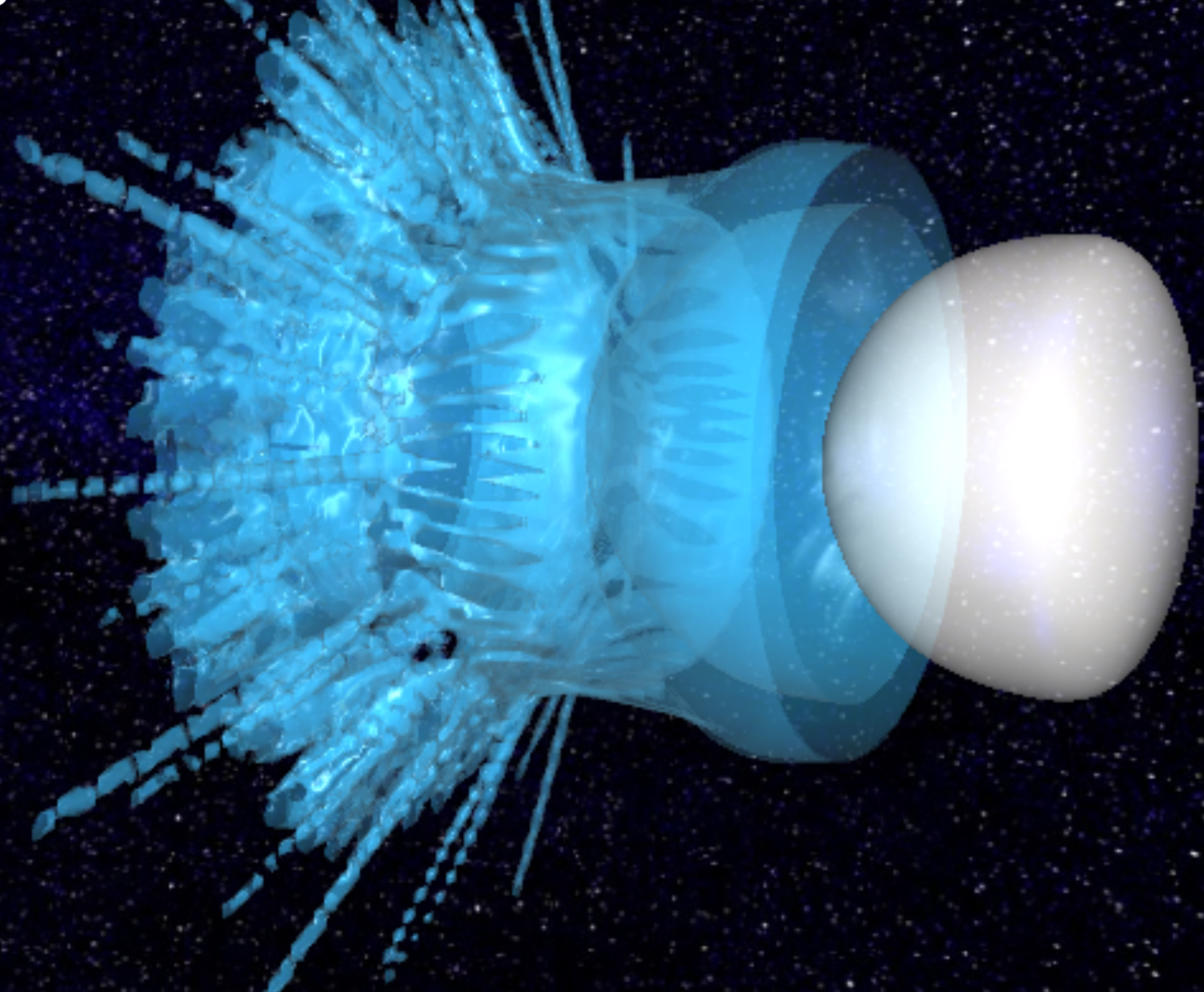
Efficient 3D envelope modeling for two-stage laser wakefield acceleration experiments



Francesco Massimo

EAC 2019

Outline

- Context
- Modeling Laser Wakefield Acceleration with a laser envelope
- First stage LWFA simulations
- Second stage LWFA simulations
- Conclusions

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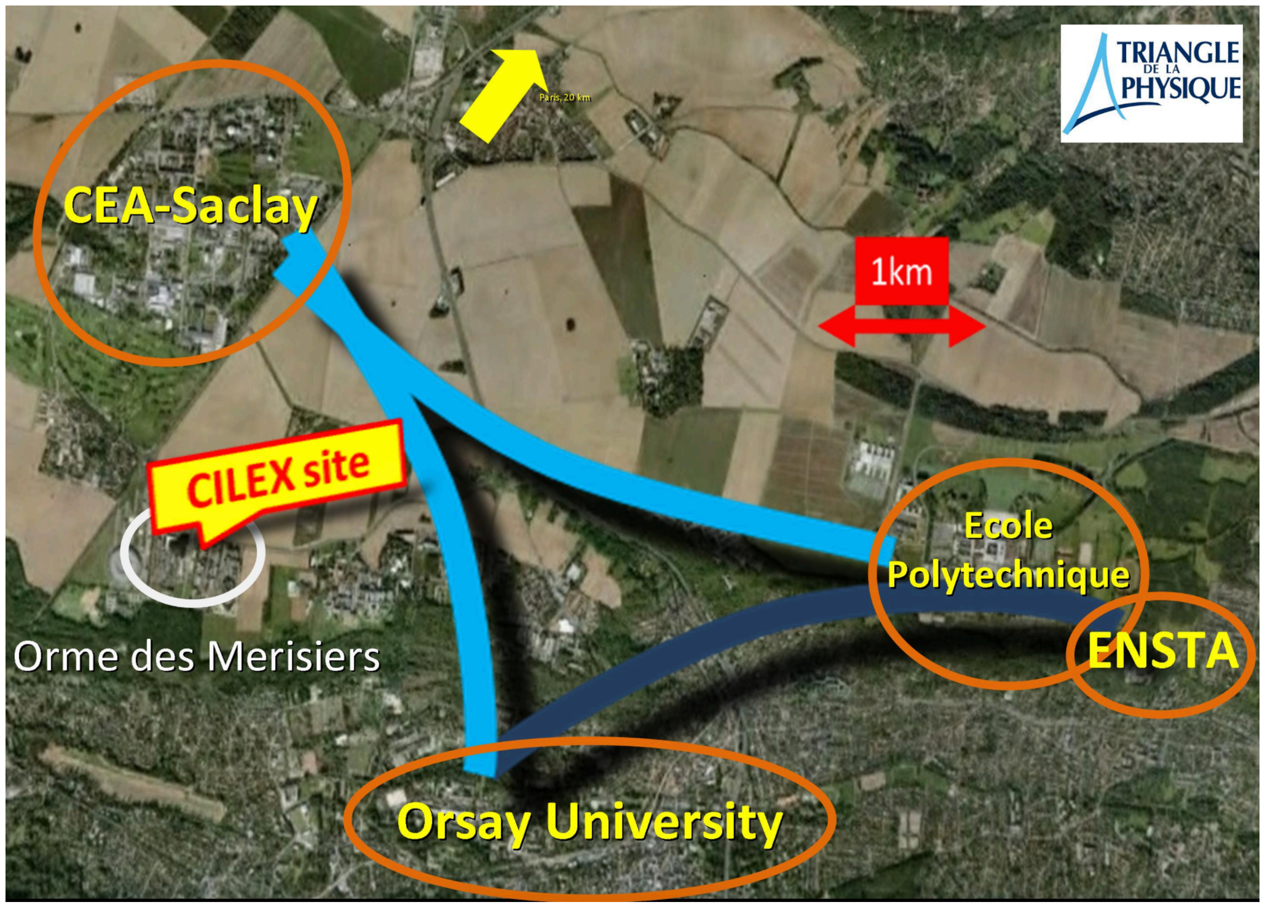
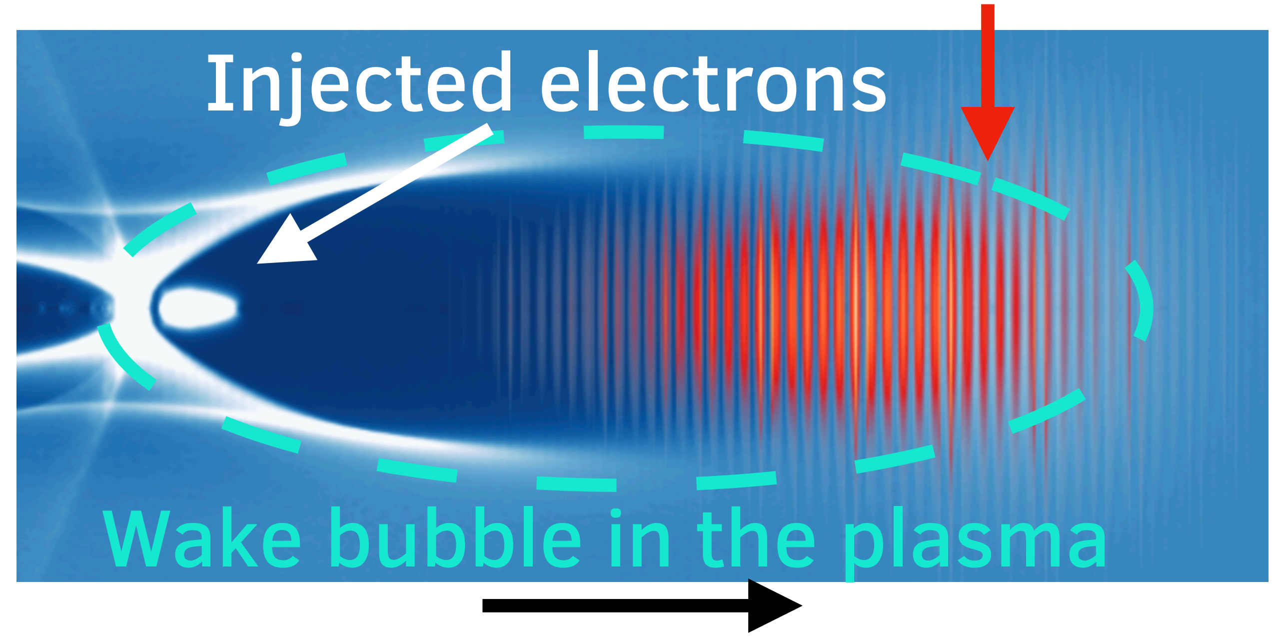
Centre Interdisciplinaire de la Lumière Extrême (CILEX)

