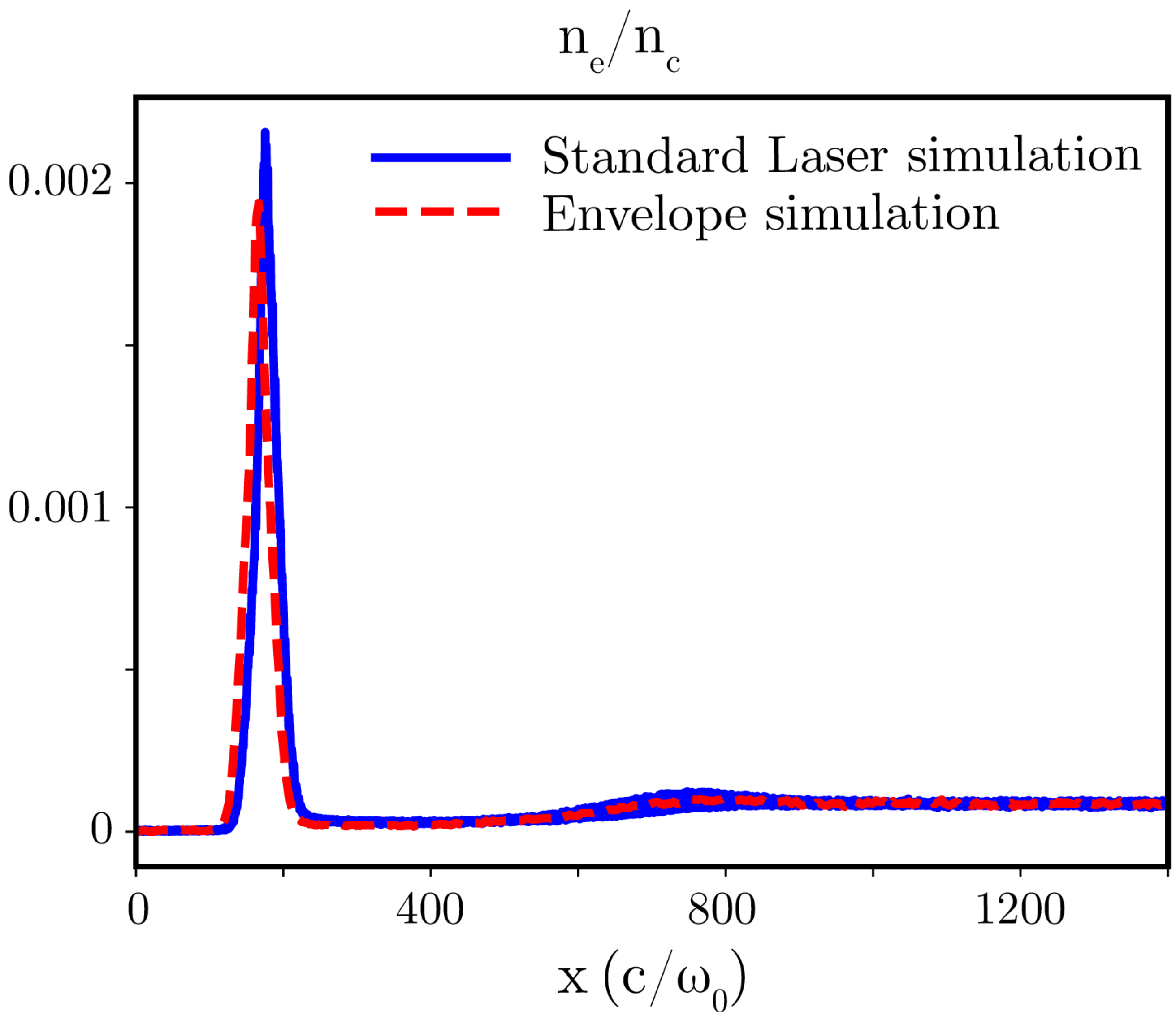
$\Delta x = 16\Delta x$

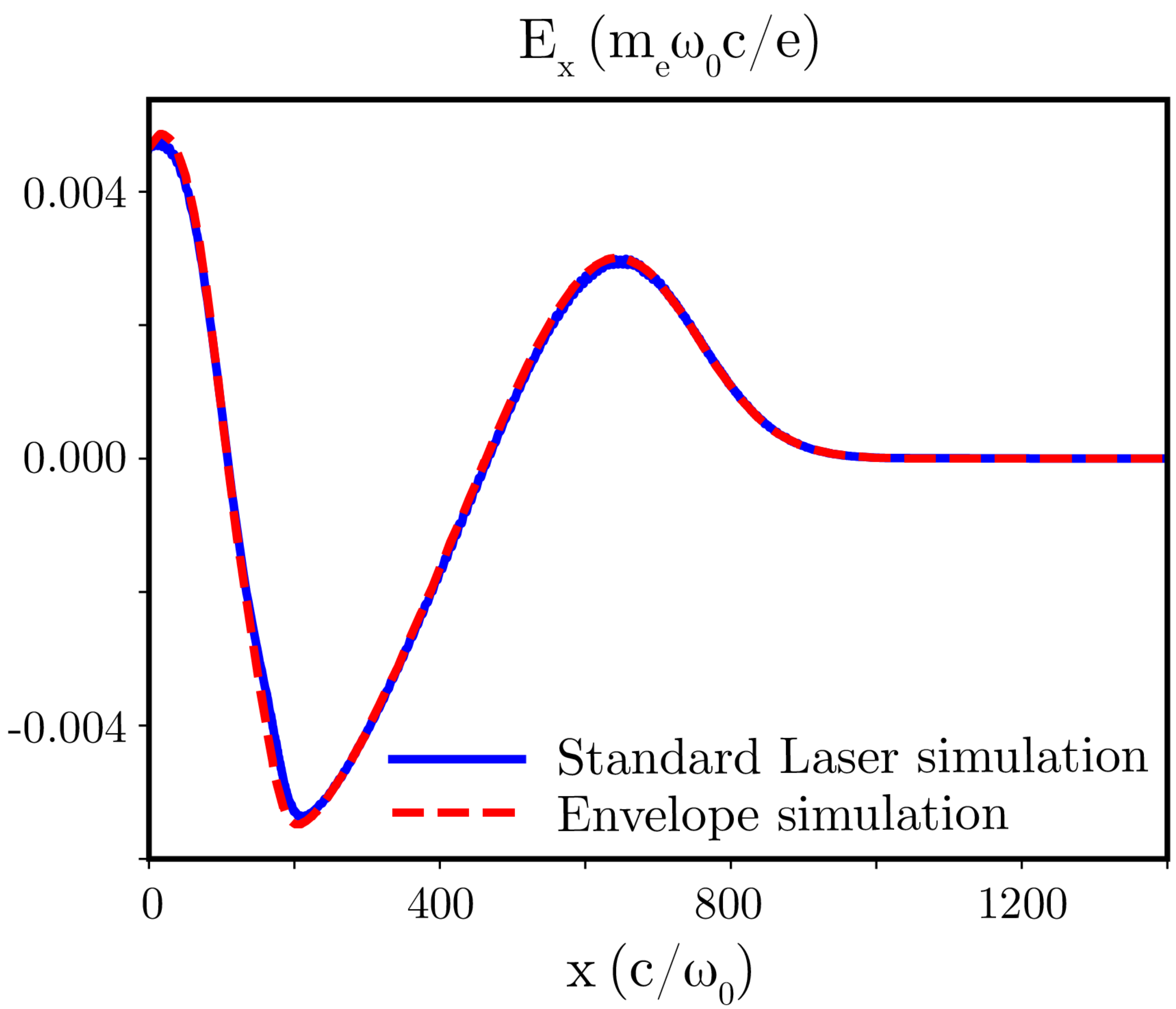
$\Delta t = 0.8\Delta x$

LWFA with external injection of relativistic electron beam



LWFA with external injection of relativistic electron beam





@3 mm

$\mathbf{T_{Envelope} = 4.4\ kh\text{-}cpu}$

$$\frac{T_{Standard\ Laser}}{T_{Envelope}} = 20!$$

Conclusions

- **Multi-stage Experiments are envisioned in the CILEX project**
- **New features have been developed in the SMILEI code**
- **Implemented of the field initialisation of relativistic beams**
- **Implemented a time-explicit 3D envelope model for the laser**
- **Envelope model + field initialisation suitable for external injection simulations**
- **Work in progress: start to end simulations of 2 stages**

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Developers of Smilei)

- Arnaud Beck, Imen Zemzemi
- Frédéric Pérez, Mickael Grech
- Julien Derouillat, Heithem Kallala, Mathieu Lobet

Developers of ALaDyn

- Alberto Marocchino
- Stefano Sinigardi,
- Davide Terzani

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For users and future developers:

Smilei) Training Workshop!