CileX Apollon



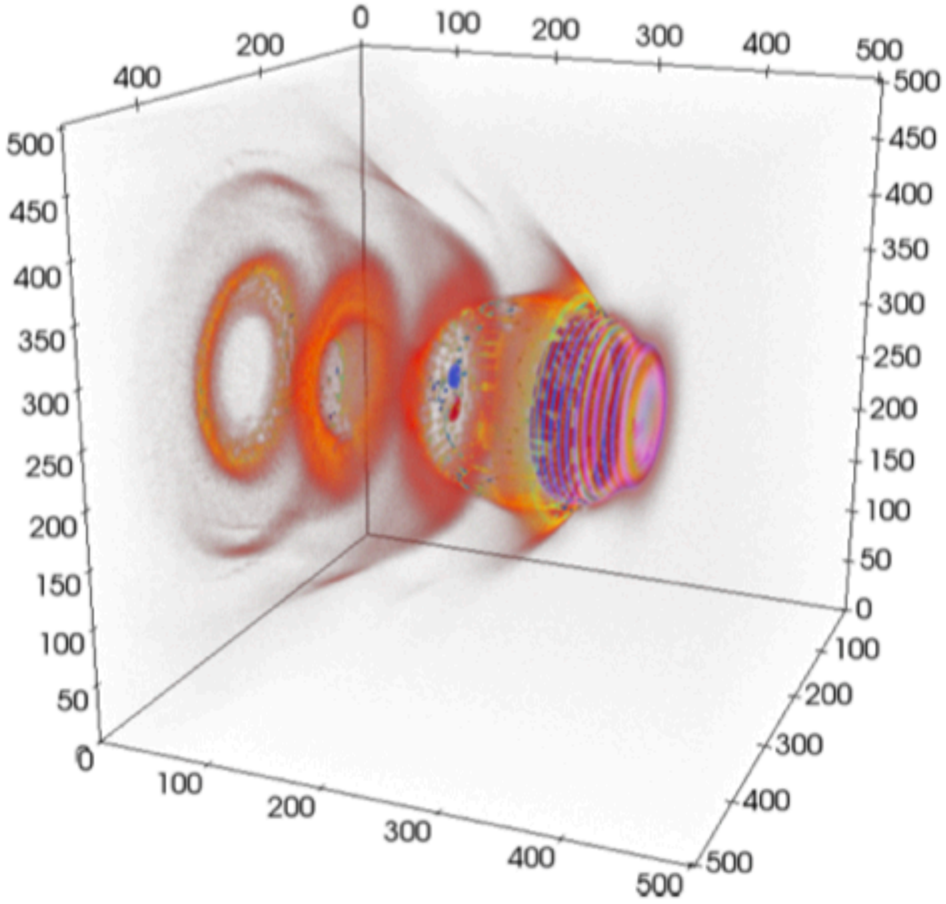
Laser Wakefield Acceleration (LWFA)

Laser Pulse



Propagation direction

PIC simulations need many resources



3D standard LWFA simulations:
1 mm plasma ~ 320 kcpu-hours ~ 10.2 k€
(36 years on 1 cpu)

→ Parallelization is mandatory
but still 320 kcpu-hours ~ 13 days on 1000 cpus …

Any trick to speed up the calculation
is most welcome

Implemented in Smilei) :

High Performance Computing (HPC) techniques
- Parallelization
- Smart Load Balancing
- Vectorisation

Techniques using physical approximations
- Azimuthal Fourier decomposition
- Envelope modeling

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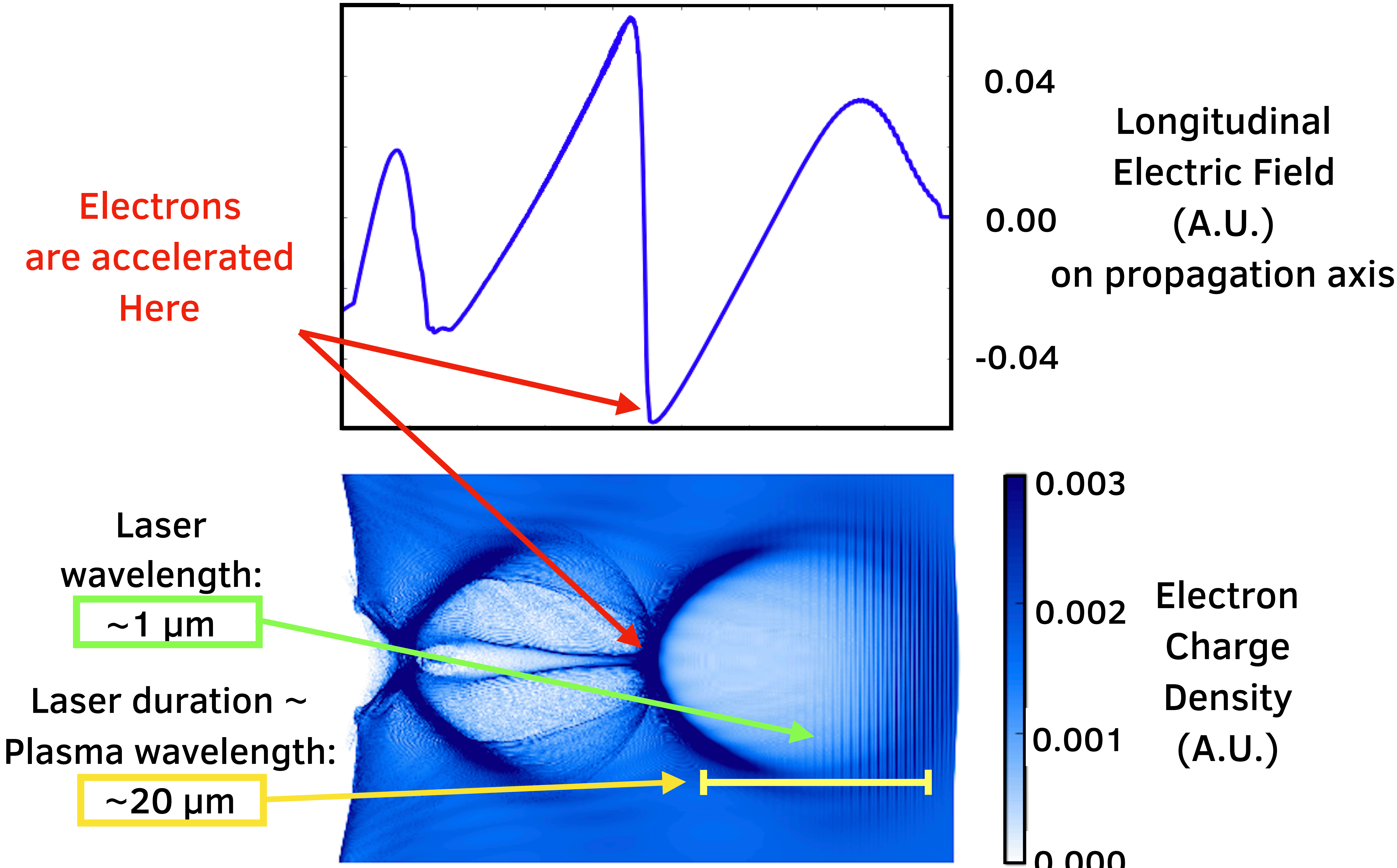
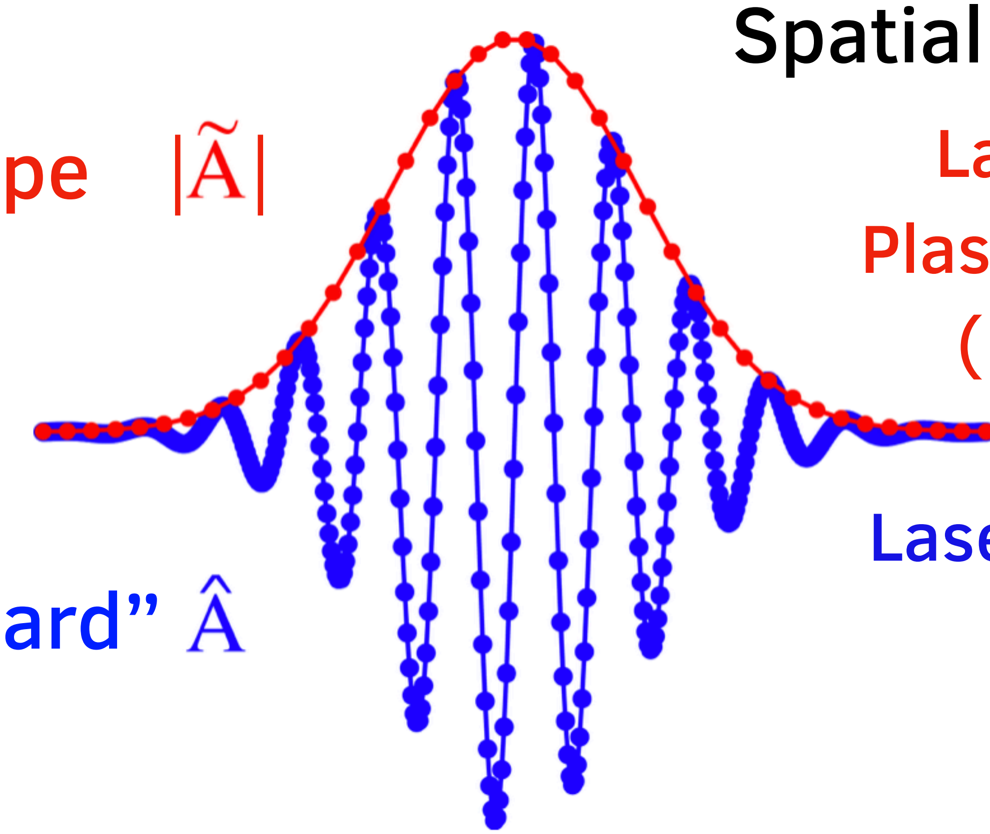
Physical scales disparity in LWFA



Laser Envelopes need less sampling points

Laser Envelope $|\tilde{A}|$



Laser "Standard" $\hat{A}$

Spatial variation scales:

Laser length ~
Plasma wavelength
(10-100 μm)

Laser wavelength
(~1 μm)

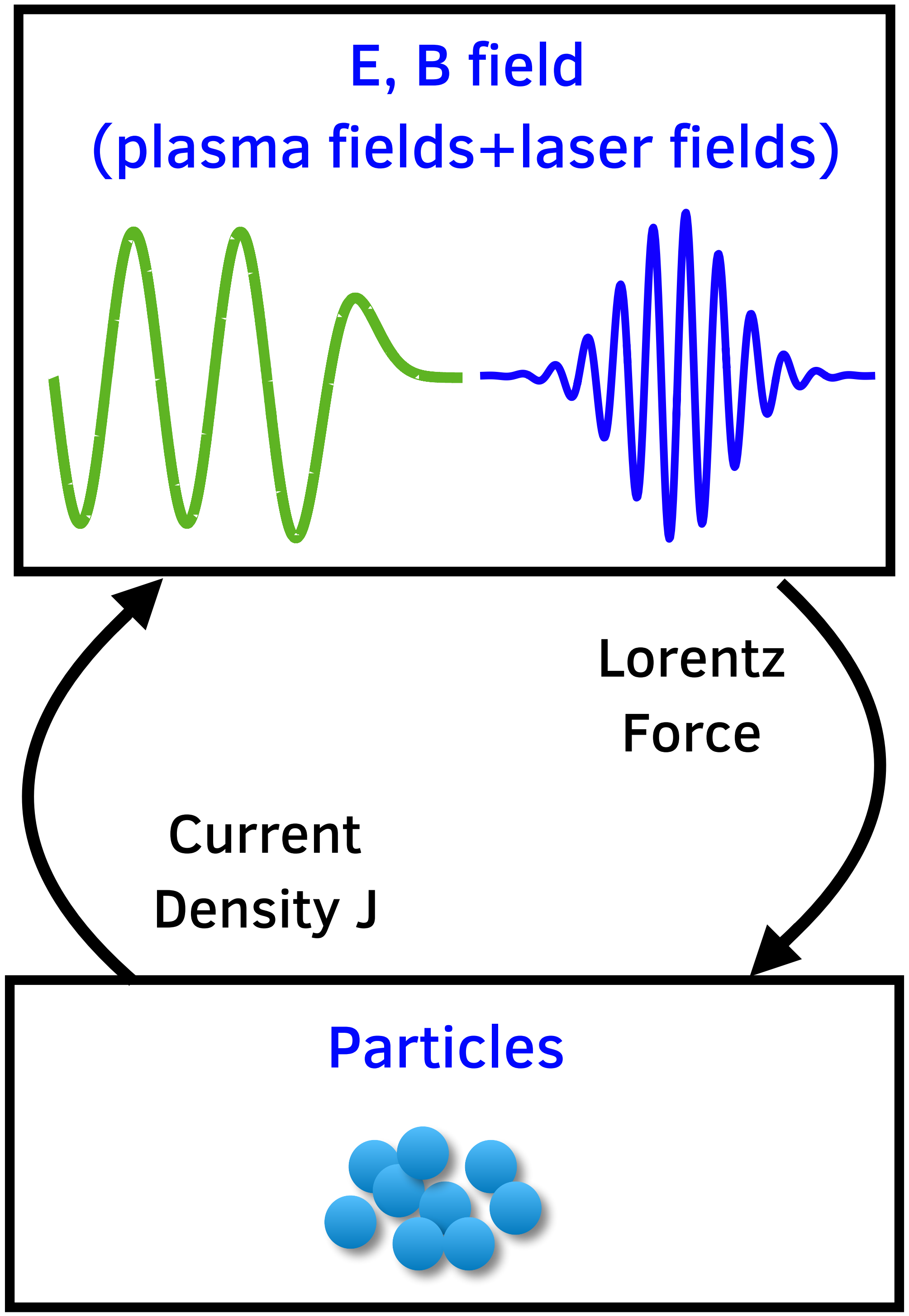
D. Terzani and P. Londrillo,
Comput. Phys. Comm. (2019)

$$\frac{\text{Points sampling Laser "Standard"}}{\text{Points sampling Laser Envelope}} = 10$$

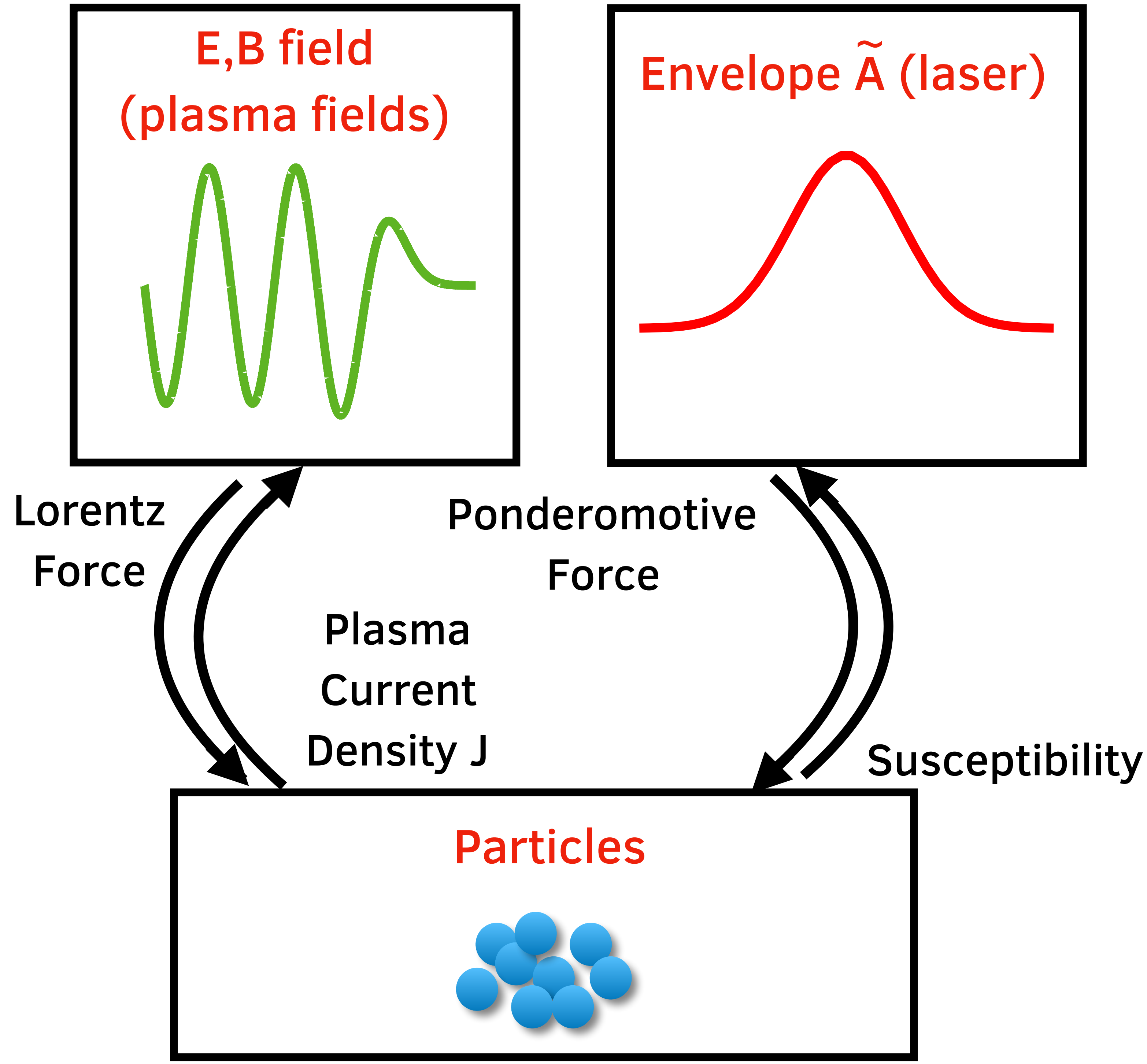
→ Larger Δx and Δt can be used!