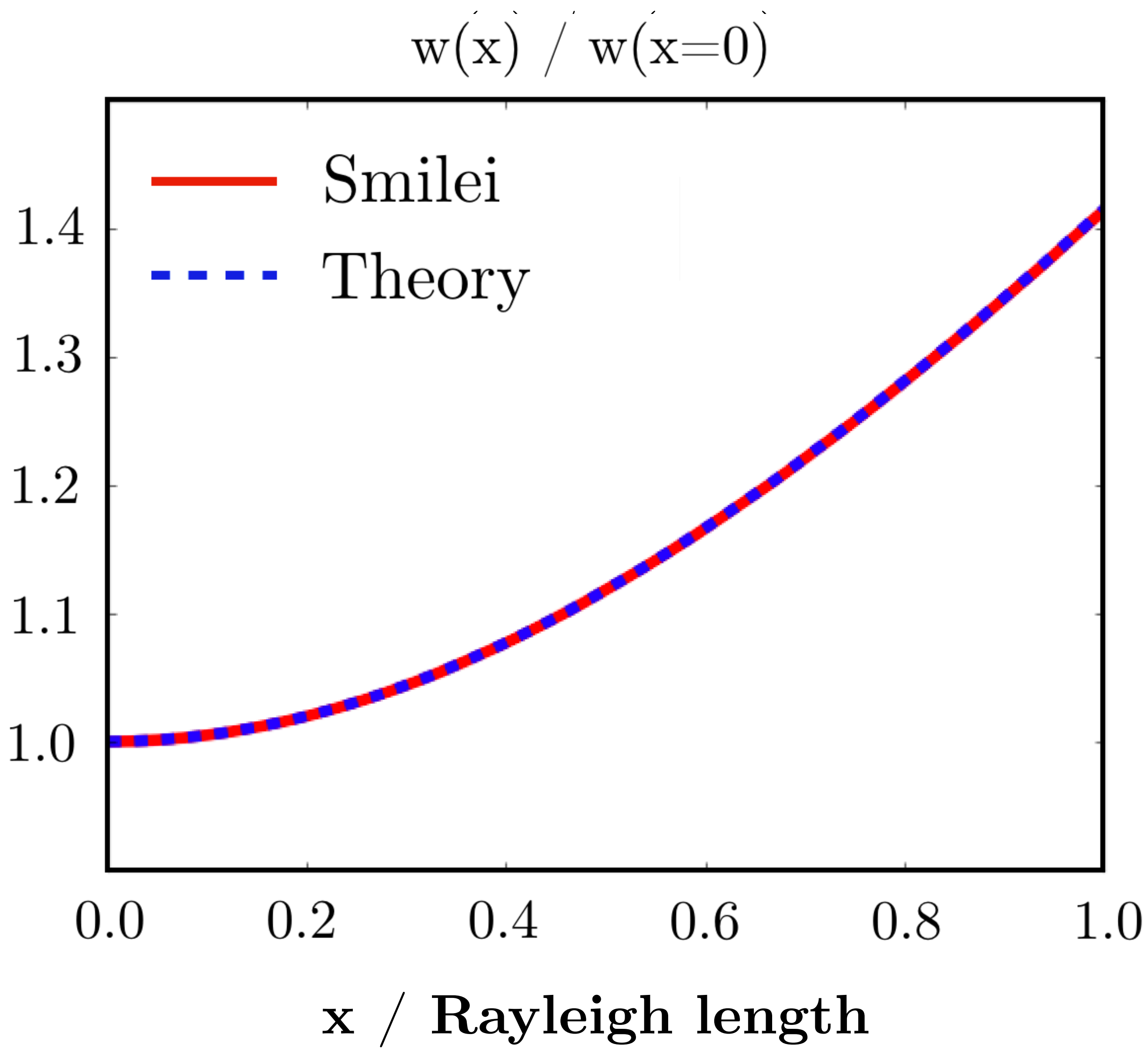
http://www.maisondelasimulation.fr/smilei/