Envelope model: separate the laser field

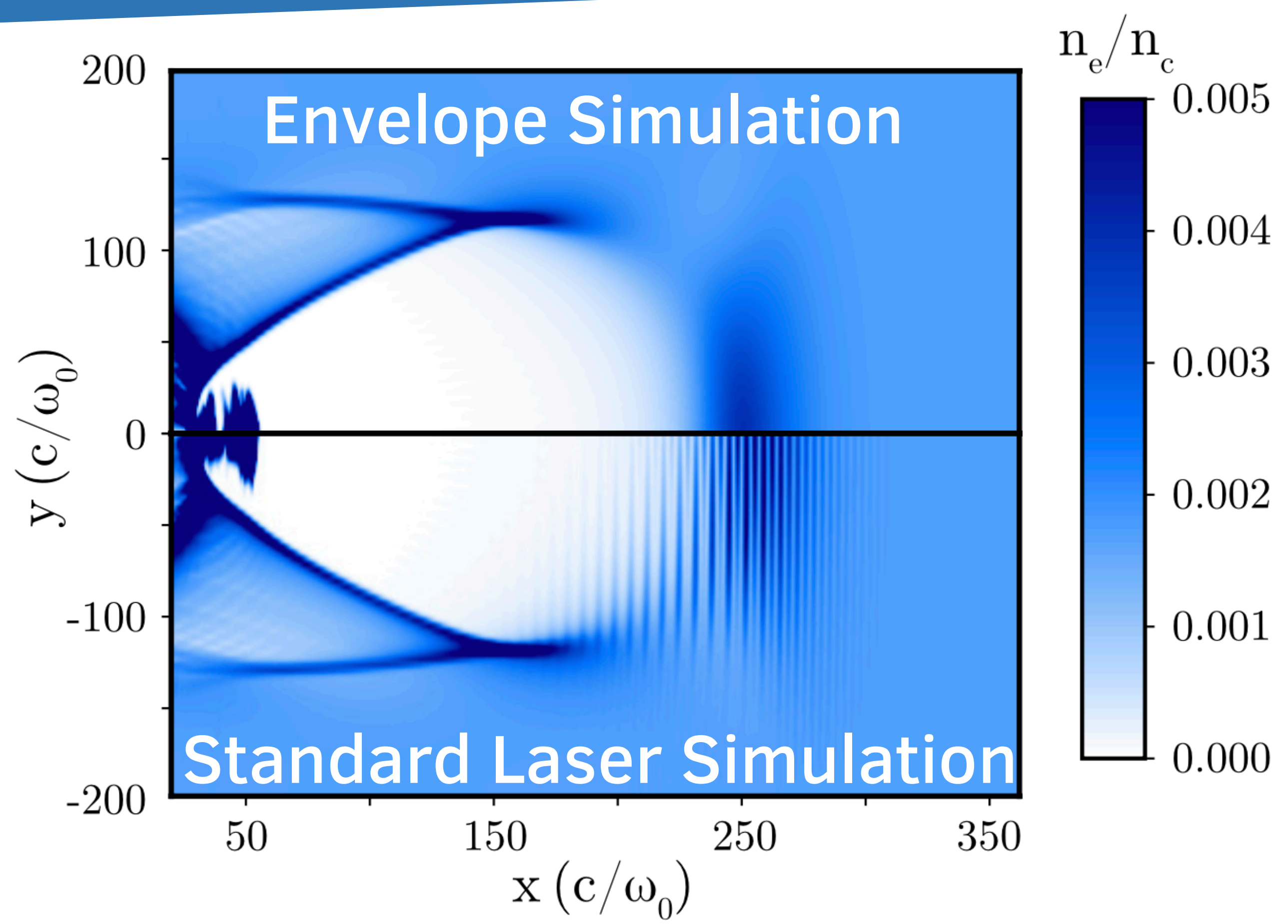
Standard PIC



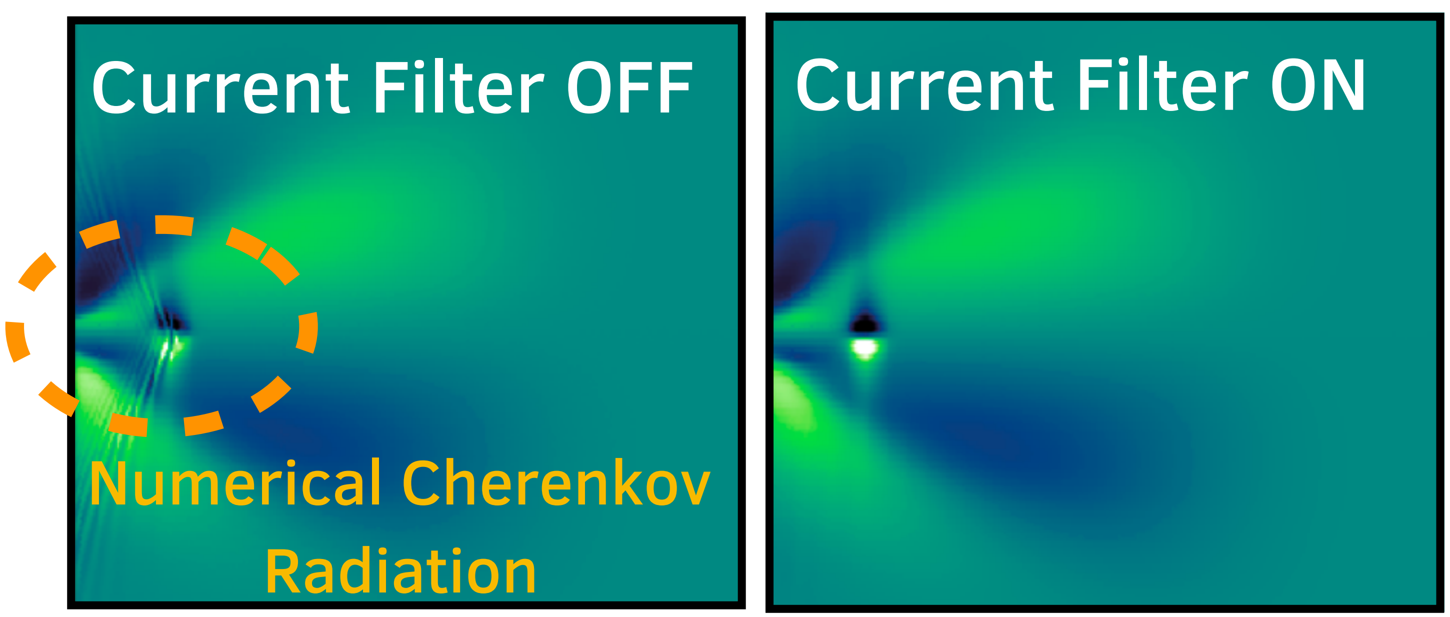
Envelope (/Ponderomotive) PIC



Envelope modeling has multiple advantages



Transverse E field, Apollon Simulations



J.-L.Vay, JCP 230 (2011)

$T_{\text{Standard PIC}}$

(1 mm of propagation):

~ 320 kcpu-hours

~ 10.2 k€

$$\frac{T_{\text{Standard PIC}}}{T_{\text{Envelope PIC}}} > 20$$

Advantages of the envelope over standard Yee solver:

- Quicker (speedup>20)
- Safe Filtering
- More accurate laser speed

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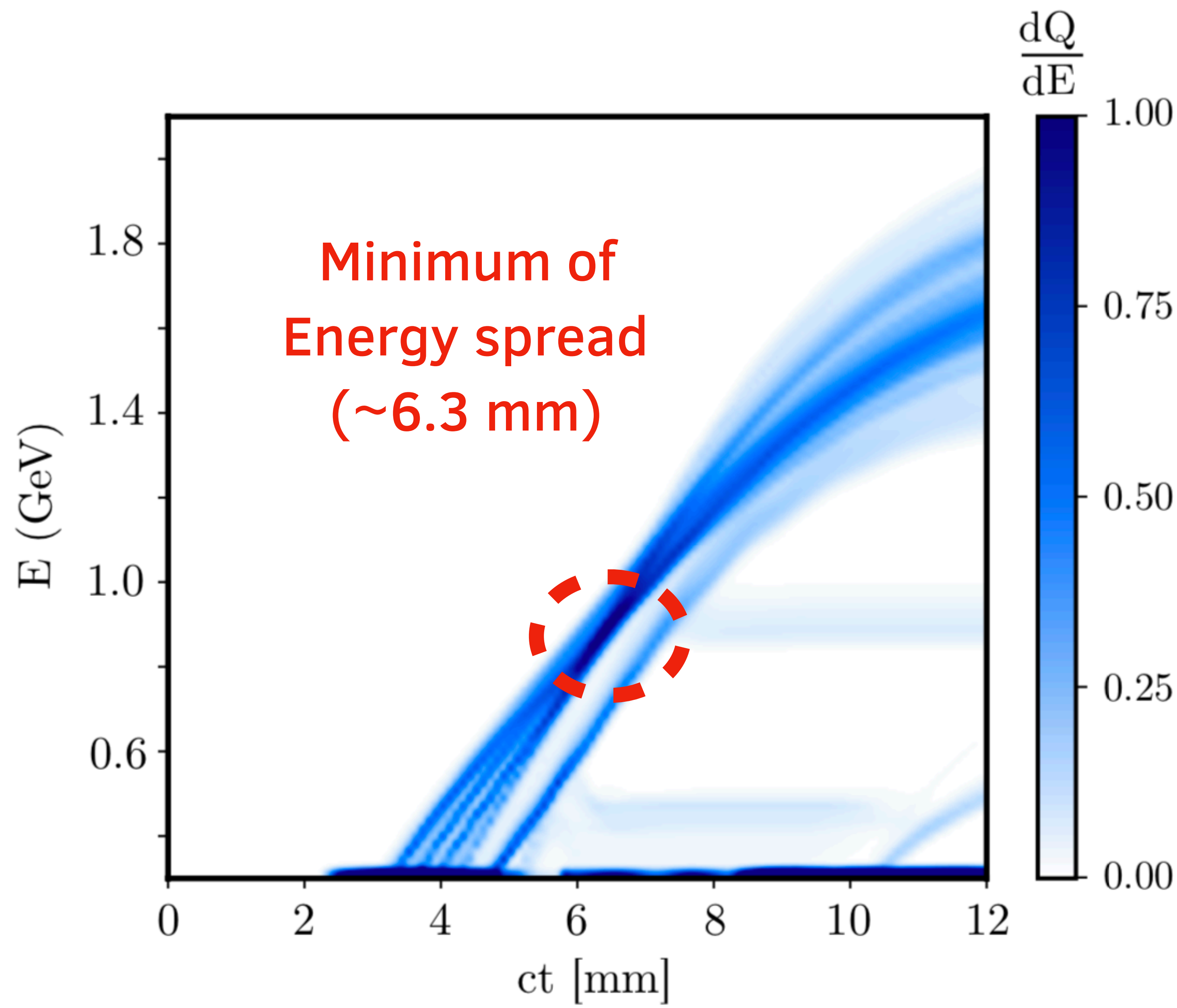
CILEX 1st stage: quick envelope simulations

Apollon 1st Stage
Example of simulation with the envelope model

Simulation	1
E_{Laser} [J]	10
P/P_{cr}	18.3
Laser w_0 [μm]	40
$n_{plasma}[10^{18}cm^{-3}]$	1.1
$L_{FWHM, Laser}$ [fs]	20
Q_{beam} [pC]	263
E_{peak}[GeV]	870
ΔE/E (%)	8.3
Distance [mm]	6.3

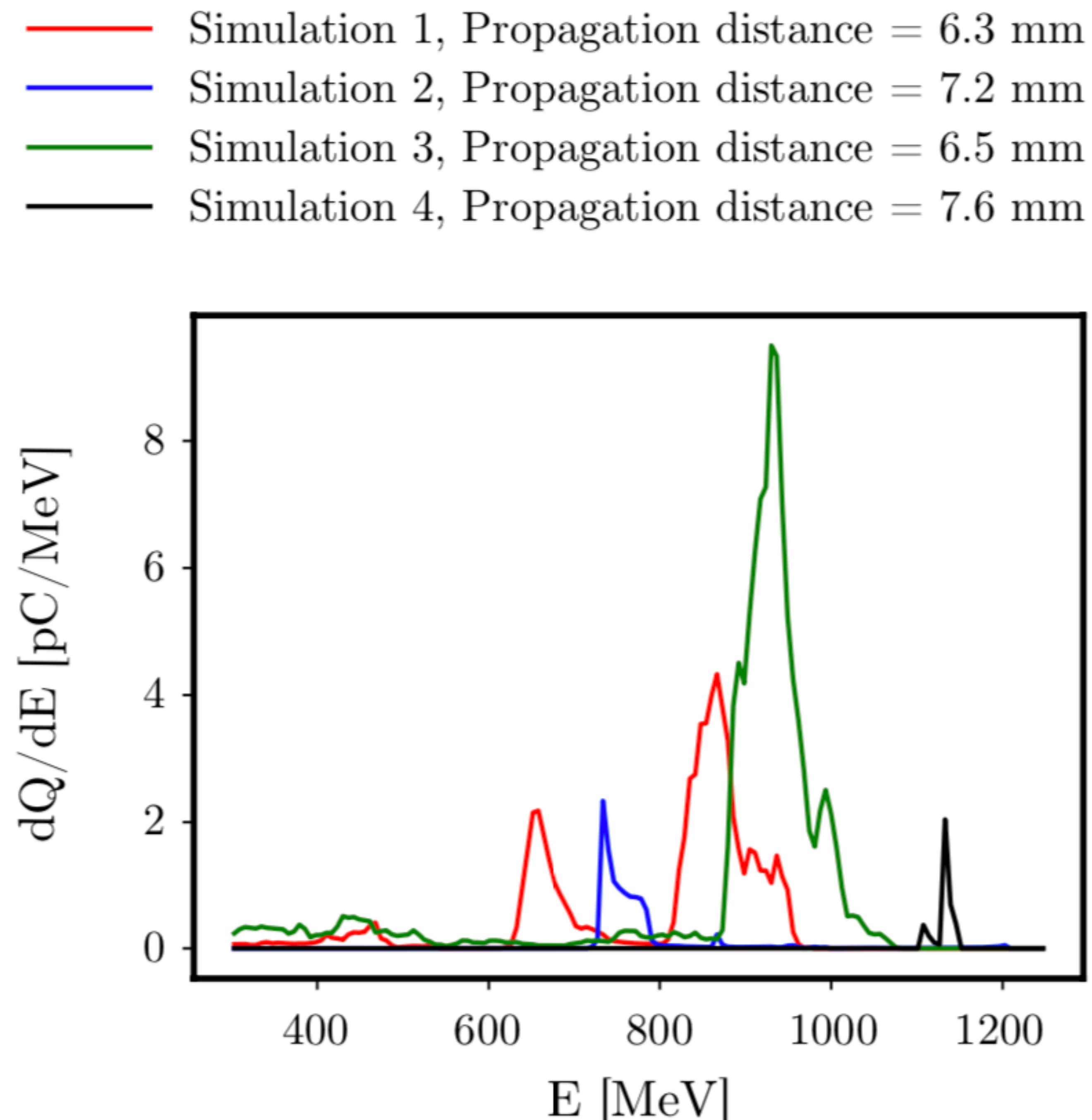


CILEX 1st stage: quick envelope simulations

Apollon 1st Stage

Possible working points studied with the envelope model

Simulation	1	2	3	4
E_{Laser} [J]	10	10	15	15
P/P_{cr}	18.3	12.0	22.0	13.3
Laser w_0 [µm]	40			
n_{plasma}[10^{18}cm^{-3}]	1.1	0.9	1.1	0.8
$L_{FWHM,\ Laser}$ [fs]	20	25	25	30
Q_{beam} [pC]	263	48	543	24
E_{peak}[GeV]	870	740	930	1130
ΔE/E (%)	8.3	3.2	6.4	2.0
Distance [mm]	6.3	7.2	6.5	7.6