Second Edition: February/March 2019

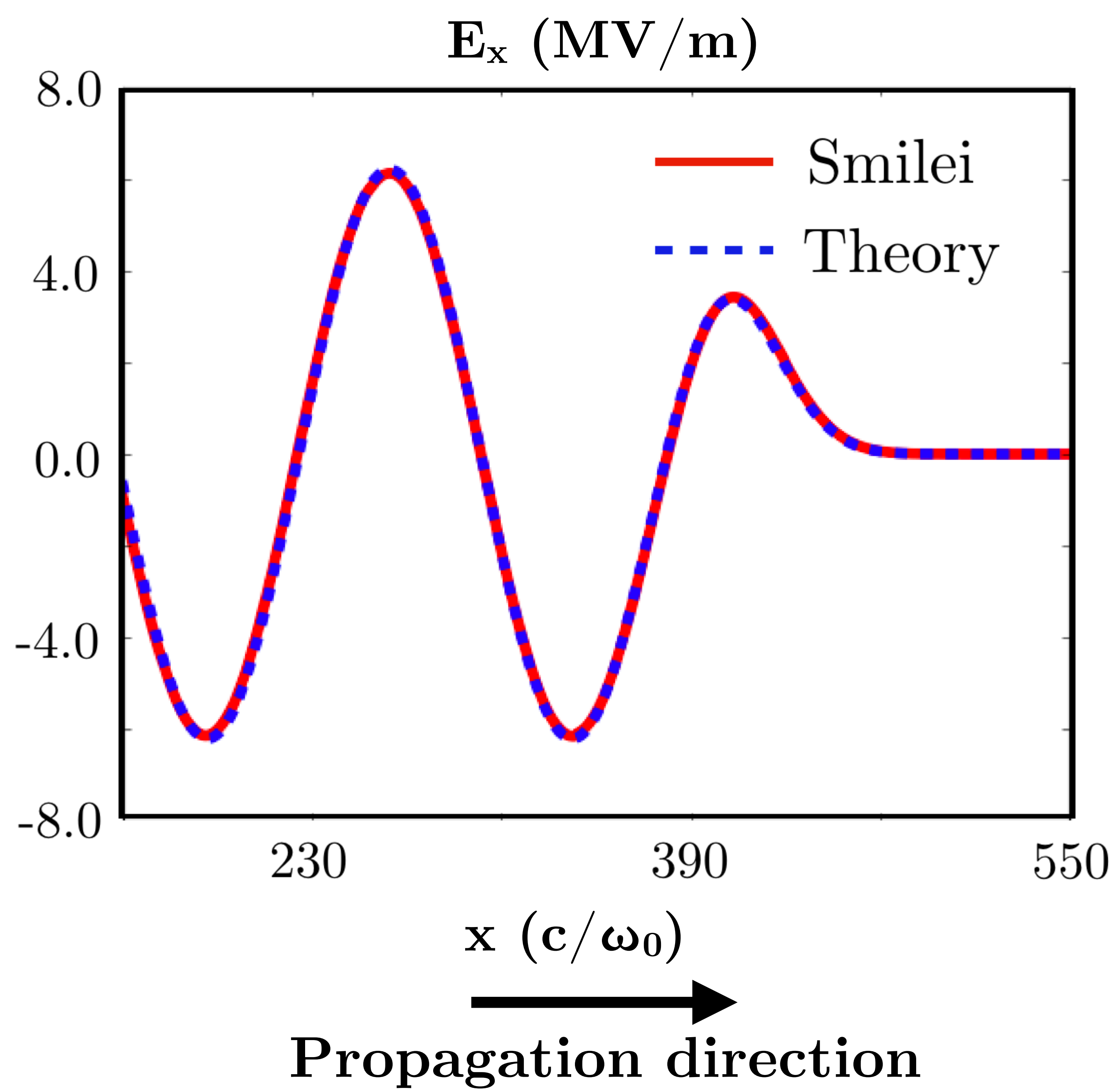
Additional slides

Gaussian Beam Laser:
Vacuum diffraction, Plasma Wakefield 1D