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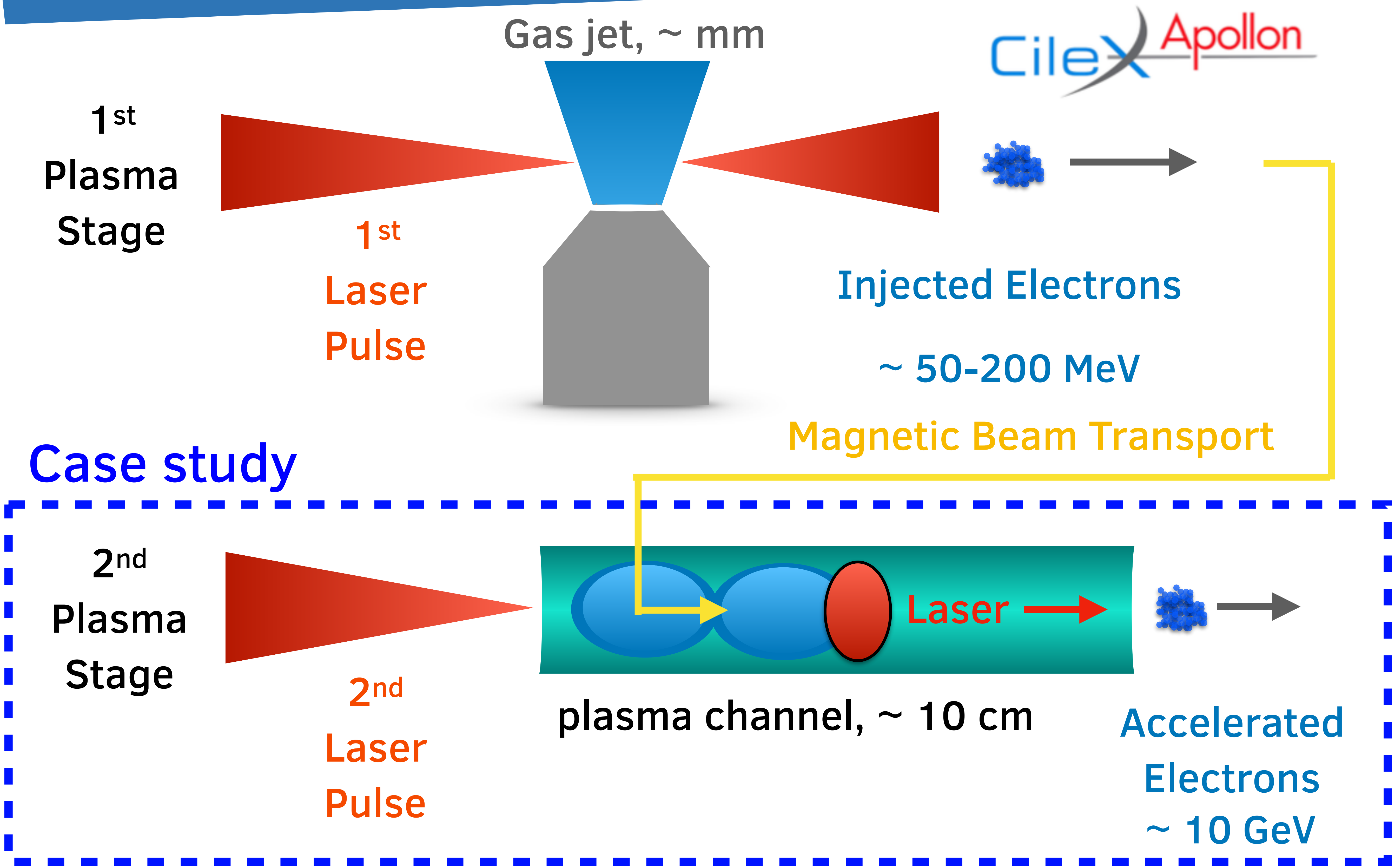
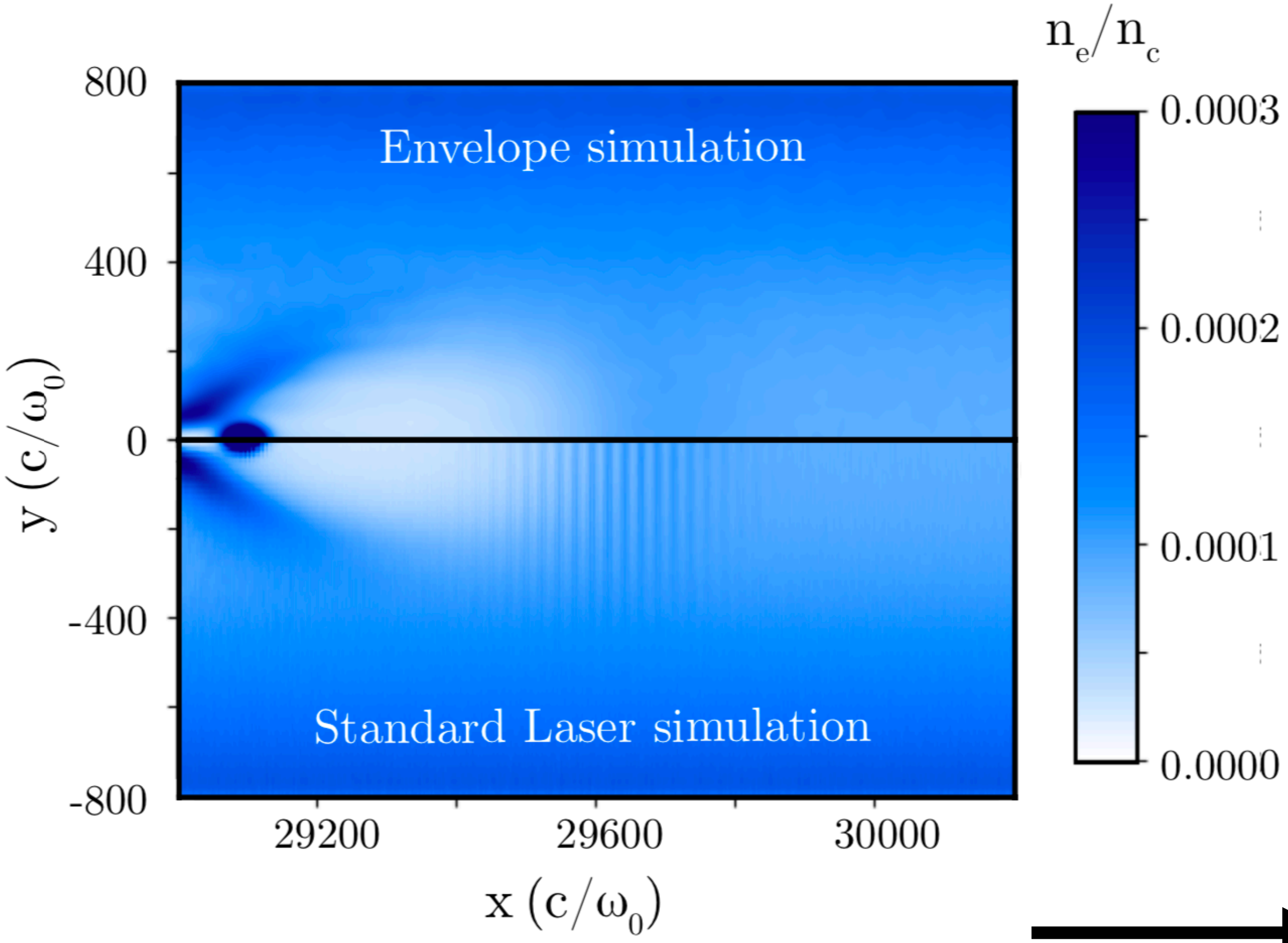
Case Study: Multistage LWFA experiments



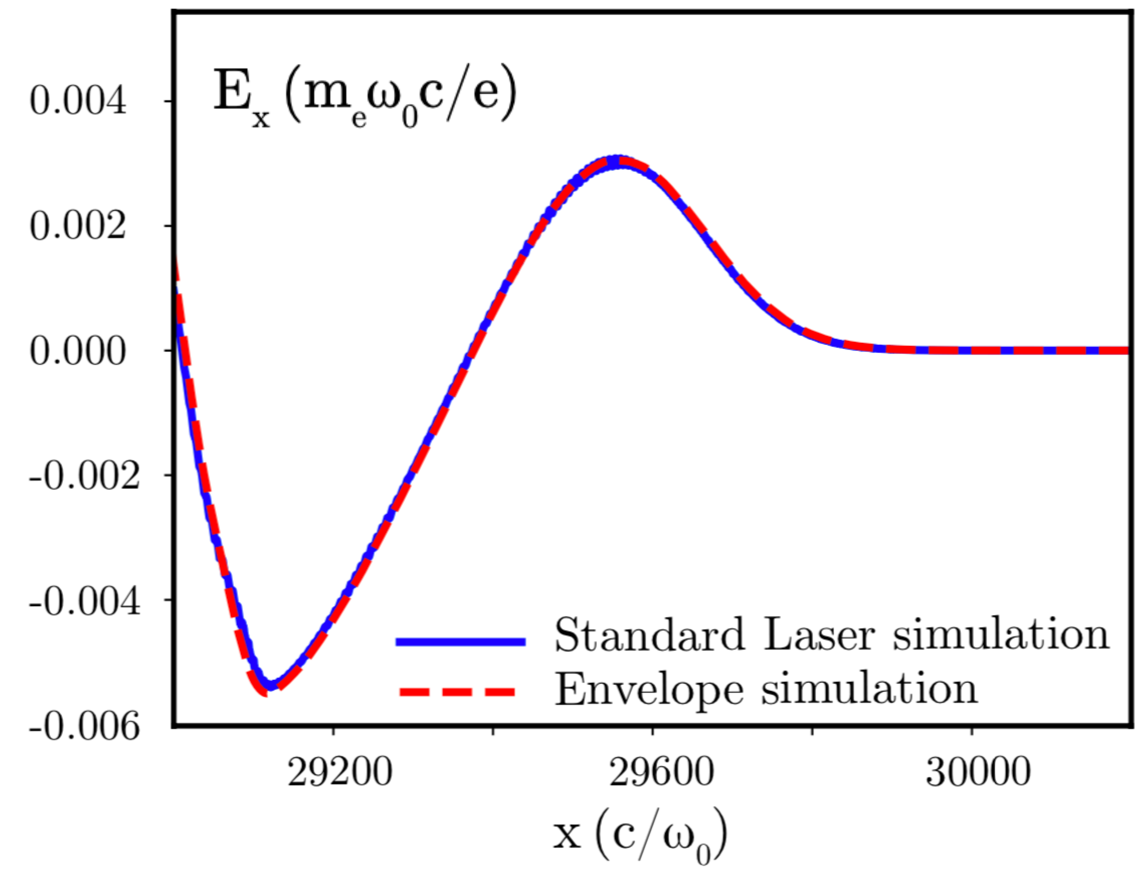
Envelope Benchmark: External injection in LWFA

Comparison @15 mm of propagation

Electron density



Longitudinal electric field



Propagation Direction

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

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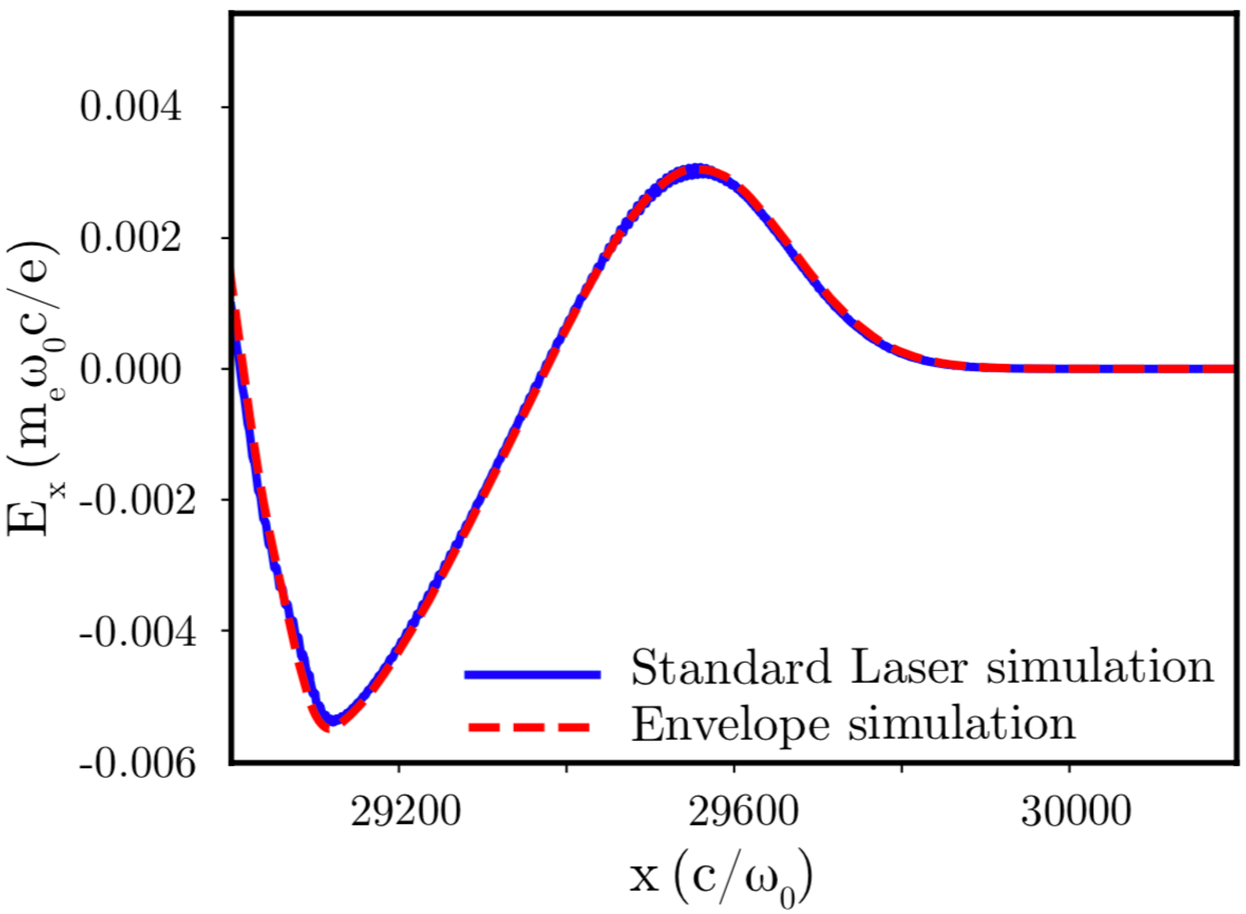
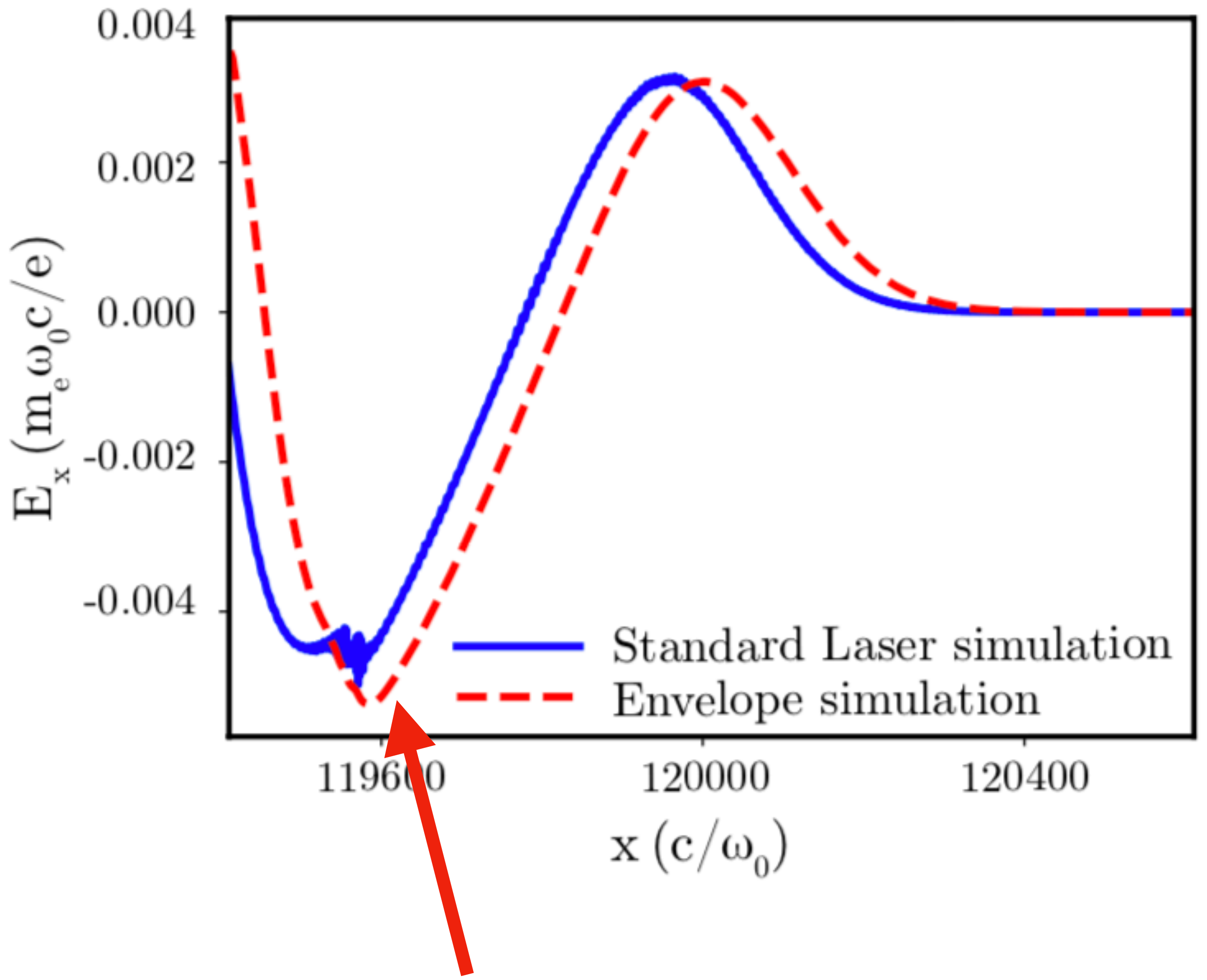
Envelope Benchmark: External injection in LWFA