Laser beam rms transverse size



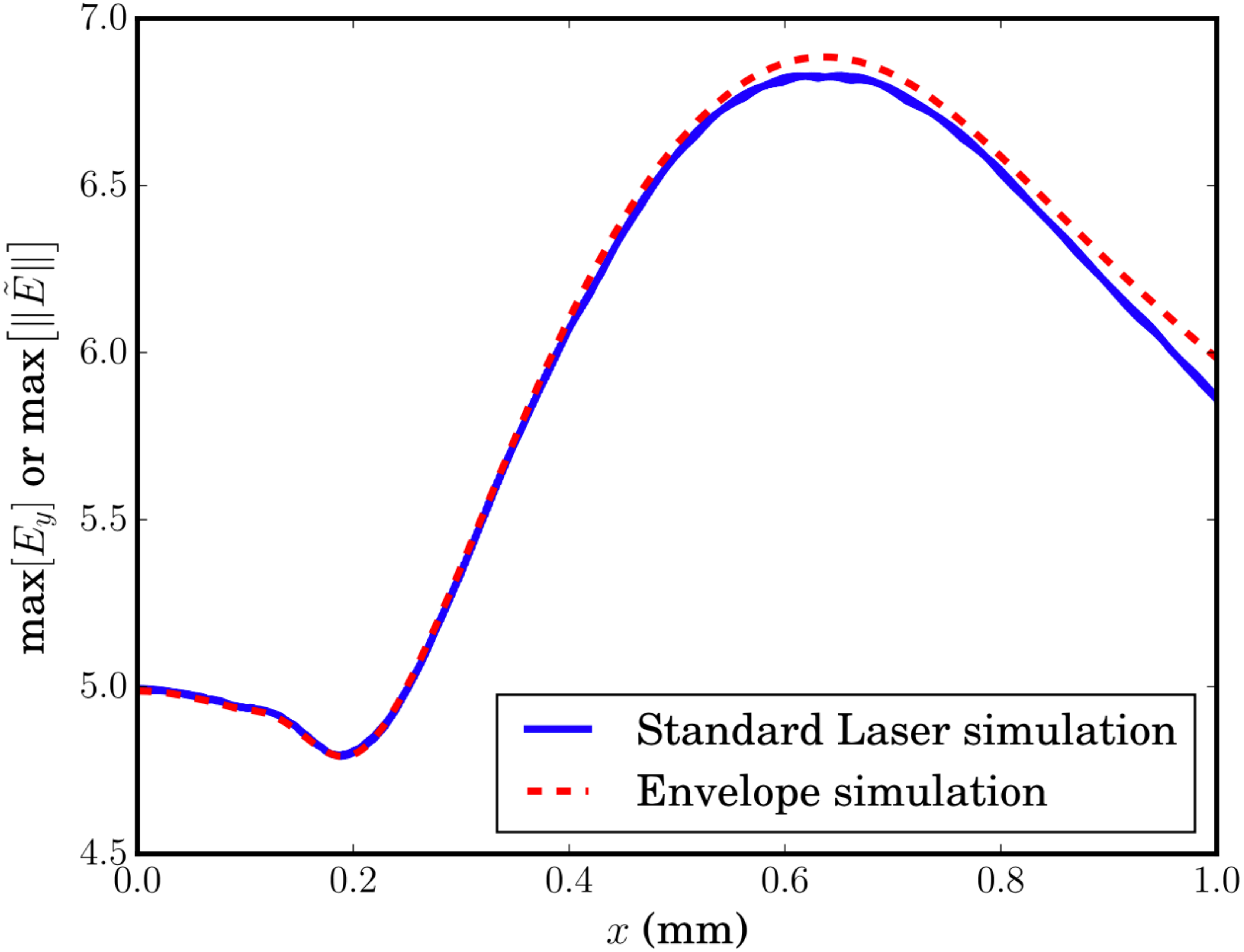
$a_0 = 0.01$, $n_0 = 3 \cdot 10^{18}$ cm^{-3},