@3.7 mm



@15 mm



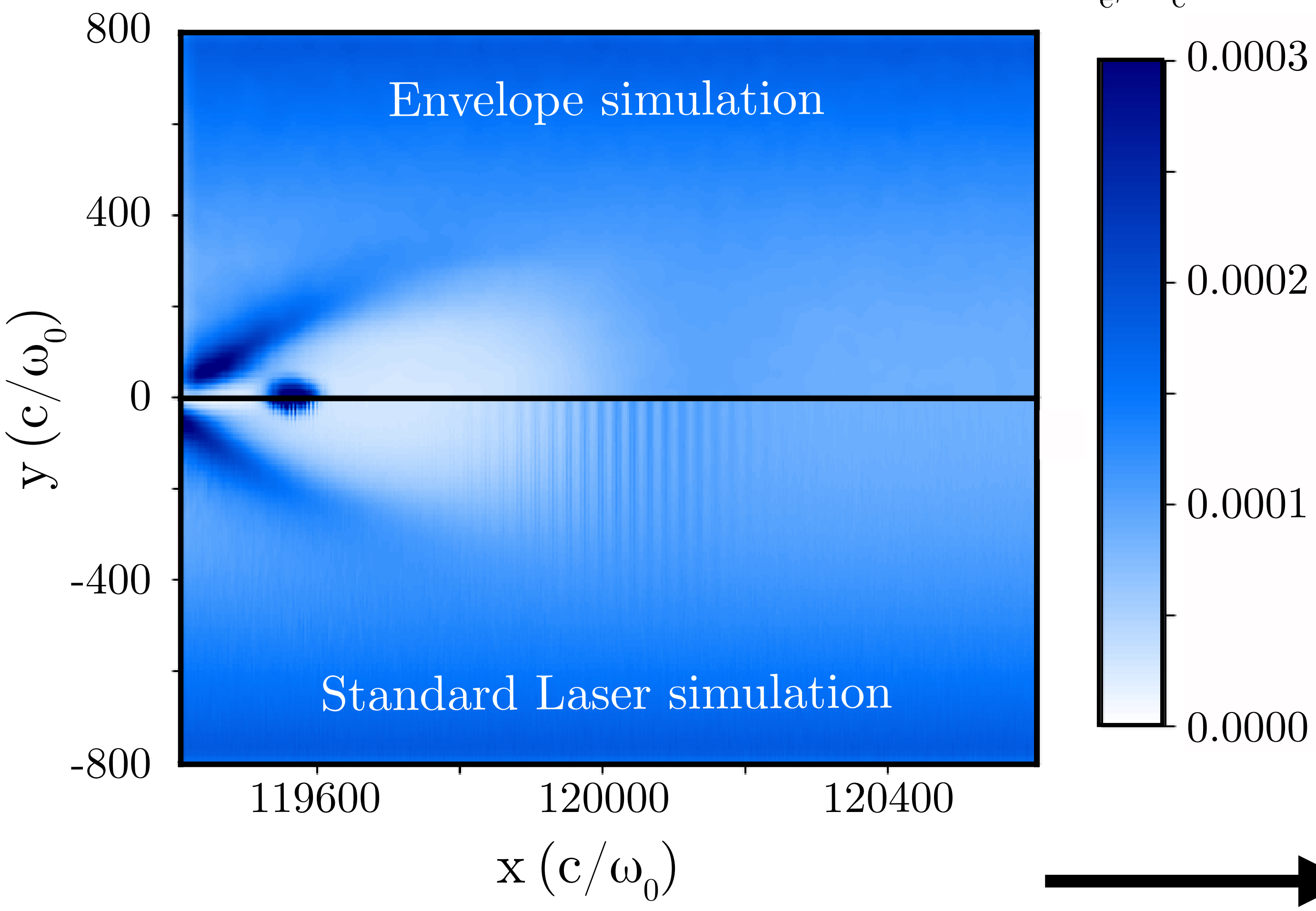
Further improvement
of numerical dispersion:
Spectral solvers
(I. Zemzemi’s thesis)

Envelope PIC less dispersive
than standard PIC

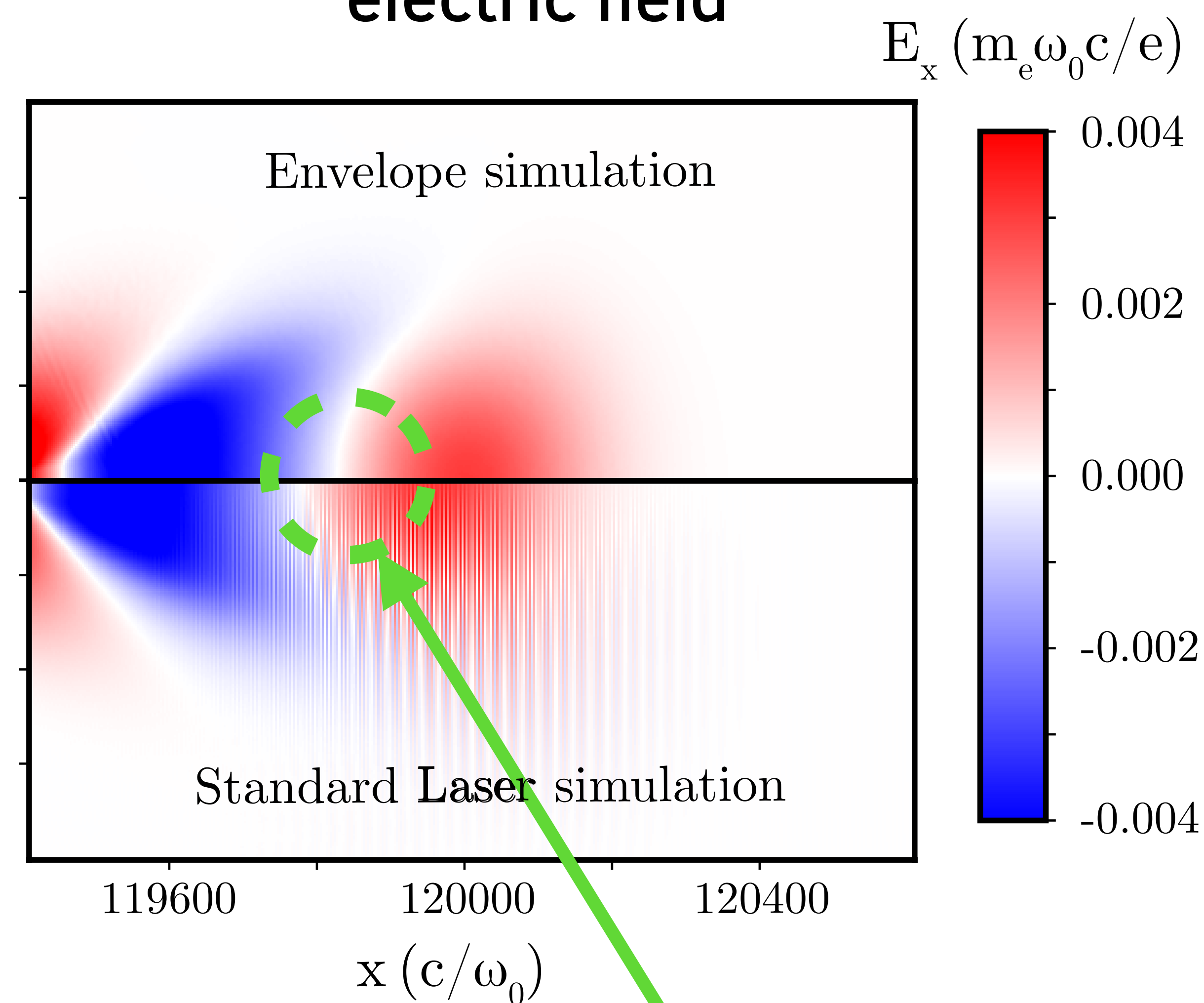
Simulation of External injection LWFA

Comparison @15 mm of propagation, Preliminary Results

Electron density



Longitudinal electric field



Propagation Direction

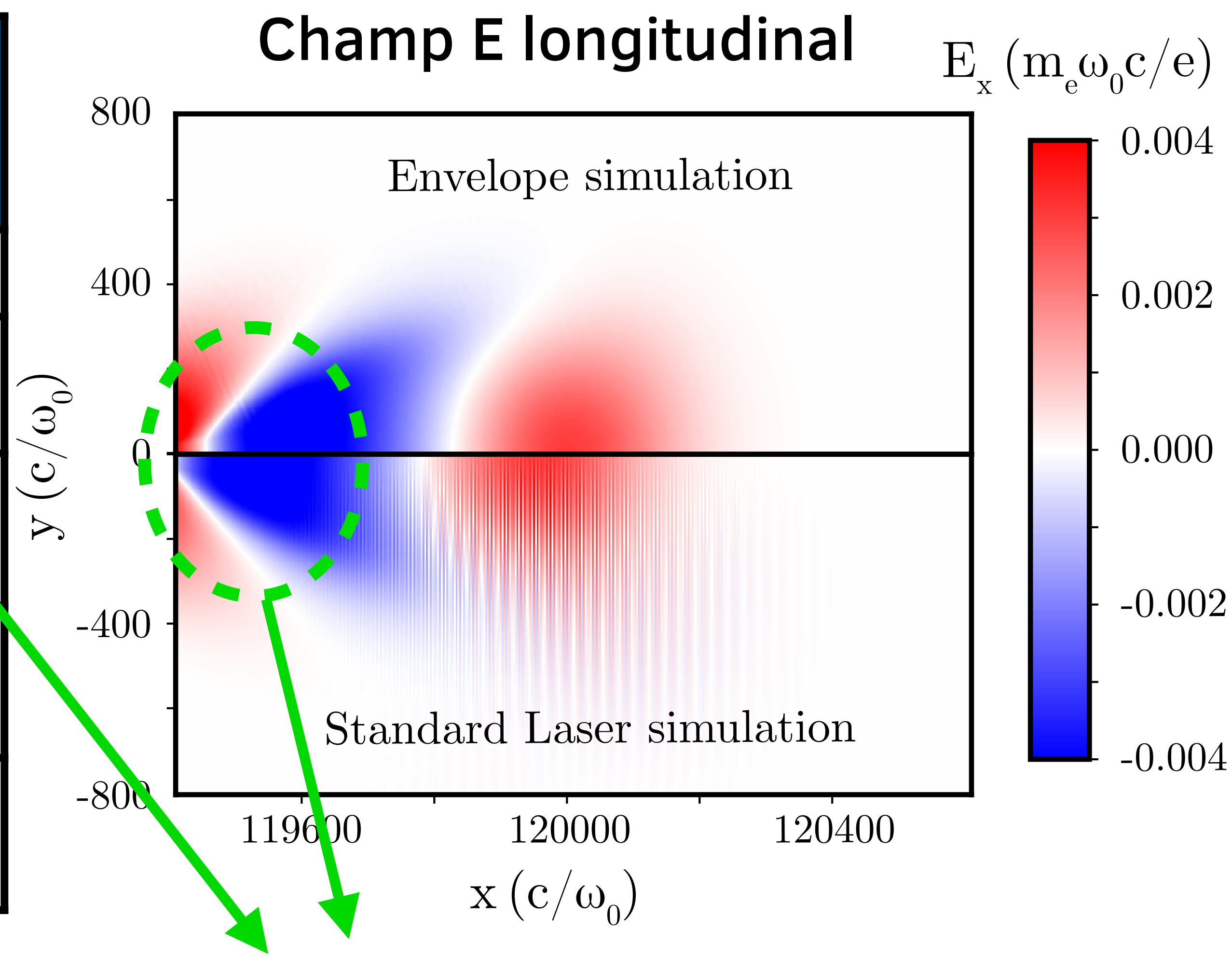
Envelope PIC less dispersive than standard PIC

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

Simulation of External injection LWFA: envelope advantages

$2^{ème}$ Stage of Apollon,
Comparison between Standard PIC and Envelope PIC

Electron Beam Parameters	Values @Injection	Standard Simulation @15mm	Envelope Simulation @15 mm
Q [pC]	30	29.98	29.94
E [MeV]	150	427	438
ΔE/E [%]	0.5	4.7	6.4
$\sigma_x, \sigma_y, \sigma_z$ [μm]	2.0, 1.3, 1.3	2.0,1.5,1.4	2.0, 1.0, 1.0
$\varepsilon_{n,y}, \varepsilon_{n,z}$ [mm-mrad]	1.0, 1.0	2.0, 2.1	1.0, 1.0



Numerical Cherenkov reduced by filtering:
- Emittance conserved
- Beam stays focused

More accurate laser speed: More accurate phase and Longitudinal phase space evolution

Conclusions and perspectives

- Time explicit (non quasi-static) 3D envelope model for the laser now available in Smilei)

- Benchmarked on long second stage simulation

- Used to study possible working points for Apollon LWFA experiments

Future developments:

- Envelope model + cylindrical geometry
- Envelope model + ionization

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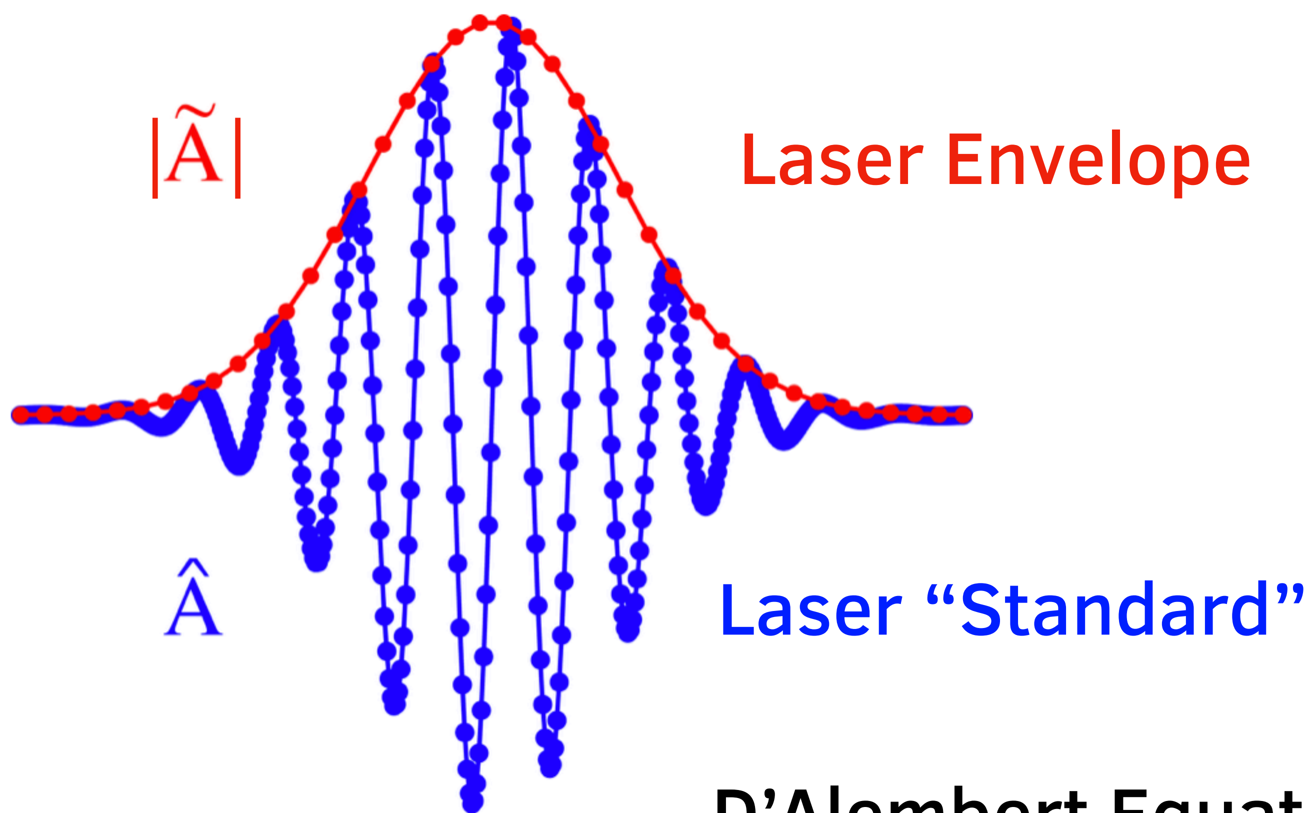
P2IO LabEx (ANR-10-LABX-0038) in the Framework "Investissements d'Avenir" (ANR-11-IDEX-0003-01) managed by Agence Nationale de la Recherche (ANR, France) provided financial support for F. Massimo

Additional slides

The Laser Envelope evolution: wave equation

D. Terzani and P. Londrillo,
Comput. Phys. Comm. (2019)



Hypothesis:

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

Laser Complex Envelope

+

D'Alembert Equation:

$$\nabla^2 \hat{A} - \partial_t^2 \hat{A} = -\hat{J}$$

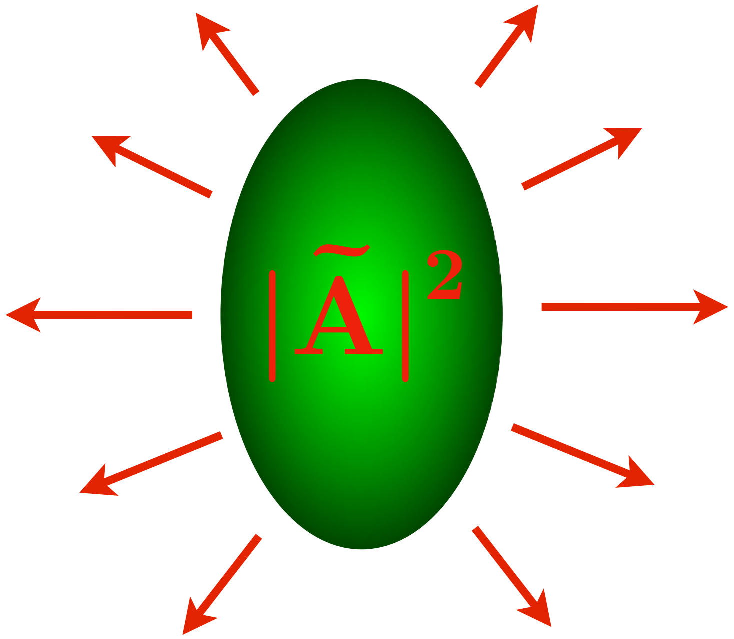
=

Envelope Equation:

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

Plasma Susceptibility

Ponderomotive Equations of motion



Ponderomotive force acts as a radiation pressure on charged particles : it expels the electrons from high-intensity zones

$F_{ponderomotive}$

Motion Equations for the macroparticles (here electrons):

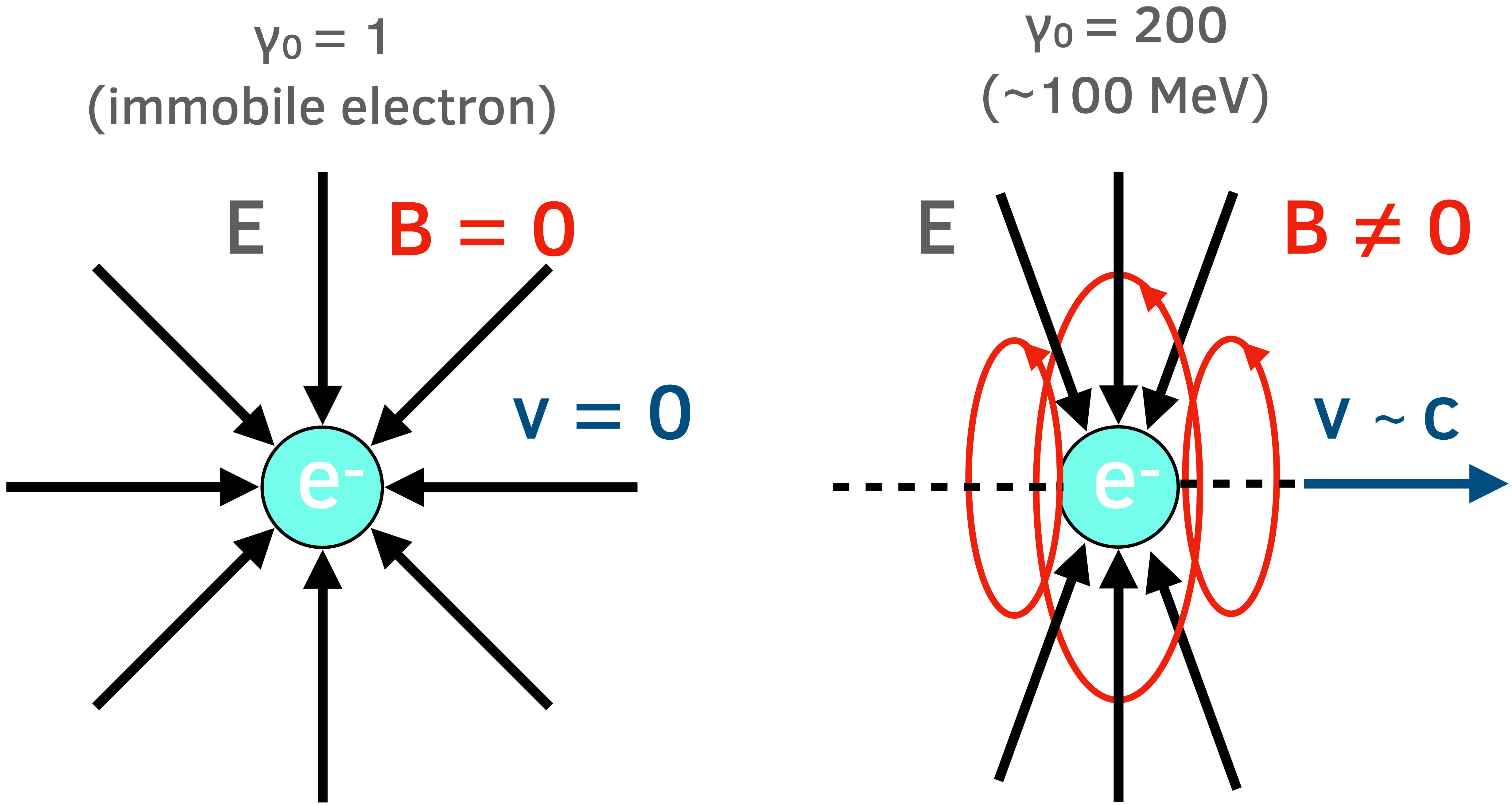
$$\frac{d\bar{\mathbf{x}}_p}{dt} = \frac{\bar{\mathbf{u}}_\mathbf{p}}{\bar{\gamma}_p}$$

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

Lorentz Force (plasma fields) + Ponderomotive Force (laser envelope)

B. Quesnel and P. Mora, Physics Review E 58, 3719 (1998)

Electromagnetic field initialization: Relativistic electron



Initialisation of Electromagnetic Fields

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"

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)