Validation test: Relativistic Self-Focusing

$a_0 = 5$, $n_0 = 3 \cdot 10^{18}$ cm^{-3},
$w_0 = 12$ μm, $L_{FWHM} = 28$ fs

8 ppc, $\Delta y = \Delta z = 3\ c/\omega_0$



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Envelope simulation

$\Delta x = 0.75\ c/\omega_0$

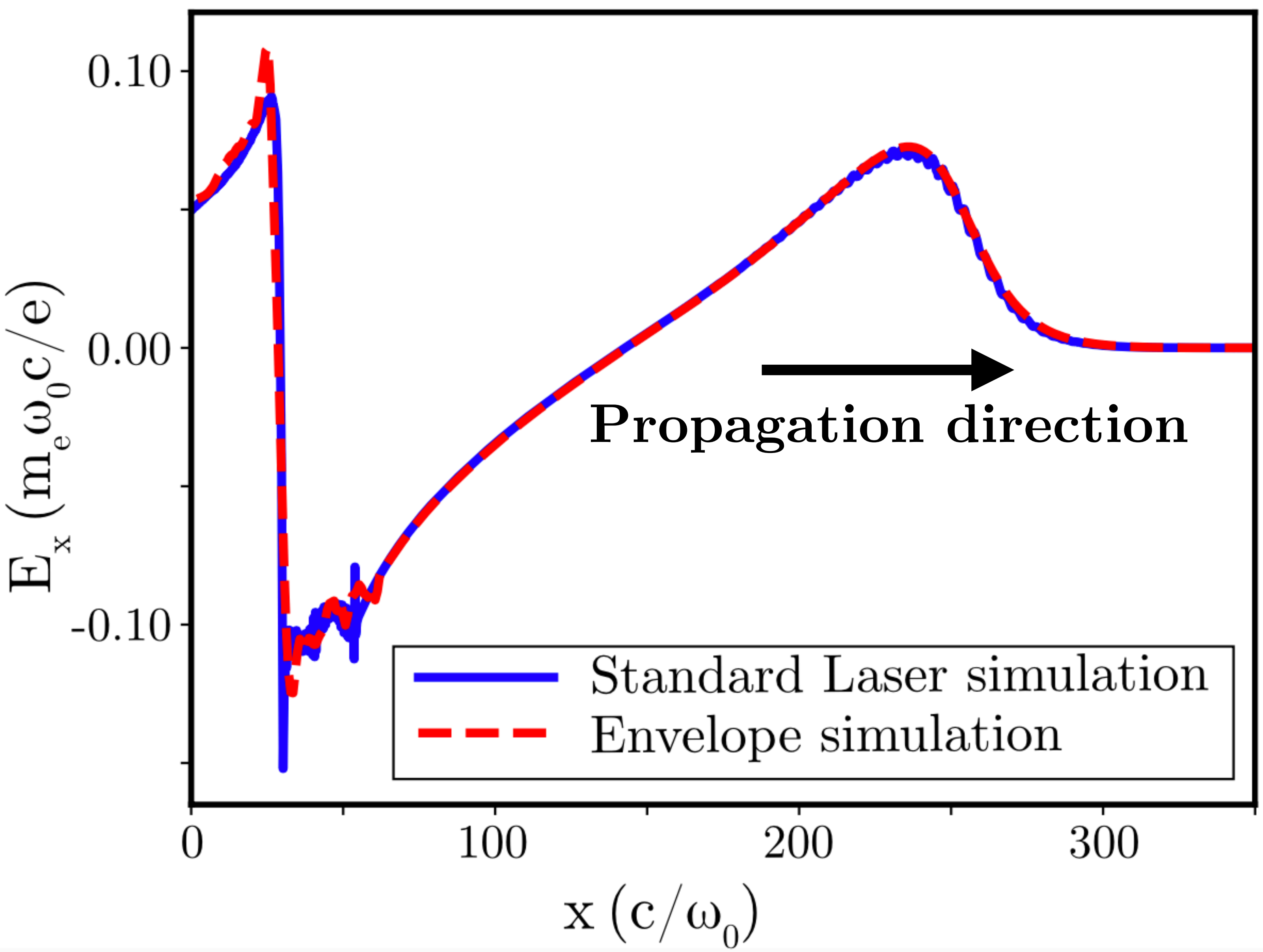
$\Delta t = 0.675\ c/\omega_0$

$$\frac{T_{\text{Standard Laser}}}{T_{\text{Envelope}}} = 20!$$

Validation test: Nonlinear LWFA, beam loading

$a_0 = 5$, $n_0 = 3 \cdot 10^{18}$ cm^{-3}, $w_0 = 12$ μm, $L_{FWHM} = 28$ fs

8 ppc, $\Delta y = \Delta z = 3\ c/\omega_0$



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Envelope simulation

$\Delta x = 0.75\ c/\omega_0$

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$$\frac{T_{\text{Standard Laser}}}{T_{\text{Envelope}}} = 20!$$

Electromagnetic field initialization: Relativistic electron